Cosmological and stellar nuclear processes

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Outline

- Big Bang Nucleosynthesis (BBN)

  $A \leq 8; \;\; T \sim 100\, keV; \;\; \rho \sim 10^{-3}\, g\, cm^{-3}$

- Nucleosynthesis in the Sun (and solar like) stars

  $A \leq 16; \;\; T \sim 1\, keV; \;\; \rho \sim 150\, g\, cm^{-3}$

The Physics of BBN

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

- Baryon density

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

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

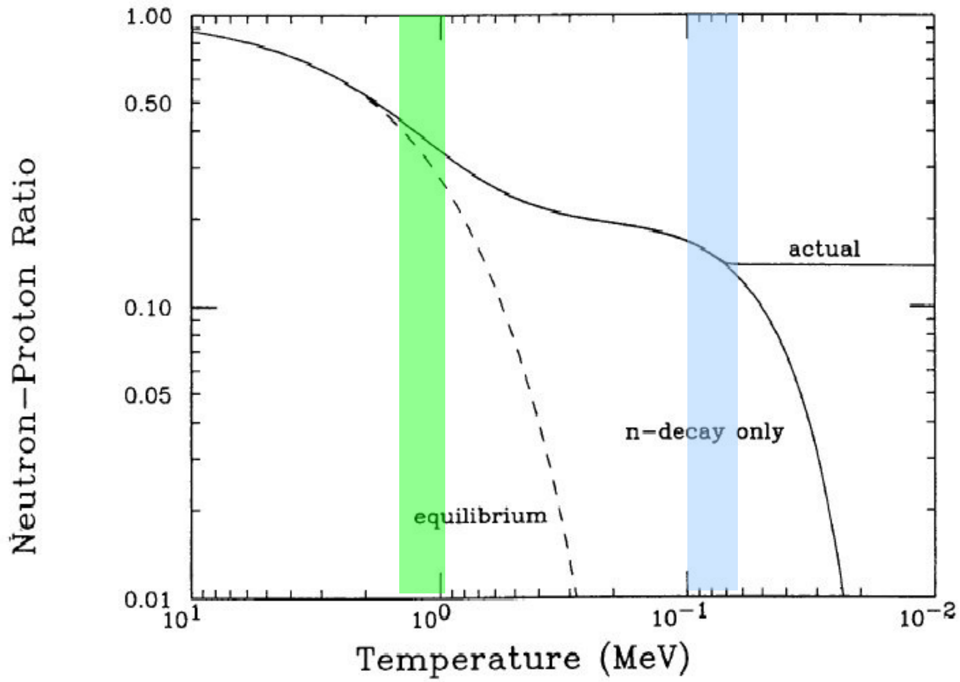
- Hubble expansion rate

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

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

Γ_W = Weak rate (ν_e +n ←→ p+e)

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



$H/\Gamma_W = 1$ → 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.

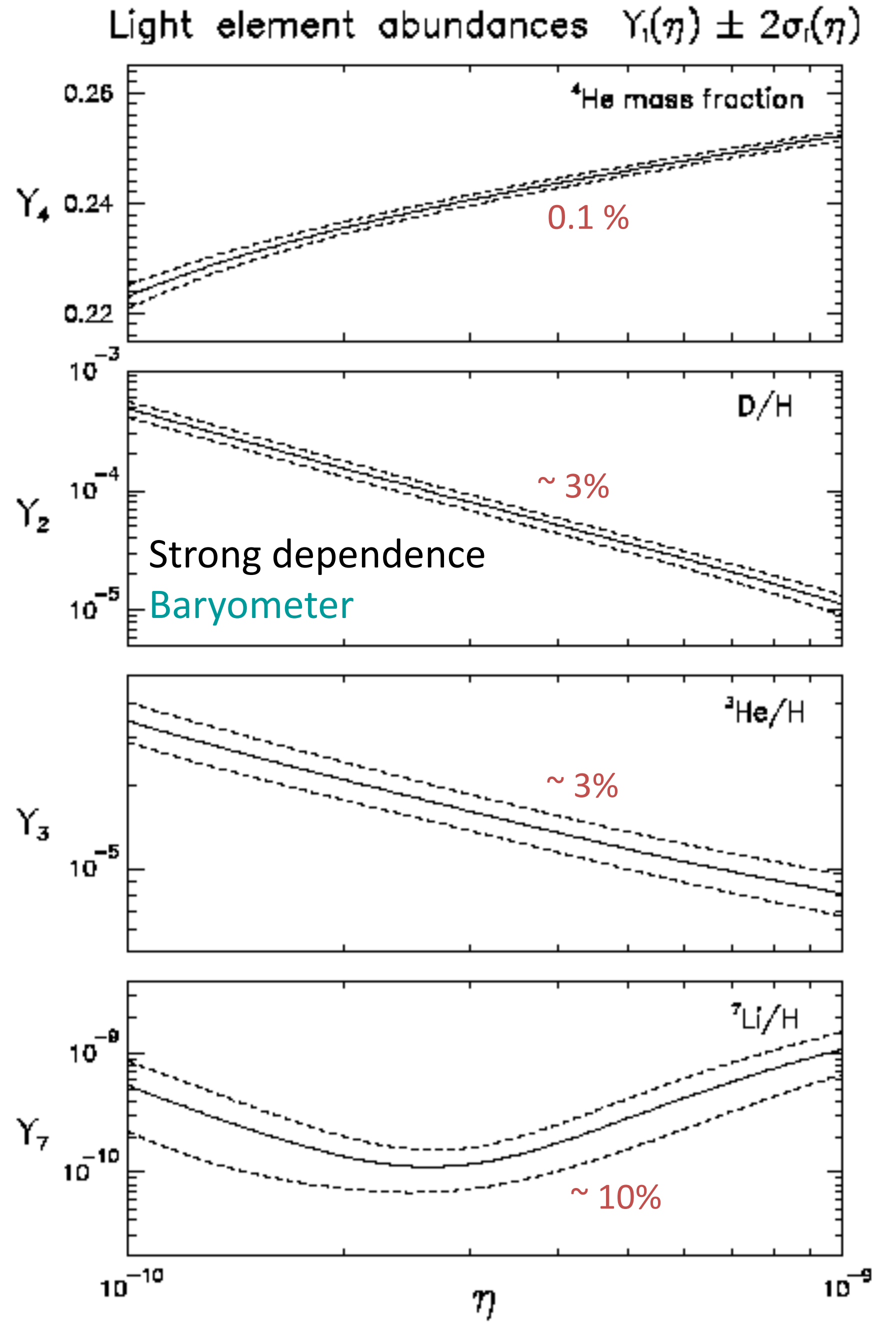
Accuracy of theoretical calculations

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).



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).

Theoretical uncertainties

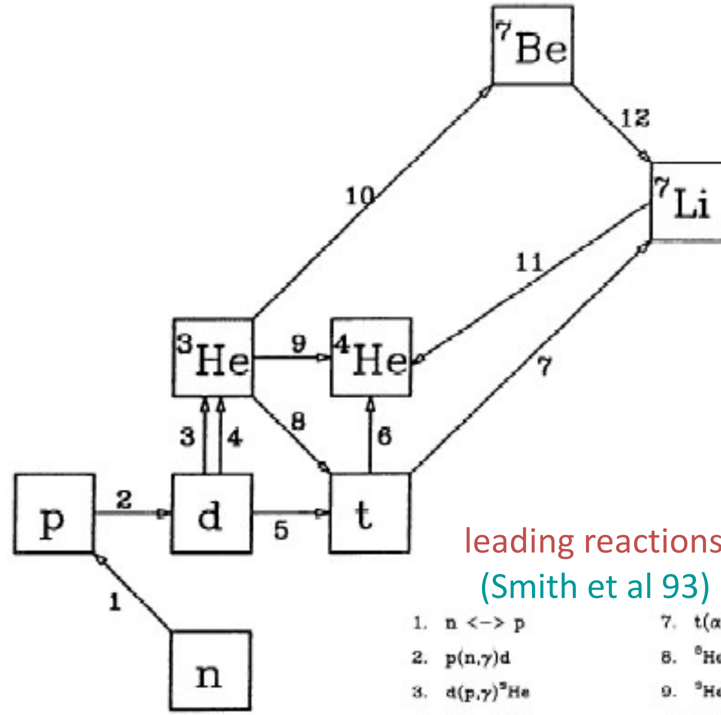
Reaction rate uncertainties translate into uncertainties in theoretical predictions:

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, Boyd et al 2010, Coc et al. 11,
Coc et al. 14, NACRE Coll. Database
SFIII → during 2024

Recent new data and evaluations
p(n,γ)D: Ando et al. 06
^{2}H(p,γ)^{3}He: Mossa et al. 2020
^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He: Leonard et al. 06, Pitrou et al 21, Pisanti et al 21, Yeh et al. 21
^{3}He(α,γ)^{7}Be: LUNA, Cyburt et al 08
^{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,γ)^{6}Li
^{6}Li(p,α)^{3}He
^{7}Be(n,α)^{4}He
^{7}Be(d,p)2 ^{4}He

The role of nuclear reactions

Leading reactions

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

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

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.

The role of nuclear reactions

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At η = 5 × 10^{-10}, ^{7}Li is mainly produced from ^{7}Be
(e^-+^{7}Be→ ^{7}Li + ν_e at "late" times):

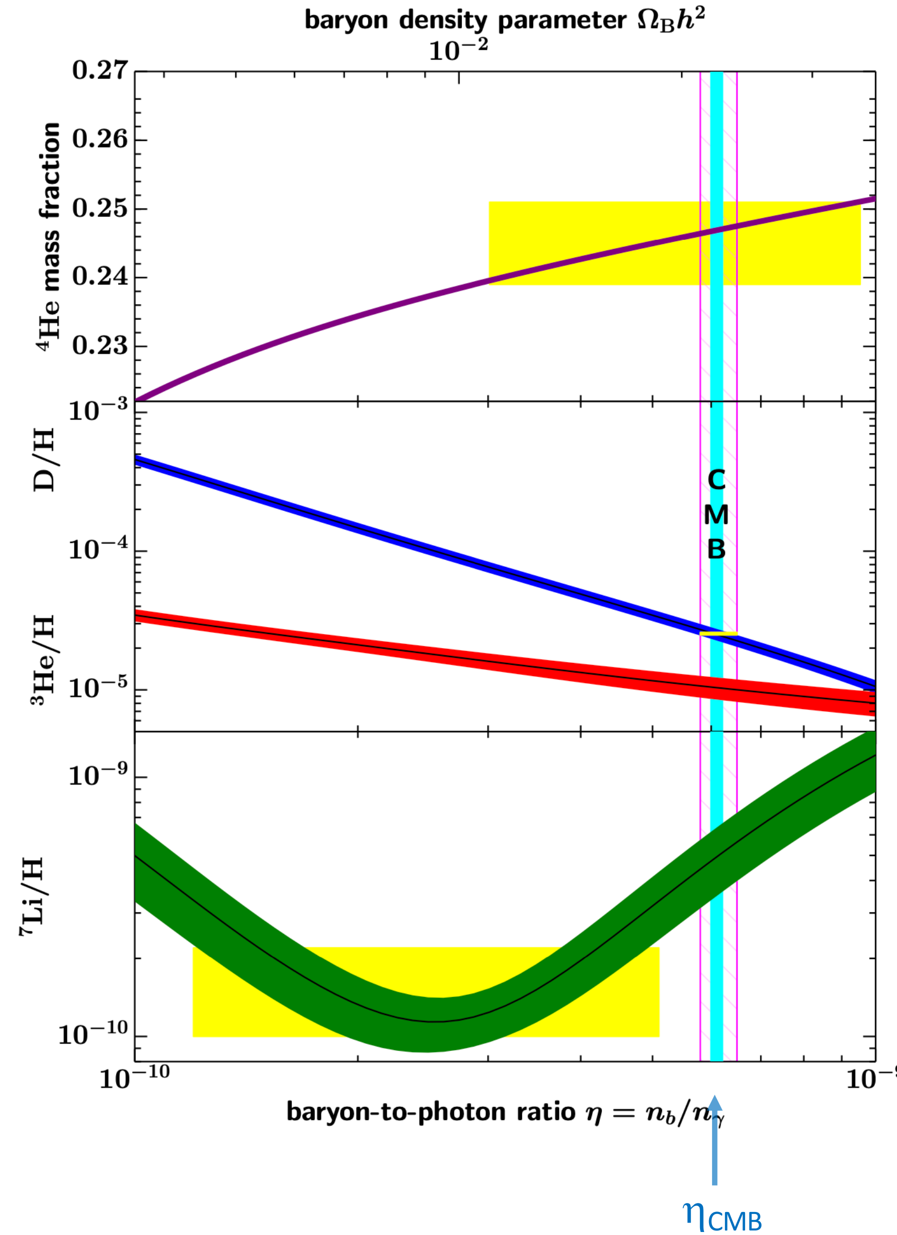
Note that: Sub-leading reactions give small log-derivatives but may be affected by large uncertainties and still contributes to the error budget.

Theory. vs. observations

PDG, 2023

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)

$$Y_p = 0.245 \pm 0.003$$



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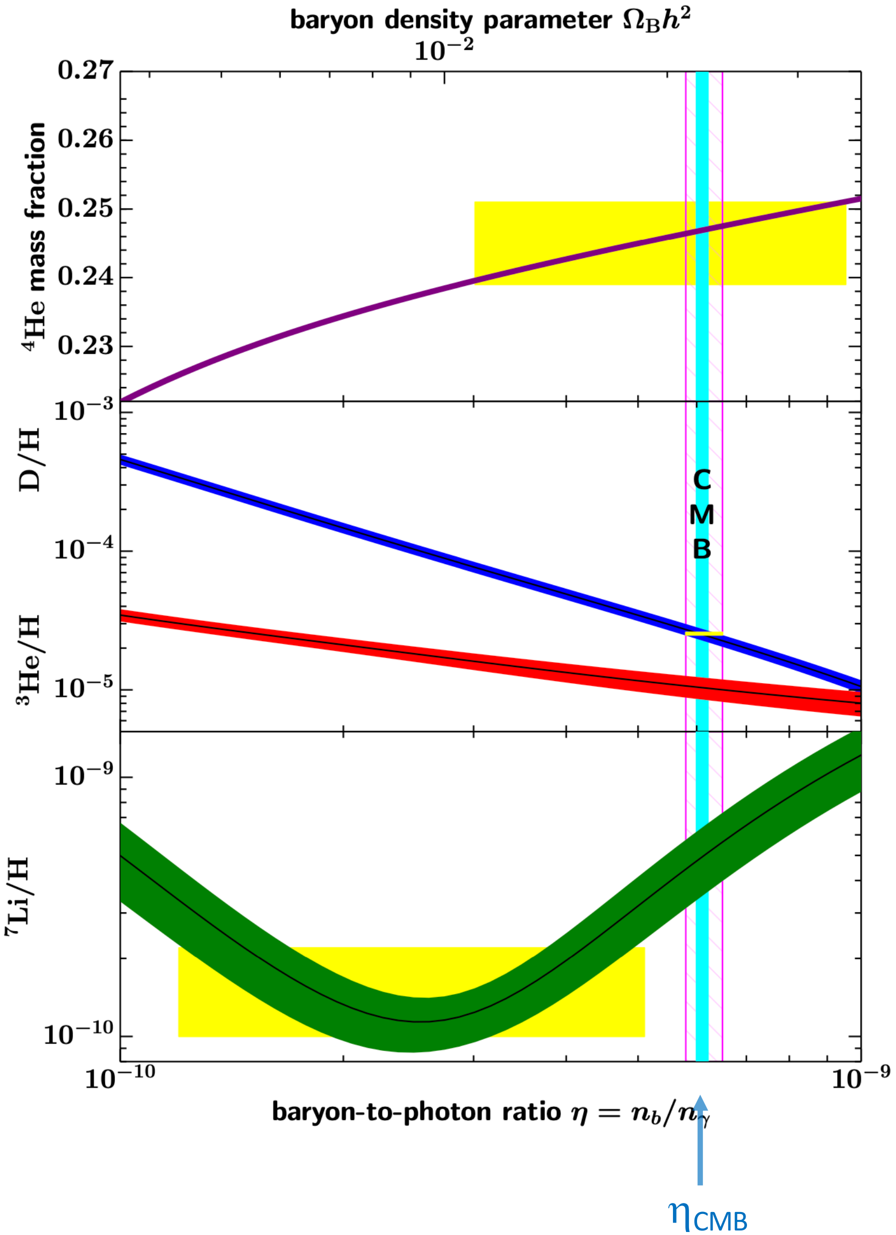
Deuterium: observed in the high-resolution spectra of QSO absorption systems at high redshift:

$$D/H\Big|_p \times 10^6 = (25.47 \pm 0.29)$$



Deuterium

The primordial abundance is obtained from the weighted mean of 11 most precise Ly-α systems:

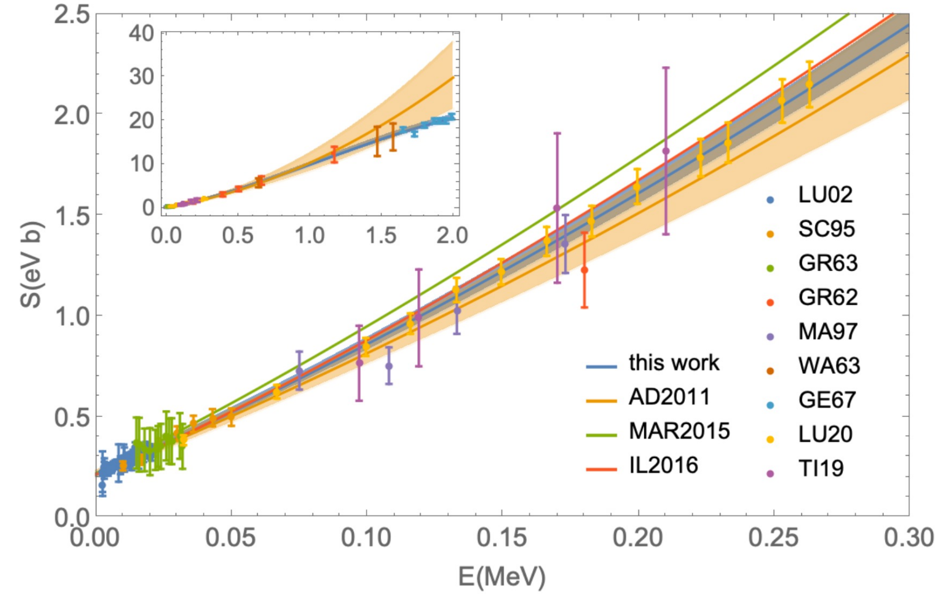
$$D/H\Big|_p \times 10^6 = (25.47 \pm 0.29)$$

N.B. The accuracy of exp. determination (1%) is better than that of theoretical predictions.

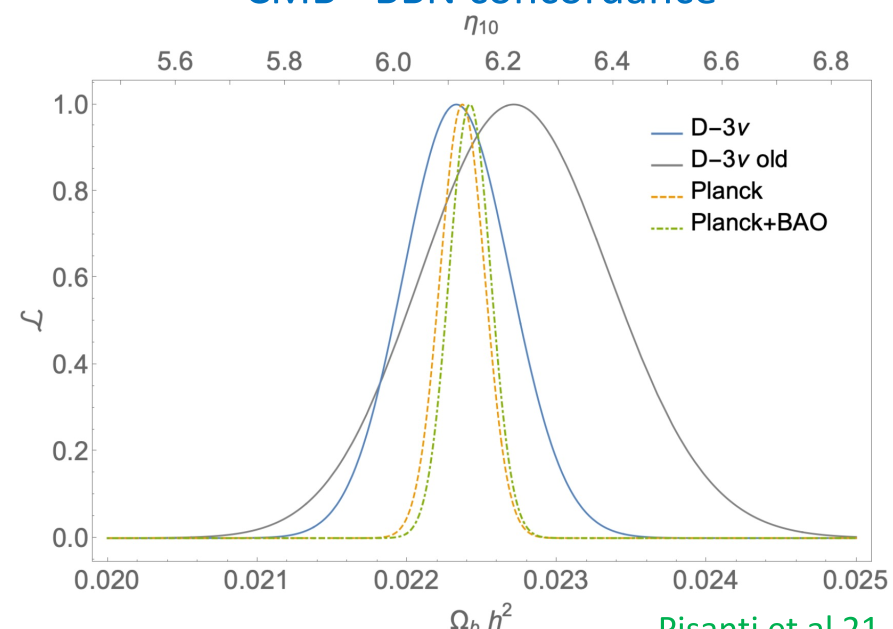
$D(p,\gamma)^3\mathrm{He}$:
recent measurements by LUNA reduced the cross section uncertainty to ~3%
[Mossa et al. 2020]

$D(d,p)^3\mathrm{H}$ and $D(d,n)^3\mathrm{He}$:
Transfer reactions dominate now the error budget (results also depends on data analysis)
[Pitrou et al 21, Pisanti et al 21, Yeh et al. 21]

$D(p,\gamma)^3\mathrm{He}$ after LUNA



CMB - BBN concordance



Pisanti et al 21

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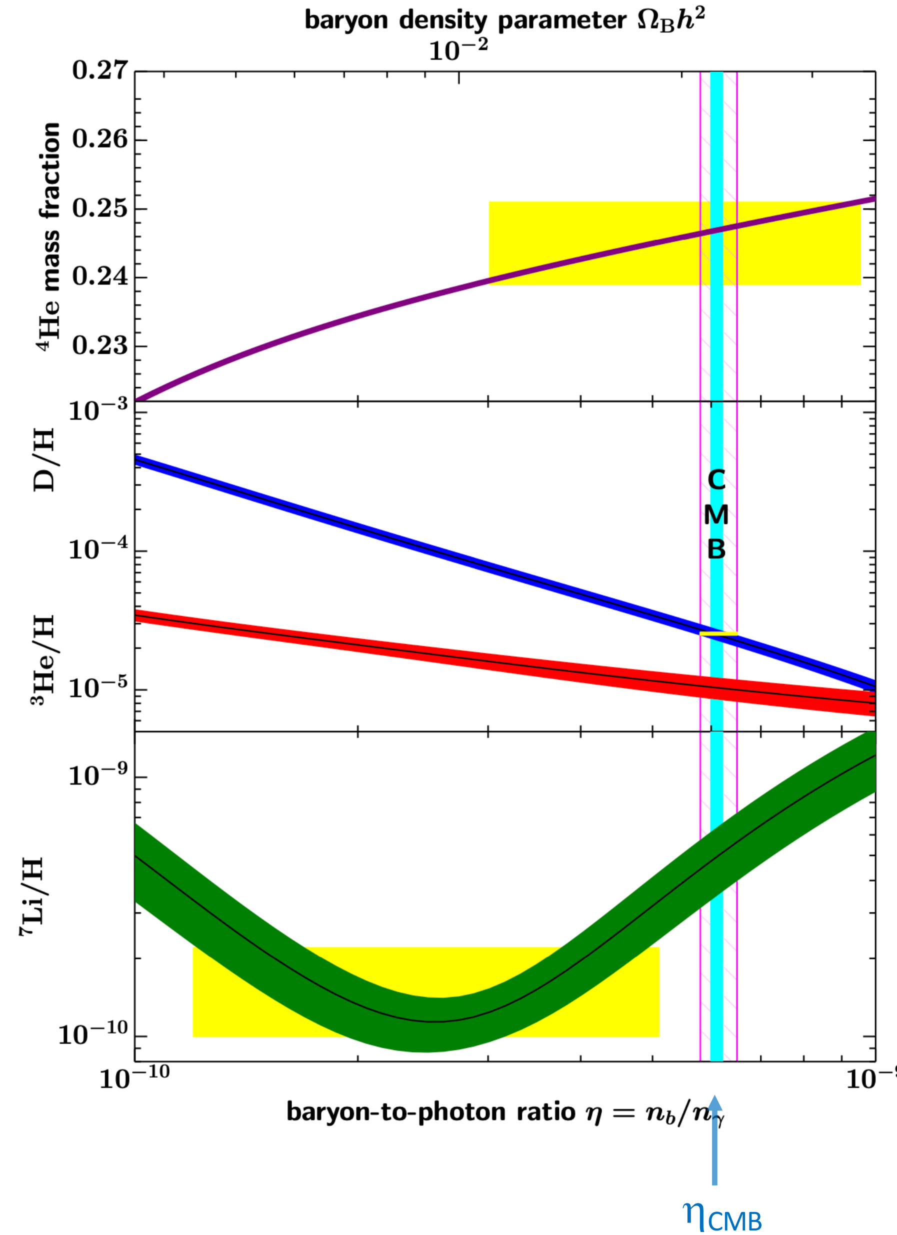
Lithium-7: observed in metal poor (Pop II) stars of our galaxy. Abundance does not vary significantly in stars with metallicities < 1/30 of solar (Spite Plateau)

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



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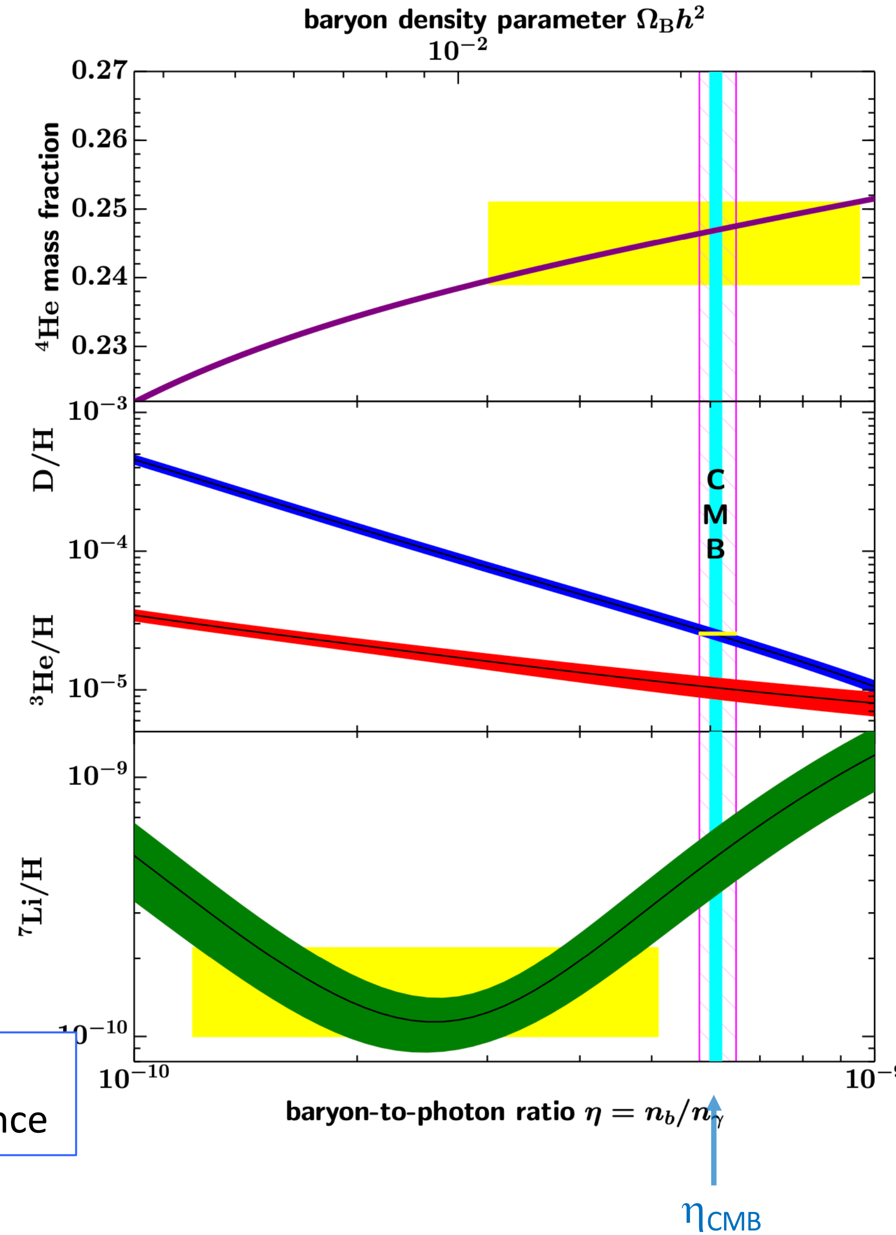
The Lithium-7 problem:
Obs. values factor 3 lower than required for concordance



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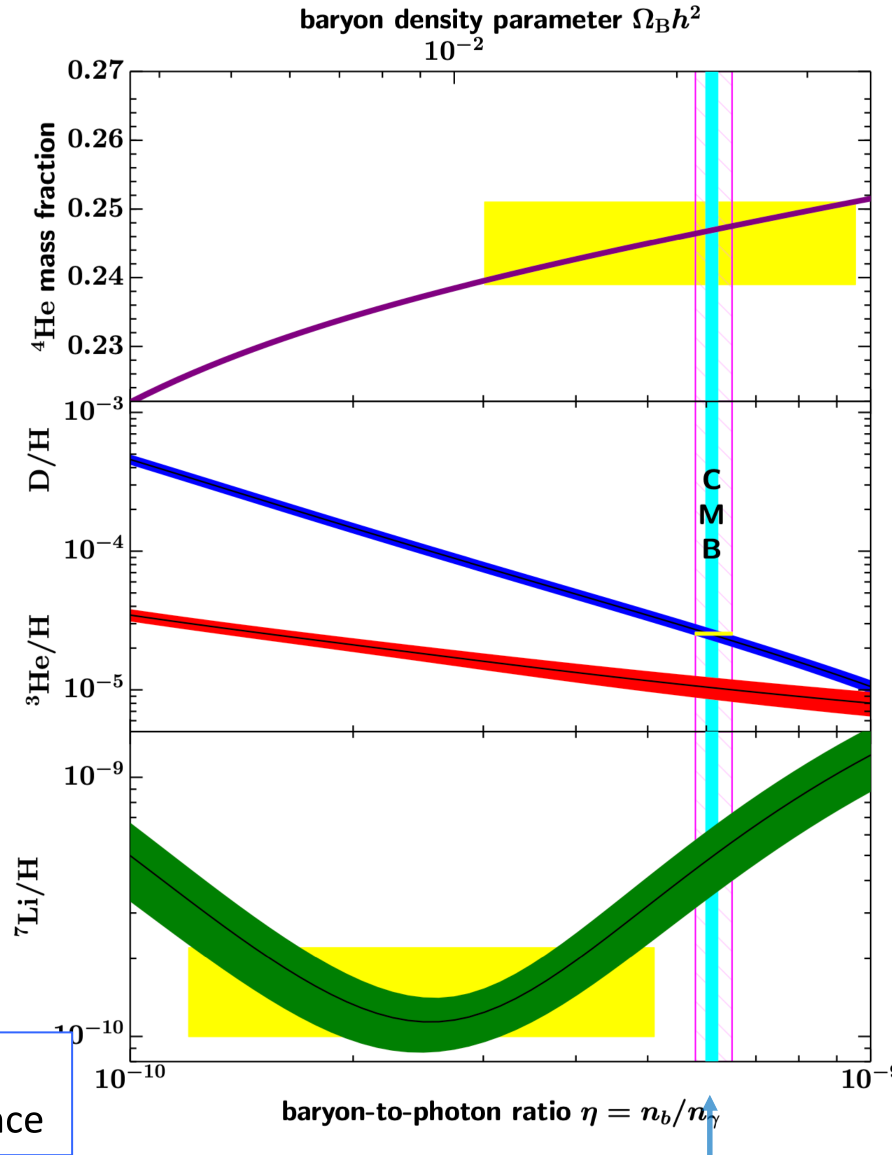


The Lithium-7 problem:
Obs. values factor 3 lower than required for concordance

Broggini et al. 2012 – The possibility of a nuclear physics solution to the ^{7}Li problem is significantly suppressed, even in the assumptions of new unknown resonances.

The role of nuclear reactions in solar models

Hydrogen Burning: PP chain and CNO cycle

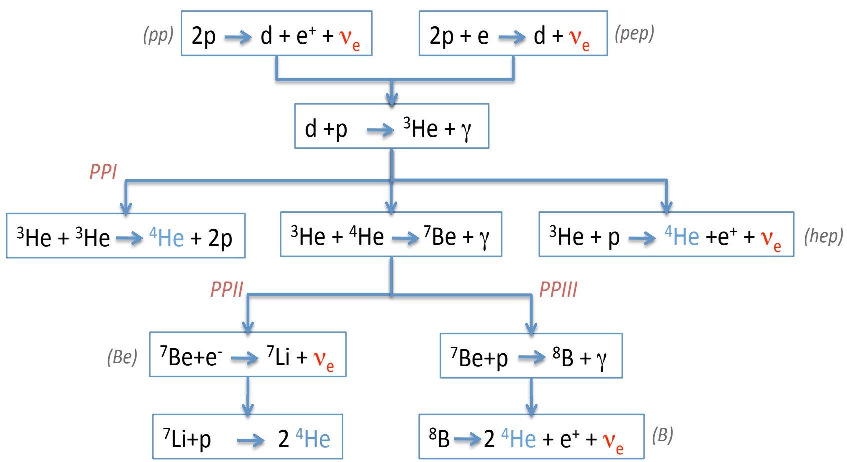
The Sun is powered by nuclear reactions that transform H into ^{4}He:

$$4H + 2e^{-} \rightarrow {}^{4}He + 2\nu_e + \text{energy}$$

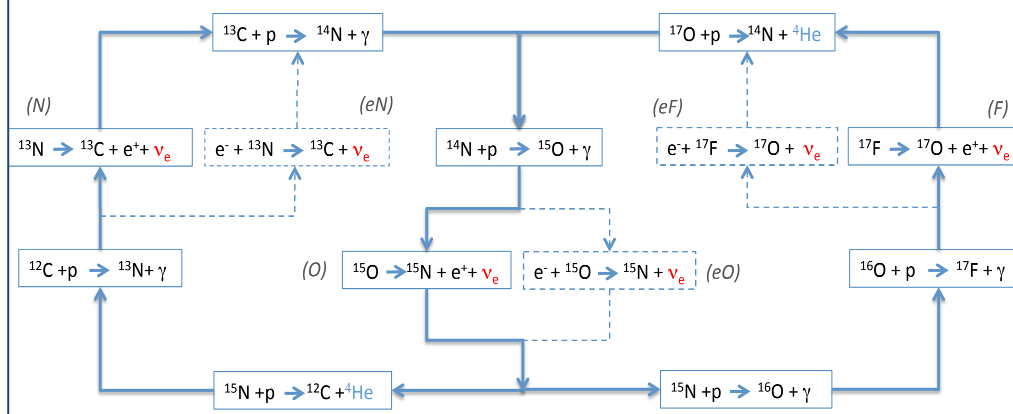
Q = 26,7 MeV (globally)

Free stream – 8 minutes to reach the earth
Direct information on the energy producing region.

The PP-chain



The CN-NO (bi-)cycle



The pp chain is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion.

CNO (bi-)cycle is responsible for about 1% of the total neutrino (and energy) budget. Important for more advanced evolutionary stages

Hydrogen Burning: PP chain and CNO cycle

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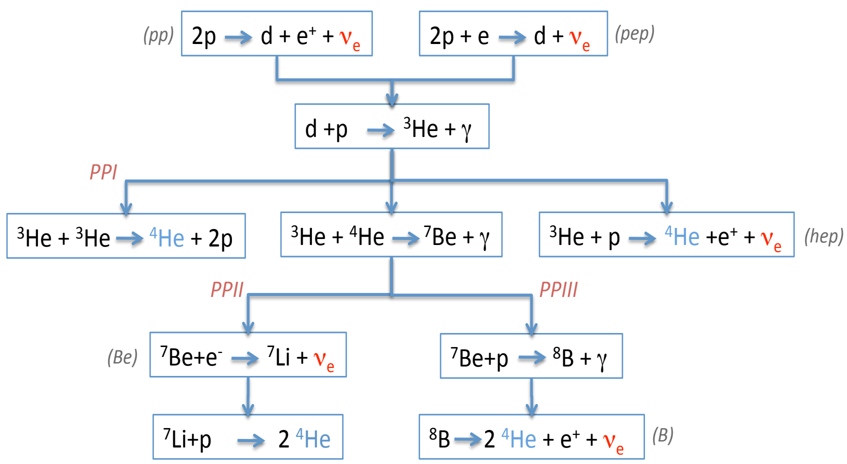

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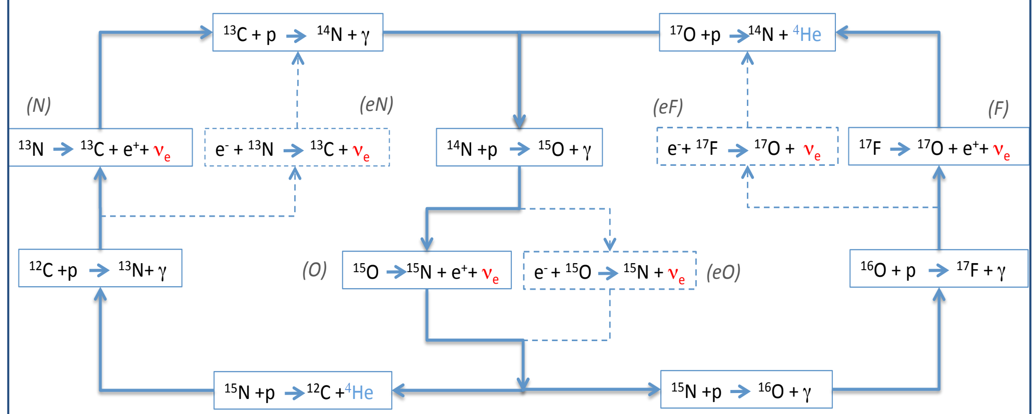


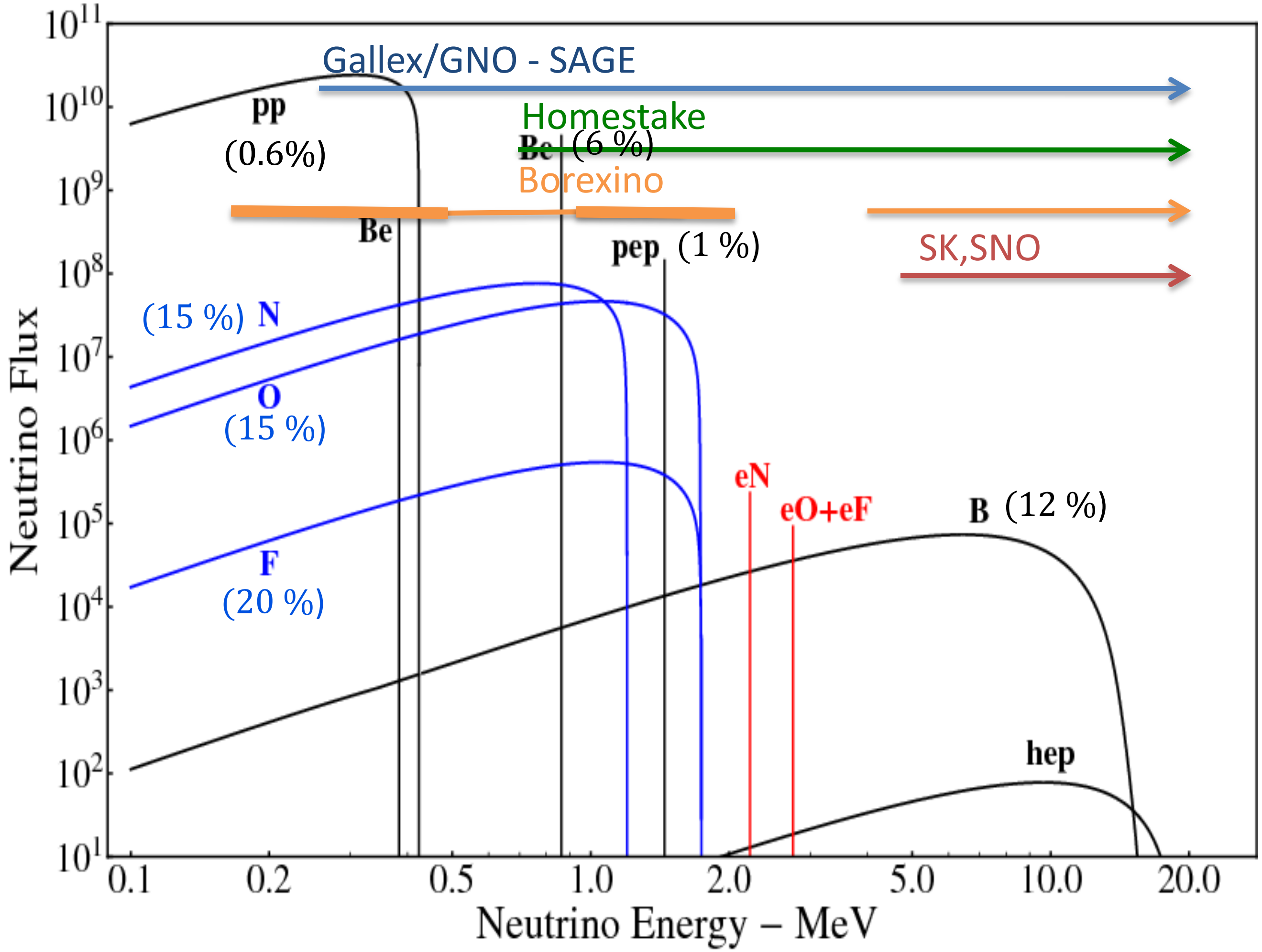
pp, pep → overall efficiency of pp chain, central temperature, pp/pep neutrino ratio

^{3}He+^{3}He, ^{3}He+^{4}He (^{3}He + p) → PPI/PPII branching (pp, ^{7}Be and hep neutrinos)

^{7}Be+e, ^{7}Be+p → PPII/PPIII branching (^{8}B neutrinos)

^{14}N+p → «bottleneck» reaction that determines the efficiency of CN-cycle (^{13}N and ^{15}O neutrinos)

The solar neutrino spectrum



The different comp. of the solar neutrinos flux have been **directly** determined with accuracy level:

pp: ~ 10%
pep: ~ 10%
^{7}Be: ~ 3 %
^{8}B: ~ 2 %
CNO: ~ 20%

Recent Milestones from **Borexino**:

- ^{7}Be (and ^{8}B) neutrino direct detection [PRL 2008]
- pp (and pep) neutrinos direct detection [Nature 2014, 2018]
- CNO neutrinos signal identification [Nature 2020, PRL 2022, arXiv: 2307.14636]

The role of nuclear reactions in solar models/1

Taking into account that the solar luminosity $L_\odot$ is observationally fixed, we understand that an enhancement of pp-reaction rate translate into a reduction of the (predicted) core temperature of the Sun, i.e.

$$\delta T_c \sim -0.13\,\delta S_{11}$$

Considering that $L_\odot = Q_{\rm I}\,\lambda_{33} + Q_{\rm II}\,\lambda_{34}$ (and assuming that ^{3}He is at equilibrium), one gets:

$$\delta\Phi(\mathrm{pp}) = -\eta\,\delta S_{34} - \frac{\eta}{2}\,(\delta S_{11} - \delta S_{33}) + \beta_{\rm pp}\,\delta T_c$$

$$\delta\Phi(\mathrm{pep}) = -\eta\,\delta S_{34} - \frac{\eta}{2}\,(\delta S_{11} - \delta S_{33}) + \beta_{\rm pep}\,\delta T_c$$

$$\delta\Phi(^7\mathrm{Be}) = \delta S_{34} + \frac{1}{2}\,(\delta S_{11} - \delta S_{33}) + \beta_{\rm Be}\,\delta T_c$$

$$\eta = \frac{\lambda_{34}}{\lambda_{11}} \simeq 0.08$$

$$\beta_{Be} \simeq 11$$

$$\beta_{pp} \simeq -\eta\beta_{Be} \simeq -0.9$$

$$\beta_{pep} \simeq \beta_{pp} - \frac{1}{2} \simeq -1.4$$

Finally, ^{8}B neutrinos constitute a largely subdominant component of the solar flux which is produced when ^{7}Be nuclei capture a proton (instead of an electron):

$$\delta\Phi(^8\mathrm{B}) = (\delta S_{17} - \delta S_{e7}) + \delta S_{34} + \frac{1}{2}\,(\delta S_{11} - \delta S_{33}) + \beta_{\rm B}\,\delta T_c$$

$$\beta_B \simeq 24$$

See e.g. Villante e Serenelli 2021 for a review

The role of nuclear reactions in solar models/2

CNO neutrino fluxes, beside depending on S_{114} and on the core temperature of the Sun, also have a linear dependence on the C+N abundance of the Sun

Indeed, the CN-NO by-cycle uses C, N and O nuclei in the core of the Sun as catalysts for hydrogen fusion.

Assuming equal C and N variations (i.e. $\delta X_{\rm N}^{\rm core} = \delta X_{\rm C}^{\rm core} \equiv \delta X_{\rm CN}^{\rm core}$), we obtain:

$$\begin{aligned} \delta\phi_{\rm O} &= \delta X_{\rm CN}^{\rm core} + \alpha\,\delta T_{\rm c} + \delta S_{114} \\ \delta\phi_{\rm N} &= \delta X_{\rm CN}^{\rm core} + \gamma\,\delta T_{\rm c} + f\,\delta S_{114} \end{aligned}$$

where $\alpha \simeq \gamma \simeq 20$ and $f \simeq 0.7$

This allow us, in principle, to test the chemical composition and the chemical evolution paradigm of the Sun (and of other stars)

N.B. There is no net production of metals in the Sun. The C+N core abundance is a proxy of initial C+N abundance of the Sun (only changed by diffusion).

The solar abundance problem

The reliable prediction of CNO (and pp) neutrinos is essential for solving the **solar abundance problem** (tension between spectroscopic abundance measurements and helioseismic inferences). Indeed:

- The (strong) dependence of neutrino fluxes on T_c can be eliminated by using ^{8}**B-neutrinos as solar thermometer;**
- The additional dependence of **CNO-neutrinos** on X_{CN} can be used to directly **infer core composition.**

In practical terms, one can form a weighted ratio of e.g. ^{8}B and ^{15}O neutrino fluxes that is:

- Essentially independent on environmental parameters (including opacity);
- **Directly proportional to Carbon+Nitrogen abundance in the solar core**

Serenelli et al., PRD 2013
See also (application to BX obs. rate):
Agostini et al, EPJ 2021
Villante & Serenelli, Frontiers 2021

$$\delta\Phi(^{15}\mathrm{O}) - x\,\delta\Phi(^{8}\mathrm{B}) \simeq \boxed{\delta X_{\mathrm{CN}}^{\mathrm{core}}} + \delta S_{114} - x\left(\delta S_{17} - \delta S_{e7} + \delta S_{34} + \frac{\delta S_{11}}{2} - \frac{\delta S_{33}}{2}\right)$$

$$x = \frac{\beta_{\mathrm{O}}}{\beta_{\mathrm{B}}} \sim 0.8$$

Probing solar composition with neutrinos

By considering

$$\frac{R^{Bx}_{CNO}}{R^{SSM}_{CNO}} = \frac{R^{Bx}_{^{15}O}}{R^{SSM}_{^{15}O}} = \frac{\Phi^{Bx}_{^{15}O}}{\Phi^{SSM}_{^{15}O}} = 1.35^{+0.24}_{-0.16}$$

Borexino CNO neutrino signal (scaled to GS98 prediction)
[Borexino: PRL 2022, arXiv: 2307.14636]

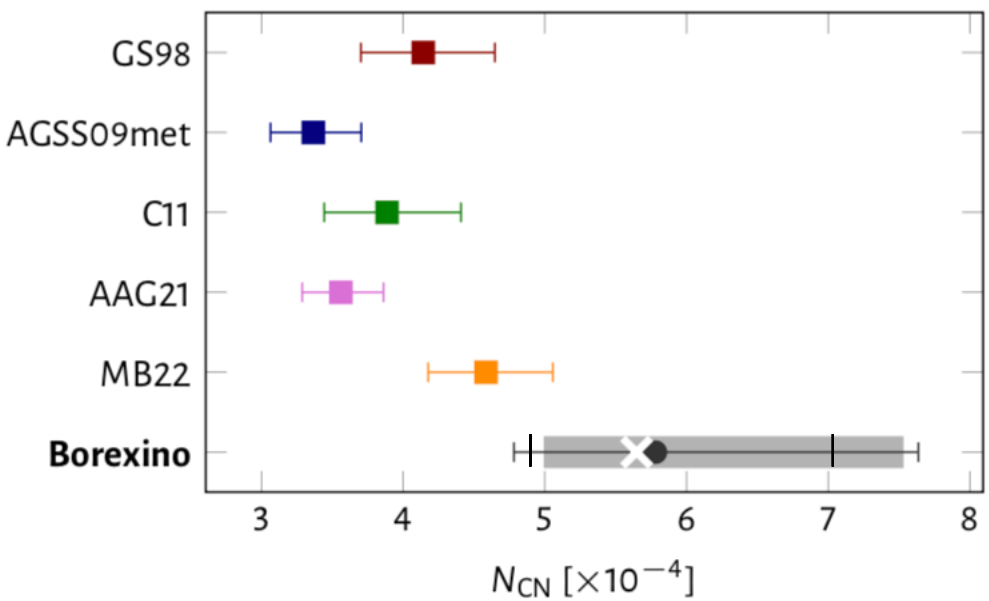
$$\frac{\Phi^{global}_{^8B}}{\Phi^{SSM}_{^8B}} = 0.96 \pm 0.027$$

^8B flux determined from global analysis (scaled to GS98 prediction)

One obtains:

$$\frac{(N_C + N_N)/N_H}{[(N_C + N_N)/N_H]^{SSM}} = 1.35 \times (0.96)^{-0.769} \times$$
$$\times \left[1 \pm \left({}^{+0.18}_{-0.12}(CNO) \pm 0.097(nucl) \pm 0.023(^8B) \pm 0.005(env) \pm 0.027(diff) \pm 0.022(O/N)\right)\right]$$

Note: reduced error wrt Borexino, PRL 2022



N.B.
This determination is robust wrt to environmental parameters variations (including opacity).

Only limited by nuclear reaction uncertainties:

$S_{114} \rightarrow 7.6\%$
$S_{17} \rightarrow 3.5\%$
$S_{34} \rightarrow 3.4\%$

Conclusions

The knowledge of nuclear reaction cross section remains a key ingredient for the correct interpretation of astrophysical and cosmological phenomena.

Solar fusion cross section III – held on July 2022
https://indico.ice.csic.es/event/30/overview
A final document should be ready during the next months

Thank you for your attention

Additional slides

Lithium-7

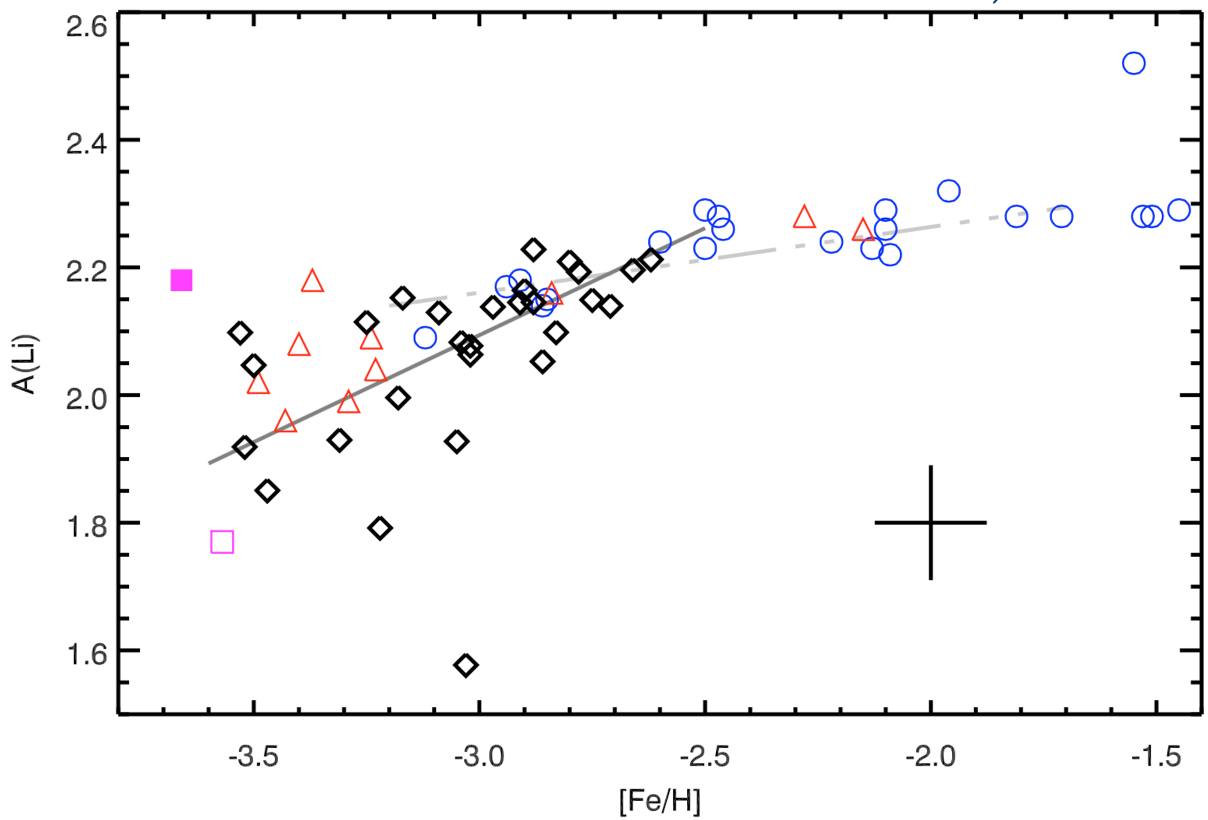
Meltdown of the spite plateau at low metallicity (<1/1000 Solar)

(?) 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



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

^{7}Li synthesis

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

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

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

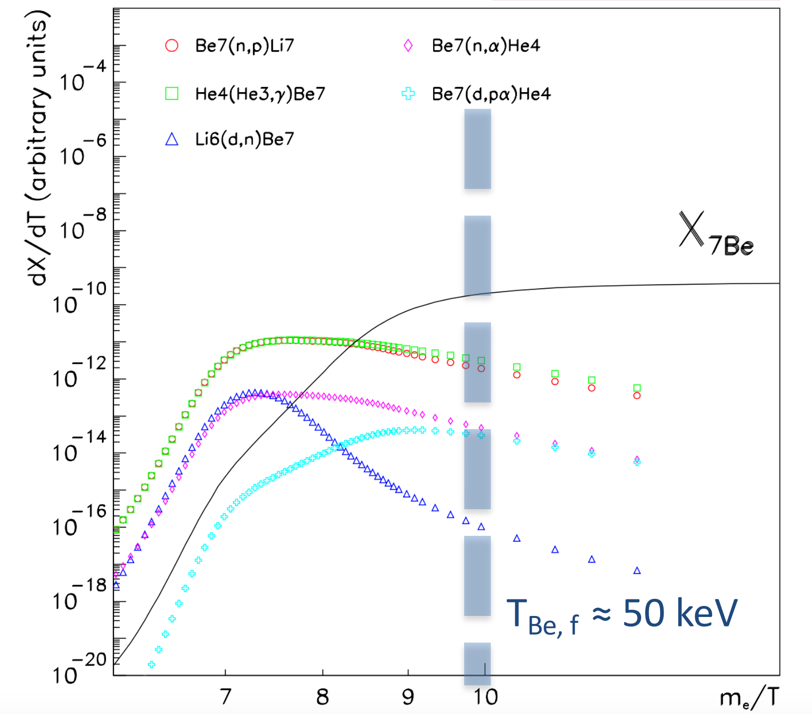
The dominant ^{7}Be production mechanism is through the reaction ^{3}He(α,γ)^{7}Be

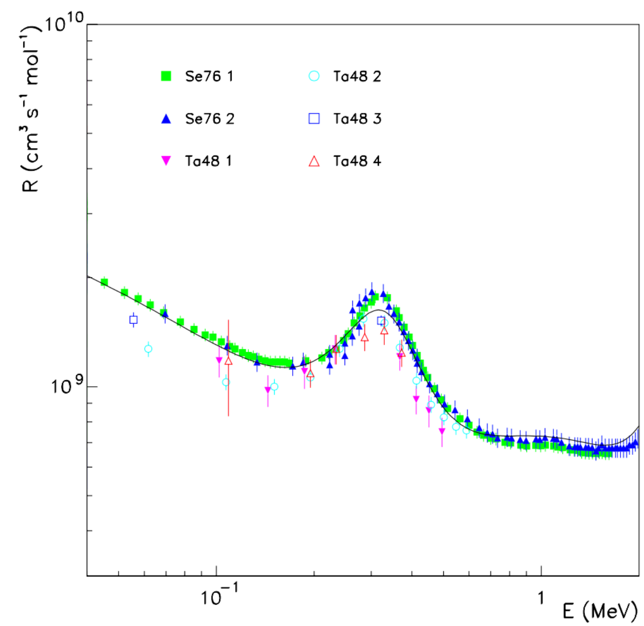
→ Studied in detail both experimentally (LUNA) and theoretically. The cross section is known to 7% uncertainty.

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





Requirements for a nuclear physics solution of the ^{7}Li problem

Additional reactions (^{7}Be+a) should be as effective as ^{7}Be(n,p)^{7}Li in destroying ^{7}Be

Taking into account the abundances of different «targets», this translates into lower limits for the ratios

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

Note that:

$$\sigma_{\rm np}(50\mathrm{keV}) \simeq 9\,\mathrm{barn}$$

(comparable with unitarity bound)

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

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

Broggini et al. 2012 – The possibility of a nuclear physics solution to the ^{7}Li problem is significantly suppressed, even in the assumptions of new unknown resonances.

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;

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;

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

- 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

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

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

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

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

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

Penetration factor

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

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

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

γ_W^2 = Wigner limiting width

Naively:

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

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:

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

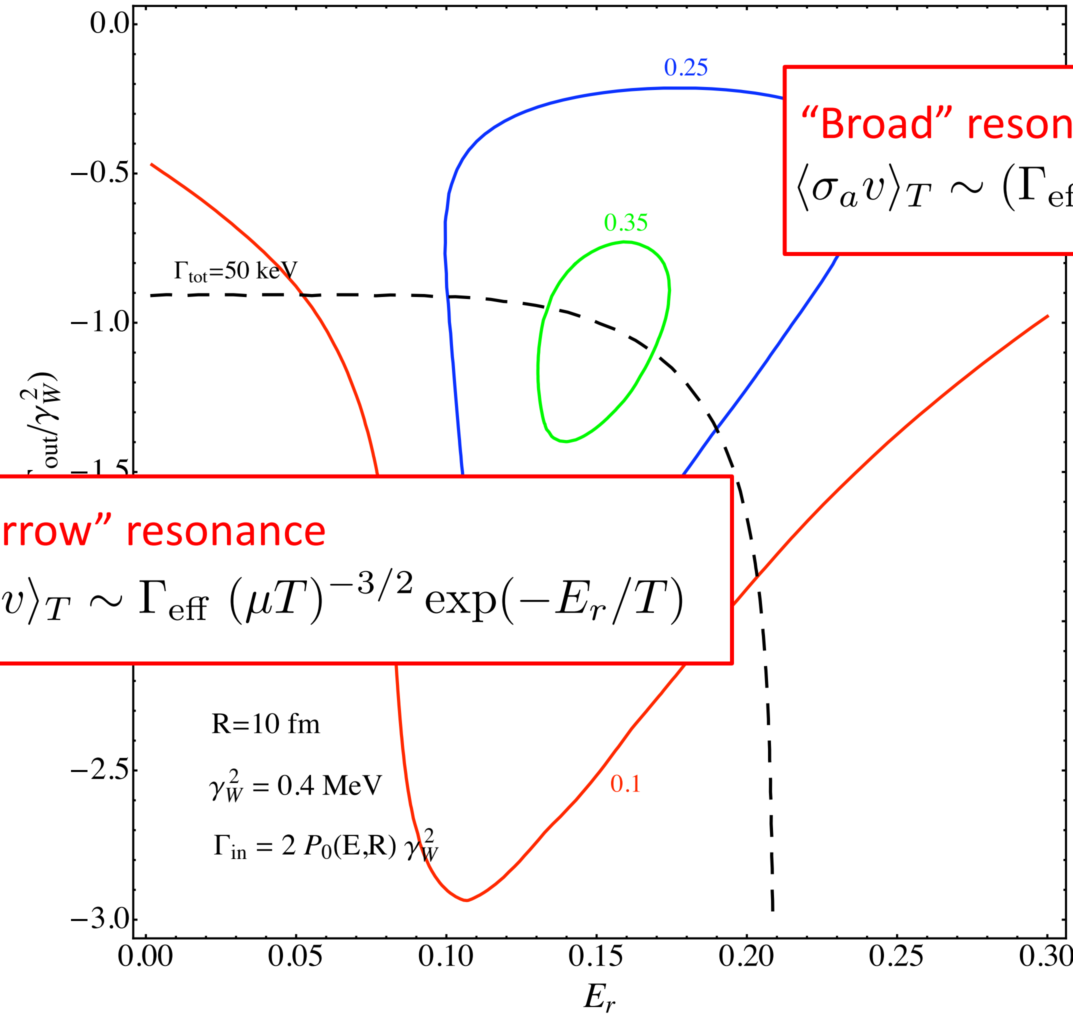
Free param.:

- E_r
- $\xi \equiv \frac{\Gamma_{\rm out}}{\gamma_{\rm in}^2}$

^{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

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

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

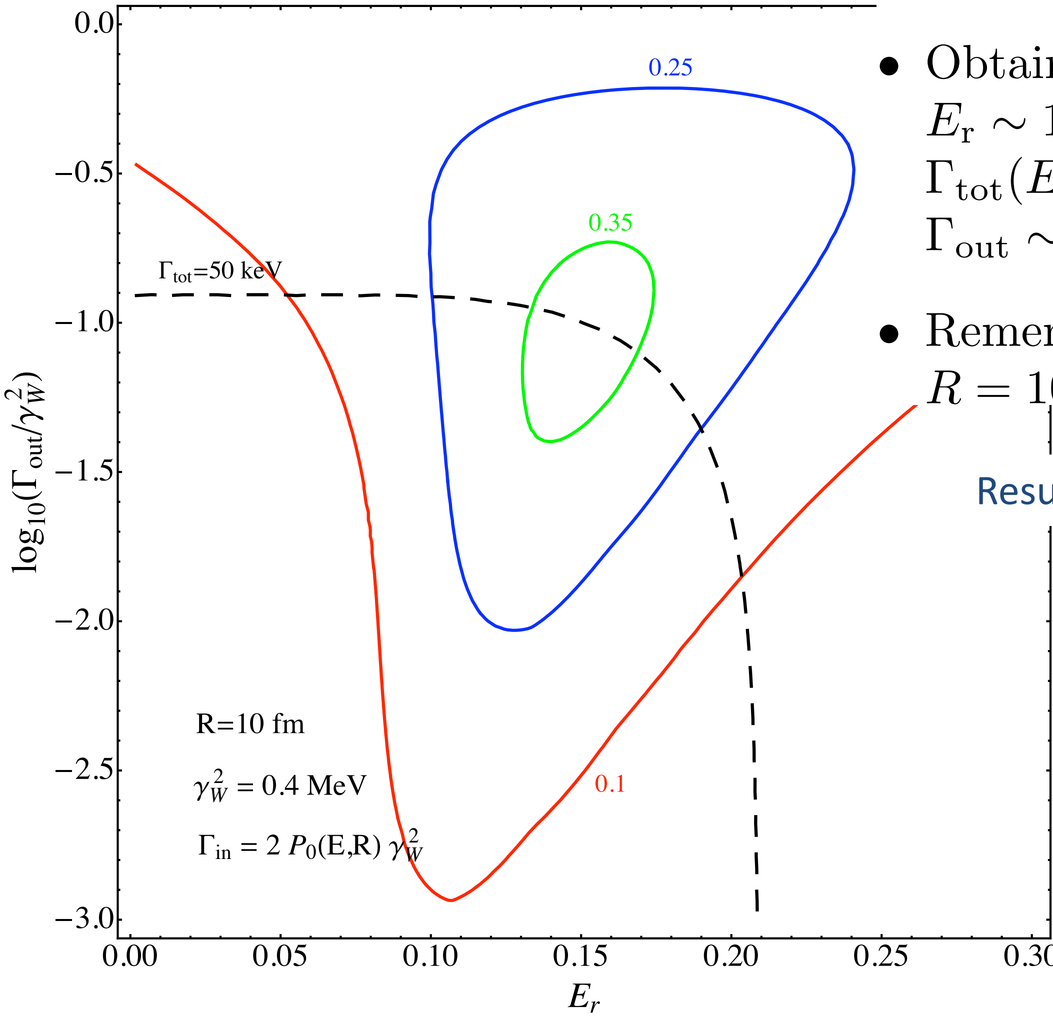
(^{7}Be + d) entrance channel

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

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

See also Angulo et al. 2005.

Broggini et al., JCAP 2012

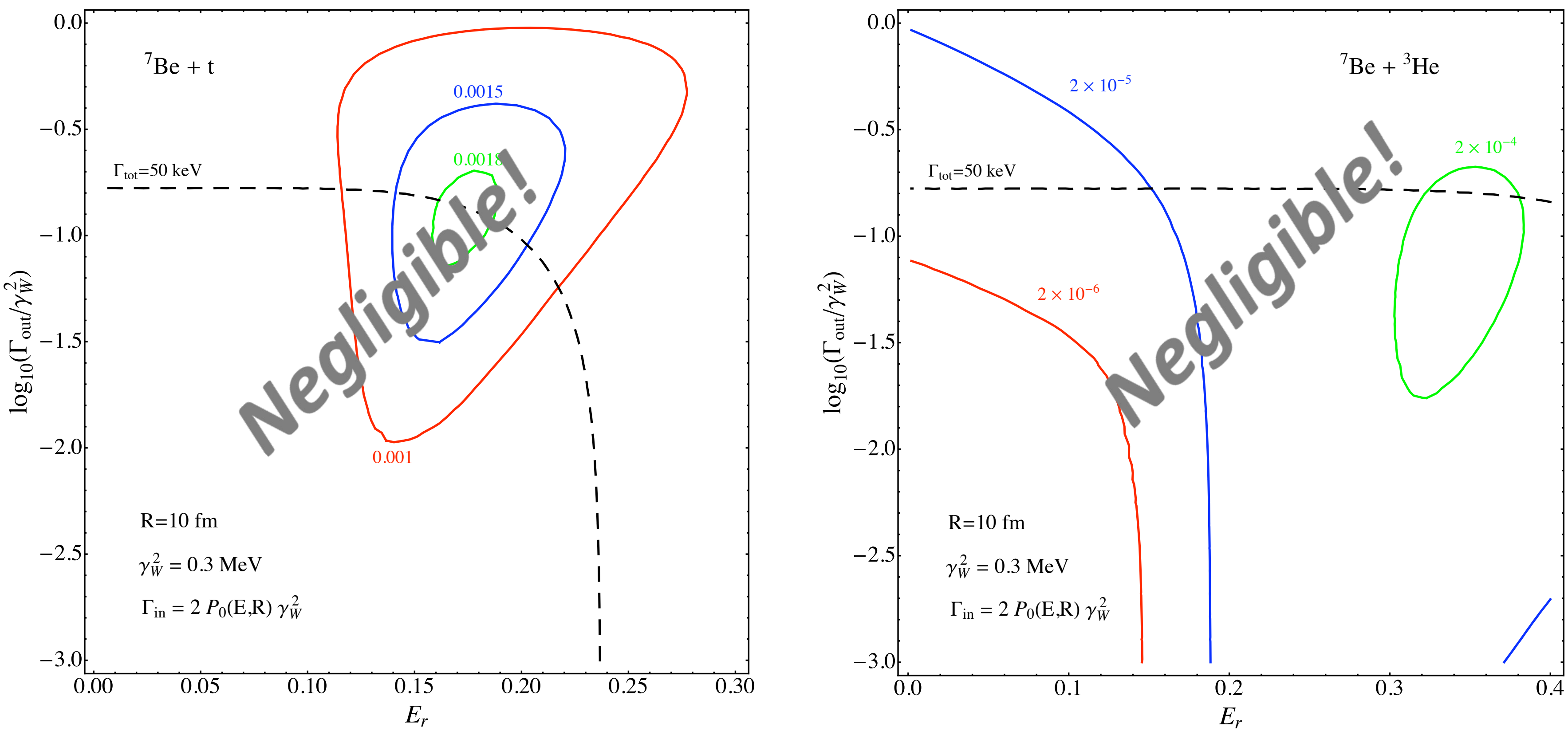


- Maximum achievable reduction $\sim 40\%$
- Obtained for:
  $E_{\rm r} \sim 150$ keV
  $\Gamma_{\rm tot}(E_r, R) \sim 45$ keV
  $\Gamma_{\rm out} \sim 35$ keV and $\Gamma_{\rm in}(E_r, R) \sim 10$ keV
- Remember:
  $R = 10$ fm

Results consistent with Cyburt et al. 2012

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

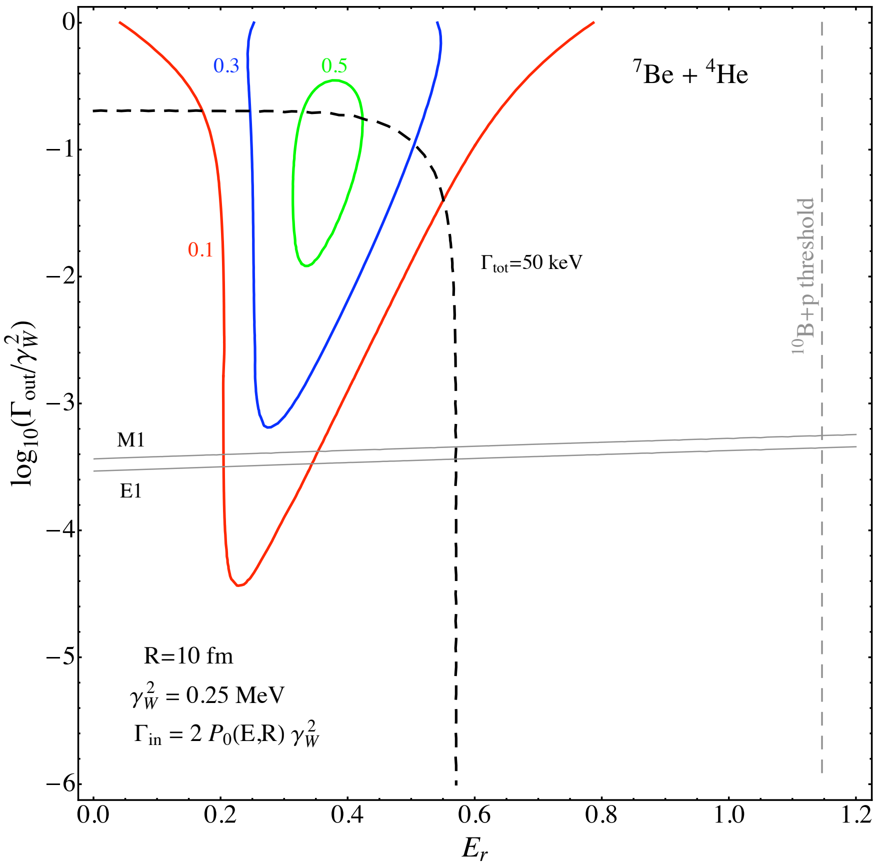
Proposed by Chakraborty, Fields and Olive 2011 as a solution:



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

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

Broggini et al., JCAP 2012



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

However:

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

Taking this into account:

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

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

Other possible solutions:

- ^{7}Li 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 ^{7}Li (^{7}Be) 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 ^{7}Li (D overproduction)

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:

Transmission coeff. (low energy)

$$\sigma_{\rm C} = \sigma_{\max}\,T_l \qquad\qquad T_l = \frac{4k}{K}\,v_l$$

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

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:

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

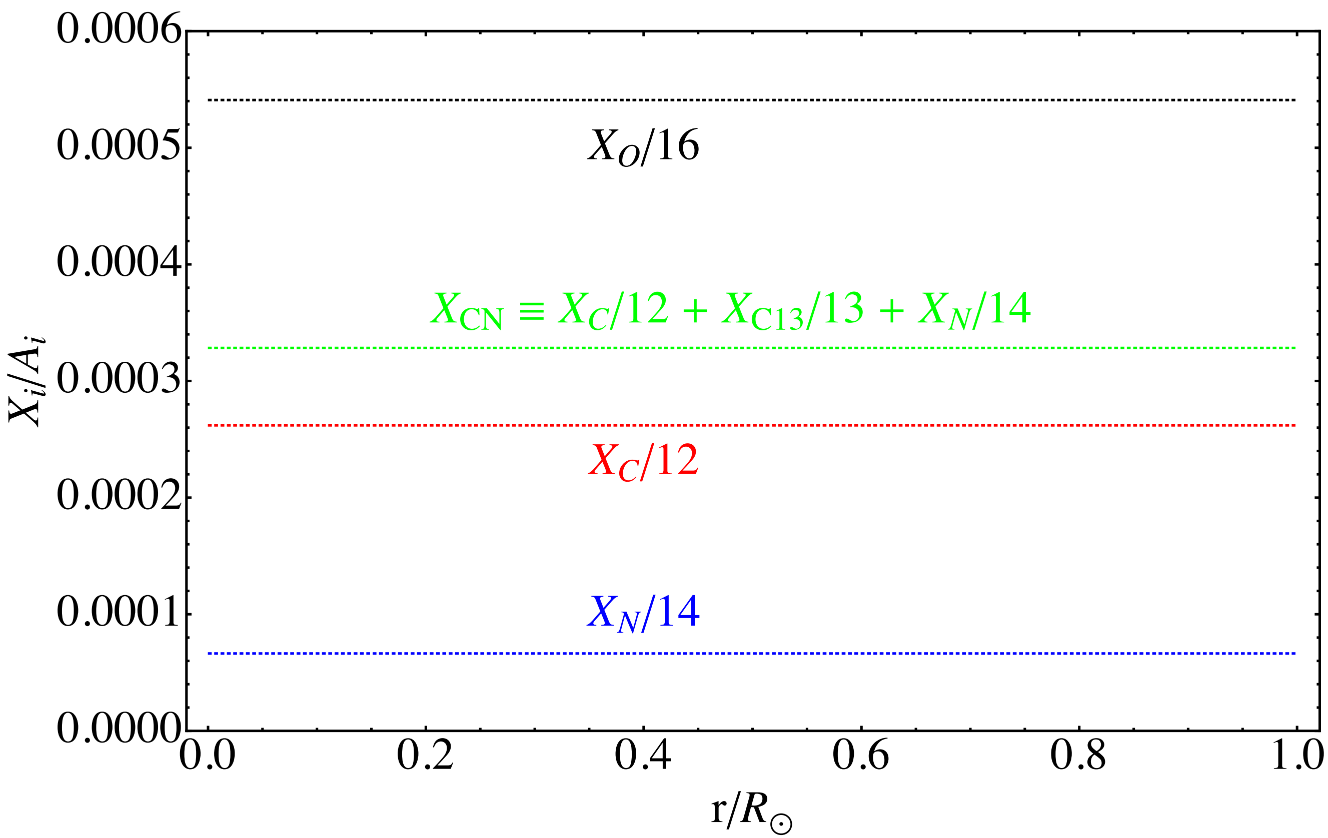
$$\left\{\begin{array}{lcl} r_0 &=& \text{class. distance closest approach} \\ k_l(r) &=& \sqrt{2\mu\,U_l(r) - k^2} \\ U_l(r) &=& \dfrac{Z_a Z_X e^2}{r} + \dfrac{l(l+1)}{2\mu r^2} \end{array}\right.$$

The SSM chemical evolution paradigm

The Sun was born (at t=0) **chemical homogenous**.

The **present** chemical composition (t=4.57Gyr) differs from the **initial** composition due to:

- *Elemental diffusion*
- *Nuclear reactions*



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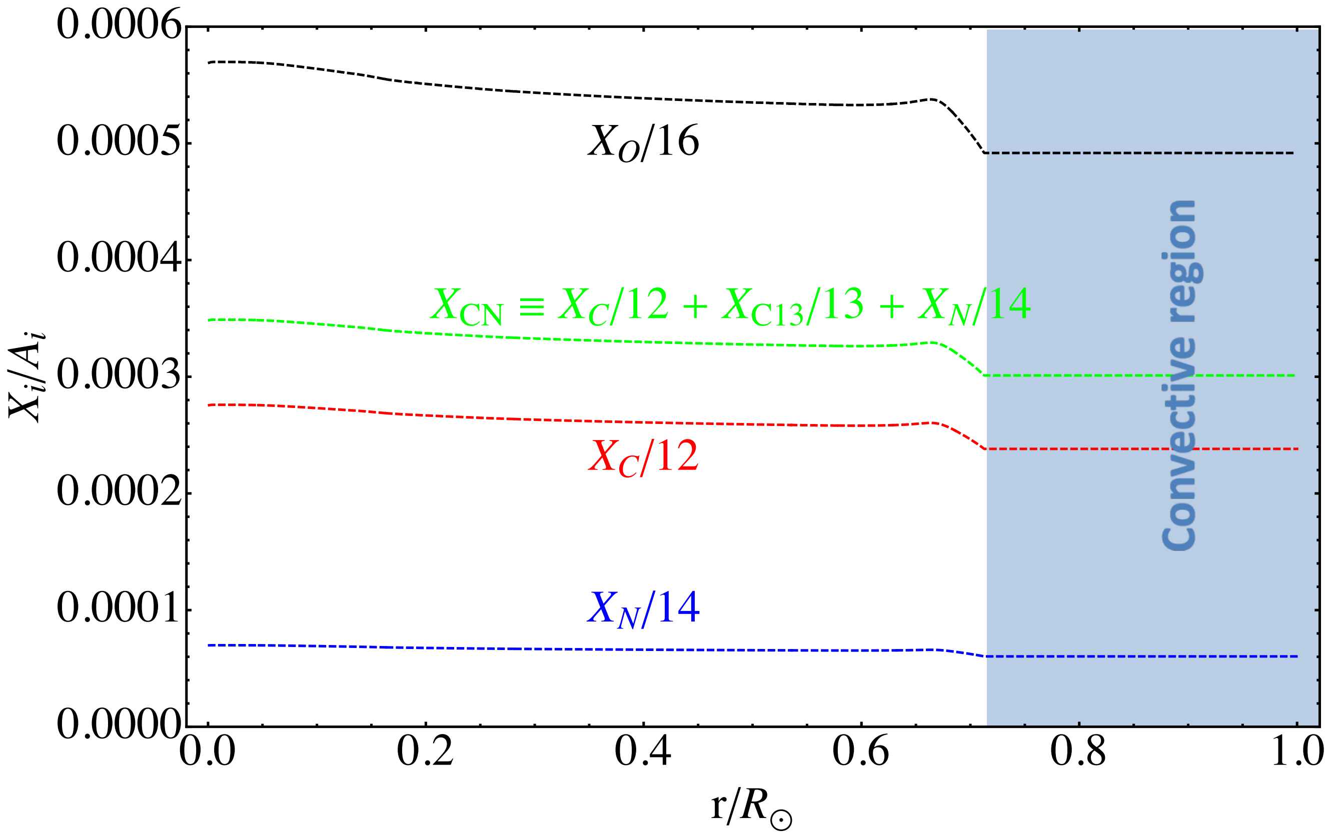

$$\frac{X_{\mathrm{i,C}} - X_{\mathrm{i,S}}}{X_{\mathrm{i,ini}}} \simeq 15\%$$

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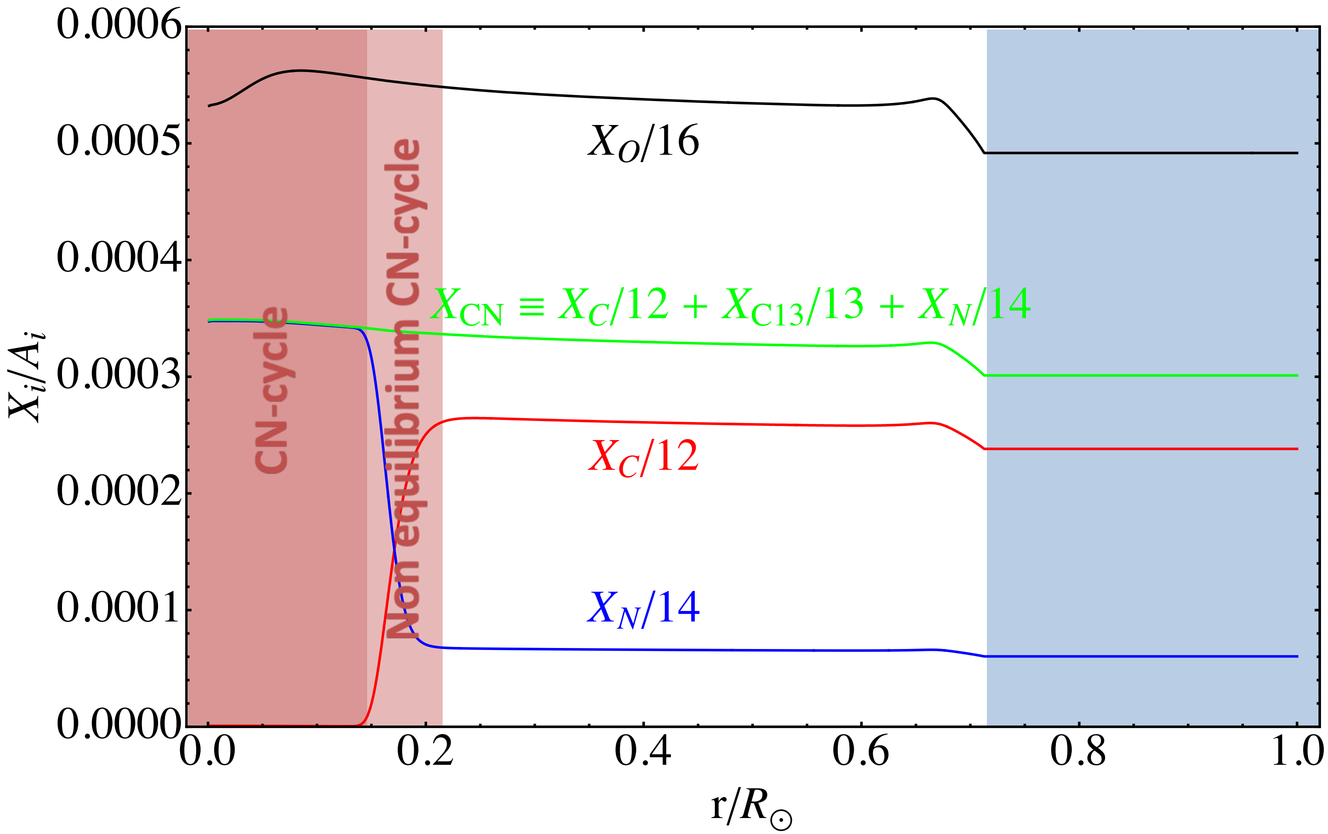

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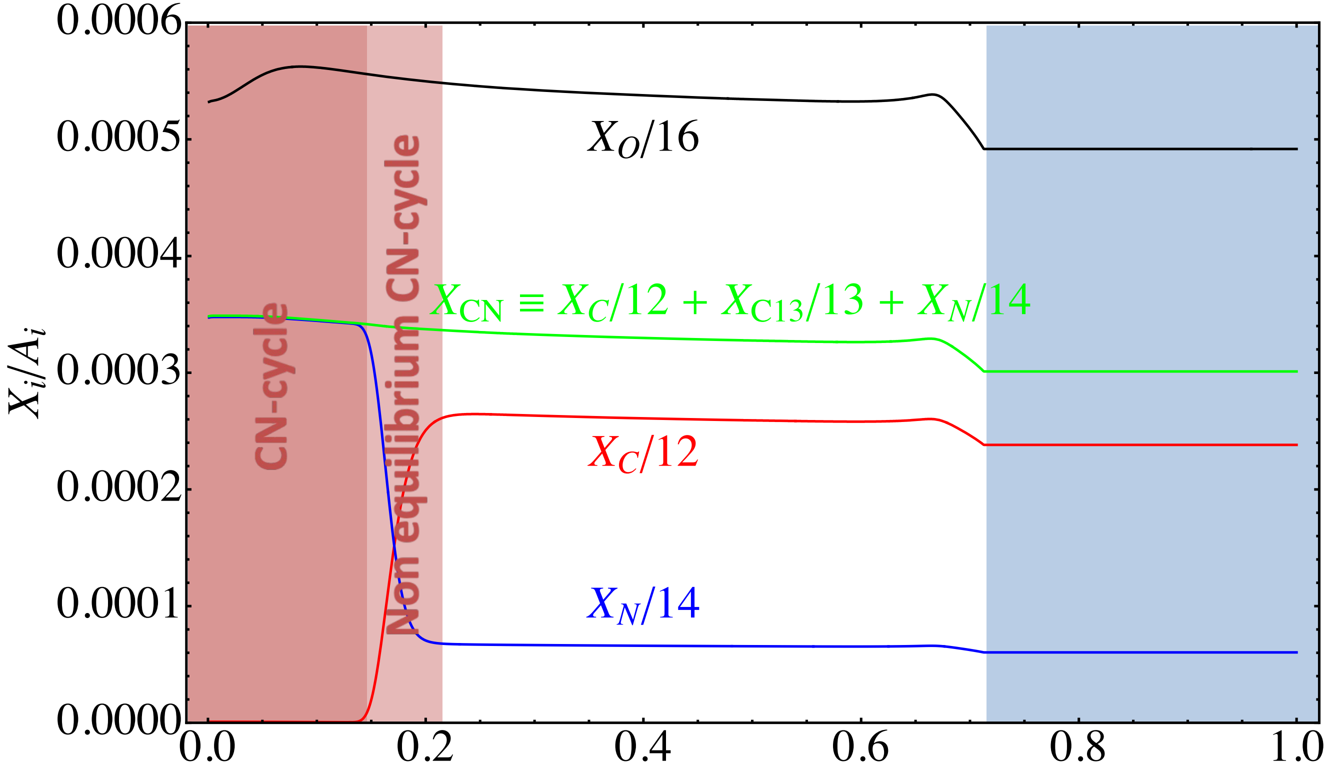

Note that nuclear reaction do not produce metals. The C+N core abundance is thus a proxy of the initial (primeval) C+N abundance of the Sun.