Primordial nucleosynthesis (with Pierre)

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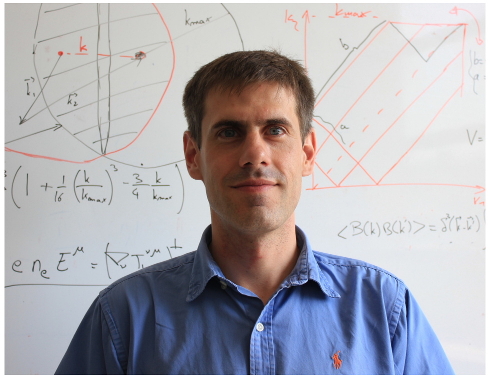


Christian Iliadis

(**UNC** at **C**hapel Hill)

Keith Olive

(**U**niversity of **M**innesota)

*or IJCLab, formerly : CSNSM + IPNO + LAL + LPT +…

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 (predictions vs observations).

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 (not very useful)
- **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

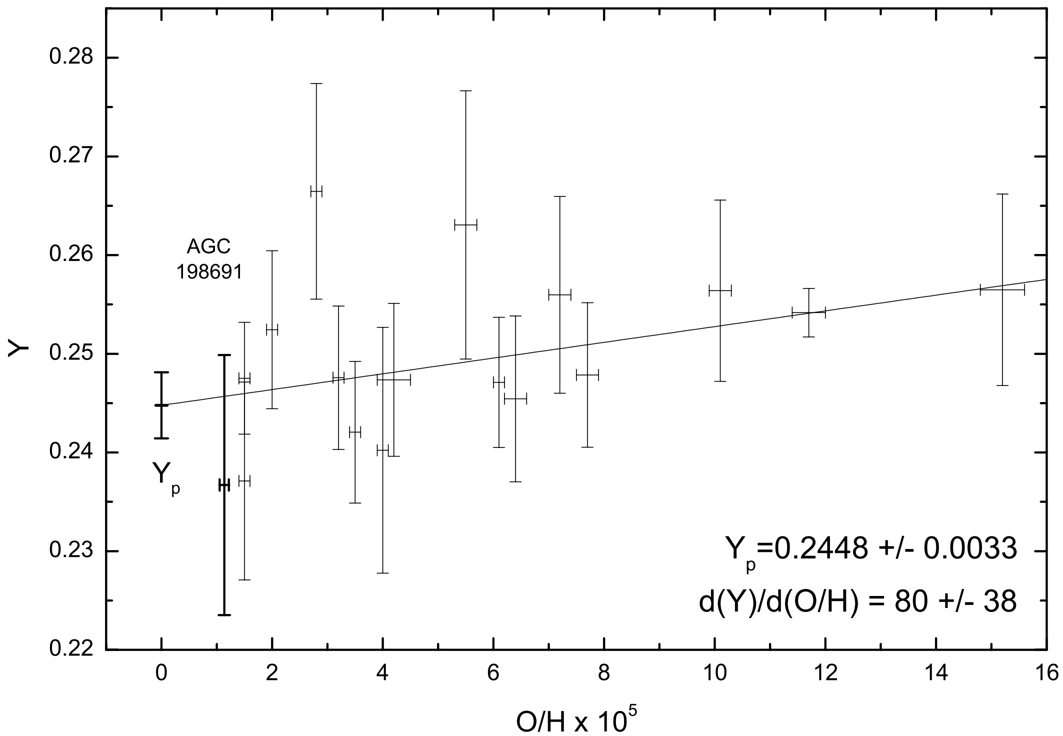
2) Possibly extrapolate to zero metallicity* : Fe/H, O/H,…. → 0

*In astrophysics: "metals" = everything beyond helium

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

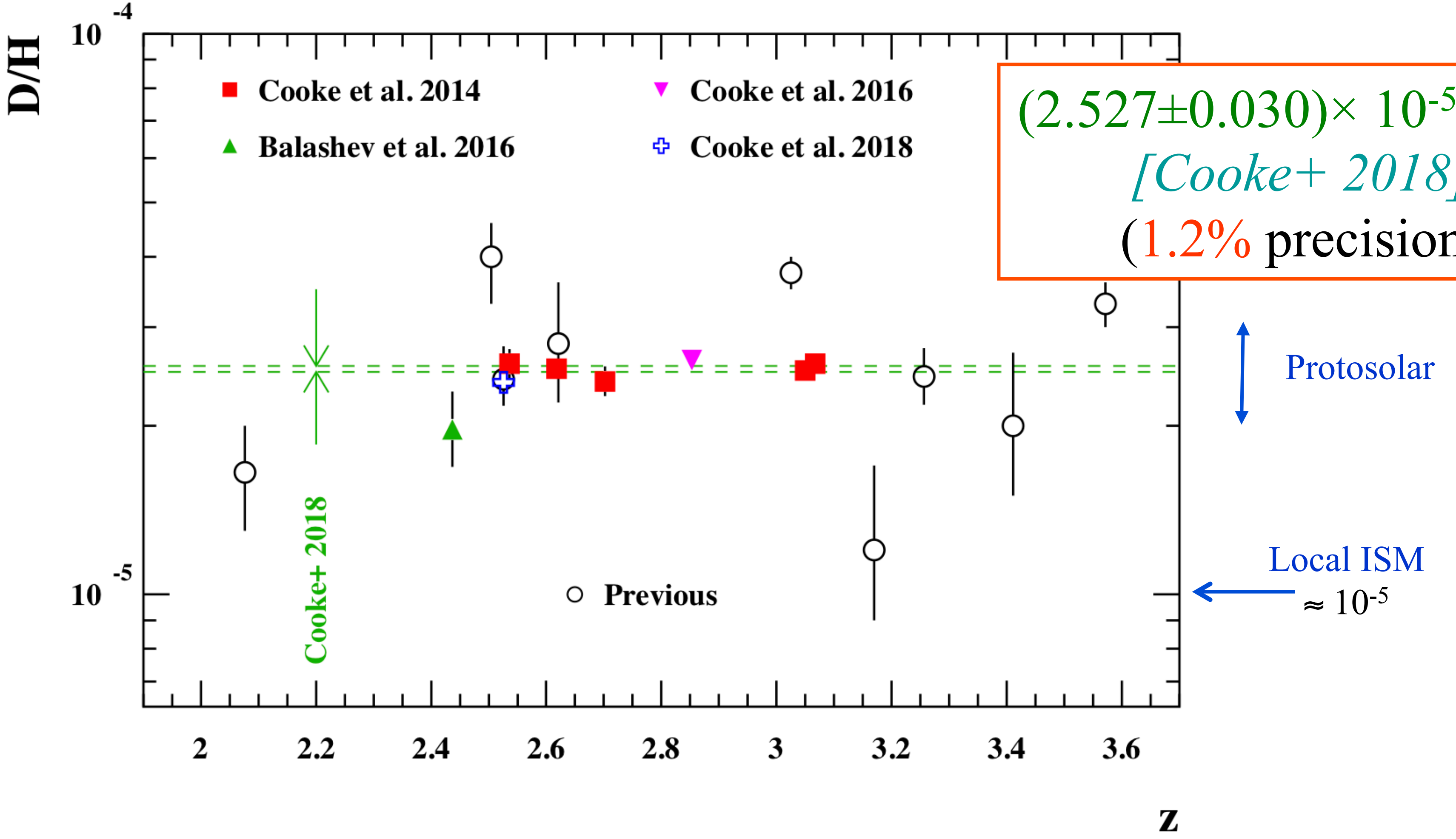
^{4}He observations in blue compact galaxies

Observations: **^{4}He** from a sample of H II regions in blue compact galaxies *[Izotov+ 2007;2014]* with additional extremely metal poor galaxies (AGC 198691) *[Aver+ 2021;2022]*



Y_p=0.2453±0.0034 (^{4}He mass fraction) *[Aver+ 2021;2022]* (1.4% precision)

D/H observations in cosmological clouds

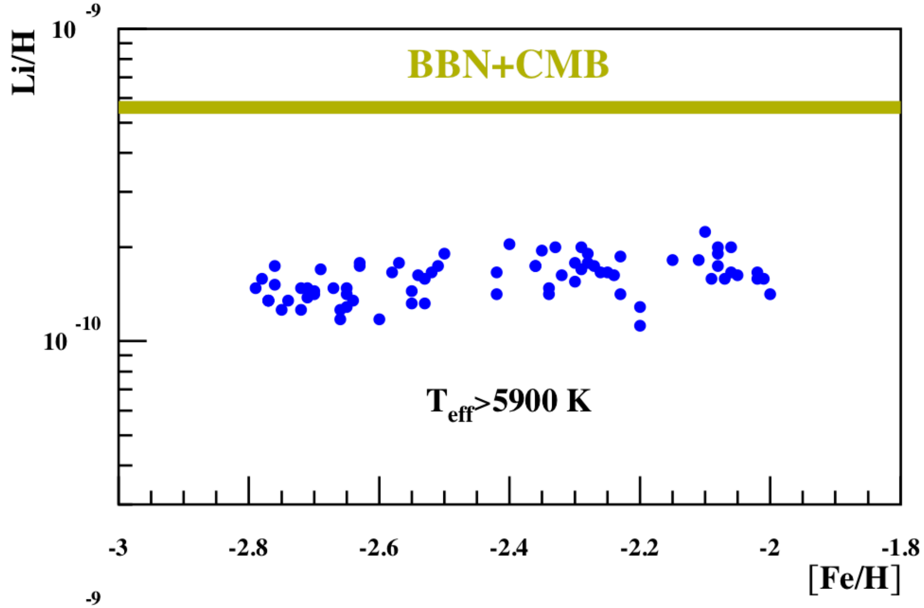


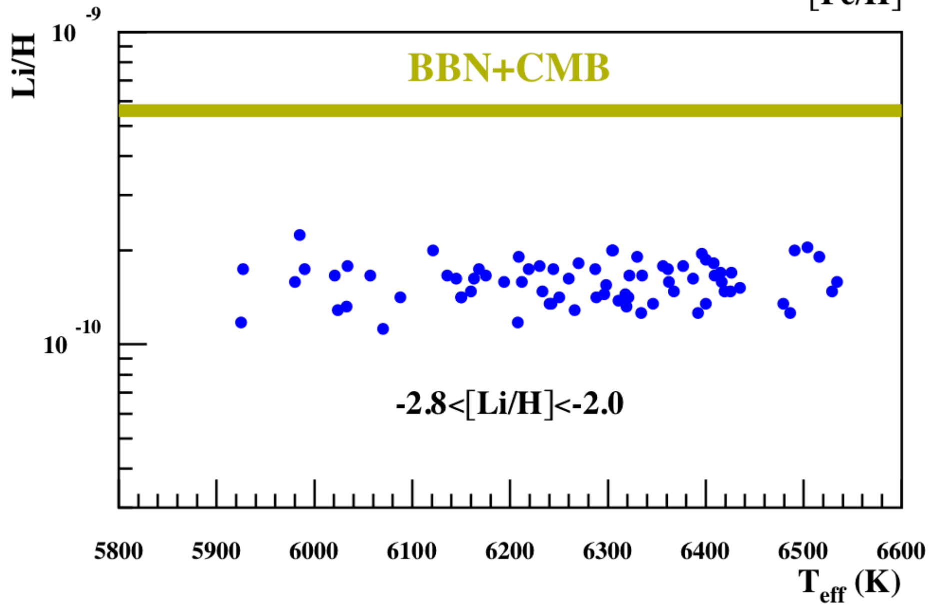
(2.527±0.030)× 10^{-5} (1-σ)
[Cooke+ 2018]
(1.2% precision)

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

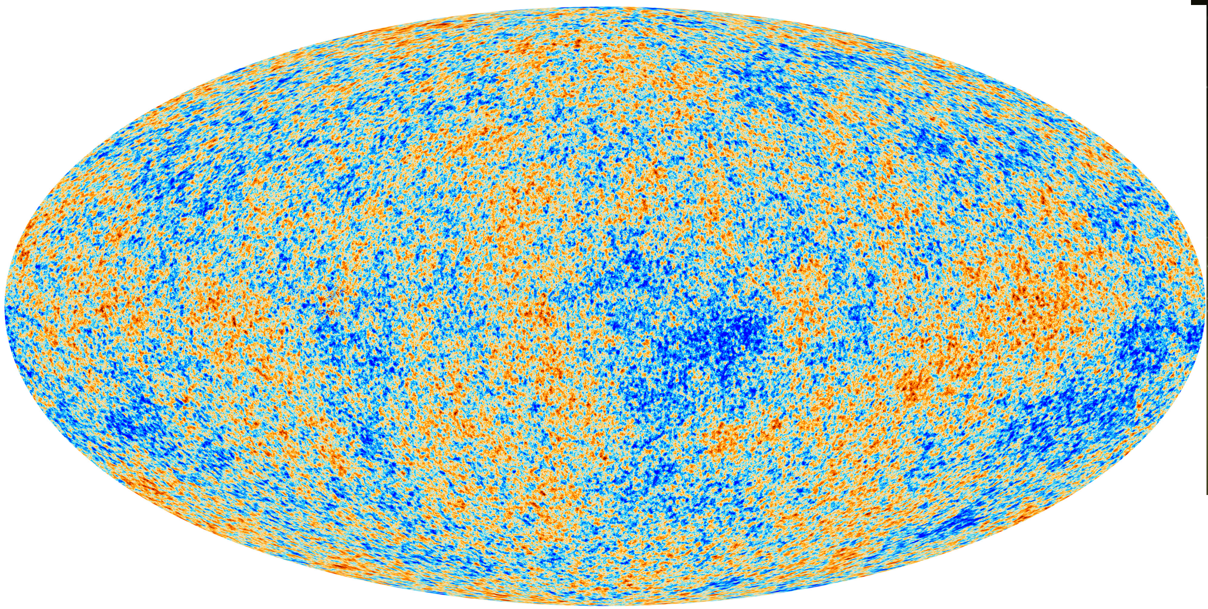
[M. Spite, priv. comm.]

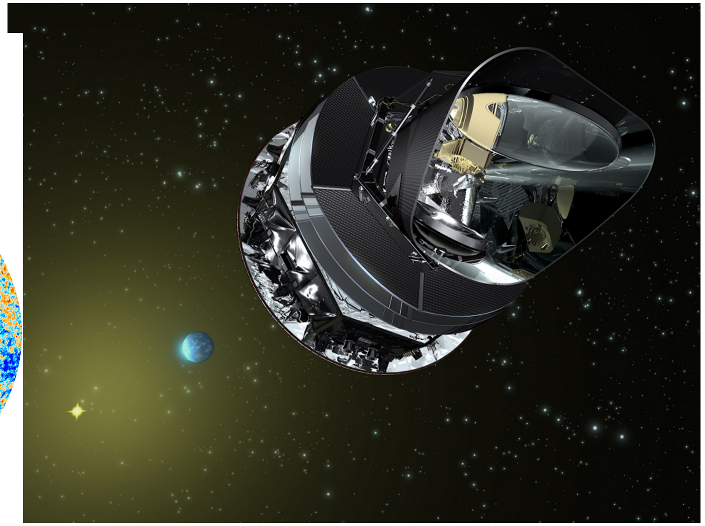




- Oldest (low metallicity) stars in galactic halo
- Lifetime of $M < 0.9\ M_\odot$ stars > 15 Gy
- For $T_{eff} > 5900$ K, no deep convection and no Li surface depletion (?)
- Li/H = $(1.58\pm0.35)\times10^{-10}$ *[Sbordone et al. 2010]*

Density components of the Universe





Some Ω values *[Aghanim+ 2020 (Planck)]*		
Radiation (CMB)	Ω_R	$5\ 10^{-5}$
Visible matter	Ω_L	≈0.003
Baryons	Ω_b	0.049
Dark Matter	Ω_c	0.262
Vacuum	Ω_Λ	0.680
Total	Ω_T	≈1.0

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

$\Omega_b h^2 = 0.02242 \pm 0.00014$

(0.6% precision)

[Alam+ 2017; Aghanim+ 2020 (Planck)]

$h = H_0 / 100$ km/s/Mpc

≈0.69-0.73

Dynamics of the expanding Universe

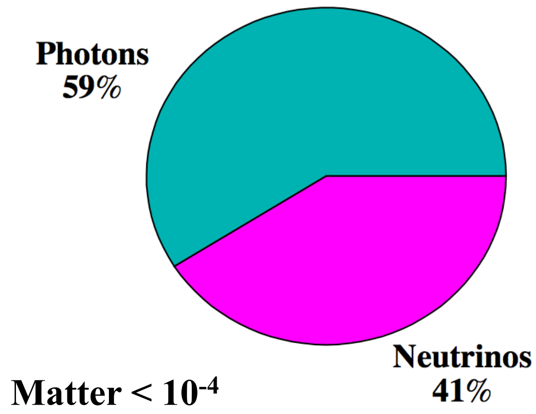
Einstein equation & Friedmann-Lemaître-Robertson-Walker metrics

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

Friedmann equation :

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

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



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

w =
- 0 (matter) $\Rightarrow a^{-3}$
- 1/3 (radiation) $\Rightarrow a^{-4}$
- -1 (Λ, dark energy) $\Rightarrow a^{0}$
- Curvature $\Rightarrow a^{-2}$

Dynamics of the expanding Universe

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

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

① $$\frac{1}{a}\frac{da}{dt} \propto \sqrt{\rho^{rad}_{e\gamma\nu}(T)} \propto \sqrt{g_*^{e\gamma\nu}(T)T^2}$$

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

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

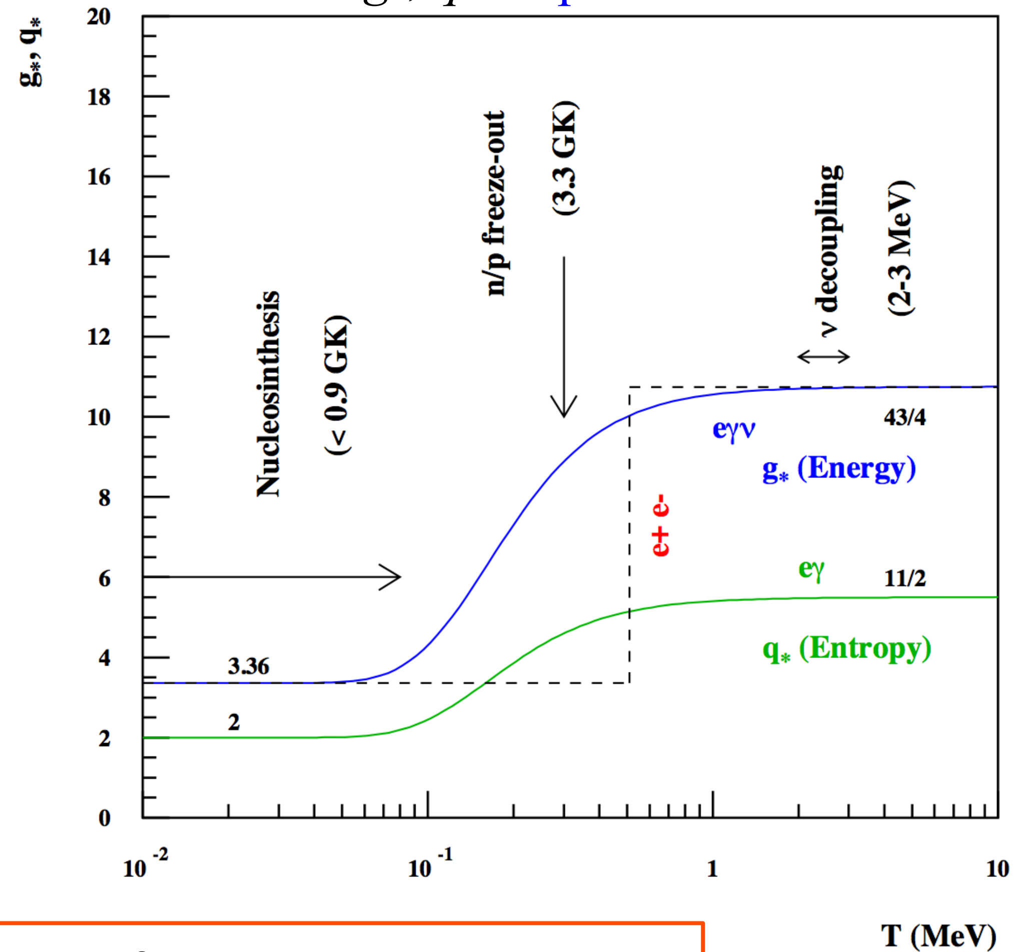
② $$a^3 T_\nu^3 = Cste$$

③ $$a^3 q_*^{e\gamma}(T) T^3 = Cste$$

Entropy constant

+ a few small corrections

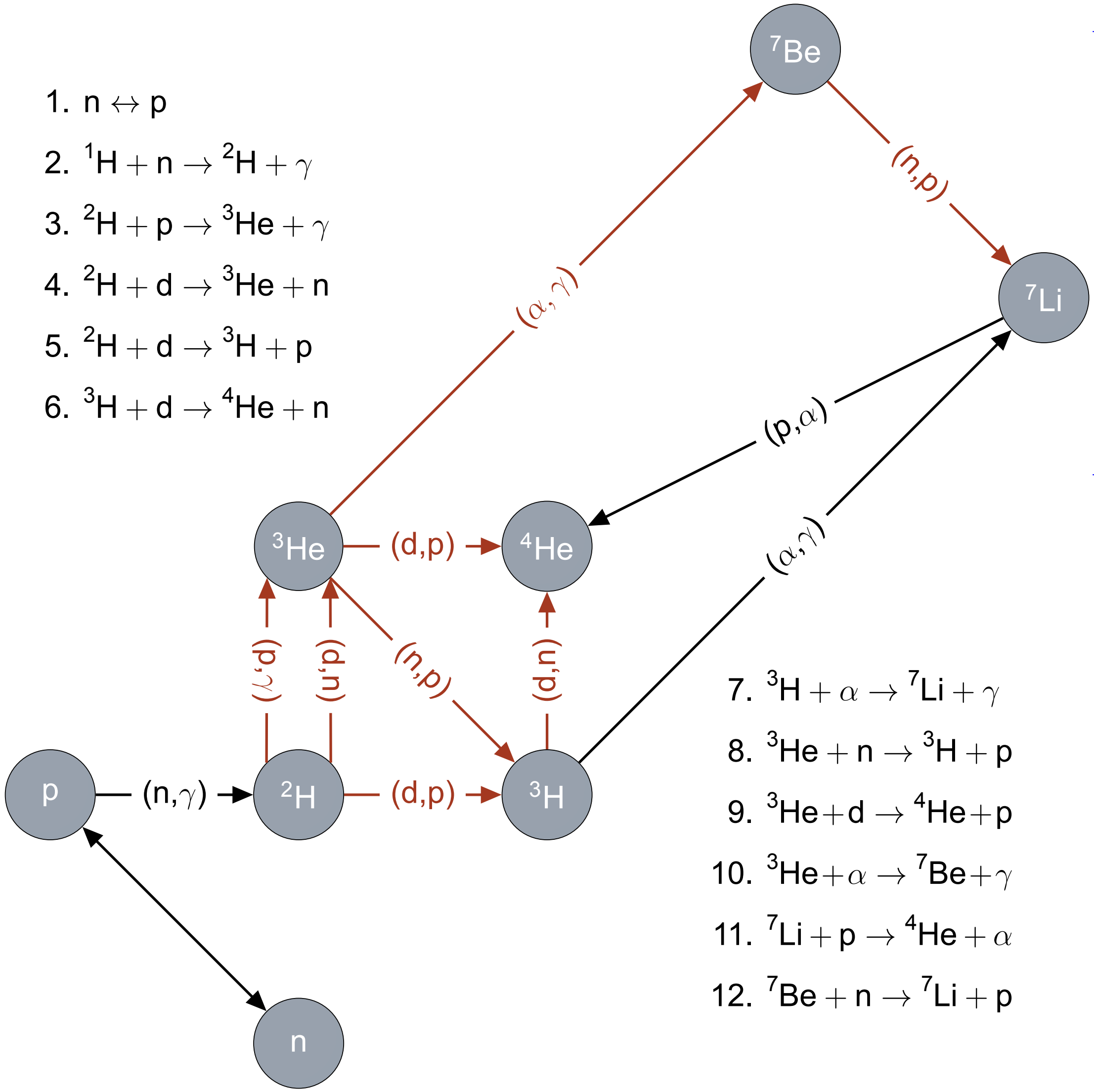
g_*, q_* = spin factors



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

Big Bang Nucleosynthesis calculations

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



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

Needs:

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

New BBN public code:

- *PRIMAT [Pitrou+ 2018]*

Other codes:

- *PArthENoPE [Gariazzo+ 2022]*
- *AlterBBN [Arbey+ 2020]*
- *IL+MN [Yeh, Olive & Fields]*

give the same results when **same reaction rates** are used

PRIMAT code

Physics Reports 754 (2018) 1–66

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Precision big bang nucleosynthesis with improved Helium-4 predictions

Cyril Pitrou [a,b,*], Alain Coc [c], Jean-Philippe Uzan [a,b], Elisabeth Vangioni [a,b]

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A new tension in the cosmological model from primordial deuterium?

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$n \leftrightarrow p$ weak reaction rates (^{4}He)

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

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

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

+ "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) $\tau_n = 879.4 \pm 0.6$s *[Zyla+ 2020]*
- Calculation of the "small corrections" (radiative corrections, finite nucleon mass corrections, finite temperature radiative corrections, weak-magnetism, QED plasma effects, incomplete neutrino decoupling) *[Pitrou+ 2018]* $\Delta Y_p \approx 1.8\%$, $\Delta(\text{D/H}) \approx 1.5\%$
- Precision e.g. *Neff=3.044* (effective number of neutrino families)

Evaluation of reaction rates for BBN

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Atomic Data and Nuclear Data Tables 88 (2004) 203–236

Atomic Data and Nuclear Data Tables

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

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The Astrophysical Journal, 600:544–552, 2004 January 10

UPDATED BIG BANG NUCLEOSYNTHESIS COMPARED WITH *WILKINSON MICROWAVE ANISOTROPY PROBE* OBSERVATIONS AND THE ABUNDANCE OF LIGHT ELEMENTS

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Received 2003 July 23; accepted 2003 September 24

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A compilation of charged-particle induced thermonuclear reaction rates
Angulo, C.; Arnould, M.; Rayet, M. *and 25 more*

2 2004ApJ...600..544C 2004/01 cited: 310
Updated Big Bang Nucleosynthesis Compared with Wilkinson Microwave Anisotropy Probe Observations and the Abundance of Light Elements
Coc, Alain; Vangioni-Flam, Elisabeth; Descouvemont, Pierre *and 2 more*

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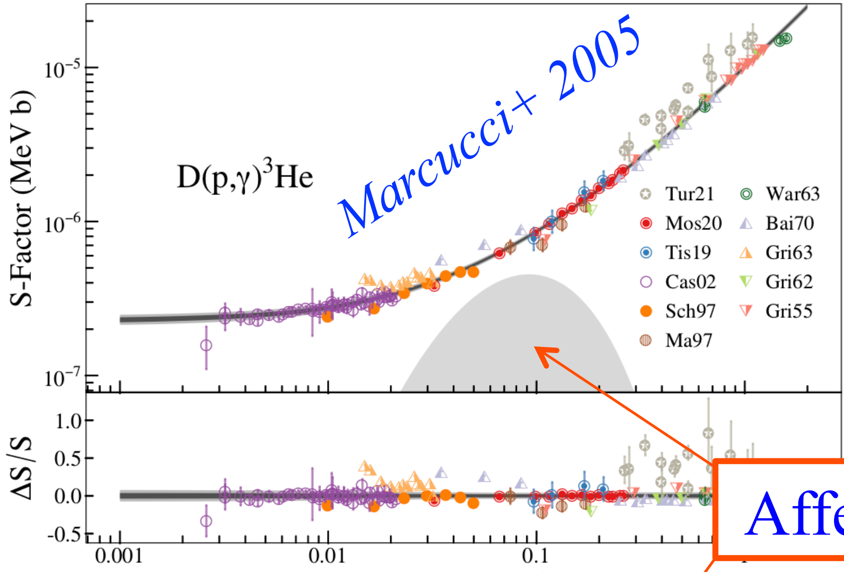
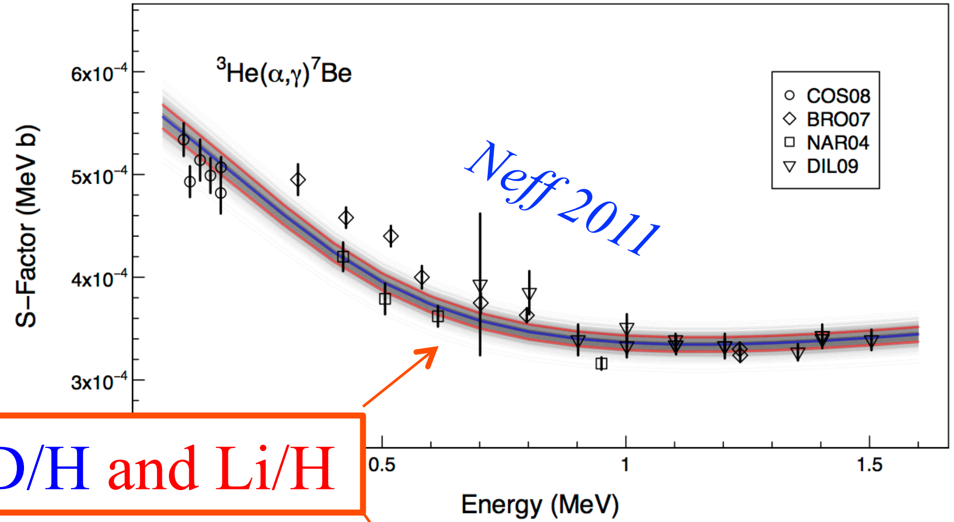
Compilation and R-matrix analysis of Big Bang nuclear reaction rates
Descouvemont, Pierre; Adahchour, Abderrahim; Angulo, Carmen *and 2 more*

4 2018PhR...754....1P 2018/09 cited: 245
Precision big bang nucleosynthesis with improved Helium-4 predictions
Pitrou, Cyril; Coc, Alain; Uzan, Jean-Philippe *and 1 more*

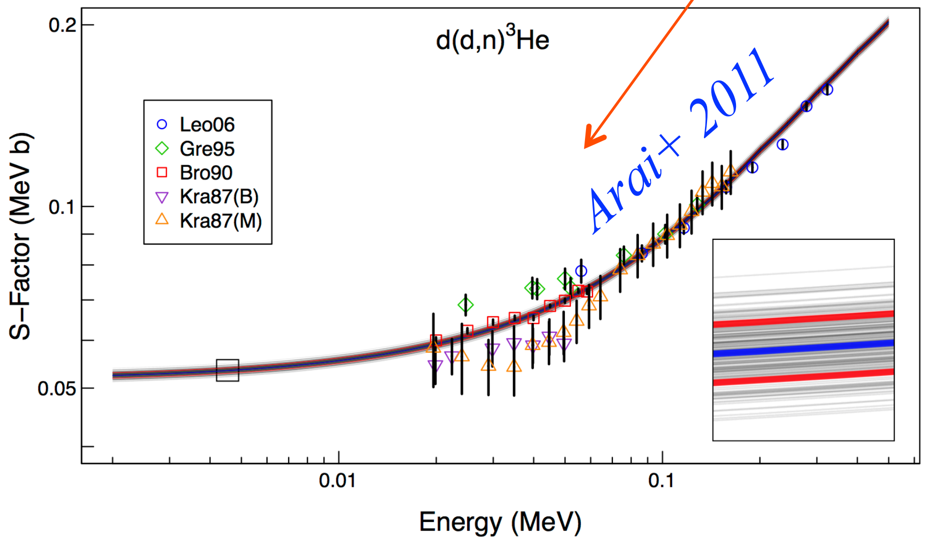
Re-evaluation of main reaction rates

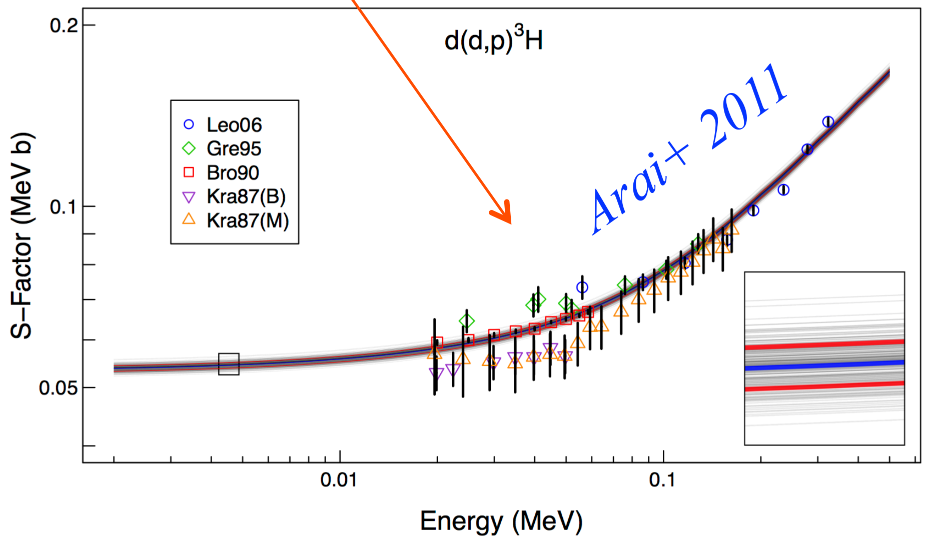
Bayesian analyses of reaction rates for BBN : $D(p,\gamma)^3He$, $D(d,n)^3He$, $D(d,p)^3H$ and $^3He(\alpha,\gamma)^7Be$ *[Moscoso+ 2021; Gómez Iñesta+2017; Iliadis+ 2016]*





Affect D/H and Li/H



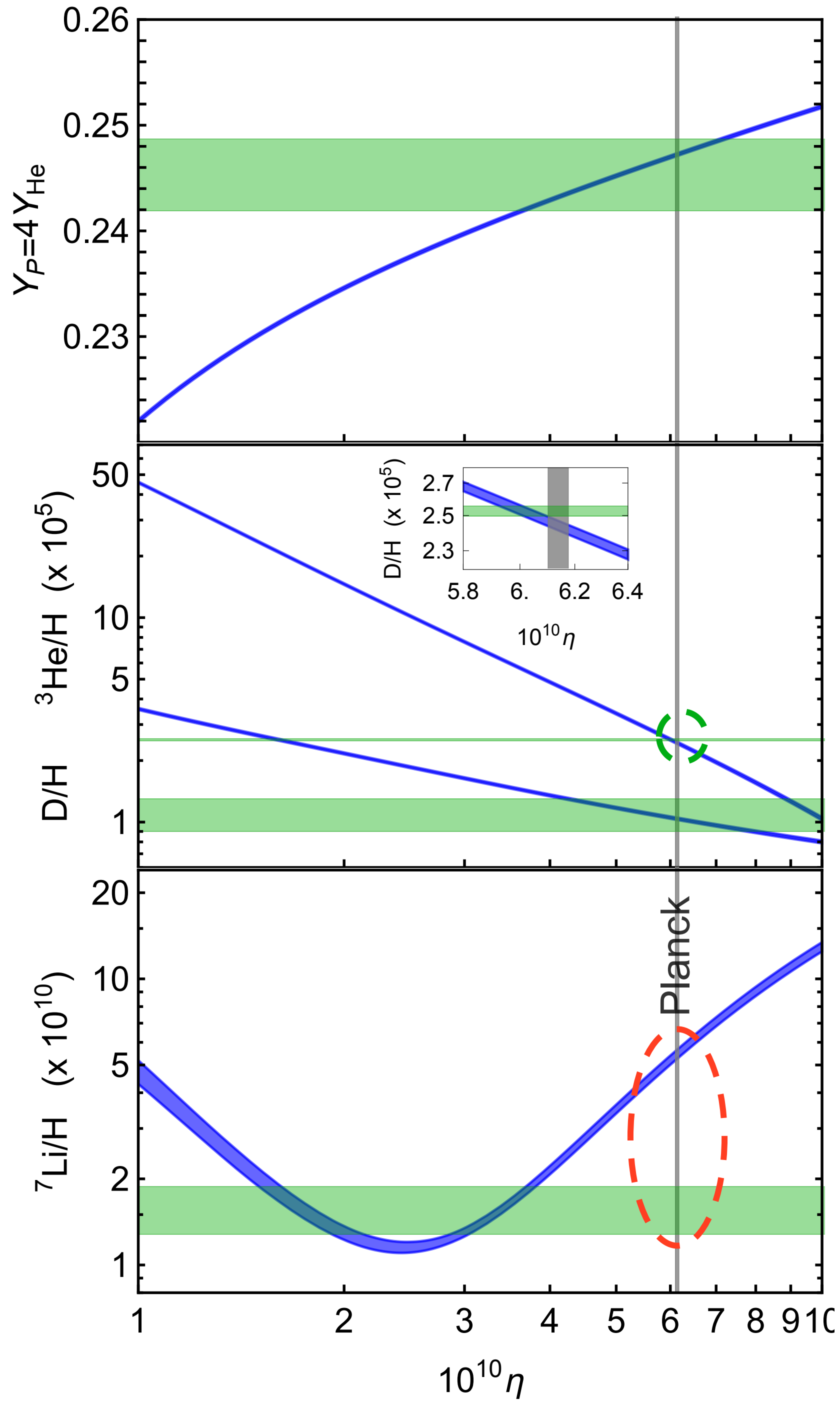


Comparison between observed and calculated abundances

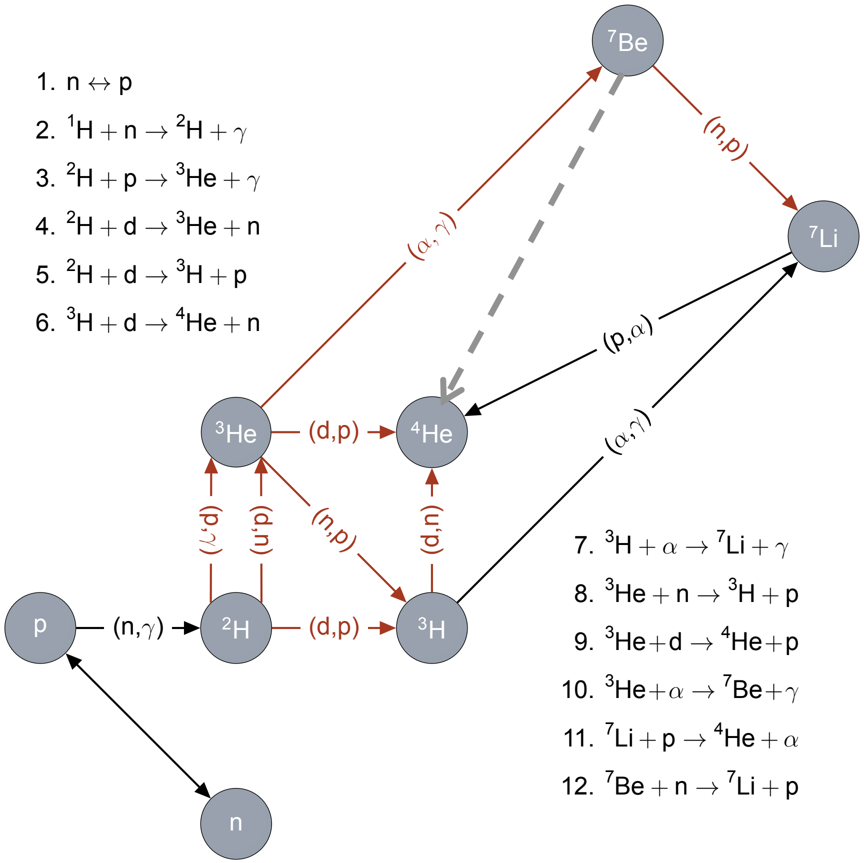
Limits (1-σ) obtained by Monte-Carlo from reaction rate uncertainties *[Pitrou + 2018;2021]*

Concordance (?) BBN, spectroscopy and CMB

- $\Omega_B h^2$ *[Planck: Alam+ 2017; Aghanim+ 2020]*
- **^{4}He** *[Aver+ 2021; 2022]*
- **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



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~~
2. Increased neutron destruction efficiency by ^{7}Be(n,p)^{7}Li(p,α)^{4}He from exotic neutron sources

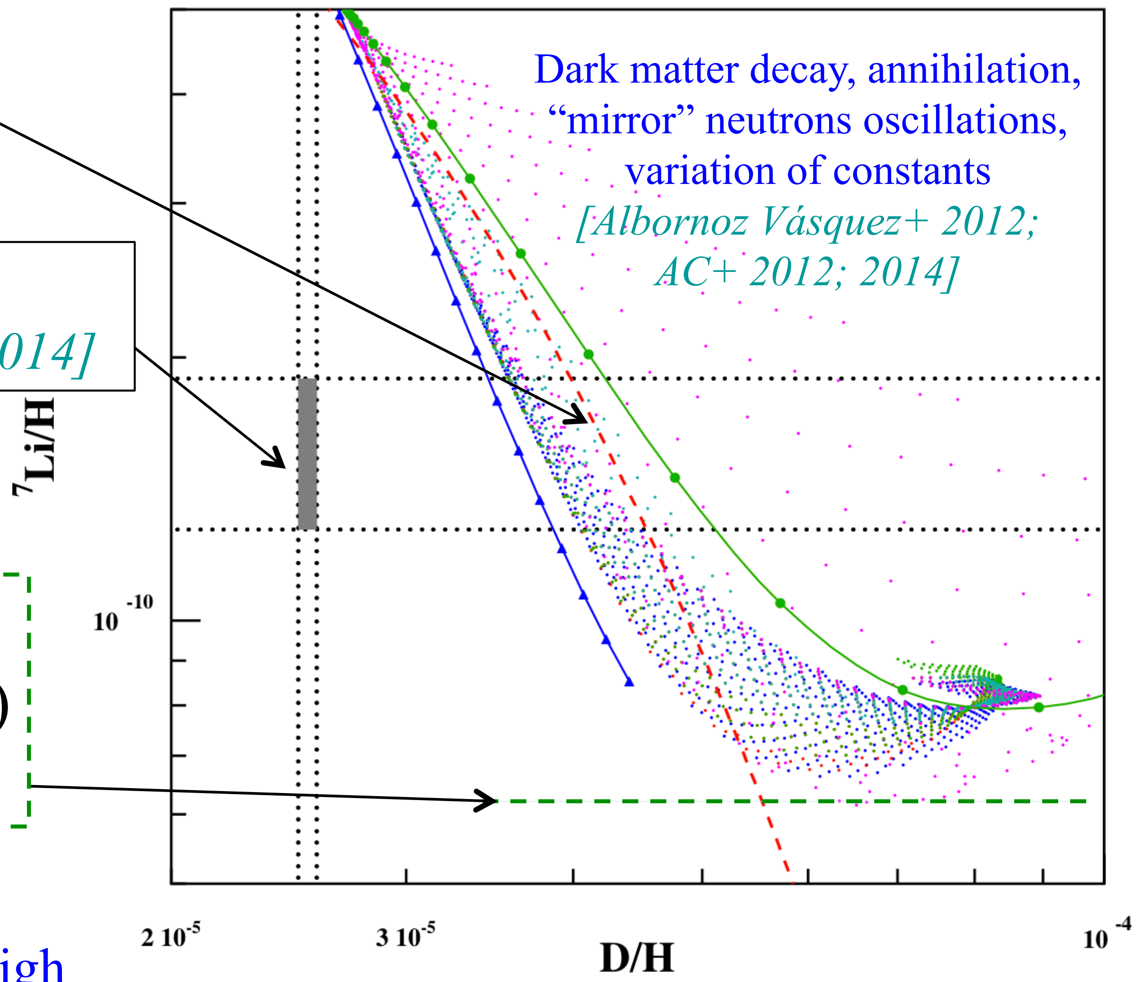
~~The limits to ^{7}Li+^{7}Be destruction by extra neutrons~~

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

^{7}Be(n,p) ⇒ ^{1}H(n,γ)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*]



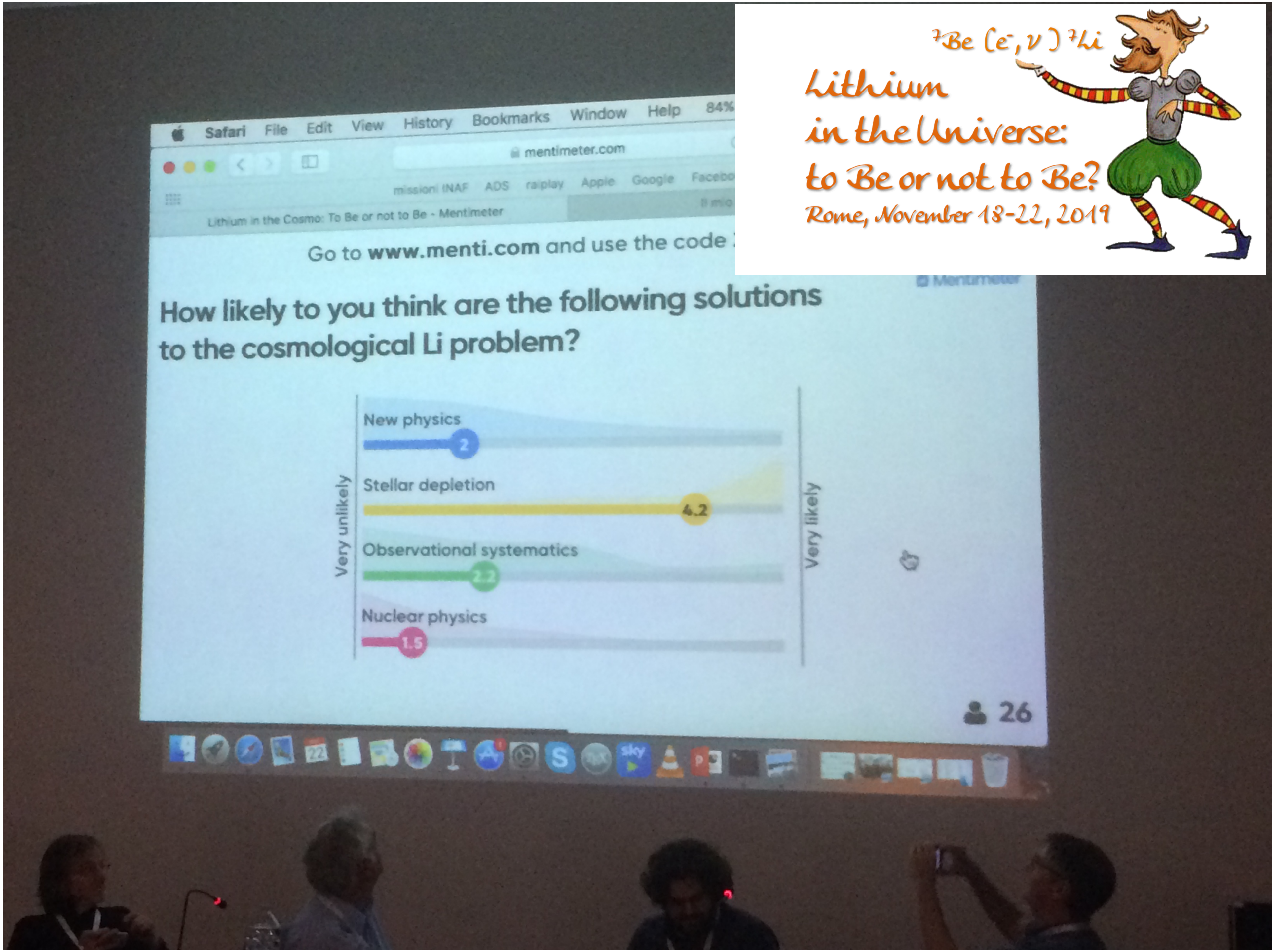
Even worse for (non-thermal) high energy neutrons *[Kusakabe+ 2004]*

Lower Li/H ⇒ higher D/H

$^{7}Be\,(e^{-},\nu)\,^{7}Li$

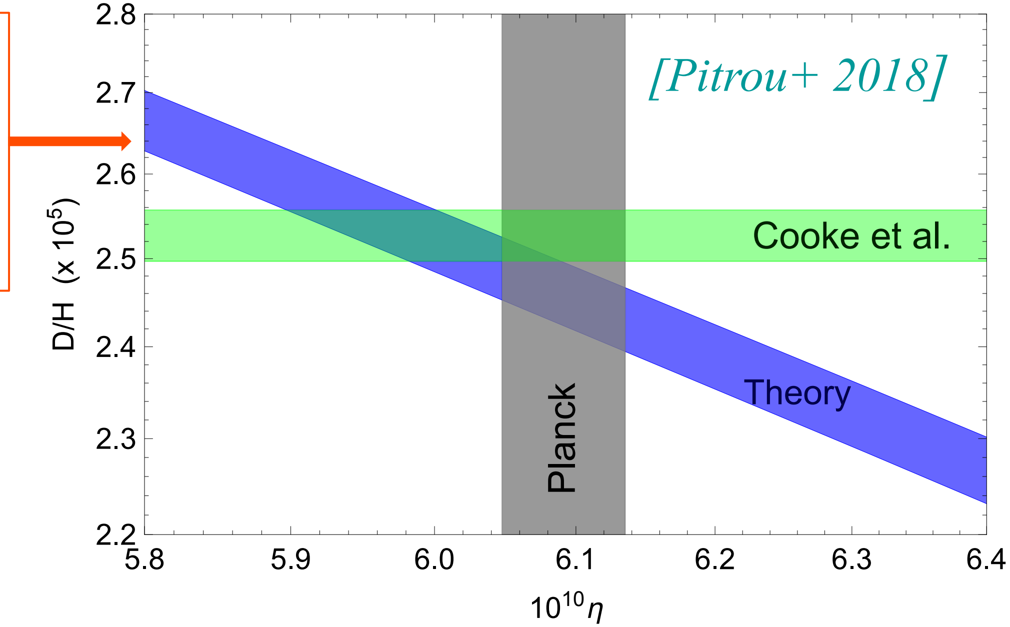
Lithium in the Universe: to Be or not to Be?

Rome, November 18-22, 2019



BBN tension on D/H

D(p,γ)^{3}He *[Iliadis+2016]*
D(d,n) & D(d,p) *[Gómez Iñesta+ 2017]*
$\Omega_b h^2$=0.02225±0.00016 *[CMB: Ade+ 2016 (Planck)]*



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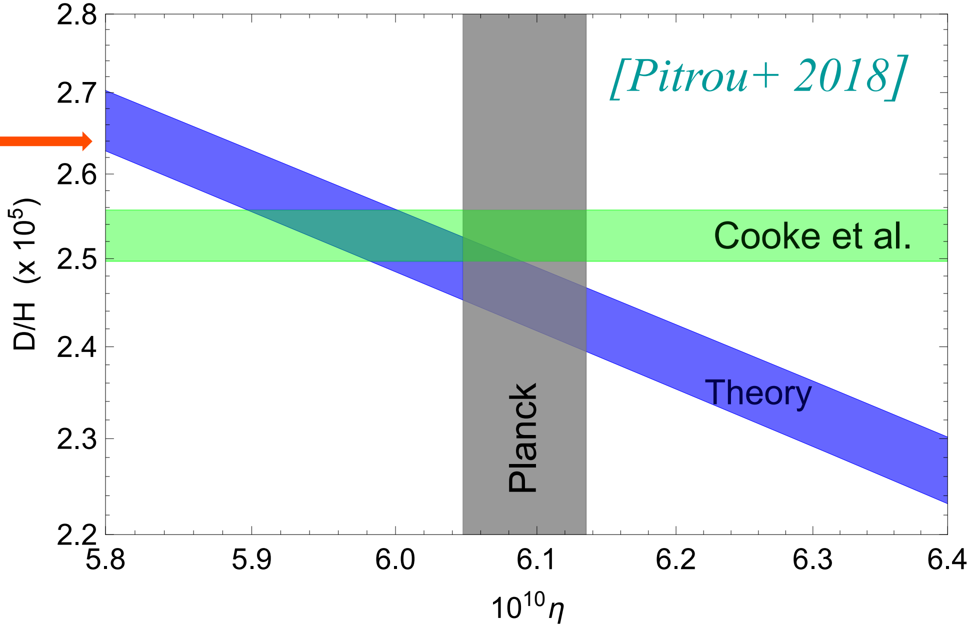
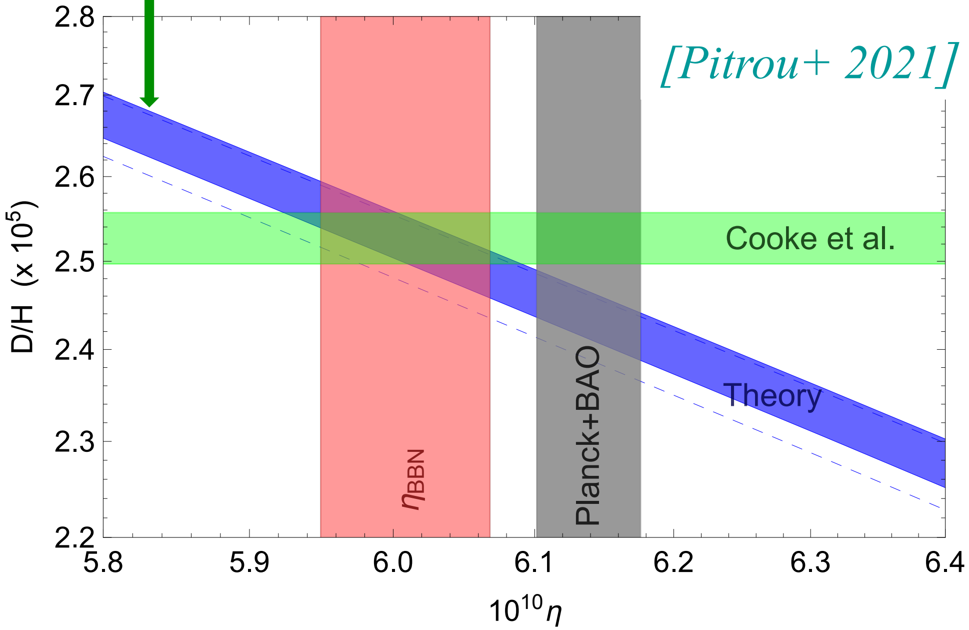
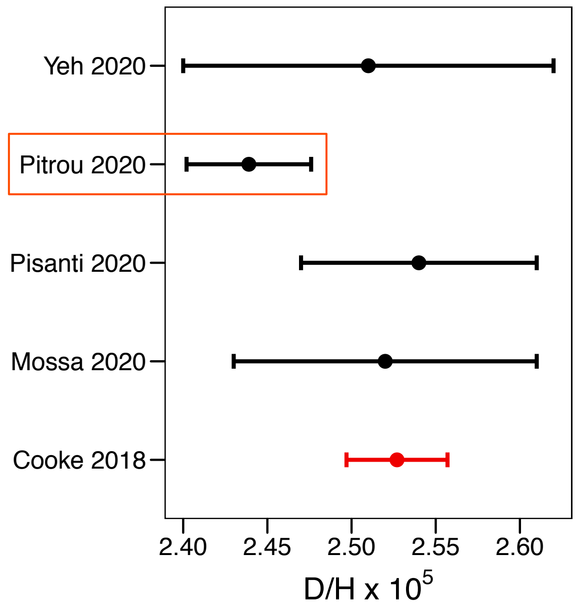


D(p,γ)^{3}He *[Mossa+ 2020 (LUNA)]*
D(d,n) & D(d,p) *[Gómez Iñesta+ 2017]*
$\Omega_b h^2$=0.02242±0.00014 *[CMB+BAO: Alam+ 2017; Aghanim+ 2020]*



1.8-σ tension



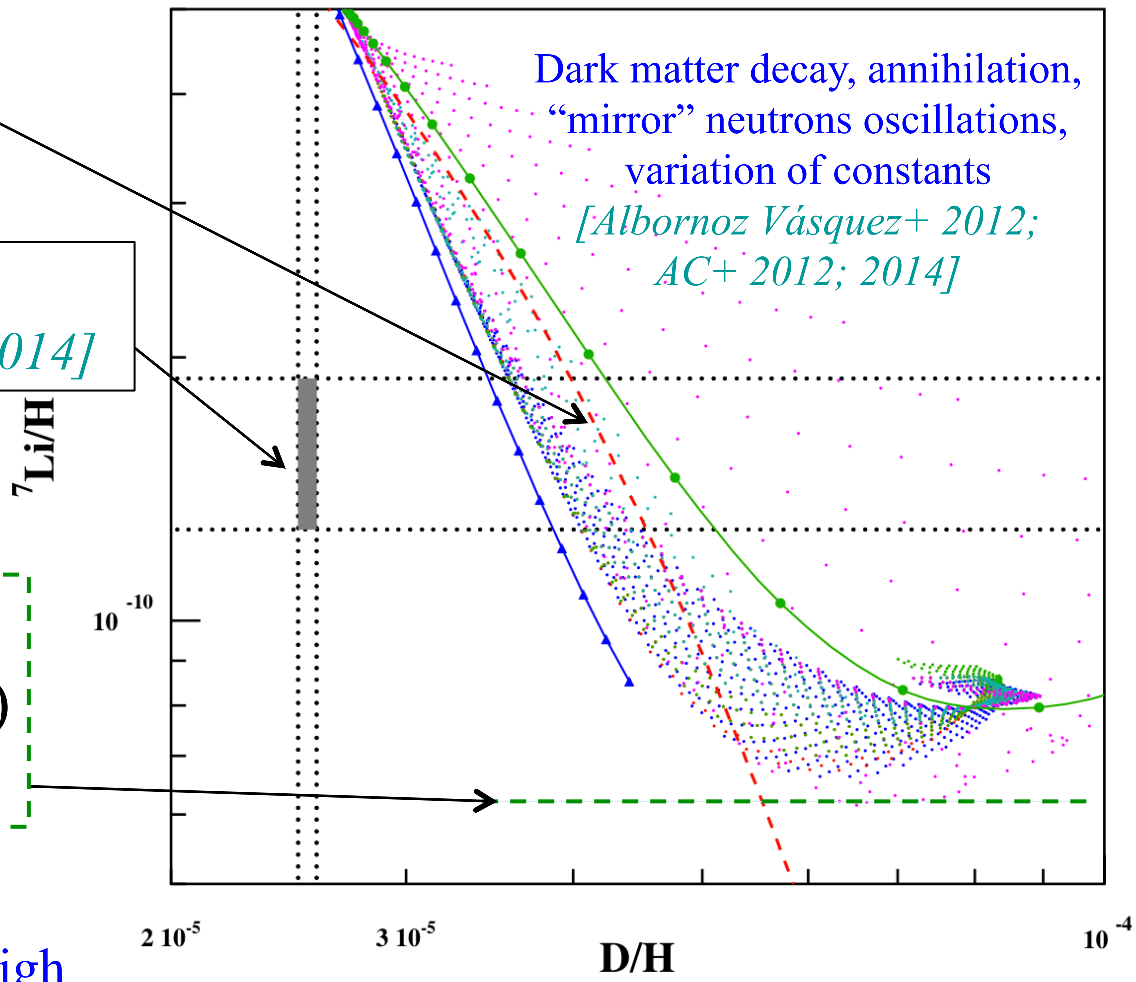
The limits to ^{7}Li+^{7}Be destruction ~~by extra neutrons~~

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

^{7}Be(n,p) ⇒ ^{1}H(n,γ)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*]



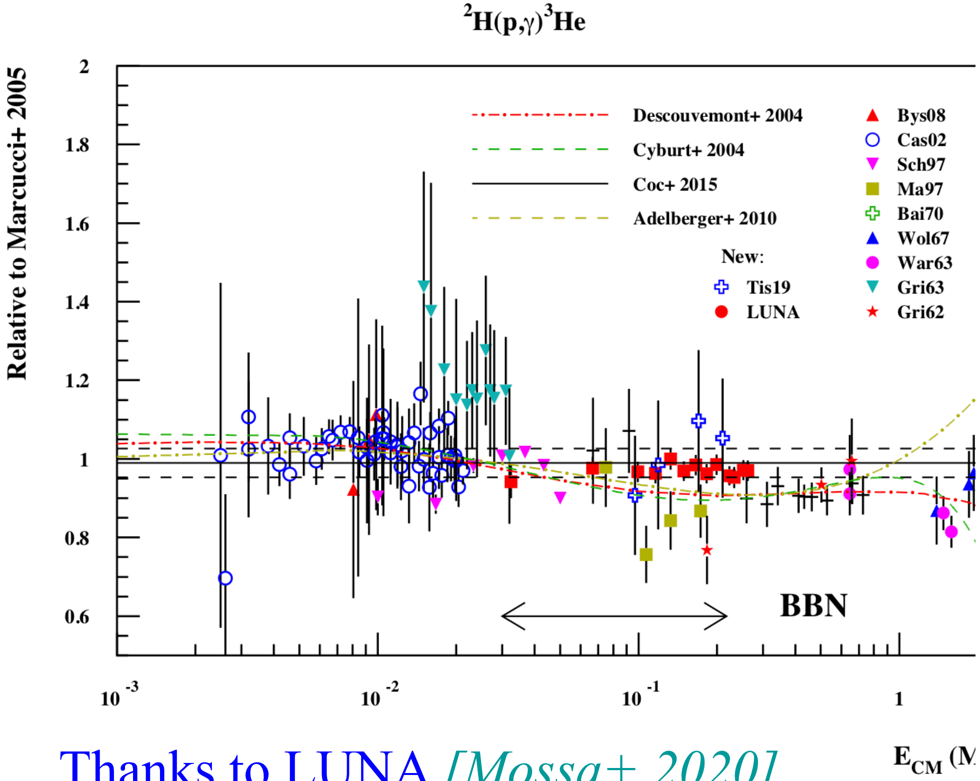
Even worse for (non-thermal) high energy neutrons *[Kusakabe+ 2004]*

Lower Li/H ⇒ higher D/H

Comparison of reaction rates : $D(p,\gamma)^3He$

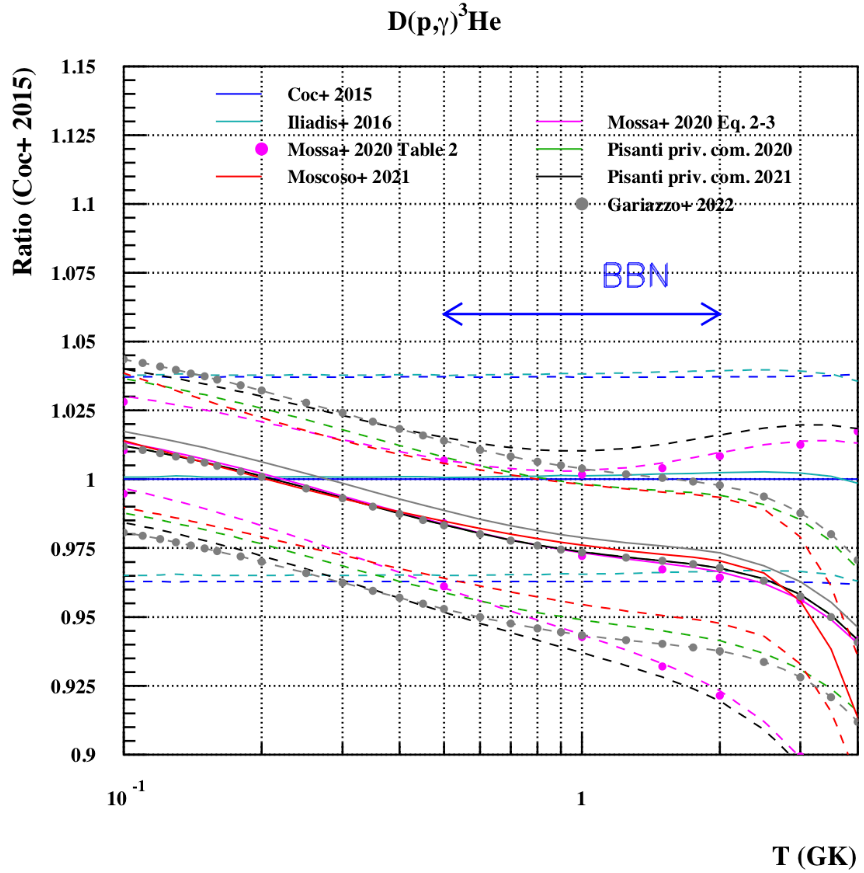
$$\frac{\Delta(D/H)}{D/H} = -0.32\times\frac{\Delta\langle\sigma v\rangle_{d(p,\gamma)^3He}}{\langle\sigma v\rangle_{d(p,\gamma)^3He}} - 0.54\times\frac{\Delta\langle\sigma v\rangle_{d(d,n)^3He}}{\langle\sigma v\rangle_{d(d,n)^3He}} - 0.46\times\frac{\Delta\langle\sigma v\rangle_{d(d,p)^3H}}{\langle\sigma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

$D(p,\gamma)^3He$, $D(d,n)^3He$ and $D(d,p)^3H$ reaction rates need to be known at a % level to match the 1.2% precision on observations!



Thanks to LUNA *[Mossa+ 2020]*

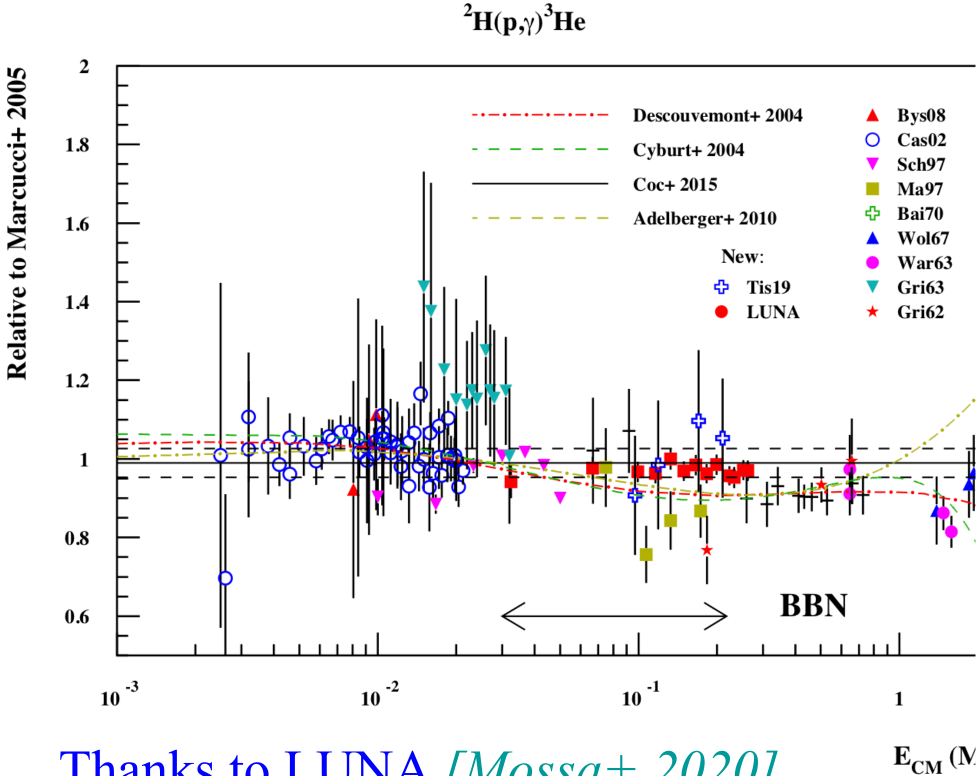
$D(p,\gamma)^3He$ rates known to ~ 2%

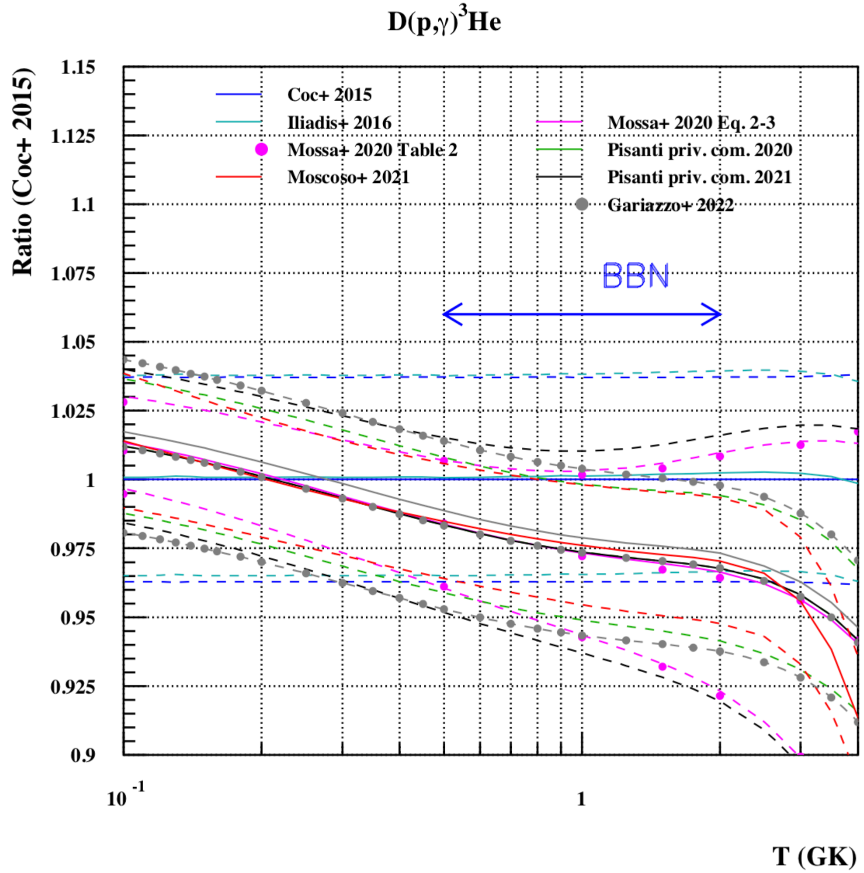


Comparison of reaction rates : $D(p,\gamma)^3He$

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

$D(p,\gamma)^3He$, $D(d,n)^3He$ and $D(d,p)^3H$ reaction rates need to be known at a % level to match the 1.2% precision on observations!

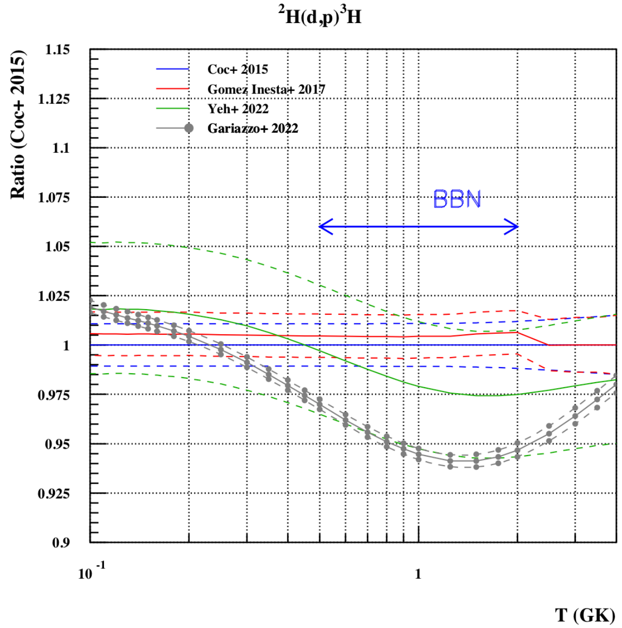


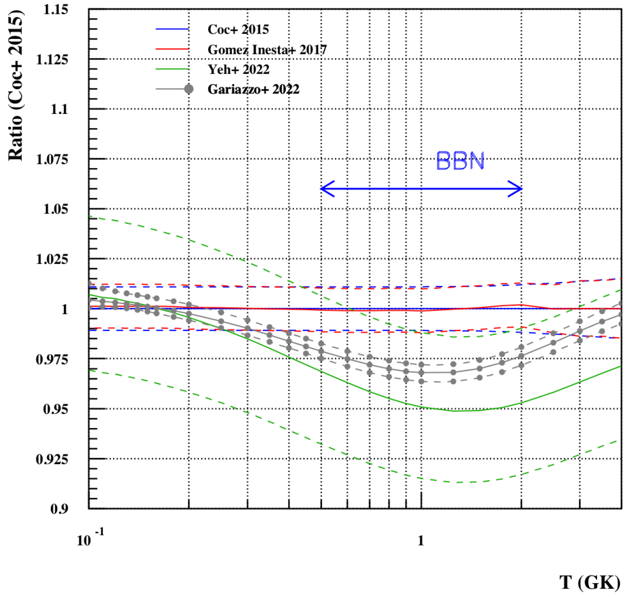


Thanks to LUNA *[Mossa+ 2020]*

$D(p,\gamma)^3He$ rates known to ~ 2%

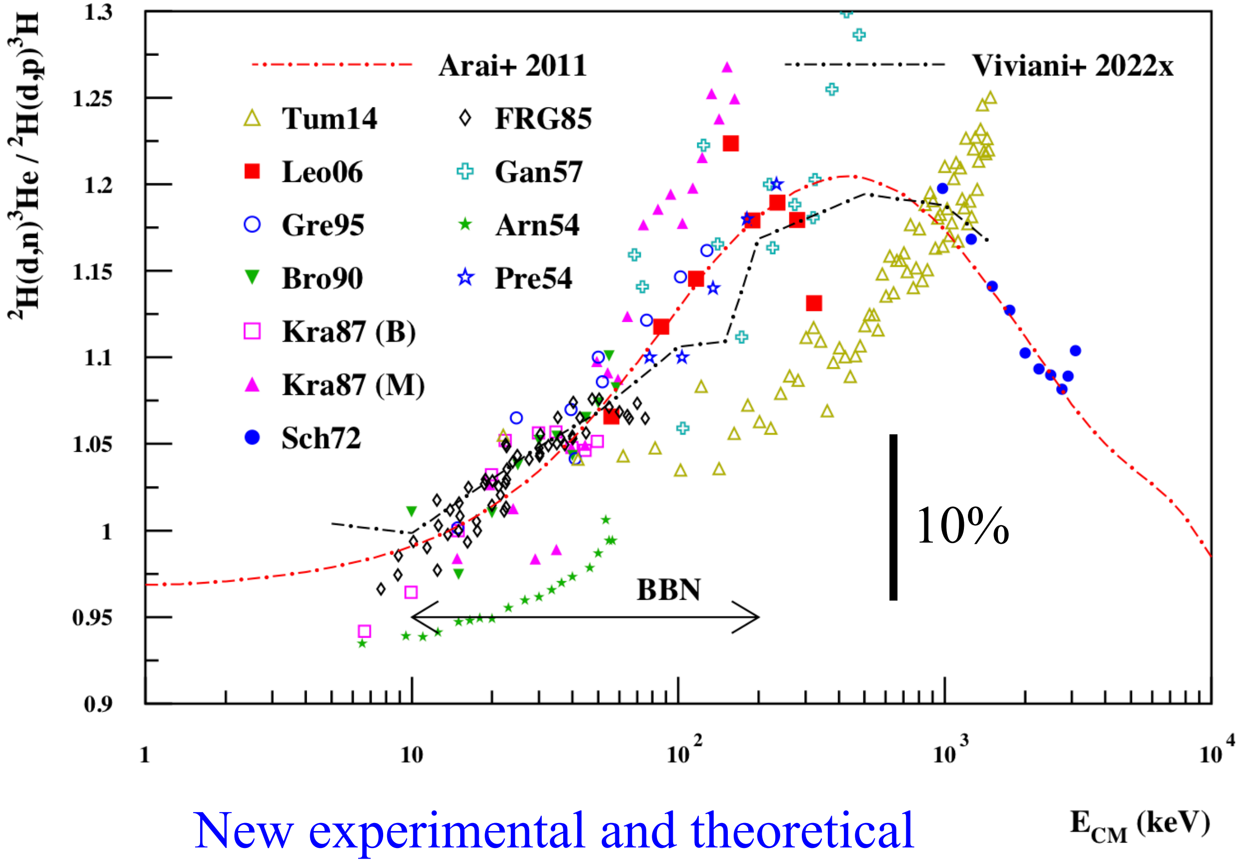
Comparison of reaction rates : D(d,n)^{3}He and D(d,p)^{3}H





At the origin of discrepancies between groups *[Pitrou+ 2021, Pisanti+ 2021, Yeh+ 2021]*

Ratio of D(d,n)^{3}He and D(d,p)^{3}H cross sections exp. and th. (to remove some of the systematics)



New experimental and theoretical studies welcomed!

Evaluation of main reaction rates

($D(p,\gamma)^3He$, $D(d,p)^3H$ and $D(d,n)^3He$)

1. Selection of experimental data sets
   - Direct measurements (no model involved)
   - Systematic uncertainties (normalization)
   - Vintage experiments (50's,60's) with few details published!

2. Selection of fitting function
   - From theory?
   - No resonances in cross sections, no structure
   - Polynomial, splines?

3. Statistical analyses
   - "Classical" $\chi 2$ minimisation
   - Bayesian

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Astronomy & Astrophysics

Effects of the variation of fundamental constants on Population III stellar evolution

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Variation of fundamental constants and the role of $A = 5$ and $A = 8$ nuclei on primordial nucleosynthesis

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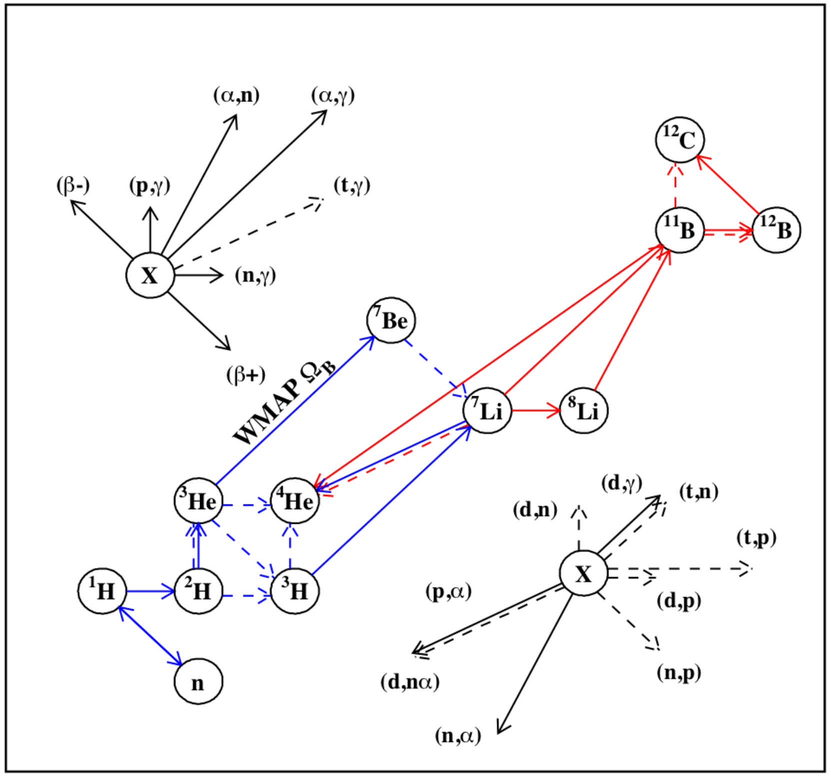
CNO seeds for first (Population III) stars

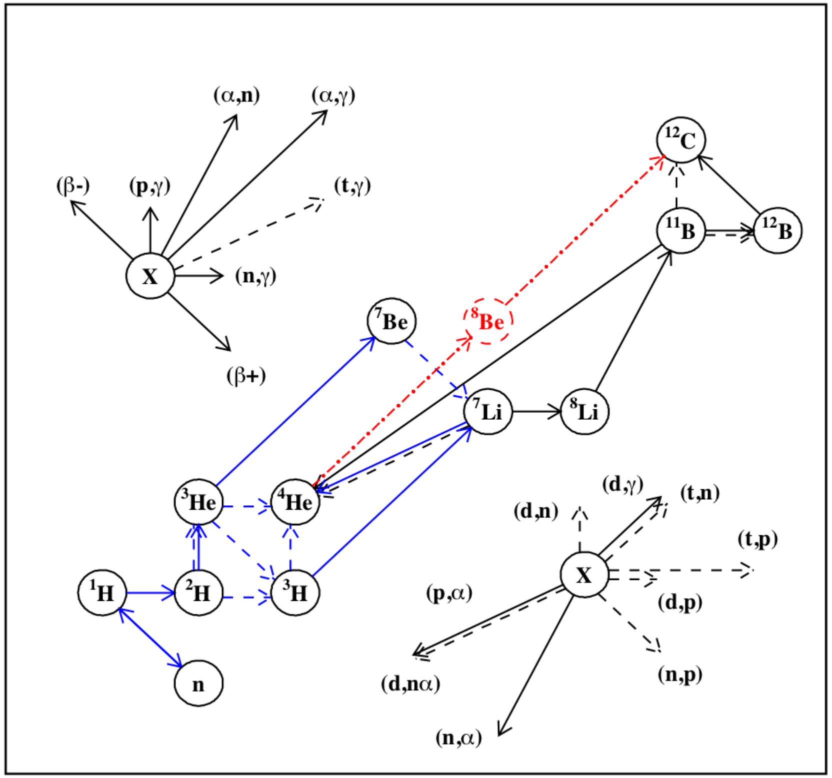
CNO/H > 10^{-13} to affect Pop III stars *[Ekström+ 2008]*



CNO/H =(0.5-3)× 10^{-15} from BBN *[Iocco + 2017; Coc+ 2012;2014]*

CNO seeds for first (Population III) stars

CNO/H > 10^{-13} to affect Pop III stars *[Ekström+ 2008]*



However, "*well known*" that a stable ^{8}Be would bridge the A=8 gap!

Variation of the fundamental constants

Physical theories involve constants

These parameters cannot be determined by the theory that introduces them; we can only measure them.

These arbitrary parameters have to be assumed constant:

- *experimental validation*
- *no evolution equation*

Very small variations, best studied on cosmological scales, from astronomical observations

See reviews : *J.-P. Uzan in* Rev. Mod Phys. *2003,* Living Rev. Relativity *2011; E. García-Berro, J. Isern & Y.A. Kubishin in* Astron. Astrophys. Rev. *2007*

Assuming that coupled variations of physical constants ($\alpha_{em,}$ $\Lambda_{QCD,}$ $G_{F,}$…) may lead to a ***stable*** ^{8}Be ***at the time of BBN*** *[Coc, Descouvemont,* ***Olive, Uzan*** *& Vangioni 2012]*

The triple-alpha reaction

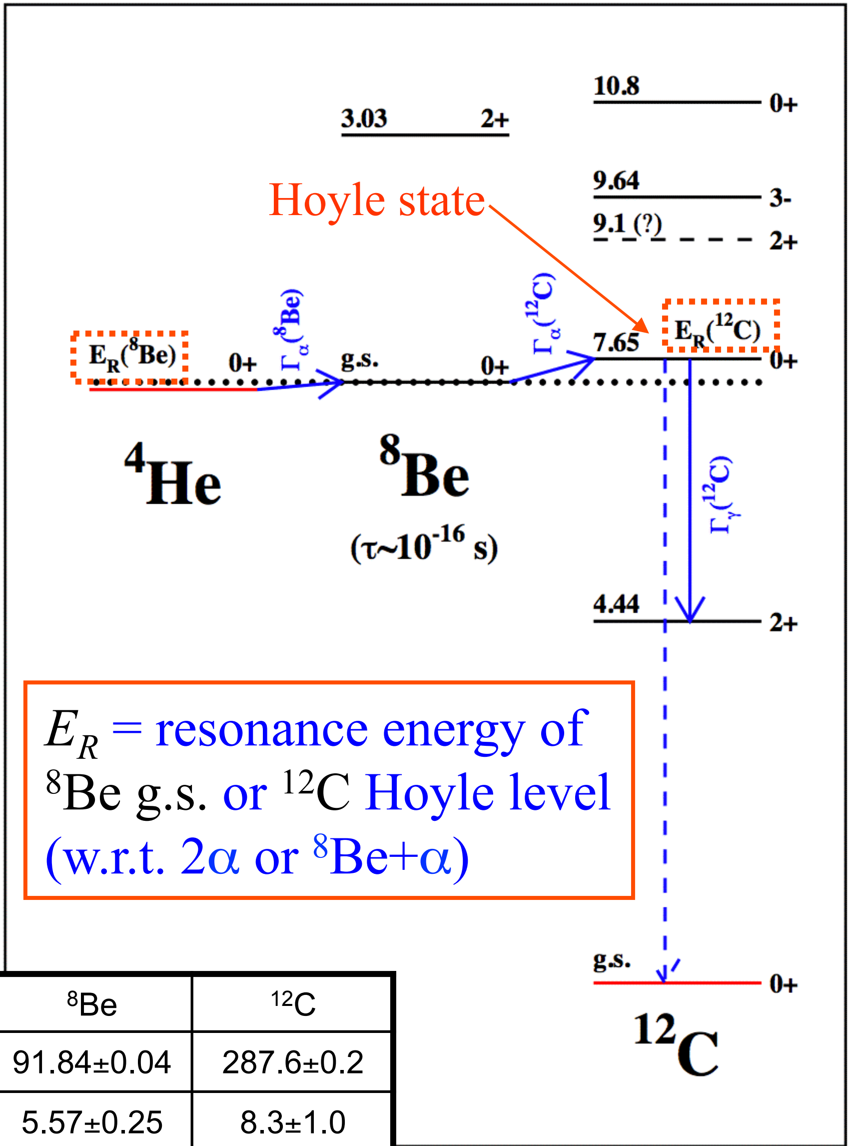
1. Equilibrium between ^4He and the short lived (~10^{-16} s) ^8Be : $\alpha\alpha \leftrightarrow {}^8Be$
2. Resonant capture to the (l=0, $J^\pi=0^+$) Hoyle state: $^8Be+\alpha \rightarrow {}^{12}C^*(\rightarrow {}^{12}C+\gamma)$

Simple formula used in previous studies

1. Saha equation (thermal equilibrium)
2. Sharp resonance analytic expression:

$$N_A^2\langle\sigma v\rangle^{\alpha\alpha\alpha} = 3^{3/2} 6 N_A^2 \left(\frac{2\pi}{M_\alpha k_B T}\right)^3 \hbar^5 \gamma \exp\left(\frac{-Q_{\alpha\alpha\alpha}}{k_B T}\right)$$

with $Q_{\alpha\alpha\alpha} = E_R(^8Be) + E_R(^{12}C)$ and $\gamma \approx \Gamma_\gamma$



E_R = resonance energy of ^8Be g.s. or ^{12}C Hoyle level (w.r.t. 2α or $^8Be+\alpha$)

Approximations

1. Thermal equilibrium
2. Sharp resonance
3. ^8Be decay faster than α capture

Nucleus	^8Be	^{12}C
E_R (keV)	91.84±0.04	287.6±0.2
Γ_α (eV)	5.57±0.25	8.3±1.0
Γ_γ (meV)	-	3.7±0.5

Nuclear microscopic calculations

- Hamiltonian:

$$H = \sum_{i=1}^{A} T(r_i) + \sum_{i<j=1}^{A} \left(V_{Coul.}(r_{ij}) + V_{Nucl.}(r_{ij}) \right)$$

Where $V_{Nucl.}(r_{ij})$ is an effective Nucleon-Nucleon interaction

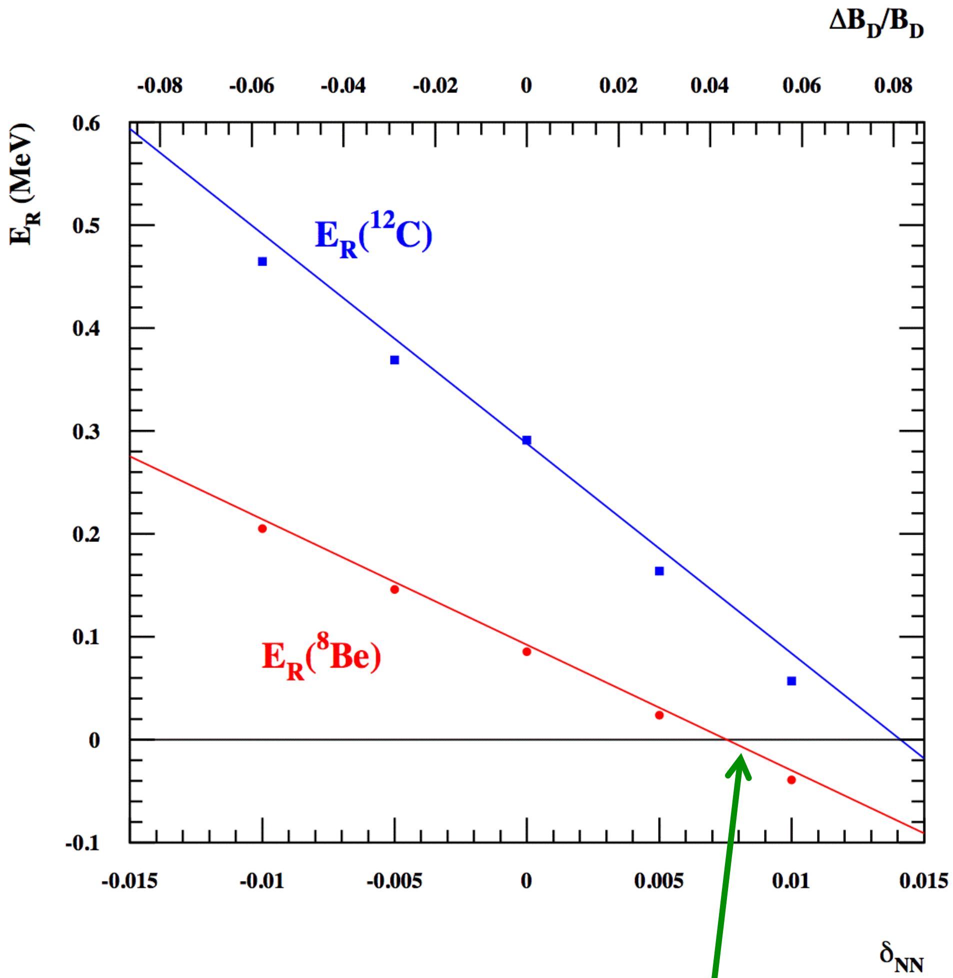
- Minnesota N-N force *[Thompson et al. 1977]* optimized to reproduce low energy N-N scattering data and B_D (deuterium binding energy)

- α-cluster approximation for $^8Be^{g.s.}$ (2α) and the Hoyle state (3α) *[Kamimura 1981]*

- Scaling of the N-N interaction

$$V_{Nucl.}(r_{ij}) \rightarrow (1+\delta_{NN}) \times V_{Nucl.}(r_{ij})$$

to obtain B_D, $E_R(^8Be)$, $E_R(^{12}C)$ as a function of δ_{NN} :



^8Be stable for N-N interaction higher by 0.75%

Numerical rate calculation

- At “low temperatures”, capture via resonance tails *[Nomoto et al. 1985]* requires numerical integration
  - Even more important when resonances are shifted upwards with larger widths

- Radiative widths : $\Gamma_\gamma(E) \propto E^{2L+1}$ (with L=2 here)

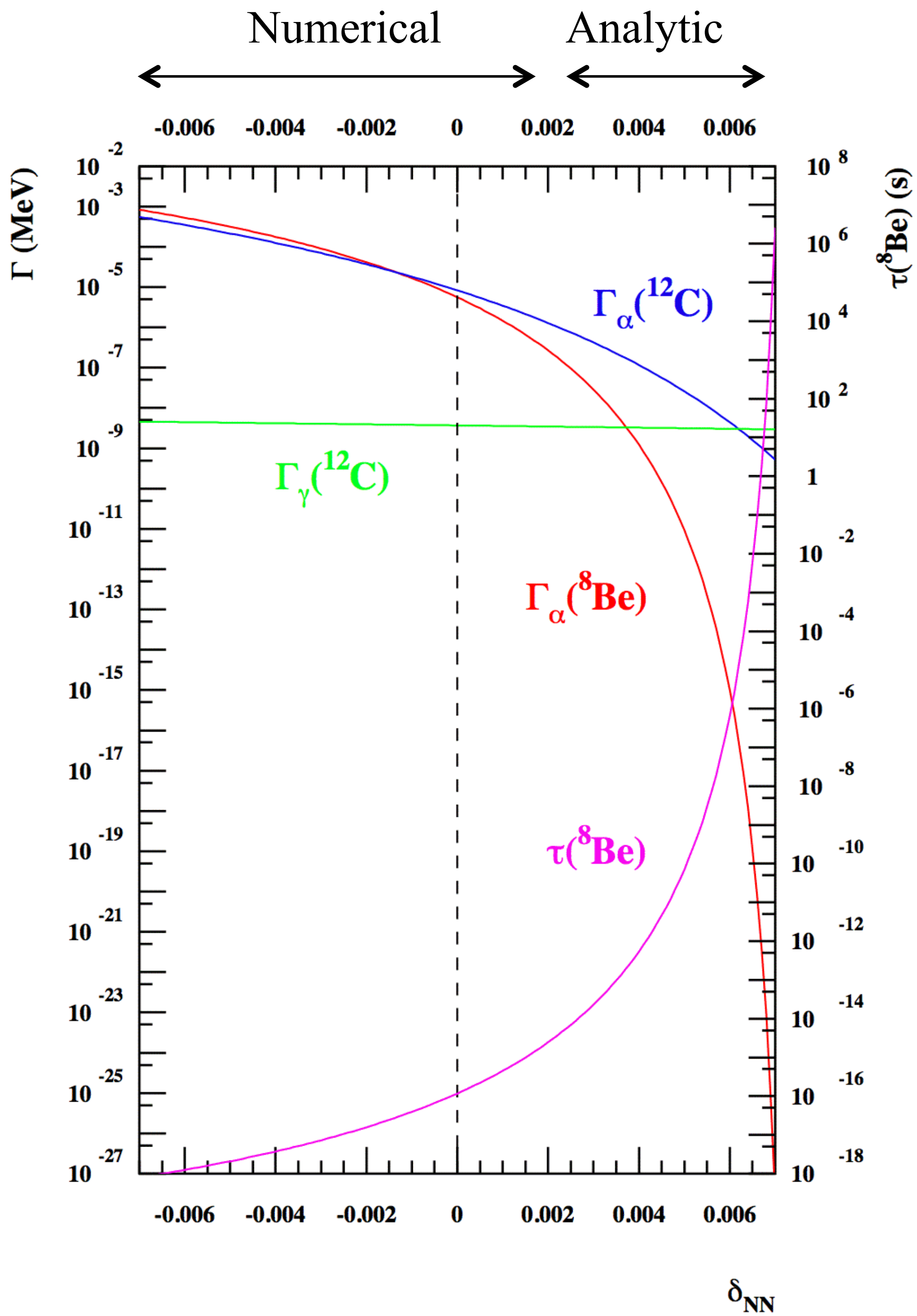
- Charged particle widths :

$\Gamma_\alpha(E) = \Gamma_\alpha(E_R)\, P_L(E,R_C) / P_L(E_R,R_C)$ with

$P_L(E,R_C) =\propto (F_L^2(\eta,kR_C)+G_L^2(\eta, kR_C))^{-1}$

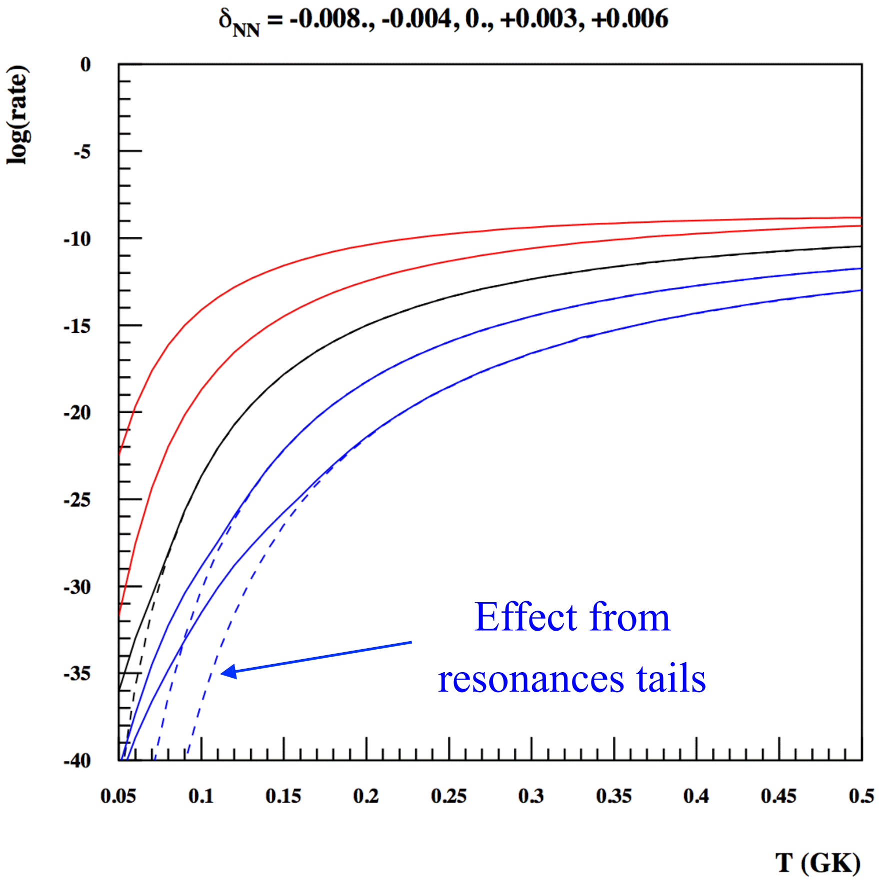
the penetrability

$\gamma \equiv \Gamma_\alpha(E)\, \Gamma_\gamma(E) / (\Gamma_\alpha(E) + \Gamma_\gamma(E)) \approx \Gamma_\gamma(E)$
if $\Gamma_\gamma(E) << \Gamma_\alpha(E)$ in analytic expression

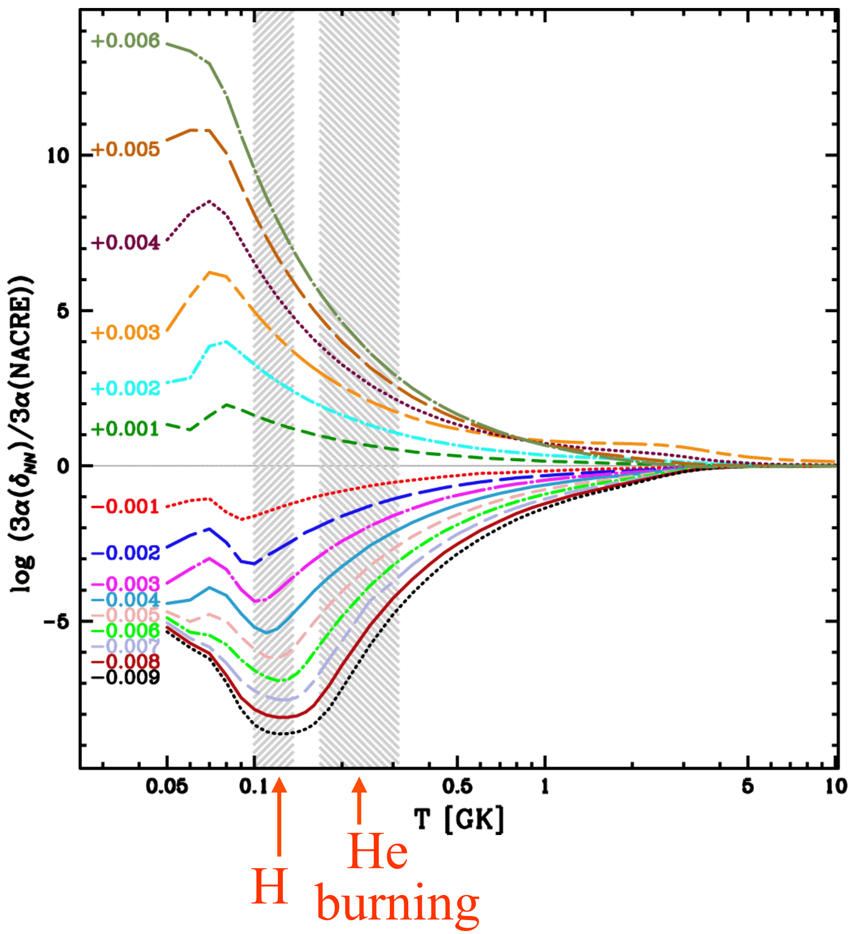


The triple-alpha with unstable ^{8}Be

Rates



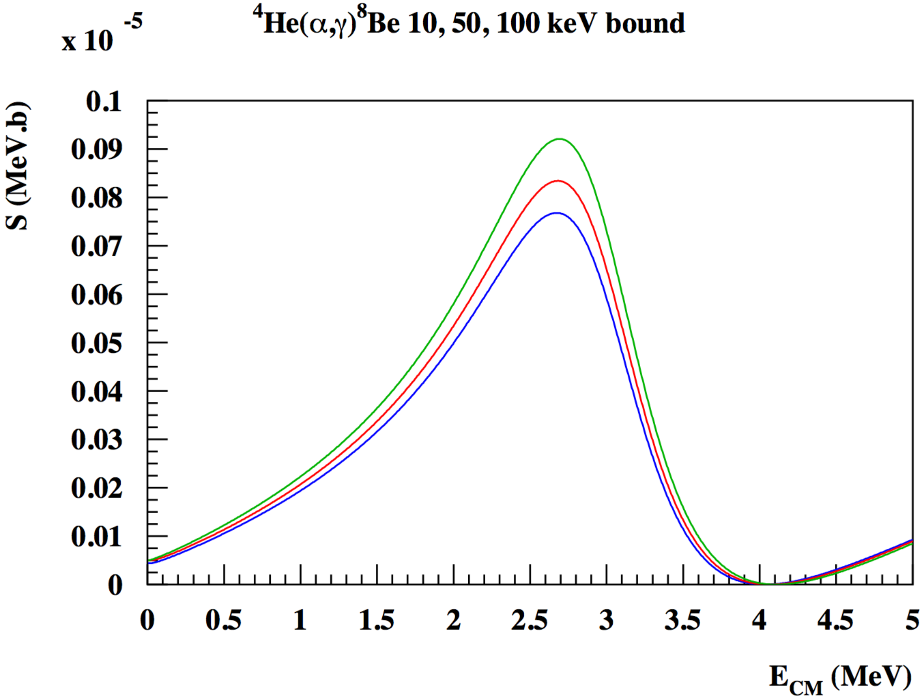
Rates / NACRE



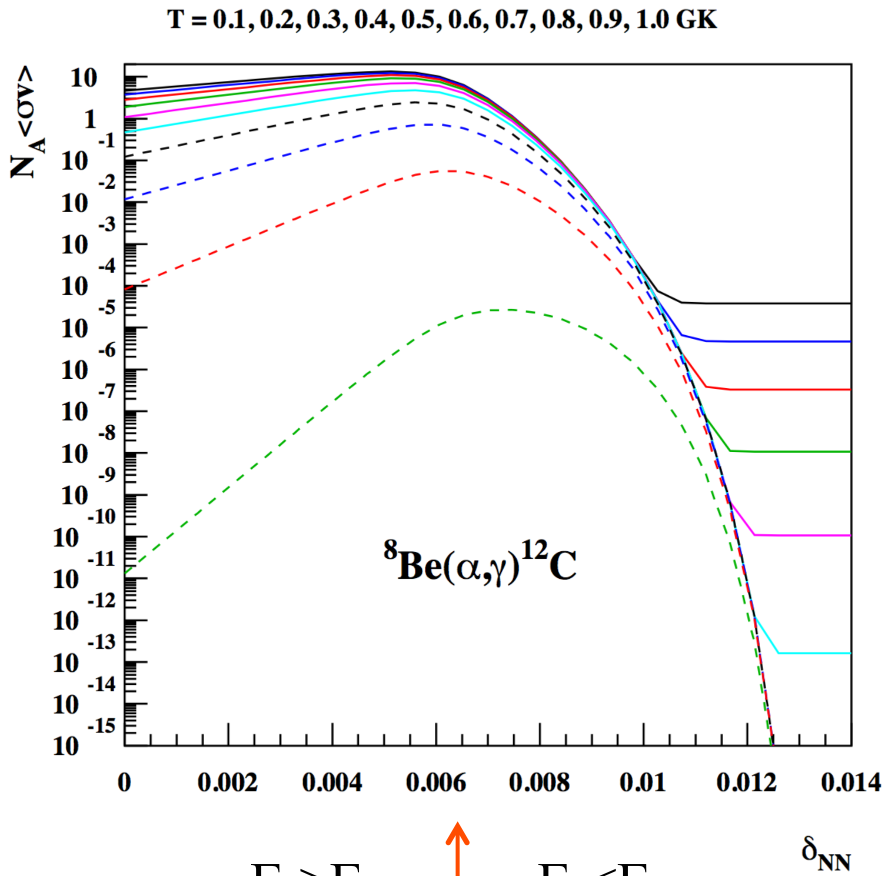
The triple-alpha with a stable ^{8}Be

^{8}Be bound by 10, 50 or 100 keV
(δ_{NN}=0.0083, 0.0116, 0.0156)

^{4}He(α,γ)^{8}Be^{bound} cross-section in continuity with unbound one
[Baye & Descouvemont 1985]



^{8}Be^{bound}(α,γ)^{12}C from sharp resonance formula



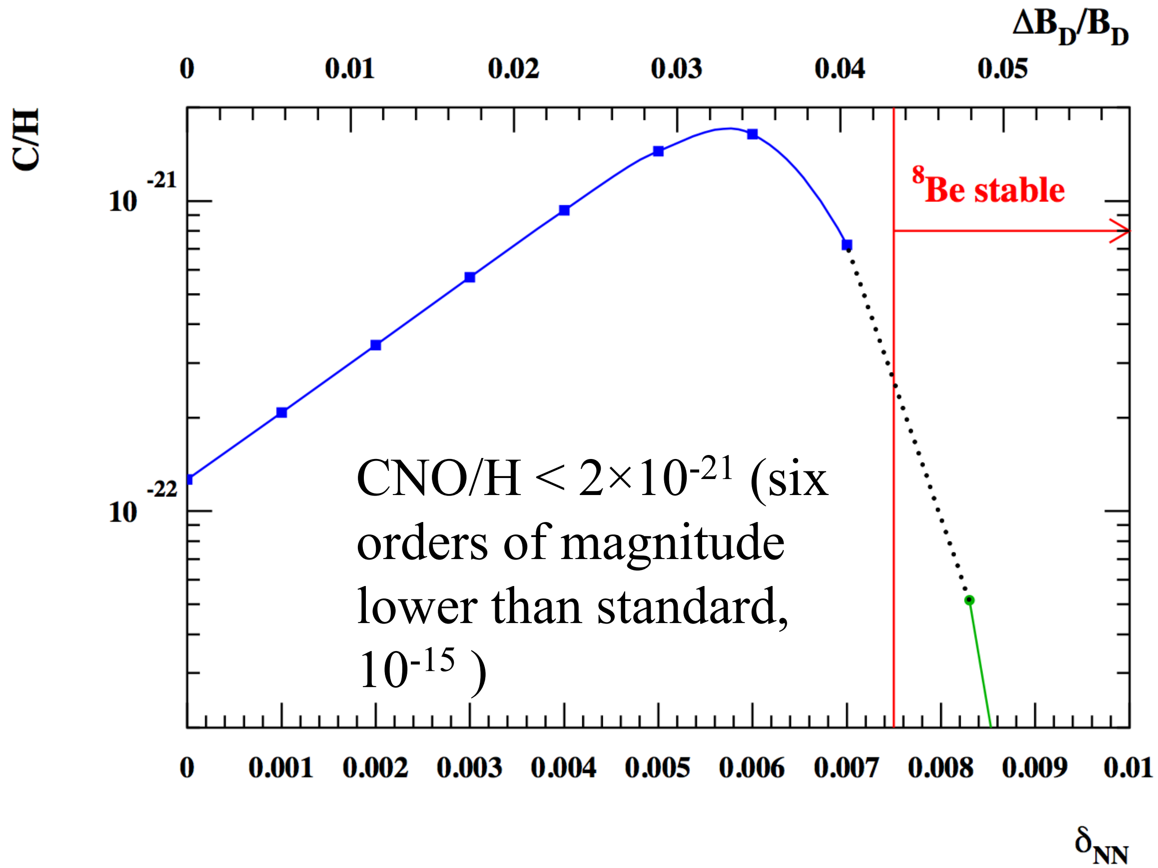
$\Gamma_\alpha > \Gamma_\gamma$ $\Gamma_\alpha < \Gamma_\gamma$

[Newton et al. 2007]

CNO production with un/stable ^{8}Be

BBN calculations *[Coc+ 2012]* with:

- ❑ Triple-alpha with shifted resonance energies (δ_{NN}<0.0075)
- ❑ ^{4}He(α,γ)^{8}Be^{bound}(α,γ)^{12}C *[Baye & Descouvemont 1985]* (δ_{NN}<0.0075)
- ❑ Other CNO producing reactions removed



- Unbound: density lower (3 body reaction) and timescale shorter than in stars!
- Bound: ^{4}He(α,γ)^{8}Be(α,γ)^{12}C too slow (two Z=2 captures)

Conclusions

- Convergence of BBN codes when same nuclear reaction rates are used
  - Mathematica code with >400 reaction network publicly available at http://www2.iap.fr/users/pitrou/primat.htm
- Standard BBN is now in the (1%) precision era for D and ^{4}He
  - We confirm a 1.8σ tension between observations/predictions of D/H with our evaluated rates + LUNA (2 codes × 2 rate analyses)
  - Calls for even better precision on ~~D(p,γ)^{3}He~~, D(d,p)^{3}H and D(d,n)^{3}He cross sections. Experimentally very challenging.
  - New physics? Plenty of models overproduce D to reduce Li!
- The Cosmological Lithium Problem is worse than ever!
  - Disagreement (factor of 3) with Li observations
    - Nuclear : excluded by experiments
    - No ^{6}Li plateau *[Lind+ 2013]* from BBN!
- BBN: a tool to explore BSM physics in the early stages of the Universe