Precision big bang nucleosynthesis with the new code *PRIMAT*

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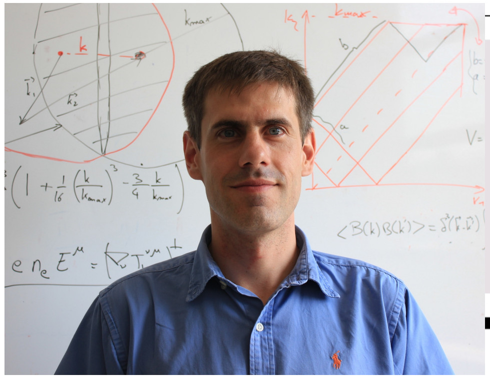
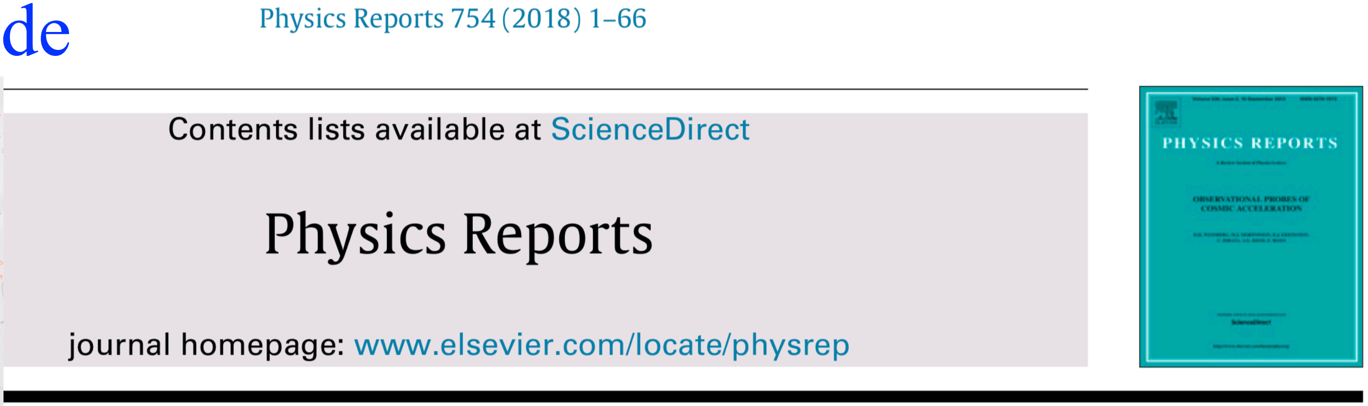
- ☐ The need for precision big bang nucleosynthesis
- ☐ The (*Mathematica* based) *PRIMAT* code
- ☐ Highly improved treatment of the n↔p weak rates
- ☐ The network from A=1 to ~20 (CNO)

PRIMAT code





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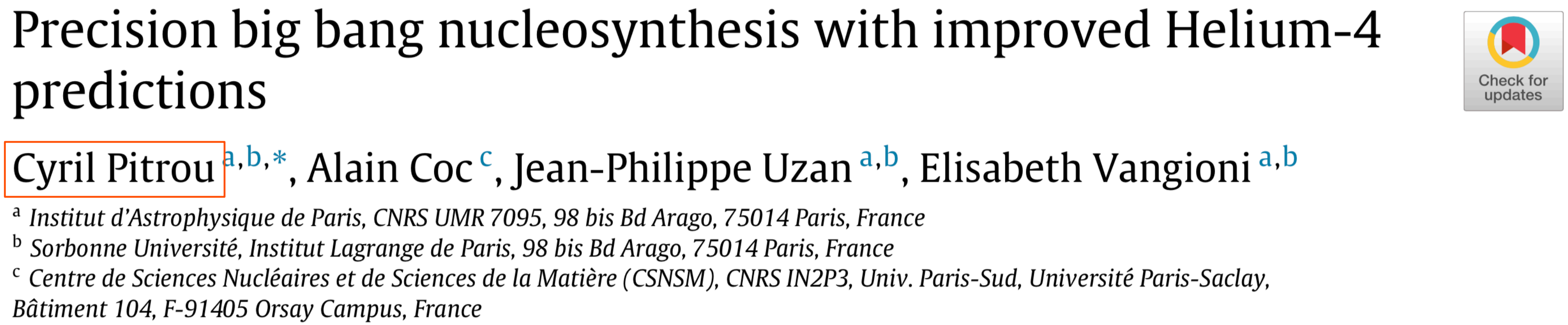

Precision big bang nucleosynthesis with improved Helium-4 predictions

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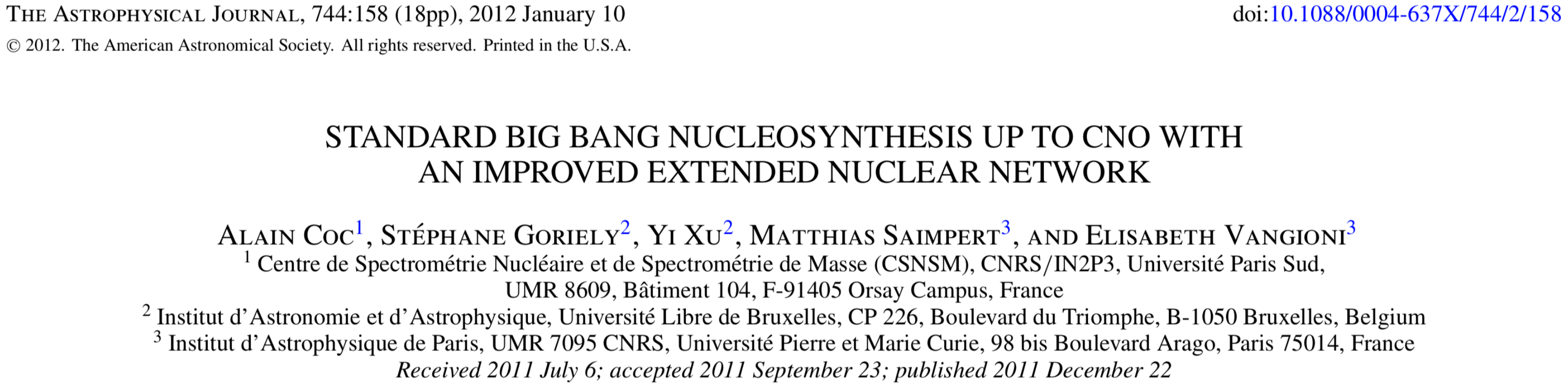
Reactions network extending to CNO



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STANDARD BIG BANG NUCLEOSYNTHESIS UP TO CNO WITH
AN IMPROVED EXTENDED NUCLEAR NETWORK

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[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium
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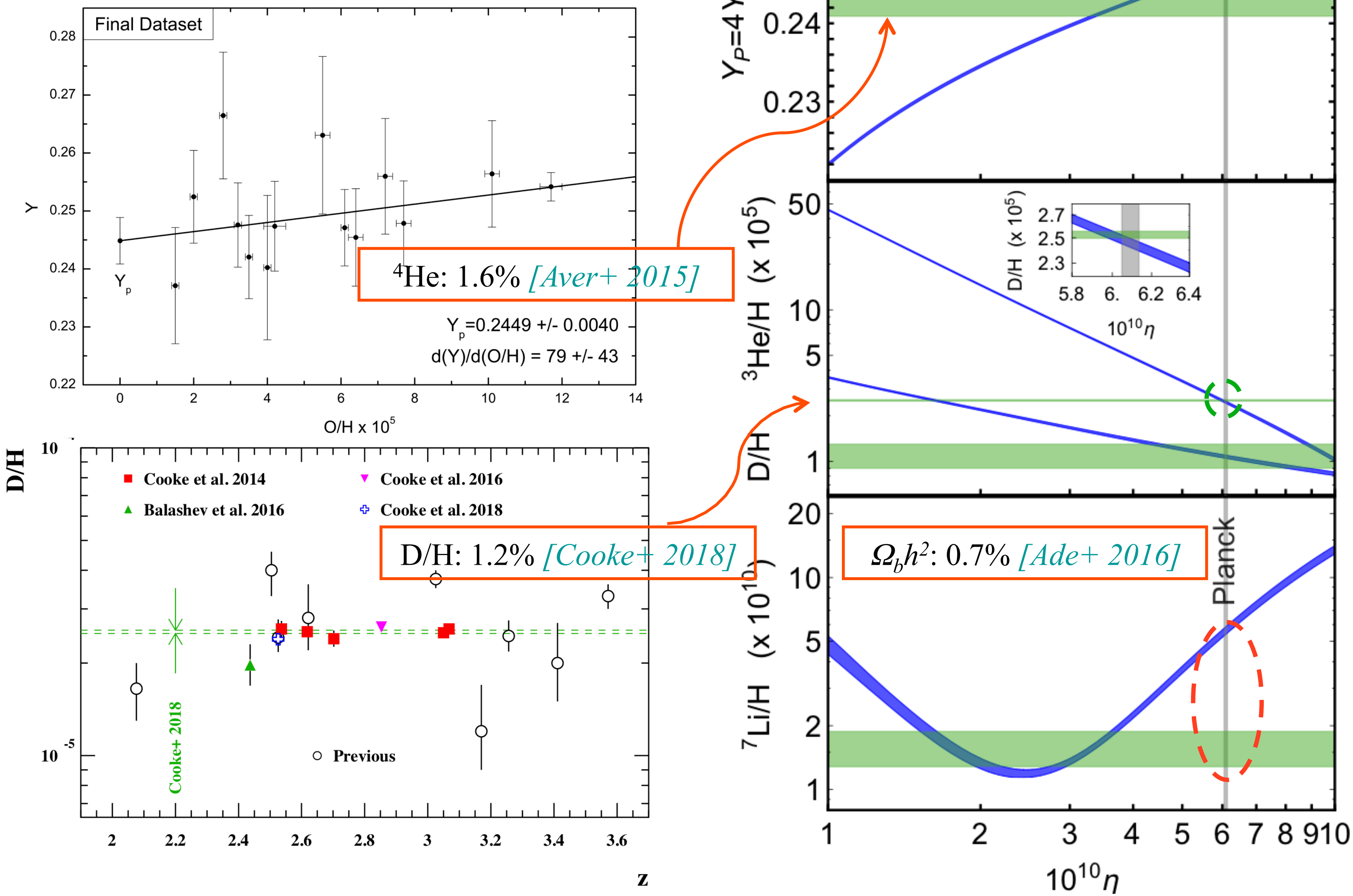
Comparison between observed and calculated abundances



^{4}He: 1.6% *[Aver+ 2015]*

D/H: 1.2% *[Cooke+ 2018]*

$\Omega_b h^2$: 0.7% *[Ade+ 2016]*

[Pitrou+ 2018]

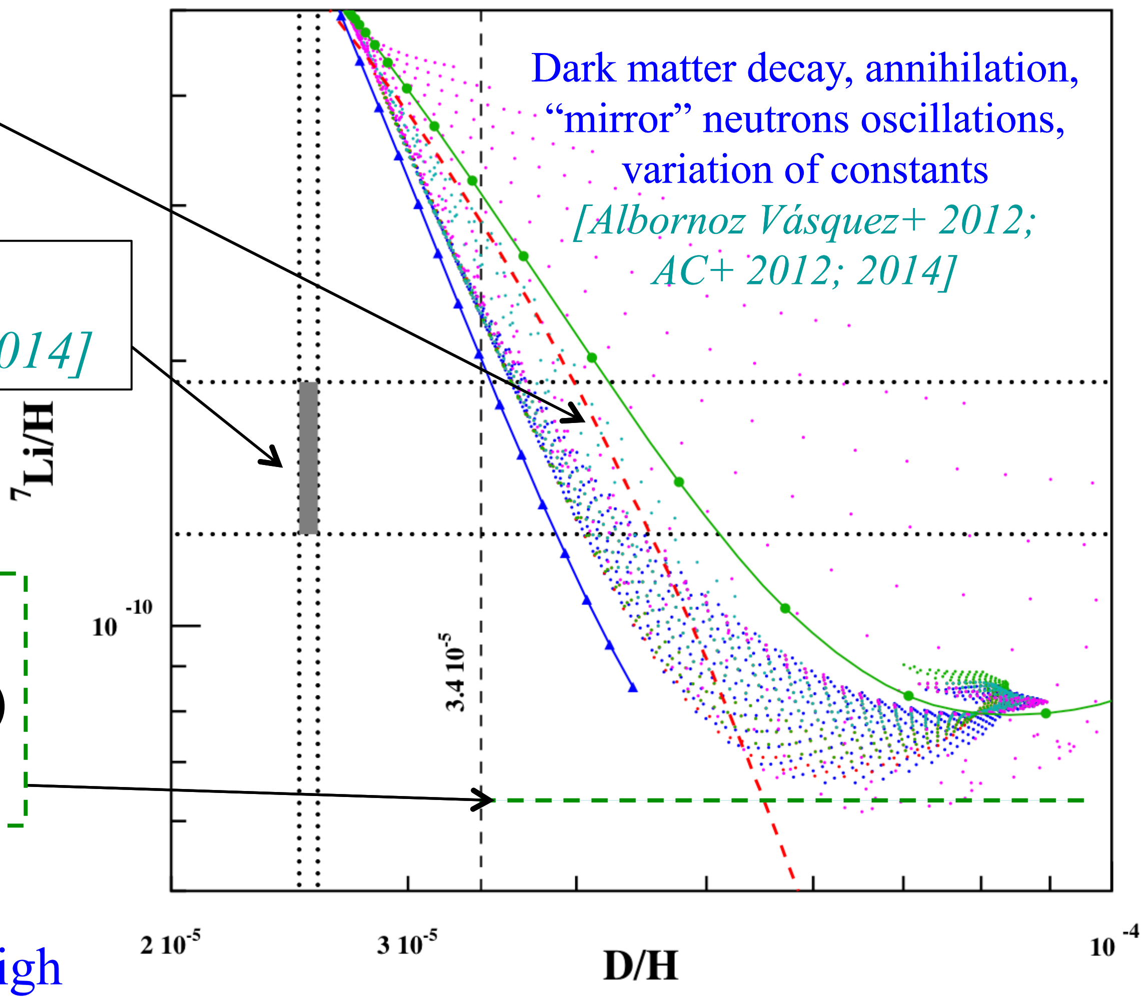
The limits to ^{7}Li+^{7}Be destruction by extra neutrons

See also e.g. *Olive+ 2012; Kusakabe+ 2014;…..*

^{7}Be(n,p) ⇒ ^{1}H(n,p)D

Li/D observational limits
[Sbordone+ 2010 × Cooke+ 2014]

^{3}He(n,p) ^{3}H(α,γ)^{7}Li and
^{7}Be(n,p)^{7}Li [when ^{7}Li(p,α)
ineffective at low *T*]



Dark matter decay, annihilation,
"mirror" neutrons oscillations,
variation of constants
*[Albornoz Vásquez+ 2012;
AC+ 2012; 2014]*

Even worse for (non-thermal) high energy neutrons *[Kusakabe+ 2004]*

Lower Li/H ⇒ higher D/H

The Paris/Orsay BBN codes

EZ_BBN (Fortran)

- Inspired from earlier codes *[J. Audouze, E. Vangioni, P. Delbourgo-Salvador]*
- Completely re-written (Fortran77) and made "EZ" (and foolproof) for nuclear physics updates and non standard physics *[Coc & Vangioni 2017 and references therein]*
- Extended network (~400 reactions) with evaluated rate uncertainties *[Coc+ 2012, Iliadis+ 2016, and many more]*
- Improved network solver by *Richard Longland*

PRIMAT (Mathematica)

- Inspired from *EZ_BBN* but completely re-written in *Mathematica [Pitrou+ 2018]*
- **Highly improved treatment of the n↔p weak rates** but otherwise **identical** reaction network and rates
- Precise and accurate results
  - New theoretical weak rates
  - Comparison EZ_BBN/PRIMAT results
  - Evaluated reaction rates data base (to be regularly updated)

n↔p weak reaction rates

$$n \to p \;:\; n \to p + e^- + \bar{\nu}_e \qquad n + e^+ \to p + \bar{\nu}_e \qquad n + \nu_e \to p + e^-$$

$$p \to n \;:\; p + e^- + \bar{\nu}_e \to n \qquad p + \bar{\nu}_e \to n + e^+ \qquad p + e^- \to n + \nu_e$$

$\lambda_{n\leftrightarrow p} \propto \sum\int$ (phase space)×(e distribution)×(ν_e distribution) dE

+ “some small corrections”

$$\lambda_{n\to pev} = C\int_1^q \frac{\varepsilon(\varepsilon-q)^2(\varepsilon^2-1)^{1/2}\,\mathrm{d}\varepsilon}{[1+\exp(-\varepsilon z)]\{1+\exp[(\varepsilon-q)z_\nu]\}} \xrightarrow[T\to 0]{} \boxed{\frac{1}{\tau_n} = C\int_1^q \varepsilon(\varepsilon-q)^2(\varepsilon^2-1)^{1/2}\,\mathrm{d}\varepsilon}$$

($q\equiv Q_{np}/m_e$, $\varepsilon\equiv E_e/m_e$, $z\equiv m_e/T_\gamma$, $z_\nu\equiv m_e/T_\nu$)

- Experimental neutron lifetime? $\Delta Y_p = +0.0002\times\Delta\tau_n$ (s)
- Calculation of the “small corrections”

“Small corrections” to the weak rates

1. radiative corrections (~1/137)
2. finite nucleon mass corrections (~T/m_N),
3. finite temperature radiative corrections
4. weak-magnetism
5. QED plasma effects
6. incomplete neutrino decoupling

[Dicus+ 1982; Seckel 1993; Dolgov+ 1997; Lopez+ 1997; Lopez & Turner 1999; Brown & Sawyer 2001;Mangano+ 2005; Pisanti+ 2008; Grohs+ 2016; and many more]

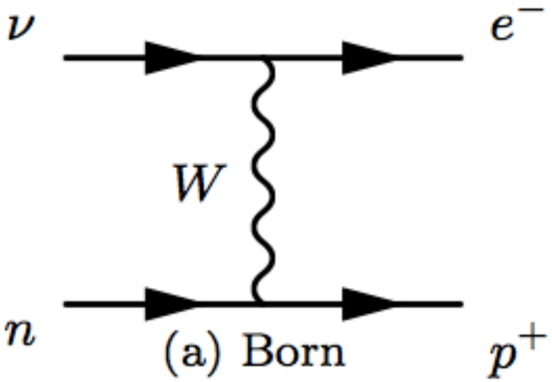
All included and calculated in a self consistent way, allowing to take into account the correlations between them, and verifying that all satisfy detailed balance

$$\begin{aligned} \dot{n}_n + 3Hn_n &= \boxed{-n_n\Gamma_{n\to p} + n_p\Gamma_{p\to n}} \\ \dot{n}_p + 3Hn_p &= \boxed{-n_p\Gamma_{p\to n} + n_n\Gamma_{n\to p}} \end{aligned} = 0$$

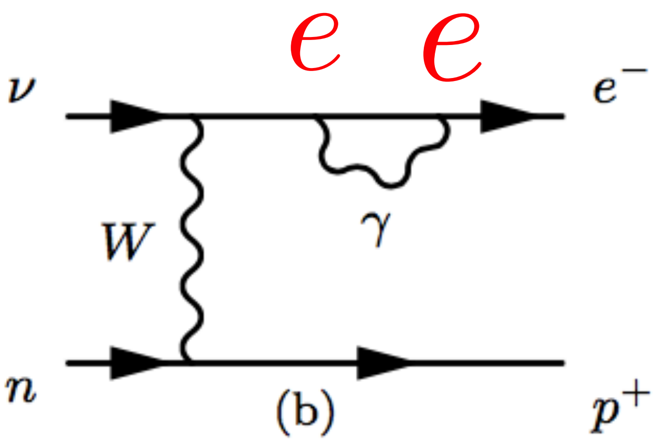
$$\boxed{\frac{\Gamma_{p\to n}}{\Gamma_{n\to p}} = \mathrm{e}^{-(m_n-m_p)/T}}$$

Radiative corrections

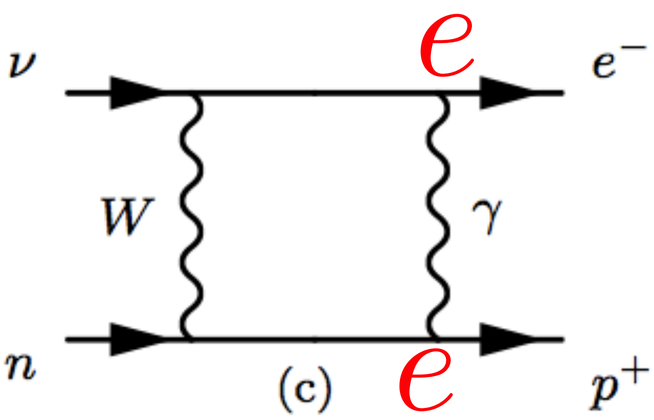
$$\frac{e^2}{4\pi} = \alpha_{\rm FS} \simeq \frac{1}{137}$$



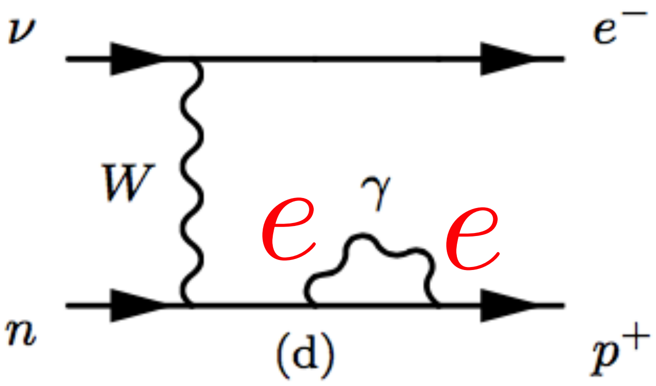
(a) Born



(b)

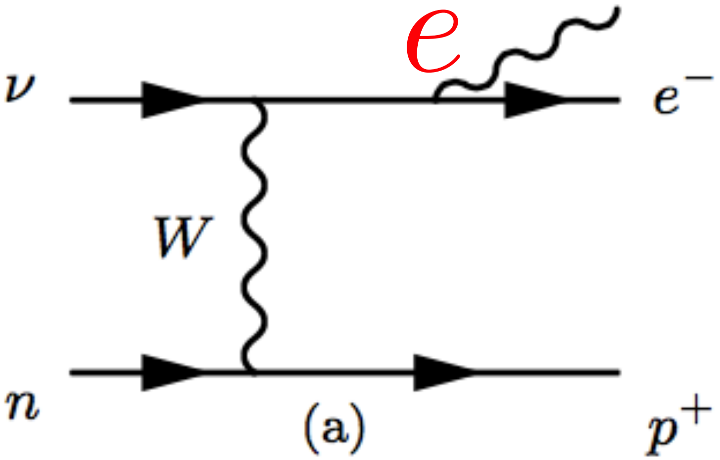


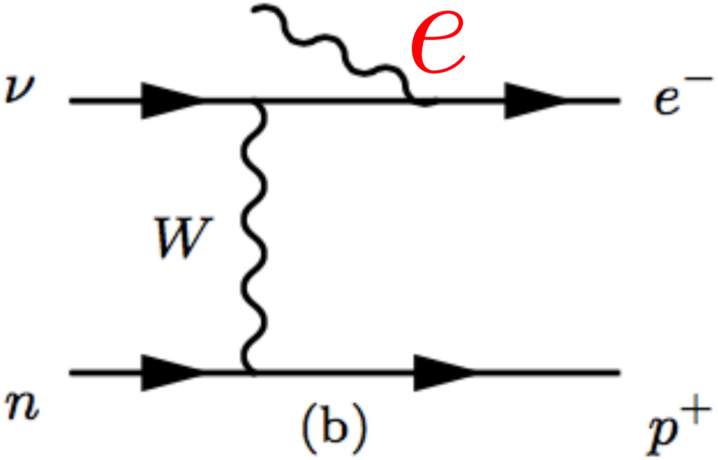
(c)

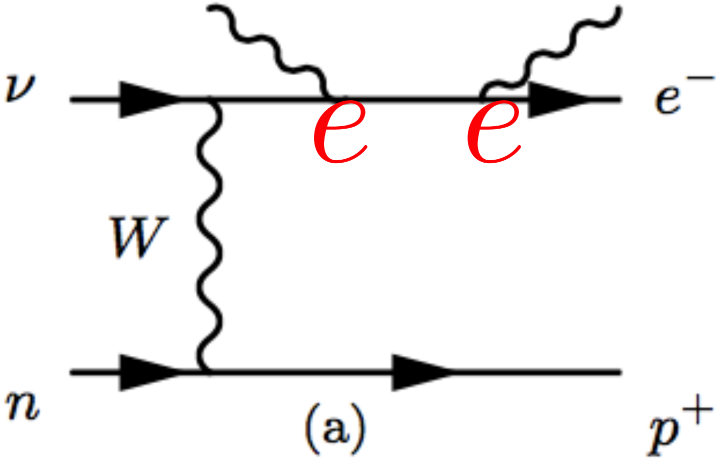


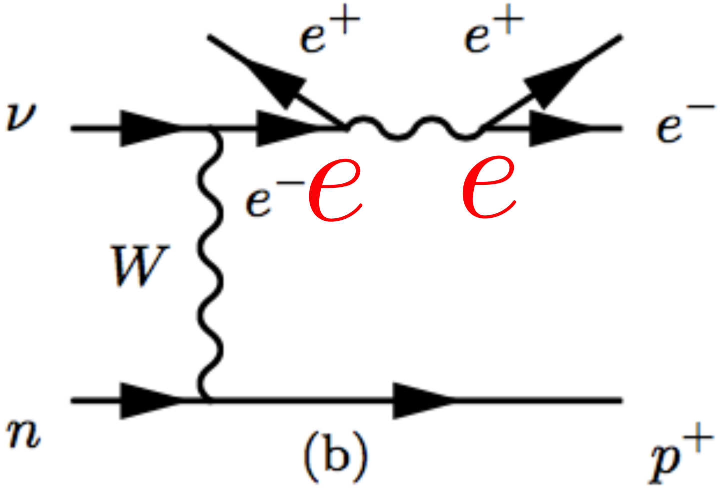
(d)

Finite temperature radiative corrections

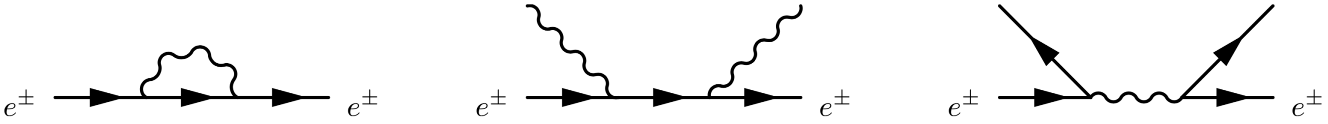








QED plasma effects



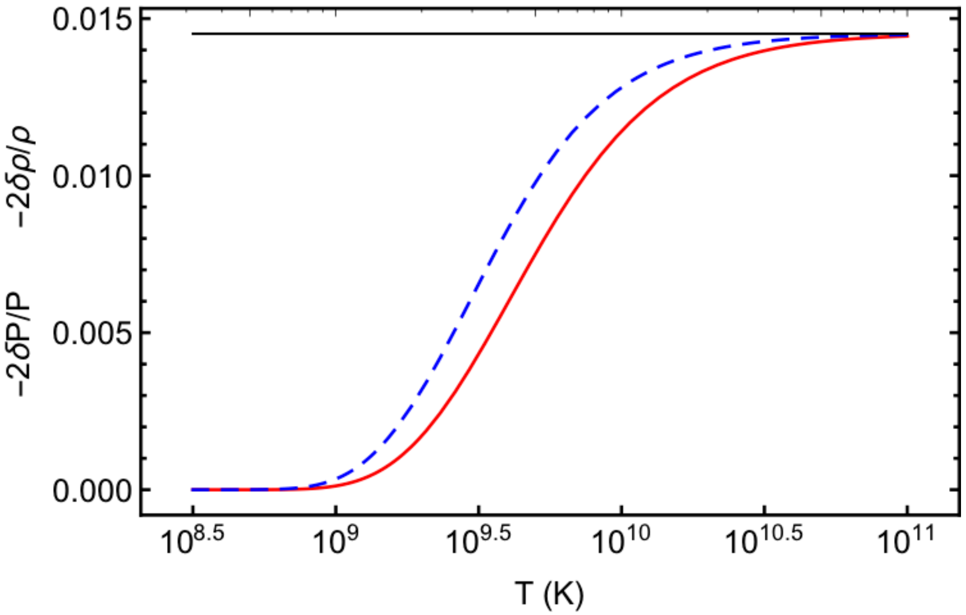
(a) Vacuum. (b) Interaction with photons. (c) Interaction with antiparticles.

Fig. 5. *Top :* electron/positron self-energy. *Bottom :* electron/positron mass shift from interaction with plasma.

(a) Vacuum. (b) Interaction with electrons or positrons.

Fig. 6. *Left :* photon self-energy. *Right :* photon mass shift from interaction with electron/positron plasma.

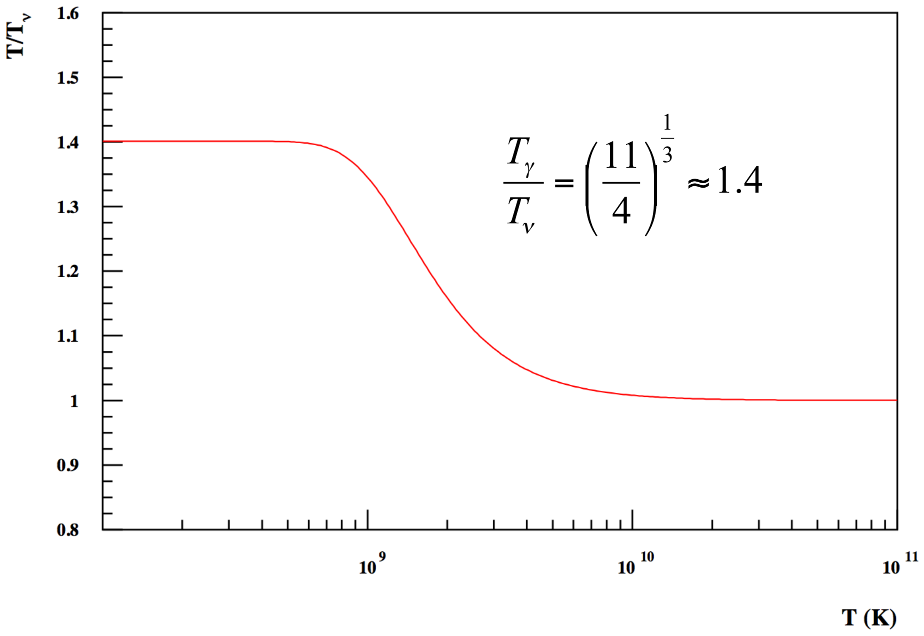
- Modify ρ_R and $p \longrightarrow$ entropy
  - expansion a(t)
  - neutrino temperature
  - e-statistics



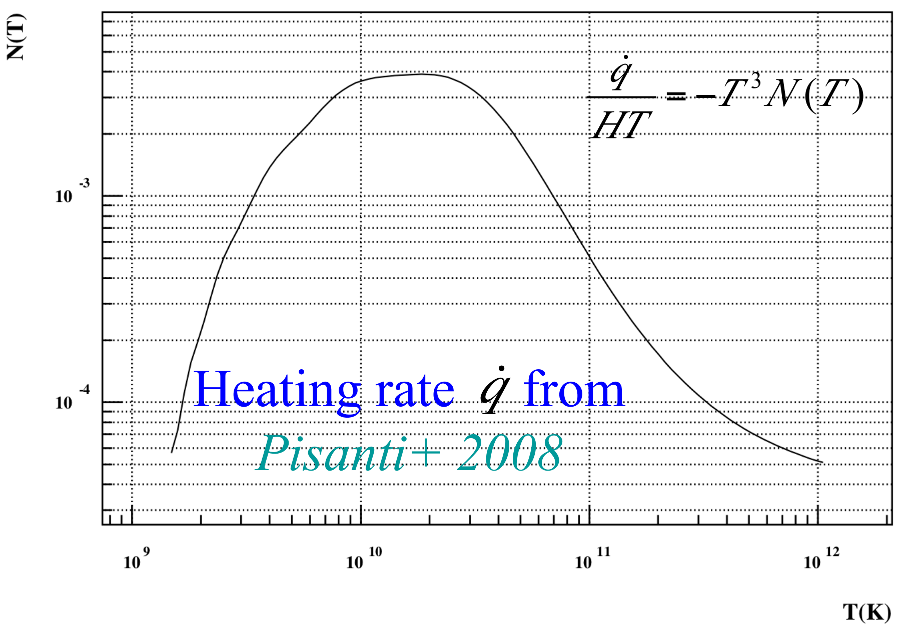
Incomplete neutrino decoupling

Complete neutrino decoupling:

- $T \approx 2/3$ MeV (20/30 GK), $\nu_e/\nu_{\mu,\tau}$ decouple from $e^+e^-\gamma$ plasma *[Dolgov 2002]*
- $T \approx 0.5$ MeV e^+e^- annihilate and reheat the photon and ions, **but not the neutrinos**
- $T \approx 0.28$ MeV (3.3 GK) n↔p freezout
- $T \approx 0.1$ MeV (0.9 GK) nucleosynthesis



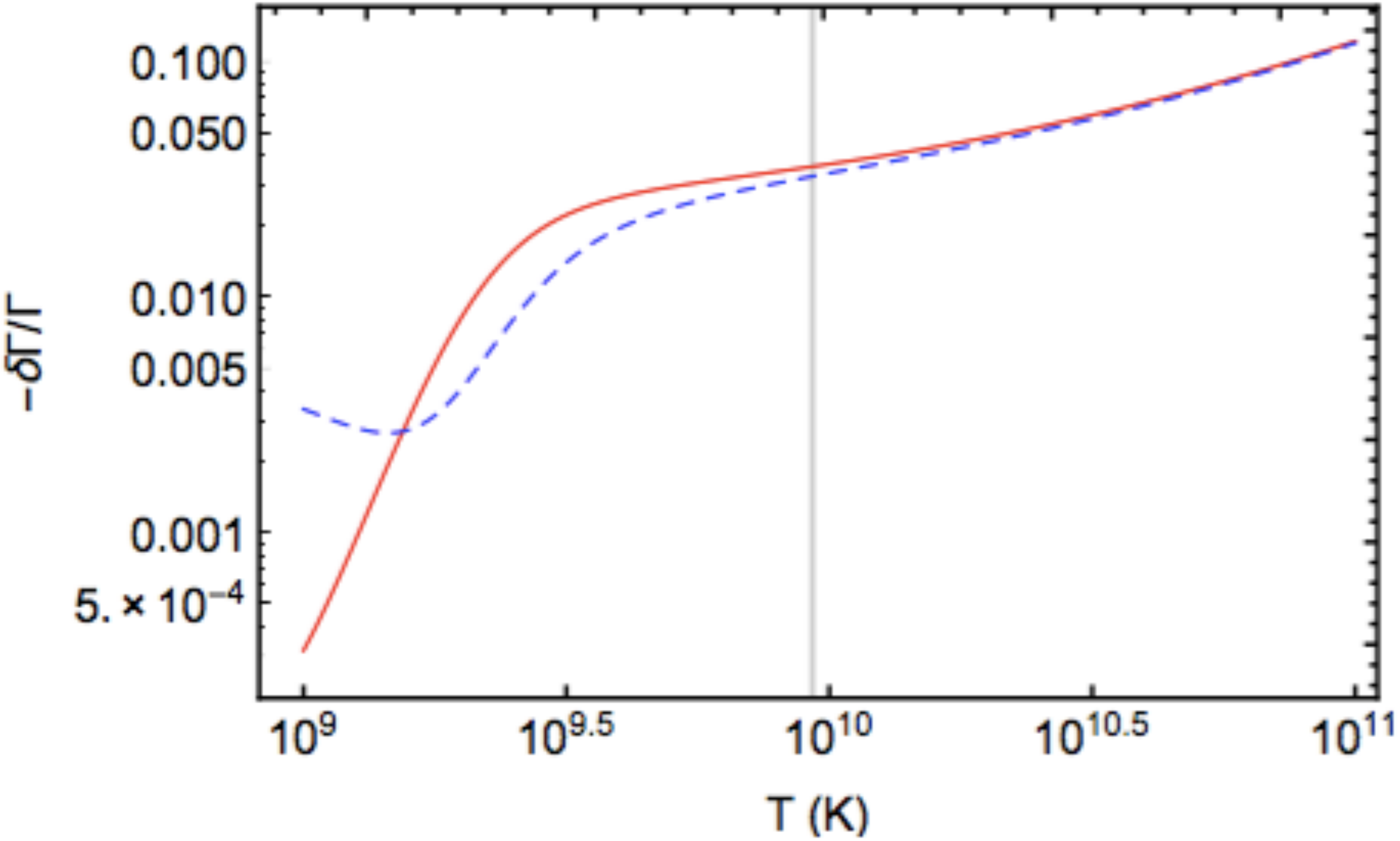
$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{\frac{1}{3}} \approx 1.4$$



$$\frac{\dot{q}}{HT} = -T^3 N(T)$$

Heating rate $\dot{q}$ from *Pisanti+ 2008*

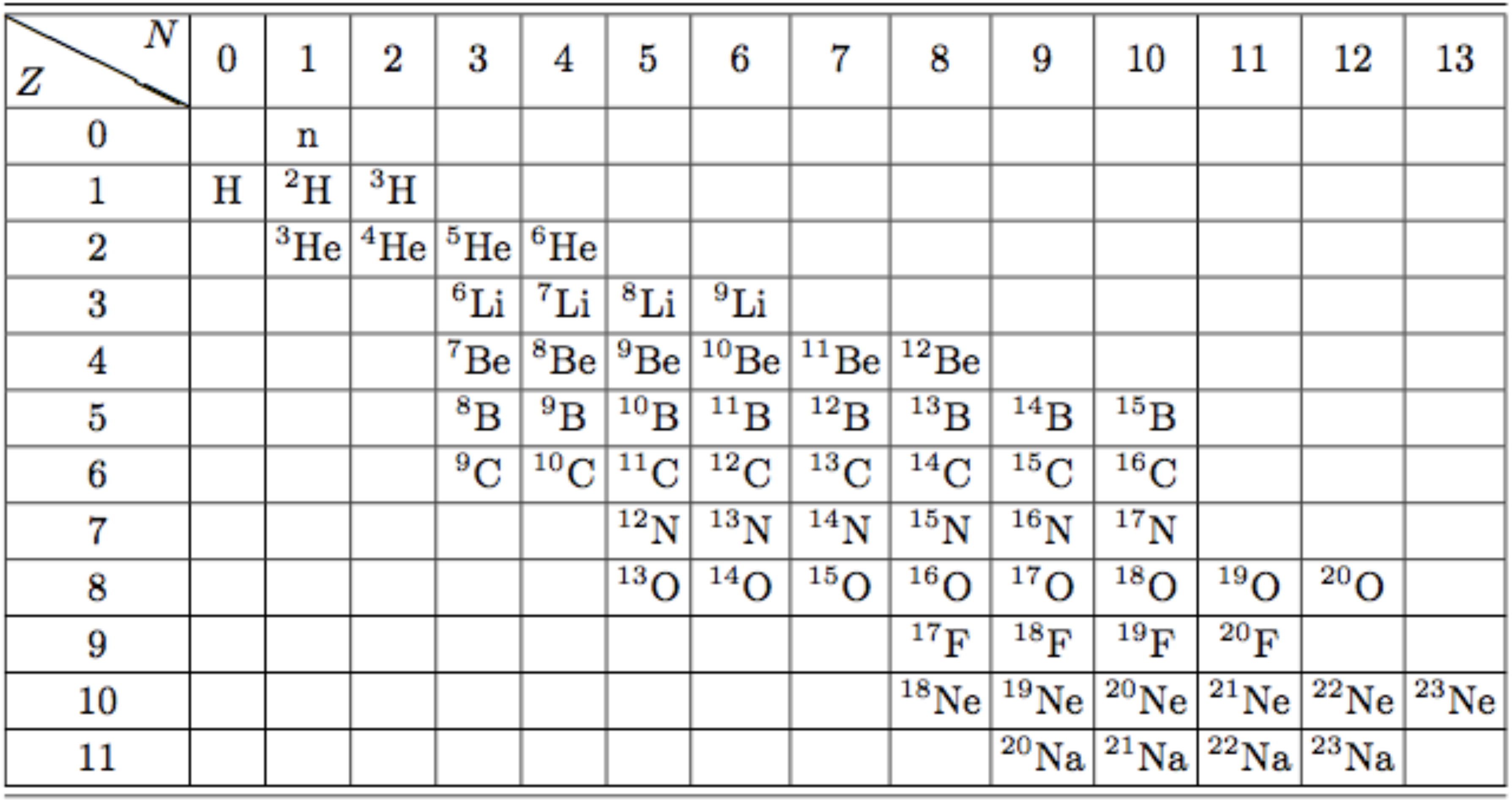
Total corrections



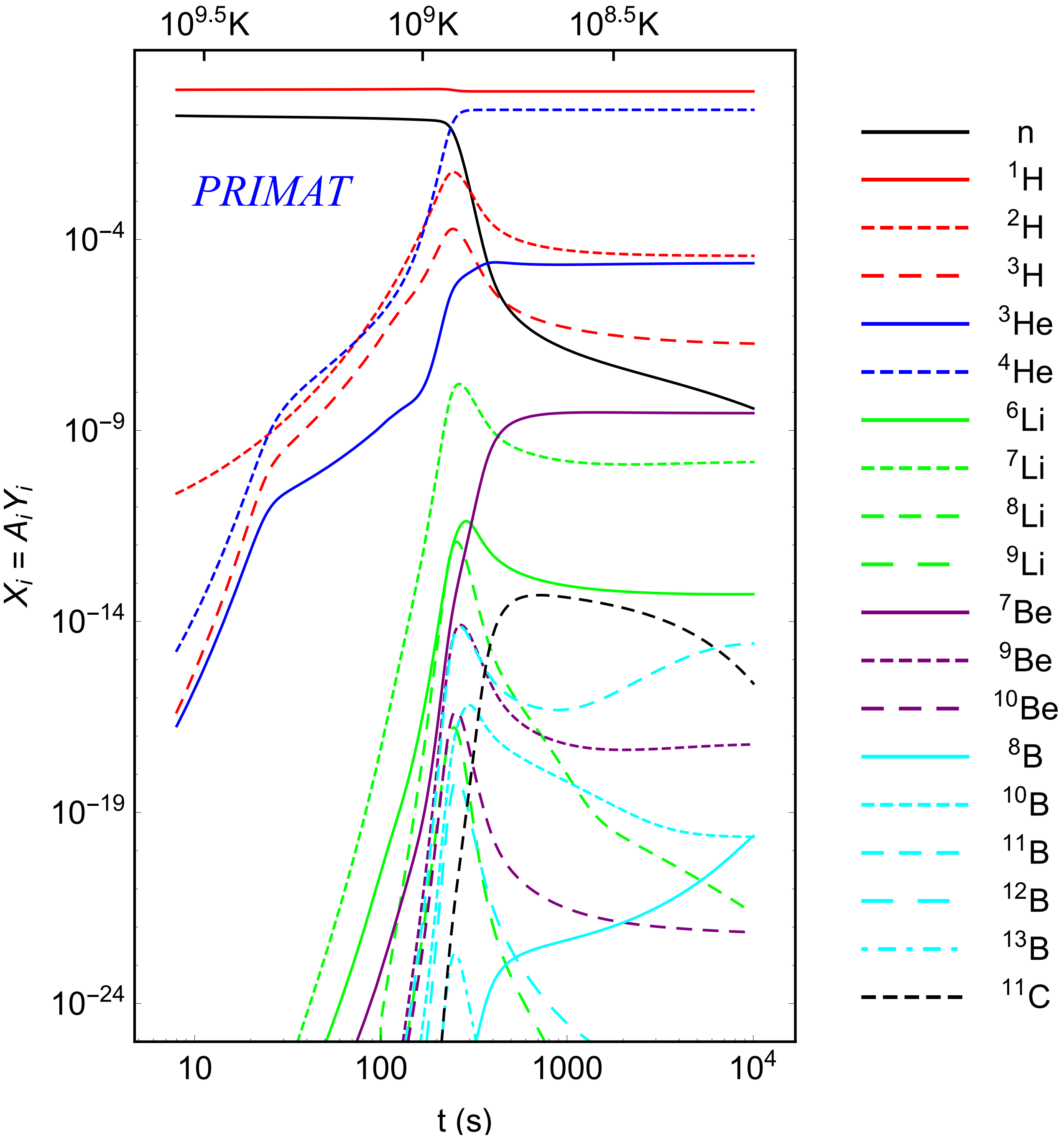
PRIMAT (PRImordial MATter)

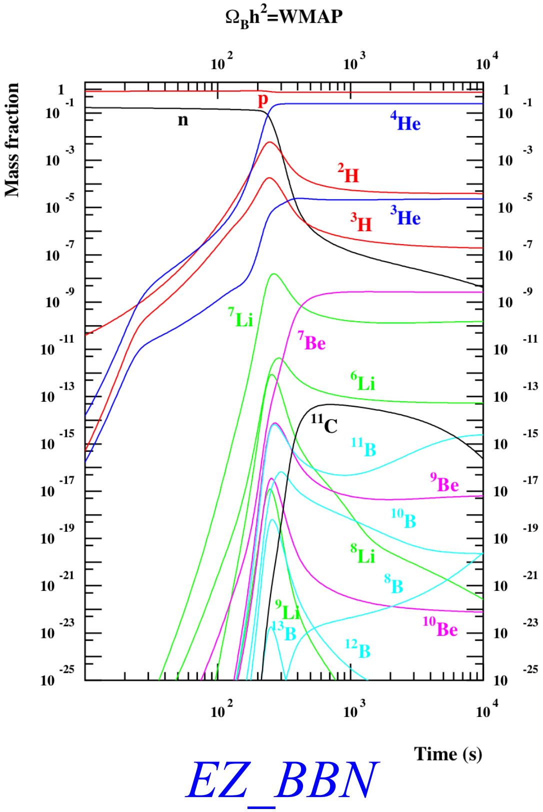
http://www2.iap.fr/users/pitrou/primat.htm

59 nuclides



N Z	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0		n												
1	H	^{2}H	^{3}H											
2		^{3}He	^{4}He	^{5}He	^{6}He									
3				^{6}Li	^{7}Li	^{8}Li	^{9}Li							
4				^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be					
5				^{8}B	^{9}B	^{10}B	^{11}B	^{12}B	^{13}B	^{14}B	^{15}B			
6				^{9}C	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C			
7						^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N			
8						^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O	
9									^{17}F	^{18}F	^{19}F	^{20}F		
10									^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne
11										^{20}Na	^{21}Na	^{22}Na	^{23}Na	


PRIMAT
$10^{9.5}$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


$\Omega_B h^2$=WMAP
Mass fraction
Time (s)
10^2
10^3
10^4
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
p
n
^{4}He
^{2}H
^{3}H
^{3}He
^{7}Li
^{7}Be
^{6}Li
^{11}C
^{11}B
^{9}Be
^{10}B
^{8}Li
^{8}B
^{9}Li
^{13}B
^{12}B
^{10}Be
EZ_BBN

Previously considered
(plus $\delta Y_P \times 10^4 = +18$ added "by hand")

New *[Pitrou+ 2018]*

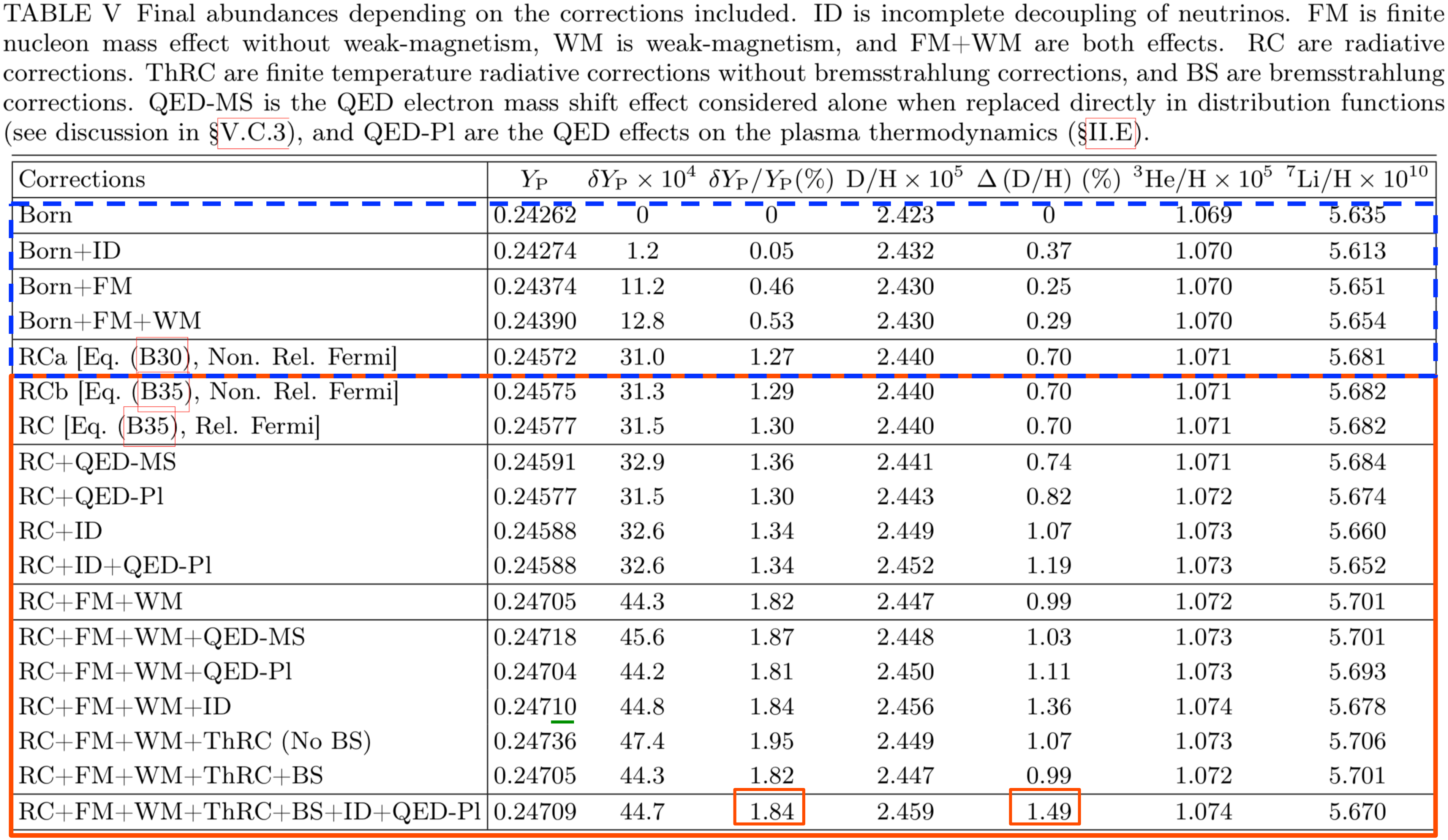
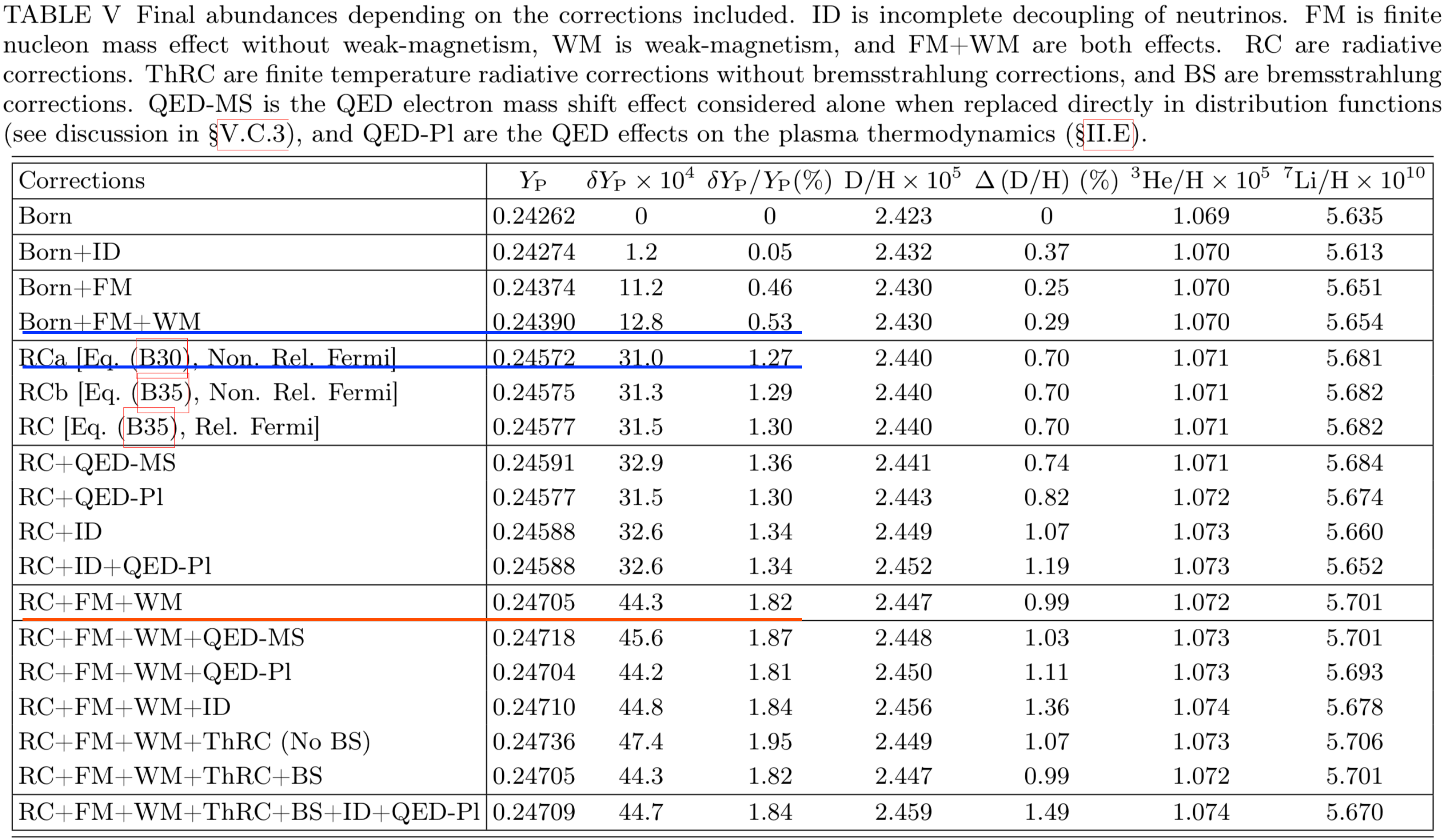


TABLE V Final abundances depending on the corrections included. ID is incomplete decoupling of neutrinos. FM is finite nucleon mass effect without weak-magnetism, WM is weak-magnetism, and FM+WM are both effects. RC are radiative corrections. ThRC are finite temperature radiative corrections without bremsstrahlung corrections, and BS are bremsstrahlung corrections. QED-MS is the QED electron mass shift effect considered alone when replaced directly in distribution functions (see discussion in §V.C.3), and QED-Pl are the QED effects on the plasma thermodynamics (§II.E).

Corrections	Y_P	$\delta Y_P \times 10^4$	$\delta Y_P/Y_P(\%)$	D/H $\times 10^5$	Δ (D/H) (%)	^{3}He/H $\times 10^5$	^{7}Li/H $\times 10^{10}$
Born	0.24262	0	0	2.423	0	1.069	5.635
Born+ID	0.24274	1.2	0.05	2.432	0.37	1.070	5.613
Born+FM	0.24374	11.2	0.46	2.430	0.25	1.070	5.651
Born+FM+WM	0.24390	12.8	0.53	2.430	0.29	1.070	5.654
RCa [Eq. (B30), Non. Rel. Fermi]	0.24572	31.0	1.27	2.440	0.70	1.071	5.681
RCb [Eq. (B35), Non. Rel. Fermi]	0.24575	31.3	1.29	2.440	0.70	1.071	5.682
RC [Eq. (B35), Rel. Fermi]	0.24577	31.5	1.30	2.440	0.70	1.071	5.682
RC+QED-MS	0.24591	32.9	1.36	2.441	0.74	1.071	5.684
RC+QED-Pl	0.24577	31.5	1.30	2.443	0.82	1.072	5.674
RC+ID	0.24588	32.6	1.34	2.449	1.07	1.073	5.660
RC+ID+QED-Pl	0.24588	32.6	1.34	2.452	1.19	1.073	5.652
RC+FM+WM	0.24705	44.3	1.82	2.447	0.99	1.072	5.701
RC+FM+WM+QED-MS	0.24718	45.6	1.87	2.448	1.03	1.073	5.701
RC+FM+WM+QED-Pl	0.24704	44.2	1.81	2.450	1.11	1.073	5.693
RC+FM+WM+ID	0.24710	44.8	1.84	2.456	1.36	1.074	5.678
RC+FM+WM+ThRC (No BS)	0.24736	47.4	1.95	2.449	1.07	1.073	5.706
RC+FM+WM+ThRC+BS	0.24705	44.3	1.82	2.447	0.99	1.072	5.701
RC+FM+WM+ThRC+BS+ID+QED-Pl	0.24709	44.7	1.84	2.459	1.49	1.074	5.670

Small corrections ≈ observational uncertainties!

Dominant corrections for Y_p



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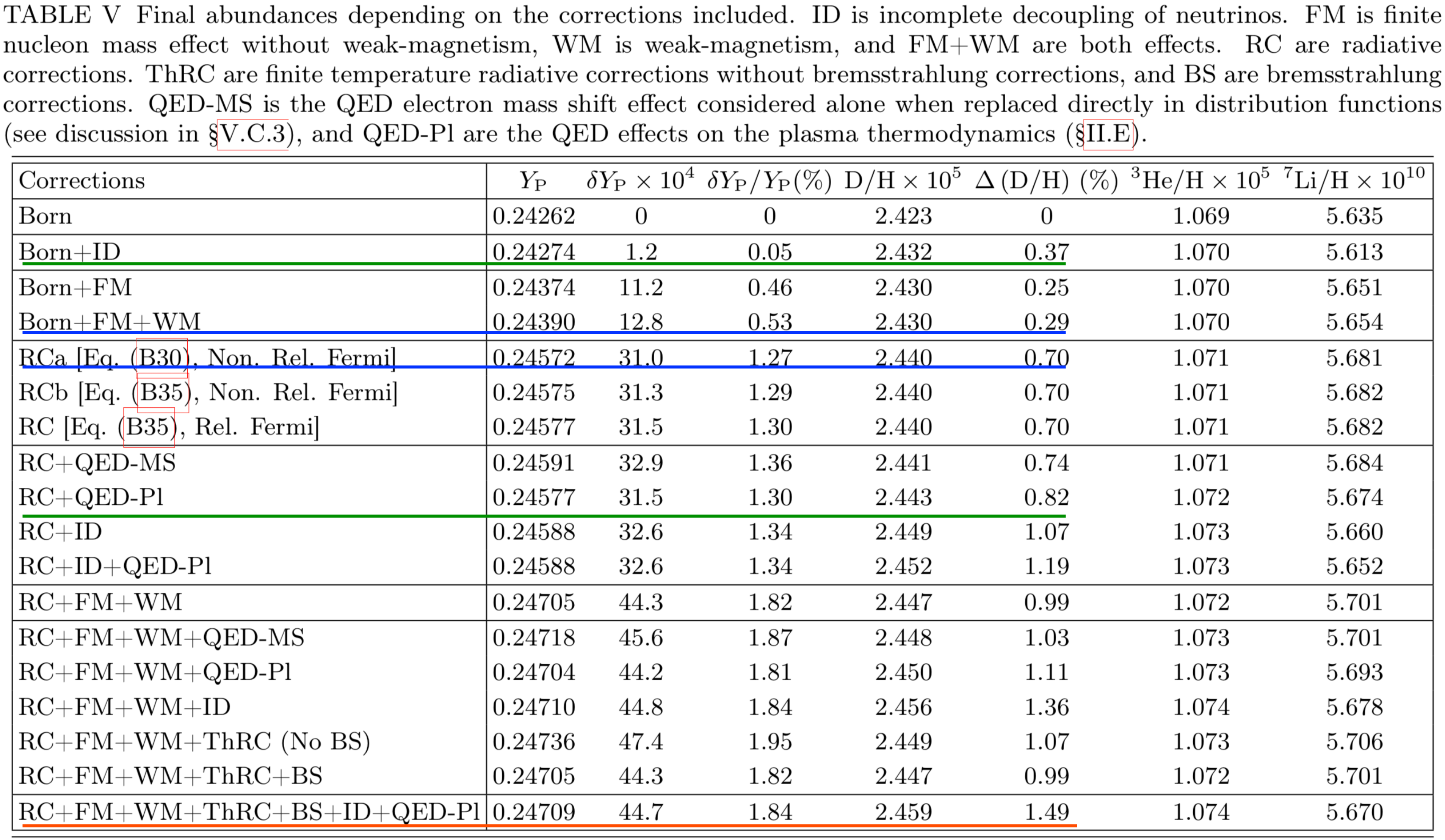
RC+FM+WM+ThRC+BS+ID+QED-Pl	0.24709	44.7	1.84	2.459	1.49	1.074	5.670

Dominant corrections for D/H



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Born+FM+WM	0.24390	12.8	0.53	2.430	0.29	1.070	5.654
RCa [Eq. (B30), Non. Rel. Fermi]	0.24572	31.0	1.27	2.440	0.70	1.071	5.681
RCb [Eq. (B35), Non. Rel. Fermi]	0.24575	31.3	1.29	2.440	0.70	1.071	5.682
RC [Eq. (B35), Rel. Fermi]	0.24577	31.5	1.30	2.440	0.70	1.071	5.682
RC+QED-MS	0.24591	32.9	1.36	2.441	0.74	1.071	5.684
RC+QED-Pl	0.24577	31.5	1.30	2.443	0.82	1.072	5.674
RC+ID	0.24588	32.6	1.34	2.449	1.07	1.073	5.660
RC+ID+QED-Pl	0.24588	32.6	1.34	2.452	1.19	1.073	5.652
RC+FM+WM	0.24705	44.3	1.82	2.447	0.99	1.072	5.701
RC+FM+WM+QED-MS	0.24718	45.6	1.87	2.448	1.03	1.073	5.701
RC+FM+WM+QED-Pl	0.24704	44.2	1.81	2.450	1.11	1.073	5.693
RC+FM+WM+ID	0.24710	44.8	1.84	2.456	1.36	1.074	5.678
RC+FM+WM+ThRC (No BS)	0.24736	47.4	1.95	2.449	1.07	1.073	5.706
RC+FM+WM+ThRC+BS	0.24705	44.3	1.82	2.447	0.99	1.072	5.701
RC+FM+WM+ThRC+BS+ID+QED-Pl	0.24709	44.7	1.84	2.459	1.49	1.074	5.670

Dominant corrections (summary)

	$\Delta Y_p \times 10^4$	Δ(D/H) (%)
Radiative corrections	31	0.70
Finite mass of nucleons	13	0.25
Incomplete neutrino decoupling		0.37
QED effects on plasma		0.12
Total	44	1.44/1.49

Comparison between BBN codes

	BBN calculations			
	^{4}He	D/H	^{3}He/H	^{7}Li/H
	$\times 10^{0}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-10}$
Observations	0.2449±0.0040	2.527±0.030	<(0.9-1.3)	1.58±0.31
EZ_BBN (Coc+2015)	0.2484±0.0002	2.45±0.05	1.07±0.03	5.61±0.26
PRIMAT (Pitrou+2018)	0.24709±0.00017	2.459±0.036	1.074±0.026	5.623±0.247

Except for ^{4}He, very good agreement between (Fortran77) *EZ_BBN* and (Mathematica) *PRIMAT* results

Comparison between BBN codes

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Cyburt+2016	0.24709±0.00025	2.58±0.13	1.0039±0.0090	4.68±0.67

Good agreement between Paris/Orsay and US (Cyburt) results

Comparison between BBN codes

	BBN calculations			
	^{4}He	D/H	^{3}He/H	^{7}Li/H
	$\times 10^{0}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-10}$
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Cyburt+2016	0.24709±0.00025	2.58±0.13	1.0039±0.0090	4.68±0.67
Yeh priv. comm	0.2472	2.449	1.076	5.633

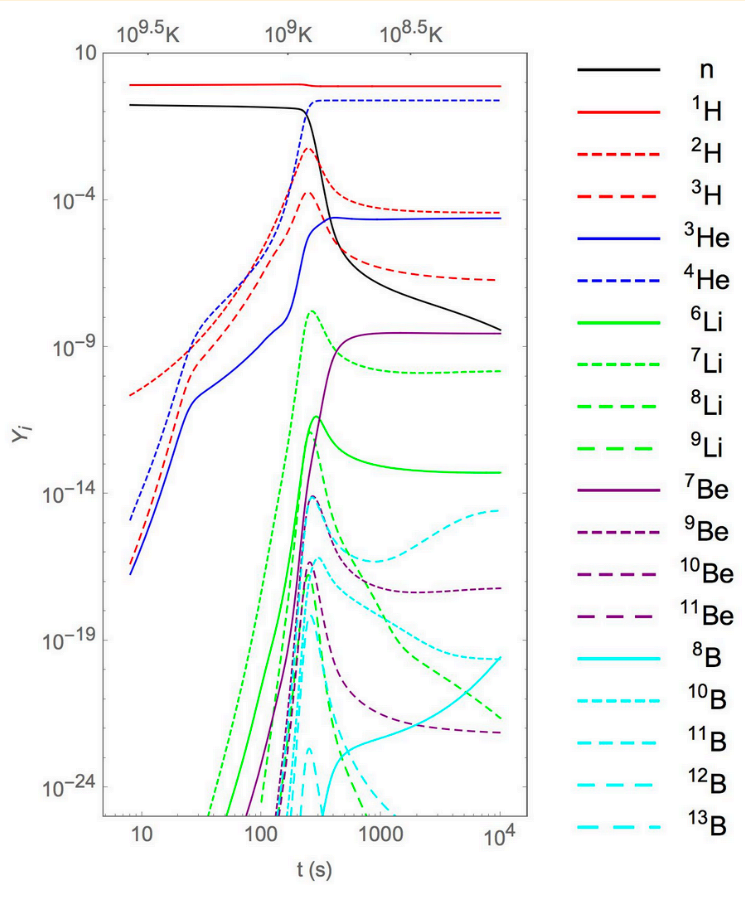
Even better if one uses the same reaction rates!
(Tsung-Han) Yeh priv. comm = *Cyburt+* 2016 code with 5 identical rates :

$D(p,\gamma)^3He$, $D(d,n)^3He$, $D(d,p)^3H$, $^7Be(n,\alpha)^4He$ & $^3He(\alpha,\gamma)^7Be$

PRIMAT

http://www2.iap.fr/users/pitrou/primat.htm

PRImordial MATter



General description

PRIMAT is a *Mathematica* code dedicated to the computation of light elements abundances at the end of the Big-Bang Nucleosynthesis (BBN). It computes the evolution of these abundances in the first minutes after the Big-Bang so as to obtain the frozen values when the temperature dropped below 10^8 degrees. It allows to explore the dependence of light elements abundances on cosmological parameters, such as baryon density or number of neutrino species, but also to estimate from a Monte-Carlo method the uncertainty in these predictions due to uncertainties in nuclear reaction rates.

Documentation

The details of the method used to solve numerically for the thermodynamics, cosmology and nuclear reactions in the early universe are available in an associated publication (arXiv:1801.08023). Please cite it along with this website if you use it in BBN related publications, using this bibtex file.

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PRIMAT public release: PRIMAT.zip

PRIMAT/

- README.txt
- PhysReptArxivVersion.pdf
- nubase2016.asc ➔ the Table of nuclear properties *[Audi+ 2017]*

- PRIMAT-Main.nb ➔ the main Mathematica “notebook” using
- BBNRatesAC2019.dat ➔ the tabulated reaction rates
- PRIMAT-Main.pdf ➔ for examination only

- PRIMAT_small_network.nb ➔ a small 12+1 reactions network using
- BBNRates_2018_12reactions.dat➔ the 12 tabulated rates

- *.m (internal)

PRIMAT/Examples/

- PRIMAT-MonteCarlo-Rates1.nb ➔ primordial abundances with MC errors at a given $\Omega_b h^2$ (check LenghMC!)

- PRIMAT-Abundances-Eta1.nb ➔ same but for η from 10^{-10} to 10^{-9} and produce the nice ^{4}He, D/H, ^{3}He/H and ^{7}Li versus η plot

- PRIMAT-Abundances-and-Plots1.nb ➔ produce nice plots of A=1 to 23 abundances as functions of time

PRIMAT/Plots (gather plots)

PRIMAT/Interpolations (storage)
PRIMAT/MonteCarlo (storage)

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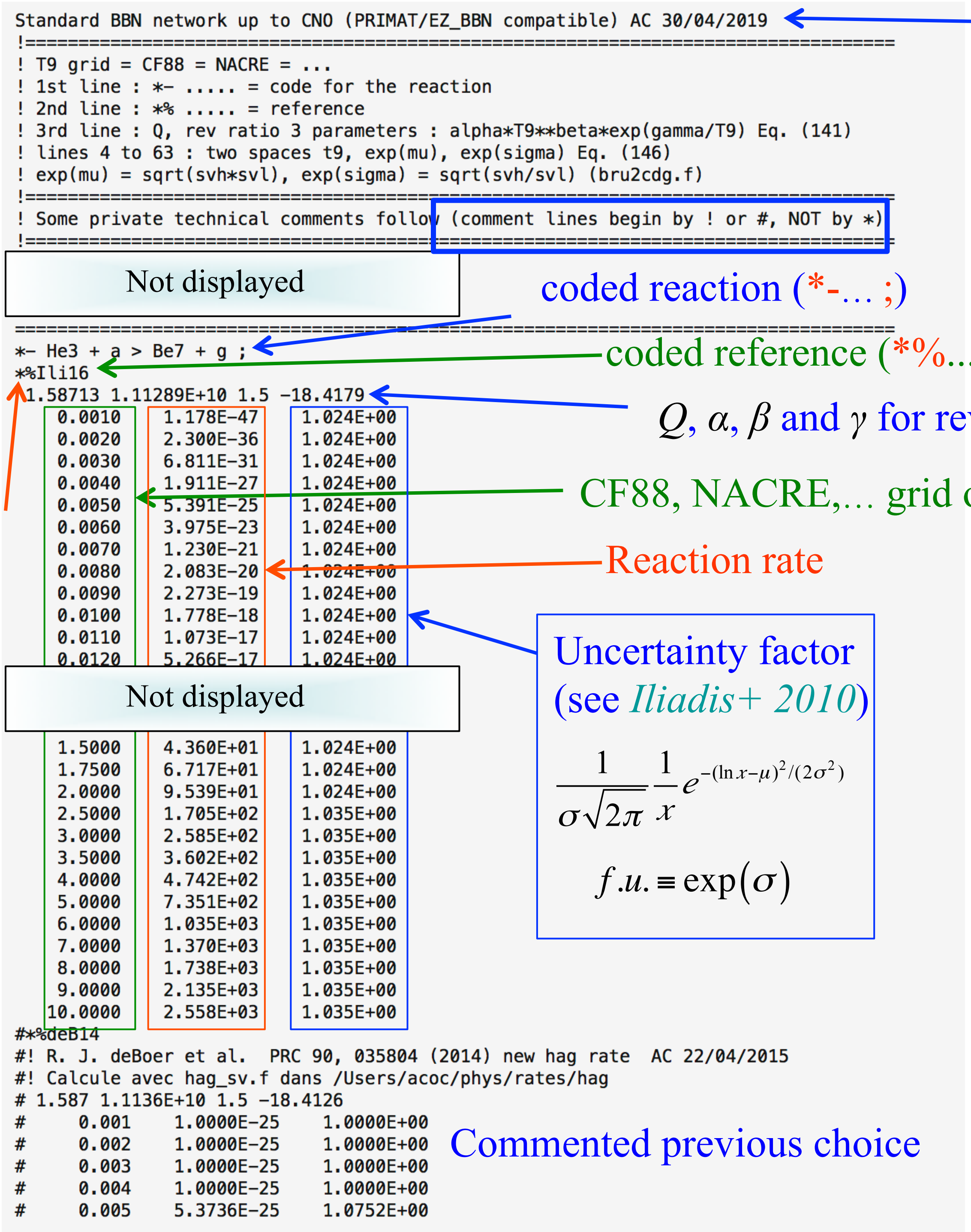


```
Standard BBN network up to CNO (PRIMAT/EZ_BBN compatible) AC 30/04/2019
!==========================================================================
! T9 grid = CF88 = NACRE = ...
! 1st line : *- ..... = code for the reaction
! 2nd line : *% ..... = reference
! 3rd line : Q, rev ratio 3 parameters : alpha*T9**beta*exp(gamma/T9) Eq. (141)
! lines 4 to 63 : two spaces t9, exp(mu), exp(sigma) Eq. (146)
! exp(mu) = sqrt(svh*svl), exp(sigma) = sqrt(svh/svl) (bru2cdg.f)
!==========================================================================
! Some private technical comments follow (comment lines begin by ! or #, NOT by *)
!==========================================================================
```

Not displayed

```
===========================================================================
*- He3 + a > Be7 + g ;
*%Ili16
1.58713 1.11289E+10 1.5 -18.4179
  0.0010   1.178E-47   1.024E+00
  0.0020   2.300E-36   1.024E+00
  0.0030   6.811E-31   1.024E+00
  0.0040   1.911E-27   1.024E+00
  0.0050   5.391E-25   1.024E+00
  0.0060   3.975E-23   1.024E+00
  0.0070   1.230E-21   1.024E+00
  0.0080   2.083E-20   1.024E+00
  0.0090   2.273E-19   1.024E+00
  0.0100   1.778E-18   1.024E+00
  0.0110   1.073E-17   1.024E+00
  0.0120   5.266E-17   1.024E+00
```

Not displayed

```
  1.5000   4.360E+01   1.024E+00
  1.7500   6.717E+01   1.024E+00
  2.0000   9.539E+01   1.024E+00
  2.5000   1.705E+02   1.035E+00
  3.0000   2.585E+02   1.035E+00
  3.5000   3.602E+02   1.035E+00
  4.0000   4.742E+02   1.035E+00
  5.0000   7.351E+02   1.035E+00
  6.0000   1.035E+03   1.035E+00
  7.0000   1.370E+03   1.035E+00
  8.0000   1.738E+03   1.035E+00
  9.0000   2.135E+03   1.035E+00
 10.0000   2.558E+03   1.035E+00
#*%deB14
#! R. J. deBoer et al.  PRC 90, 035804 (2014) new hag rate  AC 22/04/2015
#! Calcule avec hag_sv.f dans /Users/acoc/phys/rates/hag
# 1.587 1.1136E+10 1.5 -18.4126
#     0.001     1.0000E-25     1.0000E+00
#     0.002     1.0000E-25     1.0000E+00
#     0.003     1.0000E-25     1.0000E+00
#     0.004     1.0000E-25     1.0000E+00
#     0.005     5.3736E-25     1.0752E+00
```

Title (file to be updated before 2020)

$$\frac{N_A<\sigma v>_{\text{Reverse}}}{N_A<\sigma v>_{\text{Direct}}}=\alpha T_9^{\beta}\exp\left(\frac{\gamma}{T_9}\right)$$

coded reaction (*-… ;)

coded reference (*%….)

Q, α, β and γ for reverse ratio

CF88, NACRE,… grid of T_9

Reaction rate

Uncertainty factor (see *Iliadis+ 2010*)

$$\frac{1}{\sigma\sqrt{2\pi}}\frac{1}{x}e^{-(\ln x-\mu)^2/(2\sigma^2)}$$

$$f.u.\equiv\exp(\sigma)$$

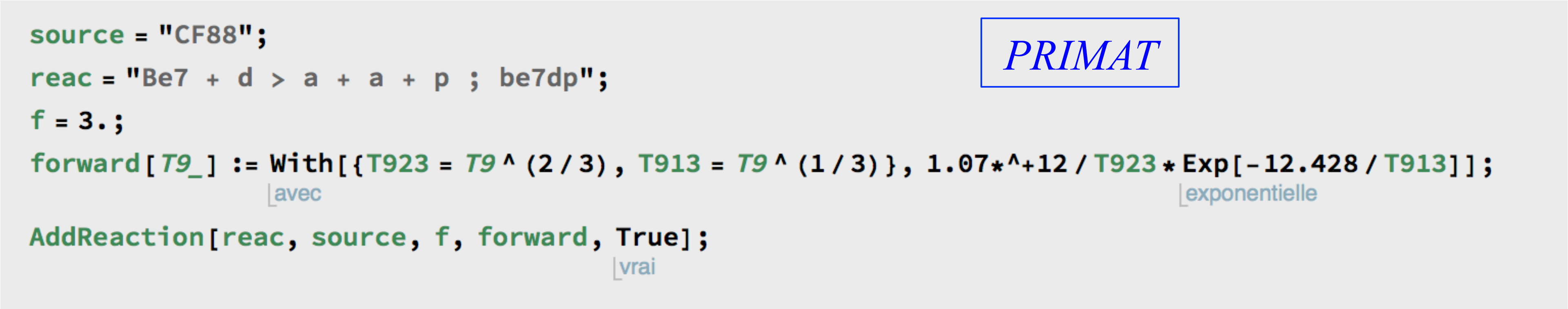
Commented previous choice

Examples of valid coding

```
*- d + d > He3 + n ;
*- t + p > a + g ; tpg
*- t + a > Li7 + g ;
*- Li6 + He3 > a + a  + p ;
*- n + Bp > p ; n decay
*- C11 > B11 + Bp ; 11C decay
```

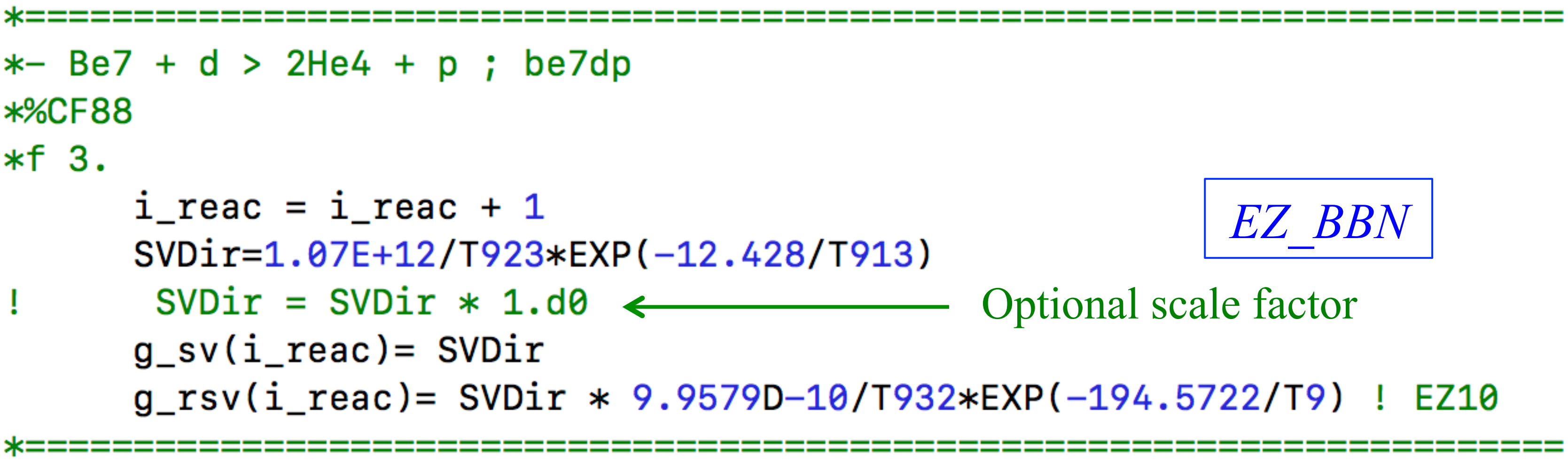
Conservation laws enforced

Analytic reaction rates



PRIMAT

```
source = "CF88";
reac = "Be7 + d > a + a + p ; be7dp";
f = 3.;
forward[T9_] := With[{T923 = T9^(2/3), T913 = T9^(1/3)}, 1.07*^+12/T923*Exp[-12.428/T913]];
AddReaction[reac, source, f, forward, True];
```



EZ_BBN

```
*=========================================================================
*- Be7 + d > 2He4 + p ; be7dp
*%CF88
*f 3.
      i_reac = i_reac + 1
      SVDir=1.07E+12/T923*EXP(-12.428/T913)
!      SVDir = SVDir * 1.d0
      g_sv(i_reac)= SVDir
      g_rsv(i_reac)= SVDir * 9.9579D-10/T932*EXP(-194.5722/T9) ! EZ10
*=========================================================================
```

Optional scale factor

Useful when rate depend on a parameter e.g. E_R

Option to change rate by global factor

Reaction rates to be updated

Distributed file of reaction rates available by the end of 2017, BBNRatesAC2019.dat (aka BBNRatesAlainCoc2018.dat) to be updated (end of 2019).

Some relevant reactions:

- ❑ D(p,γ)^{3}He* : new experimental results expected soon from LUNA
- ❑ ^{7}Be(p,n)^{7}Li* : new n_ToF results *[Damone+ 2018]* may reduce ^{7}Li by 8%. See also *Hayakawa & Ishikawa talks*
- ❑ ^{7}Be(p,α)^{4}He : new experimental results *[Barbagallo+ 2016; Hayakawa talk]* but no effect on ^{7}Li
- ❑ ^{7}Be(d,p)^{8}Be(2α) : first measurements at BBN energies *[Rijal+ 2019]* to replace *CF88*, but no effect on ^{7}Li
- ❑ reminder : ^{7}Be+^{3}He, +^{4}He no “Hoyle” level *[Hammache+ 2013]*

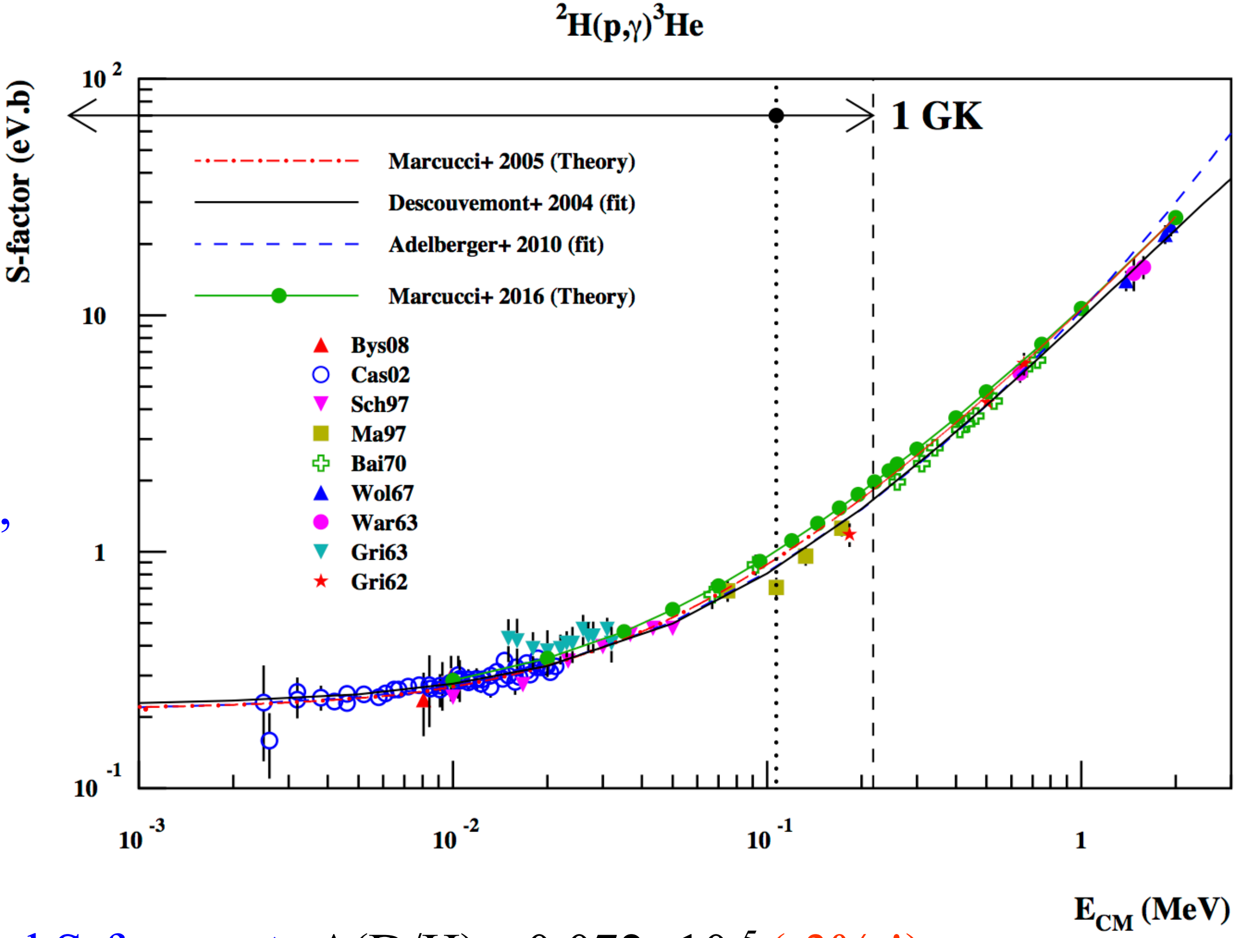
*Being (re-)evaluated *[de Souza, Iliadis et al.]*

Precision needed in reaction rate

$D(p,\gamma)^3He$ reaction rate need to be known at the % level to match the 1.2% precision on observations!

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

- New S-factor from theory, *[Marcucci+ 2016]*
- New experimental results, to appear soon, from:
  - LUNA
  - Jožef Stefan Institute



Marcucci+ 2016 theoretical S-factor ⇒ $\Delta(\mathrm{D/H}) = -0.072\times10^{-5}$ (-3% !)

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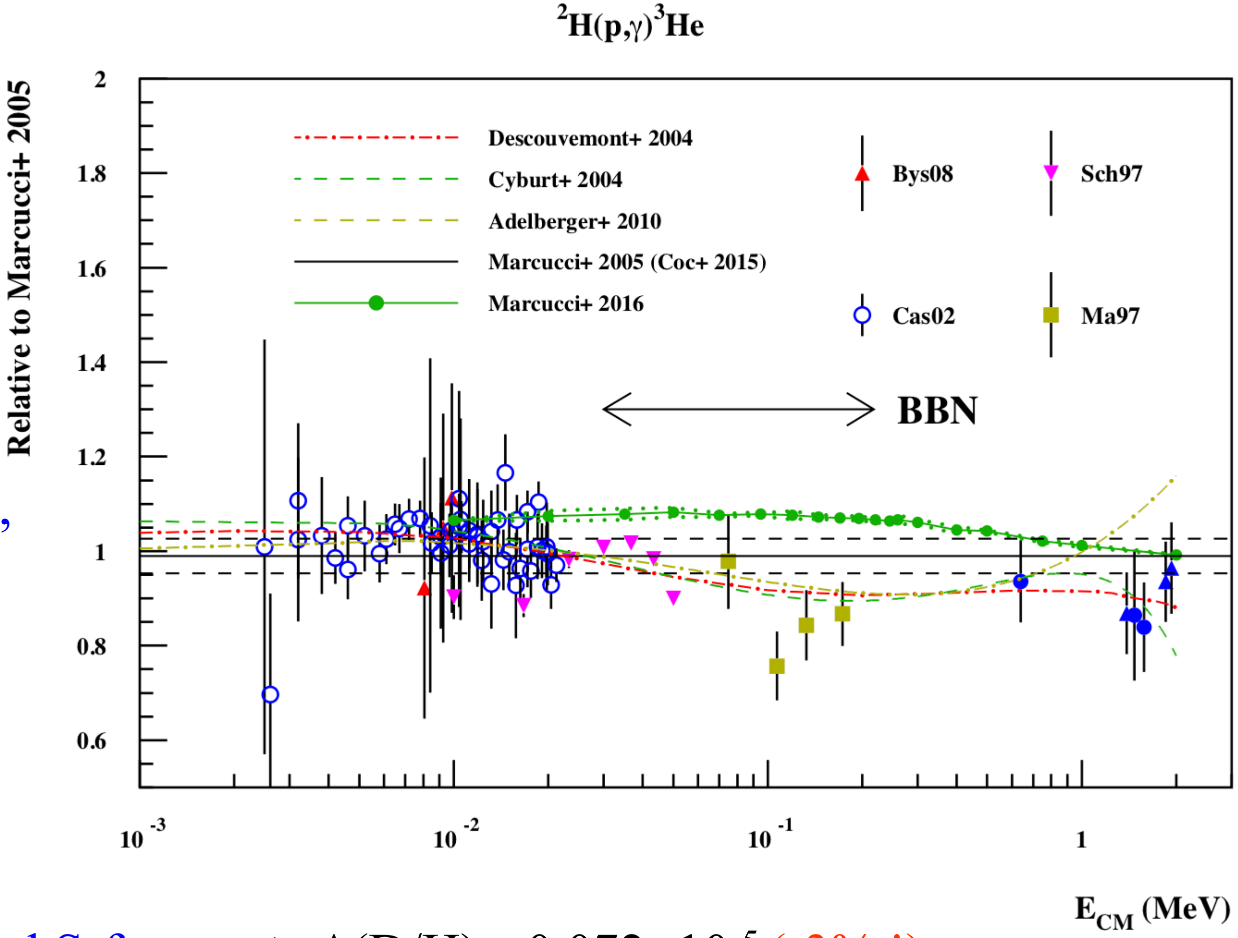
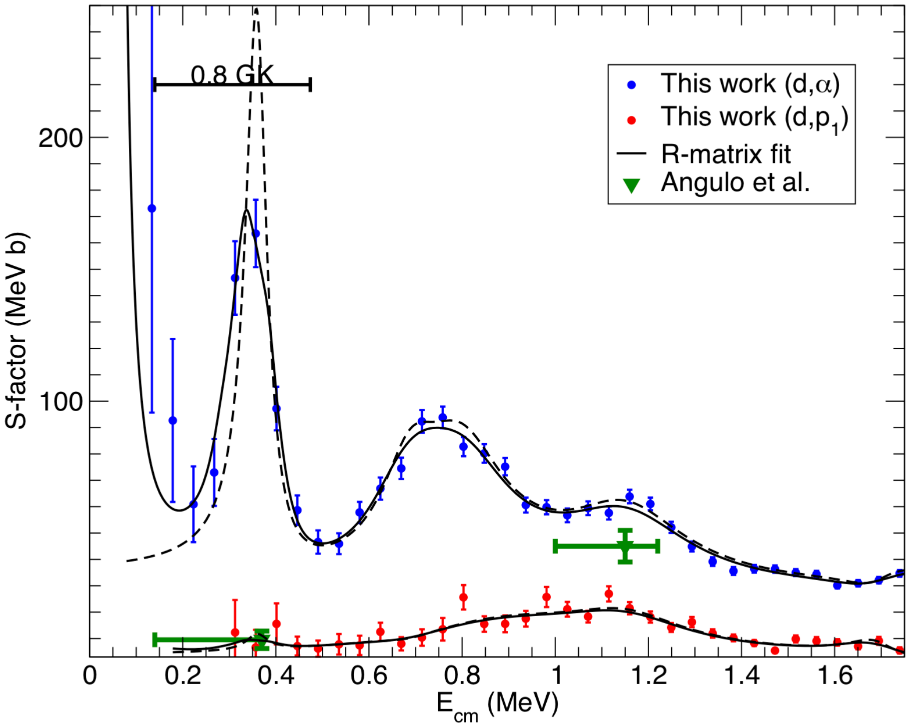
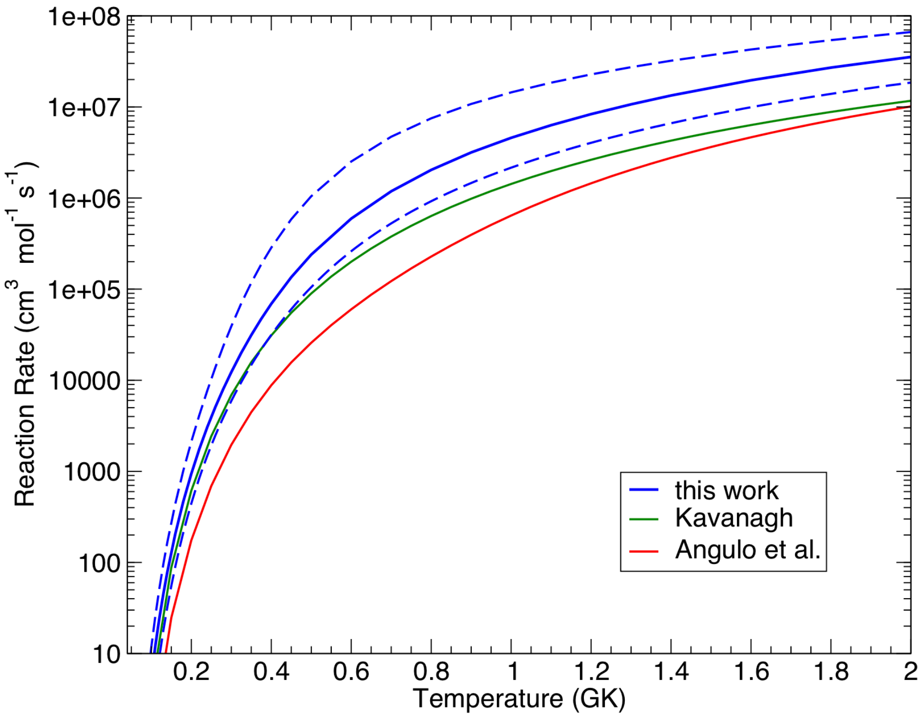


Marcucci+ 2016 theoretical S-factor ⇒ Δ(D/H)=-0.072×10^{-5} (-3% !)

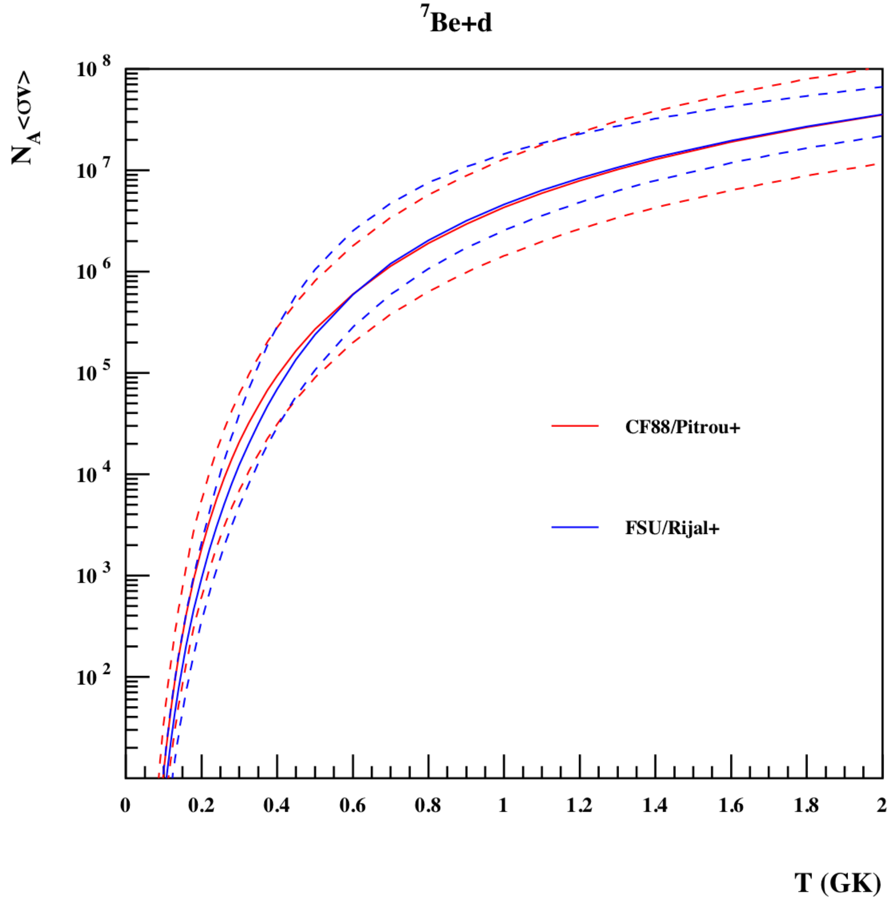
The ^{7}Be+d reactions

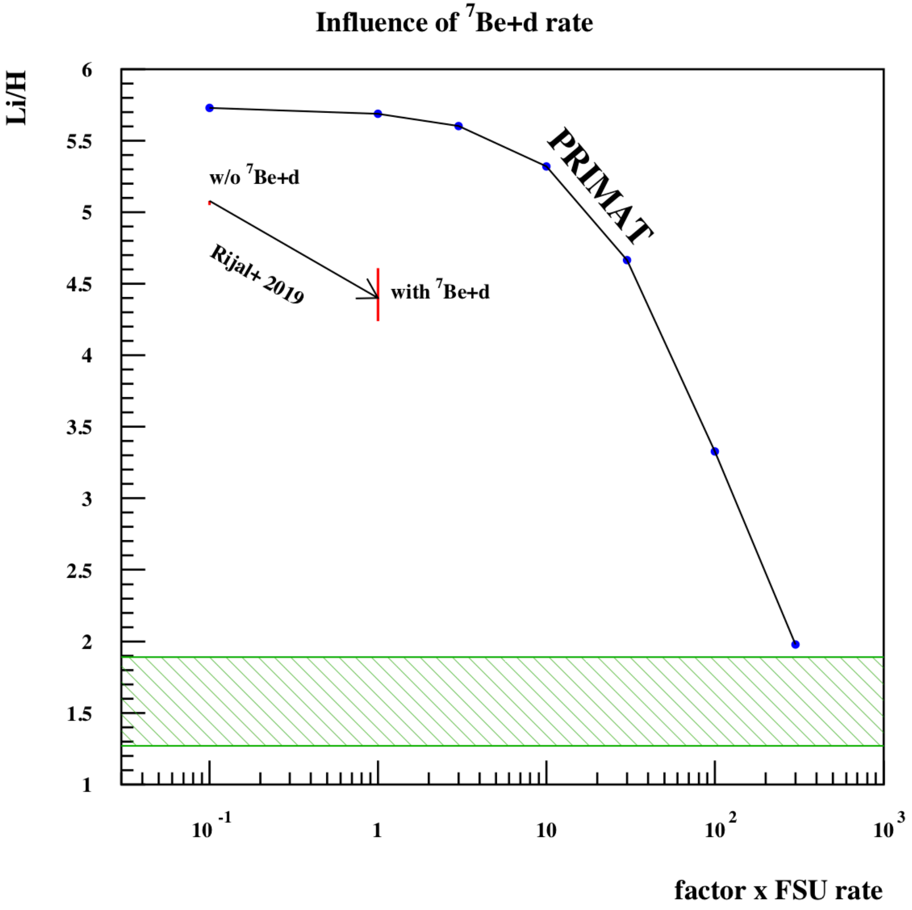
- S-factor ≈ 30 MeV.b *[Kavanagh 1960]* above BBN energies
- ^{7}Be(d,p)^{8}Be(2α) S(E_{BBN})≈ 10 MeV.b *[Angulo+ 2005]*
- Resonance? *[Chakraborty+ 2011; Cyburt & Pospelov 2009]*
- No! *[O'Malley+ 2011; Scholl+ 2011; Kirsebom & Davids 2011]*
- Yes! in ^{7}Be(d,α)^{5}Li(pα) channel *[Rijal+ 2019]* a factor of 3 increase w.r.t. *Kavanagh's* "rate"





Influence of the ^{7}Be+d rate





- No *Kavanagh* or *Angulo* “rate”; only a *Caughlan & Fowler 1988 (CF88)* rate with a factor of 3 increase w.r.t. *Kavanagh’s* data
- *PRIMAT* uses *CF88* an uncertainty factor of 3 i.e. ≈ *Rijal’s* rate!
- Need a factor of ≈100 more *[Coc+ 2004; 2011]*

Conclusions

- Standard BBN is now in the (1%) precision era for D and ^{4}He
  - Precision deuterium observations (plateau ?) call for
  - even better precision on D(p,γ)^{3}He, D(d,n)^{3}He and D(d,p)^{3}H cross sections
  - Corrections to the weak rates and improved neutron lifetime for ^{4}He
- However the lithium problem is worse than ever!
  - Disagreement (factor of 3) with Li observations
    - Nuclear : excluded by experiments
    - Cosmology or particle physics solutions overproduce deuterium
    - Stellar depletion, seemingly unavoidable, needs to be uniform
- Convergence of BBN codes when same nuclear reaction rates are used
  - Mathematica versus (±independent) Fortran versions
  - Mathematica code with >400 reaction network publicly available at http://www2.iap.fr/users/pitrou/primat.htm

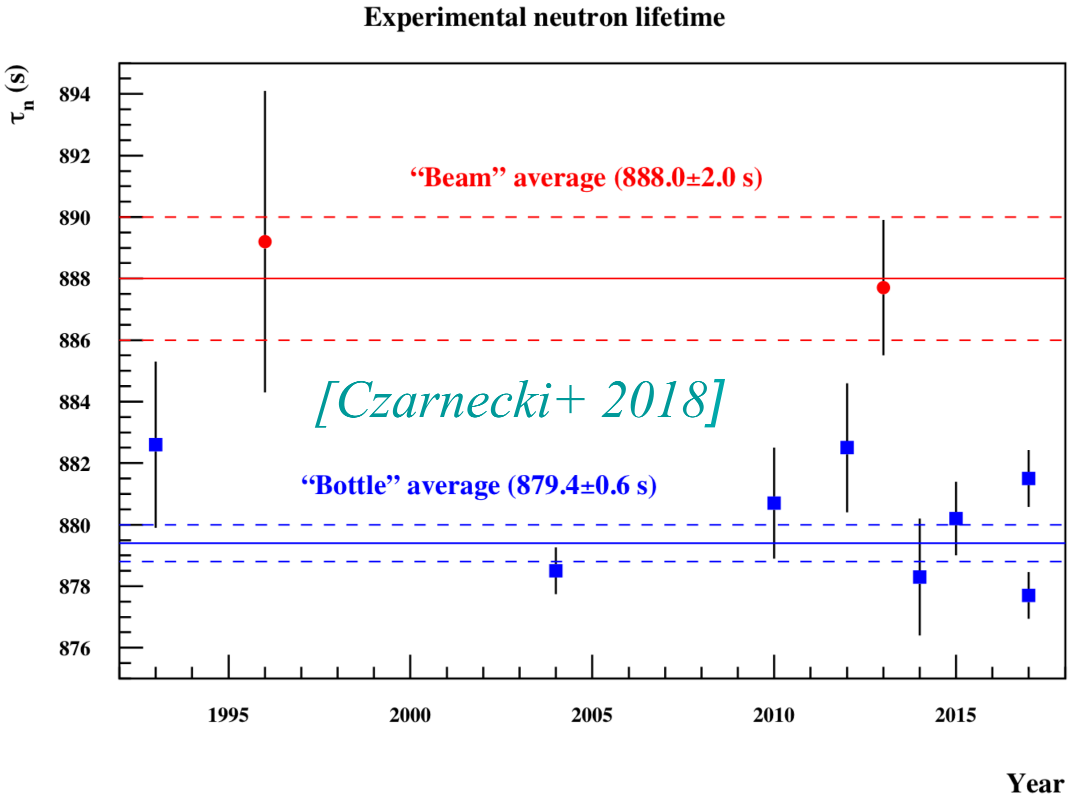
Neutron lifetime and the weak rates

Significant (3.8σ *[Pignol 2015]*) difference between:

- "beam" (protons from **beta decay only** counting) and
- "bottle" (surviving neutron counting)

experiments originating from

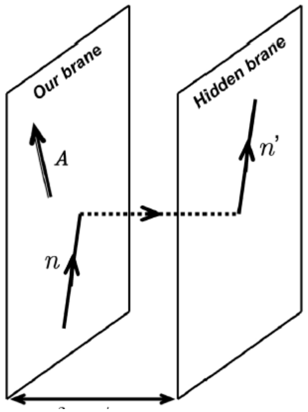
- unknown systematics or
- neutron disappearence in an other (brane/mirror) world *[Sarazin+ 2012]* or decay to DM *[Fornal & Grinstein 2018]*

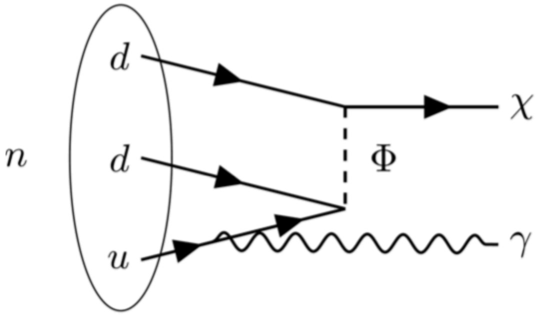


[Czarnecki+ 2018]

In BBN governed by "surviving" neutrons like in "bottle" experiments

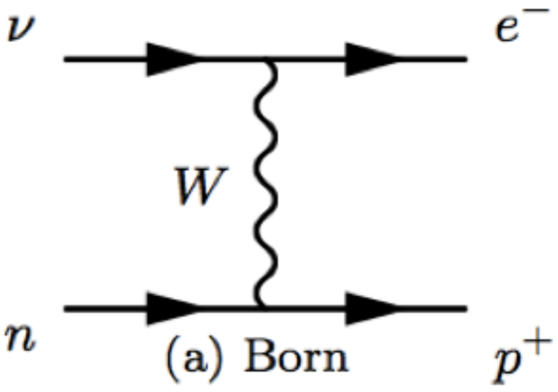
Using τ_n=879.5±0.8 s *[Serebrov+ 2017; W. Marciano priv. comm.]*, close to average of "bottle" experiments (τ_n=880.2±1.0 s in *PDG 2017*)





Interaction Hamiltonian

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



(a) Born

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

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

Axial current coupling

Weak-Magnetism