Precision primordial nucleosynthesis

(with the new code "PRIMAT")

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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" (^4He, ^2H or D, ^3He and ^7Li) primordial abundances over a range of nine orders of magnitudes.

Big Bang Nucleosynthesis probe of new physics

- 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]*
- Today, still extensively used to constraint physics beyond the Standard Model. See e.g. review by *Iocco et al. 2009*

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

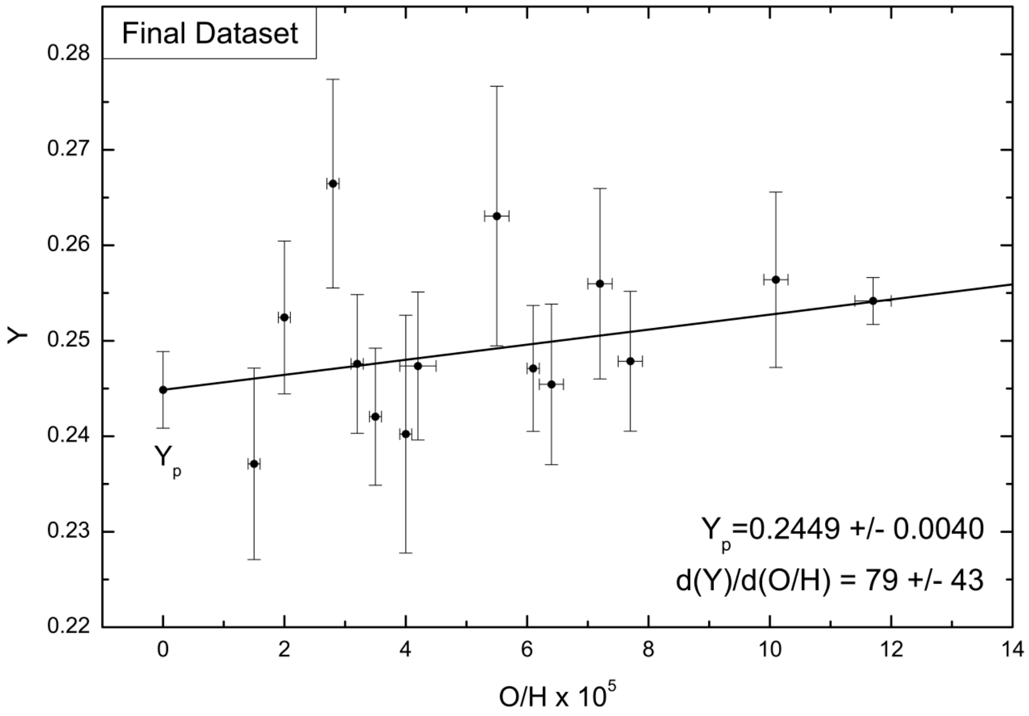
2) Extrapolate to zero metallicity* : Fe/H, O/H, Si/H,…. → 0

*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

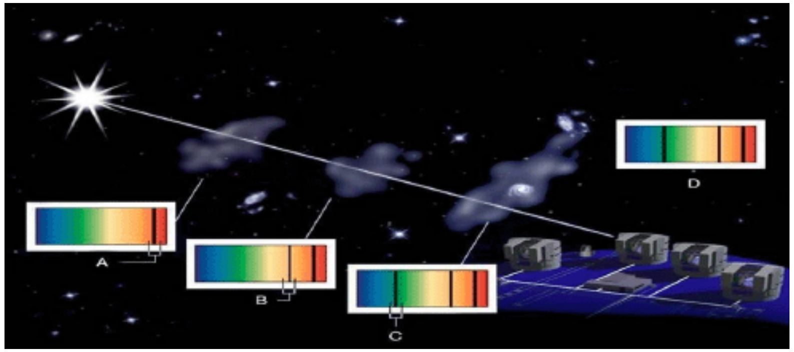
Observations: ^{4}**He** from a sample of 86 H II regions in 77 blue compact galaxies *[Izotov, Thuan & Stasinska 2007]* with additional infrared line *[Izotov, Thuan & Guseva 2014]*



Y_p = ^{4}He mass fraction

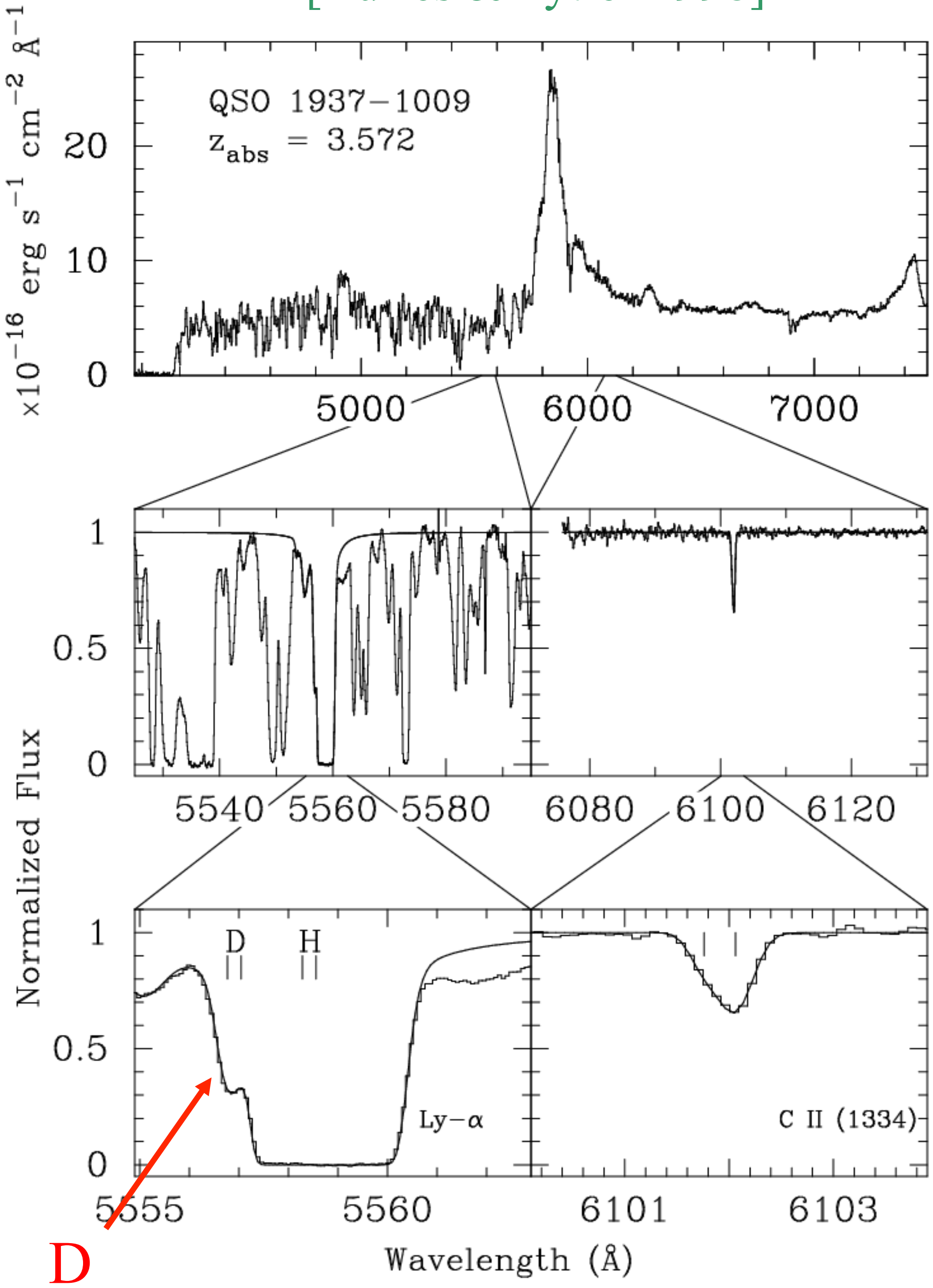
Analysis : with new atomic and collisional emission data, He I emissivity and IR line included Y_p=0.2449±0.0040 (^{4}He mass fraction) *[Aver, Olive, Porter & Skillman 2015]* (1.6% precision)

D/H observations in a cosmological cloud



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

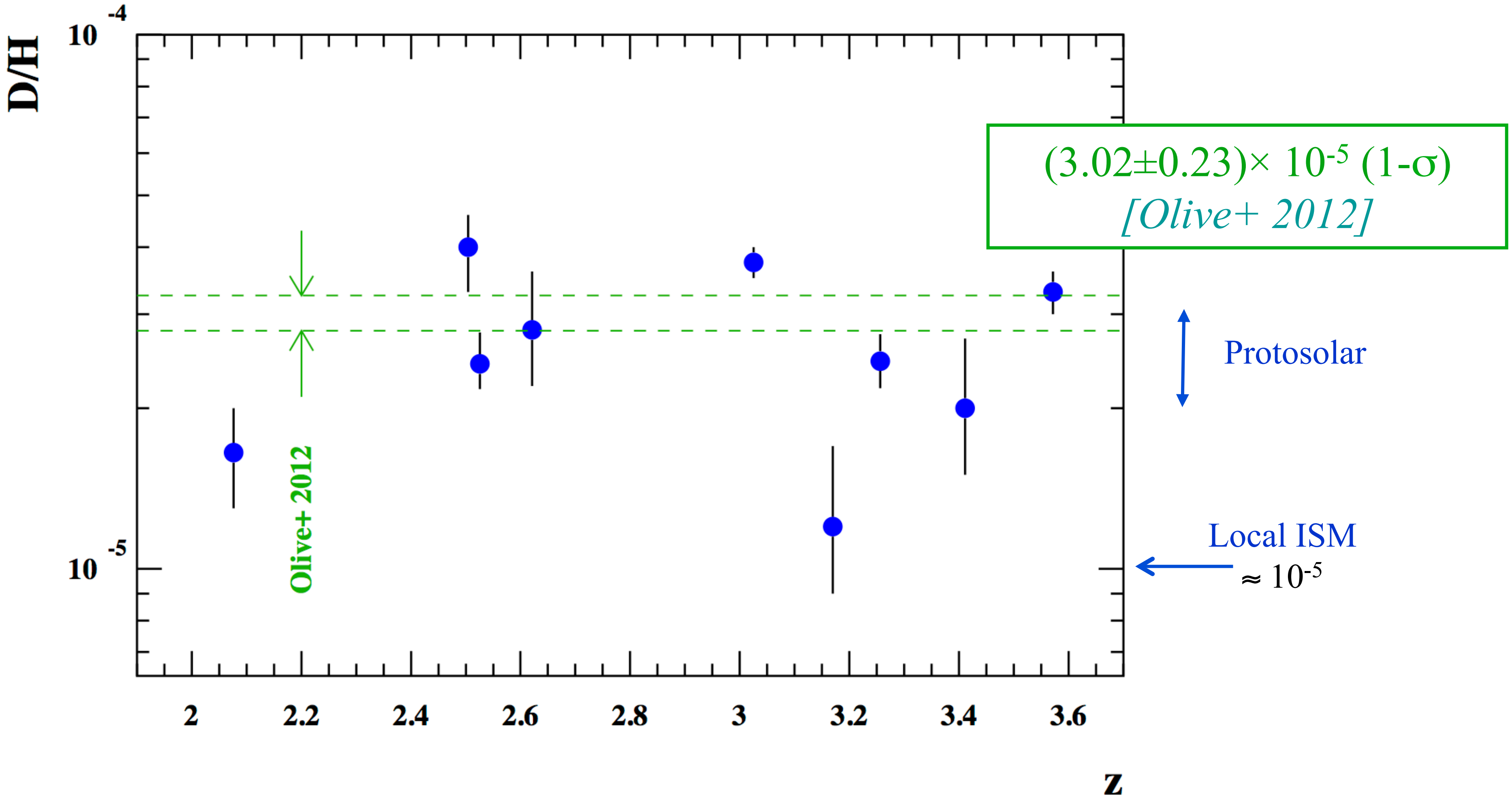
[Burles & Tytler 1998]



Observations :

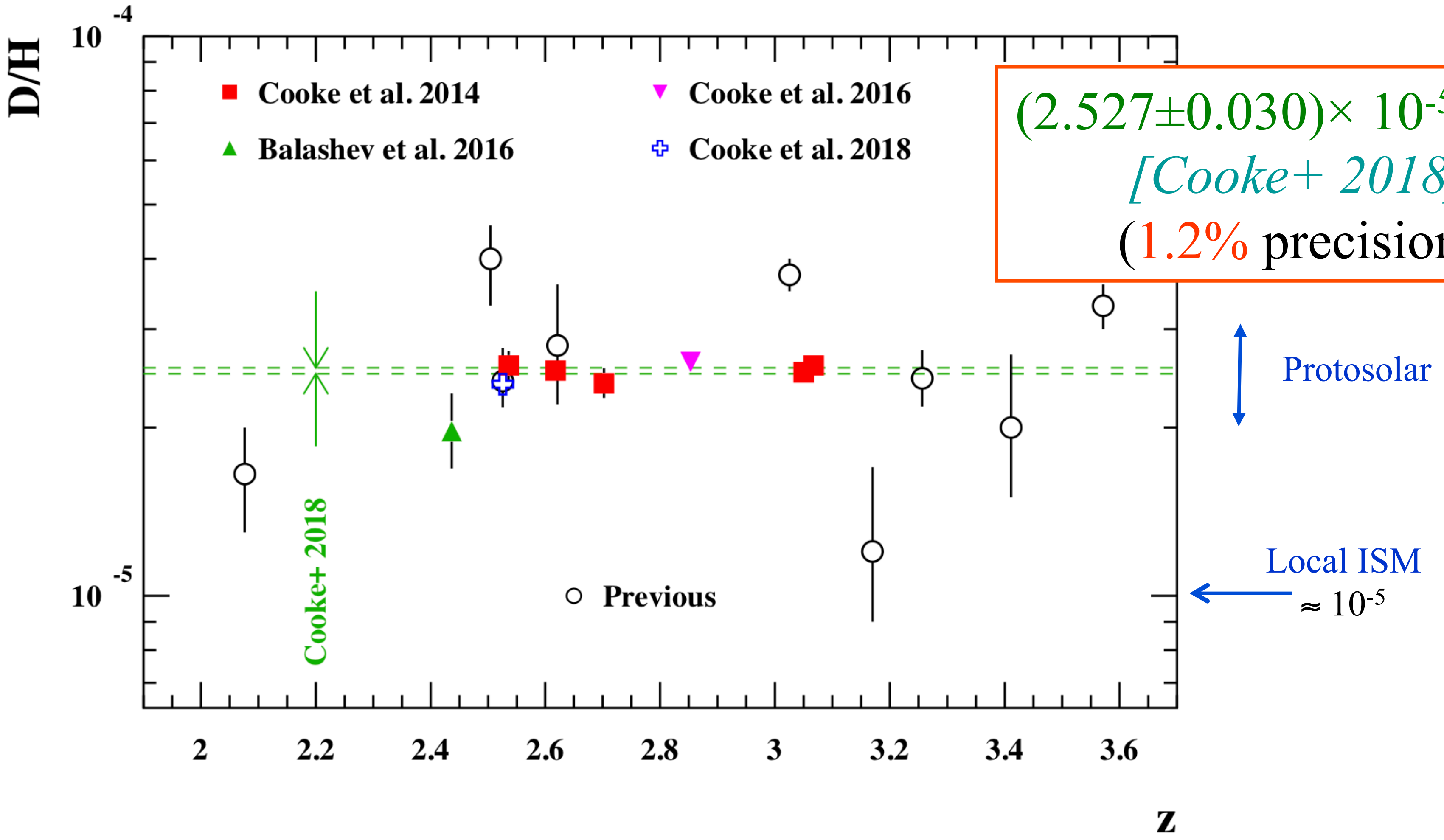
- D/H ratio at high redshift from the depth/width of absorption lines

D/H observations in cosmological clouds



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

D/H observations in cosmological clouds



(2.527±0.030)× 10^{-5} (1-σ)

[Cooke+ 2018]

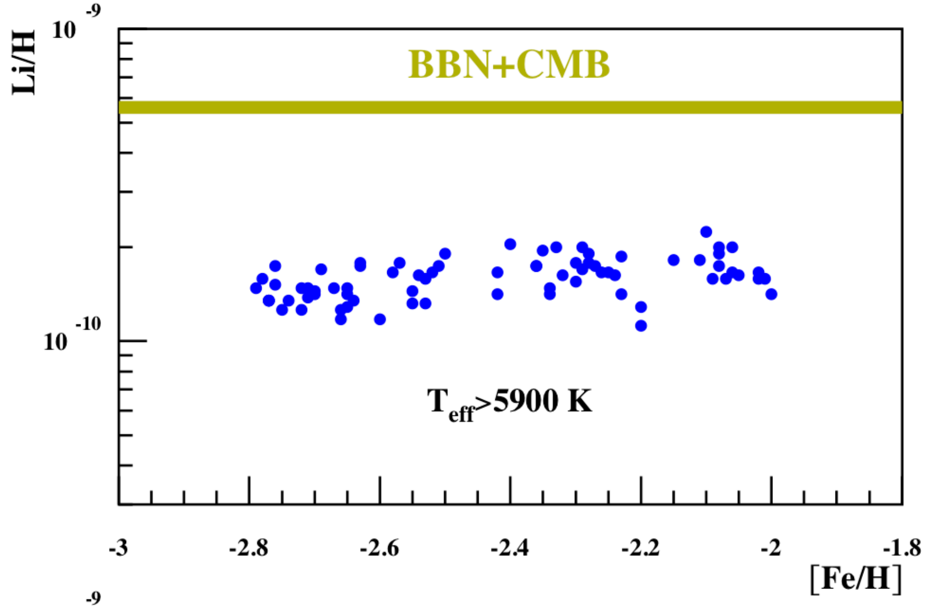
(1.2% precision)

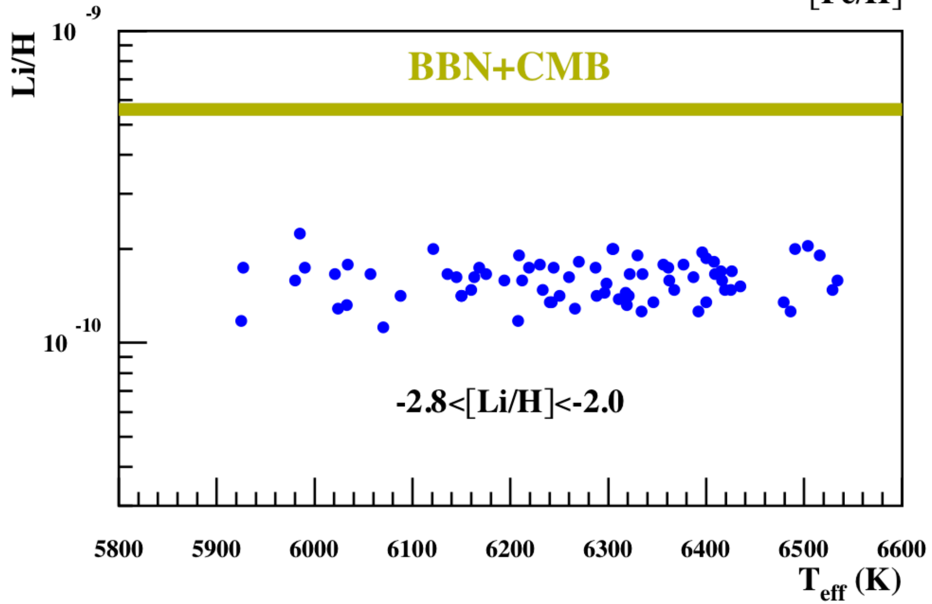
Burles & Tytler 1998; O'Meara+ 2001, 2006; Pettini+ 2001, 2008, 2012; Kirkman+ 2003, Crighton+ 2004; Srianand+ 2010; Cooke+ 2011; Fumagalli+ 2011; Cooke+ 2016; 2018

Primordial Li from observations

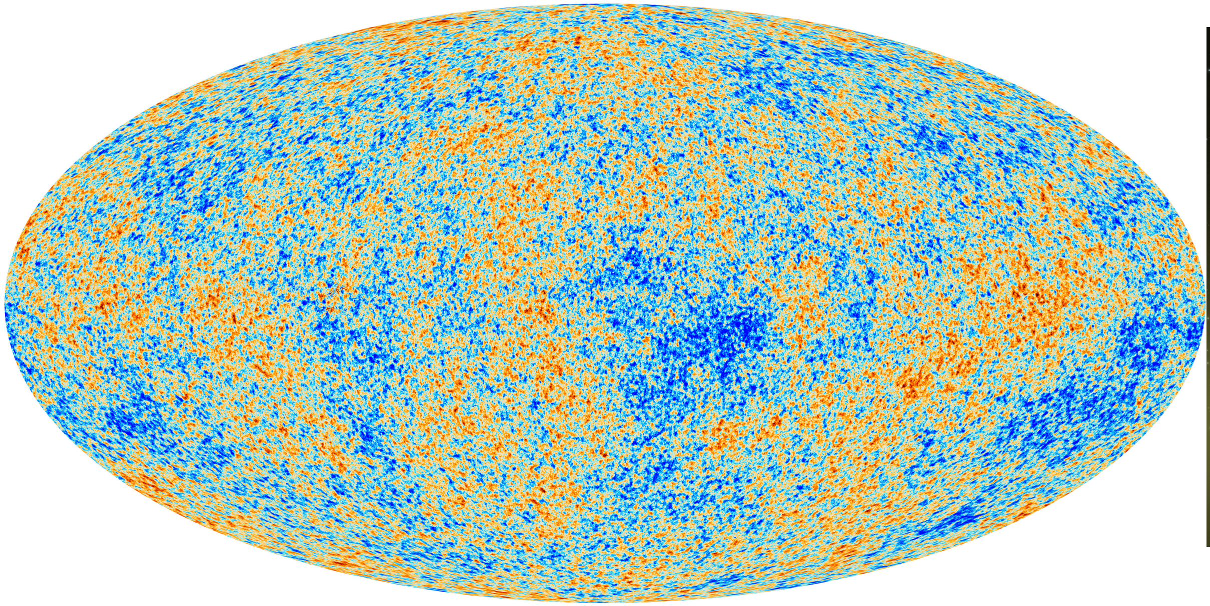
[M. Spite, priv. comm.]

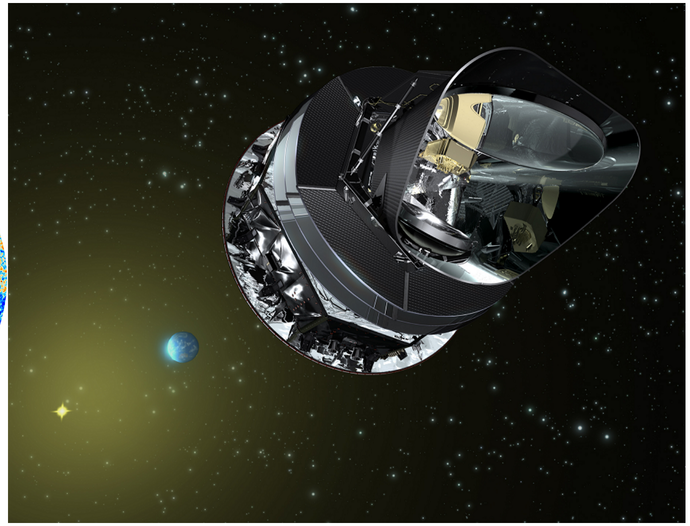
- Oldest (low metallicity) stars in galactic halo
- Lifetime of $M < 0.9\ M_{\odot}$ stars > 15 Gy
- For $T_{eff} > 5900$ K, no deep convection and no Li surface depletion (?)
- $Li/H = (1.58 \pm 0.35) \times 10^{-10}$ *[Sbordone et al. 2010]*





Density components of the Universe





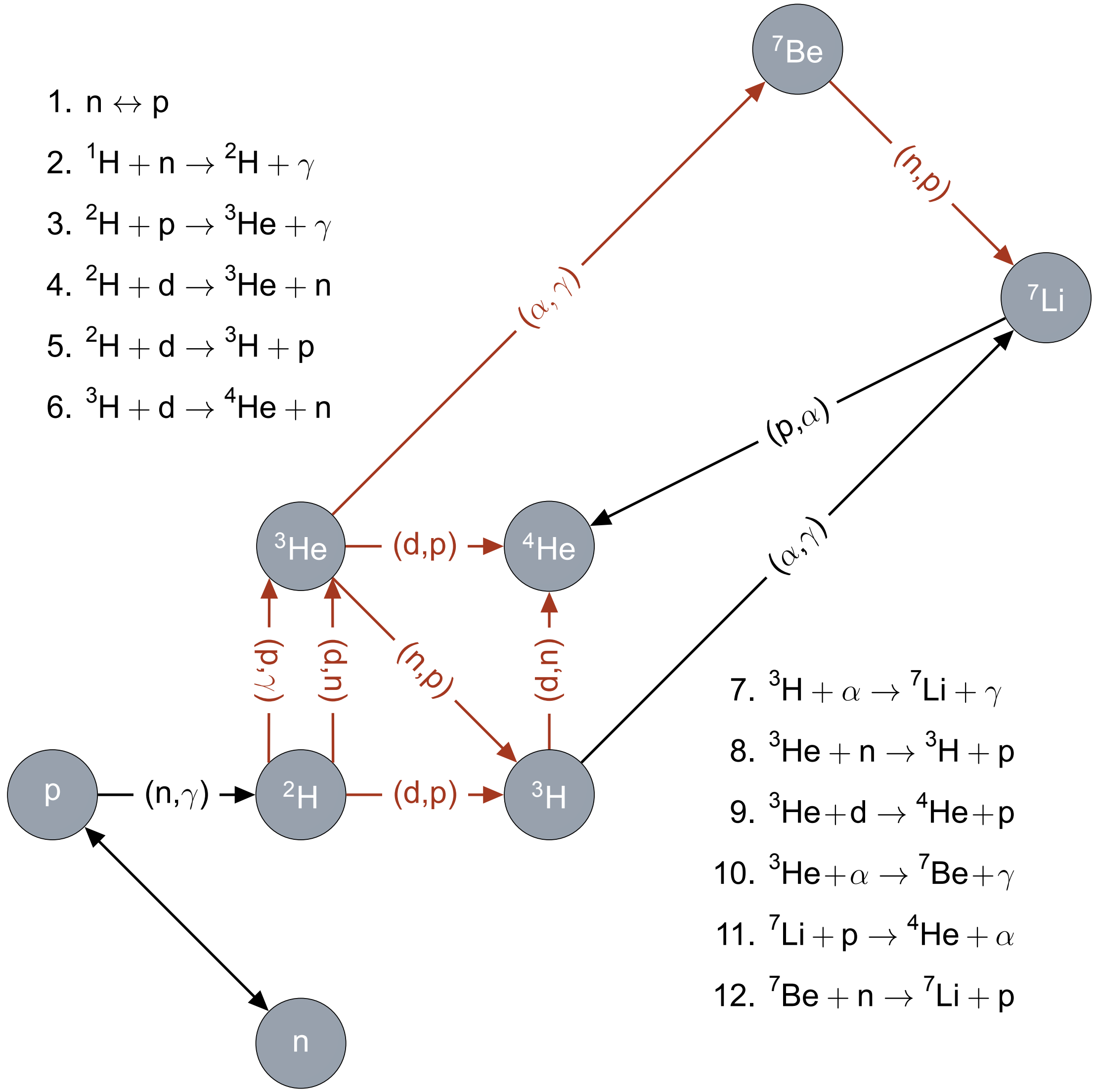
$$\Omega \equiv \rho / \rho_{Critical}$$

$h = H_0/100$ km/s/Mpc
$\approx 0.6727 \pm 0.0066$

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)]

Big Bang Nucleosynthesis calculations



Needs:

- Reaction rates (~400 to reach CNO)
- Density $\rho_b(t)$, ions and photons $T(t)$ and neutrino $T_\nu(t)$ temperatures as a function of time

New public code *PRIMAT[Pitrou+ 2018]*

Dynamics of the expanding Universe

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 :

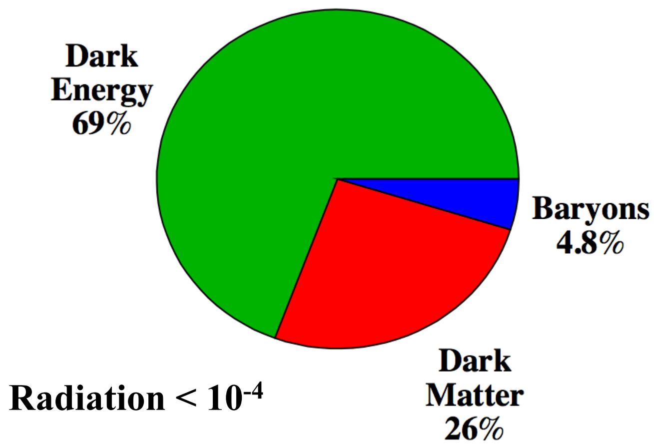
$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}(\rho_R + \rho_M + \rho_\Lambda) - \frac{k}{a^2}$$

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

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

Curvature $\Rightarrow a^{-2}$

Now.... (a≡1)



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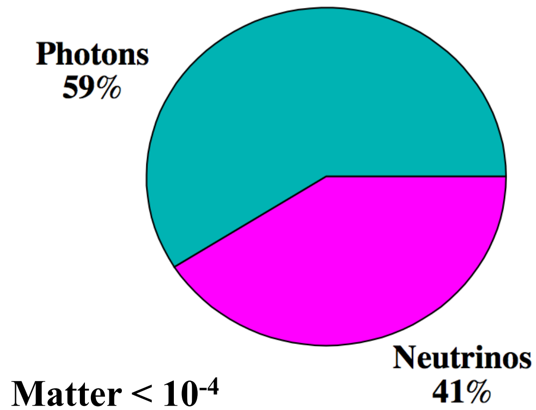
....and then ($a \approx 10^{-8}$)



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

$w =$
- 0 (matter) $\Rightarrow a^{-3}$
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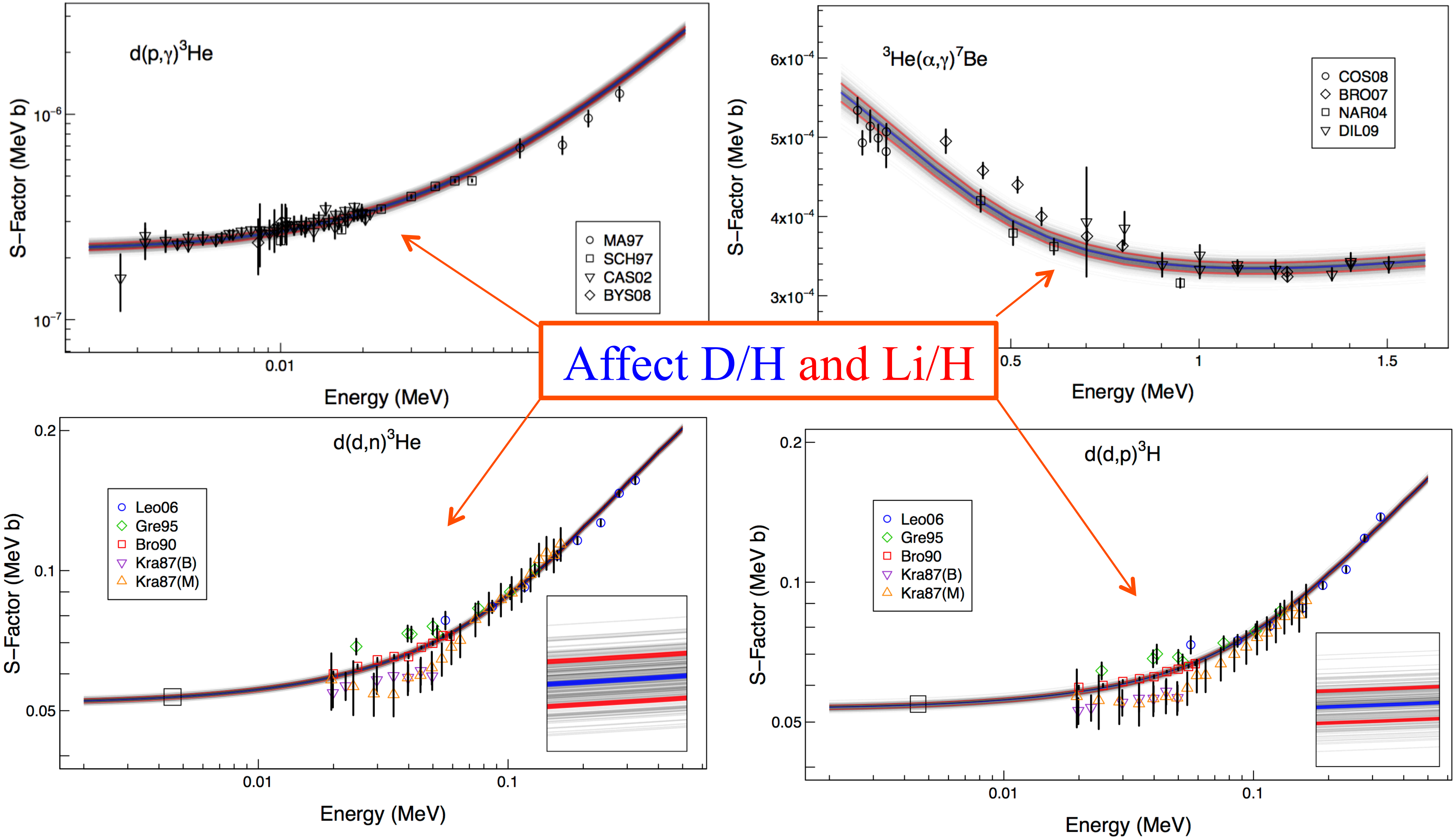
- -1 (Λ, dark energy) $\Rightarrow a^{0}$
- Curvature $\Rightarrow a^{-2}$

Re-evaluation of main reaction rates

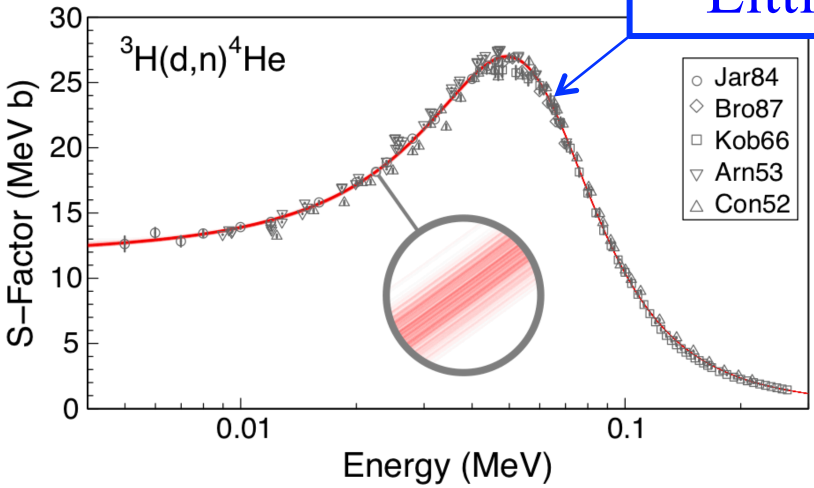
Bayesian analyses of reaction rates for BBN : D(p,γ)^{3}He, D(d,n)^{3}He, D(d,p)^{3}H and ^{3}He(α,γ)^{7}Be *[Iliadis+ 2016; Gómez Iñesta+2017]* already included in PRIMAT

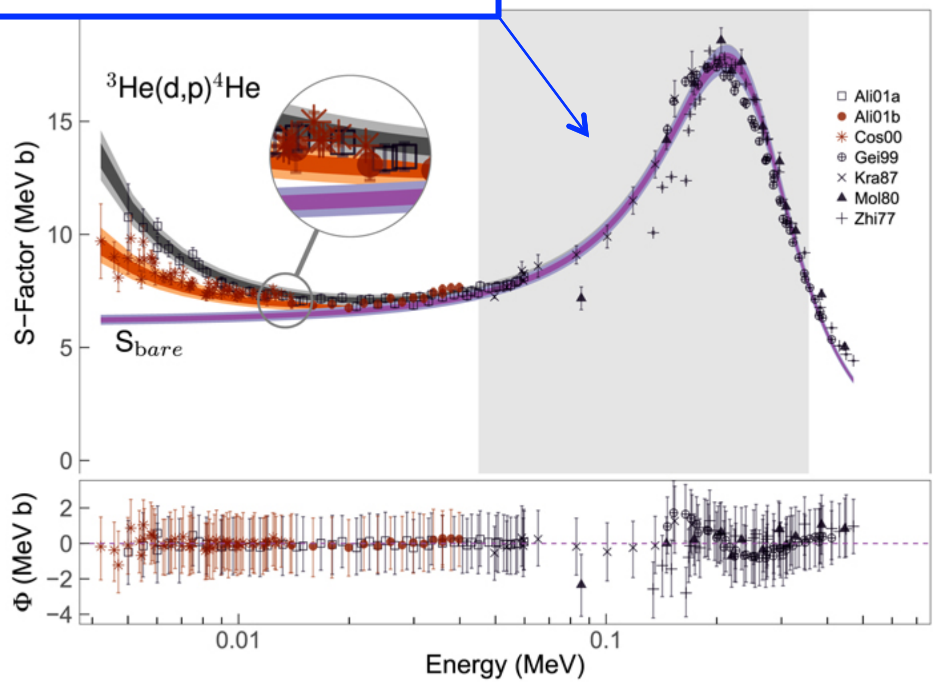


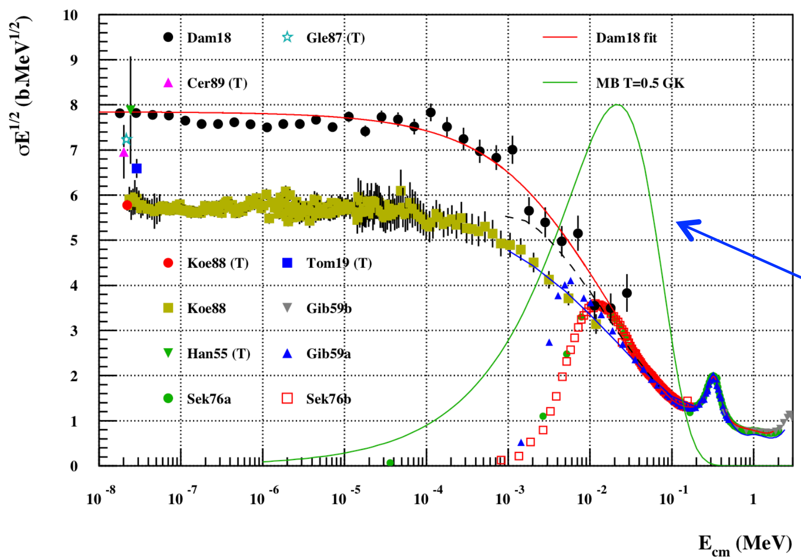
Re-evaluation of main reaction rates

Bayesian analyses of reaction rates for BBN/ including $^{3}He(d,p)^{4}He$, $^{3}H(d,n)^{4}He$ *[de Souza+2019a,b]* and $^{7}Be(n,p)^{7}Li$ *[Tan Hong Kiat+ in preparation]* to be included in PRIMAT

Little influence on BBN







Re-evaluation in progress
Direct influence on Li/H (≲8%)

n↔p weak reaction rates

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

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

$$\lambda_{n\leftrightarrow p} = C \sum \int (\text{phase space}) \times (\text{e distribution}) \times (\nu_e \text{ distribution})\ dE$$

+ "some small corrections"

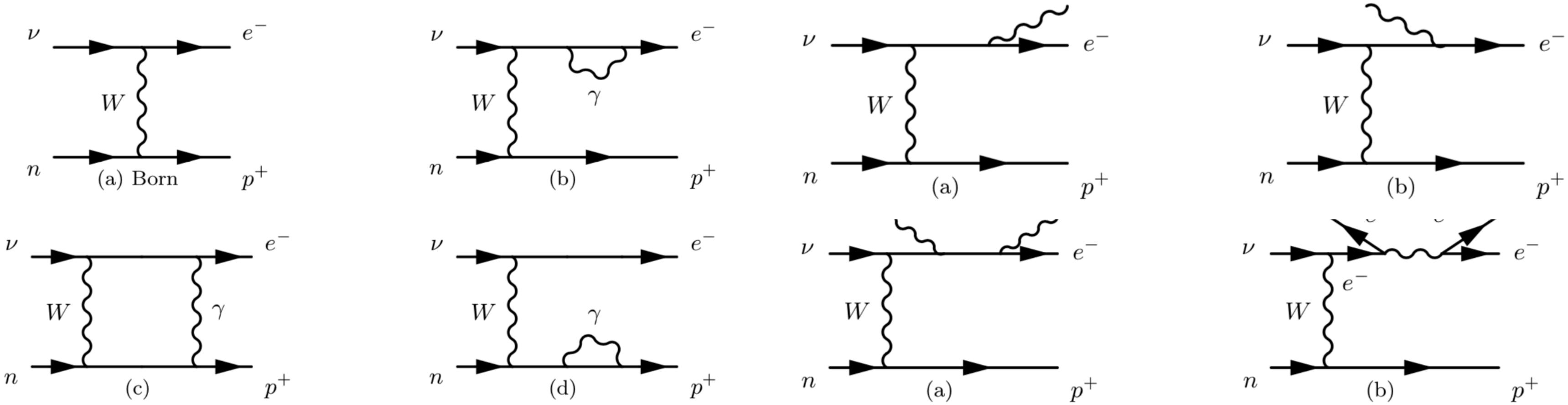
$$\lambda_{n\to pe\nu} = C \int_1^q \frac{\varepsilon(\varepsilon - q)^2 (\varepsilon^2 - 1)^{1/2}\, d\varepsilon}{[1 + \exp(-\varepsilon z)]\{1 + \exp[(\varepsilon - q) z_\nu]\}} \quad \xrightarrow[T \to 0]{} \quad \frac{1}{\tau_n} = C \int_1^q \varepsilon(\varepsilon - q)^2 (\varepsilon^2 - 1)^{1/2}\,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

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

- 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
2. finite nucleon mass corrections,
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]

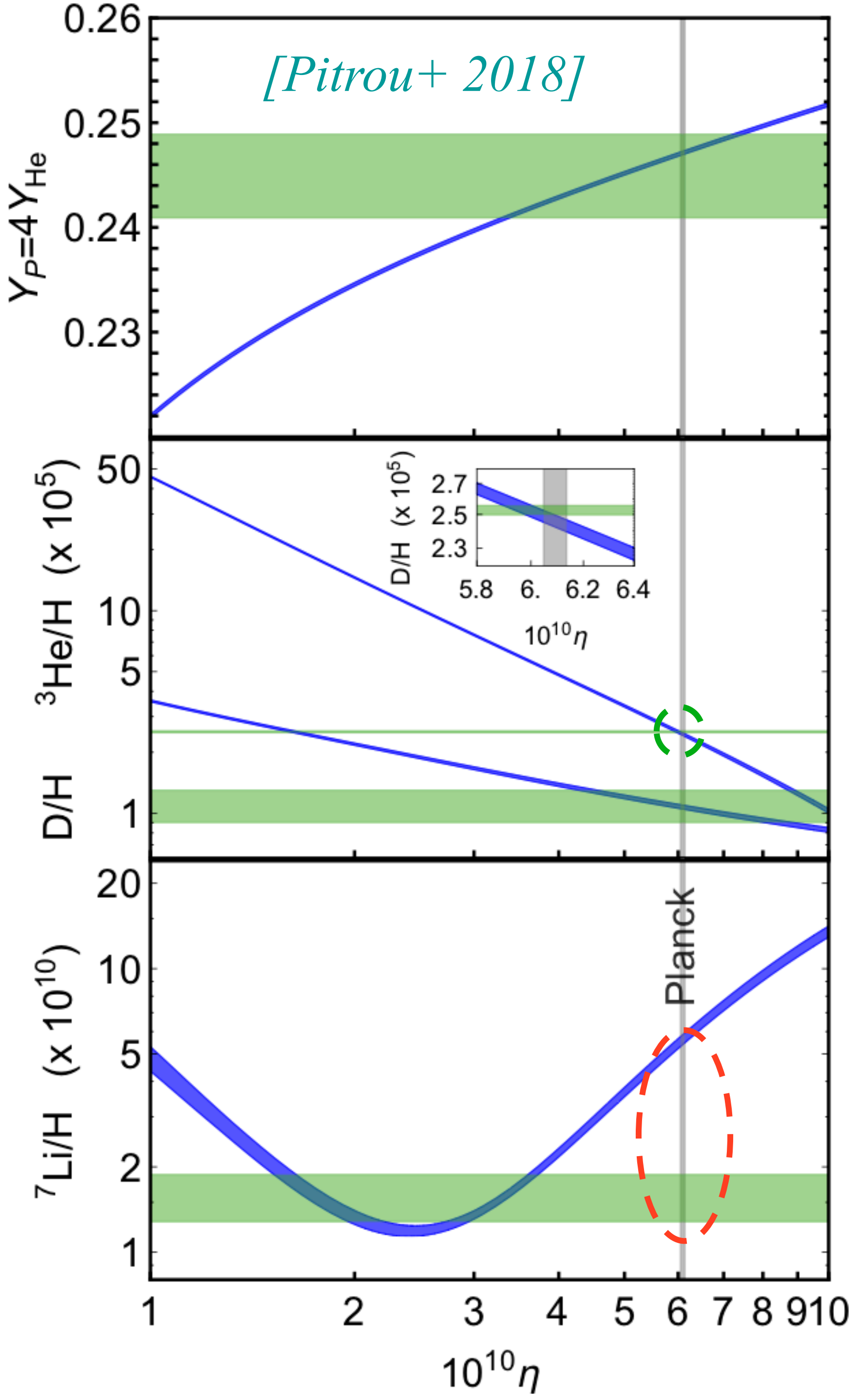
Pitrou et al. 2018 : All included and calculated in a self consistent way, allowing to take into account the correlations between them, and verifying that all satisfy detailed balance

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			
	^4He	D/H	$^3He/H$	$^7Li/H$
	$\times 10^0$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-10}$
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 ^4He, very good agreement between (Fortran77) *EZ_BBN* and (Mathematica) *PRIMAT* results
- Small corrections on weak rates ≈ observational uncertainties!

	Δ^4He[%]	Δ(D/H) [%]
Radiative corrections	0.53	0.70
Finite mass of nucleons	1.27	0.25
Incomplete neutrino decoupling		0.37
QED effects on plasma		0.12
Total	1.84	1.49

Comparison between BBN codes

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	^4He	D/H	$^3He/H$	$^7Li/H$
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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
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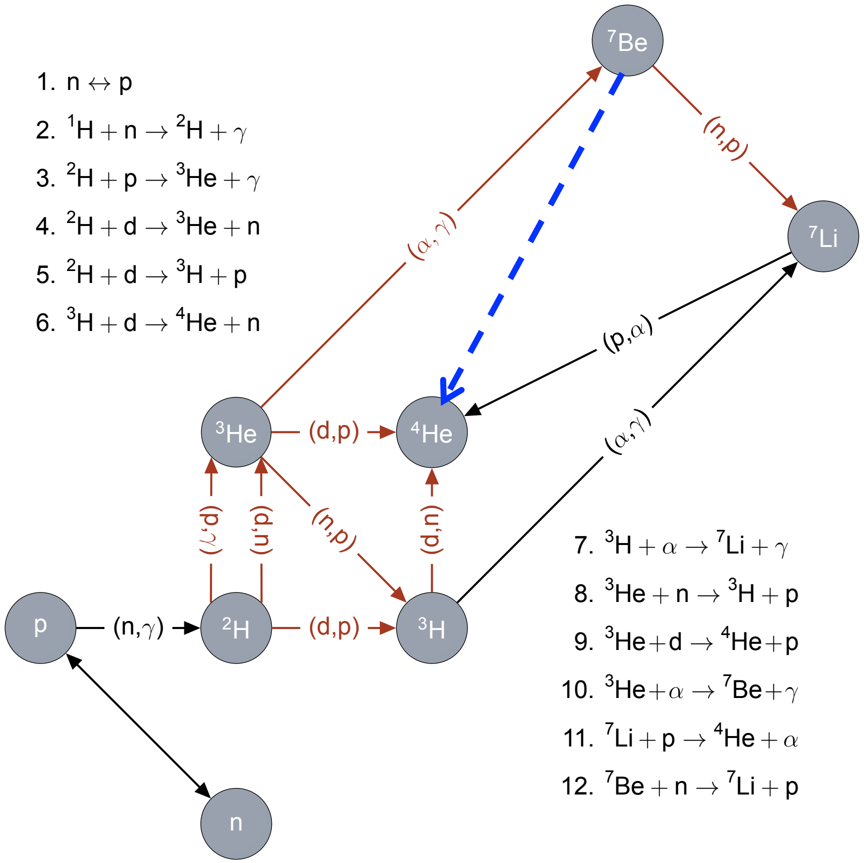
Yeh priv. comm	0.2472	2.449	1.076	5.633

Even better if one uses the same reaction rates!
(Tsung-Han) Yeh priv. comm = *Cyburt+* 2016 code with re-evaluated rates :
D(p,γ)^{3}He, D(d,n)^{3}He, D(d,p)^{3}H, ^{7}Be(n,α)^{4}He & ^{3}He(α,γ)^{7}Be

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

Nuclear solution to the Li problem ?

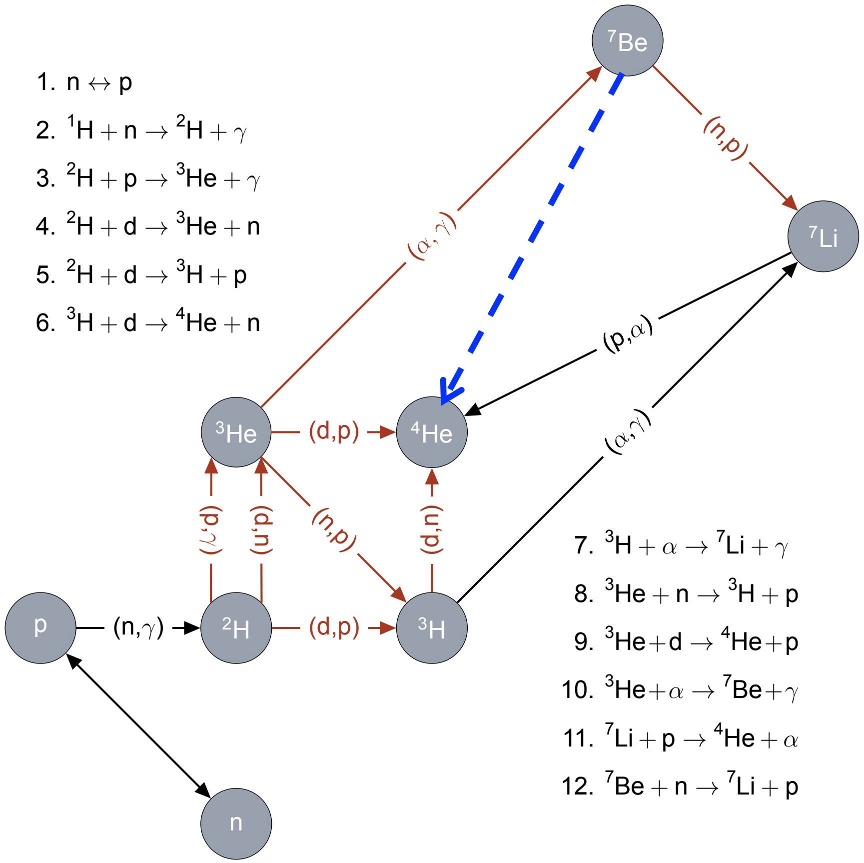


At η_{CMB} ^{7}Li from ^{7}Be post BBN decay

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

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

Nuclear solution to the Li problem ?



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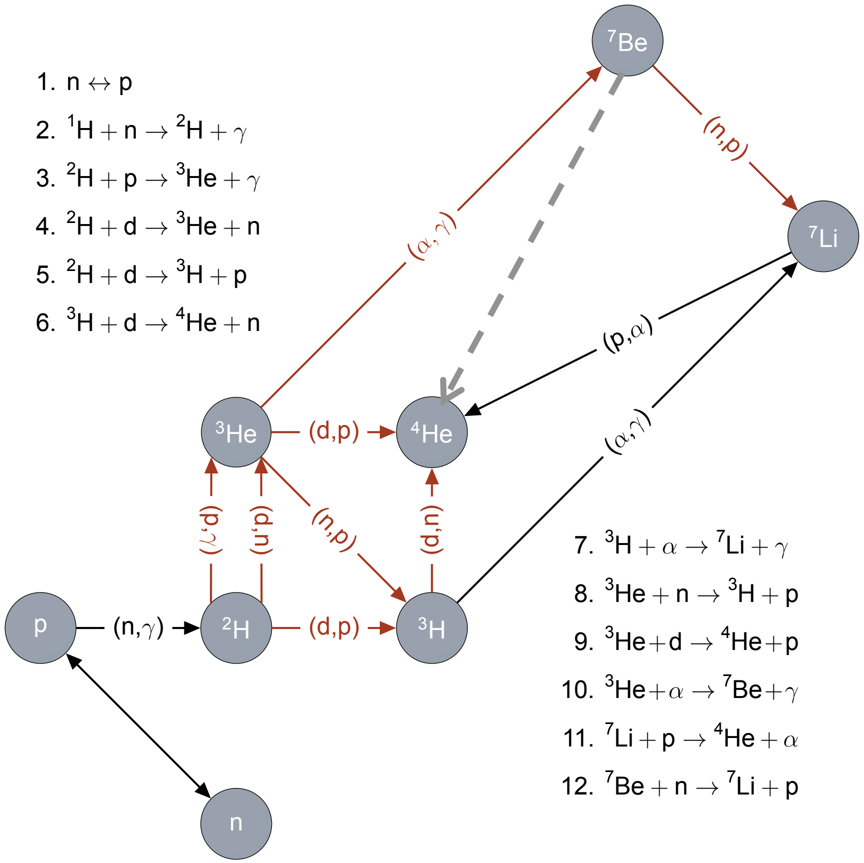
Ruled out following extensive experimental and theoretical searches *[Coc+ 2004; 2011, Angulo+ 2005, Kirsebom & Davids 2011,..... Rijal+ 2019]*.

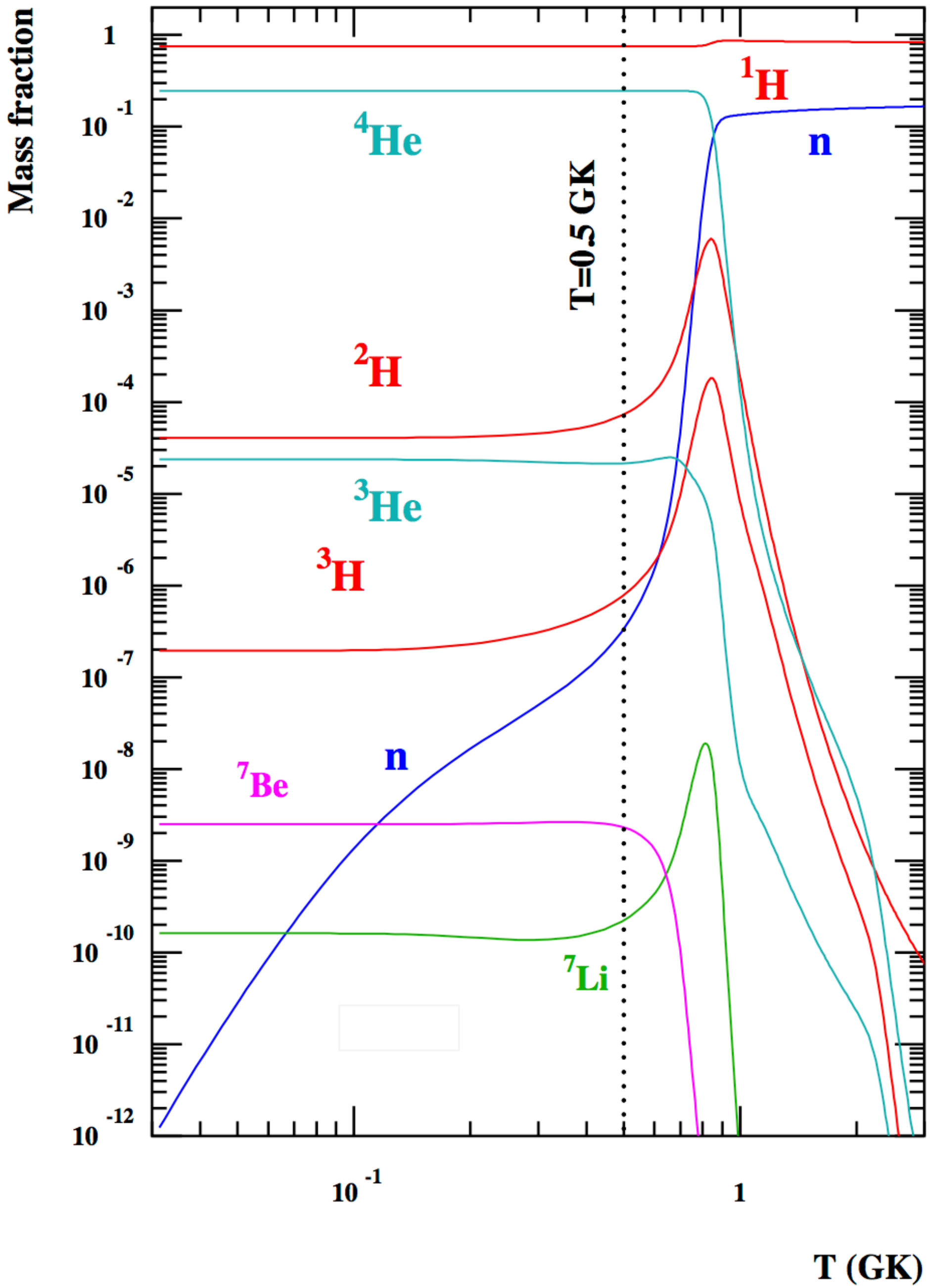
Nuclear solution to the Li problem ?



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

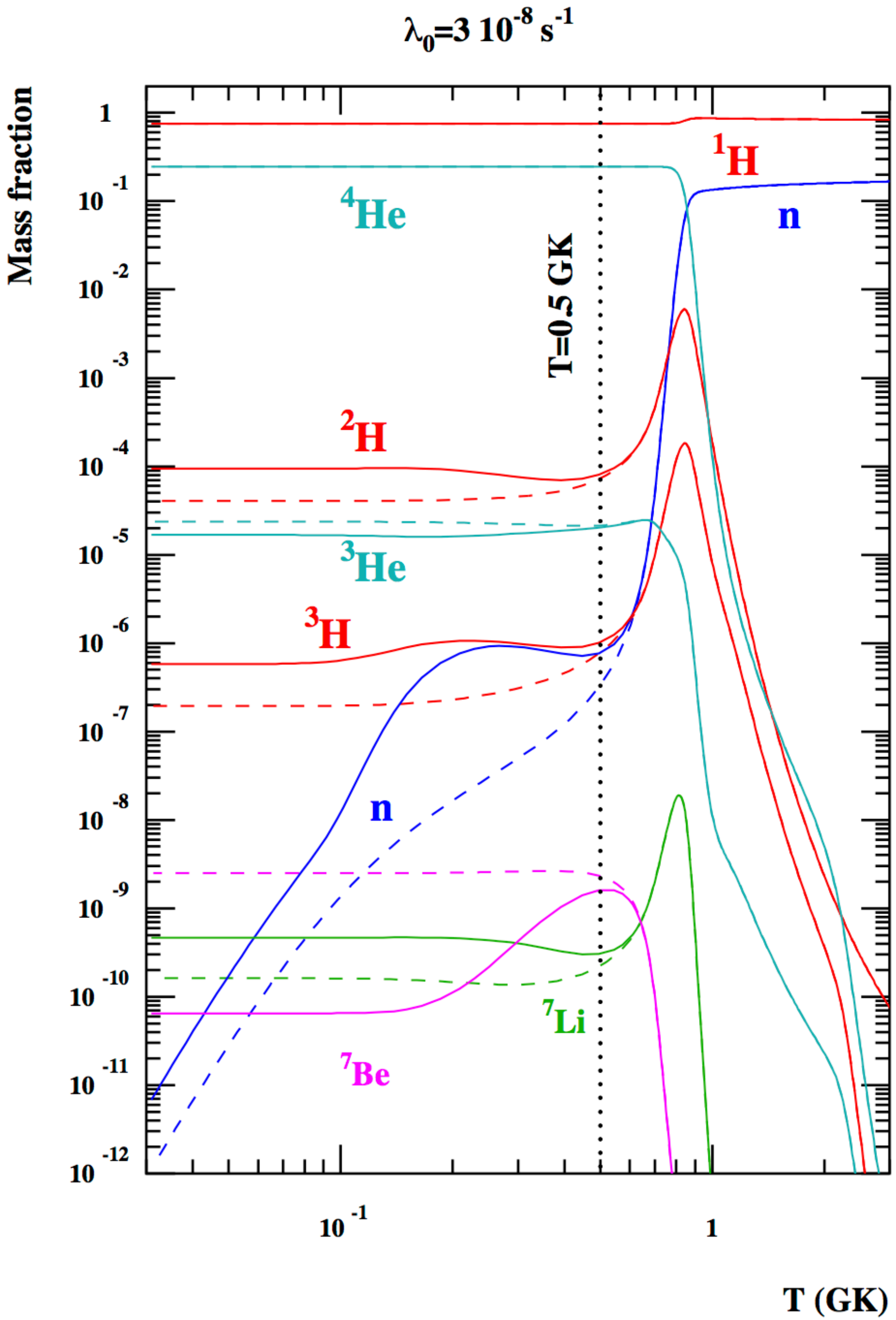
Tentatives nuclear solutions:
^{7}Be destruction by:

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



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

- By most abundant projectiles $^{7}Be(p,\gamma)^{8}B$ hindered by photo-dissociation (Q=1.375 MeV) and $^{7}Be(\alpha,\gamma)^{11}C$ 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

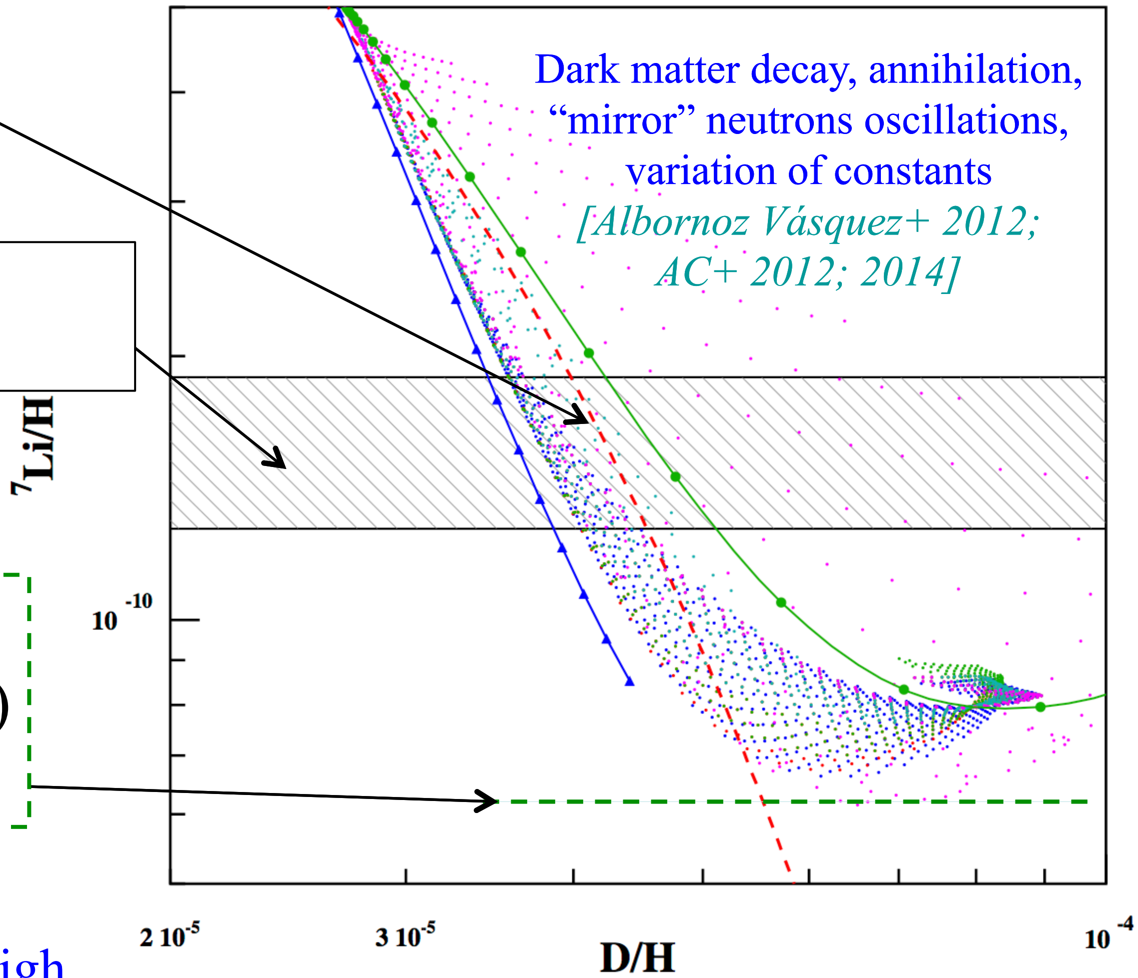
The limits to ^{7}Li+^{7}Be destruction by extra neutrons

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*]



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

Lower Li/H ⇒ higher D/H

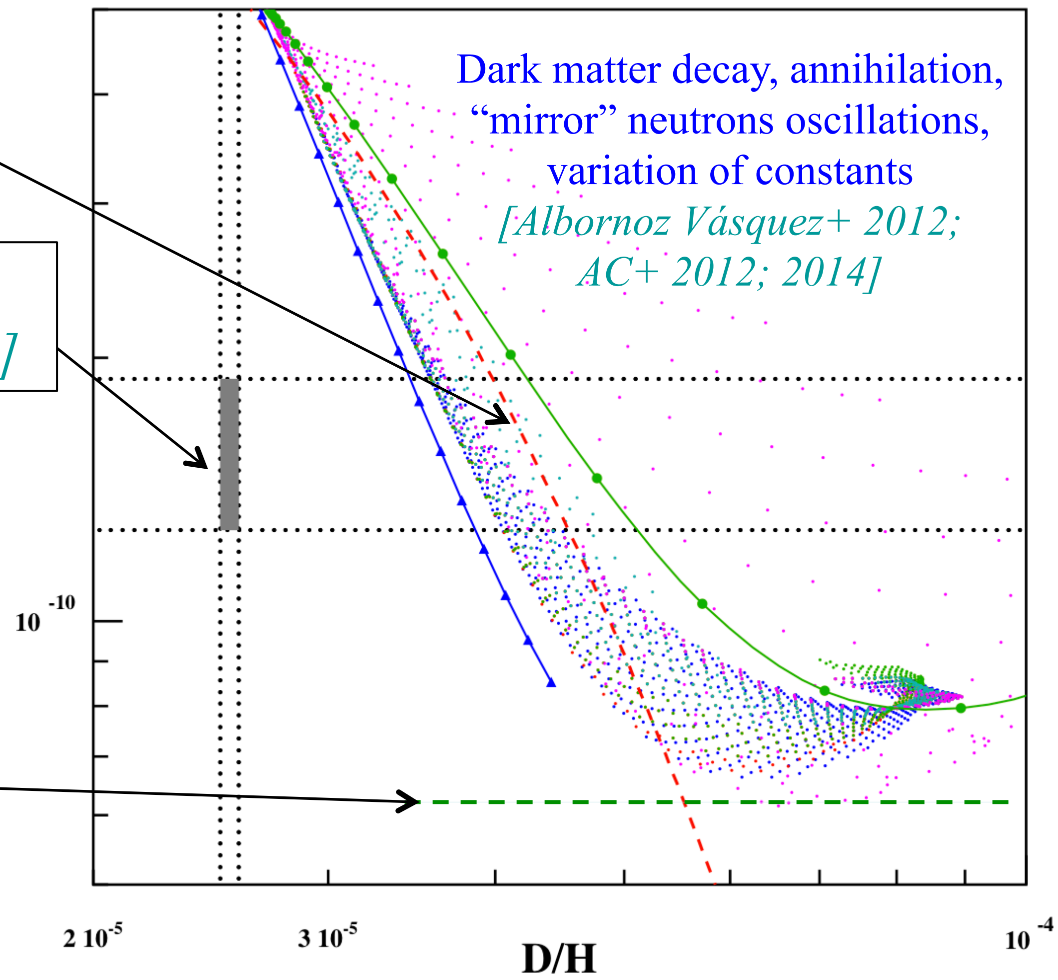
~~The limits to ^{7}Li+^{7}Be destruction by extra neutrons~~

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*]



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Precision big bang nucleosynthesis with improved Helium-4 predictions

CSNSM+IAP

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+ULB/AA

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

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Compilation and *R*-matrix analysis of Big Bang nuclear reaction rates

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THE ^{7}Be$(d,p)2\alpha$ CROSS SECTION AT BIG BANG ENERGIES AND THE PRIMORDIAL ^{7}Li ABUNDANCE

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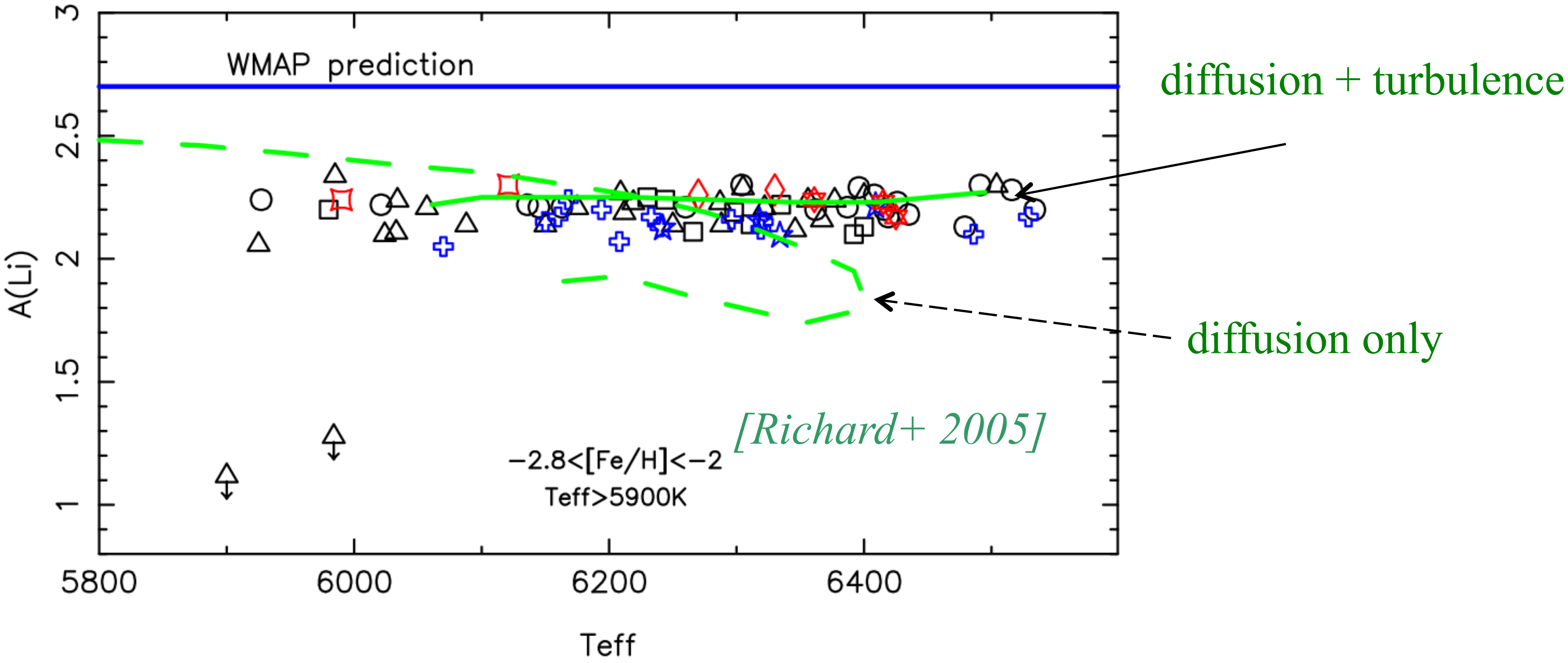
Conclusions

- Standard BBN is now in the (1%) precision era for D and ^{4}He
  - Precision deuterium observations (plateau ?) call for
  - even better precision on $D(p,\gamma)^3He$, $D(d,n)^3He$ and $D(d,p)^3H$ 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

Li stellar depletion ?

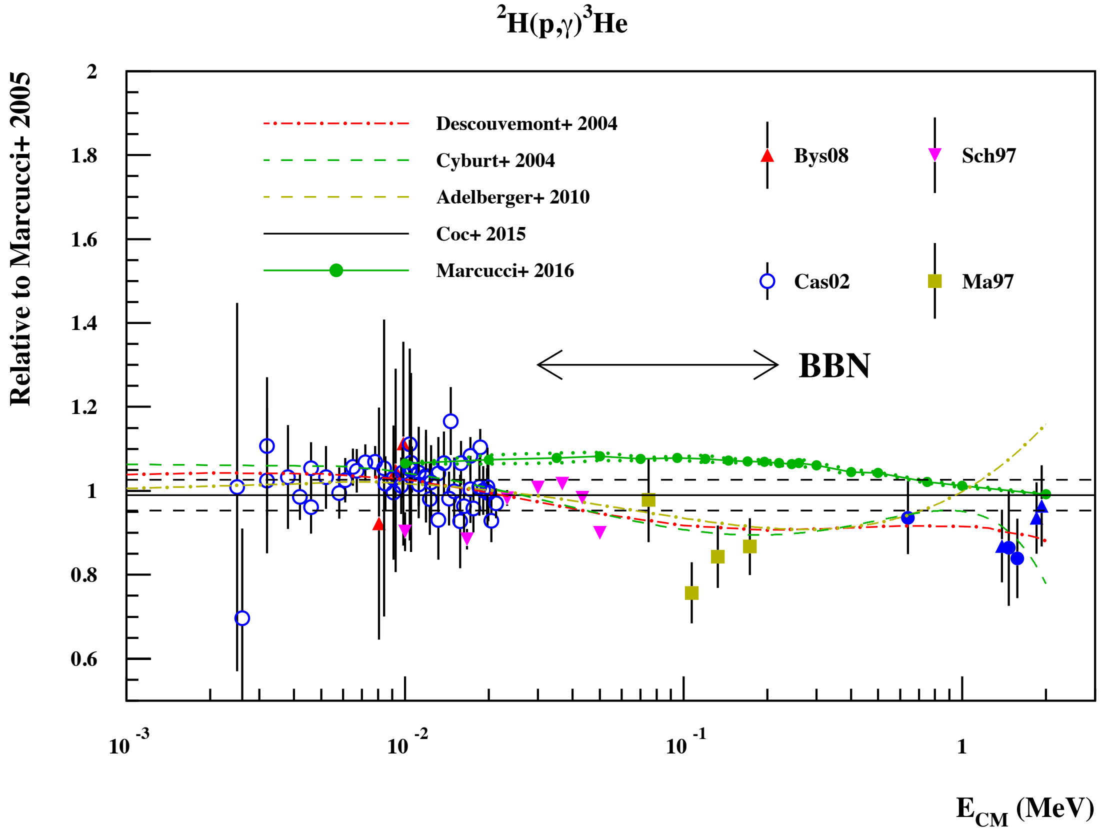
- In situ destruction (atomic diffusion + turbulence interplay)
  - Some amount of depletion, a factor of 1.5 to 2, is unavoidable because of atomic diffusion *[Michaud+ 1984]*
  - Uniformity restored by an additional mixing process *[Richard+ 2005; Korn+ 2006]*



D/H sensitivity to reaction rates

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

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



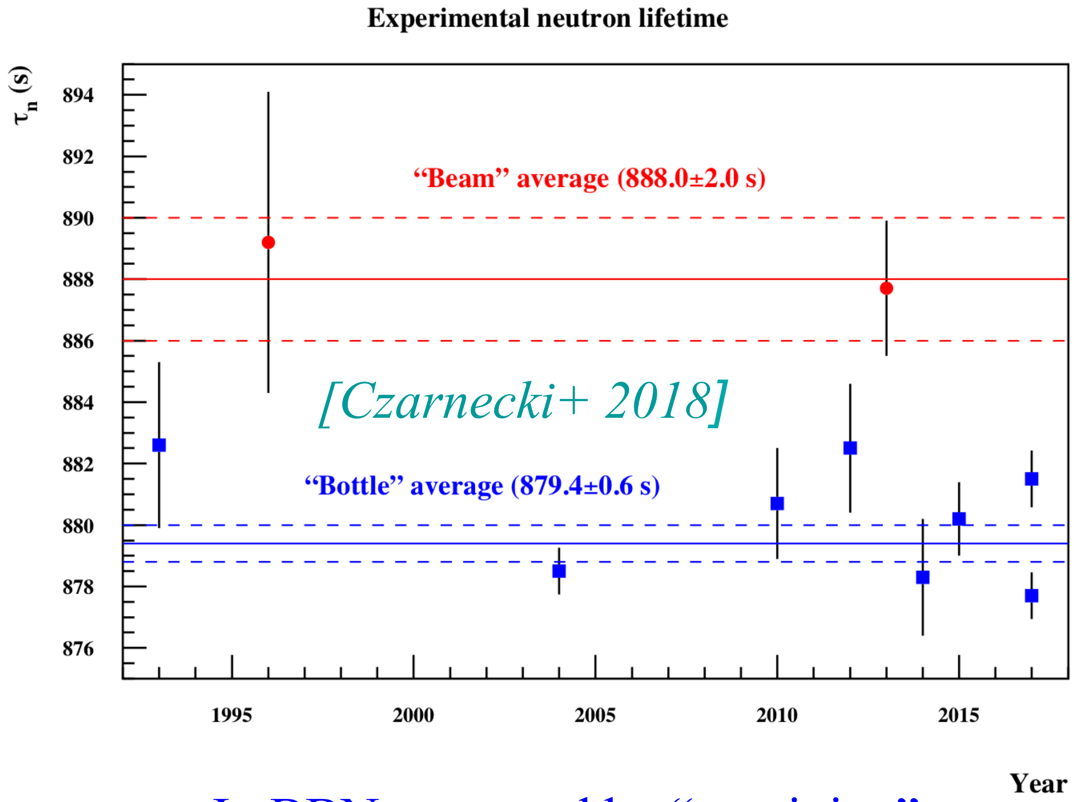
Neutron lifetime and the weak rates

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]*



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*)