Primordial Nucleosynthesis

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(**C**entre de **S**ciences **N**ucléaires et de **S**ciences de la **M**atière, Orsay)

- ☐ The expansion of the Universe and the CMB
- ☐ Primordial abundances deduced from observations
- ☐ Thermal evolution and Standard Big Bang Nucleosynthesis
- ☐ The lithium × deuterium problem
- ☐ Improved ^{4}He predictions
- ☐ A new publicly available BBN code

The three observational evidences for the Big Bang Model

1. The expansion of the Universe

   Galaxies move away from each other according to Hubble's law:
   $V = H_0 \times D$ with $H_0 \approx 70$ km/s/Mpc, the Hubble parameter (or "constant").
   More precisely distances $\propto a(t)$, the cosmological scale factor

2. The Cosmic Microwave Background radiation (CMB)

   A black body radiation at 2.7 K corresponding to the redshifted spectrum emitted when the universe became transparent

3. Primordial nucleosynthesis

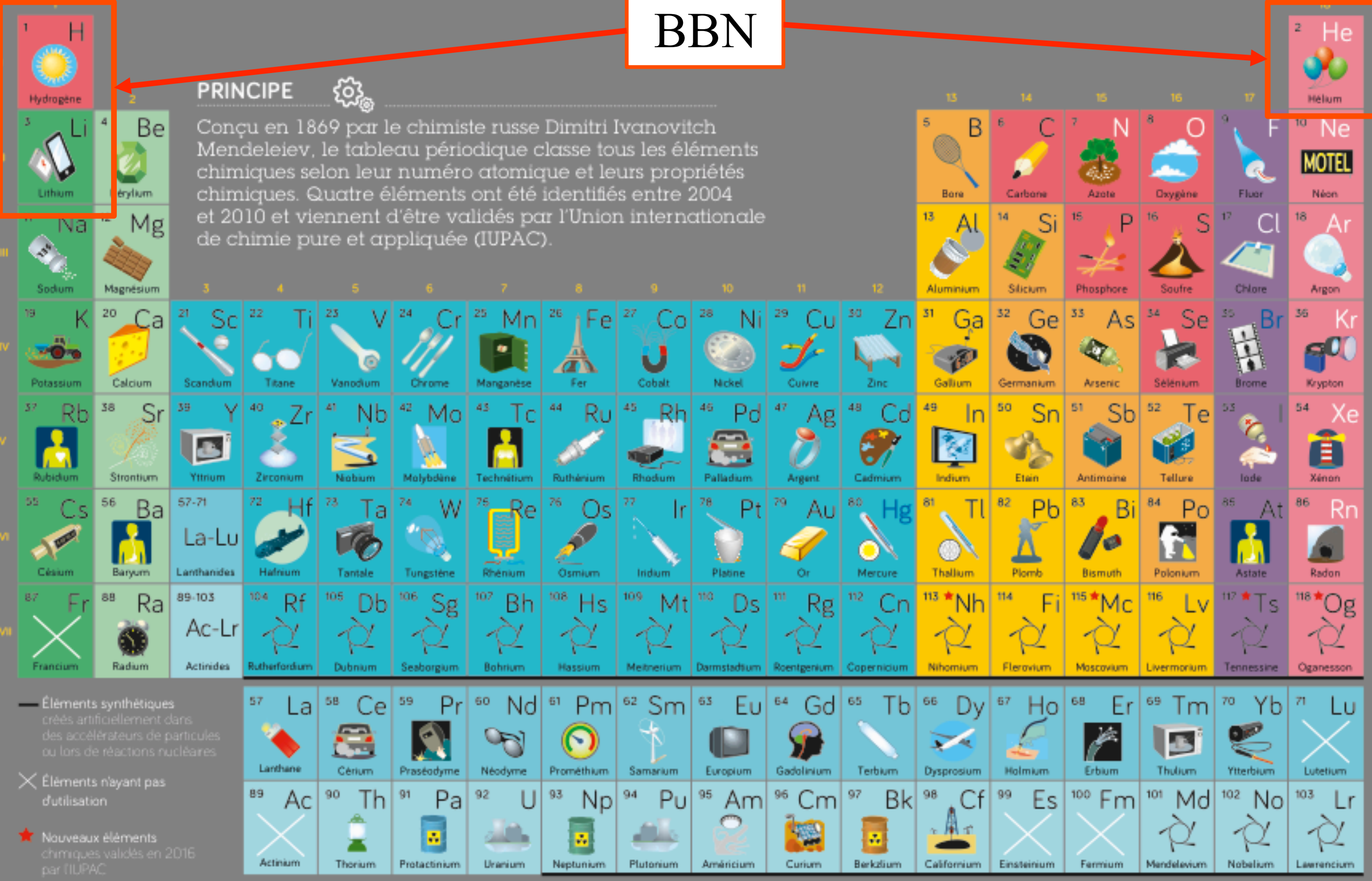
   Reproduces the "light-elements" (^{4}He, ^{2}H or D, ^{3}He and ^{7}Li) primordial abundances over a range of nine orders of magnitudes.

Le tableau de Mendeleïev

BBN

PRINCIPE

Conçu en 1869 par le chimiste russe Dimitri Ivanovitch Mendeleïev, le tableau périodique classe tous les éléments chimiques selon leur numéro atomique et leurs propriétés chimiques. Quatre éléments ont été identifiés entre 2004 et 2010 et viennent d'être validés par l'Union internationale de chimie pure et appliquée (IUPAC).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
I	1 H Hydrogène																	2 He Hélium
II	3 Li Lithium	4 Be Béryllium											5 B Bore	6 C Carbone	7 N Azote	8 O Oxygène	9 F Fluor	10 Ne Néon
III	11 Na Sodium	12 Mg Magnésium											13 Al Aluminium	14 Si Silicium	15 P Phosphore	16 S Soufre	17 Cl Chlore	18 Ar Argon
IV	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titane	23 V Vanadium	24 Cr Chrome	25 Mn Manganèse	26 Fe Fer	27 Co Cobalt	28 Ni Nickel	29 Cu Cuivre	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Sélénium	35 Br Brome	36 Kr Krypton
V	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdène	43 Tc Technétium	44 Ru Ruthénium	45 Rh Rhodium	46 Pd Palladium	47 Ag Argent	48 Cd Cadmium	49 In Indium	50 Sn Etain	51 Sb Antimoine	52 Te Tellure	53 I Iode	54 Xe Xénon
VI	55 Cs Césium	56 Ba Baryum	57-71 La-Lu Lanthanides	72 Hf Hafnium	73 Ta Tantale	74 W Tungstène	75 Re Rhénium	76 Os Osmium	77 Ir Iridium	78 Pt Platine	79 Au Or	80 Hg Mercure	81 Tl Thallium	82 Pb Plomb	83 Bi Bismuth	84 Po Polonium	85 At Astate	86 Rn Radon
VII	87 Fr Francium	88 Ra Radium	89-103 Ac-Lr Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 ★ Nh Nihonium	114 Fl Flerovium	115 ★ Mc Moscovium	116 Lv Livermorium	117 ★ Ts Tennessine	118 ★ Og Oganesson

57 La Lanthane	58 Ce Cérium	59 Pr Praséodyme	60 Nd Néodyme	61 Pm Prométhium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutétium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Américium	96 Cm Curium	97 Bk Berkélium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

— **Éléments synthétiques** créés artificiellement dans des accélérateurs de particules ou lors de réactions nucléaires

✕ Éléments n'ayant pas d'utilisation

★ Nouveaux éléments chimiques validés en 2016 par l'IUPAC

Familles

Classement des éléments en fonction d'un comportement chimique proche

- 🟥 Non-métaux
- 🟩 Métaux alcalins
- 🟩 Métaux alcalino-terreux
- 🟦 Métaux de transition
  - 🟦 Lanthanides (ou terres rares)
  - 🟦 Actinides
- 🟨 Métaux pauvres
- 🟪 Halogènes
- 🟥 Gaz rares
- 🟧 Métalloïdes

État physiques

Ne gaz | Hg liquide | Fe solide

Atome

Constituant fondamental de la matière formé par un noyau (au centre), composé de protons et de neutrons, autour duquel se répartissent des électrons en différents niveaux d'énergies appelés couches électroniques (ellipses).

Les atomes stables connus ont jusqu'à 7 couches électroniques (correspondant aux 7 lignes du tableau) dont les électrons occupent au fur et à mesure des orbitales électroniques (il existe jusqu'à 44 types de ces orbitales pouvant contenir des sous-couches électroniques : s(1), p(3), d(5) et f (7)).

Élément chimique

Ensemble des atomes caractérisés par un nombre défini de protons dans leur noyau. Ces atomes ont différentes formes possibles : les isotopes (même nombre de protons et d'électrons mais nombre différent de neutrons).

Numéro atomique : nombre de protons et d'électrons de l'élément

Symbole atomique : représentation universelle de l'élément

Périodes (I à VII)

Classement des éléments selon leur configuration électronique (pour prévoir l'évolution de leurs propriétés) : nombre d'orbitales occupées par des électrons. Les éléments de la ligne I ont 1 couche occupée, ceux de la ligne II en ont 2, etc.

Groupes (1 à 18)

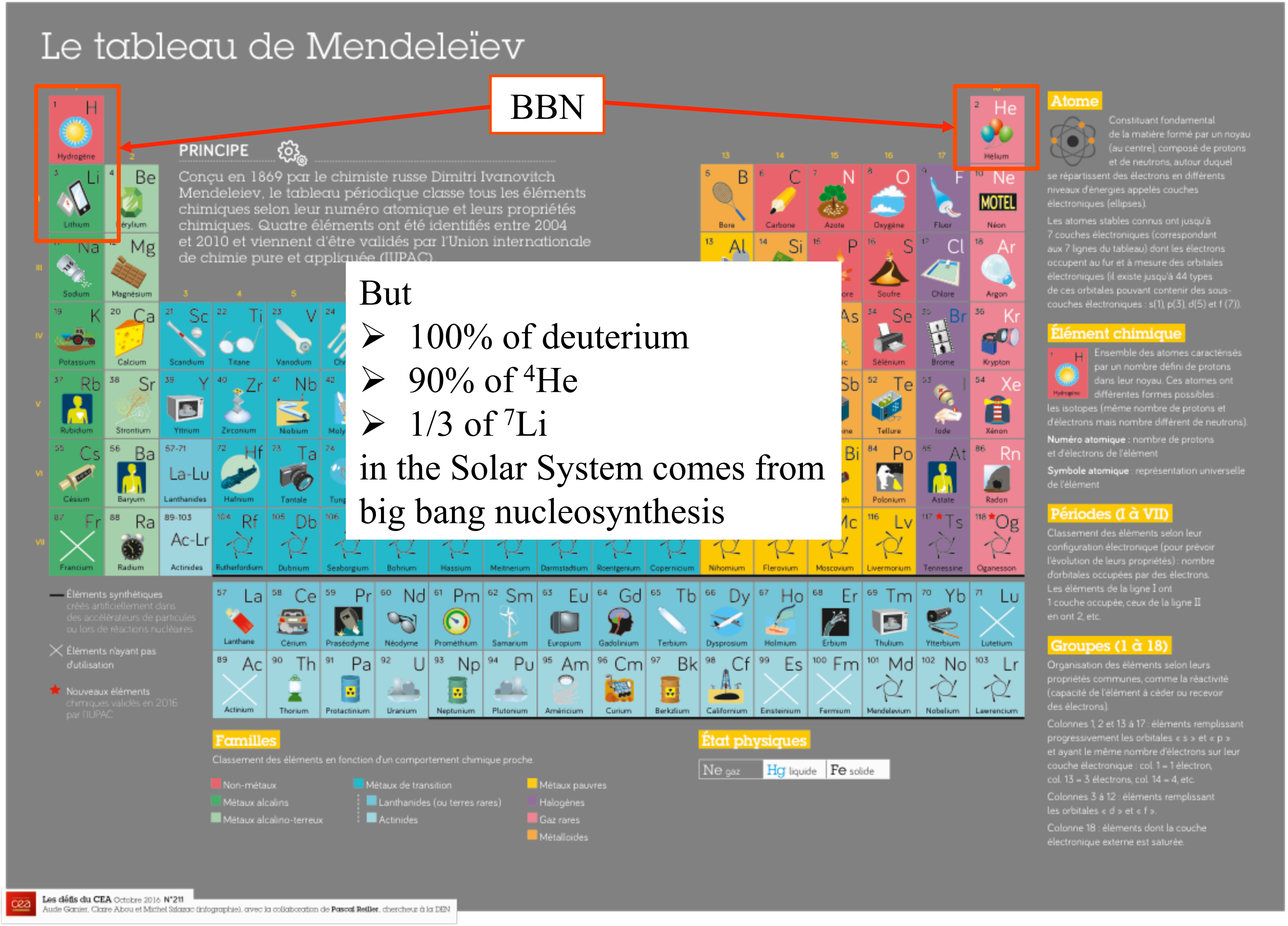
Organisation des éléments selon leurs propriétés communes, comme la réactivité (capacité de l'élément à céder ou recevoir des électrons).

Colonnes 1, 2 et 13 à 17 : éléments remplissant progressivement les orbitales « s » et « p » et ayant le même nombre d'électrons sur leur couche électronique : col. 1 = 1 électron, col. 13 = 3 électrons, col. 14 = 4, etc.

Colonnes 3 à 12 : éléments remplissant les orbitales « d » et « f ».

Colonne 18 : éléments dont la couche électronique externe est saturée.

Les défis du CEA Octobre 2016 **N°211**
Aude Ganier, Claire Abou et Michel Szlazac (infographie), avec la collaboration de **Pascal Reiller**, chercheur à la DEN



Le tableau de Mendeleïev

BBN

But
- 100% of deuterium
- 90% of ^{4}He
- 1/3 of ^{7}Li

in the Solar System comes from big bang nucleosynthesis

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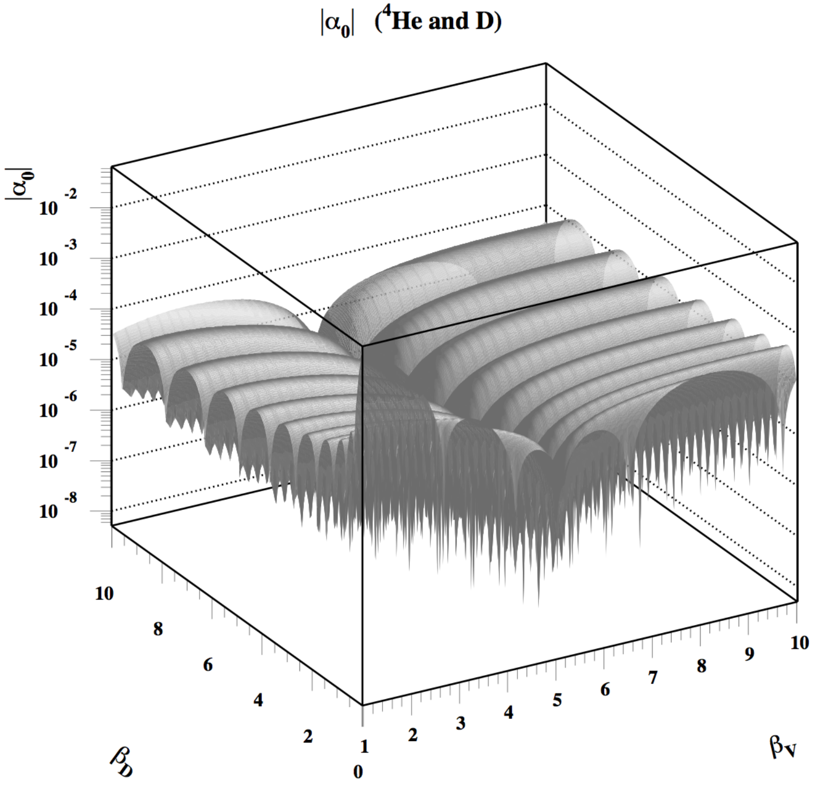
Big Bang Nucleosynthesis probe of new physics (in the 70's)

- ☐ First determination of the baryonic density of the Universe, $(1\text{-}3)\times10^{-31}\mathrm{g/cm}^3$ *[Wagoner 1973]*, need for baryonic dark matter
  - ➢ Baryonic density $\rho_B \approx 4.5\times10^{-31}\mathrm{g/cm}^3$ from the anisotropies in the Cosmic Microwave Background radiation,
- ☐ First determination of the number of light neutrino families, $N_\nu \leq 3$ *[Yang, Schramm, Steigman, Rood 1979]*
  - ➢ Number of neutrino families $N_\nu = 2.984\pm0.008$ *[LEP experiments]*
- ☐ New physics of the 20's ?

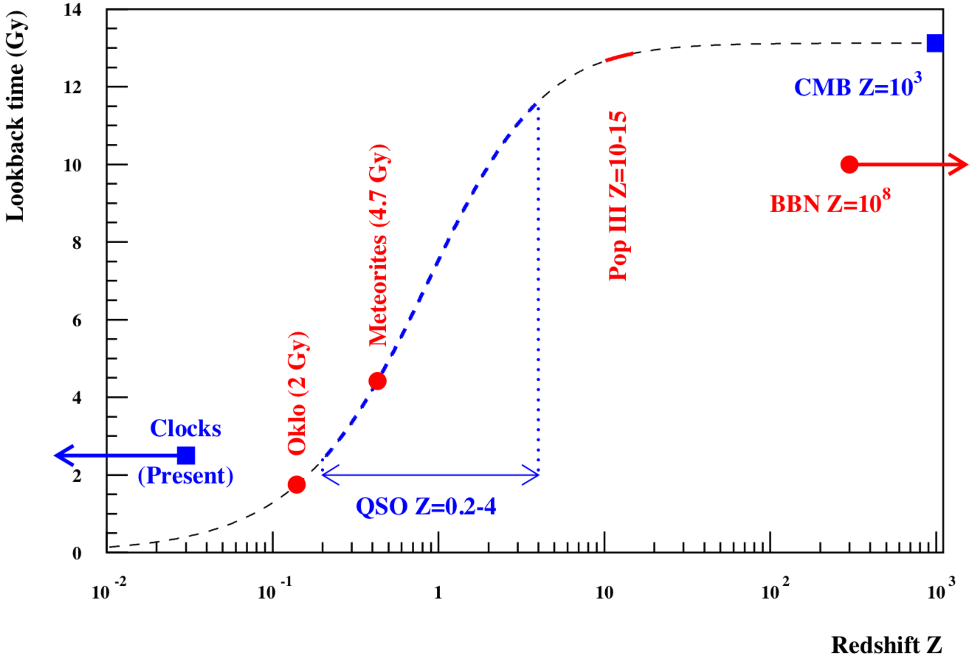
Beyond the Standard Models(s) ?

See review by *Iocco, Mangano, Miele, Pisanti & Serpico 2009*

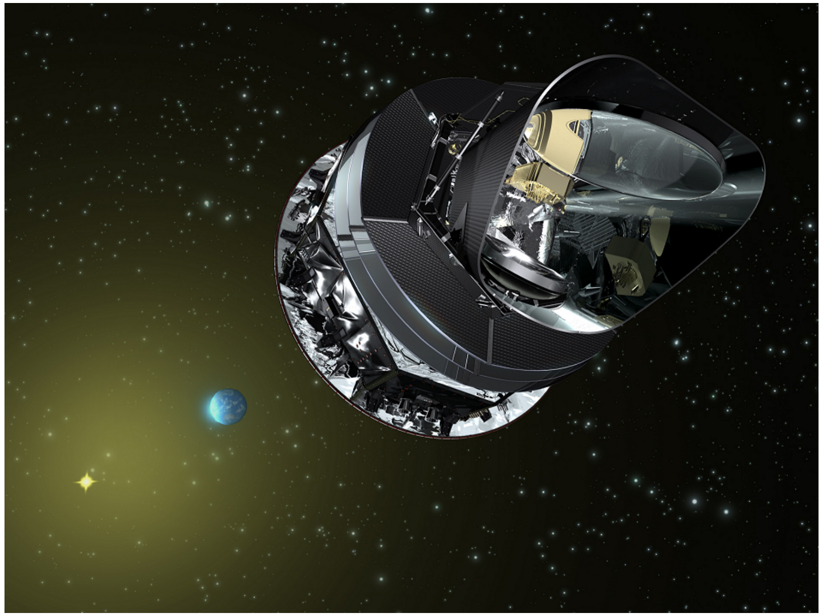
Deviation from General Relativity



Variation of constants

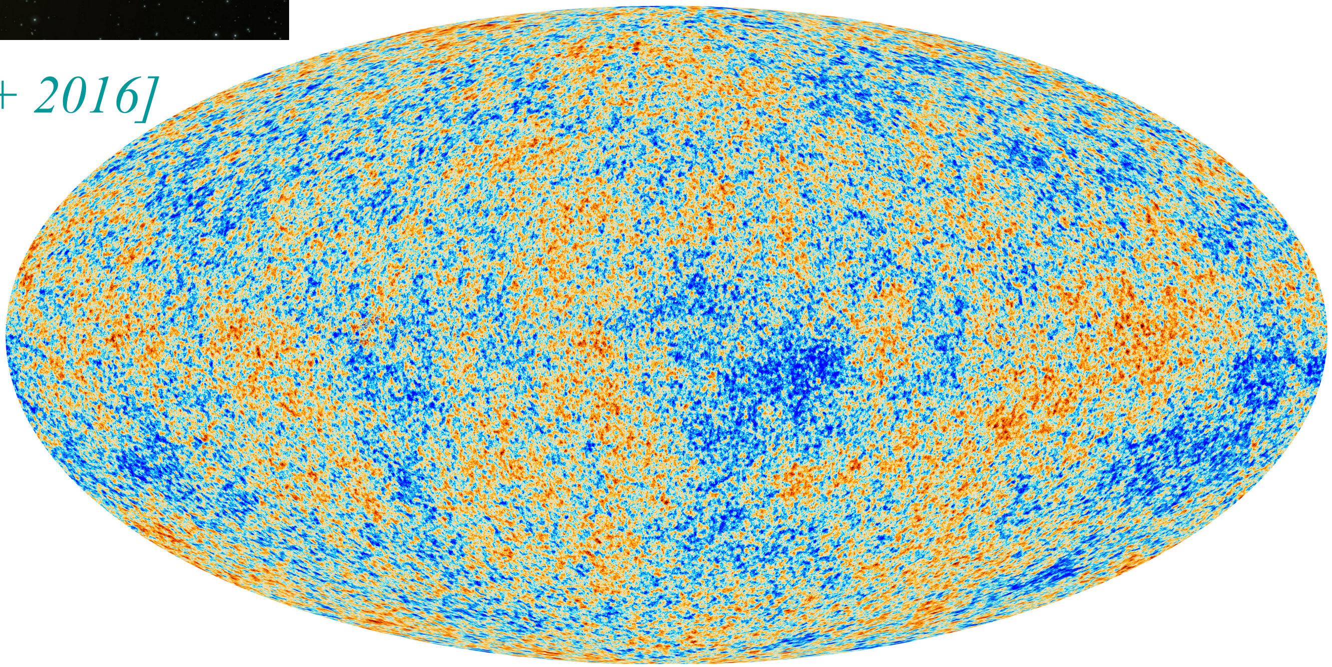


Anisotropies of the Cosmic Microwave Background



Planck *[Ade+ 2016]*

At $t \approx 0.38$ My, and $T \approx 3000$ K, "recombination" of e- and p in neutral H-atoms: the Universe becomes transparent



$T = 3000\text{ K} \rightarrow 2.7\text{ K}$
due to redshift

Anisotropies of the CMB

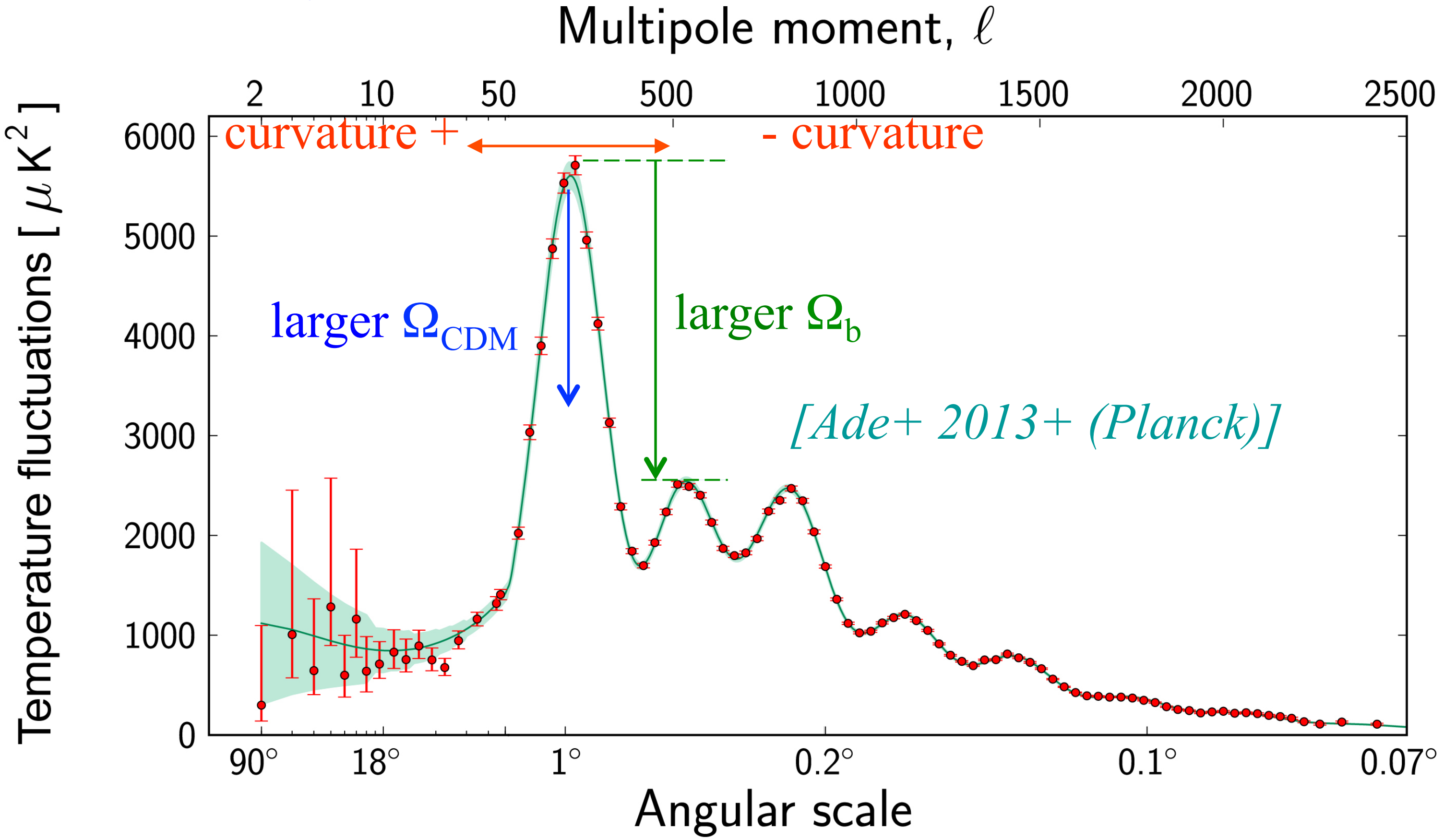
Spatial fluctuation spectrum of CMB generated by acoustic oscillations

- Pressure : photons
- Inertia : baryons

➢Geometry ($\Omega_T \approx 1$), 1st peak

➢Ω_b (2nd/1st peaks)

($\Omega \equiv \rho/\rho_{critical}$ $\Omega = 1 \Rightarrow$ flat space)



Density components of the Universe

The present day ($_0$) critical density, $\rho_{0,C}$, that corresponding to a flat universe (k=0), without cosmological constant (Λ=0):

$$\rho_{0,C} \equiv \frac{3H_0^2}{8\pi G}$$

$$\Omega \equiv \frac{\rho}{\rho_{0,C}}$$

$$\rho_{0,C} = 1.87847\ h^2 \times 10^{-29}\ \mathrm{g/cm^3}\ \text{or}\ 2.9\ h^2 \times 10^{11}\ M_{\odot}/\mathrm{Mpc}^3$$

$H_0 \equiv$ Hubble "constant" ($h=H_0$/100 km/s/Mpc $h \approx 0.6727 \pm 0.0066$)

Some Ω values *[Ade+ 2016 (Planck)]*		
Radiation (CMB)	Ω_R	$5\ 10^{-5}$
Visible matter	Ω_L	≈0.003
Baryons	Ω_b	0.049
Dark Matter	Ω_c	0.264
Vacuum	Ω_Λ	0.688
Total	Ω_T	≈1.0

$\Omega_b h^2 = 0.02225 \pm 0.00016$

(0.7% precision)

[Ade+ 2016 (Planck)]

Determination of primordial abundances

Primordial abundances :

1) Observe a set of primitive objects born when the Universe was young

- **^{4}He** in H II (ionized H) regions of blue compact galaxies
- **^{3}He** in H II regions of *our* Galaxy
- **D** in remote cosmological clouds (i.e. at high redshift) on the line of sight of quasars
- **^{7}Li** at the surface of low metallicity* stars in the halo of our Galaxy

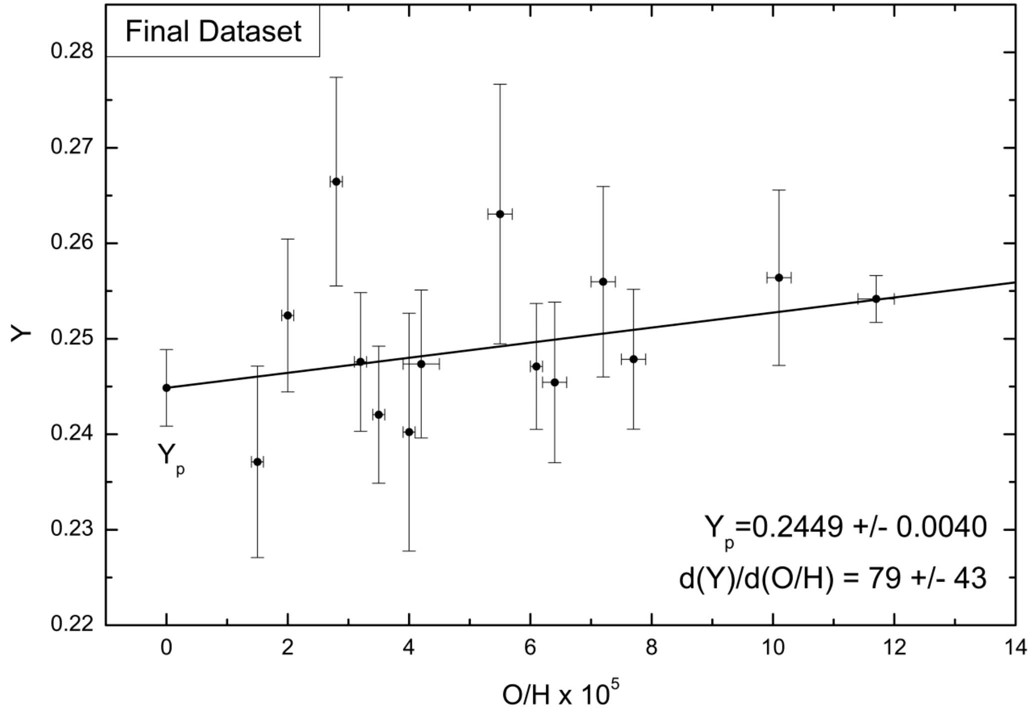
2) Extrapolate to zero metallicity* : Fe/H, O/H, Si/H,…. → 0

*In astrophysics: "metals" = everything beyond helium

Notation : $[X/H] \equiv \log(X/H) - \log(X_{\odot}/H_{\odot})$, X=Fe, O,…

^{4}He observations in blue compact galaxies

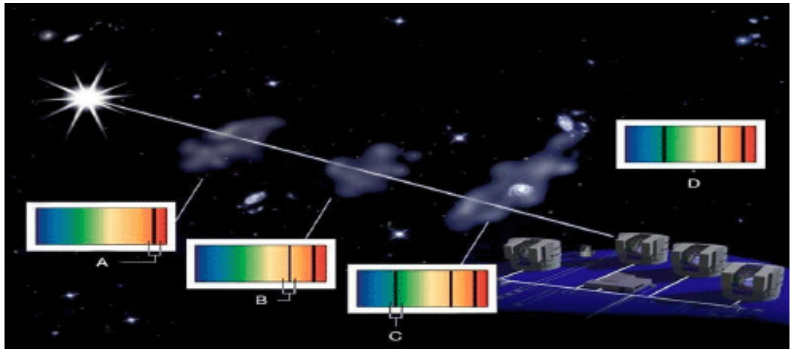
Observations: **^{4}He** from a sample of 86 H II regions in 77 blue compact galaxies *[Izotov, Thuan & Stasinska 2007]* with additional infrared line *[Izotov, Thuan & Guseva 2014]*



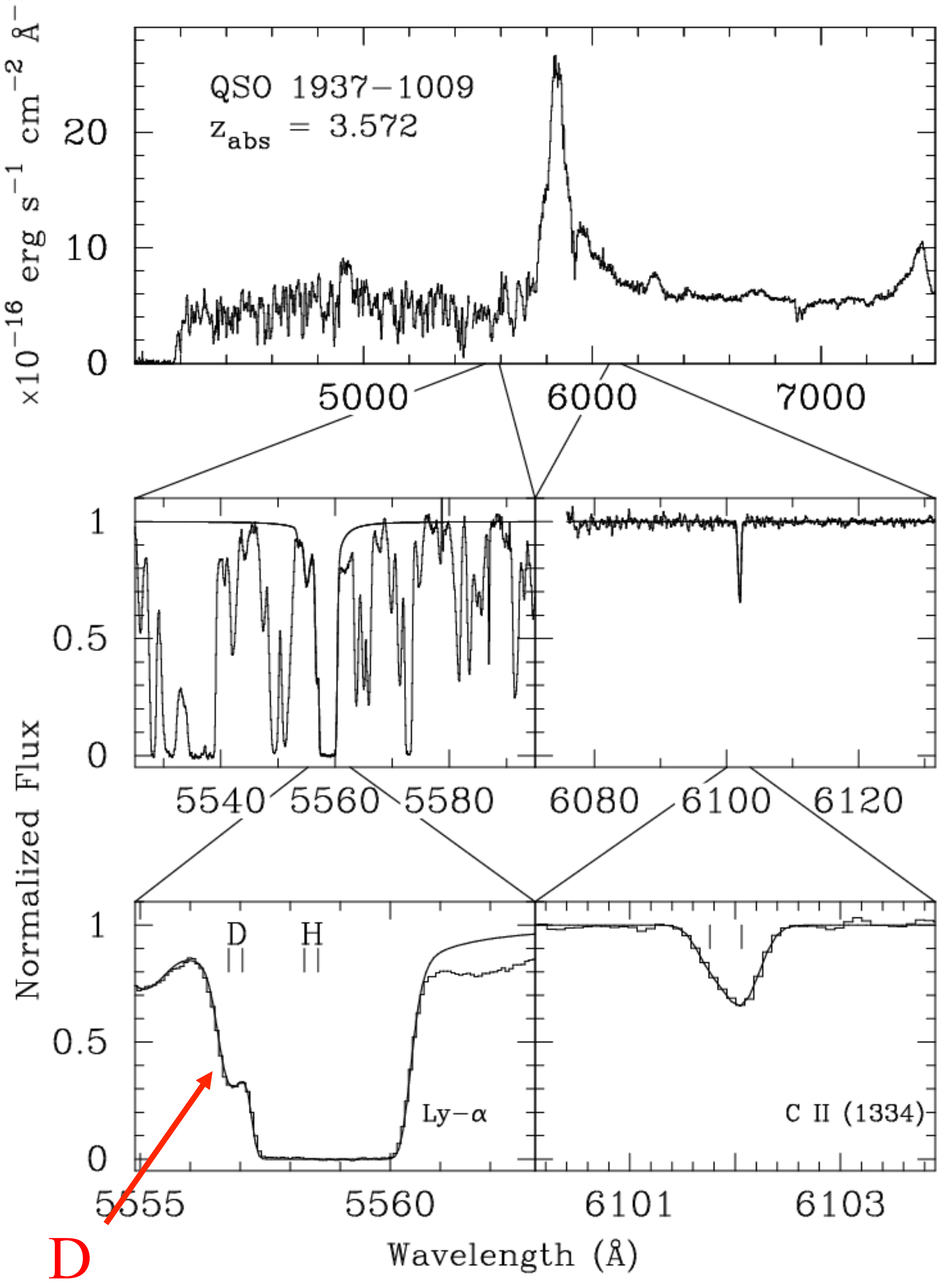
Y_p= ^{4}He mass fraction

Analysis : with new atomic and collisional emission data, He I emissivity and IR line included Y_p=0.2449±0.0040 (^{4}He mass fraction) *[Aver, Olive, Porter & Skillman 2015]* (1.6% precision)

D/H observations in a cosmological cloud



Cloud at redshift of $z = 3.6$ on the line of sight of quasar QSO 1937-1009

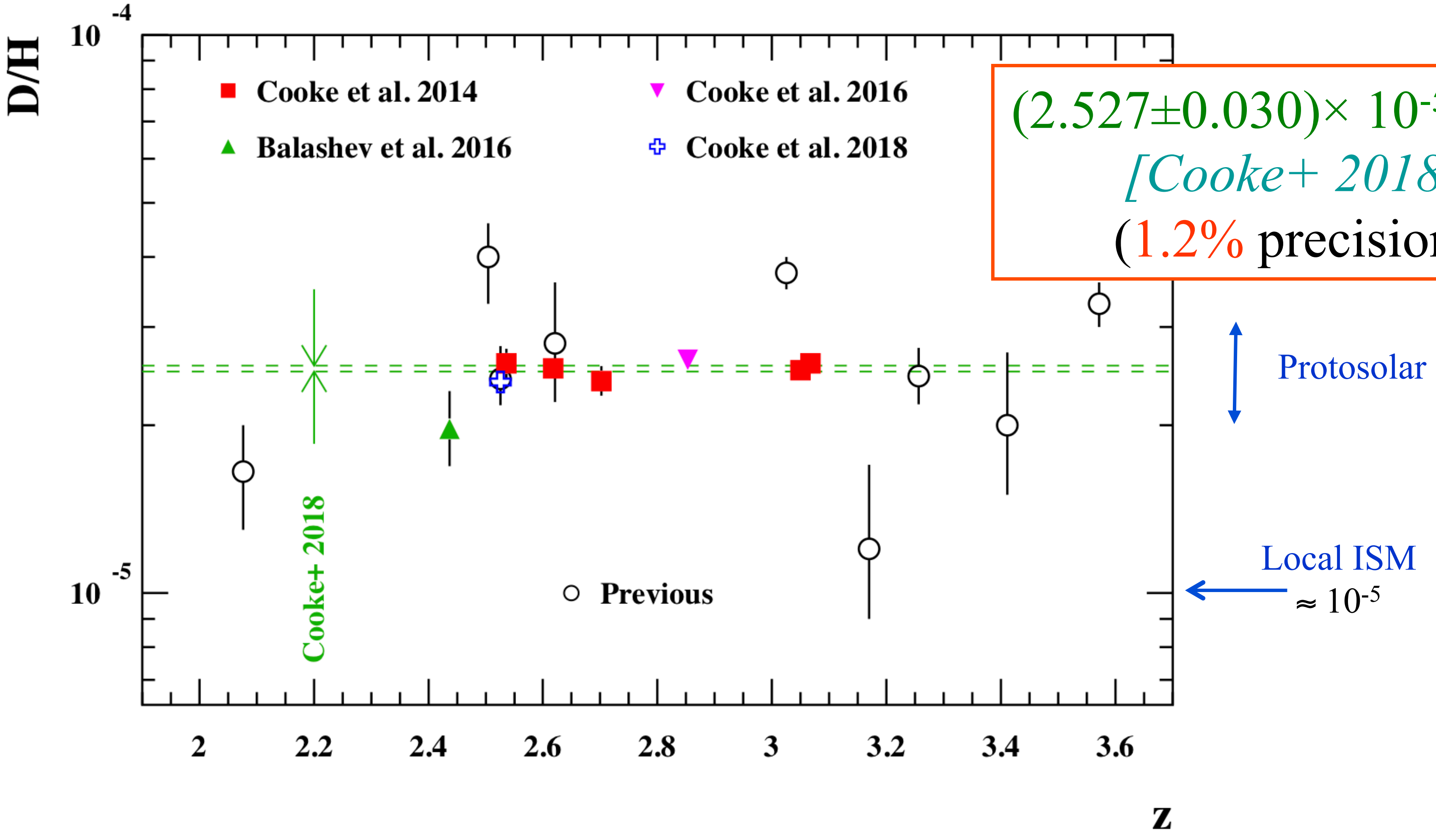


[Burles & Tytler 1998]

Observations :

- D/H ratio at high redshift from the depth/width of absorption lines

D/H observations in cosmological clouds



$(2.527 \pm 0.030) \times 10^{-5}$ (1-σ)

[Cooke+ 2018]

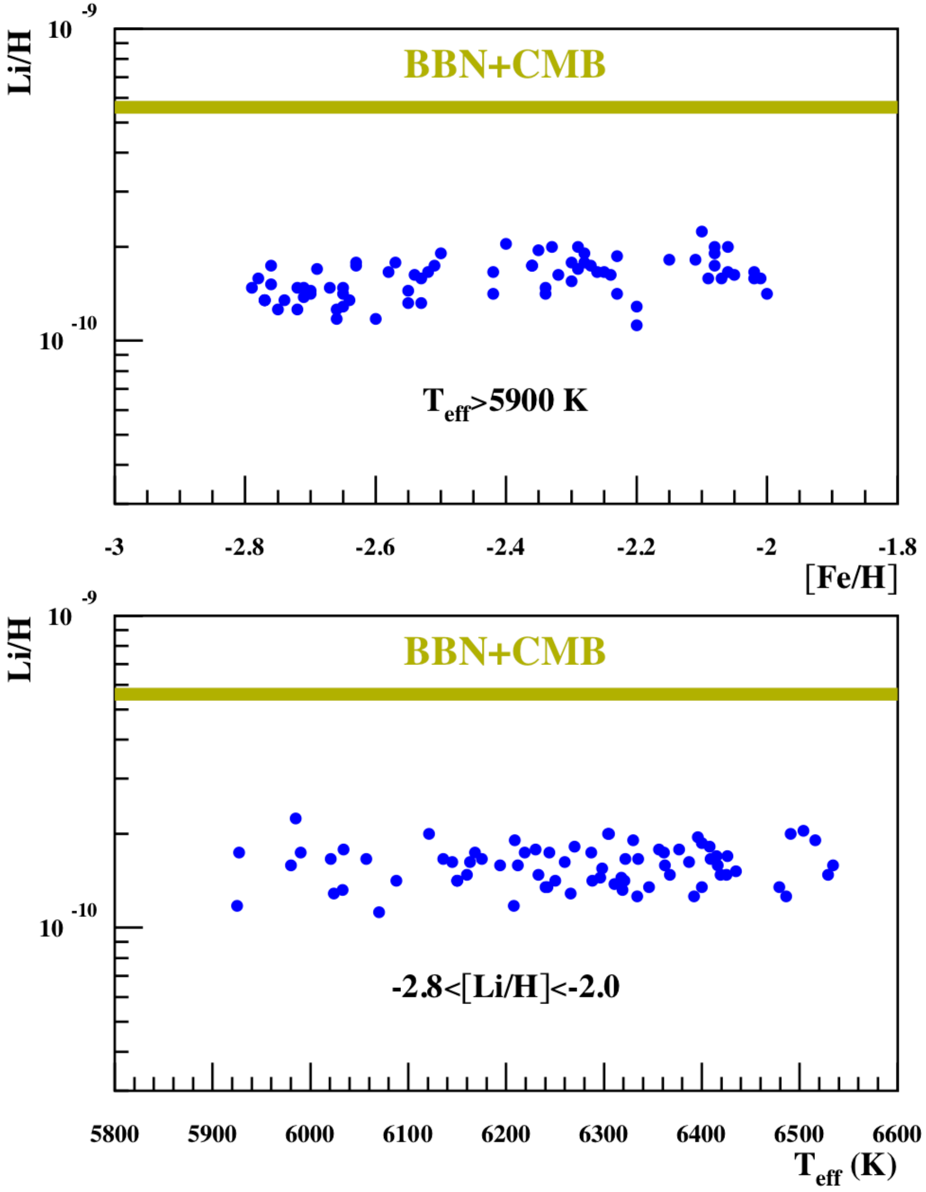
(1.2% precision)

Burles & Tytler 1998; O’Meara+ 2001, 2006; Pettini+ 2001, 2008, 2012; Kirkman+ 2003, Crighton+ 2004; Srianand+ 2010; Cooke+ 2011; Fumagalli+ 2011; Cooke+ 2016; 2018

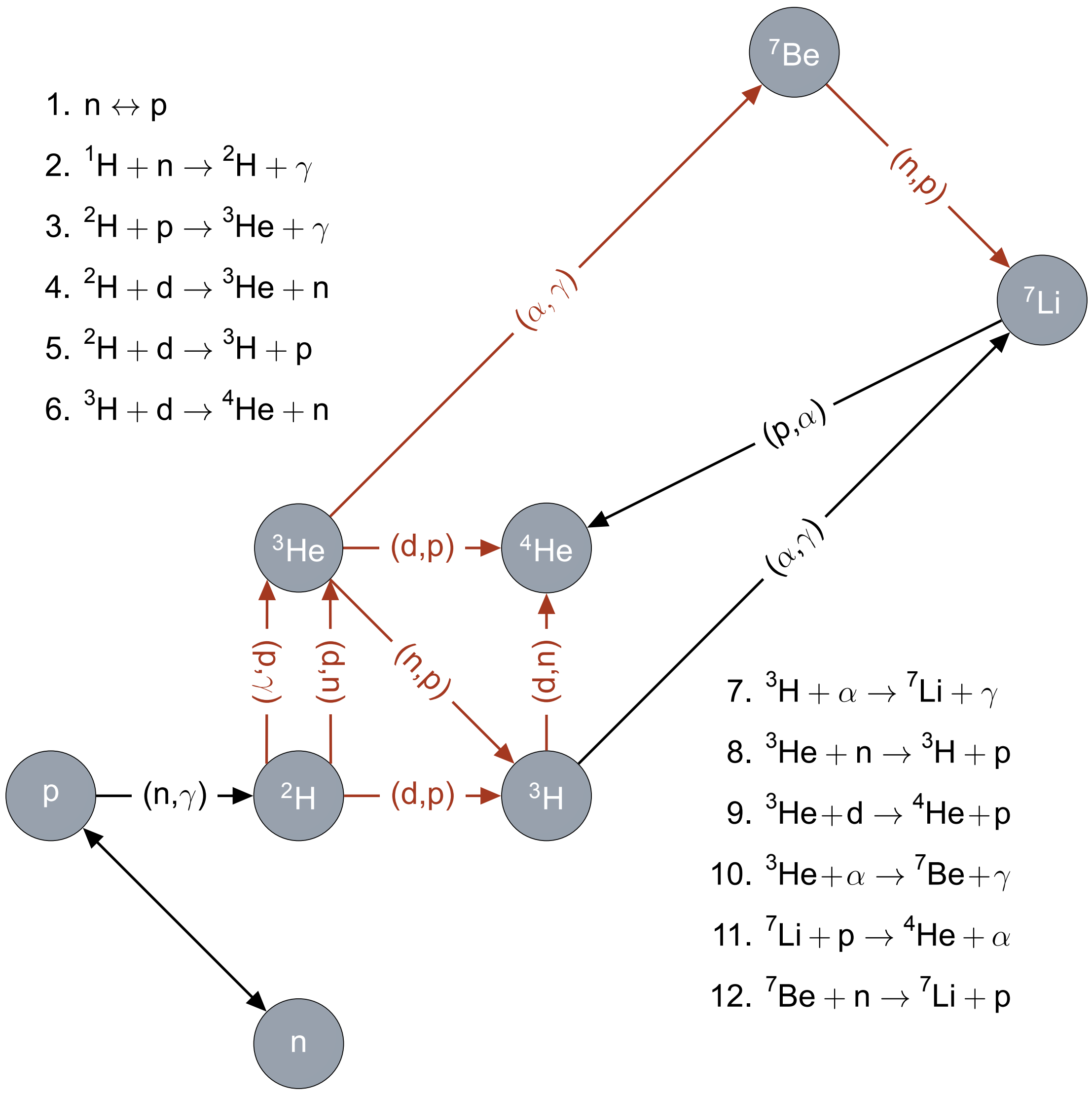
Primordial Li from observations

[M. Spite, priv. comm.]

- Lifetime of $M < 0.9\ M_\odot$ stars > 15 Gy
- Oldest (low metallicity) stars in galactic halo
- For $T_{eff} > 5900$ K, no deep convection and no Li surface depletion (?)
- Li/H = $(1.58 \pm 0.35) \times 10^{-10}$ *[Sbordone et al. 2010]*



Big Bang Nucleosynthesis calculations



1. $n \leftrightarrow p$
2. $^1H + n \rightarrow {}^2H + \gamma$
3. $^2H + p \rightarrow {}^3He + \gamma$
4. $^2H + d \rightarrow {}^3He + n$
5. $^2H + d \rightarrow {}^3H + p$
6. $^3H + d \rightarrow {}^4He + n$
7. $^3H + \alpha \rightarrow {}^7Li + \gamma$
8. $^3He + n \rightarrow {}^3H + p$
9. $^3He + d \rightarrow {}^4He + p$
10. $^3He + \alpha \rightarrow {}^7Be + \gamma$
11. $^7Li + p \rightarrow {}^4He + \alpha$
12. $^7Be + n \rightarrow {}^7Li + p$

Needs:

- Reaction rates
- Density $\rho_b(t)$, ions and photons $T(t)$ and neutrino $T_\nu(t)$ temperatures as a function of time

Dynamics of the expanding Universe (I)

Einstein equation & Friedmann-Lemaître-Robertson-Walker metrics

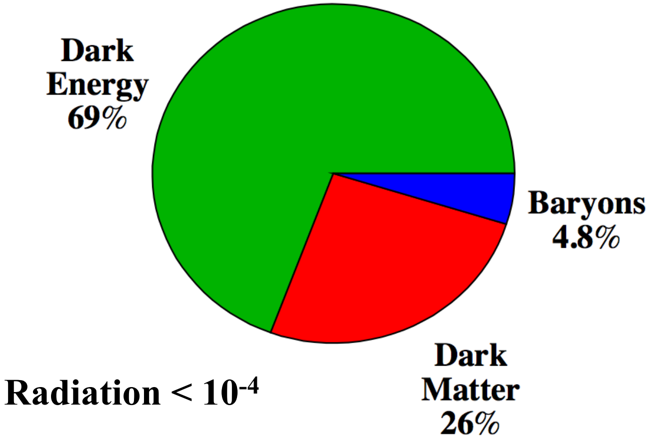
$$ds^2 = g_{\alpha\beta}dx^\alpha dx^\beta = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

a(t): scale factor

Friedmann equation :

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}(\rho_R + \rho_M + \rho_\Lambda) - \frac{k}{a^2}$$

Now.... (a≡1)



EoS: p = pressure ≡ $w \times \rho \Rightarrow \boxed{\rho \propto a^{-3(1+w)}}$

$$w = \begin{cases} 0 \text{ (matter)} & \Rightarrow a^{-3} \\ 1/3 \text{ (radiation)} & \Rightarrow a^{-4} \\ -1 \text{ (Λ, dark energy)} & \Rightarrow a^{0} \end{cases}$$

Curvature $\Rightarrow a^{-2}$

Dynamics of the expanding Universe (II)

Einstein equation & Friedmann-Lemaître-Robertson-Walker metrics

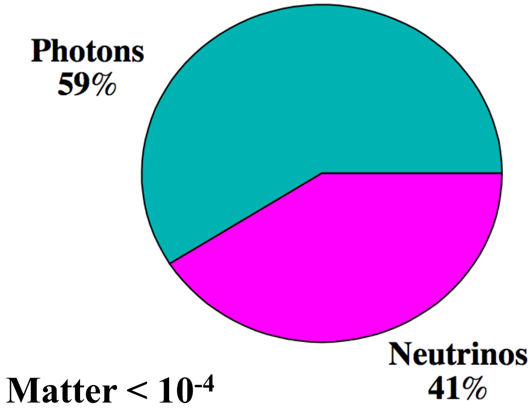
$$ds^2 = g_{\alpha\beta}dx^\alpha dx^\beta = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

a(t): scale factor

Friedmann equation :

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\left(\rho_R + \cancel{\rho_M} + \cancel{\rho_\Lambda}\right) - \cancel{\frac{k}{a^2}}$$

....and then (a≈10^{-8})



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Curvature $\Rightarrow a^{-2}$

Dynamics of the expanding Universe (III)

Cosmological distances ∝ $a \equiv (1+z)^{-1}$ (z = redshift)

Rate of expansion ∝
(radiation energy density)$^{1/2}$

① $$\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} \propto \sqrt{\rho^{rad}_{e\gamma\nu}(T)} \propto \sqrt{g_*^{e\gamma\nu}(T)}\,T^2$$

"Radiation": γ, (e^-), ν_x and antiparticles

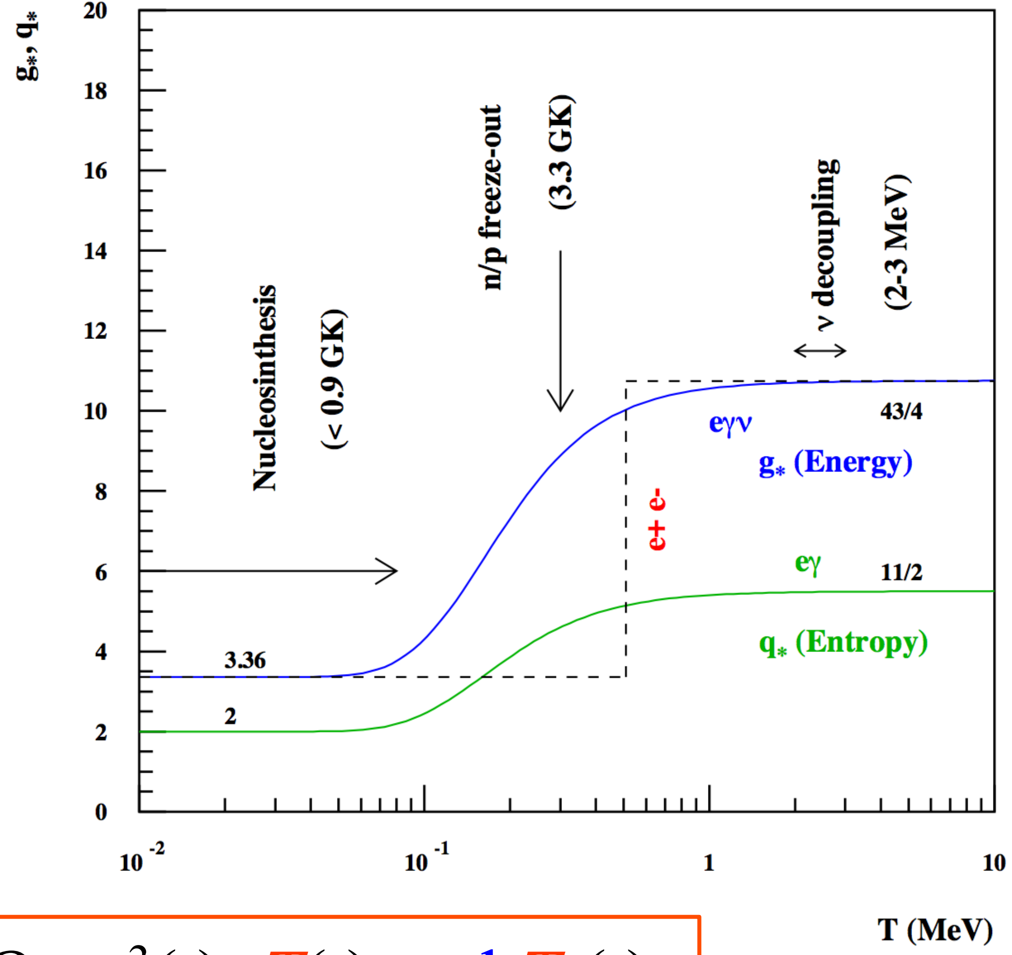
$T_\nu = T$ for $T >> 1$ MeV

② $$a^3 T_\nu^3 = Cste$$

③ $$a^3 q_*^{e\gamma}(T) T^3 = Cste$$

Entropy constant

g_*, q_* = spin factors



①+②+③ ⇒ $\rho_b(t) \propto \Omega_b\, a^{-3}(t)$, $T(t)$ and $T_\nu(t)$

Nucleosynthesis (I)

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

$$\frac{N_n}{N_p} = \exp\left[\frac{-Q_{np}}{\mathrm{k}T}\right]$$

$Q_{np} = 1.29$ MeV

Equilibrium as long as the reaction rate is faster than the expansion rate, hence breaks out when:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 << \frac{\dot{a}}{a} \propto \sqrt{g_*^{e\gamma\nu}(T)}\,T^2$$

Decoupling and freezeout when $T \approx$ 3 GK and $N_n/N_p \approx 1/6$

Nucleosynthesis (II)

Neutrons decay until T is low enough for :

$$n+p \rightarrow D+\gamma$$

becomes faster then deuterium photodisintegration

$$D+\gamma \rightarrow n+p \quad (Q = -2.2\ \mathrm{MeV})$$

Then, $t = 3$ mn, $T \approx 10^9$ K and N_n has decrased to $N_n/N_p \approx 1/7$

Nucleosynthesis starts to produce essentially ^{4}He together with traces of D, ^{3}He, ^{7}Li, ….

$$X(^4He) \approx 2X(n) \approx 2/(1+7)=0.25$$

The reactions of standard BBN

Origin of reaction rates (see *Coc+ ApJ 2014 & Pitrou+ 2018*):

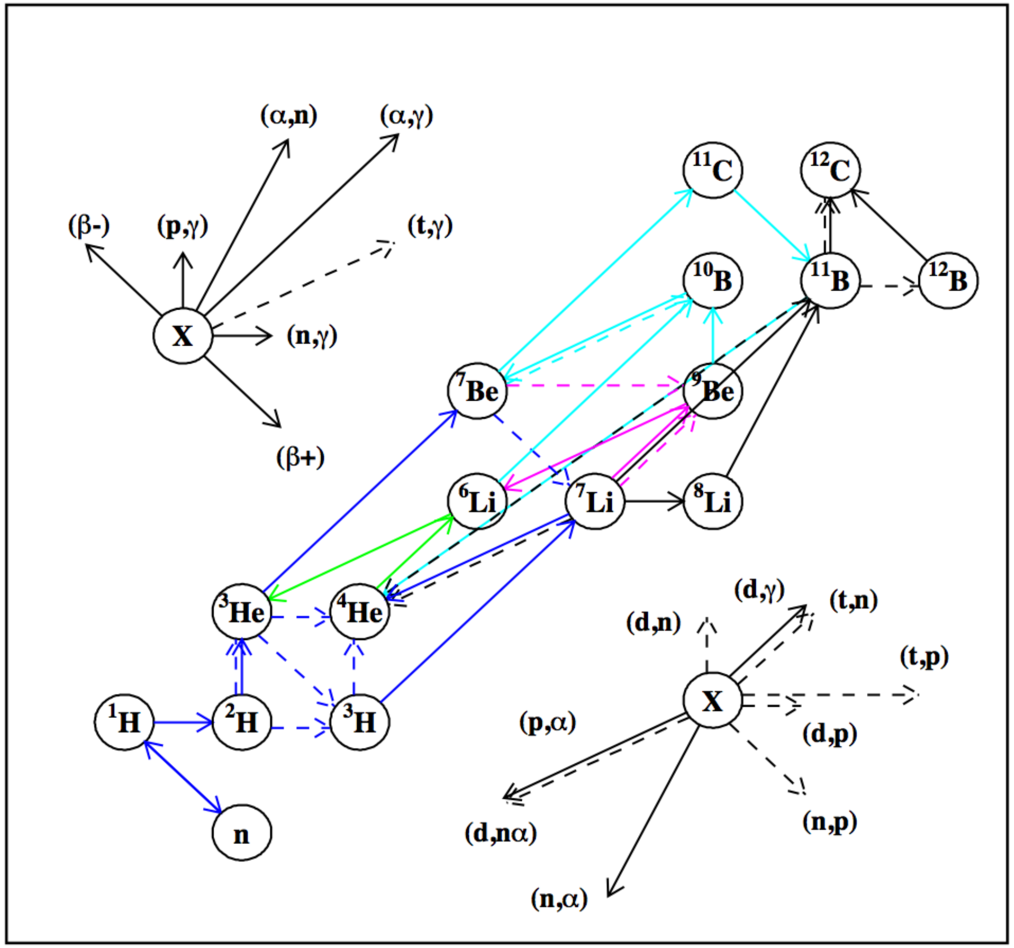
Experimental:

Evaluation of experimental nuclear data *[Descouvemont+ 2004; Angulo + 1999, Iliadis+ 2010;2016; Gómez Iñesta+2017,...]*

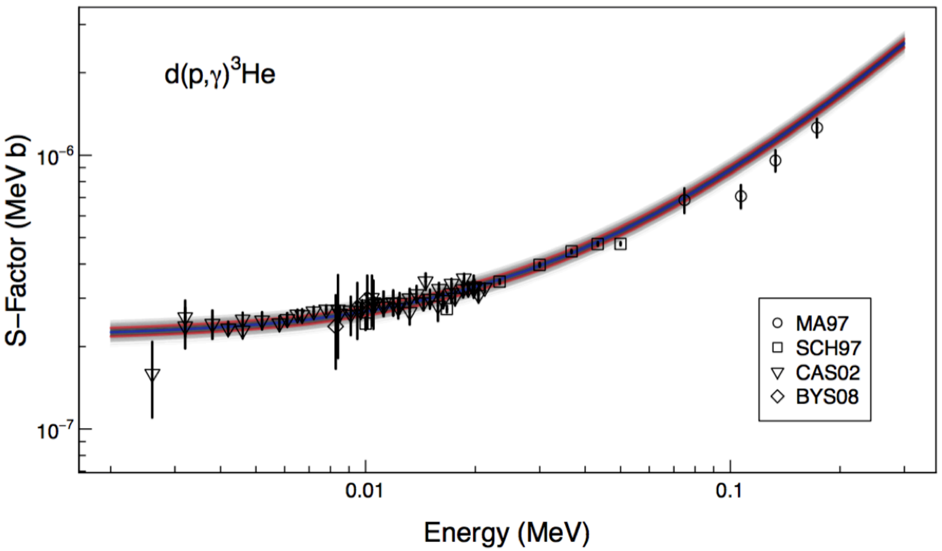
Theoretical:

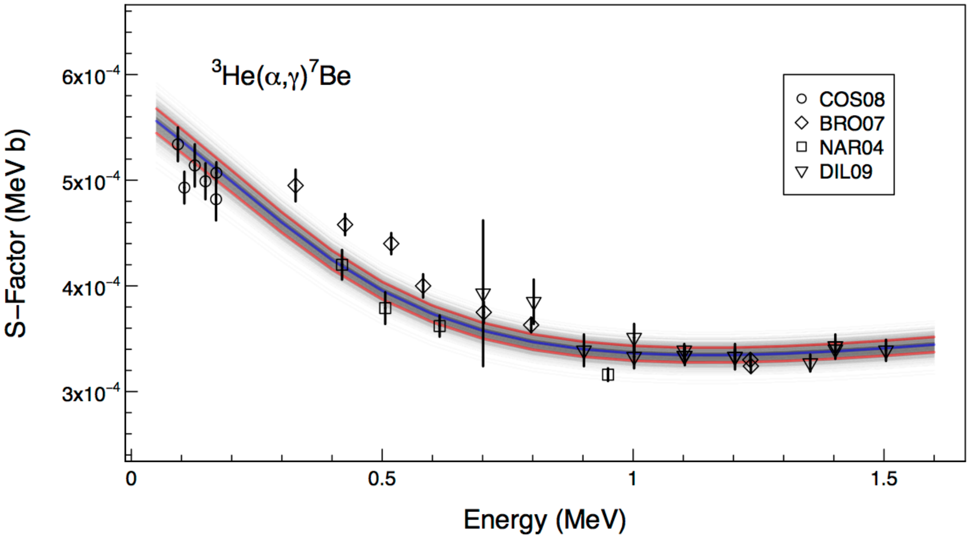
- n↔p : weak rates normalized to neutron lifetime *[Pitrou+ 2018]* (crucial for ^{4}He, see later)
- ^{1}H(n,γ)^{2}H : Two nucleons effective field theory *[Ando+ 2006]*
- Talys code *[Koning+ 2005]* for ≈270 “exotic” reactions

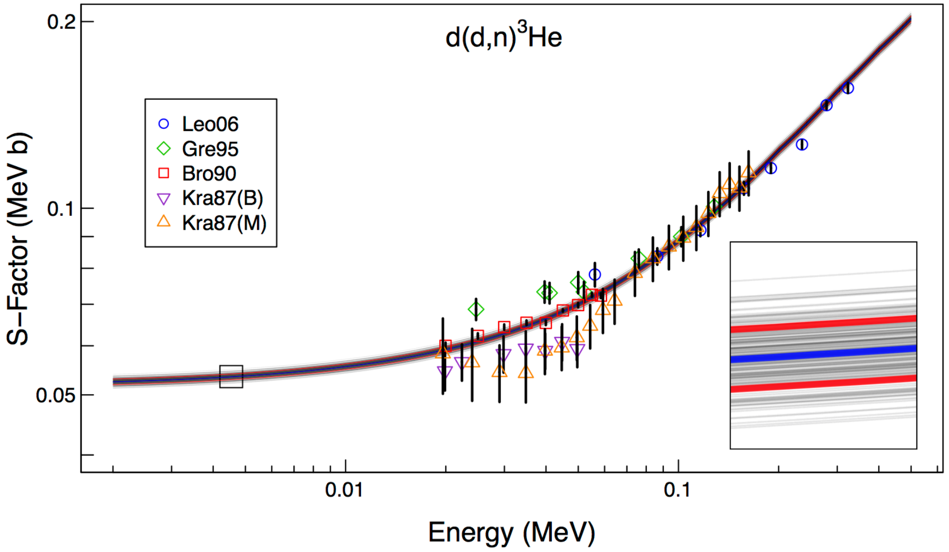
Main BBN reactions extending to CNO (out of ≈400)

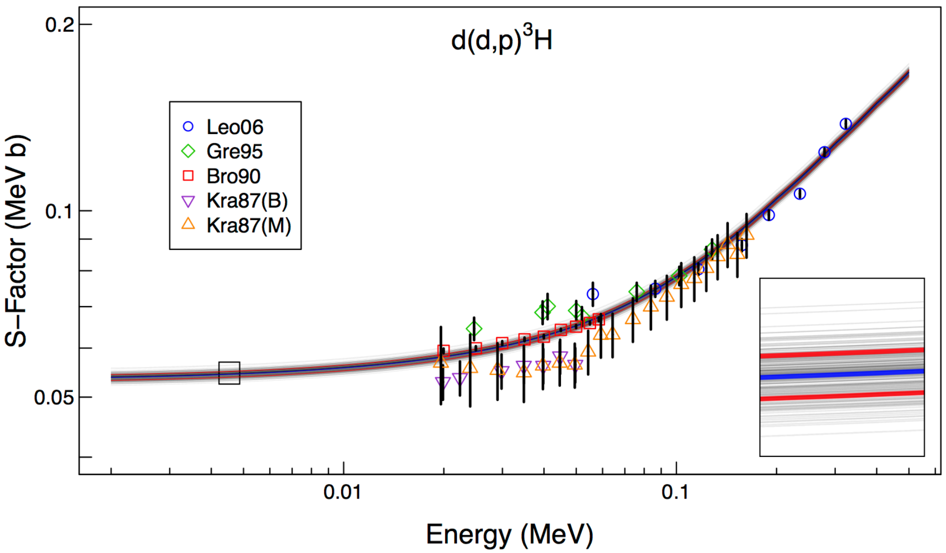


Bayesian analyses of reaction rates for BBN *[Iliadis+ 2016; Gómez Iñesta+2017; de Souza+2019a,2019b]* including D(p,γ)^{3}He, D(d,n)^{3}He, D(d,p)^{3}H, ^{3}He(α,γ)^{7}Be ^{3}He(d,p)^{4}He, ^{3}H(d,n)^{4}He, and ^{7}Be(n,p)^{7}Li *[Tan Hong Kiat+ in preparation]*





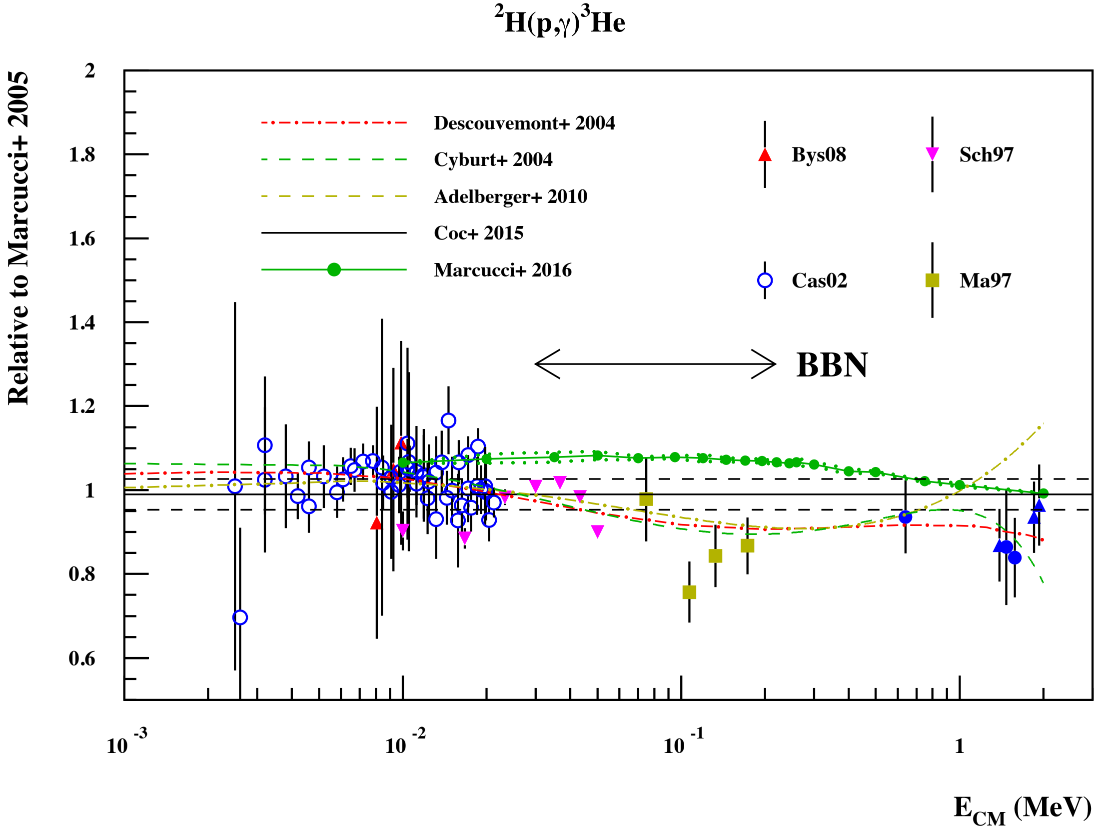




D/H sensitivity to reaction rates

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

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



n↔p weak reaction rates

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

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

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

+ “some small corrections”

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

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

- 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]

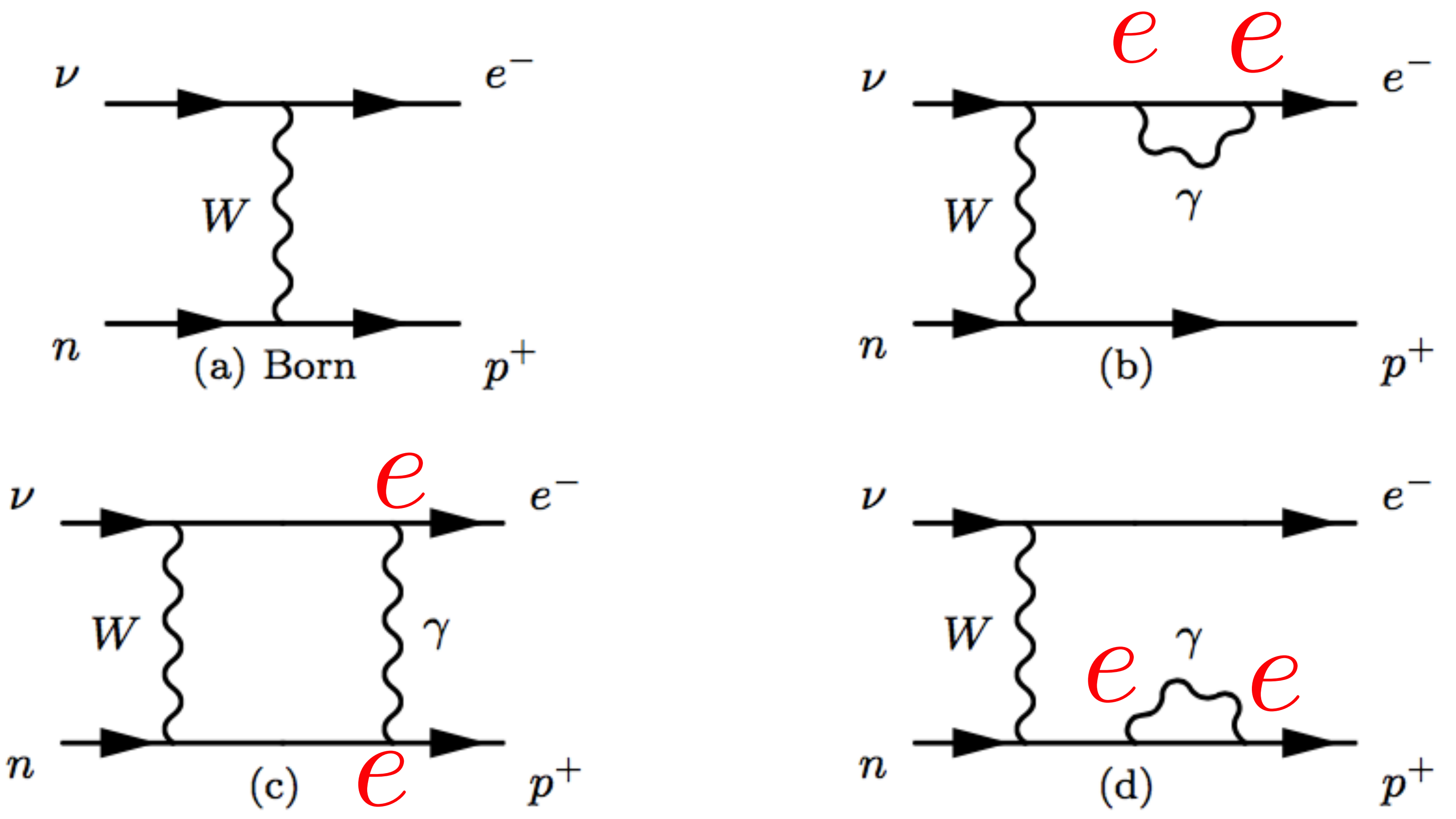
All included and calculated in a self consistent way, allowing to take into account the correlations between them, and verifying that all satisfy detailed balance *[Pitrou+ 2018]*

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

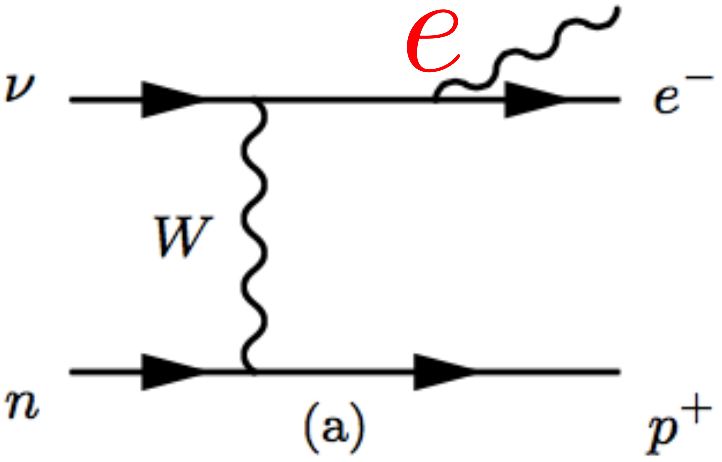
$$\boxed{\frac{\Gamma_{p\to n}}{\Gamma_{n\to p}} = \mathrm{e}^{-(m_n - m_p)/T}}$$

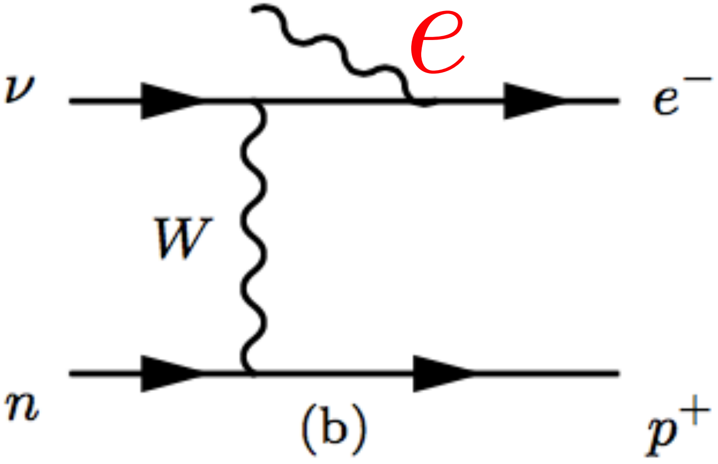
Radiative corrections

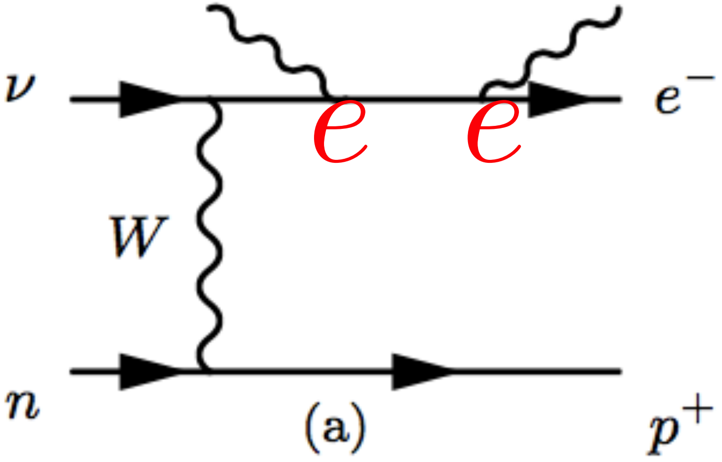
$$\frac{e^2}{4\pi} = \alpha_{\mathrm{FS}} \simeq \frac{1}{137}$$

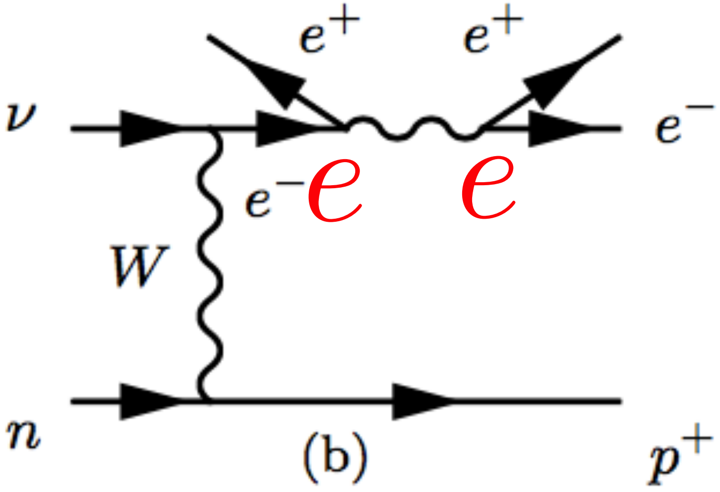


Finite temperature radiative corrections

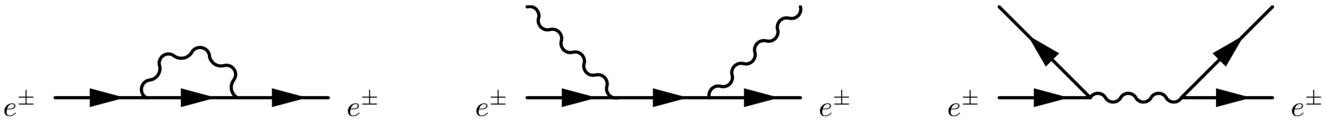








QED plasma effects



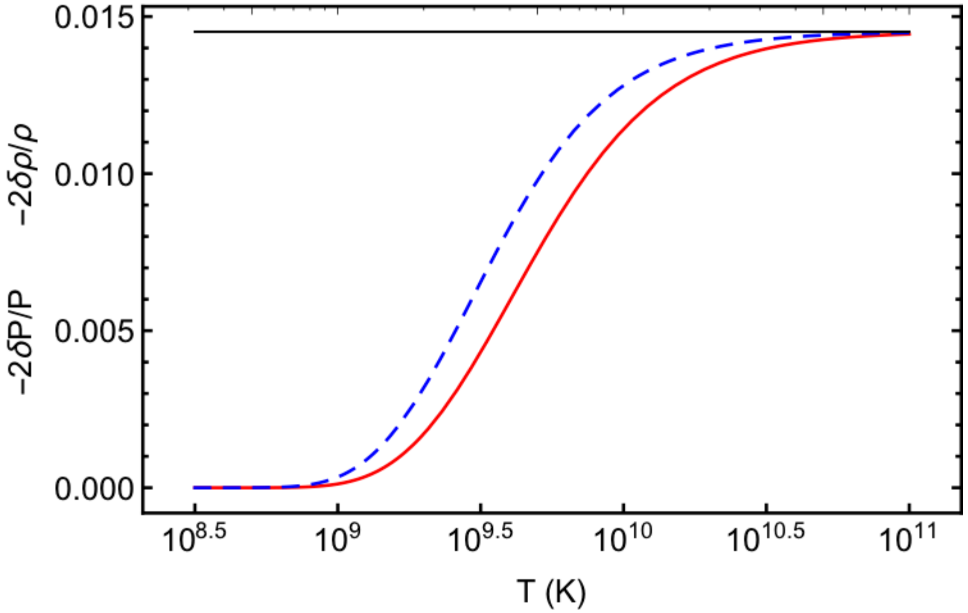
(a) Vacuum. (b) Interaction with photons. (c) Interaction with antiparticles.

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.

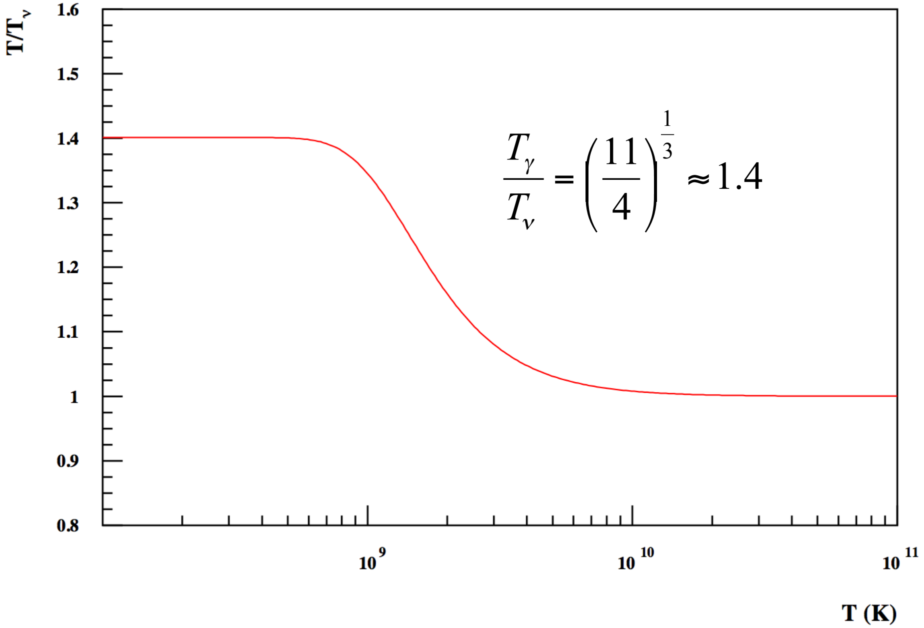
- Modify ρ_R and $p \longrightarrow$ entropy
  - expansion a(t)
  - neutrino temperature
  - e-statistics



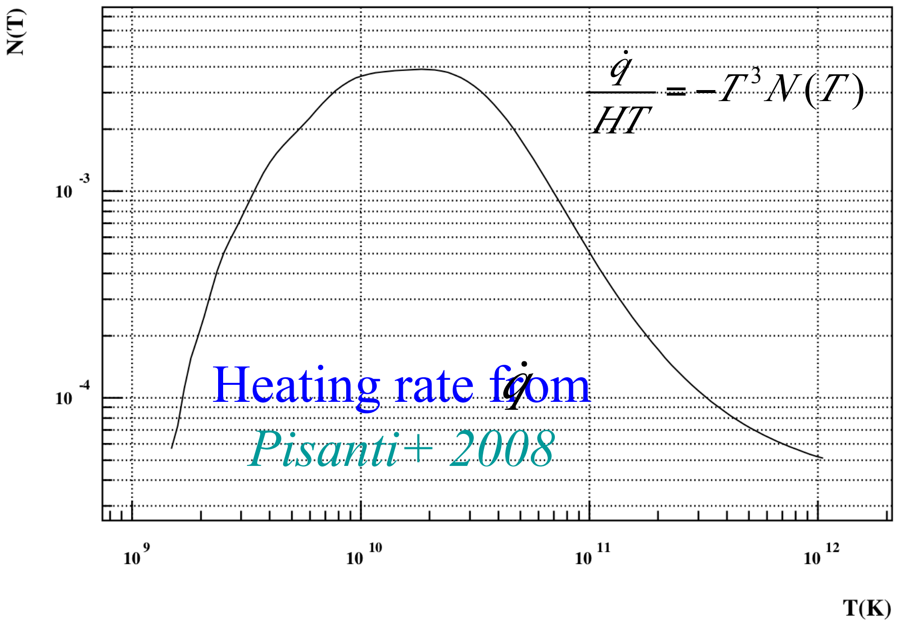
Incomplete neutrino decoupling

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



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

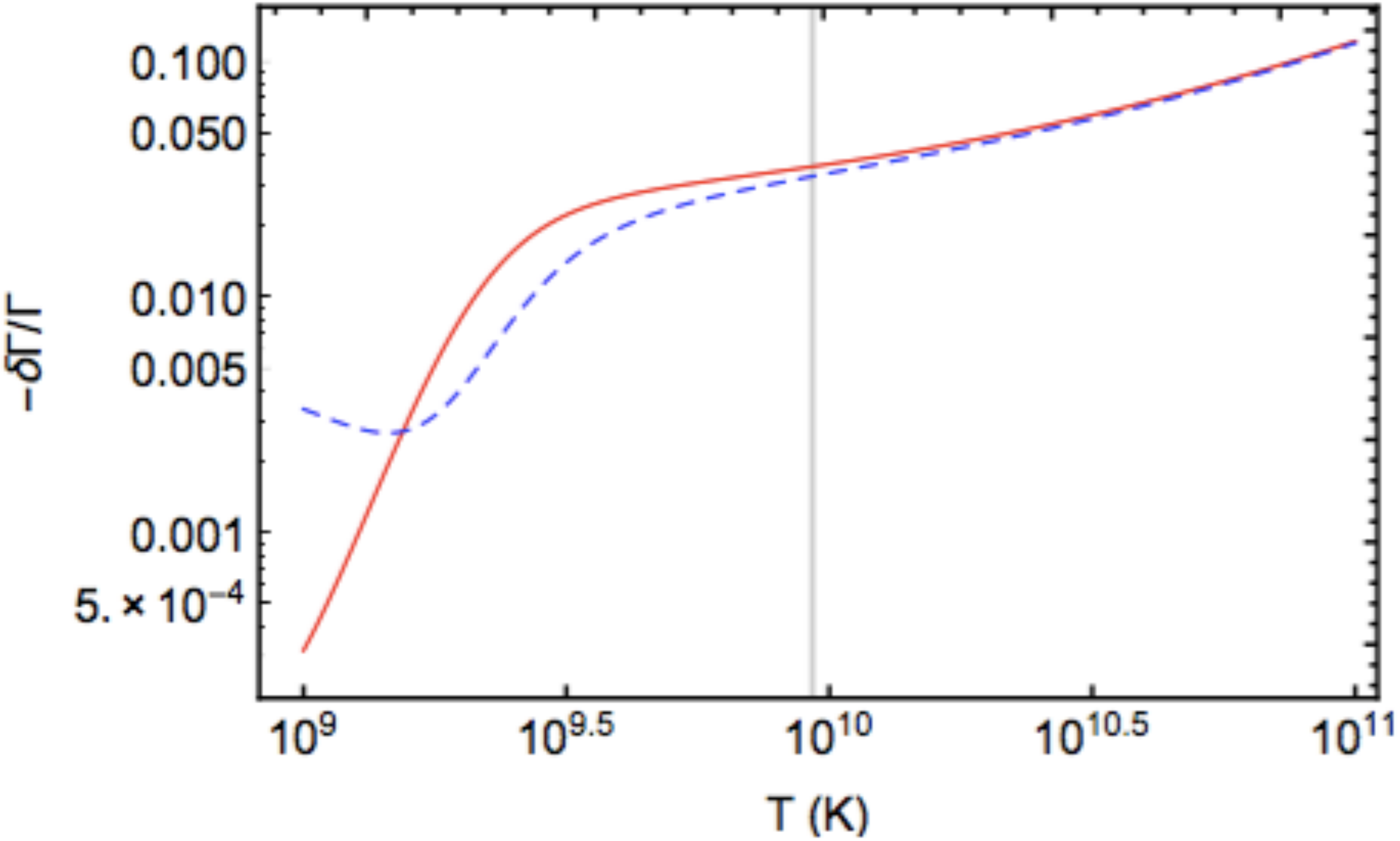


$$\frac{\dot{q}}{HT} = -T^3 N(T)$$

Heating rate from $\dot{q}$

Pisanti+ 2008

Total corrections

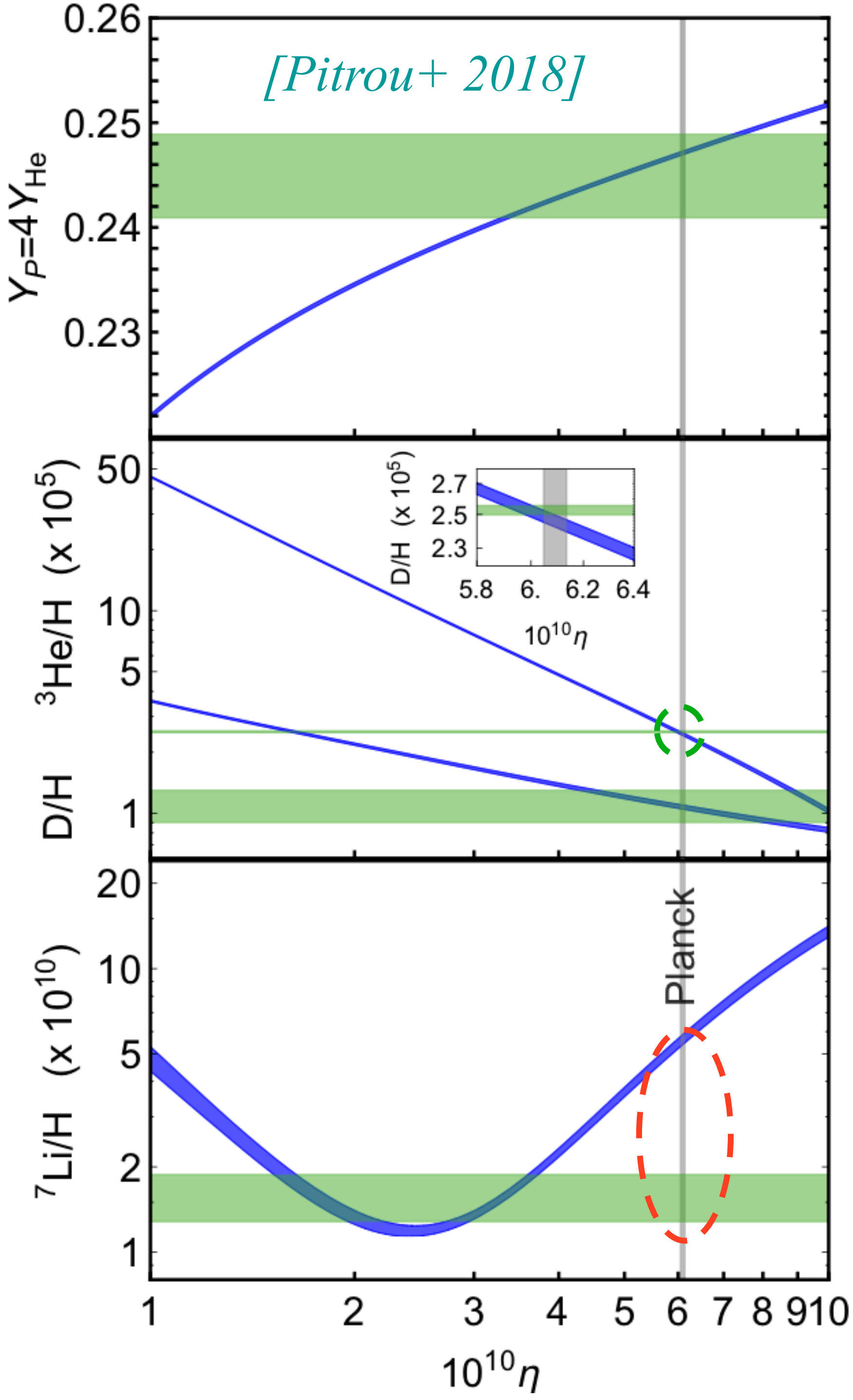


Comparison between observed and calculated abundances

Limits (1-σ) obtained by Monte-Carlo fusing *Descouvemont+ 2004; Ando+ 2006, Iliadis+; 2016; Gómez Iñesta+ 2017;…….* reaction rate uncertainties.

Concordance (?) BBN, spectroscopy and CMB

- $\Omega_B h^2$ *[Planck: Ade+ 2016]*
- **^{4}He** *[Aver+ 2015]*
- **D** *[Cooke+ 2018]*
- **^{3}He** *[Bania et al. (2002)]*
- **^{7}Li** *[Sbordone+ 2010]* : difference of a factor of ≈3 between calculated (BBN +CMB) and observed (Spite plateau) primordial lithium



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

	BBN calculations			
	^{4}He	D/H	^{3}He/H	^{7}Li/H
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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 :
$D(p,\gamma)^3He$, $D(d,n)^3He$, $D(d,p)^3H$, $^7Be(n,\alpha)^4He$ & $^3He(\alpha,\gamma)^7Be$

- The "Lithium problem": difference of a factor of ≈3 between calculated and observed primordial lithium
- Precision needed for deuterium predictions (1% on reaction rates!)

Dominant corrections for Y_p and D/H

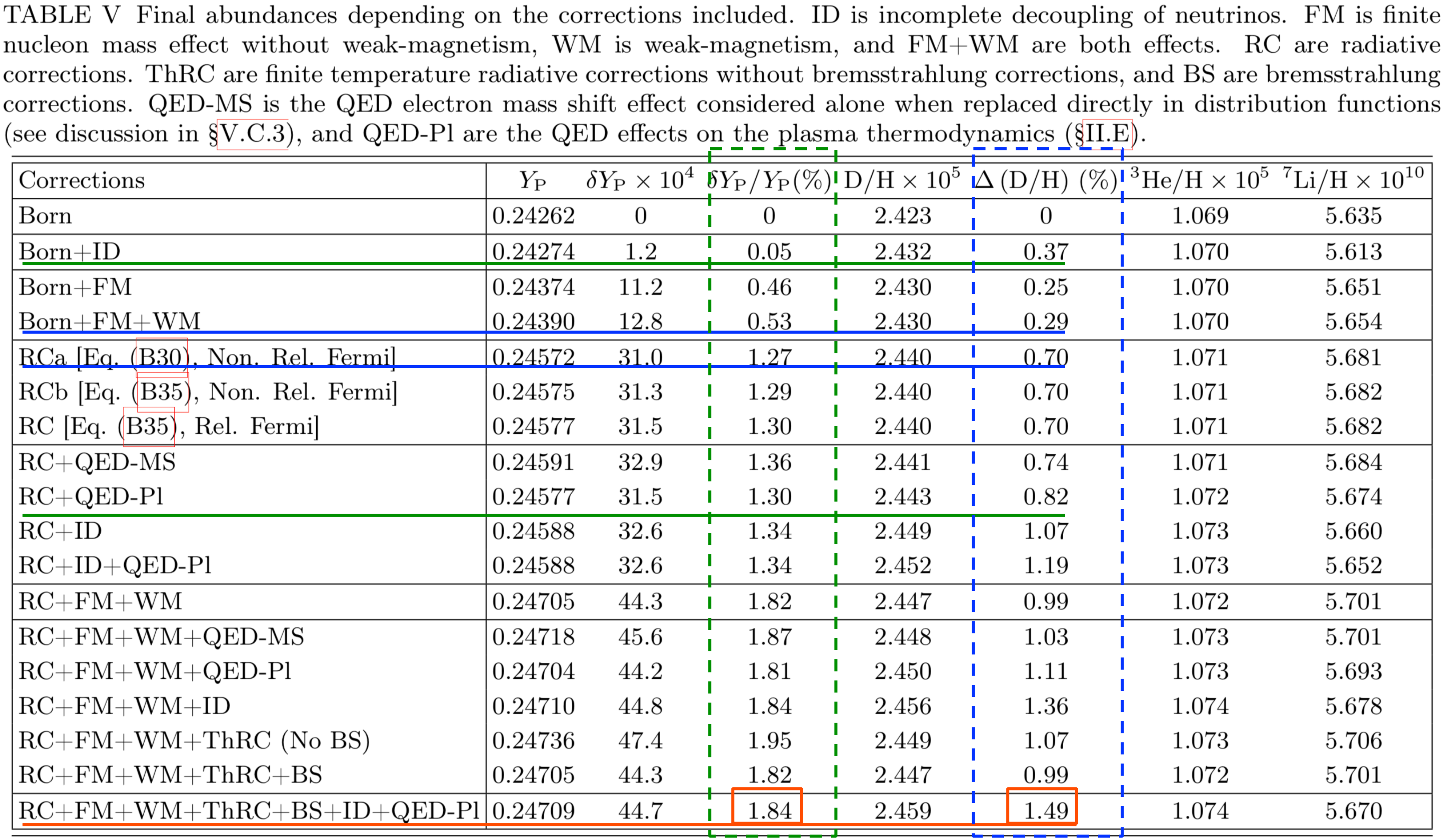
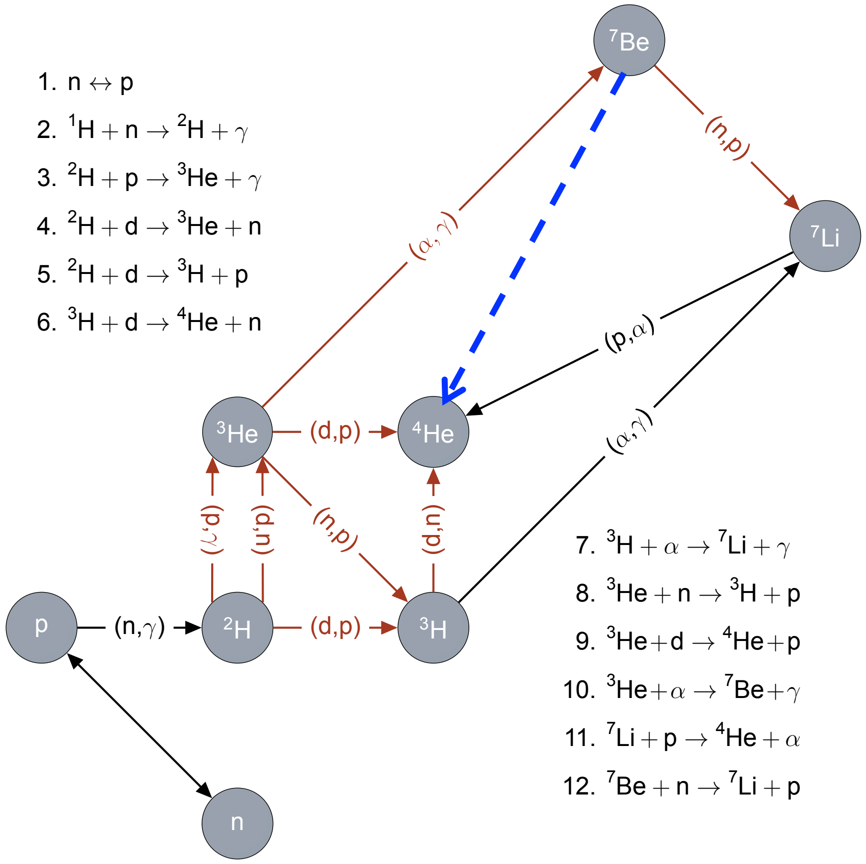


TABLE V Final abundances depending on the corrections included. ID is incomplete decoupling of neutrinos. FM is finite nucleon mass effect without weak-magnetism, WM is weak-magnetism, and FM+WM are both effects. RC are radiative corrections. ThRC are finite temperature radiative corrections without 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 × 10^5	Δ (D/H) (%)	^{3}He/H × 10^5	^{7}Li/H × 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!

Nuclear solution to the Li problem ?



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

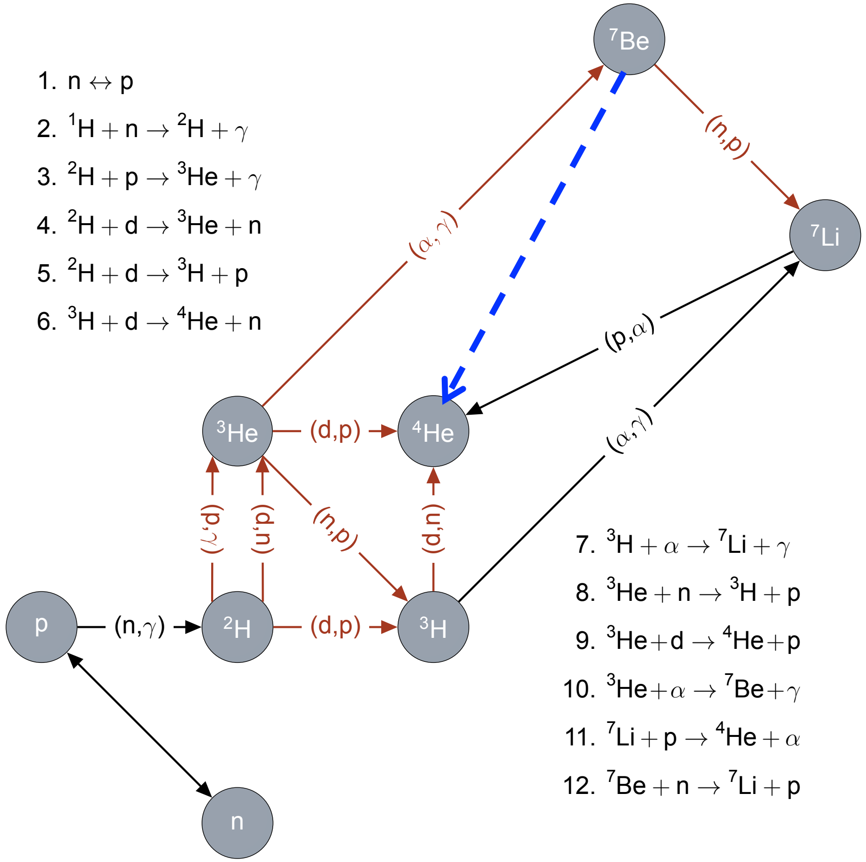
7. $^3H + \alpha \rightarrow {}^7Li + \gamma$
8. $^3He + n \rightarrow {}^3H + p$
9. $^3He + d \rightarrow {}^4He + p$
10. $^3He + \alpha \rightarrow {}^7Be + \gamma$
11. $^7Li + p \rightarrow {}^4He + \alpha$
12. $^7Be + n \rightarrow {}^7Li + p$

At η_{CMB} ^{7}Li from ^{7}Be post BBN decay

Tentatives nuclear solutions:
^{7}Be destruction by:

1. Supplementary reactions
   e.g. $^7Be(d,p)^8Be^* \rightarrow 2\alpha$

Nuclear solution to the Li problem ?



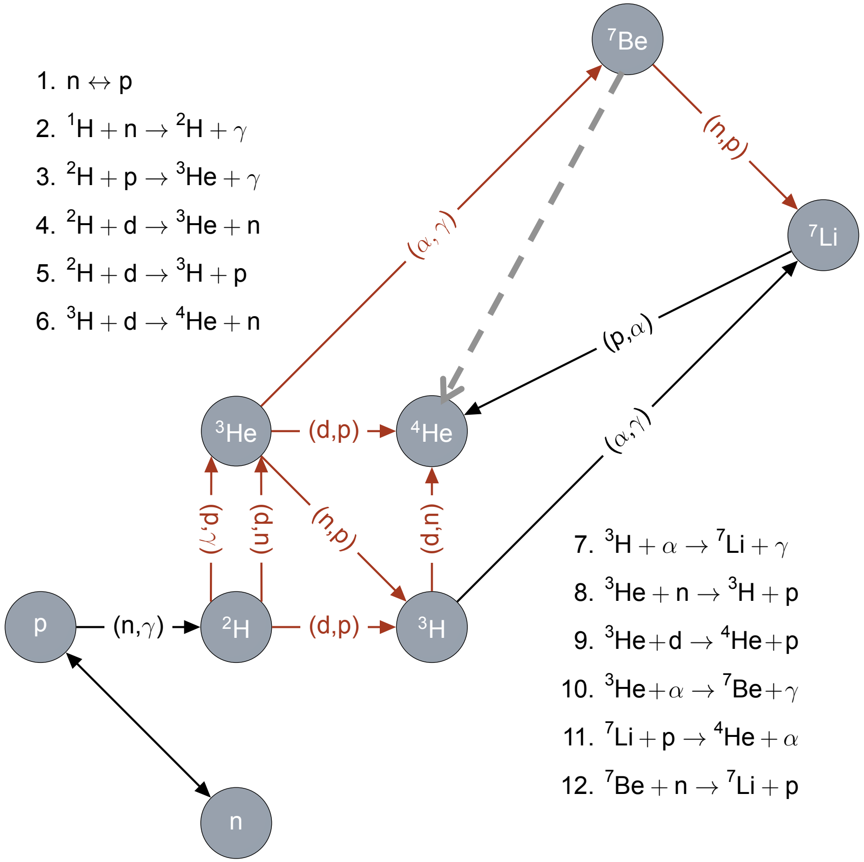
At η_{CMB} ^{7}Li from ^{7}Be post BBN decay

Tentatives nuclear solutions:
^{7}Be destruction by:

1. Supplementary reactions
   e.g. ^{7}Be(d,p)^{8}Be*→2α

Ruled out following extensive experimental and theoretical searches *[Coc+ 2004; 2011, Angulo+ 2005, Kirsebom & Davids 2011,..... Rijal+ 2019]*.

Nuclear solution to the Li problem ?



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2. $^1H + n \rightarrow {}^2H + \gamma$
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5. $^2H + d \rightarrow {}^3H + p$
6. $^3H + d \rightarrow {}^4He + n$
7. $^3H + \alpha \rightarrow {}^7Li + \gamma$
8. $^3He + n \rightarrow {}^3H + p$
9. $^3He + d \rightarrow {}^4He + p$
10. $^3He + \alpha \rightarrow {}^7Be + \gamma$
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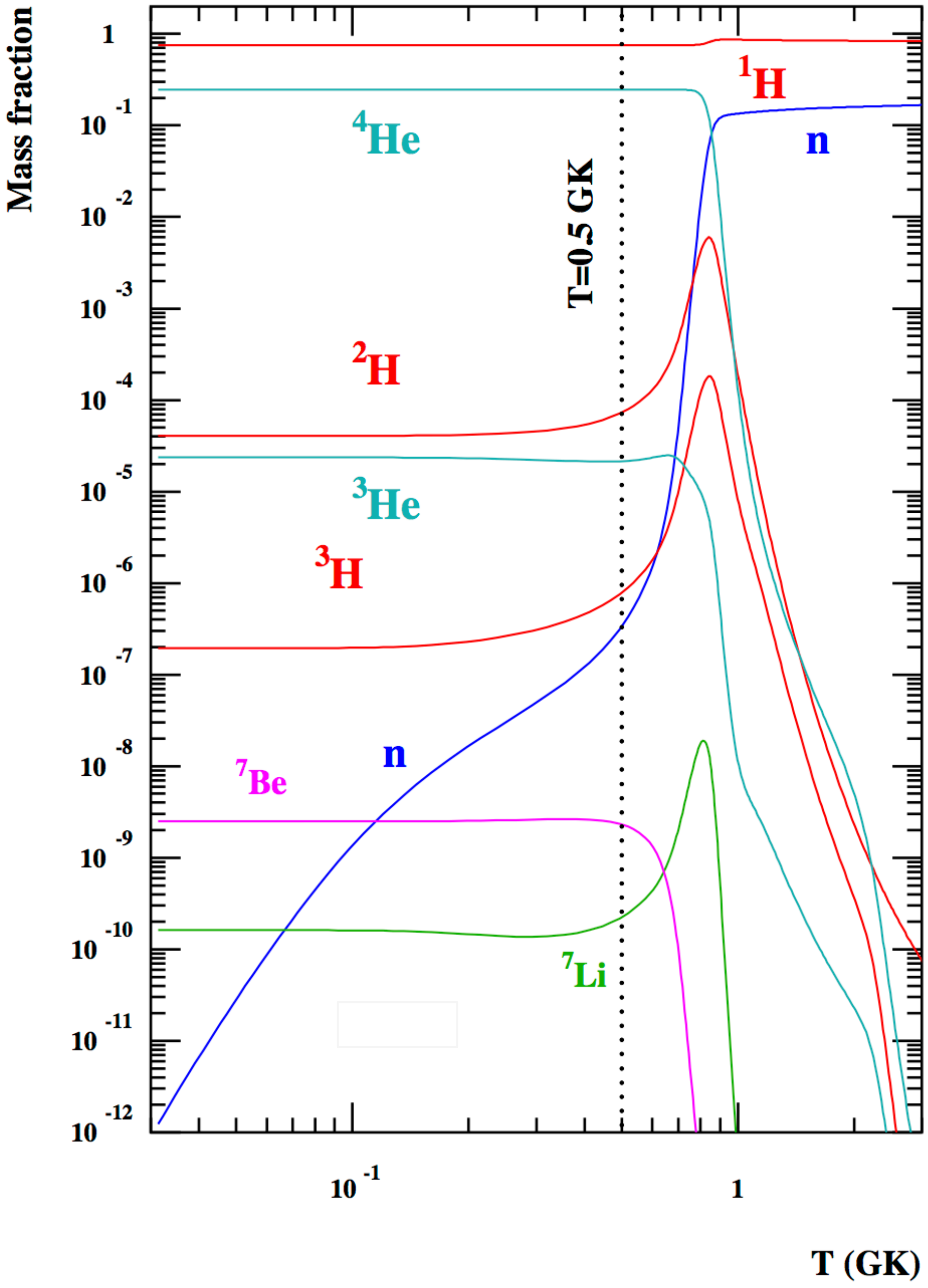
12. $^7Be + n \rightarrow {}^7Li + p$

At η_{CMB} ^{7}Li from ^{7}Be post BBN decay

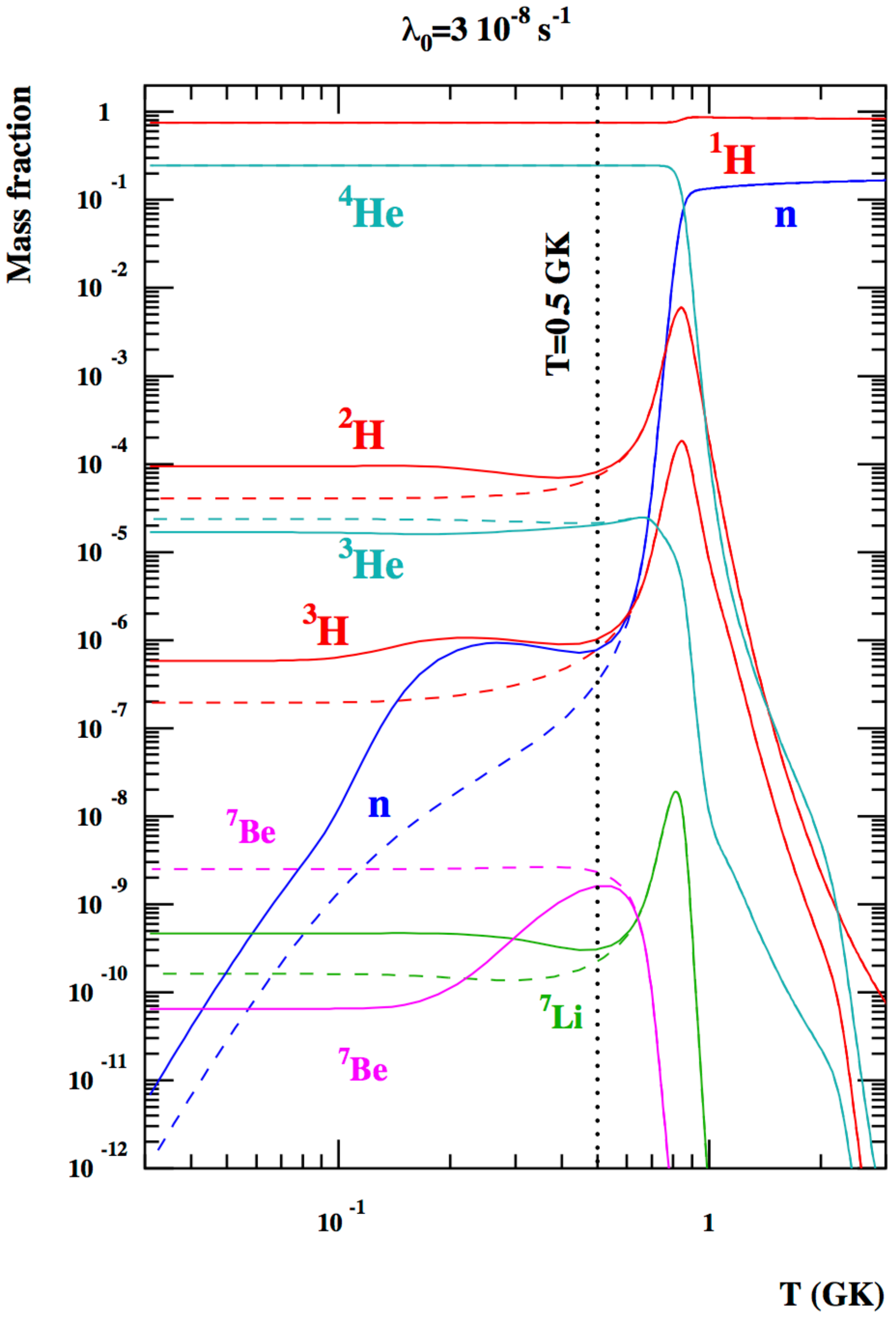
Tentatives nuclear solutions:
^{7}Be destruction by:

1. ~~Supplementary reactions e.g. ^{7}Be(d,p)^{8}Be*→2α~~
2. Increased neutron destruction efficiency by ^{7}Be(n,p)^{7}Li(p,α)^{4}He from exotic neutron sources

^{7}Be (^{7}Li) destruction



- ❑ By most abundant projectiles ^{7}Be(p,γ)^{8}B hindered by photo-dissociation (Q=1.375 MeV) and ^{7}Be(α,γ)^{11}C by Coulomb
- ❑ By less abundant projectiles but higher cross sections of overlooked reactions?
- ❑ No much activity below 0.5 GK (low charged particle rates an low neutron abundance).



Extra neutrons?

- ❑ Increased neutron abundance at *T* above 1 GK only leads to higher ^{4}He (p→d→t,^{3}He→^{4}He)
- ❑ At lower *T* (<0.5 GK)
  - ➢ ^{7}Be↘ by ^{7}Be(n,p)^{7}Li
  - ➢ D ↗ by ^{1}H(n,γ)D
  - ➢ ^{3}H ↗ by ^{3}He(n,p)^{3}H
  - ➢ ^{7}Li ↗ by ^{3}H(α,γ)^{7}Li and ^{7}Be(n,p)^{7}Li [when ^{7}Li(p,α) ineffective at low *T*]
  - ➢ Minimum in ^{7}Li+^{7}Be abundance

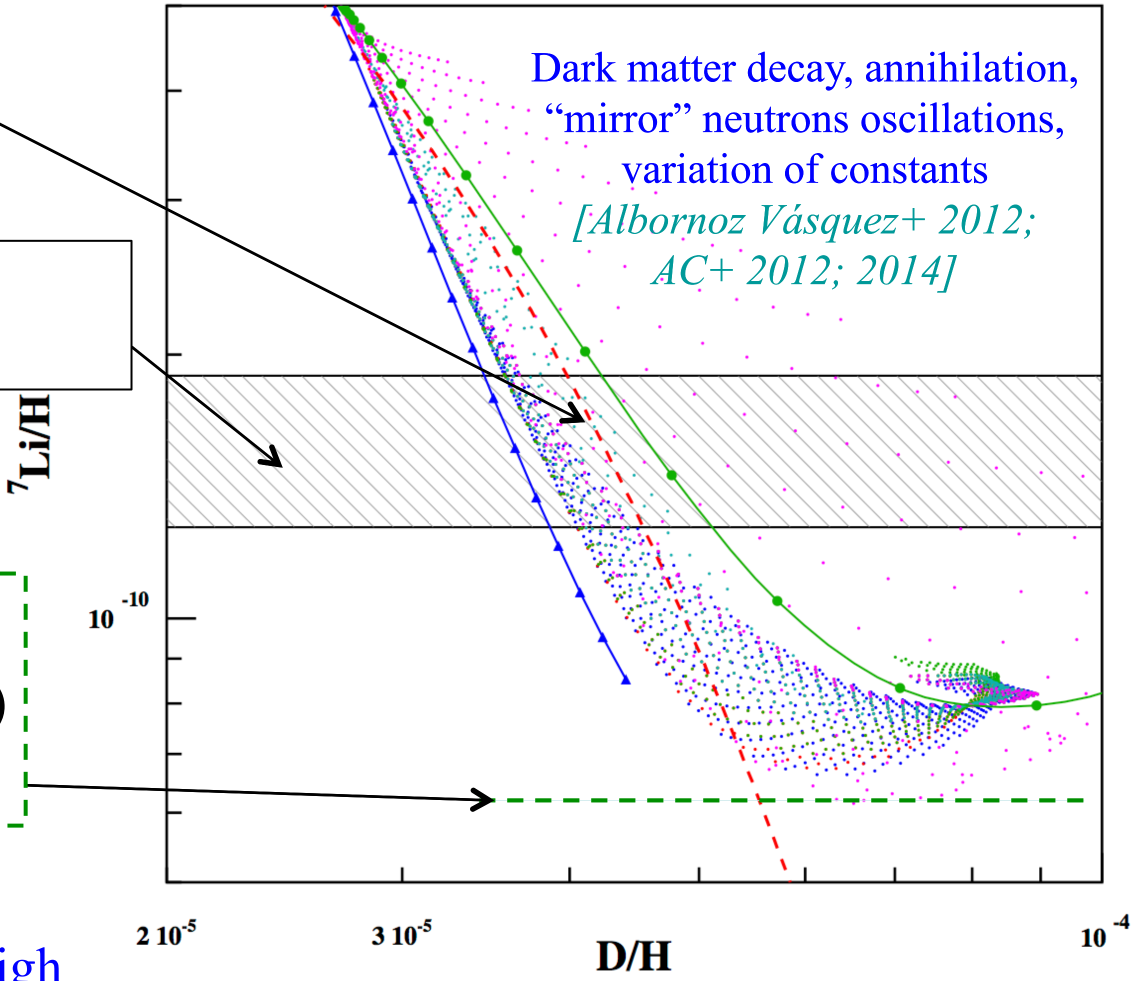
The limits to ^{7}Li+^{7}Be destruction by extra neutrons

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

^{7}Be(n,p) ⇒ ^{1}H(n,p)D

Li observational limits
[Sbordone+ 2010]

^{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

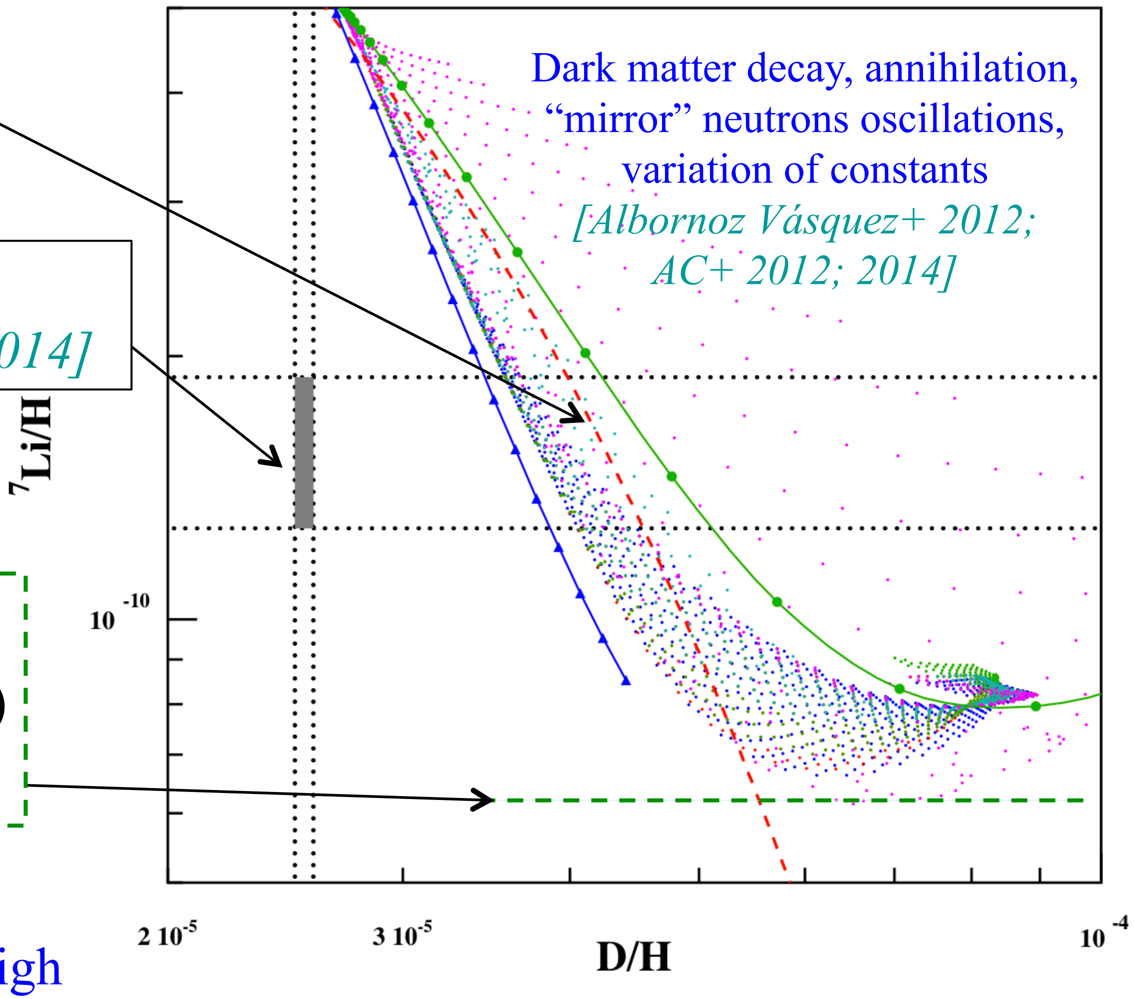
The limits to ^{7}Li+^{7}Be destruction ~~by extra neutrons~~

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*]



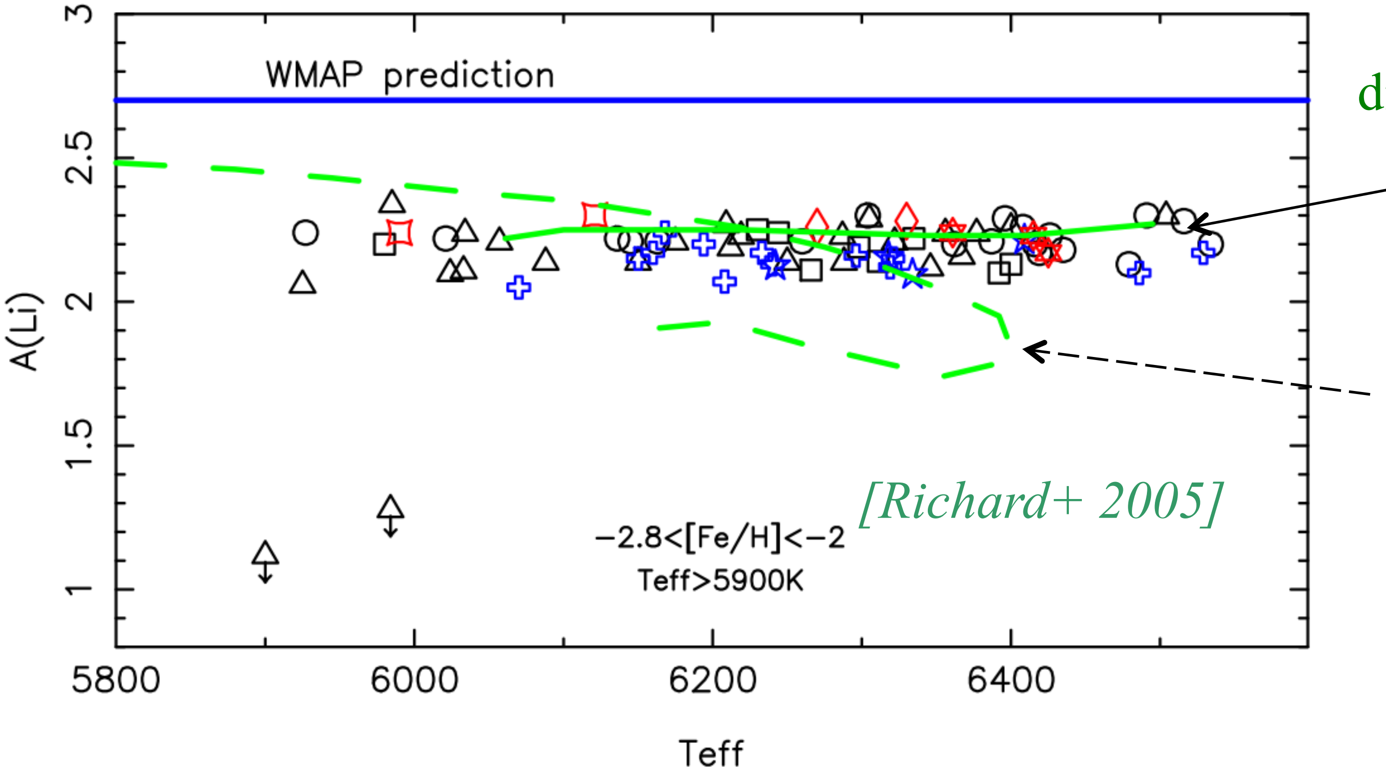
Dark matter decay, annihilation, “mirror” neutrons oscillations, variation of constants *[Albornoz Vásquez+ 2012; AC+ 2012; 2014]*

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

Lower Li/H ⇒ higher D/H

Li stellar depletion ?

- ☐ In situ destruction (atomic diffusion + turbulence interplay)
  - ➢ Some amount of depletion, a factor of 1.5 to 2, is unavoidable because of atomic diffusion *[Michaud+ 1984]*
  - ➢ Uniformity restored by an additional mixing process *[Richard+ 2005; Korn+ 2006]*

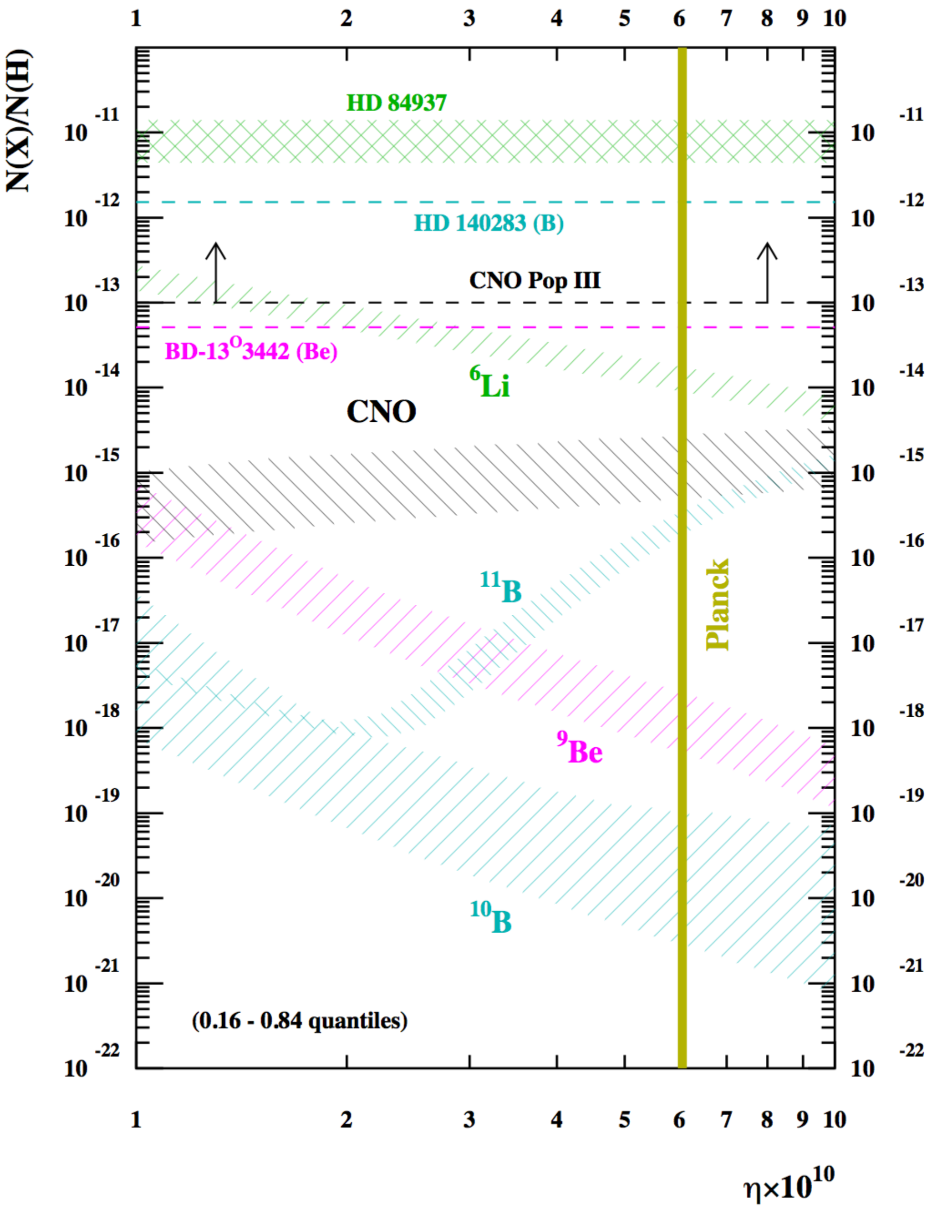


diffusion + turbulence

diffusion only

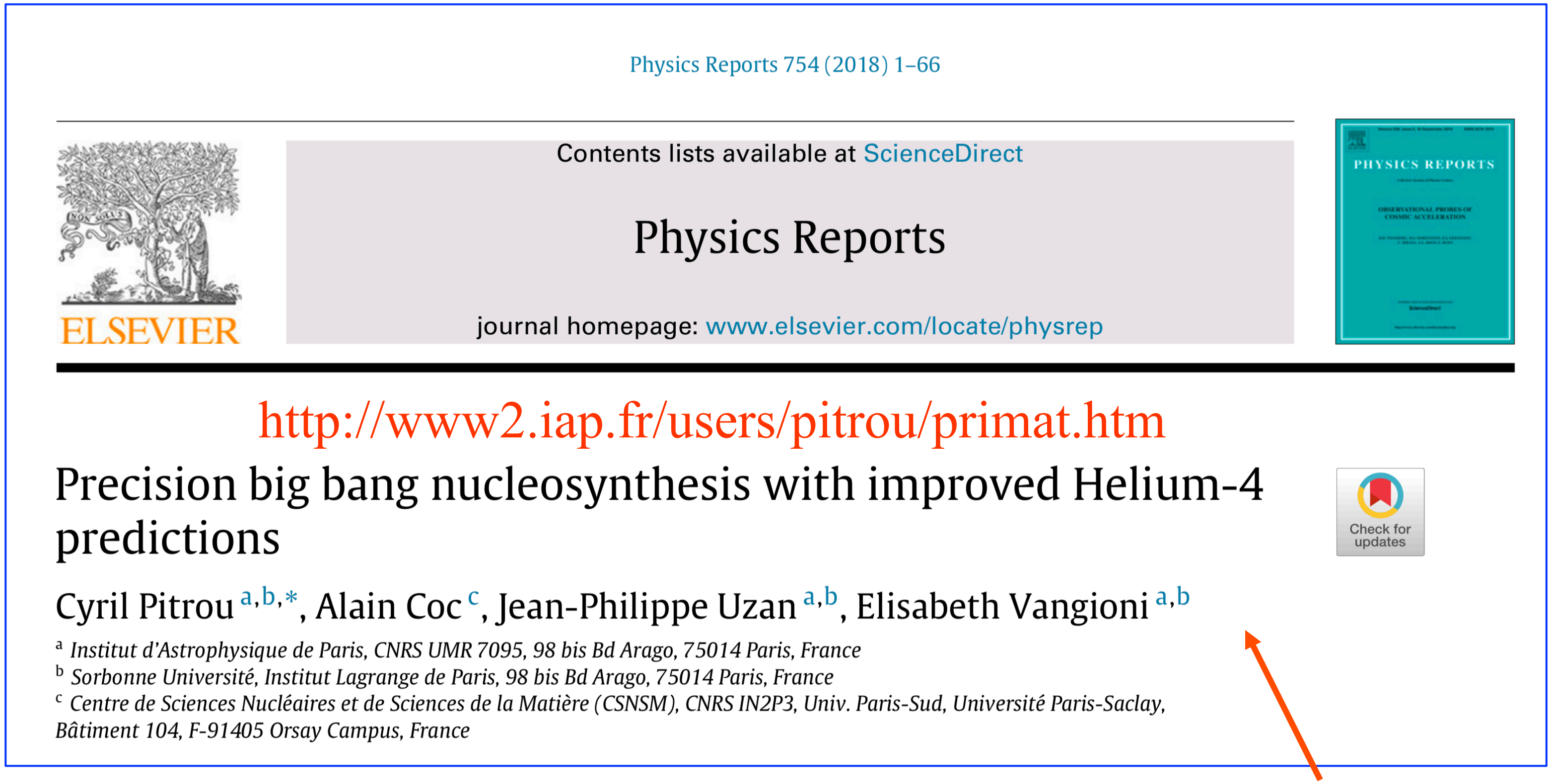
[Richard+ 2005]

Other contributions to the periodic table



- ➢ Origin of ^{6}Li, Be and B
- ➢ Seeds for the first stars CNO-cycle/pp-chain (at CNO/H ≈ 10^{-13})

Number of atoms	*[Coc et al. 2012]*	*[Coc et al. 2014]*
^{6}Li/H ($\times10^{-14}$)	1.23	0.90-1.77
^{9}Be/H ($\times10^{-19}$)	9.60	5.10-26.3
^{11}B/H ($\times10^{-16}$)	3.05	1.85-3.56
CNO/H ($\times10^{-16}$)	7.43	4.94-28.5



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Precision big bang nucleosynthesis with improved Helium-4 predictions

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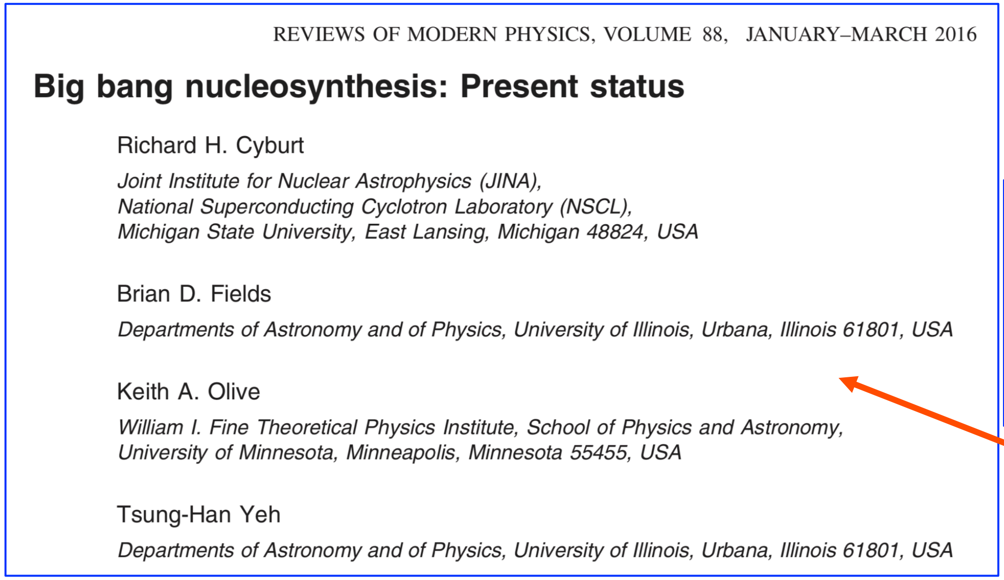

REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

Big bang nucleosynthesis: Present status

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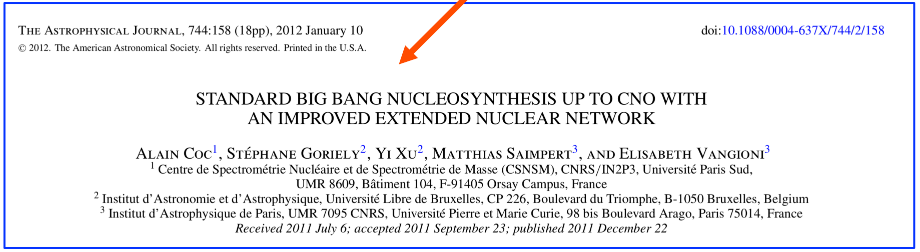
PRIMAT public BBN code with extended nuclear network



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

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Recent BBN review

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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