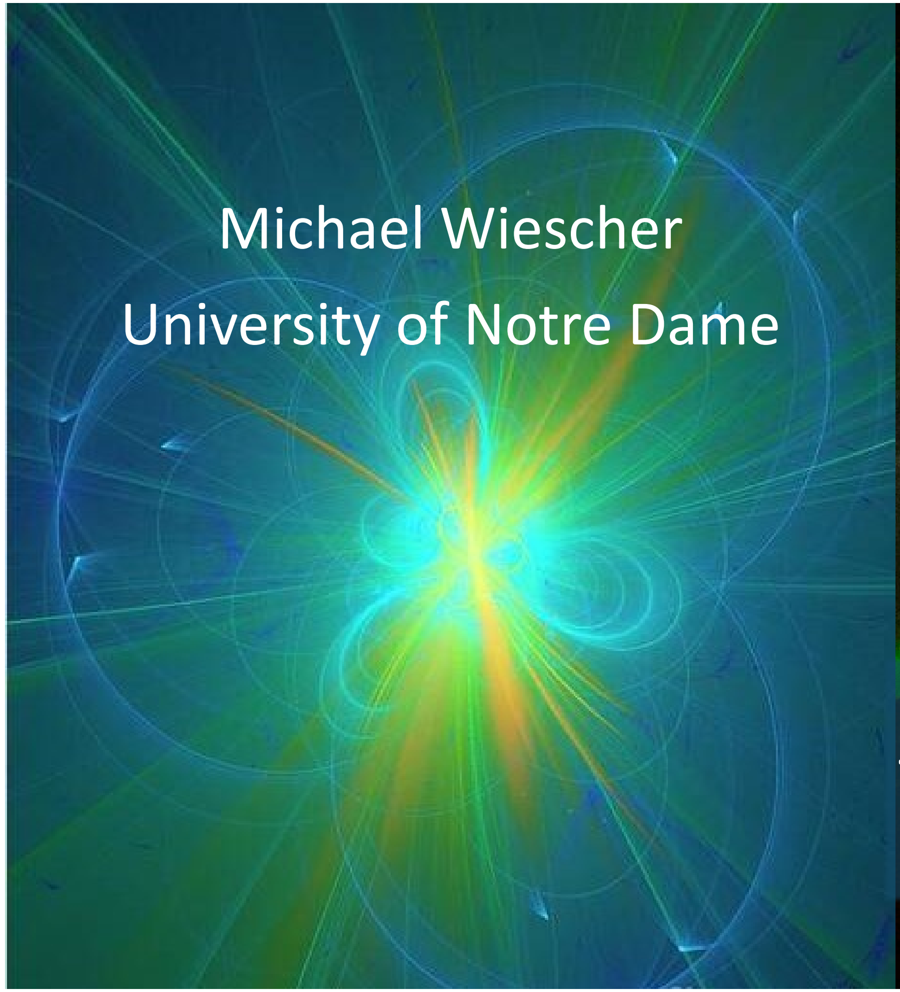
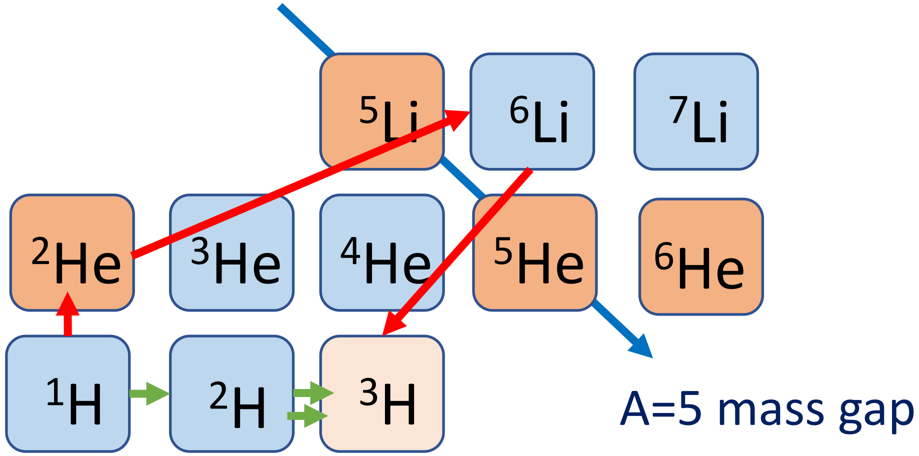
Tritium as neutron storage in explosive nucleosynthesis processes

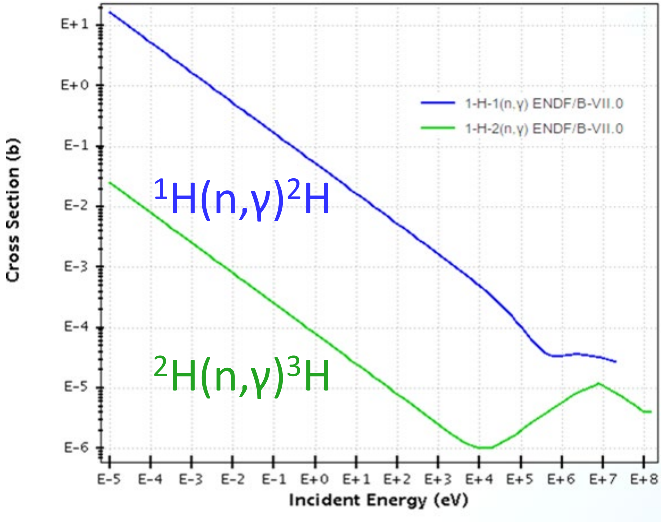


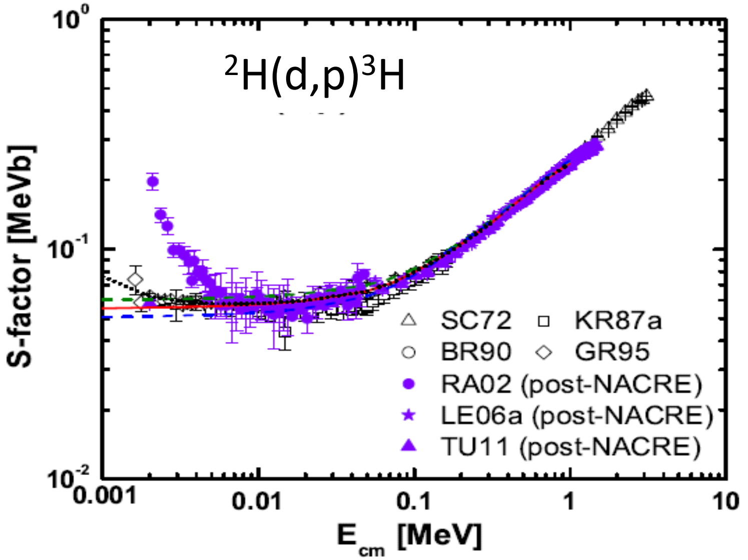
Michael Wiescher
University of Notre Dame

Formation of tritium
Tritium as neutron storage
Release of neutrons

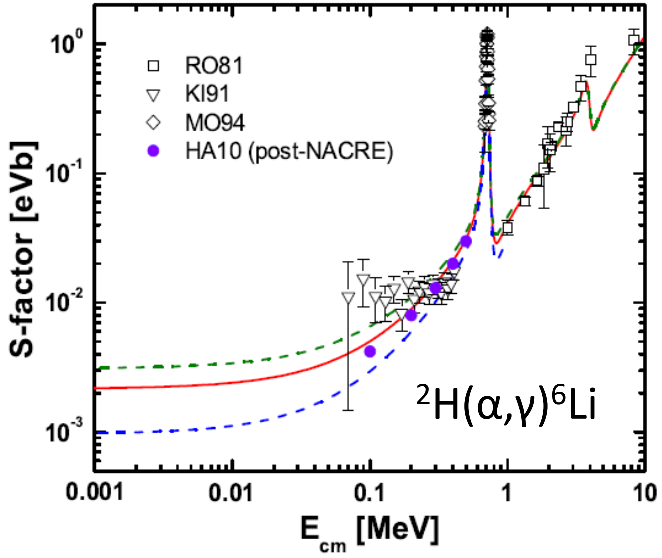
The production of tritium in hydrogen burning

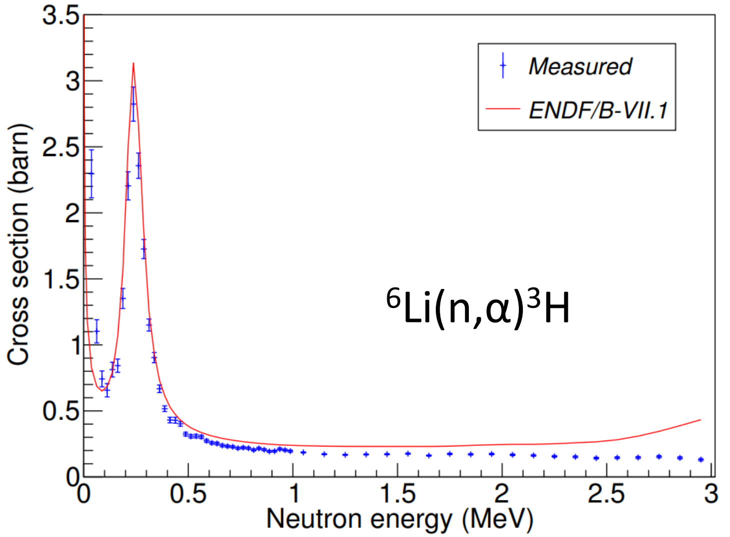






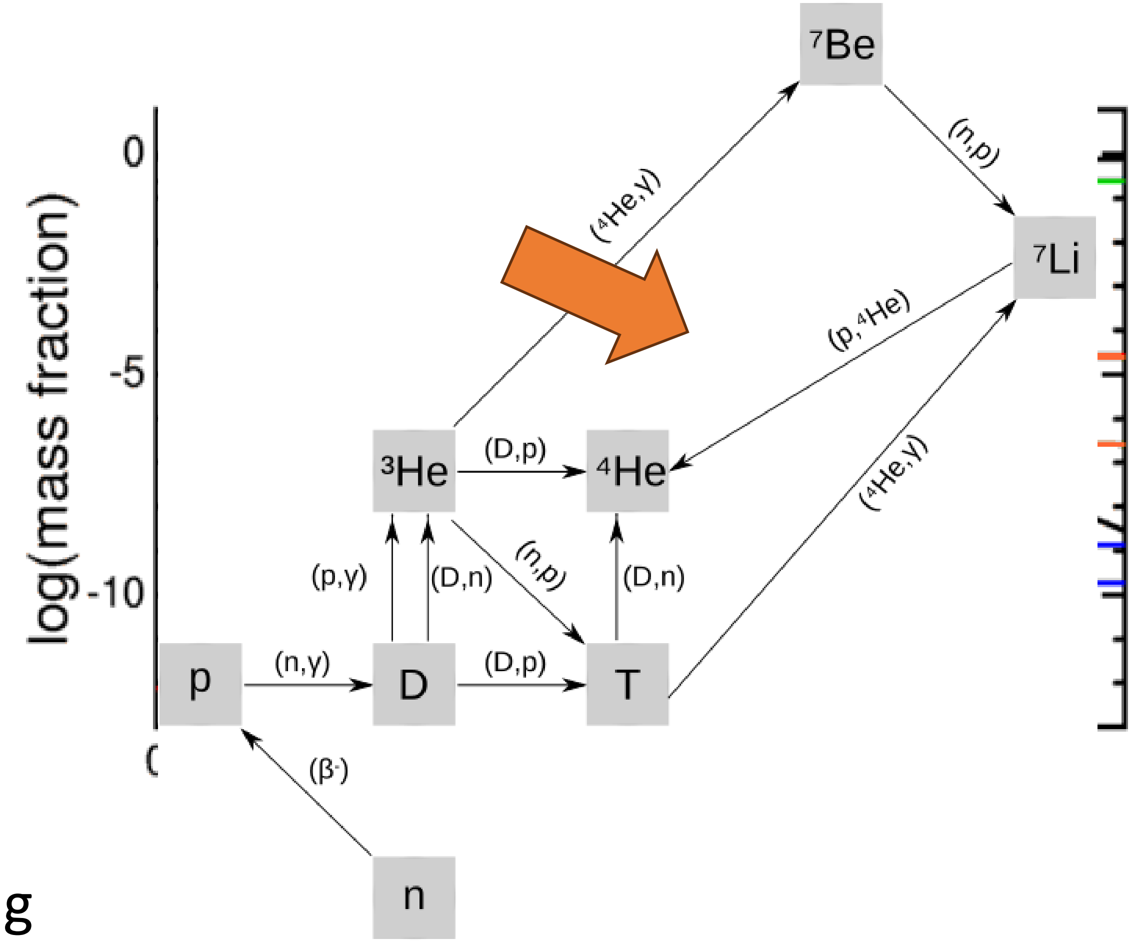
^{2}H (deuterium) absorbs neutrons with three orders of magnitude reduced probability (moderator in CANDU reactors), but an alternative is deuteron induced neutron transfer at low energies: ^{1}H(n,γ)^{2}H(d,p)^{3}H and charge exchange ^{3}He(n,p)^{3}H!





Formation of tritium as neutron store

Big Bang
nucleosynthesis building heavier elements within a 10 minute timescale



^{1}H(n,γ) ^{2}H(n,γ)/(d,p)^{3}H(α,γ)^{7}Li

^{3}H serves as intermediary storage for neutrons, facilitating the bridge of the mass 5 and mass 8 gap feeding the heavier isotopes while generating a high neutron flux if the reaction rates are competitive with inverse ^{7}Li(p,α)^{4}He process

^{7}Li(α,γ)^{11}B(α,n)^{14}N or ^{11}B(t,n)^{13}C(t,n)^{15}N

^{7}Li(t,n)^{9}Be(α,n)^{12}C(t,n)^{14}N or ^{9}Be(t,n)^{11}B(α,n)^{14}N or ^{11}B(t,n)^{13}C

Expanded Big Bang scenario based on tritium

Adopting increased tritium induced reaction rates leads to an intense secondary neutron release in a complex network of nuclear reactions!

Considered here are:

$^{3}H(t,\gamma)^{6}He(t,n)^{8}Li(\alpha,n)$ (triple-triton reaction)

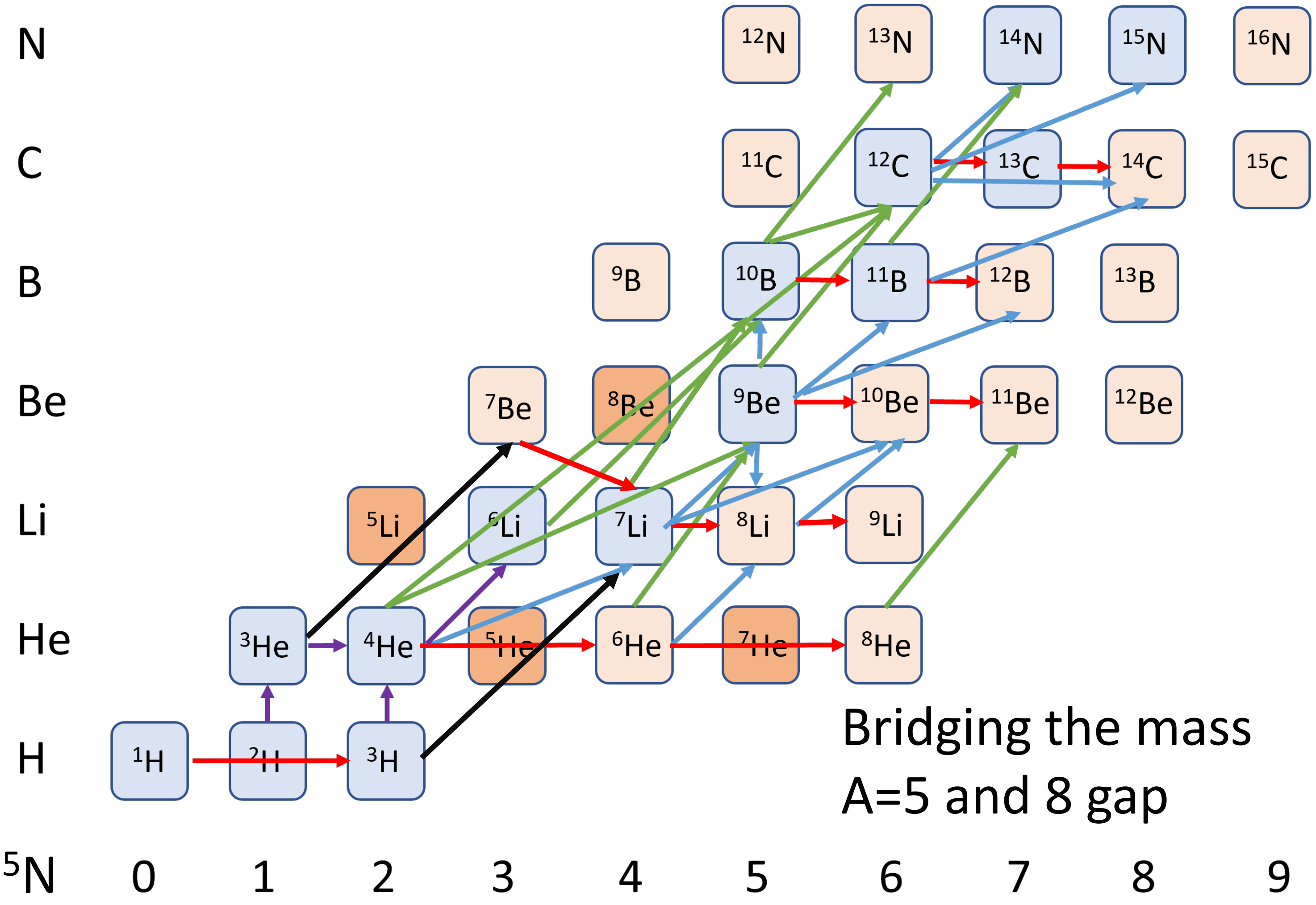
$^{7}Li(t,n)^{9}Be(\alpha,n)$

$^{9}Be(t,n)^{11}B(\alpha,n)$

$^{10}B(t,n)^{12}C(t,n)^{14}N$

$^{11}B(t,n)^{13}C(\alpha,n)$

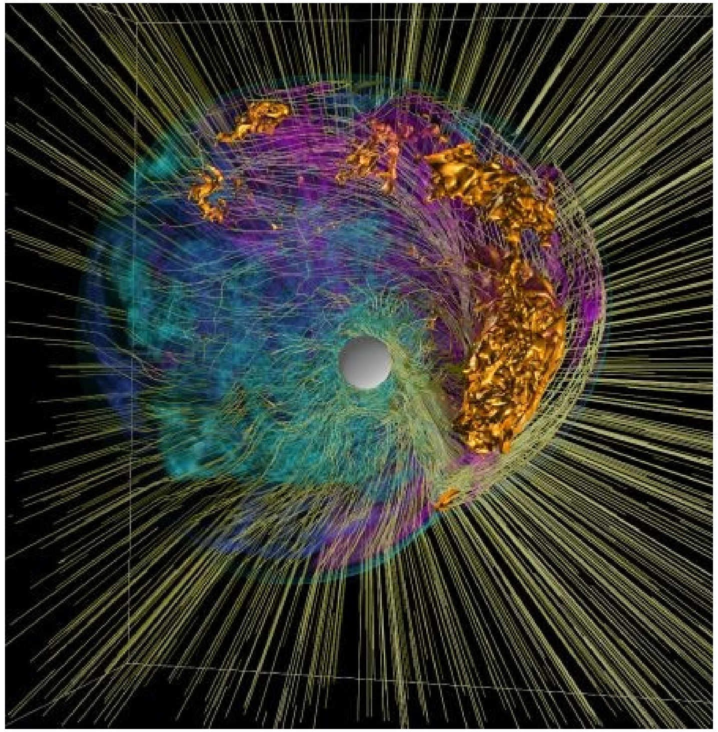
$^{4}He(t,\gamma)^{7}Li(t,n)^{9}Be(t,n)^{11}B(t,n)^{13}C(t,n)^{15}N$

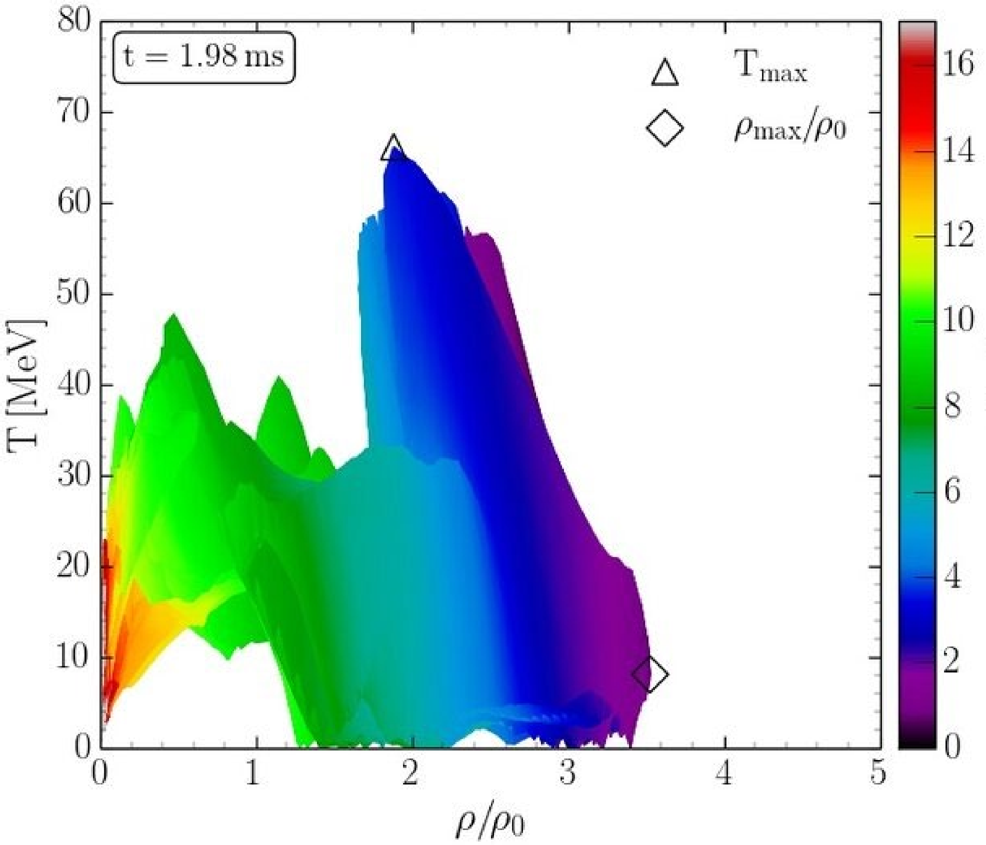


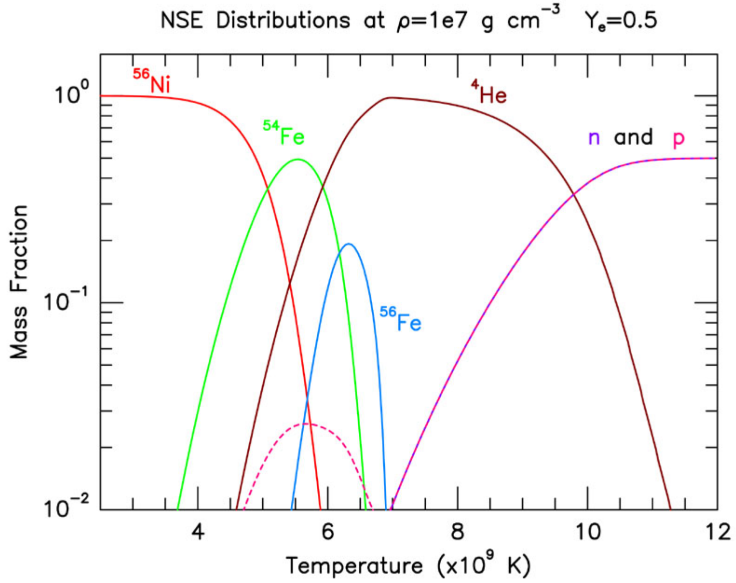
Bridging the mass A=5 and 8 gap

Rapidly expanding high density matter

Core Collapse Supernova or neutron star merger conditions rebuilding heavier elements in the neutrino driven expansion phase in statistical equilibrium. The onset is delayed by A=5 and A=8 mass gap, which needs to be bridged within milliseconds

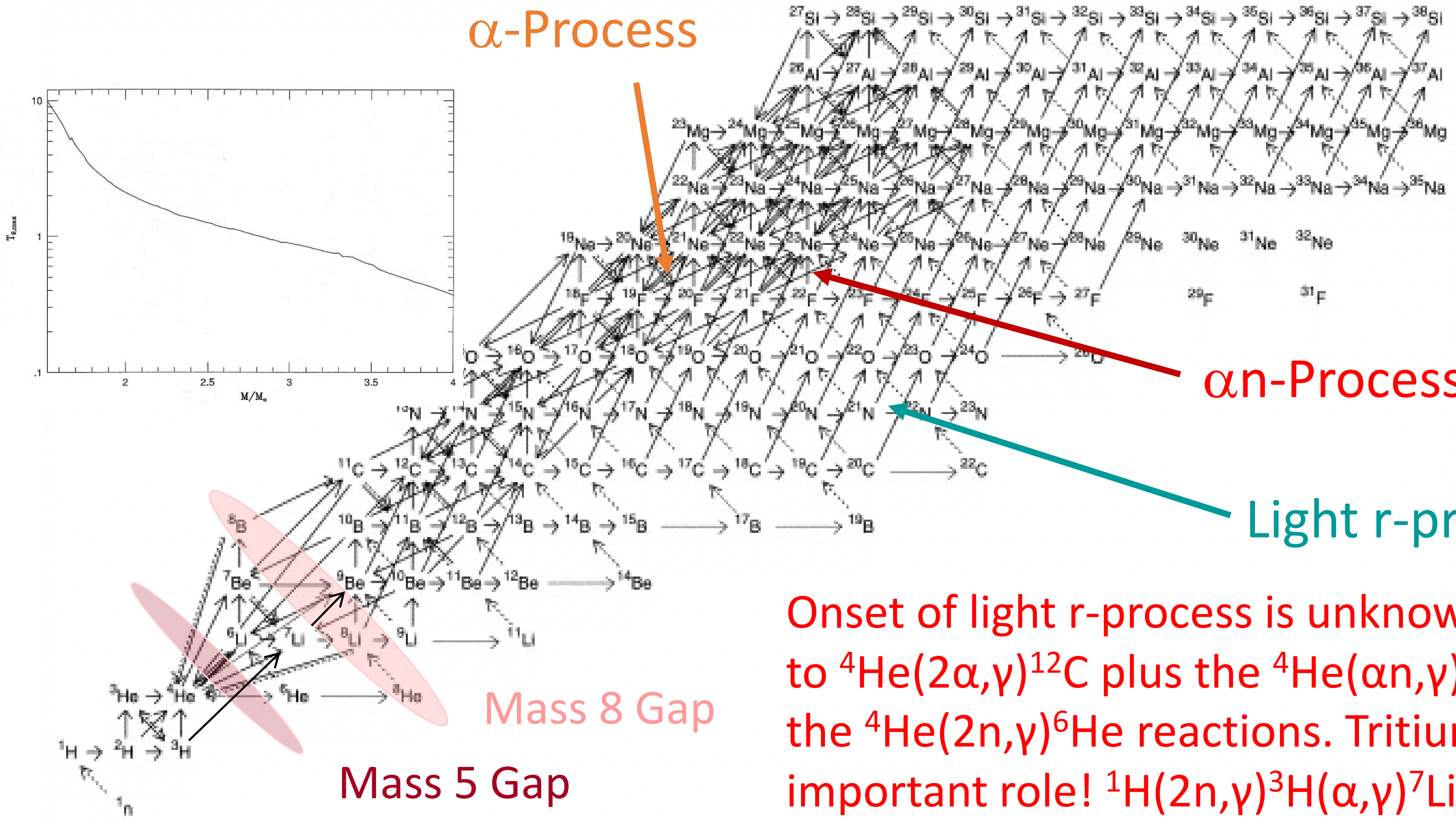






Conversion from p, n, α to ^{3}He, ^{7}Li, ^{9}Be, ^{10}B, ^{14}N with delayed release of neutrons to trigger light r-process!

Dynamical Reaction Network bridging the gap



α-Process

αn-Process

Light r-process ?

Mass 8 Gap

Mass 5 Gap

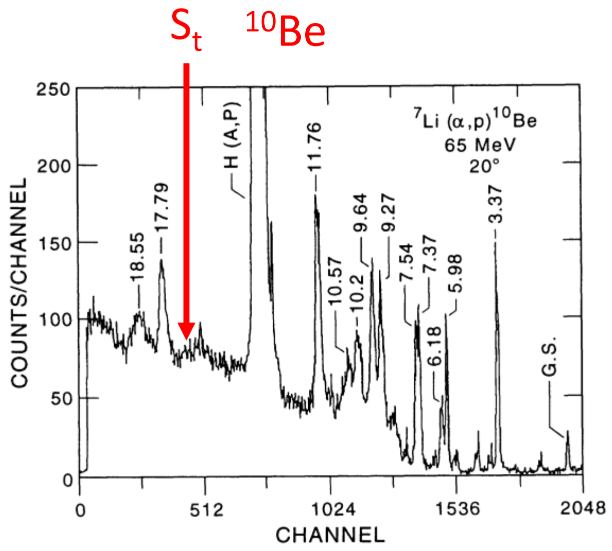
Onset of light r-process is unknown – usually reduced to ^{4}He(2α,γ)^{12}C plus the ^{4}He(αn,γ)^{9}Be(α,n) and possibly the ^{4}He(2n,γ)^{6}He reactions. Tritium may play an important role! ^{1}H(2n,γ)^{3}H(α,γ)^{7}Li(t,n)^{9}Be(α,n)!

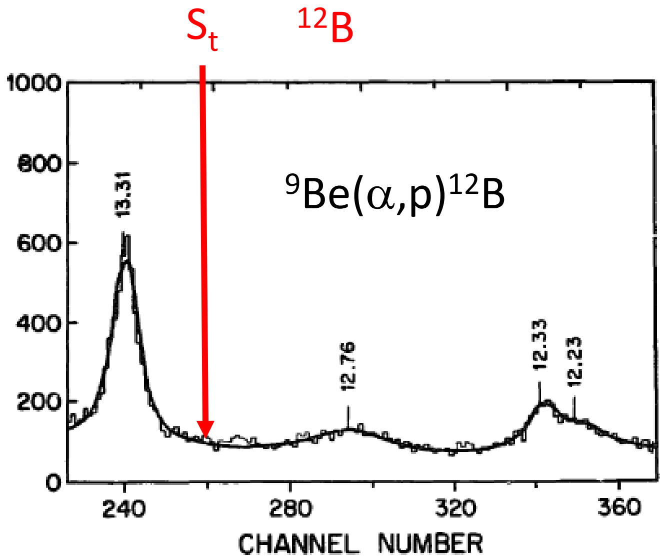
M. Terasawa, K. Sumiyoshi, T. Kajino, G. J. Mathews, and I. Tanihata, *New Nuclear Reaction Flow during r-Process Nucleosynthesis in Supernovae: Critical Role of Light, Neutron-rich Nuclei,* ApJ **562** (2001) 470

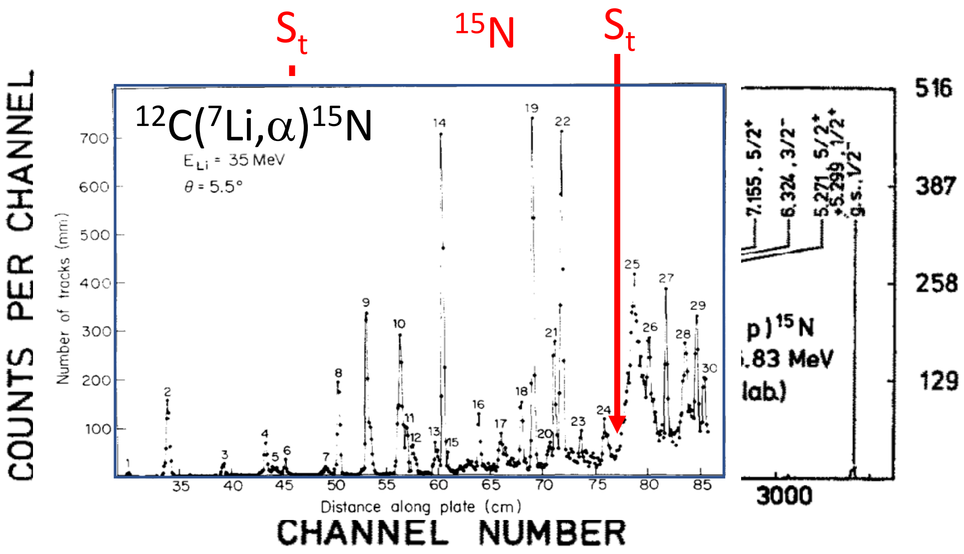
Threshold States in Capture Reactions

Coupling of tritium cluster configurations of bound states to the continuum causes according to SMEC model pronounced tritium cluster configurations near the tritium threshold in compound system!

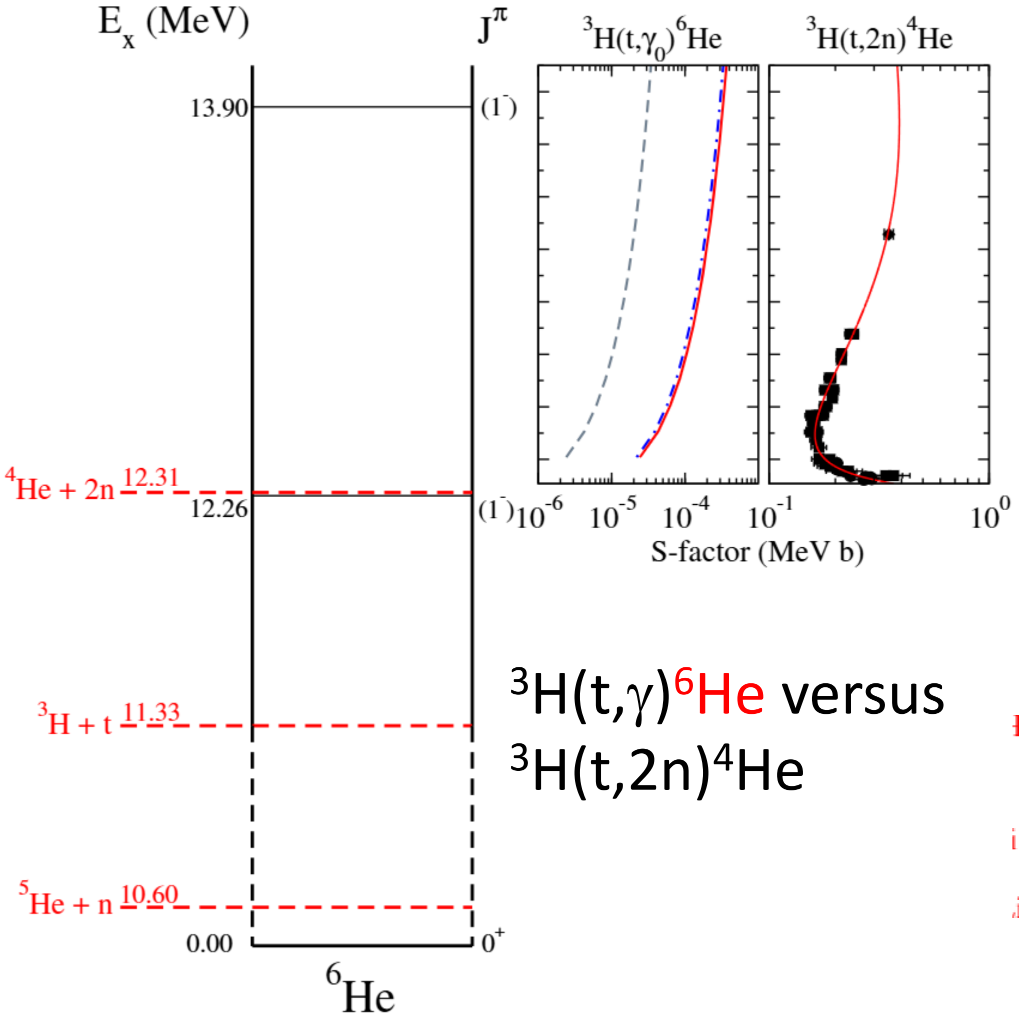
Predictions motivate re-analysis of old experimental data!



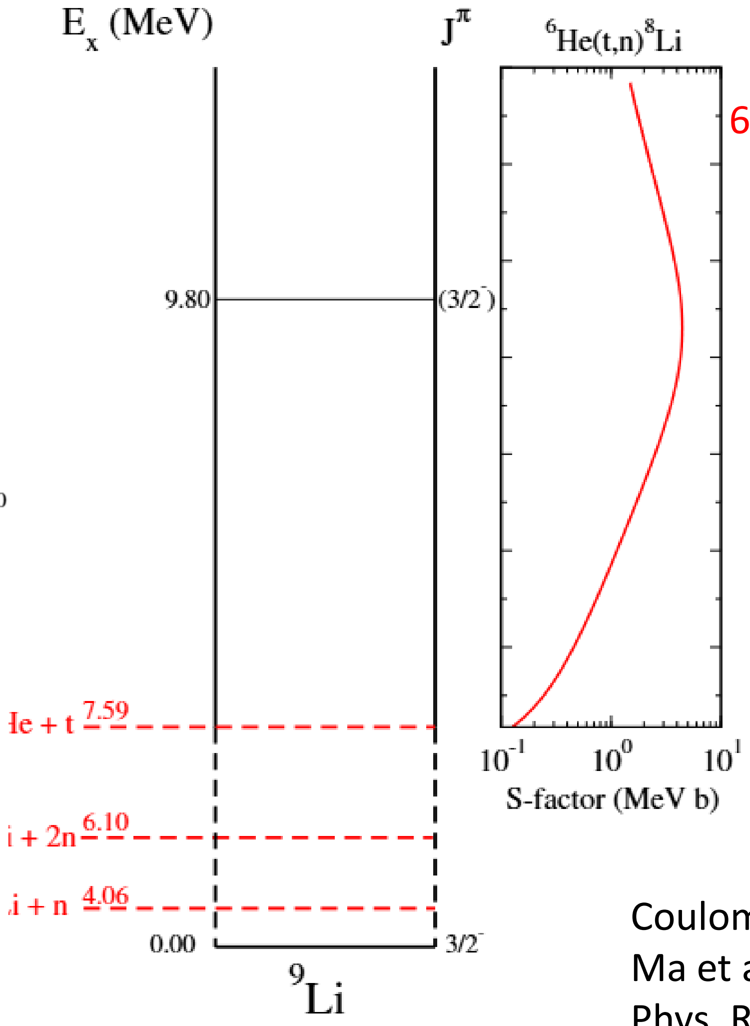




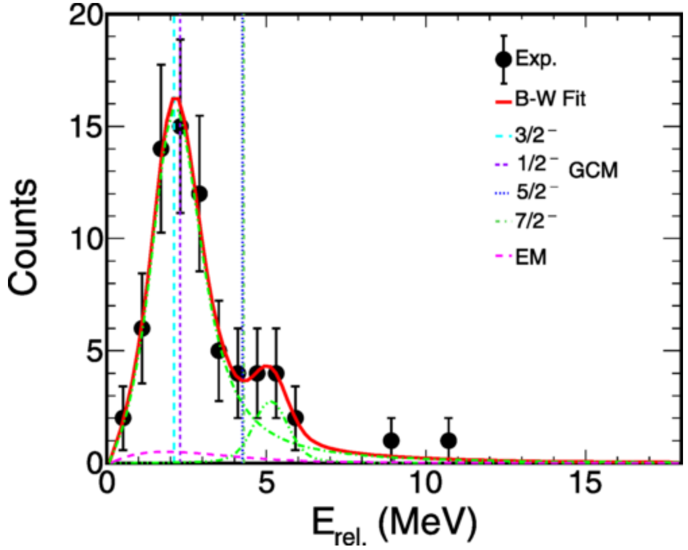
The triple-triton process on ^{6}He equilibrium



^{3}H(t,γ)^{6}He versus
^{3}H(t,2n)^{4}He

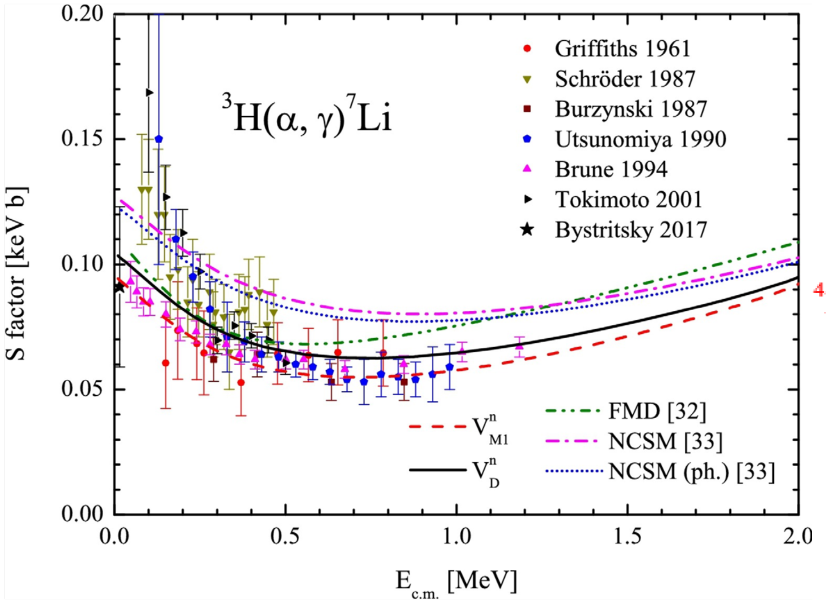


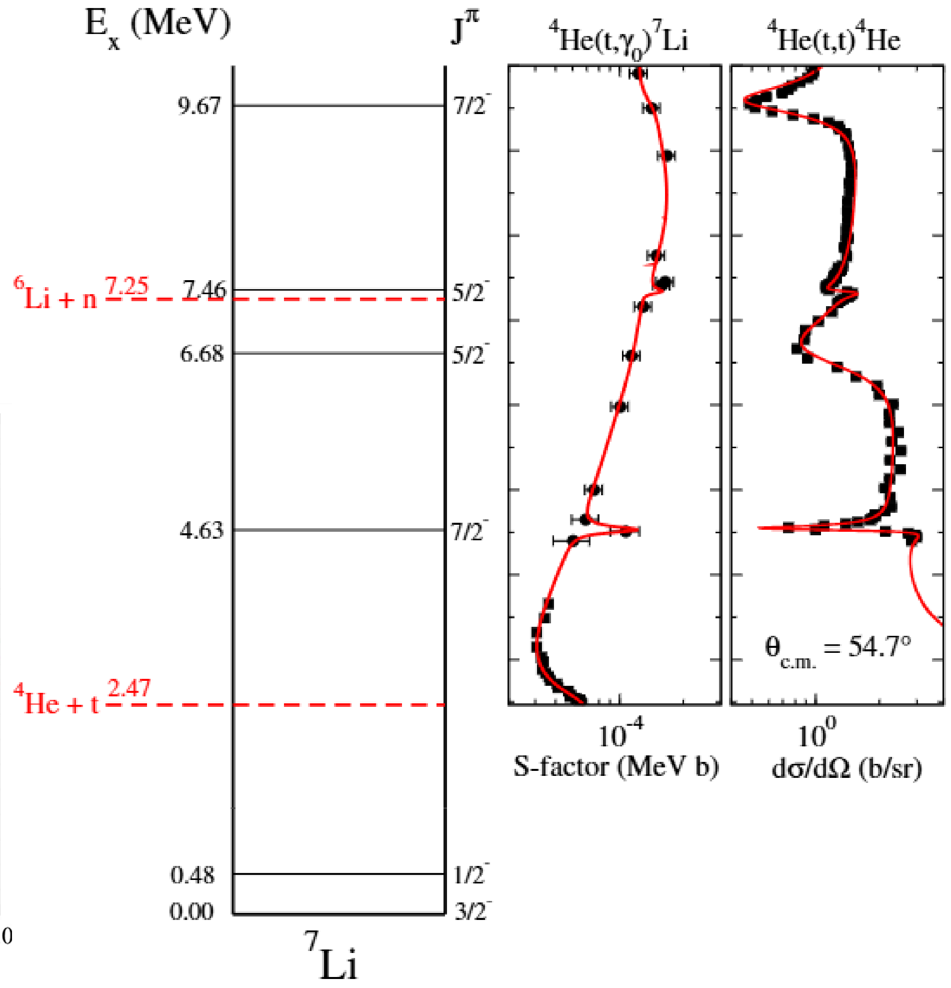
^{6}He(t,n)^{8}Li

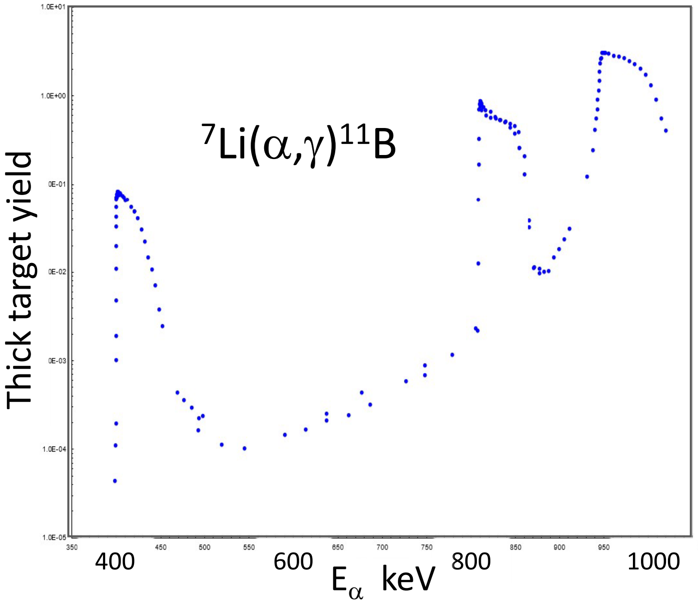


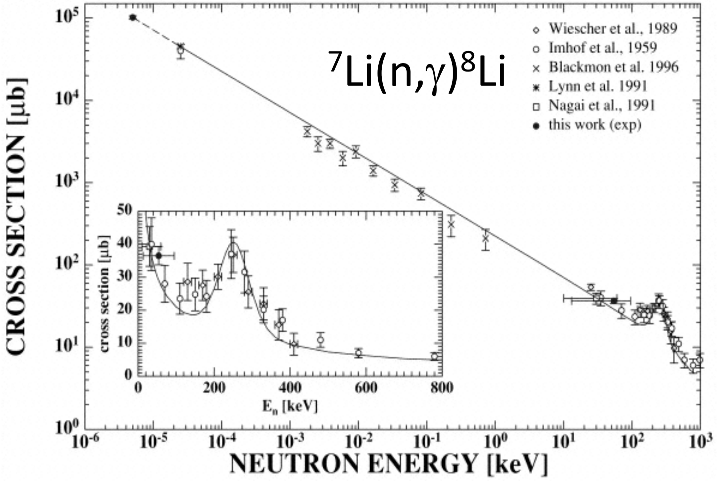
Coulomb dissociation of ^{9}Li on ^{208}Pb at 38 MeV.
Ma et al. Observation of ^{6}He+t clusters in ^{9}Li,
Phys. Rev. C **103**, (2021) L061302

$^{4}He(t,\gamma)^{7}Li$





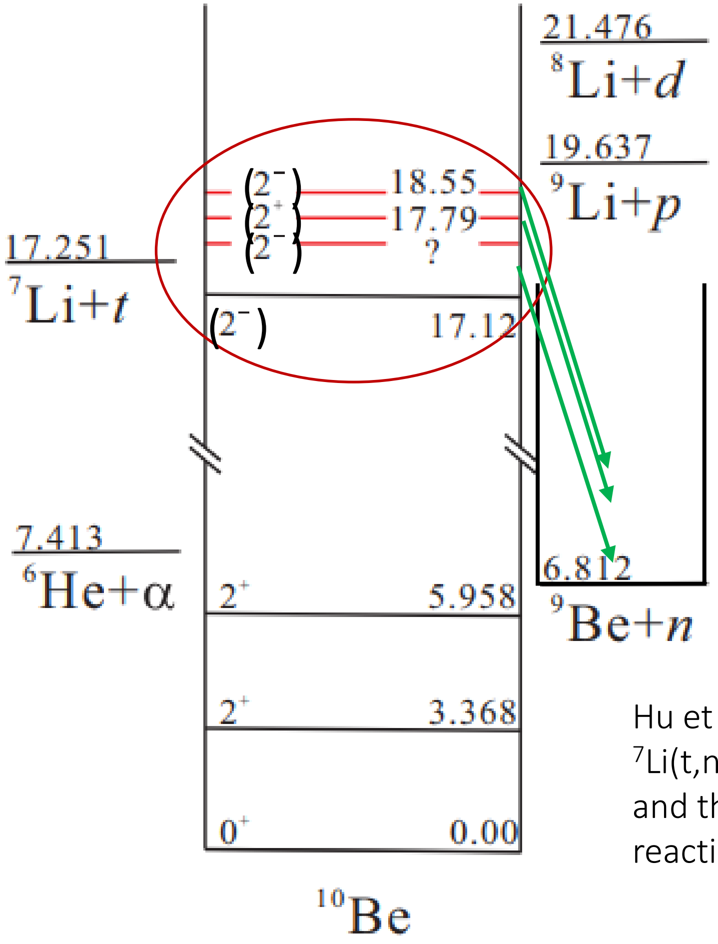




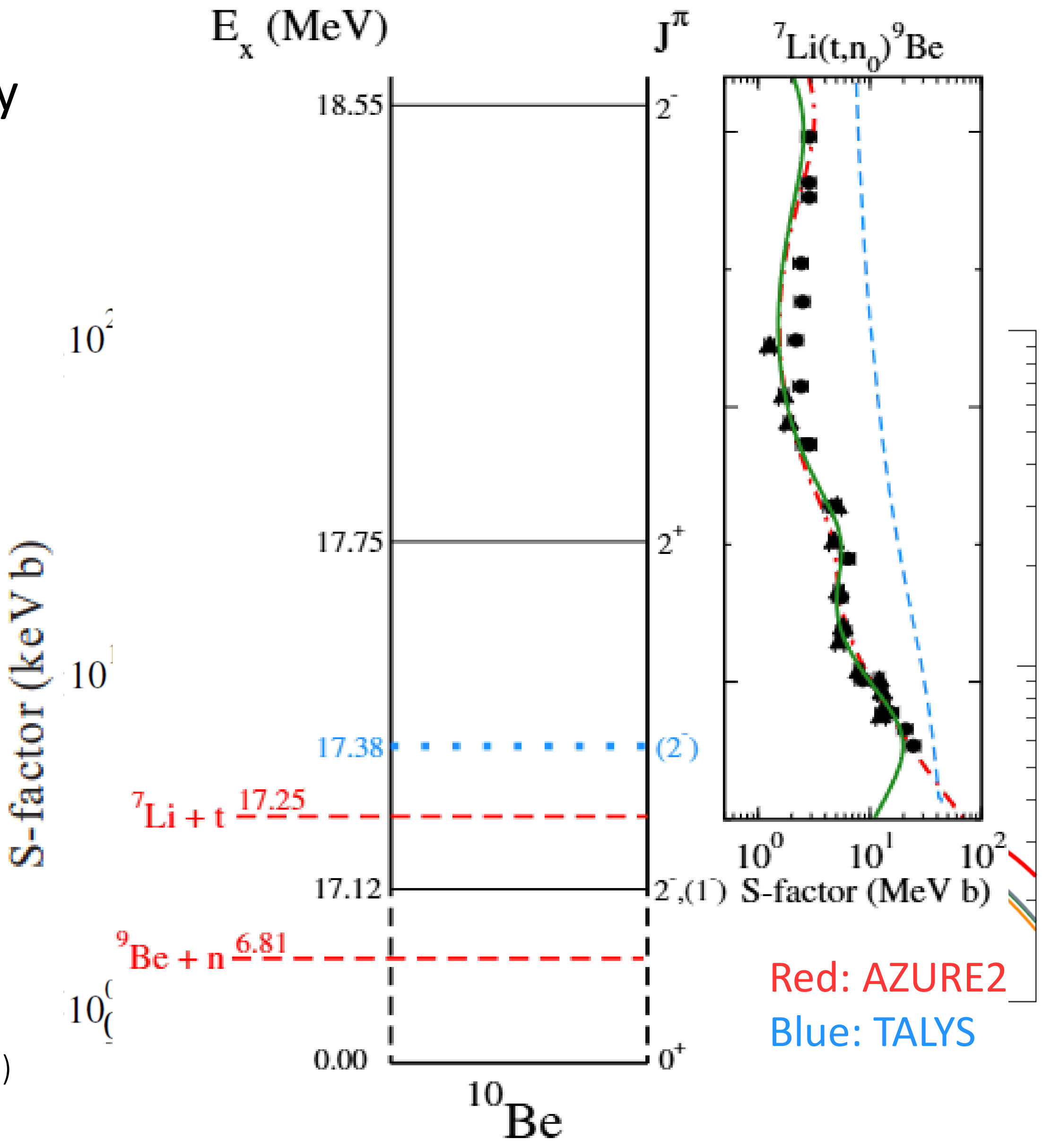
Mirror reaction to $^{3}He(\alpha,\gamma)^{7}Be$ feeding ^{7}Li as a stable element for subsequent neutron, triton, or alpha capture towards heavier masses!

^{7}Li(t,n)^{9}Be, impact of threshold states?

Impact of near threshold s-wave resonance states may cause order of magnitude increase in reaction rate!

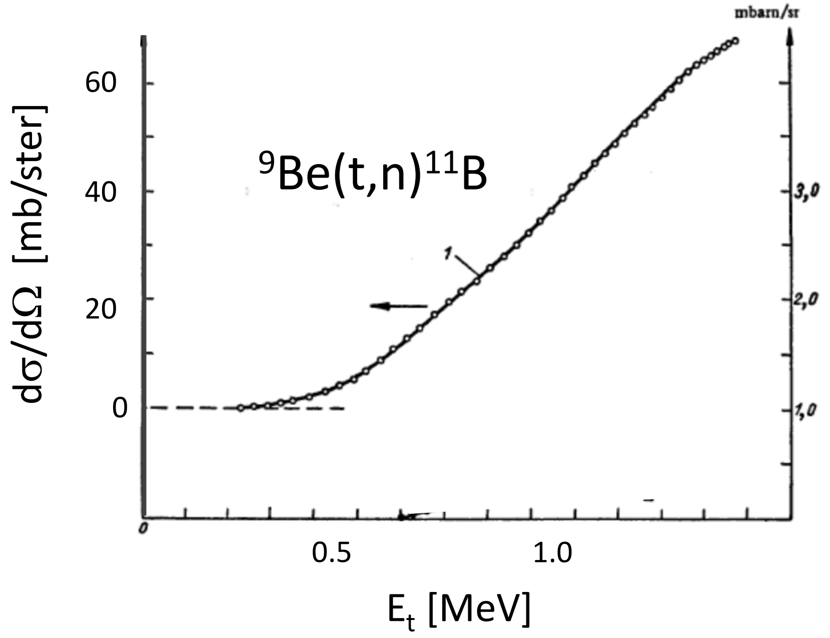


Hu et al., R-matrix analyses for the ^{7}Li(t,n)^{9}Be and ^{7}Li(^{3}He,p)^{9}Be reactions and their improved thermonuclear reaction rates, PRC 106, 045802 (2022)



Red: AZURE2
Blue: TALYS

^{9}Be(t,n)^{11}B, impact of threshold states?



R-matrix calculation based on:

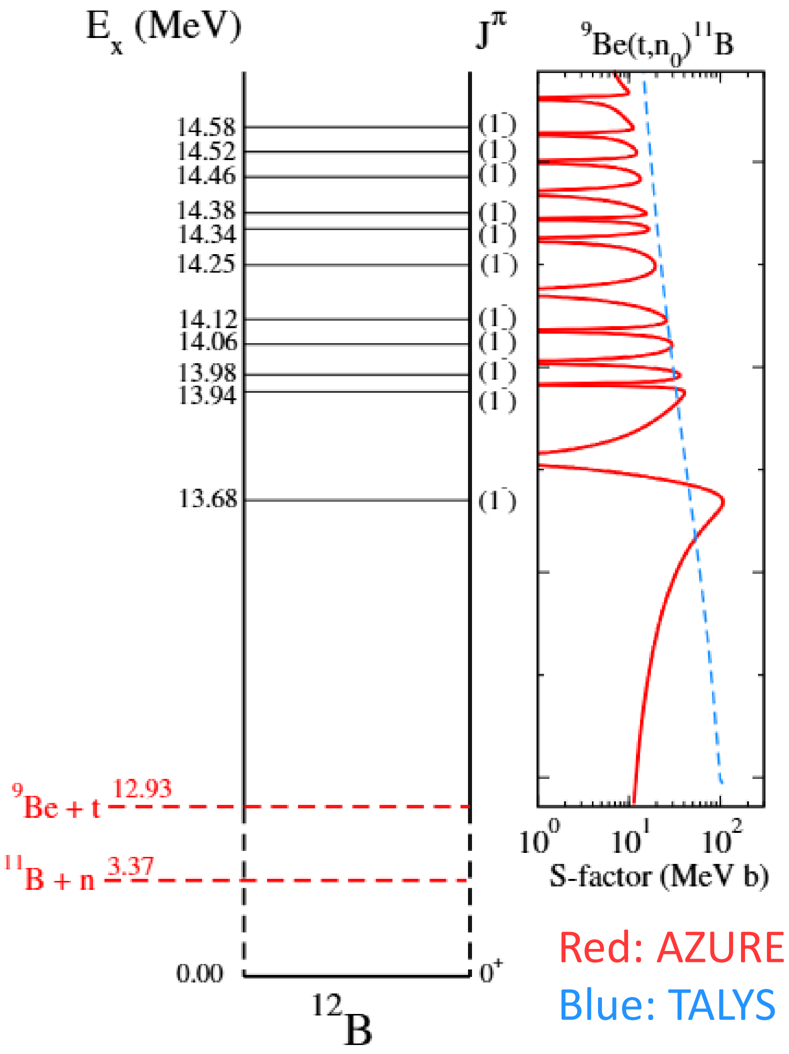
^{9}Be(t,n)^{11}B reaction data,

^{11}B(n,γ)^{12}B reaction data

^{11}B(n,n)^{11}B scattering data

^{9}B(α,p)^{12}B transfer data

^{9}B(^{7}Li,α)^{12}B transfer data



Red: AZURE2

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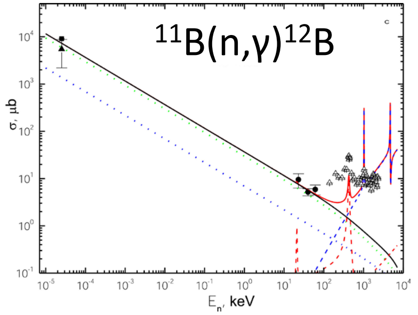
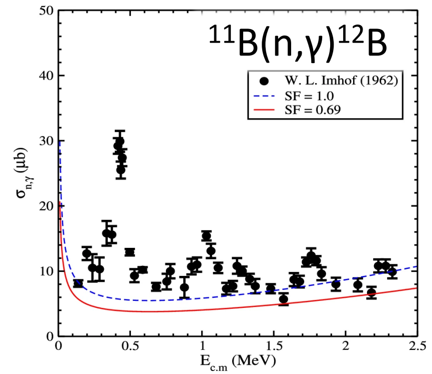
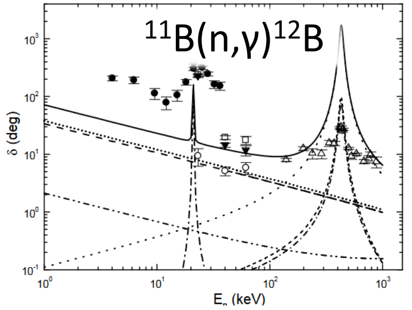






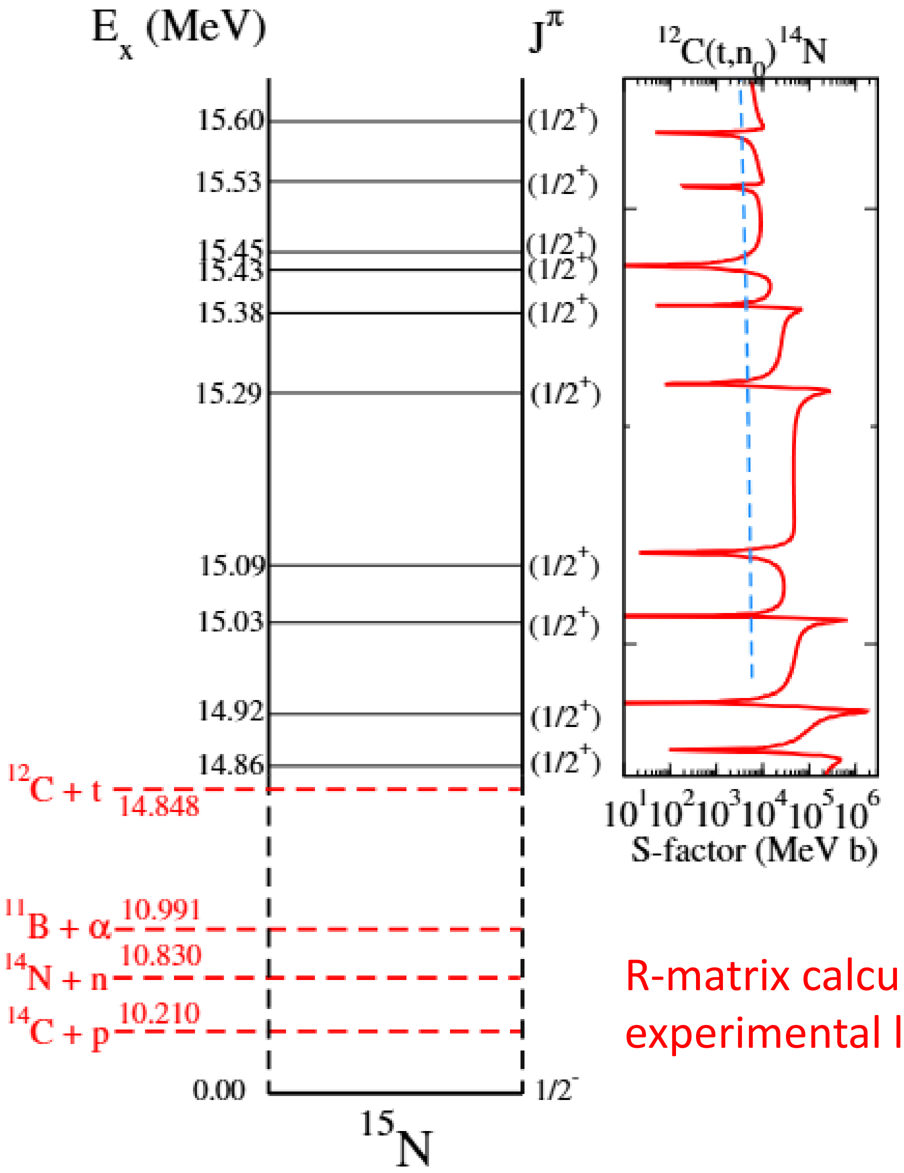
Inverse ^{11}B(n,t) coupled with ^{11}B(n,n') for mapping the decay. New studies are being proposed at LANSCE or n-ToF!

^{12}C(t,n)^{14}N, impact of threshold states in ^{15}N?

Neutron capture leading to 4He with subsequent neutron release:

Delay by: $$\tau_i = \sum_i \frac{A_i}{X_i} \cdot (\rho \cdot N_A \langle \sigma v \rangle_i)^{-1}$$

As for example:
^{4}He(t,γ)^{7}Li(t,n)^{9}Be(α,n)^{12}C(t,n)^{14}N
or any other sequence in the network leading to ^{12}C with subsequent tritium induced neutron release



Red: AZURE2
Blue: TALYS

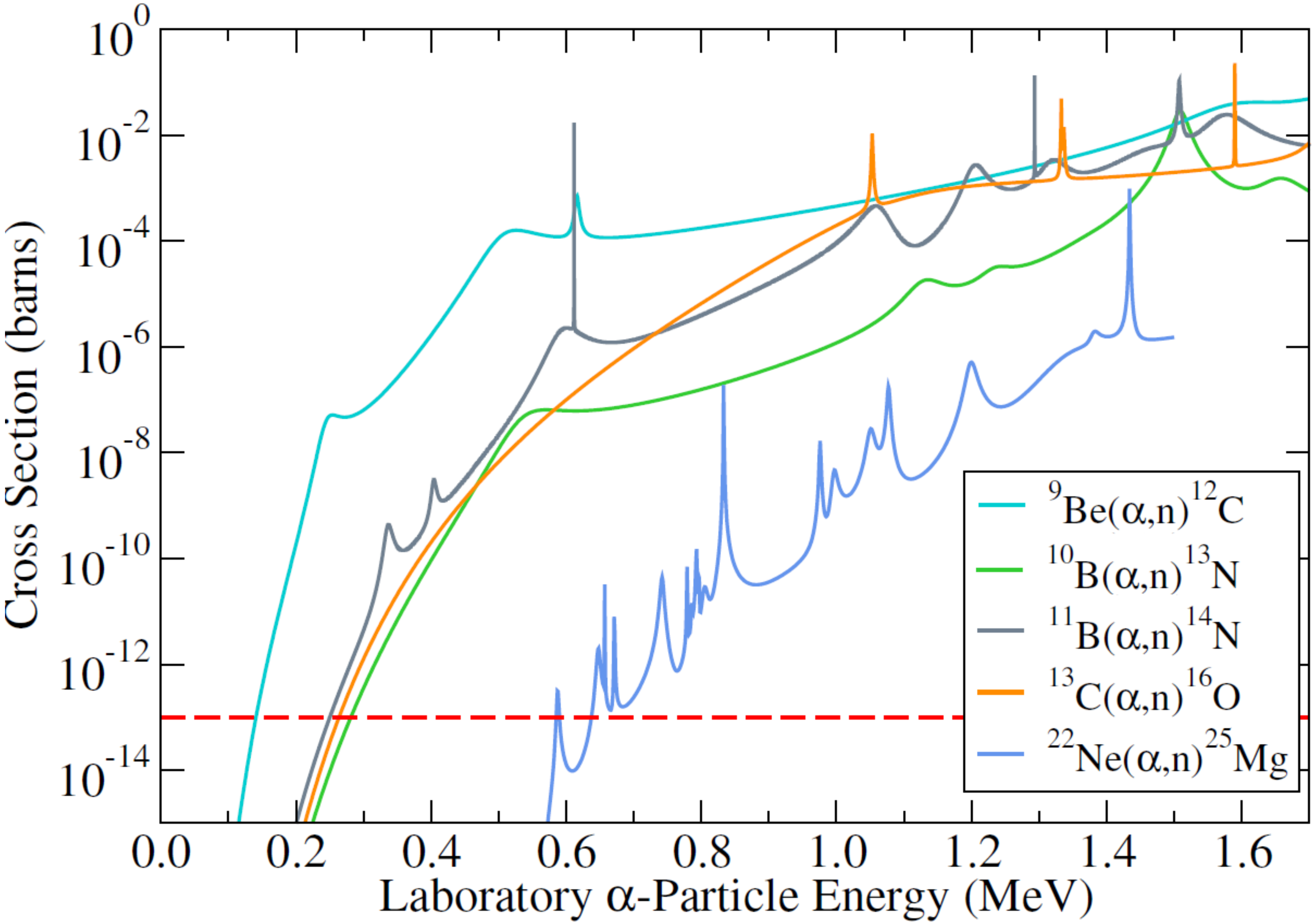
R-matrix calculation based on experimental level parameters

Feeding the strongest neutron sources

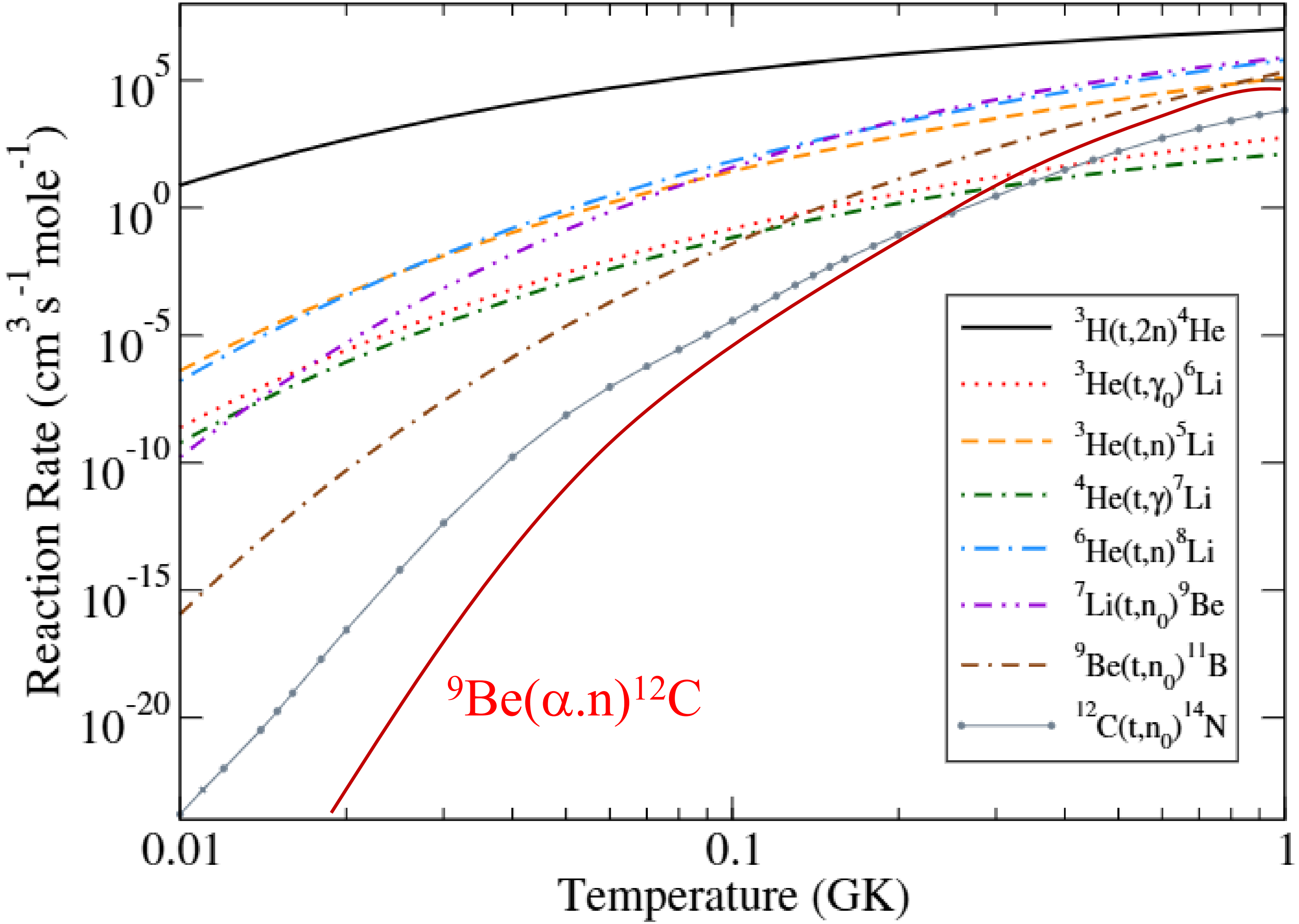
$^{7}Li(t,n)^{9}Be$
$^{7}Li(t,n)^{9}Be(\alpha,n)$
$^{7}Li(\alpha,\gamma)^{11}B(\alpha,n)$
$^{7}Li(t,n)^{9}Be(t,n)^{11}B(\alpha,n)$
$^{7}Li(t,n)^{9}Be(t,n)^{11}B(t,n)^{13}C(\alpha,n)$

At higher energies:
$^{7}Li(t,n)^{9}Be(\alpha,2n)$
$^{7}Li(t,n)^{9}Be(\alpha,n)^{10}B(\alpha,n)$

Neutrons, stored in tritium will be released via (t,n) and (α,n) reactions may provide a strong but substantially delayed neutron flux for building heavier elements.



Tritium induced neutron sources



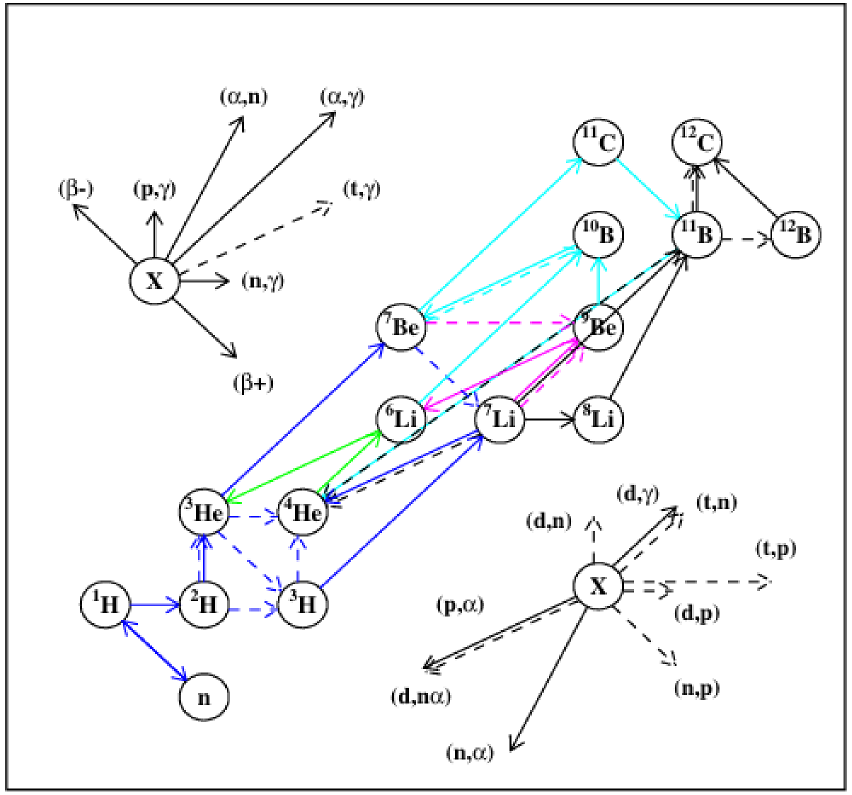
The here discussed tritium induced neutron sources are all considerably stronger than the strongest known alpha induced neutron source. The role of tritium depends on the tritium abundances generated in the first moments of the explosive event, BB or SN. It also depends on the reliability of the here proposed reaction data.

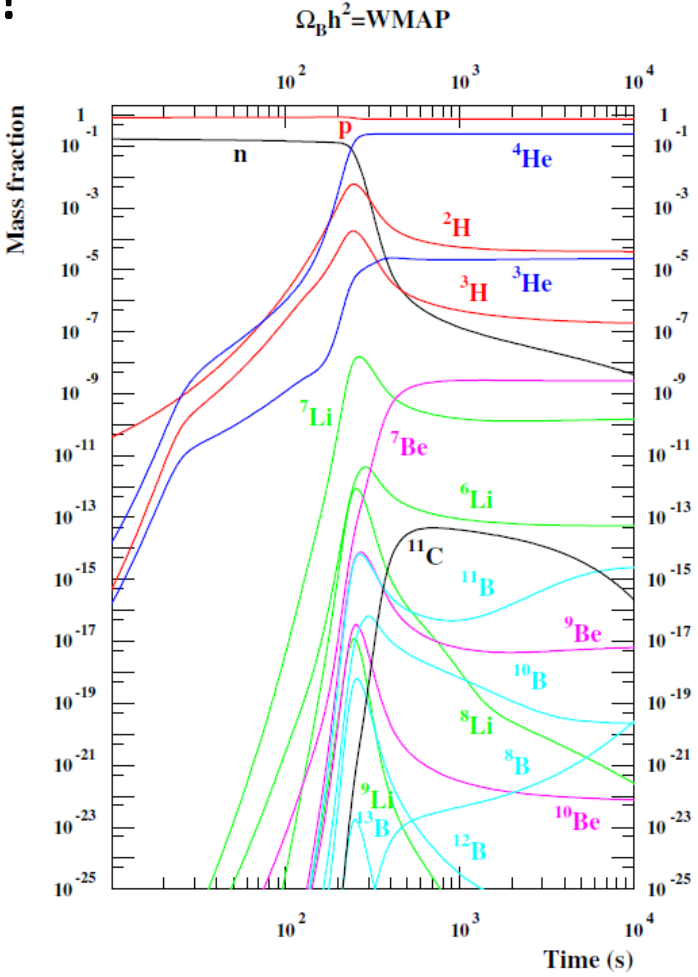
Experimental verification is clearly necessary!

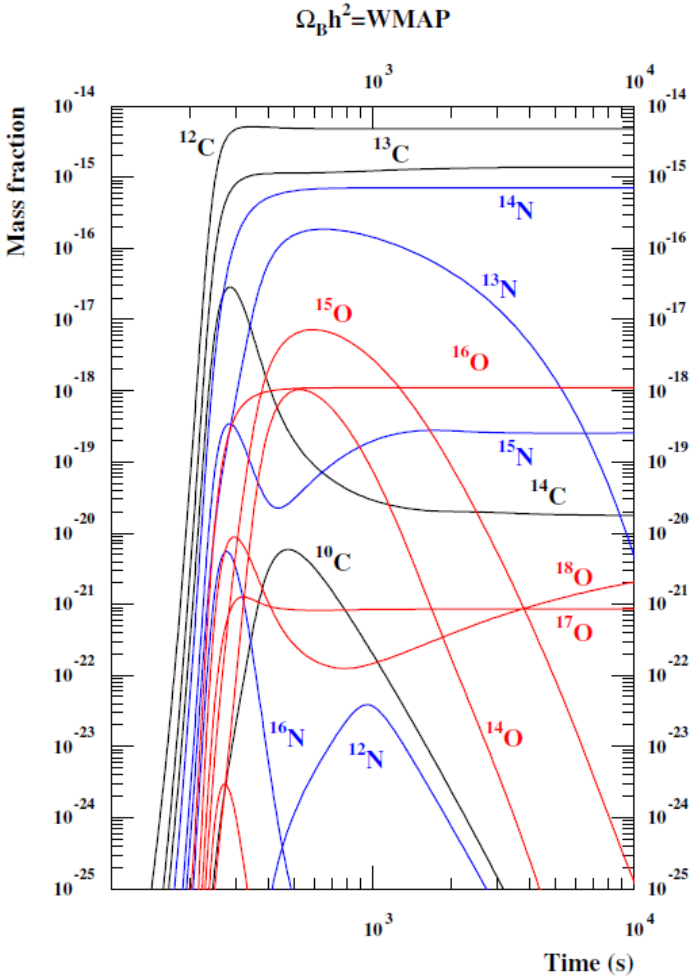
Consequences?

Based on earlier simulations?

Alain Coc et al. Standard Big Bang Nucleosynthesis with an improved extended nuclear network. Astrophysical Journal, 744:158 (2012).





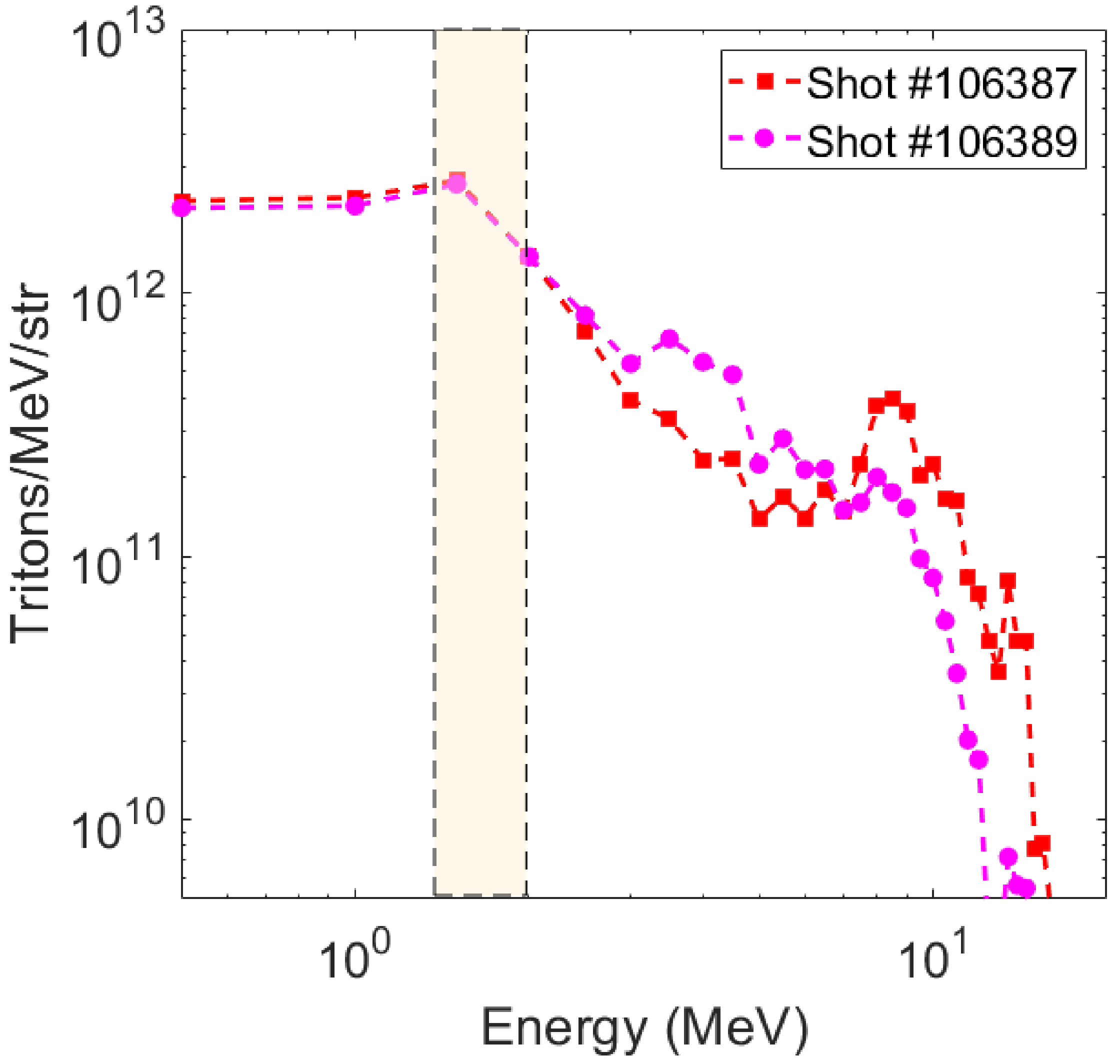


Will enhanced tritium rates change this picture of light isotope abundance developments?
Will new rates address the frequently discussed Li problem? Better data are needed!

Experiments with tritons at accelerator or OMEGA

Plans and Projects

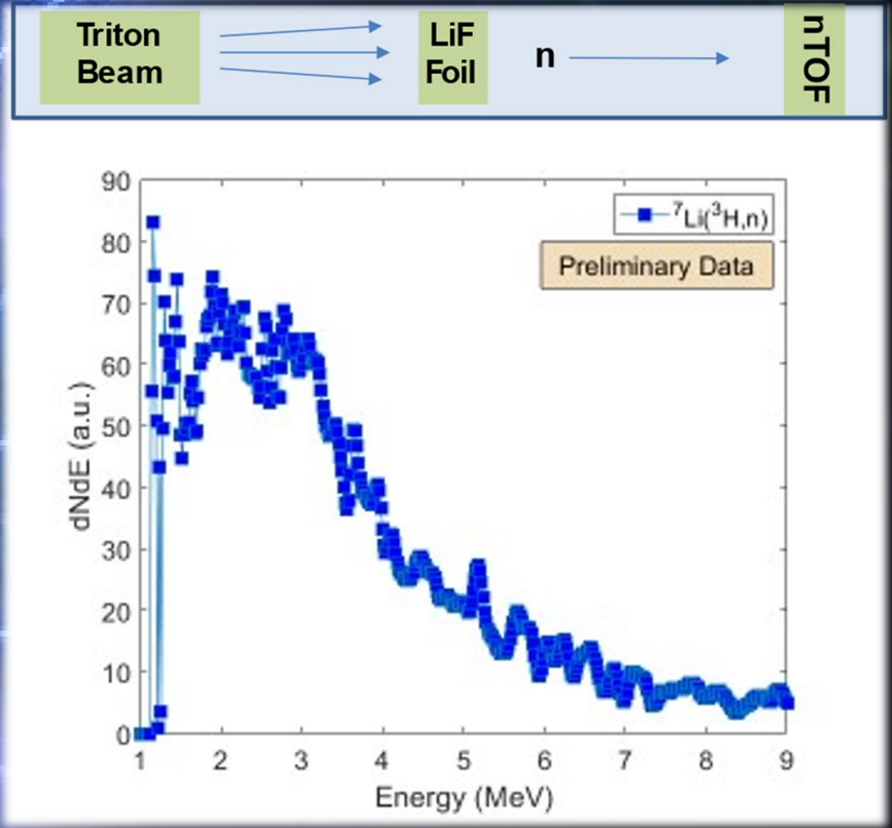
1. A(α,p)B tritium stripping experiments to populate tritium cluster states at tritium threshold. (Local exploration effort via A(α,p) or A(^{7}Li,α) at the NSL Enge spectrograph)
2. B(t,t’) inelastic scattering experiments at FSU
3. Purchase of a tritium target through Air Force Academy grant for inverse kinematic experiments e.g. ^{3}H(^{7}Li,n), ^{3}H(^{10}B,n), ^{3}H(^{12}C,n) (Mike Febbraro)
4. ^{9}Be(n,t) and ^{11}B(n,t) experiments at LANSCE/LANL or n_ToF/CERN facilities (Hye Young Lee)
5. High flux tritium beam production at OMEGA and OMEGA-OPAL plasma facility (Ani Aprahamian, Chad Forrest)



Conclusion

Neutron poison and neutron sources generate a balance in the neutron budget

Neutron storage in tritium facilitates neutron transfer and delayed neutron release not yet fully considered in astrophysics simulation of fast nucleosynthesis processes!



Acknowledgement:

Ani Aprahamian, Carl Brune, James de Boer, Maria Gatu Johnson, Chad Forrest