UNIVERSITY OF Hull

E.A. Milne Centre for Astrophysics

Nuclear Astrophysics
Stellar Evolution and Nucleosynthesis
Lecture I & II

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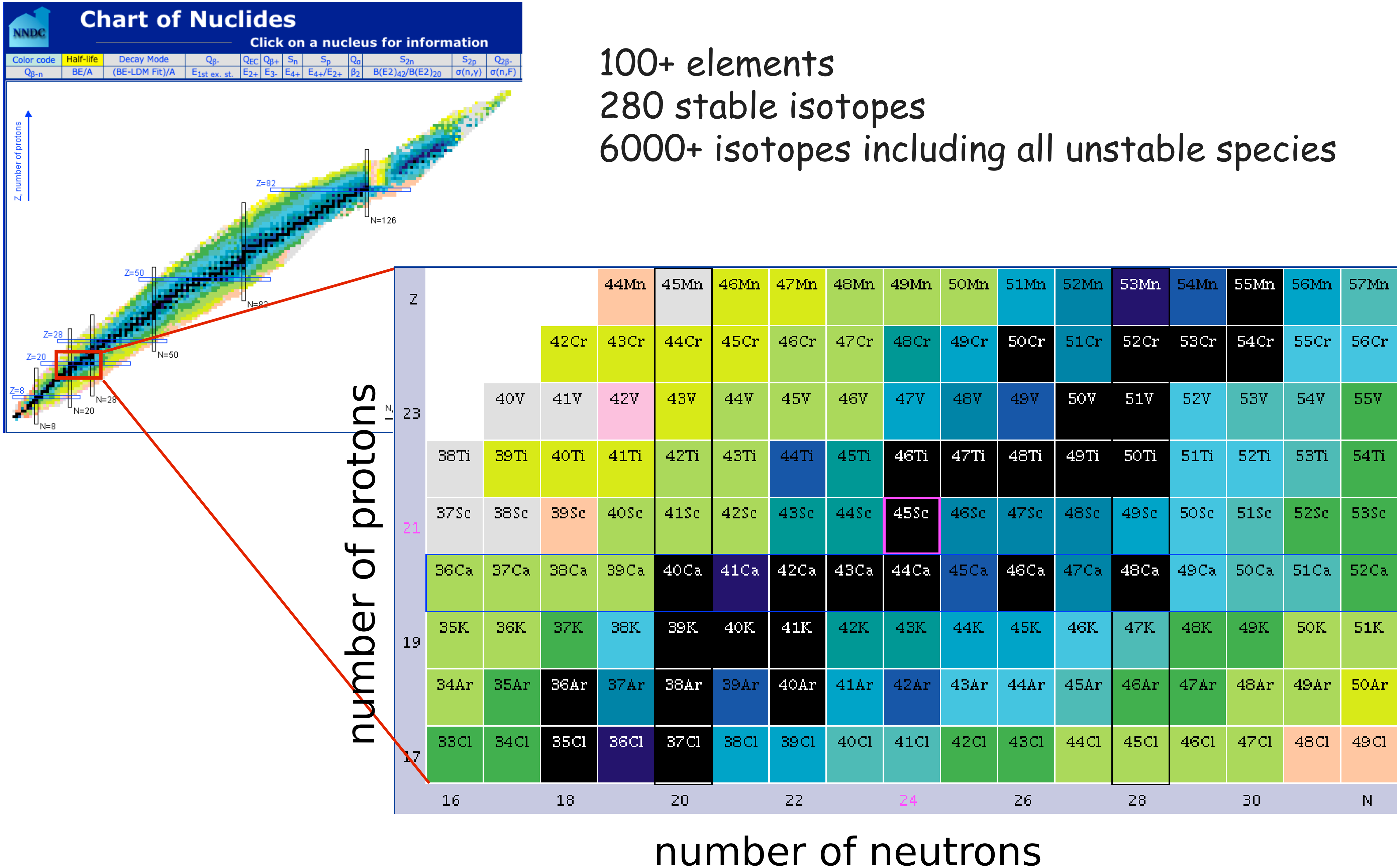
www.nugridstars.org

NUGRID

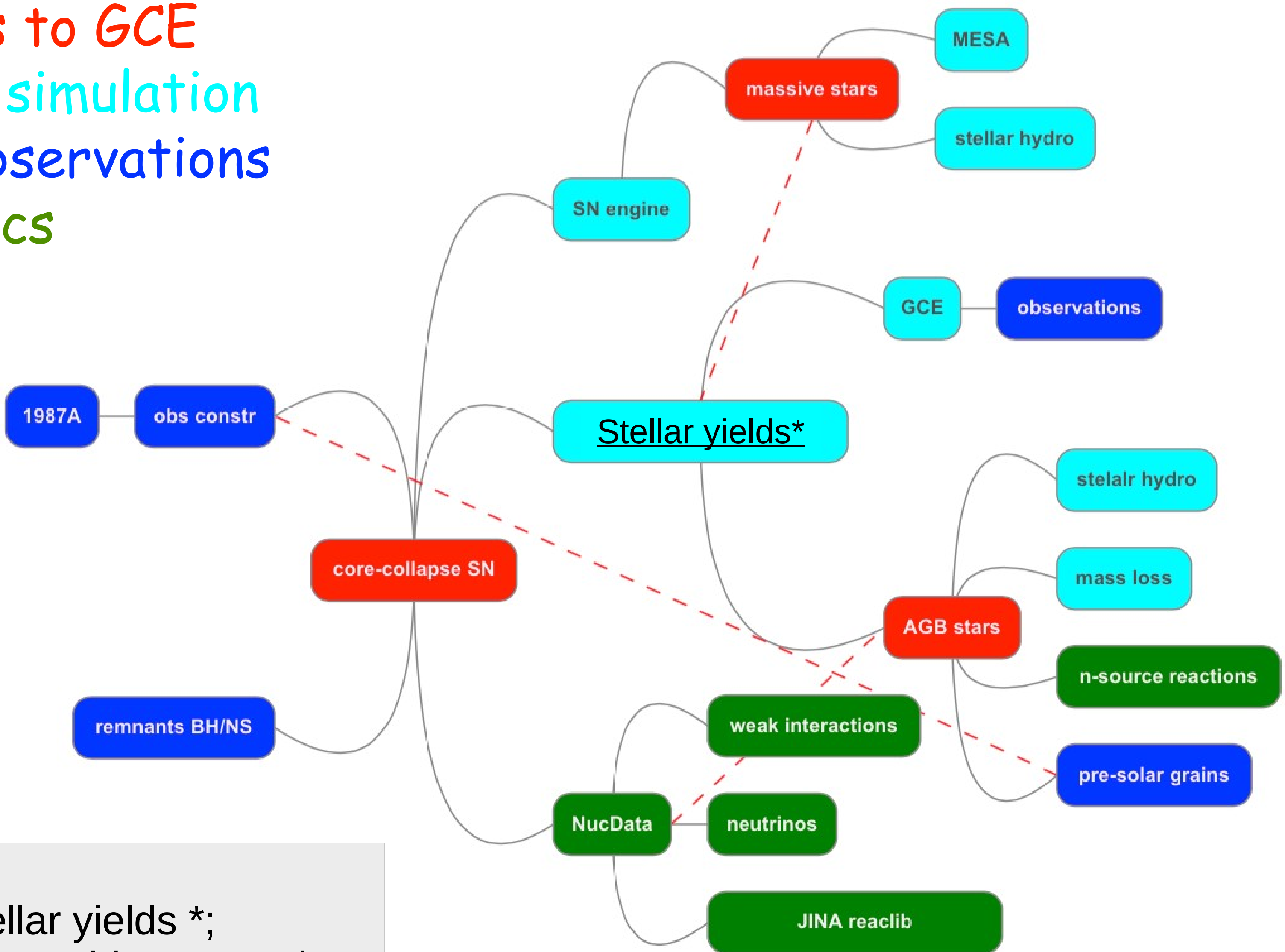
JINA-CEE

Nuclear astrophysics goal = study how elements are made in stars

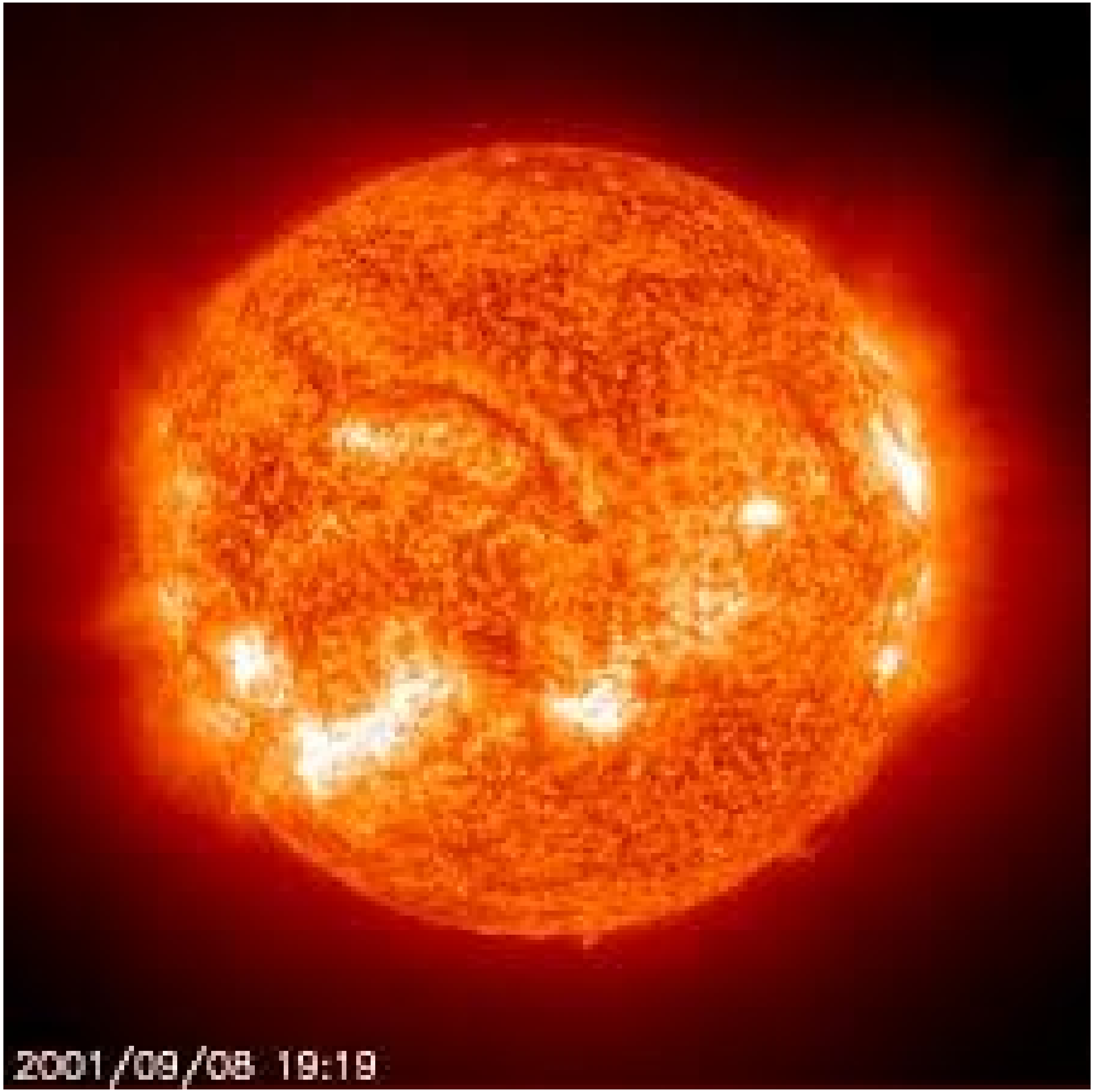
100+ elements
280 stable isotopes
6000+ isotopes including all unstable species



- contributions to GCE
- astrophysics simulation
- astronomy observations
- nuclear physics



My job:
1) calculate stellar yields *;
2) connect these subjects together and provide answers.



SOHO satellite

Sun: 1 M_{sun} ; 1 AU ; 1 R_{sun}

1 M_{sun} ~ $2*10^{30}$ Kg

1 AU = 1./63241,1 lyr

1 lyr = $9,461*10^{12}$ Km

1 R_{sun} = 695700 Km

Hull-Chiang Mai = 8943 Km

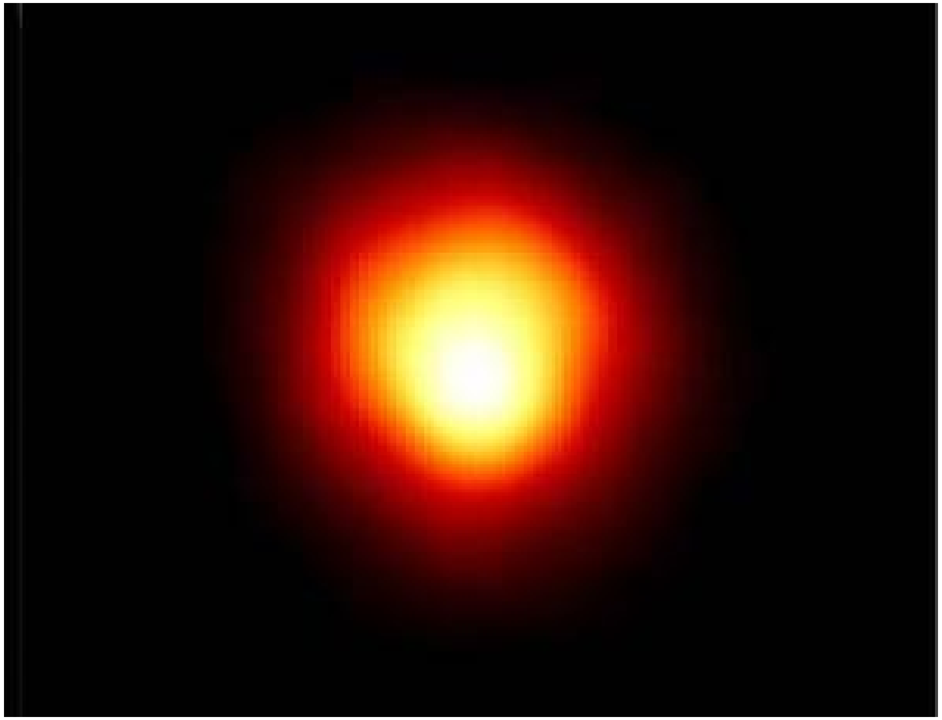
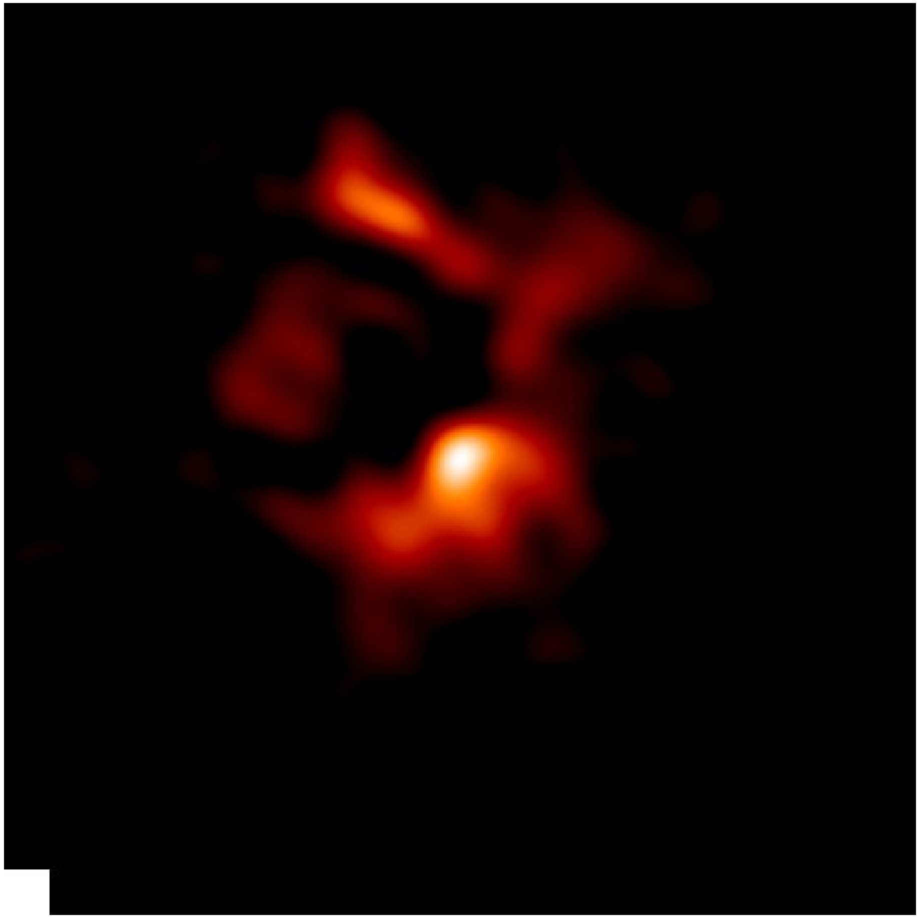


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

Betelgeuse (α-Ori):
- 19 M_{sun}
- 650 lyr
- 1180 R_{sun}

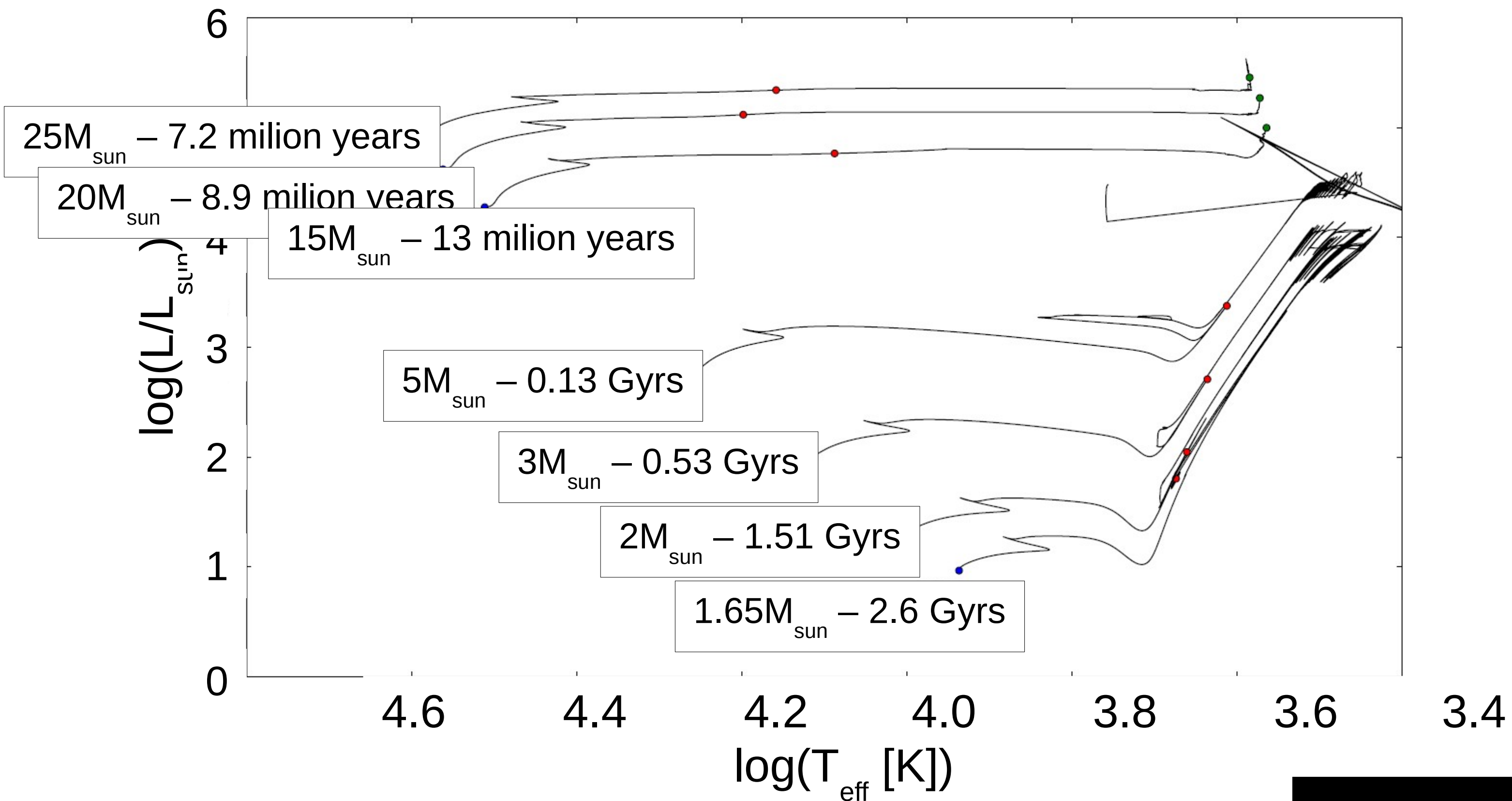


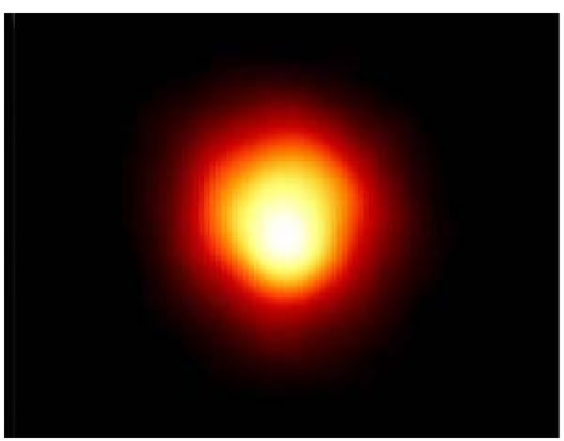
Tuthill et al. 2000, A&A, Keck Telescope

CWLeo (IRC+10216):

- 400 lyr
- 250 R_{sun}

HR diagram





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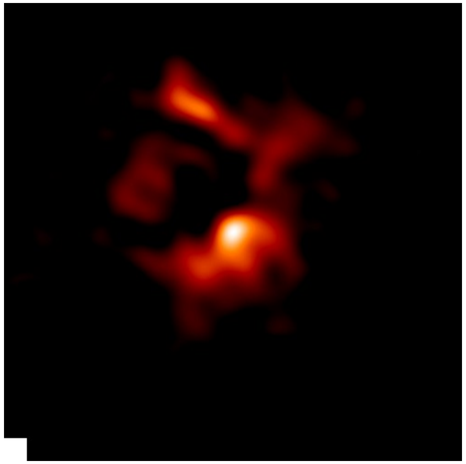
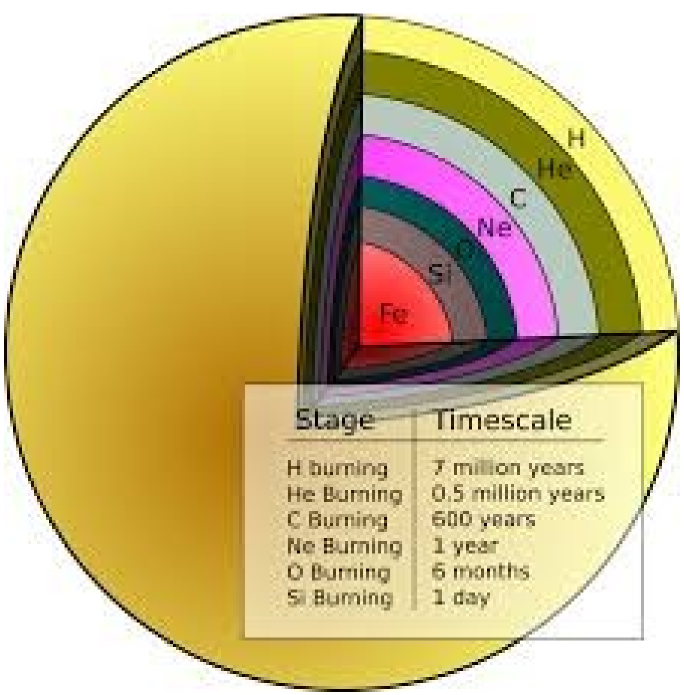


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

Tuthill et al. 2000, A&A, Keck Telescope



> 10 solar masses

Supernovae

- The term Supernova was introduced by Baade & Zwicky (1934) to describe extra-luminous novae;
- Following the discovery of neutrons in 1932, Zwicky (1938) proposed that supernovae are made by the collapse of a massive star to a star made of neutrons.
- Energy released: 10^{53} ergs, but most SNe Are 10^{51} ergs, 1 foe = 1 Bethe

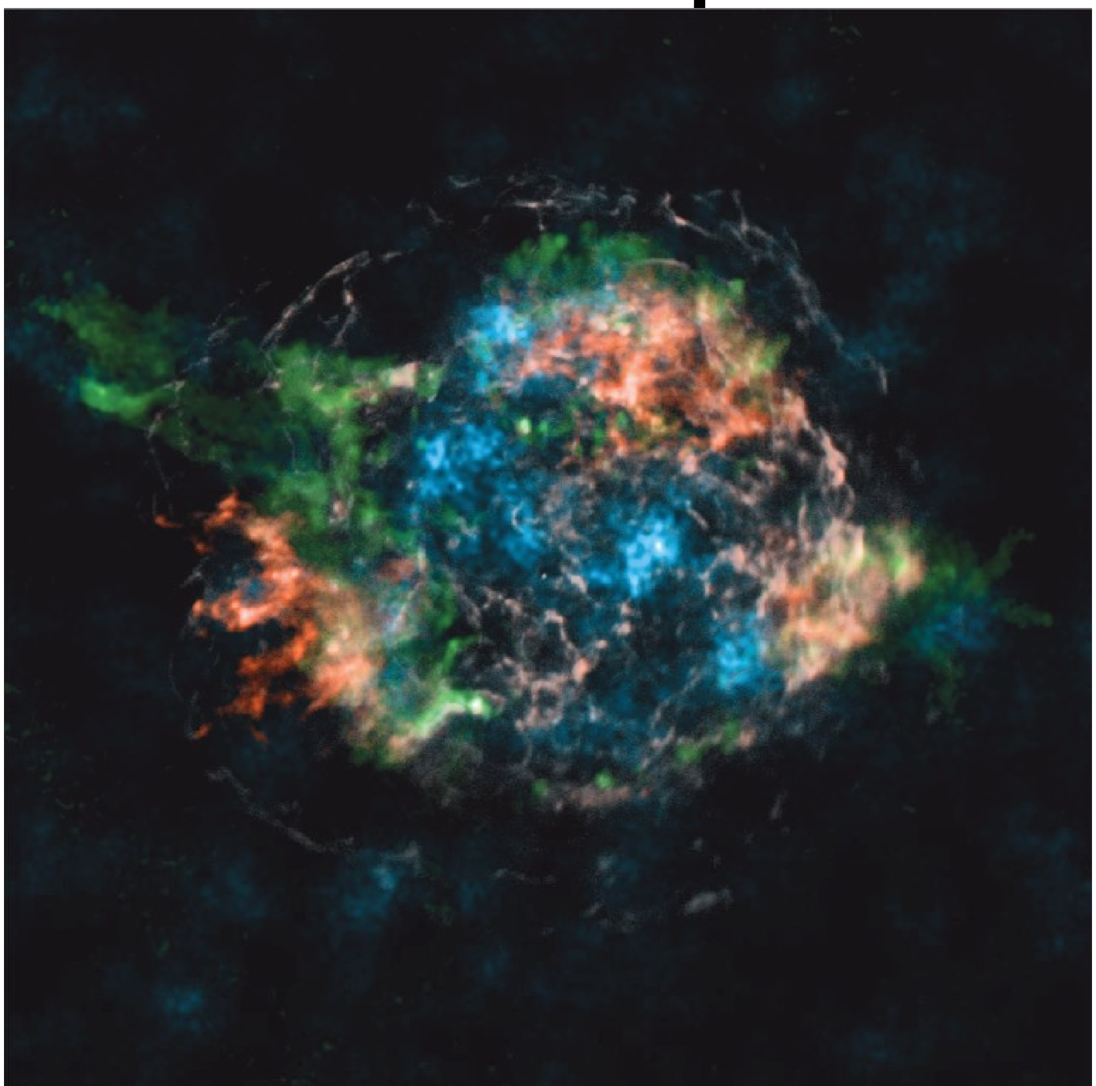

Fritz Zwicky


Hans Bethe

Main Supernova engines

- Massive star collapsing to a neutron star (Baade & Zwicky 1934)
- Thermonuclear explosion of a star (Hoyle & Fowler 1960);
- Both exists in nature: CCSNe and SNIa

Massive stars can explode: Core Collapse SN explosion



Grefenstette et al. 2014, Nature (NuSTAR data)

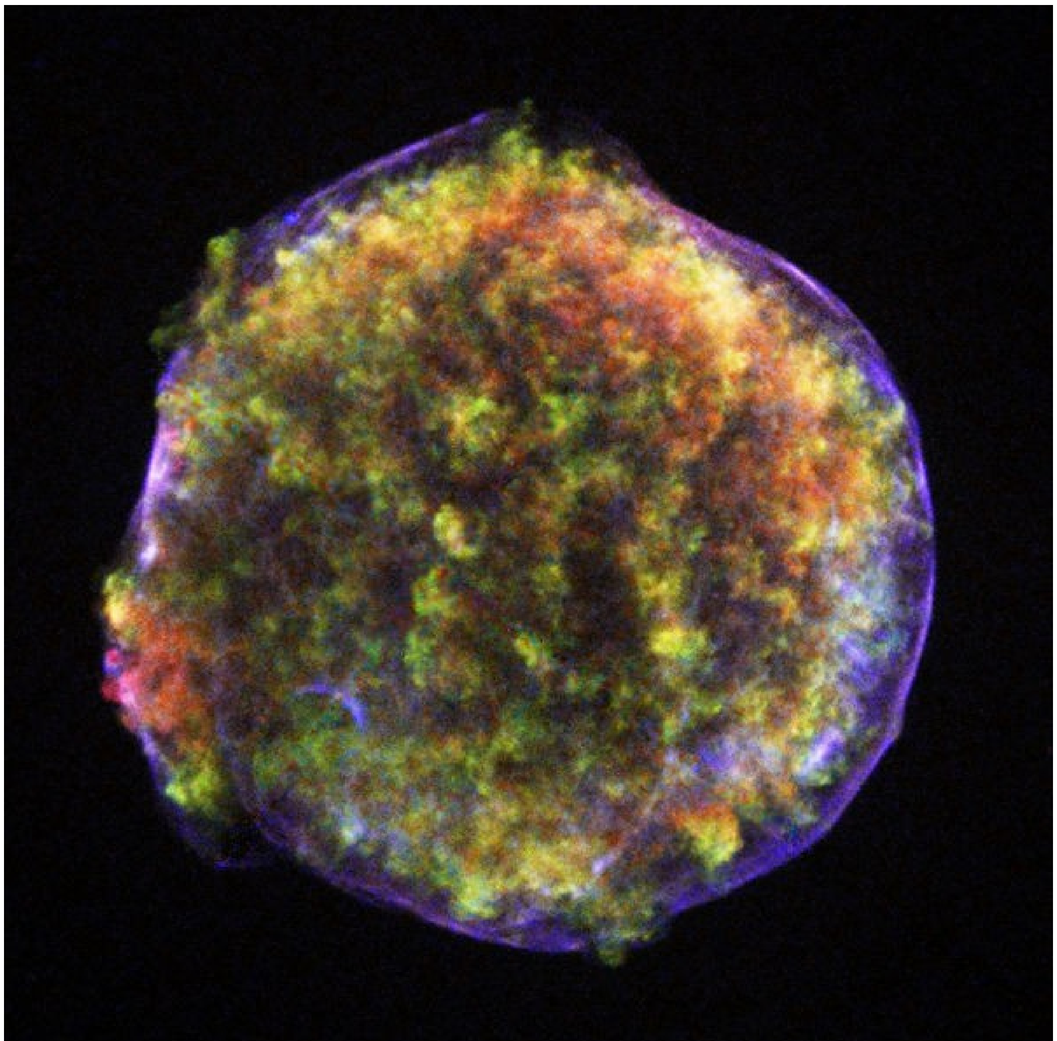
Cas A

11000 ly

~ 300 years ago

Recent review:
Mueller B. 2016, PASA

Smaller stars can explode too: Thermonuclear SN explosions



X-Ray, Chandra obs.

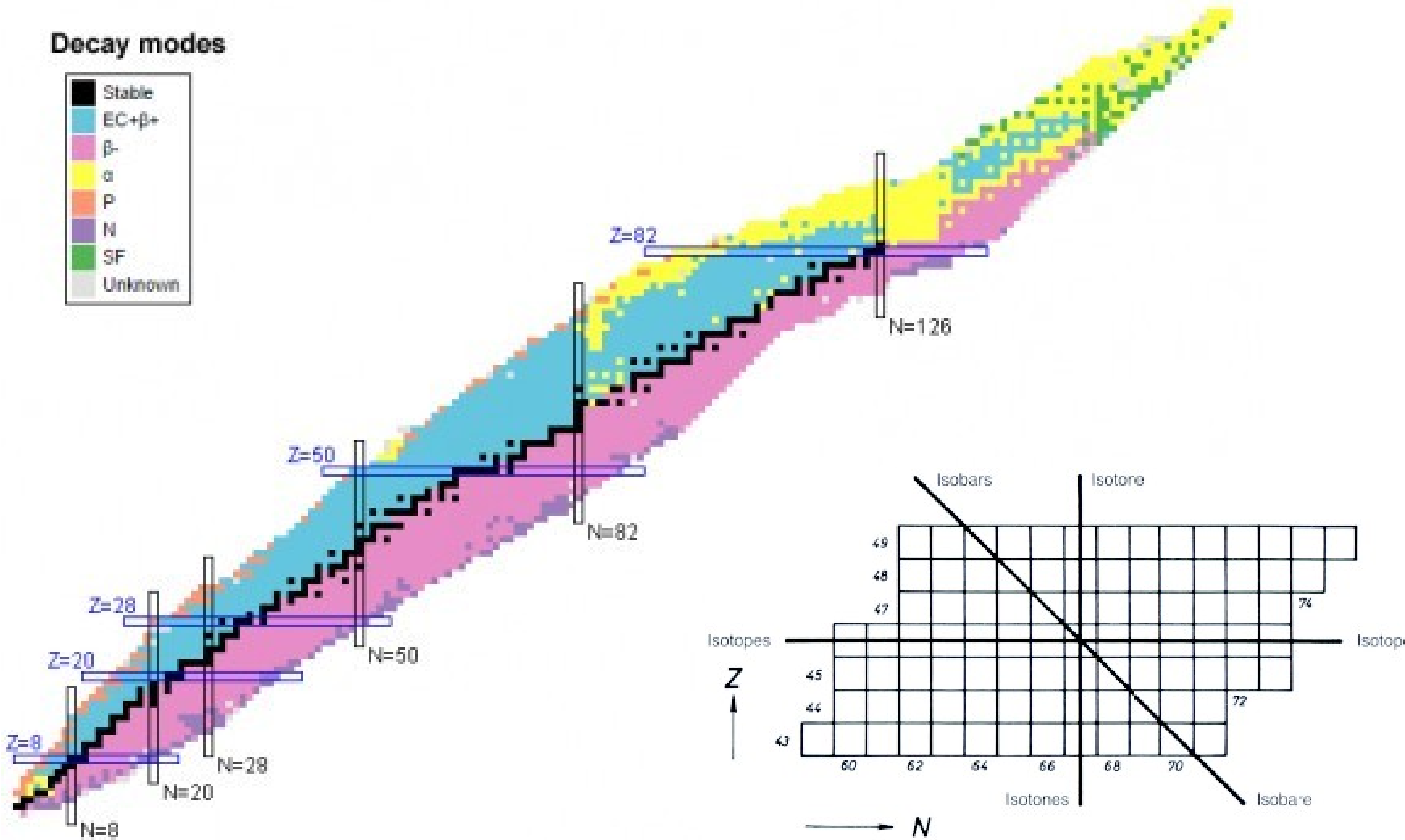
B Cas

~ 9000 ly

~ Nov 1572

Recent review:
Hillebrandt W. et al. 2013, Frontiers of Physics

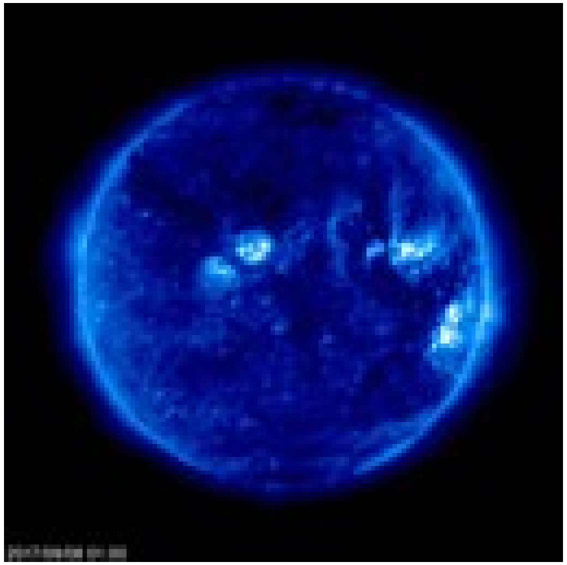
Nucleosynthesis in stars: production of isotopes and elements



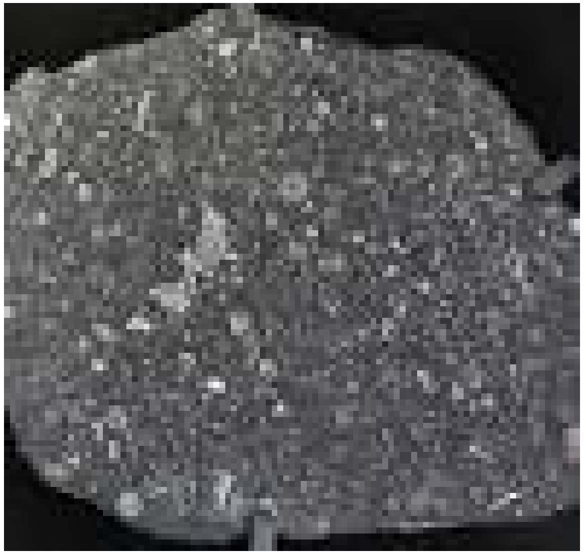
Stable elements are made of stable isotopes
For astronomers, usually C12 ~ C and O16 ~ O.

^{14}O 1.18 m β^+	^{15}O 2.04 m β^+	^{16}O 99.762 0.038 mb	^{17}O 0.038	^{18}O 0.2 0.00886 mb
^{13}N 9.96 m β^+	^{14}N 99.634 0.041 mb	^{15}N 0.366 0.0058 mb	^{16}N 7.13 s β^-	^{17}N 4.17 s β^-
^{12}C 98.89 0.0154 mb	^{13}C 1.11 0.021 mb	^{14}C 5.70 ka 0.00848 mb, β^-	^{15}C 2.45 s β^-	^{16}C 747.00 ms β^-

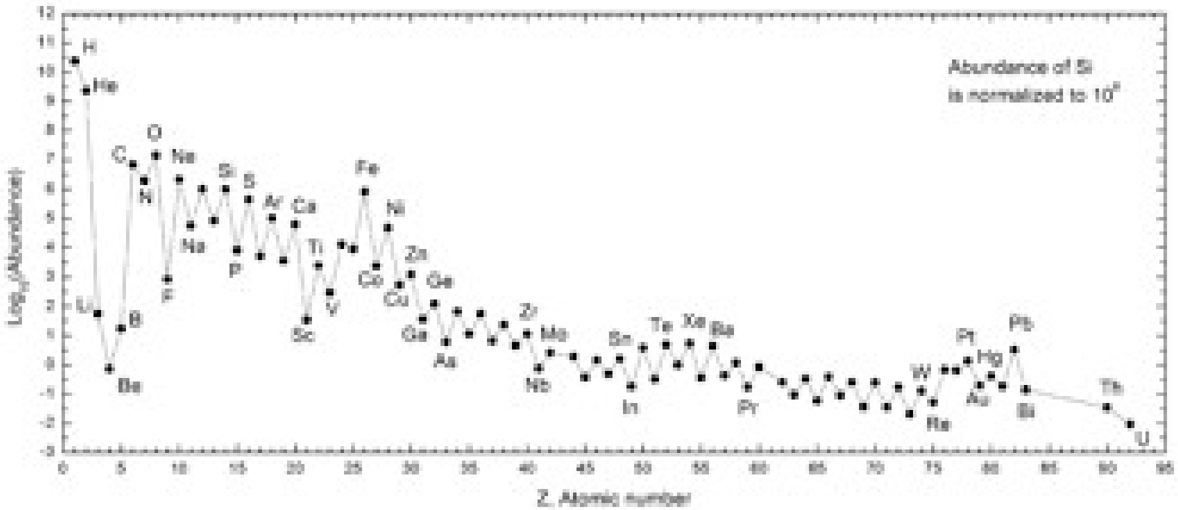
What is the origin of the elements... nearby?



Soho image of the Sun (Extreme ultraviolet Imaging Telescope)



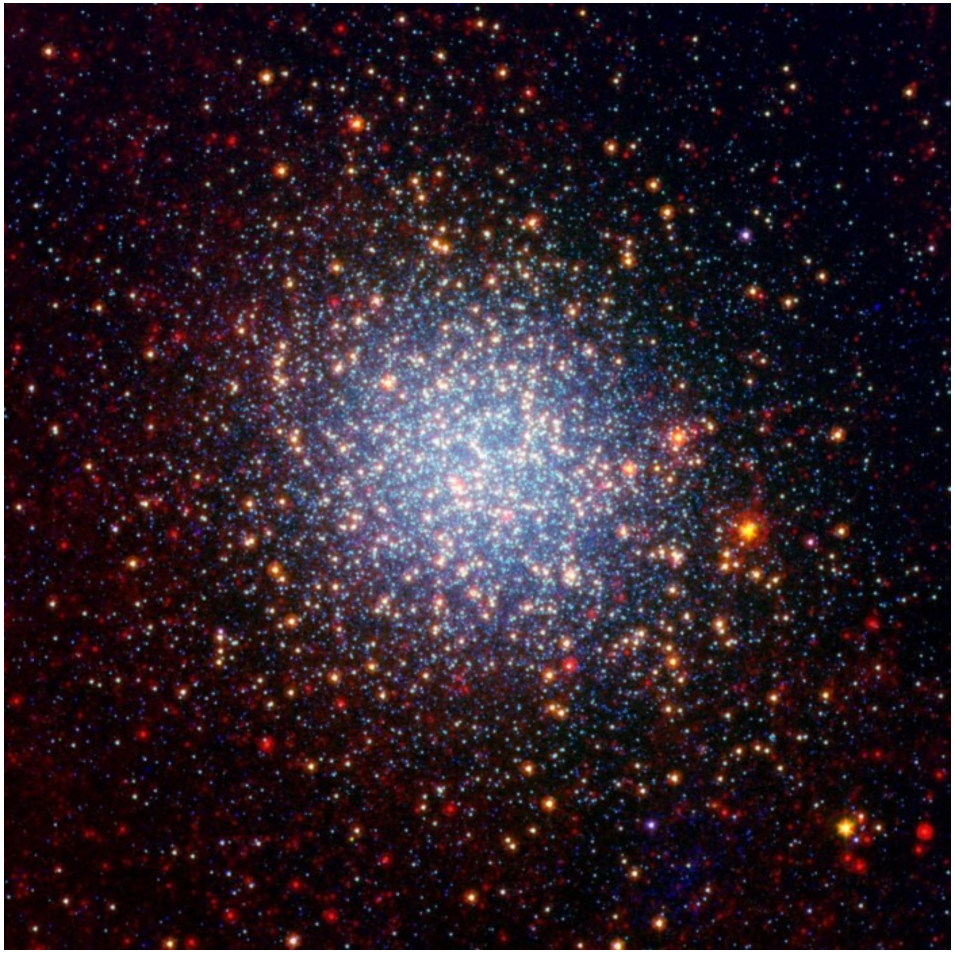
Allende Meteorite (1969)



… or far away?

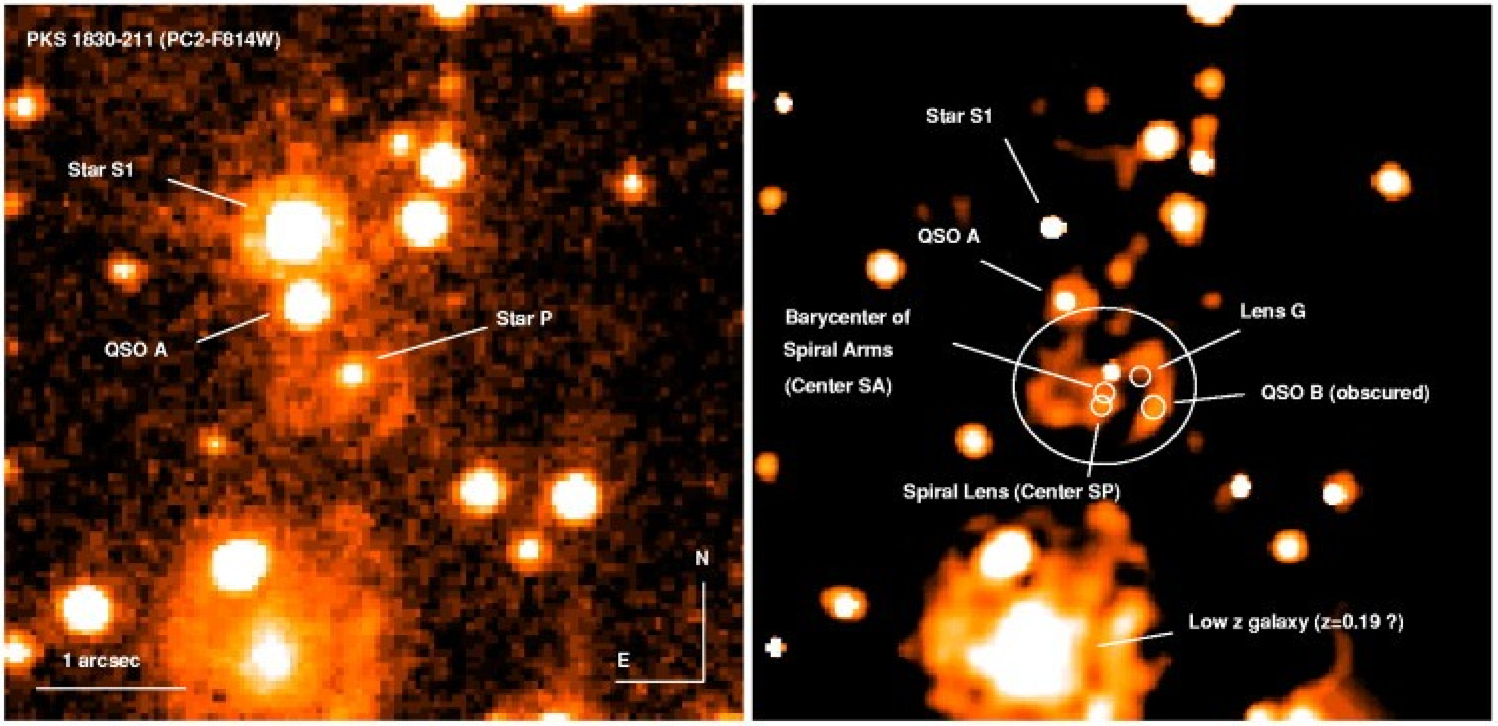
Omega Centauri stellar cluster:

Distance ~ 15800 lyr
Radius ~ 86 lyr
Mass ~ $4 \cdot 10^6$ Msun
~20 times less metals than in the Sun



Spitzer telescope, via wikimedia commons

...or even more far away?



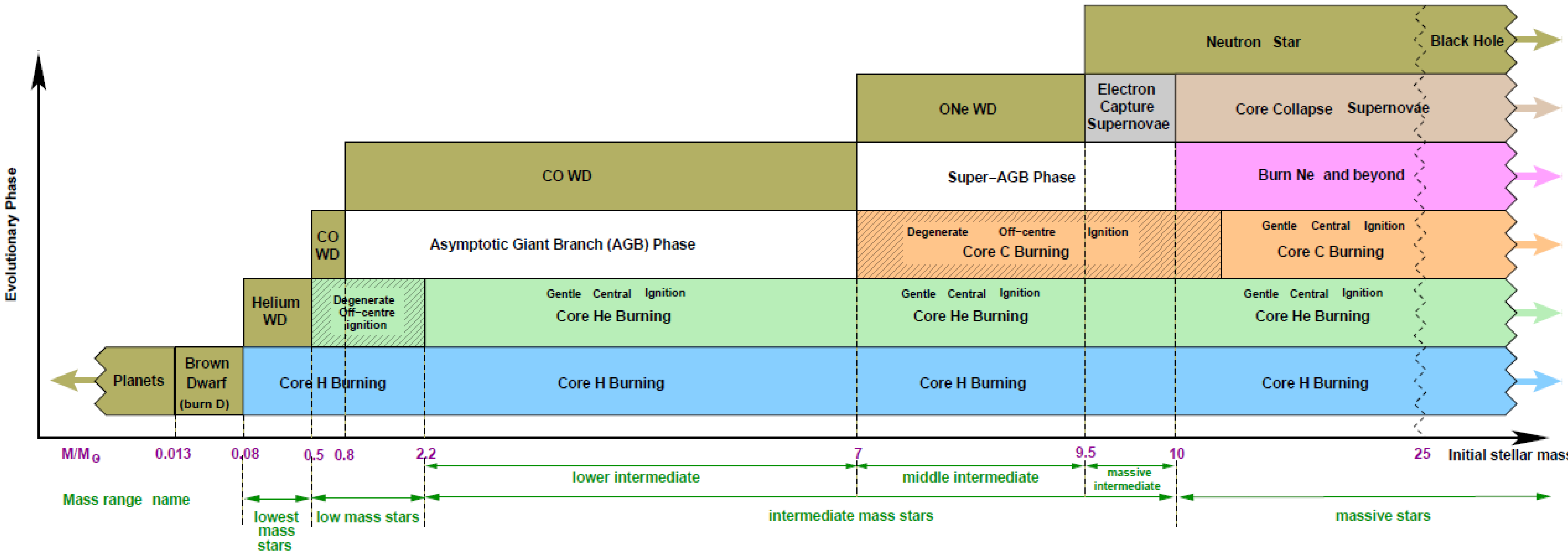
Quasar PKS 1830-211: Courbin+A&A 2002

Absorption line from a spiral galaxy between the quasar and us:
Quasar: redshift Z ~ 2.5
Galaxy Age/distance: z=0.89 corresponds to a look back time of 7.2 Gyr, yielding an age ≤ 6 Gyr
C, N, O, S observed from integrated lines (Muller+06)

Outline and topics

- Definition: low-mass stars, intermediate-mass stars and massive stars;
- Nuclear physics in stars: how to make elements
- Low-mass stars and Asymptotic Giant Branch (AGB) Stars
- The slow neutron capture process: s-process
- The intermediate neutron capture process: i-process
- Nucleosynthesis in massive stars
- The r-process

Stars forming WD and NS



Karakas & Lattanzio 2014, PASA

Stellar structure equations (a simpler version)

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

Hydrostatic equilibrium
(gravity in balance with pressure)

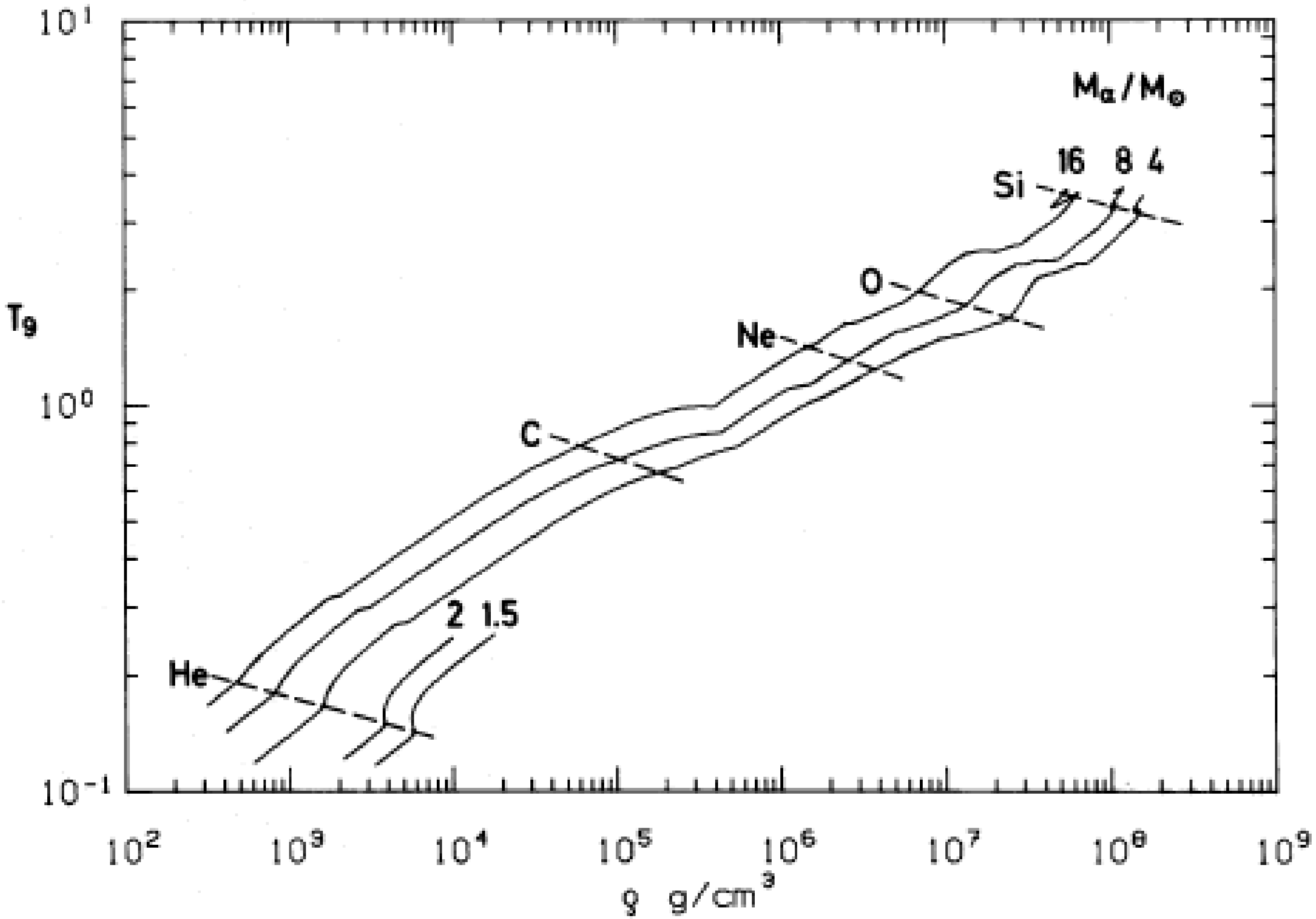
$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

Mass conservation

$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

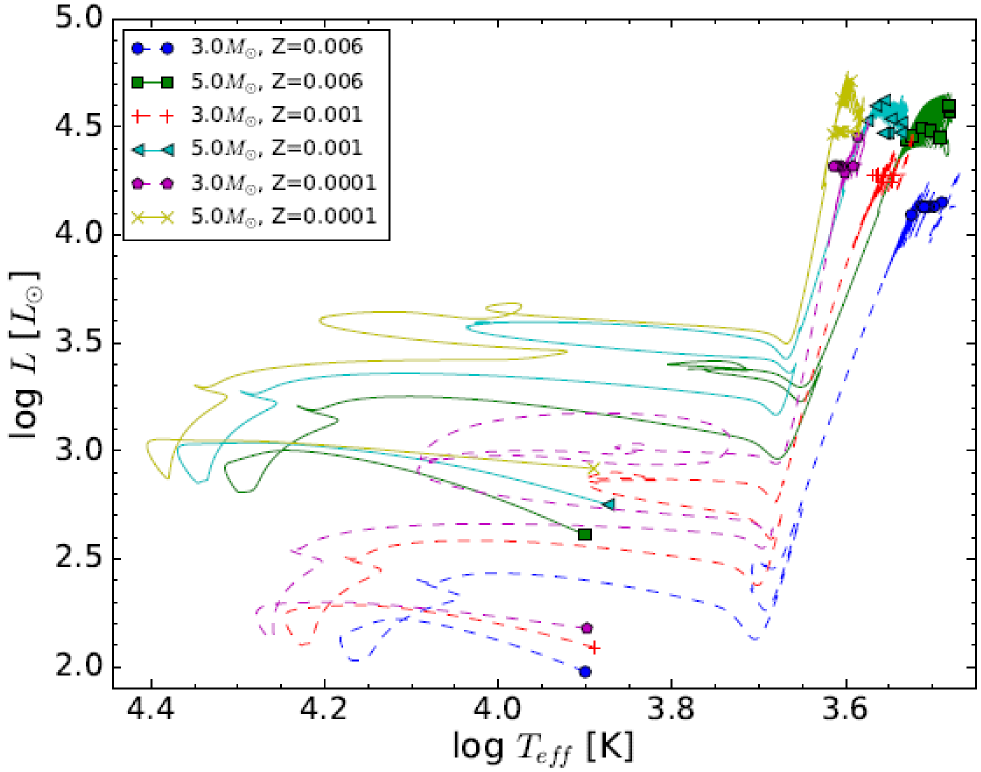
Energy conservation

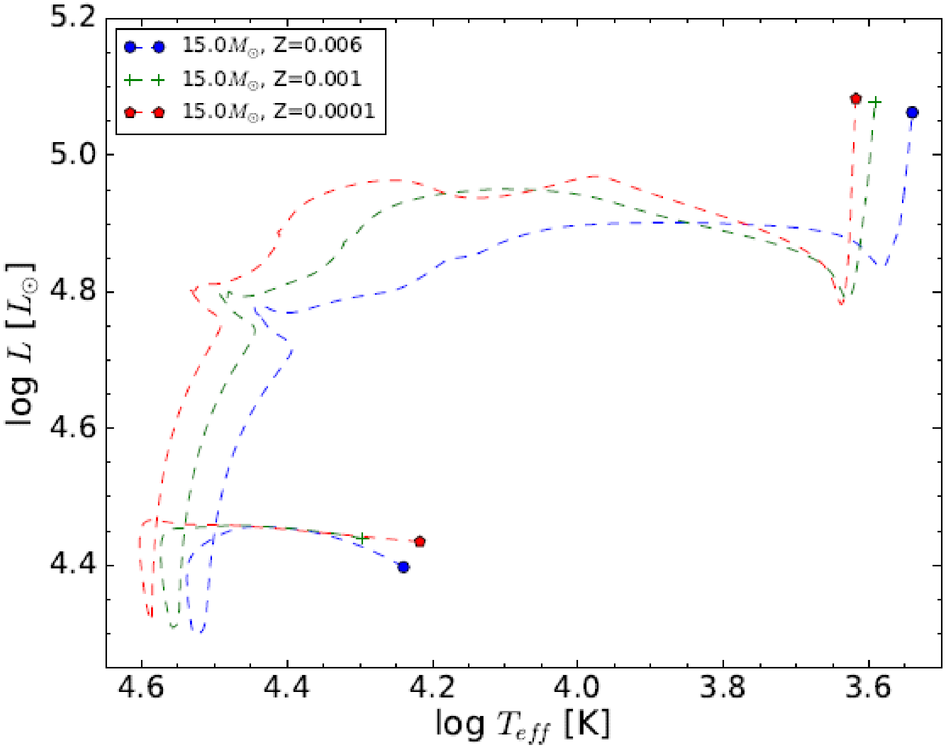
Structure evolution inside



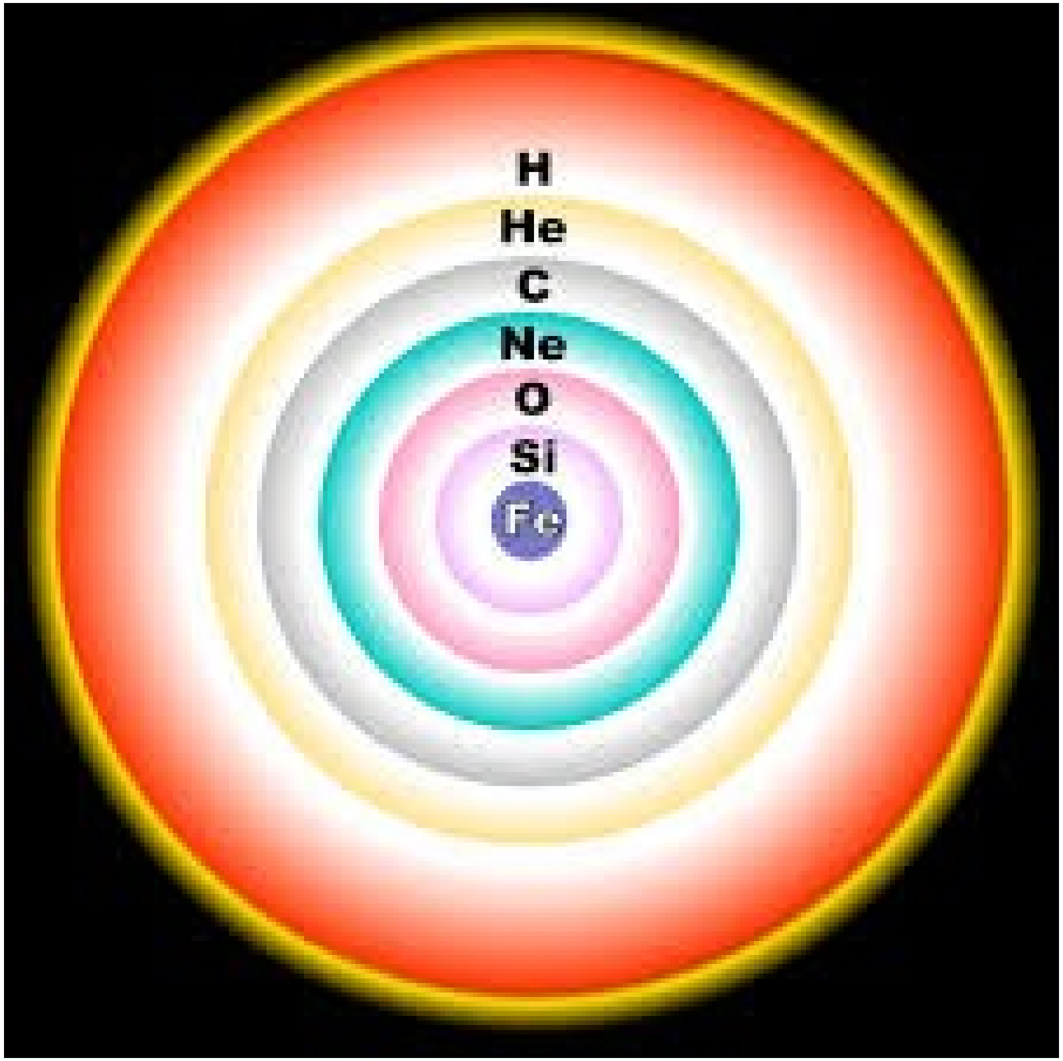
Thielemann & Arnett 1985 ApJ

Structure evolution outside





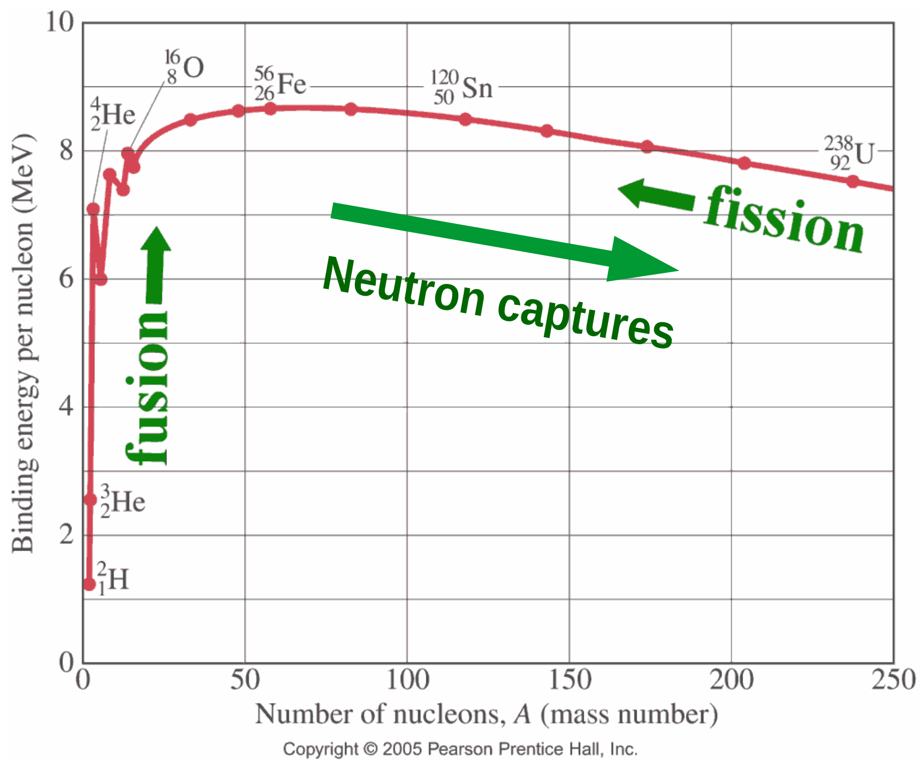
Ritter, MP+ 2018 MNRAS



Nuclear physics is crucial for stellar structure evolution and for making elements

Binding energies: how nuclei stick together

The binding energy increases roughly with A.
<u>Binding energy per nucleon B/A</u>:

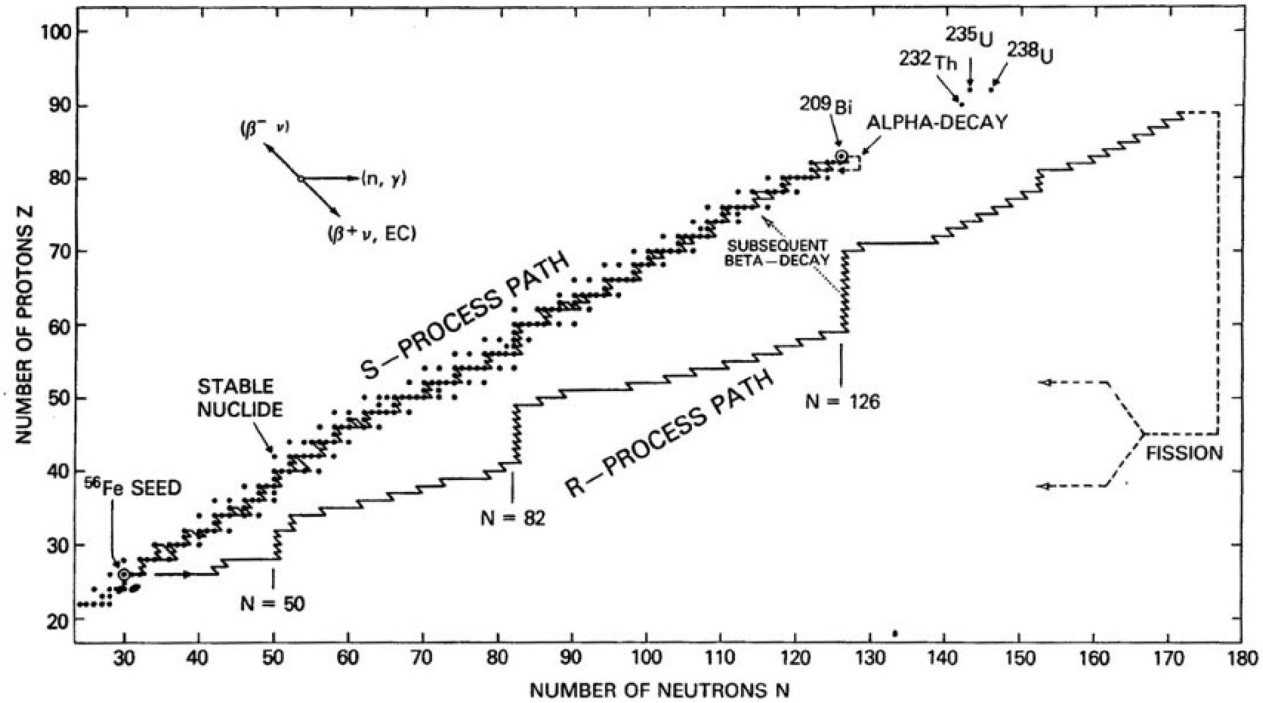


- Binding energy roughly constant ~8 MeV
- Maximum near A=56 (iron)
- Energy gain by fusion of small nuclei or fission of large ones
- At low masses: binding energy large when A is a multiple of 4

List of neutron capture processes

- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) - 10^{18} n cm$^{-3} < N_n < 10^{20}$ n cm^{-3};
- The i process - 10^{14} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- Neutron capture triggered by the Ne22(α,n)Mg25 in massive AGB stars and super-AGB stars - $N_n < 10^{14}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n <$ few 10^{12} n cm^{-3}.

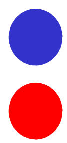
Paths of neutron capture processes



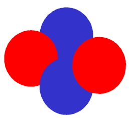
Cauldrons in the cosmos, 1988

Nuclear reactions: Chadwick experiment (1932)

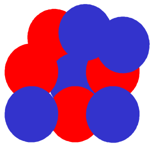
Neutron
Proton



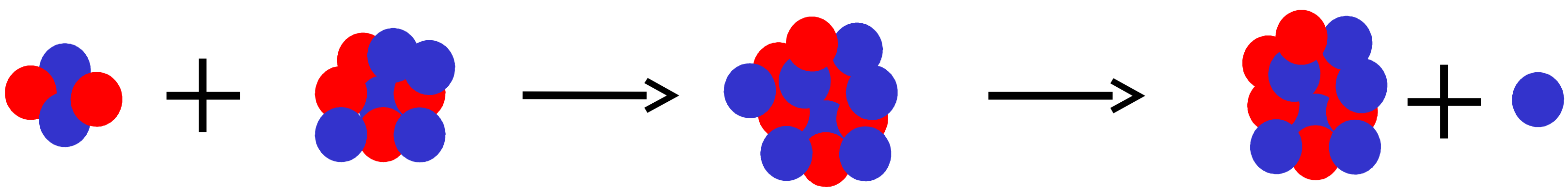
Helium



Beryllium



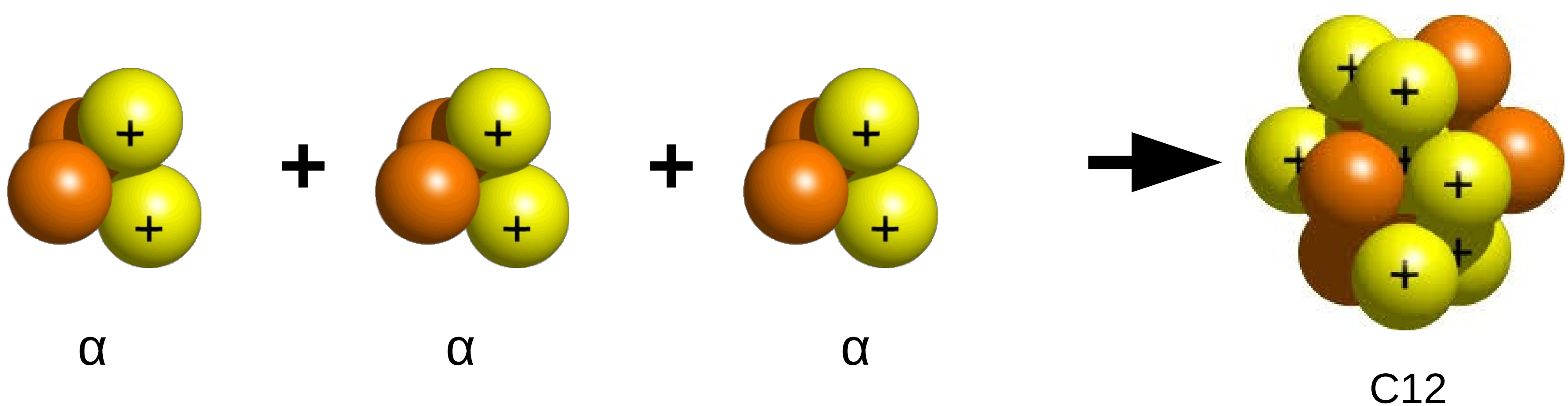
$$^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{13}_{6}\mathrm{C} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n}$$



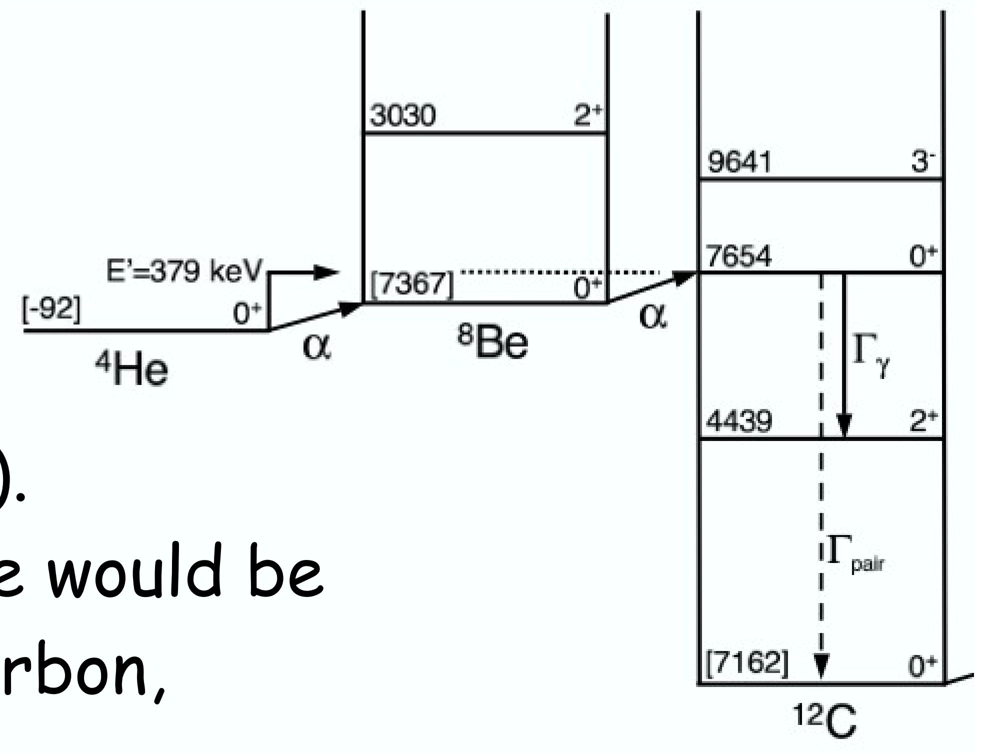
2 neutrons + 5 neutrons = 7 neutrons = 6 neutrons + 1 neutron
2 protons + 4 protons = 6 protons = 6 protons

3α reaction: a nice story about how we are all here

- Step 1: Two alpha particles <---> ^{8}Be:
  - ^{8}Be is unstable, and decays back to 2 alpha particles in ~ 10^{-16} seconds → 1 ^{8}Be every 10^{9} alpha particles.
- Step 2: ^{8}Be + alpha <---> ^{12}C:
  - Low probability, high energies required



- The 12C in nature should be orders of magnitudes lower than what we observe!
- But in 1957 Cook, Fowler, Lauritsen and Lauritsen at Kellogg Radiation Laboratory at Caltech discovered a state allowing to build ^{12}C in step 2 (at **7.654 MeV**).
- Without this state, there would be basically no metals, no carbon, no oxygen..



Iliadis et al.

Fred Hoyle's predicted the existence of the Hoyle state few years earlier...

...but no noble prize

Low-mass stars
Intermediate-mass stars
High-mass stars

Nuclear burning stages

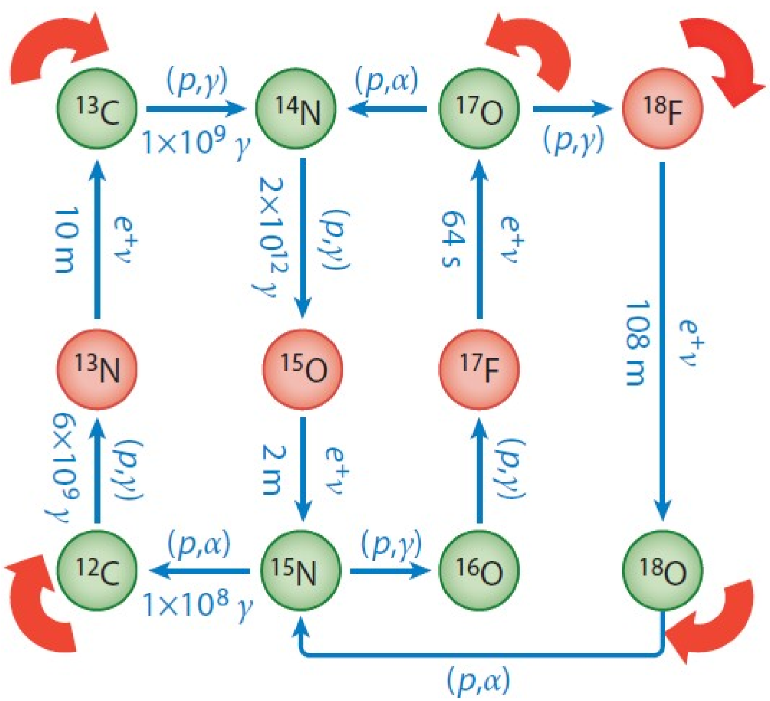
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2–0.4	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

From: Alex Heger

See also Jones et al. 2013, ApJ

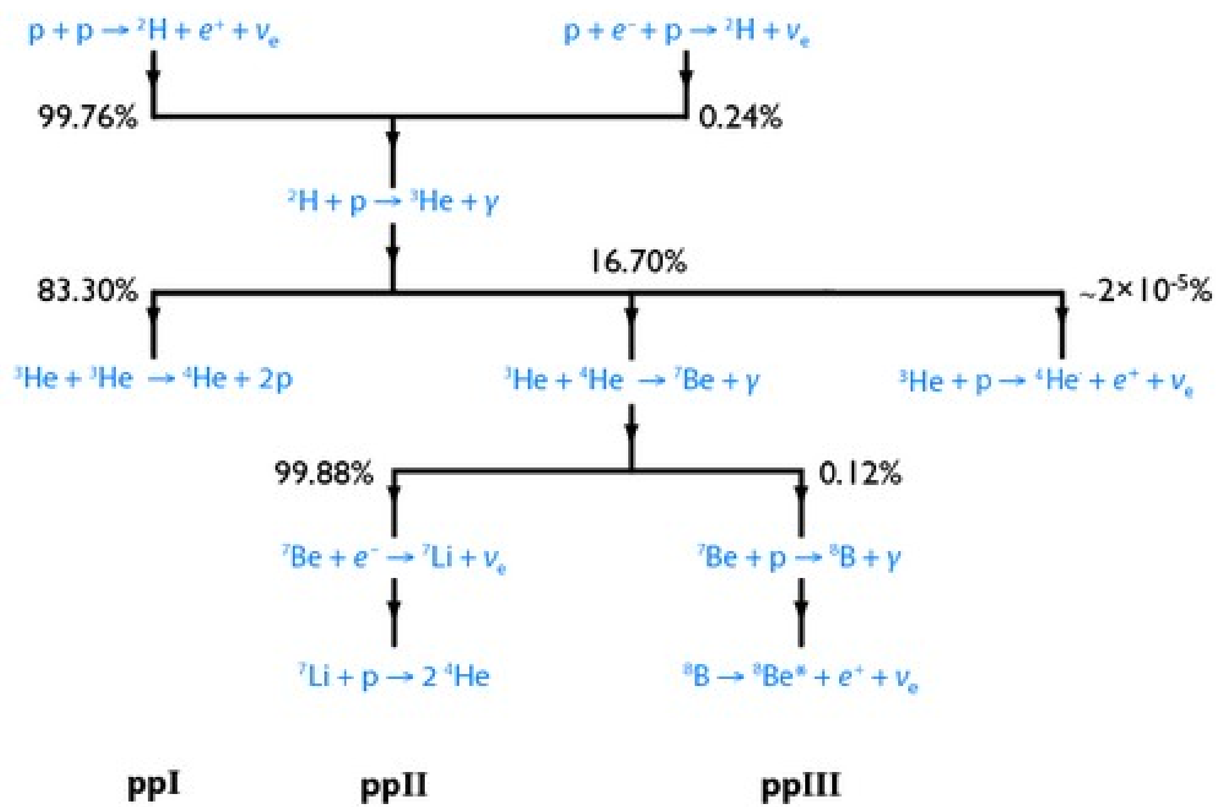
Introduction to the evolutionary stages in stars: H burning

Cold CNO cycle



Wiescher+ 2010, Annu. Rev. Nucl. Part. Sci.

pp chain



Adelberger+ 2011, RevMP

He burning

IMPORTANT REACTIONS IN HELIUM BURNING

Energy generation:

$^{4}\text{He}(2\alpha,\gamma)^{12}\text{C}(\alpha,\gamma)^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$

Neutron source:

$^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^{+})^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}\begin{cases}(\alpha,\gamma)^{26}\text{Mg}\\(\alpha,n)^{25}\text{Mg}\end{cases}$

High-temperature burning with effective $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$:

$^{22}\text{Ne}(n,\gamma)^{23}\text{Ne}(\beta^{-})^{23}\text{Na}(n,\gamma)^{24}\text{Na}(\beta^{-})^{24}\text{Mg}$

$^{20}\text{Ne}(n,\gamma)^{21}\text{Ne}(\alpha,n)^{24}\text{Mg}$

$^{24}\text{Mg}(n,\gamma)^{25}\text{Mg}(n,\gamma)^{26}\text{Mg}(n,\gamma)^{27}\text{Mg}(\beta^{-})^{27}\text{Al}$

$^{27}\text{Al}(n,\gamma)^{28}\text{Al}(\beta^{-})^{28}\text{Si}(n,\gamma)^{29}\text{Si}$ + further *s*-processing

Thielemann & Arnett 1985 ApJ

C-burning

Panel a)

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

$^{12}C(^{12}C,p)^{23}Ne$

$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C(\alpha,n)^{16}O$ $\qquad$ $^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$

$^{25}Mg(n,\gamma)^{26}Mg(p,\gamma)^{27}Al$

$^{16}O(\alpha,\gamma)^{20}Ne$

$^{20}Ne(n,\gamma)^{21}Ne$

Panel b)

$^{16}O(\alpha,\gamma)^{20}Ne$

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

$^{12}C(^{12}C,p)^{23}Na$
- $(p,\alpha)^{20}Ne$
- $(p,\gamma)^{24}Mg$
- $(\alpha,p)^{26}Mg$

$^{22}Ne(\alpha,n)^{25}Mg(p,\gamma)^{26}Al(\beta^{+})^{26}Mg(p,\gamma)^{27}Al$

$^{22}Ne(p,\gamma)^{23}Na$

$^{20}Ne(n,\gamma)^{21}Ne(\alpha,n)^{24}Mg$

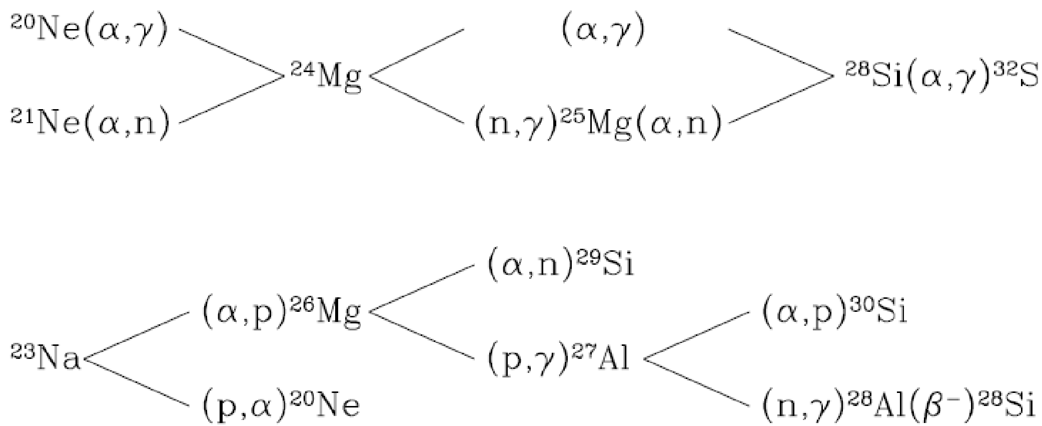
$^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{12}C(n,\gamma)^{13}C(\alpha,n)^{16}O$

Chieffi+1998 ApJ

Ne-burning

$^{20}Ne(\gamma,\alpha)^{16}O$



$^{22}Ne(\alpha,n)^{25}Mg$

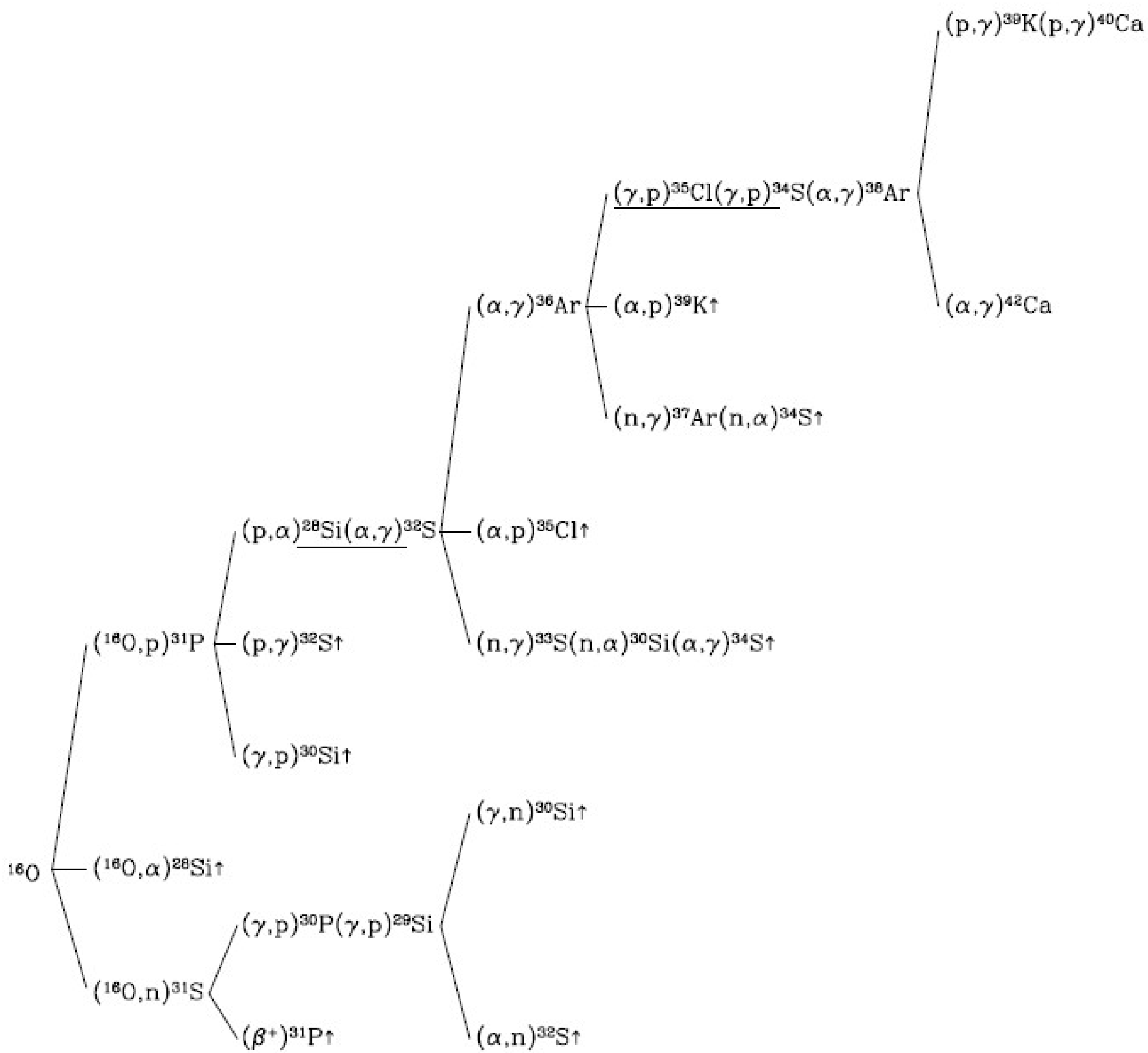
$^{20}Ne(n,\gamma)^{21}Ne$

$^{28}Si(n,\gamma)^{29}Si(n,\gamma)^{30}Si$

$^{25}Mg(n,\gamma)^{26}Mg$

Chieffi+1998 ApJ

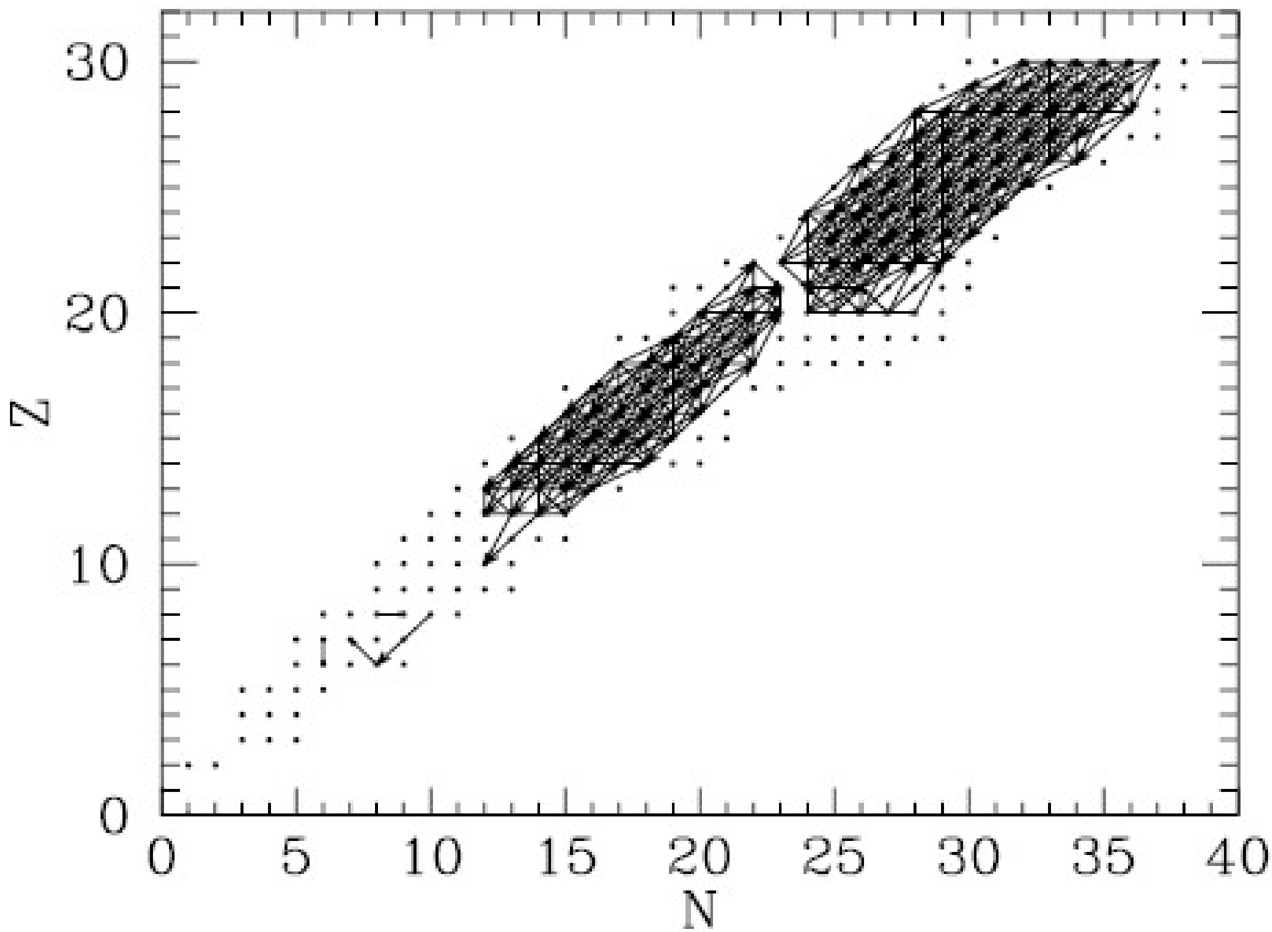
O-burning



Chieffi+1998 ApJ

Si-burning

Chieffi+1998 ApJ



Reactions network approaching QSE

Reaction Links between the Two QSE Groups in Silicon Burning

Basic reactions:

$\boxed{^{38}Ar}\ (\alpha,\gamma)$, $\boxed{^{39}K}\ (\alpha,p)$ $\ ^{42}Ca(\alpha,p)^{45}Sc$

^{45}Sc:
- $(p,\gamma)^{46}Ti$
- $(n,\gamma)^{46}Sc(p,n)^{46}Ti$
- $(\gamma,p)^{44}Ca$:
  - $(\alpha,n)^{47}Ti$
  - $(p,n)^{44}Sc(\gamma,p)^{43}Ca$: $(n,\gamma)^{44}Ca$; $(\gamma,n)^{42}Ca$
- $(p,n)^{45}Ti(n,\alpha)^{42}Ca$

^{46}Ti:
- $(p,\gamma)^{47}V(n,p)$, (n,γ) } $^{47}T(n,\gamma)$ (^{48}Ti)
- $(\alpha,n)^{49}Cr(n,\gamma)$ (^{50}Cr)
- (α,p) (^{49}V)
- $(\gamma,\alpha)^{42}Ca$

Additional reactions in high-temperature burning:

$^{47}V(p,\gamma)^{48}Cr(n,\gamma)^{49}Cr(n,\gamma)$ (^{50}Cr)

$^{47}Ti(p,\gamma)^{48}V(n,p)$ (^{48}Ti)

Important reactions in low-temperature burning:

$\boxed{^{40}Ar}\ (\alpha,n)$, $^{42}Ca(n,\gamma)$ } $^{43}Ca(n,\gamma)^{44}Ca(n,\gamma)^{45}Ca(n,\gamma)^{46}Ca$

$^{46}Ca(p,\gamma)$, $^{46}Sc(n,\gamma)$ } $^{47}Sc(p,n)^{47}Ti(n,\gamma)$ (^{48}Ti)

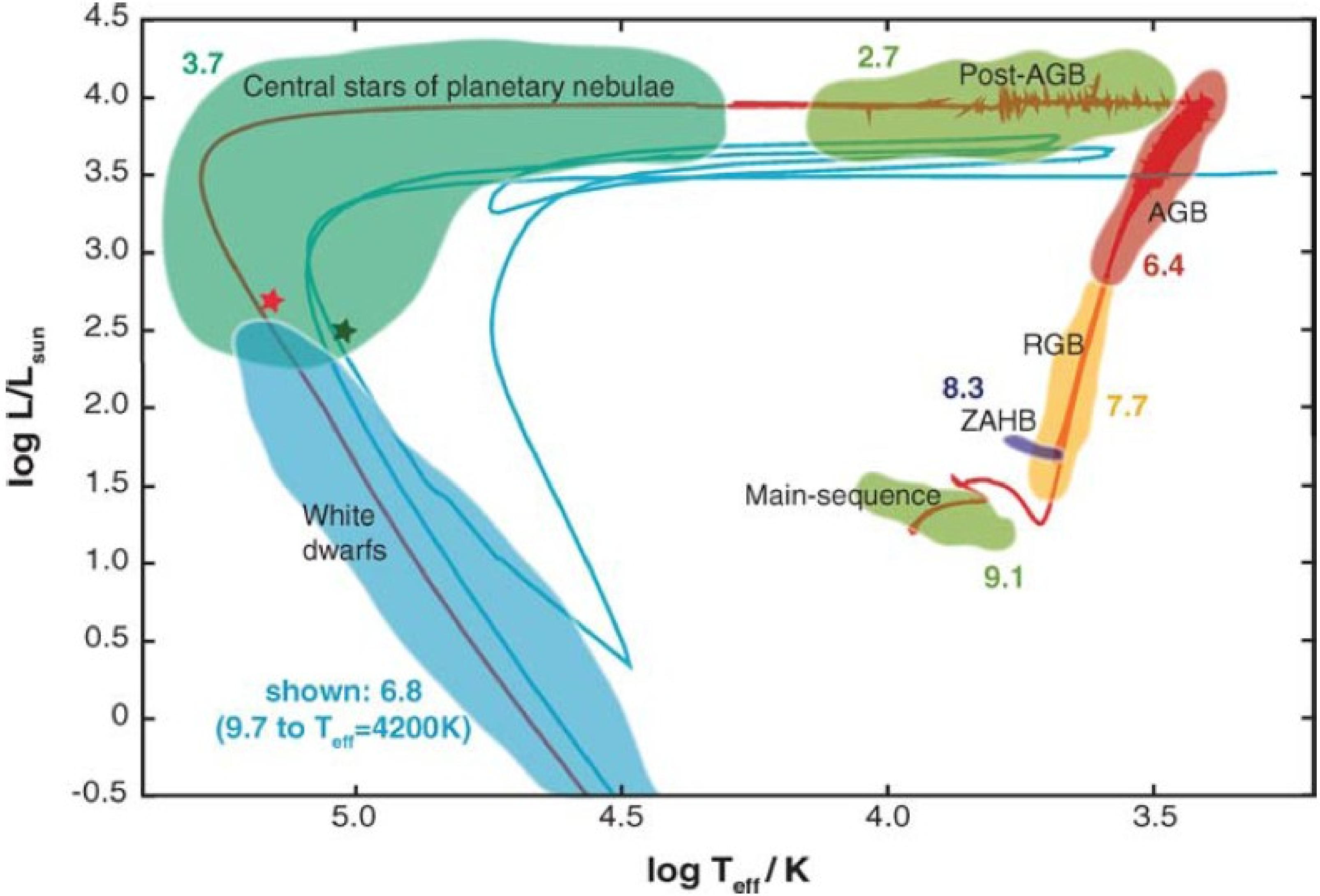
$^{46}Ca(n,\gamma)^{47}Ca(n,\gamma)^{48}Ca(p,n)^{48}Sc$:
- (p,n) (^{48}Ti)
- $(n,\gamma)^{49}Sc(p,n)$ (^{49}Ti)

Note.—□ Members of the first QSE group; ○ members of the second QSE group.

Thielemann & Arnett 1985 ApJ

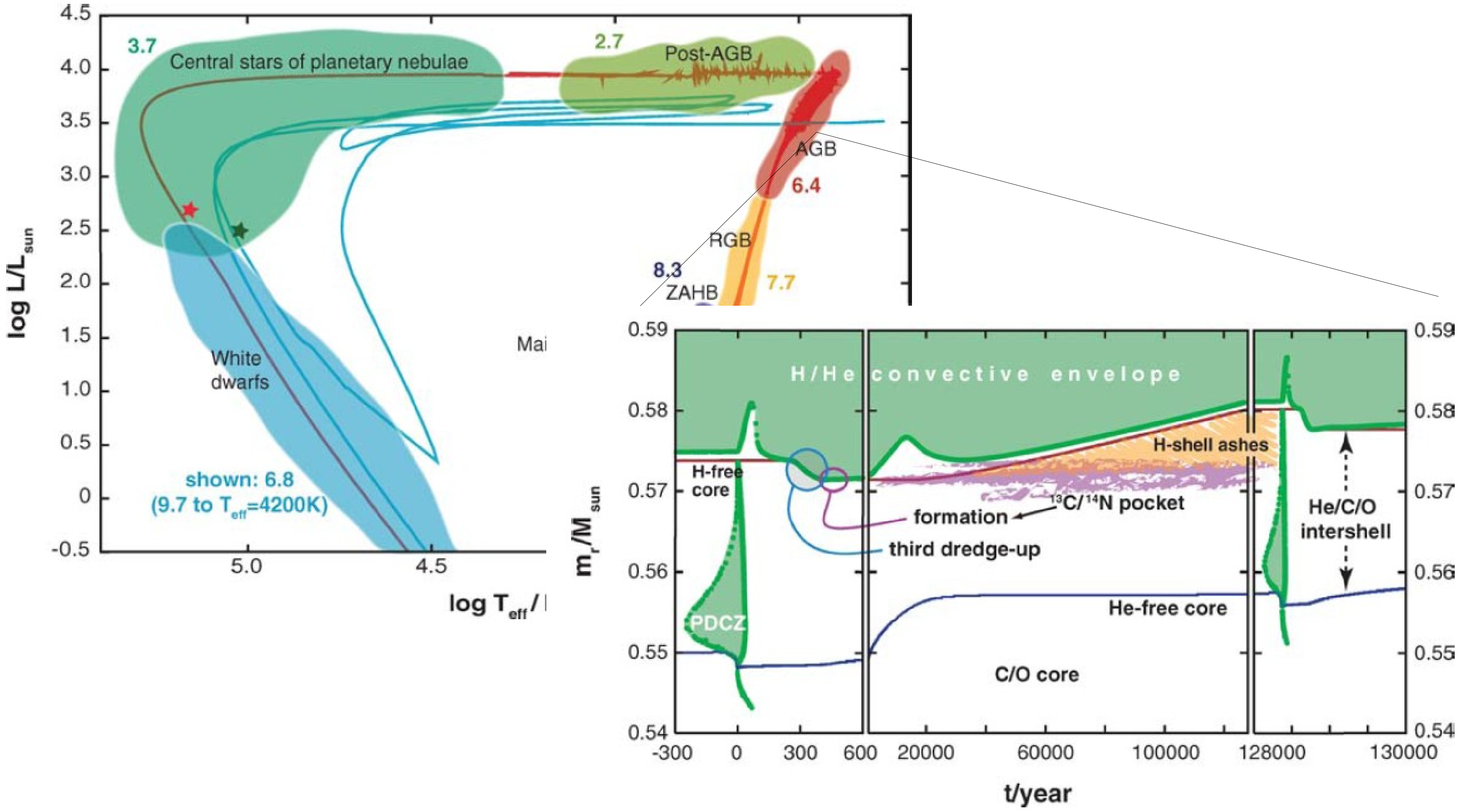
Stellar nucleosynthesis:
Low mass stats

Low-mass stars: HR diagram



Herwig 2005, ARAA

Low-mass stars: HR diagram



Herwig 2005, ARAA

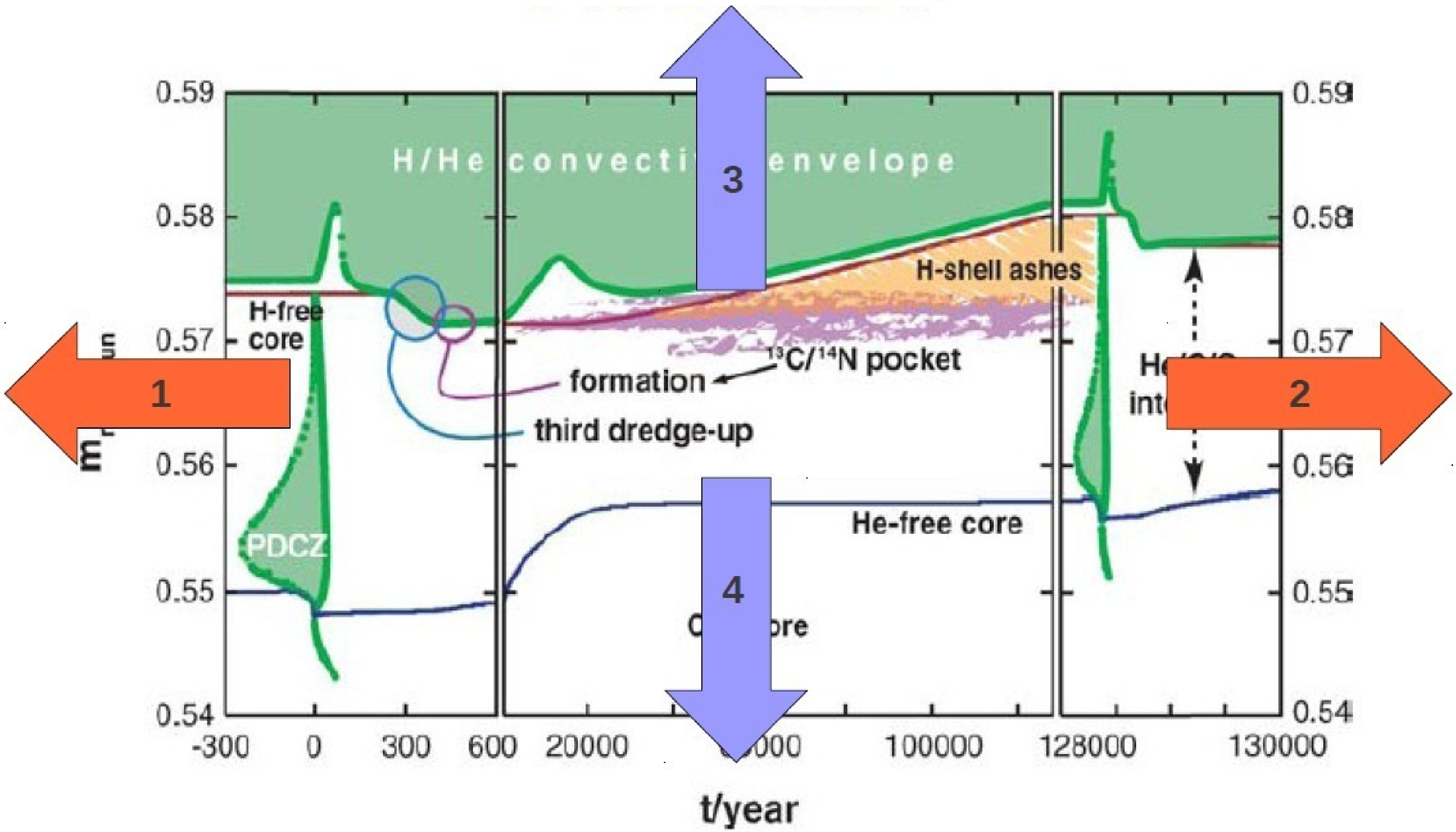
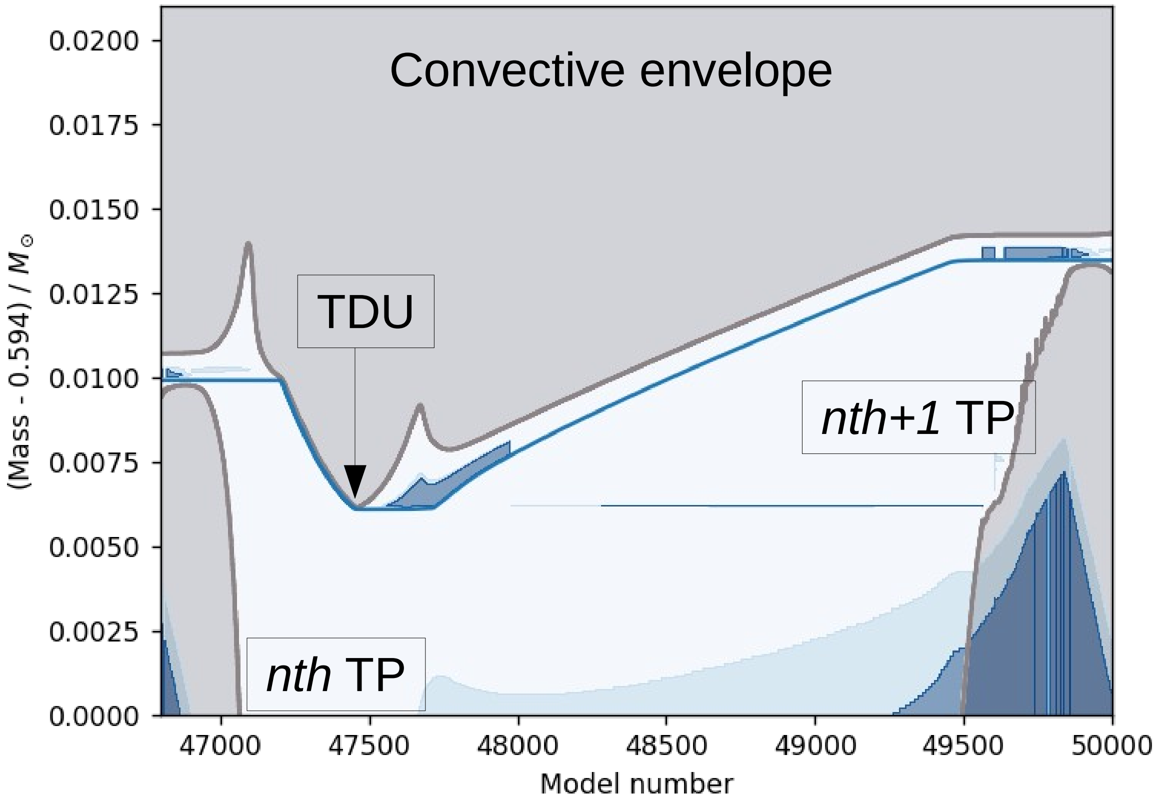


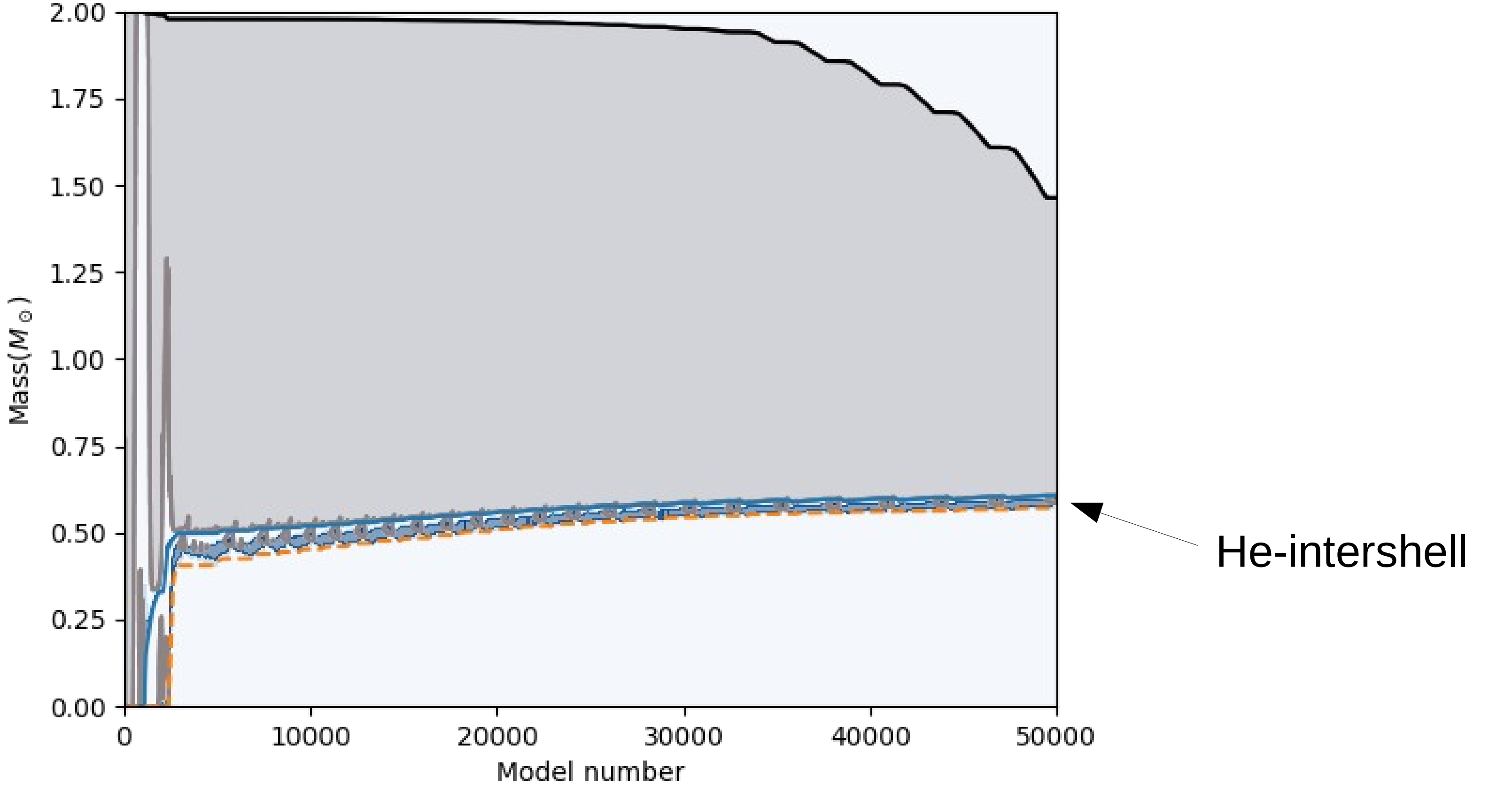
Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

Zooming in the stellar structure: the Third Dredge-Up (TDU)



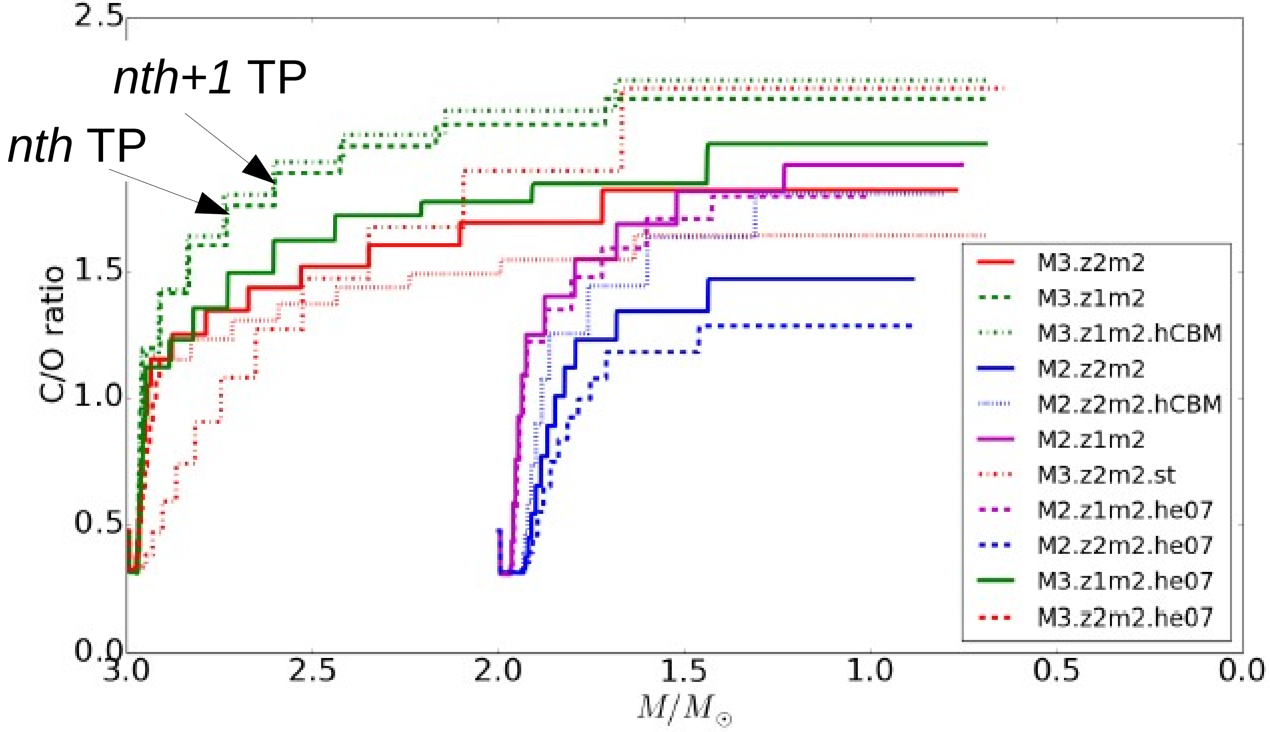
Ritter+2018 MNRAS
M=2Msun, Z=0.01

Without zooming...



Ritter+2018 MNRAS
M=2Msun, Z=0.01

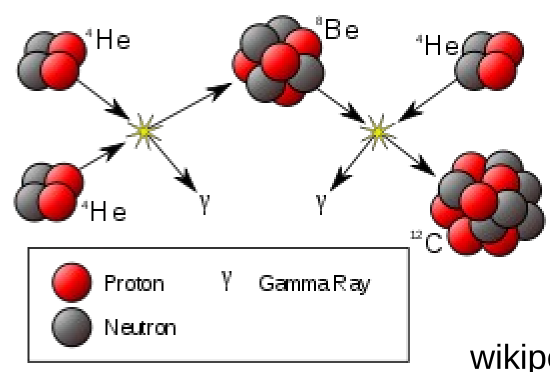
Nucleosynthesis in AGB stars



Battino, MP+ 2016

In the Sun, and in the ISM, there is more O than C... AGB stars make more C than O, so the AGB envelope becomes C-rich after few TPs, before loosing that C in the ISM.

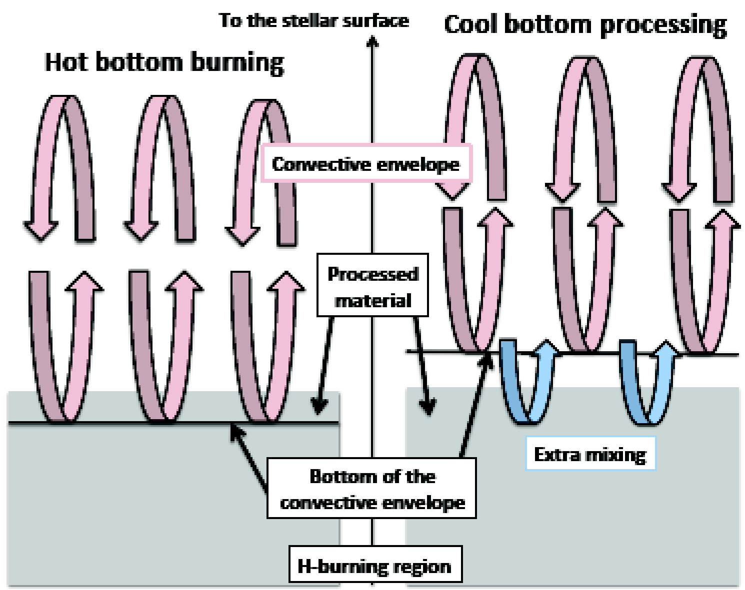
<u>Source of C</u>: activation of 3α rate in the He intershell.



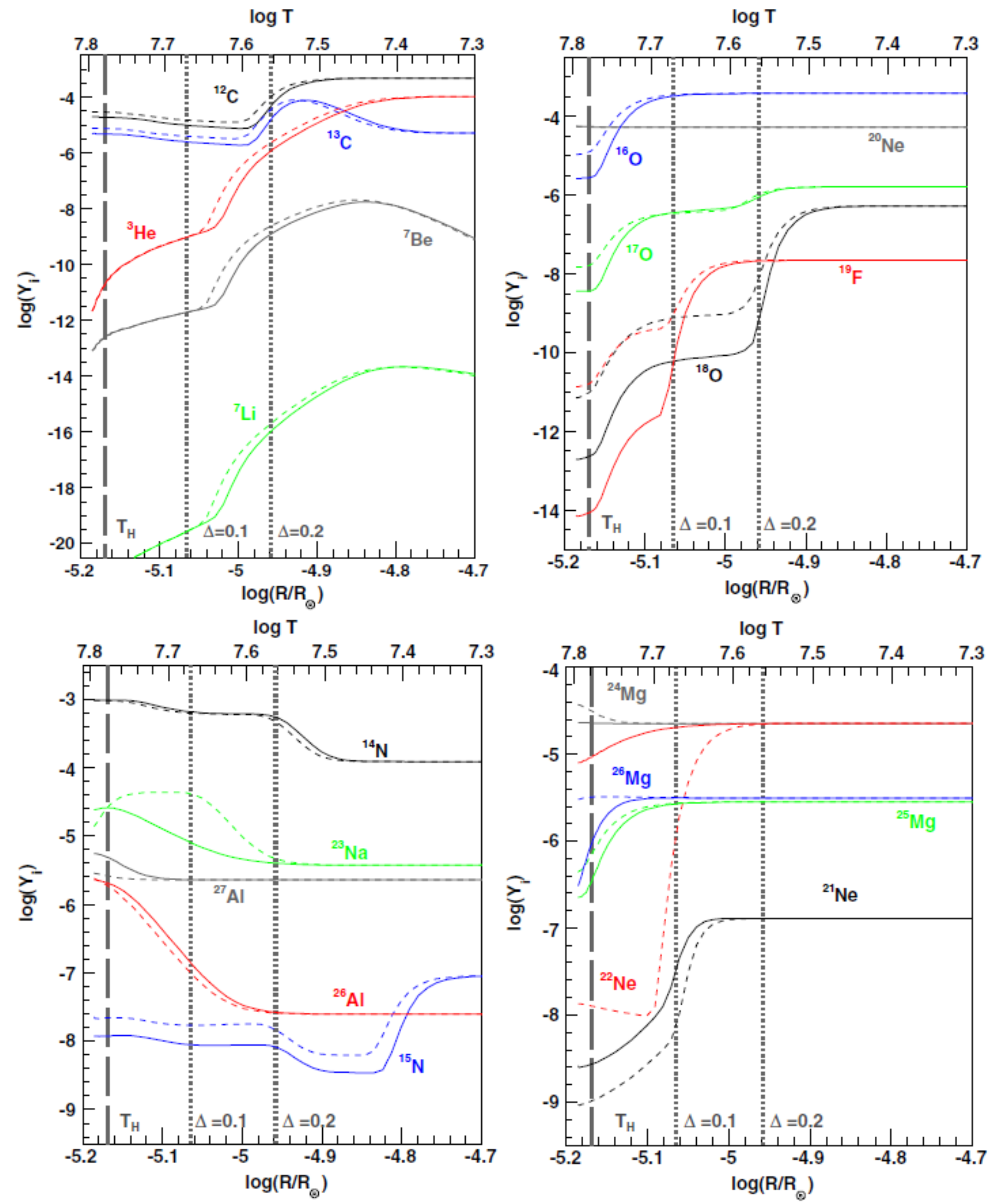
wikipedia

Nucleosynthesis in AGB stars II

Proton-capture nucleosynthesis at the bottom of the AGB envelope, just above the H shell.



CBP vs HBB: Lugaro+2017, Nat.Ast.



Palmerini+2011, ApJ

The slow-neutron capture process in AGB stars

1952ApJ...116...21M

SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S

PAUL W. MERRILL
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received February 27, 1952

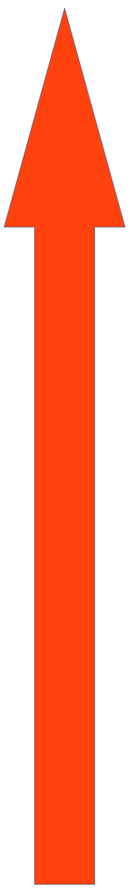
Observation of Tc in AGB stars:
s-process ongoing!

Basic vocabulary and quantities

- Neutron exposure: $\tau = \int v_T N_n(t)\, dt$
- Neutron density: $N_n = X_n \bullet \rho \bullet N_A$
- s-process seeds: Fe, Ne-Na
- s-process poisons: ^{14}N, ^{25}Mg, ^{20}Ne, ^{22}Ne,...
- s-process source: $^{13}C \rightarrow {}^{13}C(\alpha,n){}^{16}O$, $^{22}Ne \rightarrow {}^{22}Ne(\alpha,n){}^{25}Mg$

List of neutron capture processes

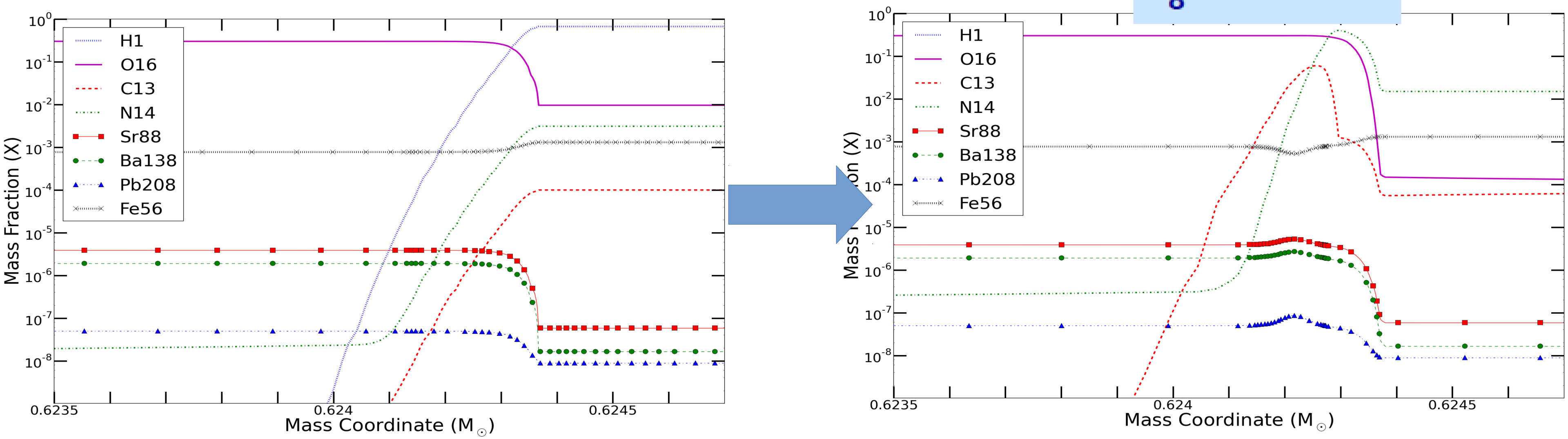
- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) - 10^{18} n cm$^{-3} < N_n < 10^{20}$ n cm^{-3};
- The i process - 10^{14} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- Neutron capture triggered by the Ne22(α,n)Mg25 in massive AGB stars and super-AGB stars - $N_n < 10^{14}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n <$ few 10^{12} n cm^{-3}.



N_n

Formation of the C13-pocket

T_8 ~ 0.9-1



$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$

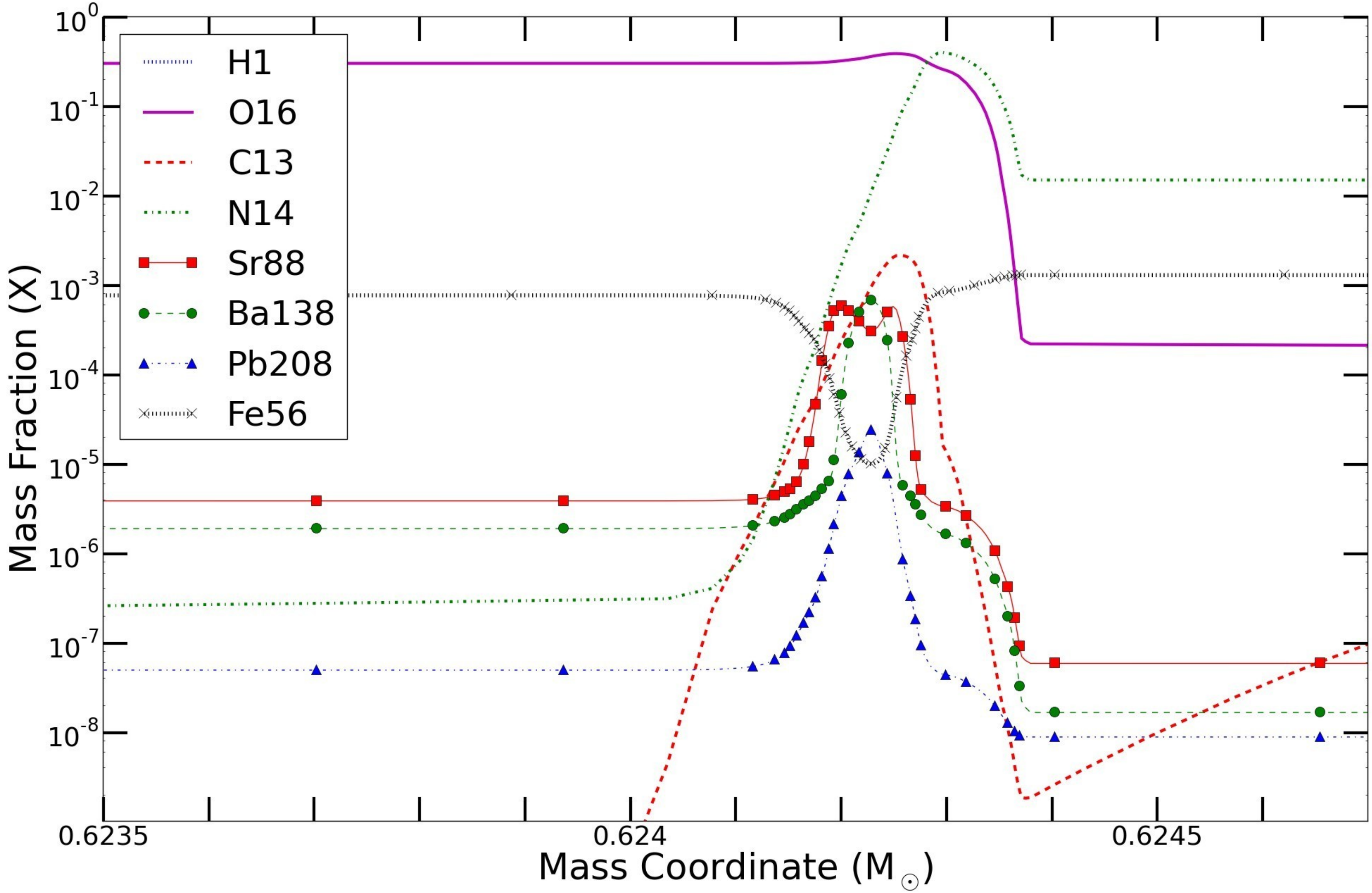
10^7 n/cm^3

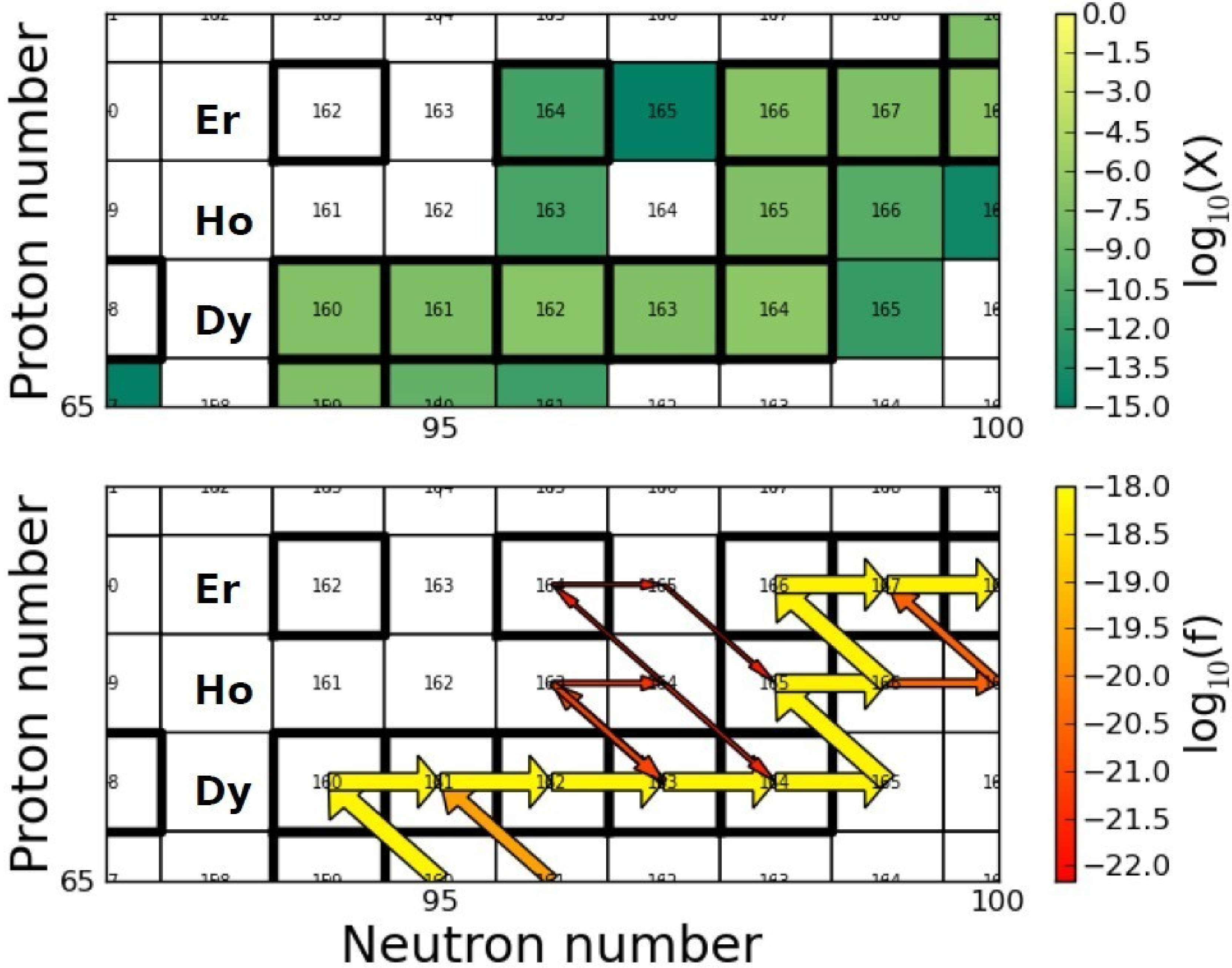
~95% of the total neutron expsure

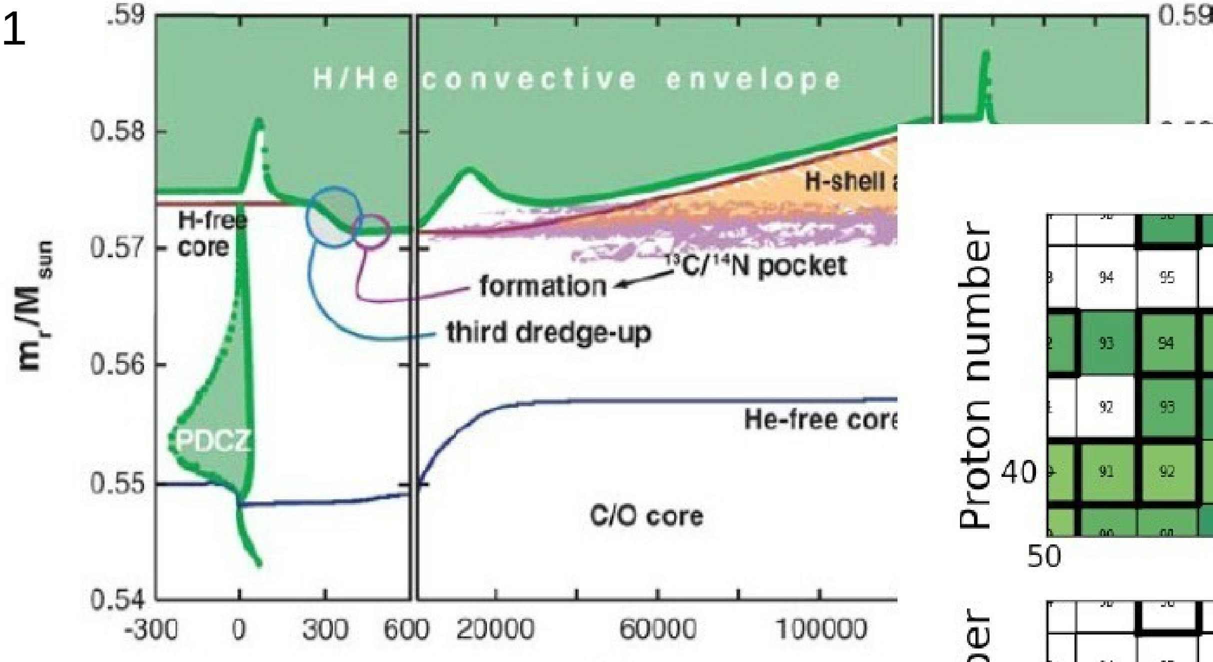
What is (are) the physics mechanism(s) driving the formation of the C13-pocket ?

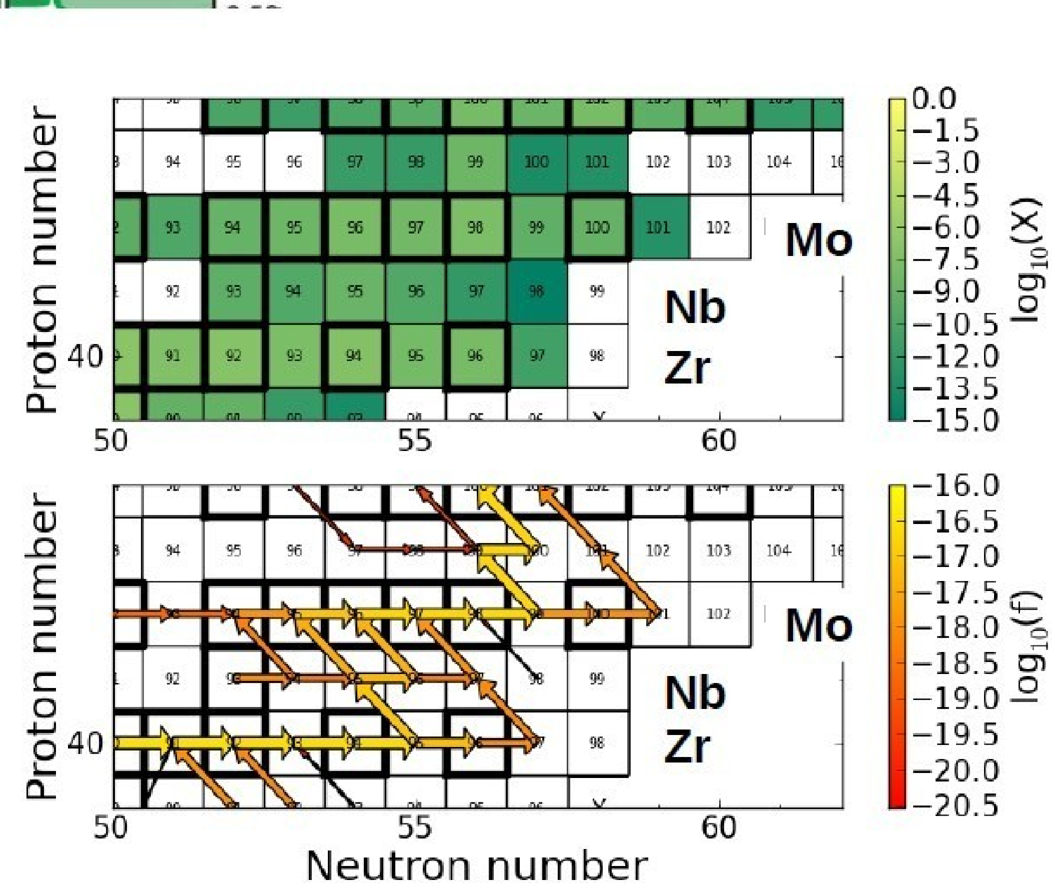
Snapshot of the 13C-pocket once C13 is gone:

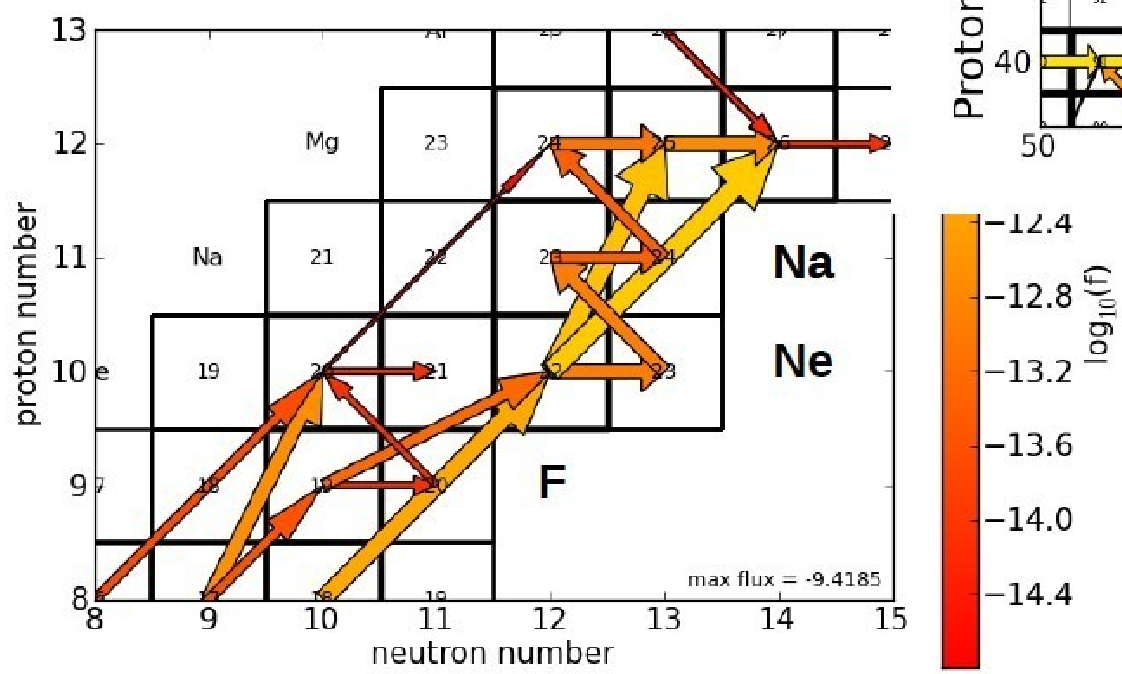
Battino et al. 2016




Proton number
Er
Ho
Dy
162
163
164
165
166
167
161
162
163
164
165
166
160
161
162
163
164
165
65
95
100
0.0
−1.5
−3.0
−4.5
−6.0
−7.5
−9.0
−10.5
−12.0
−13.5
−15.0
$\log_{10}(X)$
Proton number
Er
Ho
Dy
162
163
161
162
65
95
100
Neutron number
−18.0
−18.5
−19.0
−19.5
−20.0
−20.5
−21.0
−21.5
−22.0
$\log_{10}(f)$



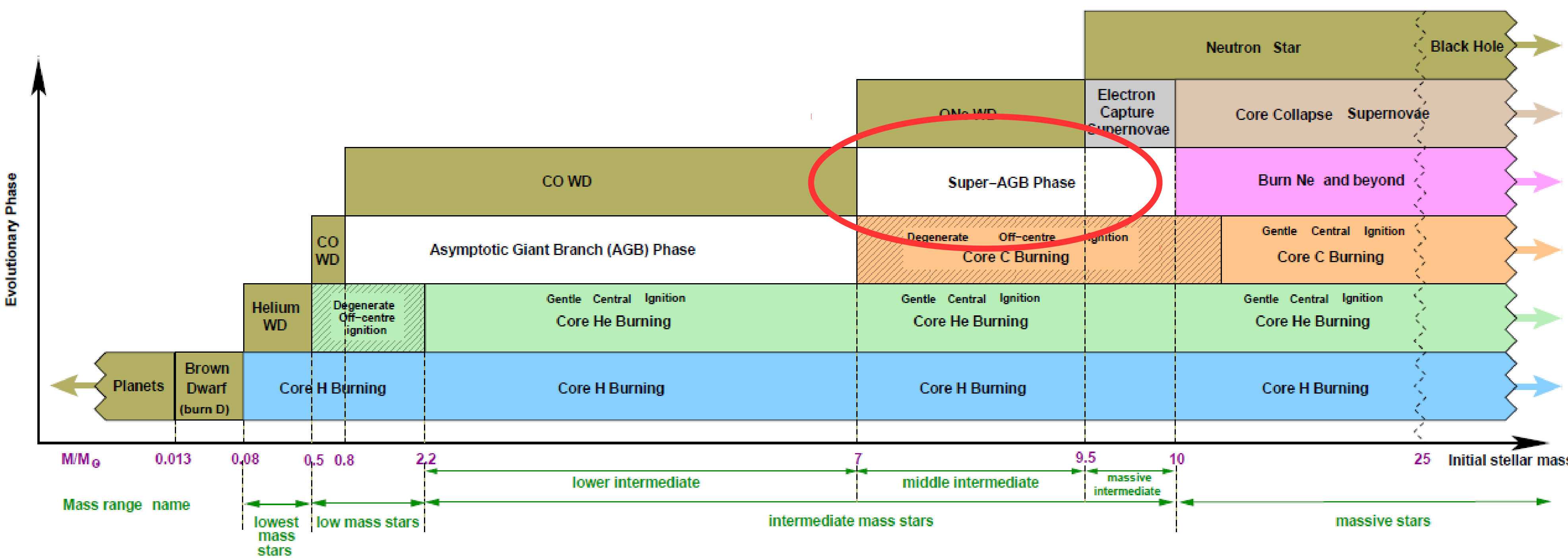




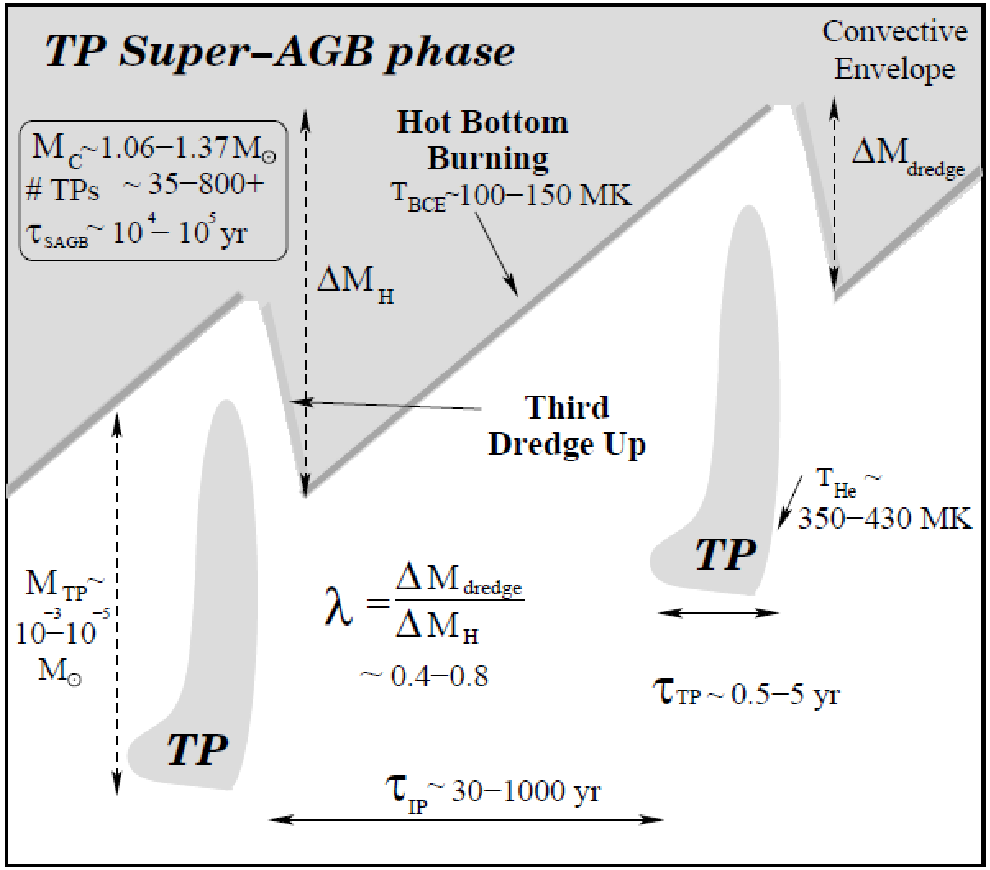
s-process during
the Thermal Pulse
Ne22(a,n)Mg25 activation -

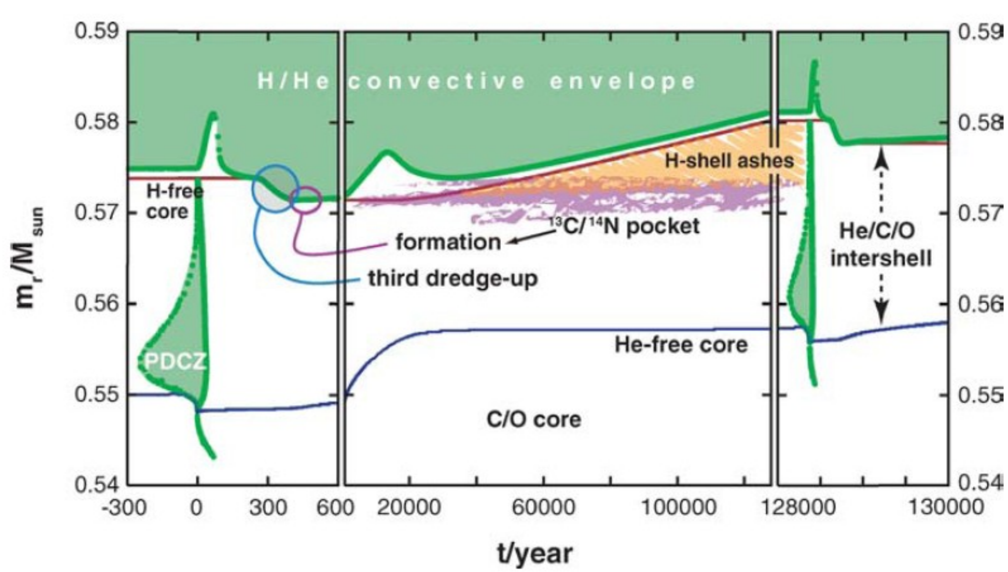
N_n peak > 10^{10} cm^{-3}

Super-AGB stars



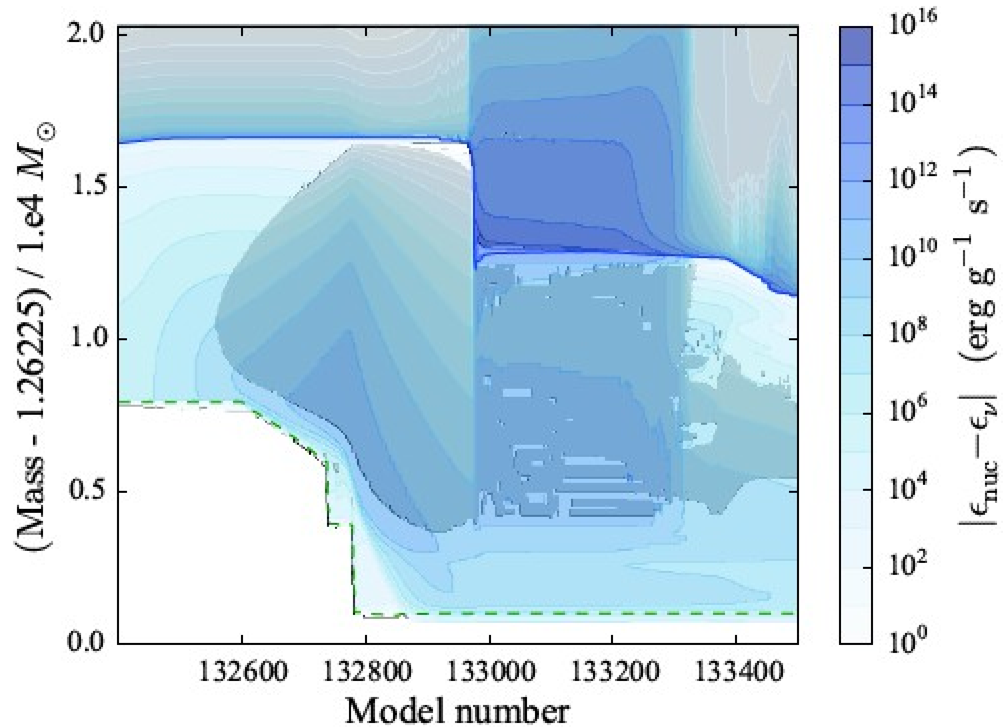
Doherty+2014



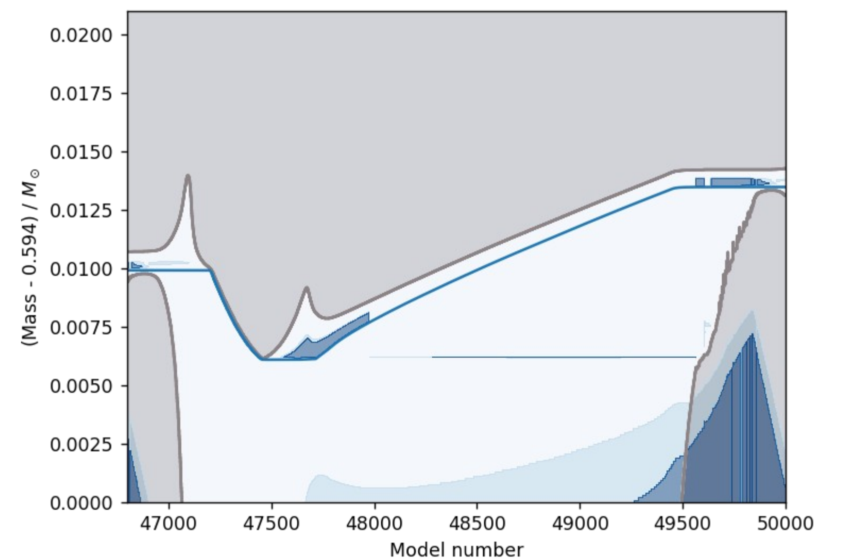


Thermal Pulses and H ingestion

Jones, MP et al. 2016 MNRAS



M=7Msun, Z=0.0001



M=2Msun, Z=0.01

Thermal Pulses in Super-AGB stars can trigger ingestion of fresh H from the envelope, during the convective He burning. This is completely different from the low-mass case we saw before.

The i process

THE ASTROPHYSICAL JOURNAL, **212**:149–158, 1977 February 15
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1977

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

JOHN J. COWAN AND WILLIAM K. ROSE
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

stellar/hydro

ABSTRACT

We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the $^{14}N(n, p)^{14}C$ reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

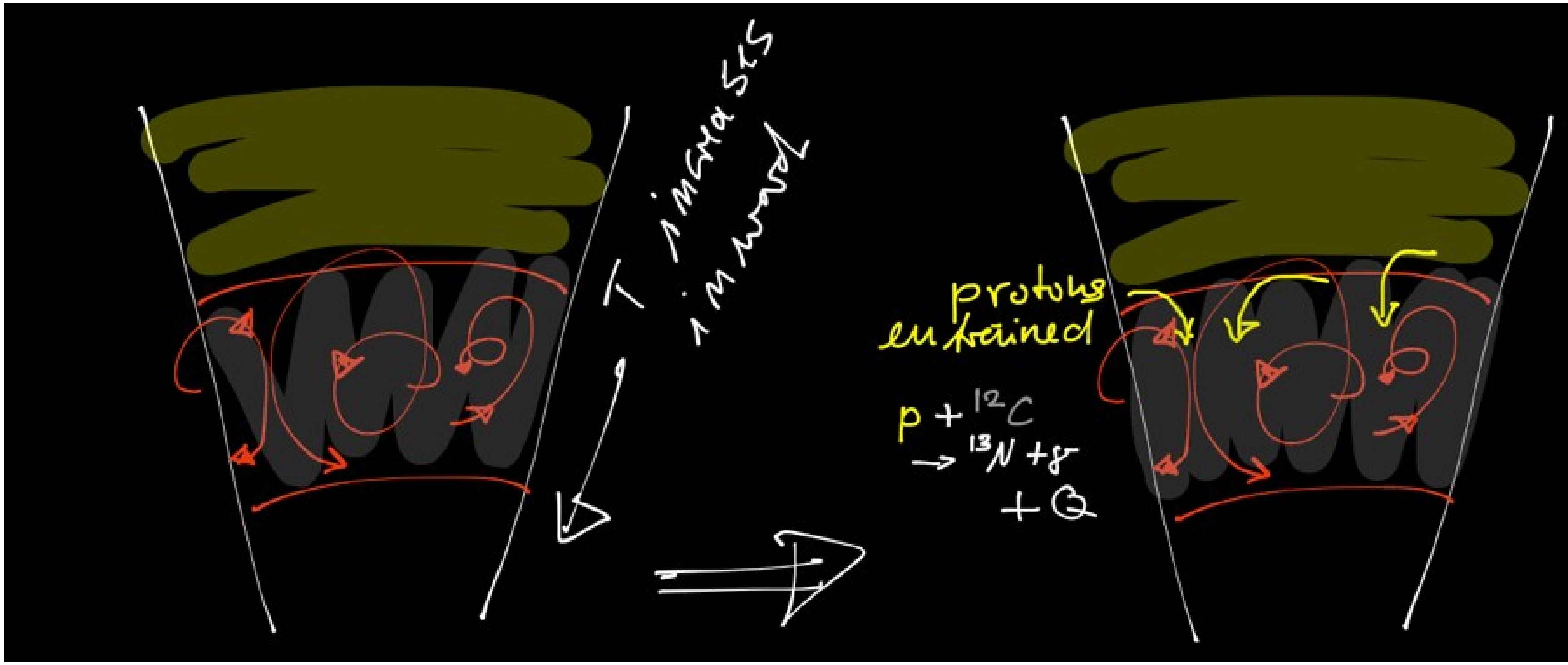
We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the $^{13}C(\alpha, n)^{16}O$ reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.

nuclear/stellar

List of neutron capture processes

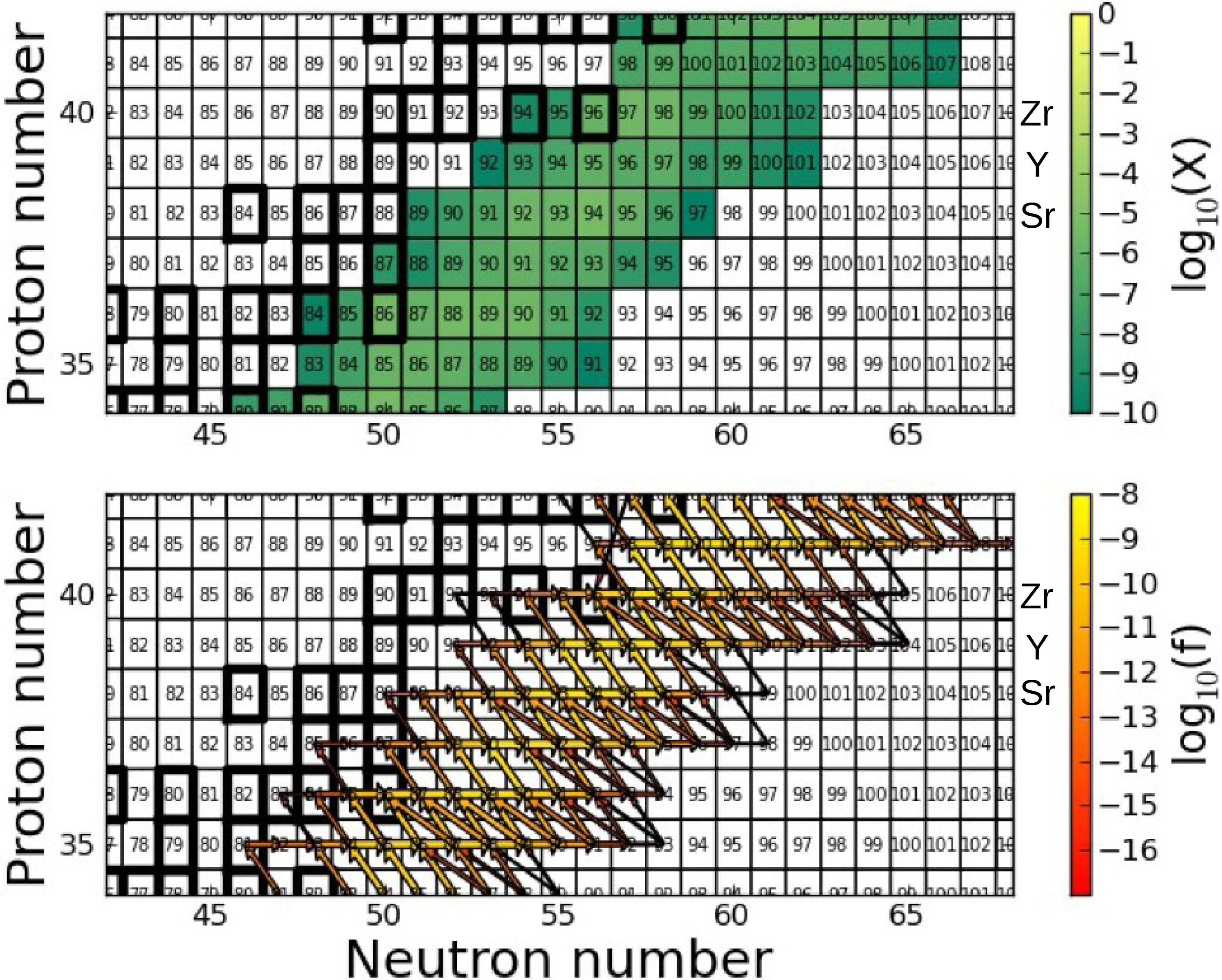
- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) - 10^{18} n cm$^{-3} < N_n < 10^{20}$ n cm^{-3};
- The i process - 10^{14} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- Neutron capture triggered by the Ne22(α,n)Mg25 in massive AGB stars and super-AGB stars - $N_n < 10^{14}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n <$ few 10^{12} n cm^{-3} .



N13 and/or C13 are mixed <u>for hours</u> in regions with typical He-burning temperatures (T9 ~ 0.25-0.3 GK), <u>together with Fe-seed rich material.</u>

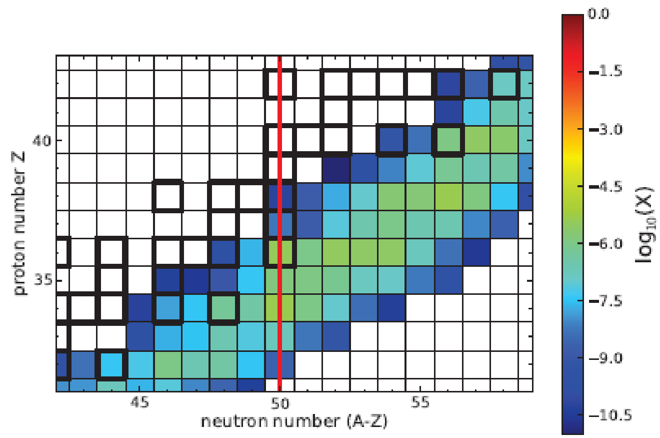
Main source of neutrons: C13(α,n)O16
Neutron density: few $10^{14} – 10^{16}$ n cm^{-3}

Nucleosynthesis properties of the i process: Se-Nb



Relevant nuclear reaction rates for the i process

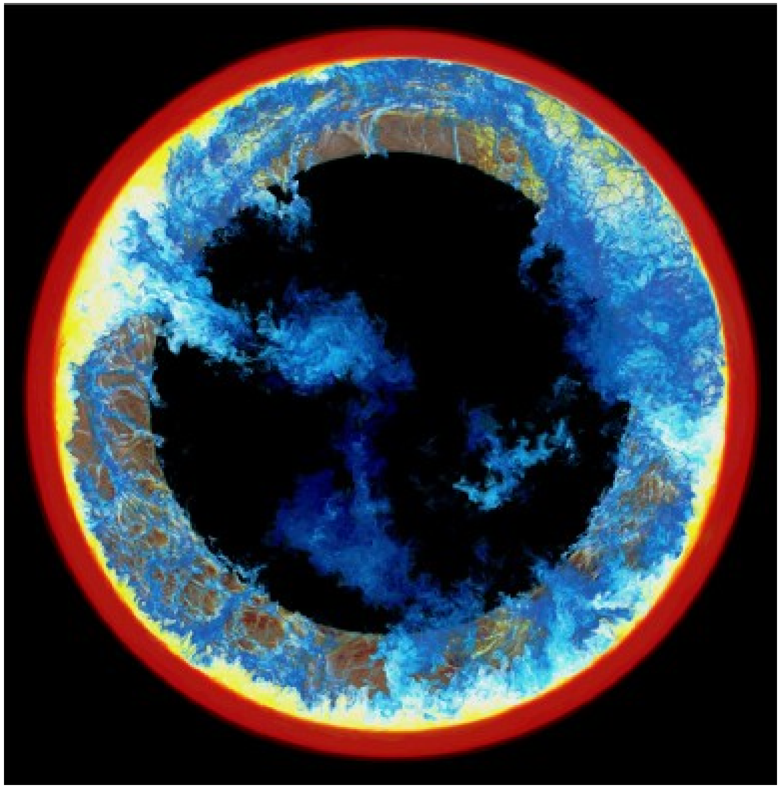
- (n,γ) rates from the valley of stability up to ~10 neutron-rich isotopes far from the valley of stability;
- β decay network;
- (β,n) delayed-neutron emission network.



(a) Isotopic chart for the first neutron magic peak, $N = 50$, at $t = 1.9 \times 10^{-4}$ years.

Most recent results for the hydrodynamics of H ingestion:

(Cost of a resolved simulation of H ingestion for 20 hr star time: ~ 500K $)



Cost of adding one more virtual isotope or fluid in the simulations:

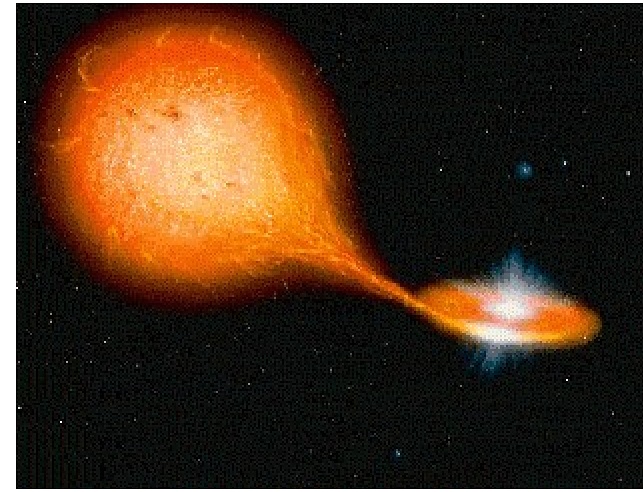
... + 

+ Herwig et al. 2014, ApJL 792
+ Woodward et al. 2015, ApJ 798, 49

Falk Herwig
UVIC

+ For other hydrodynamics simulations of H ingestion (at low metallicity): Mokak et a. 2011 A&A, Stancliffe et al. 2011 ApJ

Artist conception of the WD and the binary system



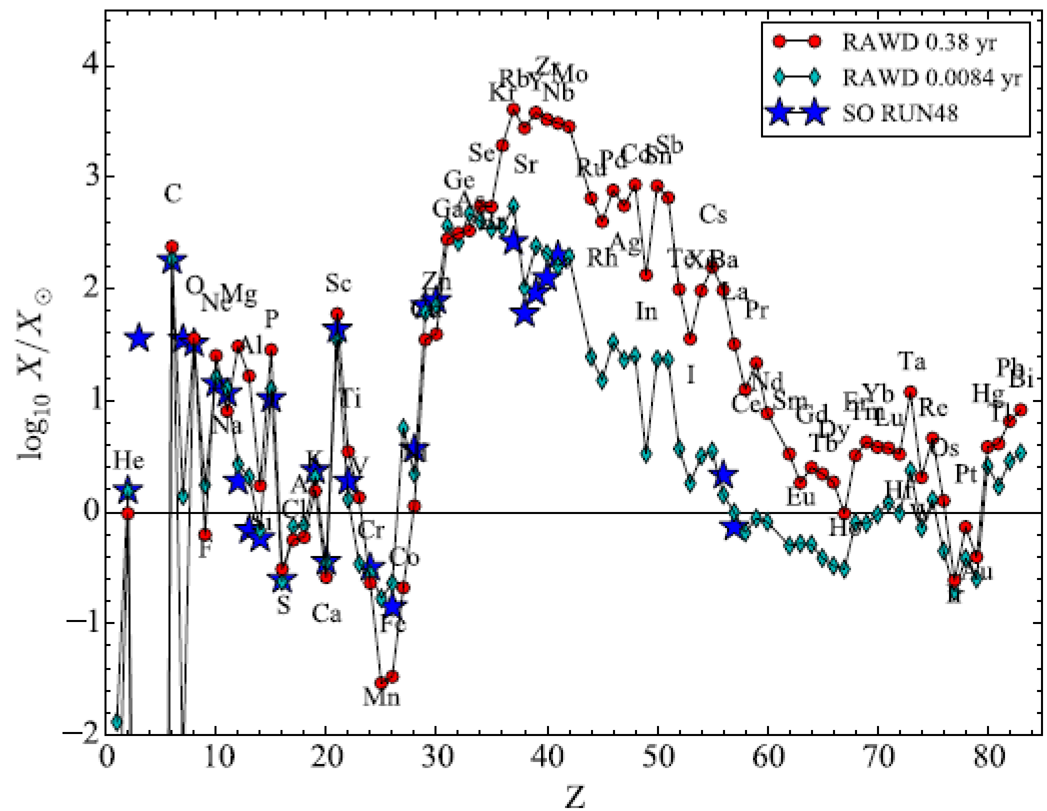
Why do we care?

The Milky Way present-day star formation rate is $\sim 2\,M_\odot\ \mathrm{yr}^{-1}$ (Chen et al. 2014). A fraction of ~ 0.08 of this will go into low-mass AGB stars ($1.5\,M_\odot \leqslant M_{\mathrm{ini}} \leqslant 3\,M_\odot$) that produce the main s process, and they return $\sim 70\%$ of their mass to the ISM. Therefore, $\approx 0.1\,M_\odot\ \mathrm{yr}^{-1}$ of s-process enriched material is returned by low-mass AGB stars. This material is enriched by ~ 2 compared to the initial abundance of heavy elements (e.g., Lugaro et al. 2003).

As a lower limit, we adopt for the RAWD rate the presently estimated rate of SNe Ia from the single-degenerate channel, $2 \times 10^{-4}\ \mathrm{year}^{-1}$ (Chen et al. 2014). If one assumes that for each RAWD $\sim 0.5\,M_\odot$ of H-rich material can be accreted, and ejected enriched with i-process elements (assuming $\eta_{\mathrm{He}} = 0$), then $\approx 0.0001\,M_\odot\ \mathrm{yr}^{-1}$ of i-process enriched material is returned by RAWDs with an enrichment factor of ~ 1000 (Figure 4).

The ratio of the contributions of elements made by both low-mass AGB stars and RAWDs is then

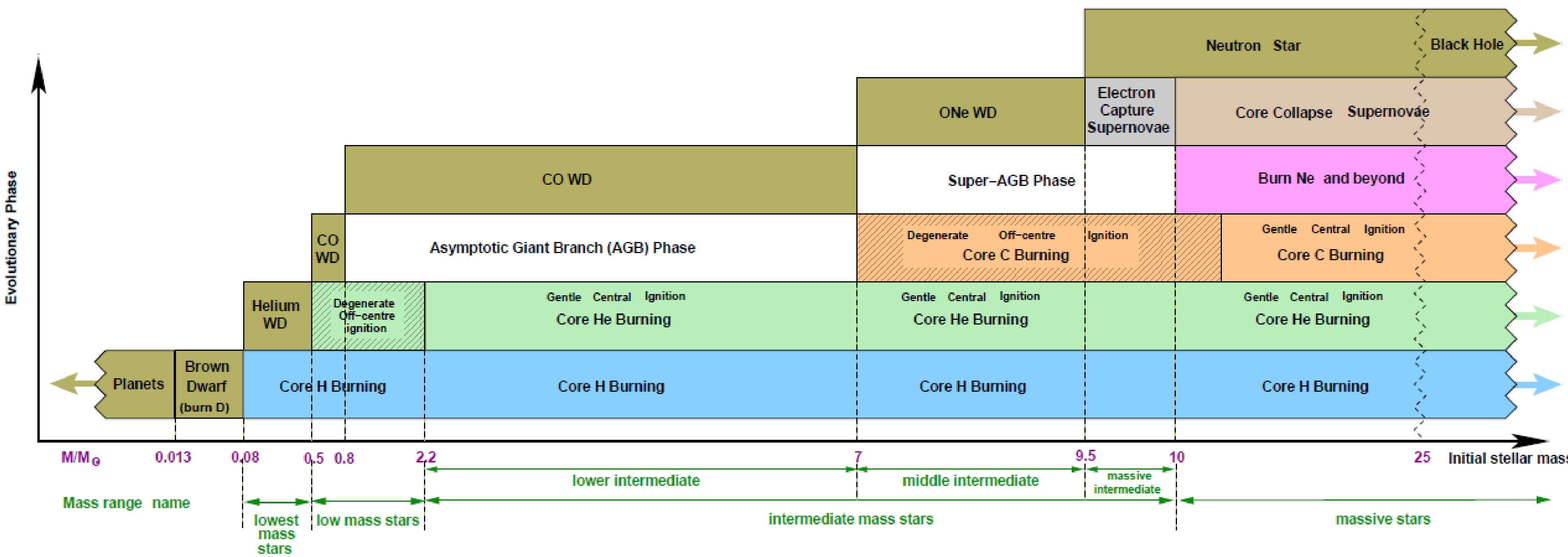
$$\frac{\text{AGB contribution}}{\text{RAWD contribution}} = \frac{0.1\,M_\odot\ \mathrm{yr}^{-1}}{0.0001\,M_\odot\ \mathrm{yr}^{-1}} \times \frac{2}{1000} = 2.0.$$



Examples of i-process abundance patterns

Stellar nucleosynthesis: Massive stats

Stars forming WD and NS



Karakas & Lattanzio 2014, PASA

Baking oxygen now...

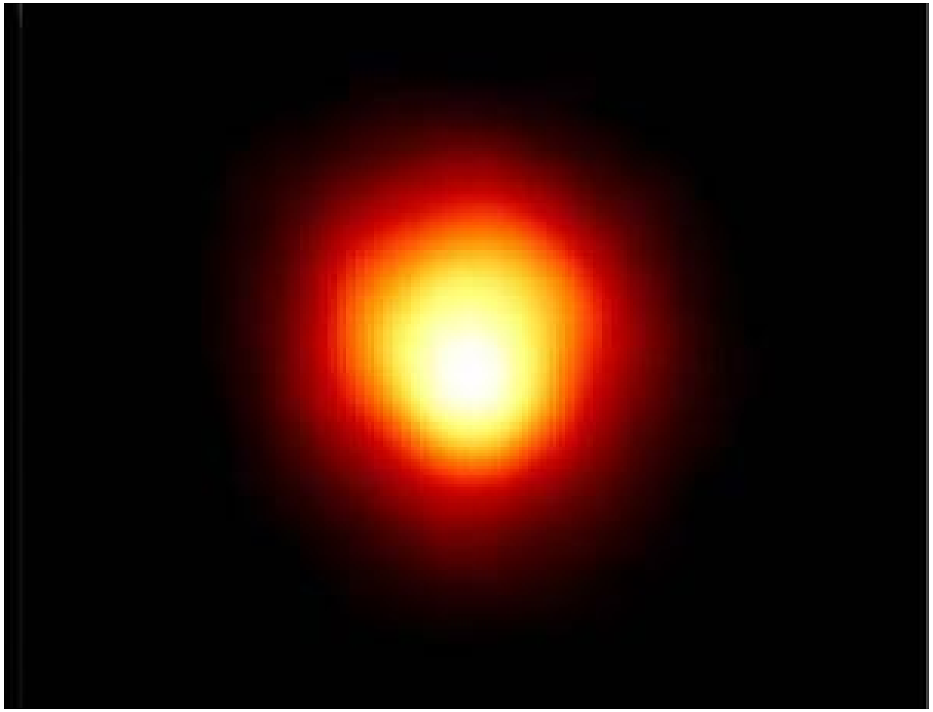


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

Betelgeuse (α-Ori):

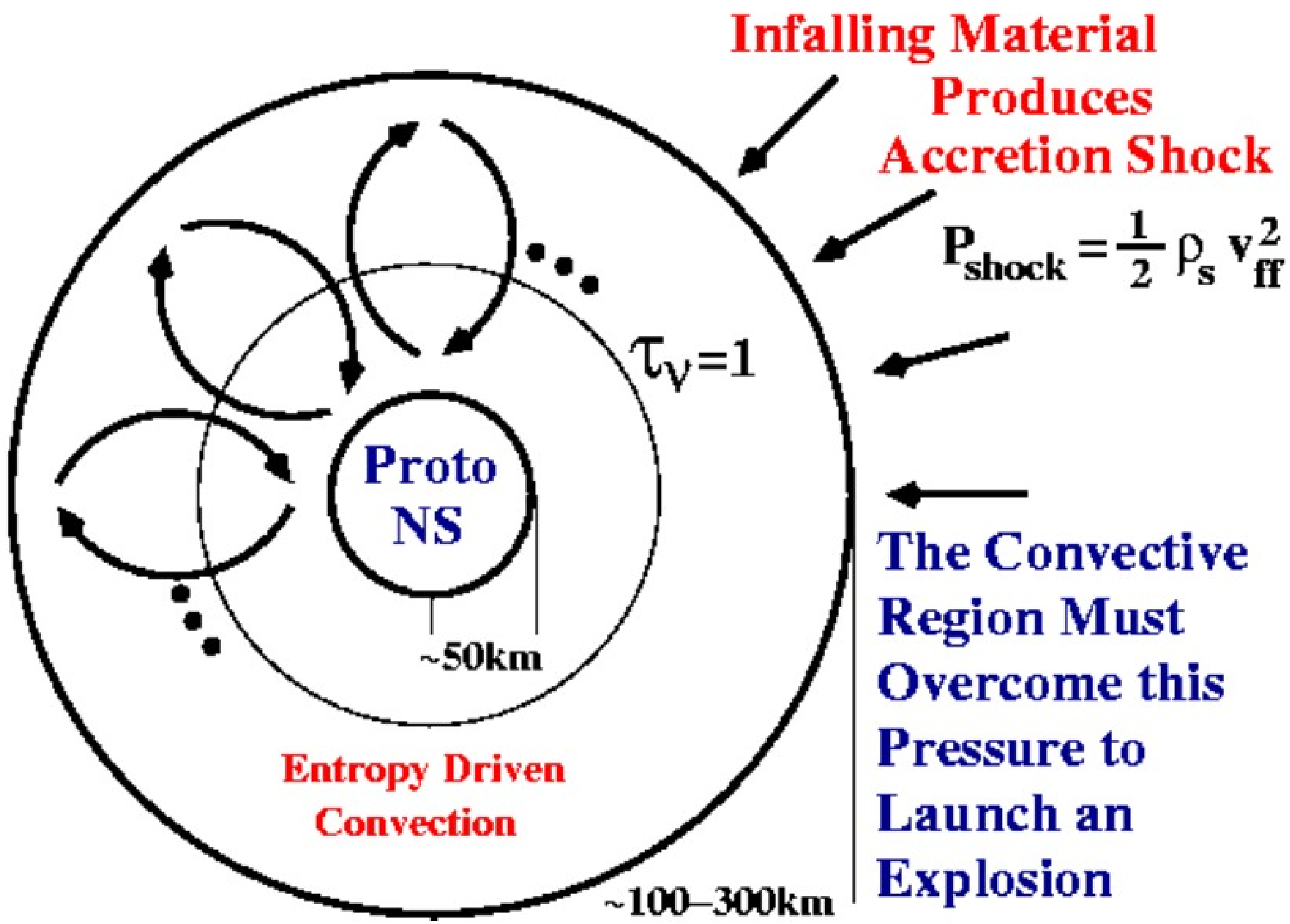
$\sim 19\ M_{sun}$

$\sim 650\ ly$

$\sim 1180\ R_{sun}$

1:2 atoms in the centre of α-Orionis is oxygen

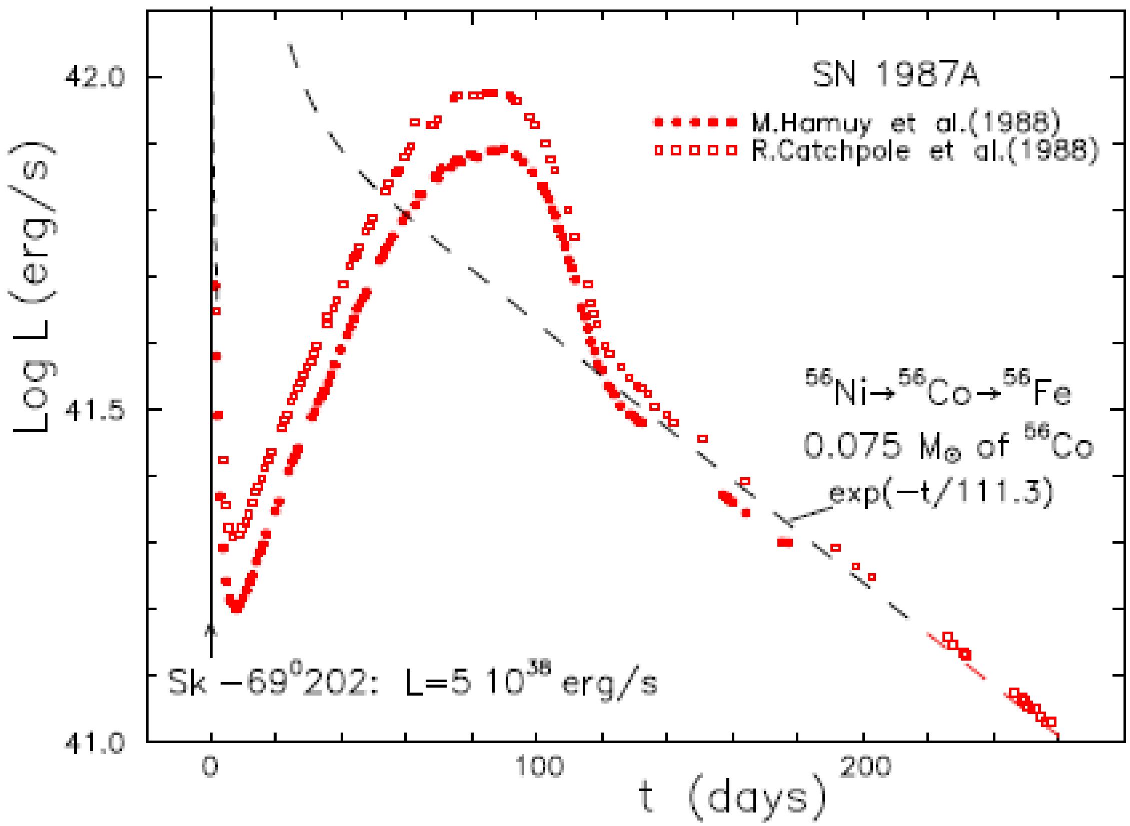
Neutrino-driven SN mechanism



Fryer 1999

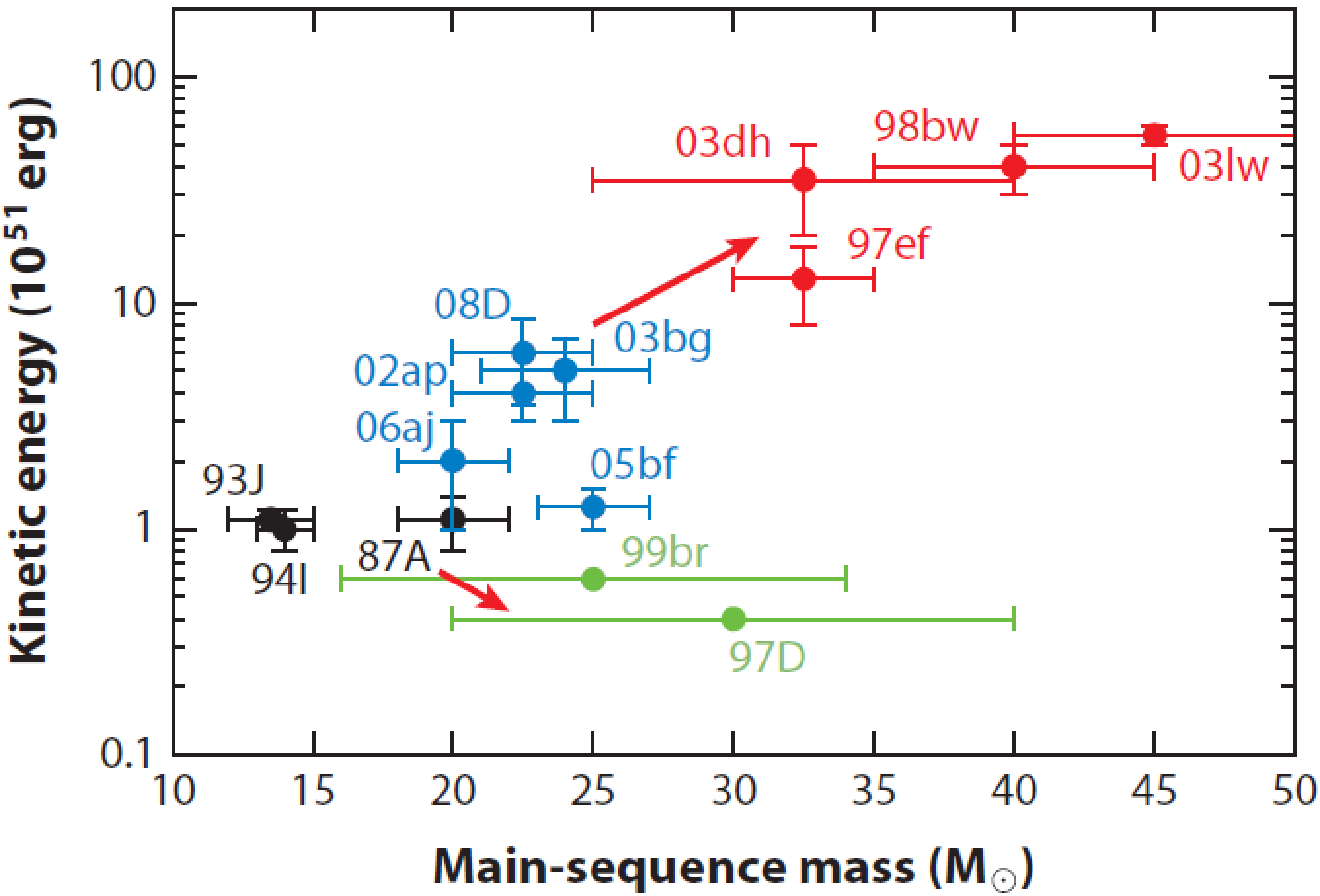
C. Fryer

SN light curve: how we "see" SNe first



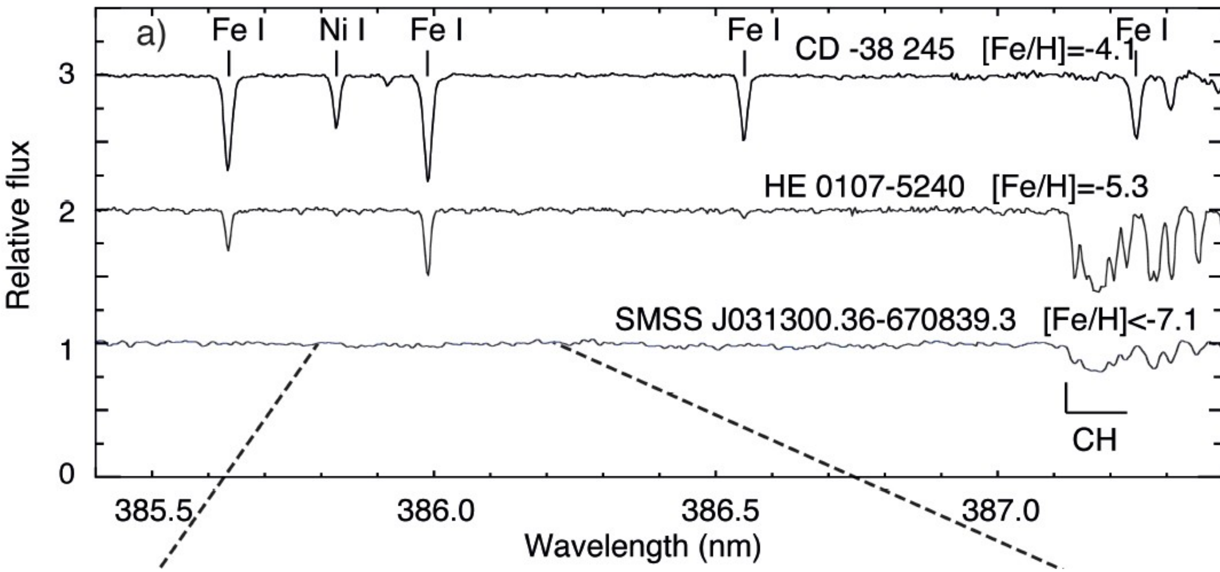
Nadyozhin & Imshennik 2005

The CCSNe zoo

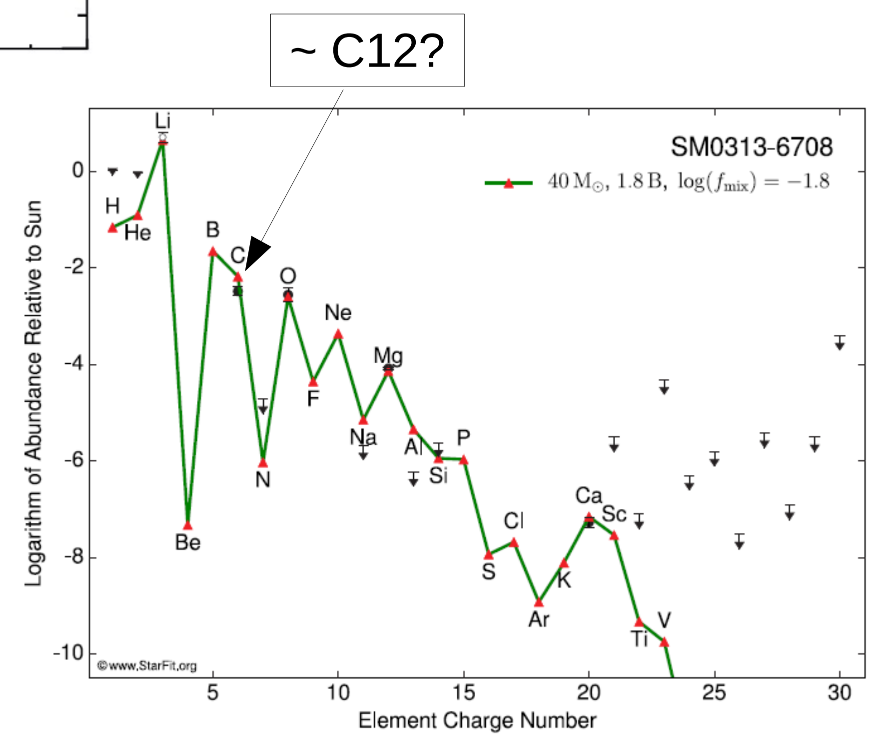


Nomoto et al. 2013 ARAA

Proof of an old CCSN with no Fe ejected



Keller+2014, Nature



The Keller star (SM0313-6708):

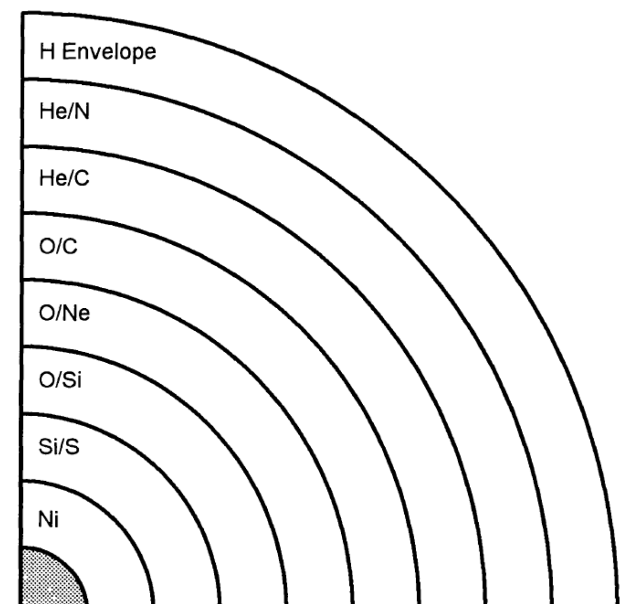
- metal-poor
- [C/Fe] >> Sun

Bessel+2015, ApJ
Nordlander+2017, A&A

Explosive nucleosynthesis in CCSNe

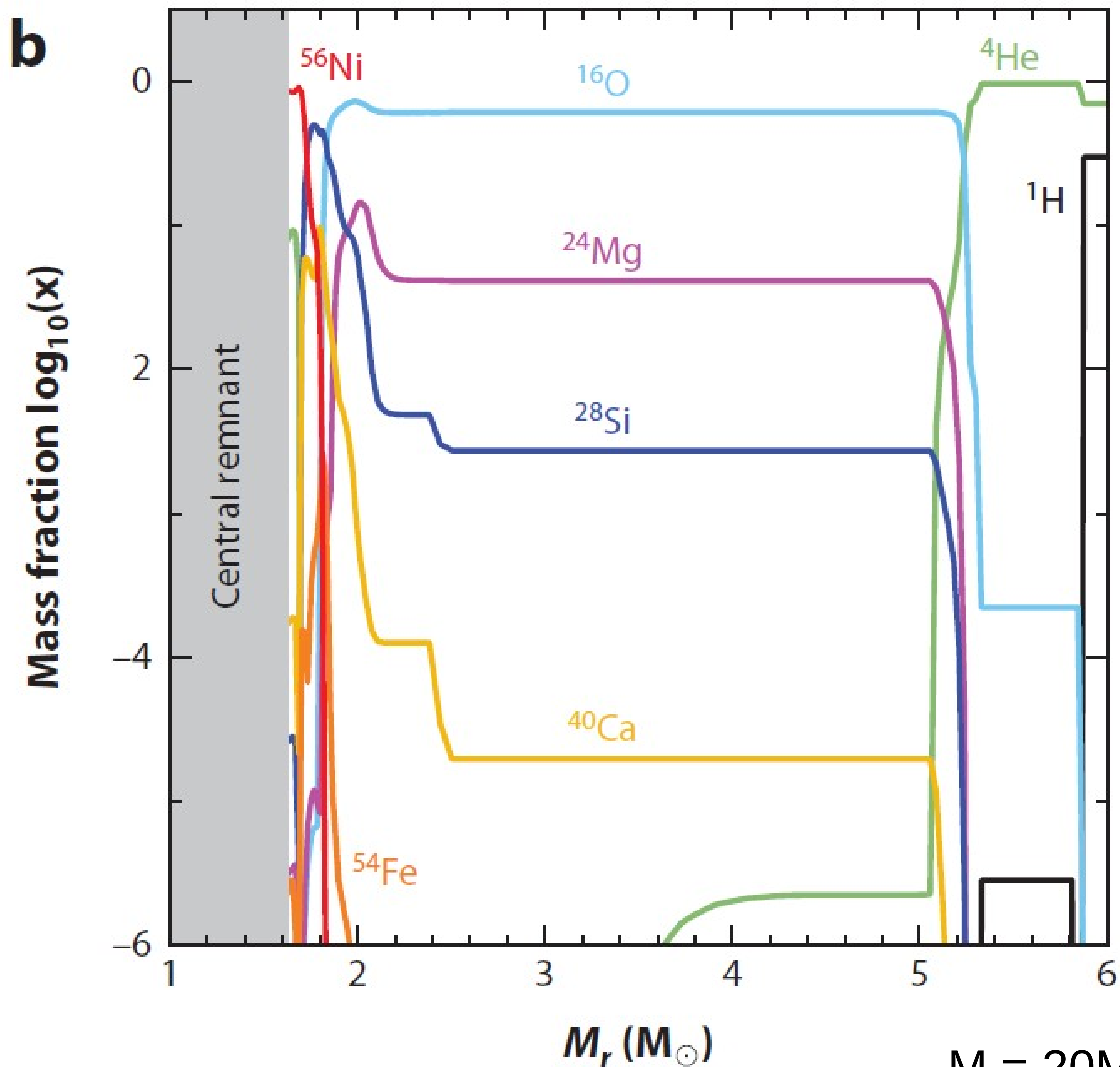
- Can we still divide in "burning stages"? Burning happening in the timescale of a second or less;
- Intermediate explosive conditions are crucial
- The progenitor preSN structure is crucial
- Possible classification

  of the SN ejecta?



Meyer+1995, GeCoA

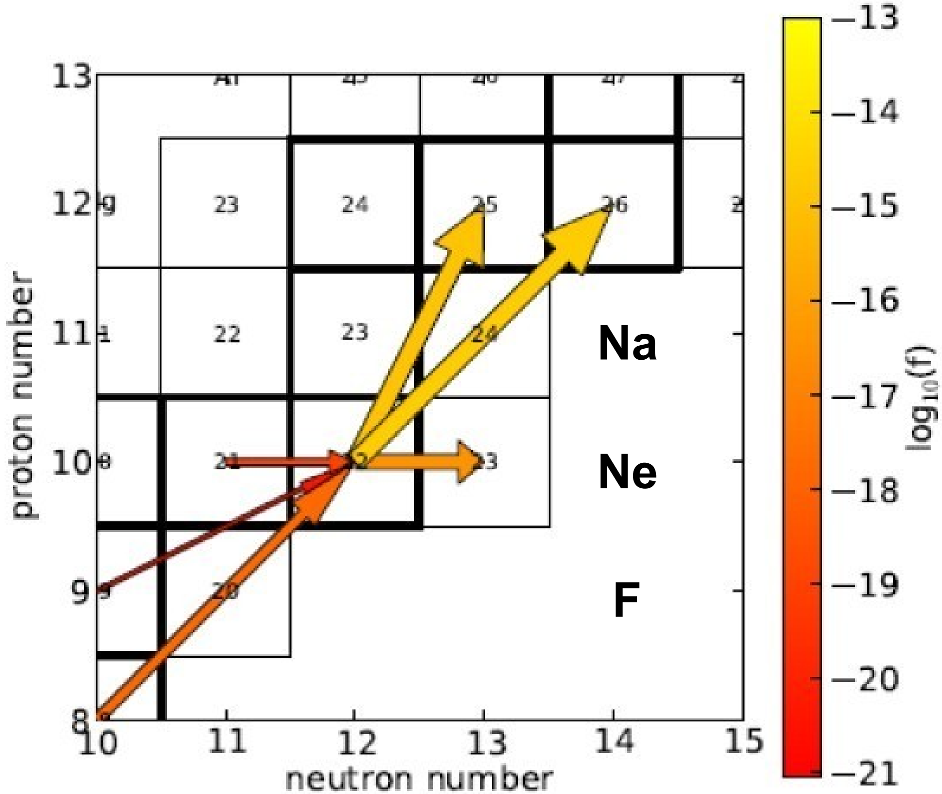
Example of SN ejecta



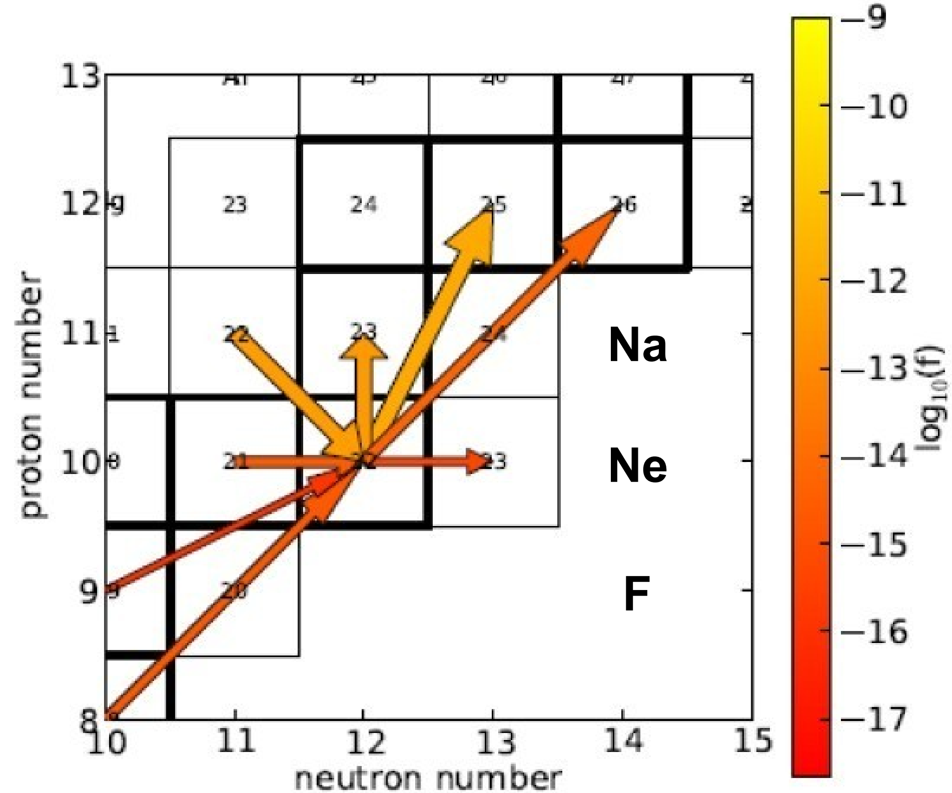
M = 20M$_{sun}$, Nomoto+2013 ARAA

The s-process in massive stars

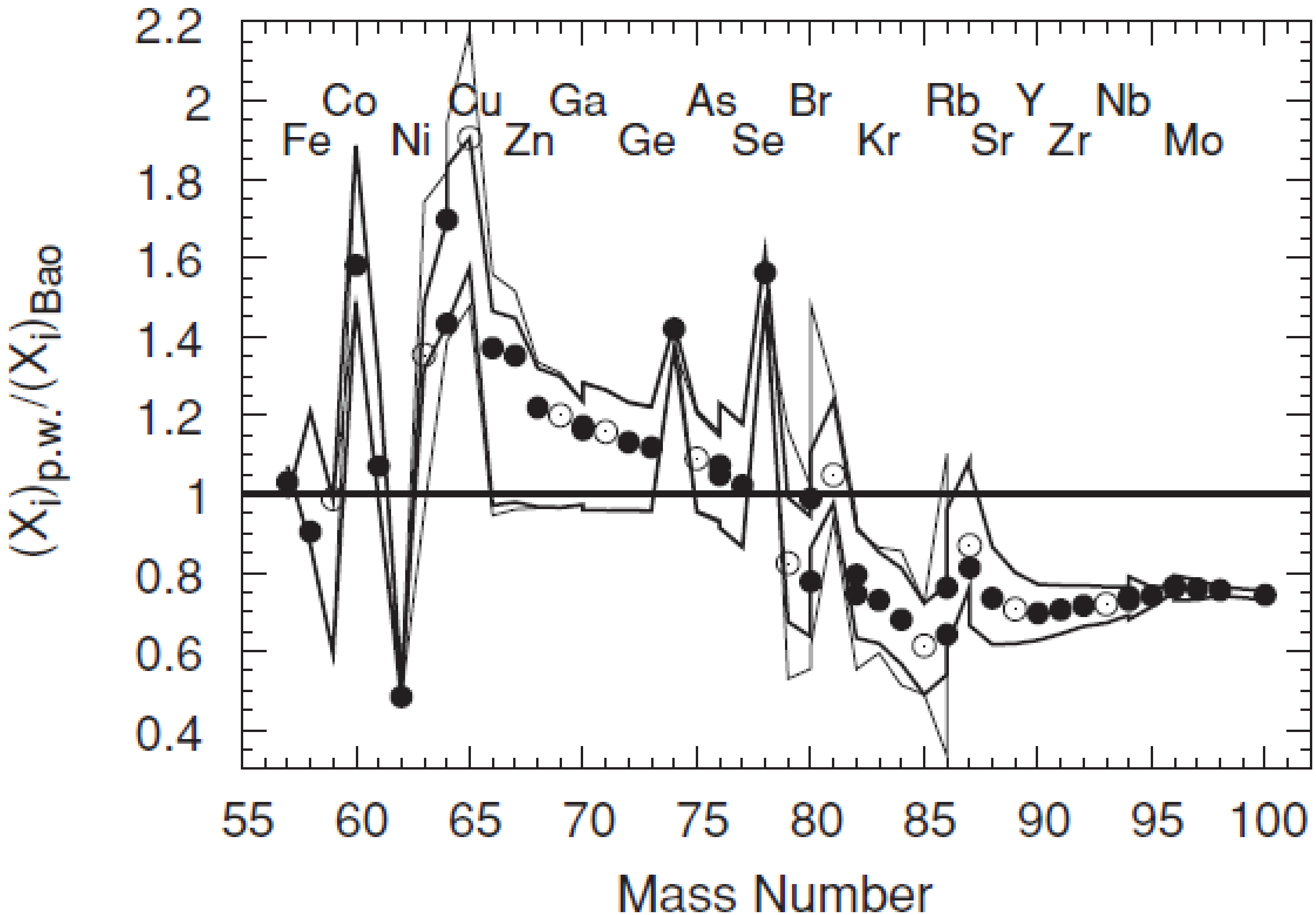
Ne22(α,n)Mg25: main neutron source of the weak s-process in massive stars.



Ne22 nucleosynthesis
in He-burning conditions
(T9 ~ 0.3)



Ne22 nucleosynthesis
in C-burning conditions
(T9 ~ 1)



Pignatari, et al. 2010, ApJ

The n process

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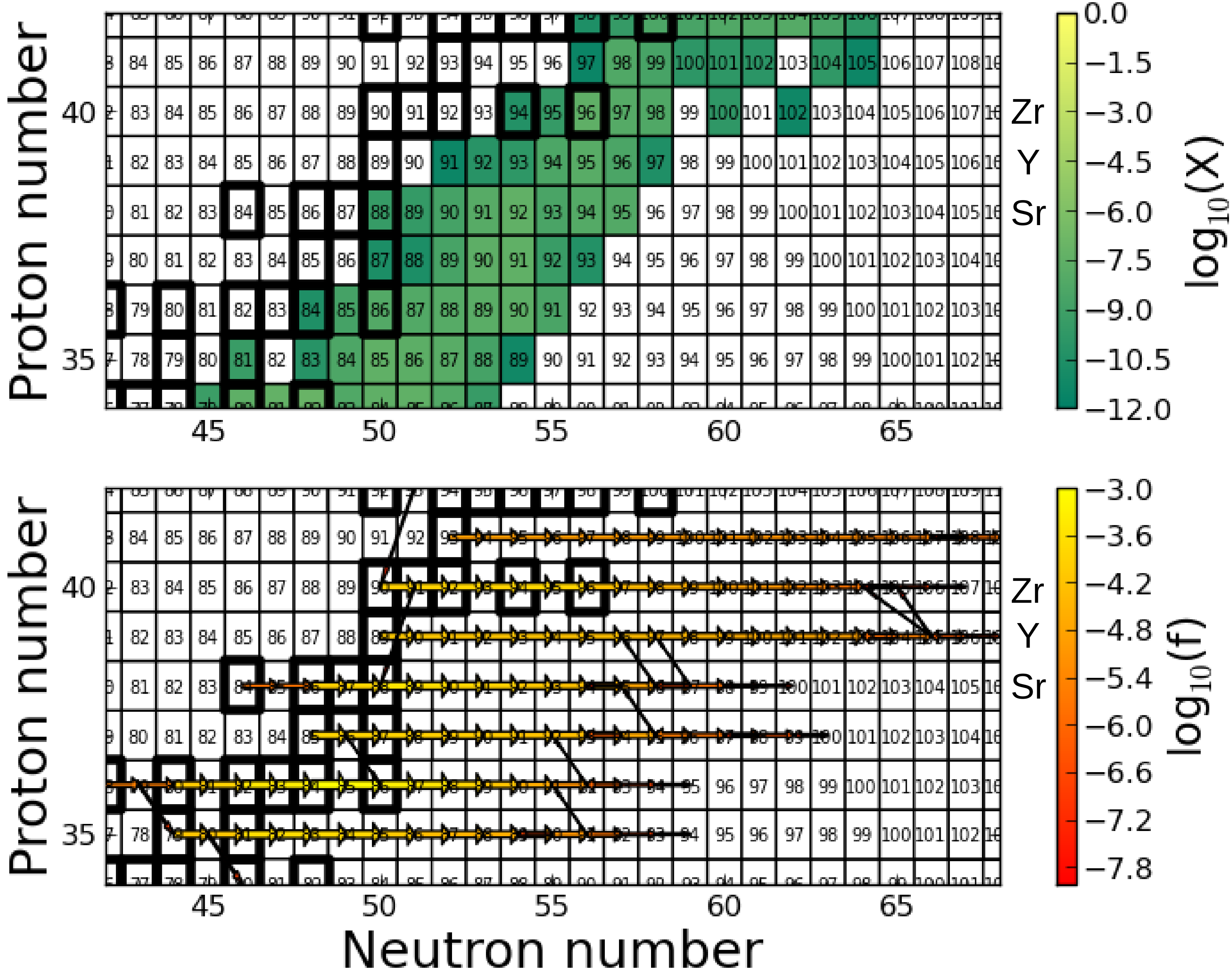
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – N_n < few 10^{12} n cm^{-3} .

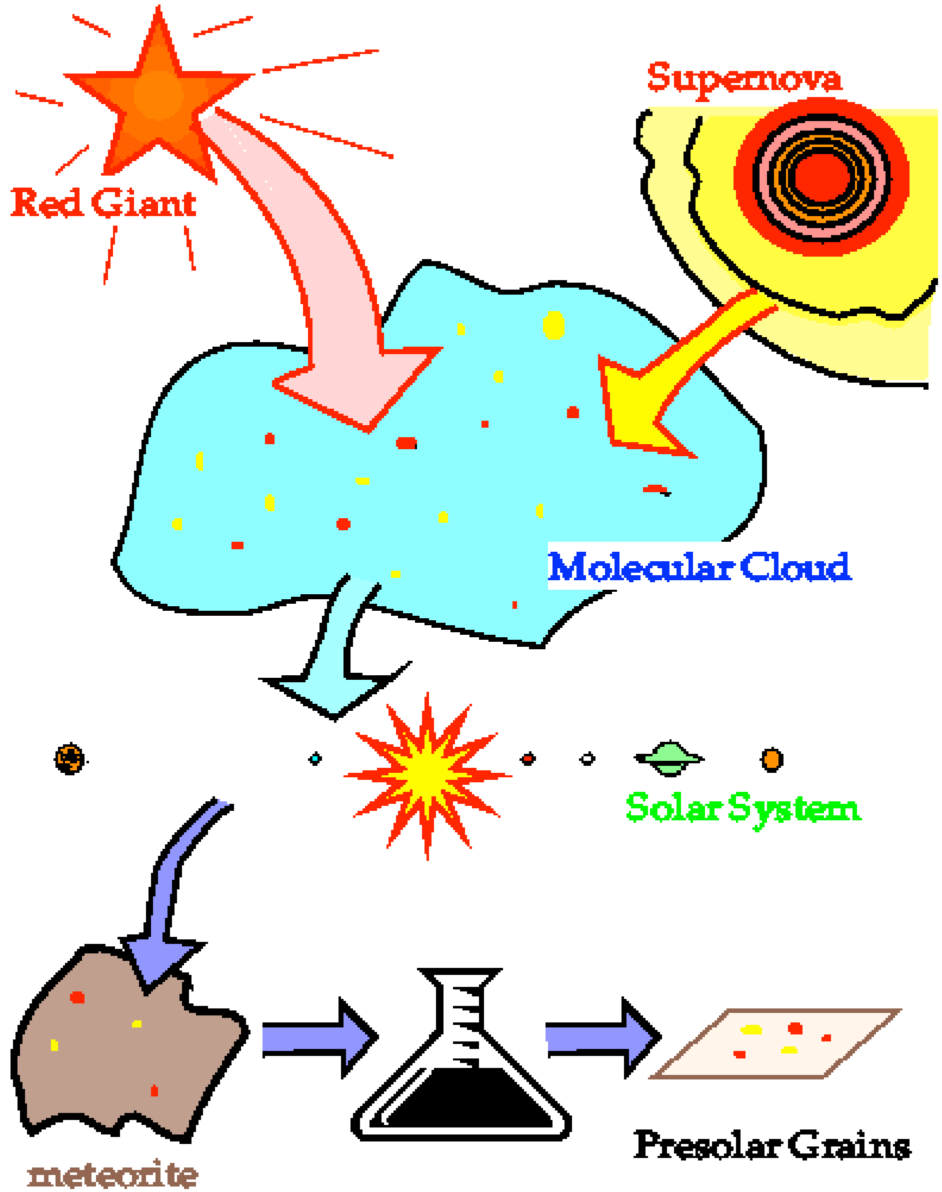
N_n

Nucleosynthesis properties of the n process: Se-Nb

(Blake & Schramm 1976)

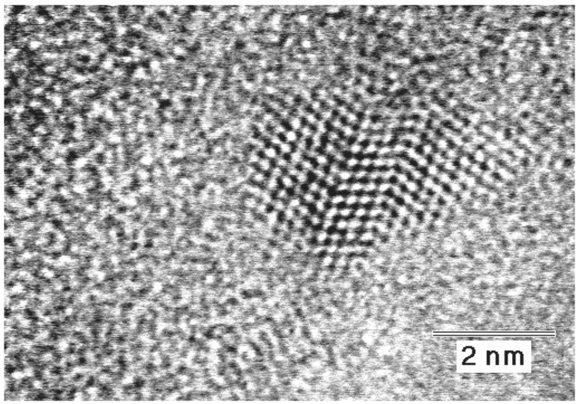


Presolar grains from meteorites



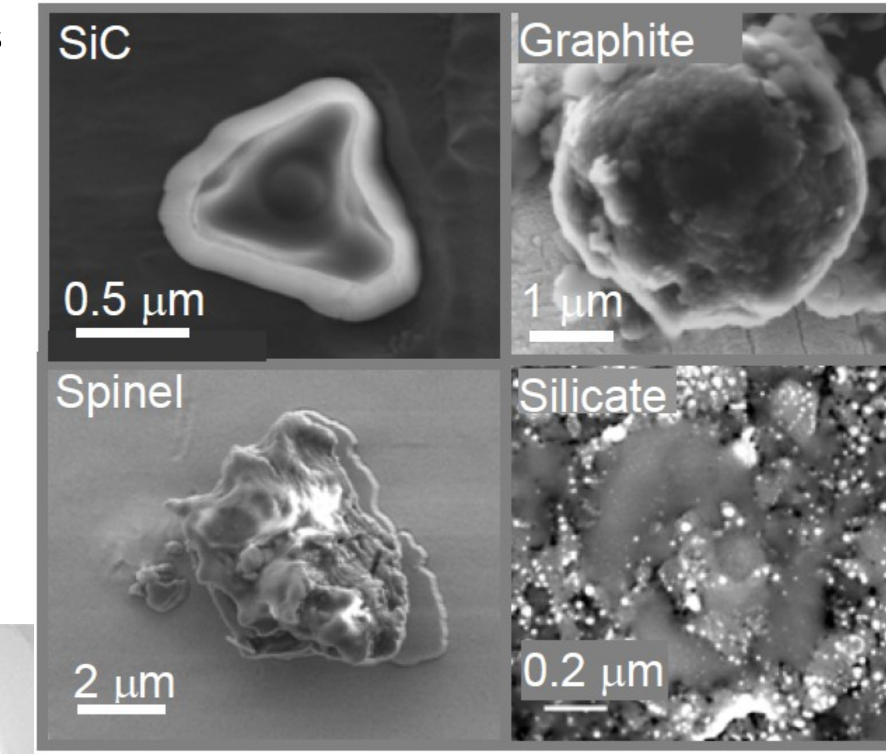
Presolar grains zoo (The Art Gallery)

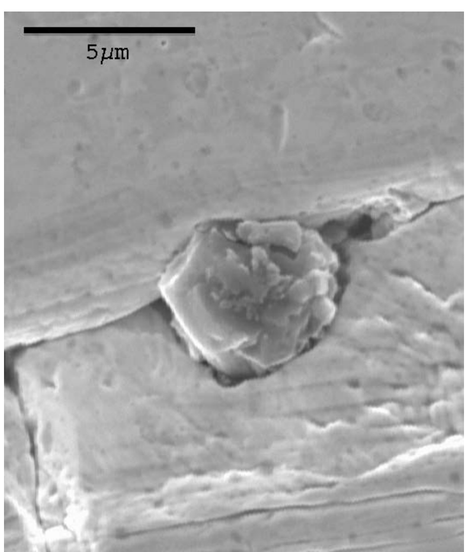
Nano-diamonds



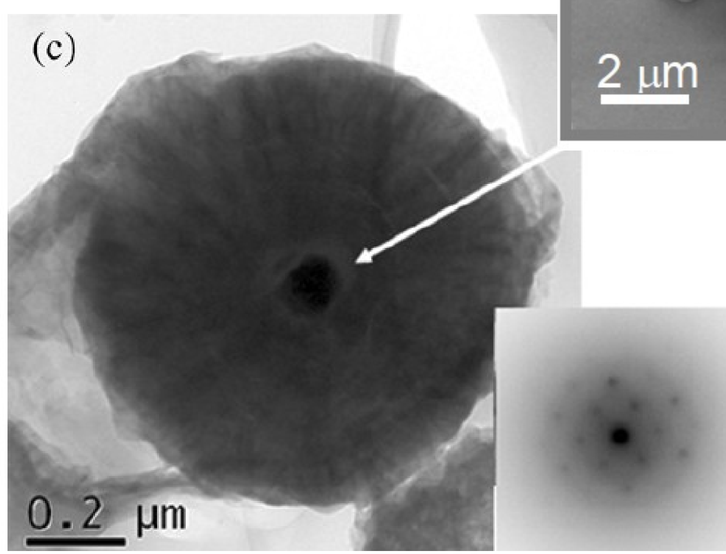
F. Banhart (MPI for Metal Research, Stuttgart)

Hoppe 2010 PoS





From Reto Trappitsch (Uni of Chicago)

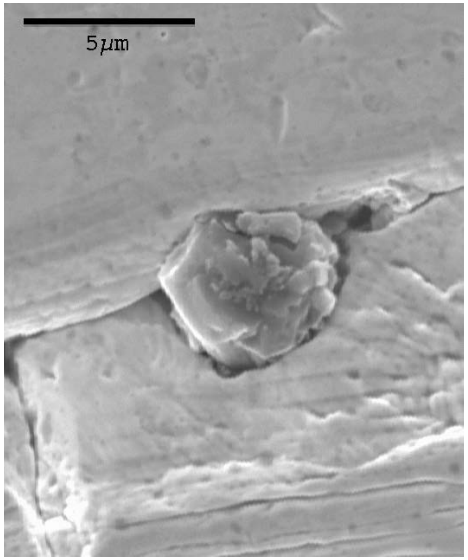


Croat et al. 2010, AJ 139

Graphite (and a SiC in the center)

For a review:
Zinner 2014, Tr. Geo.

SiC-X grain

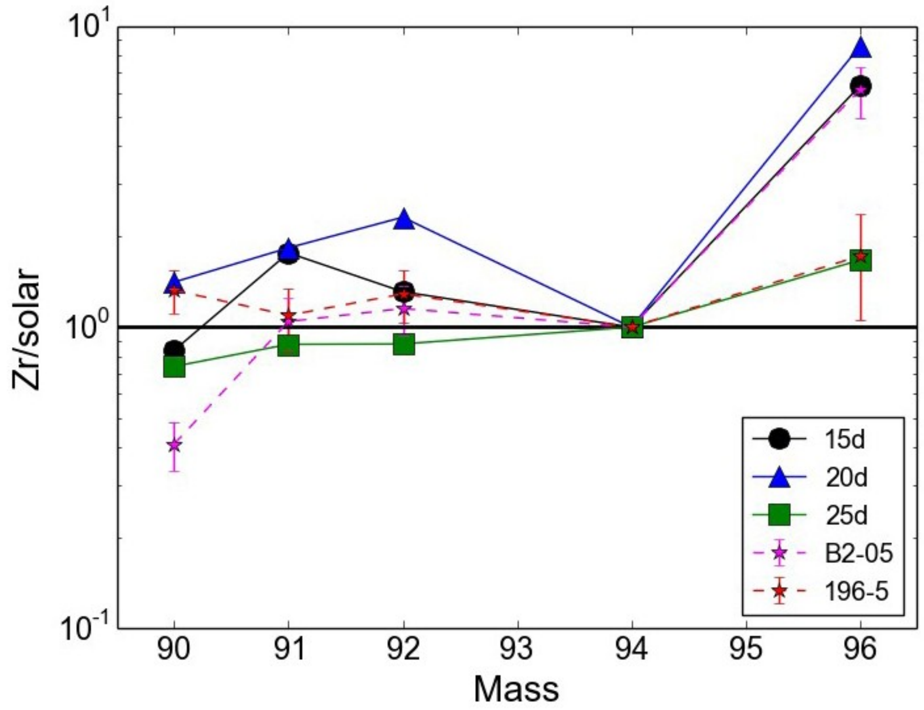


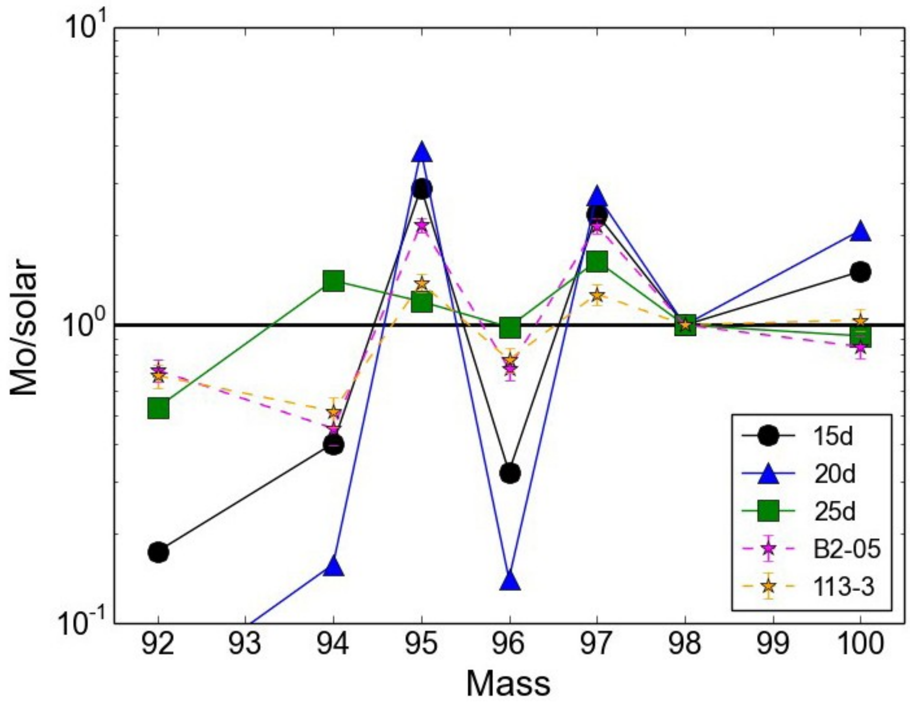
From Reto Trappitsch (Uni of Chicago)

Signature of the n-process measured for heavy elements (Sr, Zr, Mo, Ru, Ba) in presolar SiC-X grains, found intact in meteorites
- Review: Zinner 2014 TrGeo

- Main neutron source: Ne22(α,n)Mg25

CCSN models vs observations:



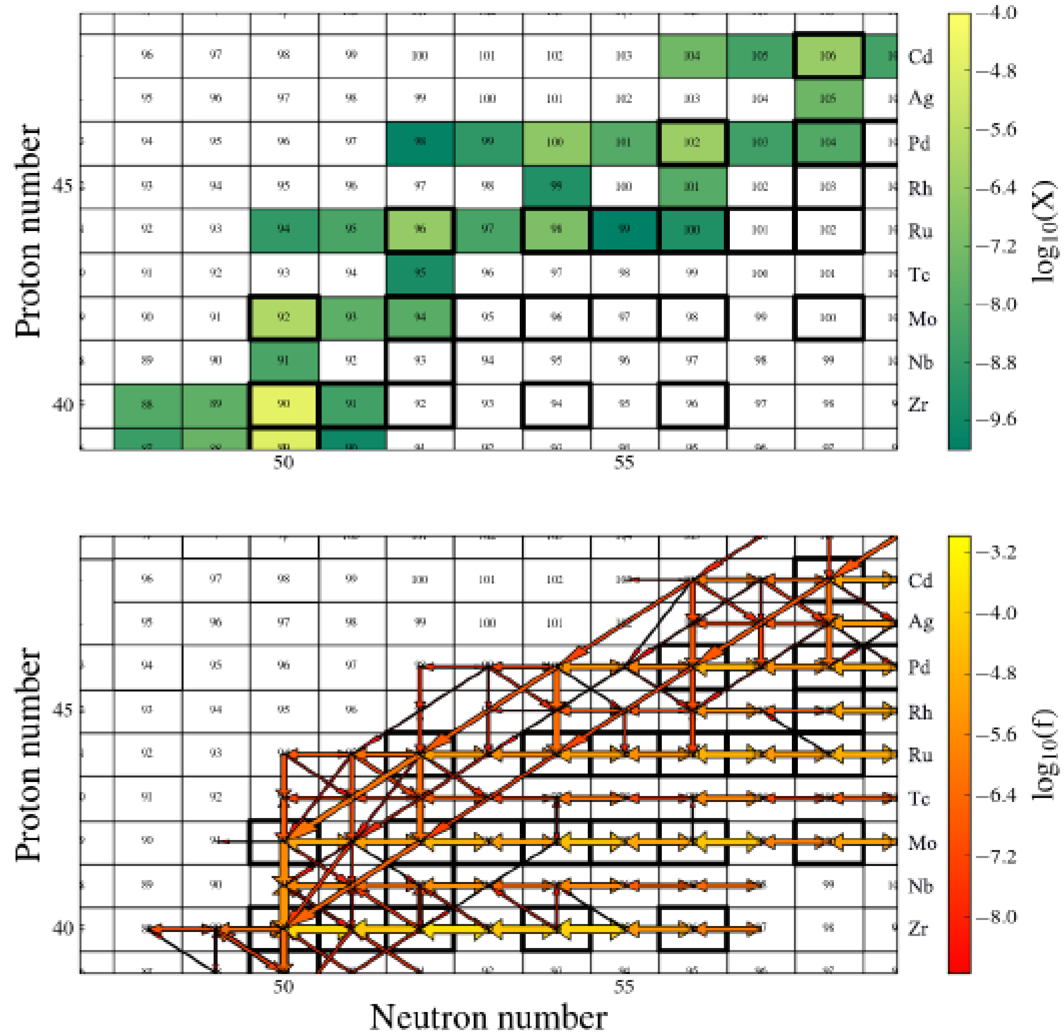


MP+2018, GeCoA

The γ-process

Relevant nuclear reactions:

- (γ,n),
- (γ,p),
- (γ,α)

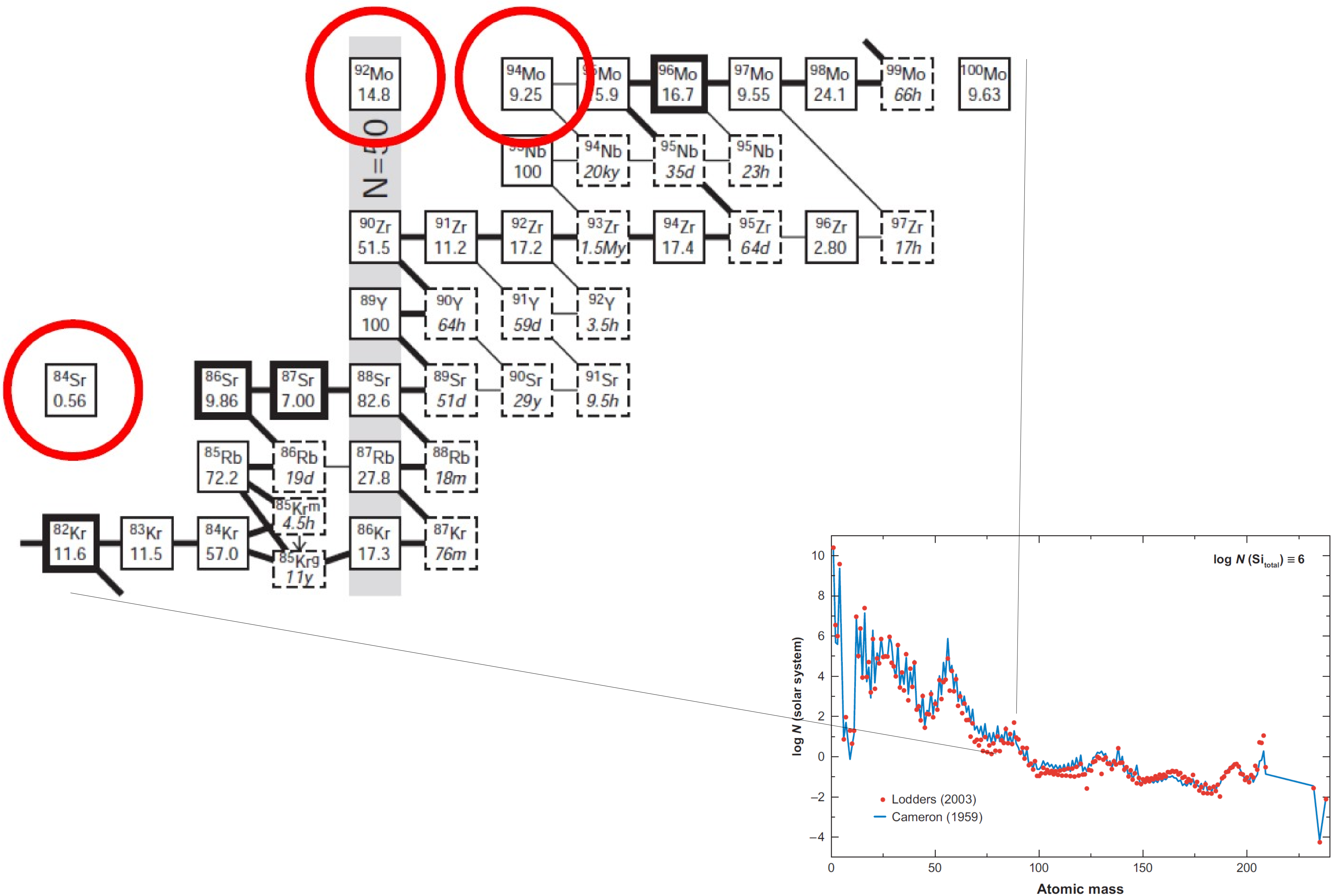


MP+2016, IJMPE

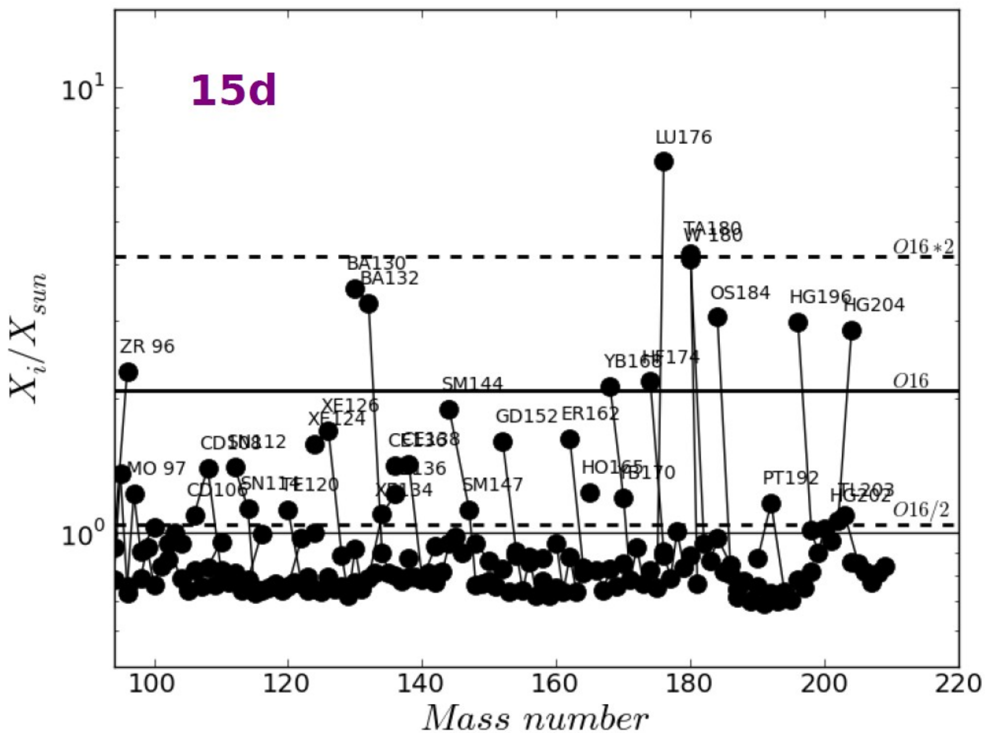
Zr-Cd mass region

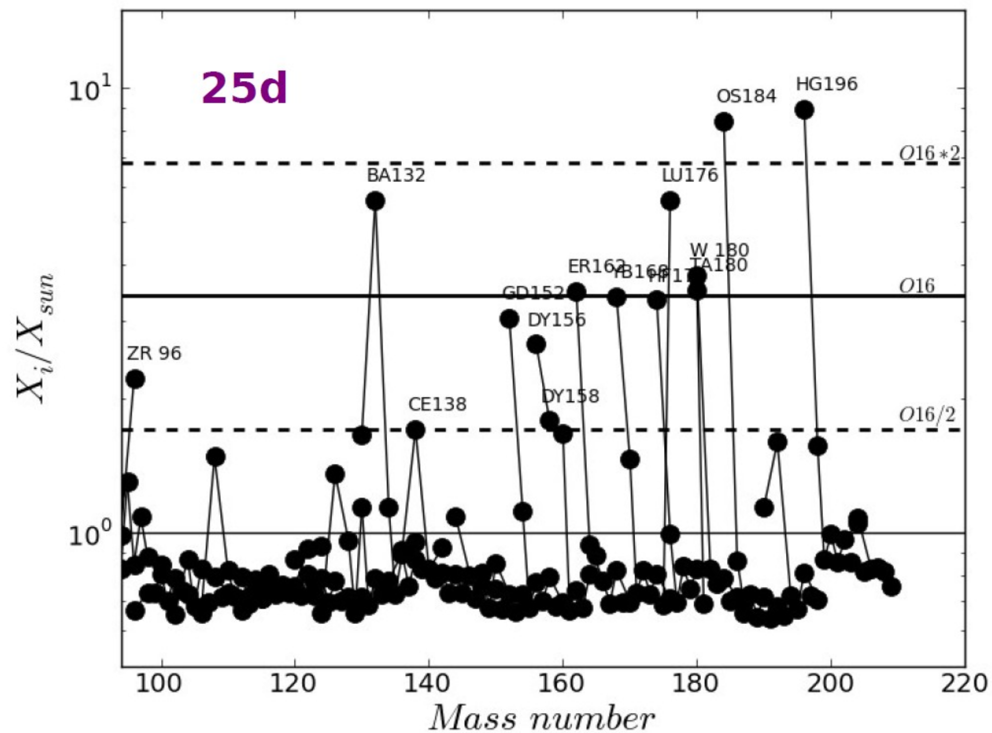
γ-process trajectory from CCSN

T_{peak} = 2.95 GK


92Mo 14.8
94Mo 9.25
96Mo 16.7
97Mo 9.55
98Mo 24.1
99Mo 66h
100Mo 9.63
94Nb 20ky
95Nb 35d
95Nb 23h
100
N = 50
90Zr 51.5
91Zr 11.2
92Zr 17.2
93Zr 1.5My
94Zr 17.4
95Zr 64d
96Zr 2.80
97Zr 17h
89Y 100
90Y 64h
91Y 59d
92Y 3.5h
84Sr 0.56
86Sr 9.86
87Sr 7.00
88Sr 82.6
89Sr 51d
90Sr 29y
91Sr 9.5h
85Rb 72.2
86Rb 19d
87Rb 27.8
88Rb 18m
85Krm 4.5h
82Kr 11.6
83Kr 11.5
84Kr 57.0
85Krg 11y
86Kr 17.3
87Kr 76m
log N (Si$_{total}$) ≡ 6
Lodders (2003)
Cameron (1959)
log N (solar system)
Atomic mass
10
8
6
4
2
0
−2
−4
0
50
100
150
200

- The p-only distribution is quite different for different CCSN models.
- The initial progenitor mass can be one of the relevant parameters to keep into account.





- Models: M = $15M_{sun}$ and M = $25M_{sun}$ MP+2016

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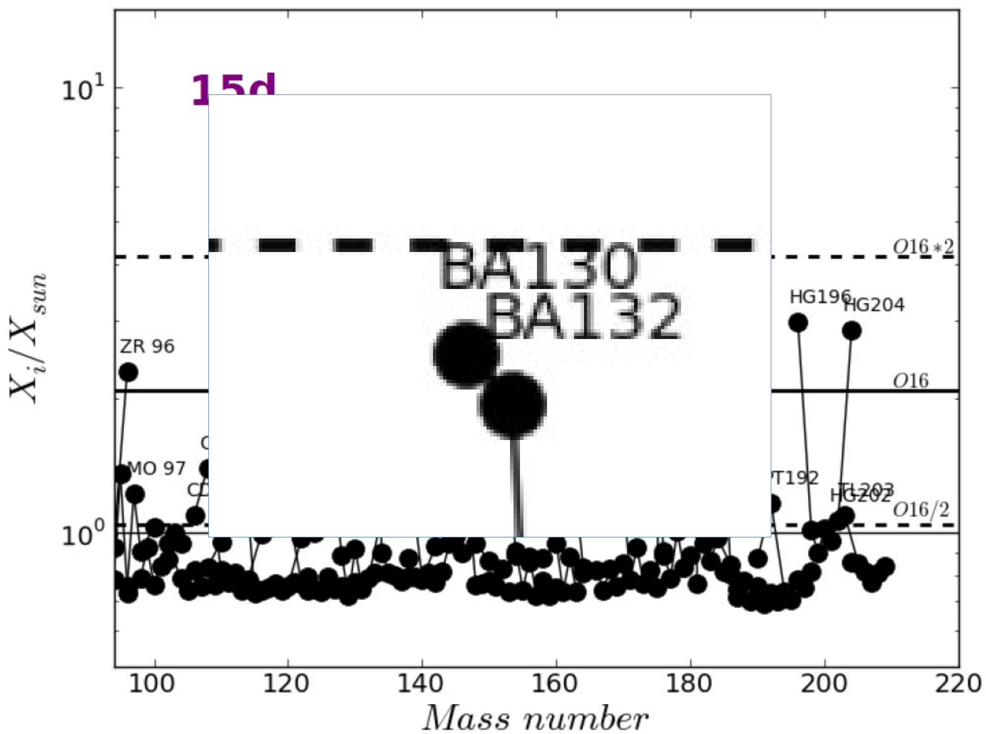
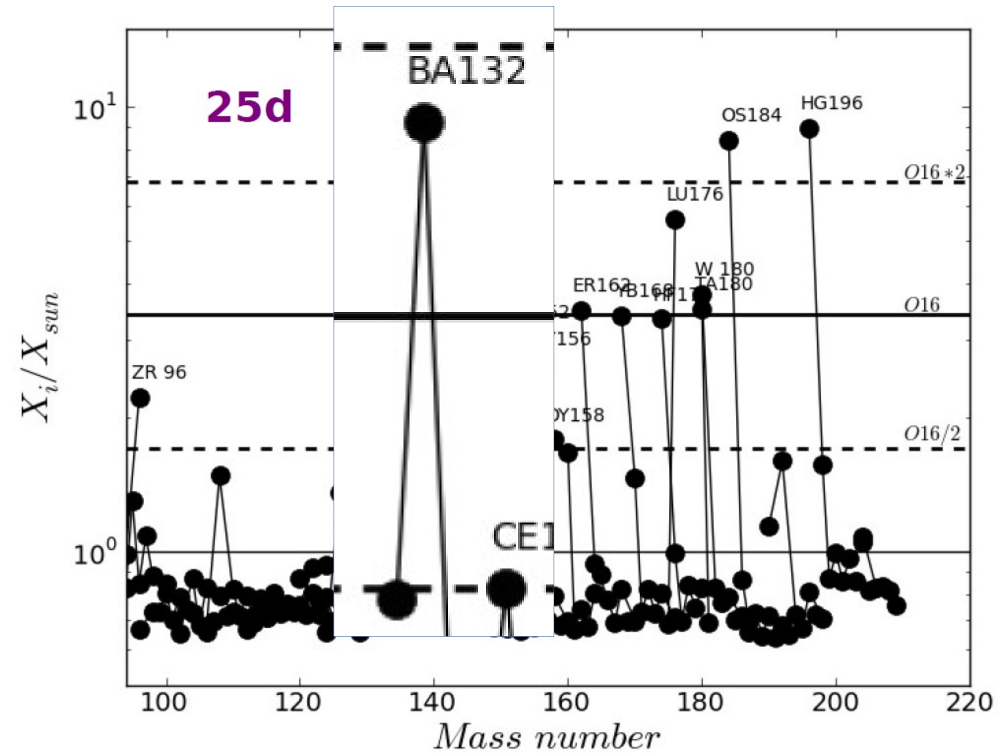




- Models: M = 15M_{sun} and M = 25M_{sun} MP+2016

Baking gold: the r process

^{197}Tl 2.84 h β^+	^{198}Tl 5.30 h β^+	^{199}Tl 7.42 h β^+	^{200}Tl 1.09 d β^+	^{201}Tl 3.04 d β^+
^{196}Hg 0.15 204 mb	^{197}Hg 2.67 d β^+	^{198}Hg 9.97 173 mb	^{199}Hg 16.87 374 mb	^{200}Hg 23.1 115 mb
^{195}Au 186.11 d β^+	^{196}Au 6.17 d β^+	^{197}Au 100 582 mb	^{198}Au 2.70 d 840 mb, β^-	^{199}Au 3.14 d β^-
^{194}Pt 32.967 365 mb	^{195}Pt 33.832 860 mb	^{196}Pt 25.242 183 mb	^{197}Pt 19.89 h β^-	^{198}Pt 7.163 92.2 mb
^{193}Ir 62.7 994 mb	^{194}Ir 19.28 h β^-	^{195}Ir 2.50 h β^-	^{196}Ir 52.00 s β^-	^{197}Ir 5.80 m β^-

From Chao Sam Phraya National Museum in Ayutthaya

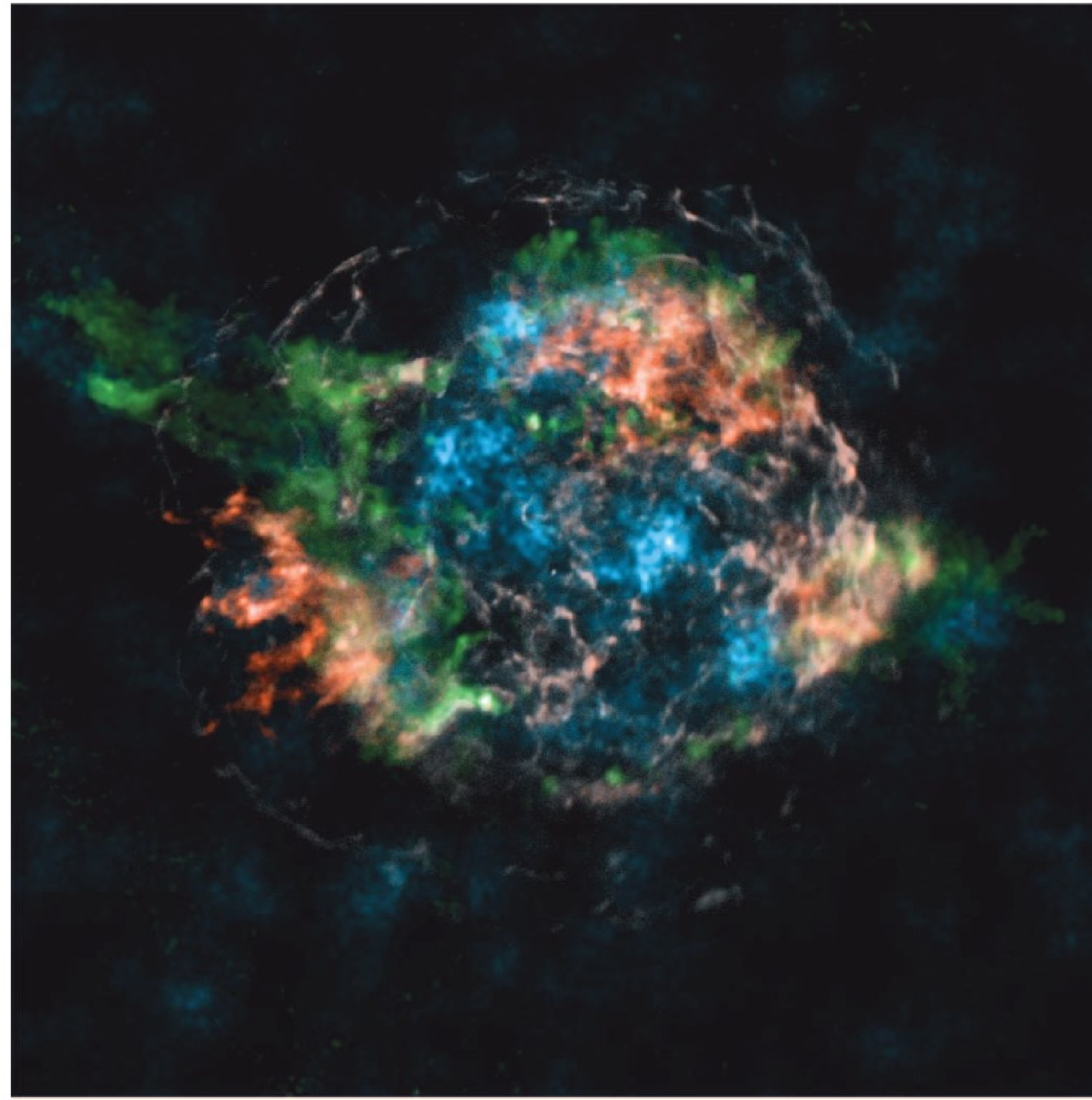
All the gold atoms in that cup were made in the same star?
What type of star?

CCSN remnant

Cassiopea A

11000 ly

~ 300 years ago



Grefenstette et al. 2014, Nature
(NuSTAR telescope data)

CCSN remnant

Cassiopea A

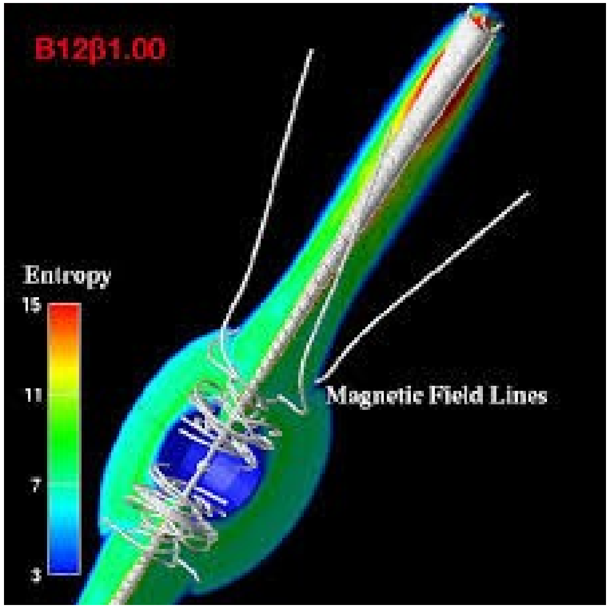
11000 ly

~ 300 years ago

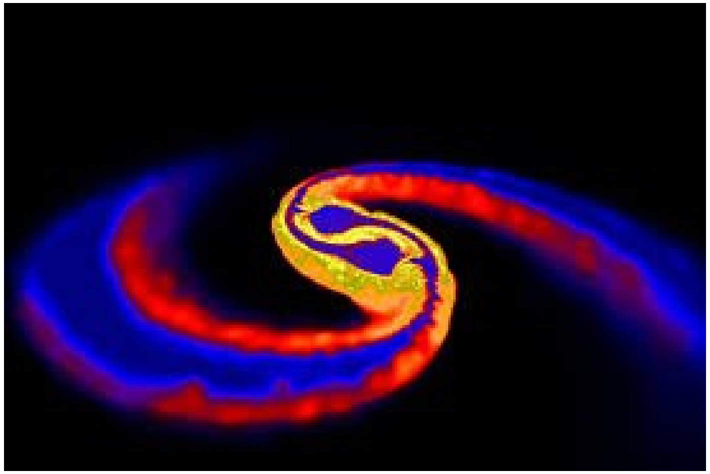
Grefenstette et al. 2014, Nature
(NuSTAR telescope data)

The r-process sources: short summary

Anomalous Supernovae:
e.g., jetSNe → magnetars
0.2 ≤ protons/neutrons ≤ 0.4



Neutron Star Mergers:
protons/neutrons ≤ 0.1



Why making the r-process is so difficult?

- Today the most supported scenarios are neutron-star mergers and Magnetically Driven Jets from Supernovae (e.g., Thielemann+2011).
- Neutrino-driven winds from CCSNe do not seem to have the conditions to host the r-process. Why?

$2\alpha(n,\gamma)^{9}Be(\alpha,n)^{12}C$.... from Woosley & Hoffman 1992 ApJ:

bound nuclei, and the final composition will differ from what would be calculated in NSE. This is the α-rich freeze-out. [If the mass fractions of free neutrons and α-particles are both large, the assembly of α-particles to ^{12}C may be amplified by a factor typically of order 10 by the neutron-catalyzed reaction sequence $^{4}He(\alpha n, \gamma)^{9}Be(\alpha, n)^{12}C$ (Delano & Cameron 1971 and Appendix A below), but the requirements on density remain approximately the same.]

Previous calculations have shown, for small values of the

Silver

What is the main process that made that same silver in stars?

What to do to solve the mysteries of silver and gold? Some numbers..

HST:
- Total costs until now ~ 11 Bi USD
- Operation ~ 100mi USD/year
- Observational cost ~ 10-50K USD/hour

TRIUMF laboratory, Vancouver, Canada

Nuclear experiment to get better nuclear rates:
- Operation cost ~ 2-10K GBP/hour
- Total cost depends on the length of the experiment.

Resources

- Textbooks:
  - Kippenhahn & Weigert, Clayton, Rolfs & Rodney, Kavalier & Hansen, Prialnik
- The most important resource:
  - NASA-ADS: http://adsabs.harvard.edu/abstract_service.html
  - ArXiv: https://arxiv.org/