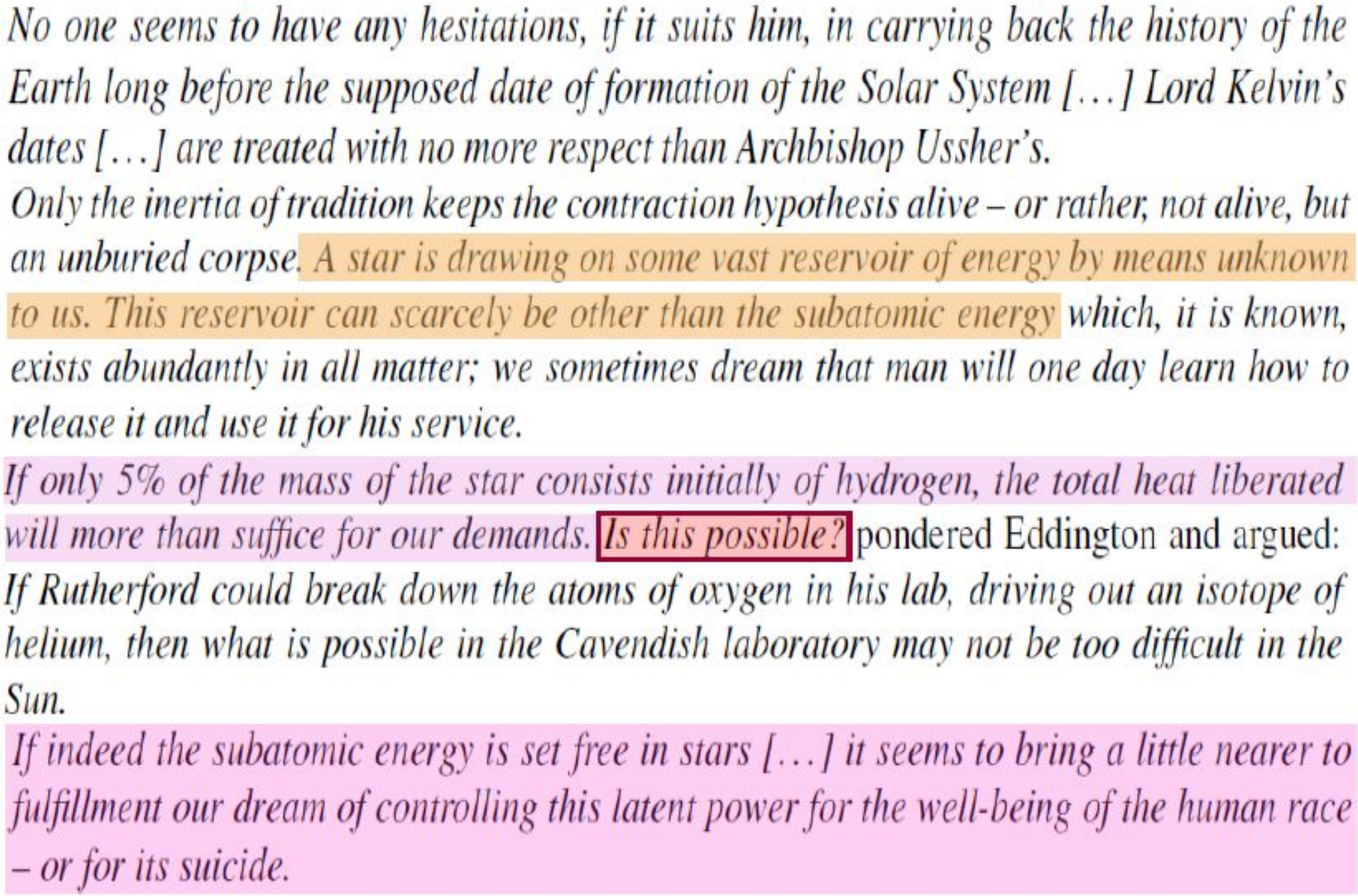
James Webb
Telescope
December 2023

Ani
Aprahamian
University of Notre Dame
aapraham@nd.edu

The energy source of the Sun

Eddington's Presidential address to the British Association (24/8/1920)



No one seems to have any hesitations, if it suits him, in carrying back the history of the Earth long before the supposed date of formation of the Solar System […] Lord Kelvin's dates […] are treated with no more respect than Archbishop Ussher's.

Only the inertia of tradition keeps the contraction hypothesis alive – or rather, not alive, but an unburied corpse. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service.

If only 5% of the mass of the star consists initially of hydrogen, the total heat liberated will more than suffice for our demands. Is this possible? pondered Eddington and argued:

If Rutherford could break down the atoms of oxygen in his lab, driving out an isotope of helium, then what is possible in the Cavendish laboratory may not be too difficult in the Sun.

If indeed the subatomic energy is set free in stars […] it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race – or for its suicide.

1925: Cecilia Payne

H and He are the most abundant elements in stellar atmospheres

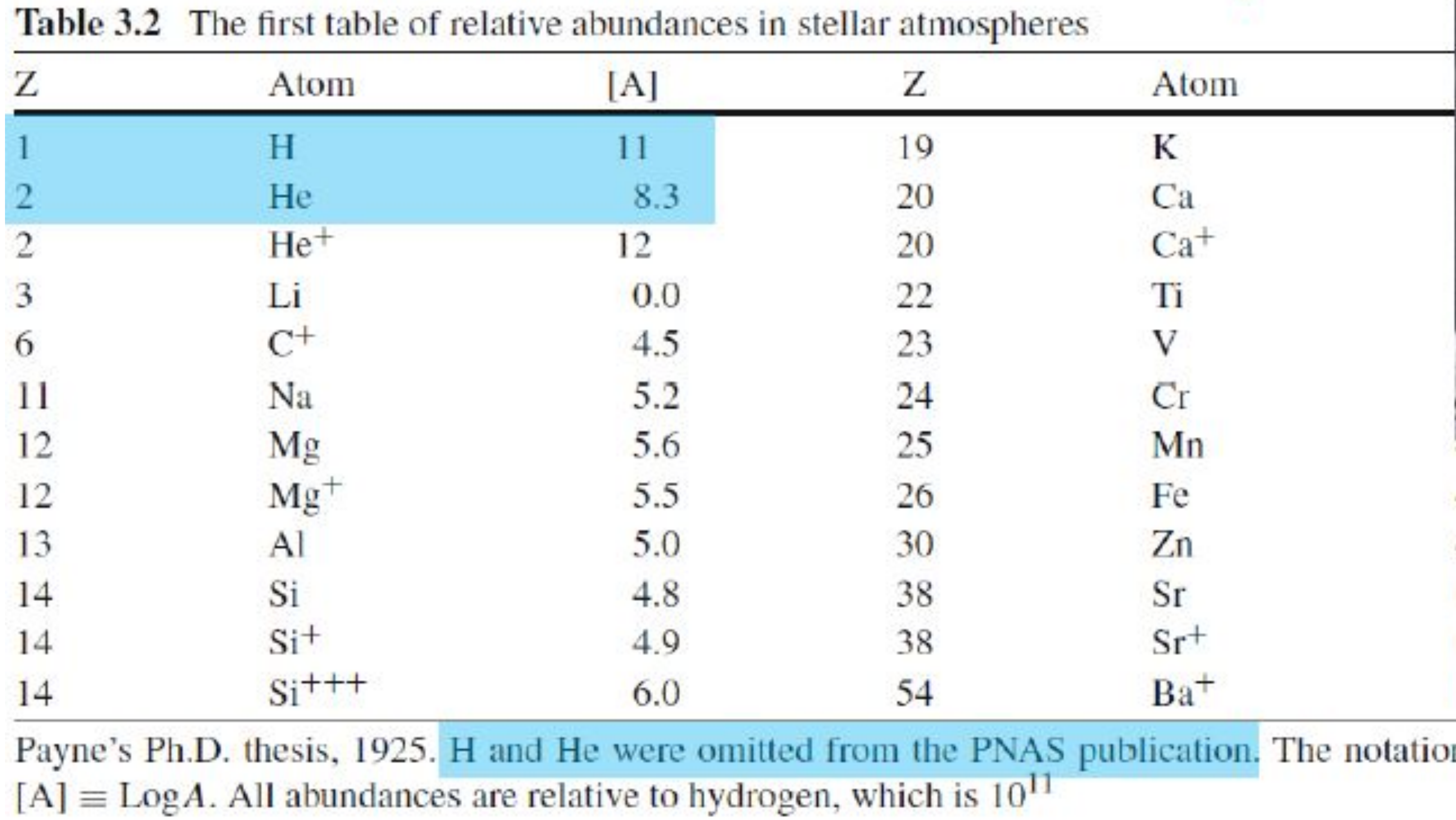
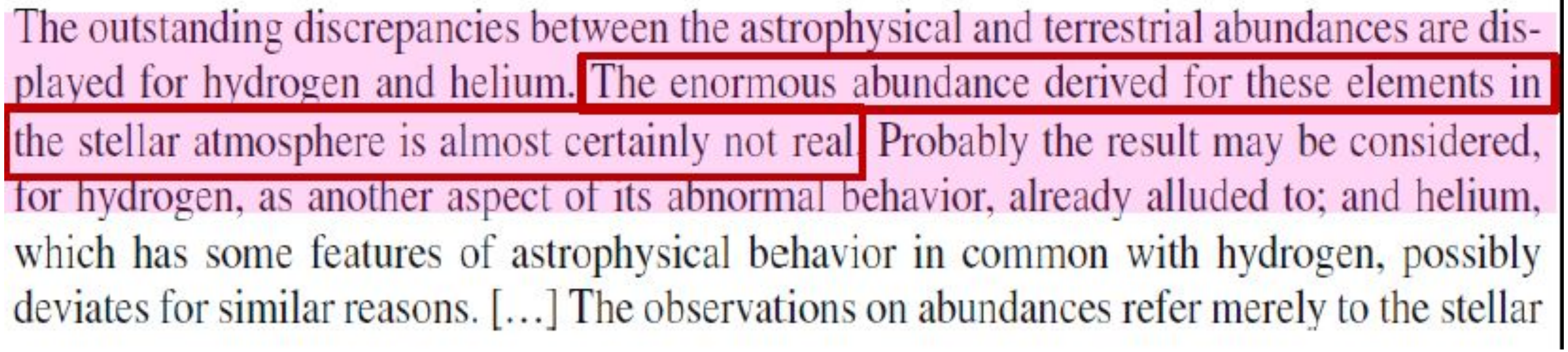


Table 3.2 The first table of relative abundances in stellar atmospheres

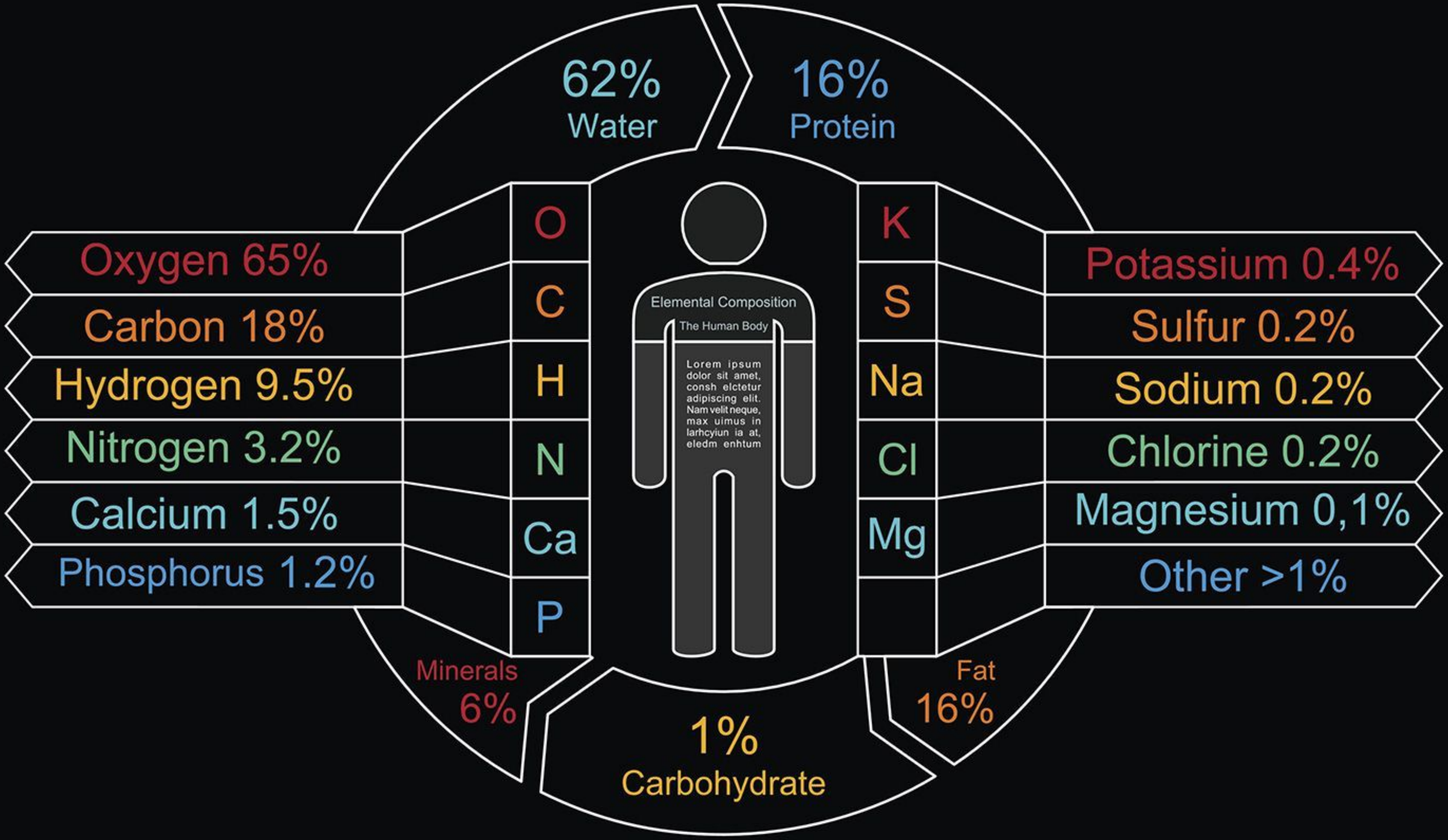
Z	Atom	[A]	Z	Atom	
1	H	11	19	K	
2	He	8.3	20	Ca	
2	He^+	12	20	Ca^+	
3	Li	0.0	22	Ti	
6	C^+	4.5	23	V	
11	Na	5.2	24	Cr	
12	Mg	5.6	25	Mn	4.0
12	Mg^+	5.5	26	Fe	4.8
13	Al	5.0	30	Zn	4.2
14	Si	4.8	38	Sr	1.8
14	Si^+	4.9	38	Sr^+	1.5
14	Si^{+++}	6.0	54	Ba^+	1.1

Payne's Ph.D. thesis, 1925. H and He were omitted from the PNAS publication. The notation is [A] ≡ Log*A*. All abundances are relative to hydrogen, which is 10^{11}

Astronomer:
Harvard
University



The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result may be considered, for hydrogen, as another aspect of its abnormal behavior, already alluded to; and helium, which has some features of astrophysical behavior in common with hydrogen, possibly deviates for similar reasons. […] The observations on abundances refer merely to the stellar



Elemental Composition

The Human Body

Lorem ipsum dolor sit amet, consh elctetur adipiscing elit. Nam velit neque, max uimus in larhcyiun ia at, eledm enhtum

62% Water

16% Protein

Minerals 6%

1% Carbohydrate

Fat 16%

Oxygen 65%

Carbon 18%

Hydrogen 9.5%

Nitrogen 3.2%

Calcium 1.5%

Phosphorus 1.2%

O C H N Ca P

K S Na Cl Mg

Potassium 0.4%

Sulfur 0.2%

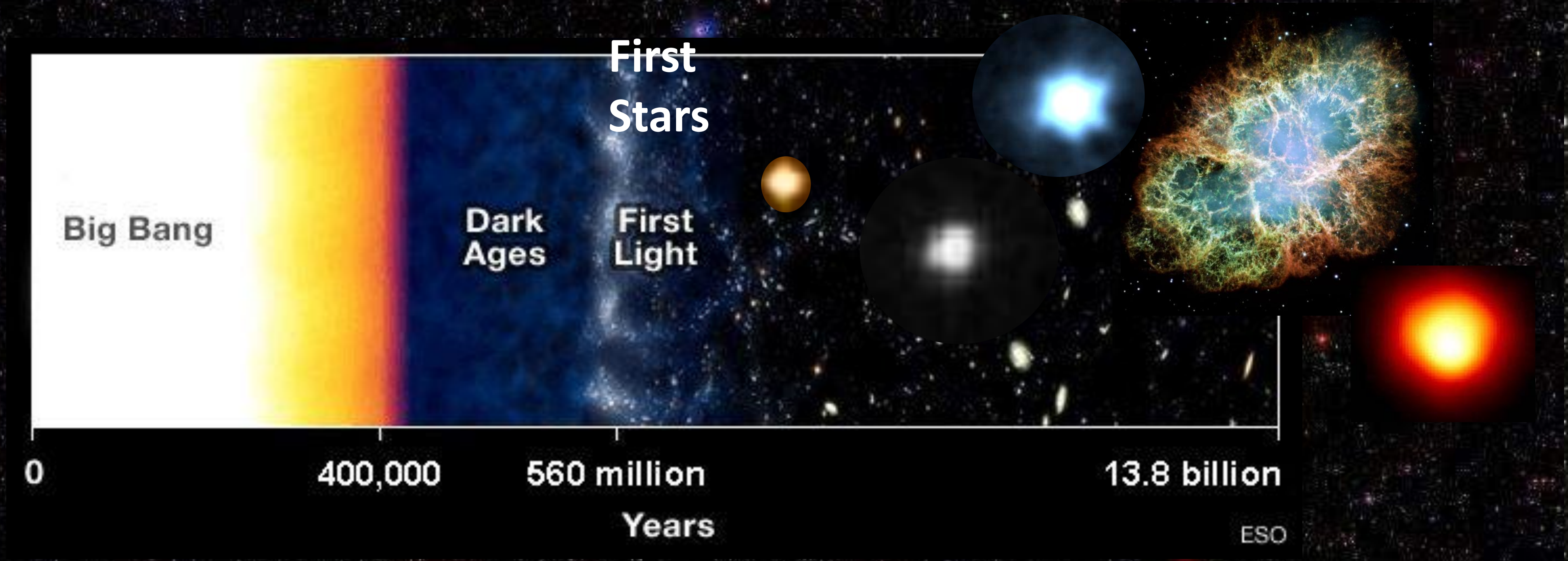
Sodium 0.2%

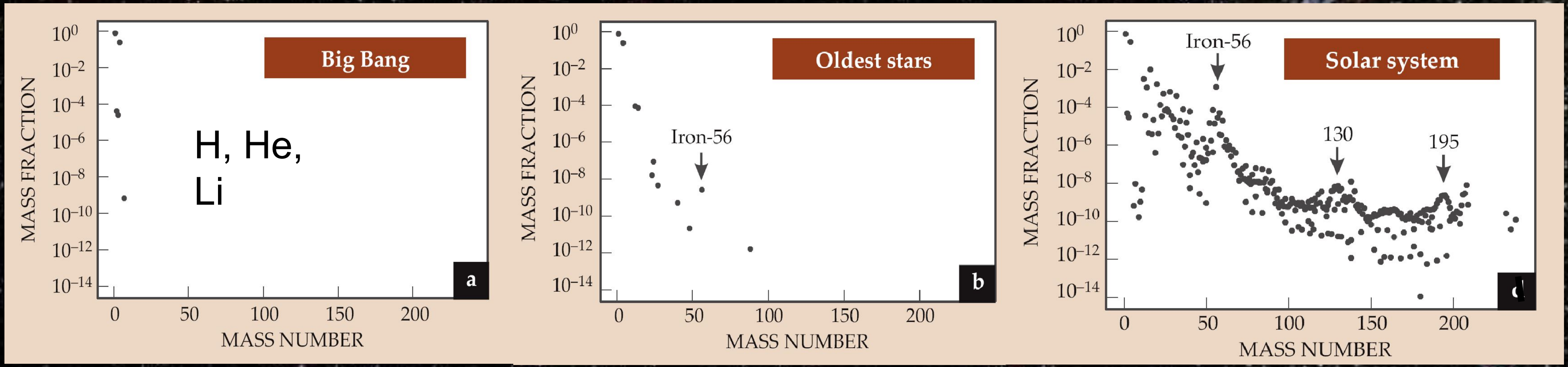
Chlorine 0.2%

Magnesium 0,1%

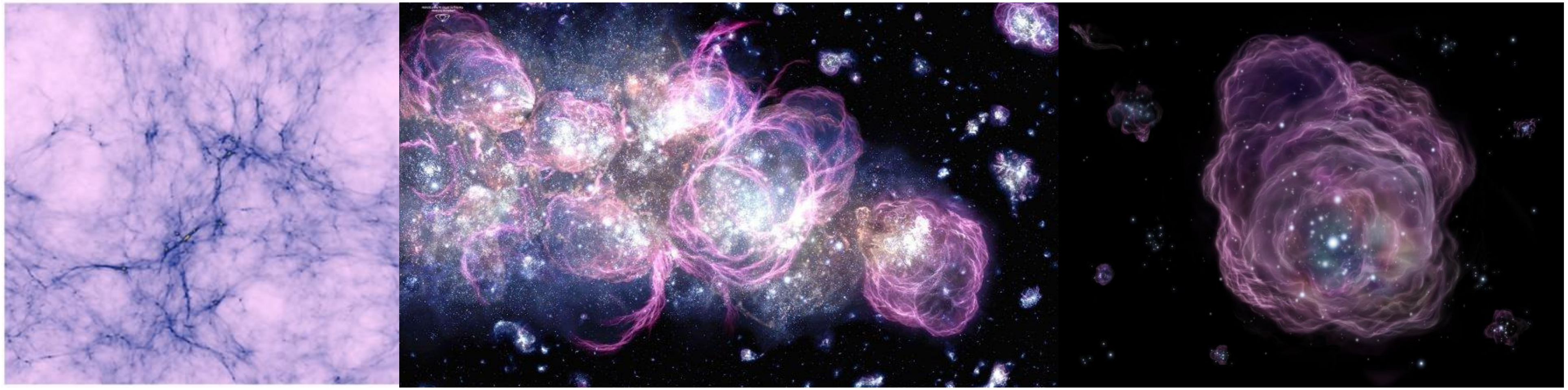
Other >1%

Galactic Chemical Evolution

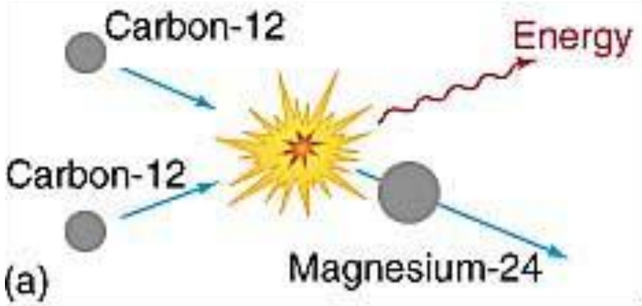




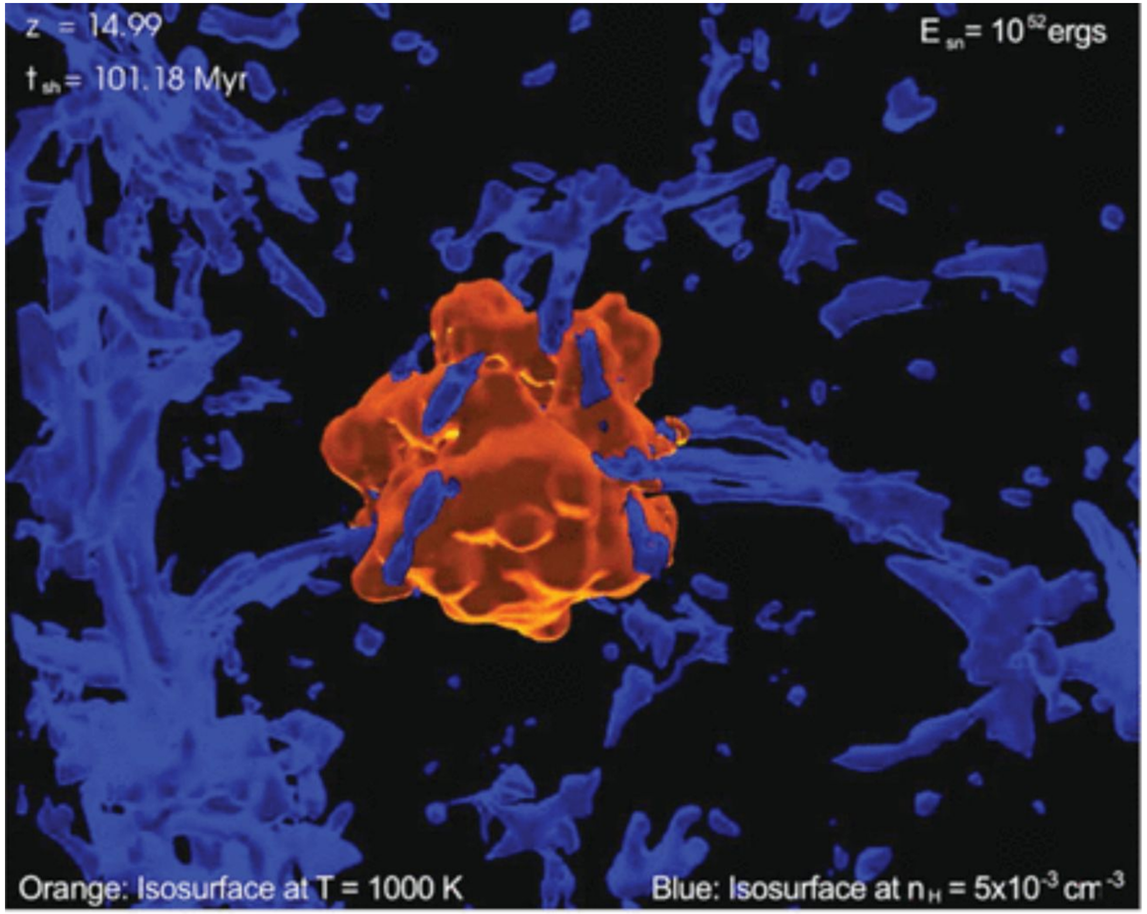
Fusion Reactions in Stars

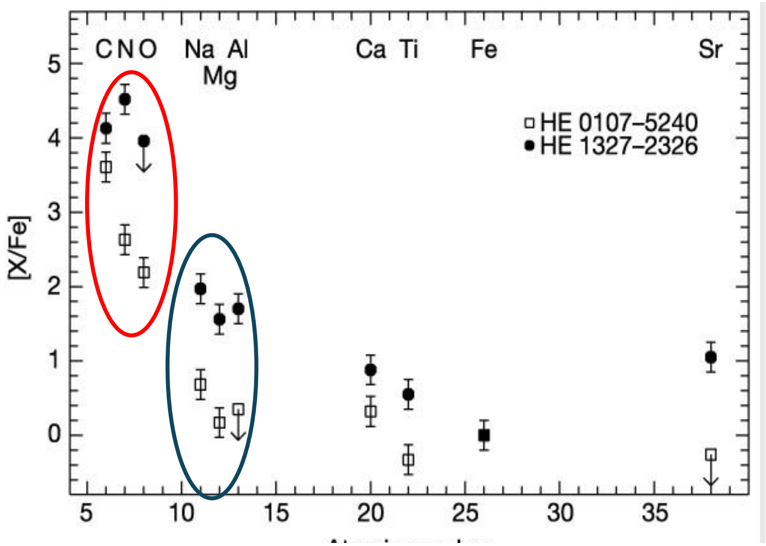


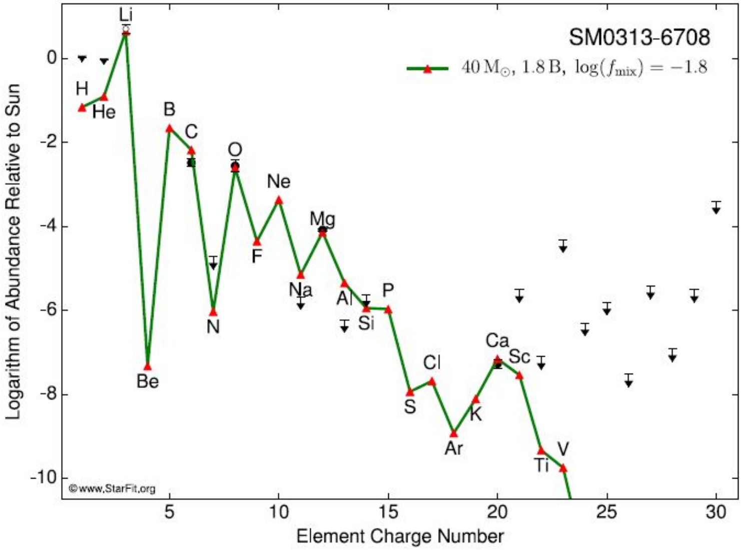
- First stars: fusion for mid-mass elements
- Late stars: post-red-giant stellar evolution, carbon and oxygen burning
- Ignition of type Ia supernovae
- Ignition of superbursts



The first supernova

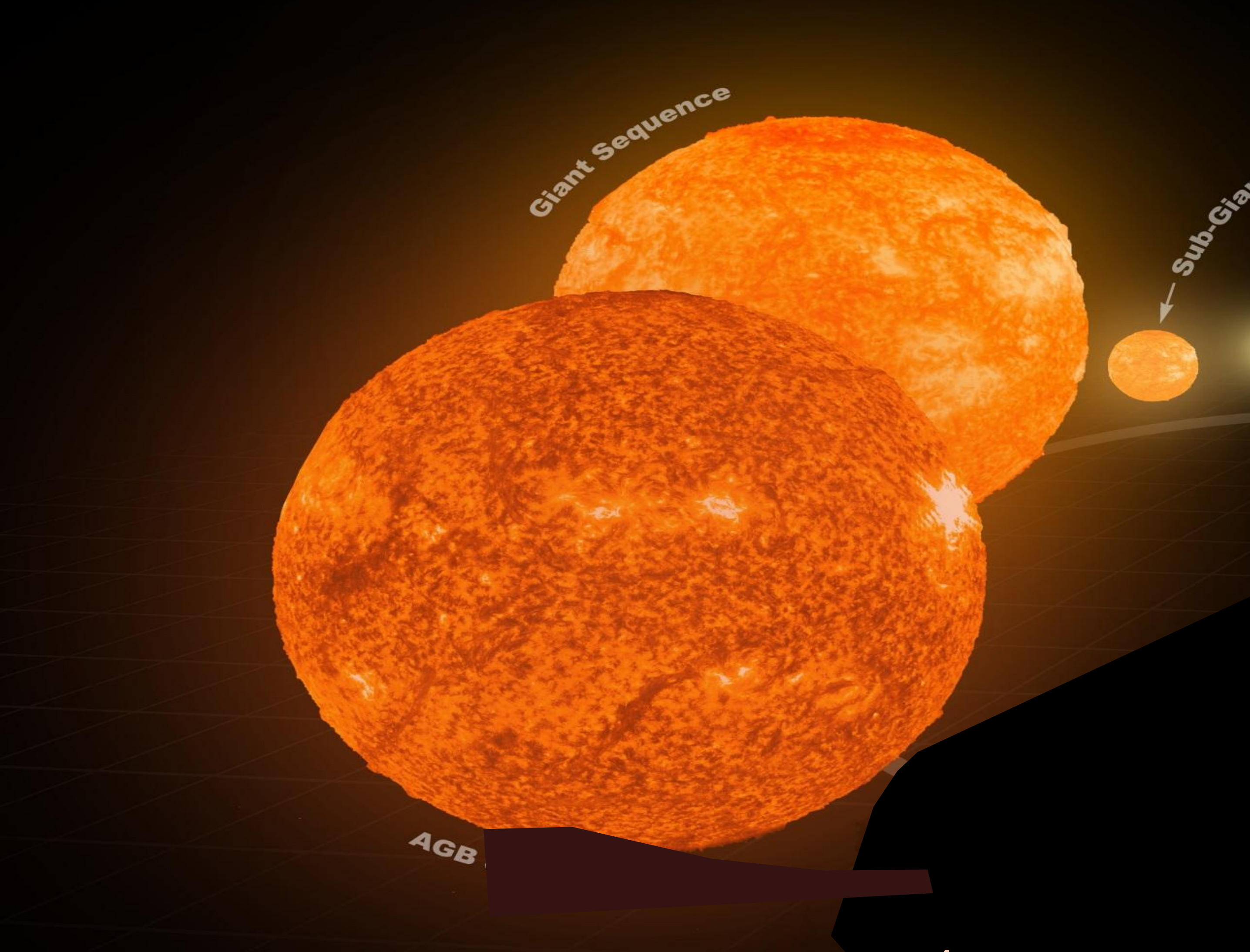


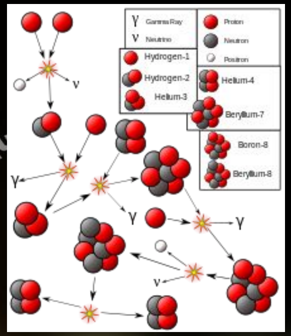


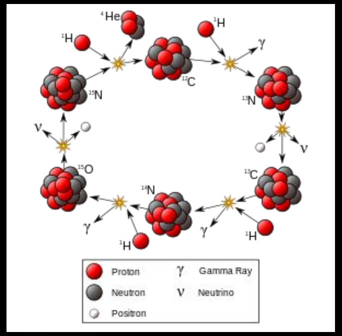


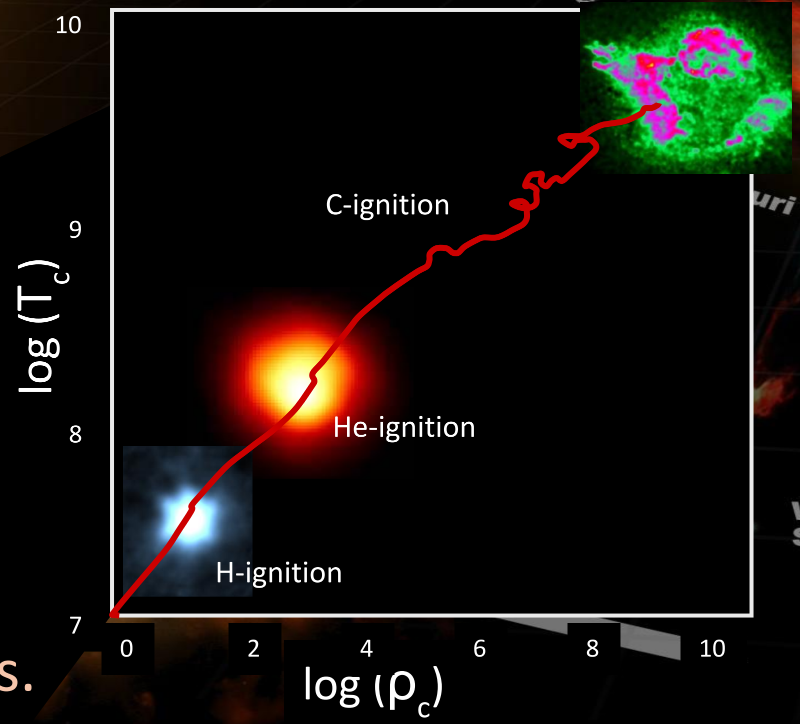
The first supernovae explode, ejecting carbon, nitrogen, oxygen, magnesium, silicon, and iron as seed for the next star generation.

From Hydrogen to Helium Burning.



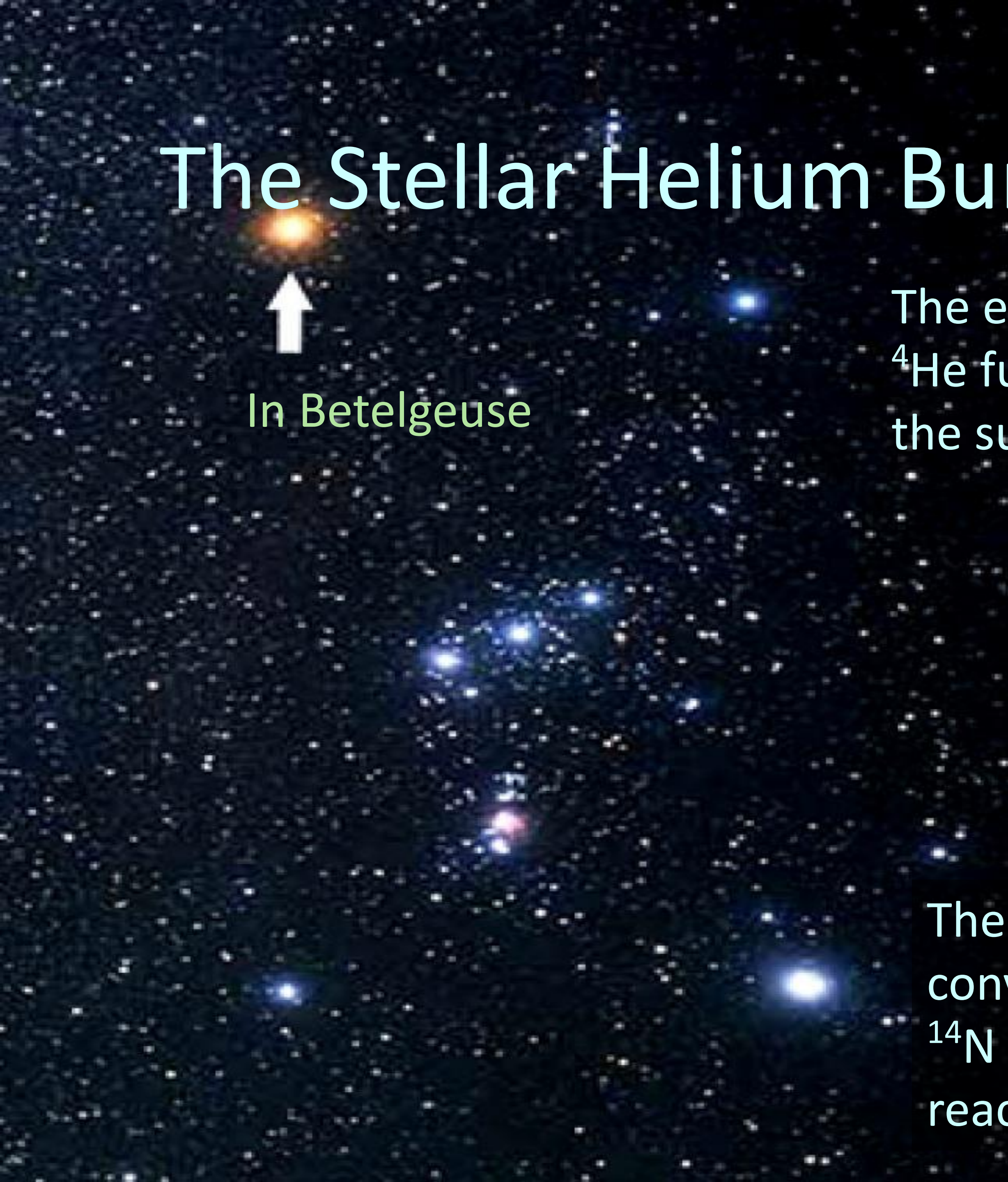




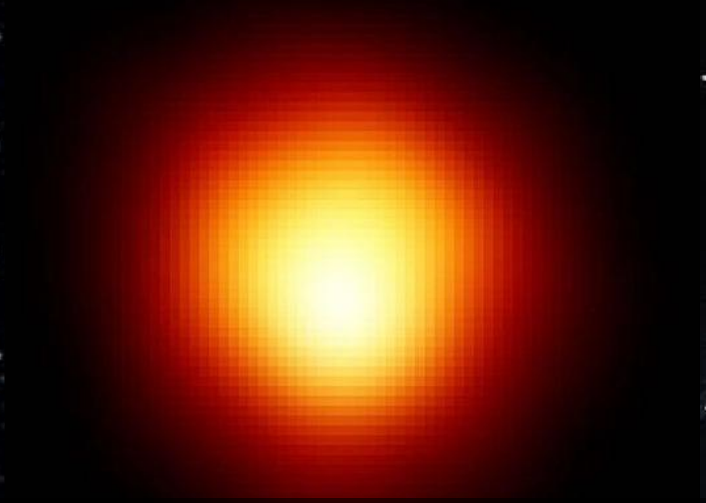


Ashes of hydrogen burning: ^{4}He from the pp-chains and ^{4}He and ^{14}N from CNO cycles.

The Stellar Helium Burning

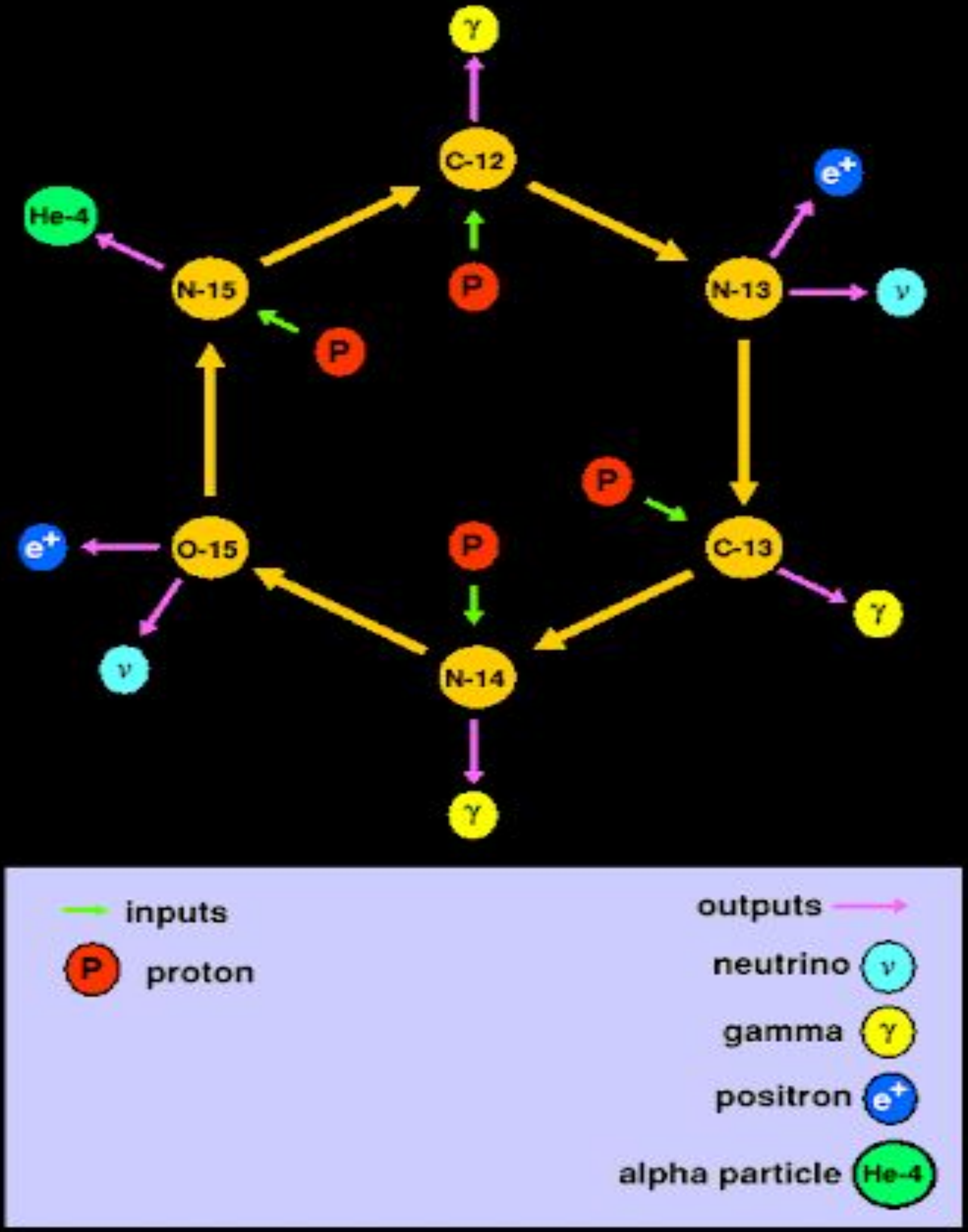


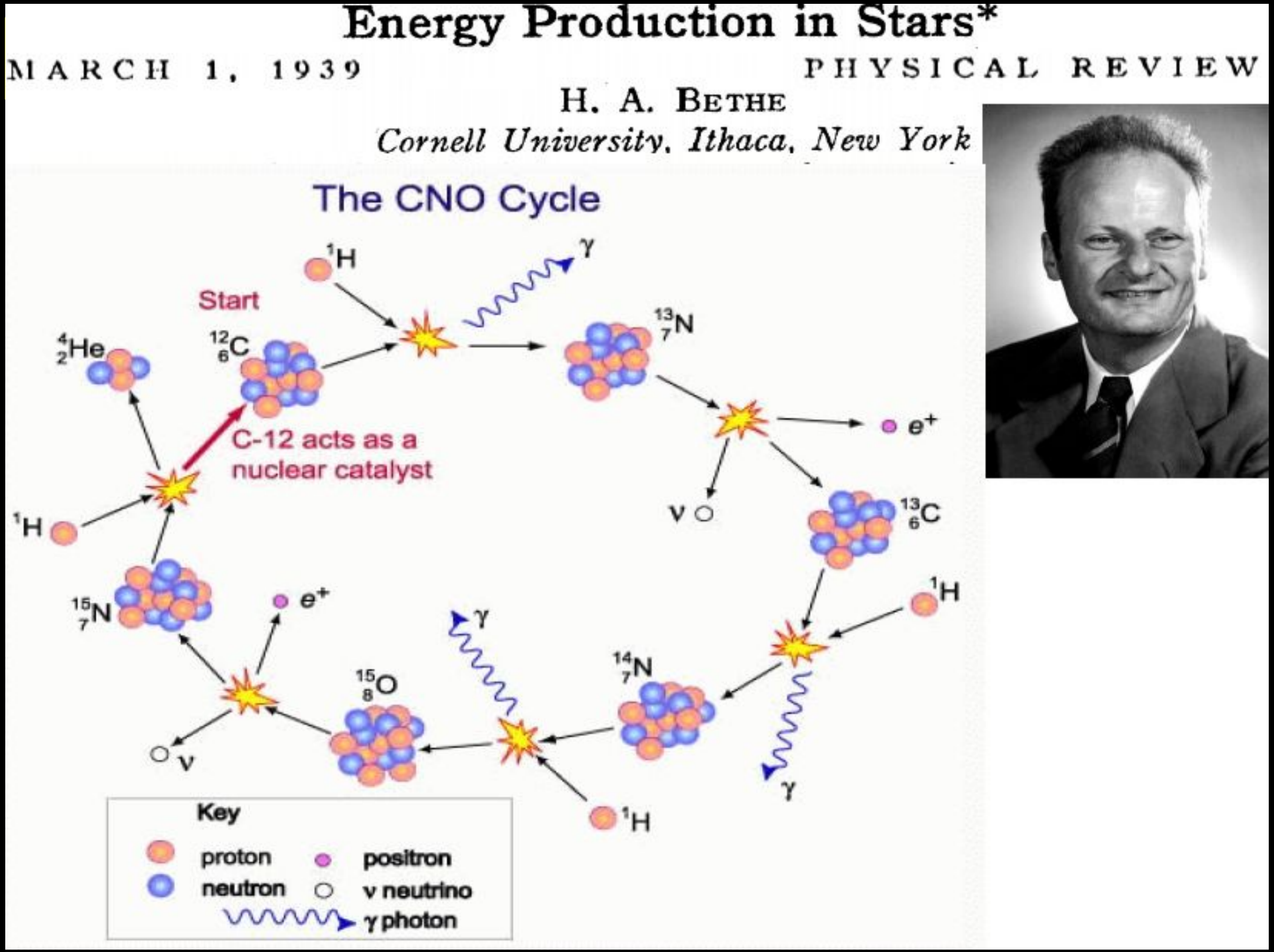
The energy is generated by burning the ^{4}He fuel through the triple α process and the subsequent $^{12}C(\alpha,\gamma)^{16}O$ reaction.



The ^{14}N ashes of the CNO cycles is converted into neutrons and ^{25}Mg via the $^{14}N\ (\alpha,\gamma)^{18}F(\beta\nu^{+})^{18}O\ (\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ reaction sequence!

CNO cycle…..





Energy Production in Stars*

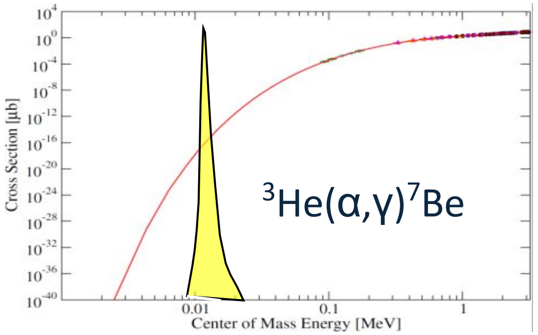
MARCH 1, 1939 PHYSICAL REVIEW

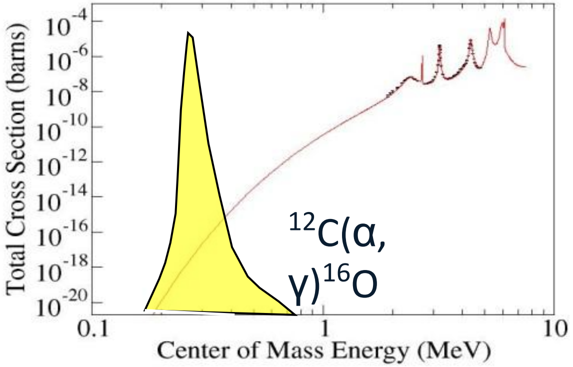
H. A. BETHE

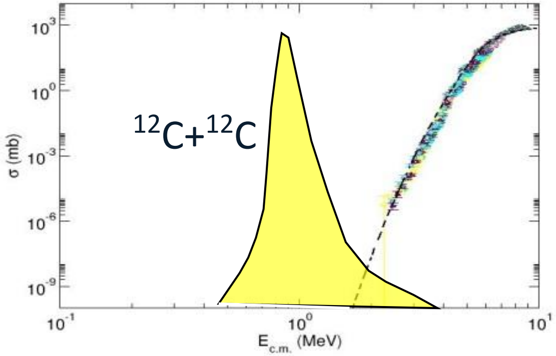
Cornell University, Ithaca, New York

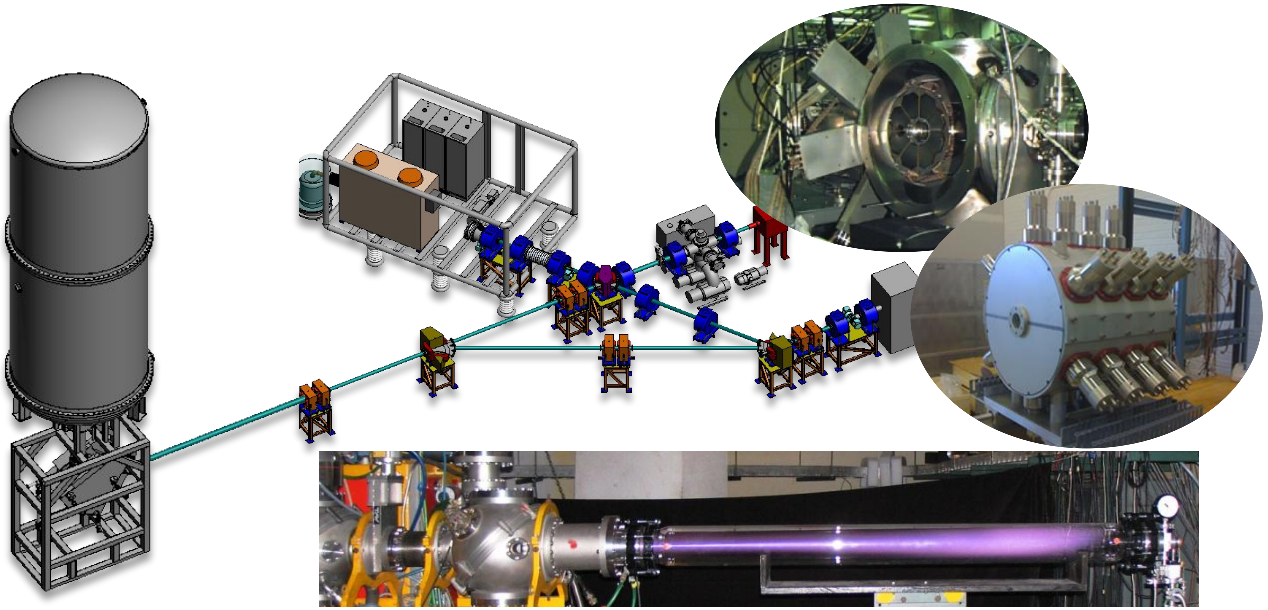
JINA–CEE

Experiments with Charged Particles



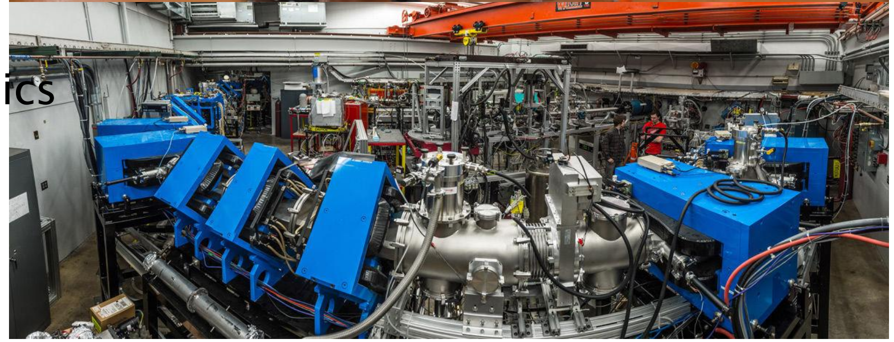




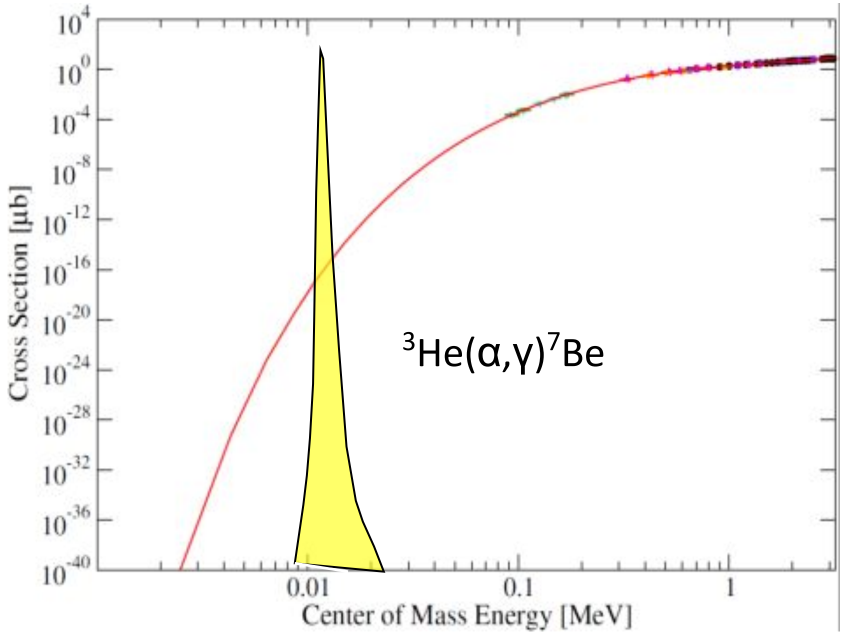


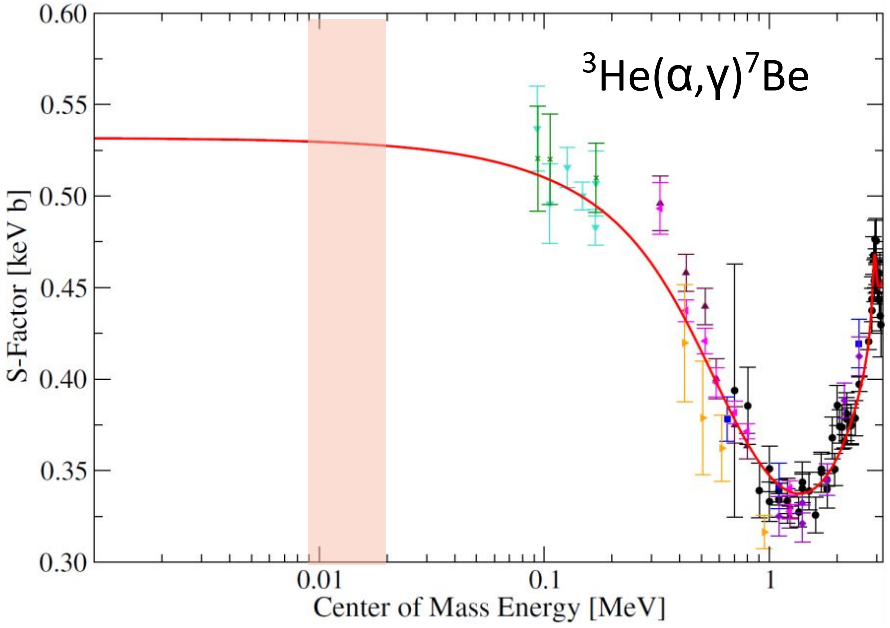
Forward kinematics underground with radiation detection

inverse kinematics with recoil separation and detection



Nuclear reactions in context

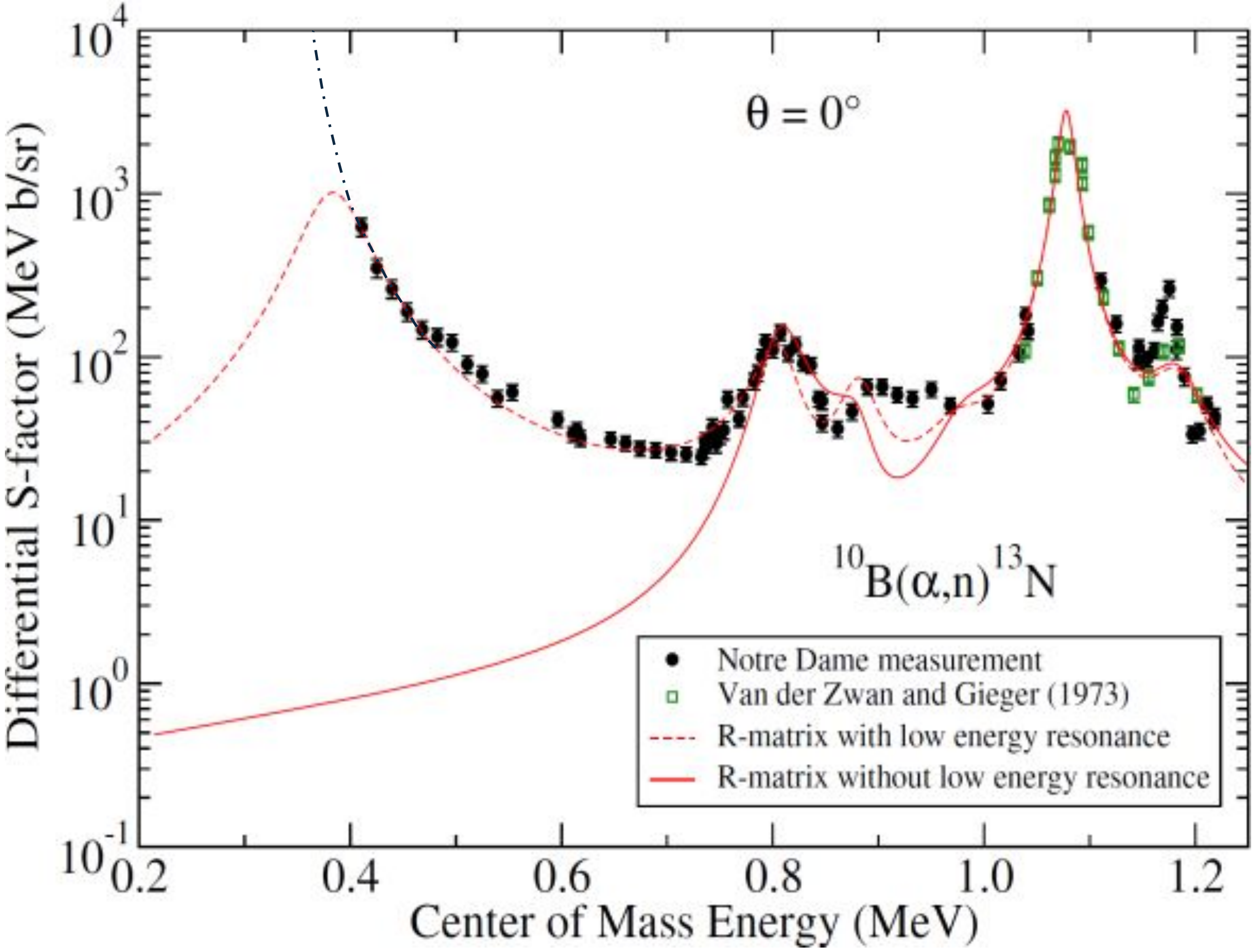




A direct measurement of a charged particle cross section for stellar burning is more than unlikely! A comprehensive analysis of the reaction rate at stellar energies, requires a full understanding of the reaction mechanism and the reaction components to be fully integrated into the extrapolation process. First principle nuclear models are limited, phenomenological models (R-matrix) are limited, but multi-channel approach with a wide-range of data seem promising!

JINA–CEE

First experimental results^{10}B(α,n)^{13}N



Further studies towards lower energies scheduled for late March 2019!

Neutron background sources are:

Cosmogenic neutrons

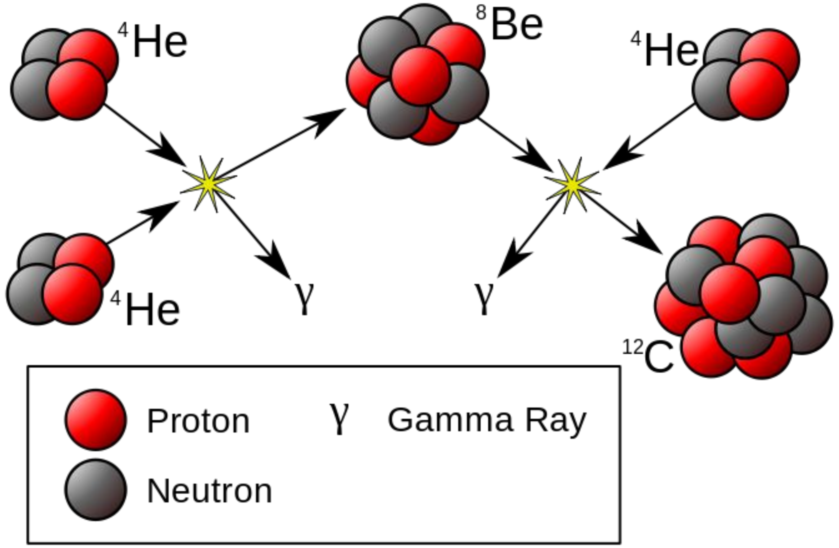
Radiogenic neutrons

Beam induced neutrons

Other reactions presently under investigation: ^{11}B(α.n), ^{10}B(α,d), ^{7}Li(α,γ), ^{6}Li(α,γ)

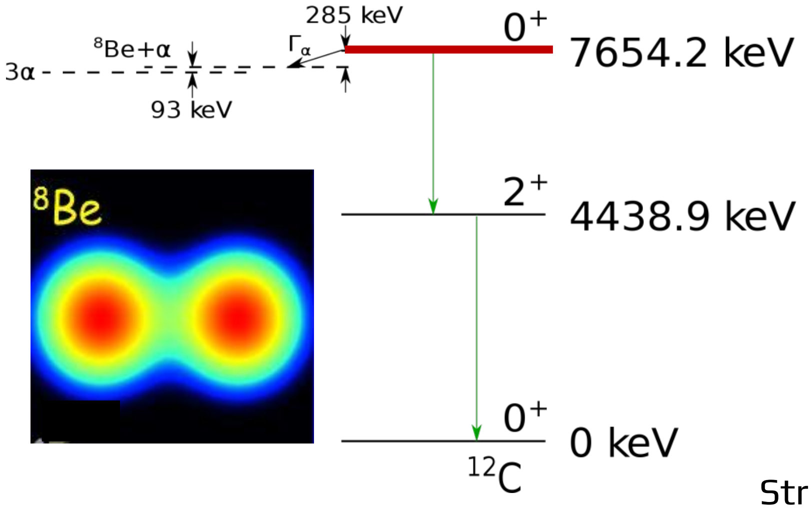
As well as back-processing reactions: ^{10}B(p,α)

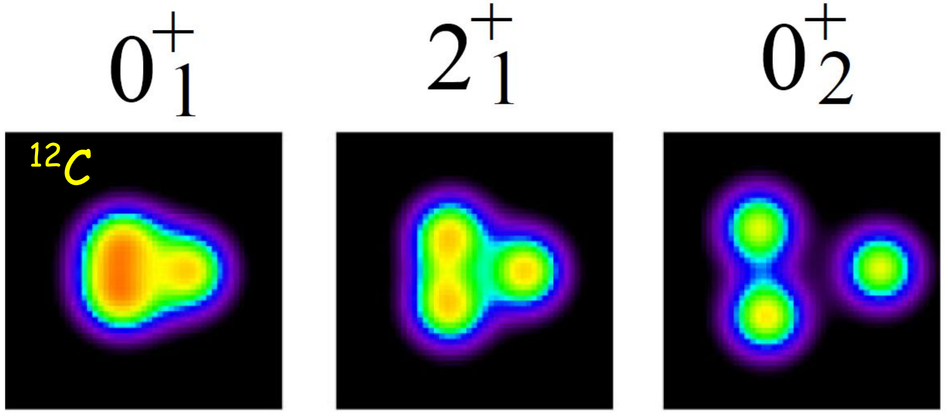
The triple-alpha-process



Three particle fusion that may occur by different reaction pathways:

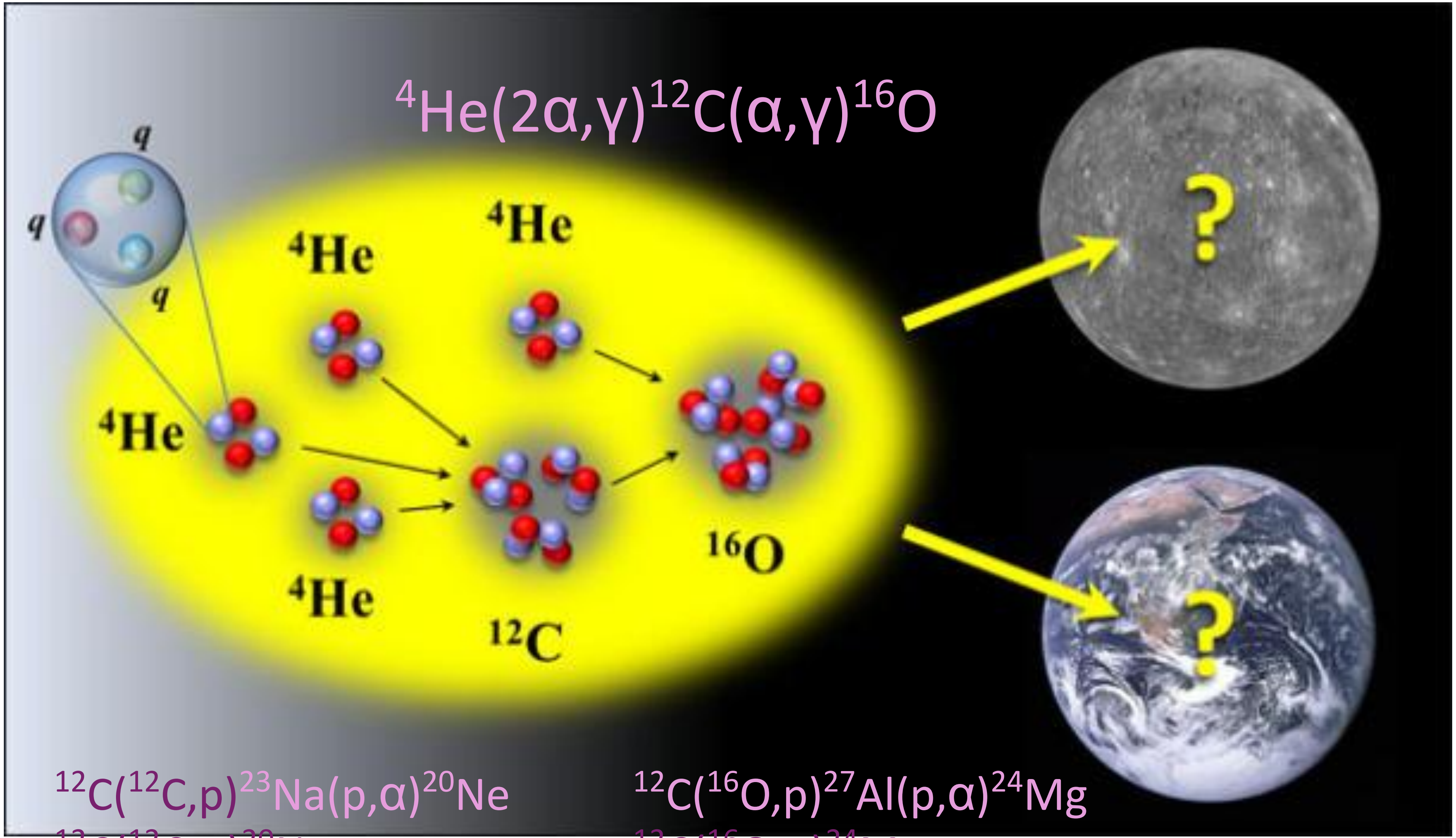
- Single step process (more likely for high density environments
- Two step sequence (handicap is short-lived ^{8}Be in equilibrium abundance)
- Unbound 0^{+} alpha-cluster state in ^{12}C (Hoyle state) saves the day since it adds a resonant component.





Structure simulations by Kanada En'yo and co-workers

Life and Death: Helium Burning: The Cosmo-Chemistry of Carbon and Oxygen



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

${}^{12}\mathrm{C}({}^{12}\mathrm{C},p){}^{23}\mathrm{Na}(p,\alpha){}^{20}\mathrm{Ne}$

${}^{12}\mathrm{C}({}^{12}\mathrm{C},\alpha){}^{20}\mathrm{Ne}$

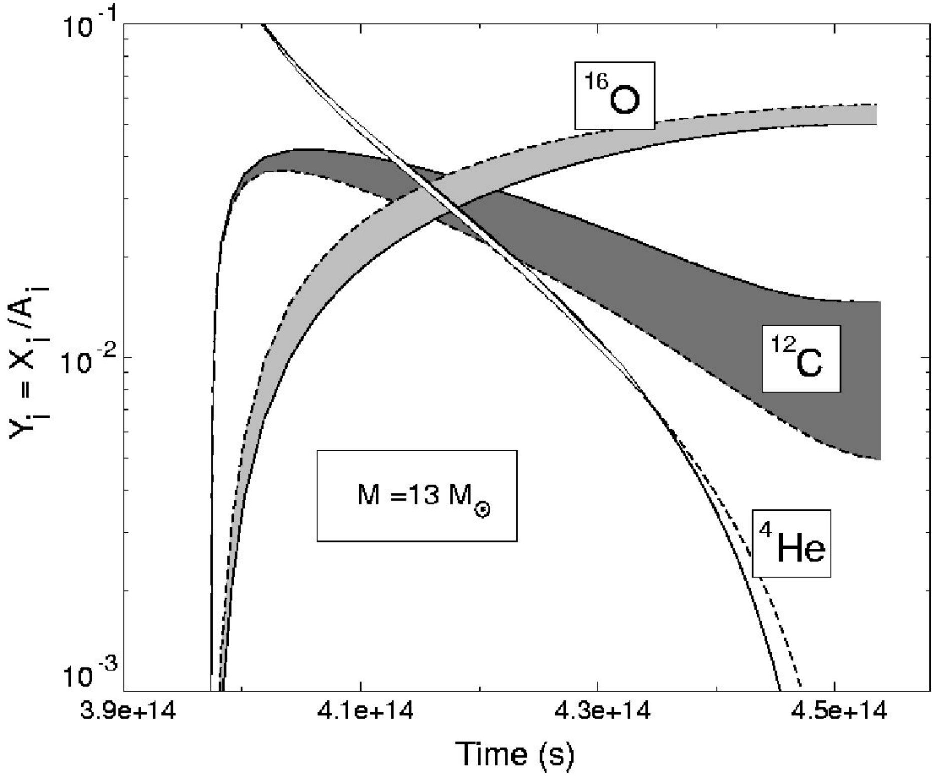
${}^{12}\mathrm{C}({}^{16}\mathrm{O},p){}^{27}\mathrm{Al}(p,\alpha){}^{24}\mathrm{Mg}$

${}^{12}\mathrm{C}({}^{16}\mathrm{O},\alpha){}^{24}\mathrm{Mg}$

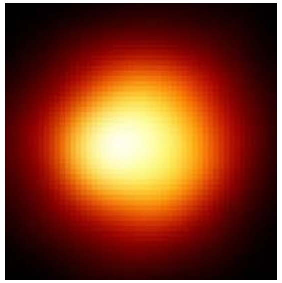
The “holy Grail”

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**

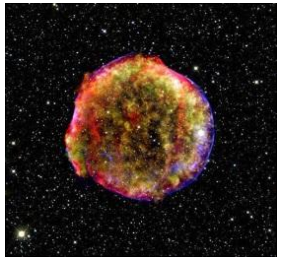
$^{12}C(\alpha,\gamma)^{16}O$ determining the early **$^{12}C/^{16}O$** ratio



- Late Stellar Evolution
determines Carbon and/or Oxygen phase

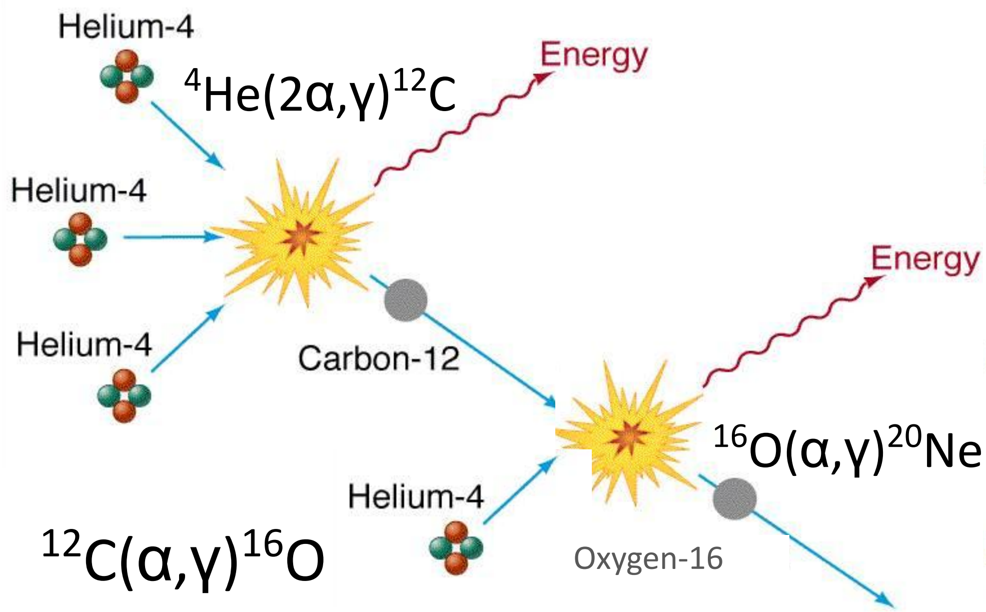


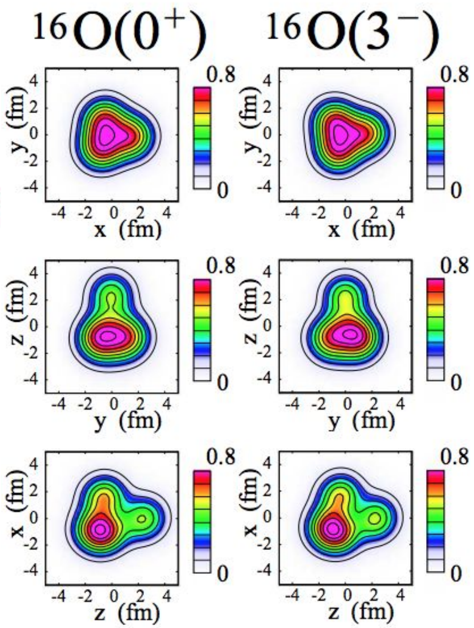
- Type Ia Supernova
central carbon burning of C/O white dwarf

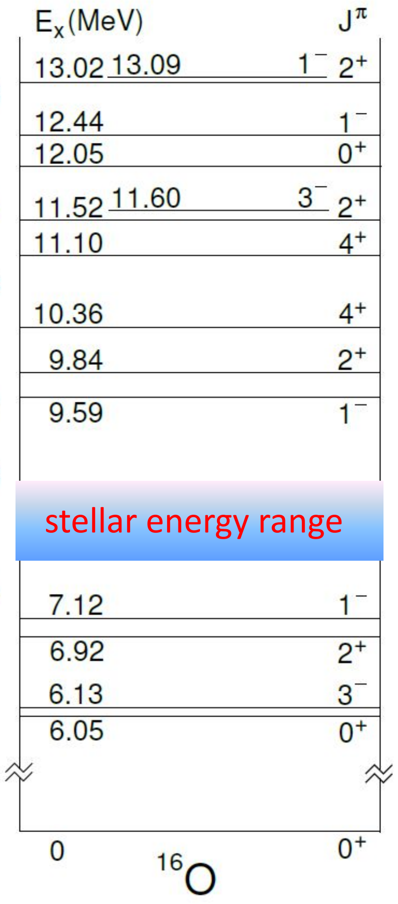


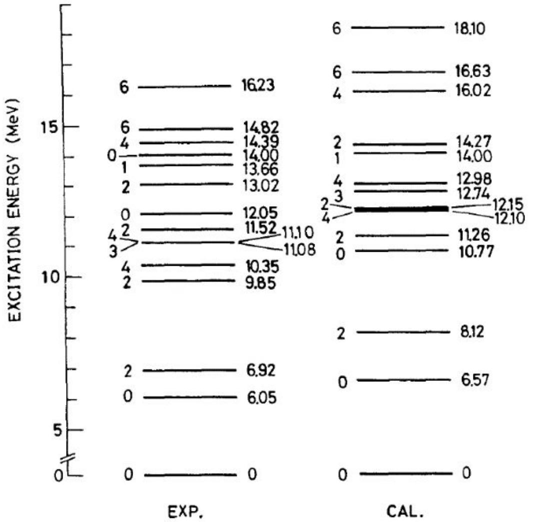
- Type II Supernova
shock-front nucleosynthesis in C and He shells of pre-supernova star

Cluster Structure of ^{16}O

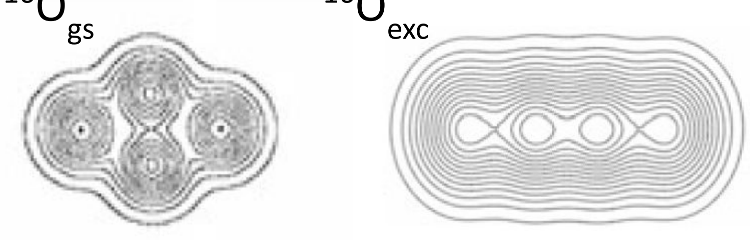






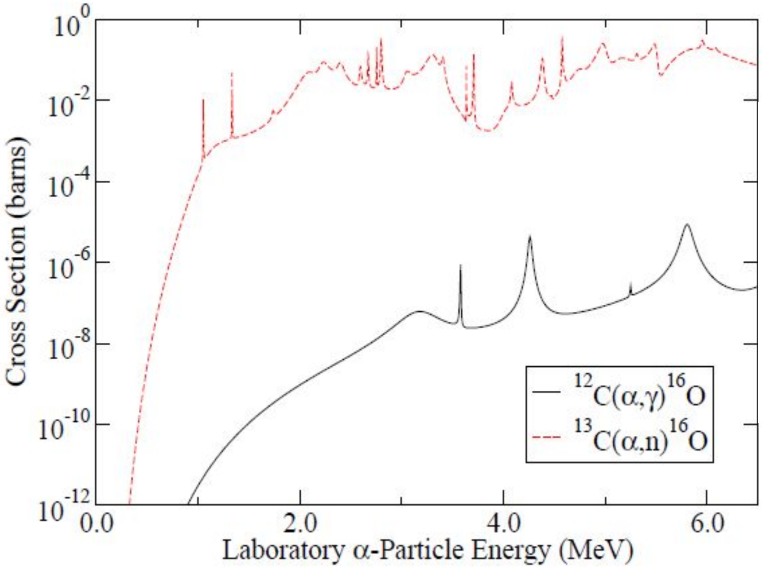


Structure simulations by Kanada En'yo et al.

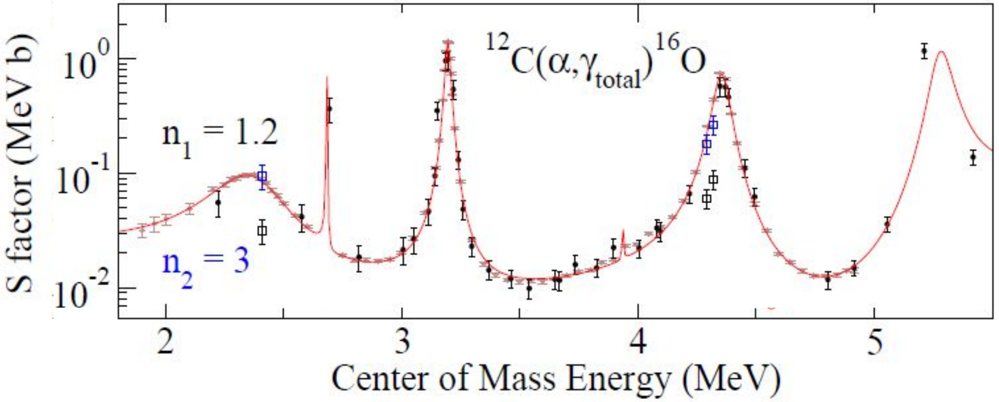


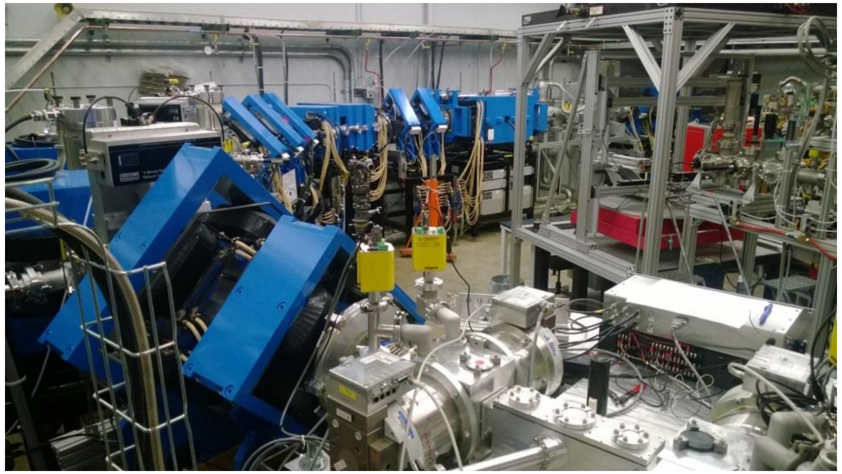
Alpha cluster structure configurations in ^{16}O

Experimental Efforts > 50 yrs

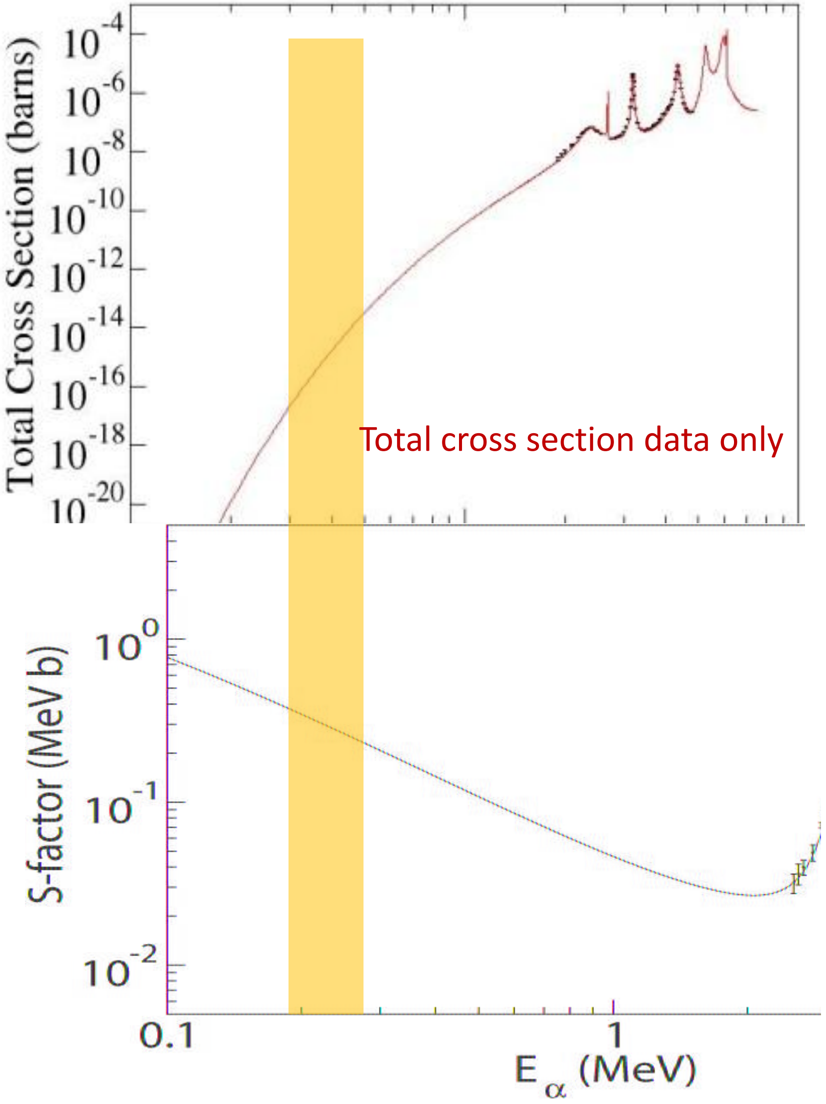


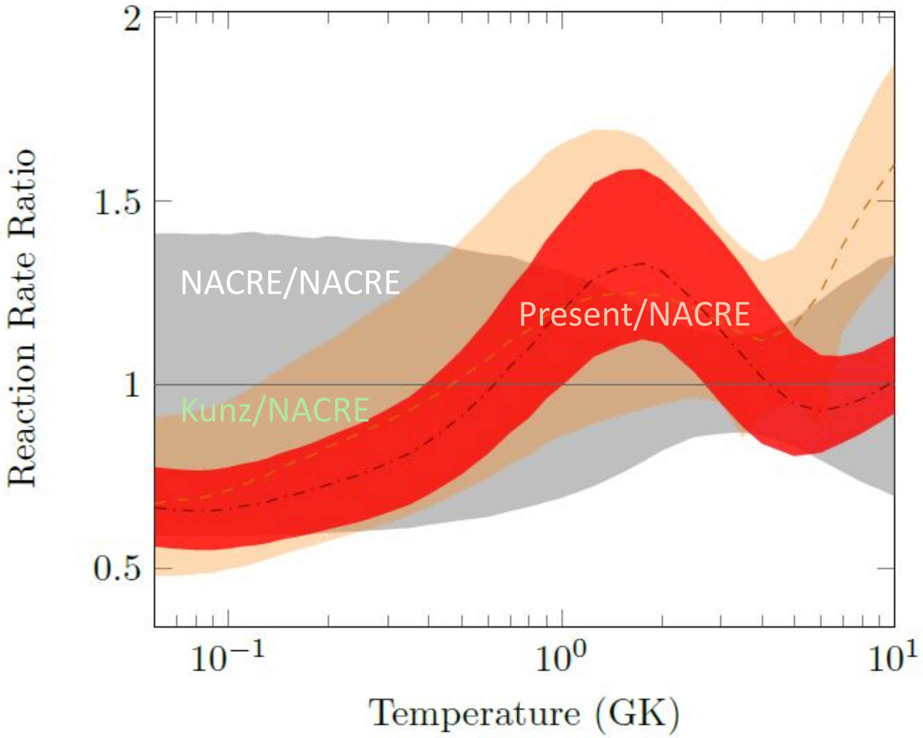
Conversion of cross section data to S-factor





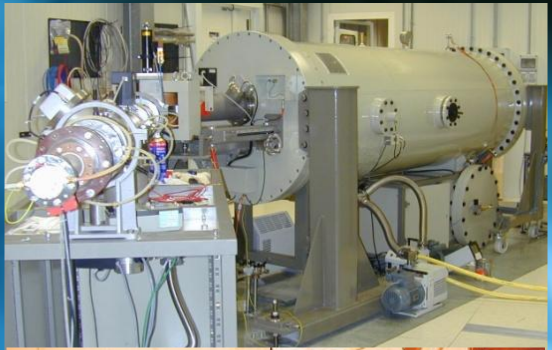
R-Matrix Analysis phenomenology, but …



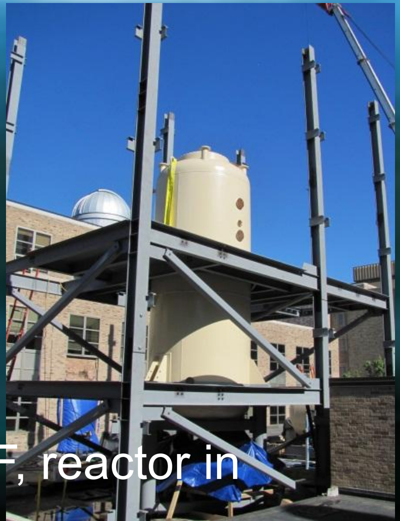


R-matrix (AZURE) based cross section extrapolation on the basis of all existing reaction data through ^{16}O compound nucleus give 15%-20% uncertainty in reaction rate extrapolation.

Experimental Techniques

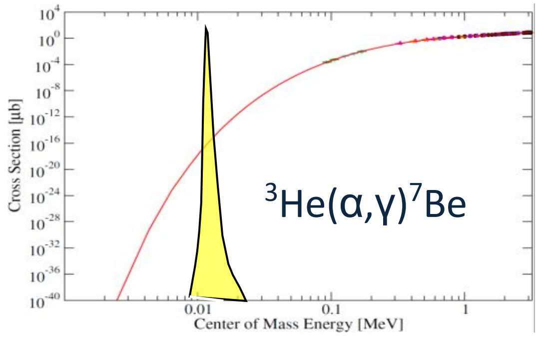


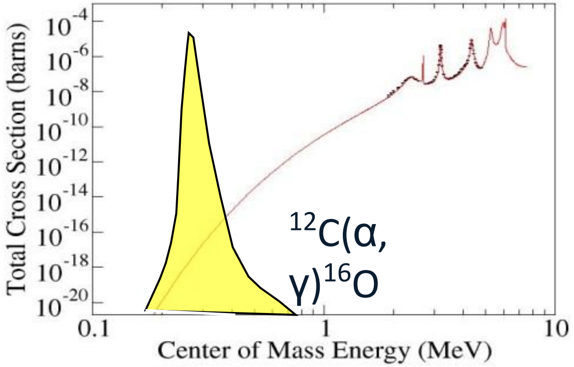
Laboratory based nucleosynthesis

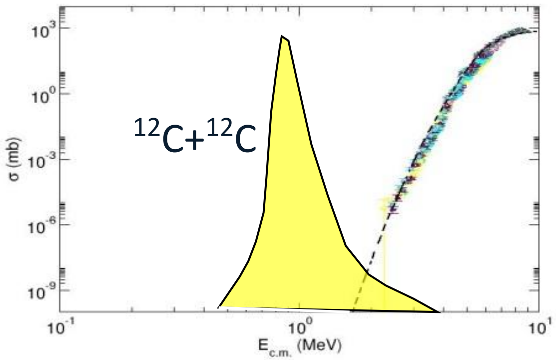


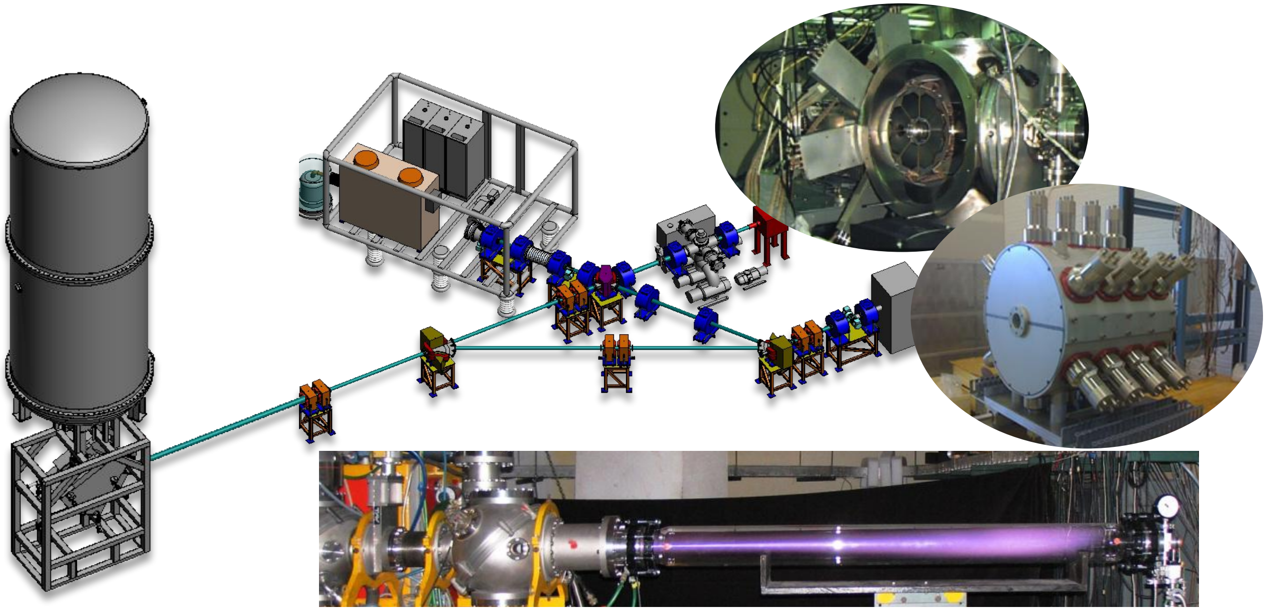
LUNA, LENA..SECAR, ND, FRIB,LANL, NTOF, reactor in Munich

Experiments with Charged Particles



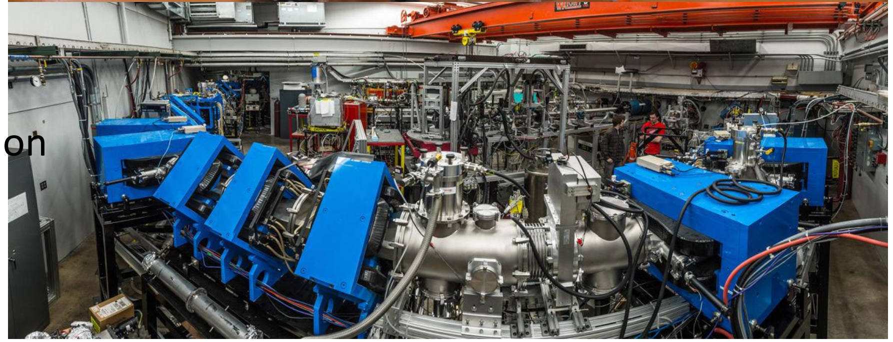




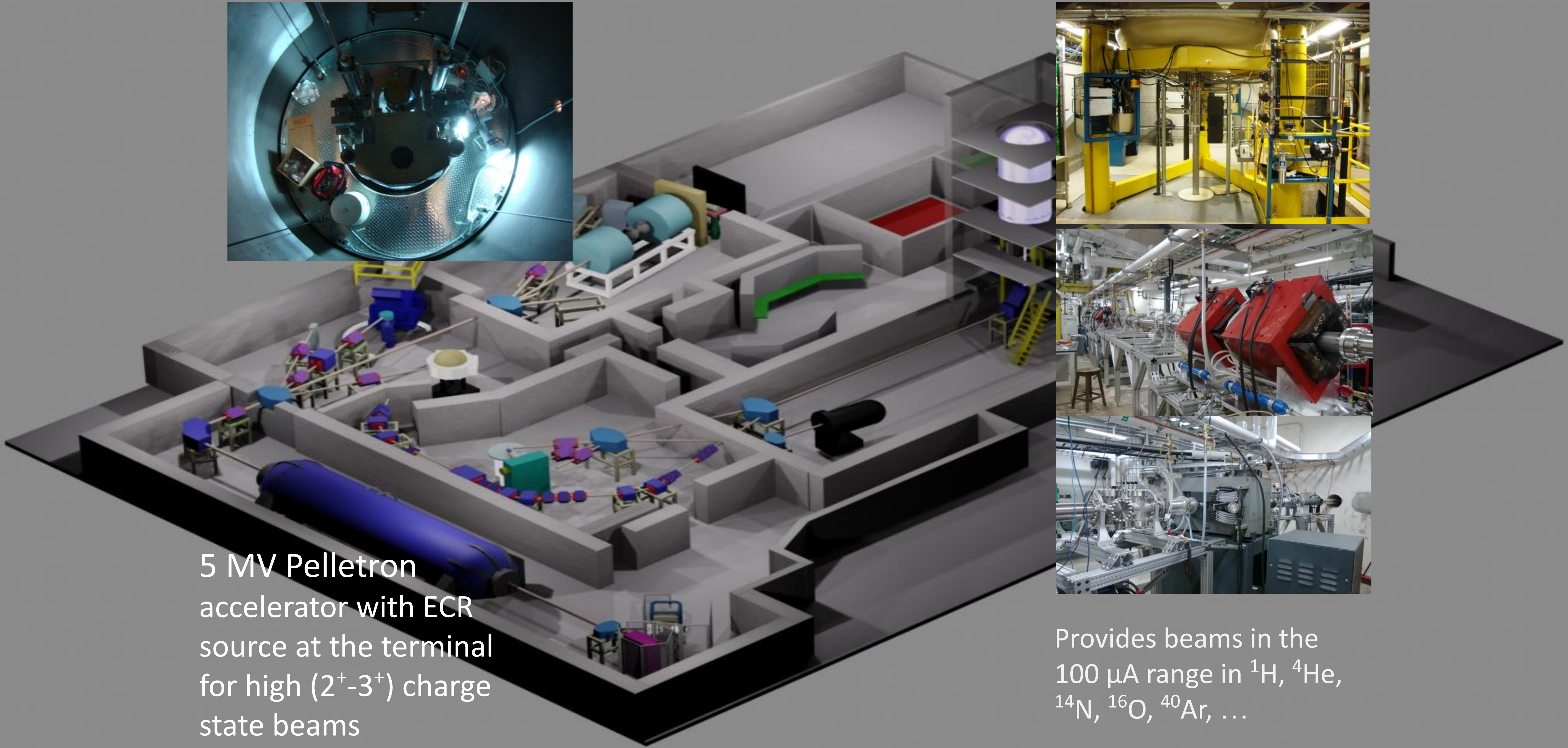


Forward kinematics underground with radiation detection

inverse kinematics with recoil separation and detection



Experimental Facilities at Notre Dame

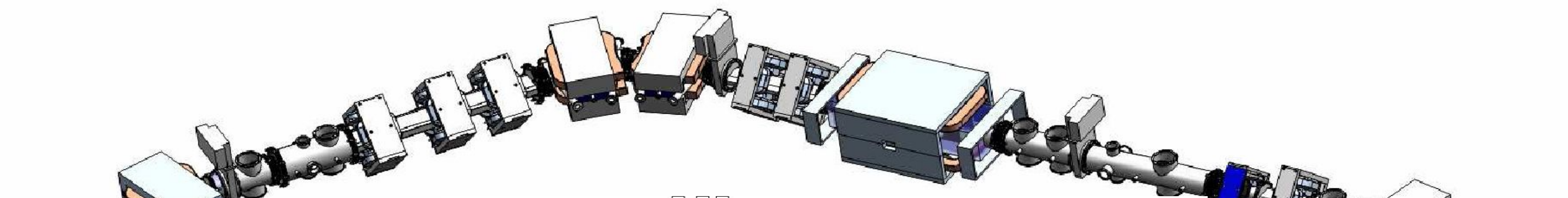


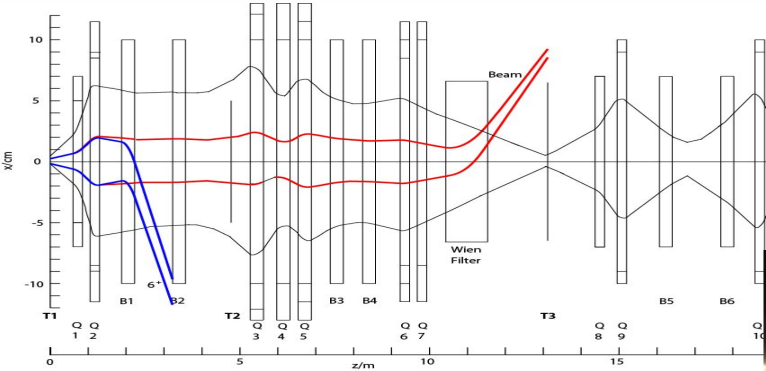
5 MV Pelletron accelerator with ECR source at the terminal for high (2^+-3^+) charge state beams

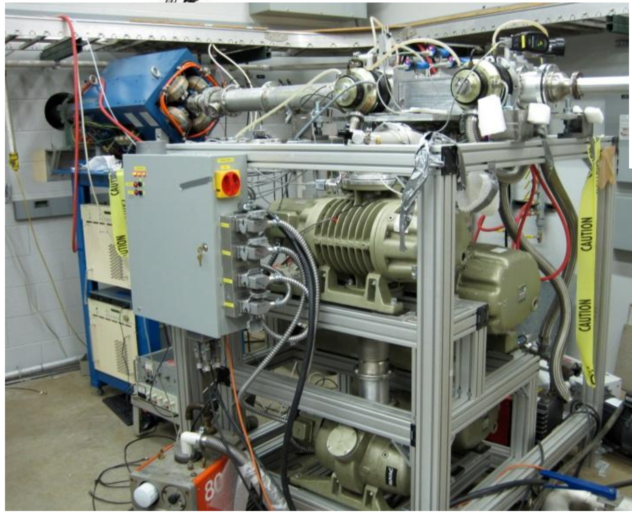
Provides beams in the 100 µA range in ^{1}H, ^{4}He, ^{14}N, ^{16}O, ^{40}Ar, …

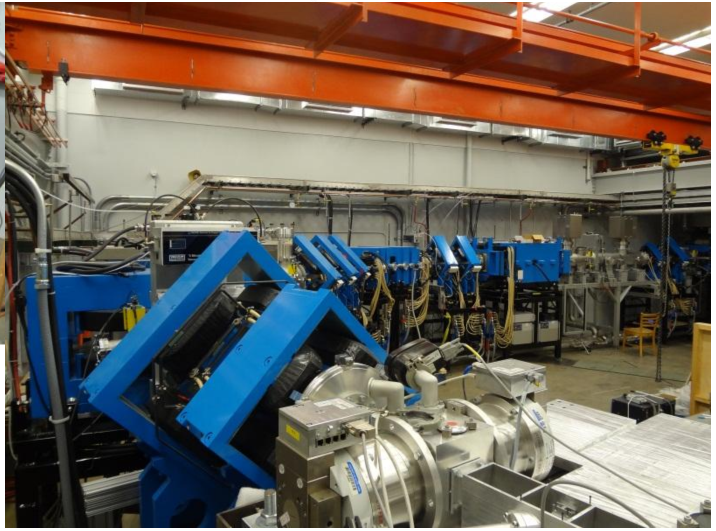
St. George Separator

Strong **G**radient **E**lectro-magnetic **O**nline **R**ecoil separator for capture **G**amma ray **E**xperiments







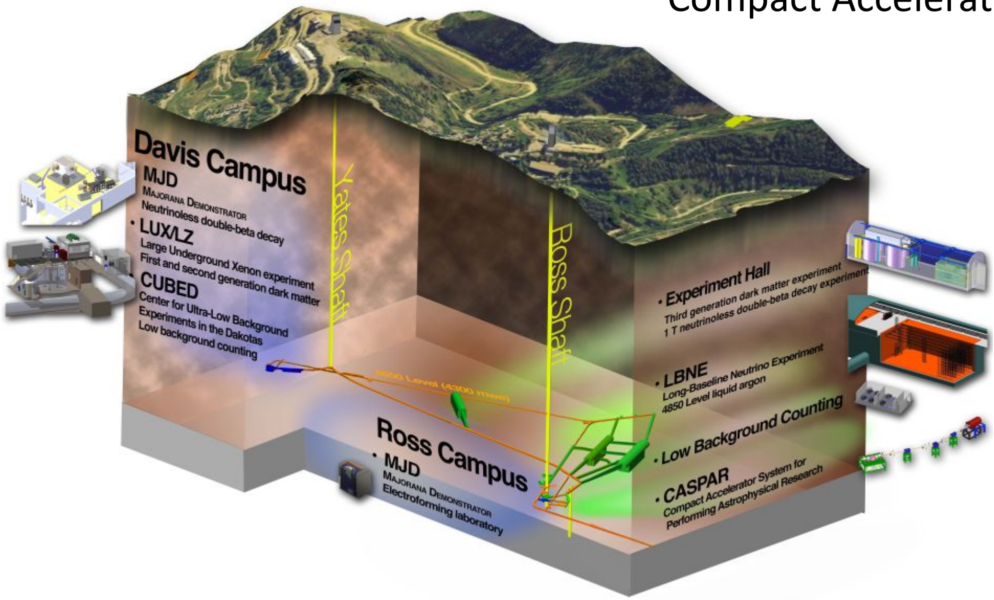


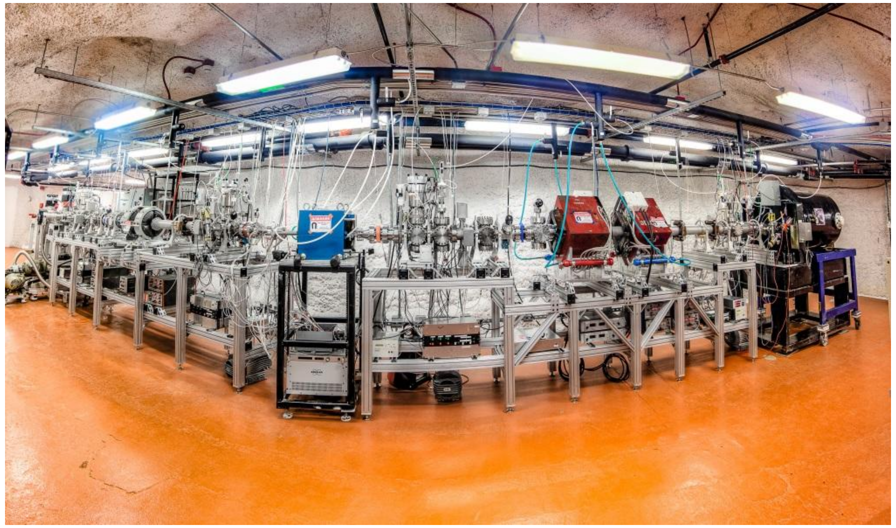
HIPPO jet gas target system
(**HI**gh **P**ressure **PO**int-like gas target)

CASPAR Facility one mile under ground

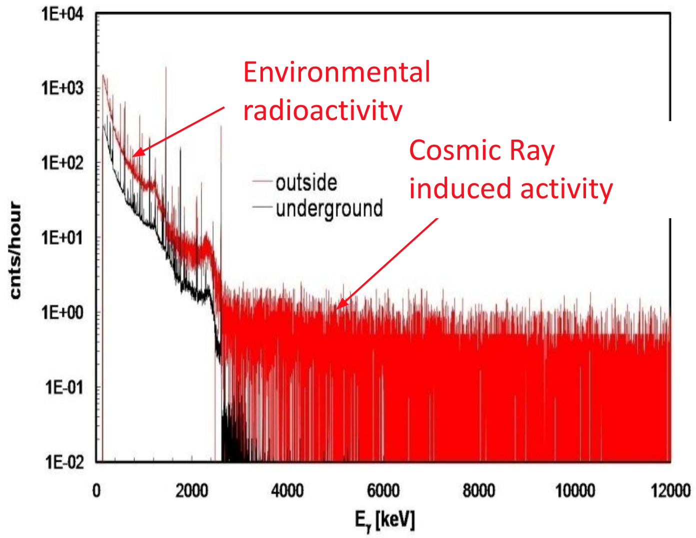
CASPAR underground accelerator

Compact Accelerator for Performing Astrophysical Research

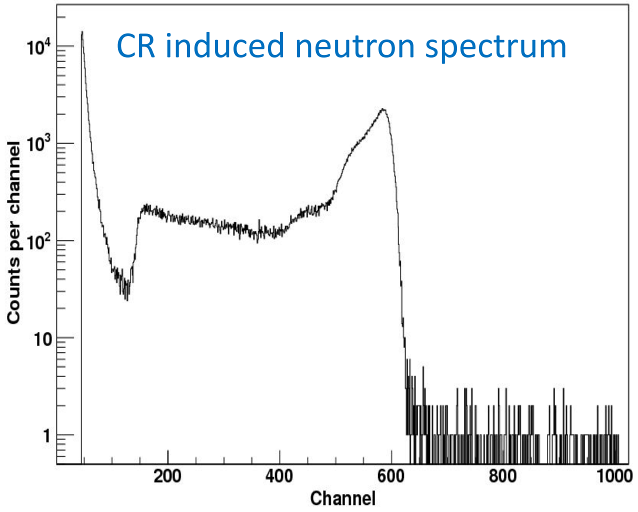


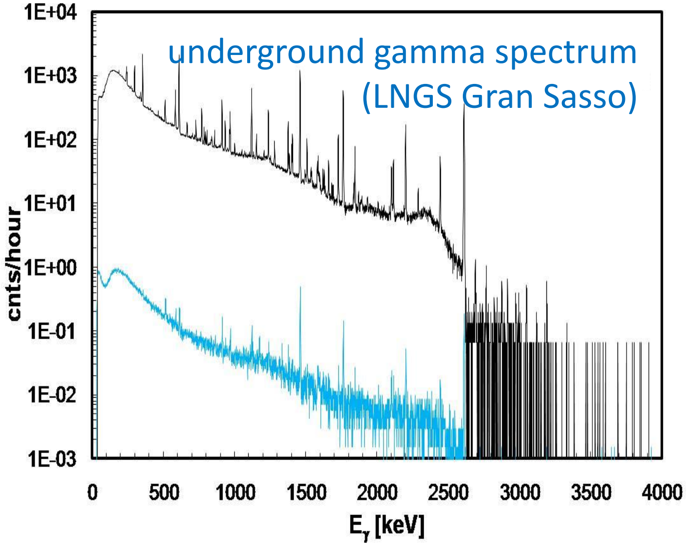


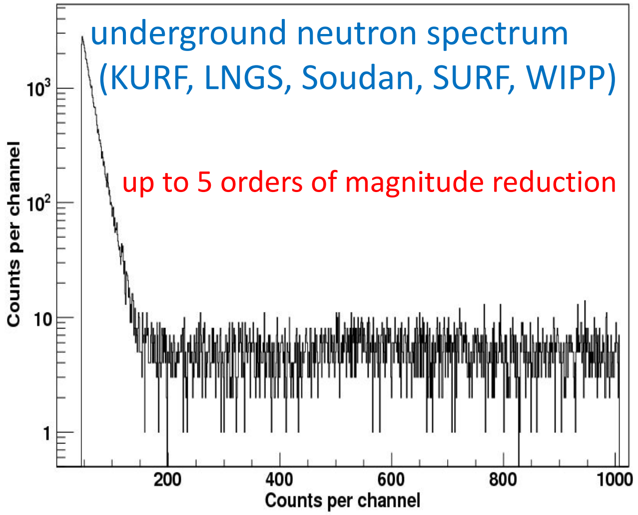
Advantage of underground physics


Environmental radioactivity

Cosmic Ray induced activity

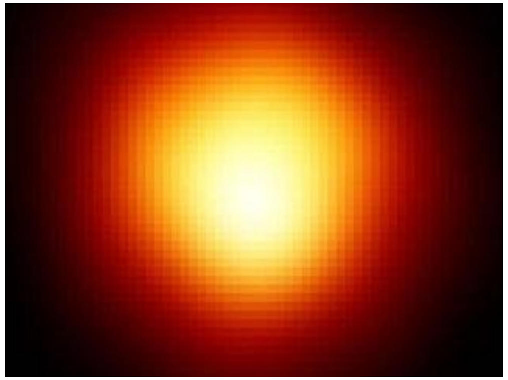

CR induced neutron spectrum


underground gamma spectrum (LNGS Gran Sasso)


underground neutron spectrum (KURF, LNGS, Soudan, SURF, WIPP)

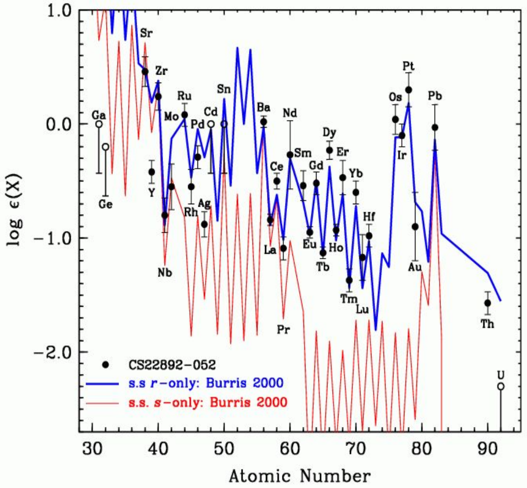
up to 5 orders of magnitude reduction

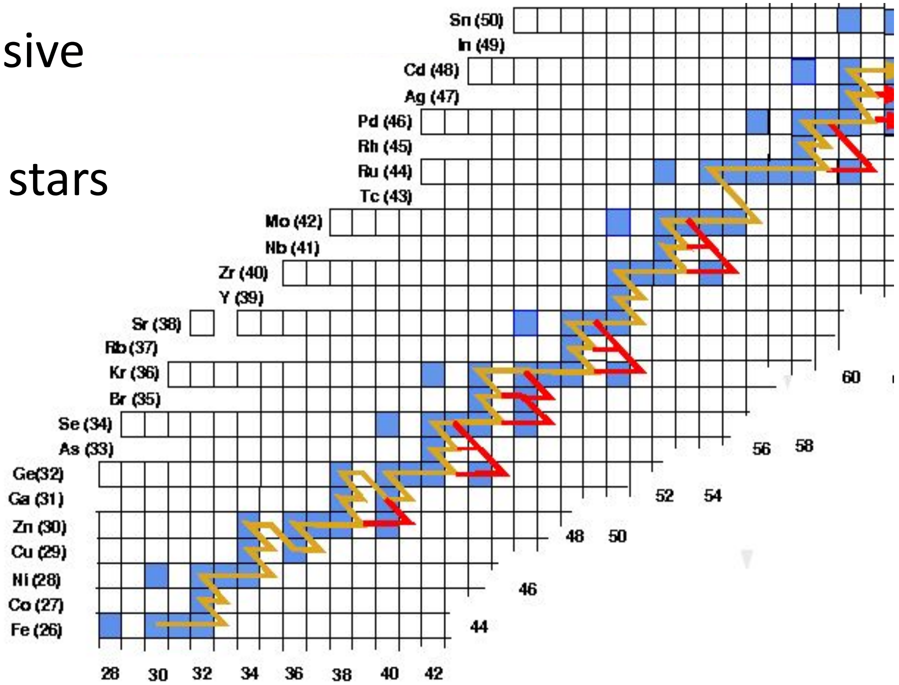
s-process and the origin of heavy elements



Weak s-process in massive stars

Main s-process in AGB stars



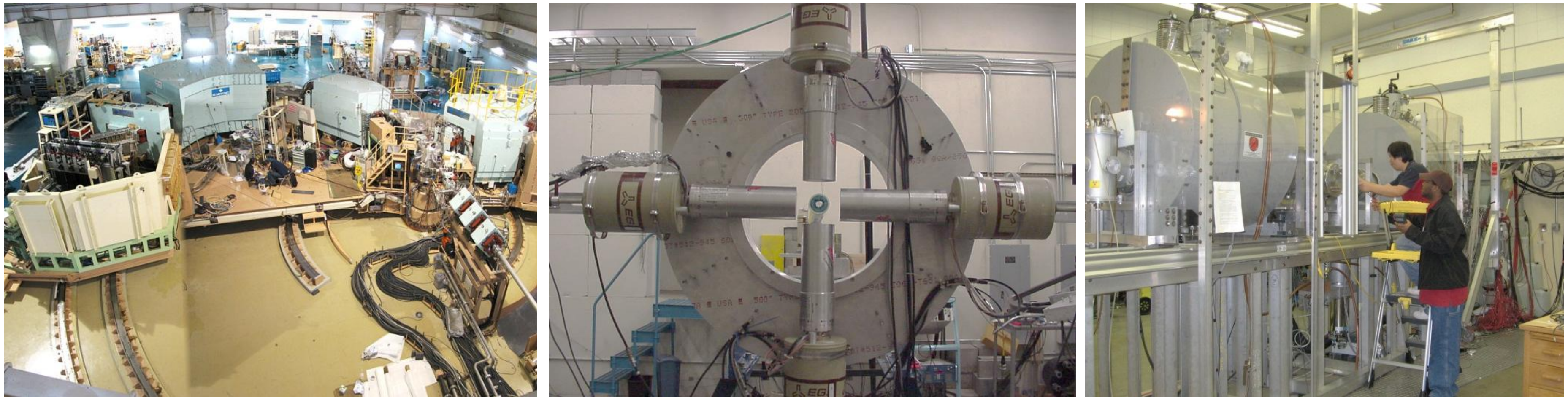


Open questions:

1. neutron sources $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$ …
2. branching points and n-capture on long-lived isotopes
3. n-capture on thermally excited and isomeric states
4. impact on p-process (seed) and r-process (yield) abundances

Indirect techniques to probe low energy nuclear structure and reaction features

Reaction rates are nuclear physics! Nuclear structure and reaction theory is necessary for providing guidance and setting limits!



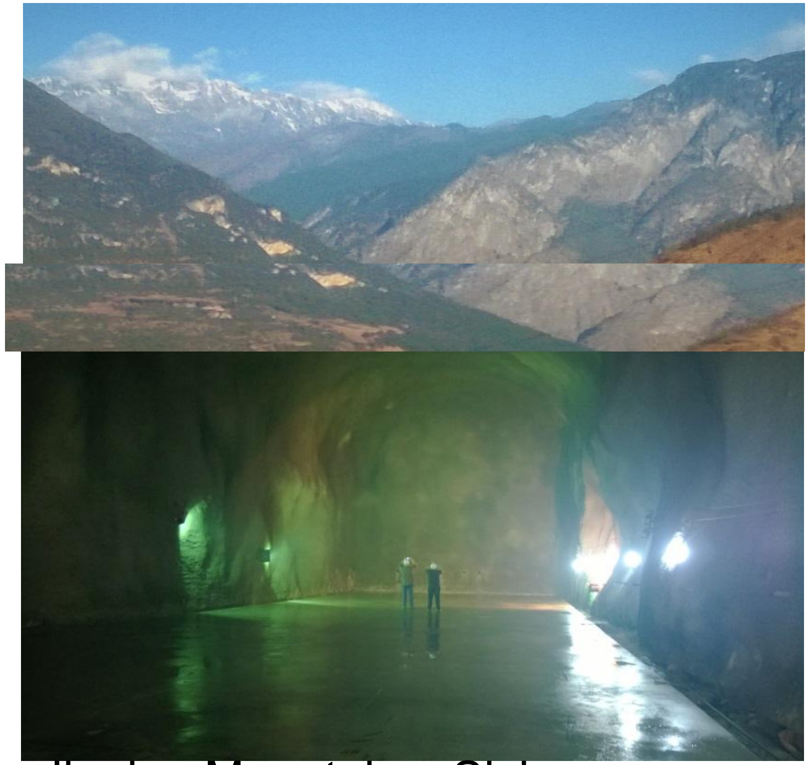
Single particle or alpha transfer are used as surrogates, THM/ANC methods, alpha scattering, lifetime measurements, Coulomb dissociation studies, all provide a scale for low energy extrapolation! Yet, direct measurements close to the stellar energy range are the ultimate goal!

Two Ways towards improved Experiments for stellar Helium Burning

Background reduction by moving to cosmic ray free underground environments (LUNA, JUNA, CASPAR) or to inverse kinematics techniques with recoil separators (DRAGON, St. GEORGE, ERNA)

Light ion on heavy target measuring light reaction product yield in reduced background environment, limited by detection efficiency.

Heavy ion on light target measuring ion recoil yield, limited by initial beam intensity and acceptance of recoil separator

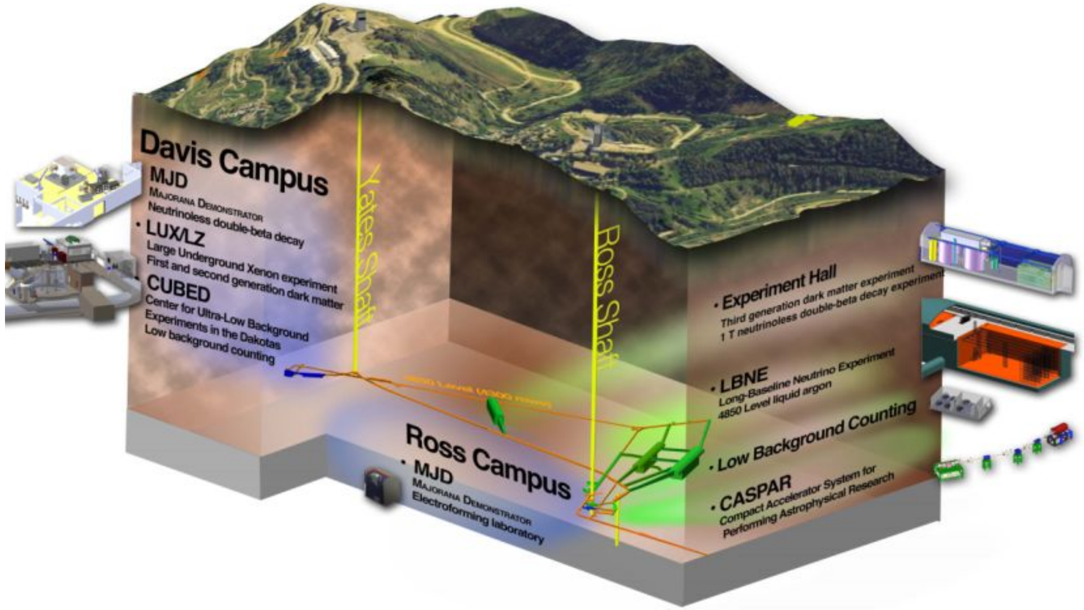


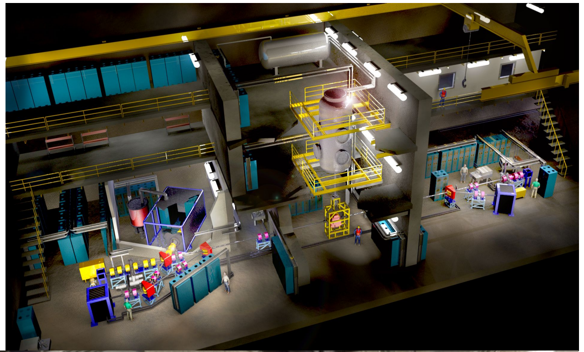
Jinping Mountains: Sichuan

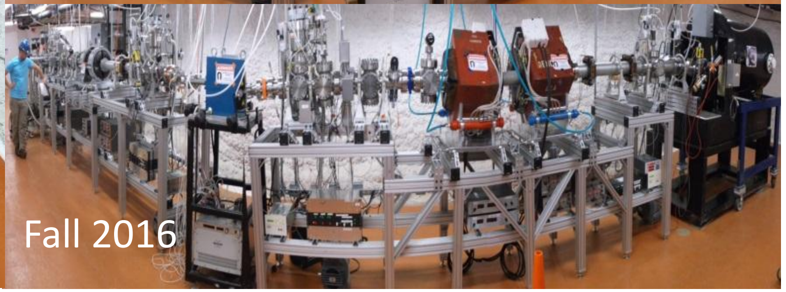
The CASPAR Underground Accelerator,

DIANA project on hold; DIANA demonstrator project being initiated with NSF, ND, CSM, SDSM&T & SURF funding

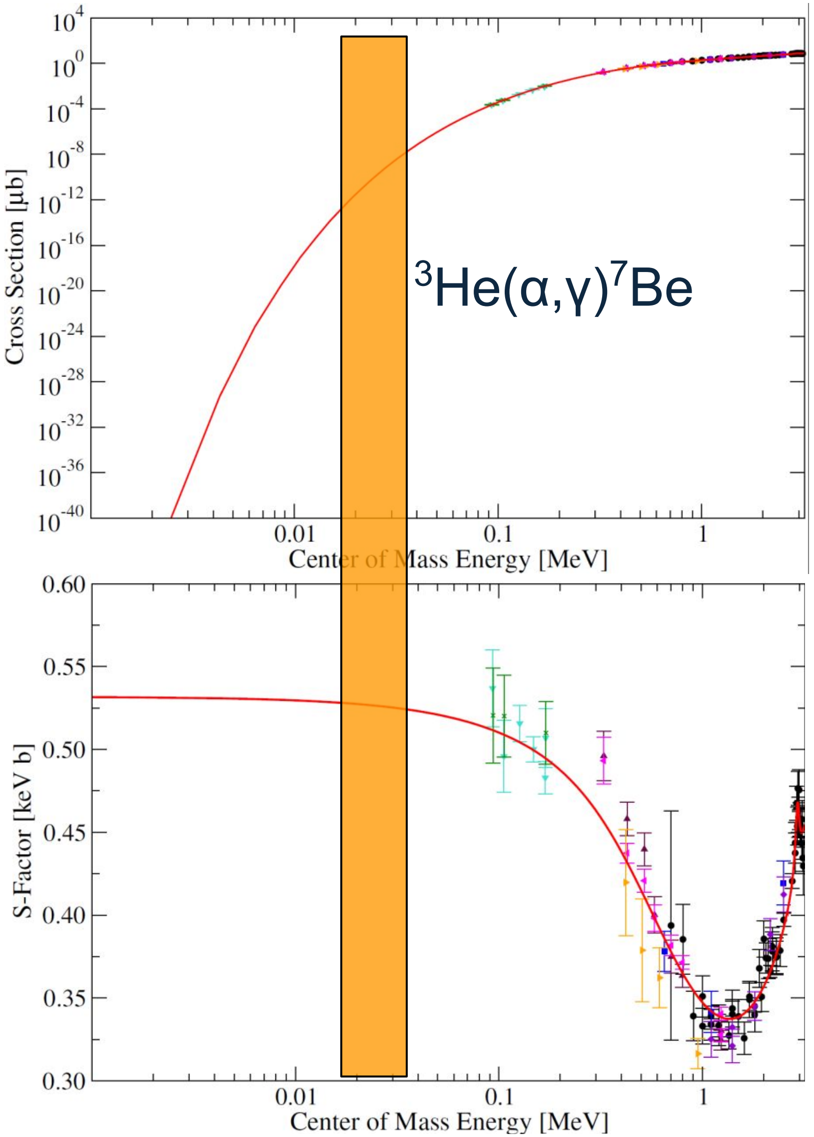
CASPAR (**C**ompact **A**ccelerator **S**ystem for **P**erforming **A**strophysical **R**esearch)

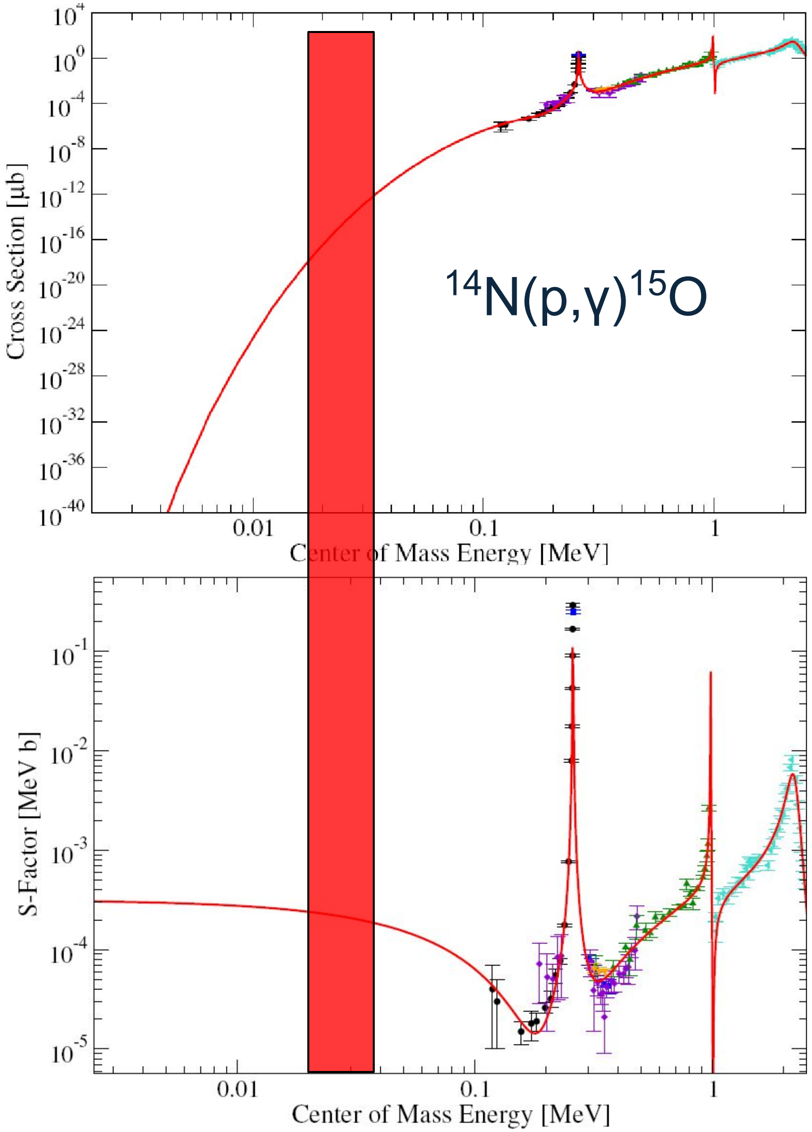






The two most critical rates

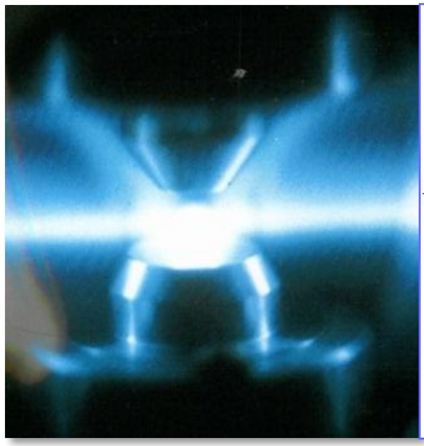


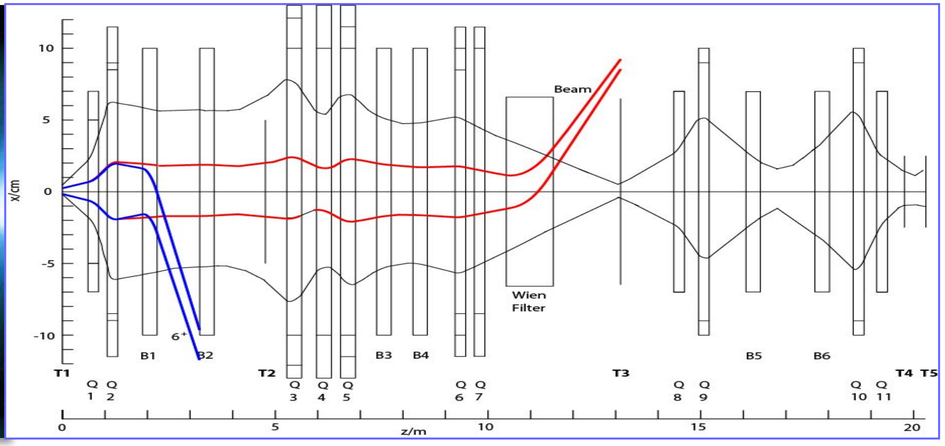


Summary of H and He burning…

- Improvements in astronomical and cosmo-chemical observation techniques drive field
- **Nuclear reaction rates** remain a dominant uncertainty for reliable model predictions
- Cluster structure configurations dictate helium burning reaction strength
- Alternative indirect experimental techniques from ANC to THM measurements should be utilized.
- New experimental initiatives using either recoil techniques or background free deep underground facilities open new opportunities

Counting with Separators





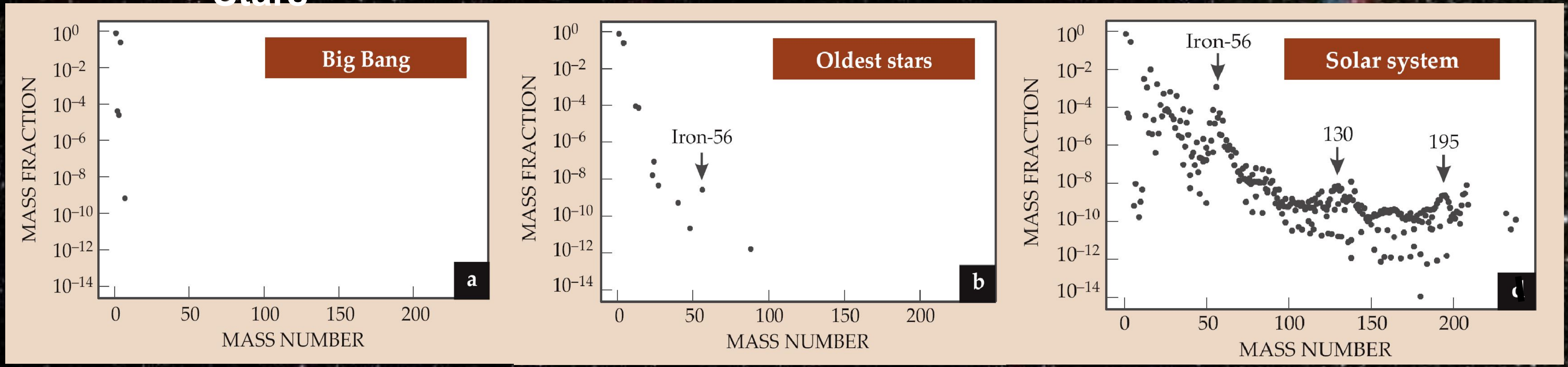
Separation ratio of reaction products to primary beam 10^{-18} !

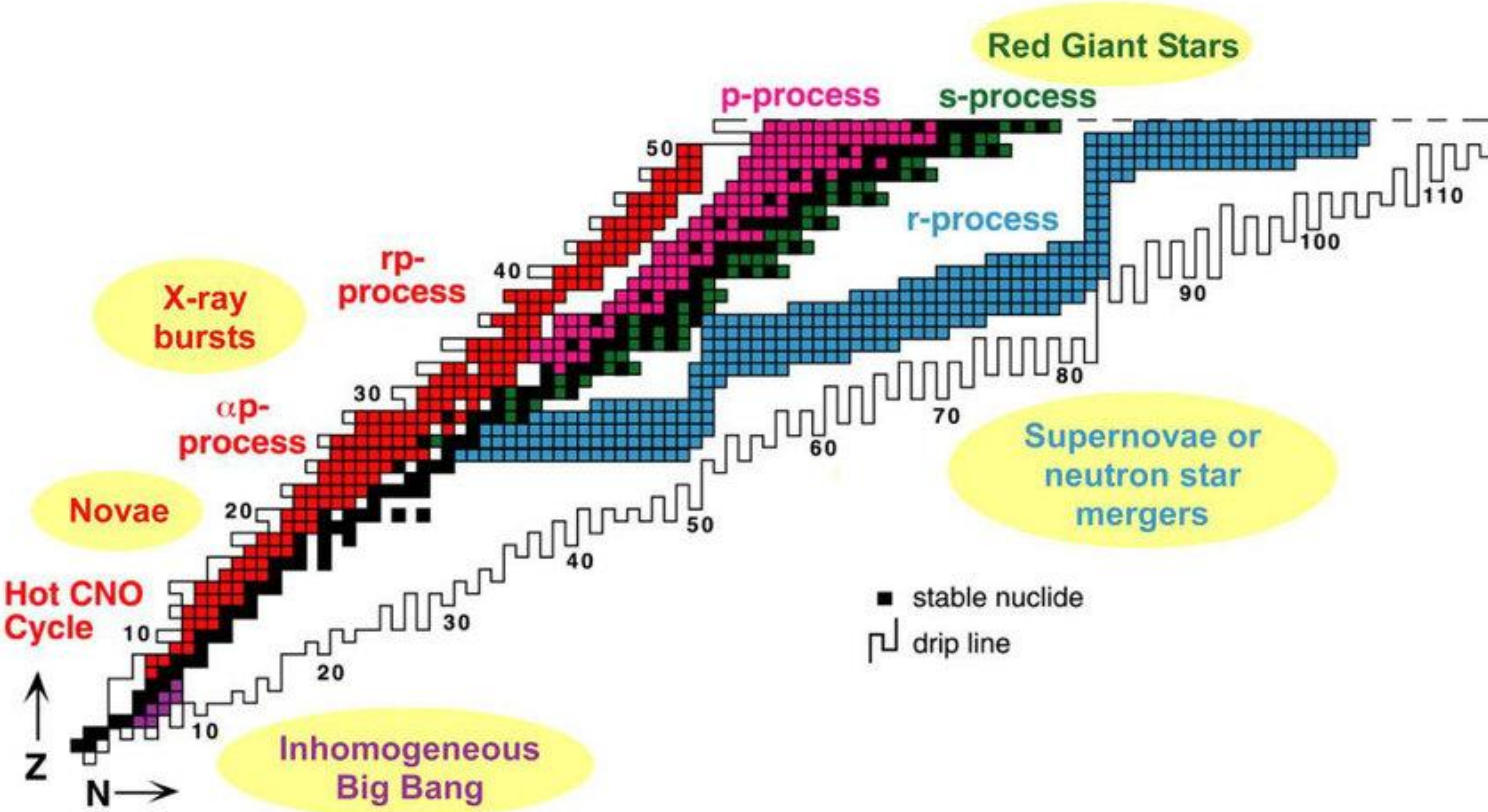
Strong **G**radient **E**lectro-magnetic **O**nline **R**ecoil separator for capture **G**amma ray **E**xperiments

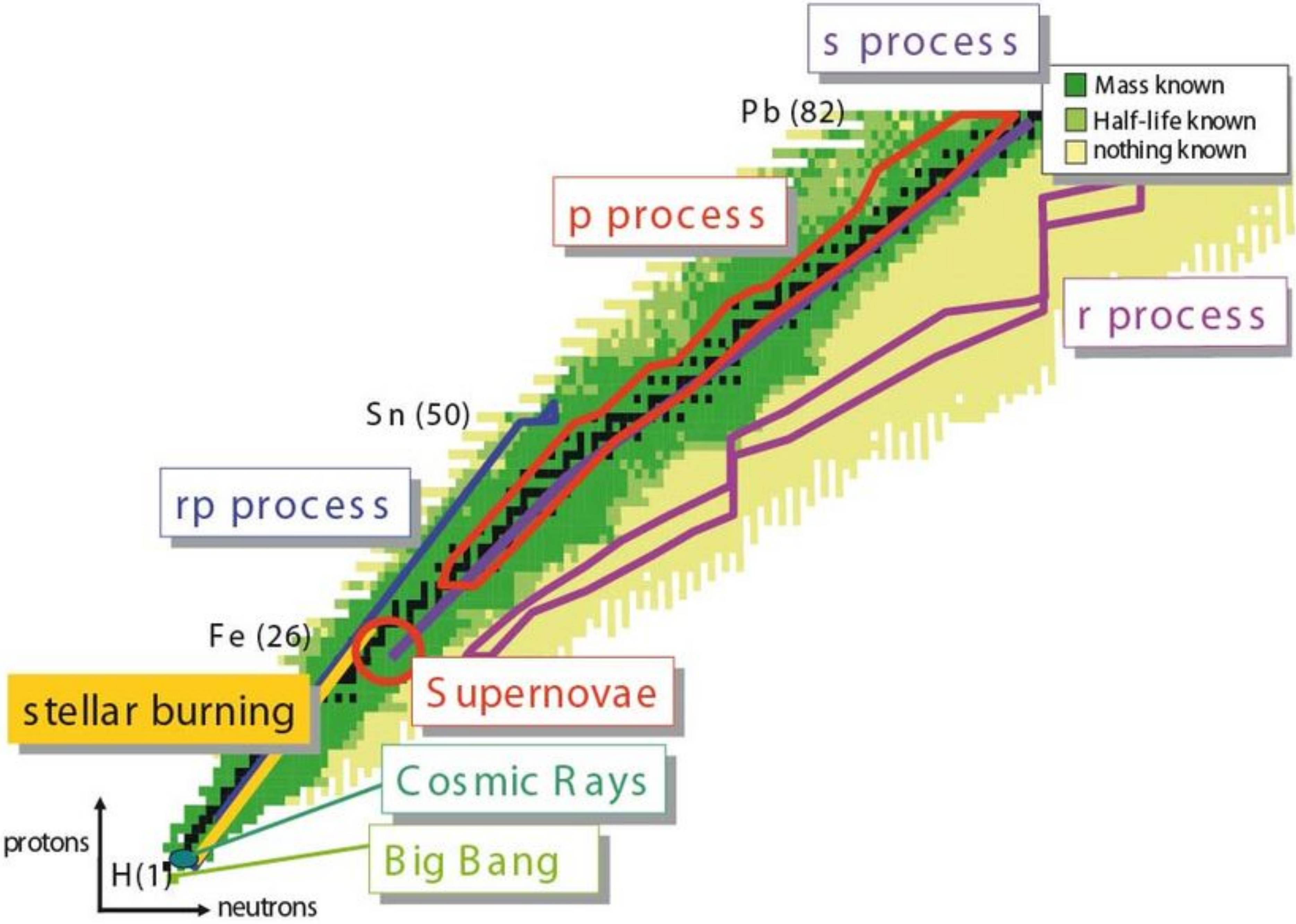
Neutron Sources in Stars

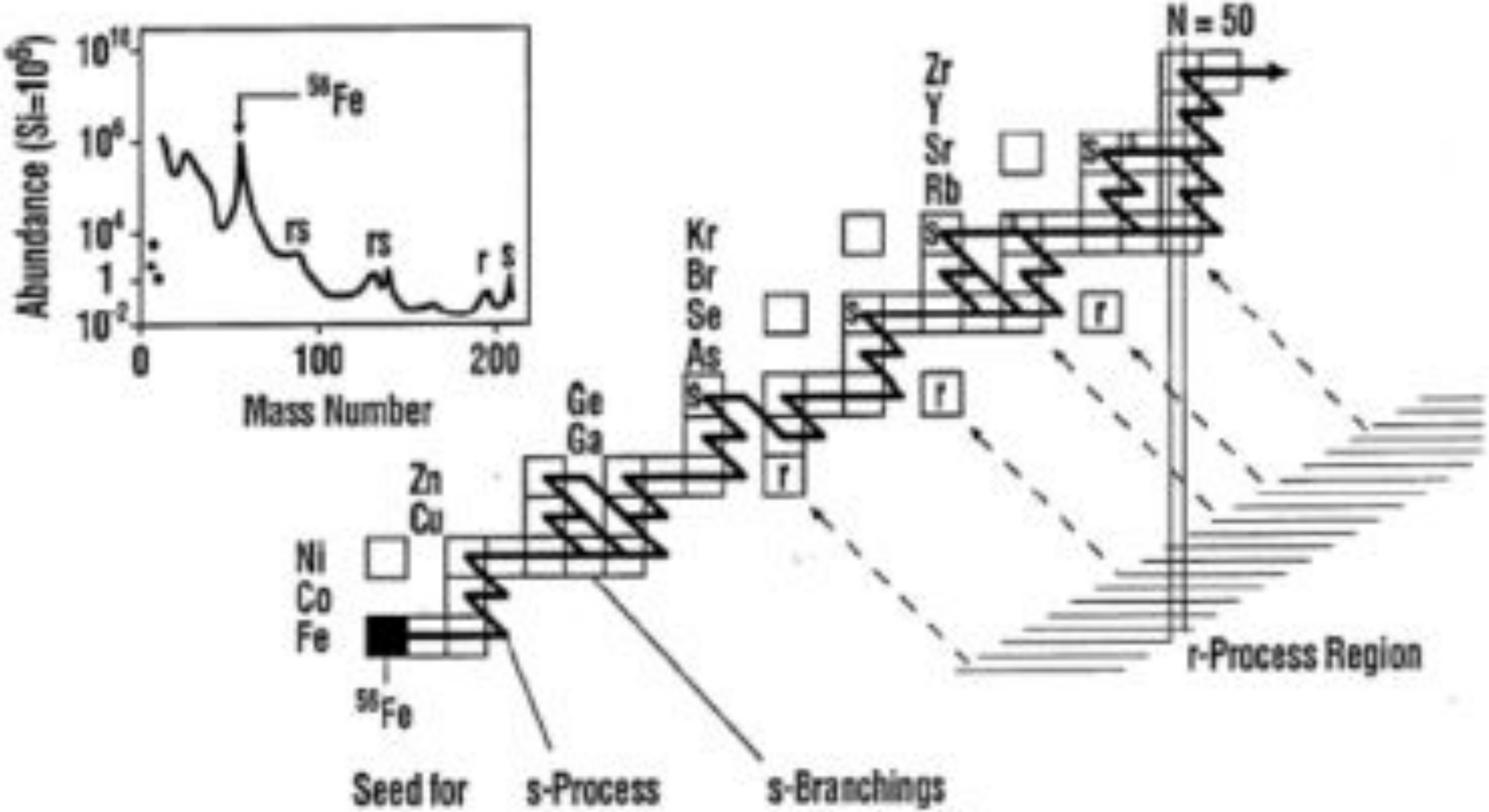
Galactic Chemical Evolution

First Stars




Red Giant Stars
p-process
s-process
r-process
rp-
process
X-ray
bursts
αp-
process
Novae
Hot CNO
Cycle
Inhomogeneous
Big Bang
Supernovae or
neutron star
mergers
■ stable nuclide
drip line
Z
N
10
20
30
40
50
10
20
30
40
50
60
70
80
90
100
110


s process
Mass known
Half-life known
nothing known
Pb (82)
p process
r process
Sn (50)
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
Big Bang
protons
H(1)
neutrons


Abundance (Si=10^6)
10^10
10^6
10^4
1
10^-2
0
100
200
Mass Number
56Fe
rs
rs
r
s
N = 50
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
s
s
s
s
r
r
r
56Fe
r-Process Region
Seed for
s-Process
s-Branchings

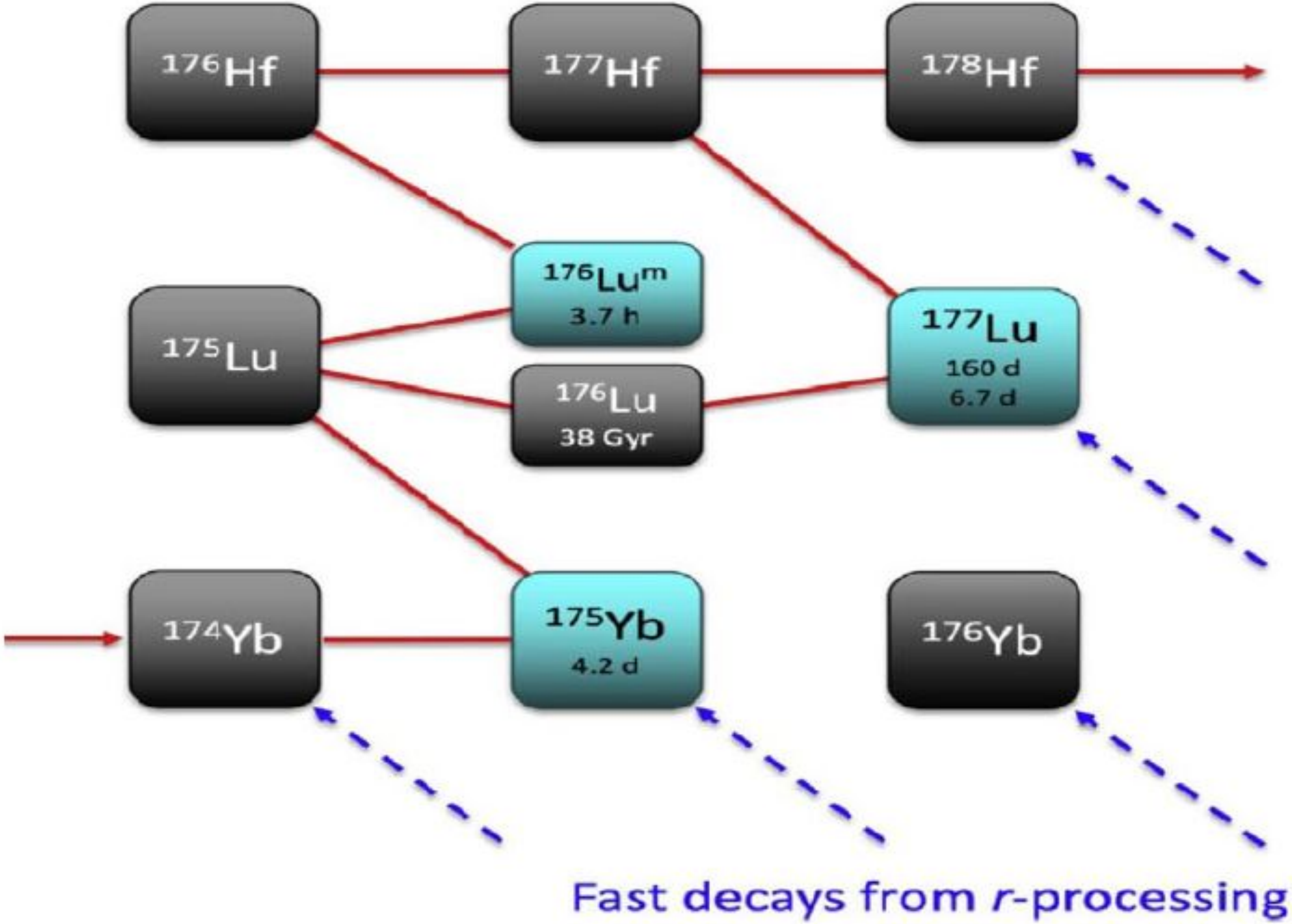
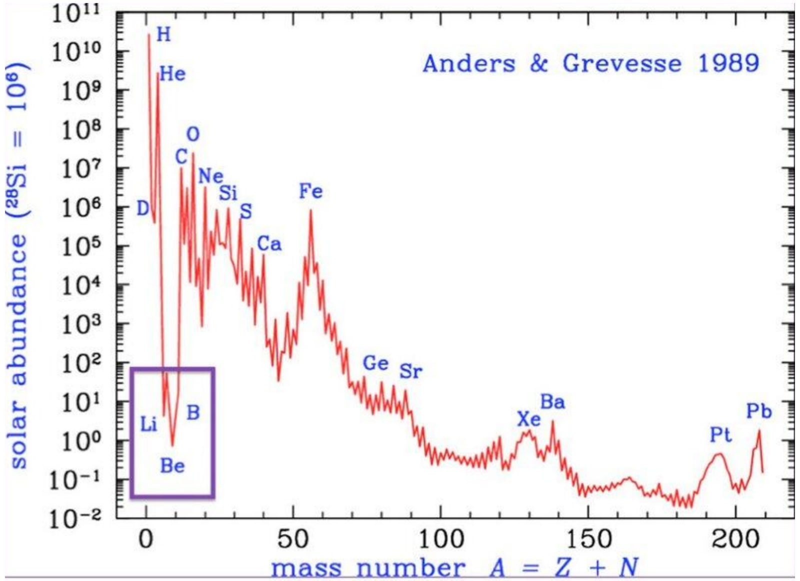
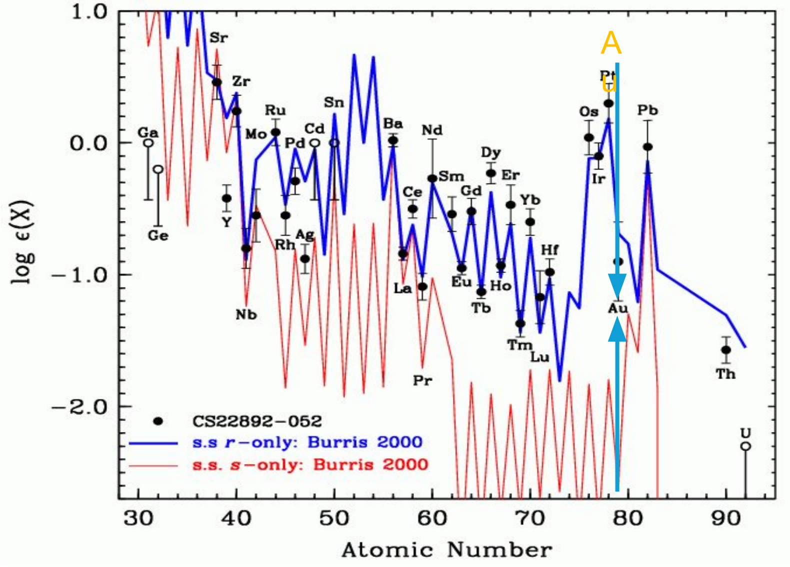
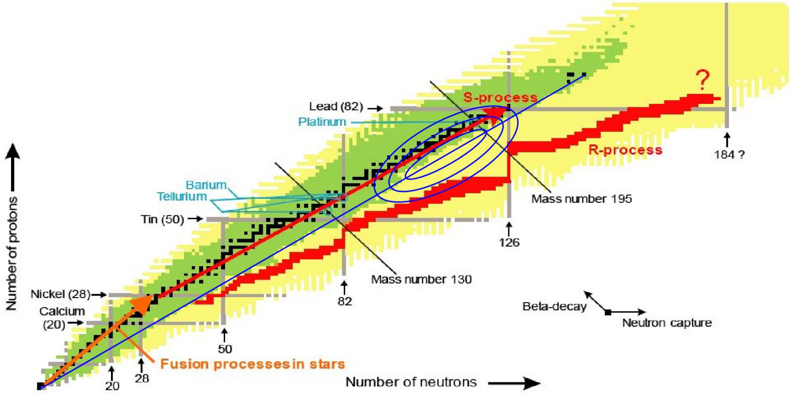


Fig. 4 The branching of ^{176}Lu and ^{176}Hf from Ref [23].

The observation and origin of heavy elements



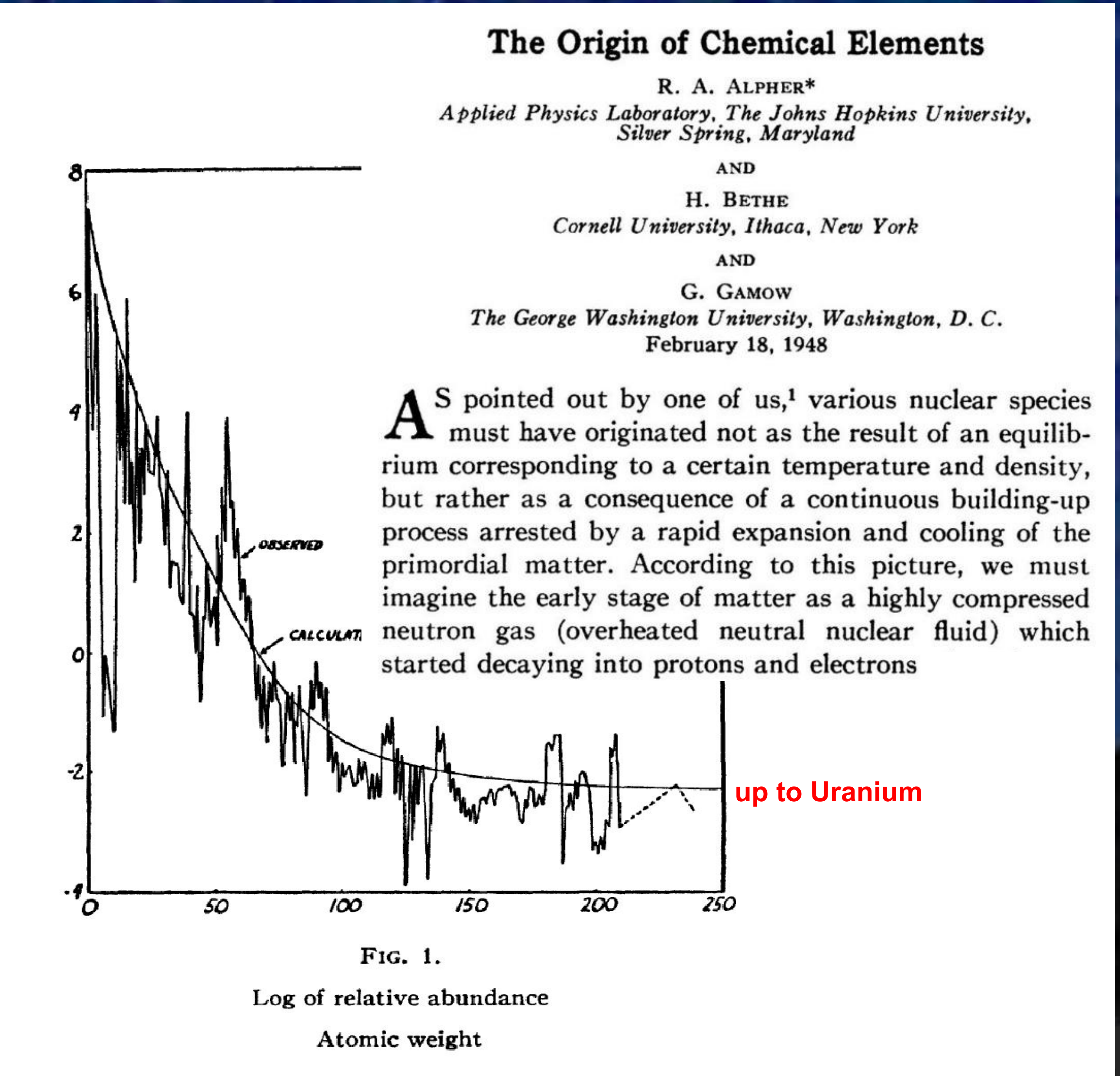




Early Ideas

- Neutron Sources in Hydrogen Burning Stars
- The αβγ-Process in the Primeval Atom
- Bridging the Gap?

The first idea of instantaneous origin



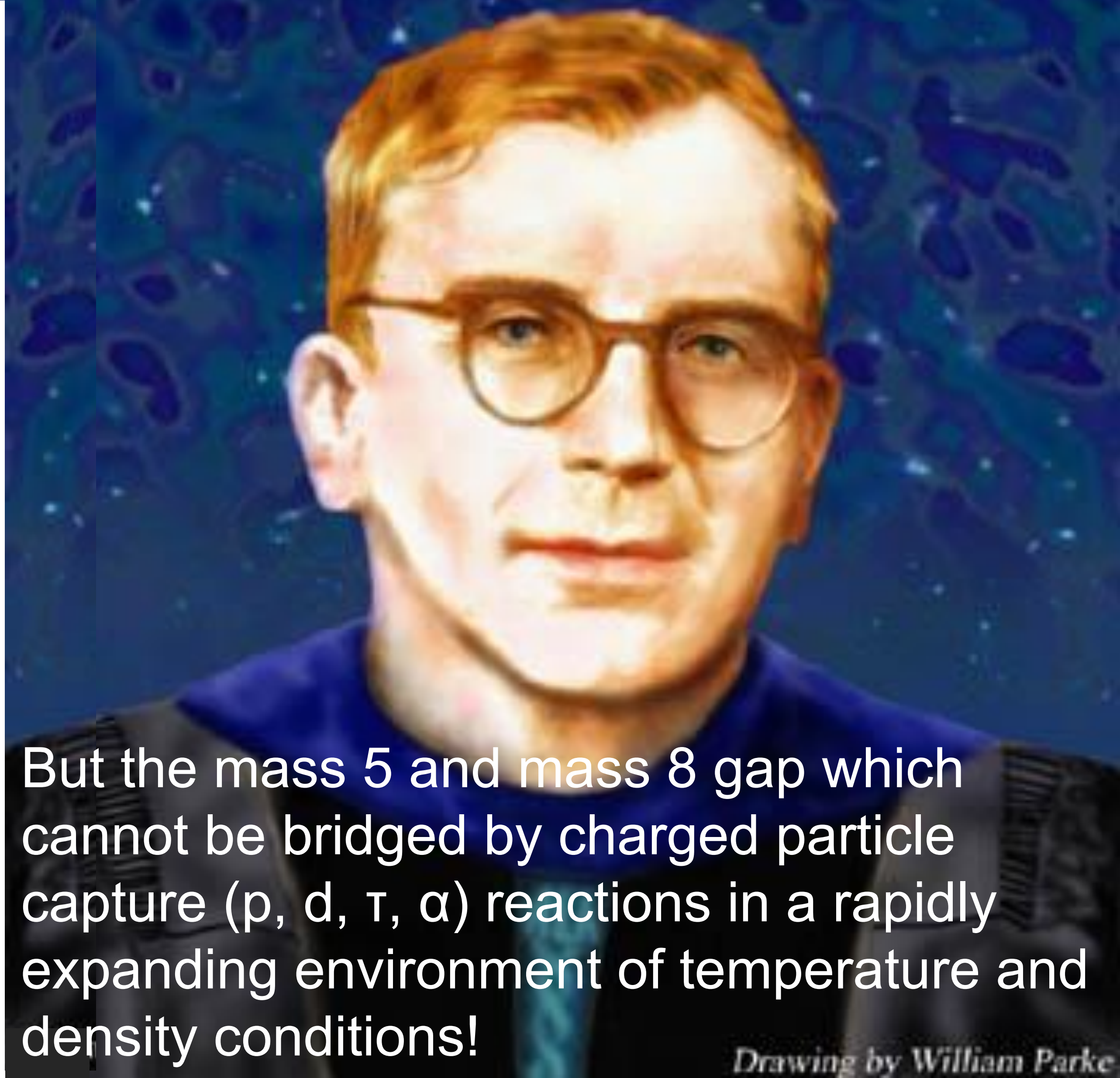
The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
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

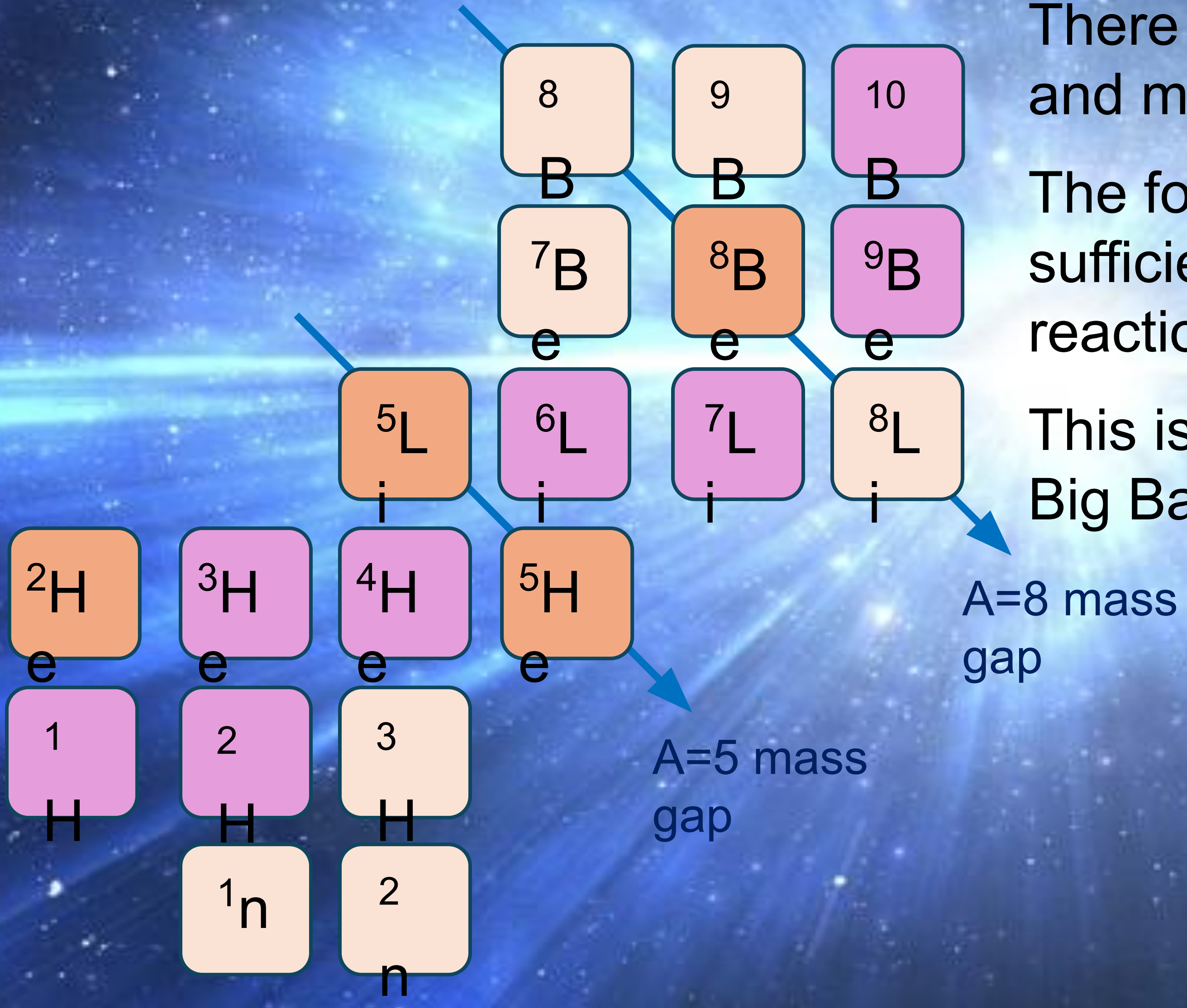
Fig. 1.
Log of relative abundance
Atomic weight



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

Drawing by William Parke

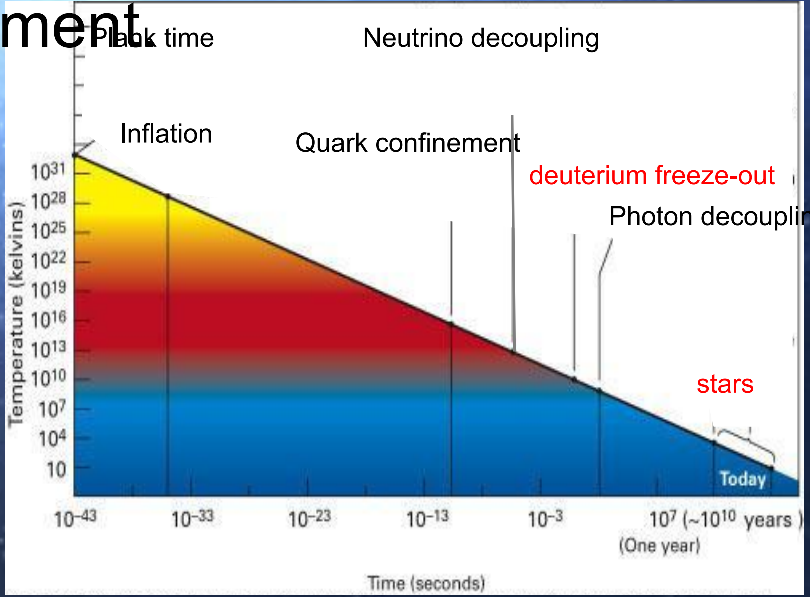
The Mass A=5 and A=8 Mass Gap



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!

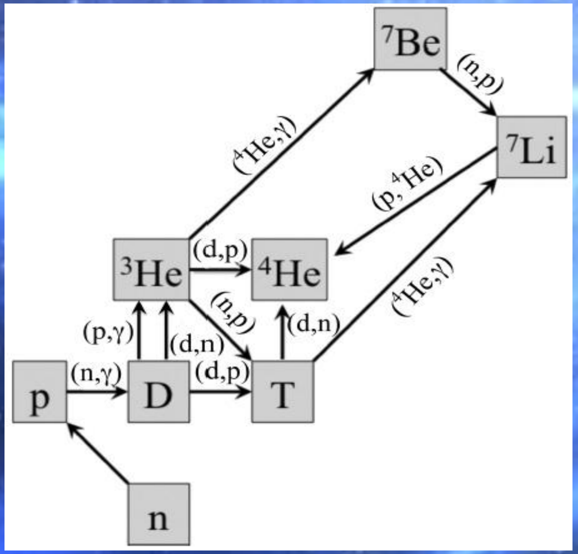
This is a challenge in the rapidly expanding Big Bang environment.

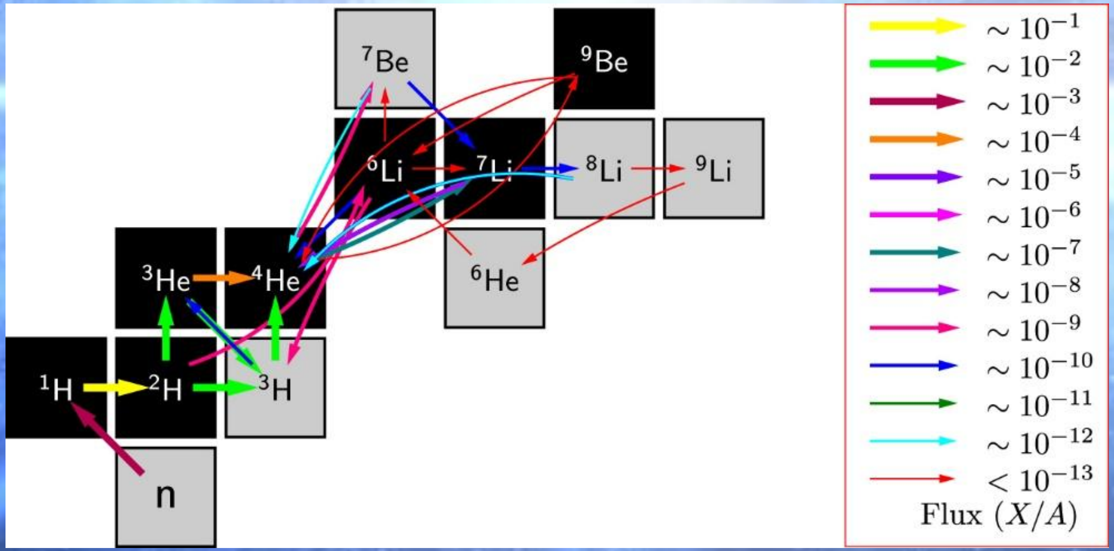


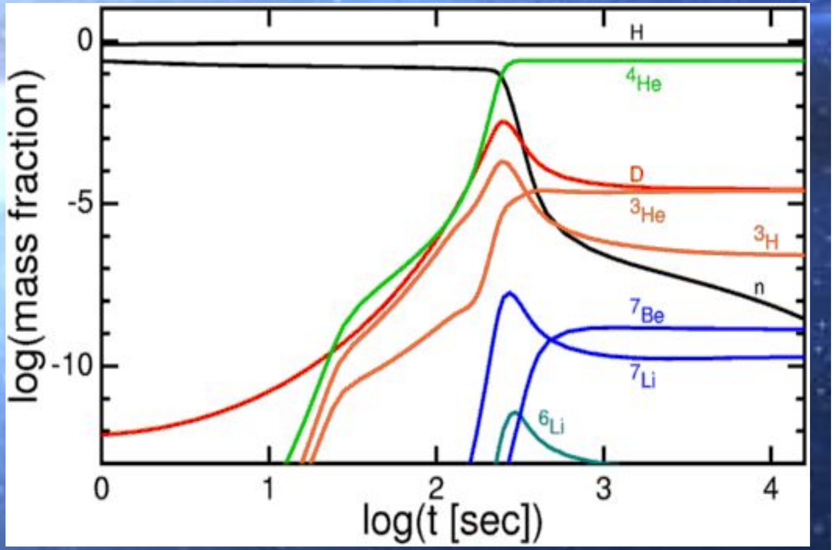
Big Bang Nucleosynthesis

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!







Early Universe Neutron Production

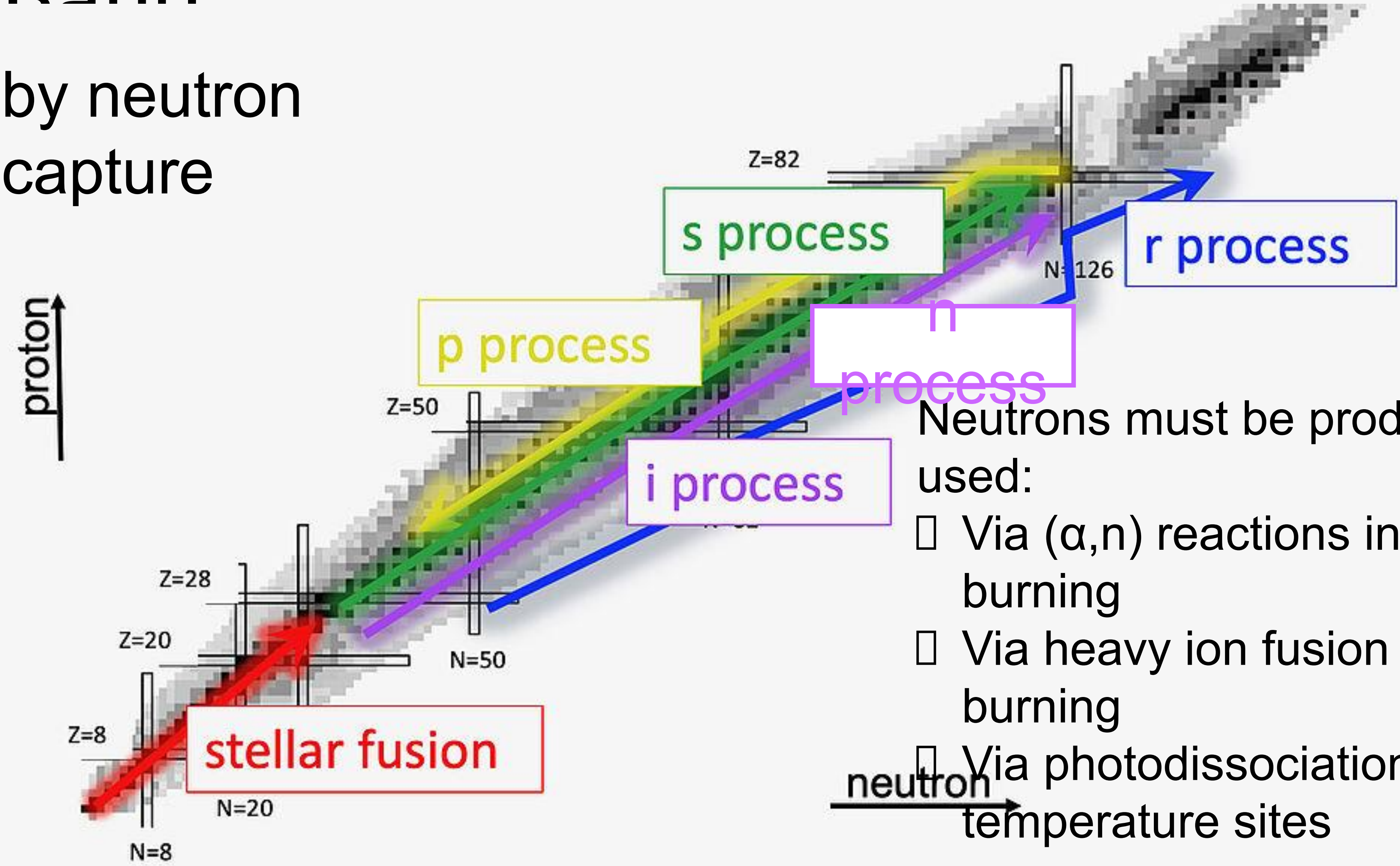
- Primordial neutrons are converted to ^{4}He according to existing simulations!
- Neutrons need to be generated in stars to build heavy elements!

The Question of Neutron Sources

- The Sites of the weak and strong s-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

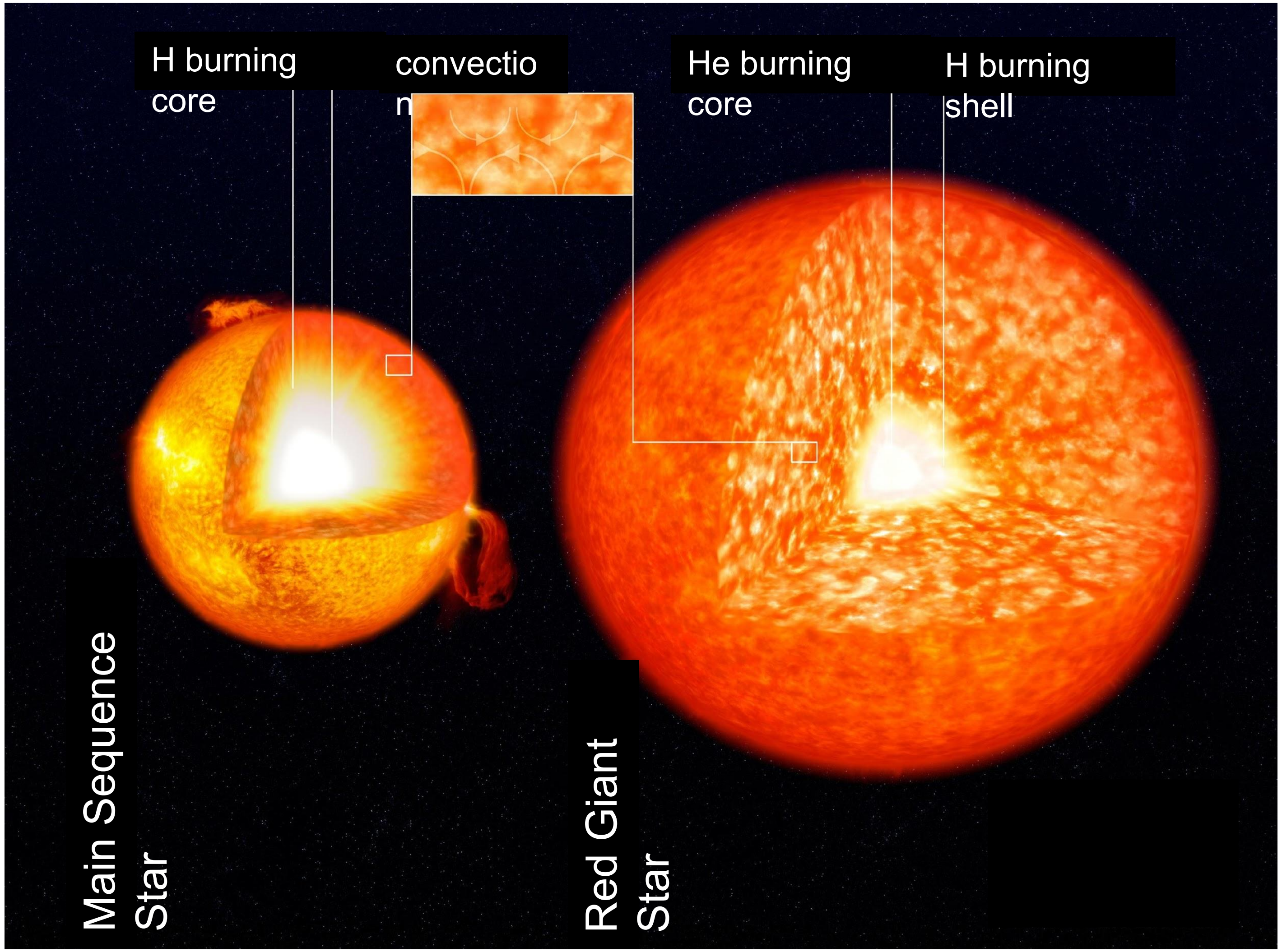
by neutron capture



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(α,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 $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{-}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$

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

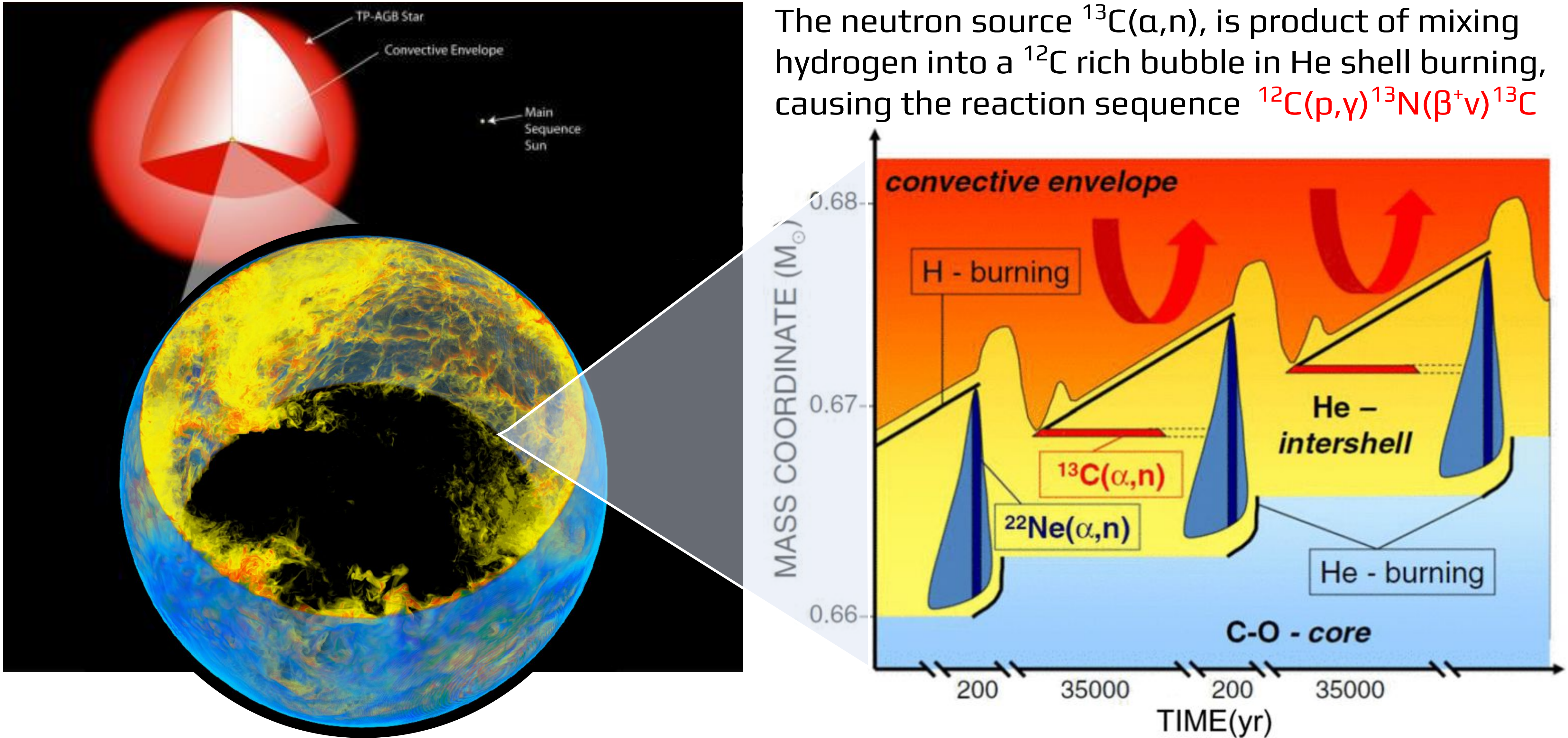
$$Q=-478.34\ \mathrm{keV}$$

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

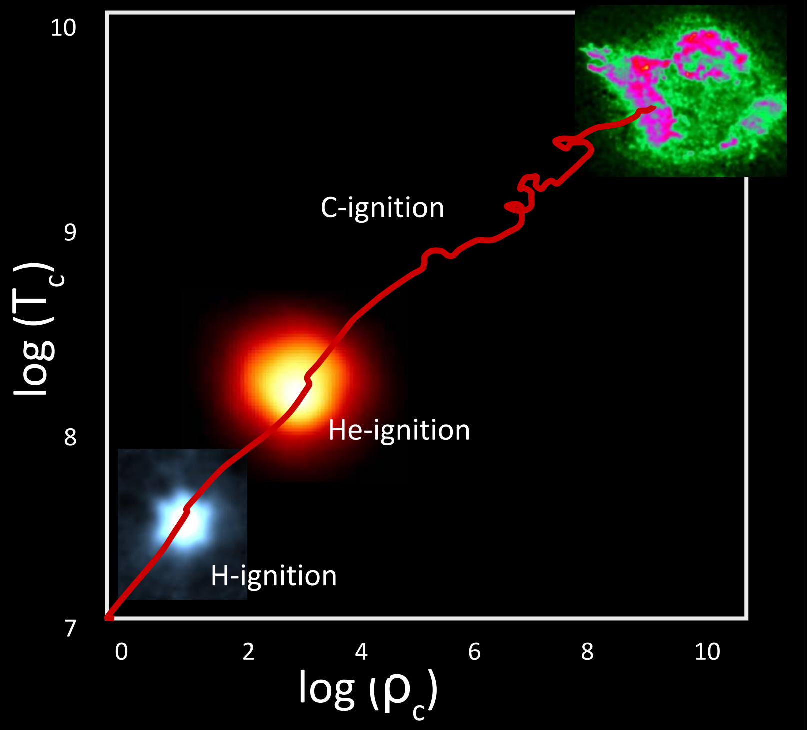
Weak s-process products are transferred by deep convection to surface and emitted by radiation pressure.

The main s-process in AGB stars: neutrino signatures

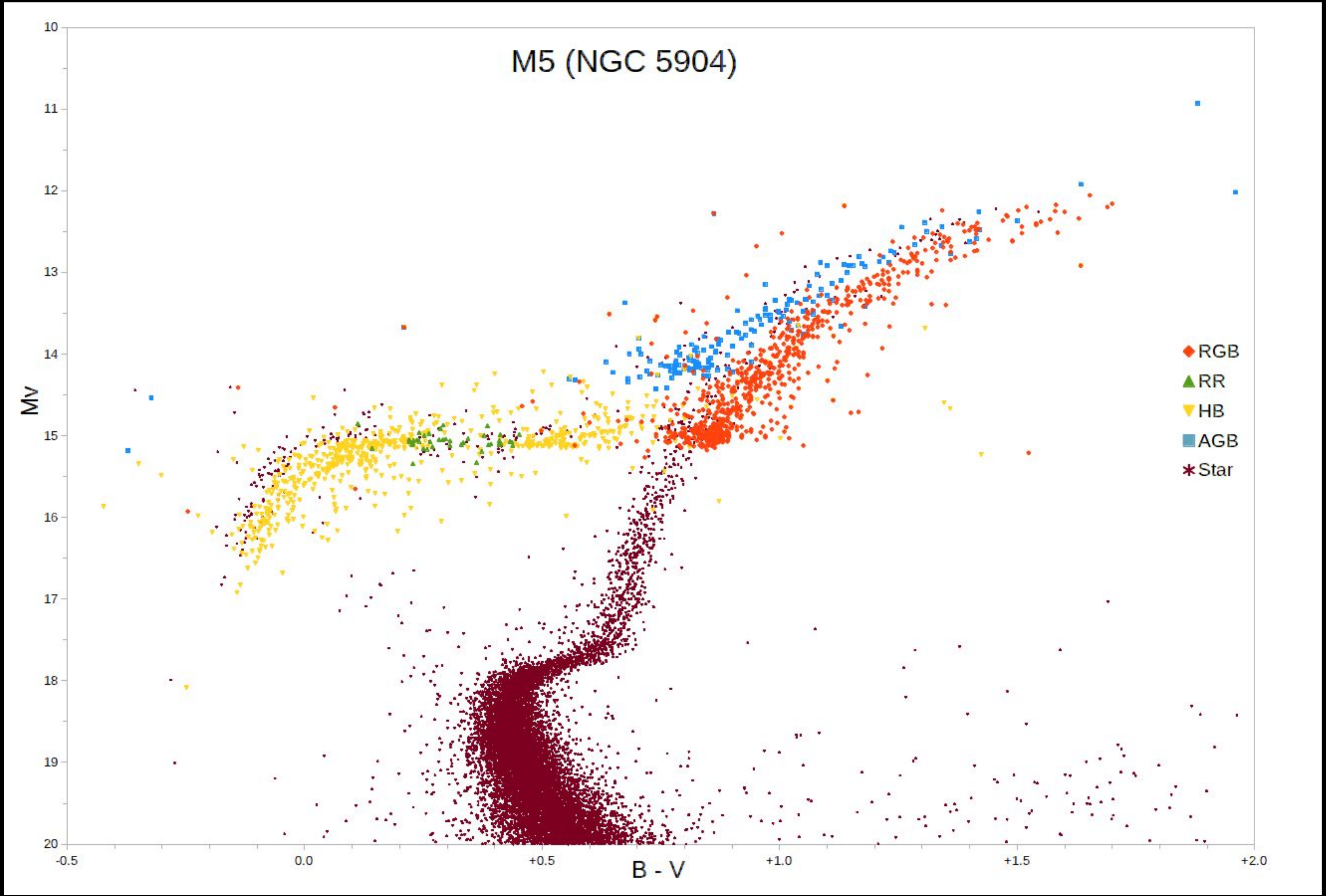
The neutron source ^{13}C(α,n), is product of mixing hydrogen into a ^{12}C rich bubble in He shell burning, causing the reaction sequence $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$



AGB stars



10
9
8
7
log (T$_c$)
0
2
4
6
8
10
log (ρ$_c$)
C-ignition
He-ignition
H-ignition

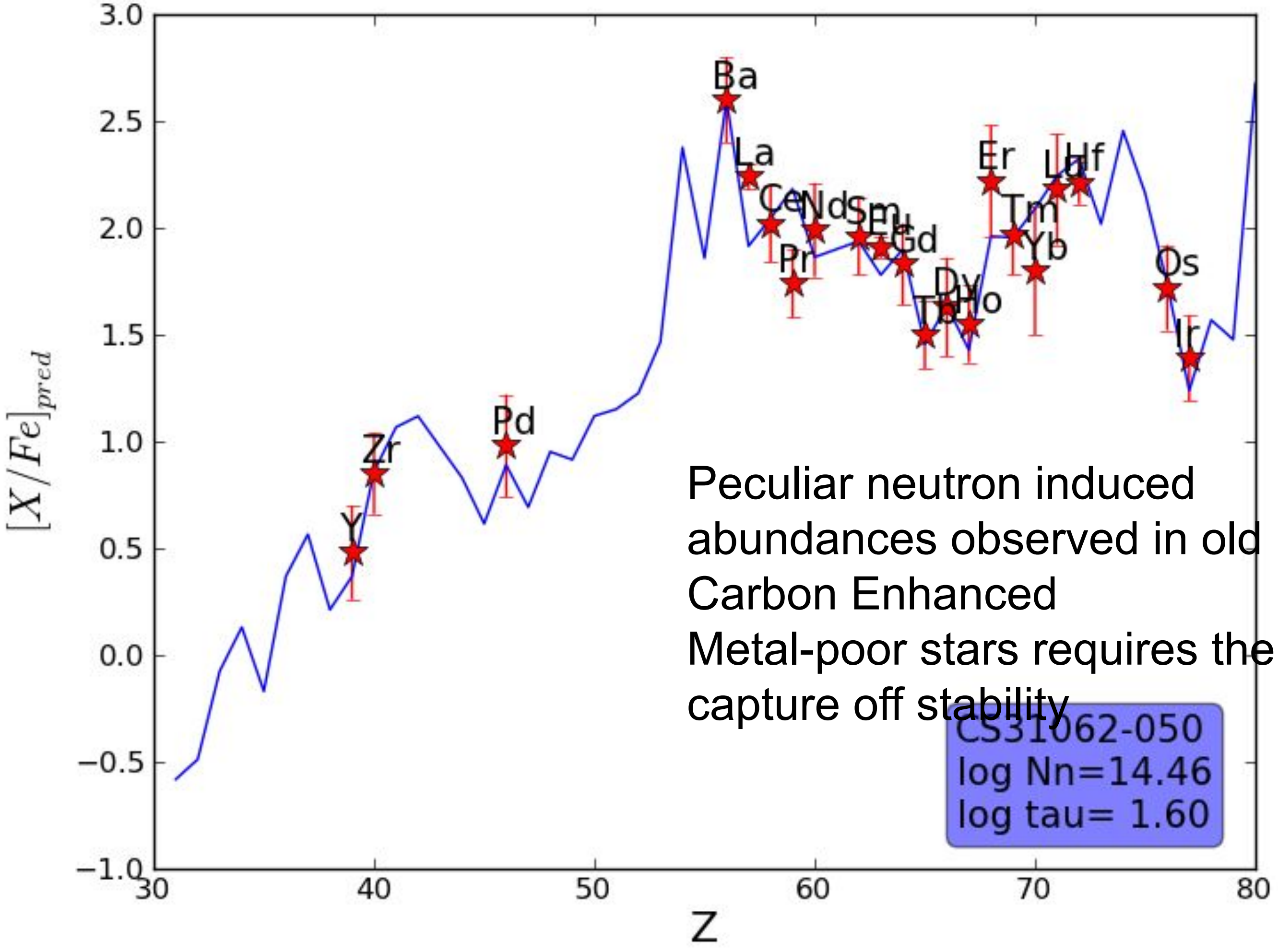


M5 (NGC 5904)
Mv
10
11
12
13
14
15
16
17
18
19
20
B - V
-0.5
0.0
+0.5
+1.0
+1.5
+2.0
RGB
RR
HB
AGB
Star

Neutron Source Speculations

- The Sites of the i-Process in CEMP stars
- Convection and accretion stimulated sources
- Alternative sources in first stars

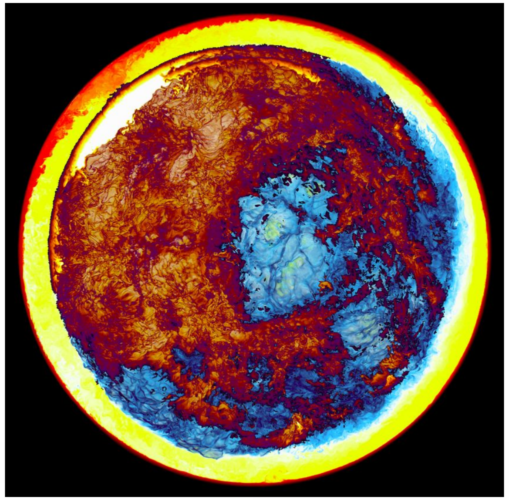
The intermediate (i-) process in early stars

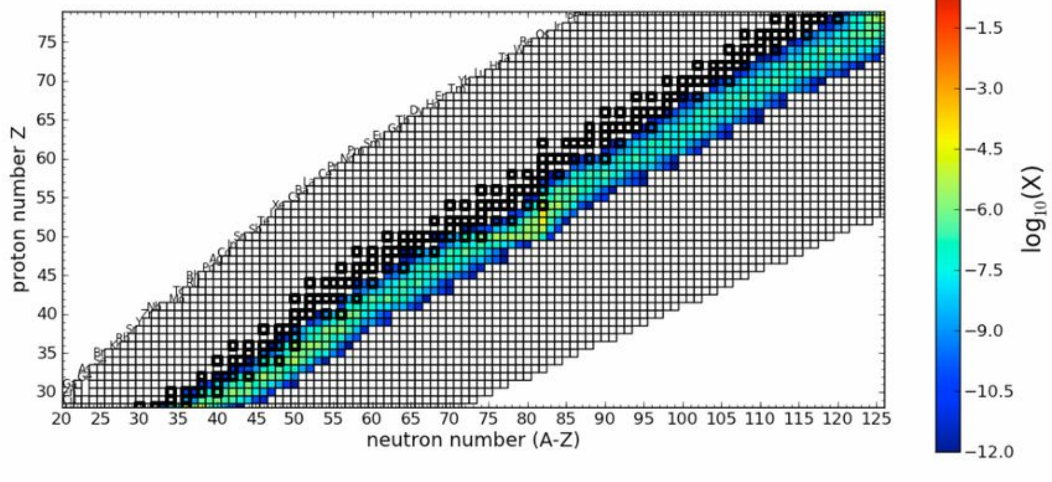


Peculiar neutron induced abundances observed in old Carbon Enhanced Metal-poor stars requires the capture off stability

CEMP - AGB star deep convective environments

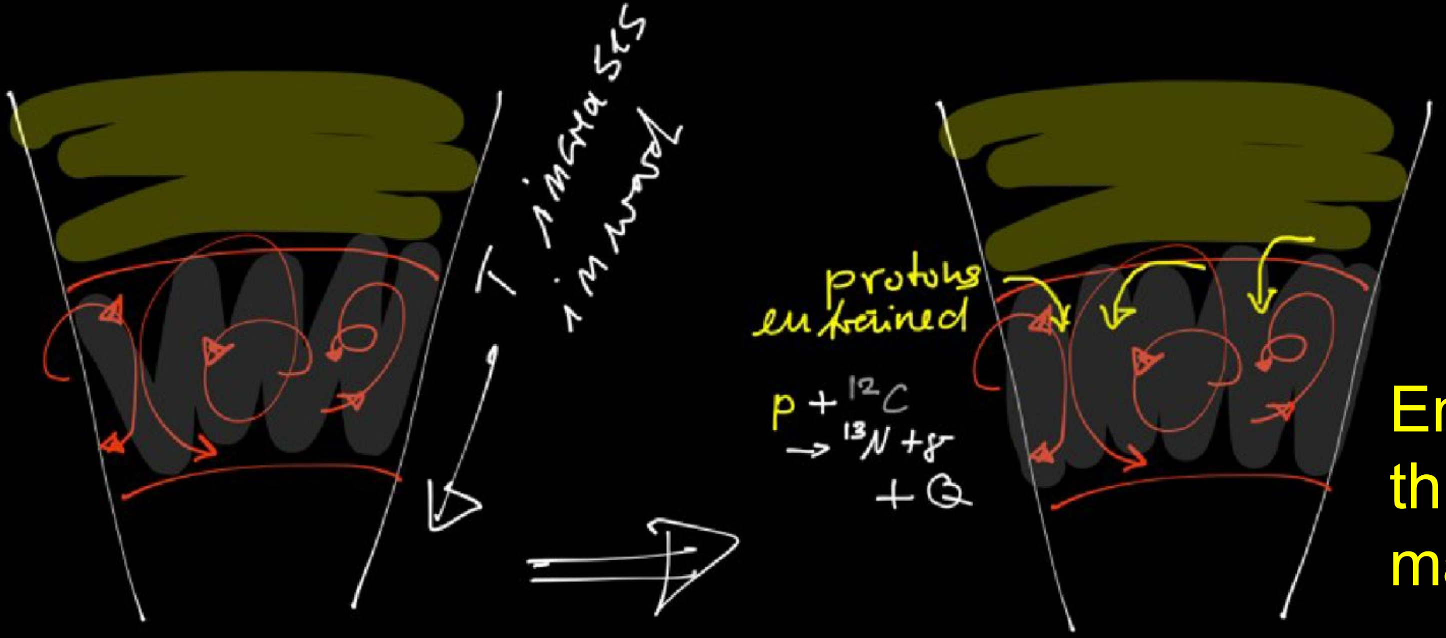
Accreting White Dwarfs





The i-process in early deep convective stars

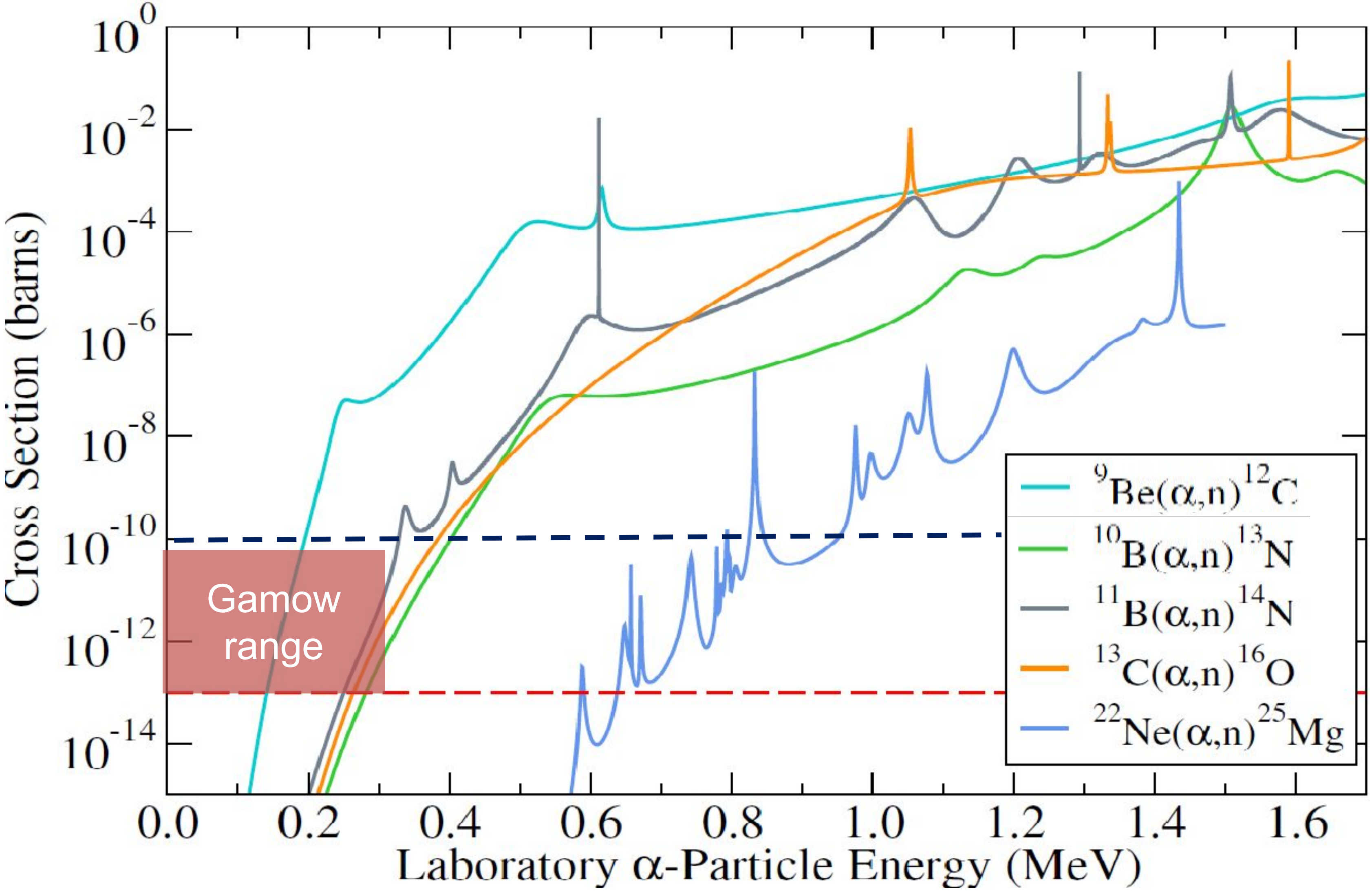
- A neutron flux of 10^{15} n/cm^{2}s is needed to explain i-process abundances
- Model adopted by Cowan and Rose (1977)



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

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

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

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

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

A possible enhancement through alpha clusters resonances

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

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

Deuterons as catalyst isotope

⇒ $^{4}\mathrm{He}(d,\gamma)^{6}\mathrm{Li}(\alpha,\gamma)\mathbf{^{10}B(\alpha,n)}^{13}\mathrm{N}(\beta)\mathbf{^{13}C(\alpha,n)}^{16}\mathrm{O}$

^{9}Be production

^{4}He(αn,γ)^{9}Be
^{7}Li(^{3}He,p)^{9}Be
^{7}Li(^{2}H,γ)^{9}Be
^{7}Li(^{3}H,n)^{9}Be

^{9}Be(α,n)^{12}C

^{10}B production

^{6}Li(α,γ)^{10}B
^{9}Be(p,γ)^{10}B

^{10}B(α,n)^{13}N
^{13}C(α,n)^{16}O

^{11}B production

^{7}Li(α,γ)^{11}B
^{9}Be(p,γ)^{11}B
^{11}C(β ν)^{11}B

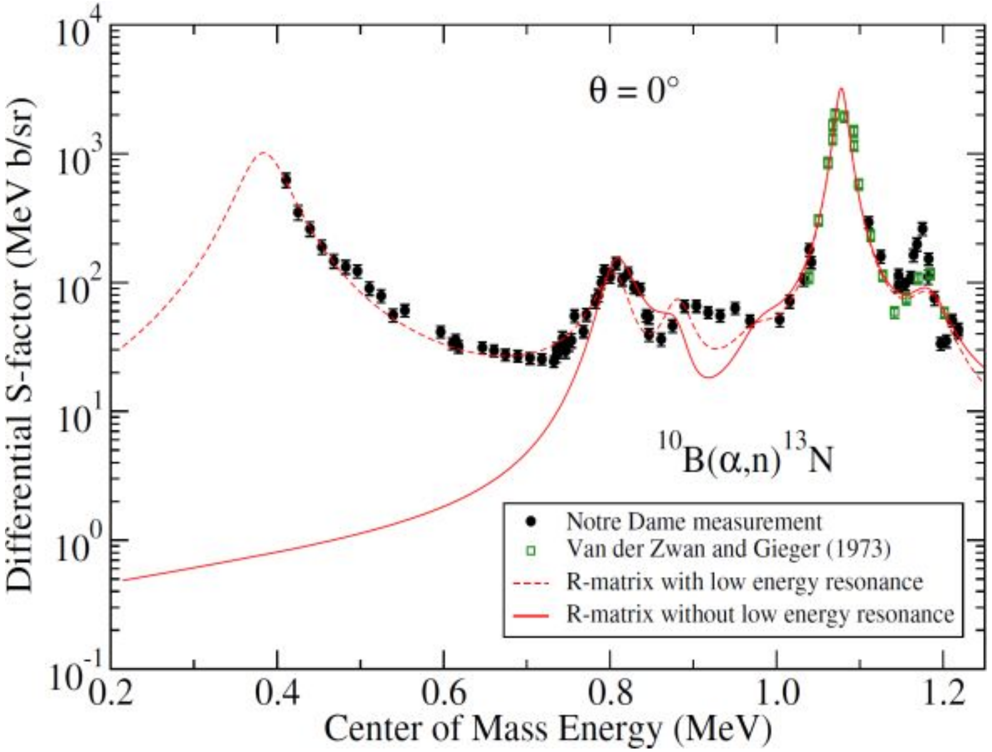
^{11}B(α,n)^{14}N

Most of the reaction rates go back to FCZ75 and CF88, very limited amount on new data! Extremely limited amount on low energy data.

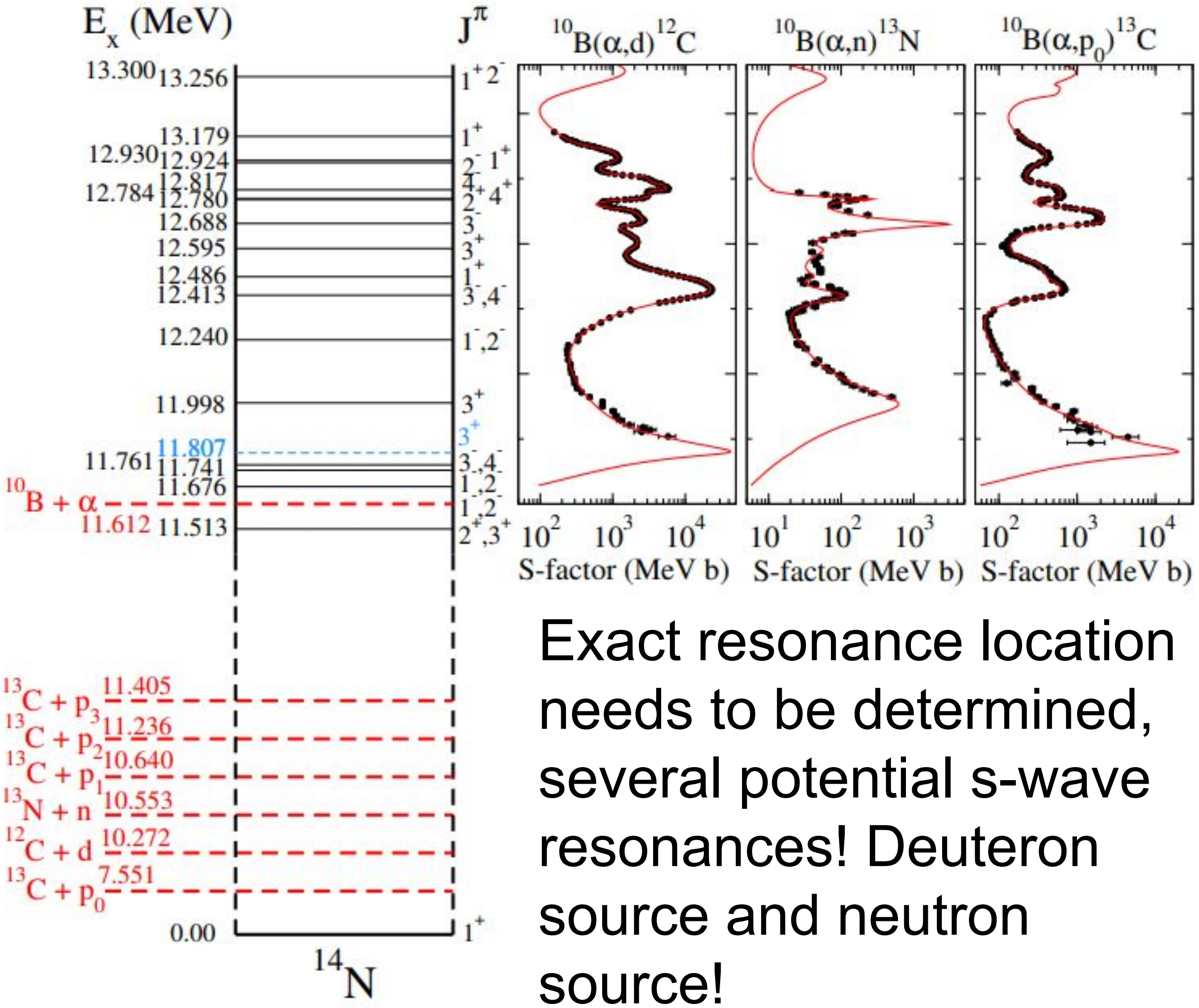
Most of the systems, e.g. ^{9}Be, ^{10}B, ^{11}B are characterized by alpha –cluster structures, 2α⊗n, 2α⊗d, and 2α⊗t, respectively. These structures typically emerge as resonances near the alpha thresholds. Broad resonance in ^{6}Li(α,γ)^{10}B at 730 keV and at 945 keV in ^{7}Li(α,γ)^{11}B.

^{10}B(α,n) unexpected threshold resonance

which also appears in other channels

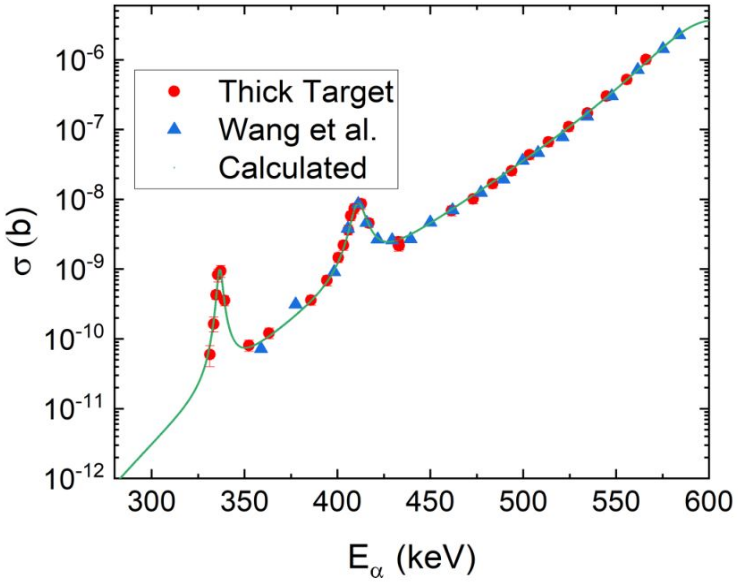


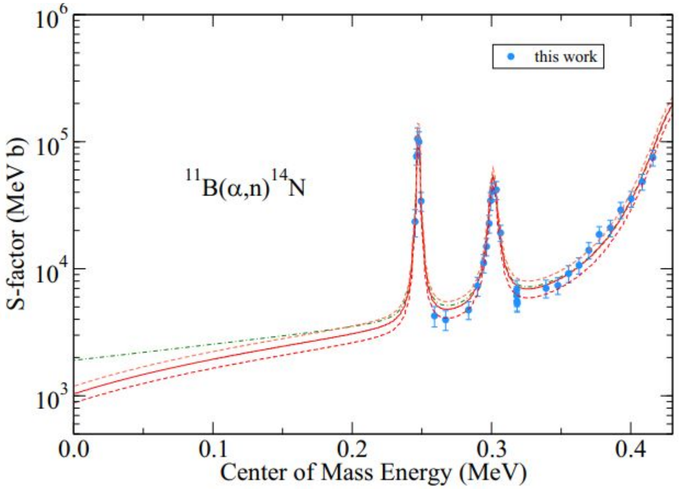
This would provide a source for neutrons in first star environments

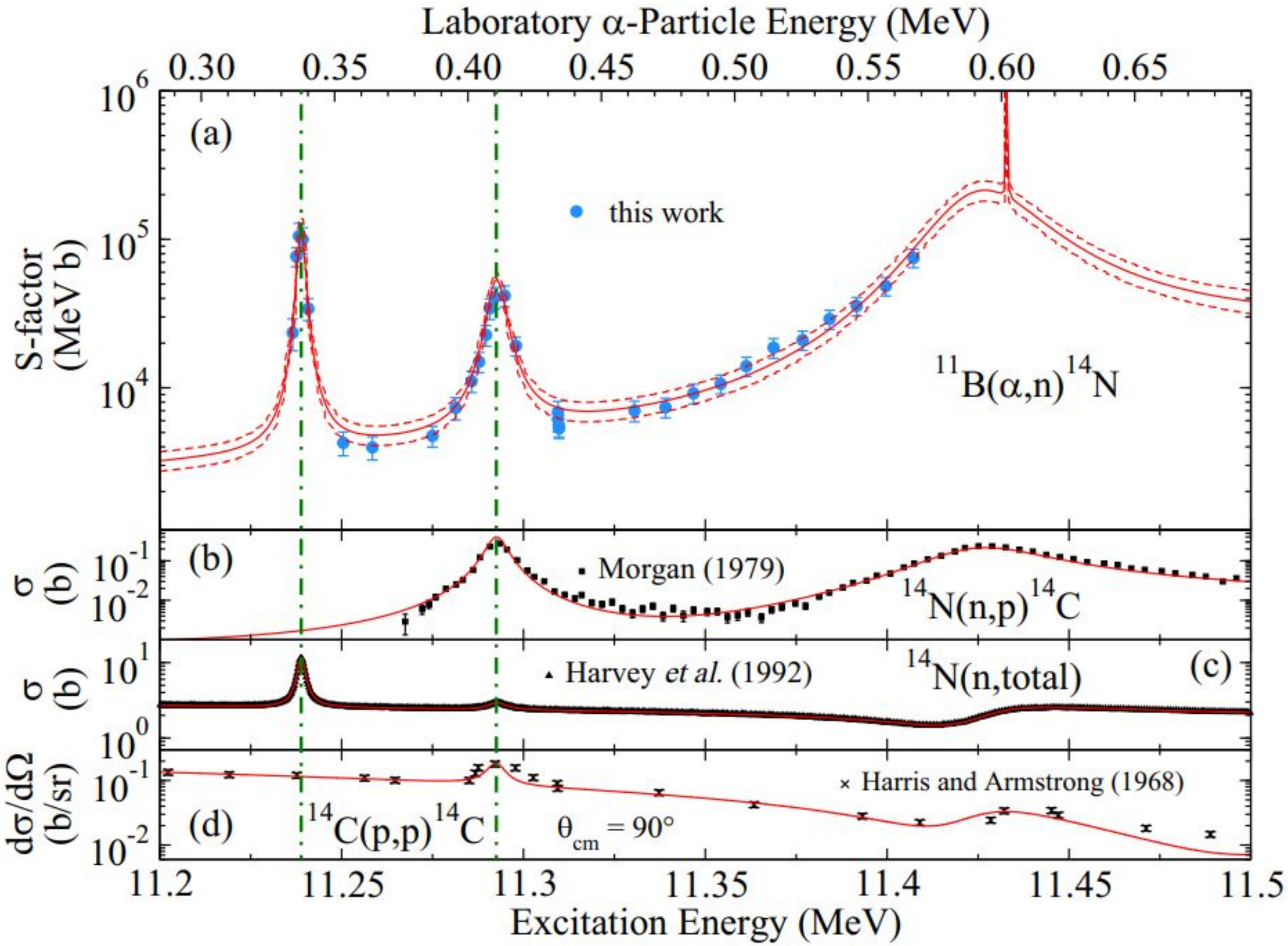


Exact resonance location needs to be determined, several potential s-wave resonances! Deuteron source and neutron source!

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

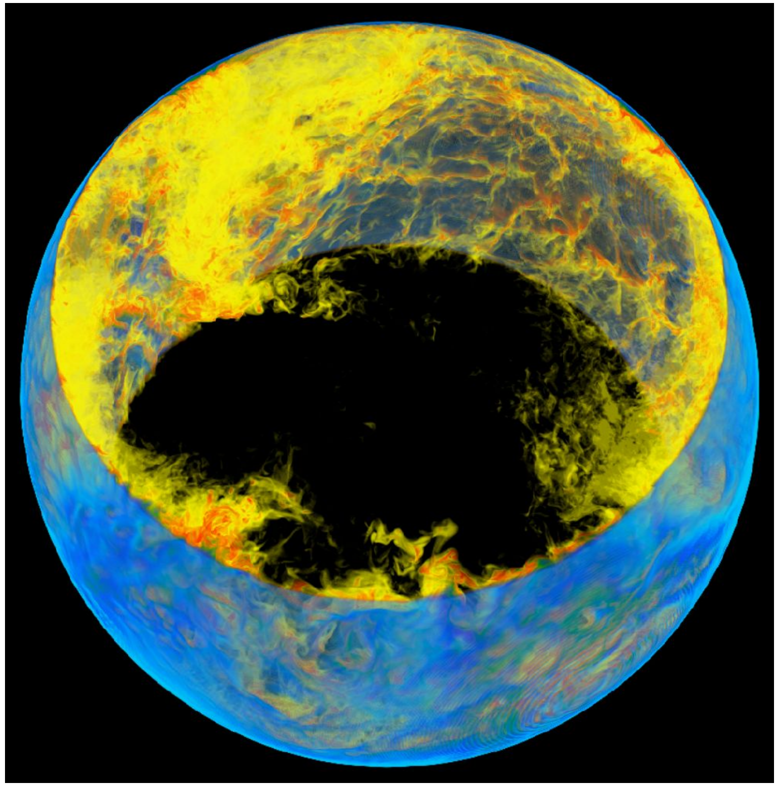


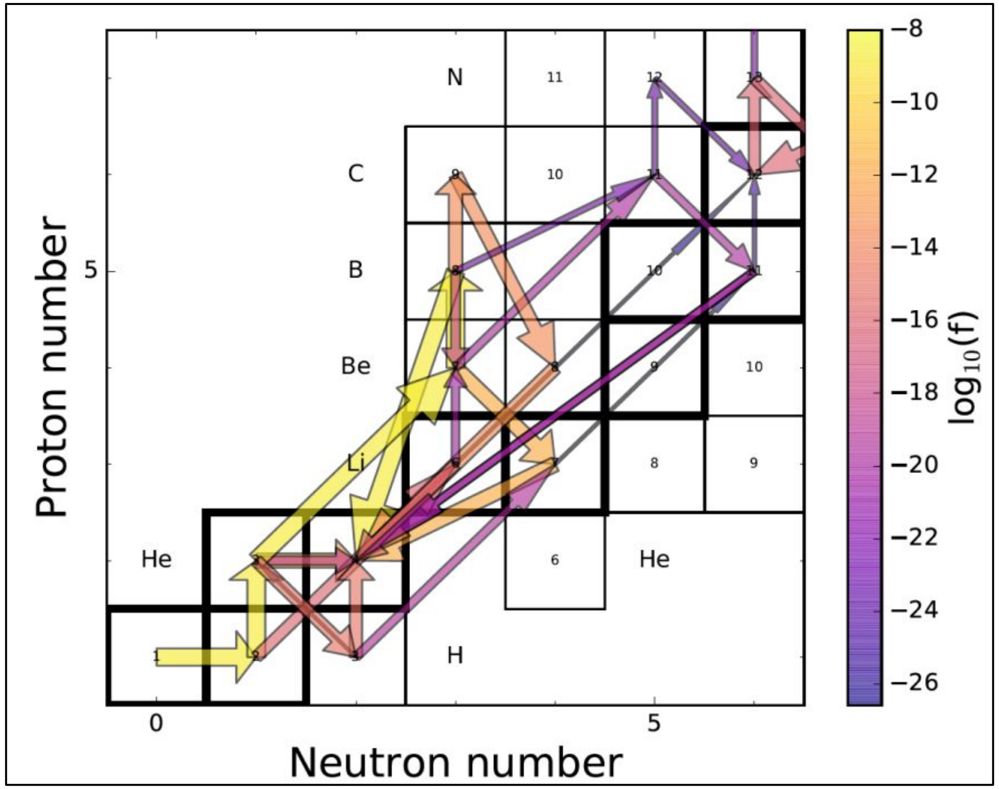




Multi-channel, multi-level R-matrix fit taking all data on reactions through the compound nucleus into account.

Neutron seed production





^{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

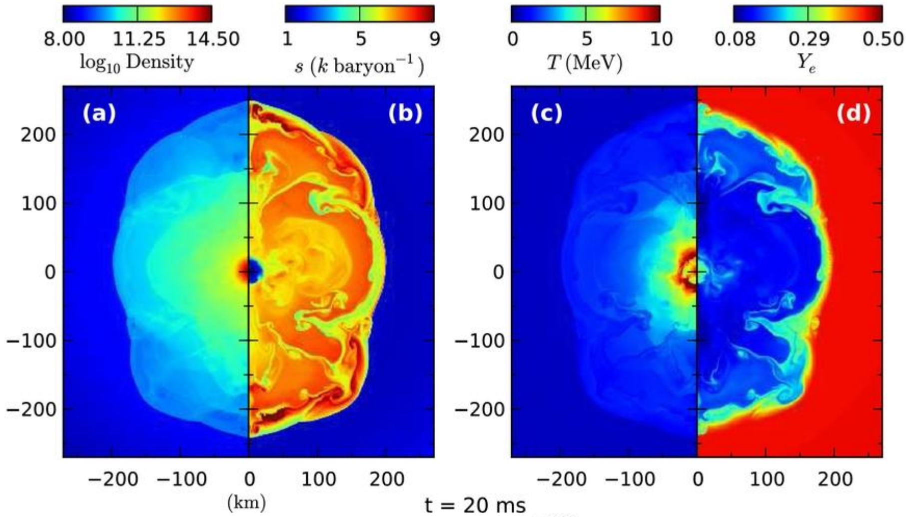
- Neutron sources for the r-process
- Neutron sources for the n-process

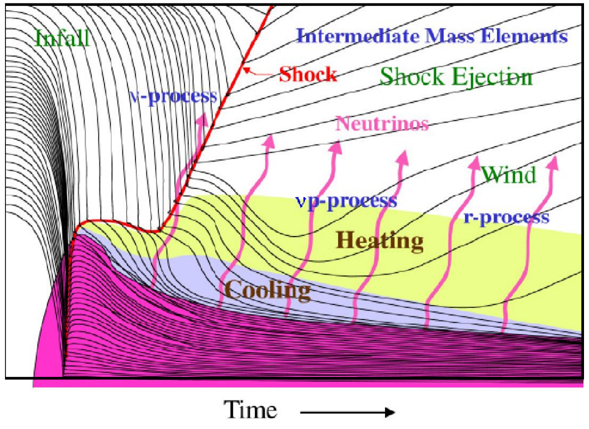
Core collapse to high densities and temperatures

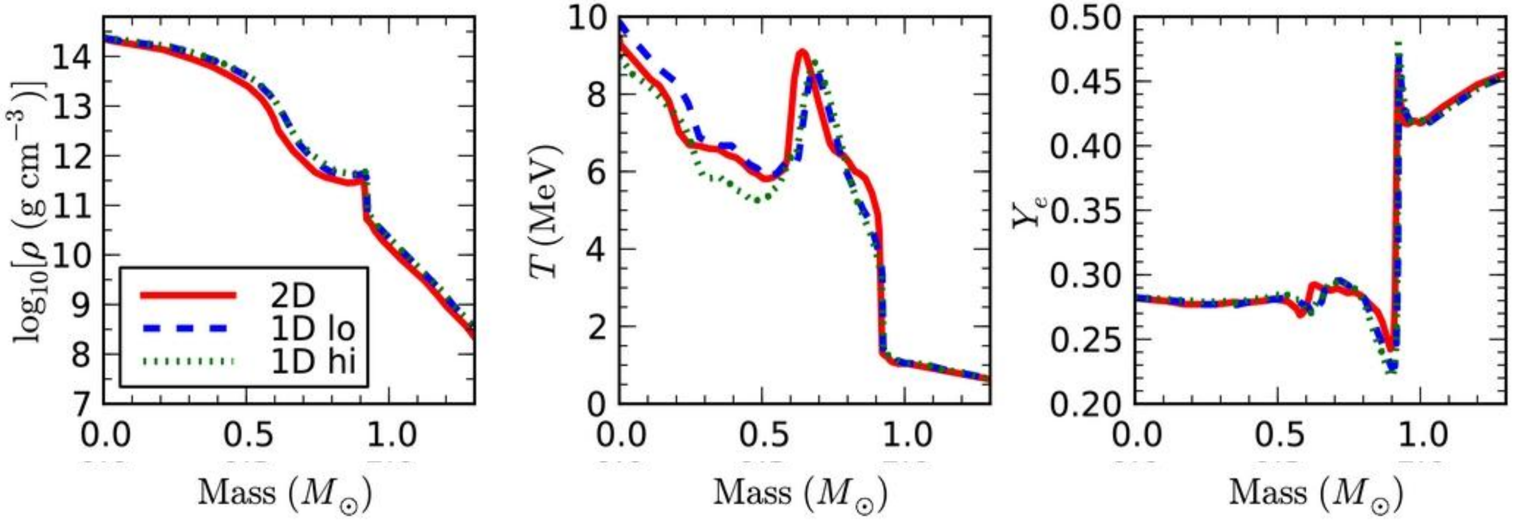
Neutrons are produced in core collapse SN or on merging neutron star reaching extreme densities by nuclear-statistical equilibrium (NSE), which indicates full chemical equilibrium among all of the involved nuclear reactions. For high temperature and density conditions the equilibrium shifts to p, n,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

$Y_e=(n_{e^-}-n_{e^+}))/nb=1/(1+N_n/N_p)$





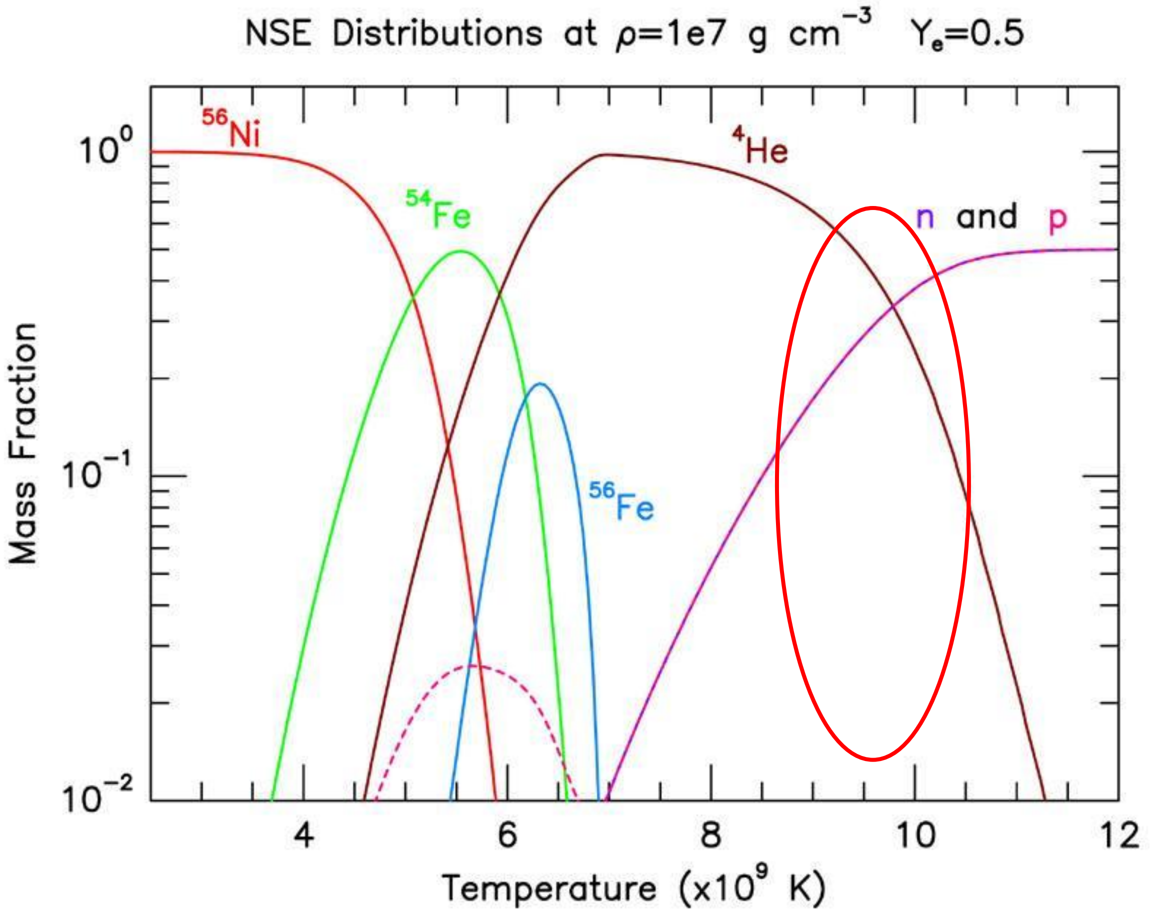


Chemical Equilibrium at high Densities and Temperatures

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

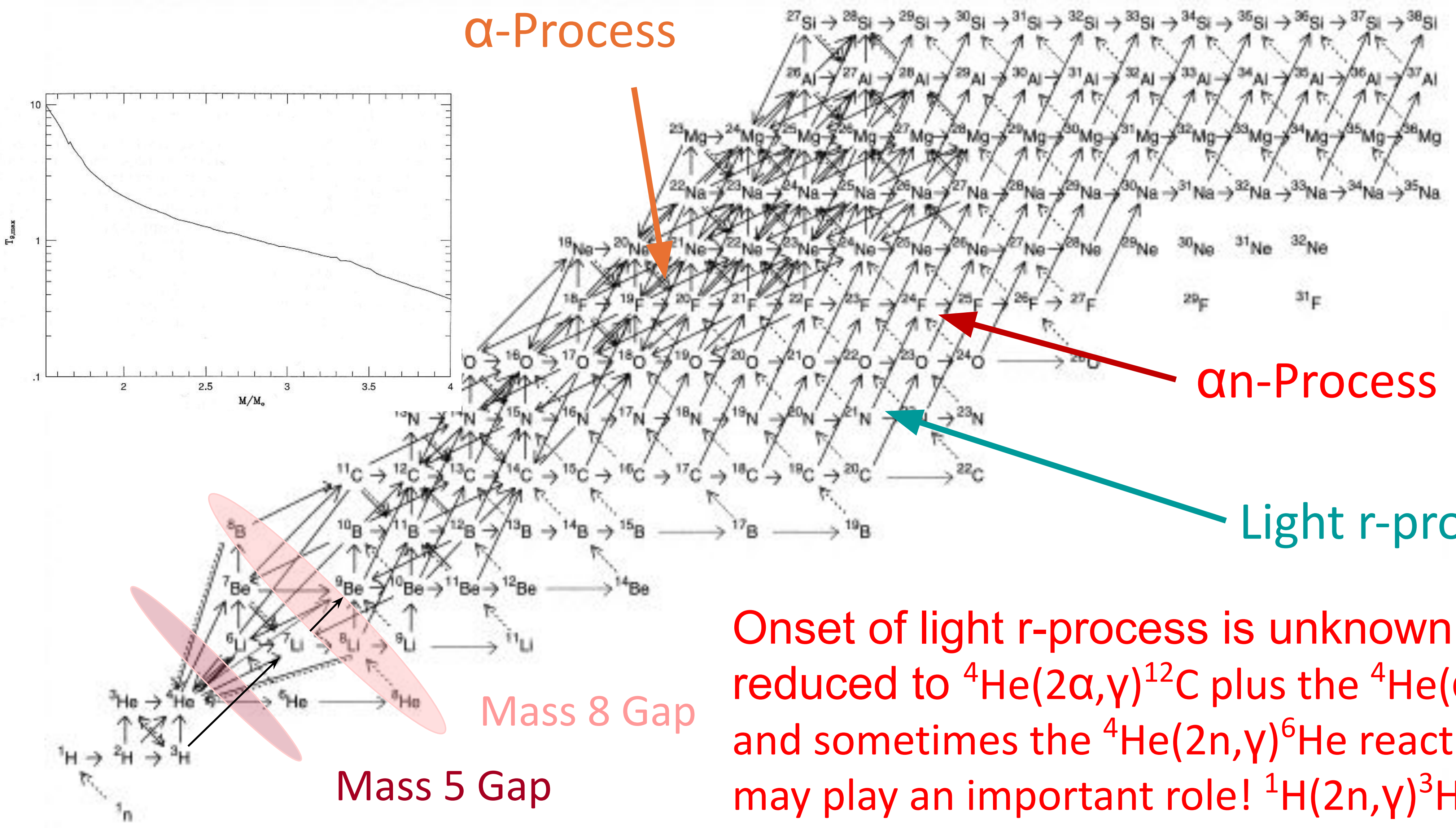
High ρ: Massive nuclei
High T: Light nuclei
Median T: Tightly bound nuclei.

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)

Dynamical Reaction Network bridging the gap



α-Process

αn-Process

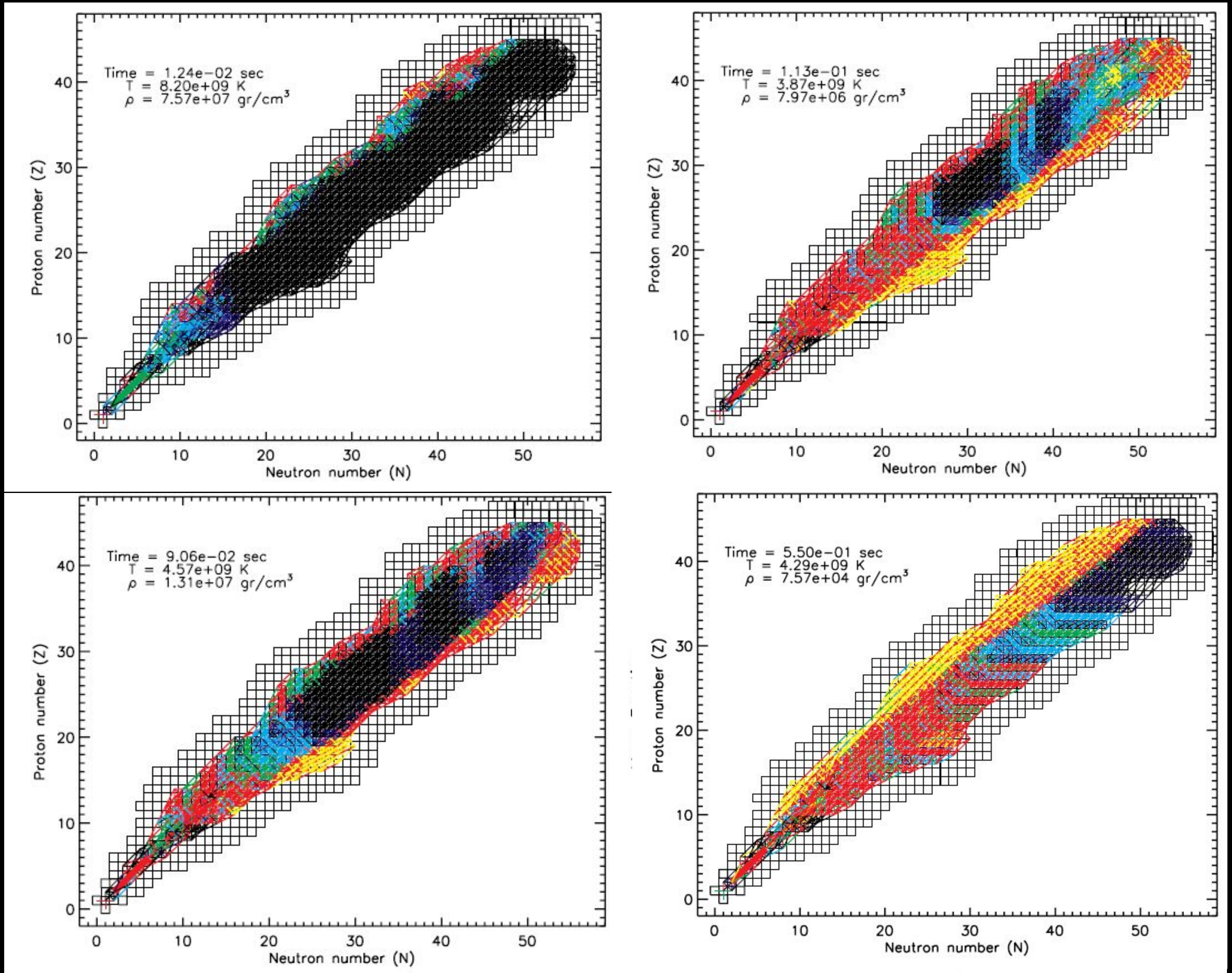
Light r-process ?

Mass 8 Gap

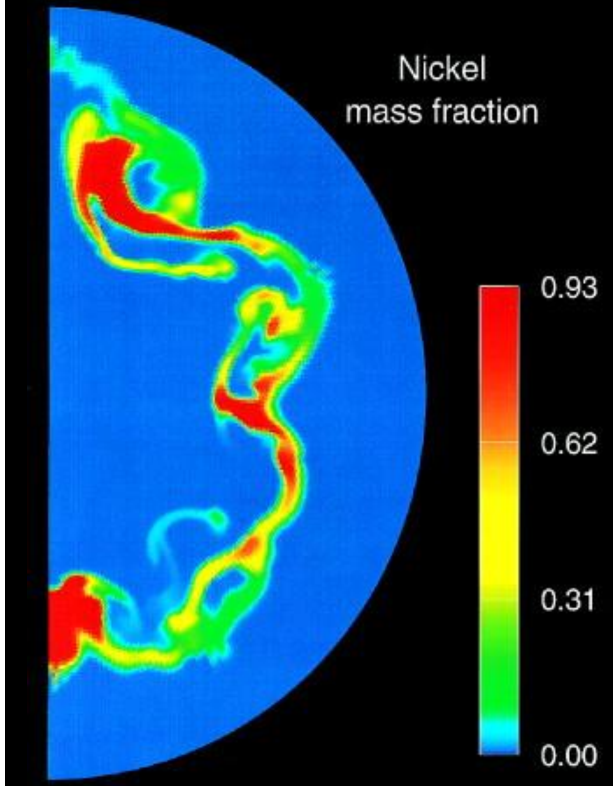
Mass 5 Gap

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 sometimes 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)!

Explosive burning in shock front

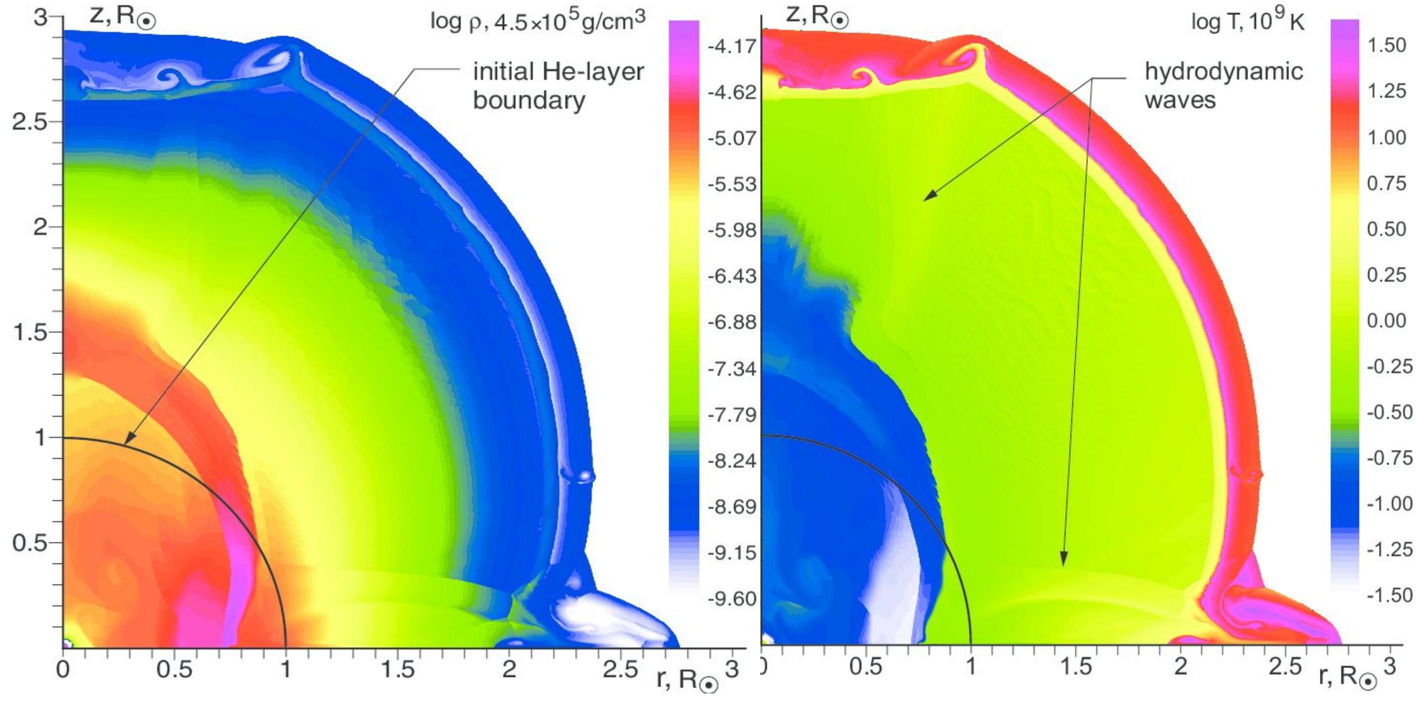


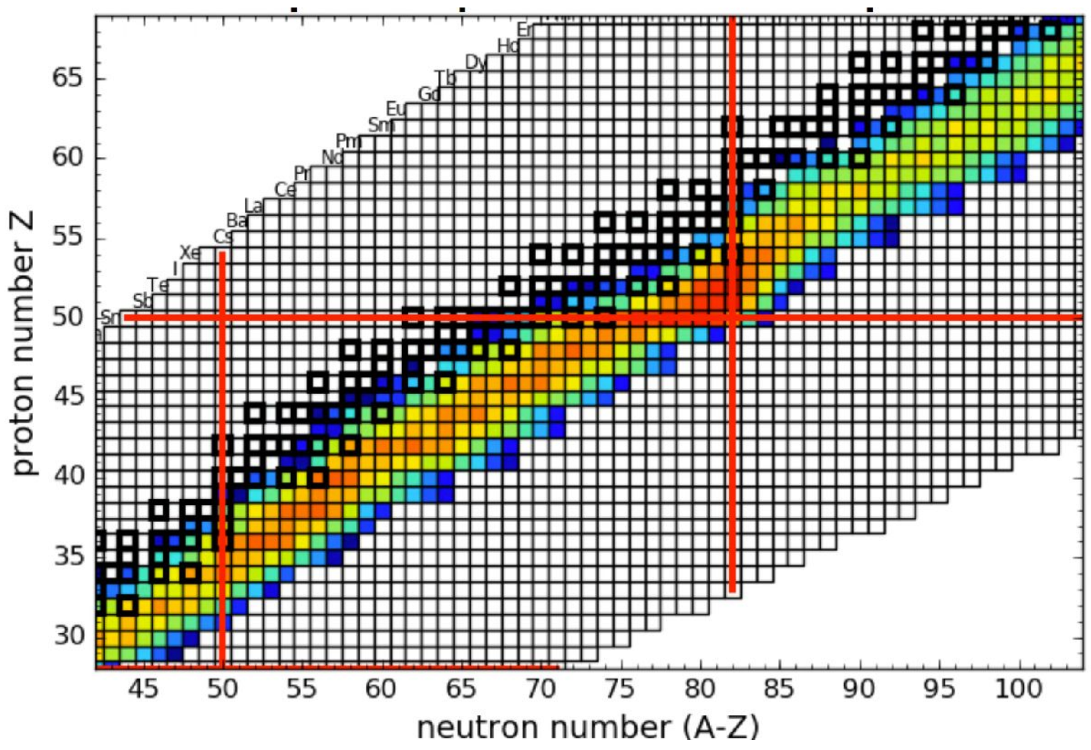
Initial dissociation towards p, n, ^{4}He
Re-association is stat. equilibrium towards ^{56}Ni with gradual cooling through expansion.



Neutron sources for the n-process

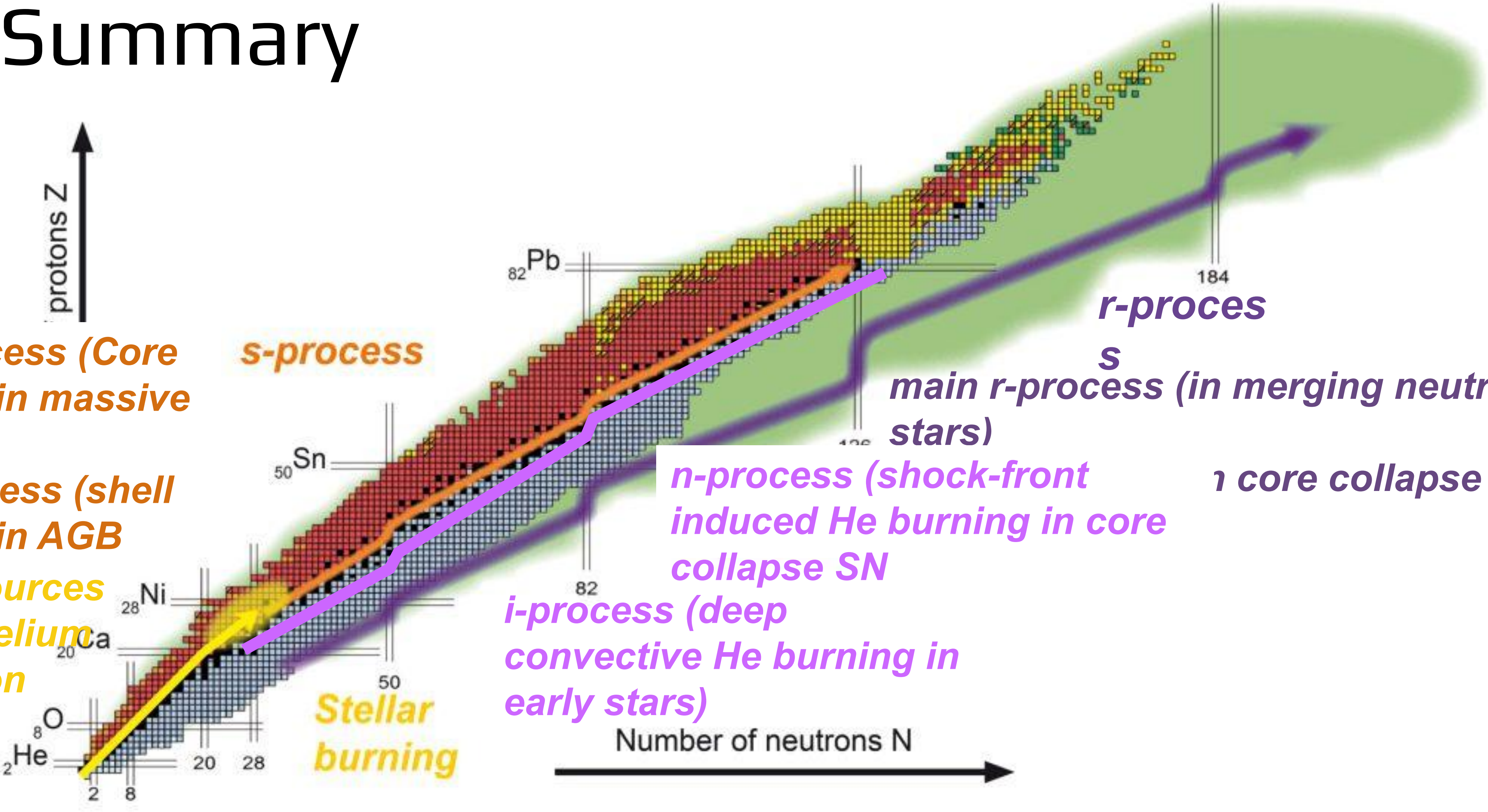
Supernova shock passes through the helium burning layer with large amounts of unprocessed ^{22}Ne (this depends on the ^{22}Ne(α,γ) reaction rate), sudden increase in temperature, density and pressure releases the neutron flux from ^{22}Ne(α,n)! The reaction rate is dominated by the 830 keV cluster resonance!





Possibly other (α,n) sources along the way

Summary



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

r-process

main r-process (in merging neutron stars)

core collapse SN)

n-process (shock-front induced He burning in core collapse SN

i-process (deep convective He burning in early stars)

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