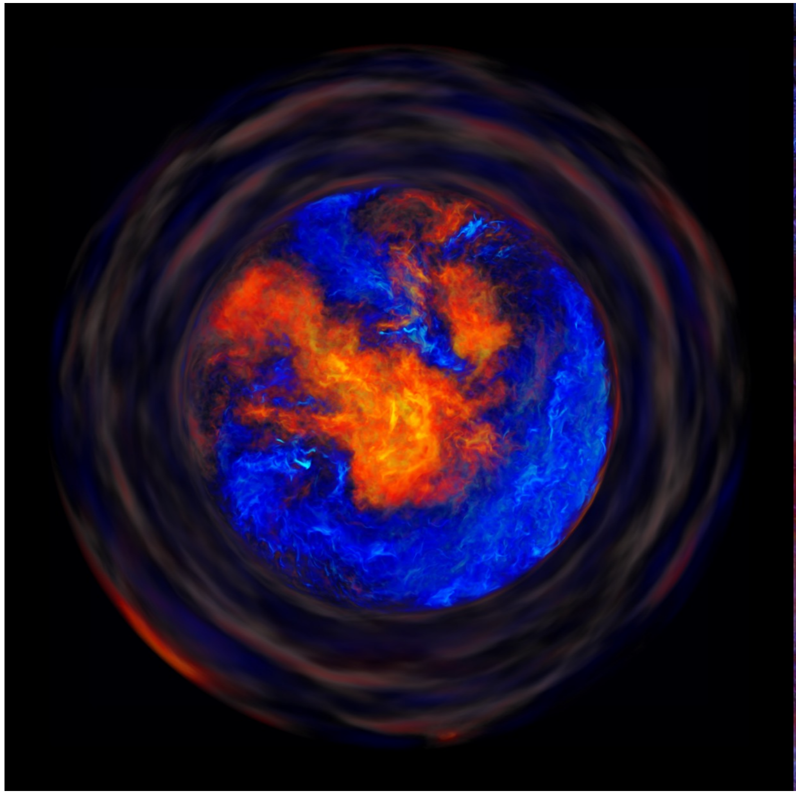
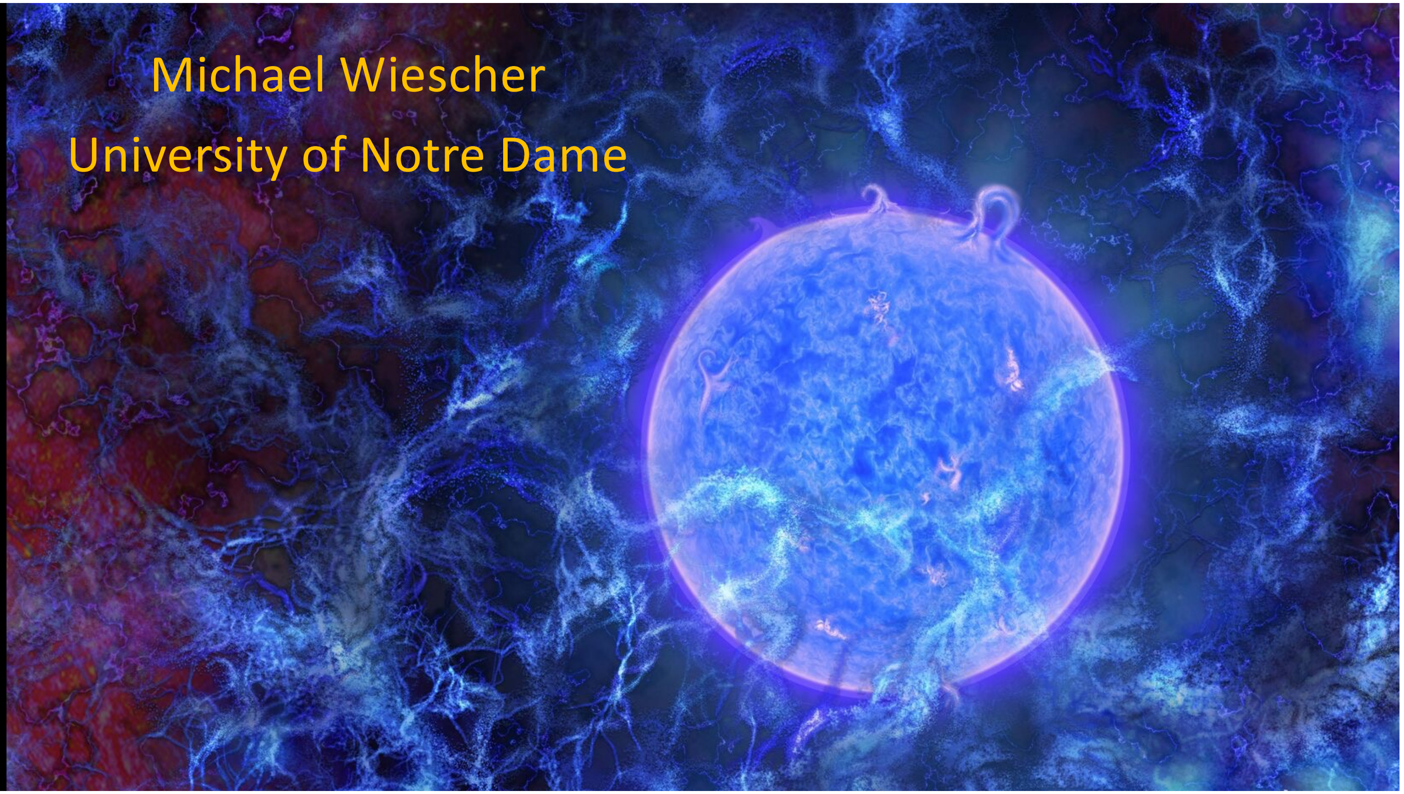
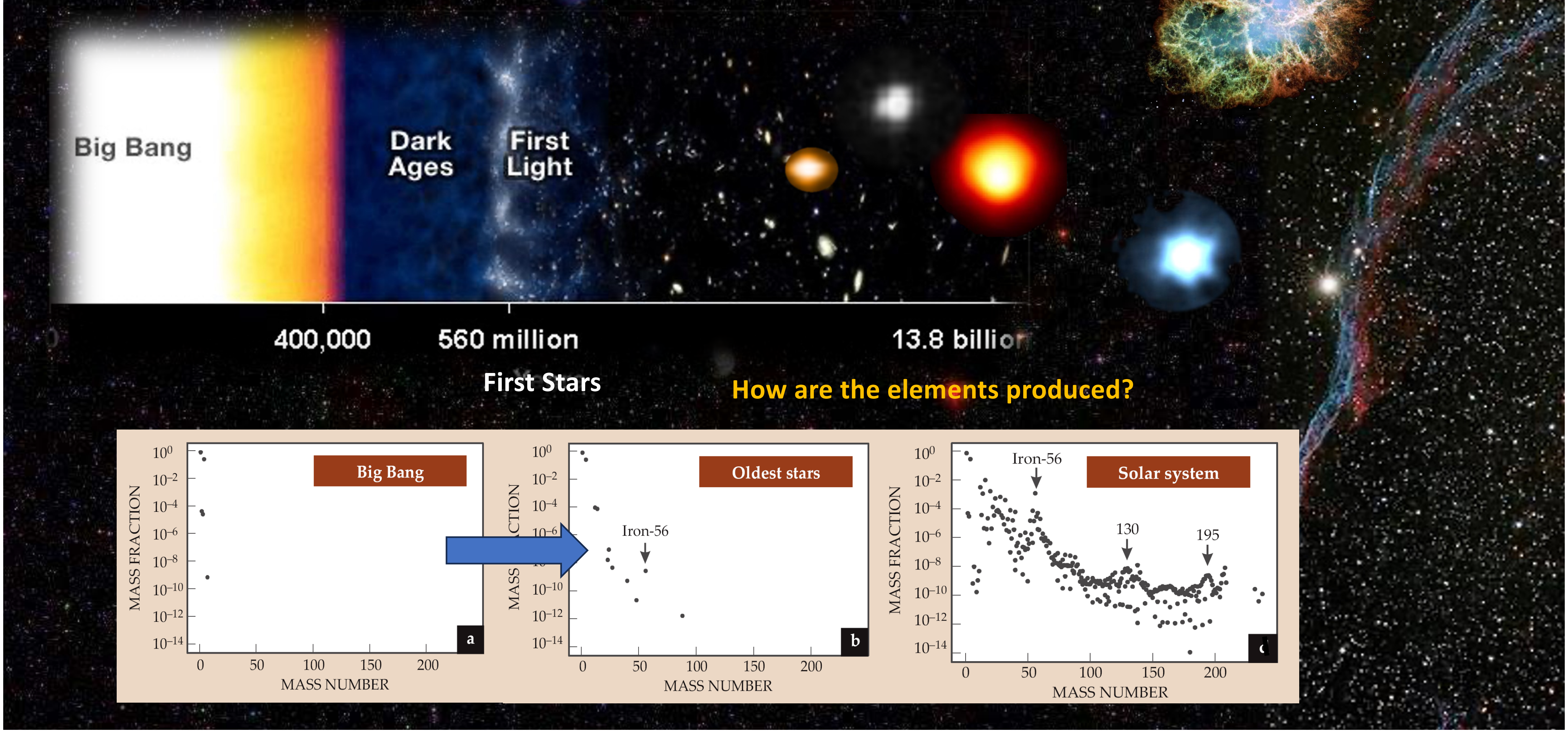
Nuclear Reactions in First Stars





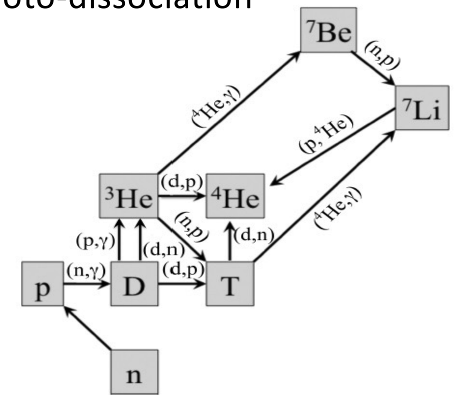
Michael Wiescher
University of Notre Dame

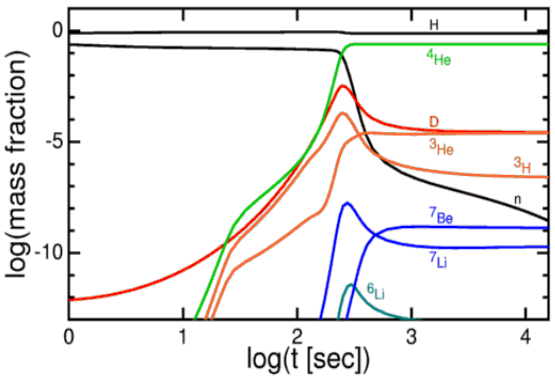
First Steps in Galactic Chemical Evolution

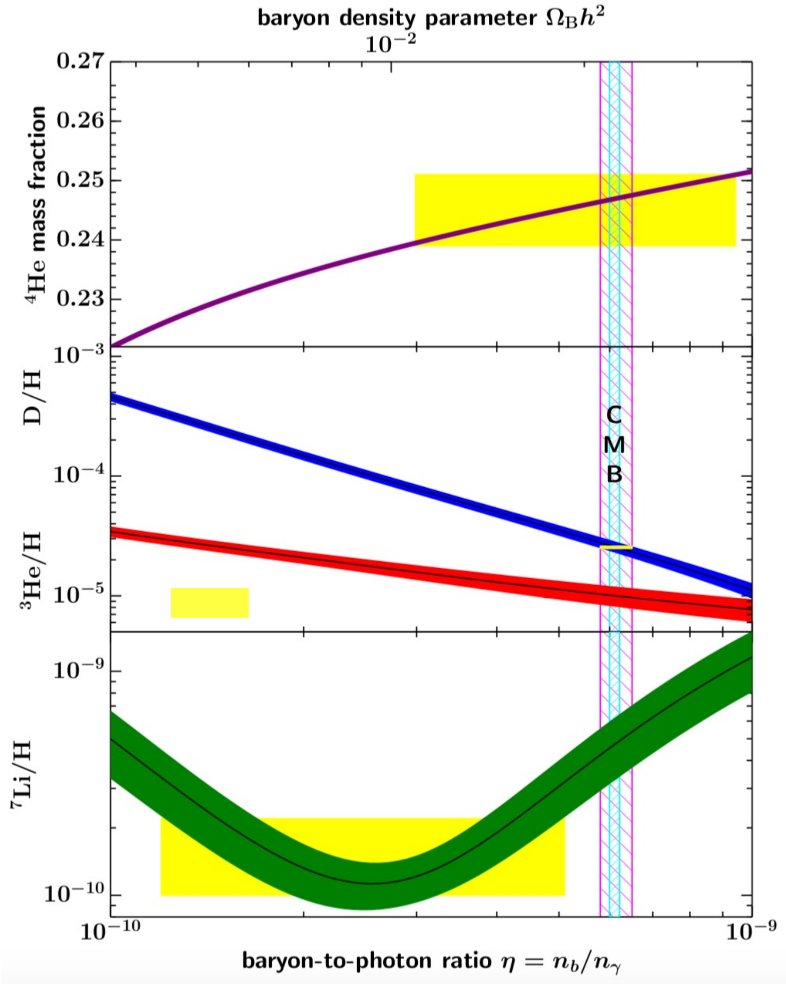


The cosmological ^{7}Li problem

Onset of nucleosynthesis with the freeze out of deuterium photo-dissociation





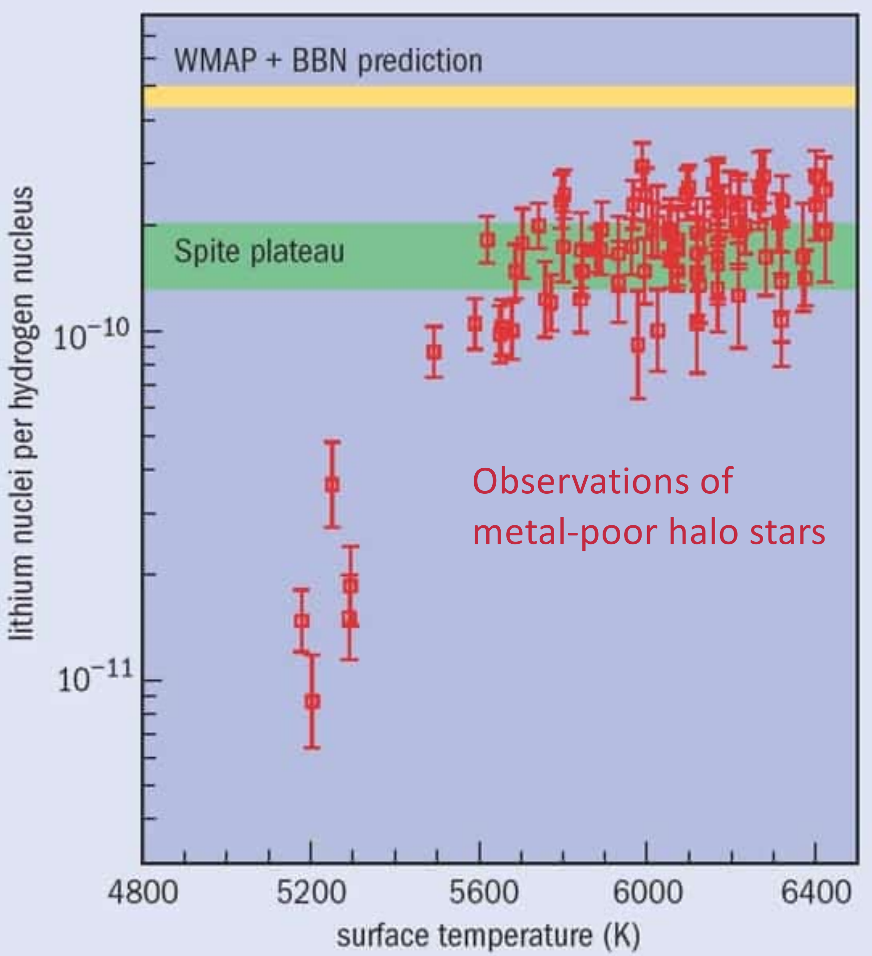


^{7}Li abundance observed in old stars is substantially lower than predicted by SBBM!

Possible Solutions

1. Problems with Big Bang nucleosynthesis reactions (tritium)
2. Stellar physics in first stars (Li diffusion)
3. Nuclear physics in first stars (present proposal)
4. Beyond standard model

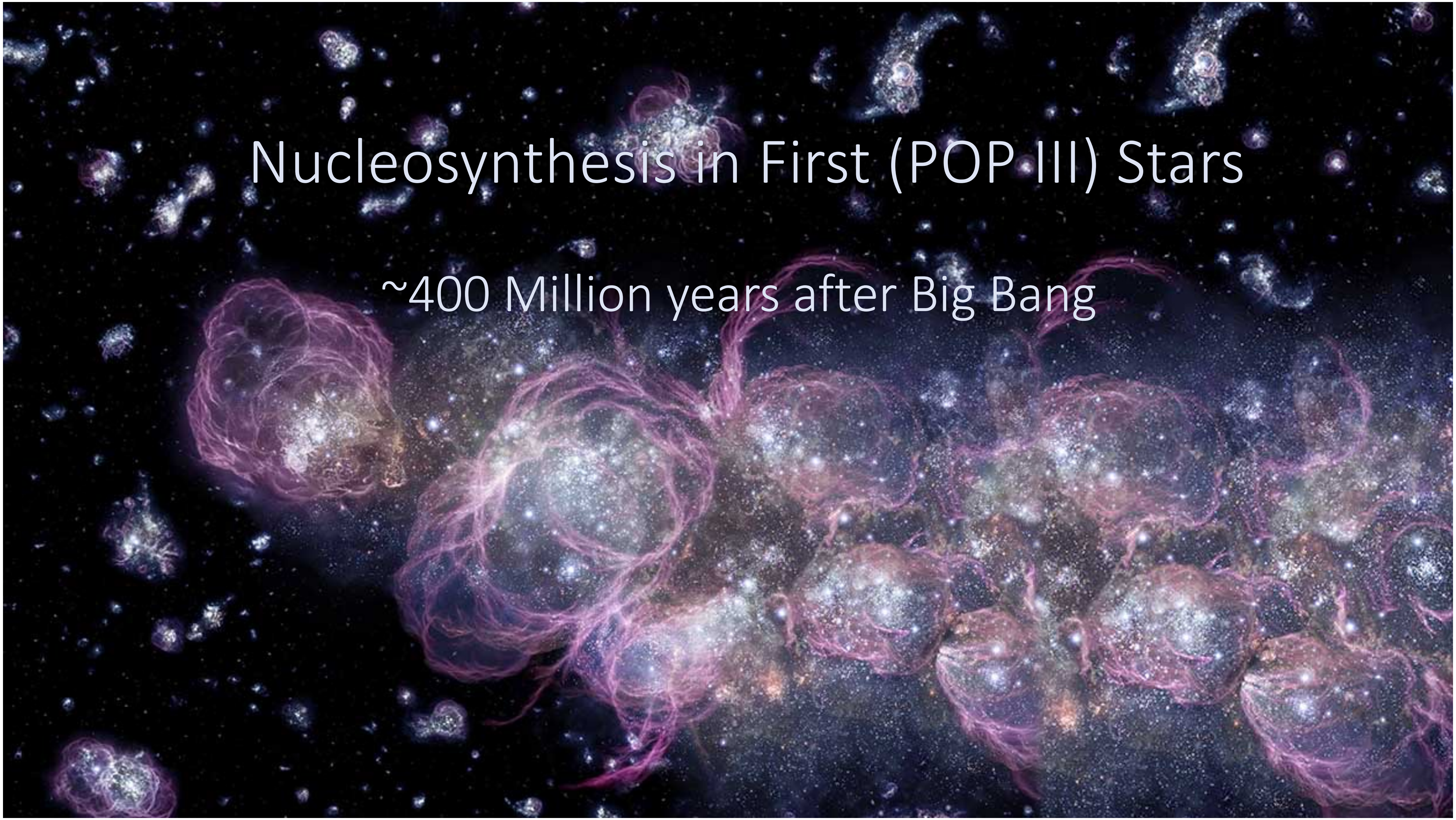
Fixing the ^{7}Li problem by considering first stars



$$\frac{d\,^7Be}{dt} = {}^3He\langle\alpha,\gamma\rangle + {}^{10}B\langle p,\alpha\rangle - \lambda_e\ {}^7Be - {}^7Be\langle p,\gamma\rangle - {}^7Be\langle\alpha,\gamma\rangle - {}^7Be\langle n,p\rangle$$

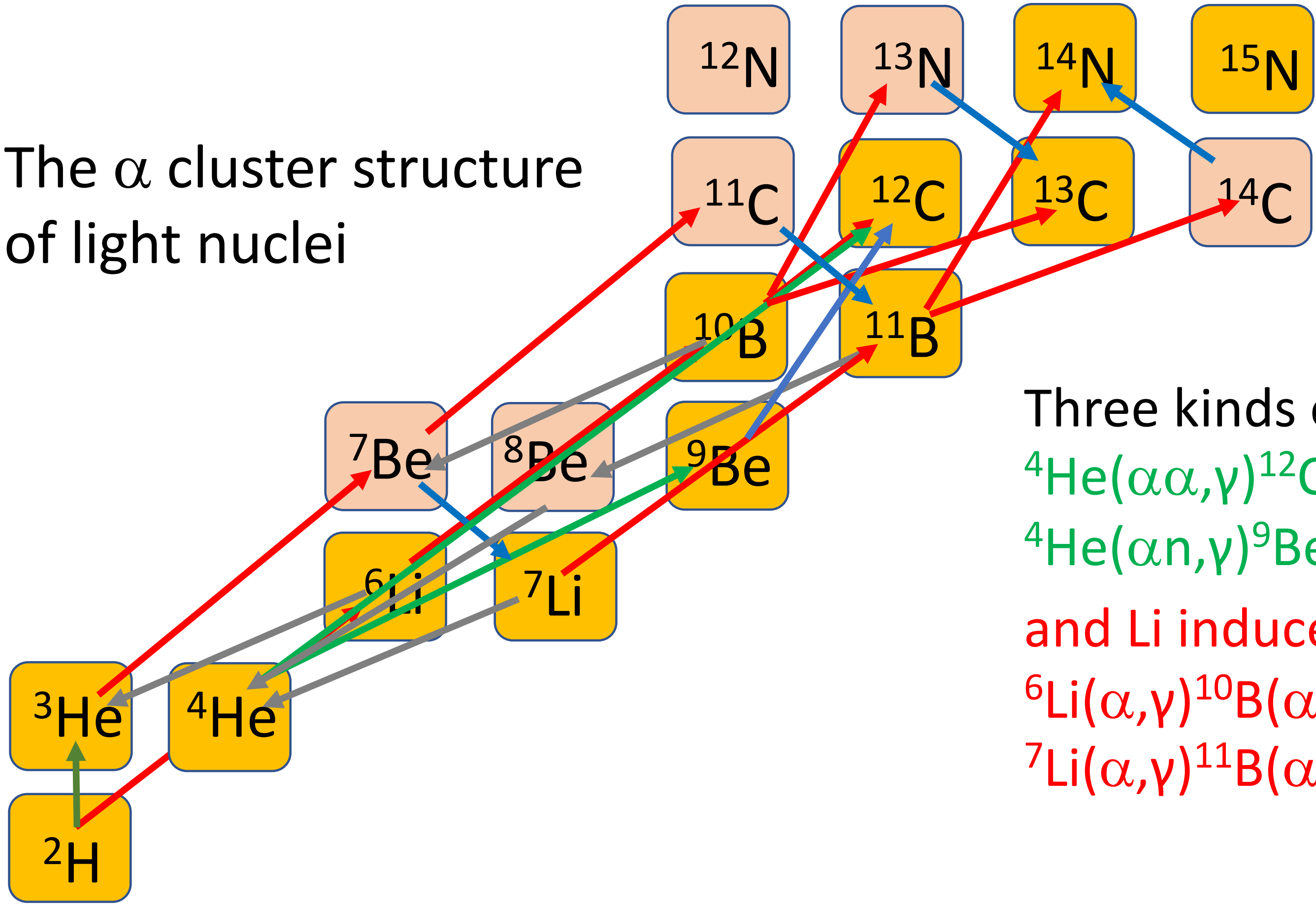
$$\frac{d\,^7Li}{dt} = \lambda_e\ {}^7Be + {}^7Be\langle n,p\rangle - {}^7Li\langle p,\alpha\rangle - {}^7Li\langle\alpha,\gamma\rangle$$

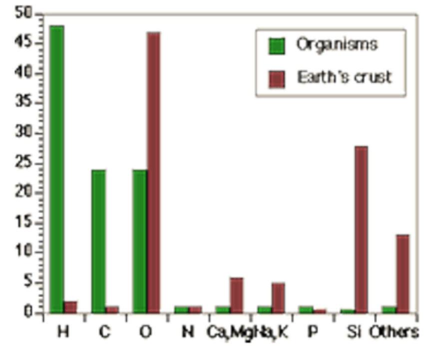
Production of ^{7}Be by and conversion of ^{7}Be to ^{7}Li and reduction of ^{7}Be to ^{11}C / ^{11}B by alpha capture!
Reduction of ^{7}Li with additional alpha capture


Nucleosynthesis in First (POP III) Stars
~400 Million years after Big Bang

The stepping stones for bridging the gap

The α cluster structure of light nuclei





Three kinds of particle fusion reactions:

$^{4}He(\alpha\alpha,\gamma)^{12}C$

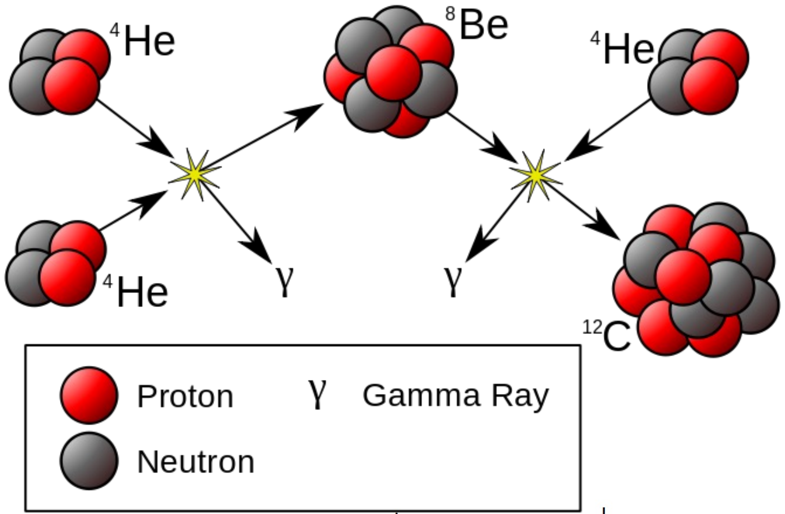
$^{4}He(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$

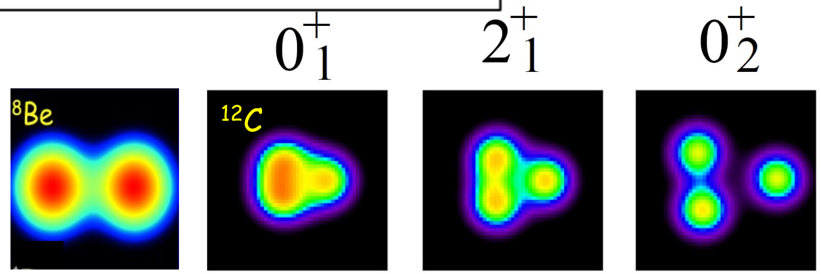
and Li induced capture processes:

$^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$ deuteron cycle

$^{7}Li(\alpha,\gamma)^{11}B(\alpha,n)^{14}N$ neutron source

Nuclear Reactions facilitated by Clusters





Structure simulations by Kanada En'yo and co-workers

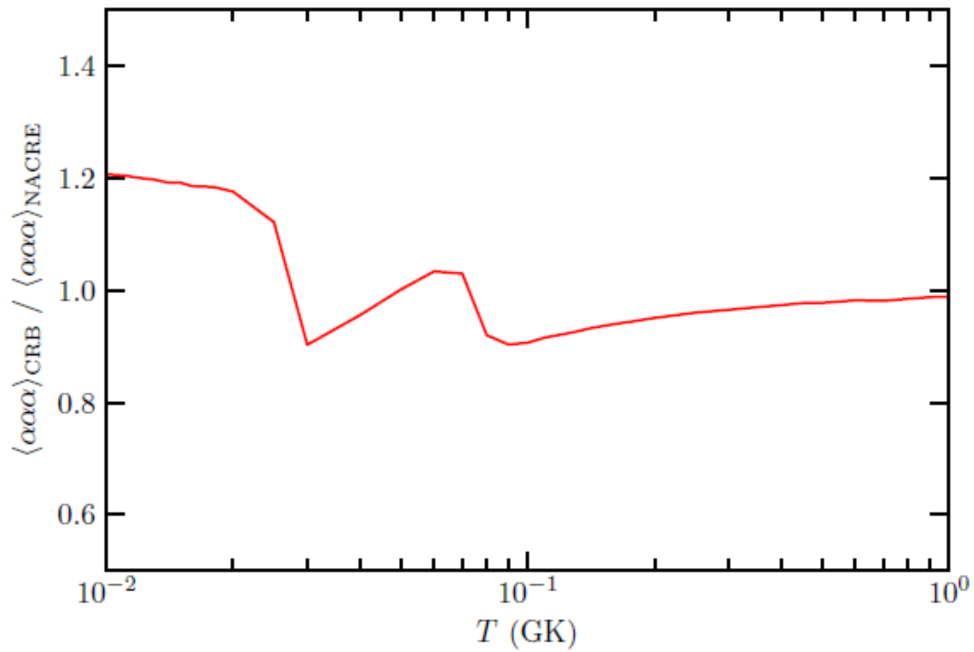
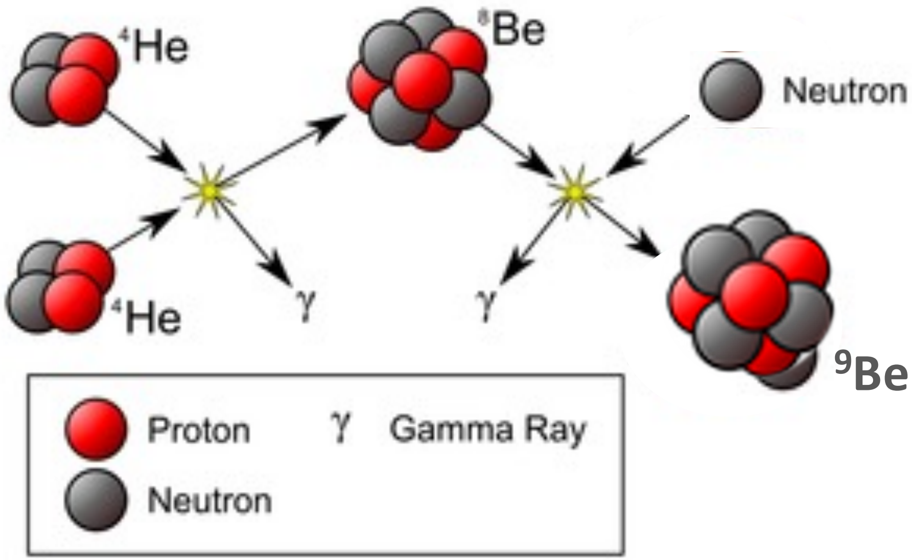


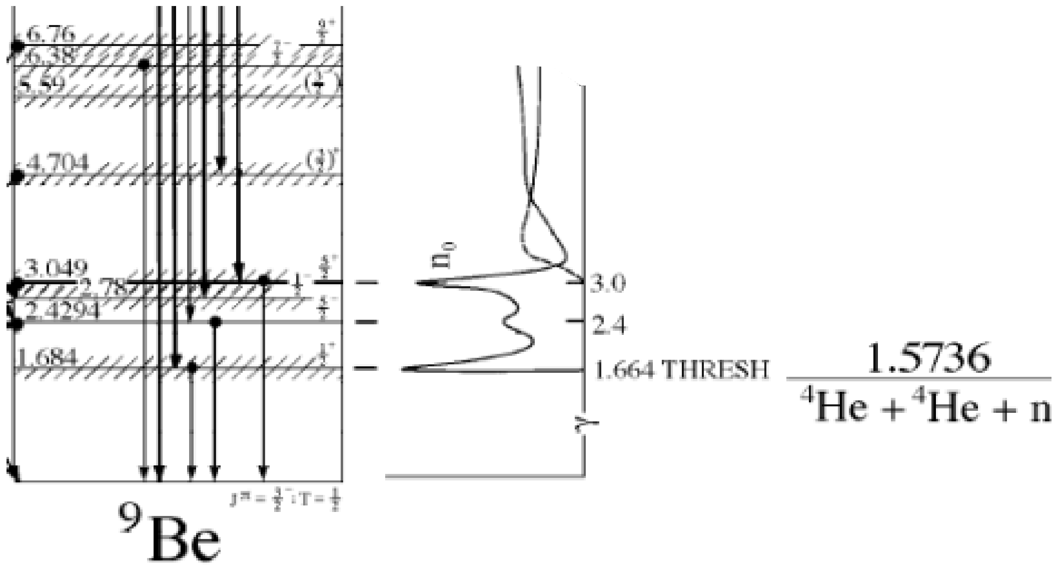
FIG. 3. The ratio of the full calculation of the reaction rate to that given in 1999 by the NACRE collaboration [1].

Taking into account a possible neutron flux?

$^4He(\alpha n,\gamma)^9Be$



Followed by $^9Be(\alpha,n)^{12}C$



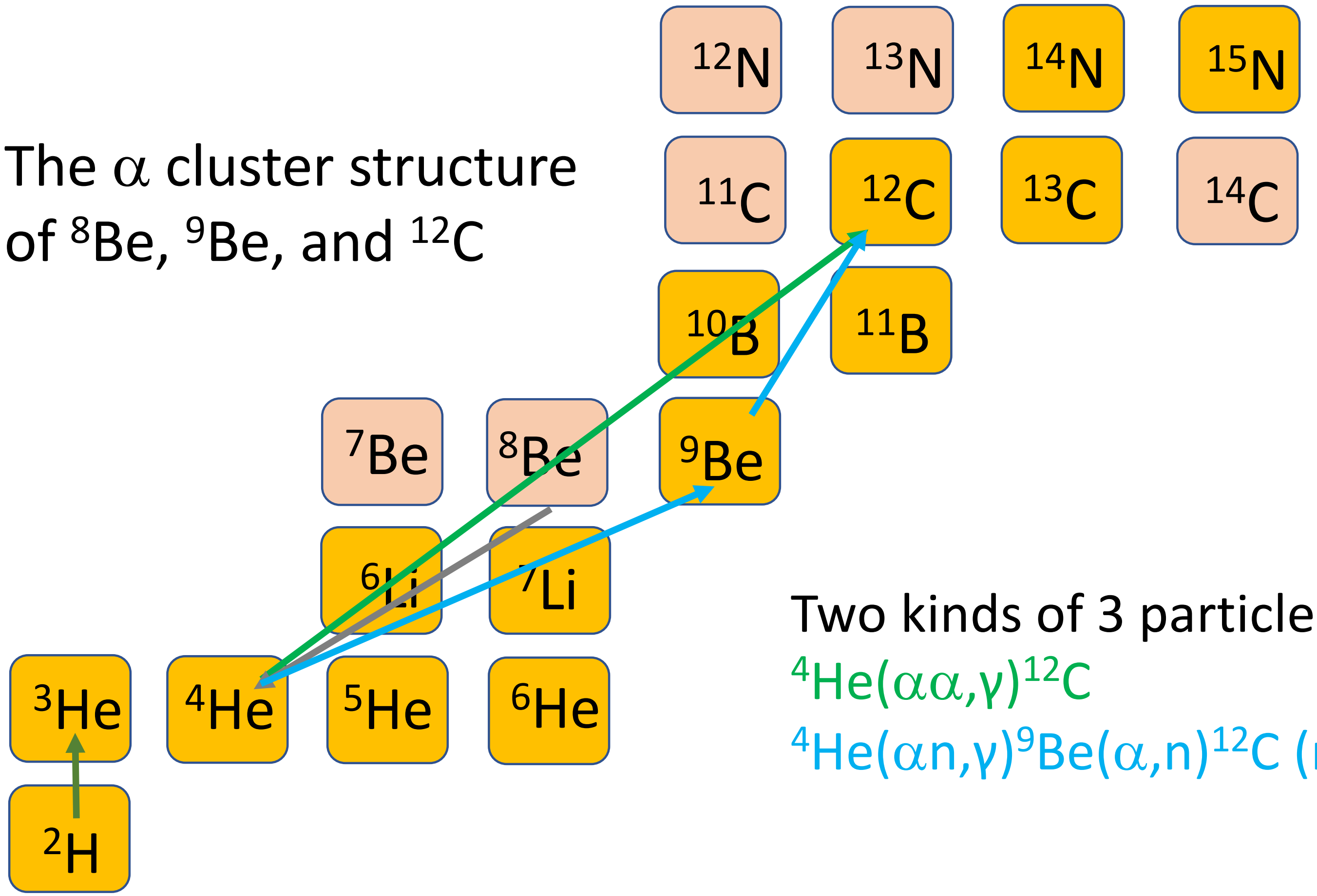
Two-neutron capture reactions in supernovae neutrino bubbles

J. Görres, H. Herndl, I. J. Thompson, and M. Wiescher

Phys. Rev. C **52**, 2231 (**1995)**

The triple α flow

The α cluster structure of ^{8}Be, ^{9}Be, and ^{12}C



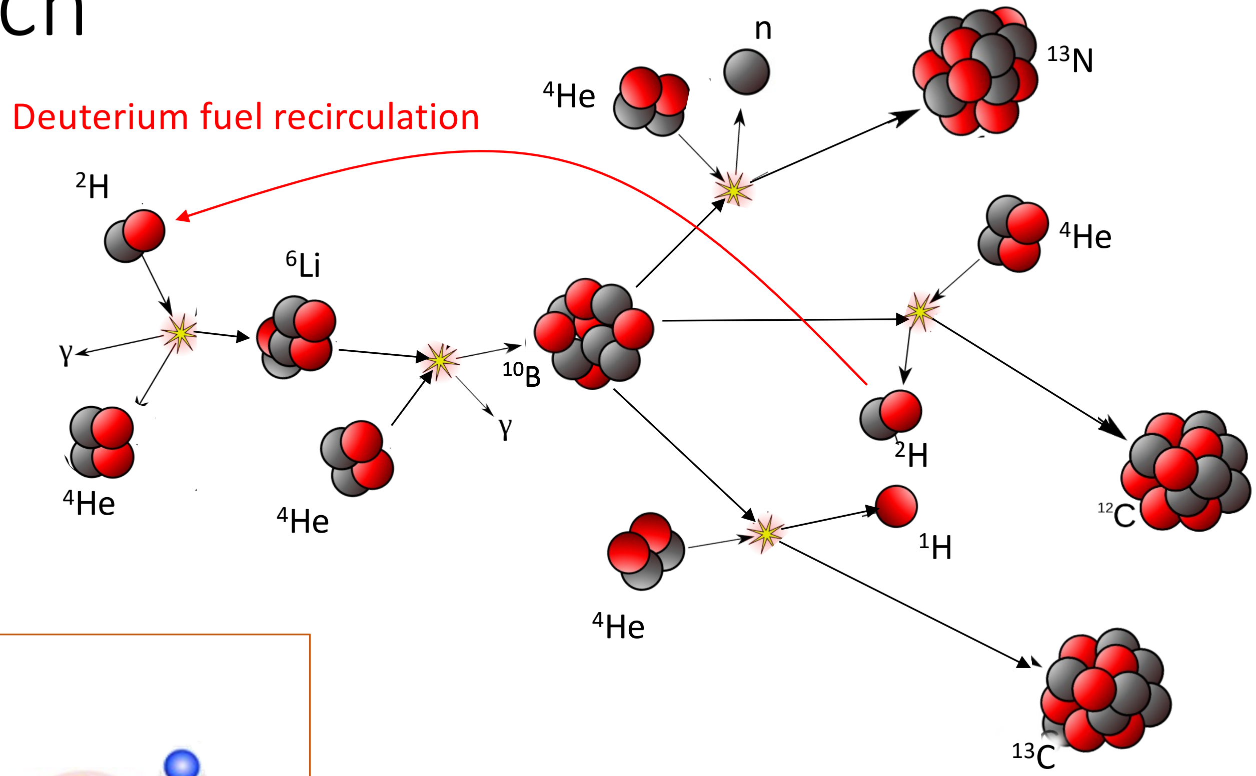
Two kinds of 3 particle fusion reactions:

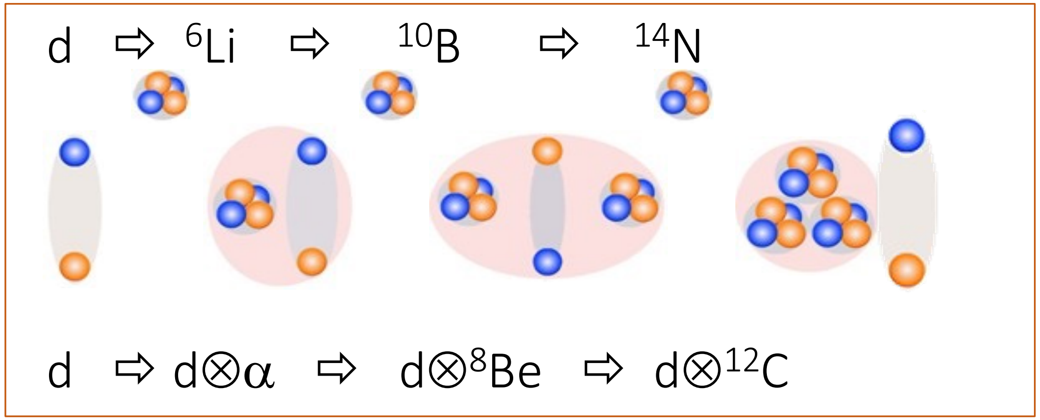
^{4}He($\alpha\alpha$,γ)^{12}C

^{4}He(αn,γ)^{9}Be(α,n)^{12}C (requires neutrons)

^{6}Li-^{10}B-CNO branch

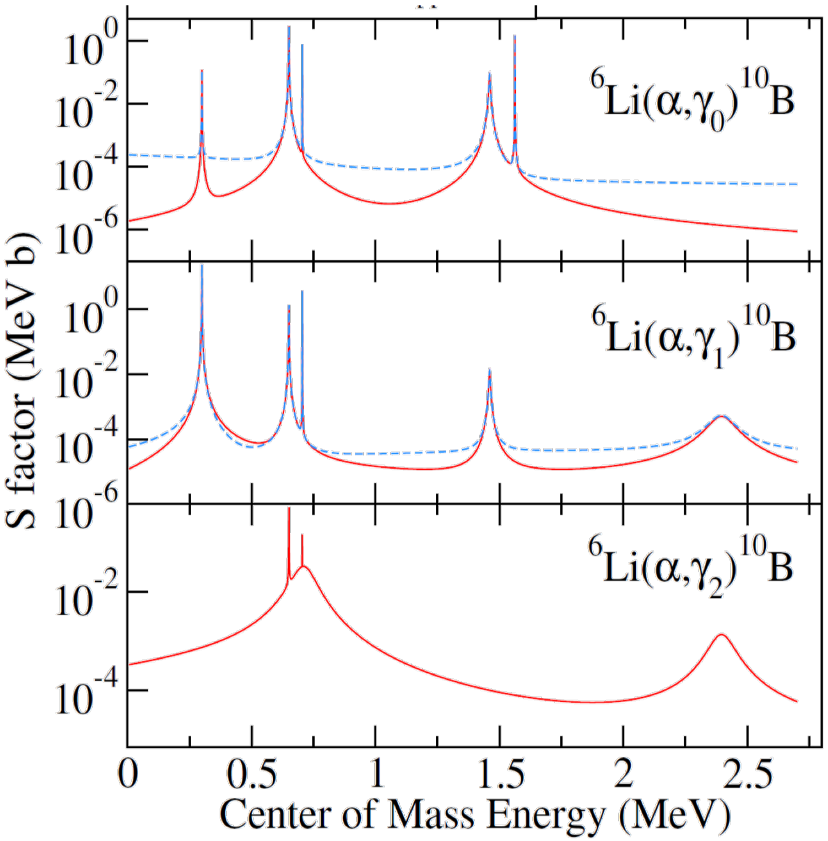
An alpha capture induced reaction cycle on primordial deuterium feeding ^{12}C with some efficiency depending on the proton induced back processing to ^{4}He and ^{7}Li!



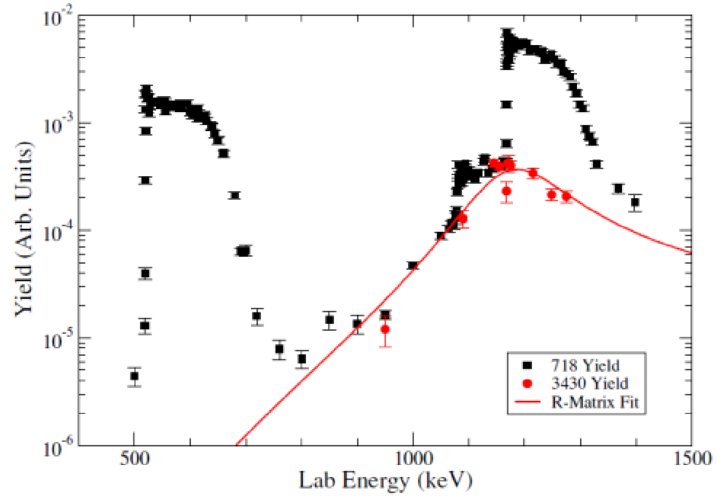


Cluster configurations of the ^{6}Li, ^{10}B and ^{14}N compound nuclei near the alpha thresholds increase the reaction rates!

The $^{6}Li(\alpha,\gamma)^{10}B$ reaction

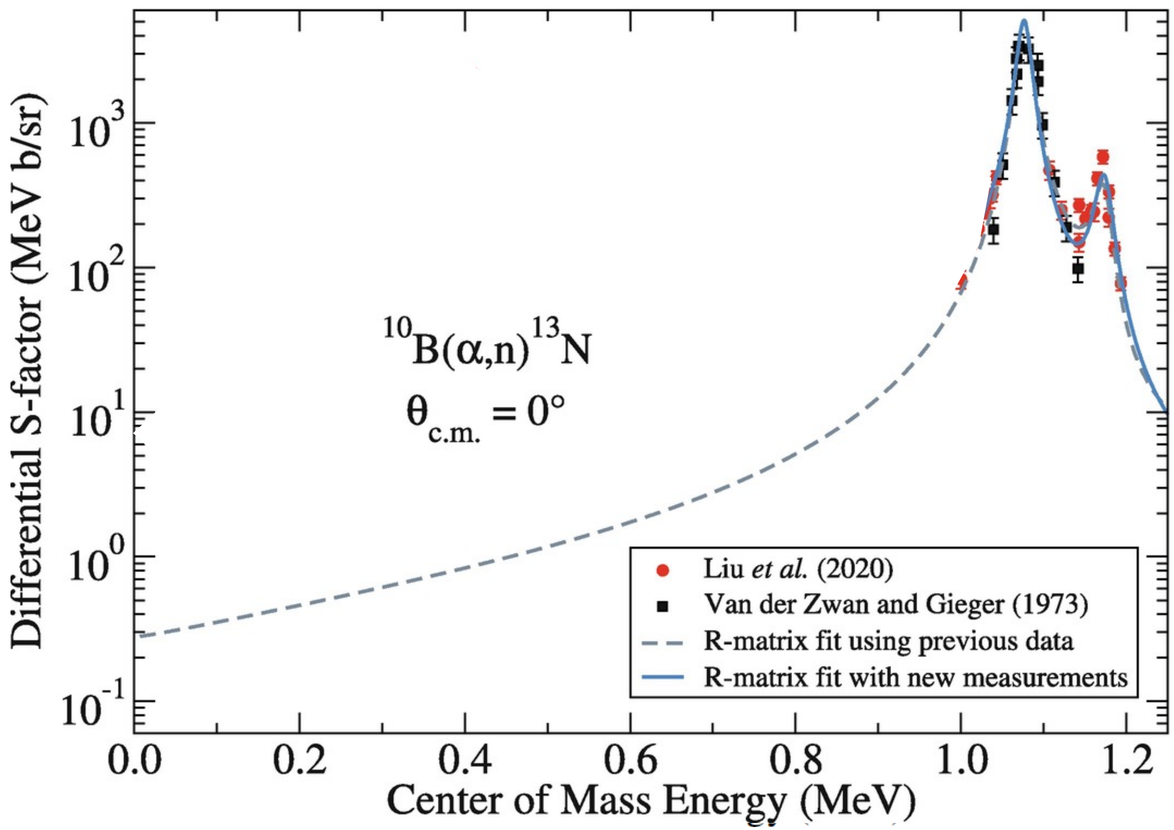


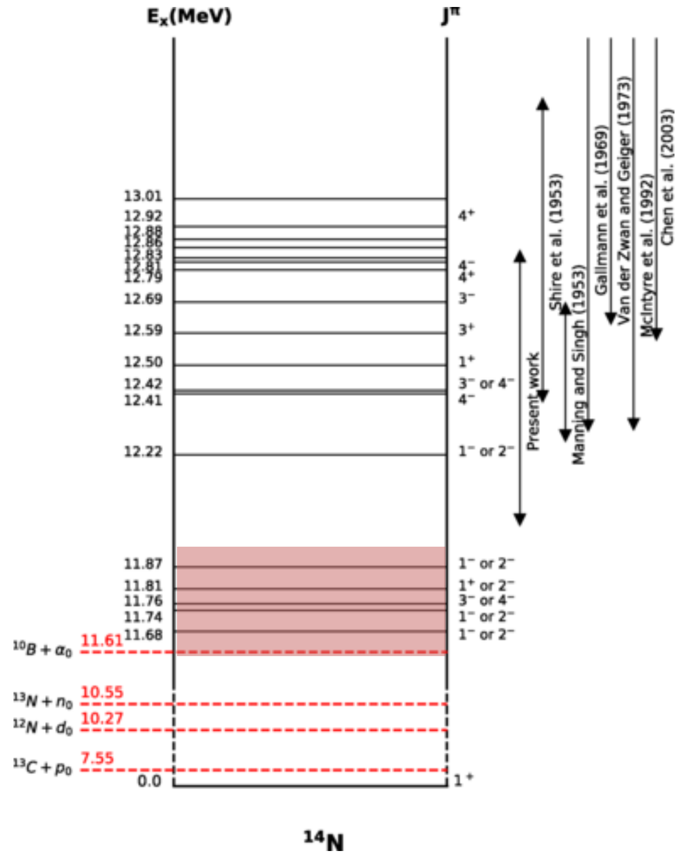
Strong but narrow resonances at ~500 , 1060, and 1150 keV, with one broad state at ~1200 keV, tailing into the low energy range.



Several states and broad interfering resonances and direct capture transitions, adding to the uncertainty at low energy! Narrow low energy resonances need to be re-studied and dc component identified!

The $^{10}B+\alpha$ reaction channels



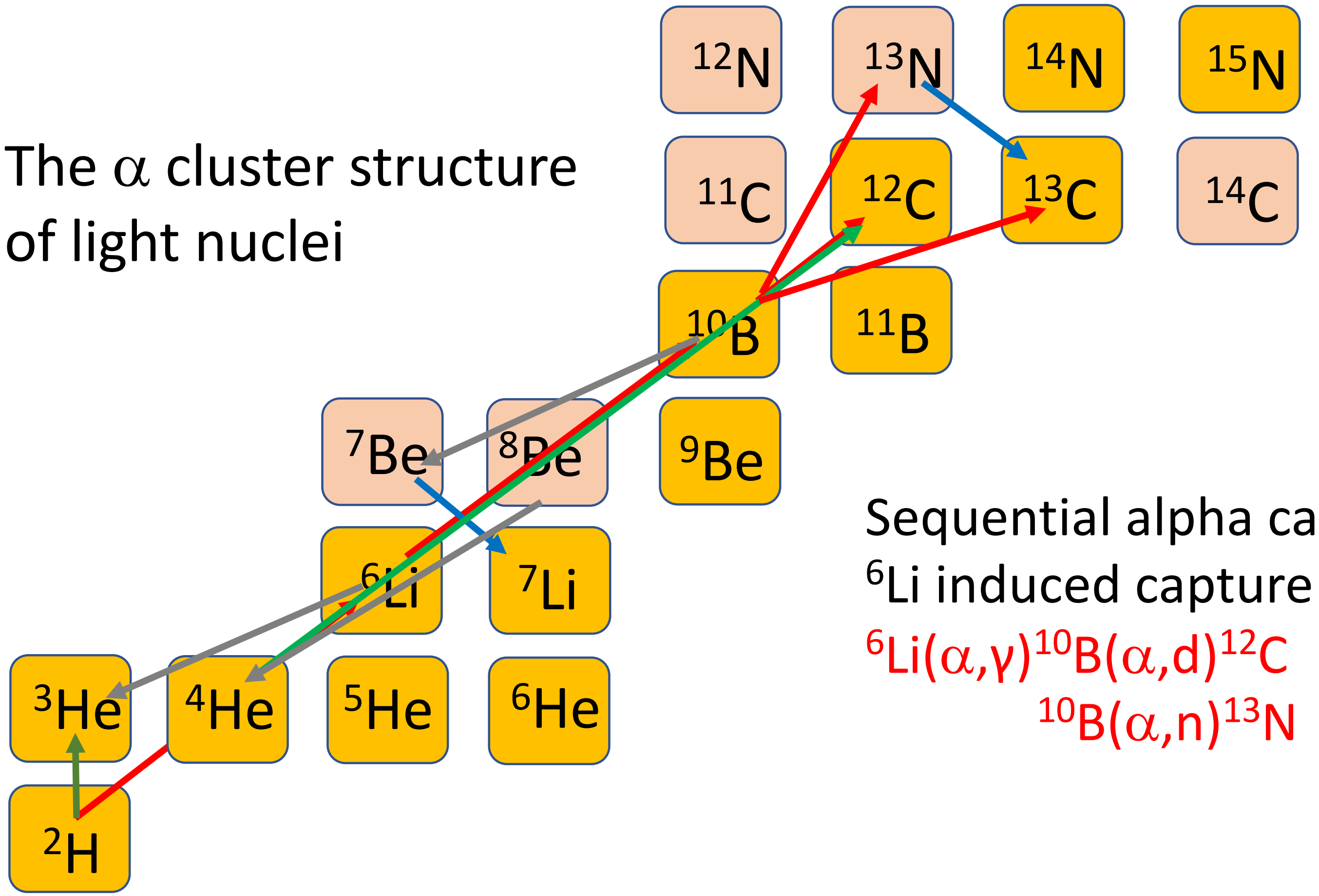


At least two orders of magnitude increase, due to alpha-cluster resonance!

Resonance energy needs experimental confirmation! Further increase in rate is possible!

The ^{6}Li-^{10}B chain

The α cluster structure of light nuclei

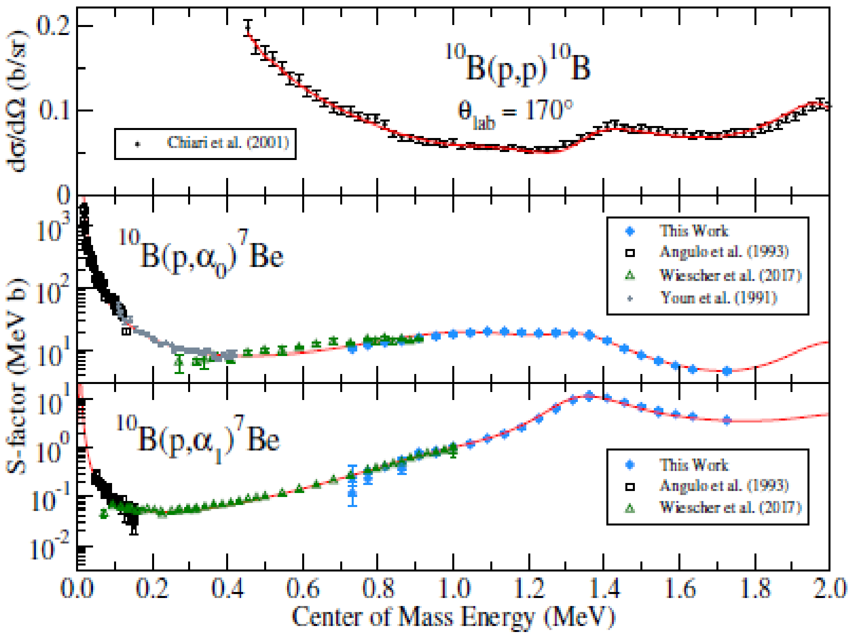


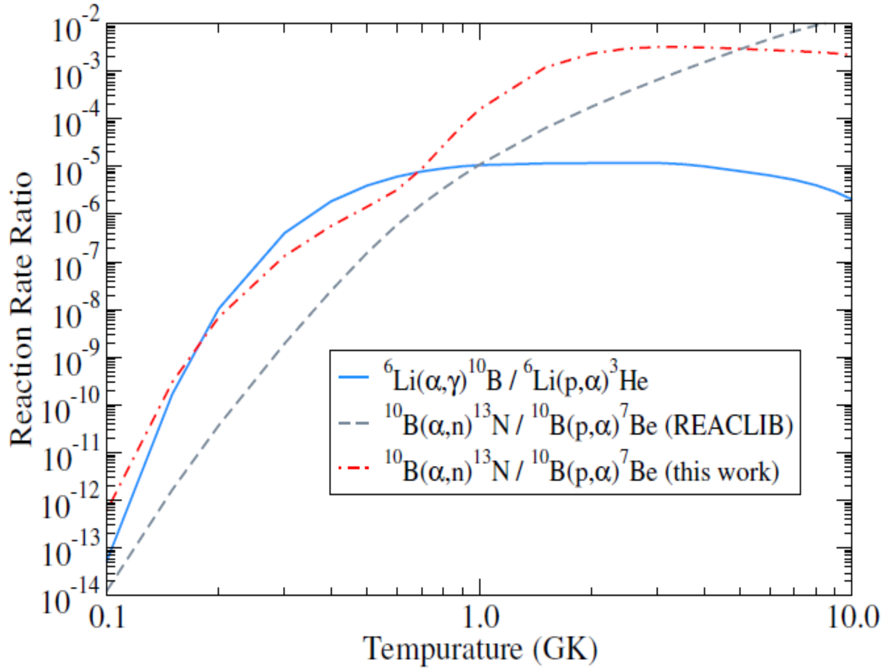
Sequential alpha capture chain via ^{6}Li induced capture processes:

$^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$ deuteron cycle

$^{10}B(\alpha,n)^{13}N$ neutron source

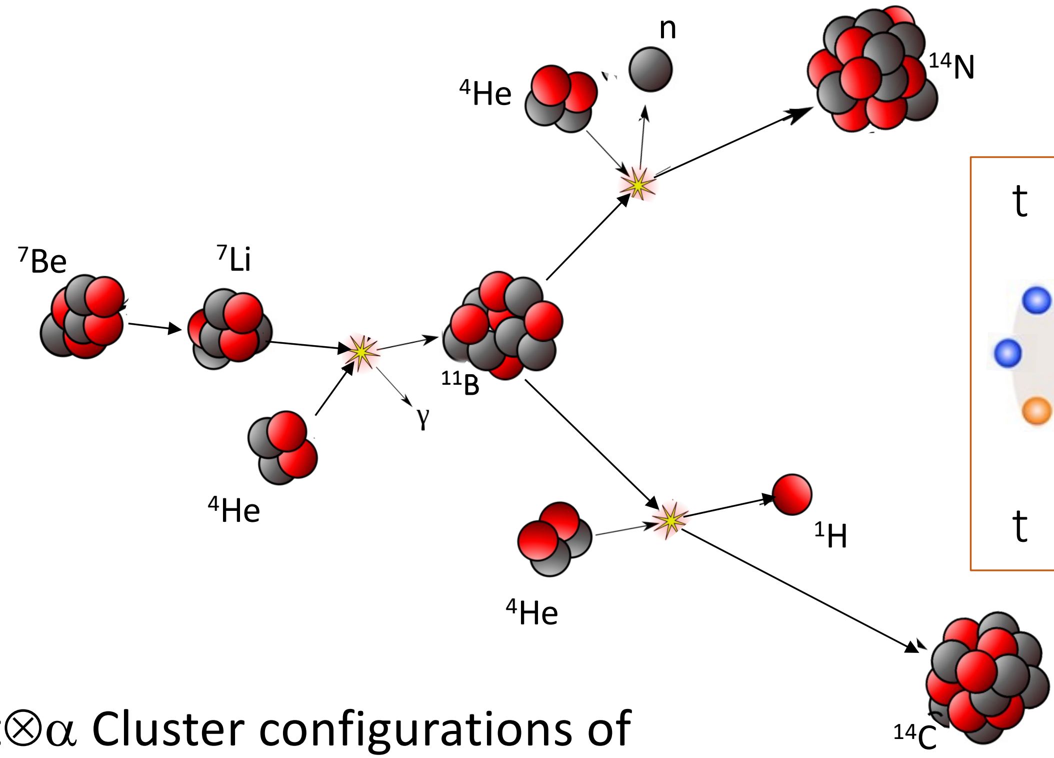
But back-processing to ^{7}Be and therefore ^{7}Li



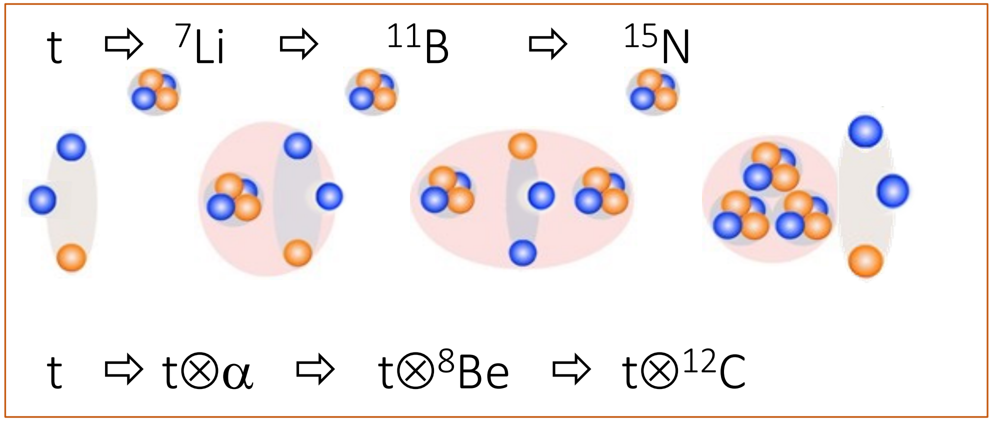


Present rates suggest a several orders of magnitude difference but alpha cluster configurations and local helium enhanced environments may change the ratio !

Alternative ^{7}Li-^{11}B-branch



Potential neutron source in first star environment!



t⊗α Cluster configurations of the ^{7}Li, ^{11}B, and ^{14}N compound nuclei may form alpha clusters at the threshold!

Are there threshold cluster states in the Li and B isotopes?

The $^{7}Li(\alpha,\gamma)^{11}B$ reaction previous data

PHYSICAL REVIEW C VOLUME 29, NUMBER 4 APRIL 1984

Resonant alpha capture by ^{7}Be and ^{7}Li

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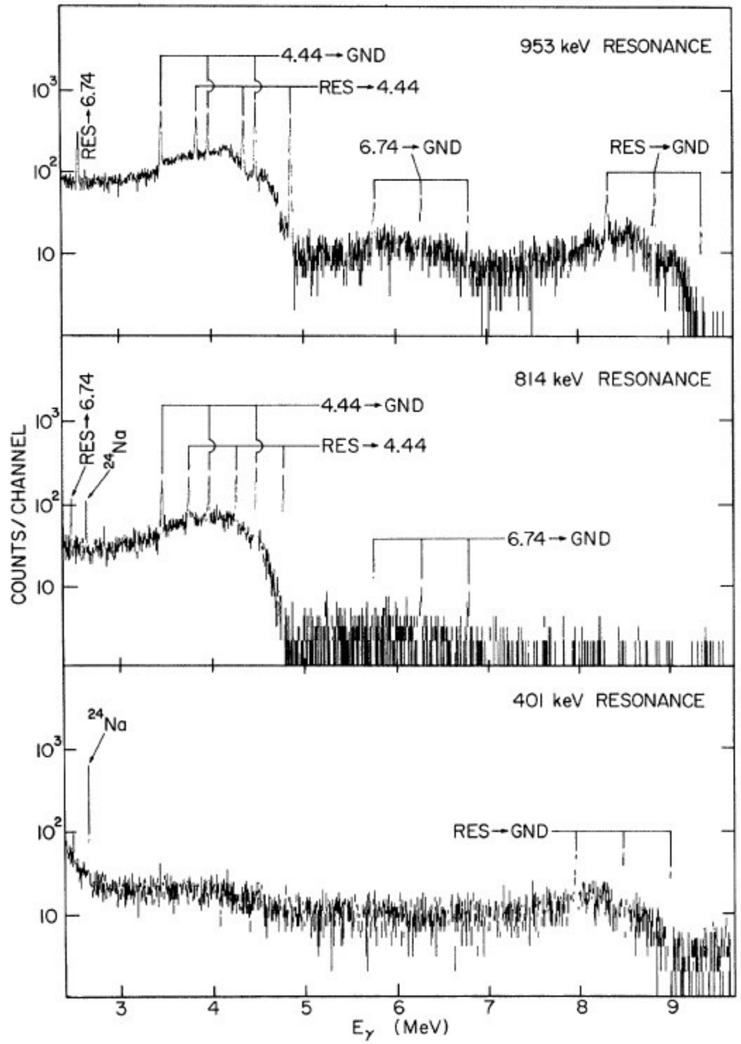
(Received 2 December 1983)



Eur. Phys. J. A **21**, 355–358 (2004)
DOI 10.1140/epja/i2003-10212-2

THE EUROPEAN PHYSICAL JOURNAL A

Absolute resonance strengths in the $^{6,7}Li(\alpha,\gamma)^{10,11}B$ reactions

Gy. Gyürky[1,a], Zs. Fülöp[1], E. Somorjai[1], G. Kiss[1,2], and C. Rolfs[3]

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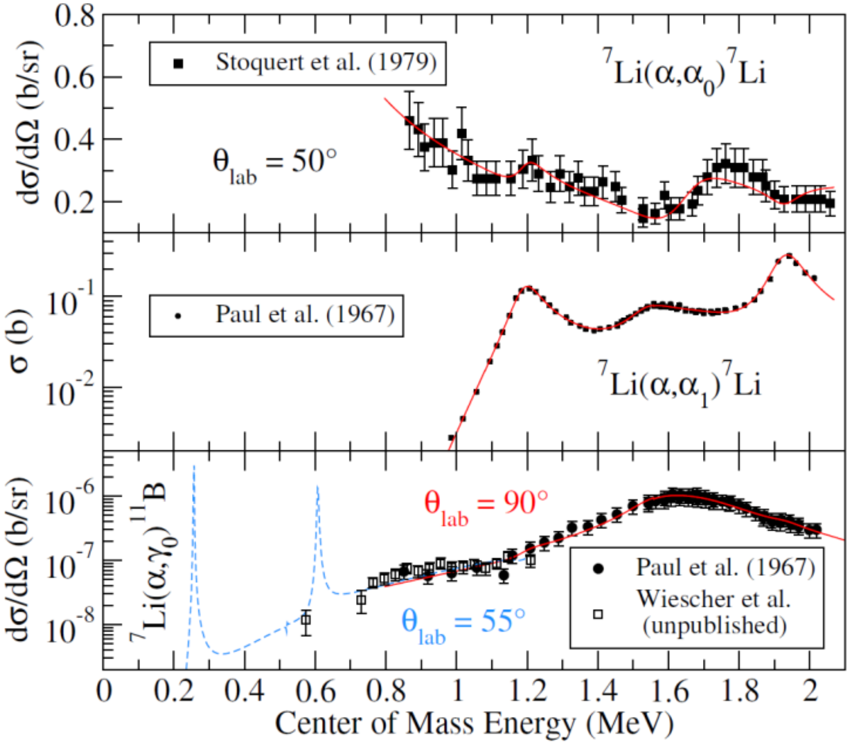
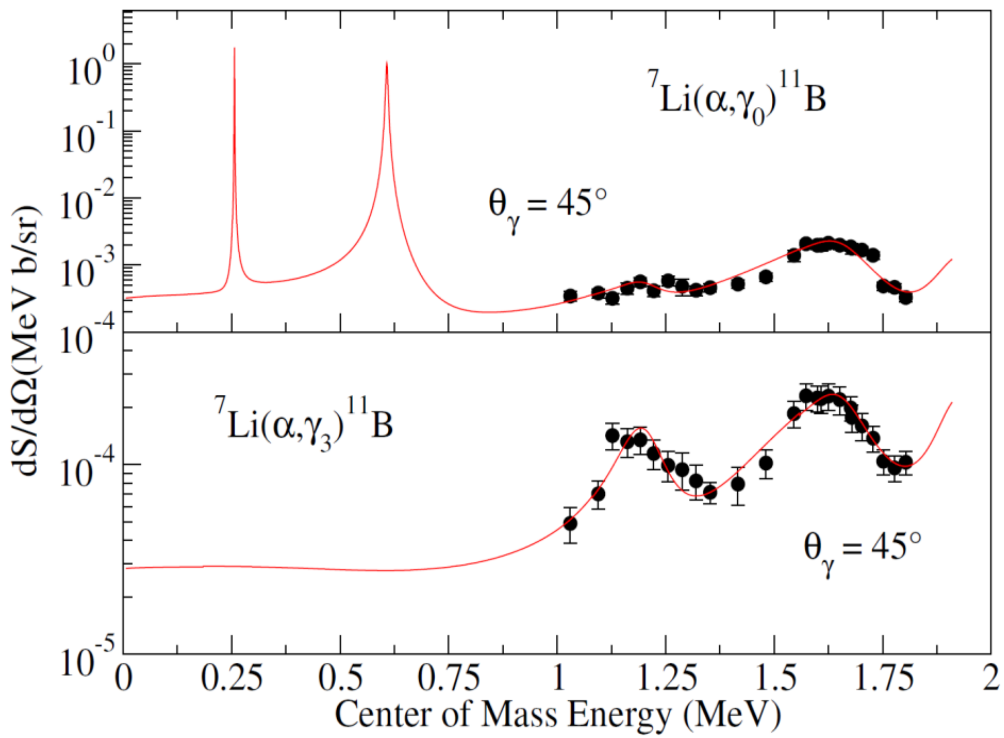
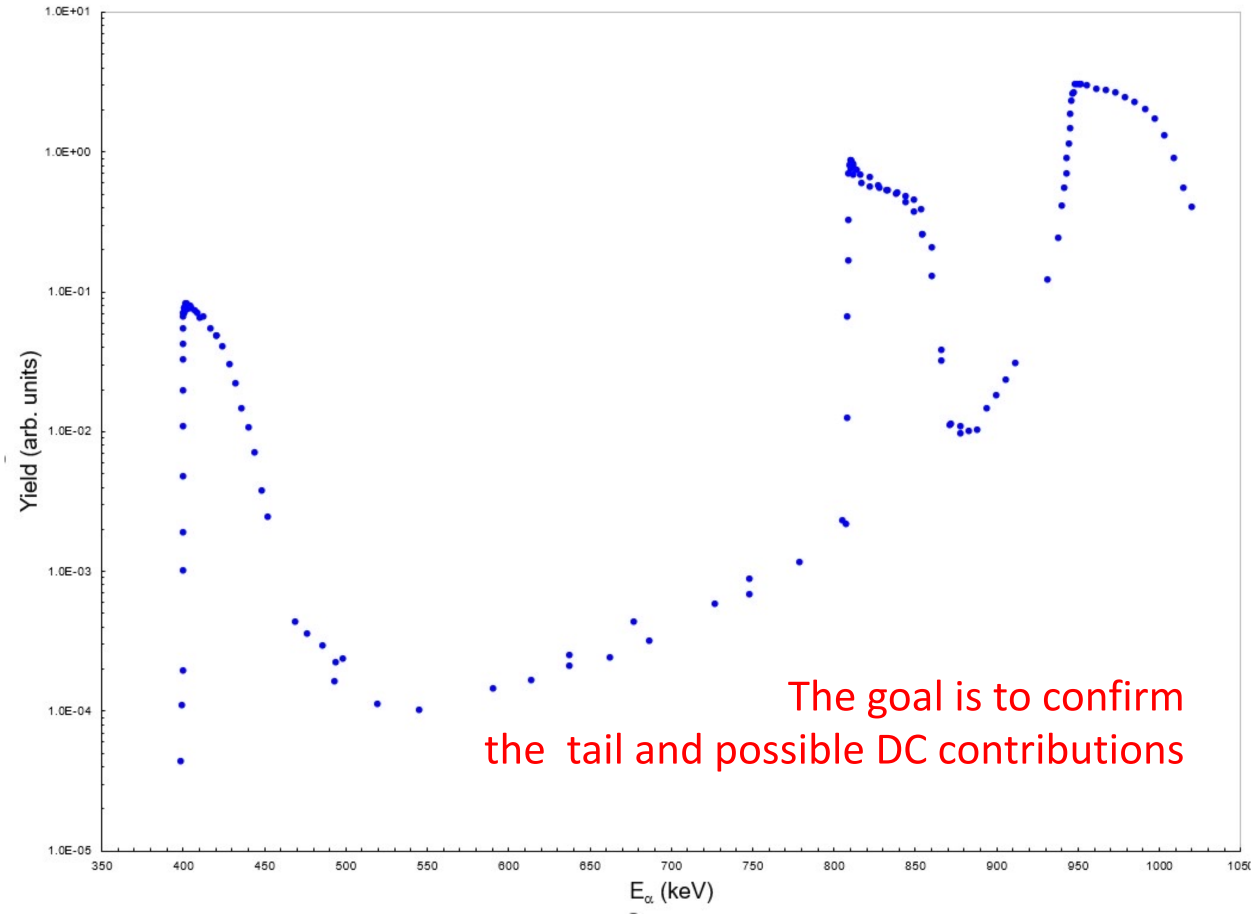
The $^{7}Li(\alpha,\gamma)^{11}B$ reaction recent NSL data



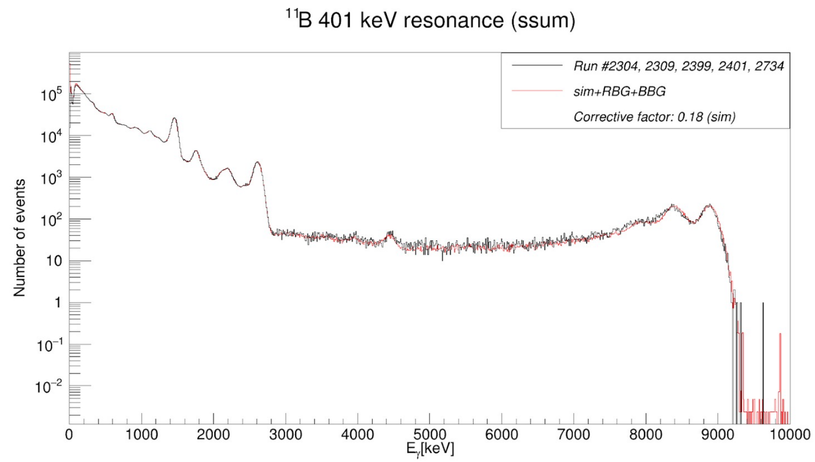


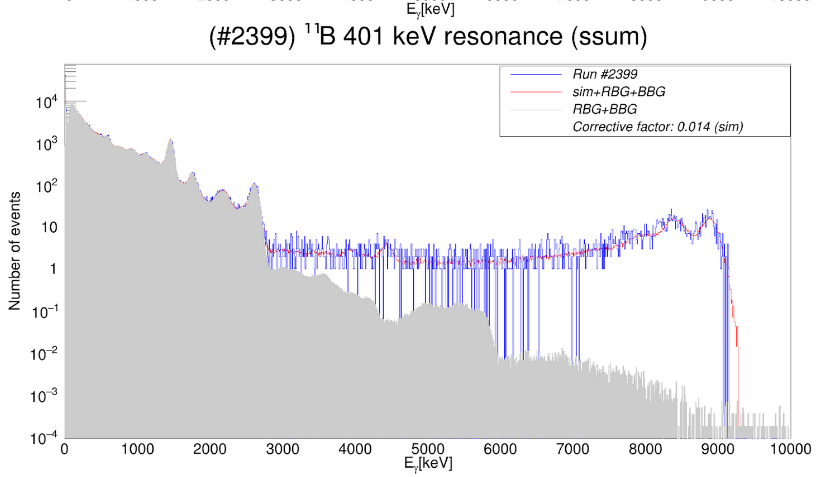
Incomplete measurements, but CASPAR studies expanded the range to 400 keV

The $^{7}Li(\alpha,\gamma)^{11}B$ reaction, new CASPAR data

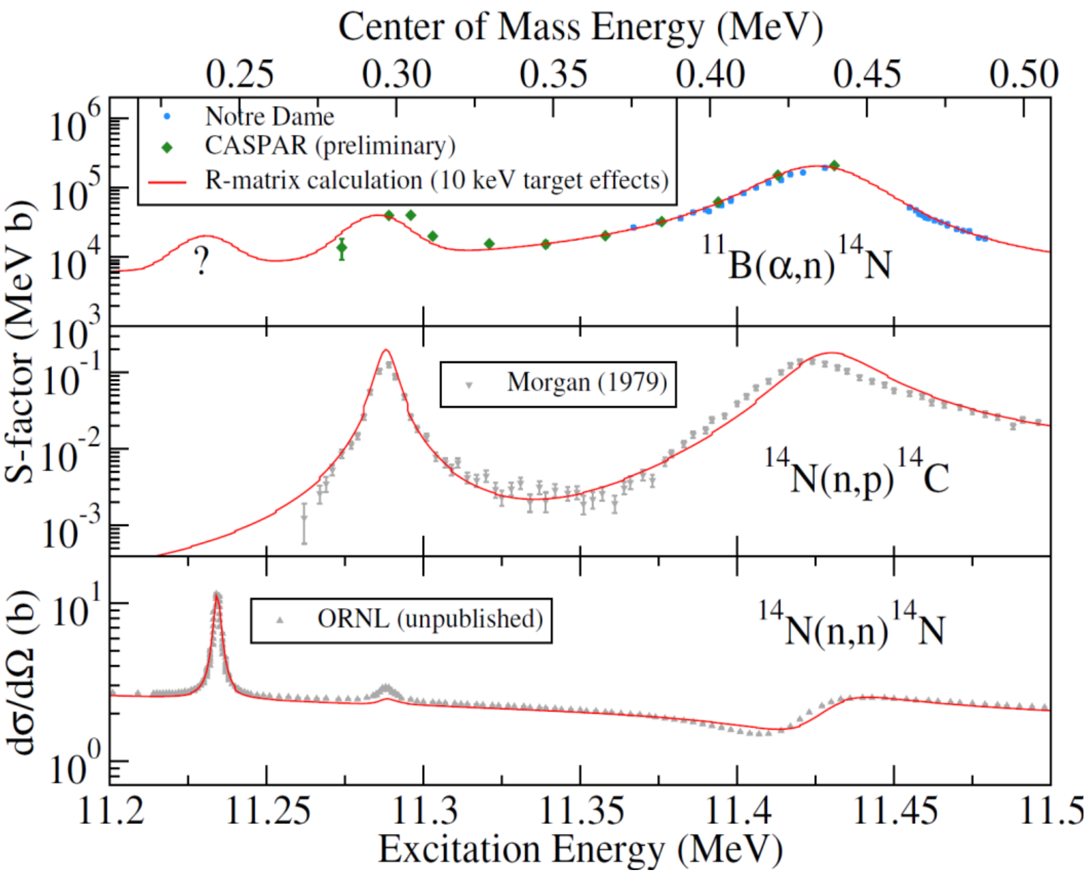


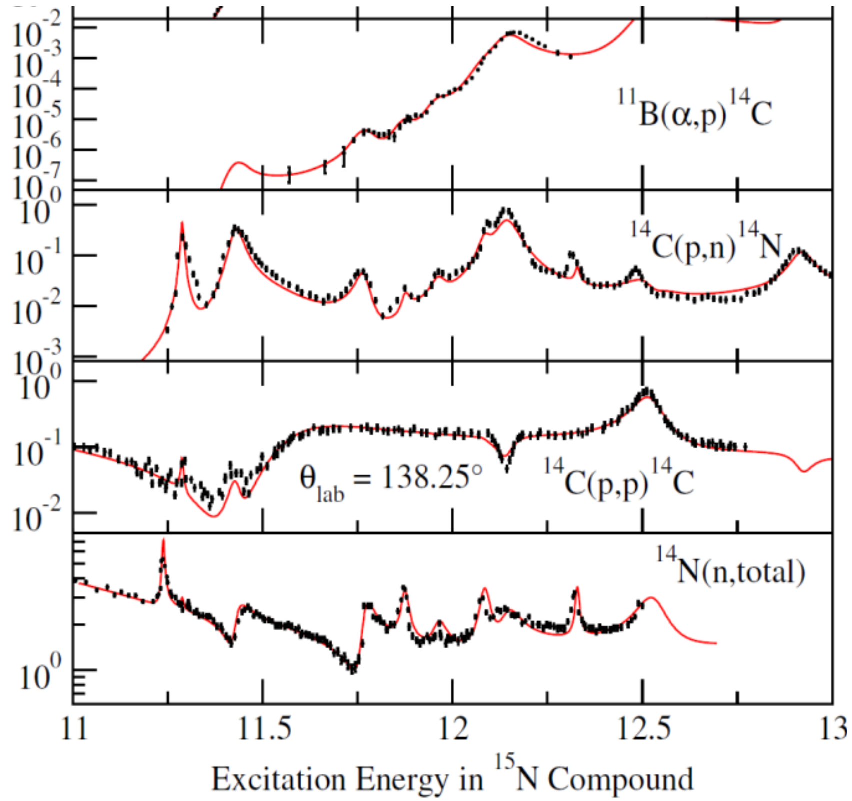
The goal is to confirm
the tail and possible DC contributions





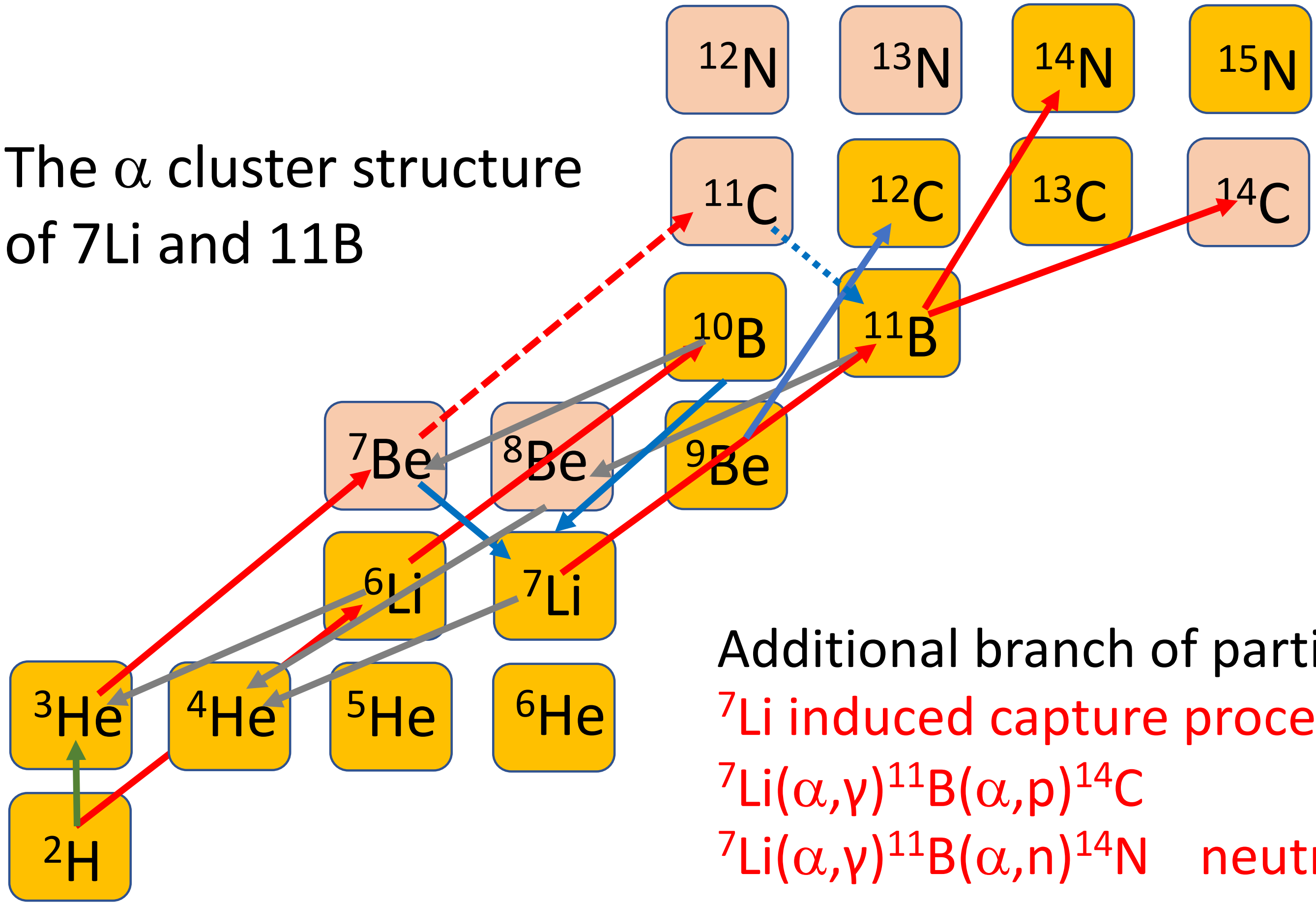
The $^{11}B+\alpha$ channels





^{7}Li-^{11}B-CNO branch

The α cluster structure
of 7Li and 11B



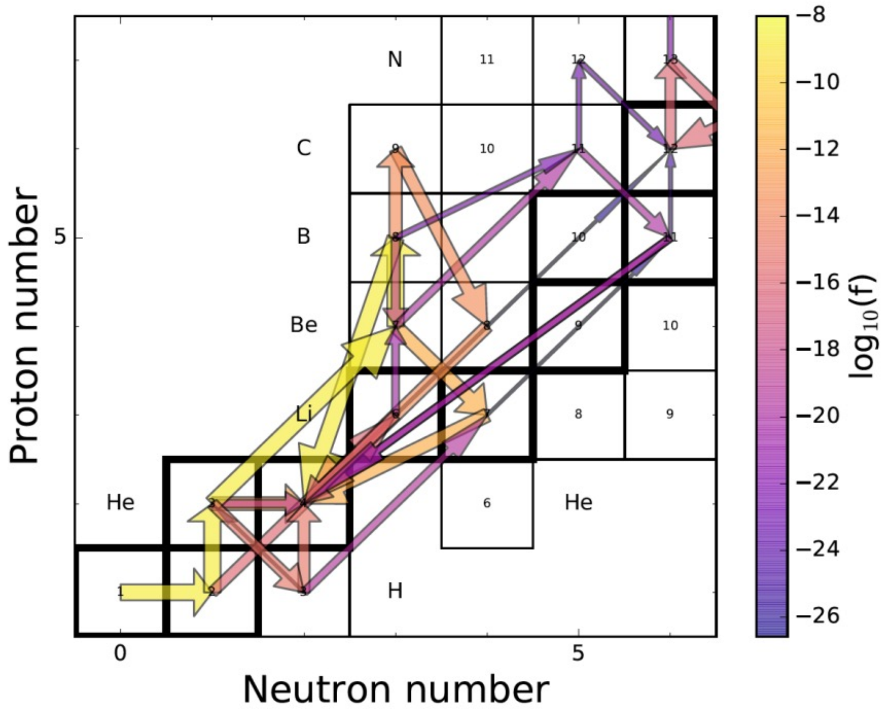
Additional branch of particle fusion reactions:

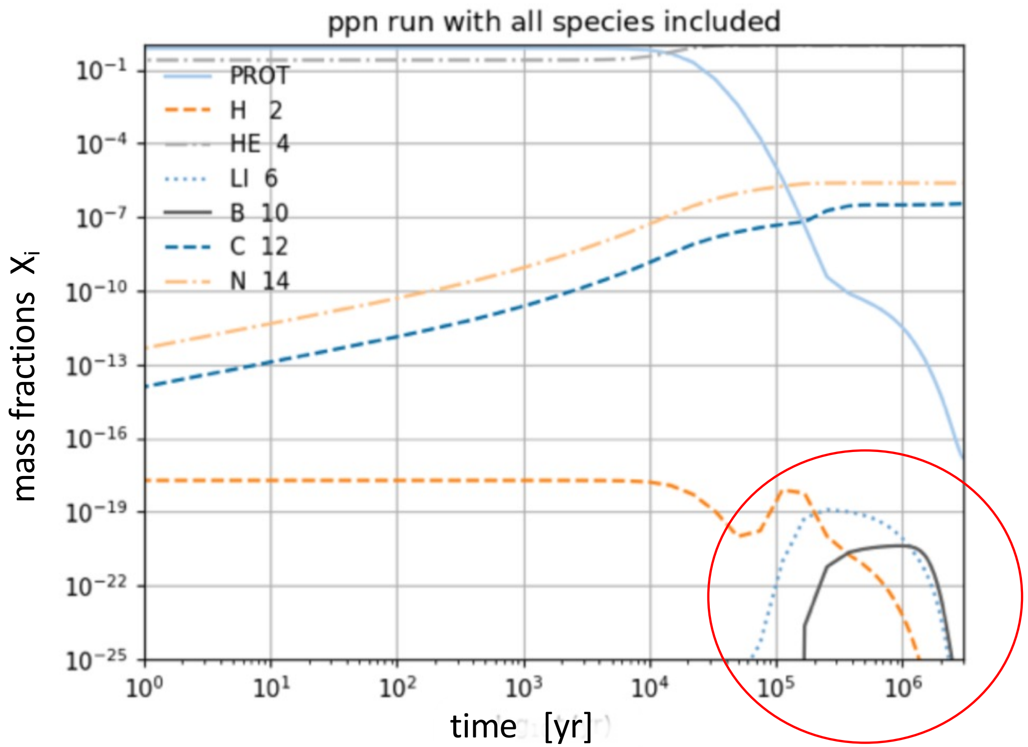
^{7}Li induced capture processes:

^{7}Li(α,γ)^{11}B(α,p)^{14}C

^{7}Li(α,γ)^{11}B(α,n)^{14}N neutron source

NuGRID results in simulating first stars





Reaction path depends sensitively on temperature and abundance conditions.
With decline of hydrogen in pp-chains, alpha induced reactions take over.

Summary and Conclusion

- Formation of first stars appears to be a random mechanism
- Primordial Elements provide fuel for first stars
- Several ways to bridge the A=5,8 gaps
- Efficiency depends on fuel supply and fuel cycling
- Modeling is promising, but …
- Additional data and additional simulations are needed to come to a conclusive picture