Neutron Sources in Stars

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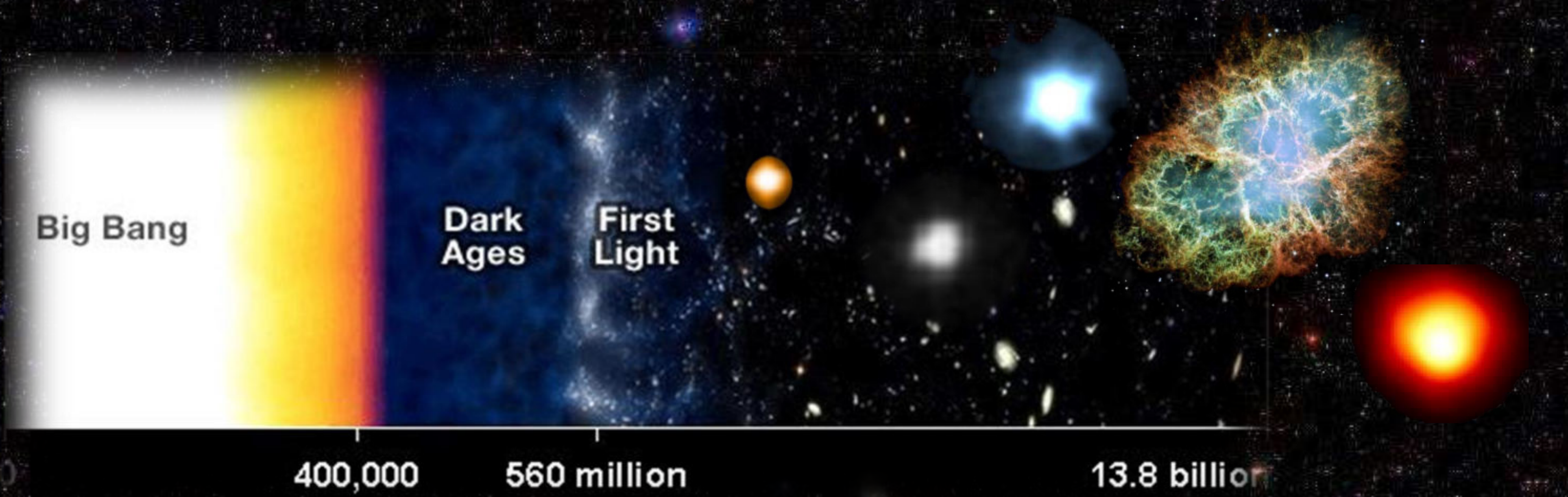
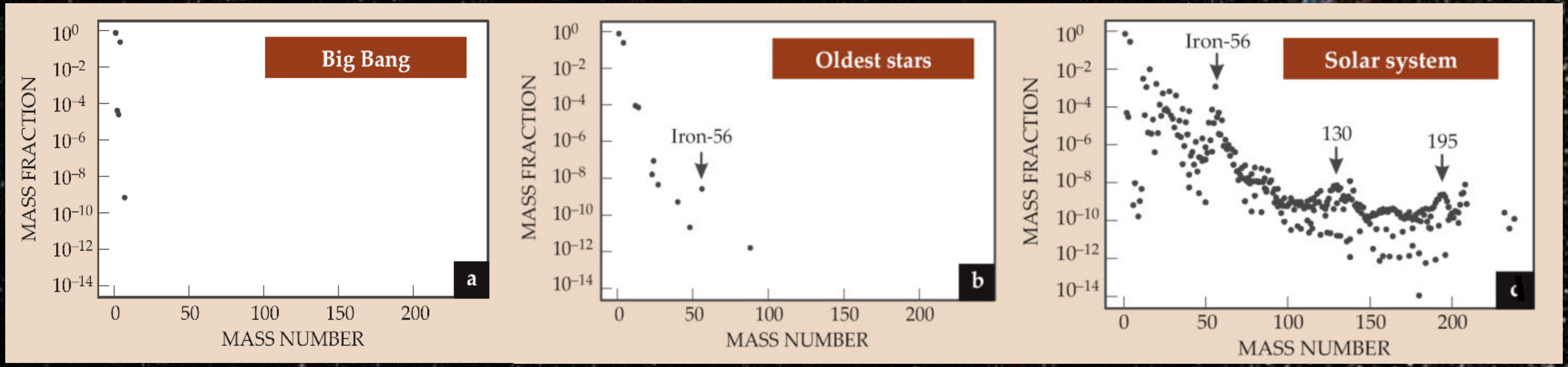
Early ideas about neutron sources
Neutron sources in primordial stars
Neutron sources in CEMP stars for the i-process
Neutron sources for the main s-process
Neutron sources for the weak s-process
Neutron sources for the n-process
Neutrons sources for the r-process

Galactic Chemical Evolution



First Stars



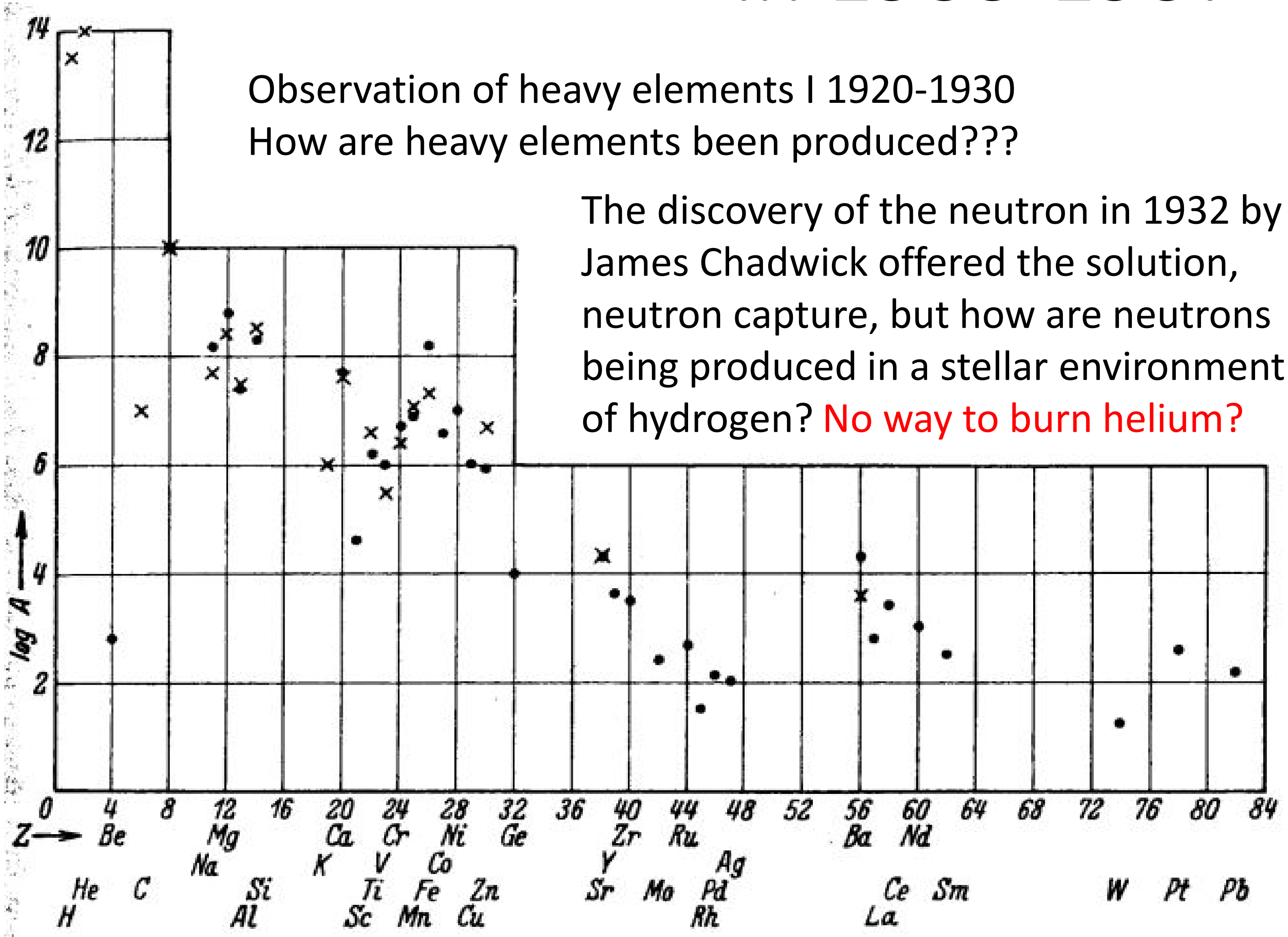
Early Ideas

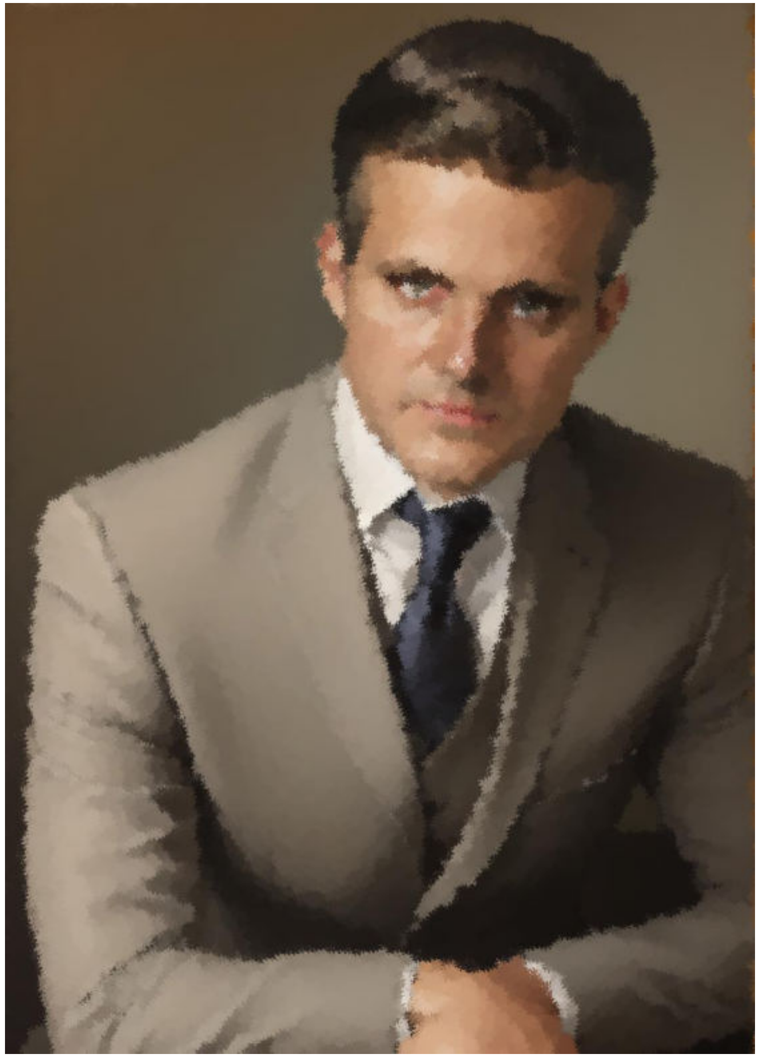
- Neutron Sources in Hydrogen Burning Stars
- The $\alpha\beta\gamma$-Process in the Primeval Atom
- Bridging the Gap?

The Origin of Heavy Elements in 1933-1937

Observation of heavy elements I 1920-1930
How are heavy elements been produced???

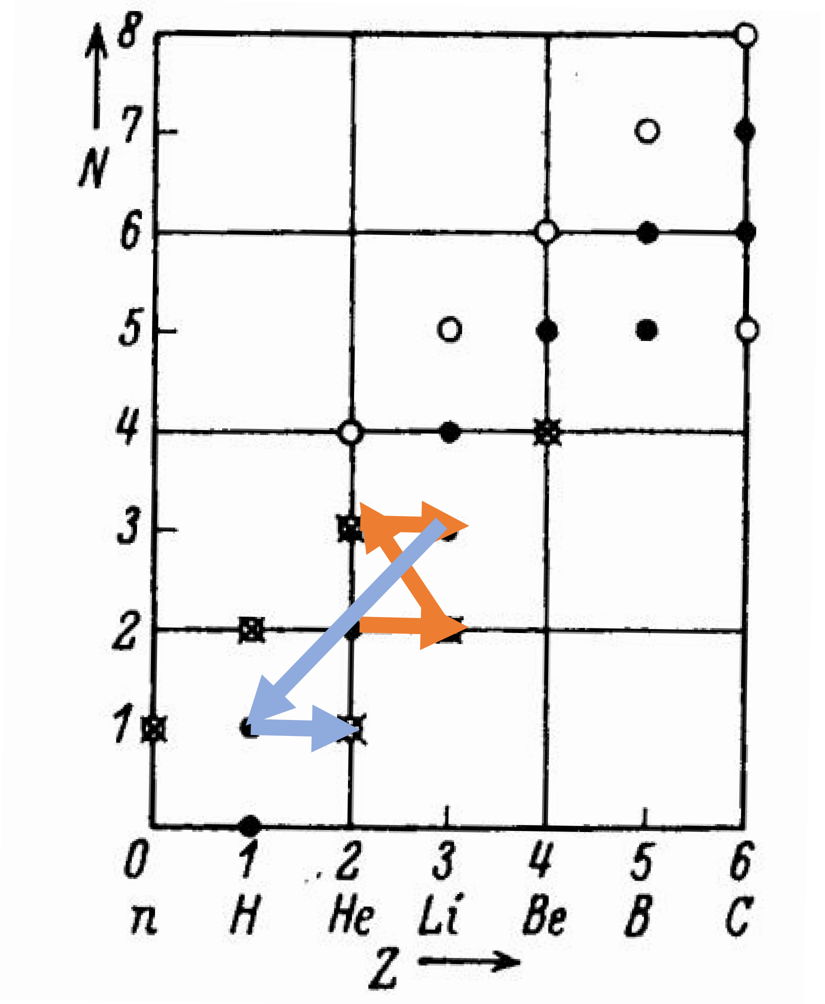
The discovery of the neutron in 1932 by James Chadwick offered the solution, neutron capture, but how are neutrons being produced in a stellar environment of hydrogen? No way to burn helium?





Carl Friedrich von Weizsäcker

The assumption of particle stability of A=5



Über Elementumwandlungen im Innern der Sterne. I.

Von C. F. v. Weizsäcker.

Physik. Zeitschr. XXXVIII, 1937.

1. ${}^{4}_{2}He + {}^{1}_{1}H = {}^{5}_{3}Li$;
2. ${}^{5}_{3}Li\beta^{+} \rightarrow {}^{5}_{2}He$;
3. ${}^{5}_{2}He + {}^{1}_{1}H = {}^{4}_{2}He + {}^{2}_{1}D$.

Die Deuteronen können durch den Prozeß ${}^{2}_{1}D + {}^{2}_{1}D = {}^{3}_{2}He + {}^{1}_{0}n$ Neutronen erzeugen;

Production of neutrons in stellar hydrogen burning by a cyclic process with deuterons as catalyzers, but neither ^{5}He nor ^{5}Li are particle stable!

The first idea of instantaneous origin

The Origin of Chemical Elements

R. A. ALPHER*
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AND

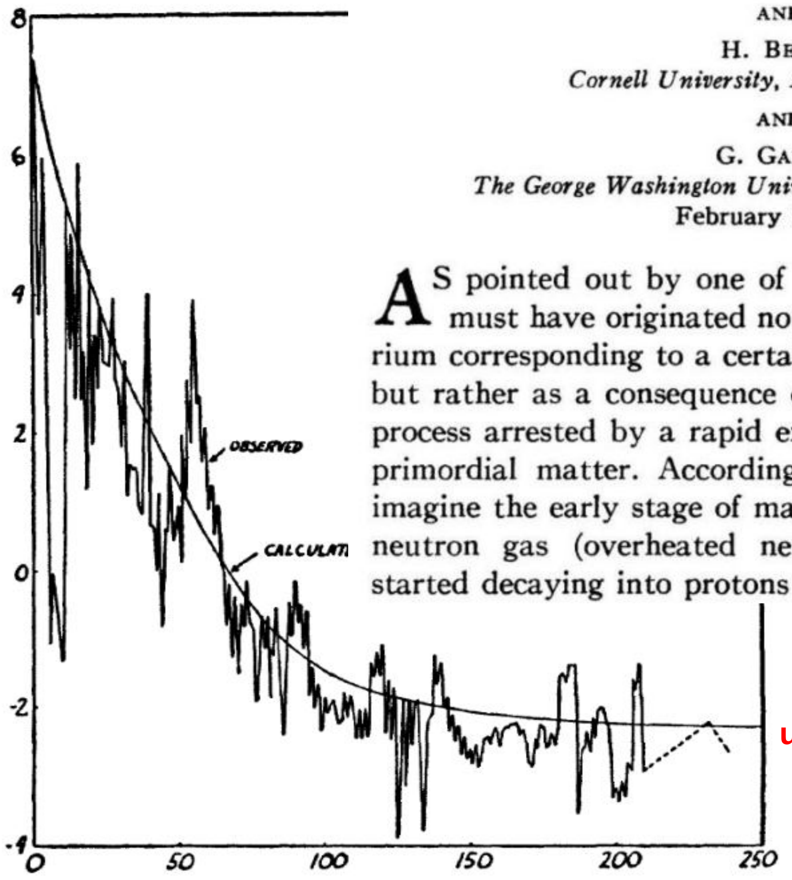
H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons

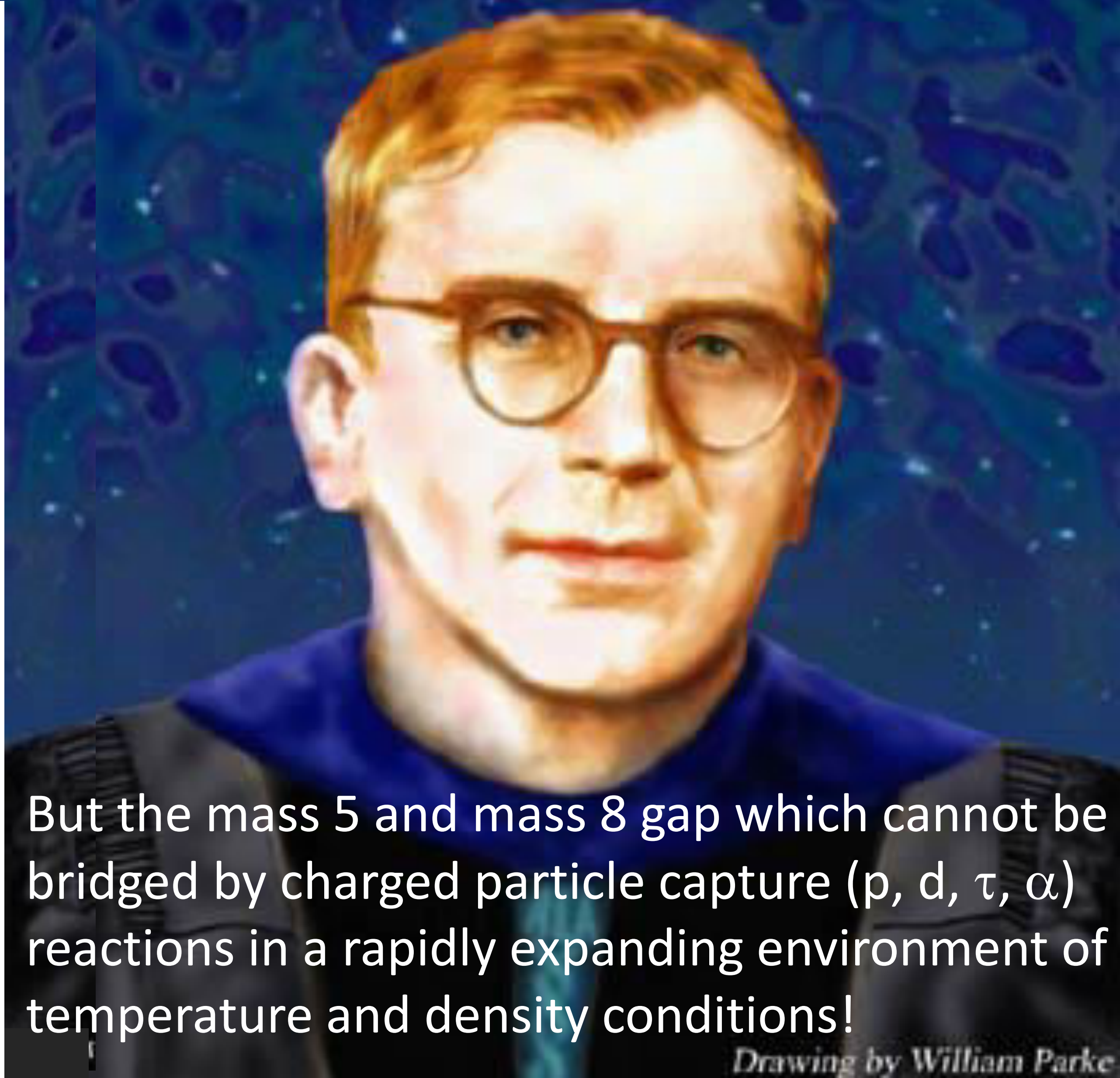


up to Uranium

FIG. 1.

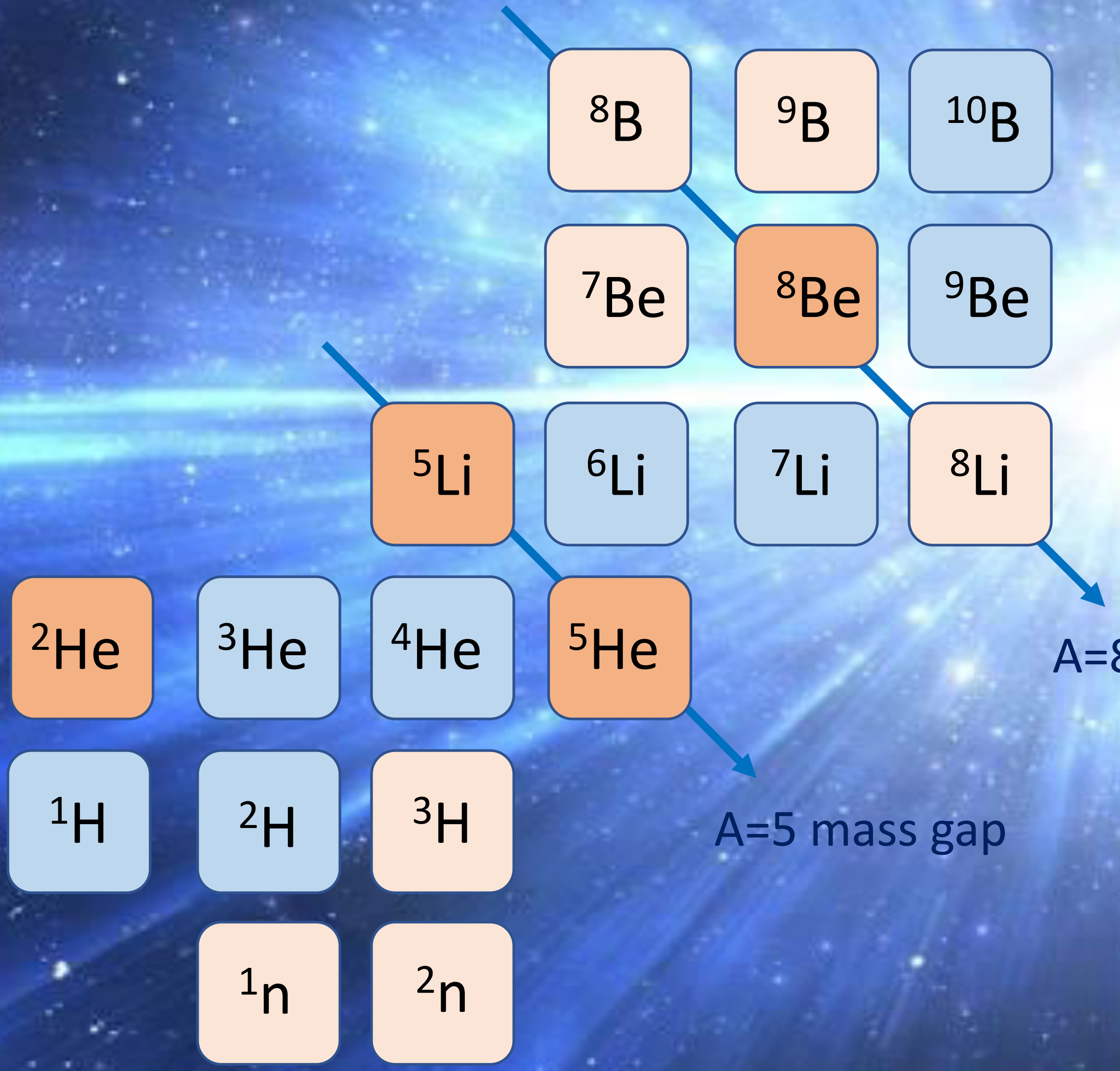
Log of relative abundance

Atomic weight



But the mass 5 and mass 8 gap which cannot be bridged by charged particle capture (p, d, τ, α) reactions in a rapidly expanding environment of temperature and density conditions!

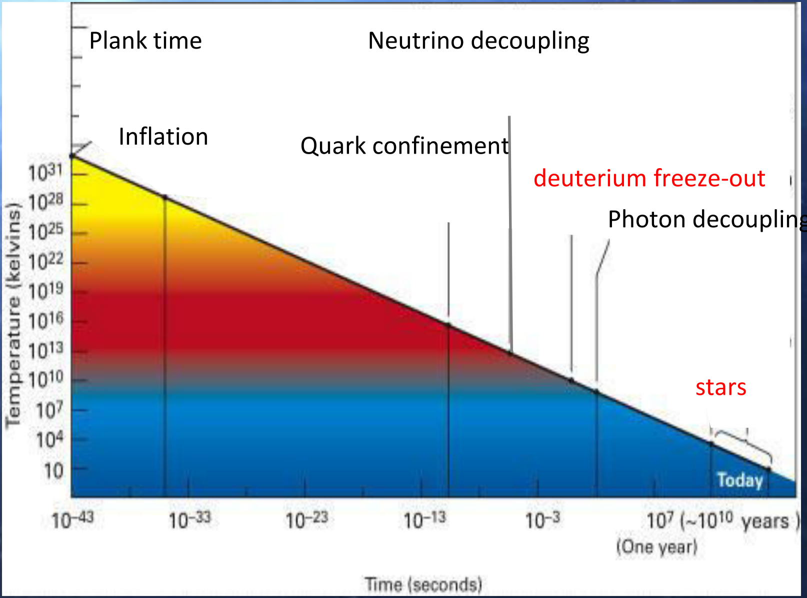
The Mass A=5 and A=8 Mass Gap



There are no stable nuclei with mass A=5 and mass A=8 in the universe!

The formation of heavier nuclei requires sufficient to jump these two gaps by nuclear reaction processes!

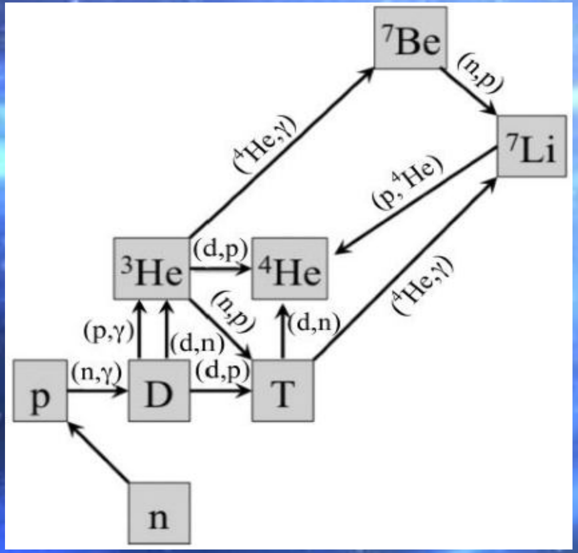
This is a challenge in the rapidly expanding Big Bang environment.

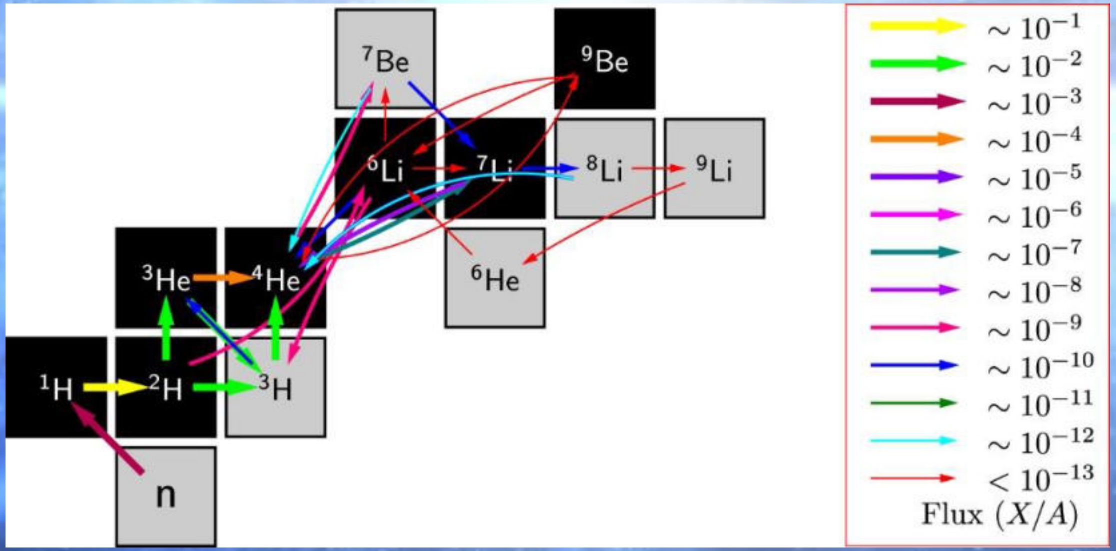


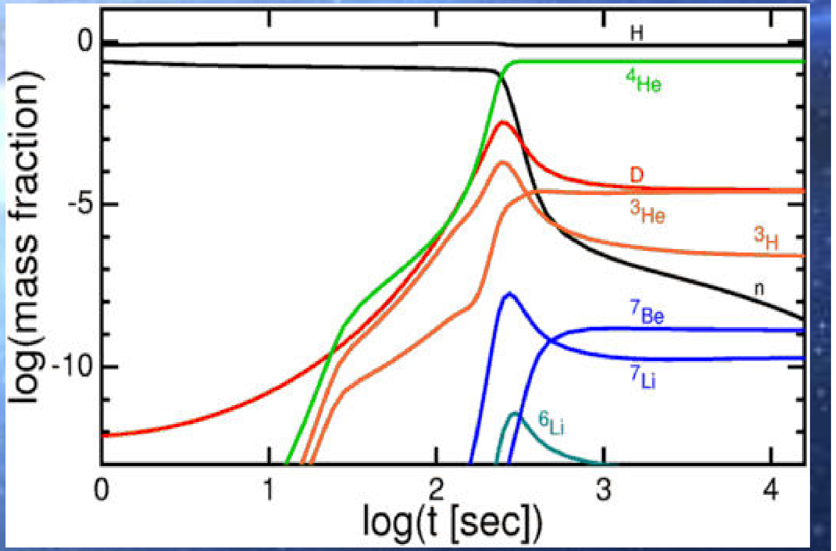
Big Bang Nucleosynthesis

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

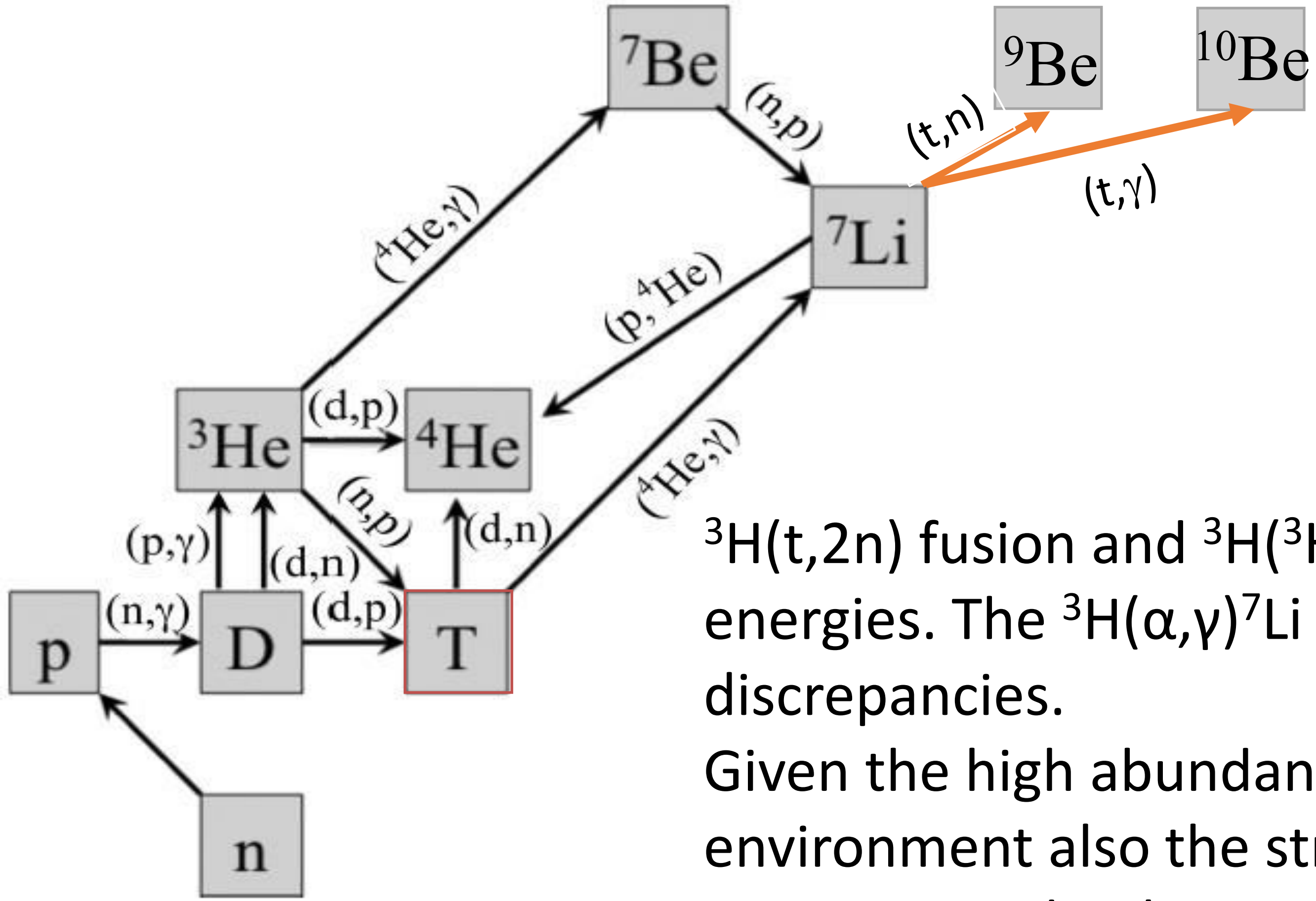
The mass A=5 gap prohibits the production of substantial amounts of lithium and beryllium.
The mass A=8 gap prohibits the production of heavier elements such as boron, carbon, and beyond!







We need to expand on tritium reaction studies

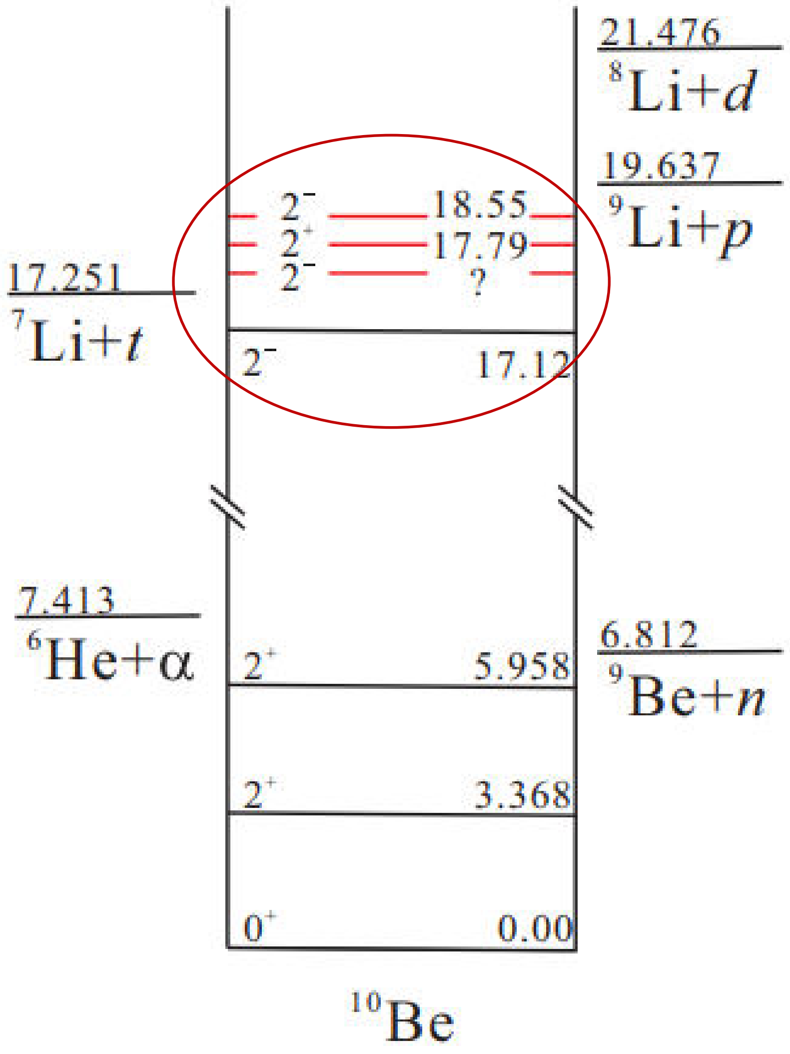


The neglect of these tritium reactions may explain why the observed ^{7}Li abundance is three times lower than predicted! Subsequent ^{9}Be(α,n)^{12}C may generate neutrons and ^{12}C.

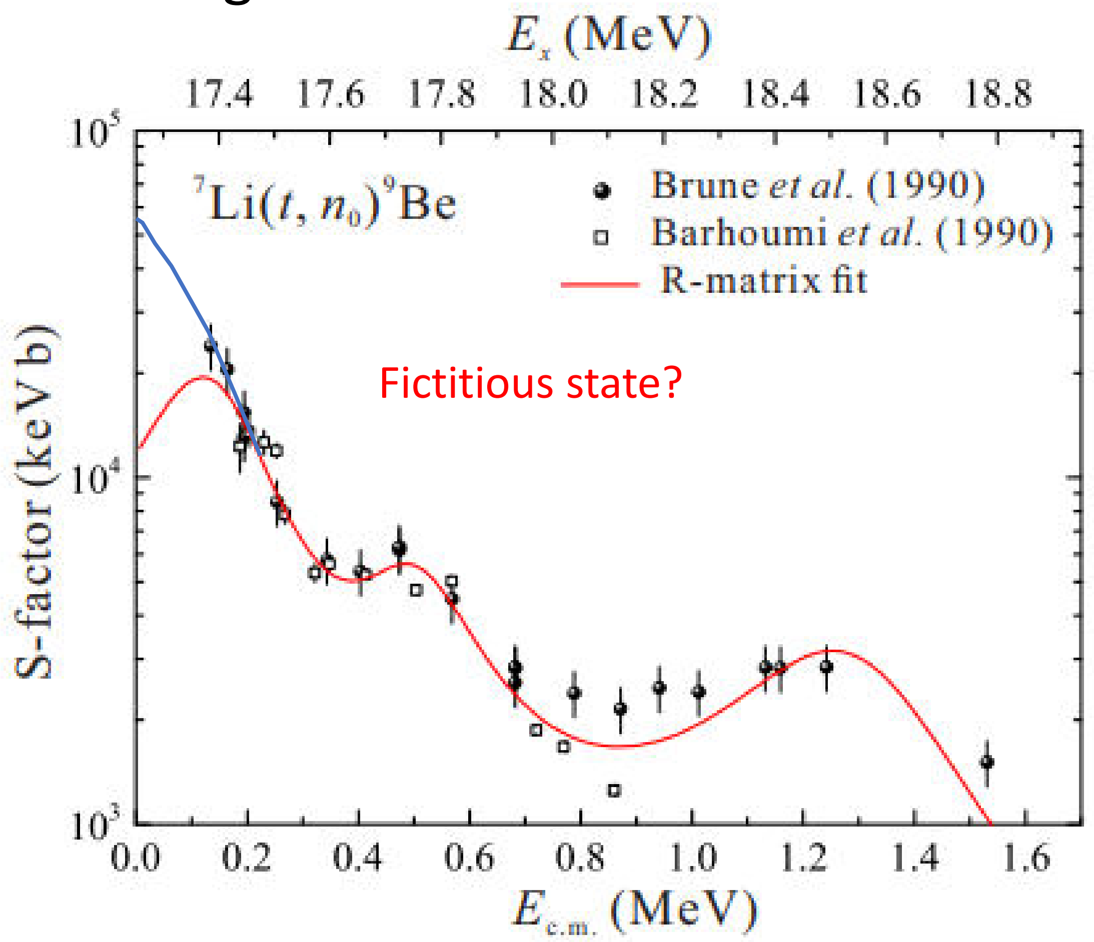
^{3}H(t,2n) fusion and ^{3}H(^{3}He,pn) fusion require further studies at low energies. The ^{3}H(α,γ)^{7}Li fusion studies show pronounced discrepancies.

Given the high abundances of tritium in the early Big Bang environment also the strength of the subsequent ^{7}Li(t,n)^{9}Be reaction need to be investigated as possible solution of Lithium problem.

Impact of threshold states?



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



Early Universe Neutron Production

Most primordial neutrons are converted to ^4He according to existing simulations

Remaining questions which requires better experiments!

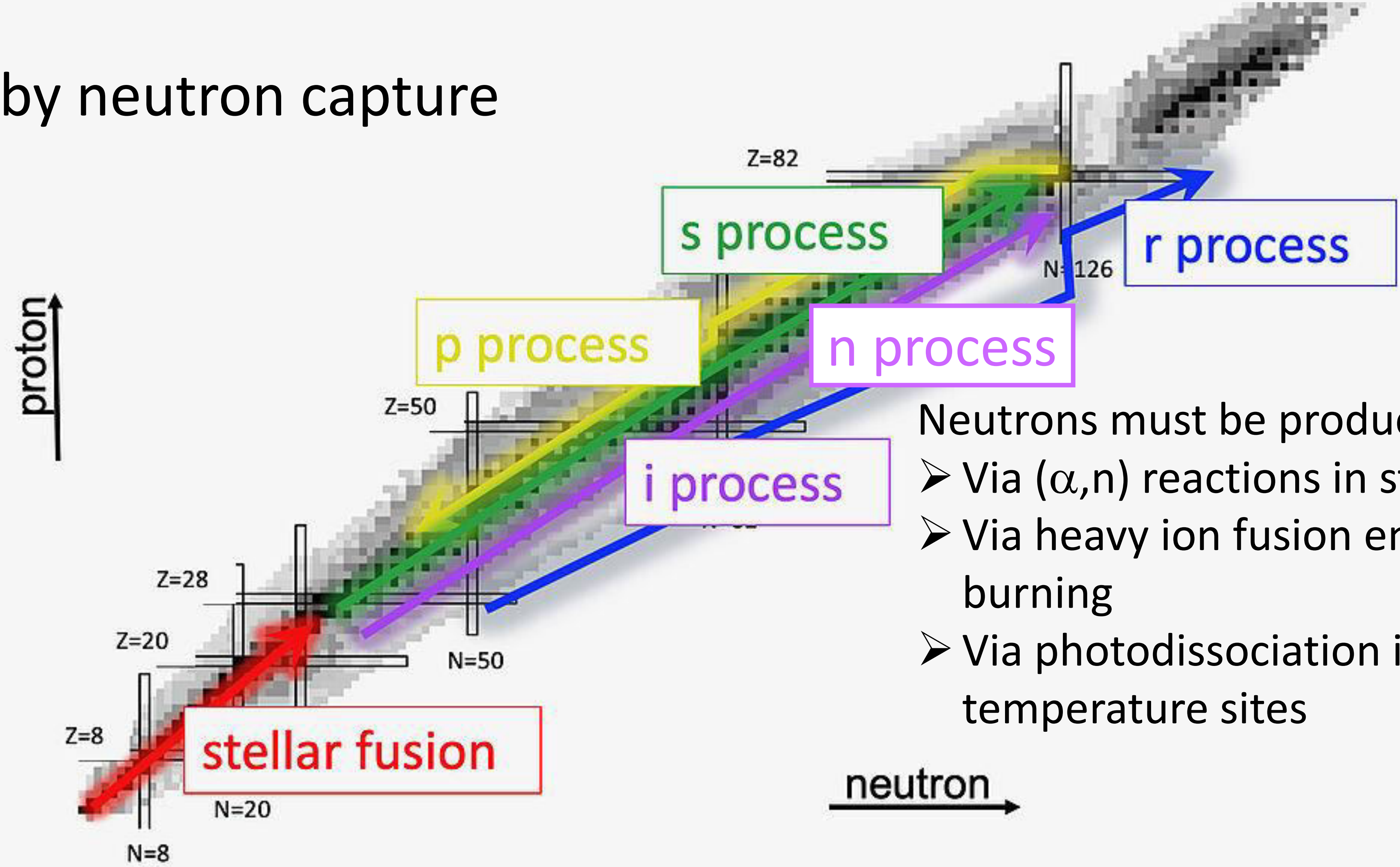
$^7Li(t,n)^9Be(\alpha,n)^{12}C$ release of neutrons and link to ^{12}C production?

The Question of Neutron Sources

- The Sites of the s-, i-, and n-Process
- Stellar Environments and Mechanisms
- Status of $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$

The origin of the heavy elements after the Big Bang

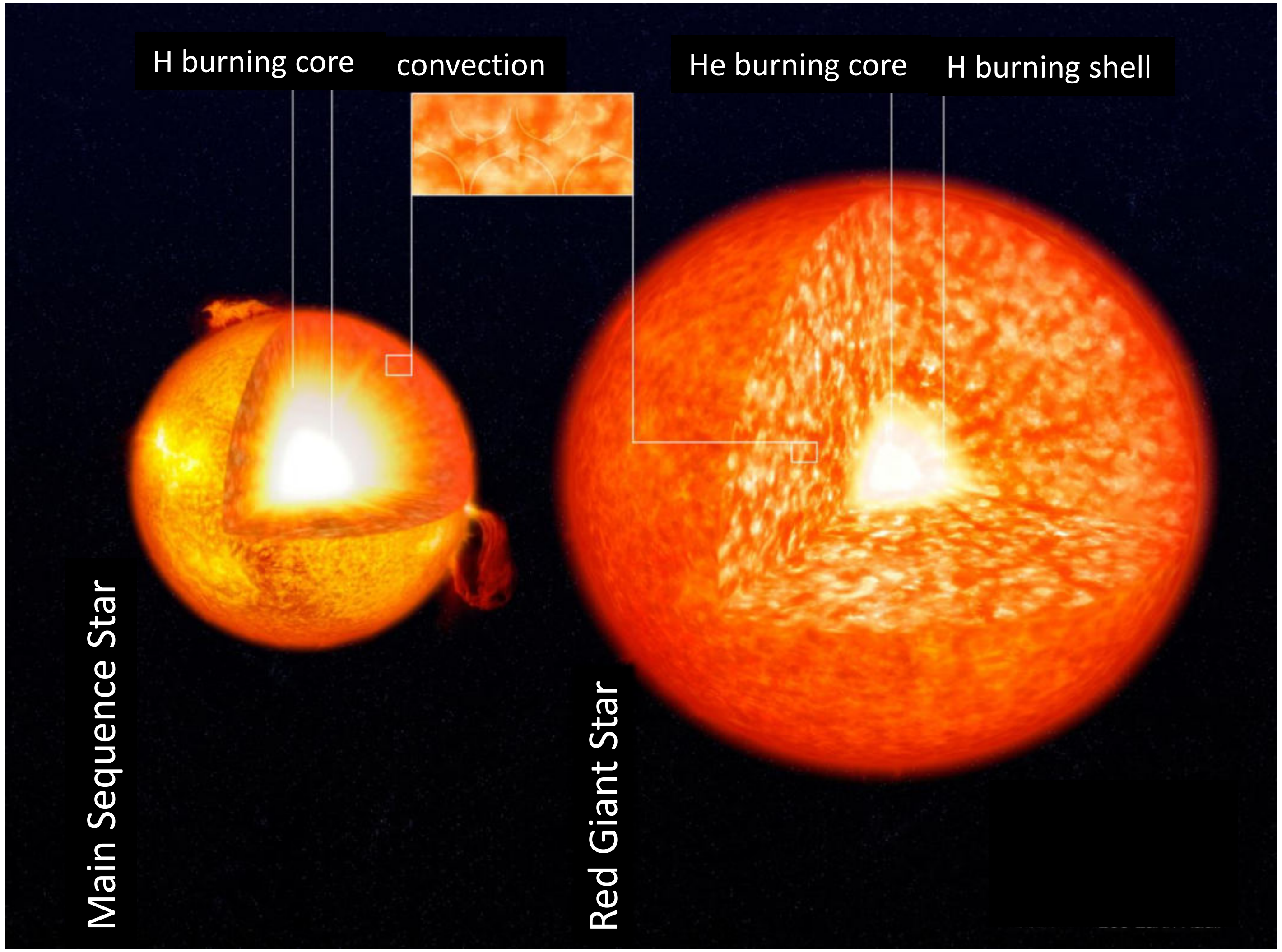
by neutron capture



Neutrons must be produced before being used:

- Via (α,n) reactions in stellar helium burning
- Via heavy ion fusion emission in heavy ion burning
- Via photodissociation in high density temperature sites

The weak s-Process in Massive Red Giant Stars



The neutron source $^{22}Ne(\alpha,n)$ is initiated by the ^{14}N ashes of the CNO cycle during hydrogen burning. With contraction and heating of the core the neutron source is triggered by the sequence $^{14}N(\alpha,\gamma)^{18}F(\beta\text{-}\nu)^{18}O(\alpha,\gamma)^{22}Ne$

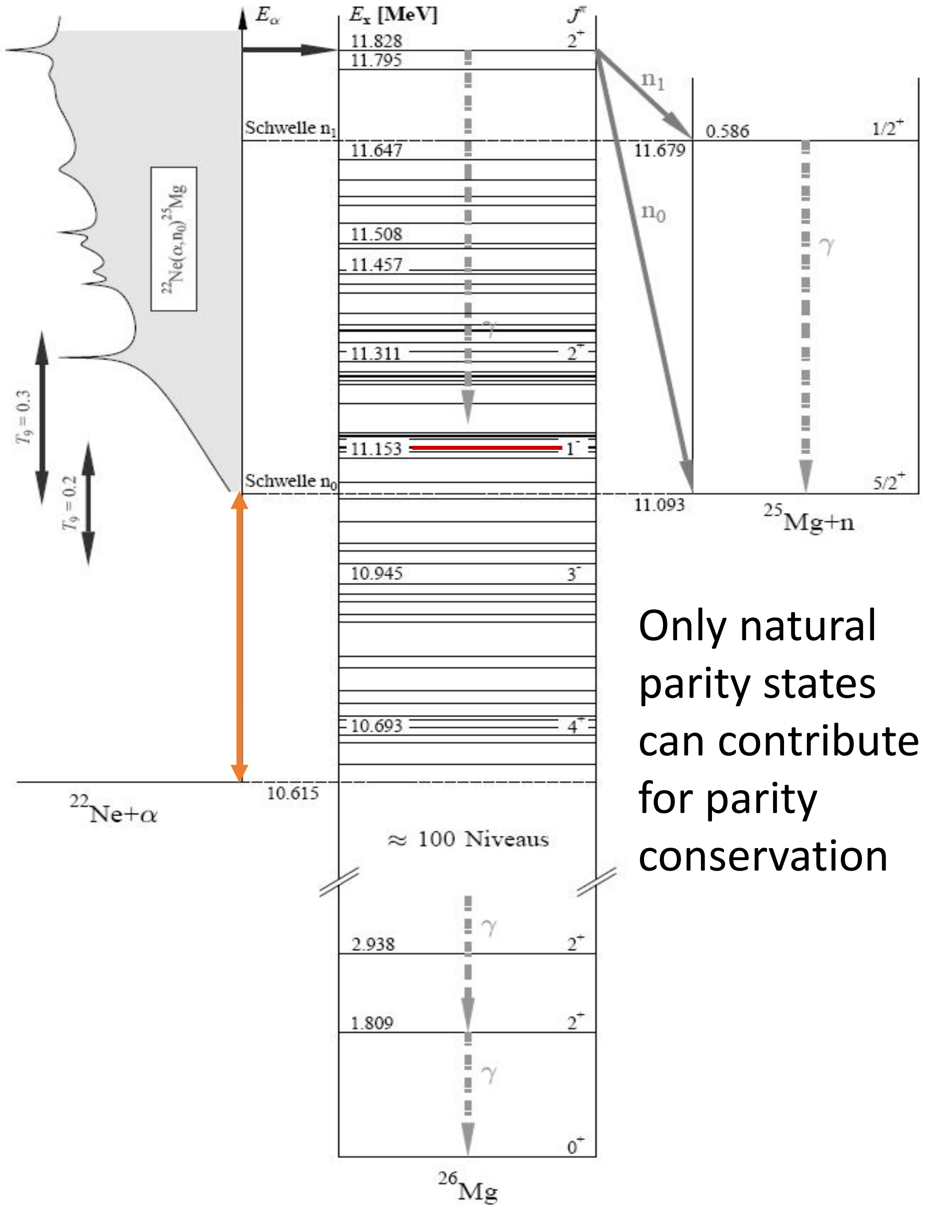
However, $^{22}Ne(\alpha,n)^{25}Mg$ has a negative Q-value,

$$Q=-478.34 \text{ keV}$$

and ignites only towards the end of core helium burning, when ^{4}He fuel is nearly gone. Question is, how efficient is $^{22}Ne(\alpha,\gamma)^{26}Mg$ in processing ^{22}Ne away prior to ignition of $^{22}Ne(\alpha,n)$?

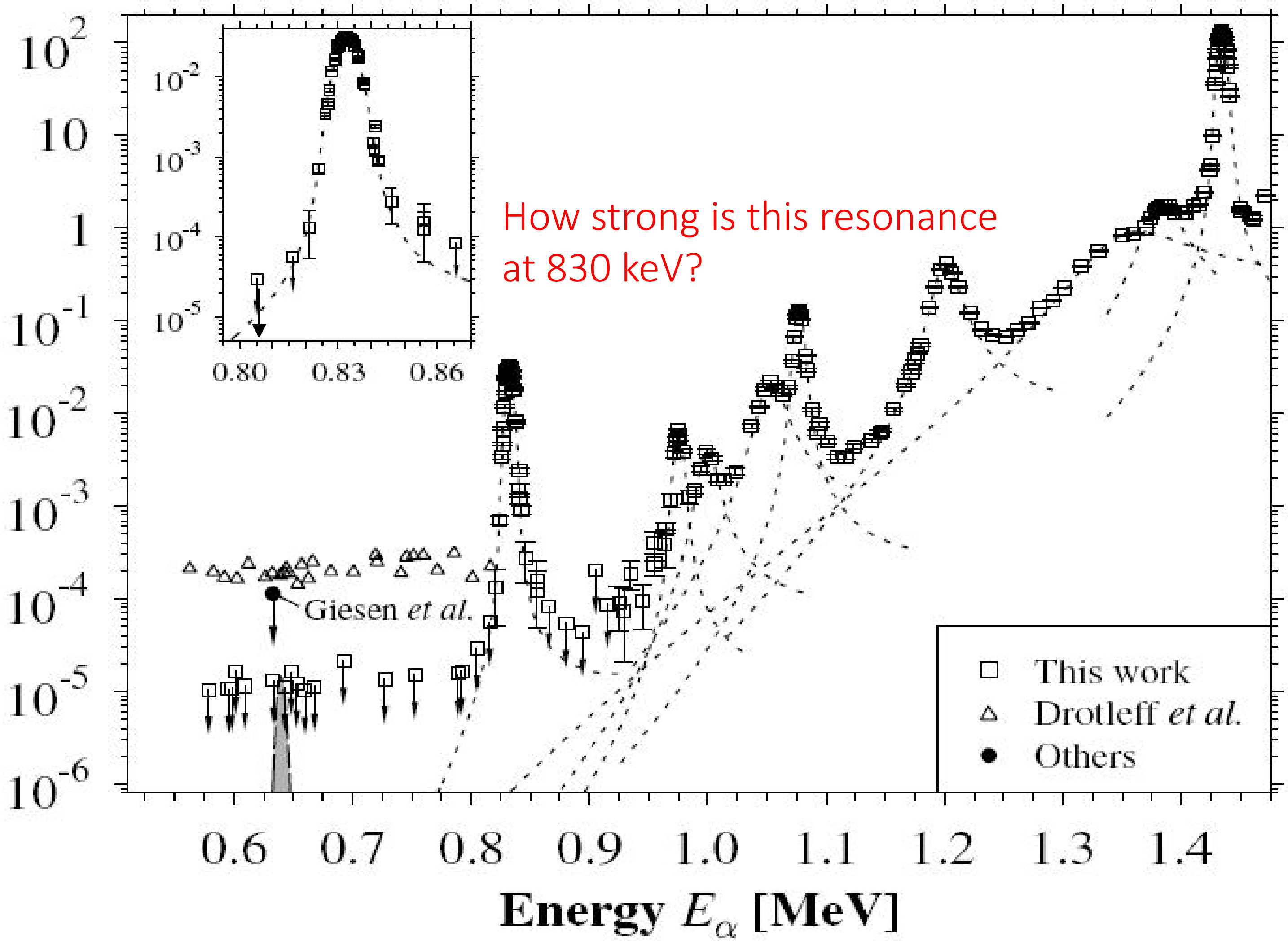
Weak s-process products are transferred by deep convection to surface and emitted by radiation pressure.

$^{22}Ne(\alpha,n)^{25}Mg$ - levels and excitation curve



Only natural parity states can contribute for parity conservation

Pronounced α cluster configuration 5α⊗2n

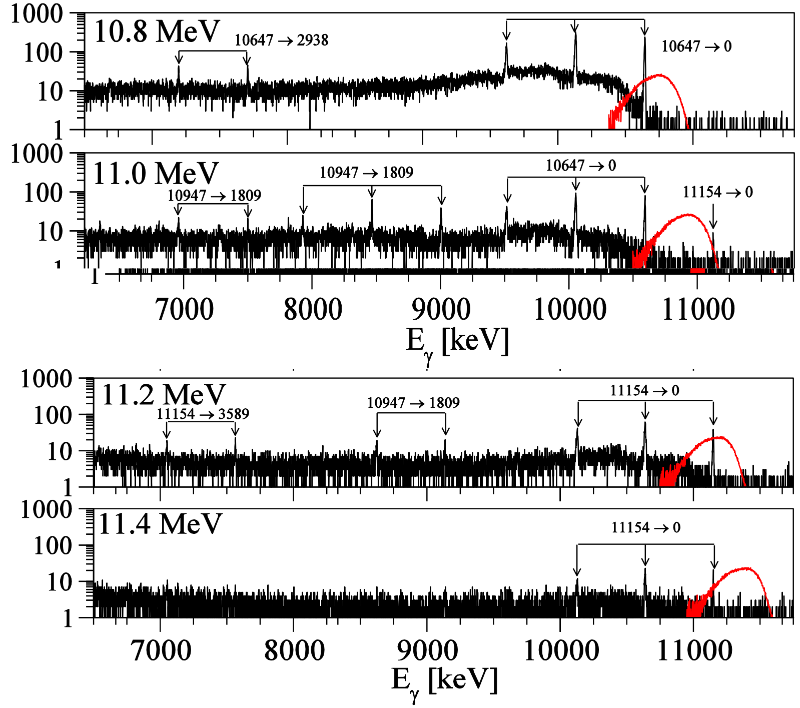


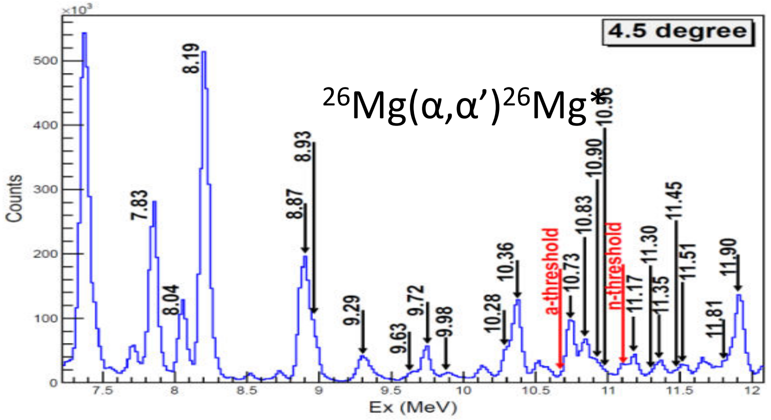
How strong is this resonance at 830 keV?

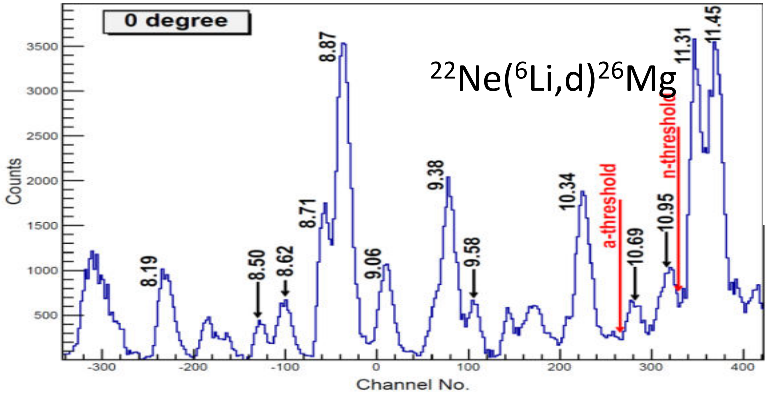
^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg

The importance of complementary measurements to investigate the nuclear structure of the compound system (^{26}Mg).

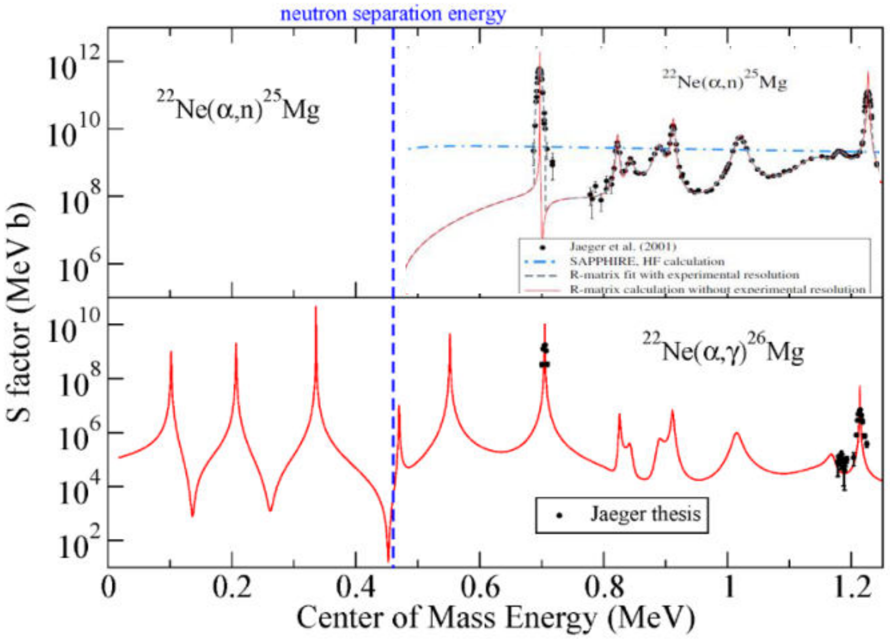
Alternative Approaches using photon beams: Mapping the excitation range in ^{26}Mg with: ^{26}Mg(γ,γ')^{26}Mg* and ^{26}Mg(γ,n)^{25}Mg at HIγS, TUNL and ^{25}Mg(n,γ)^{26}Mg at n_ToF, CERN





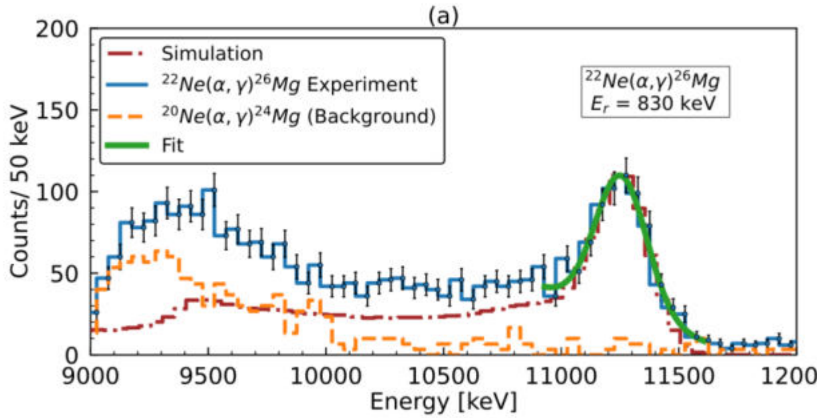


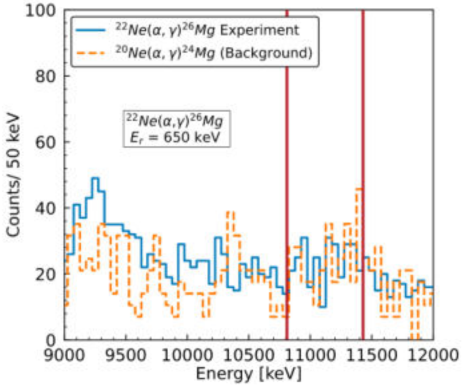
Indirect measures with scattering or transfer: Mapping the excitation range in ^{26}Mg with: ^{26}Mg(α,α')^{26}Mg* & ^{22}Ne(^{6}Li,d)^{26}Mg at RCNP, Osaka

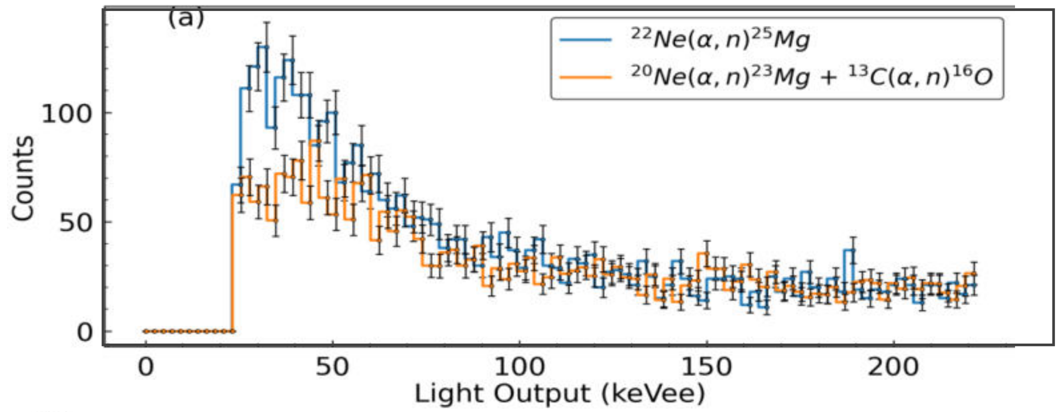


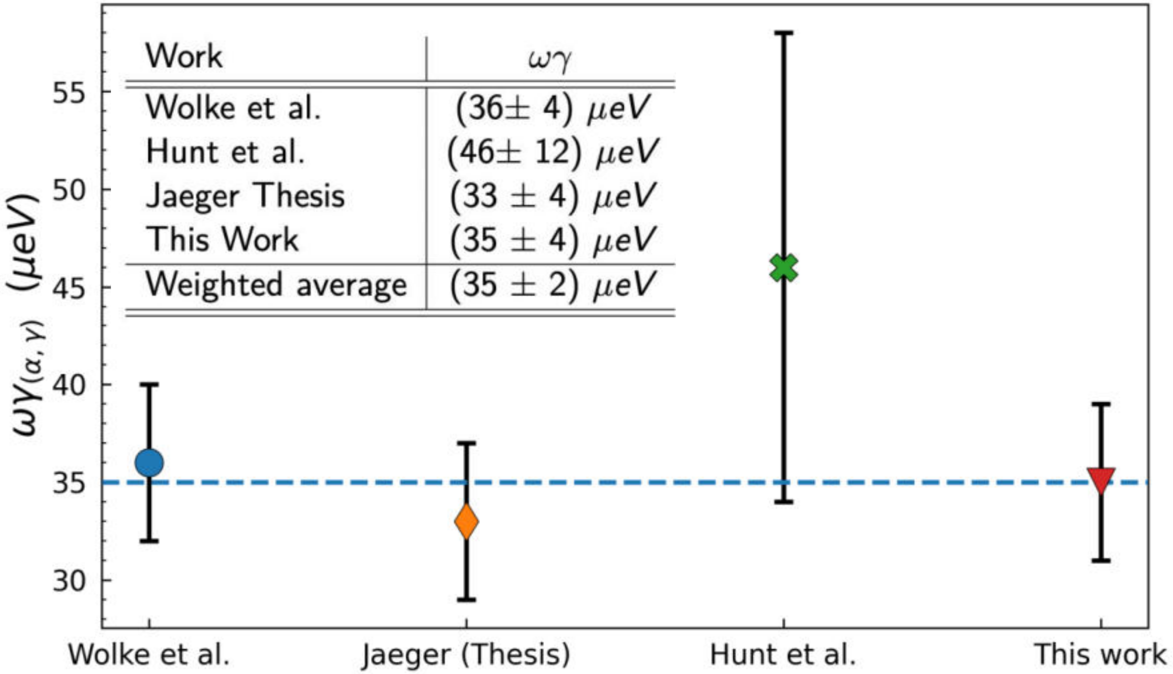
Several resonances predicted for the ^{22}Ne(α,γ)^{26}Mg channel, but strength & possible interference remain unknown!

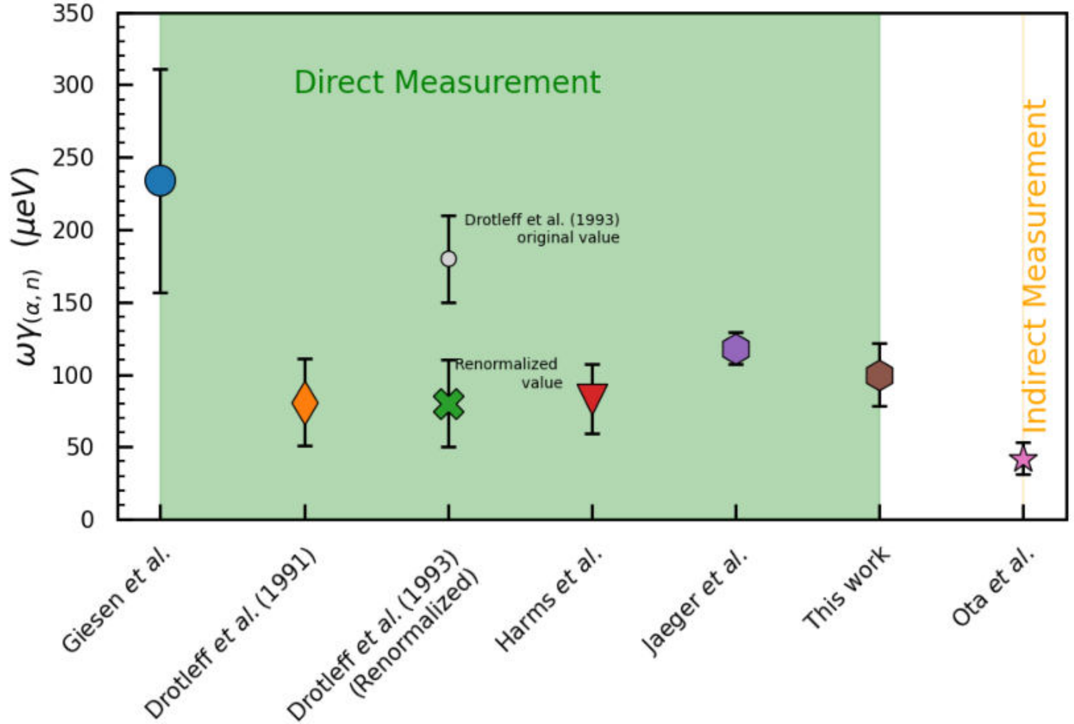
Lowest observed resonance at 830 keV



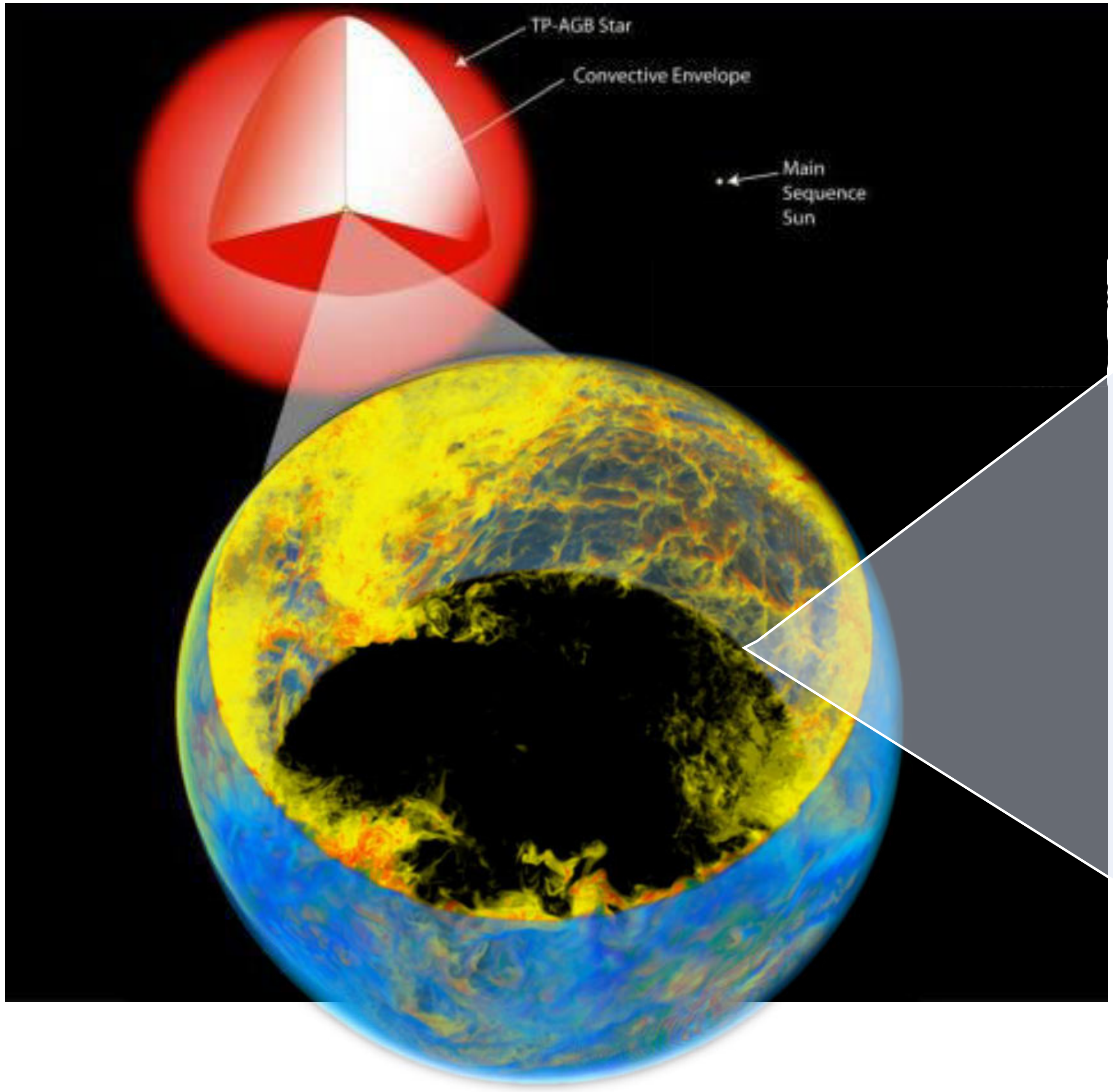




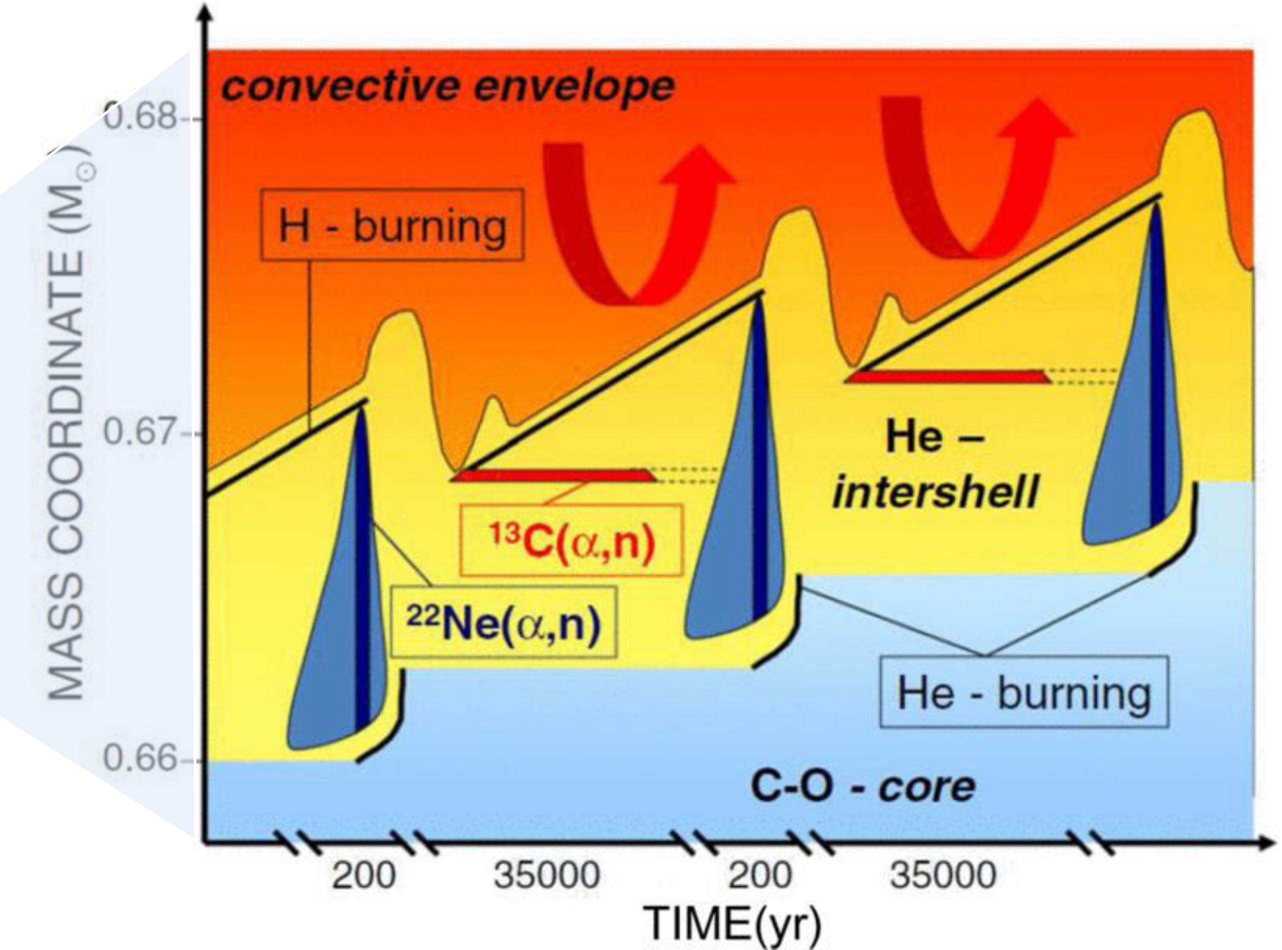




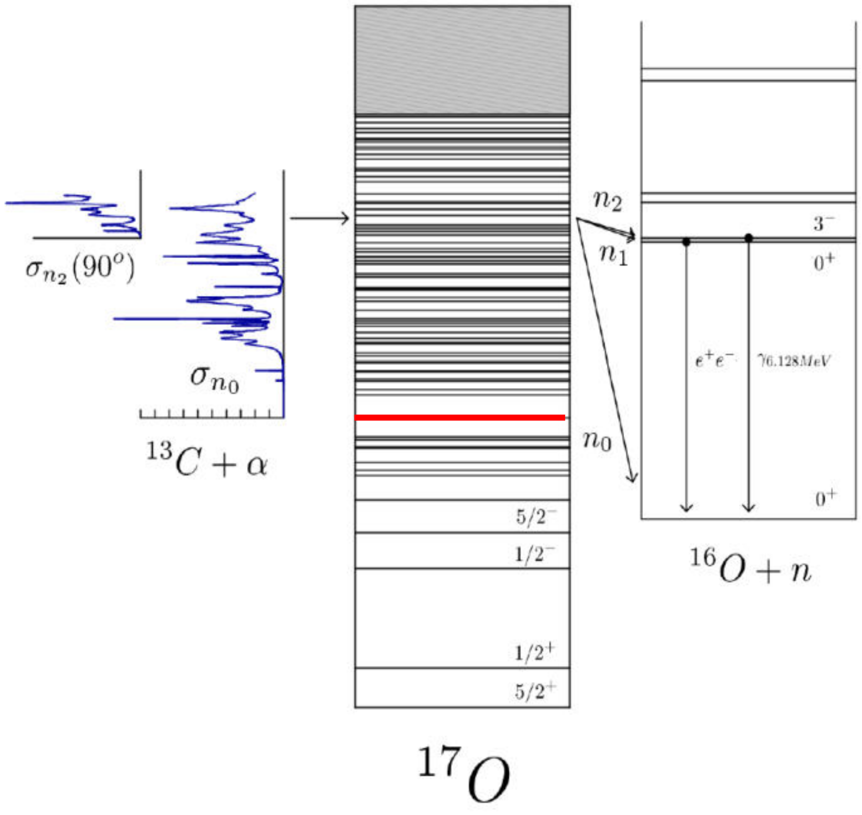
The main s-process in AGB stars



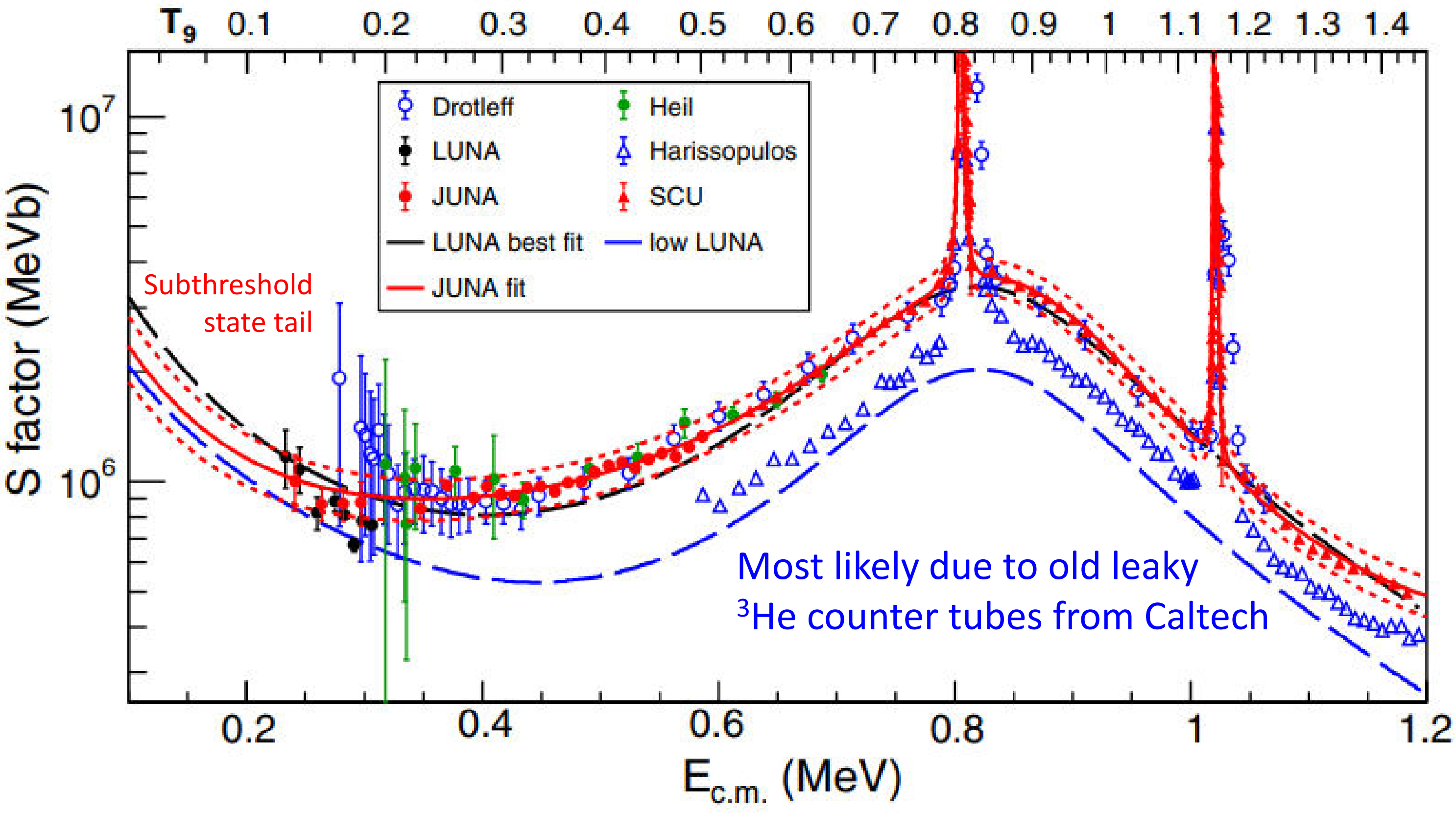
The neutron source $^{13}C(\alpha,n)$, is product of mixing hydrogen into a ^{12}C rich bubble in He shell burning, causing the reaction sequence $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$



$^{13}C(\alpha,n)^{16}O$ - levels and excitation curve

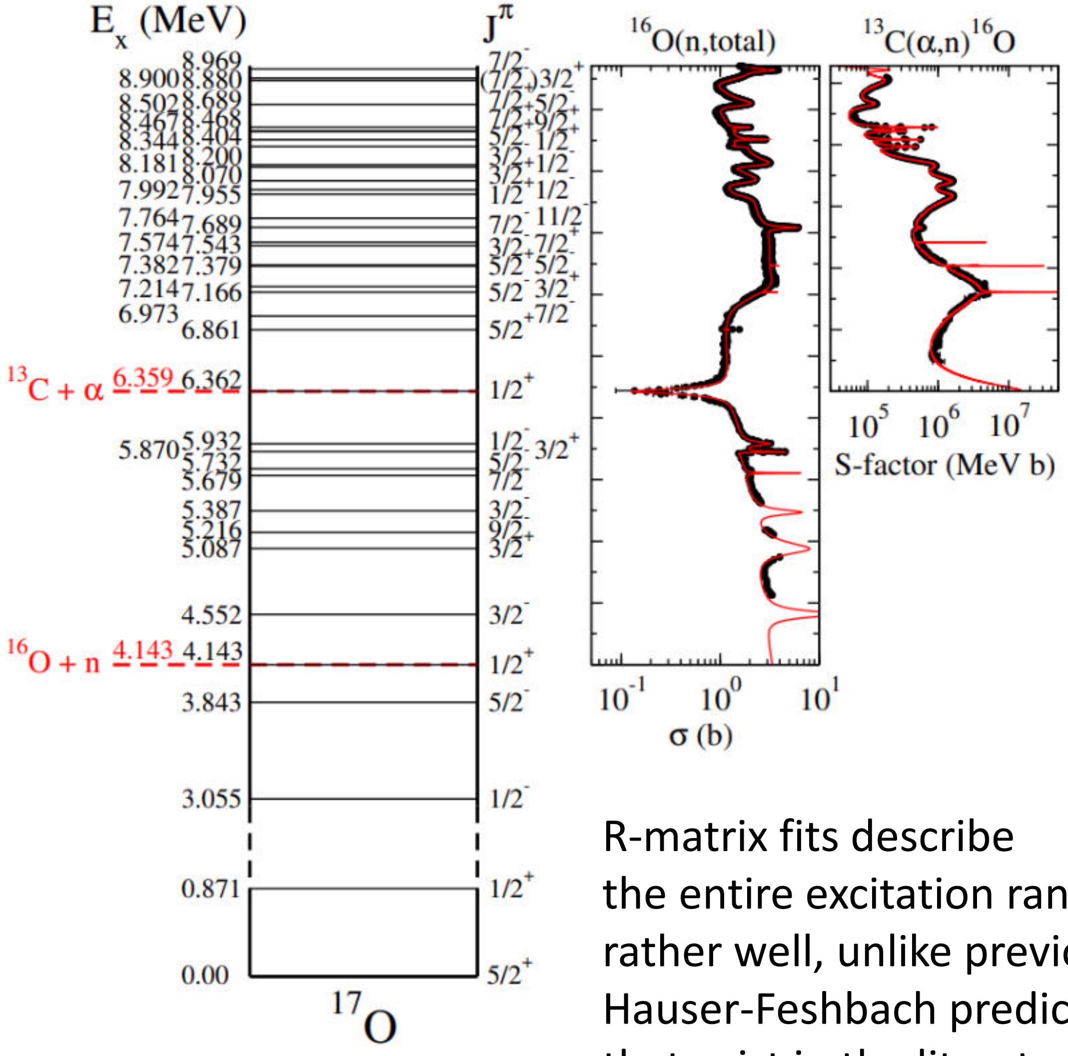


New neutron channels open up towards higher energies!

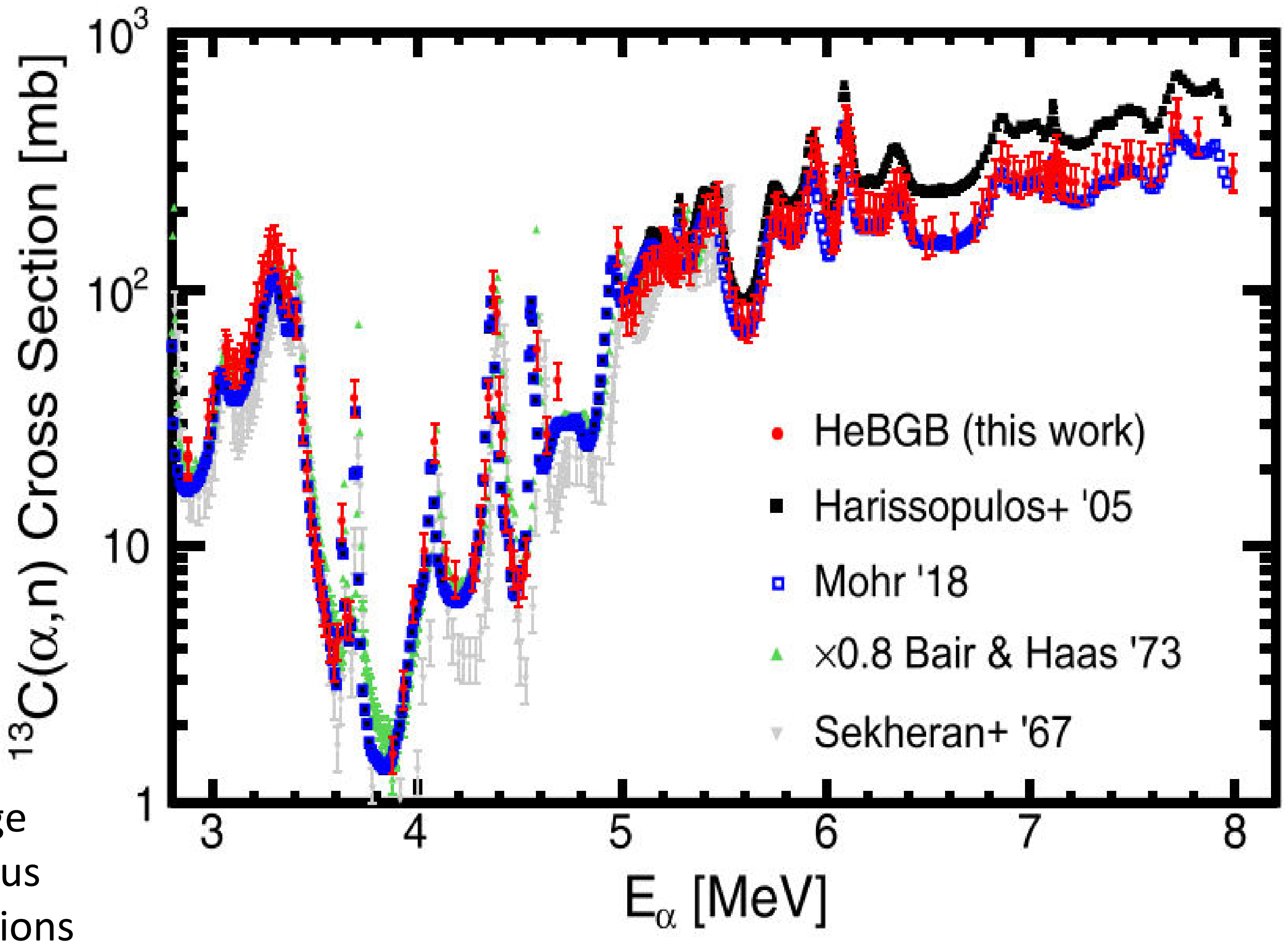


Inconsistencies in the data for a long time between Drotleff & Heil and Harrisopulos, consistent data for LUNA and JUNA!

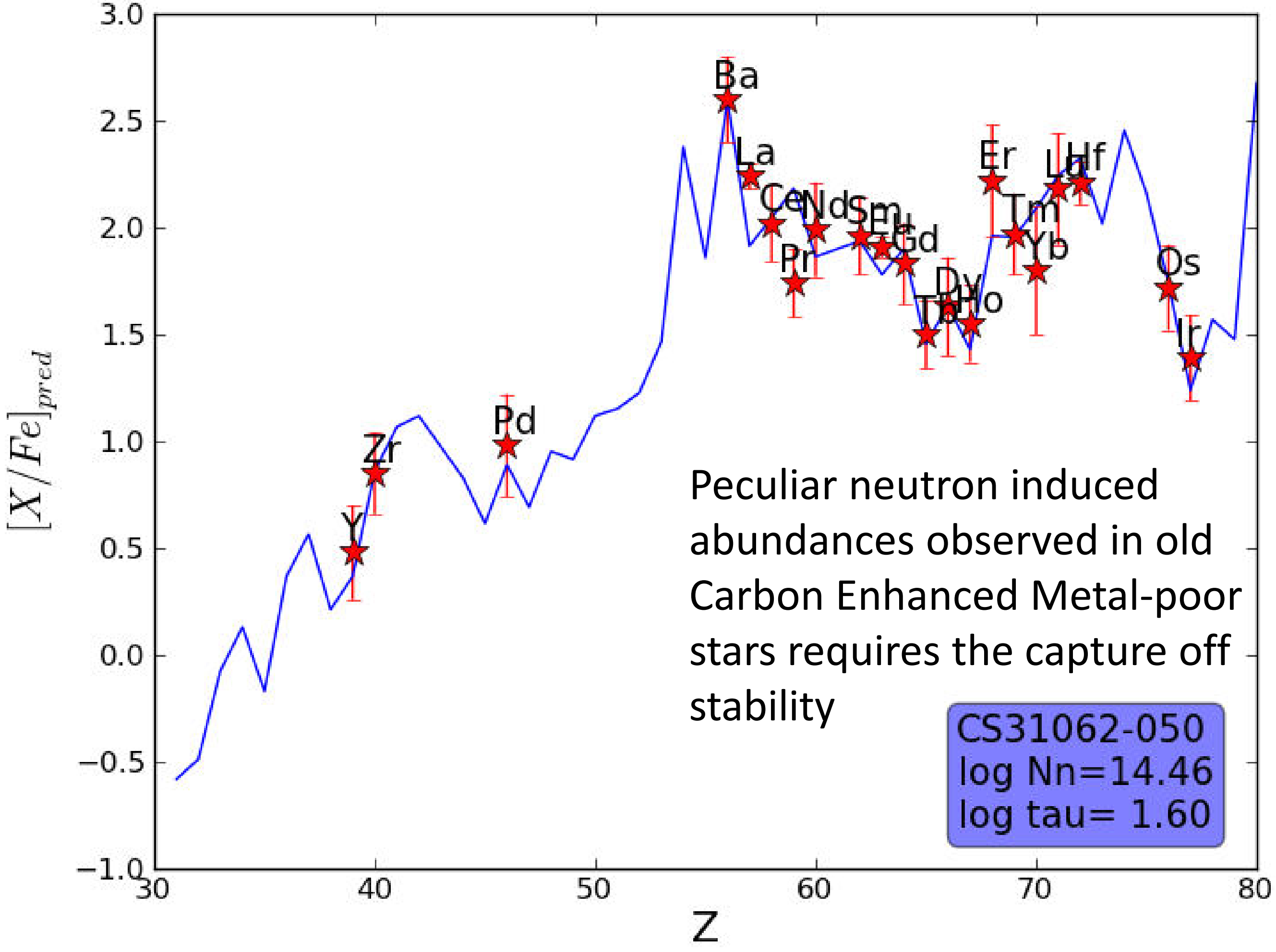
$^{13}C(\alpha,n)^{16}O$ - neutrino detector background



R-matrix fits describe
the entire excitation range
rather well, unlike previous
Hauser-Feshbach predictions
that exist in the literature!



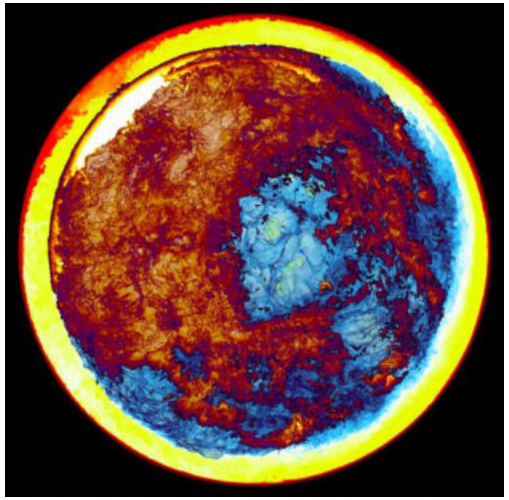
The intermediate (i-) process in early stars

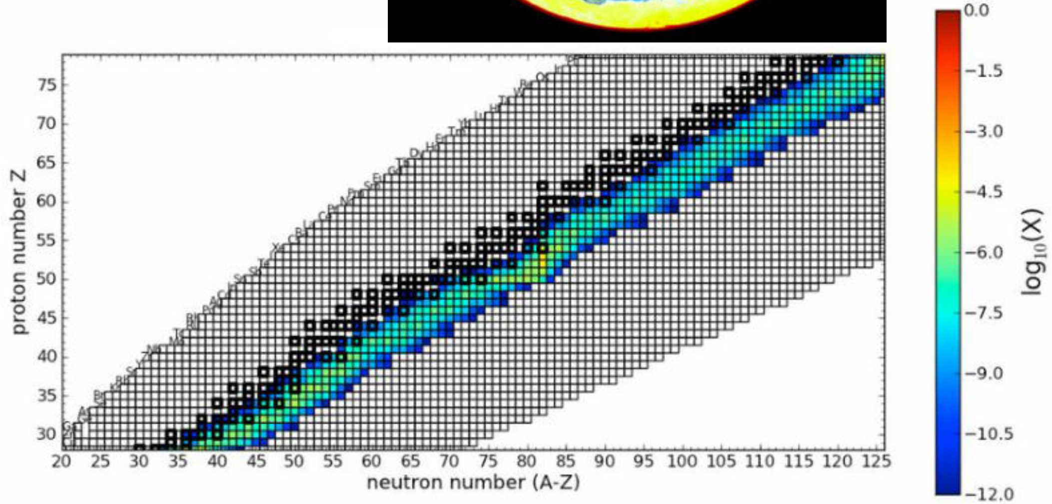


Peculiar neutron induced abundances observed in old Carbon Enhanced Metal-poor stars requires the capture off stability

CEMP - AGB star deep convective environments

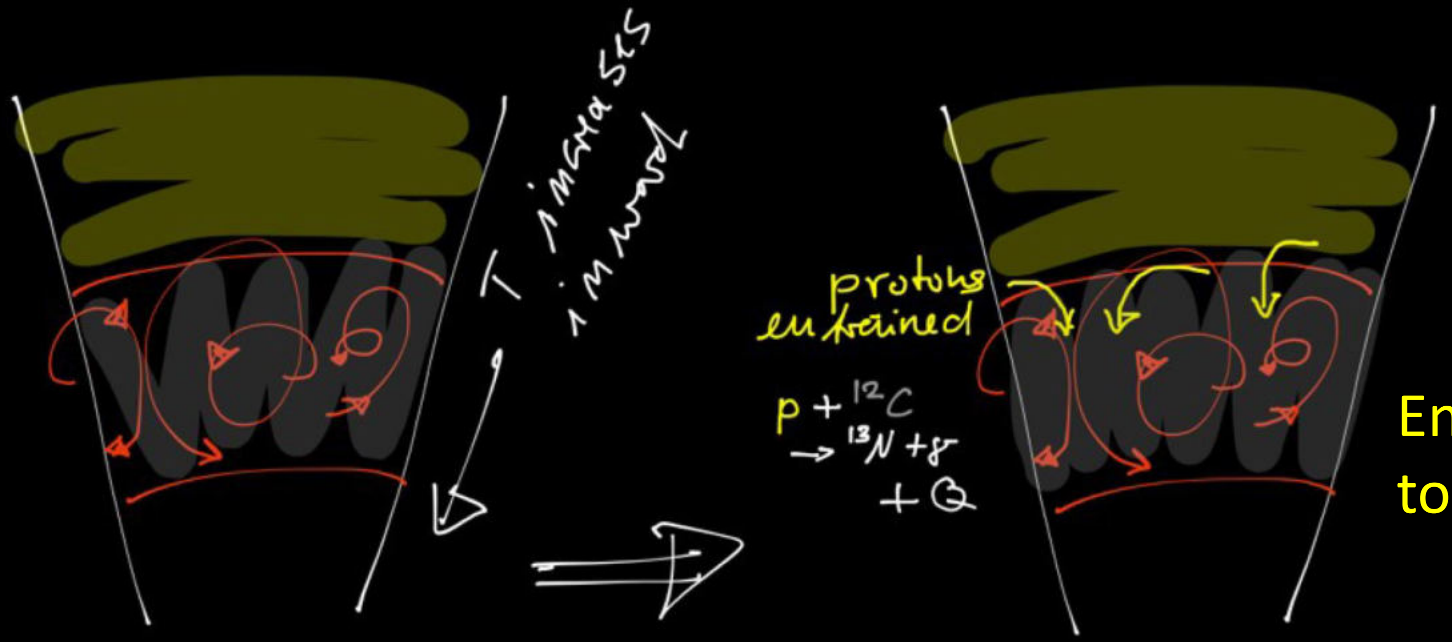
Accreting White Dwarfs





The i-process in early deep convective stars

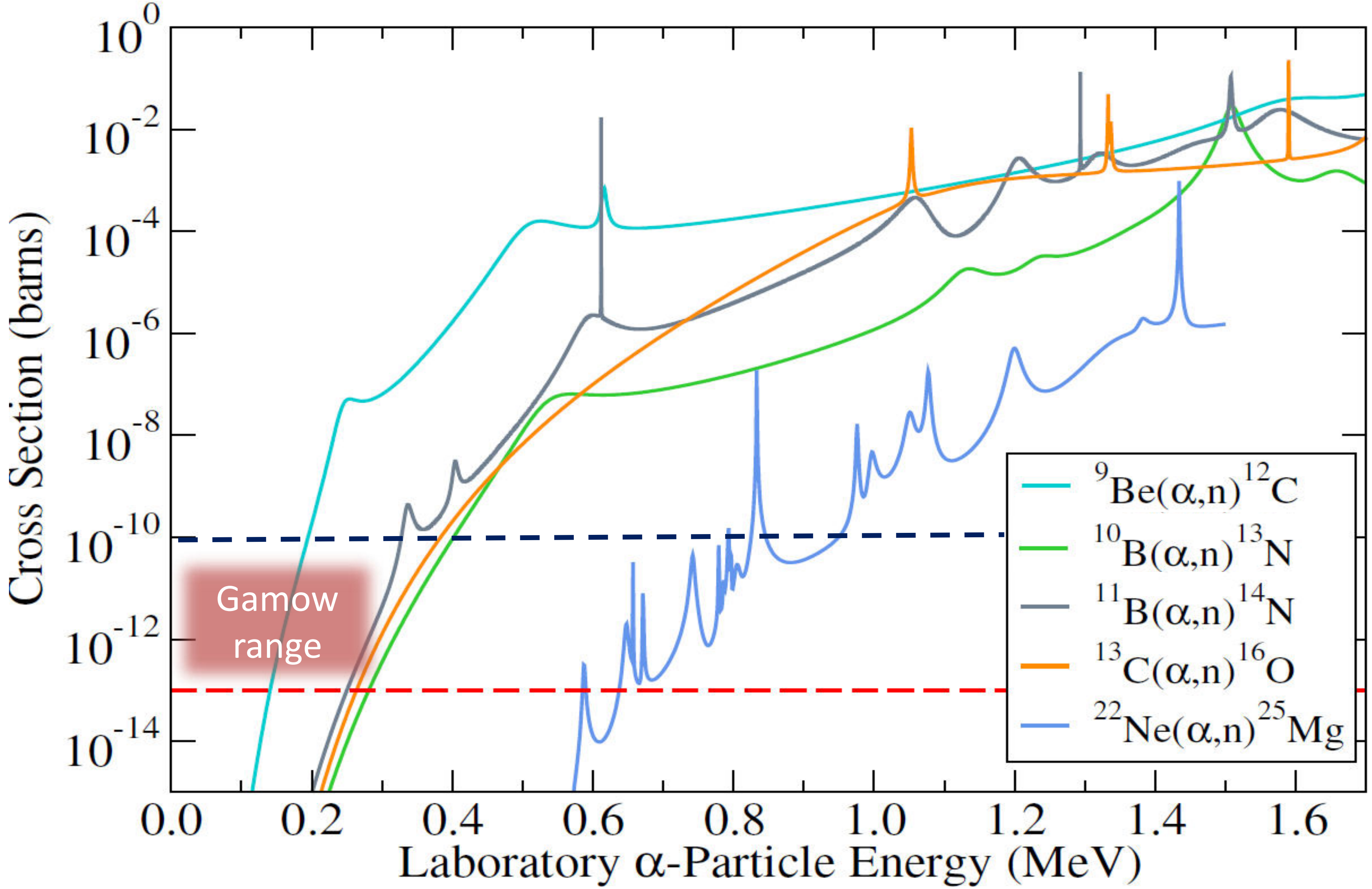
- A neutron flux of 10^{15} n/cm^{2}s is needed to explain i-process abundances
- Model adopted by Cowan and Rose (1977)



Enhances the rate by three to five orders of magnitude

- Strong hydrogen intershell mixing with $^{13}N \Rightarrow {}^{13}C$ at higher temperatures drive the reaction rate of $^{13}C(\alpha,n)$ to higher temperatures.
- While this model seems to work, other neutron sources might be available in the context of dynamic early star environments such as accreting white dwarfs.

Alternative neutron sources in He burning



The flux depends on the abundance or an efficient production process of the seed nuclei.

Neutron sources in primordial stars

Four ways to by-pass the mass 5 & 8 gaps, feeding the CNO elements:

$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

Alpha clusters as catalytic compound structure

$\Rightarrow\ ^{4}\mathrm{He}(2\alpha,n)\mathbf{^{9}Be(\alpha,n)}^{12}\mathrm{C}$

$^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\alpha,\gamma)^{15}\mathrm{O}$

A possible enhancement through alpha clusters resonances

$\Rightarrow\ ^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\beta)\mathbf{^{11}B(\alpha,n)}^{14}\mathrm{N}$

$^{4}\mathrm{He}(d,\gamma)^{6}\mathrm{Li}(\alpha,\gamma)^{10}\mathrm{B}(\alpha,d)^{12}\mathrm{C}$

Deuterons as catalyst isotope

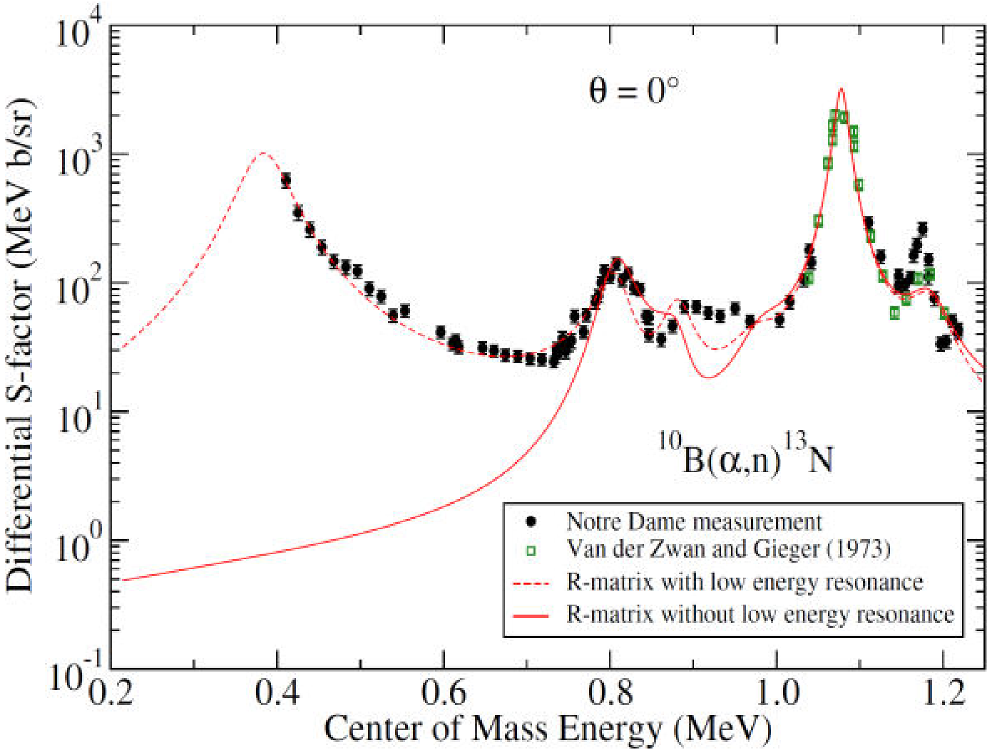
$\Rightarrow\ ^{4}\mathrm{He}(d,\gamma)^{6}\mathrm{Li}(\alpha,\gamma)\mathbf{^{10}B(\alpha,n)}^{13}\mathrm{N}$

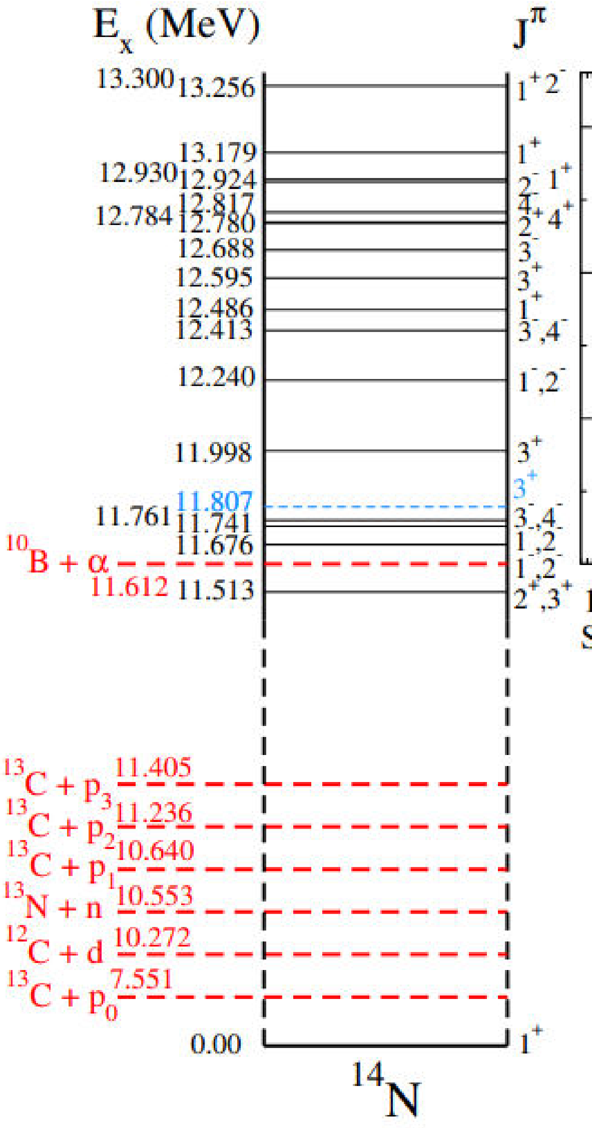
^{9}Be production	^{10}B production	^{11}B production
$^{4}He(\alpha n,\gamma)^{9}Be$ $^{7}Li(^{3}He,p)^{9}Be$ $^{7}Li(^{2}H,\gamma)^{9}Be$	$^{6}Li(\alpha,\gamma)^{10}B$ $^{9}Be(p,\gamma)^{10}B$	$^{7}Li(\alpha,\gamma)^{11}B$ $^{9}Be(p,\gamma)^{11}B$ $^{11}C(\beta^{+}\nu)\ ^{11}B$
⬇	⬇	⬇
$^{9}Be(\alpha,n)^{12}C$	$^{10}B(\alpha,n)^{13}N$	$^{11}B(\alpha,n)^{14}N$

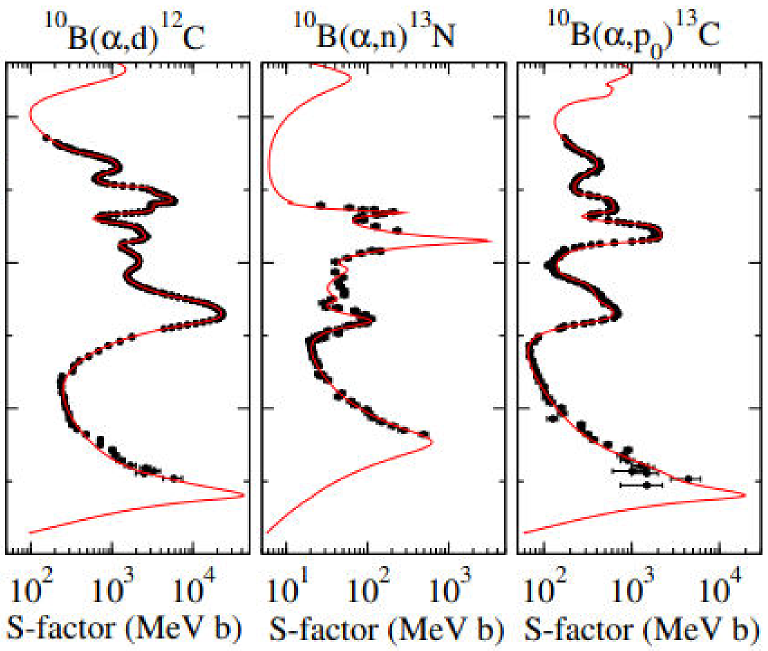
Most of the reaction rates go back to FCZ 75 and CF88, very limited amount on new data! Extremely limited amount on low energy data.

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

$^{10}B(\alpha,n)$ unexpected threshold resonance which also appears in other channels



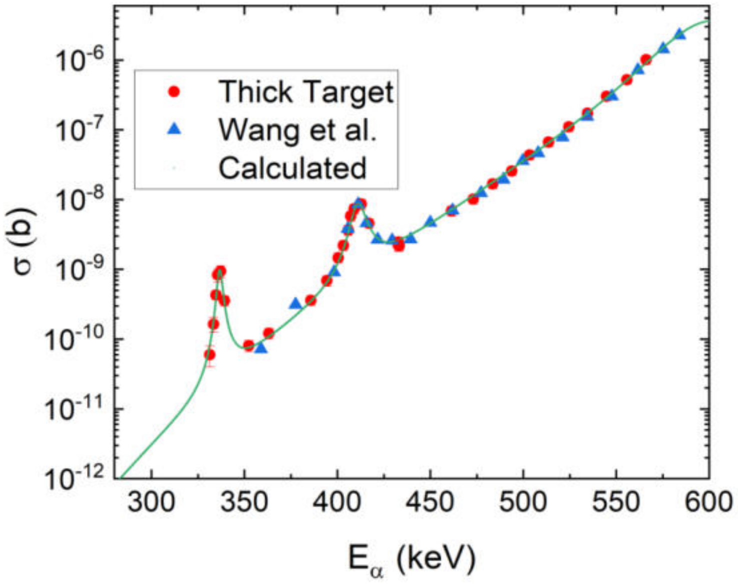


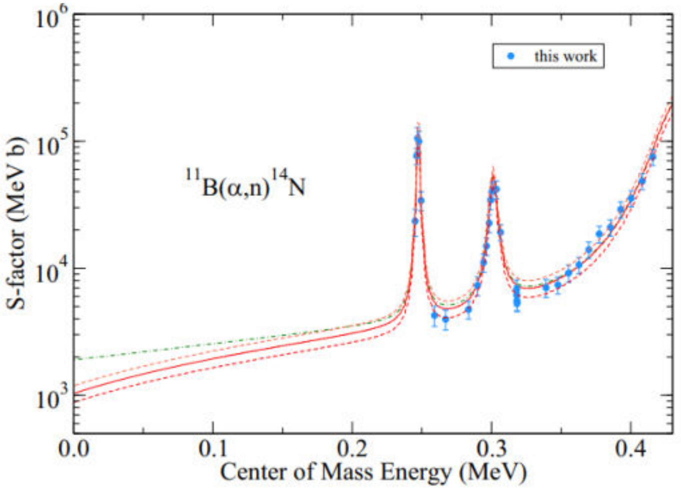


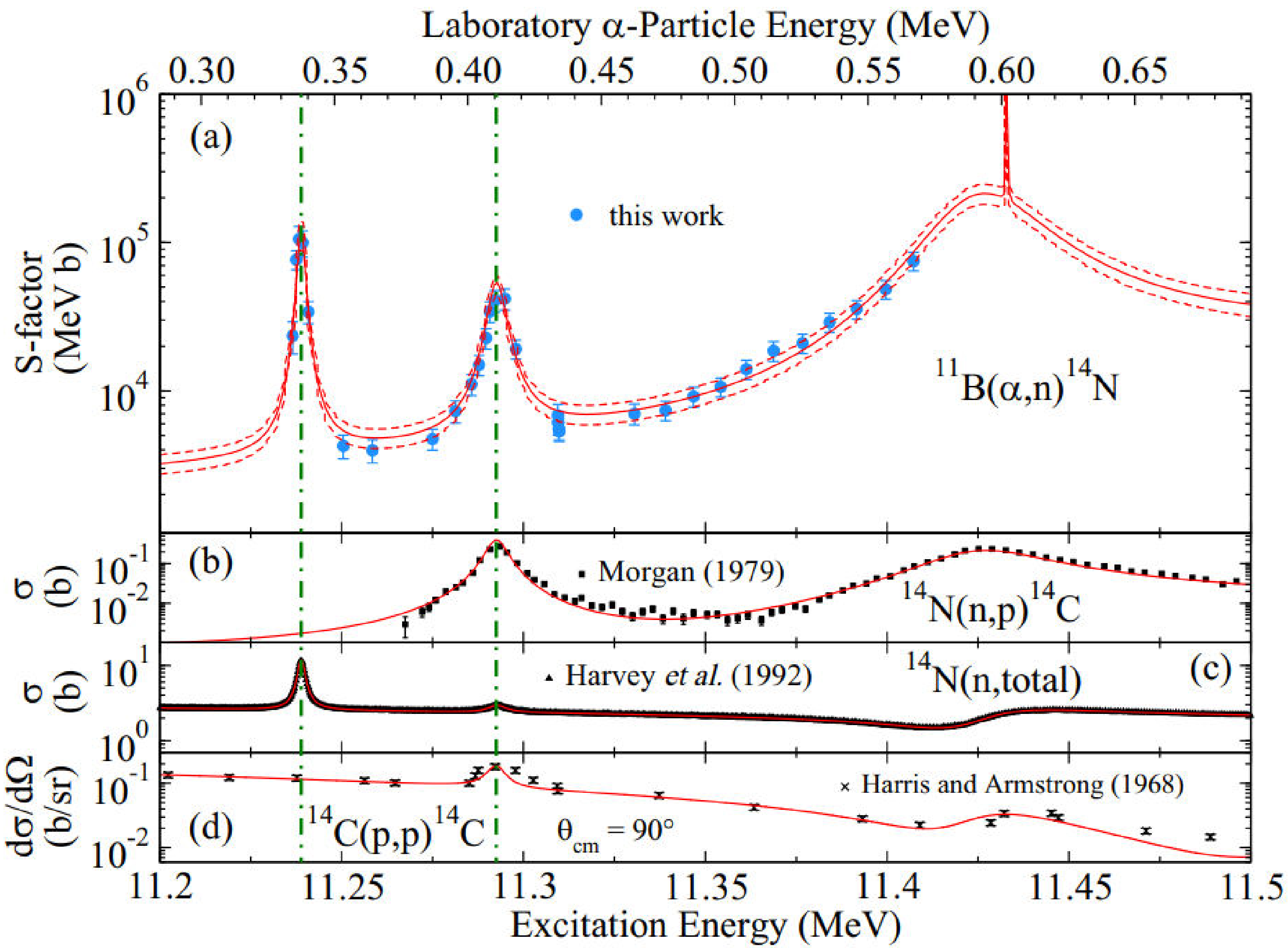
Exact resonance location needs to be determined, several potential s-wave resonances! Deuteron source and neutron source!

This would provide a source for neutrons in first star environments

$^{11}B(\alpha,n)$, two low energy resonances







Multi-channel, multi-level R-matrix fit taking all data on reactions through the compound nucleus into account.

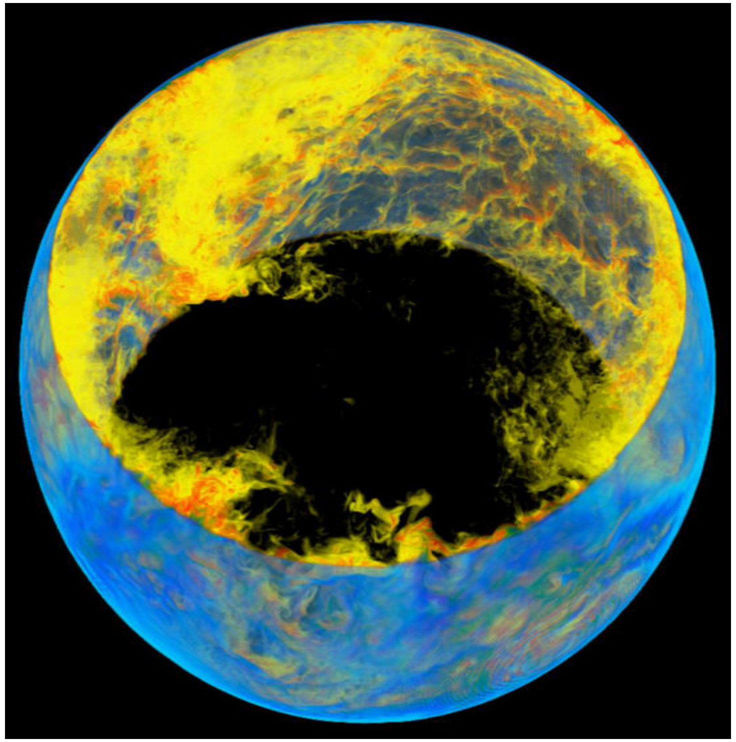
Neutron seed production

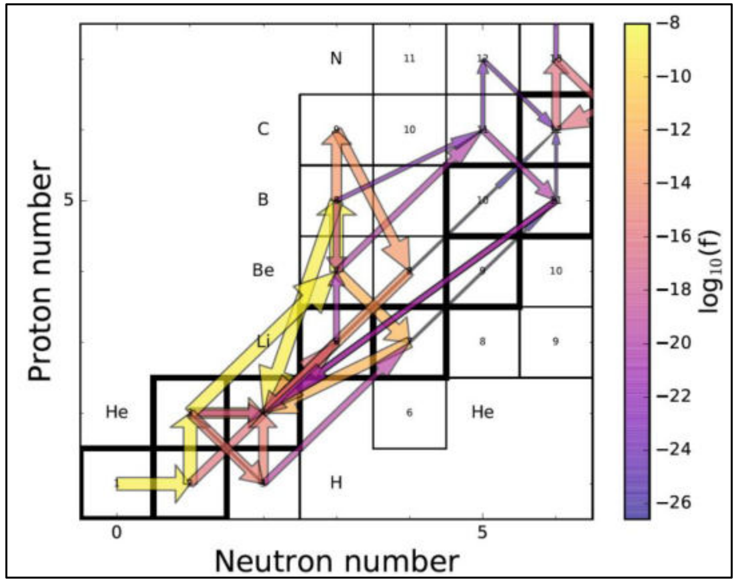
^{22}Ne, as product of the CNO ashes ^{14}N in massive star core He burning:
$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$

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

^{9}Be, and ^{10,11}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 will be available that may serve as neutron source.





Neutron sources for the r-process

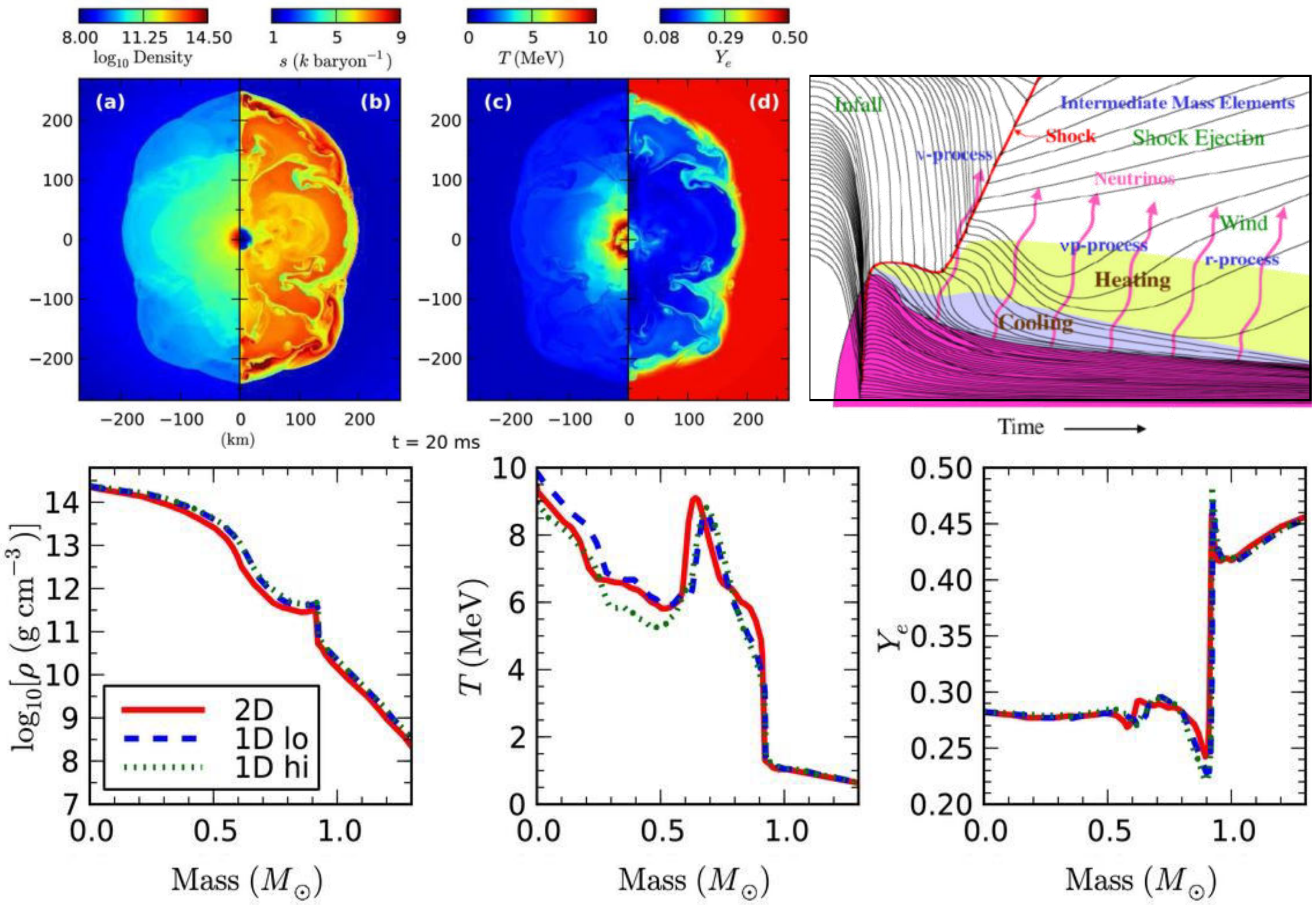
- Neutron sources for the r-process
- Neutron sources for the n-process

Core collapse to high densities and temperatures

Neutrons are produced in core collapse SN or on merging neutron star reaching extreme densities by nuclear-statistical equilibrium (NSE), which indicates full chemical equilibrium among all of the involved nuclear reactions. For high temperature and density conditions the equilibrium shifts to p, n, and α dominated abundance distribution.

Y_e is the electron to baryon fraction and smaller Y_e provide more neutrons by electron capture on protons!

$Y_e=(n_e^- - n_e^+)/nb=1/(1+N_n/N_p)$

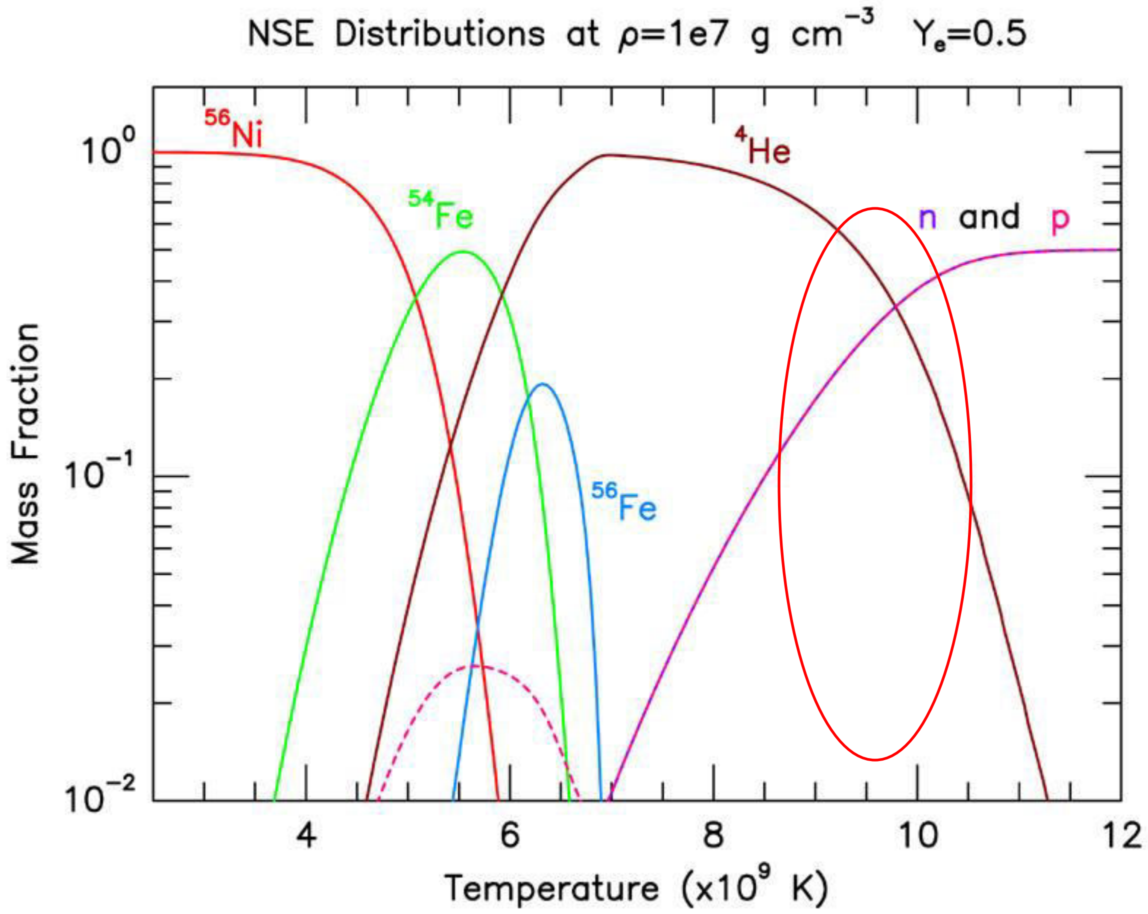


Chemical Equilibrium at high Densities and Temperatures

$$Y_{Z,N} = G_{Z,N} \cdot \left(\rho \cdot N_A\right)^{A-1} \cdot \left(\frac{2\pi \cdot \hbar^2}{m_u \cdot kT}\right)^{\frac{3}{2}\cdot(A-1)} \cdot e^{\frac{B_{Z,N}}{kT}} \cdot Y_n^N \cdot Y_p^Z$$

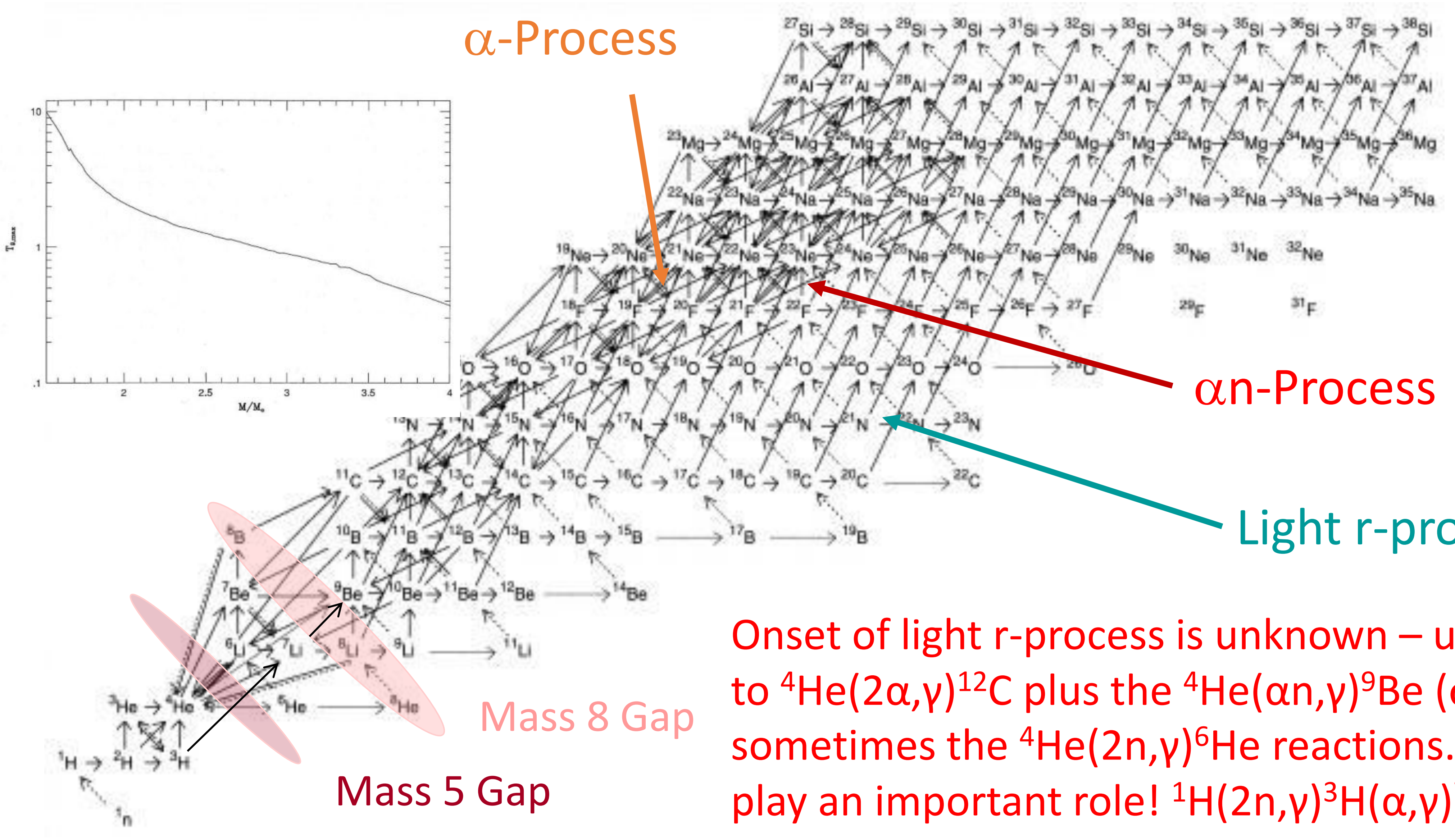
High ρ:	Massive nuclei
High T:	Light nuclei
Median T:	Tightly bound nuclei.

With the expansion of the shock follows a gradual change in abundance distribution on a timescale determined by assembling, the n, p, α nuclei to heavier nuclei. That timing depends on the associated rates.



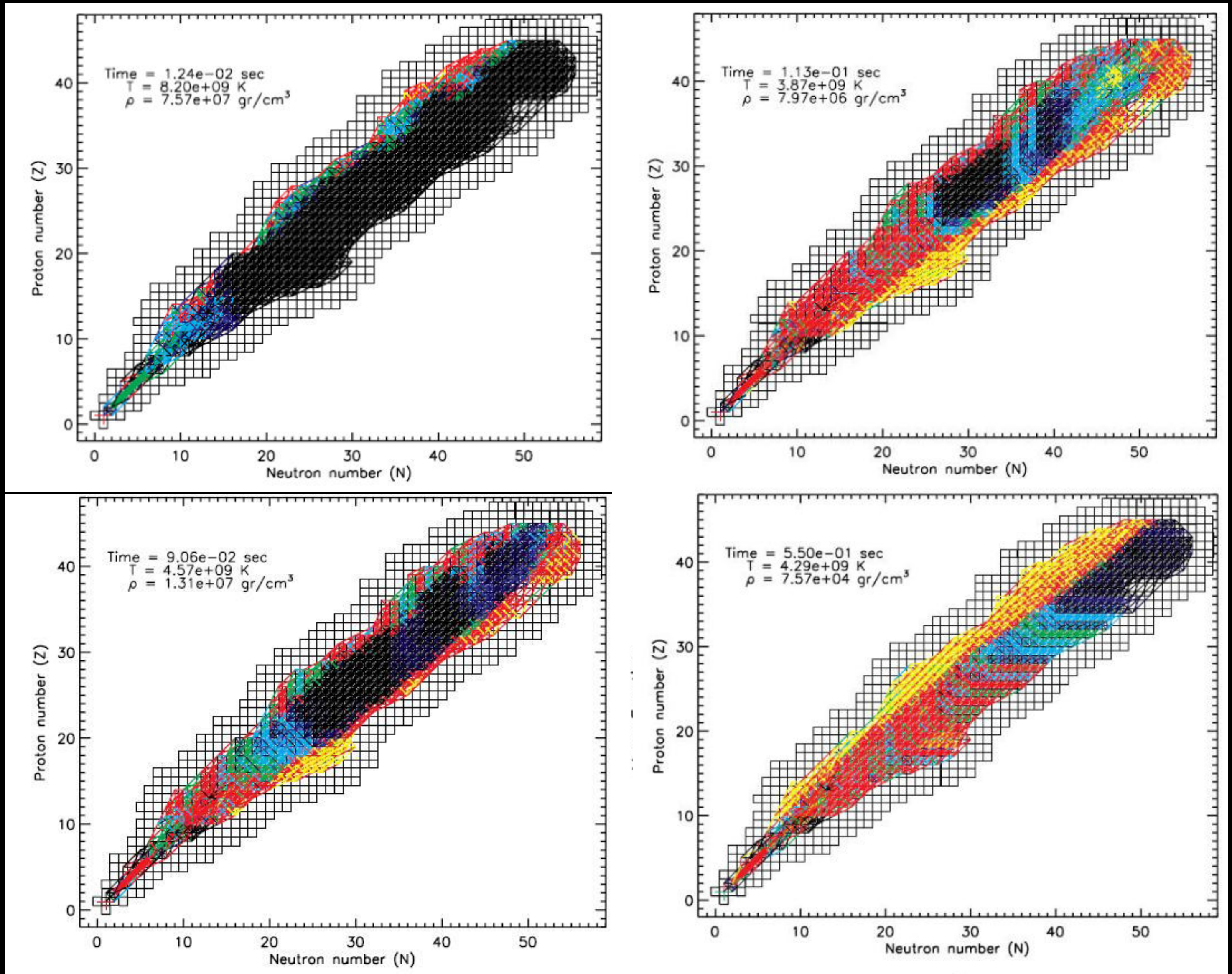
Neutron Star Mergers and Nucleosynthesis of Heavy Elements
F.-K. Thielemann, M. Eichler, I.V. Panov, and B. Wehmeyer.
Annual Review of Nuclear and Particle Science 67 (2017) 253-274.

Dynamical Reaction Network bridging the gap

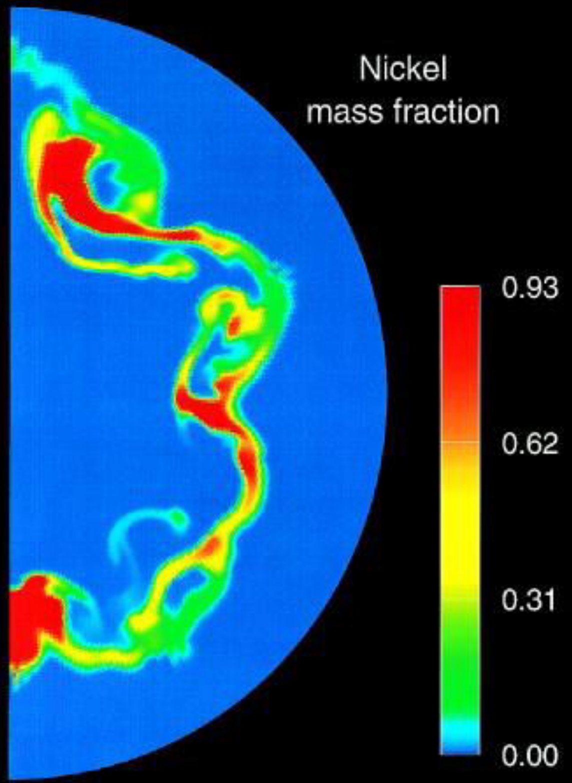


Onset of light r-process is unknown – usually reduced to $^{4}He(2\alpha,\gamma)^{12}C$ plus the $^{4}He(\alpha n,\gamma)^{9}Be$ (α,n) and sometimes the $^{4}He(2n,\gamma)^{6}He$ reactions. Tritium may play an important role! $^{1}H(2n,\gamma)^{3}H(\alpha,\gamma)^{7}Li(t,n)^{9}Be(\alpha,n)$!

Explosive burning in shock front

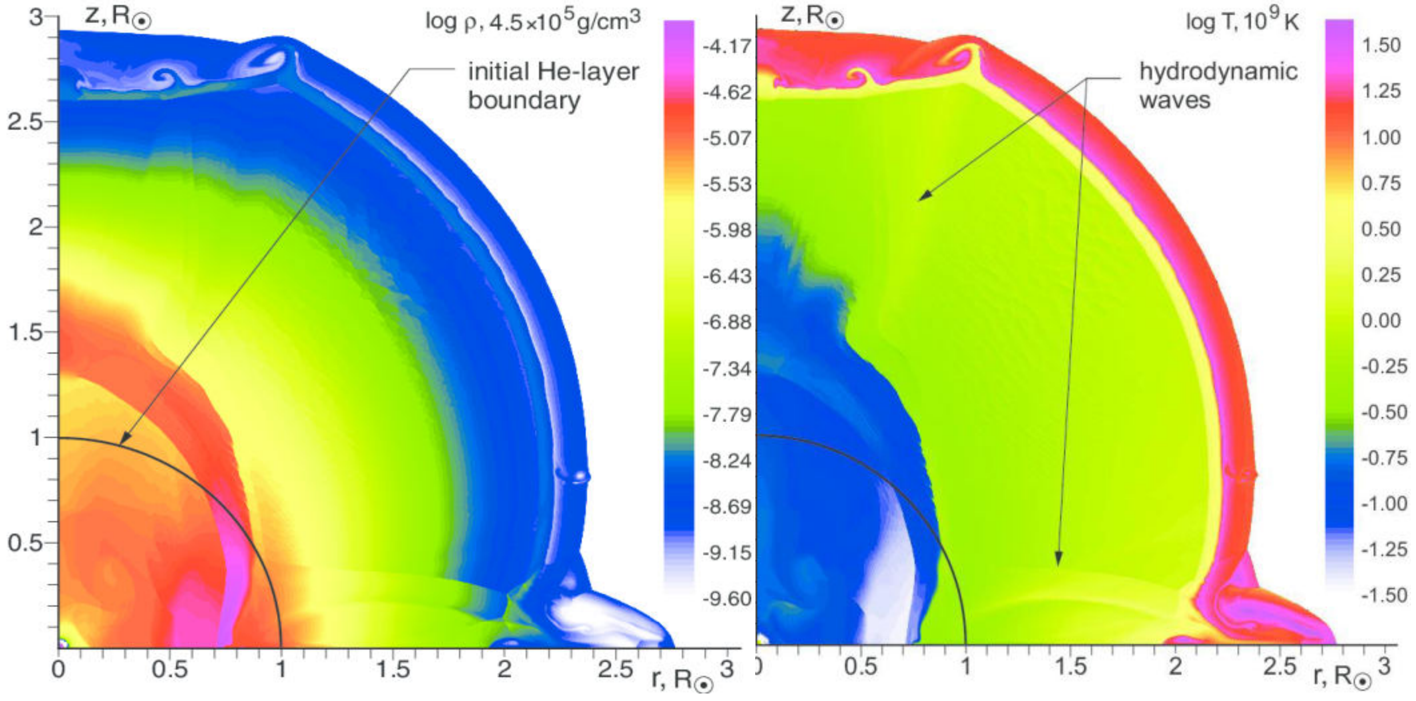


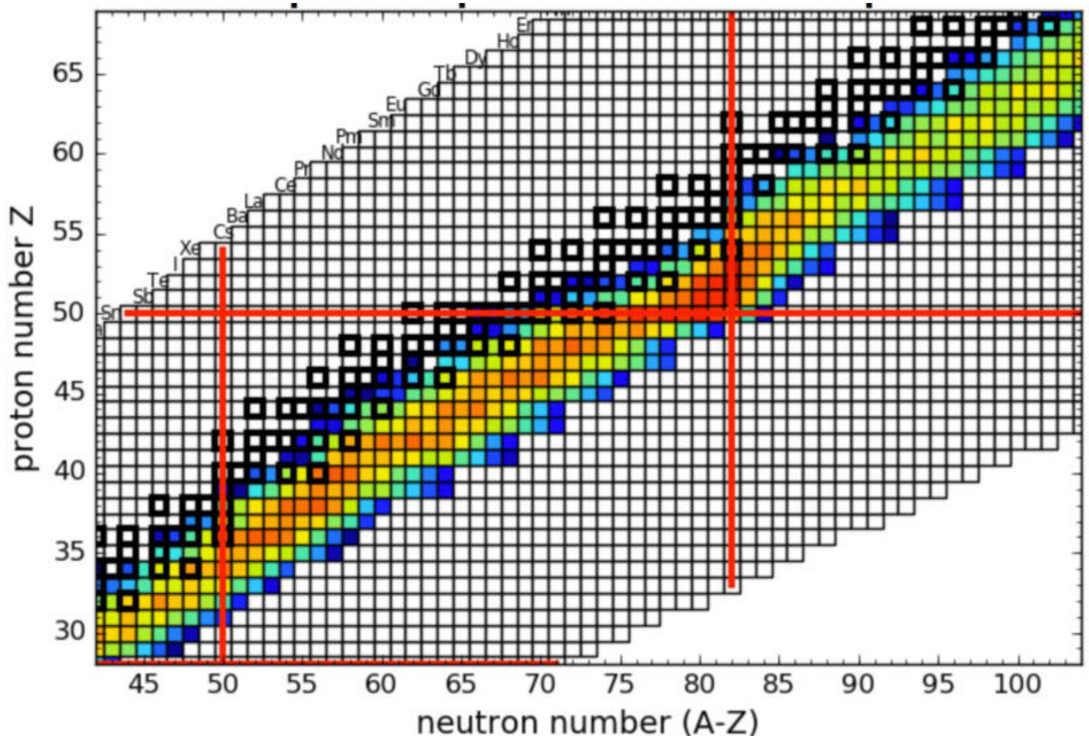
Initial dissociation towards p, n, ^{4}He
Re-association is stat. equilibrium towards ^{56}Ni with gradual cooling through expansion.



Neutron sources for the n-process

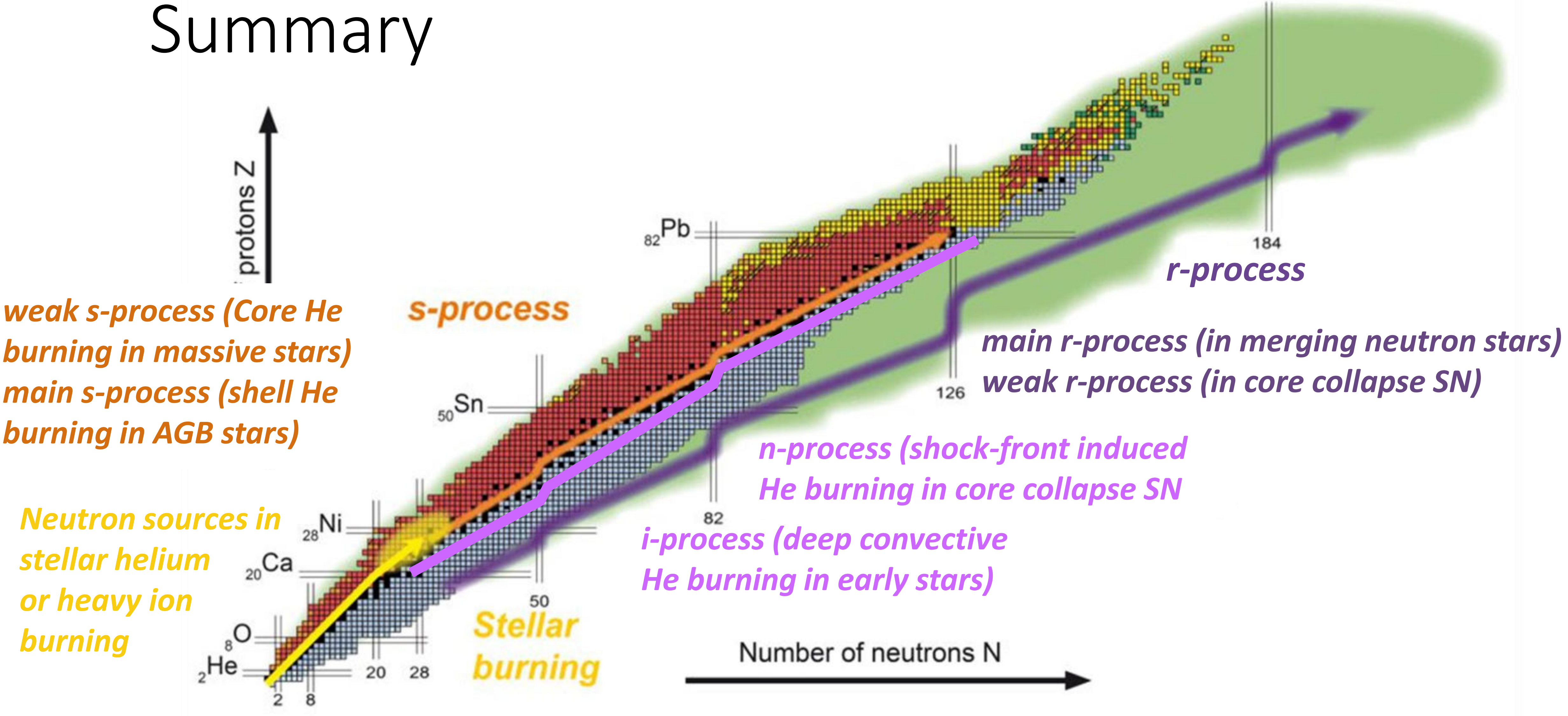
Supernova shock traverses helium burning layer with large amounts of unprocessed ^{22}Ne (this depends on the ^{22}Ne(α,γ) reaction rate), sudden increase in temperature, density and pressure releases the neutron flux from ^{22}Ne(α,n)! The reaction rate is dominated by the 830 keV cluster resonance!





Possibly other (α,n) sources along the way

Summary



protons Z
Number of neutrons N
$_{82}$Pb
$_{50}$Sn
$_{28}$Ni
$_{20}$Ca
$_{8}$O
$_{2}$He
2
8
20
28
50
82
126
184
s-process
r-process
Stellar burning
weak s-process (Core He burning in massive stars)
main s-process (shell He burning in AGB stars)
Neutron sources in stellar helium or heavy ion burning
main r-process (in merging neutron stars)
weak r-process (in core collapse SN)
n-process (shock-front induced He burning in core collapse SN
i-process (deep convective He burning in early stars)

Acknowledgement to ND/ORNL team and neutron detectors

New detector arrangements, deuterated scintillator detector arrays and a ^{3}He counter system with 24 ^{3}He ultra clean ^{3}He tubes and 2 ^{3}He spectrometers.

Very successful collaborative effort with ORNL!