Precision Big-Bang Nucleosynthesis with improved He-4 predictions

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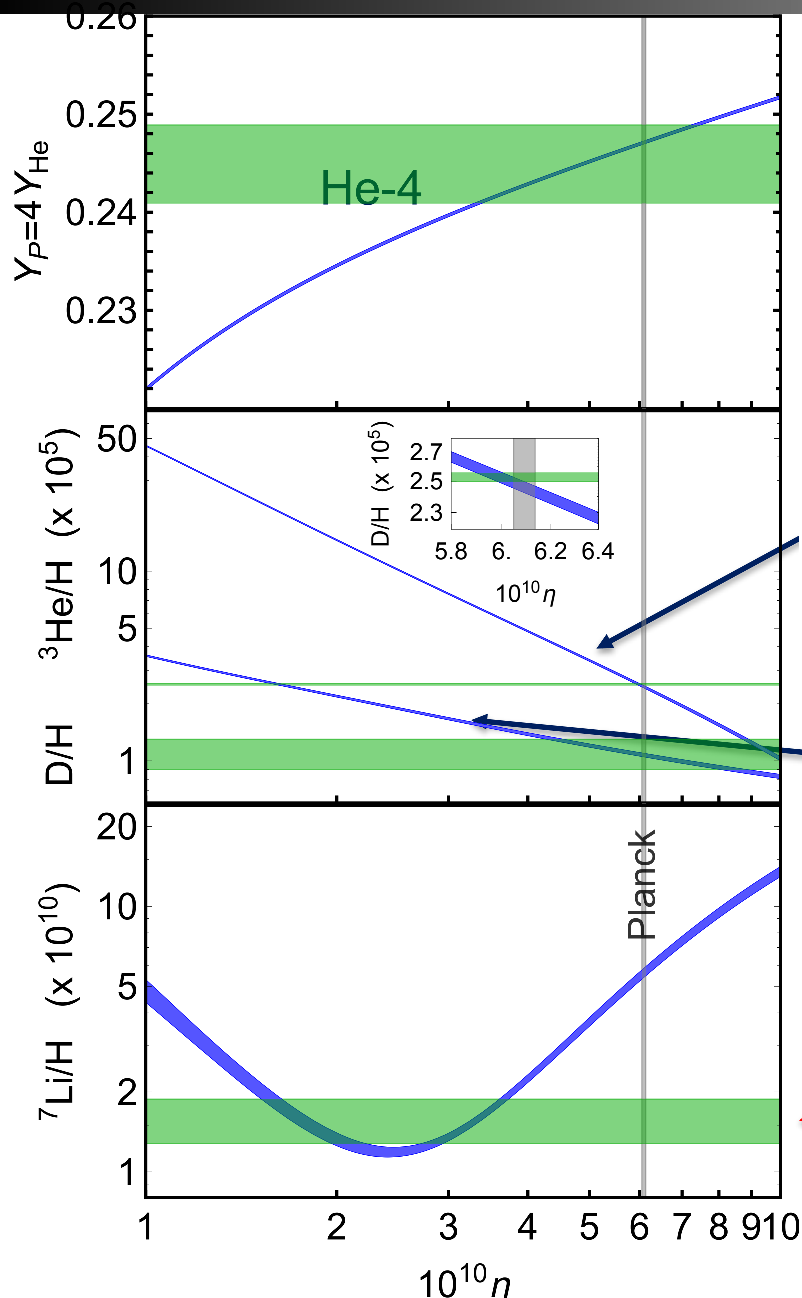
PRIMAT http://www2.iap.fr/users/pitrou/primat.htm (1801.08023)

Why precision for BBN ?



Baryons abundance

Aver et al. 2015

$$Y_P = 0.2449 \pm 0.0040\,,$$ 1.6 %

Deuterium

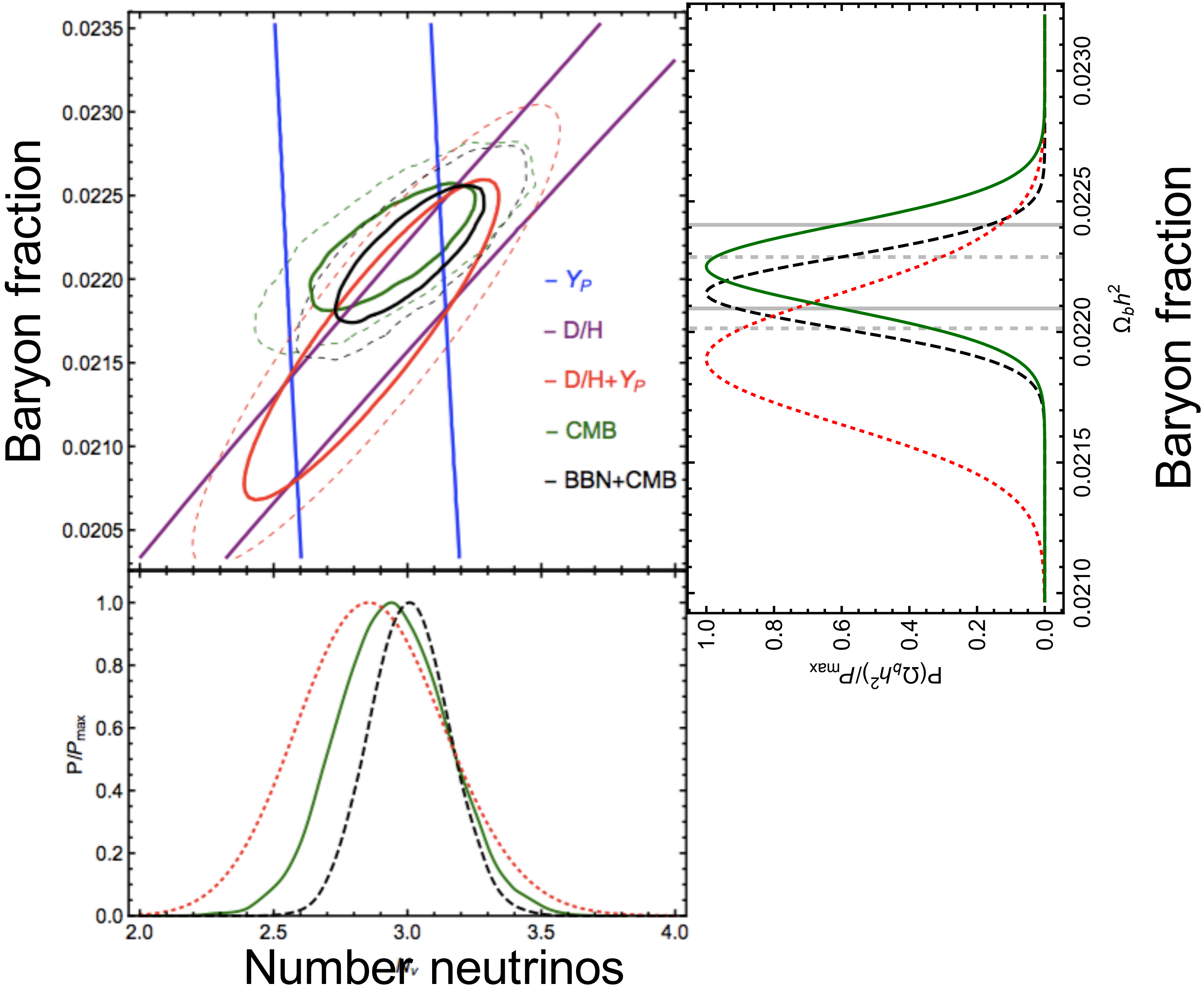
$$D/H = (2.527 \pm 0.030) \times 10^{-5}$$ 1.2 %

Cooke et al. 2017

He-3

Li-7

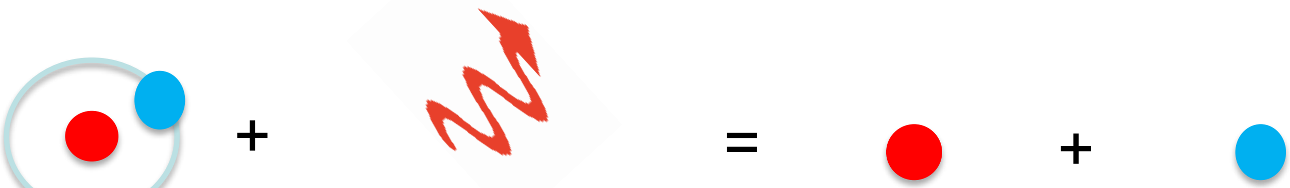
Lithium problem



Baryon fraction
0.0235
0.0230
0.0225
0.0220
0.0215
0.0210
0.0205
– Y_P
– D/H
– D/H+Y_P
– CMB
– BBN+CMB
P/P_{max}
1.0
0.8
0.6
0.4
0.2
0.0
2.0
2.5
3.0
3.5
4.0
Number neutrinos
$P(\Omega_b h^2)/P_{max}$
$\Omega_b h^2$
Baryon fraction

Typical BBN energies

Chemical reaction

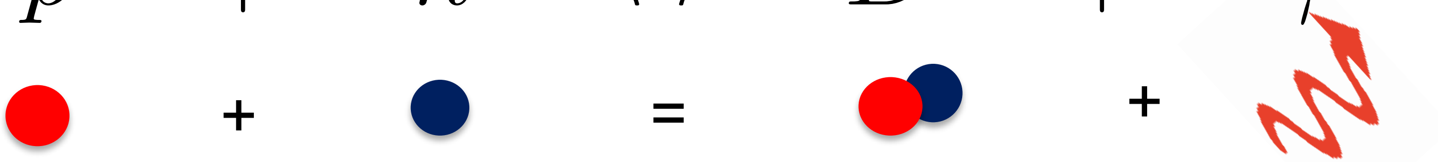


$$E = 13.6eV$$

$$H \quad + \quad \gamma \quad \leftrightarrow \quad p^{+} \quad + \quad e^{-}$$

Nuclear reaction

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

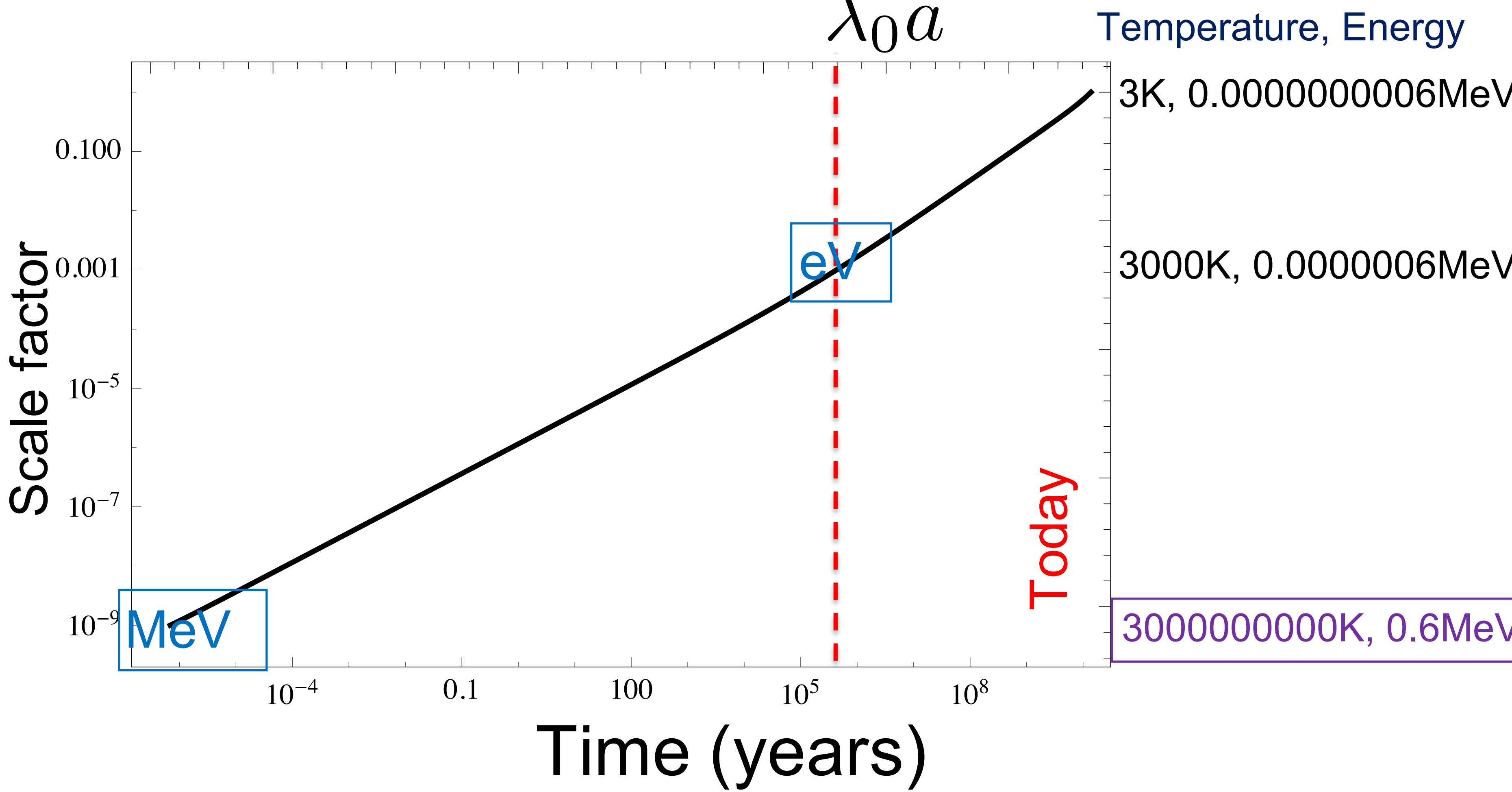


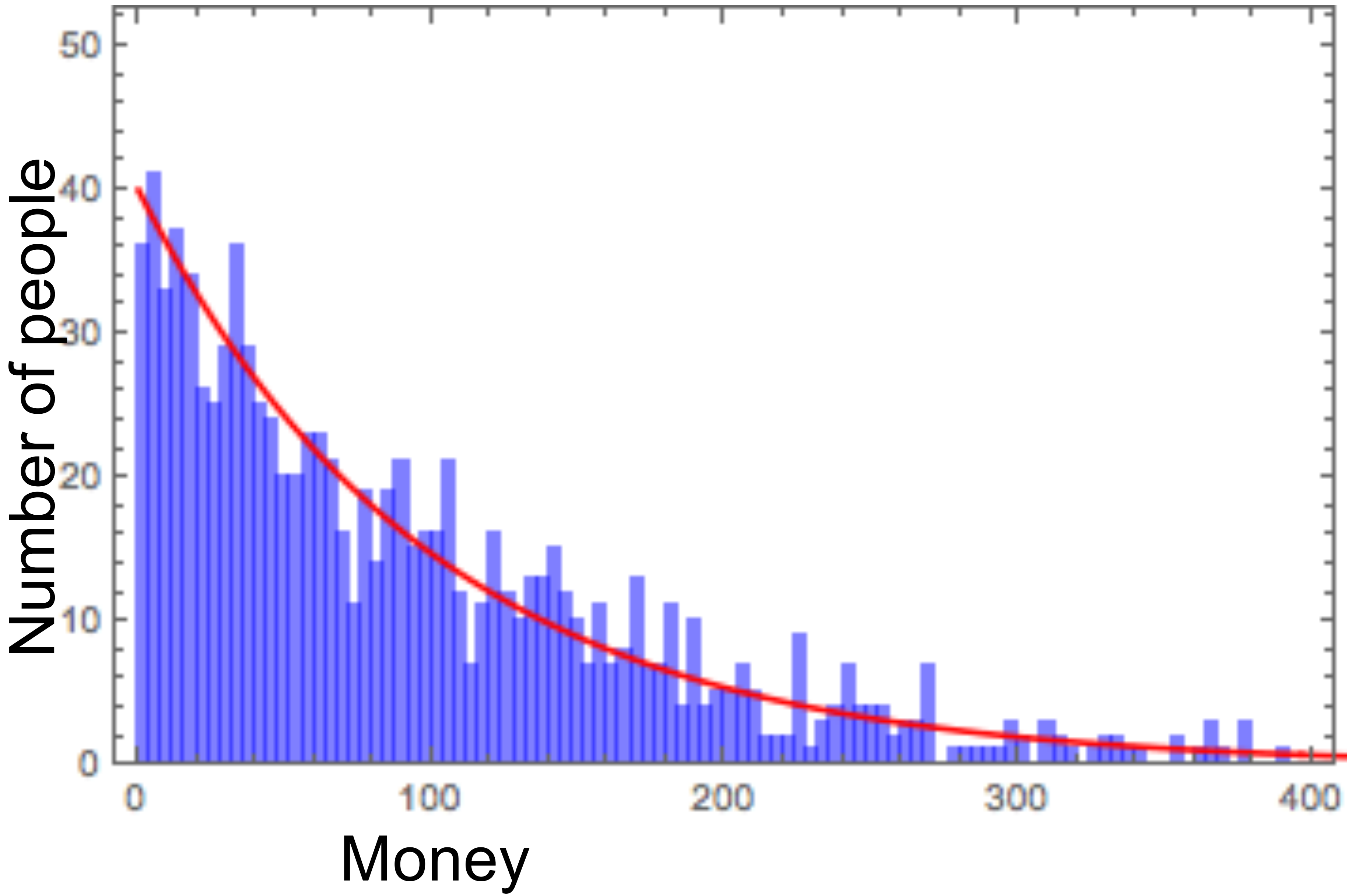
$$2.2MeV = 2220000eV$$

938.2 + 939.5 = 1875.5 + 2.2

Cosmic scaling

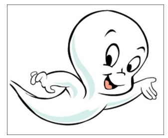
$$E = 2.70\, k_B T = \frac{hc}{\lambda_0 a}$$




Number of people
Money
0
10
20
30
40
50
0
100
200
300
400

Neutron abundances

Weak interactions

+  = +

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

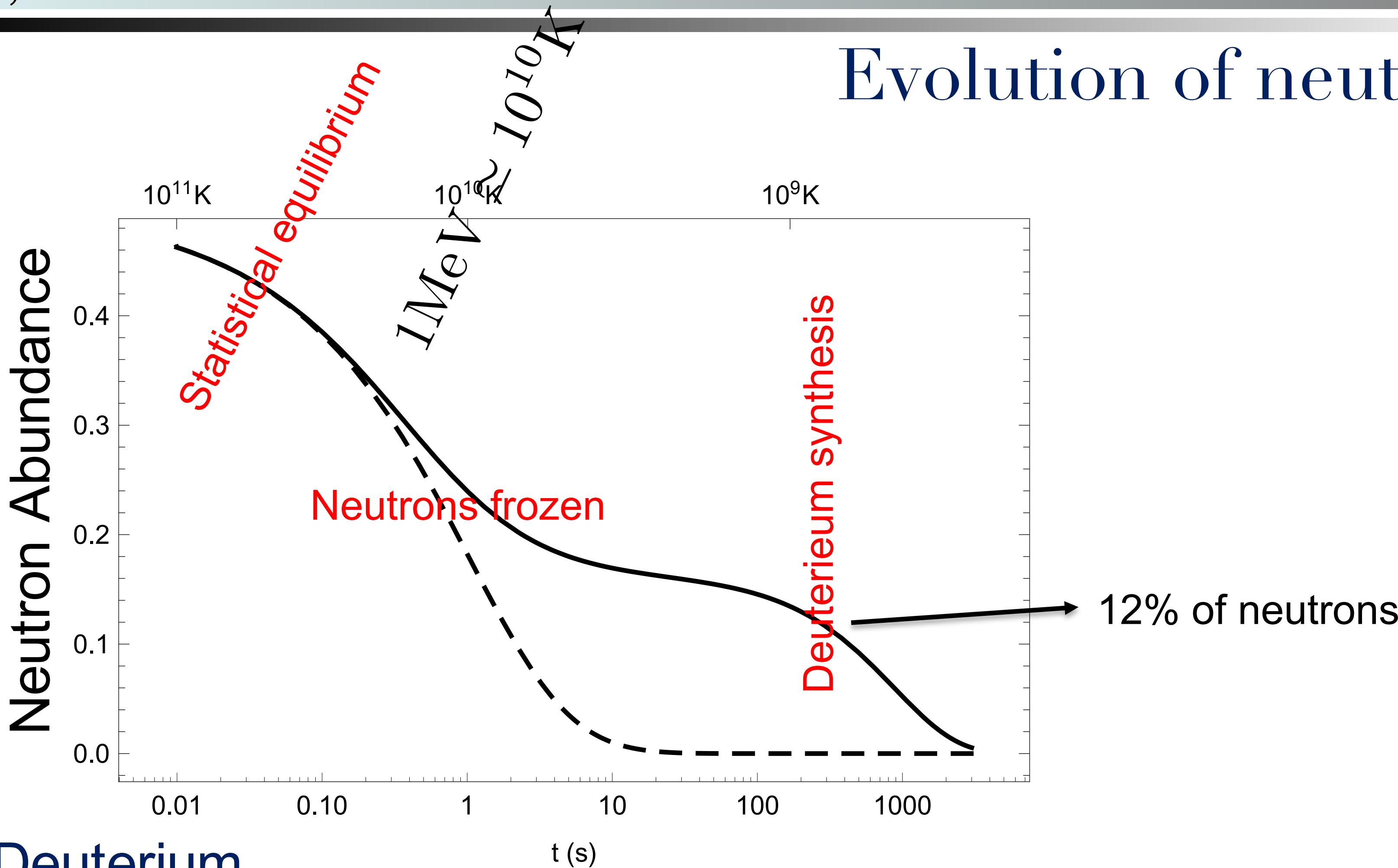
If enough interactions, then statistical equilibrium

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

Protons $$n = \mathrm{e}^{-\frac{938.2}{k_B T}}$$

Neutrons $$n = \mathrm{e}^{-\frac{939.5}{k_B T}} = \mathrm{e}^{-\frac{938.2}{k_B T}} \mathrm{e}^{-\frac{1.3}{k_B T}}$$

Evolution of neutrons



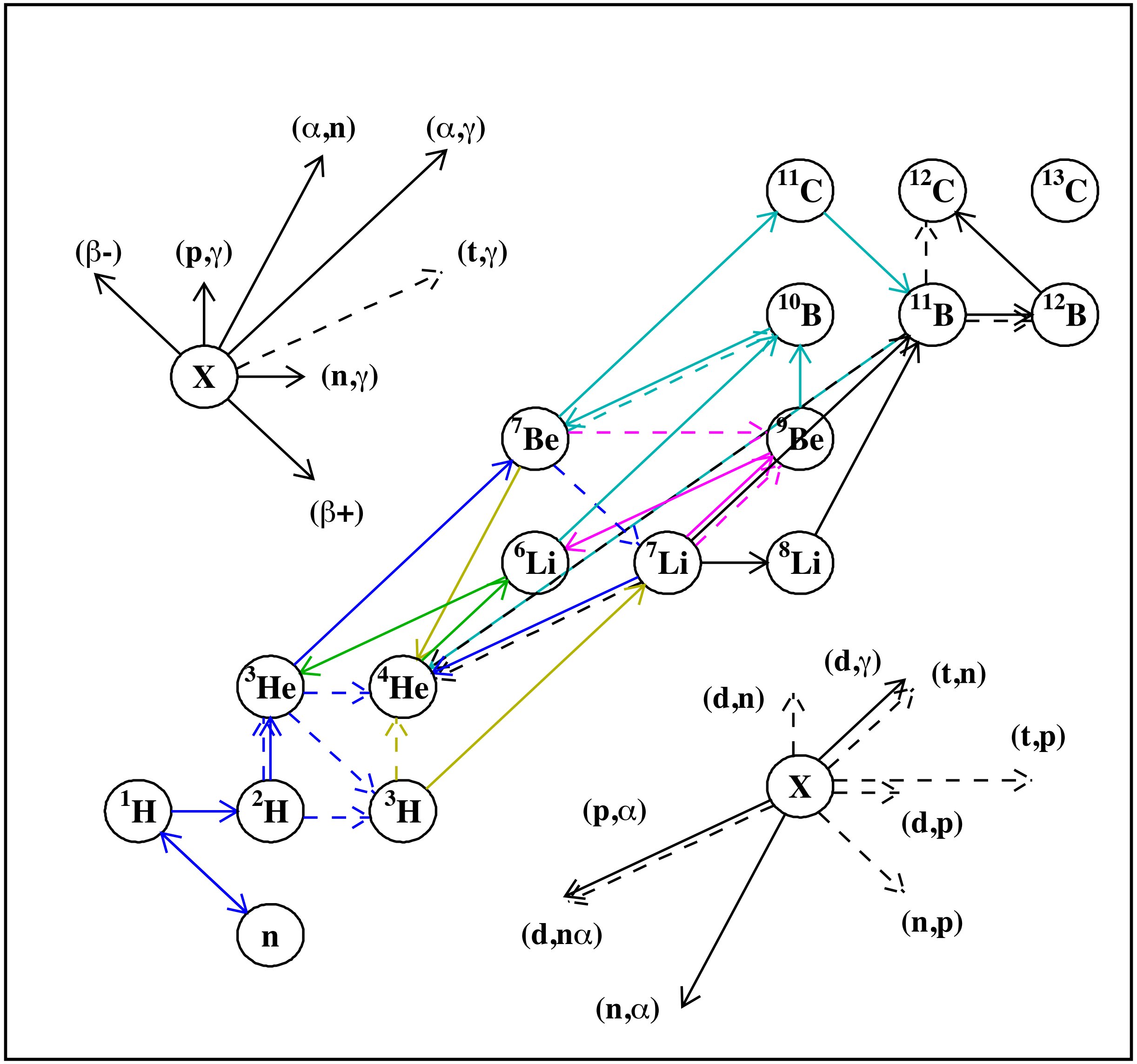
Deuterium

Baryons : $2.4\ 10^{-7}\,\mathrm{cm}^{-3}$

Photons : $411\,\mathrm{cm}^{-3}$

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

Other reactions

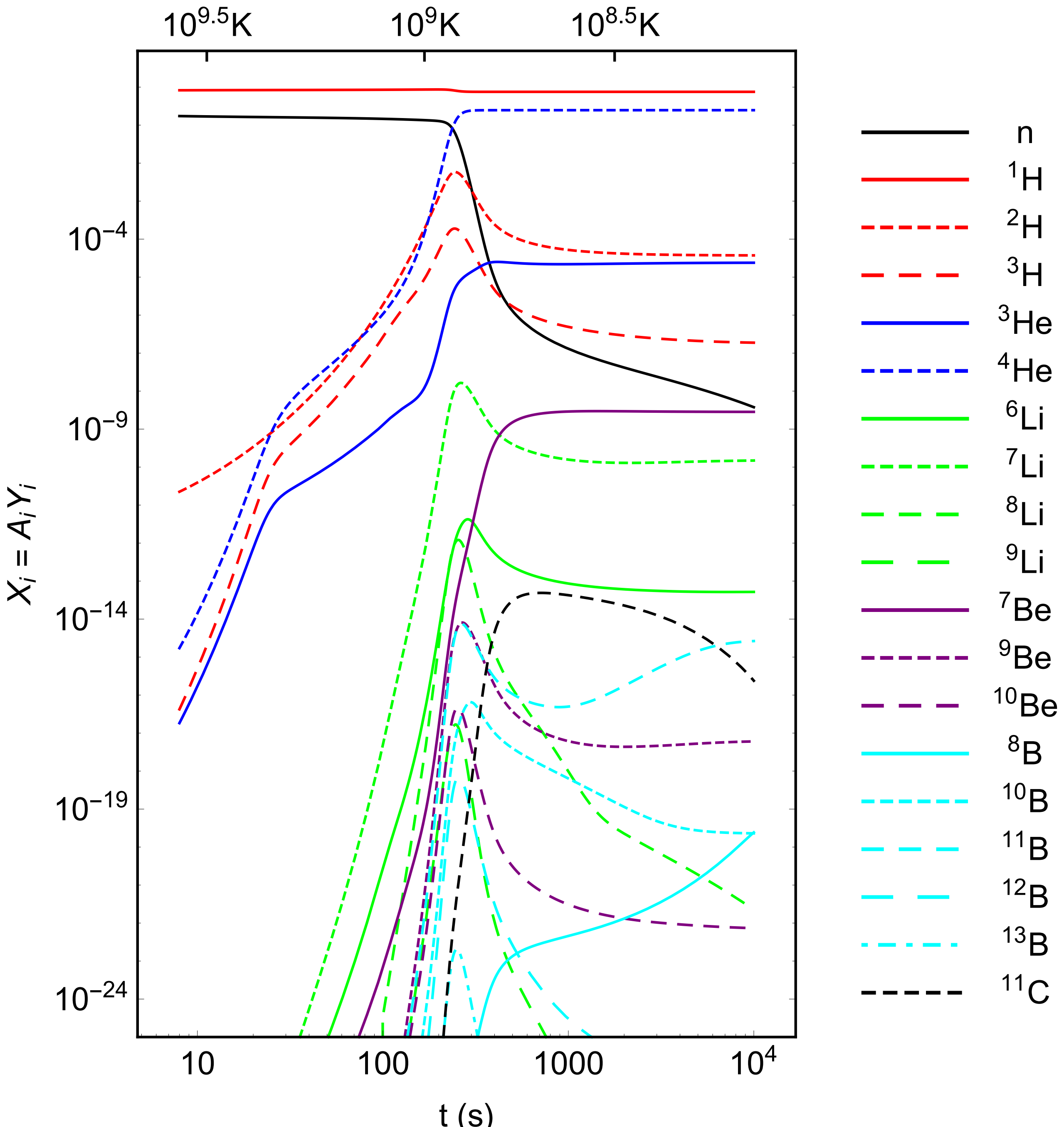


Nuclear Reactions

$$Y_i \equiv \frac{n_i}{n_{\rm tot}}$$

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

Creation Destruction


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

Precision BBN

Numerical Method

1) Solve for plasma (and cosmology) t, a, T

2) Compute weak rates *with all small corrections*

3) Solve nuclear network (uncertainty on nuclear rates)

Plasma thermodynamics

$$sa^3 = \mathrm{Cte} \qquad s = \frac{\rho + P}{T}$$

Conservation of Entropy

$$a(T) \leftrightarrow T(a)$$

Solve for cosmological evolution

$$\rho_{\rm plasma} = \rho_{e^+} + \rho_{e^-} + \rho_\gamma$$

$$\rho_{\rm rad} = \rho_{\rm neutrinos} + \rho_{\rm plasma}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{\rm tot}(T(a))$$

Allows to obtain a(t) and t(a)

QED Plasma effects

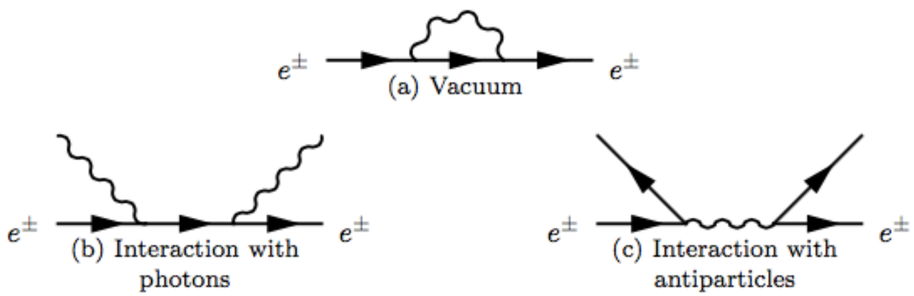


FIG. 5 *Top :* electron/positron self-energy. *Bottom :* electron/positron mass shift from interaction with plasma.

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

Incomplete decoupling of neutrinos

Around 0.511 MeV $e^+ + e^- \rightarrow 2\gamma$

However there are some residual $e^+ + e^- \rightarrow \nu + \bar{\nu}$

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

$$
\begin{aligned}
n+\nu &\leftrightarrow p+e^- \\
n &\leftrightarrow p+e^- + \bar{\nu} \\
n+e^+ &\leftrightarrow p+\bar{\nu}
\end{aligned}
$$

1) Born approximation

2) Finite nucleon mass effects

3) Radiative corrections at T=0 (virtual photons)

4) True photons corrections (bremsstrahlung)

5) Finite temperature radiative corrections

BORN approximation method

$$E_n - E_p = \Delta + \delta Q$$

$$\Delta = m_n - m_p.$$

Born order

Finite nucleon mass corrections

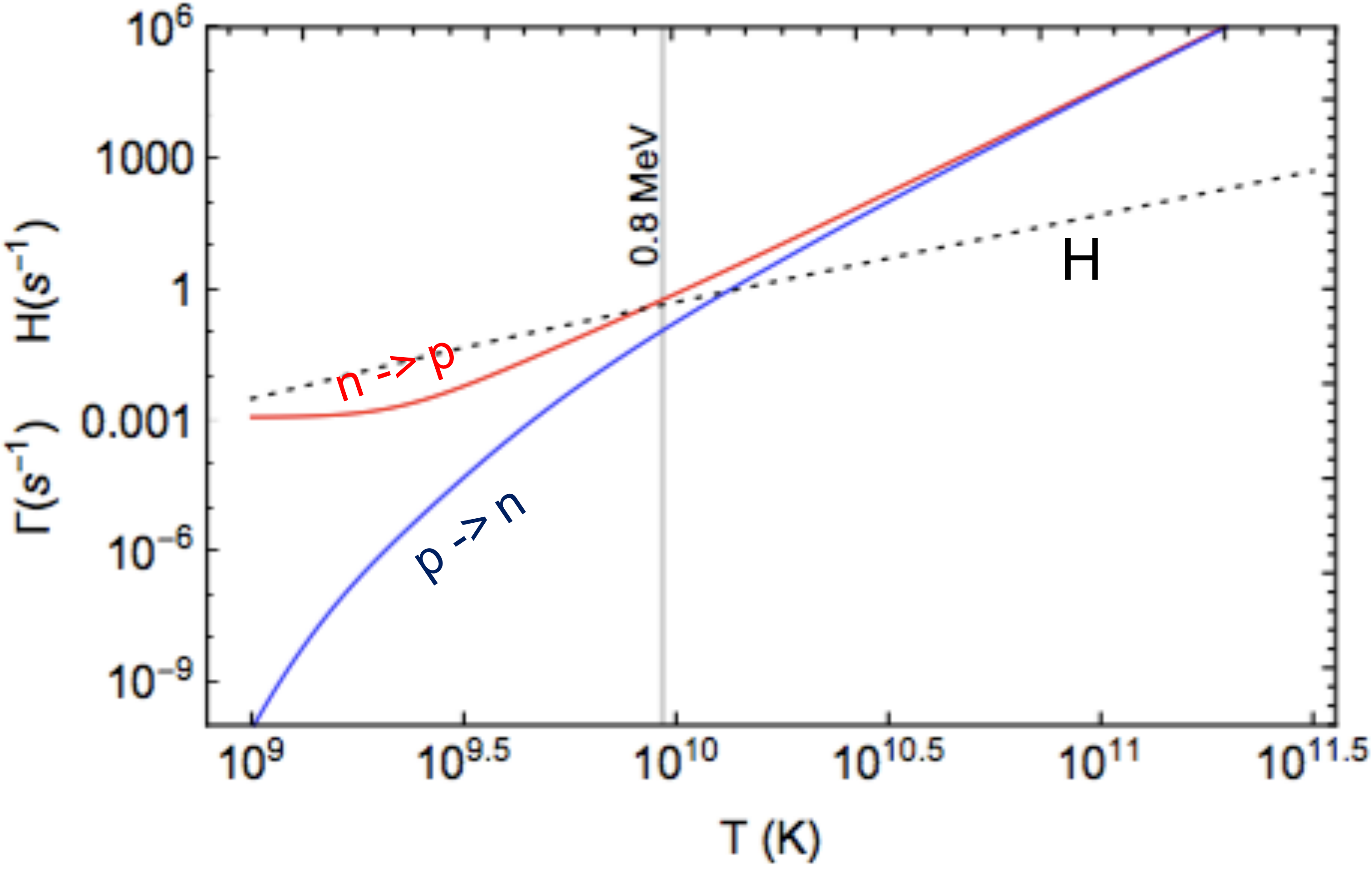
$$\delta(E_n - E_p + E_\nu - E_e) = \delta(\Sigma) + \delta'(\Sigma)\delta Q + \frac{1}{2}\delta''(\Sigma)(\delta Q)^2 + \dots$$

$$\Sigma \equiv \Delta + E_\nu - E_e$$

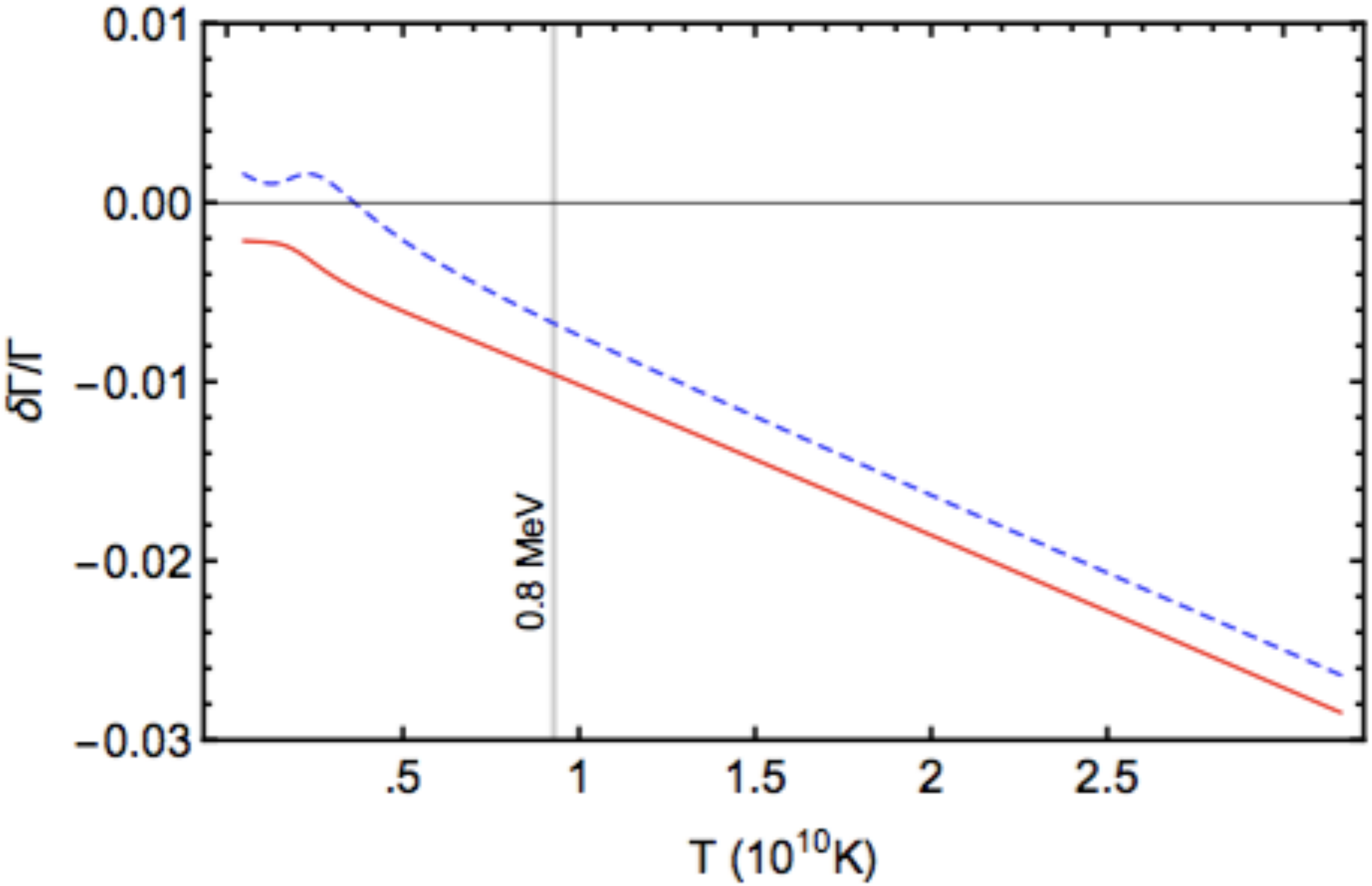
Same kind of expansion for the matrix element $|M|^2$

$$\Gamma_{n\to p} = \bar{\Gamma}_{n\to p} + \delta\Gamma_{n\to p}$$

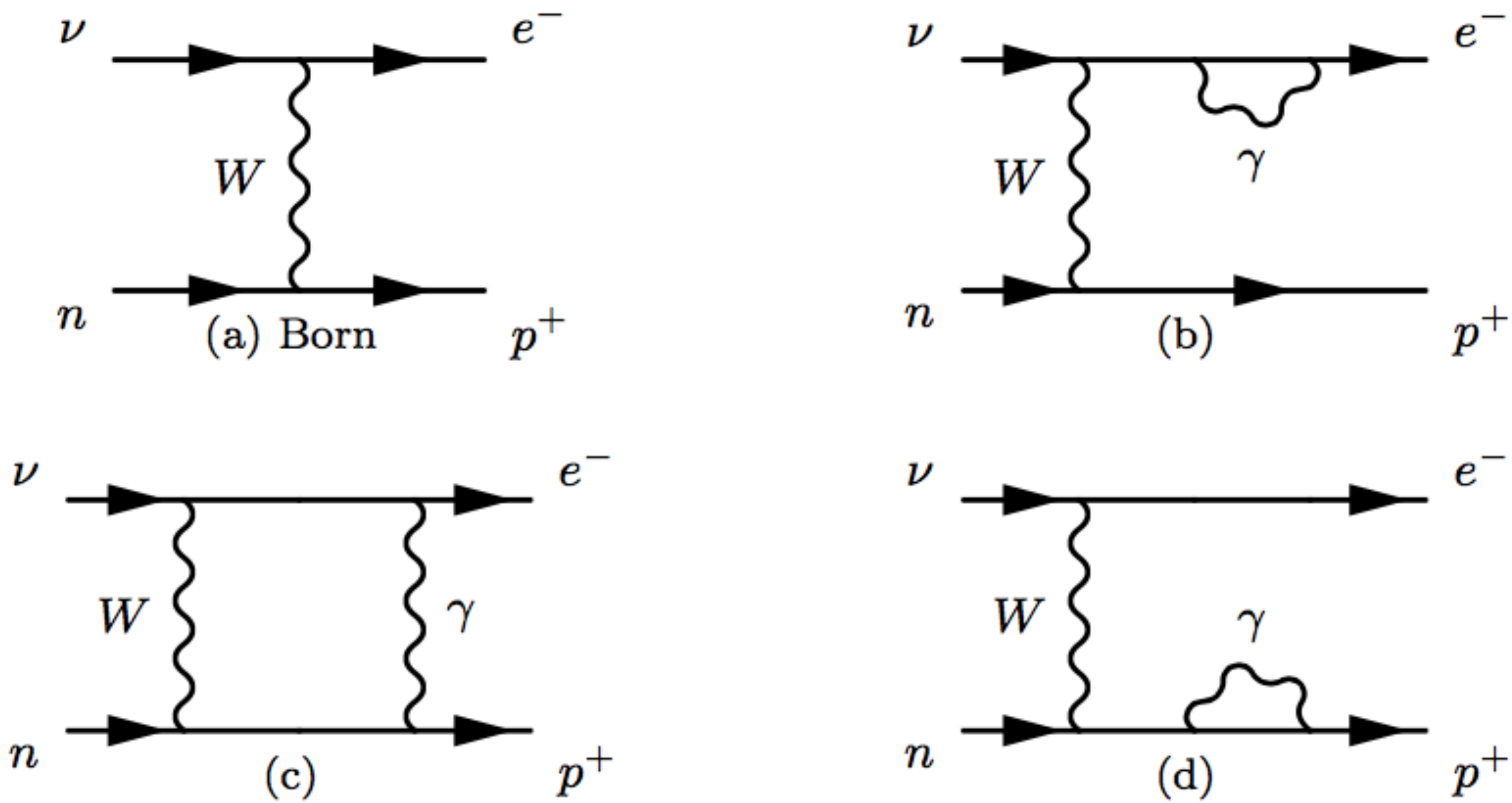
BORN approximation rates



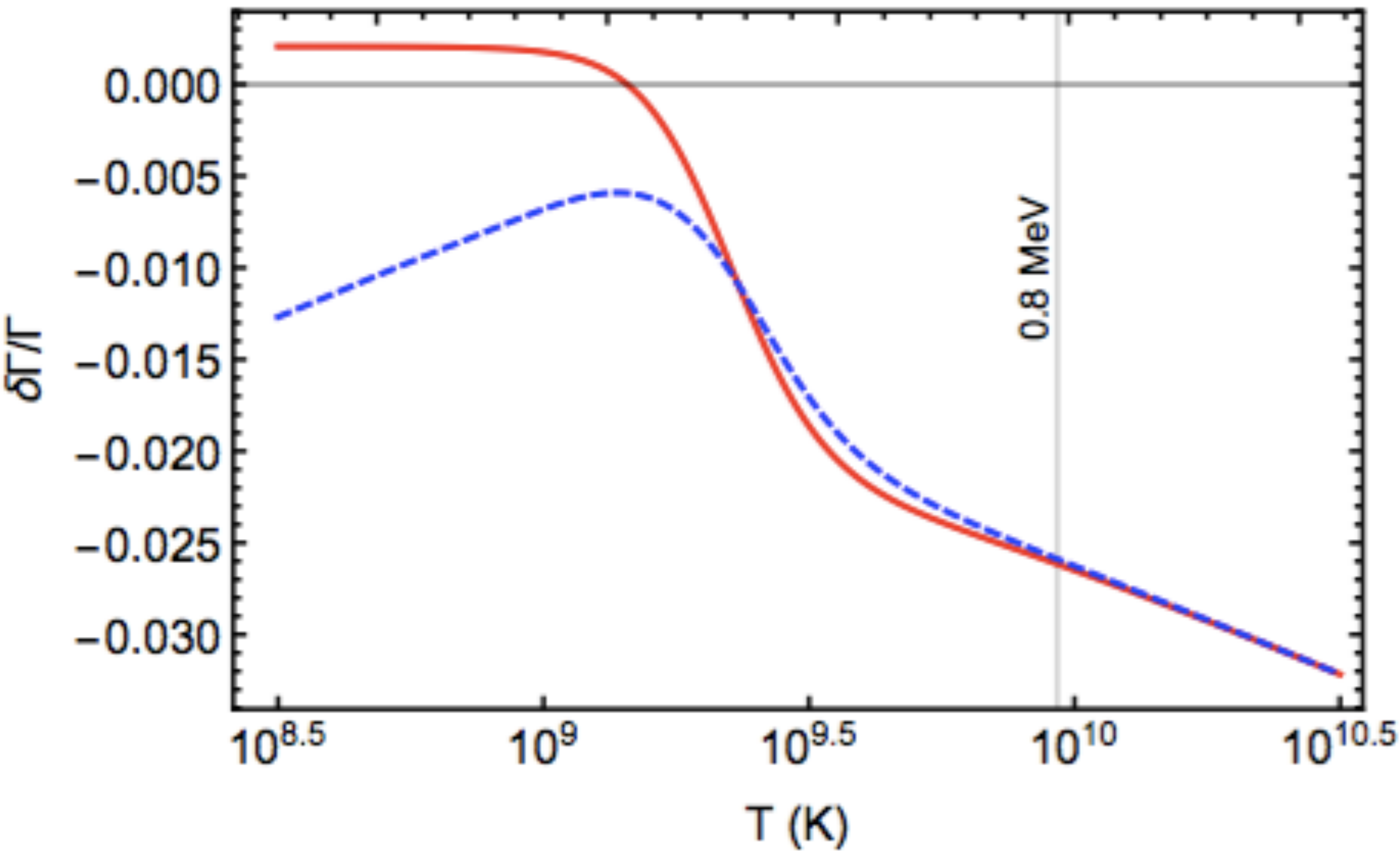
Finite nucleon mass corrections



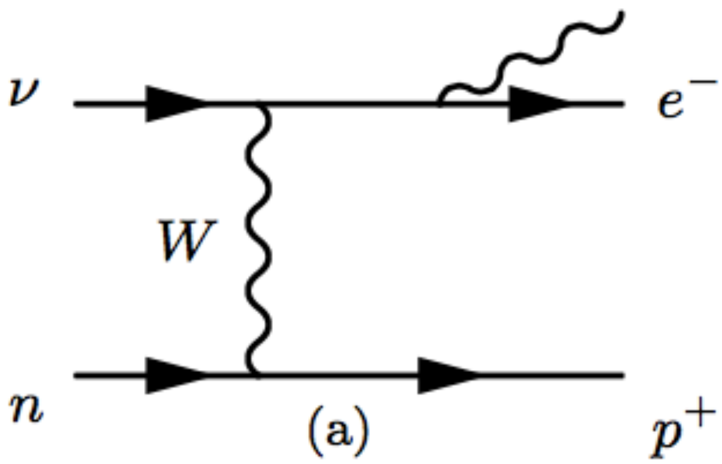
Radiative corrections

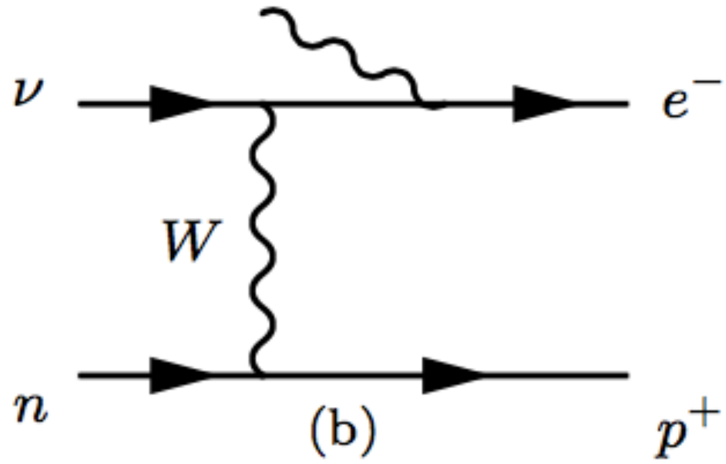


Radiative corrections

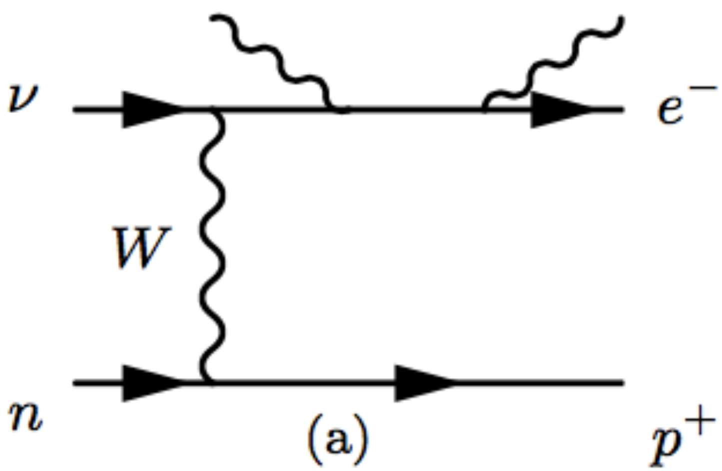


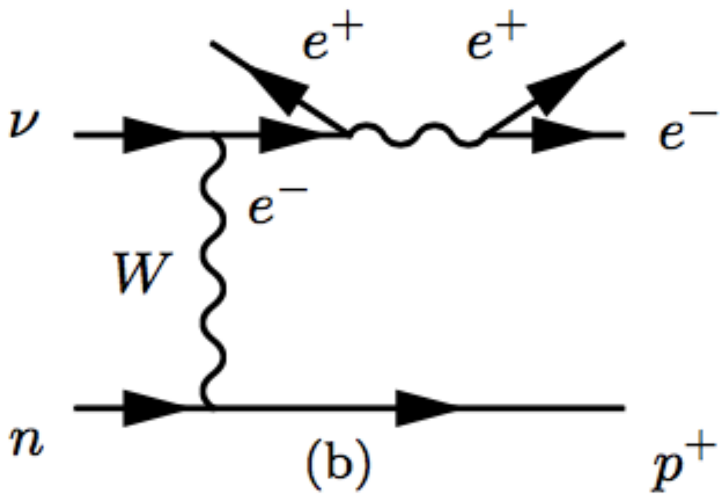
True photons



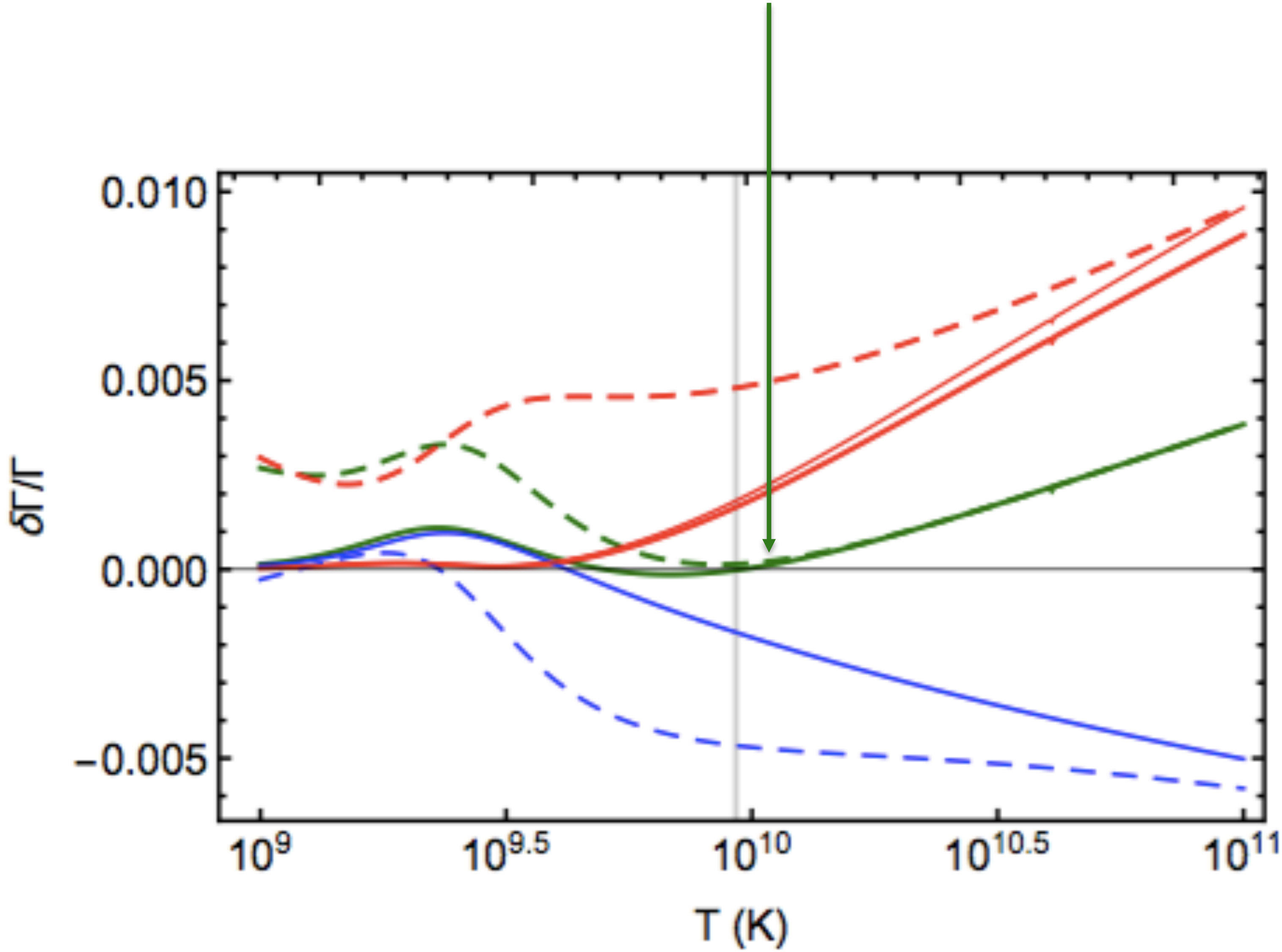


Finite Temperature corrections

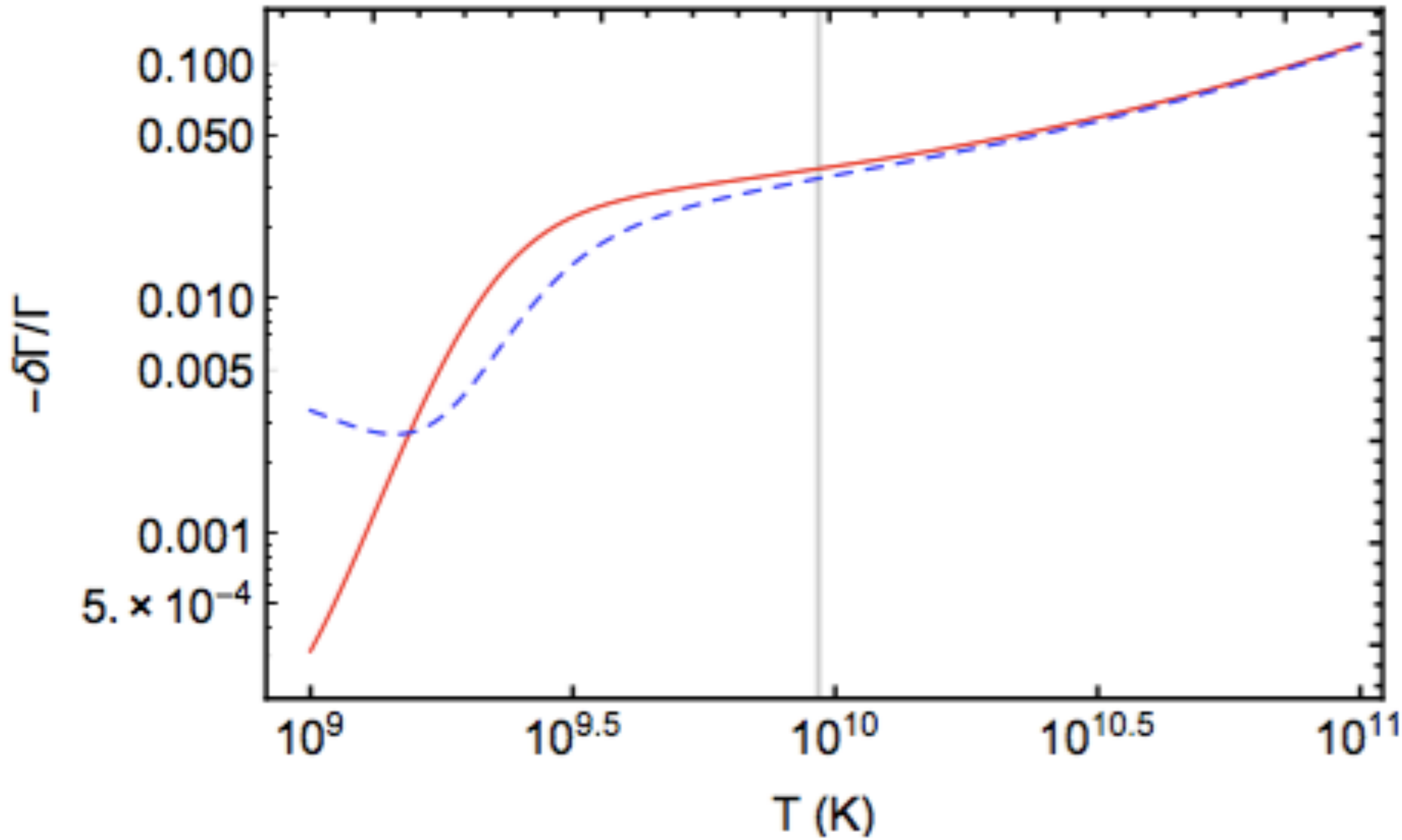




True photons and Finite temperature corrections



Total corrections



Size of corrections

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

Corrections	Y_P	$\delta Y_P \times 10^4$	$\delta Y_P/Y_P(\%)$	$D/H \times 10^5$	Δ (D/H) (%)	$^3He/H \times 10^5$	$^7Li/H \times 10^{10}$
Born	0.24276	0	0	2.424	0	1.069	5.637
Born+ID	0.24289	1.2	0.05	2.433	0.37	1.070	5.615
Born+FM	0.24388	11.2	0.46	2.430	0.25	1.070	5.654
Born+FM+WM	0.24404	12.5	0.53	2.431	0.29	1.070	5.657
RCa [Eq. (B30), Non. Rel. Fermi]	0.24586	31.0	1.27	2.441	0.70	1.071	5.684
RCb [Eq. (B35), Non. Rel. Fermi]	0.24589	31.3	1.29	2.441	0.70	1.071	5.685
RC [Eq. (B35), Rel. Fermi]	0.24591	31.5	1.30	2.441	0.70	1.071	5.685
RC+QED-MS	0.24602	32.9	1.36	2.442	0.74	1.071	5.687
RC+QED-Pl	0.24591	31.5	1.30	2.444	0.82	1.072	5.677
RC+ID	0.24602	32.6	1.34	2.450	1.07	1.073	5.663
RC+ID+QED-Pl	0.24602	32.6	1.34	2.453	1.19	1.073	5.655
RC+FM+WM	0.24720	44.4	1.83	2.448	0.99	1.072	5.704
RC+FM+WM+QED-MS	0.24733	45.7	1.88	2.449	1.03	1.073	5.706
RC+FM+WM+QED-Pl	0.24719	44.3	1.82	2.451	1.11	1.073	5.696
RC+FM+WM+ID	0.24725	44.9	1.85	2.457	1.36	1.074	5.681
RC+FM+WM+ThRC (No BS)	0.24751	47.5	1.96	2.450	1.07	1.073	5.709
RC+FM+WM+ThRC+BS	0.24720	44.4	1.83	2.448	0.99	1.072	5.704
RC+FM+WM+ThRC+BS+ID+QED-Pl	0.24724	44.8	1.85	2.460	1.49	1.074	5.673

He-4 correction 1.85%

Deuterium correction 1.49%

Thank you