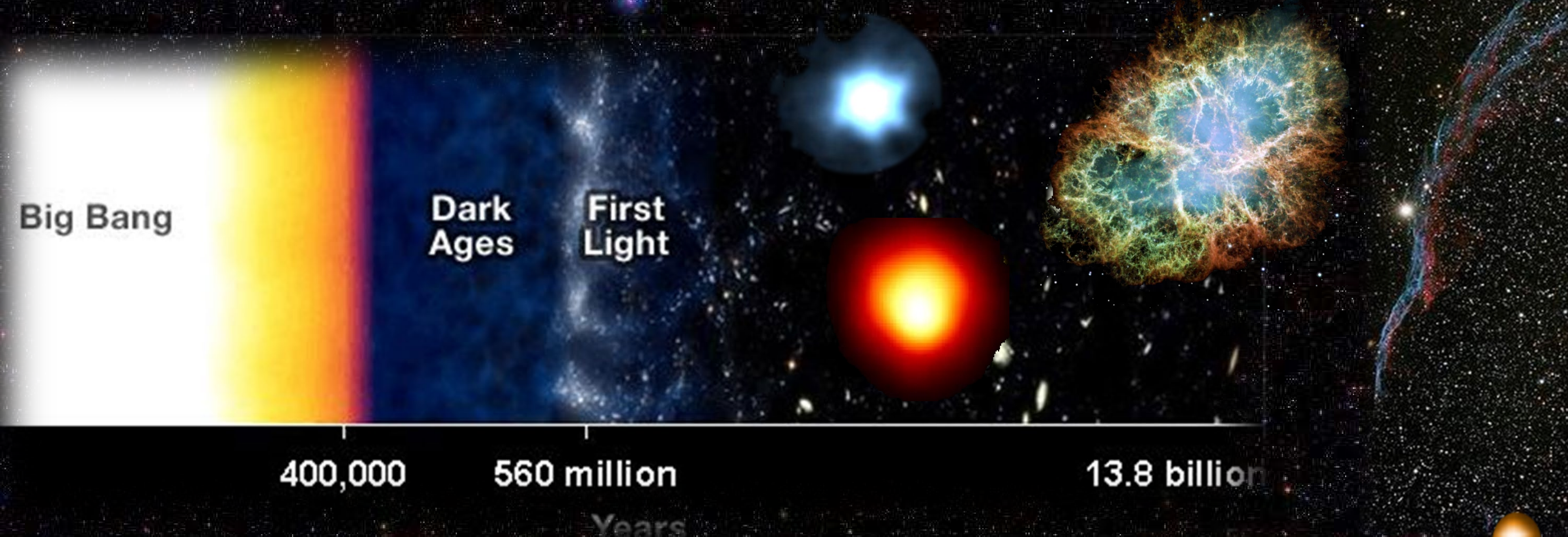
Nuclear cluster configurations at the threshold and the onset of the formation of elements in primordial stars

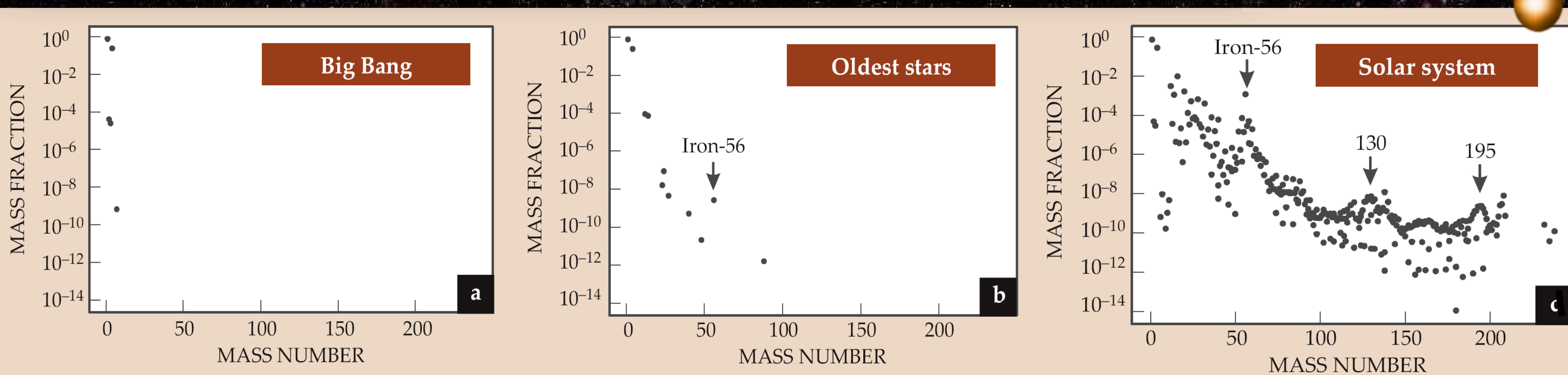
Michael Wiescher

University of Notre Dame

1. Big Bang and Early Star Evolution
2. From Primordial to CNO Elements
3. Light Isotope Clusters
4. Experimental Resources at Notre Dame and CASPAR
5. The Carbon Oxygen Production in the Early Universe
6. The i-Process in Early Stars

Galactic Chemical Evolution



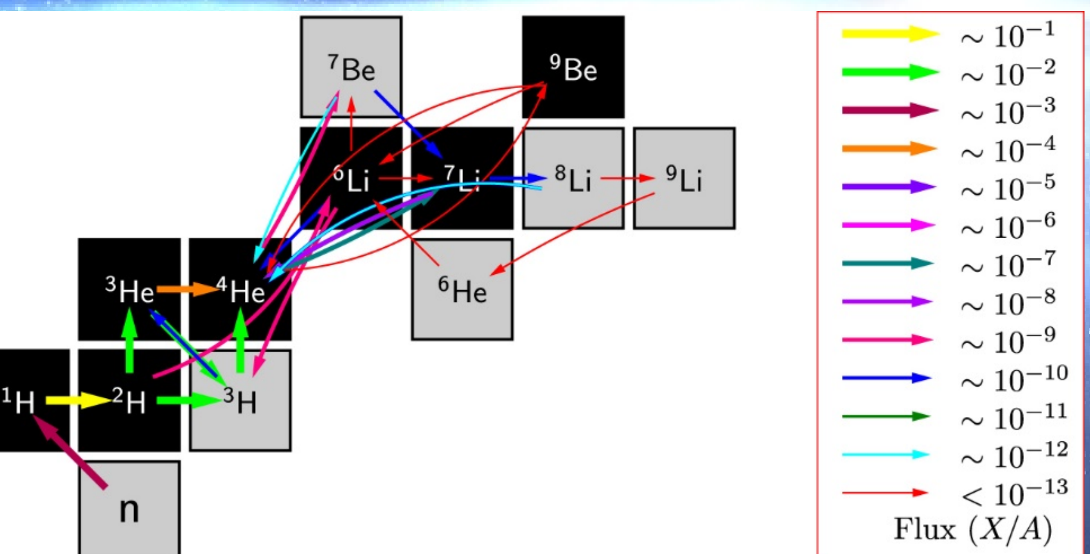


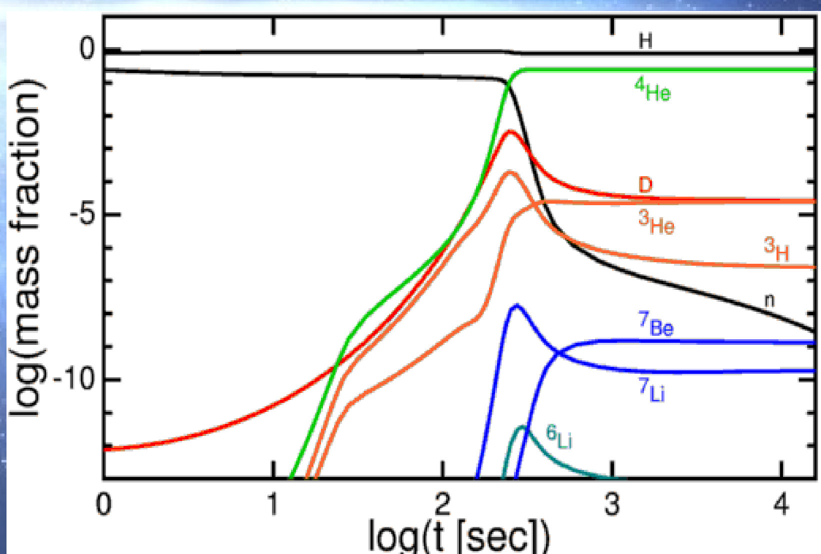
Big Bang and Early Star Evolution

Big Bang Nucleosynthesis

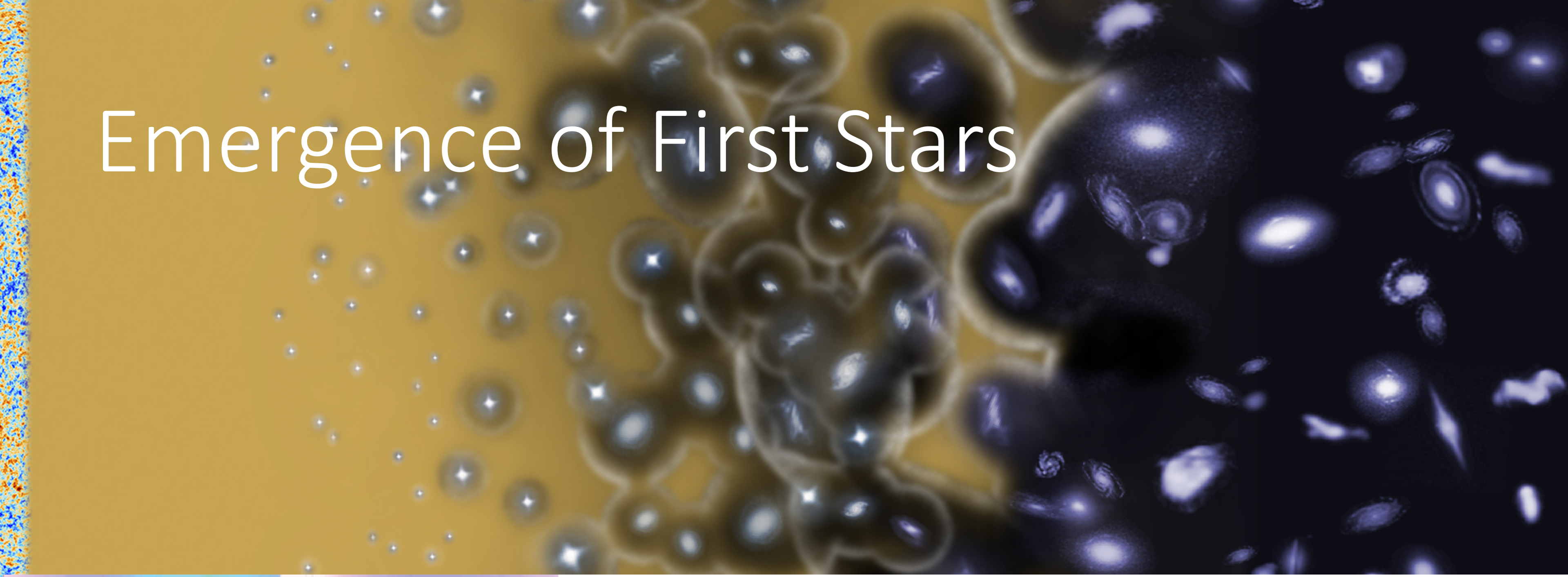
The origin of the primordial elements, H, He, Li

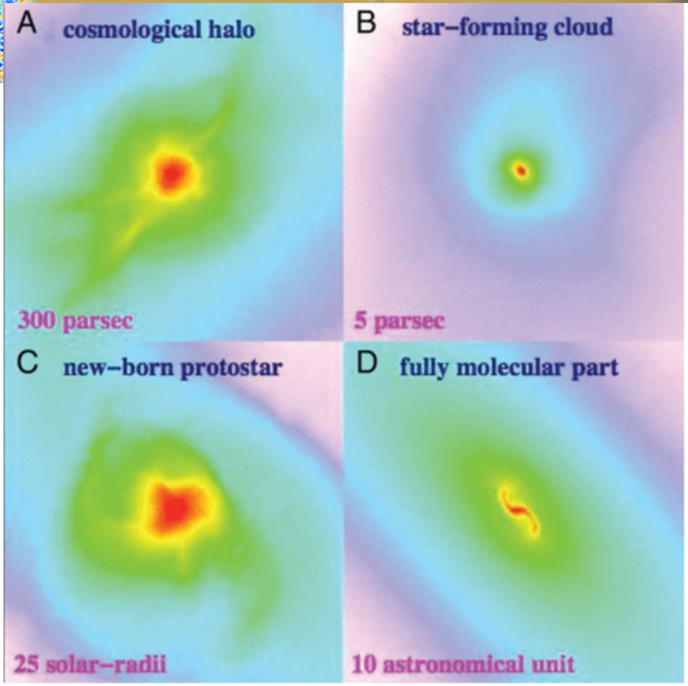
with the Li problem: only a third of the predicted ^7Li is observed and up to a thousand times of the predicted ^6Li is observed in early stars

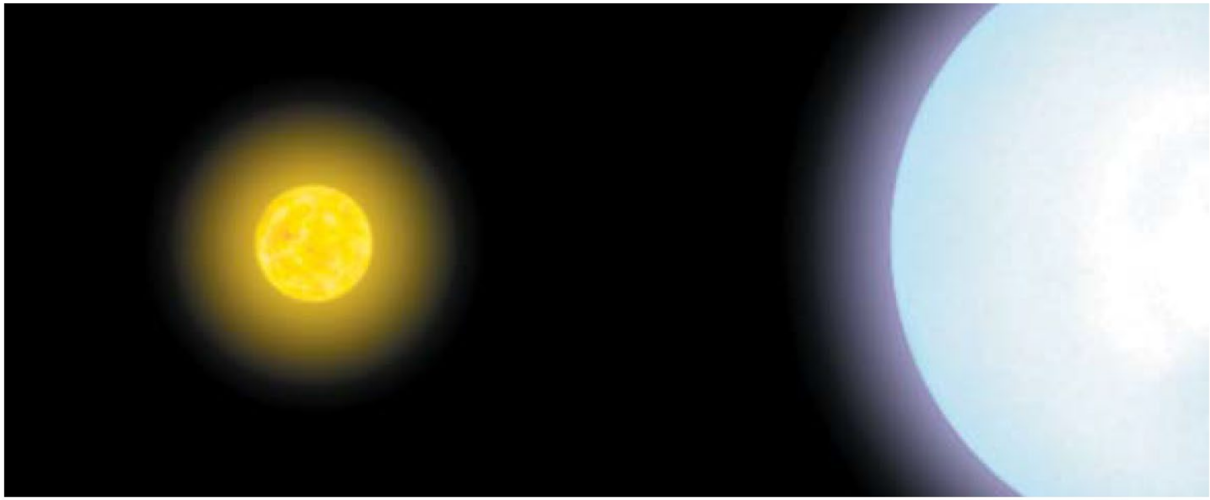




Emergence of First Stars







SUN

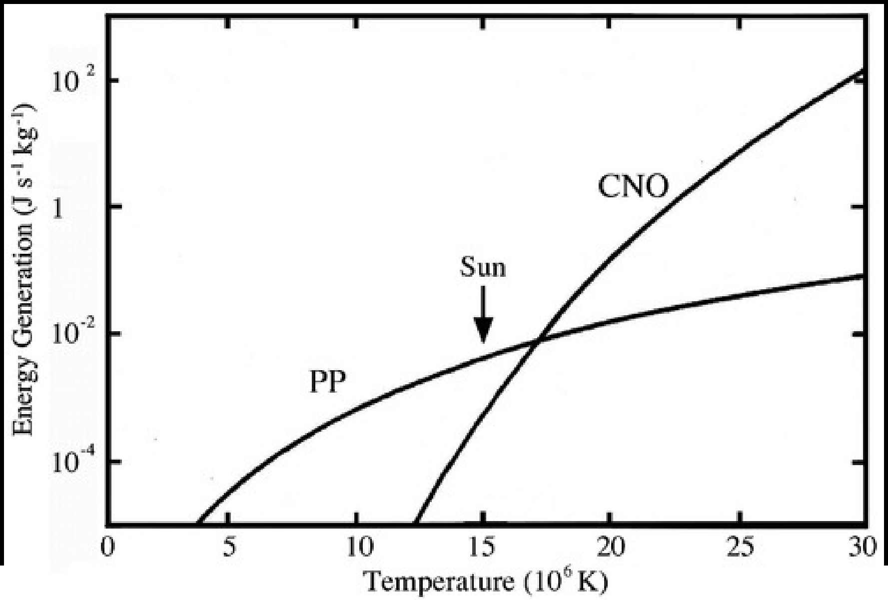
MASS: 1.989×10^{30} kilograms
RADIUS: 696,000 kilometers
LUMINOSITY: 3.85×10^{23} kilowatts
SURFACE TEMPERATURE: 5,780 kelvins
LIFETIME: 10 billion years

FIRST STARS

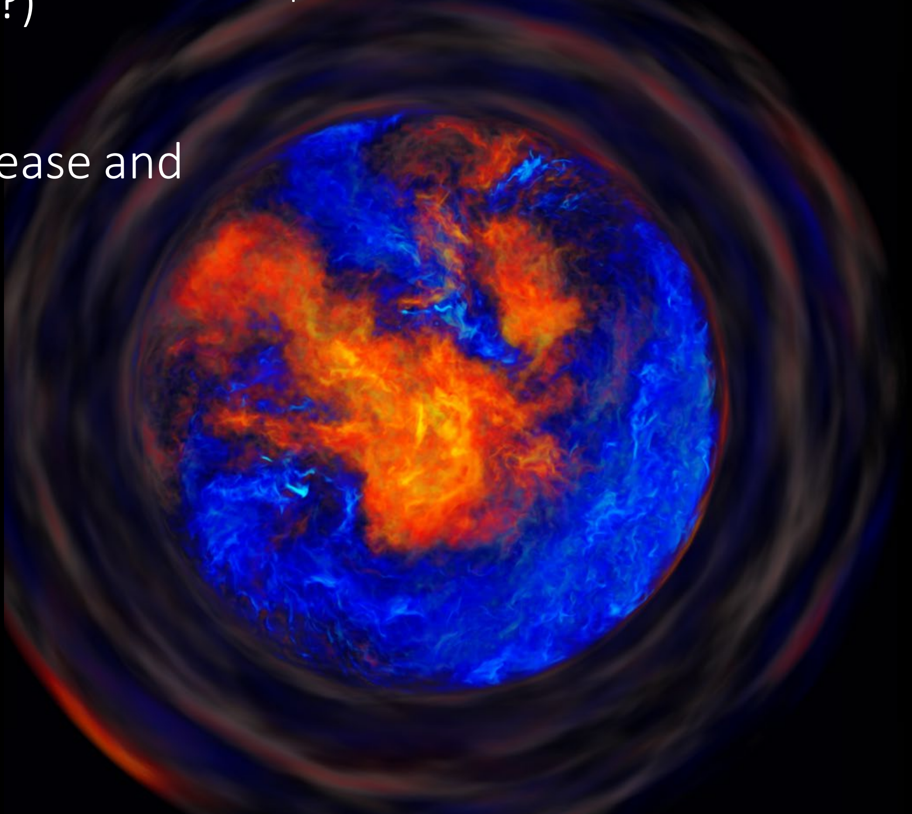
MASS: 100 to 1,000 solar masses
RADIUS: 4 to 14 solar radii
LUMINOSITY: 1 million to 30 million solar units
SURFACE TEMPERATURE: 100,000 to 110,000 kelvins
LIFETIME: 3 million years

First generation conditions

- They are made of primordial material
- They are very massive (10-100-1000 $M_{\odot}$?)
- They contract under gravitational force
- No CNO cycle to generate the energy release and internal pressure for stabilization
- Collapse to form first supernovae



Red/orange: convective outward flow
Blue/turquoise: convective inward flow

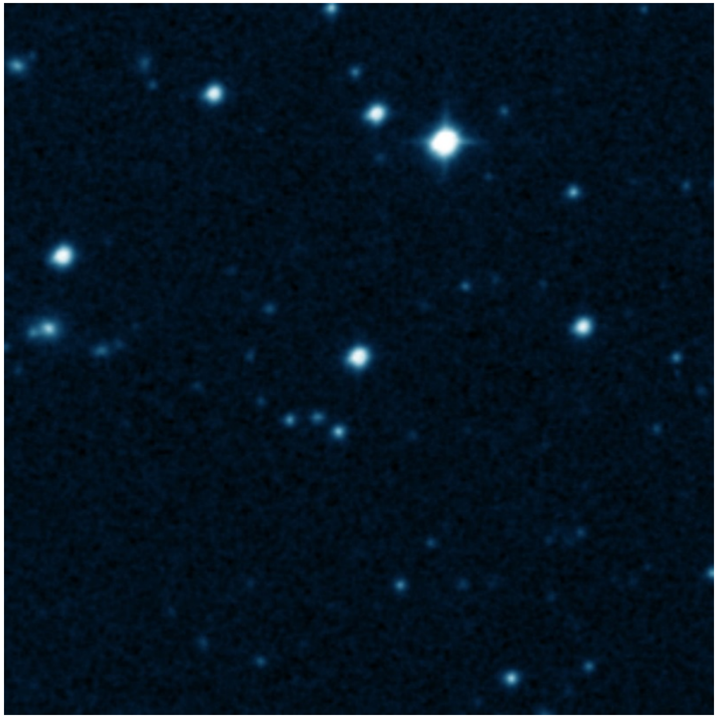


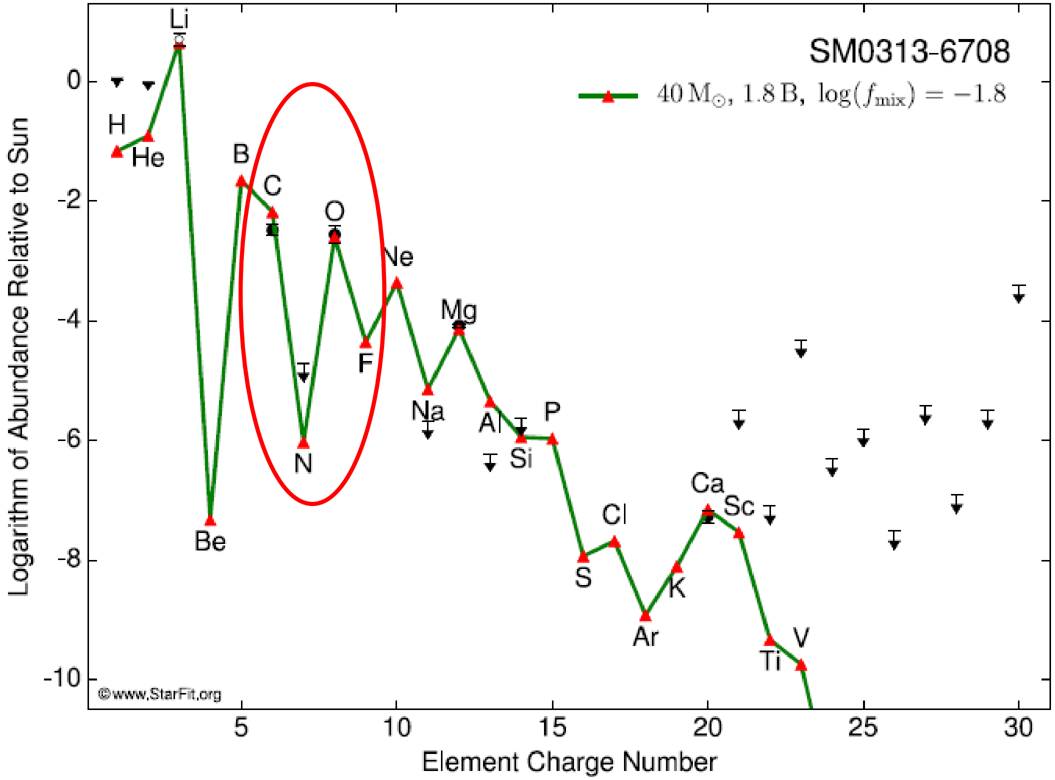
How can carbon be formed?

NuGrid model, courtesy Falk Herwig

From Primordial to CNO Elements

Early Stars
and Early Element Synthesis





The element abundance pattern for SMSS 0313–6708 compared to model values.

SC Keller *et al. Nature* **000**, 1-4 (2014) doi:10.1038/nature12990

How are the CNO elements being formed, what are the subsequent steps in the cosmochemistry in first stars?

Modes of converting primordial isotopes

The pp chains are too slow (no ^{12}C, no CNO) for stabilizing a massive 1^{st} generation star → hot pp-chains, deuteron cycle, triple alpha process!

Three ways to by-pass the mass 5 and mass 8 gaps:

^{4}He(2α,γ)^{12}C

Alpha clusters as catalytic compound structure

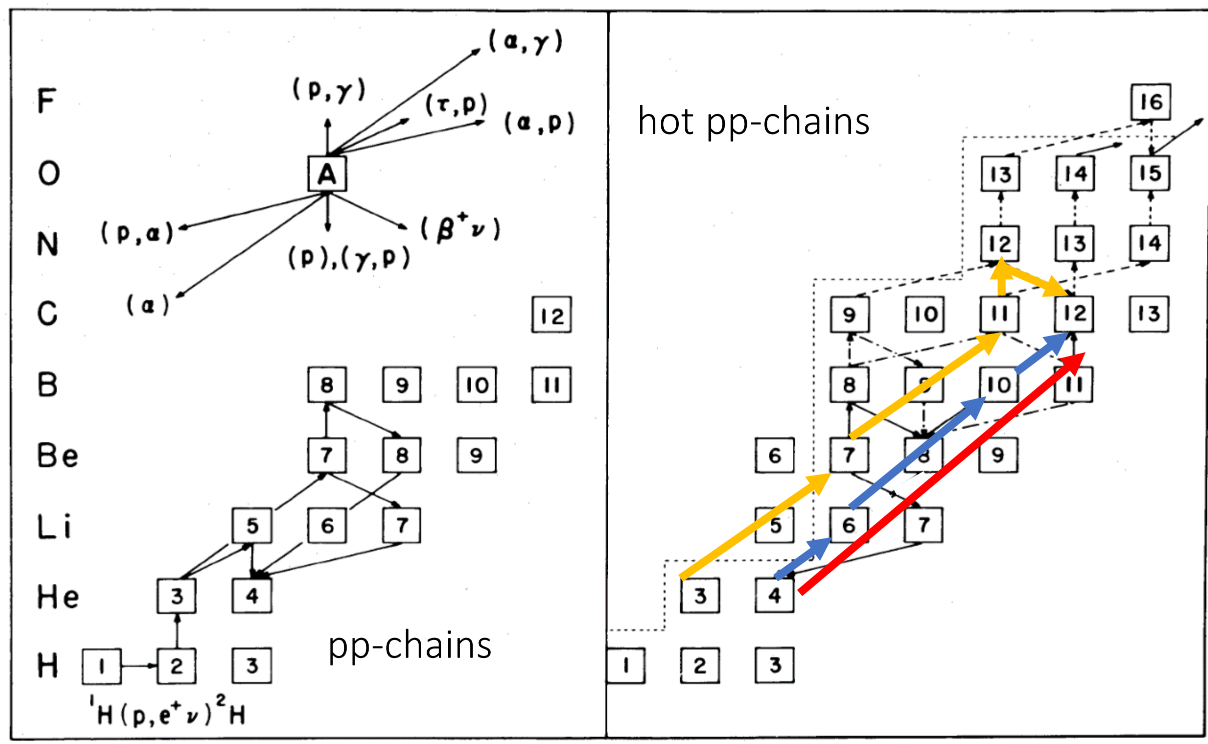
^{4}He(d,γ)^{6}Li(α,γ)^{10}B(α,d)^{12}C

Deuterons as catalyst isotope

^{3}He(α,γ)^{7}Be(α,γ)^{11}C(p,γ)^{12}N

^{12}N(β^{+}ν)^{12}C

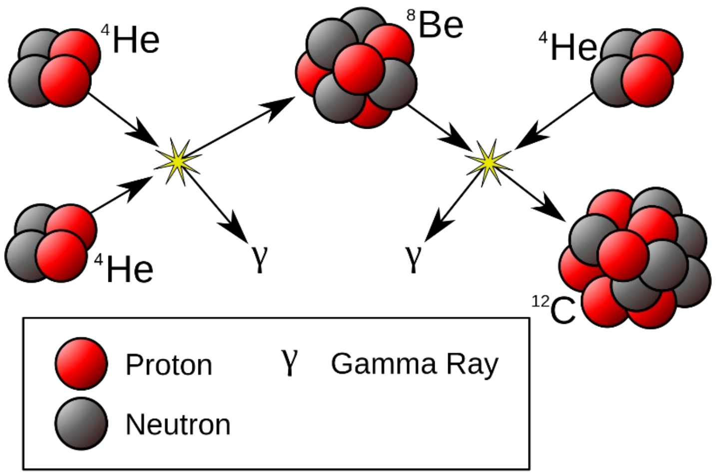
The ^{7}Be link to the hot pp-chains

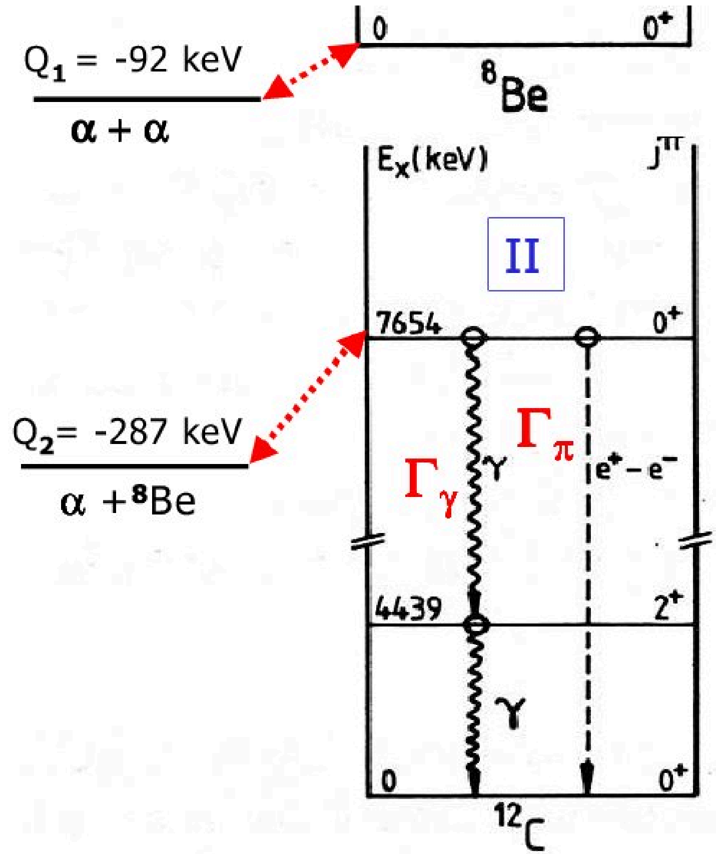


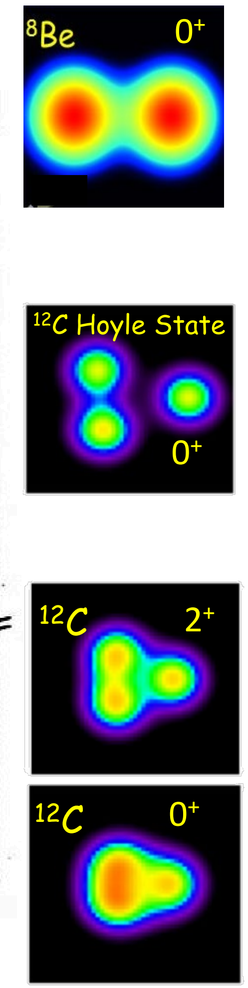
THE ASTROPHYSICAL JOURNAL, 343:352–364, 1989 August 1

Light Isotope Clusters

Triple alpha process







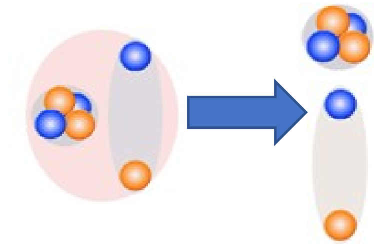
Facilitated by the cluster structure of the ^{8}Be and the ^{12}C Hoyle State

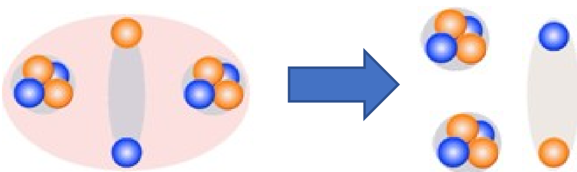
Y. Kanada En'yo, M. Kimura, A. Ono, Prog. of Theo. Exp. Phys..2012 (2012) 01A202

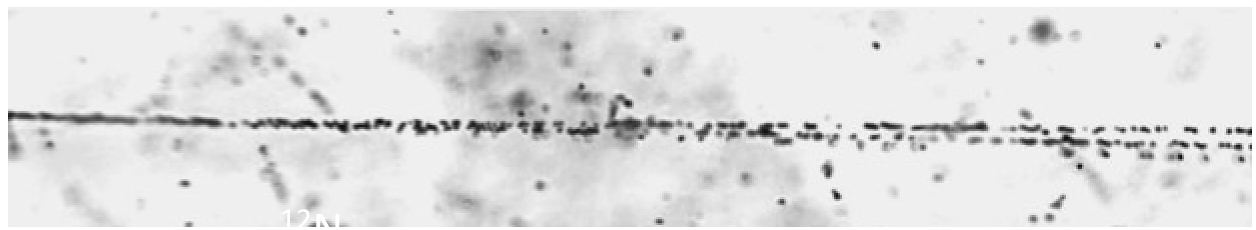
Three particle fusion that may occur by different reaction pathways:

- Single step process (more likely for high density environments
- Two step sequence (handicap is short-lived ^{8}Be in equilibrium abundance)
- Unbound 0^+ alpha-cluster state in ^{12}C (Hoyle state) saves the day since it adds a resonant component.

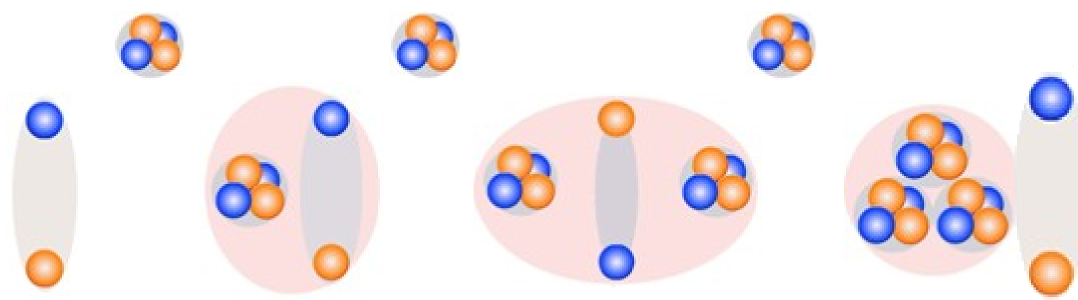
CR Dissociation and LE Capture







d ⇨ ^{6}Li ⇨ ^{10}B ⇨ ^{14}N



d ⇨ d⊗α ⇨ d⊗^{8}Be ⇨ d⊗^{12}C

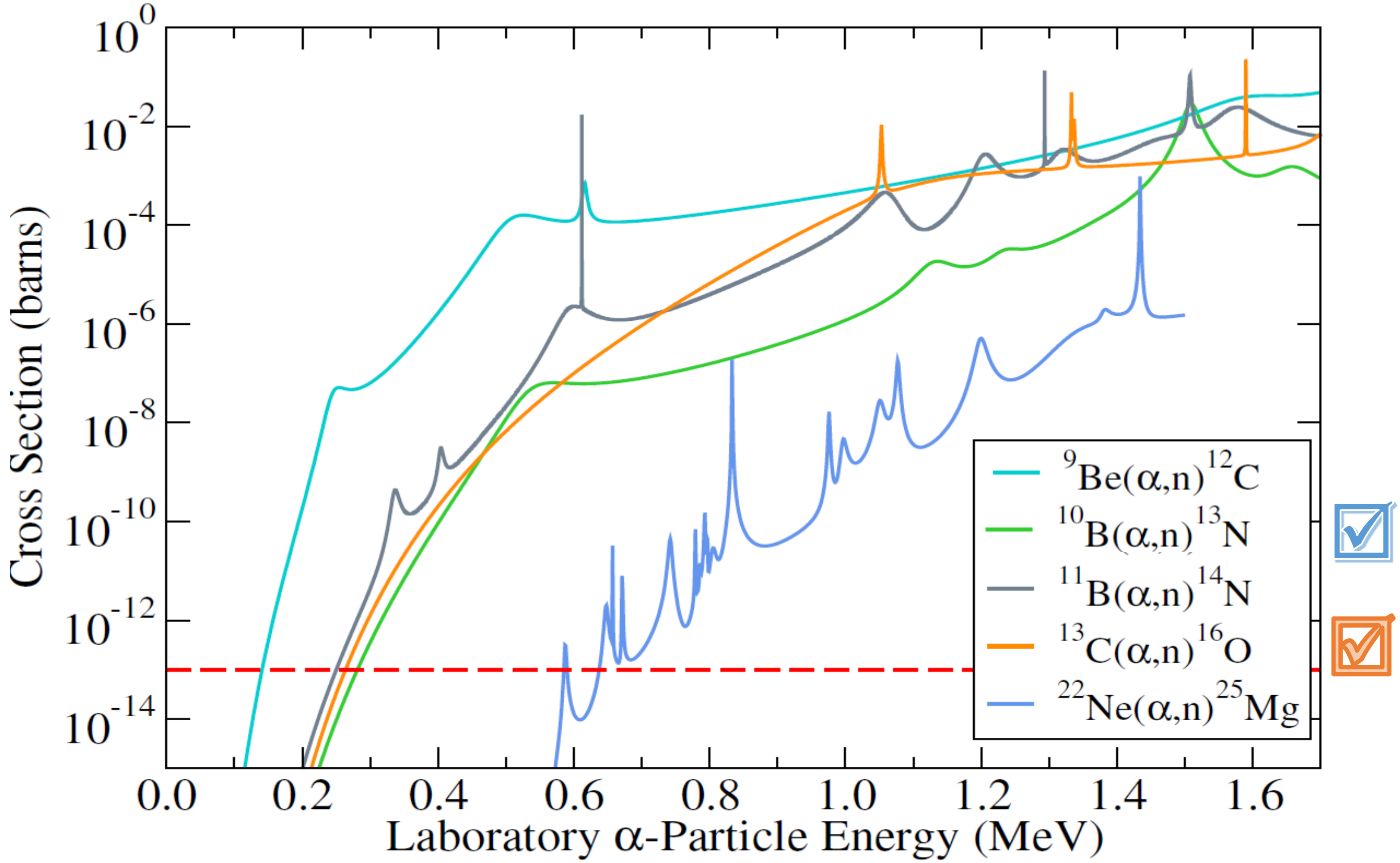
Nuclear dissociation and nuclear reactions are facilitated by nuclear structure and nucleon clustering!

^{9}Be production	^{10}B production	^{11}Be production
On primordial fuel	On primordial fuel	On primordial fuel
^{4}He(αn,γ)^{9}Be	^{4}He(d,γ)^{6}Li	^{3}He(α,γ)^{7}Be(e^{-})^{7}Li
^{7}Li(^{3}He,p)^{9}Be	^{9}Be(p,α)^{6}Li	^{7}Be(α,γ)^{11}C(β^{+})^{11}B
^{7}Li(^{2}H,γ)^{9}Be	^{6}Li(α,γ)^{10}B	^{7}Li(α,γ)^{11}B
	^{9}Be(p,γ)^{10}B	
↓	↓	↓
^{9}Be(α,n)^{12}C	^{10}B(α,n)^{13}N	^{11}B(α,n)^{14}N

Most of the reaction rates go back to FCZ 75 and CF88, very limited amount on new data! Extremely limited amount on low energy data.

Most of the systems, e.g. ^{9}Be, ^{10}B, ^{11}B are characterized by alpha – cluster structures, 2α⊗n, 2α⊗d, and 2α⊗t, respectively. These structures typically emerge as resonances near the alpha thresholds. Broad resonance in ^{6}Li(α,γ)^{10}B at 730 keV and at 945 keV in ^{7}Li(α,γ)^{11}B.

Possible neutron sources in first stars?

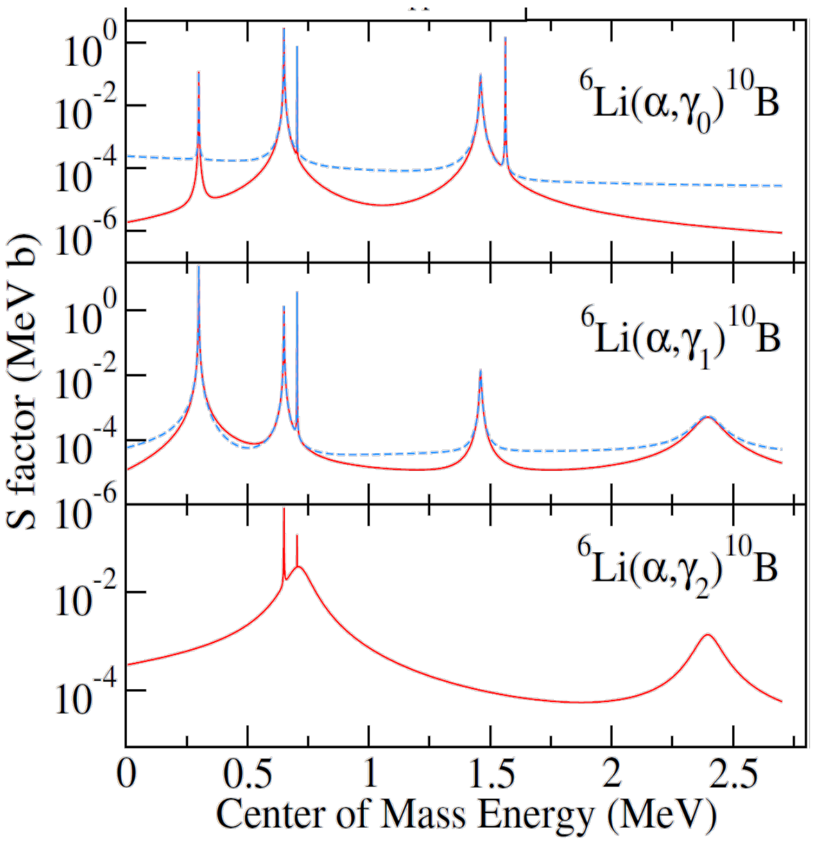


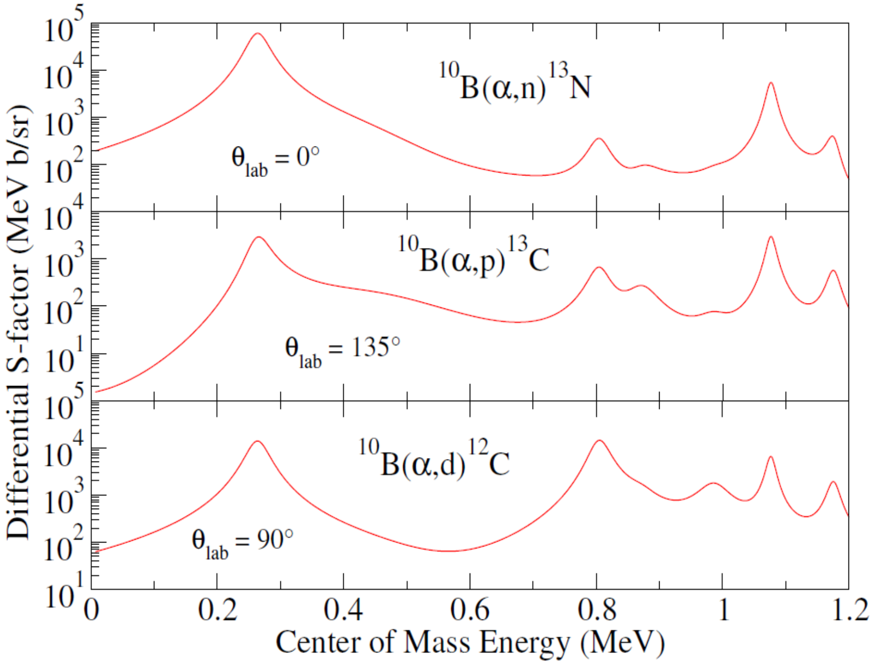
Where do the seed isotopes come from?

Reaction cross sections characterized by broad resonances

$^{6}Li(\alpha,\gamma)$ $^{10}B(\alpha,x)$ $^{14}N(\alpha,\gamma)$

d ⇨ ^{6}Li ⇨ ^{10}B ⇨ ^{14}N
d ⇨ d⊗α ⇨ d⊗^{8}Be ⇨ d⊗^{12}C

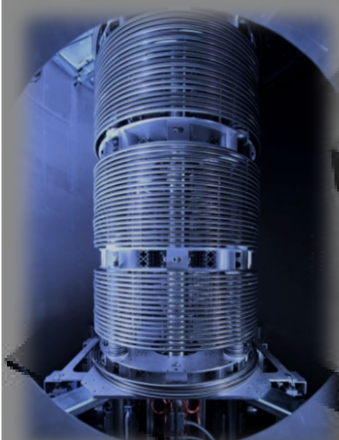


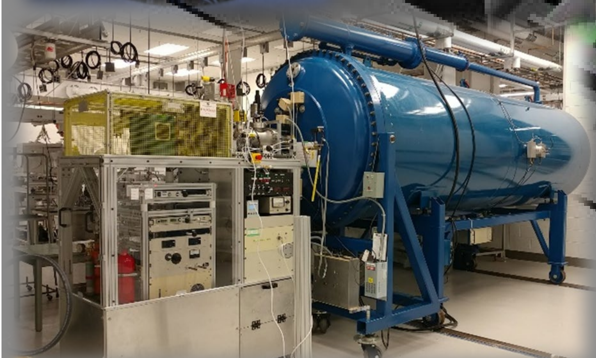


Anticipated cross sections are dominated by broad resonant structures corresponding to alpha cluster threshold states

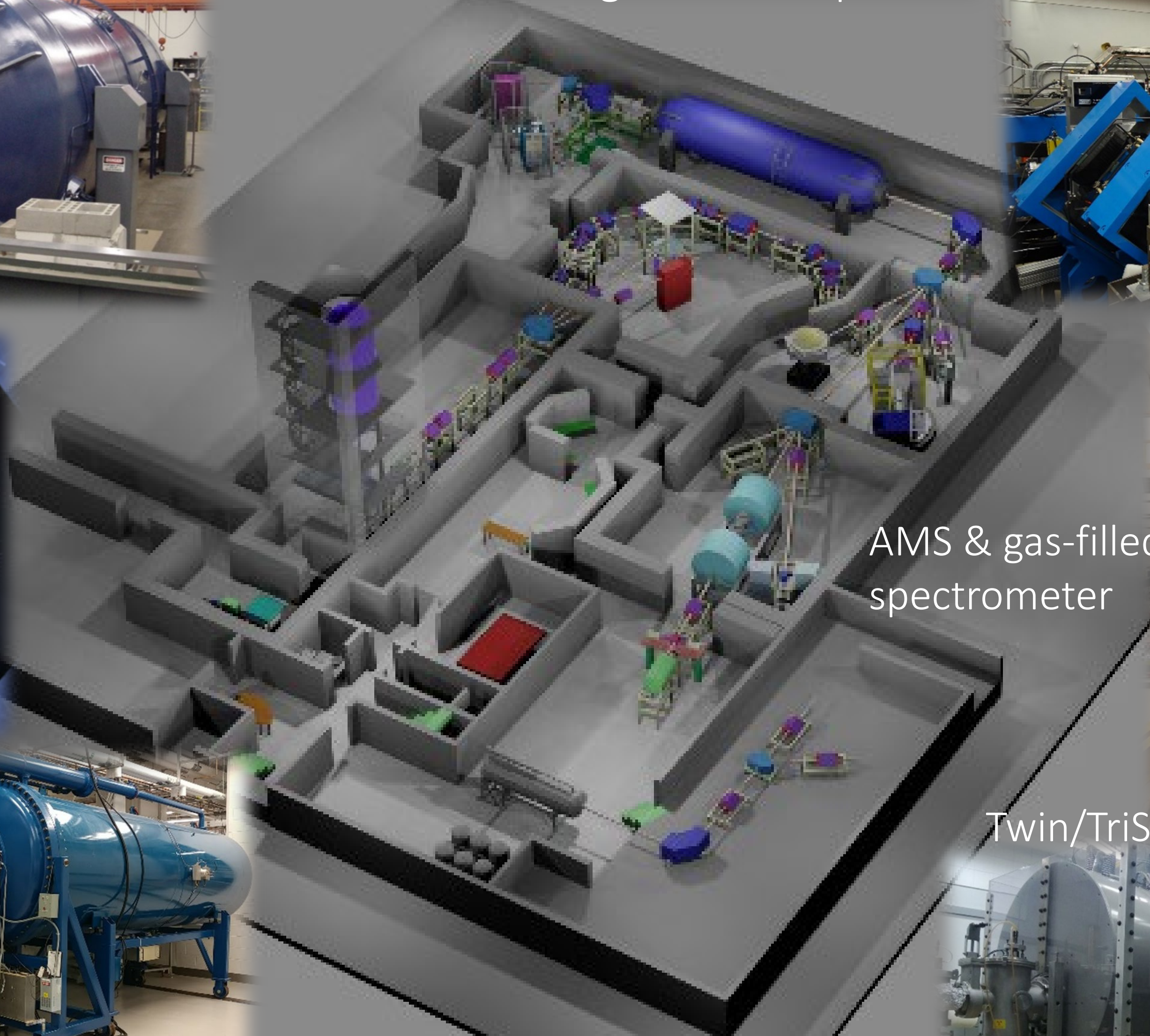
Experimental Resources at Notre Dame and CASPAR

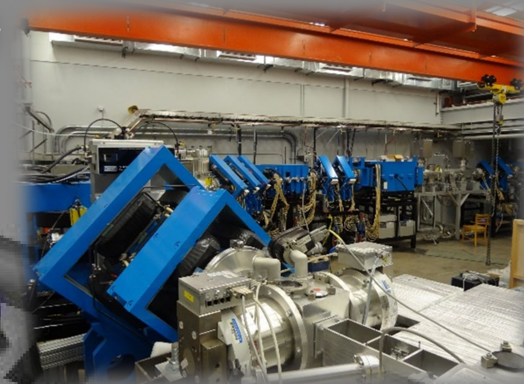
Experimental facilities at Notre Dame



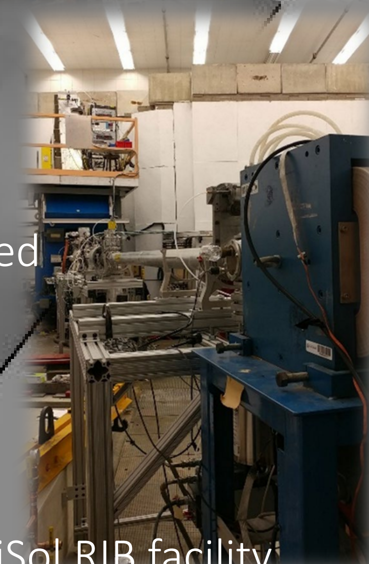


St George Recoil Separator



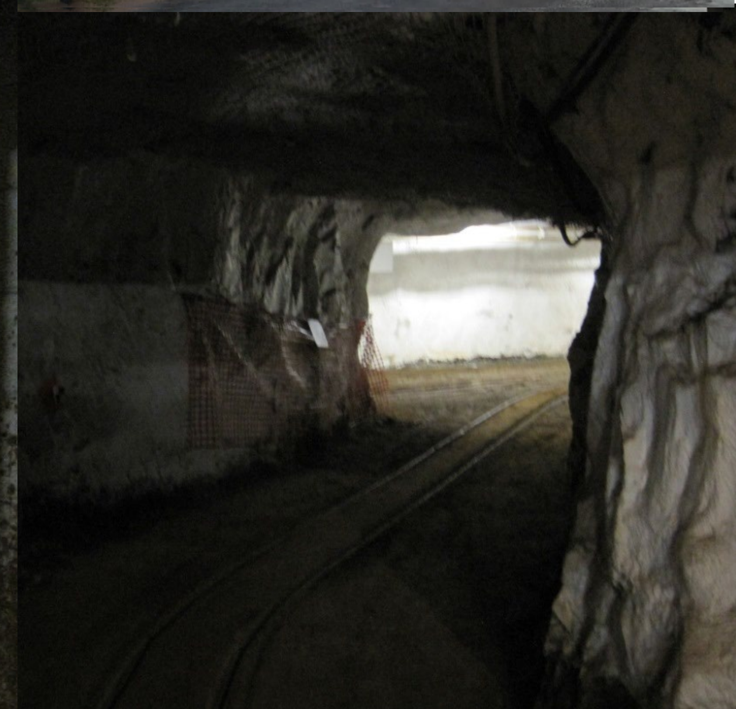


AMS & gas-filled spectrometer

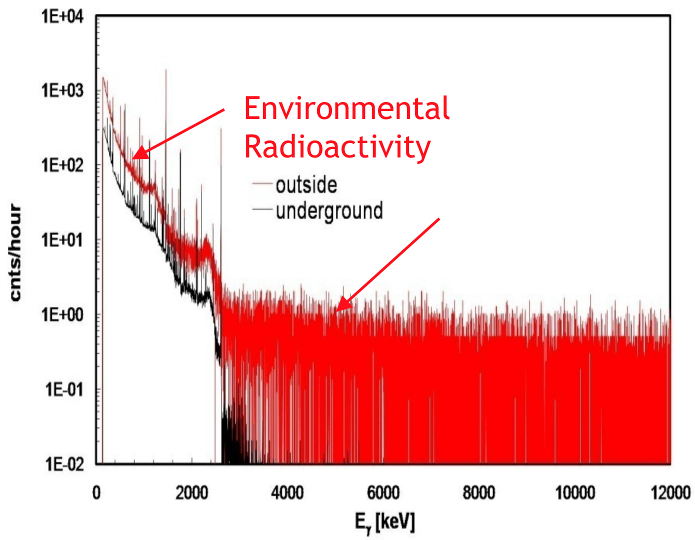


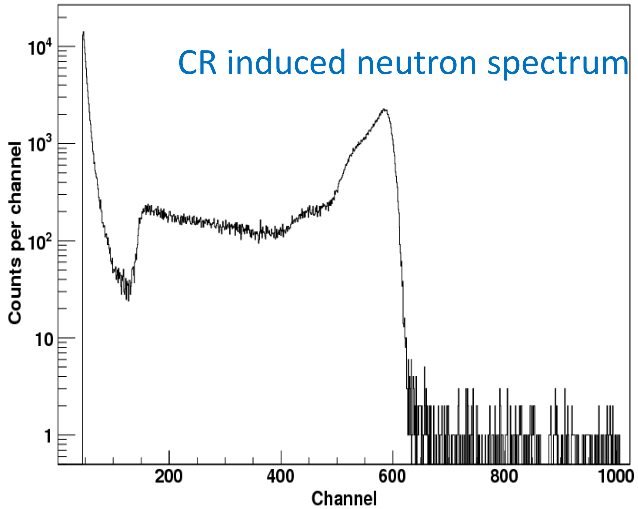
Twin/TriSol RIB facility

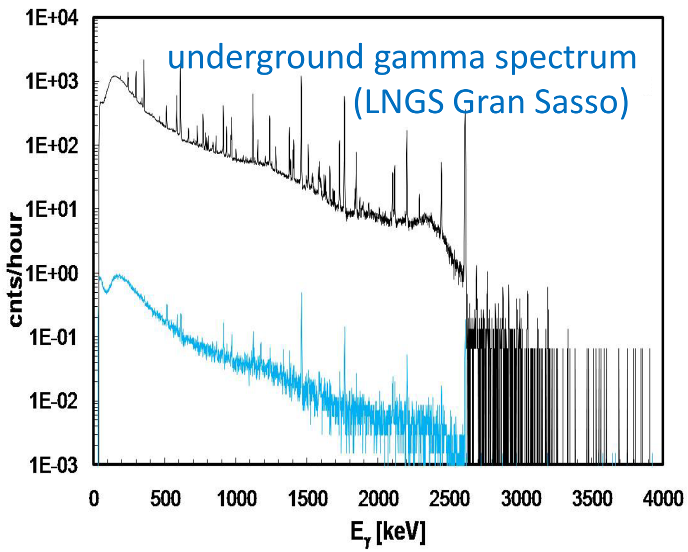
CASPAR Facility one mile under ground

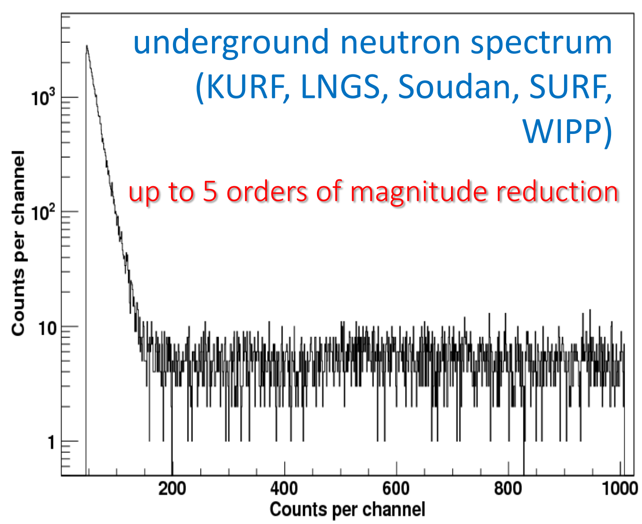


Advantage of underground physics



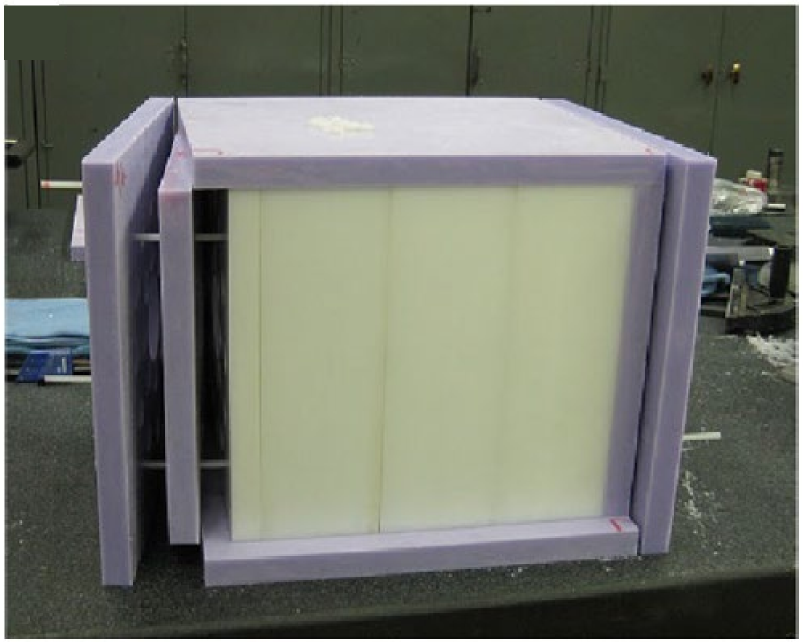


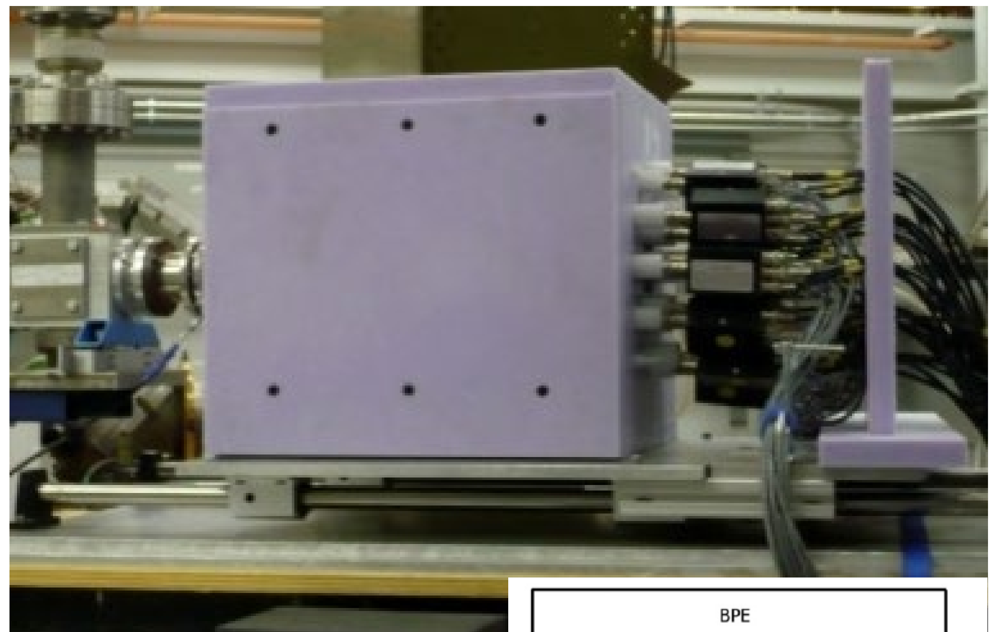


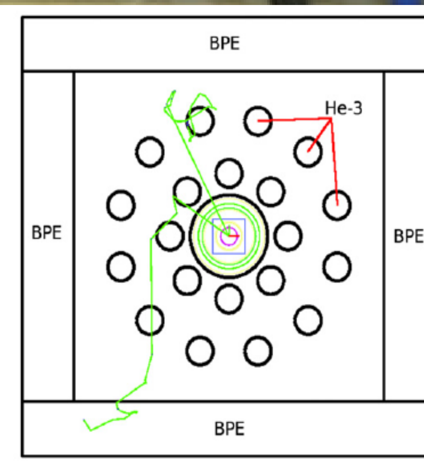


Neutron detection techniques

Standard ^{3}He counter system with 24 ^{3}He tubes – problems with beam induced neutron background, e.g. $^{13}C(\alpha,n)$.







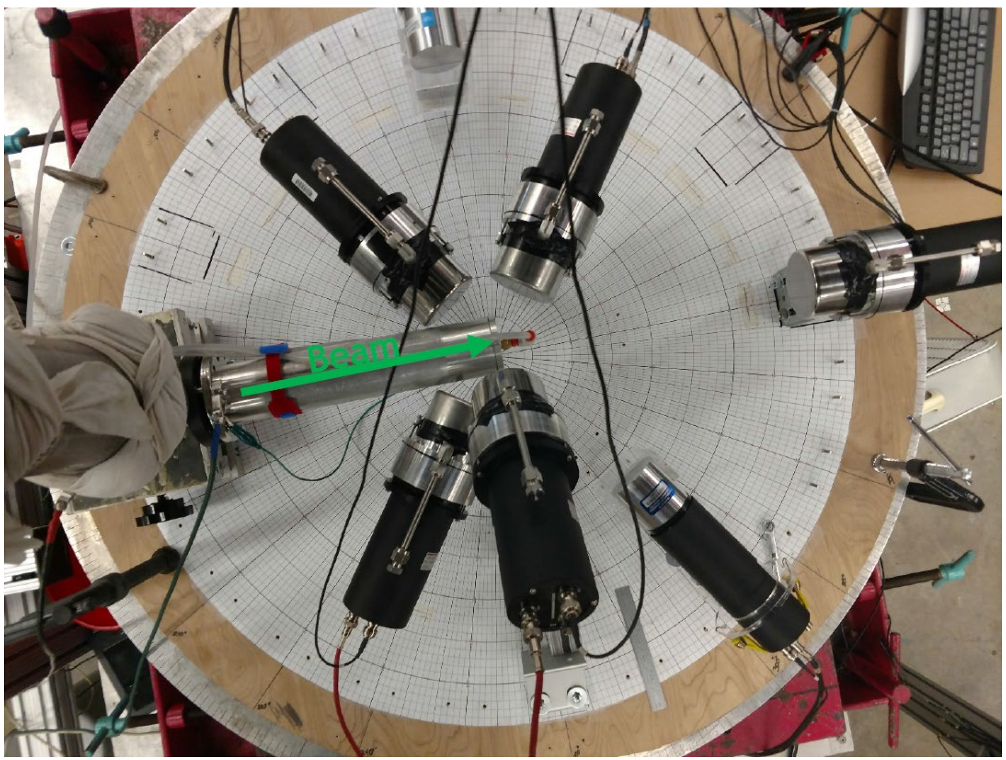
Notre Dame 3He gas tube system

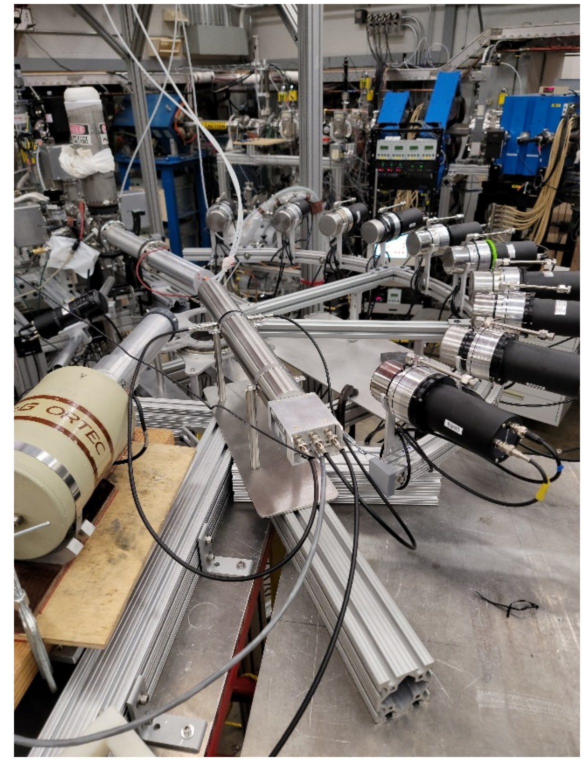
S. Falahat, et al. A ^{3}He neutron detector for the measurement of (a,n) reactions. NIM A 700 (2013) 53-59

New neutron detection techniques

Alternative development for better event identification are deuterated liquid scintillators with response function analysis.

EJ315

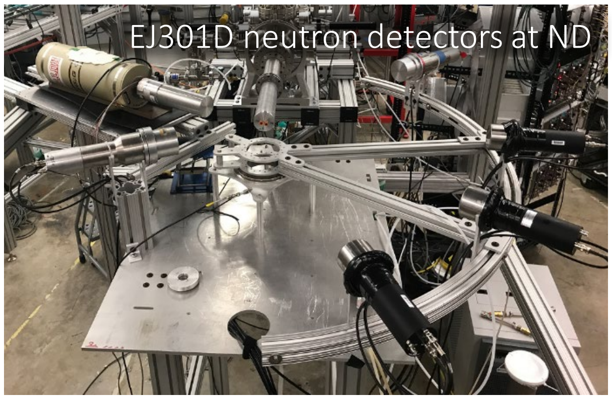


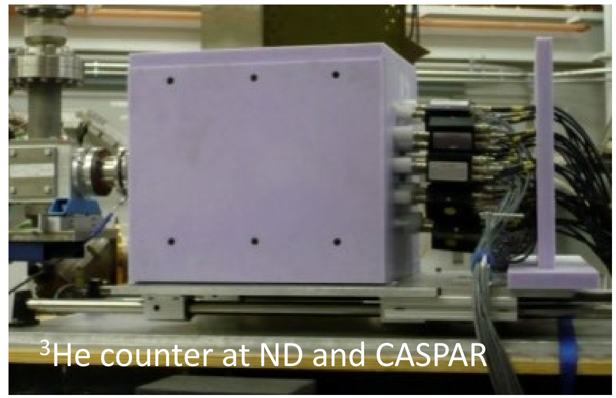


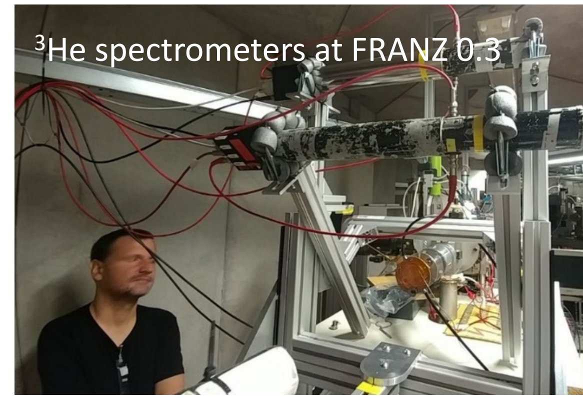
C_6D_6 deuterated polyethylene detectors

M. Febbraro, et al. The ORNL Deuterated Spectroscopic Array — ODeSA, NIM A 946 (2019) 162668

$^{10}B(\alpha,n)$, $^{11}B(\alpha,n)$ at CASPAR, Frankfurt, and Notre Dame

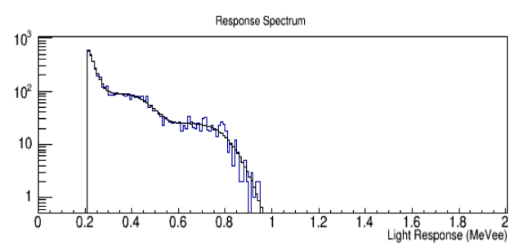


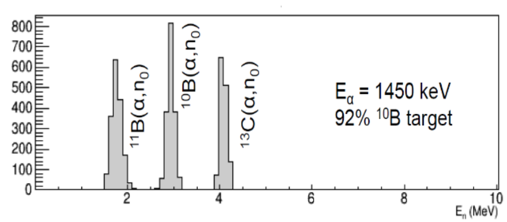


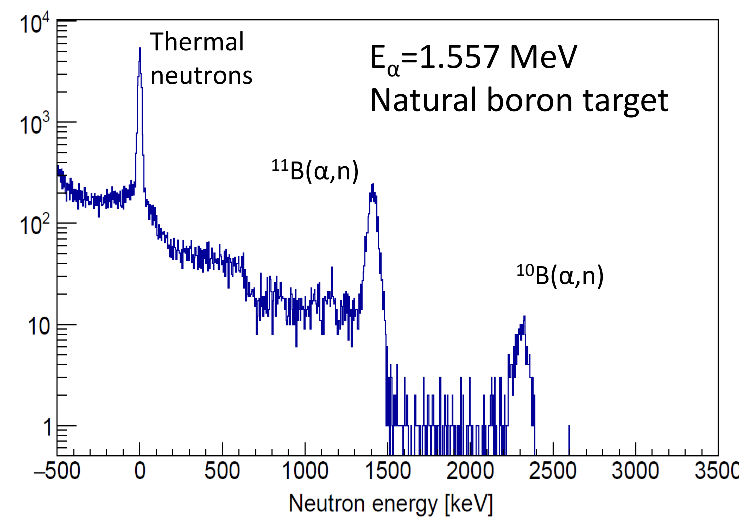


Combination of different detector types to identify $^{10}B(\alpha,n)$ and $^{11}B(\alpha,n)$ neutron components:

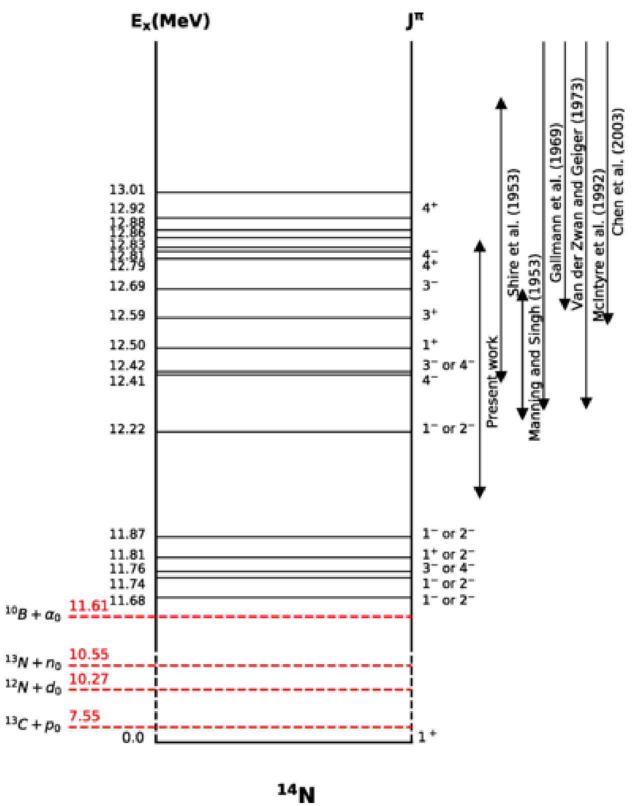
- deuterated scintillators,
- ^{3}He counters for thermalized neutrons,
- ^{3}He spectrometers.

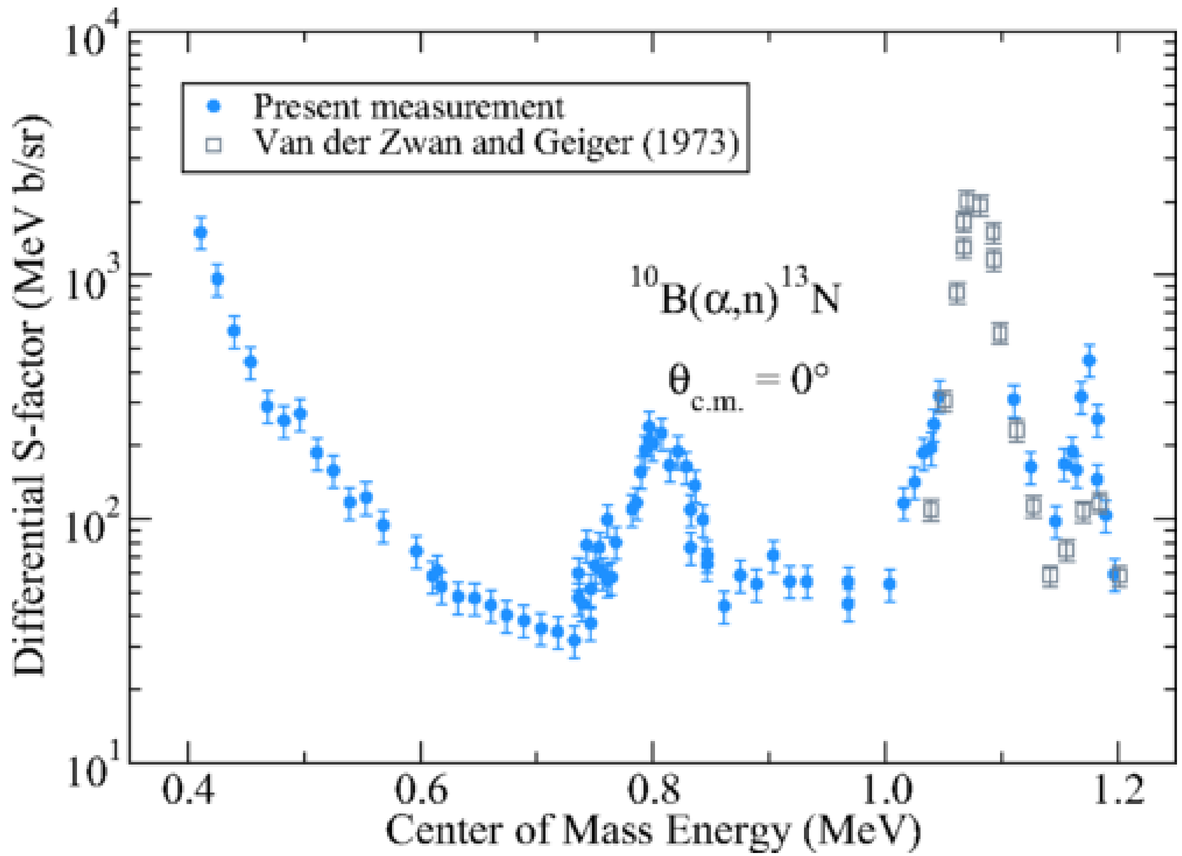






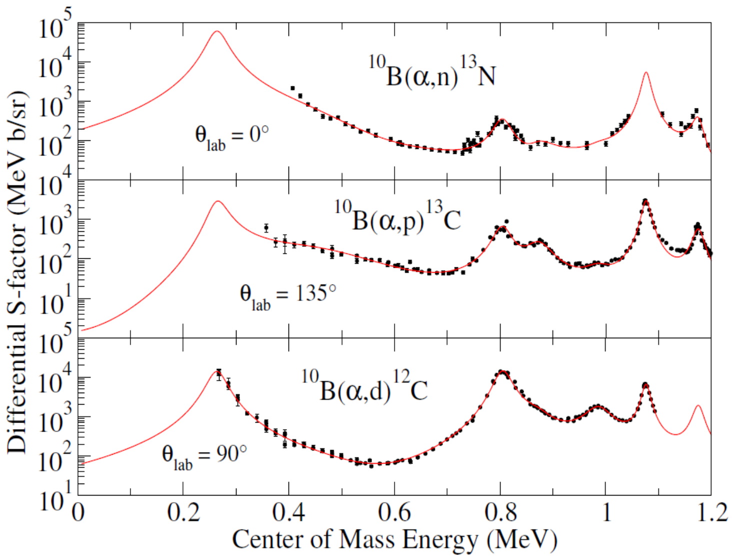
The $^{10}B(\alpha,n)$ reaction

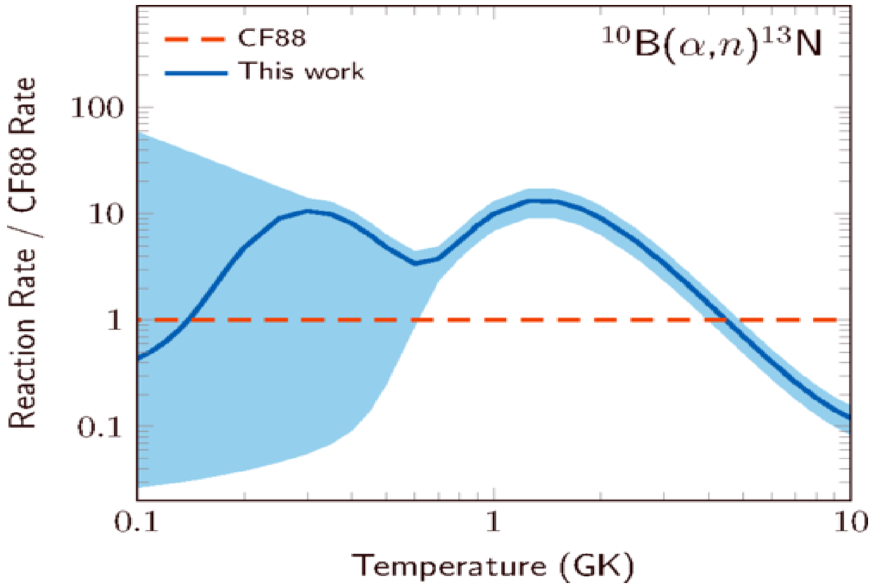


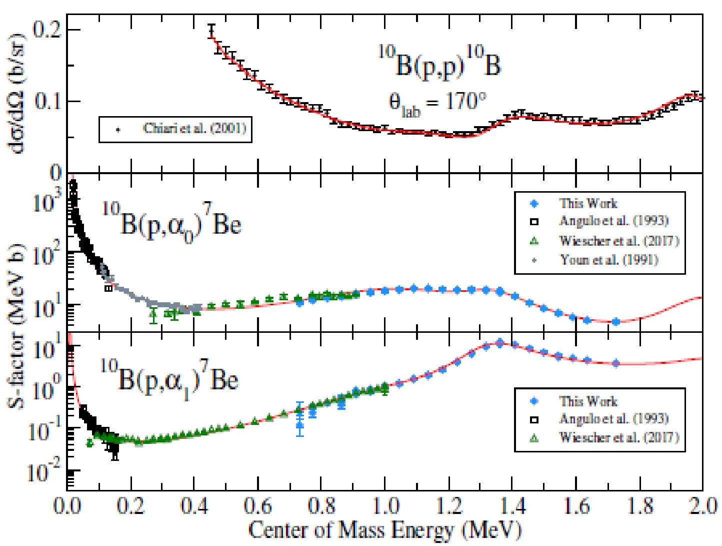


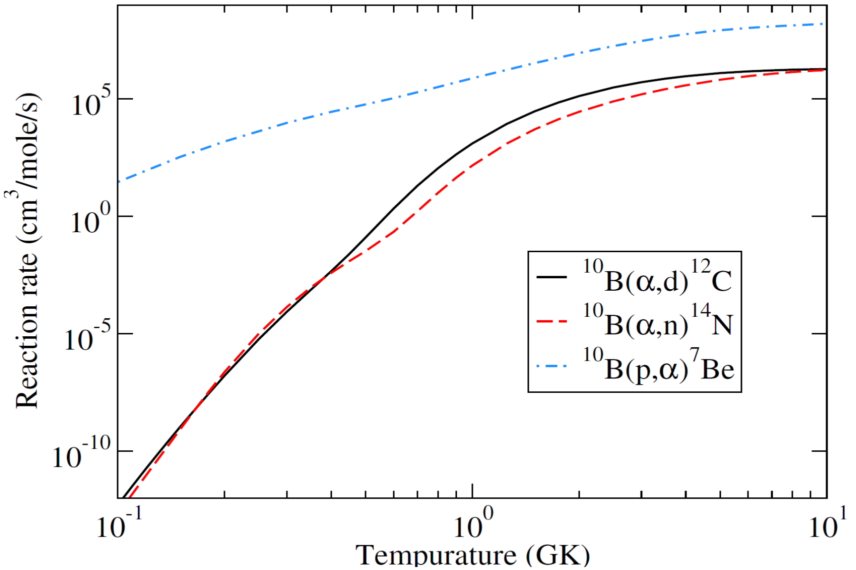
Near threshold increase of s-factor indicates pronounced cluster resonance which increases the reaction rate by several orders of magnitude, however, like in the 13C case the 10B(p,α) reaction remains stronger that the 10B(α,n) process. This requires highly convective conditions!

The ^{10}B+α versus the ^{10}B+p reaction





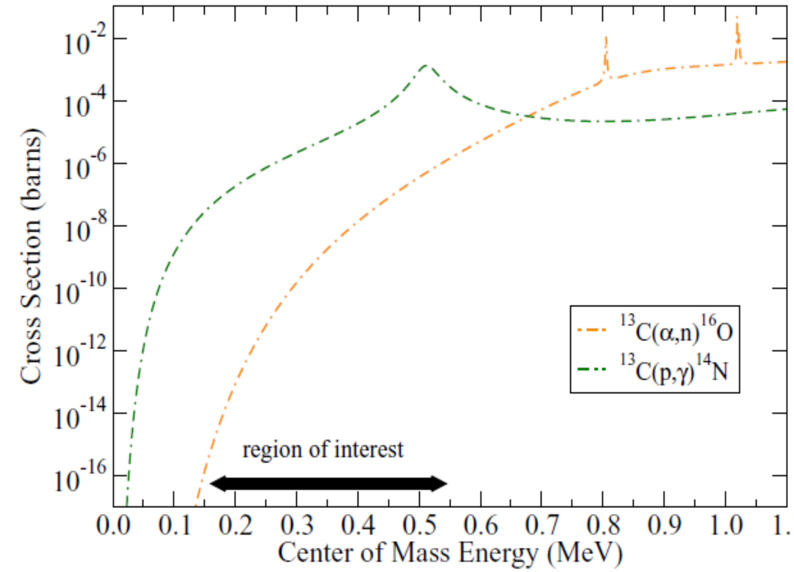


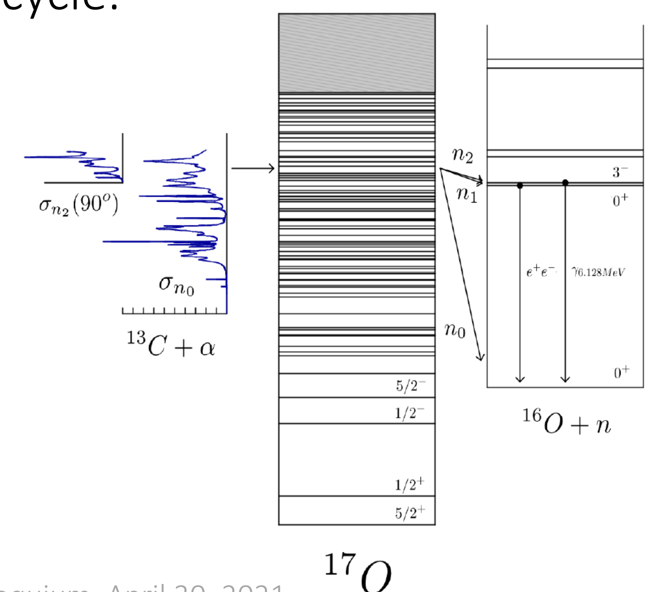


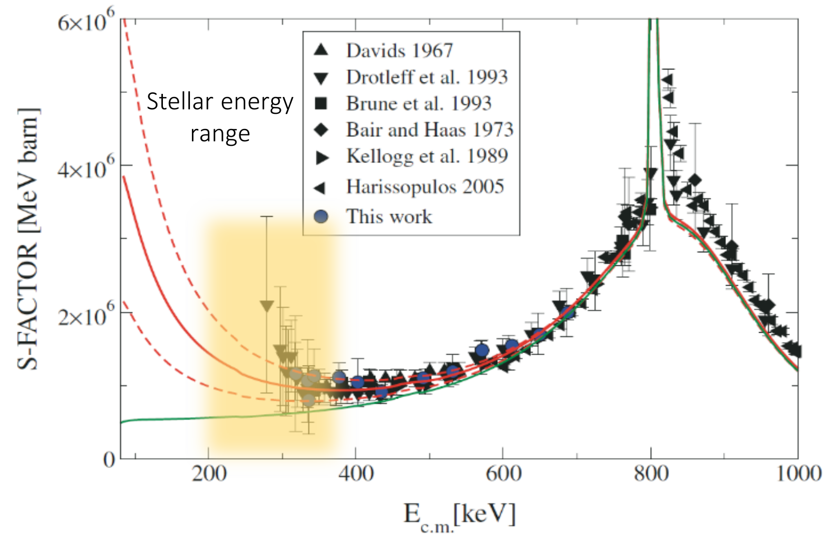
The $^{13}C(\alpha,n)$ reaction

The reaction is characterized by one of the strongest cross sections for producing neutrons in s- and i-process.

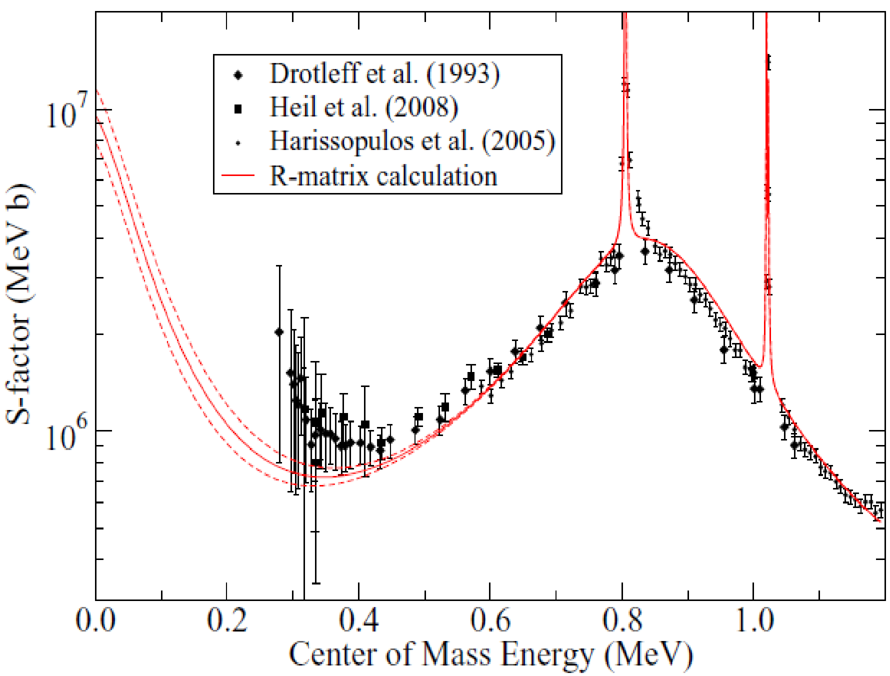
Yet, it is only efficient in a very helium rich environment with negligible hydrogen content because of the considerably stronger $^{13}C(p,\gamma)^{14}N$ reaction that drives the CNO cycle.

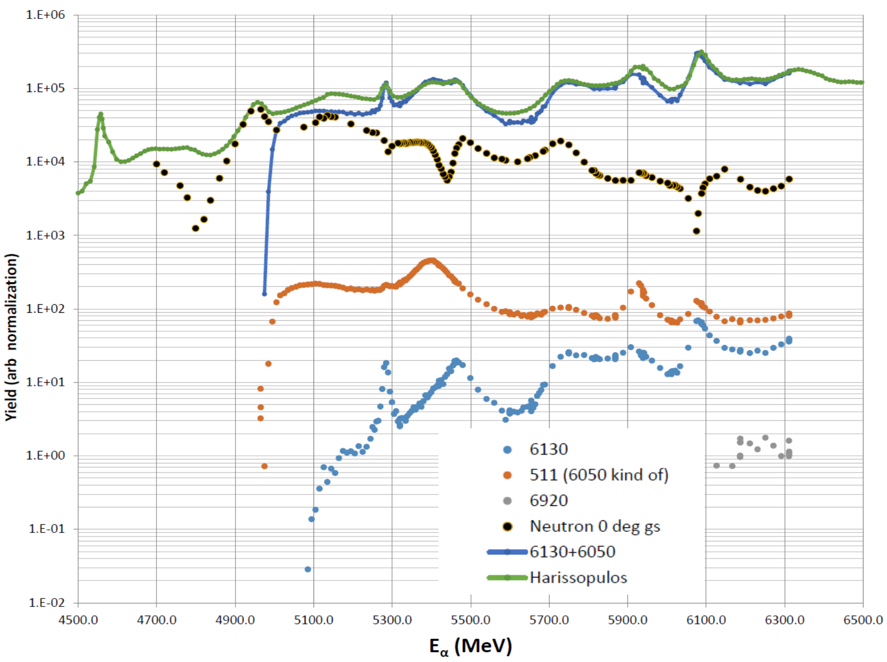






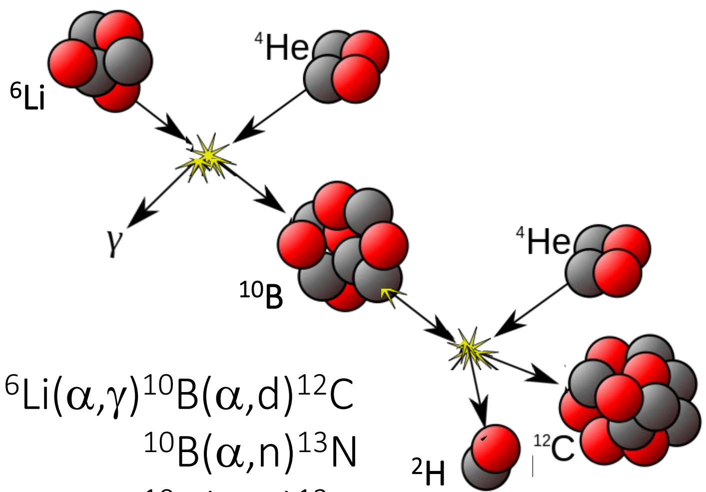
Recent Results – the predictive power of R-matrix theory





The Carbon Oxygen Production in the Early Universe

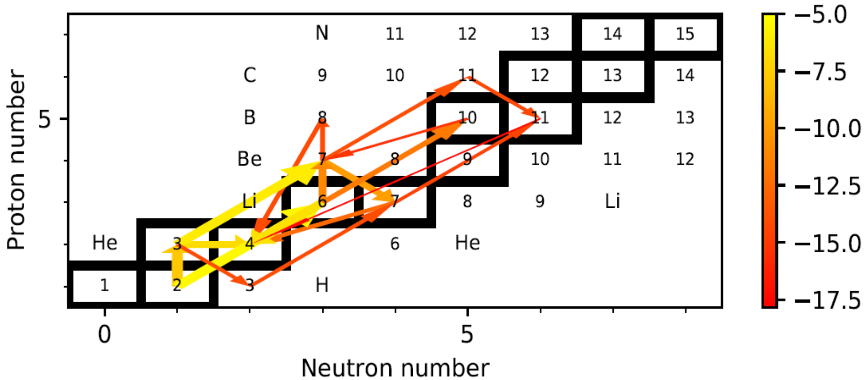
Exploring alternative paths



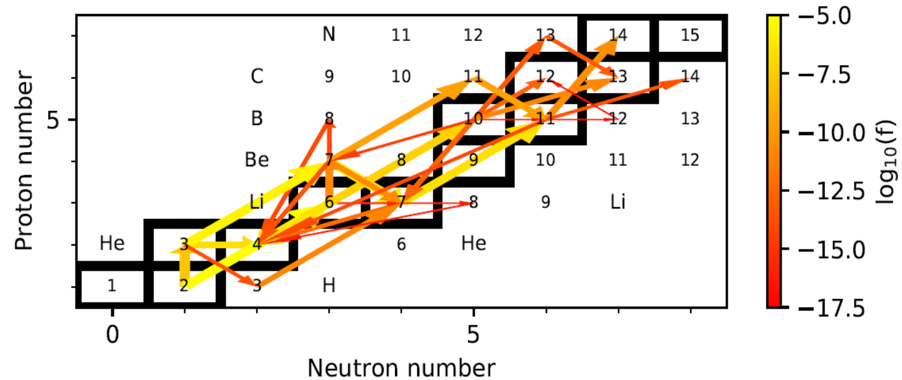
The $^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$
$^{10}B(\alpha,n)^{13}N$
$^{10}B(\alpha,p)^{13}C$

Recent low energy studies at the CASPAR underground accelerator show pronounced cluster resonances near the alpha threshold, enhancing the reaction rates by several orders of magnitude!

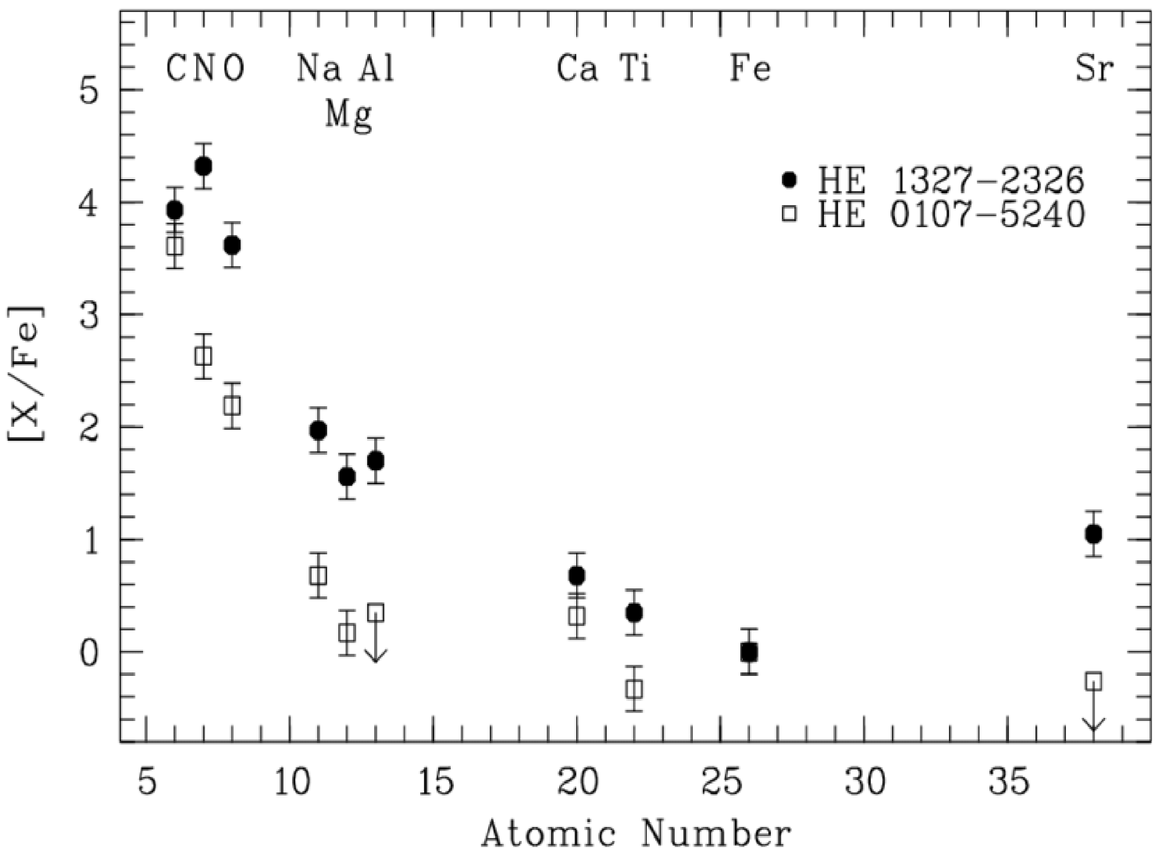
After 1 hour



After 10 months



From primordial to CNO material



From CNO processing towards higher abundances in increasingly dense and highly convective environment, processing towards higher mass range:

$^{12}C(\alpha,\gamma)^{16}O$ establishes $^{12}C/^{16}O$ ratio

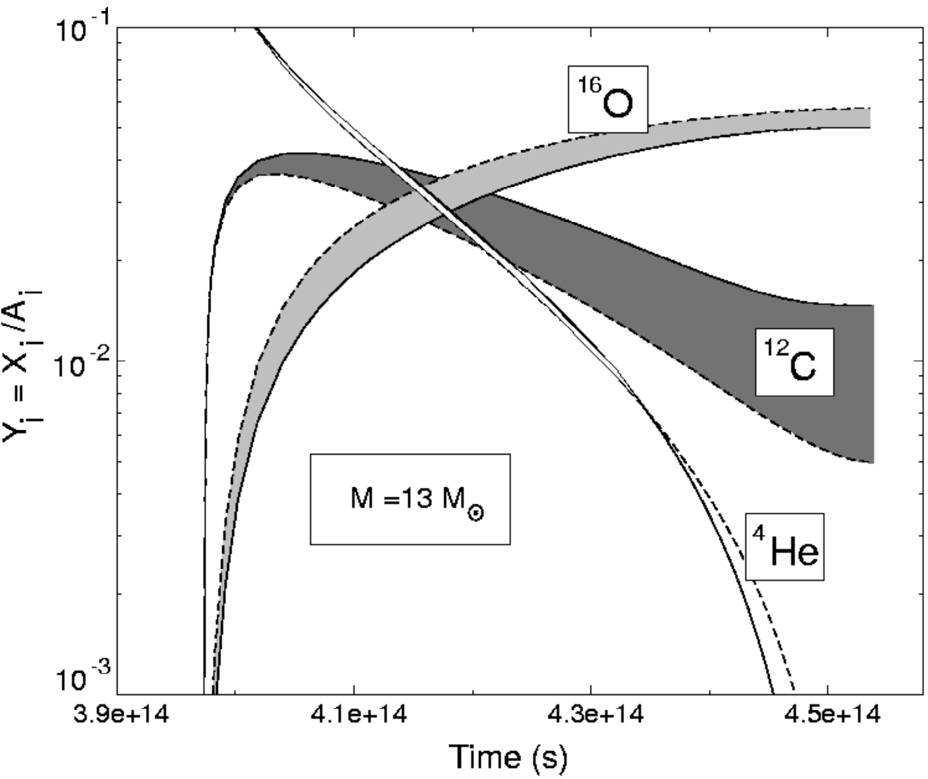
$^{13}C(\alpha,n)^{16}O$ provides early star neutron flux

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ might act as an additional neutron source.

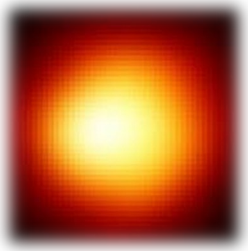
$^{19}F(p,\gamma)^{20}Ne$ provides a break-out feeding the elements in the NeNa cycle and beyond up to Ca.

The “holy Grail”

The step after carbon is being formed in a high temperature density environment:
$^{12}C(p,\gamma)^{13}N$ triggering the CNO cycle leading to ^{14}N
$^{12}C(\alpha,\gamma)^{16}O$ determining the early $^{12}C/^{16}O$ ratio



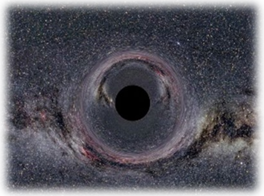
- Late Stellar Evolution
determines Carbon and/or Oxygen phase



- Type Ia Supernova
central carbon burning of C/O white dwarf

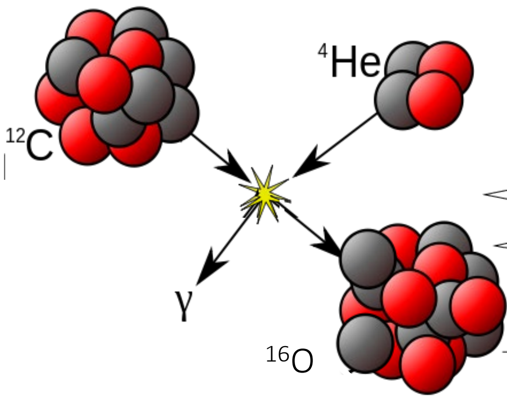
- Type II Supernova
shock-front nucleosynthesis in C and He shells of pre-supernova star

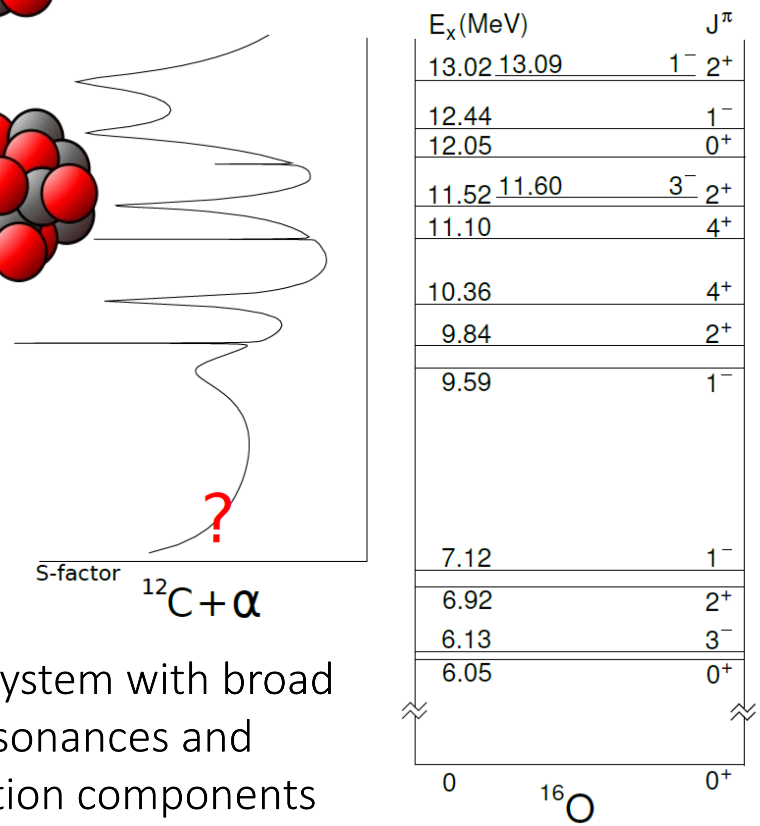
- Massive Black Hole Gap
Sets limits for Pair-Production Supernova causing a mass gap

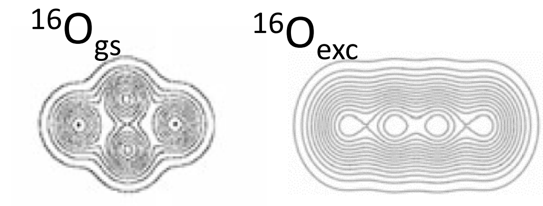


Cluster Structure of ^{16}O

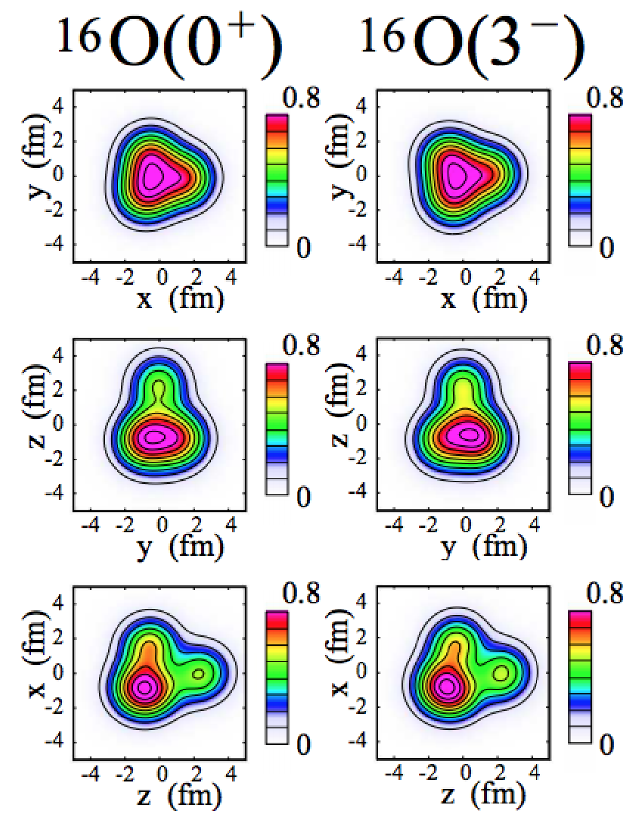
The $^{12}C(\alpha,\gamma)^{16}O$





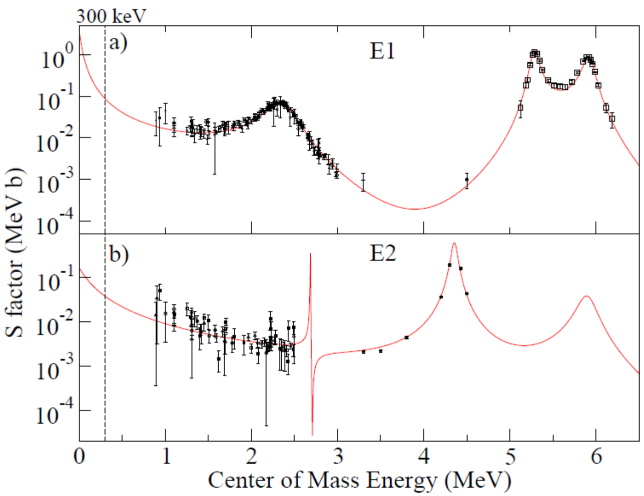


Alpha cluster structure configurations in ^{16}O

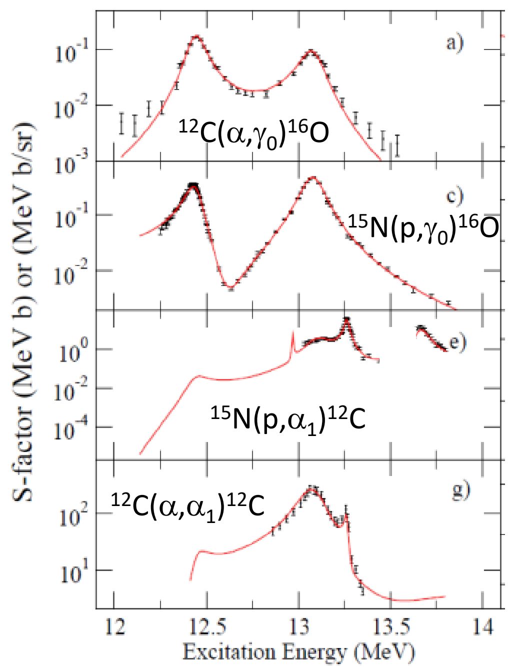


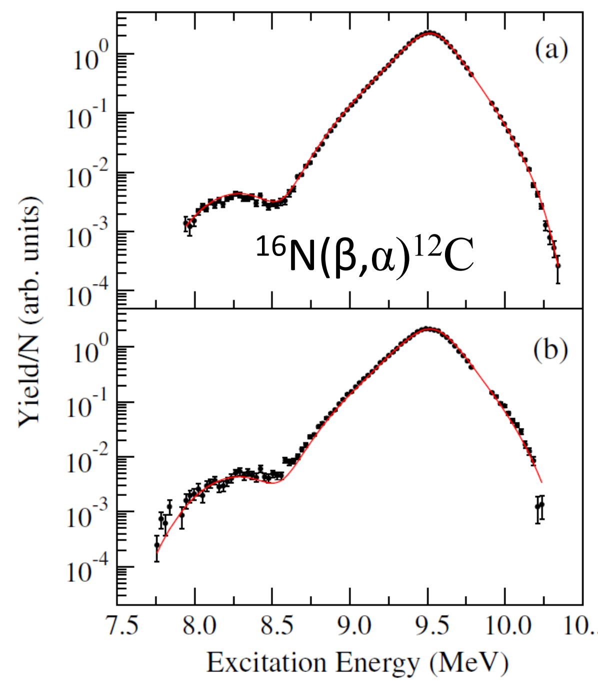
^{16}O is a very complex system with broad interfering 0^+, 1^-, 2^+ resonances and E2 direct capture reaction components directly interfering with the 2^+ resonances.

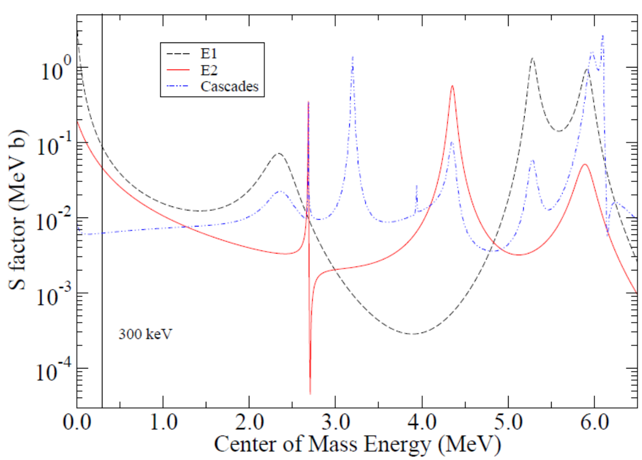
Direct Capture, Resonances, Subthreshold States and Interference between all of them



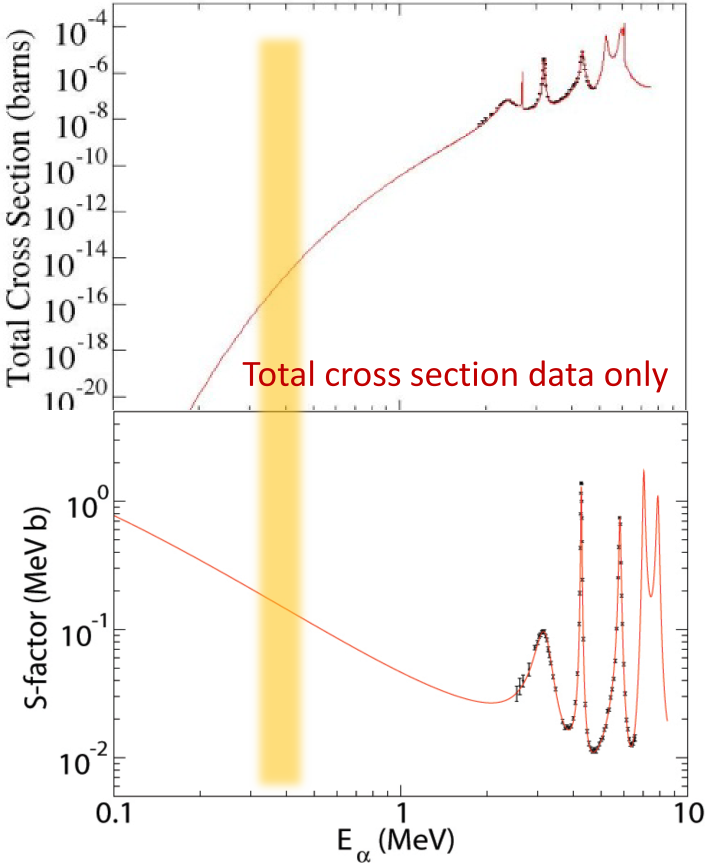
No first principle calculations possible? Phenomenological fits of all data available through all reaction channels possible for the compound nucleus ^{16}O!

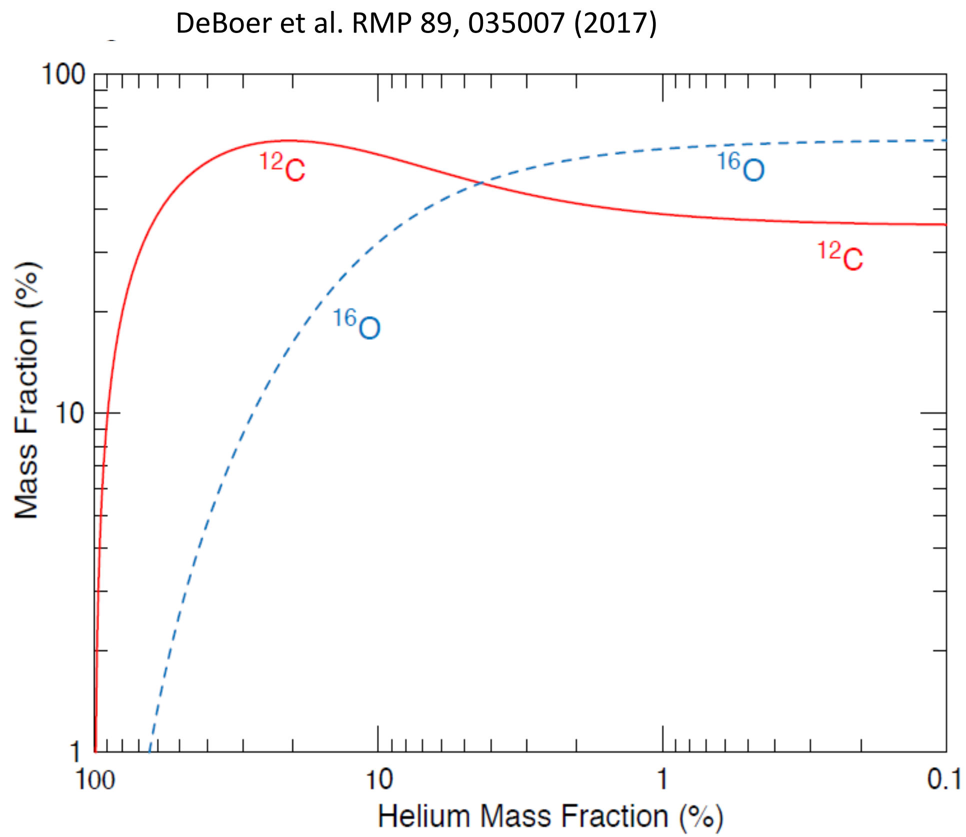






R-Matrix Analysis and Reaction Rate

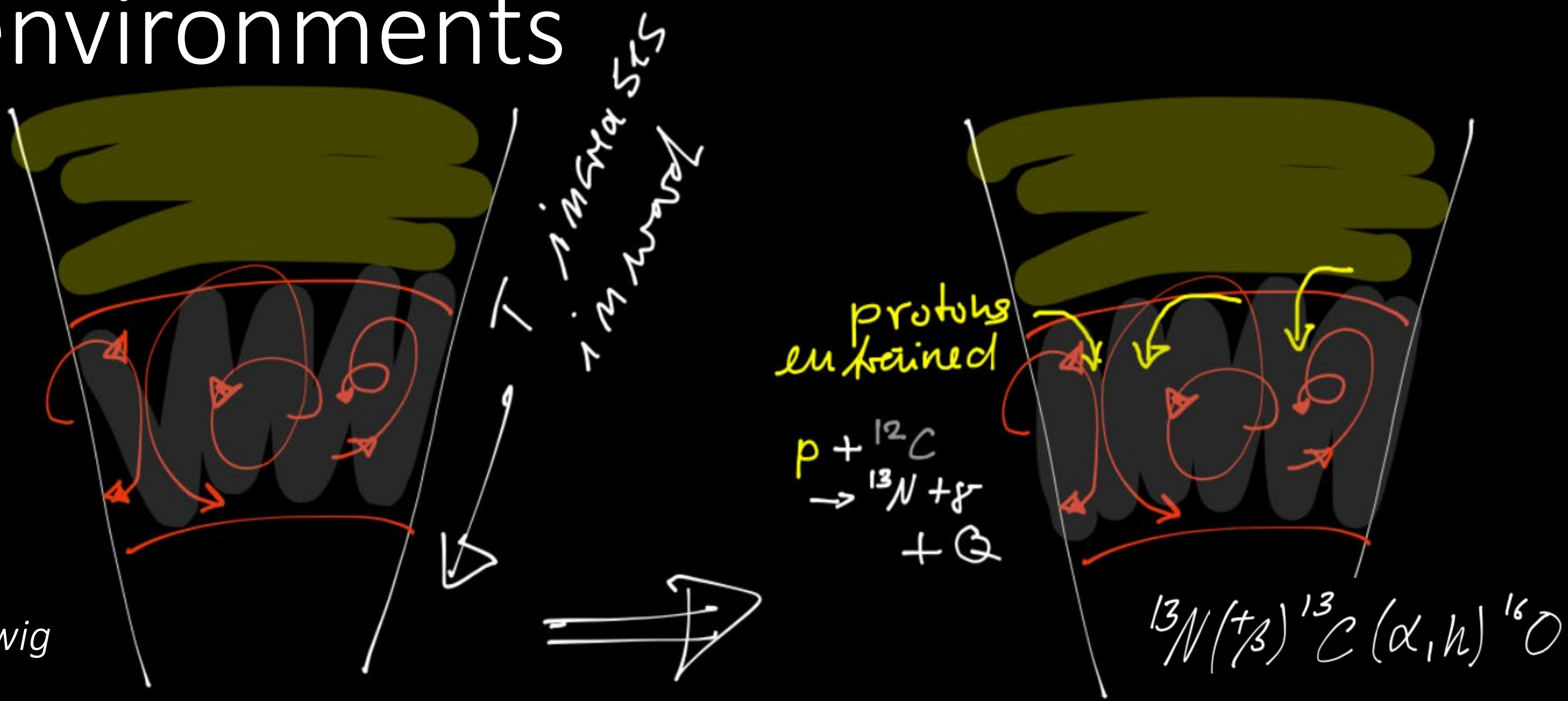




R-matrix (AZURE) based cross section extrapolation on the basis of all existing reaction data through ^{16}O compound nucleus give 15%-20% uncertainty in the reaction rate. ^{16}O dominates the abundances.

The i-Process in Early Stars

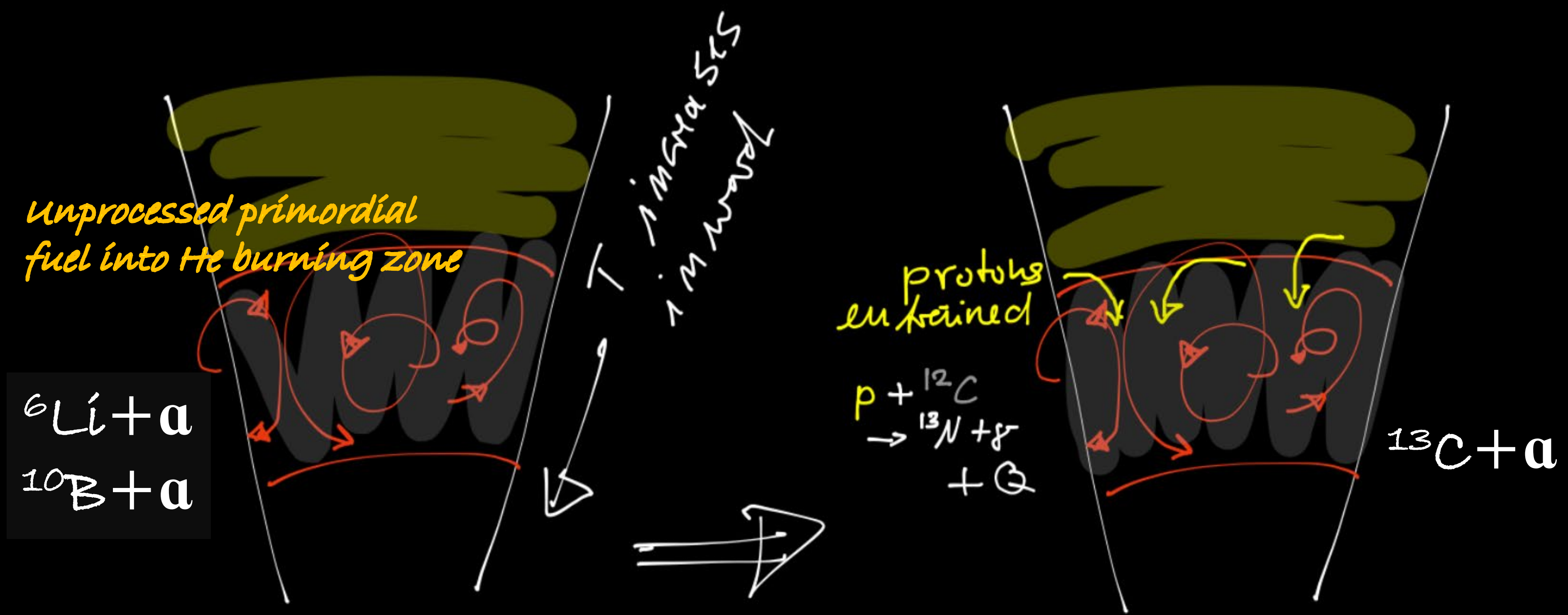
The i-process in fast convective environments



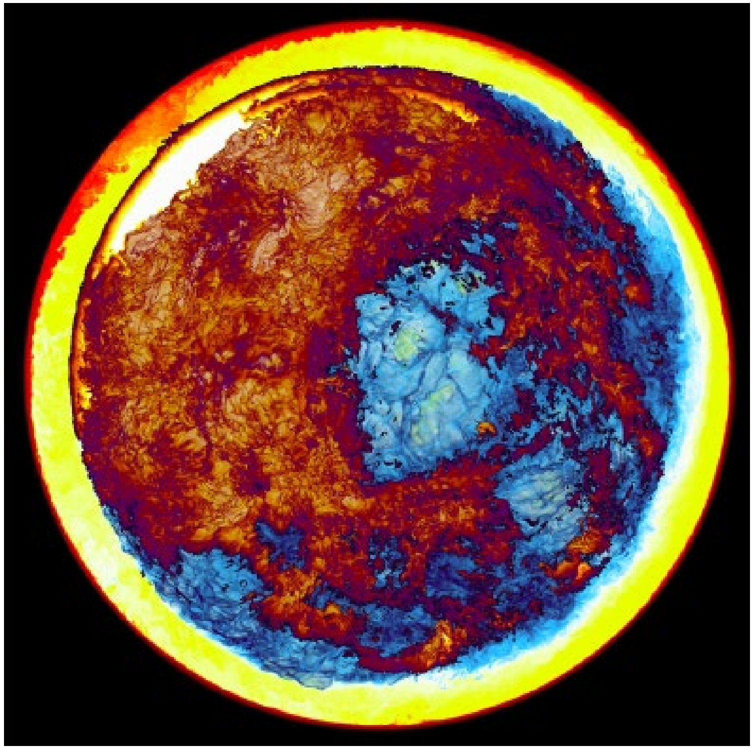
Falk Herwig

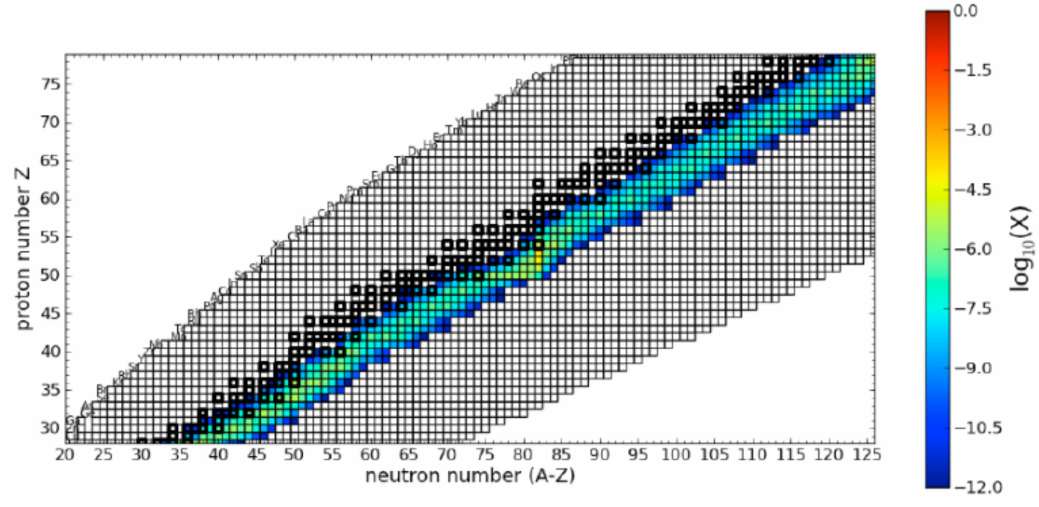
- ➢Model adopted by Cowan and Rose (1977), mixing of protons into ^{12}C enriched helium burning shell, triggering $^{12}C(p,\gamma)^{13}N$
- ➢Convective mixing of ^{13}N into hot regions while decaying to ^{13}C, triggering$^{13}C(\alpha,n)$ reaction at higher temperatures.
- ➢Generating s neutron flux of 10^{15} n/cm^{2}s which explain heavy element abundance distribution in early stars
- ➢Other neutron sources might be available in early star environments!

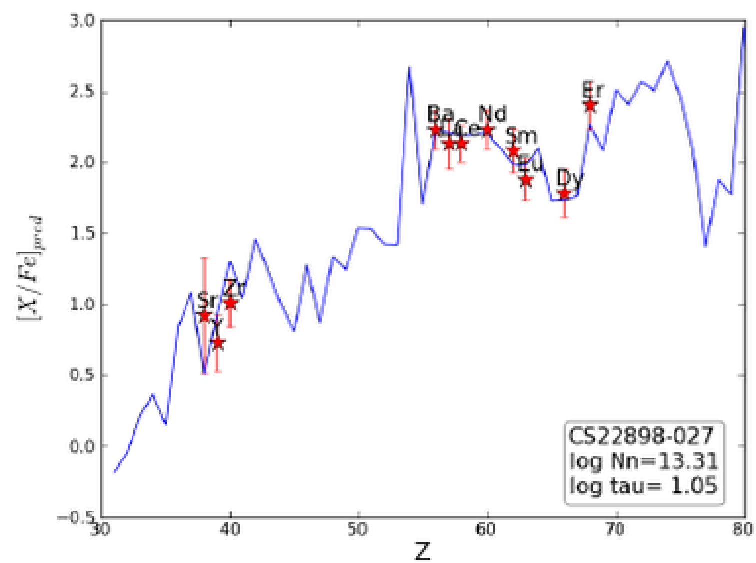
Broader concepts of the i-process in a deep convective environment



The i-process in early stars







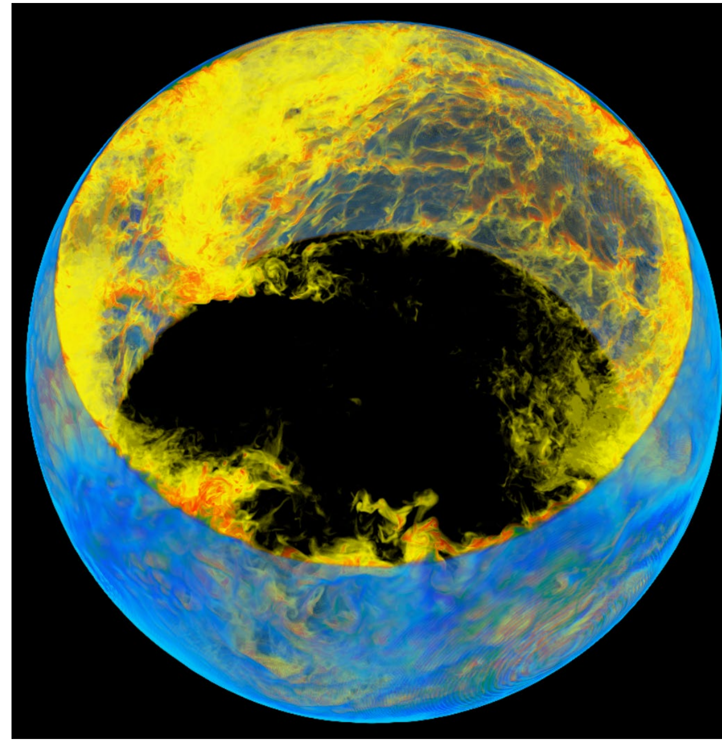
A hemisphere with mixtures of entrained H-rich gas and He+C-rich gas of the He PDCZ. The energy release rate from the burning of ingested H is shown in very dark blue, yellow, and white.

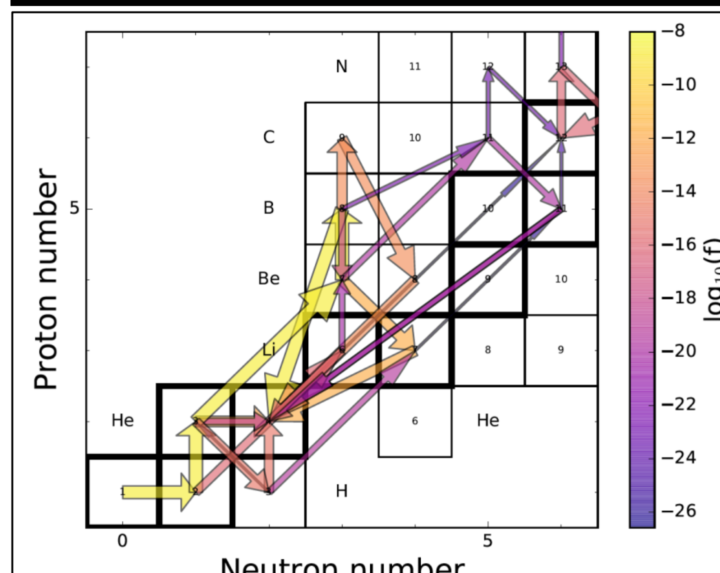
Neutron sources and neutron seeds

^{13}C, as product of mixing hydrogen into a ^{12}C rich bubble in He shell burning, causing $^{12}C(p, \gamma)^{13}N(\beta^{+}\nu)^{13}C$

^{9}Be, and ^{10}B induced (α,n) reactions have been traditionally neglected, because of the extremely low observed abundances of these seeds.

In primordial star burning environments they may play a key role in the nucleosynthesis patterns and an appreciable equilibrium abundance might be available that may serve as neutron source.





Conclusion

- First star environment provide new and different nucleosynthesis environment due to fuel and dynamic contraction and convectio conditions!
- The mass 5 and 8 gap can be bridged by the triple alpha process, but also by sequences of alpha capture reactions on lithium isotopes! (Lithium problem)
- Neutron production for an early i-process is possible through alph cluster configuraions!
- Traditional nucleosynthesis network is insufficient, dynamic mixi and convective processes need to be considered.
- More experimental effort, experimental data, and theoretical understanding and interpretation of reactions contributions is necessary using either phenomenological or first principle mode

Acknowledgement

For experimental effort

Axel Boeltzig (INFN Gran Sasso, Italy)
James DeBoer (ND)
Mike Febbraro (ORNL)
Joachim Görres (ND)
Orlando Gomez (ND)
August Gula (ND)
Dan Robertson (ND)
Philipp Scholz (ND)
Shahina Shahina (ND)
Anna Simon (ND)

For discussions and excha

Andreas Best (Naples, Italy)
Pavel Denissenkov (Victoria, Canad
Falk Herwig (Victoria, Canada)
Gianluca Imbriani (Naples. Italy)
Xiaodong Tang (Lanzhou, China)