Big Bang Nucleosynthesis: a short review

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The Physics of BBN

The abundances of ^{4}He, D, ^{3}He, ^{7}Li produced by BBN depends on the following quantities:

Deuterium bottleneck $T_N \approx -\frac{B_d}{\ln(\eta)} \approx 0.1$ MeV

- Baryon density

$$\eta \equiv \frac{n_B}{n_\gamma}$$

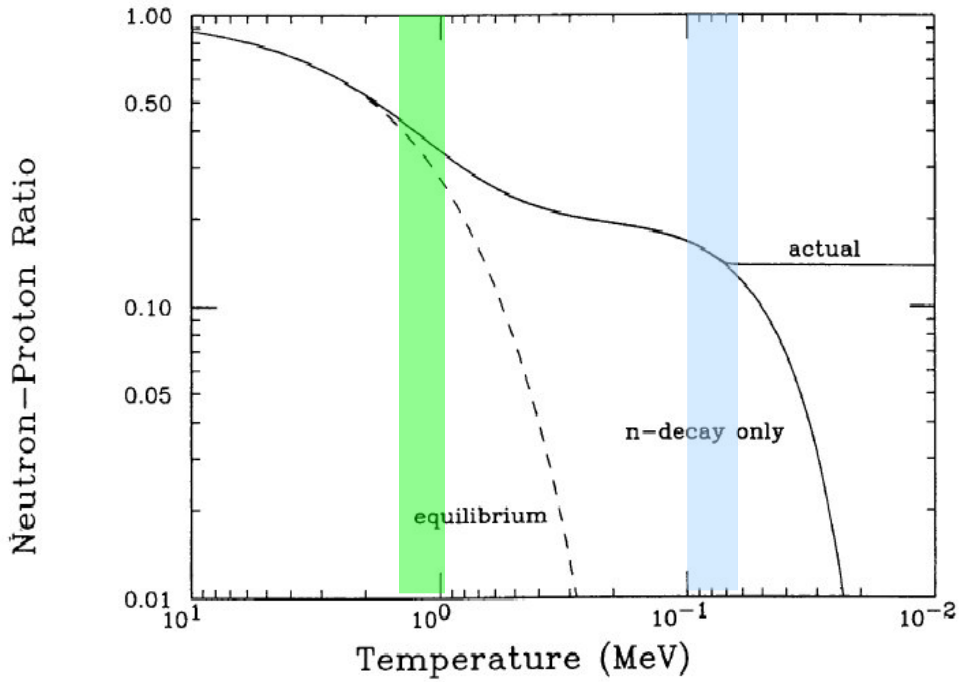
$$\Omega_B h^2 \approx 3.7\ 10^7\ \eta$$

- Hubble expansion rate

$$H \approx g_*^{1/2}\ G_N^{1/2}\ T^2$$

$$g_* = 10.75 + \frac{7}{4}(N_\nu - 3)$$

Γ_W = Weak rate (ν_e +n ←→ p+e)



$H/\Gamma_W = 1$ → Weak interaction freeze-out $T_W \approx 1\,\text{MeV} \cdot (g_* / 10.75)^{1/6}$

- Essentially all neutrons surviving till the onset of BBN used to build ^{4}He
- D, ^{3}He, ^{7}Li are determined by a complex nuclear reaction network.

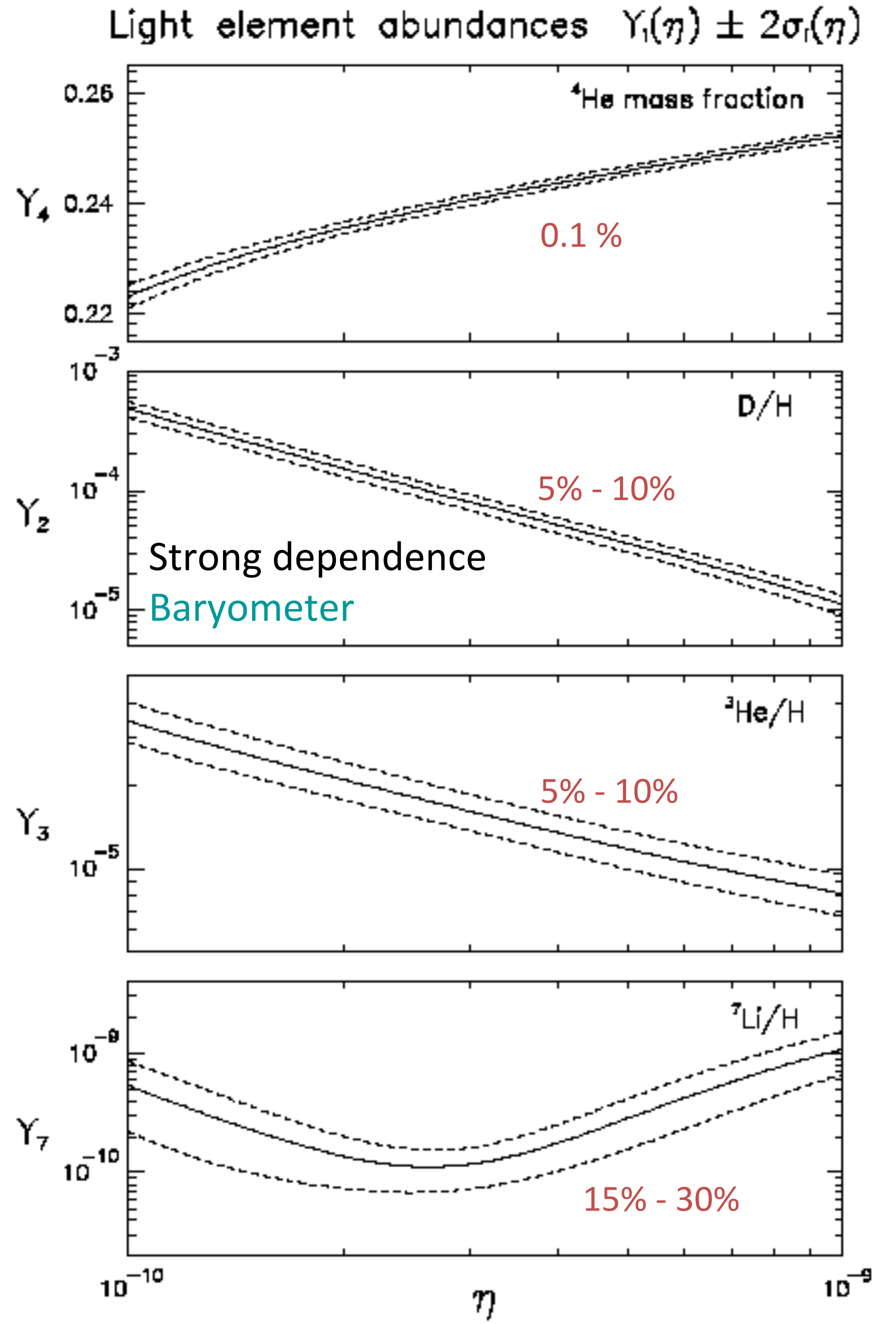
Accuracy of theoretical calculations

Accuracy of ^{4}He calculation at the level of 0.1% (but beware of neutron lifetime …).

High precision codes (Lopez & Turner 1999, Esposito et al. 1999) take directly into account effects due to :

- zero and finite temperature radiative processes;
- non equilibrium neutrino heating during $e^{\pm}$ annihilation;
- finite nucleon masses;
- ………

These effects are included “a posteriori” in the “standard” code (Wagoner 1973, Kawano 1992).



Theoretical uncertainties

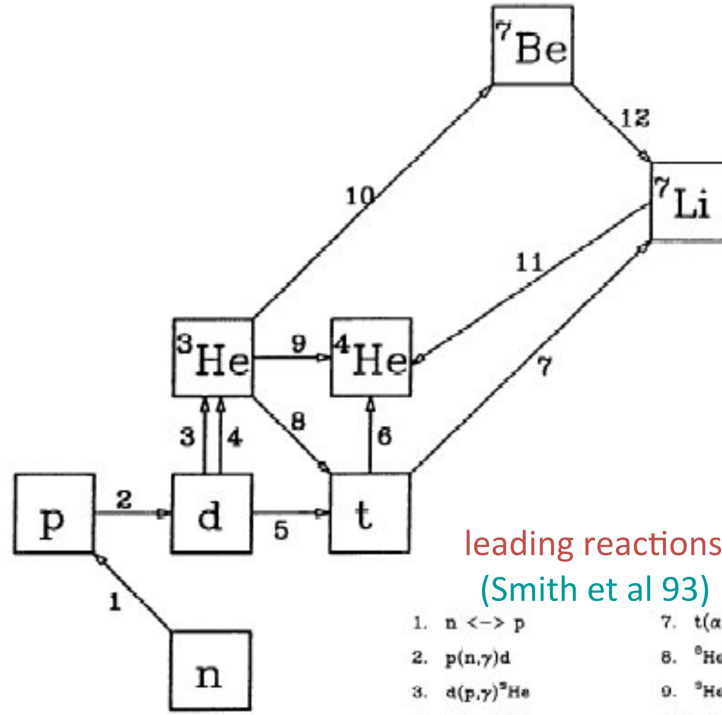
Reaction rate uncertainties translate into uncertainties in theoretical predictions:

Monte-Carlo evaluation of uncertainties
Krauss & Romanelli 90,
Smith et al 93,
Kernan & Krauss 94

Semi-analytical evaluation of the error matrix
Fiorentini, Lisi, Sarkar, Villante, 98
Lisi, Sarkar, Villante, 00

Re-analysis of nuclear data
Nollet & Burles 00, Cyburt et al 01,
Descouvement et al. 04, Cyburt et al. 04,
Serpico et al. 04, Coc et al. 11, Coc et al. 14
NACRE Coll. Database

Recent new data and evaluations
p(n,γ)D: Ando et al. 06
^{2}H(p,γ)^{3}He: LUNA
^{3}He(α,γ)^{7}Be: LUNA, Cyburt et al 08
^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He: Leonard et al. 06
^{2}H(α,γ)^{6}Li: LUNA



leading reactions
(Smith et al 93)

1. n <-> p
2. p(n,γ)d
3. d(p,γ)^{3}He
4. d(d,n)^{3}He
5. d(d,p)t
6. t(d,n)^{4}He
7. t(α,γ)^{7}Li
8. ^{3}He(n,p)t
9. ^{3}He(d,p)^{4}He
10. ^{3}He(α,γ)^{7}Be
11. ^{7}Li(p,α)^{4}He
12. ^{7}Be(n,p)^{7}Li

Sub-leading reactions
(see Serpico et al. 04)

^{4}He$(d,\gamma)^6$Li
^{6}Li$(p,\alpha)^3$He
^{7}Be$(n,\alpha)^4$He
^{7}Be$(d,p)2\,^4$He

BBN without computers:

(Esmailzaldeh et al 1991)

The abundance of a generic element evolves according to the rate equations:

$$\frac{dY_i}{dt} = n_{\rm B}\left[\sum_{j,k} Y_j\, Y_k\, \langle \sigma_{jk}\, v\rangle_T - Y_i \sum_l Y_l\, \langle \sigma_{il}\, v\rangle_T\right] . \quad \longrightarrow \quad Y_i(T) = \frac{C_i(T)}{D_i(T)}$$

A good approx. is obtained by studying the quasi-fixed point of the above equation:

$$Y_i \sim \left.\frac{C_i}{D_i}\right|_{T=T_{i,\rm f}}$$

$T_{i,f}$ = Freeze-out temperature

$$D_i, C_i \ll H$$

$$\begin{cases} C_{\rm i} = n_{\rm B} \sum_{j,k} Y_j\, Y_k\, \langle \sigma_{jk}\, v\rangle_T \\ D_{\rm i} = n_{\rm B} \sum_l Y_l\, \langle \sigma_{il}\, v\rangle_T \end{cases}$$

The abundance Y_i of each element is approximately determined by a selected number of *creation and destruction processes* at a characteristic freeze-out temperature $T_{i,f}$ (≈10-100 keV).

The role of nuclear reactions

Logarithmic derivatives of the primordial abundances Y_i wrt the rates of the nuclear cross sections S_j

$$\lambda_{i,j} \equiv \frac{\partial \ln Y_i}{\partial \ln S_j}$$

Leading reactions

For $\eta \approx 5\ 10^{-10}$, we obtain:

Reaction	^{4}He	d	^{7}Li	^{3}He
n lifetime	0.72	0.41	0.39	0.14
$p(n,\gamma)d$	0.00	-0.19	1.37	0.09
$d(p,\gamma)^3$He	0.00	-0.34	0.61	0.40
$d(d,n)^3$He	0.01	-0.53	0.69	0.19
$d(d,p)t$	0.01	-0.46	0.06	-0.26
^{3}He$(n,p)t$	0.00	0.02	-0.28	-0.17
$t(d,n)^4$He	0.00	0.00	-0.01	-0.01
^{3}He$(d,p)^4$He	0.00	-0.02	-0.74	-0.74
^{3}He$(\alpha,\gamma)^7$Be	0.00	0.00	0.98	0.00
$t(\alpha,\gamma)^7$Li	0.00	0.00	0.02	0.00
^{7}Be$(n,p)^7$li	0.00	0.00	-0.71	0.00
^{7}Li$(p,\alpha)^4$He	0.00	0.00	-0.04	0.00

Based on Fiorentini, Lisi, Sarkar and Villante, 1998

Note that: Sub-leading reactions give small log-derivatives but may be affected by large uncertainties and still contributes to the error budget.

Theoretical error budget

(Over)simplifying from Coc et al. JCAP 2014:
The contribution of different reaction rates to theoretical error budget can be expressed as:

$$C_{j,k} \sim \frac{1}{\sigma_{j,\mathrm{tot}}}\left[Y_j \frac{\partial \ln Y_j}{\partial \ln S_k}\,\delta S_k\right] \sim (\pm)\frac{\sigma_{j,k}}{\sigma_{j,\mathrm{tot}}}$$

Rate uncert. δS_k

$\delta Y_4 \approx 0.1\%$

Reaction	$C_{\mathrm{He4},k}$	Rate uncert. δS_k
$1/\tau_n$	-0.9677	≈ 0.13% [pdg]
^{3}He(t,np)^{4}He	0.1151	
D(d,n)^{3}He	0.1282	≈ 2-3% [leo06]
D(d,p)^{3}H	0.1296	≈ 2-3% [leo06]

Table 5. Correlations with ^{4}He.

$\delta Y_2 \approx 3\%$

Reaction	$C_{\mathrm{D},k}$	Rate uncert. δS_k
D(p,γ)^{3}He	-0.7790	≈ 5% [des04]
D(d,n)^{3}He	-0.4656	≈ 2-3% [leo06]
D(d,p)^{3}H	-0.4082	≈ 2-3% [leo06]

Table 6. Correlations with D.

$\delta Y_3 \approx 3\%$

Reaction	$C_{\mathrm{He3},k}$
D(p,γ)^{3}He	0.6699
D(d,n)^{3}He	0.1640
D(d,p)^{3}H	-0.1897
^{3}He(d,p)^{4}He	-0.6841

Table 7. Correlations with ^{3}He.

$\delta Y_7 \approx 8\%$

Reaction	$C_{\mathrm{Li7},k}$	Rate uncert. δS_k
^{7}Be(n,α)^{4}He	-0.3057	factor ten [???]
^{7}Be(d,p)2^{4}He	-0.2079	
D(p,γ)^{3}He	0.4043	≈ 5% [des04]
D(d,n)^{3}He	0.1547	≈ 2-3% [leo06]
^{3}He(d,p)^{4}He	-0.2232	
^{3}He(α,γ)^{7}Be	0.7107	≈ 8% [Cyb08]

Table 8. Correlations with ^{7}Li.

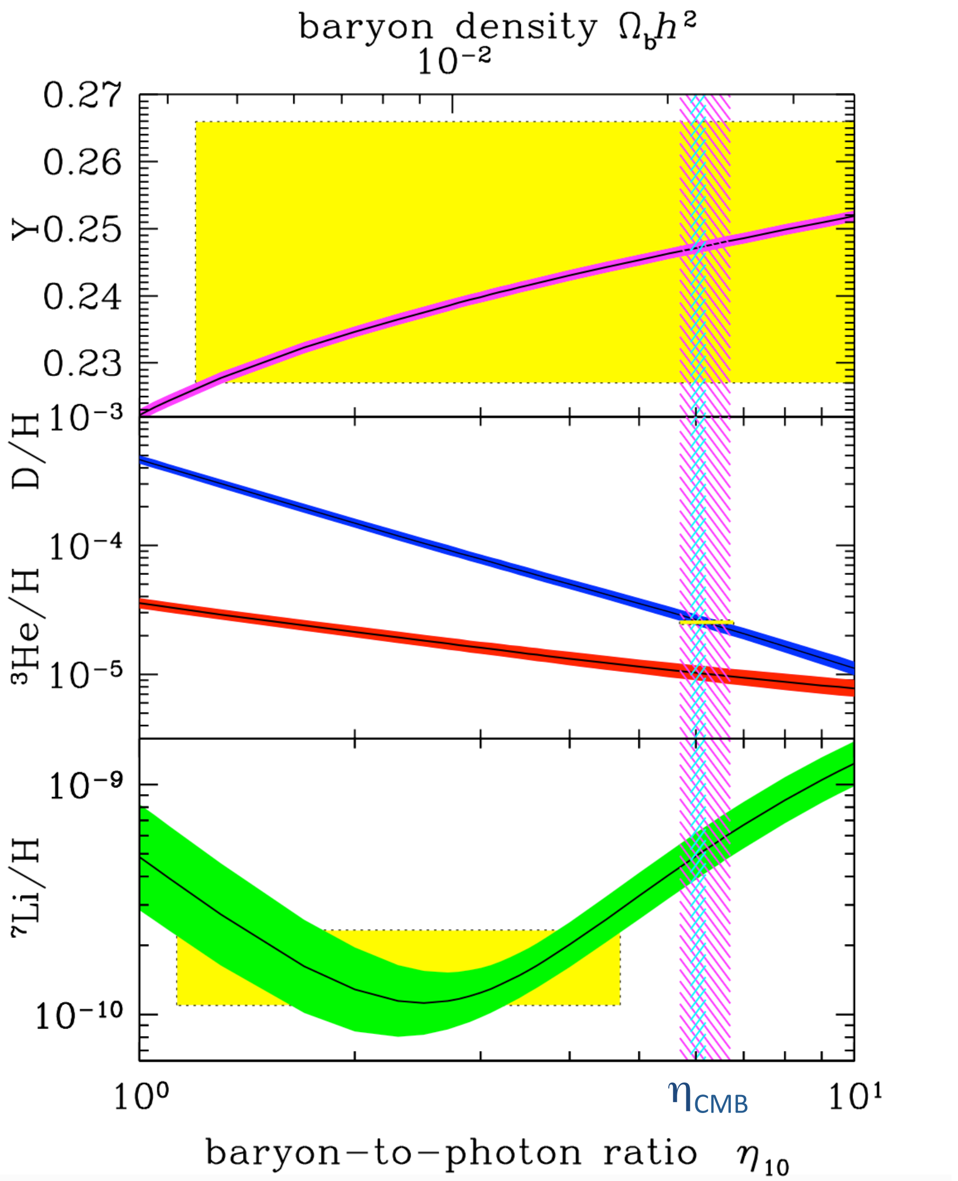
[des04] – Descouvemont et al., At. Data and Nucl. Data Tables, 2004
[cyb08] – Cyburt and Davids, Phys Rev C, 2008
[leo06] – Leonard et al., Phys Rev C 2006

Theory. vs. observations

Helium 4: determined by extrapolating to Z=0 the (Y,Z) relation or by averaging Y in extremely metal poor HII regions (N and O used as metallicity tracers)

$$Y_{\rm p} = 0.2465 \pm 0.0097$$

Aver et al, JCAP 2013



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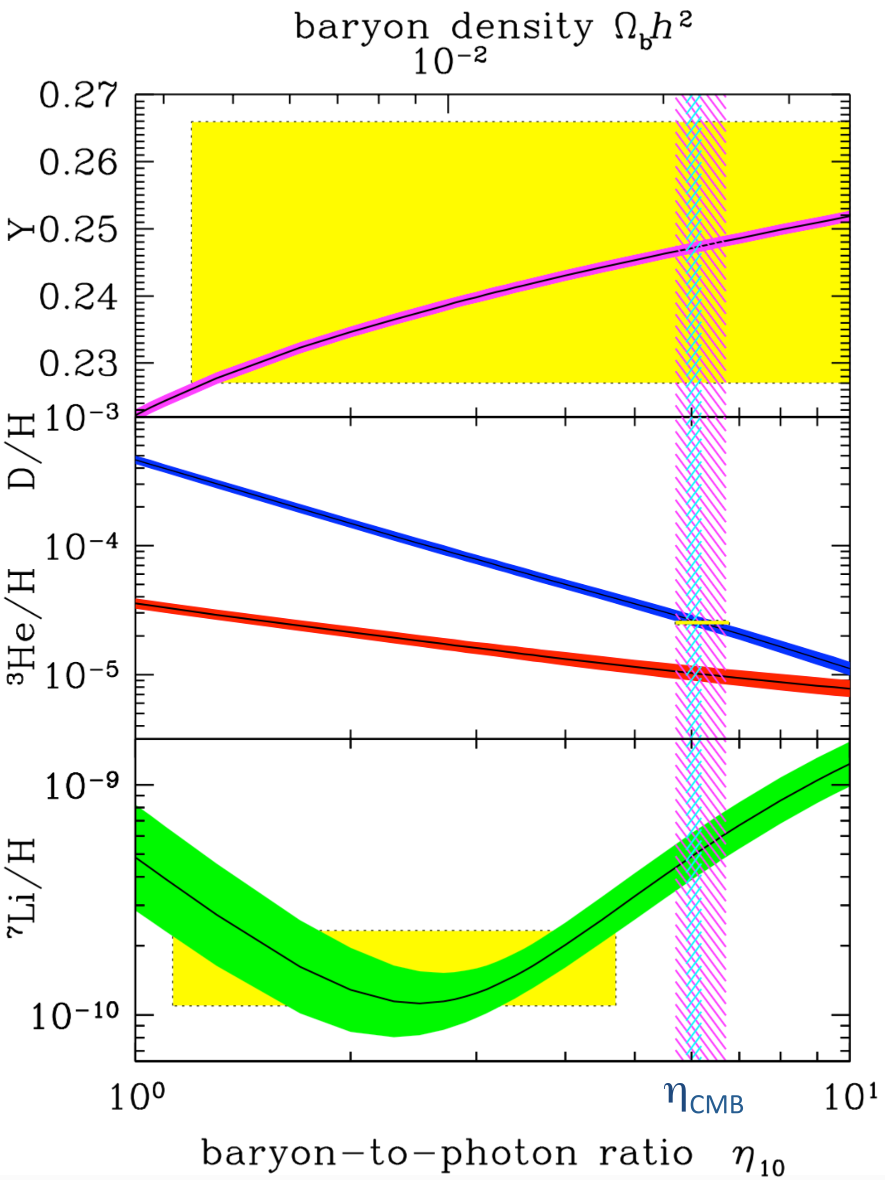
Deuterium: observed in the high resolution spectra of QSO absorption systems at high redshift:

$$D/H|_p = (2.53 \pm 0.04) \times 10^{-5}$$

Cooke et al, ApJ 2014



Deuterium

The primordial abundance is obtained from the weighted mean of 5 damped Lyman-α systems:

$$D/H|_p = (2.53 \pm 0.04) \times 10^{-5}$$

To be compared with the predicted value for $\eta = \eta_{CMB}$:

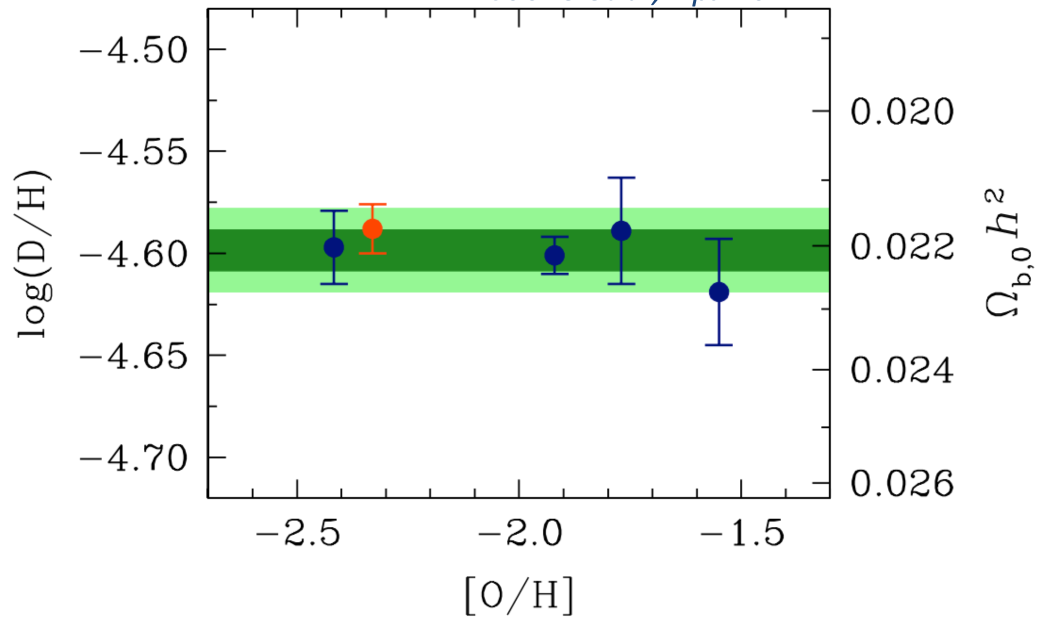
$$D/H|_p = (2.65 \pm 0.08) \times 10^{-5}$$

Coc et al, JCAP 2014

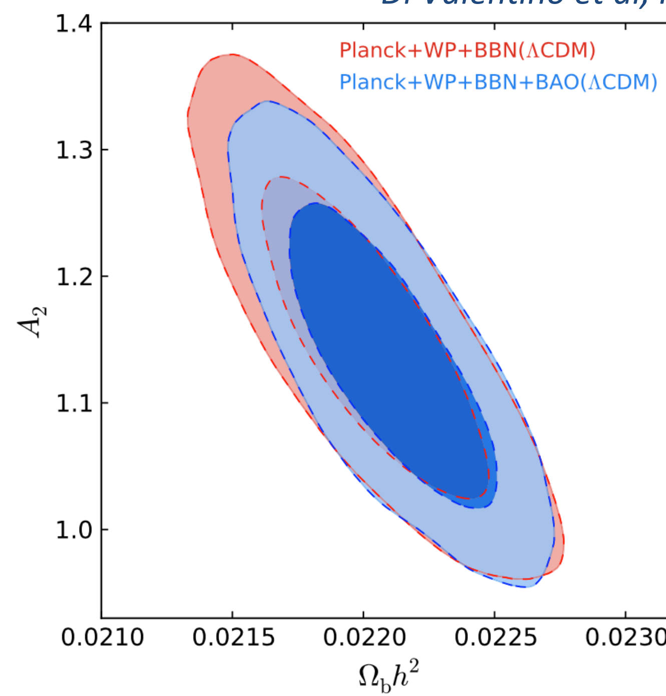
The two values above are consistent at 1σ

- $N_{eff} = 3.28 \pm 0.28$
- A_2 = rescaling factor of $^2H(p,\gamma)^3He \geq 1$ (1σ)

Cooke et al, ApJ 2014



Di Valentino et al, Prd 2014



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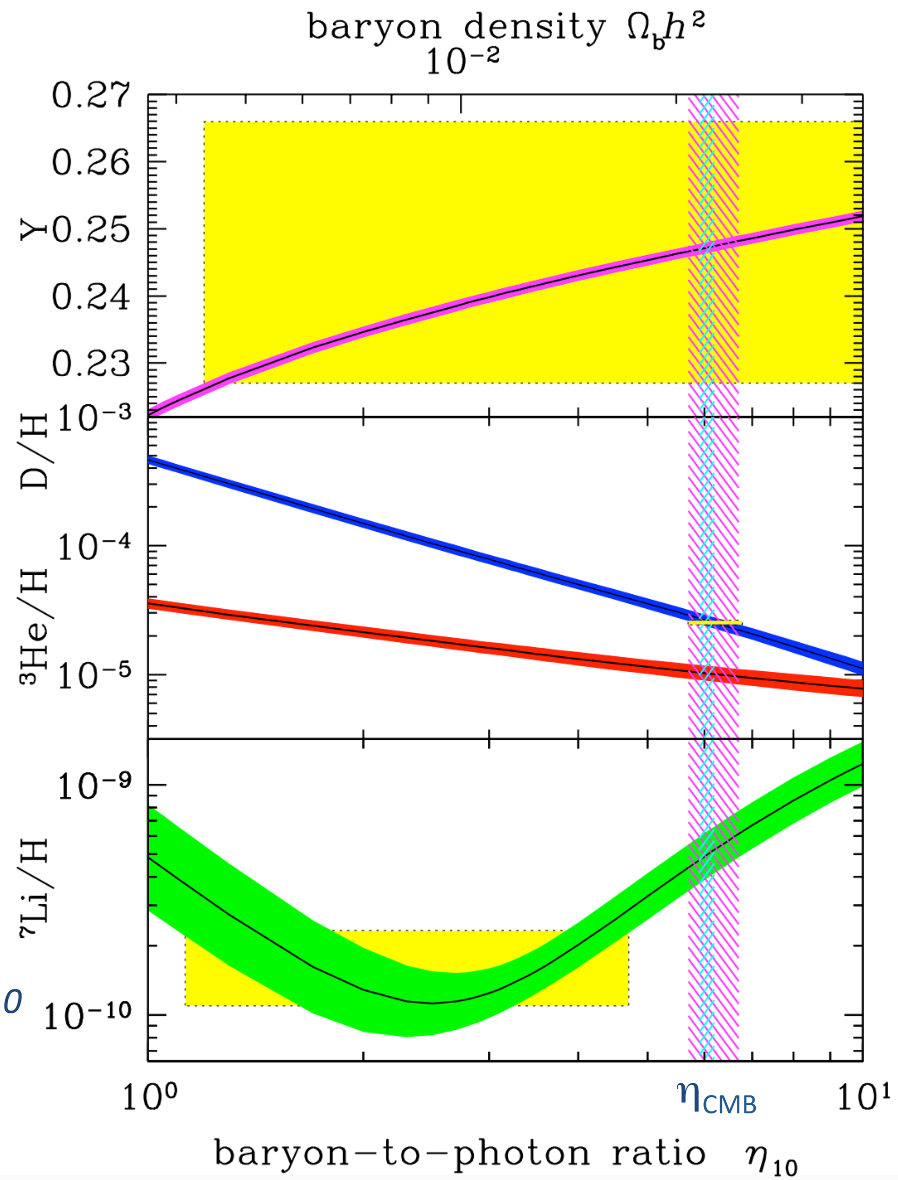
Lithium-7: observed in metal poor (Pop II) stars of our galaxy. Abundance does not vary significantly in stars with metallicities < 1/30 of solar (Spite Plateau)

$$Li/H|_p = (1.6 \pm 0.3) \times 10^{-10}$$

Sbordone et al, A&A 2010



Lithium-7

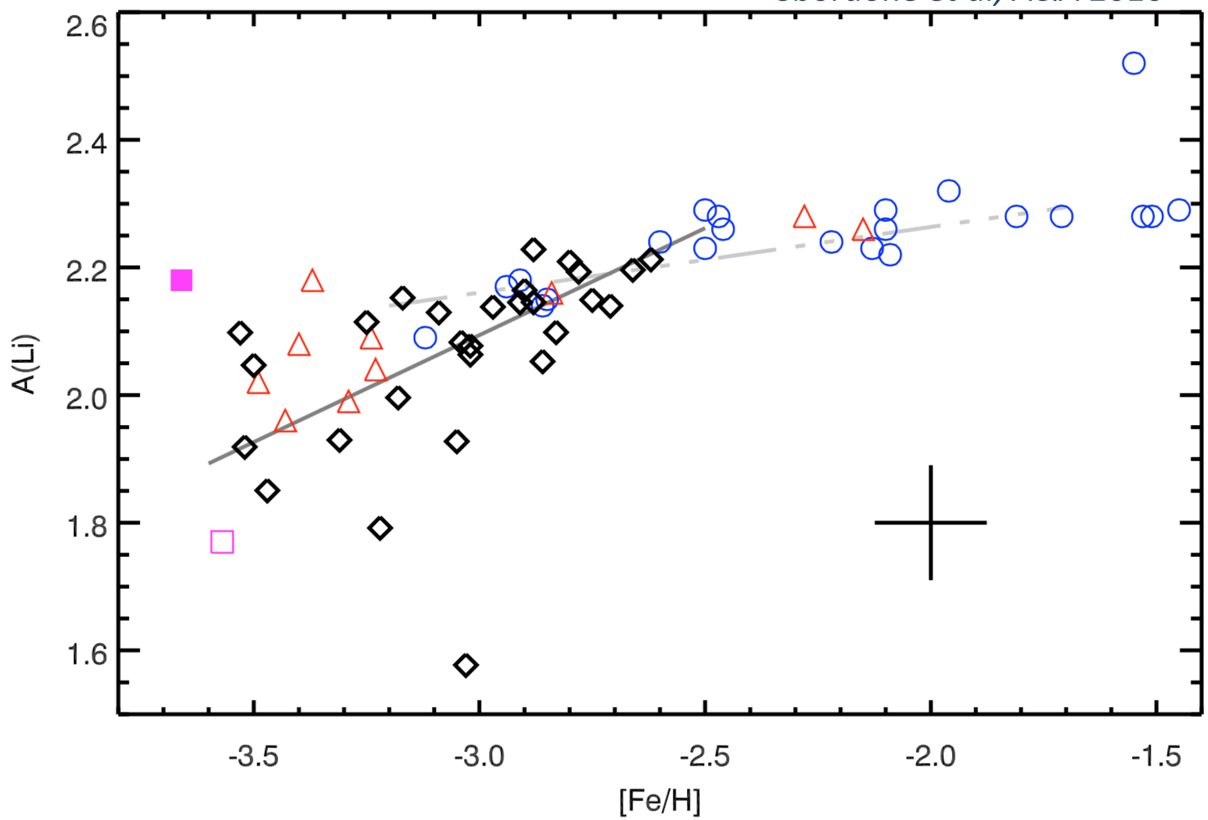
Meltdown of the spite plateau at low metallicity (<1/1000 Solar)

(?) Something is depleting Lithium in very metal poor stars

The primordial value is obtained from stars with -2.8 < [Fe/H] < -1.5

$$\mathrm{Li/H}|_{\mathrm{p}} = (1.6 \pm 0.3) \times 10^{-10}$$

Sbordone et al, A&A 2010



$$[\mathrm{Fe/H}] \equiv \log_{10}[(\mathrm{Fe/H})/(\mathrm{Fe/H})_{\odot}]$$

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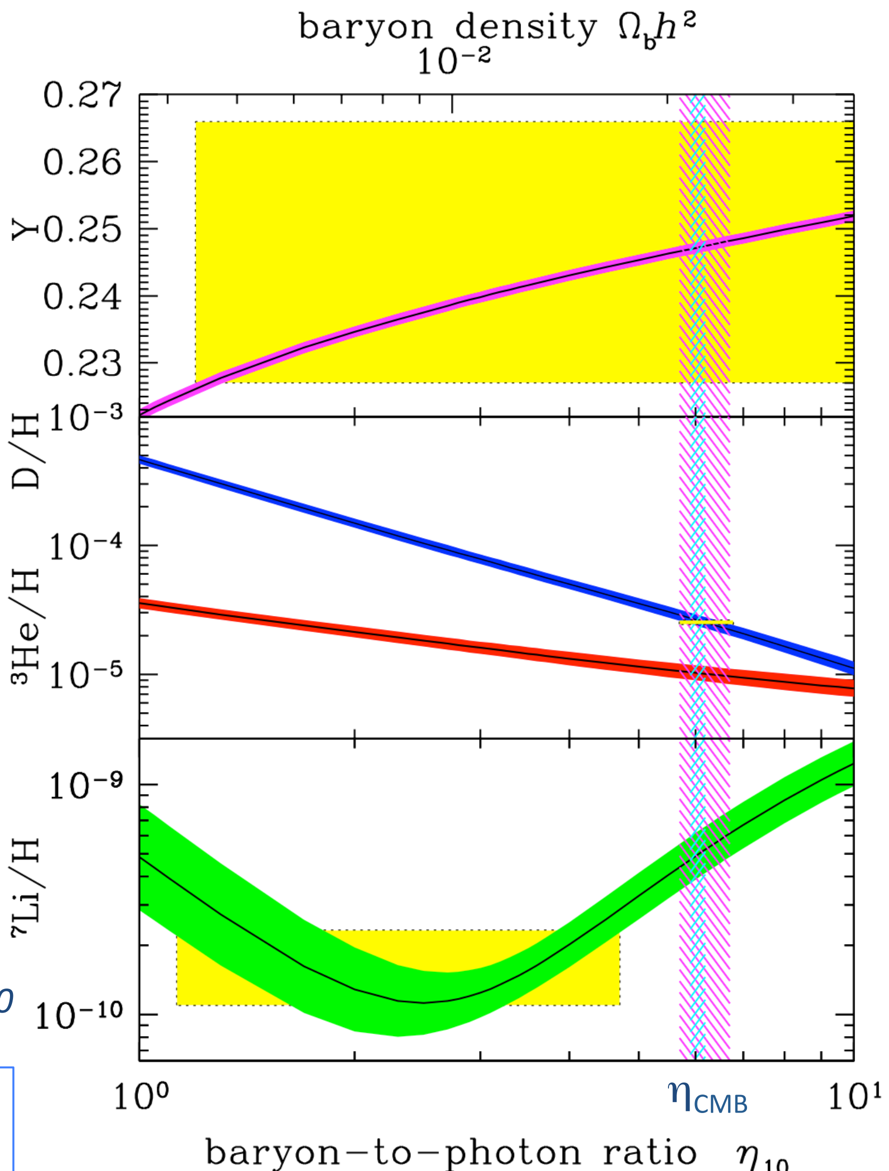


The Lithium-7 problem:

Observational values are factor 3 lower than required to obtain concordance

Primordial nucleosynthesis of CNO (and other) elements

(from Coc et al., JCAP 2014; see also Iocco et al. JCAP 2007)

Primordial abundance of ^{6}Li:

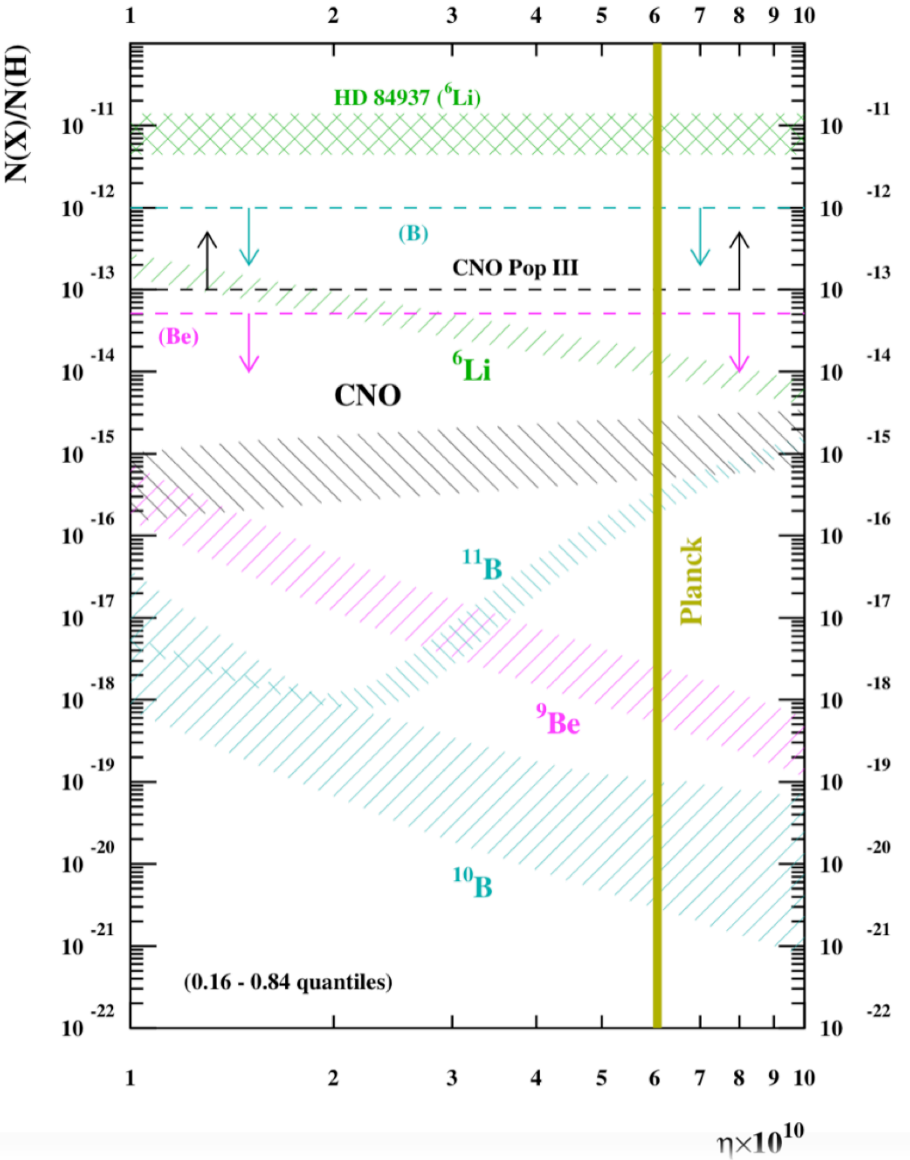
$$^6\mathrm{Li/H} = (0.9 - 1.8) \times 10^{-14}$$

Error budget dominated by D(α,γ)^{6}Li reaction recently measured by LUNA

The claim of ^{6}Li/H plateau at 10^{-11} has not been confirmed

Primordial abundance of CNO is at the level of:

$$\mathrm{CNO/H} = (5 - 30) \times 10^{-16}$$



^{7}Li synthesis

At $\eta = 6 \times 10^{-10}$, ^{7}Li is mainly produced from ^{7}Be (e^-+^{7}Be→ ^{7}Li + ν_e at "late" times):

$$Y_{\rm Li} \sim Y_{\rm Be} \sim \left.\frac{C_{\rm Be}}{D_{\rm Be}}\right|_{T=T_{\rm Be,f}}$$

$T_{\rm Be,\,f} \approx 50$ keV

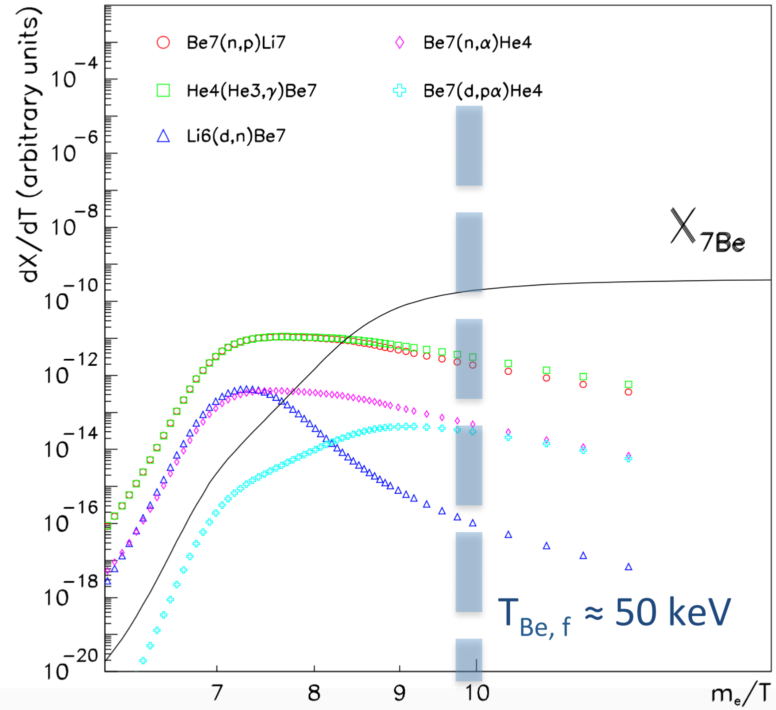
The dominant ^{7}Be production mechanism is through the reaction ^{3}He(α,γ)^{7}Be

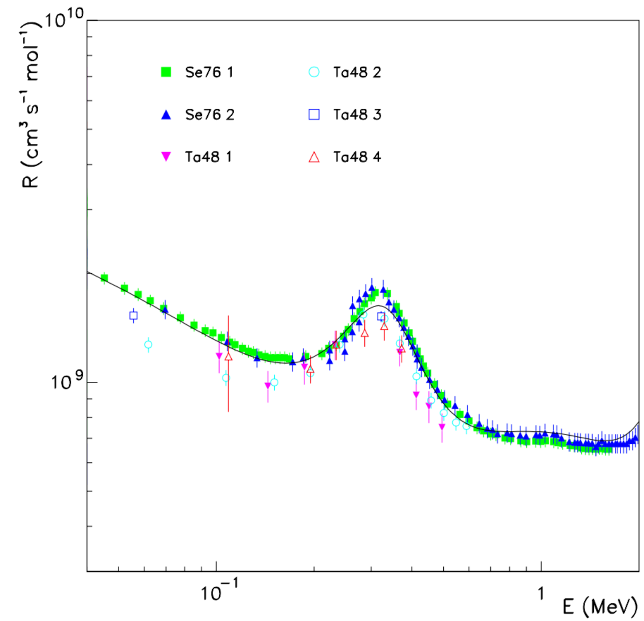
→ Studied in detail both experimentally (LUNA) and theoretically. The cross section is known to 7% uncertainty.

The dominant ^{7}Be destruction channel is through the process ^{7}Be(n,p)^{7}Li

→ Experimental data obtained from direct data and reverse reaction. R matrix fit to expt. data provide the reaction rate with 1% accuracy.

Serpico et al., 2004





A nuclear physics solution to the ^{7}Li problem?

A formalism to describe the response of ^{7}Li to a generic (temperature dependent) modification of the nuclear reaction rates.

Motivated by:

$$Y_{\rm Li} \sim Y_{\rm Be} \sim \left.\frac{C_{\rm Be}}{D_{\rm Be}}\right|_{T=T_{\rm Be,f}}$$

We write:

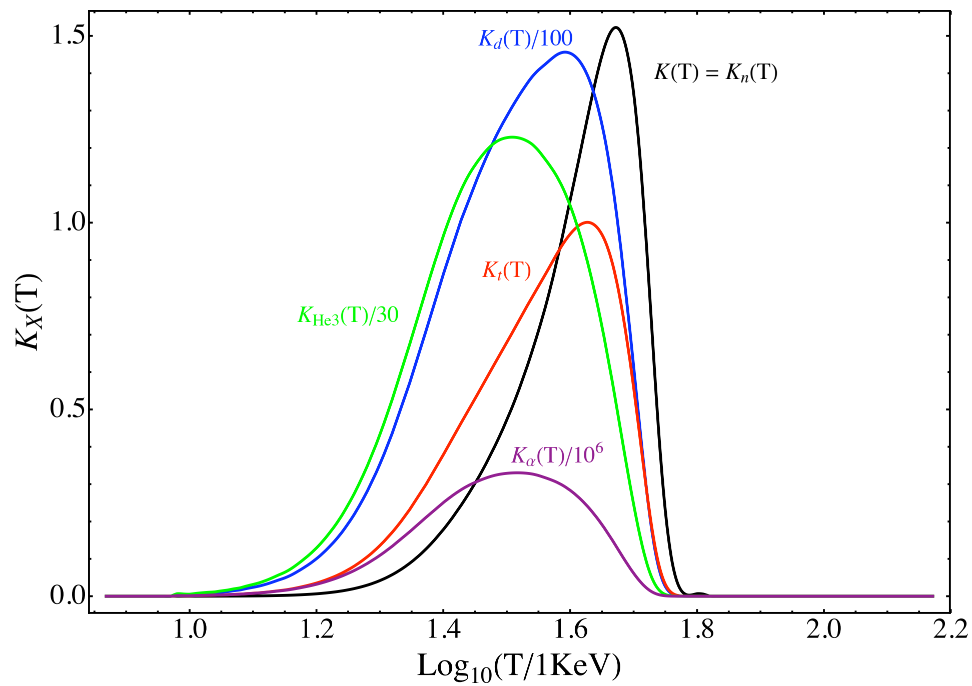
$$\delta X_{\rm Li} = \int \frac{dT}{T}\, K(T)\, \delta D_{\rm Be}(T)$$

where:

$$X_{\rm Li} = \frac{1}{Y_{\rm Li}}$$ → **inverse** ^{7}Li abundance

$$\delta X_{\rm Li} = \frac{X_{\rm Li}}{\overline{X}_{\rm Li}} - 1$$

$$\delta D_{\rm Be}(T) = \frac{D_{\rm Be}(T)}{\overline{D}_{\rm Be}(T)} - 1$$



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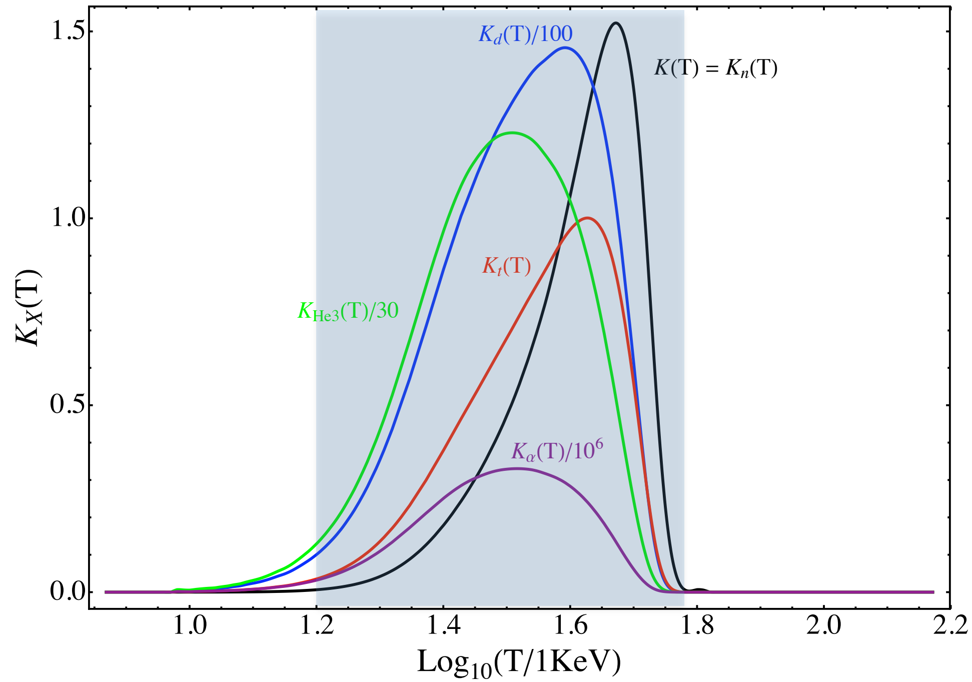


$$T \simeq 10 - 60\ {\rm keV}$$

Based on Broggini, Canton, Fiorentini, FLV, 2012

The ^{7}Li synthesis – the role of different channels

$$\delta D_{\rm Be}(T) = \frac{D_{\rm Be}(T)}{\overline{D}_{\rm Be}(T)} - 1$$

Considering that:

$$\begin{aligned} \overline{D}_{\rm Be}(T) &\simeq n_{\rm B}\,\overline{Y}_{\rm n}(T)\,\langle\overline{\sigma}_{\rm np}v\rangle_T \\ D_{\rm Be}(T) &= n_{\rm B}\sum_a Y_a(T)\,\langle\sigma_a v\rangle_T \end{aligned}$$

$\overline{\sigma}_{\rm np}$ = cross section of $^{7}{\rm Be} + n \rightarrow {}^{7}{\rm Li} + p$

Dominant ^{7}Be destruction channel (97% of the total)

$\sigma_{\rm a}$ = cross section of $^{7}{\rm Be} + a \rightarrow$ anything

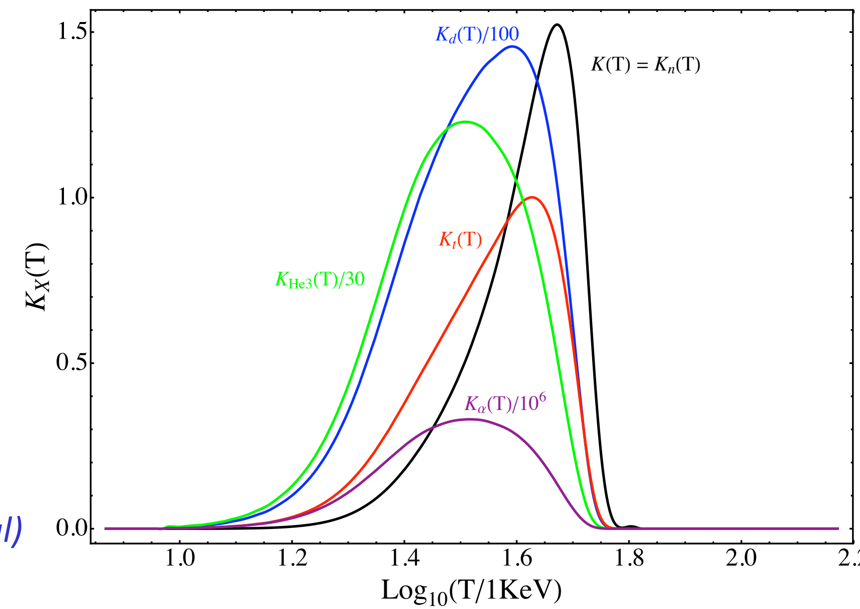
Indicates a generic additional ^{7}Be destructing process

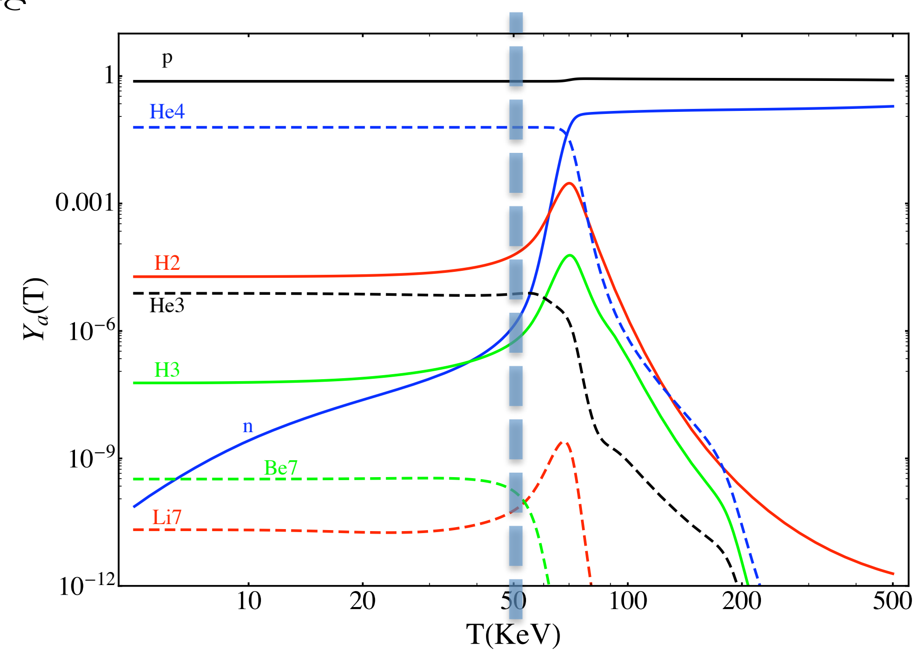
One obtain:

$$\delta X_{\rm Li} = \sum_a \int \frac{dT}{T}\,K_a(T)\,\frac{\langle\sigma_a v\rangle_T}{\langle\overline{\sigma}_{\rm np}v\rangle_T}$$

where:

$$K_a(T) = K(T)\frac{\overline{Y}_a(T)}{\overline{Y}_{\rm n}(T)}$$





The requirements to solve the ^{7}Li problem

$$R_a \equiv \frac{\langle \sigma_a v \rangle_T}{\langle \overline{\sigma}_{\rm np} v \rangle_T} \quad at \quad T \simeq 10 - 60\,\text{keV}$$

To obtain a reduction of the ^{7}Li abundance by a factor 2 or more:

- $R_{\rm n} \geq 1.5$ for additional reactions in the $^7\text{Be} + n$ channel
- $R_d \geq 0.01$ for reactions in the $^7\text{Be} + d$ channel
- $R_t \geq 1.5$ for reactions in the $^7\text{Be} + t$ channel
- $R_{\rm He3} \geq 0.03$ for reactions in the $^7\text{Be} + {}^3\text{He}$ channel
- $R_{\rm He4} \geq 4 \times 10^{-6}$ for reactions in the $^7\text{Be} + {}^4\text{He}$ channel

Suppressed by Coulomb barrier (for the d, t, ^{3}He and ^{4}He channels)

Note that:

The cross section of ^{7}Be(n,p)^{7}Li reaction is extremely large

$\sigma_{\rm np}(50\text{keV}) \simeq 9\,\text{barn}$ *Comparable with unitarity bound*

The (^{7}Be+n) channel

$$^7\mathrm{Be}(n,p)^7\mathrm{Li}$$

- ✓ Dominant contribution to ^{7}Be destruction (97%). Very well studied;
- ✓ Data obtained either from direct measurements or from reverse reaction;
- ✓ R-matrix fits to expt. data determine the reaction rate with ≈ **1% accuracy;**
- ✓ Extremely large cross section (*close to unitarity bound*).

$$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$$

- ✓ **No experimental data** exist in the BBN energy range;
- ✓ Upper limit $\sigma_{n\alpha}$ < 1mb at thermal energies from Bassi et al 1963;
- ✓ Old estimate from Fowler (1967) used in BBN codes (with factor 10 uncertainty);
- ✓ Second most important contribution to ^{7}Be destruction (2.5 %);
- ✓ (One of the) largest contribution to ^{7}Li error budget;

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It is unlikely that $^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$ can become comparable to $^7\mathrm{Be}(n,p)^7\mathrm{Li}$ …

Due to parity conservation of strong interactions:

- $^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$ requires p-wave (l=1) collision;

$$\sigma_{\mathrm{n}\alpha}/\sigma_{\mathrm{np}} \sim T_1/T_0 \sim 2\,\mu\,E\,R^2 \leq 0.2$$
$$(E = 50 \text{ keV};\ R = 10 \text{ fm})$$

- The ^{8}Be excited states relevant for $^7\mathrm{Be}(n,p)^7\mathrm{Li}$ do not have an α exit channel.

… but a measure at BBN energies would be extremely useful

Other relevant ^{7}Be destruction channel?

Possible only if new unknown resonances (^{7}Be + a → C^{*} → b + Y) are found:

Bretit-Wigner expression

$$\sigma = \frac{\pi\,\omega}{2\mu\,E}\frac{\Gamma_{\rm in}\Gamma_{\rm out}}{(E-E_r)^2+\Gamma_{\rm tot}^2/4}$$

$$\begin{aligned} E_r &= \text{resonance energy} \\ \Gamma_{\rm in} &= \text{width of the entrance channel} \\ \Gamma_{\rm out} &= \text{width of the exit channel} \\ \Gamma_{\rm tot} &= \Gamma_{\rm in} + \Gamma_{\rm out} + \ldots \end{aligned}$$

$$\omega = \frac{2J_{C^*}+1}{(2J_a+1)(2J_7+1)}$$

The resonance width $\Gamma_{\rm in}$ (and $\Gamma_{\rm out}$) can be expressed as the product:

$$\Gamma_{\rm in} = 2P_l(E,R)\;\gamma_{\rm in}^2,$$

Penetration factor

$$P_l(E,R) \equiv kR\,\nu_l$$

The reduced width γ_{in}^2 has to be smaller than :

$$\gamma_{\rm in}^2 \leq \gamma_{\rm W}^2 = \frac{3}{2\mu R^2}$$

γ_W^2 = Wigner limiting width

Naively:

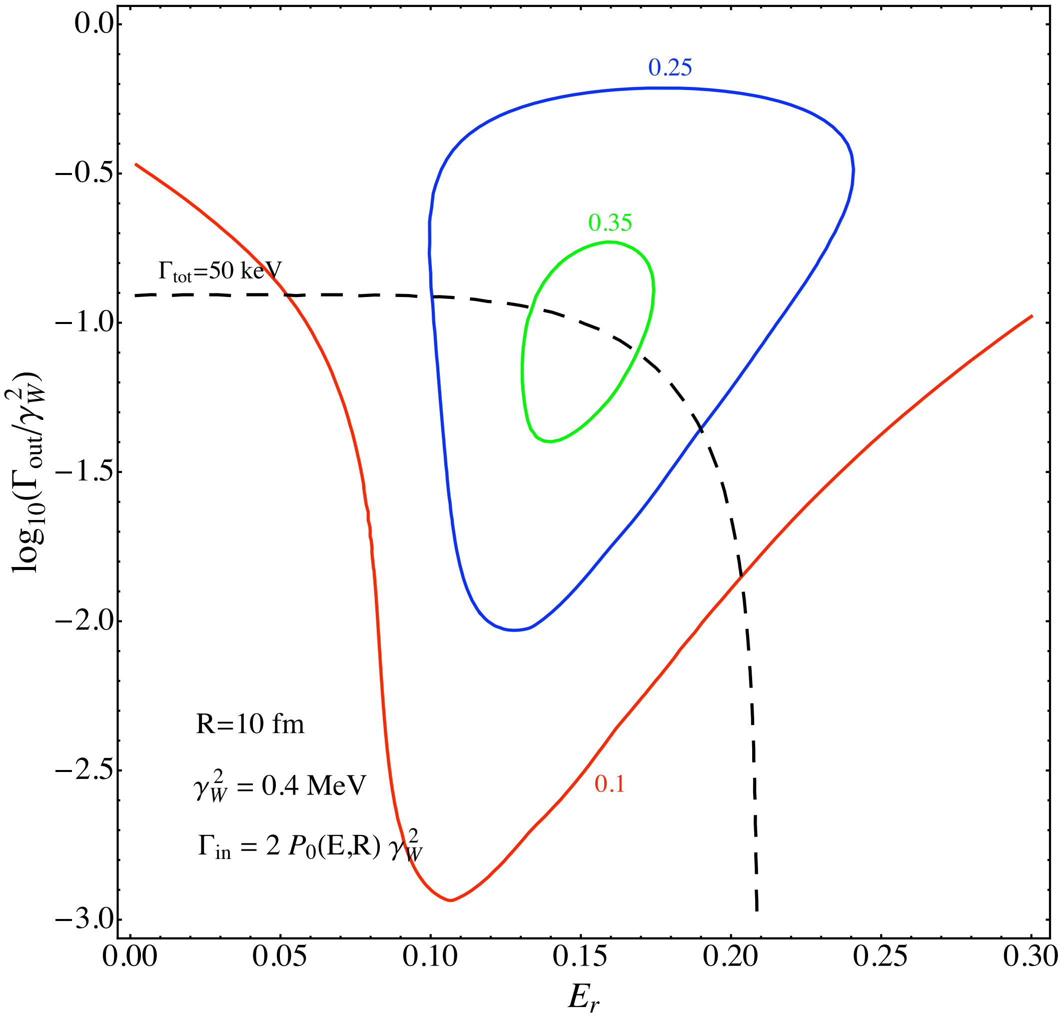
$$\gamma_{\rm in}^2 \sim f \sim \frac{v}{R} \;\; \text{with} \;\; v \sim \frac{P}{\mu} \sim \frac{1}{R\mu}$$

(^{7}Be + d) entrance channel

Iso-countours for: $$\delta Y_{\mathrm{Li}} = 1 - \frac{Y_{\mathrm{Li}}}{\overline{Y}_{\mathrm{Li}}}.$$

Suggested as a solution of the ^{7}Li problem by Coc et al. 2004 and Cyburt et al. 2012.

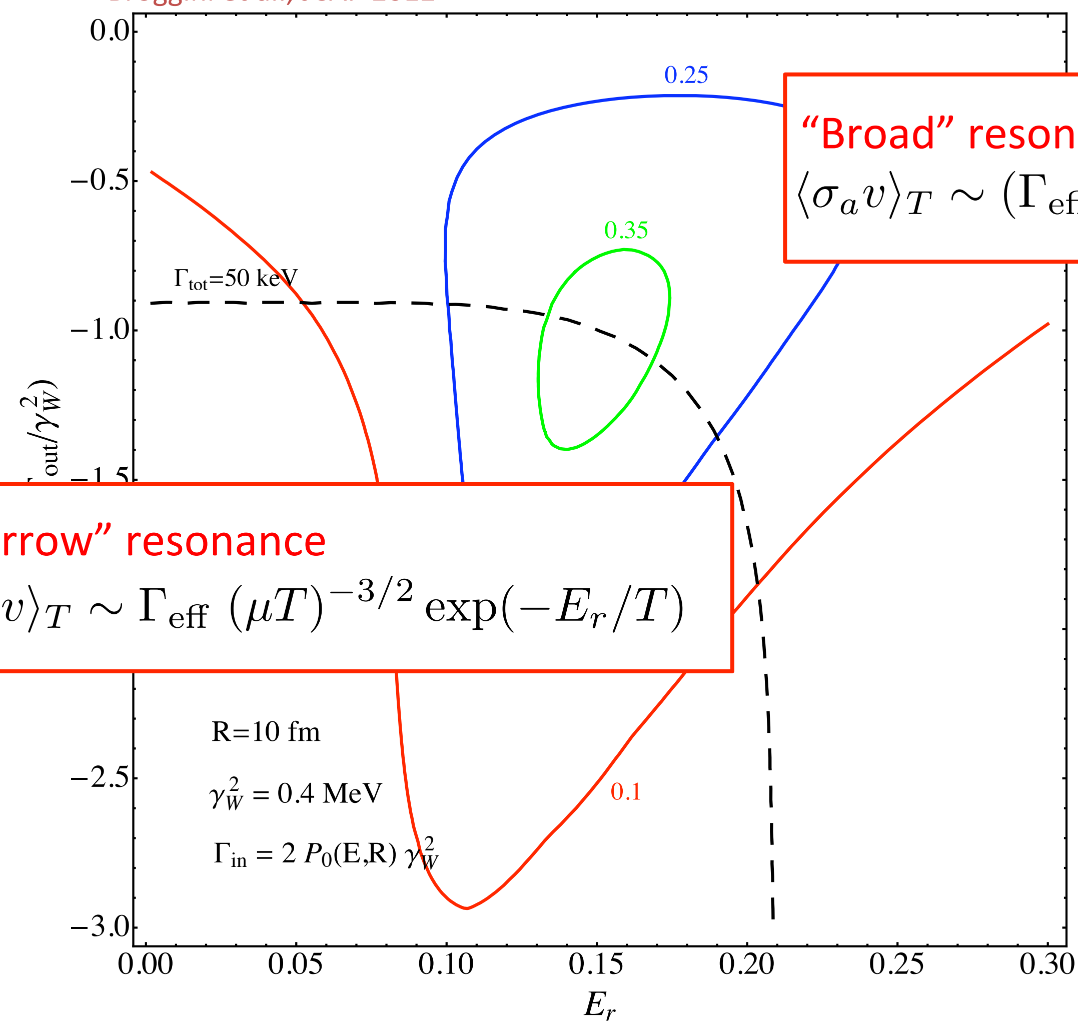
See also Angulo et al. 2005.



^{7}Be + d entrance channel

Note that: it exists a "maximal achievable reduction of ^{7}Li":

Broggini et al., JCAP 2012



"Broad" resonance

$$\langle \sigma_a v \rangle_T \sim (\Gamma_{\rm eff}/\Gamma_{\rm tot})\ \mu^{-1/2}\ T^{-3/2}$$

"Narrow" resonance

$$\langle \sigma_a v \rangle_T \sim \Gamma_{\rm eff}\ (\mu T)^{-3/2} \exp(-E_r/T)$$

$$\Gamma_{\rm eff} = \frac{\Gamma_{\rm in}\Gamma_{\rm out}}{\Gamma_{\rm tot}}$$

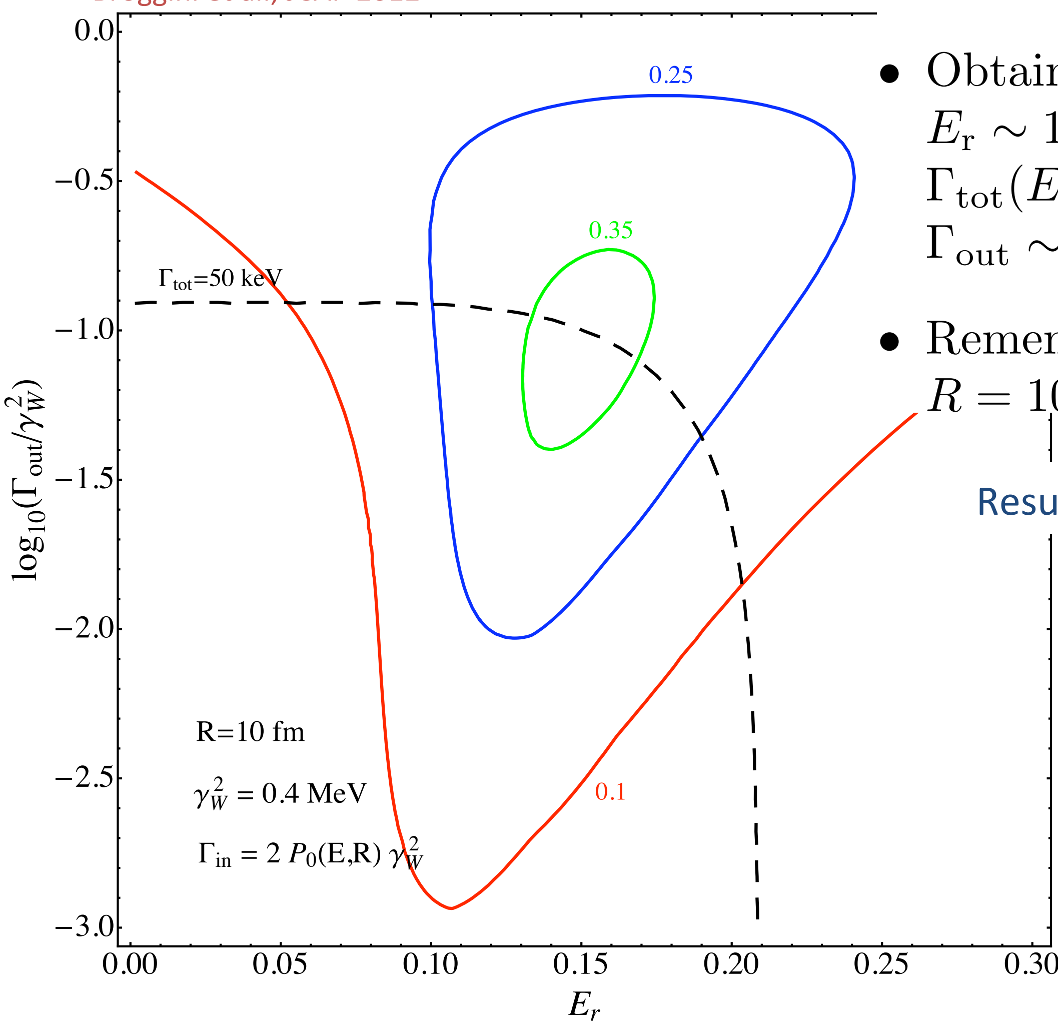
(^{7}Be + d) entrance channel

Suggested as a solution of the ^{7}Li problem by Coc et al. 2004 and Cyburt et al. 2012.

See also Angulo et al. 2005.

Iso-countours for: $\delta Y_{\rm Li} = 1 - \frac{Y_{\rm Li}}{\overline{Y}_{\rm Li}}.$

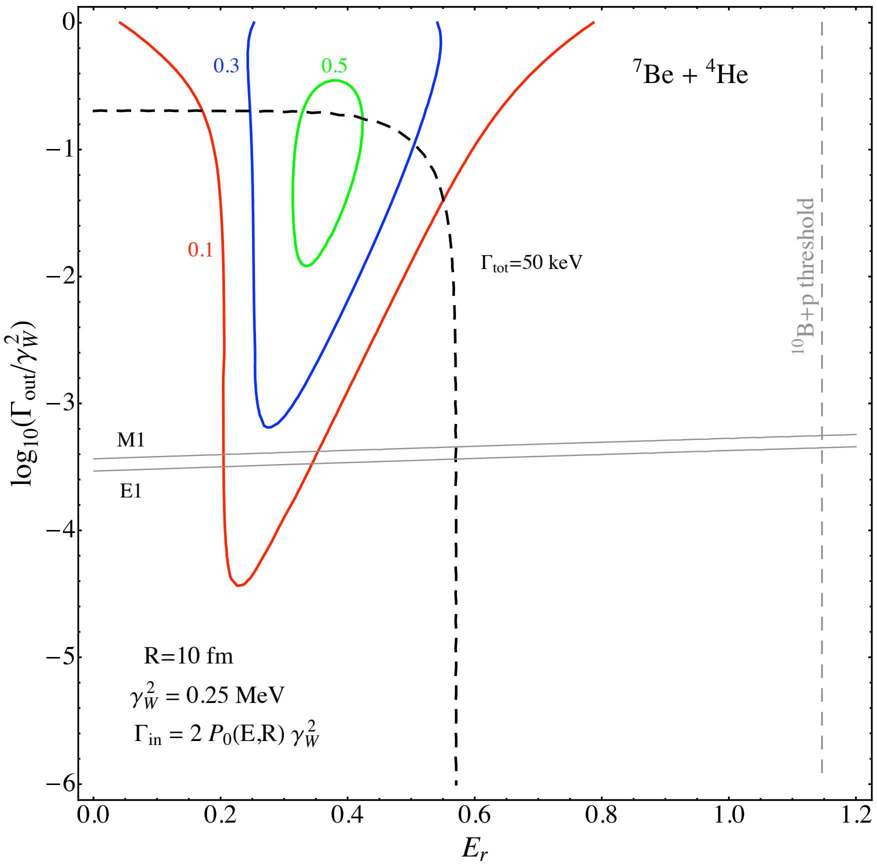
Broggini et al., JCAP 2012



- Maximum achievable reduction $\sim 40\%$
- Obtained for:
  $E_{\rm r} \sim 150$ keV
  $\Gamma_{\rm tot}(E_r, R) \sim 45\,{\rm keV}$
  $\Gamma_{\rm out} \sim 35\,{\rm keV}$ and $\Gamma_{\rm in}(E_r, R) \sim 10\,{\rm keV}$
- Remember:
  $R = 10$ fm

Results consistent with Cyburt et al. 2012

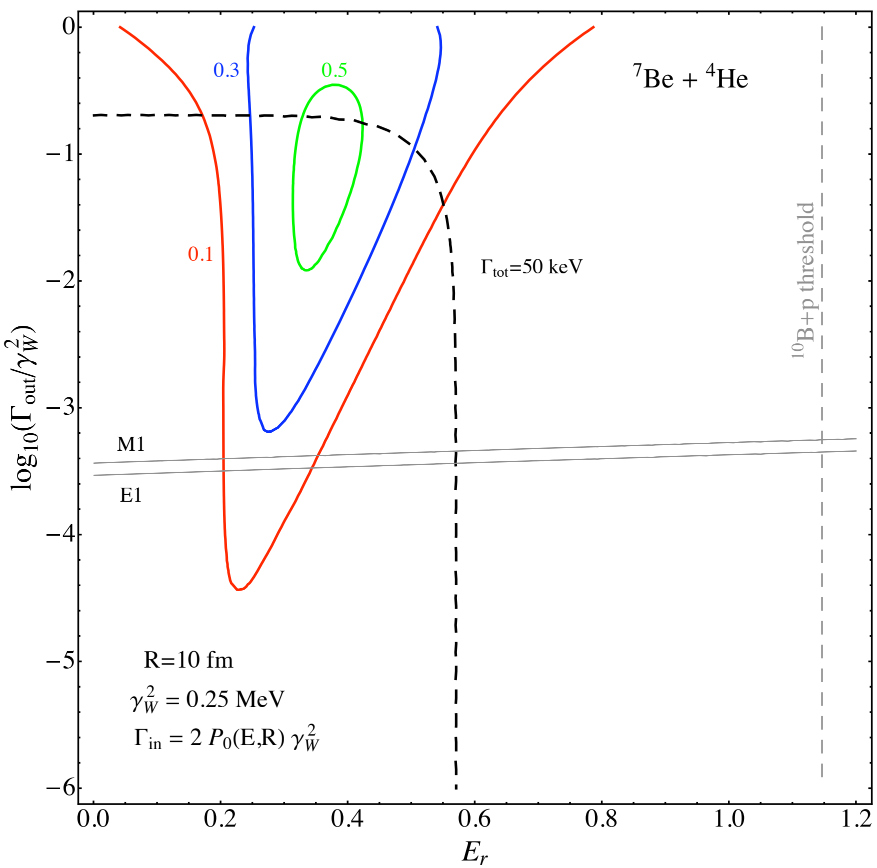
(^{7}Be + ^{4}He) entrance channel



- Maximum achievable reduction $\sim 55\%$
- Obtained for:
  $E_r \sim 360$ keV
  $\Gamma_{tot}(E_r, R) \sim 21$ keV
  $\Gamma_{out} \sim 19$ keV and $\Gamma_{in}(E_r, R) \sim 1.5$ keV.
- Strong Coulomb suppression compensated by the fact that the $\alpha/n \sim 10^6$

(^7Be + ^4He) entrance channel

Broggini et al., JCAP 2012



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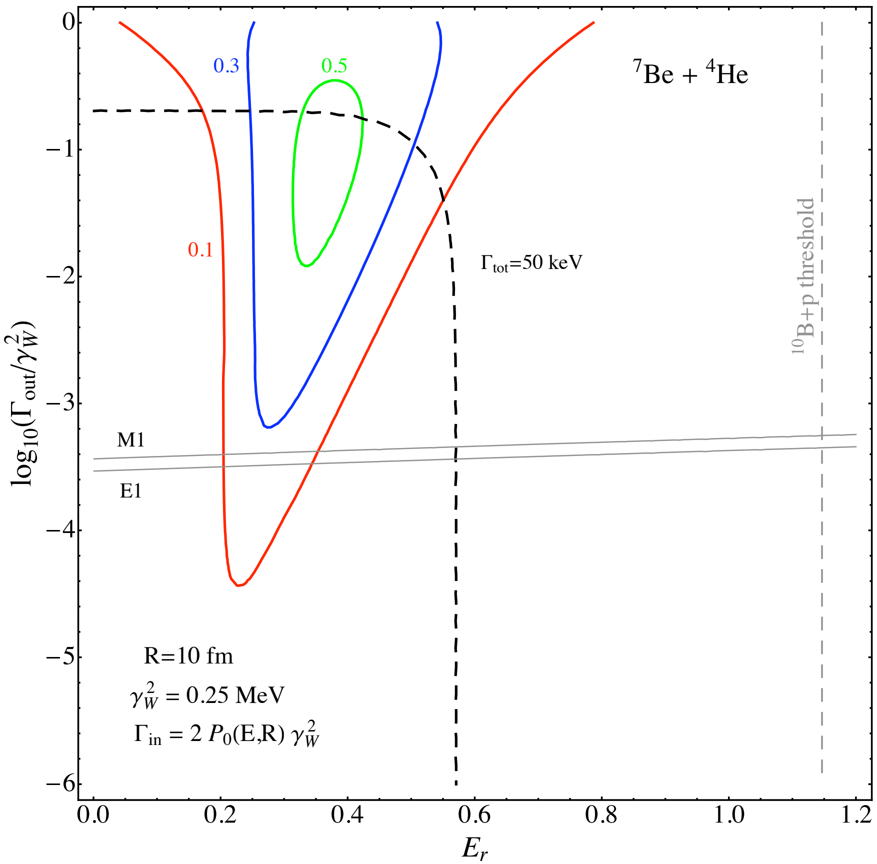
However:

- For $E_r \leq 1.15$ MeV, no particle exit channels for the coumpound nucleus ^{11}C
- Only possible electromagnetic transitions: $\Gamma_{out} \leq 100$ eV

(^{7}Be + ^{4}He) entrance channel

Broggini et al., JCAP 2012



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However:

- For $E_r \leq 1.15$ MeV, no particle exit channels for the coumpound nucleus ^{11}C
- Only possible electromagnetic transitions: $\Gamma_{out} \leq 100$ eV

Taking this into account:

- Maximum achievable reduction: $\sim 25\%$
- Obtained for:
  $E_r \sim 270$ keV
  $\Gamma_{tot}(E_r, R) \sim 160$ eV
  $\Gamma_{out} \sim 100$ eV and $\Gamma_{in}(E_r, R) \sim 60$ eV

The experimental situation

^{7}Be + d

- It exists an excited state in ^{9}B at 16.71 MeV ($E_r = 220$ keV)
- Ruled out as a solution of the cosmic ^{7}Li problem by **Kirsebom et al. 2011**
- A non negligible suppression requires the existence of a new (not yet discovered) excited state of ^{9}B around $E_r \sim 150\,$keV.
- **O'Malley et al. 2011** analyzed this possibility. The data show no evidence and allow to set an upper limit on the total resonance width at the level of $\sim 1\,$keV.

^{7}Be +^{4}He (and ^{7}Be + ^{3}He)

- **Hammache et al. 2013** studied ^{10}C and ^{11}C via the reactions $^{10}\mathrm{B}(^{3}\mathrm{He}, t)^{10}\mathrm{C}$ and $^{11}\mathrm{B}(^{3}\mathrm{He}, t)^{11}\mathrm{C}$.
- The results do not support $^{7}\mathrm{Be} +^{3}\mathrm{He}$ and $^{7}\mathrm{Be} +^{4}\mathrm{He}$ as possible solutions for the 7Li problem.

In conclusion

The cosmic lithium problem is still open:

- the possibility of a nuclear physics solution is unlikely in light of the recent theoretical analysis and experimental efforts (note, however, that $^7Be(n,\alpha)^4He$ still not measured at BBN energies).

Other possible solutions:

- ^7Li destruction (depletion) in stars favored by diffusion, rotationally induced mixing, or pre-main-sequence depletion → generally requires ad hoc mechanism and fine tuning of stellar parameters

- New physics effects that decrease the promordial ^7Li (^7Be) production:

    - non standard neutron sources (produced by decay, annihilation, oscillations);
    - non extensive statistics;
    - time variation of the fundamental constants;
    - .....

Note that: these scenarios are generally constrained by interplay between D and ^7Li (D overproduction)

Additional slides

Useful relations about nuclear reactions:

The partial reaction cross section of a generic process ^{7}Be + a cannot be larger than:

$$\sigma_{\max} = (2l+1)\,\frac{\pi}{k^2} = (2l+1)\,\frac{\pi}{2\mu\,E}$$

$$\left\{\begin{array}{lcl} l & = & \text{angular momentum} \\ \mu & = & \text{reduced mass} \\ E & = & \text{energy (CoM)} \end{array}\right.$$

Low-energy reactions are suppressed due tunnelling through the Coulomb and/or centrifugal barrier. Modelling the interaction potential by a square well with a radius R:

$$\sigma_C = \sigma_{\max}\, T_l$$

Transmission coeff. (low energy)

$$T_l = \frac{4k}{K}\, v_l$$

$$\left\{\begin{array}{lcl} k & = & \text{relative momentum (outside)} \\ K & = & \text{relative momentum (inside)} \\ v_l & = & \text{penetration factor} \end{array}\right.$$

For neutrons:

$$\begin{array}{lcl} v_0 & = & 1 \\ v_1 & = & \dfrac{x^2}{1+x^2} \\ & \cdots\cdots & \end{array}$$

$$x \equiv k\,R = \sqrt{2\mu\,E}\;R$$

For charged nuclei:

$$v_l = \frac{k_l(R)}{k}\;\exp\left[-2\int_R^{r_0} k_l(r)\,dr\right],$$

$$\left\{\begin{array}{lcl} r_0 & = & \text{class. distance closest approach} \\ k_l(r) & = & \sqrt{2\mu\,U_l(r) - k^2} \\ U_l(r) & = & \dfrac{Z_a Z_X e^2}{r} + \dfrac{l(l+1)}{2\mu r^2} \end{array}\right.$$

Other relevant ^{7}Be destruction channel?

Possible only if new unknown resonances are found. We rewrite Breit-Wigner :

$$\sigma_a = \frac{\pi\,\omega\,P_l(E,R)}{2\mu\,E}\,\frac{2\,\xi}{\left[(E-E_r)/\gamma_{\rm in}^2\right]^2+\left[2P_l(E,R)+\xi\right]^2/4} \qquad \xi \equiv \frac{\Gamma_{\rm out}}{\gamma_{\rm in}^2}$$

In order to maximise the cross section, we assume:

- $\gamma_{\rm in}^2 = \gamma_{\rm W}^2(R)$
- $\Gamma_{\rm tot} = \Gamma_{\rm in} + \Gamma_{\rm out}$
- s-wave entrance channel ($l = 0$)
- $J_{C^*} = J_a + J_{\rm Be}$, i.e. ω has the maximum value allowed by angular momentum conservation

With these assumptions:

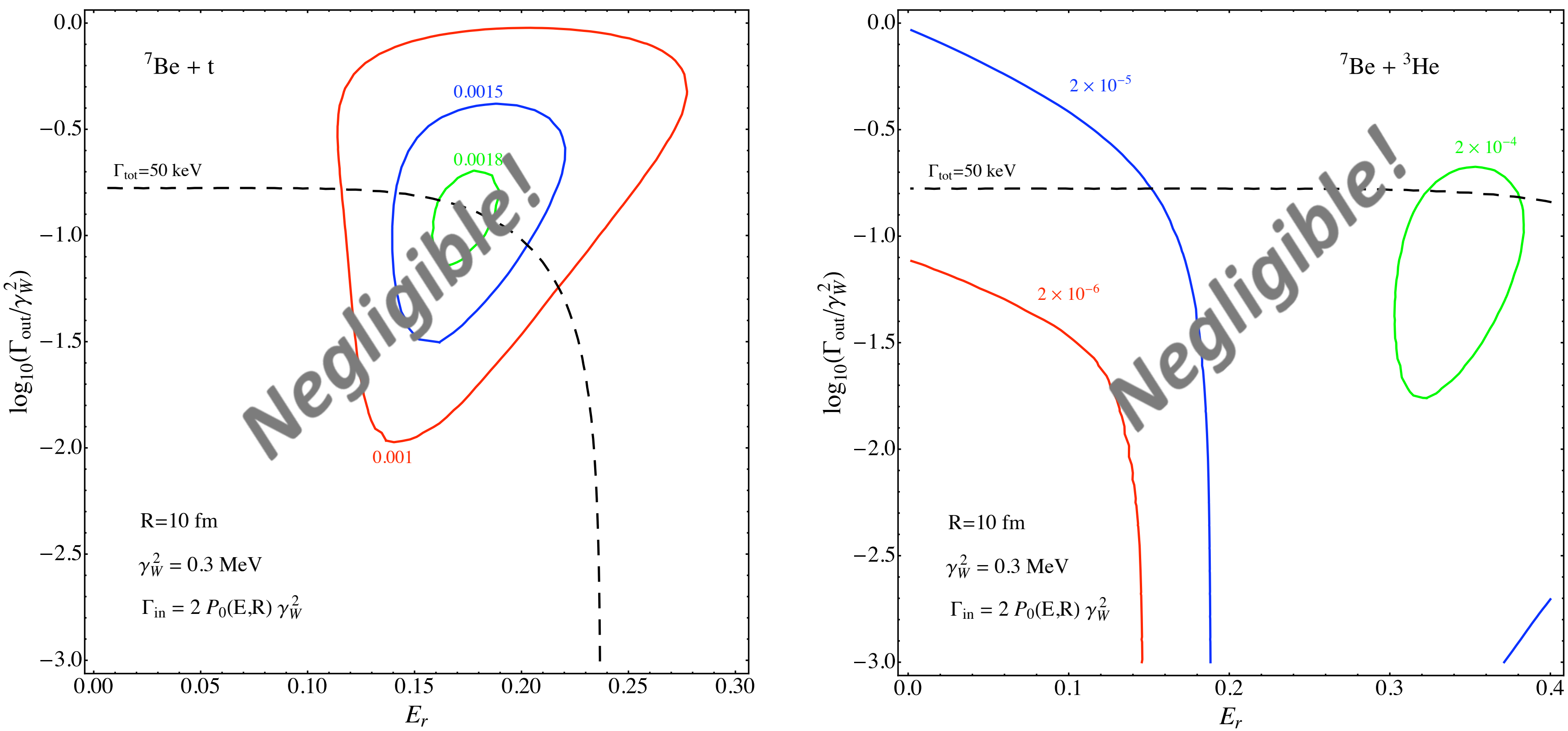
Free param.:

$$\sigma_a = \frac{\pi\,\omega\,P_0(E,R)}{2\mu\,E}\,\frac{2\xi}{\left[(E-E_r)/\gamma_{\rm W}^2(R)\right]^2+\left[2\,P_0(E,R)+\xi\right]^2/4}.$$

$$\left\{\begin{array}{l} E_r \\ \xi \equiv \dfrac{\Gamma_{\rm out}}{\gamma_{\rm in}^2}\end{array}\right.$$

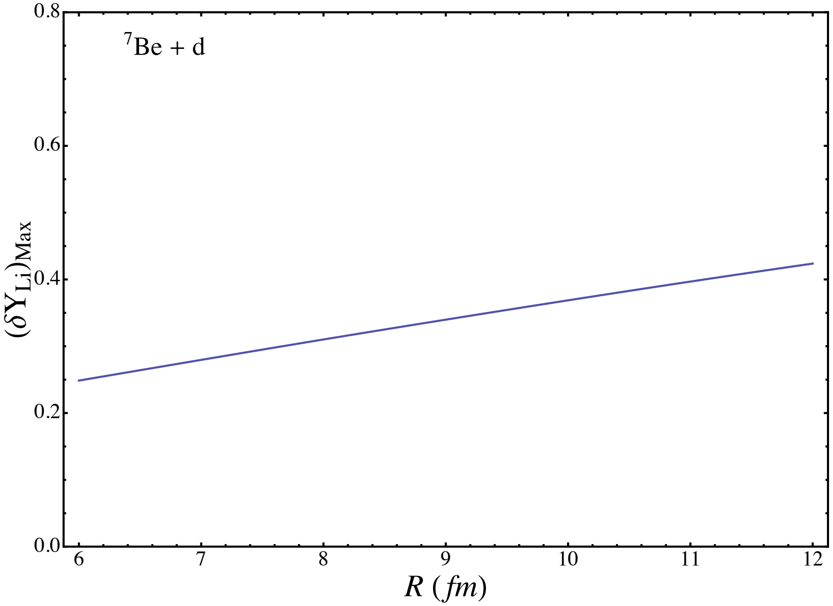
(^{7}Be + t) and (^{7}Be + ^{3}He) entrance channels

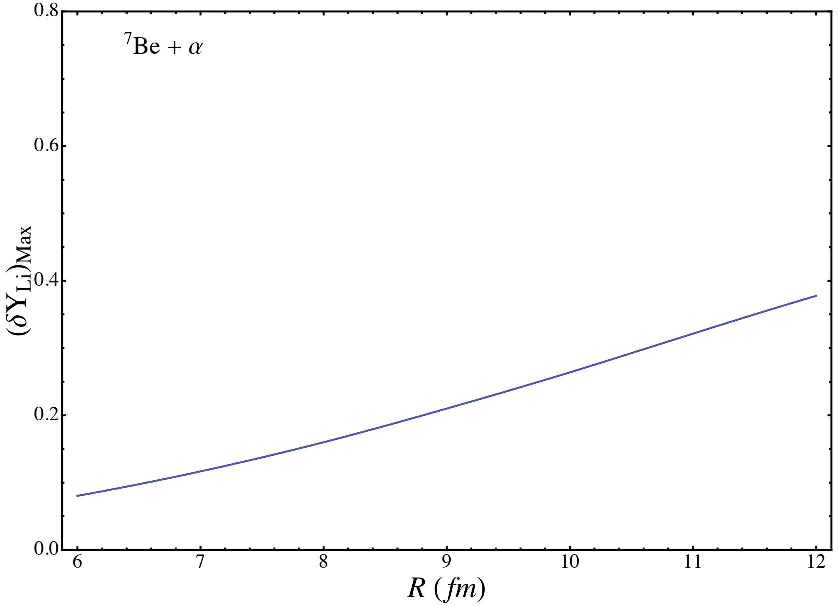
Proposed by Chakraborty, Fields and Olive 2011 as a solution:



Results of Chakraborty et al. 2011 are artifacts from using the narrow resonance approximation outside its regime of application

Dependence on the entrance channel radius





- The maximum achievable reduction $(\delta Y_{\mathrm{Li}})_{\max}$ is an increasing function of the assumed entrance channel radius R.
- Large values for R are needed to solve the cosmic ^{7}Li problem (much larger than the sum of the radii of the involved nuclei).