Stellar Nucleosynthesis Components for GCE

Raphael HIRSCHI
Keele Uni, UK

SHEN @ Keele: L. Scott, E. Kaiser
in collaboration with:
GVA code: G. Meynet, A. Maeder, C. Georgy, S. Ekström, P. Eggenberger, A. Choplin and C. Chiappini (IAP, D)
VMS: N. Yusof, H. Kassim (UM, KL, Malaysia), P. Crowther (Sheffield), O. Schnurr (IAP)
Nucleo: F.-K. Thielemann, U. Frischknecht, T. Rauscher (Basel, CH/Herts, UK) N. Nishimura
NUGRID: F. Herwig (Victoria, Canada), M. Pignatari (Hull), C. Fryer, S. Jones (LANL),
J. den Hartogh (Konkoly Obs., H), Laird (York), UChicago, UFrankfurt, …
MESA: B. Paxton (KITP), F. X. Timmes, (UArizona, US)
SNe: K. Nomoto (IPMU, J), C. Frohlich, M. Gilmer (NCSU), A. Kozyreva (Tel Aviv,Il), T. Fischer (W.,P)
HYDRO: C. Meakin, D. Arnett (UArizona), C. Georgy (GVA), M. Viallet (MPA),
F. Roepke, L. Horst (HITS, D), P. Edelmann (Newcastle, UK), A. Cristini (Uoklahoma,US)

Keele is Not Kiel (Germany) But Where is it?

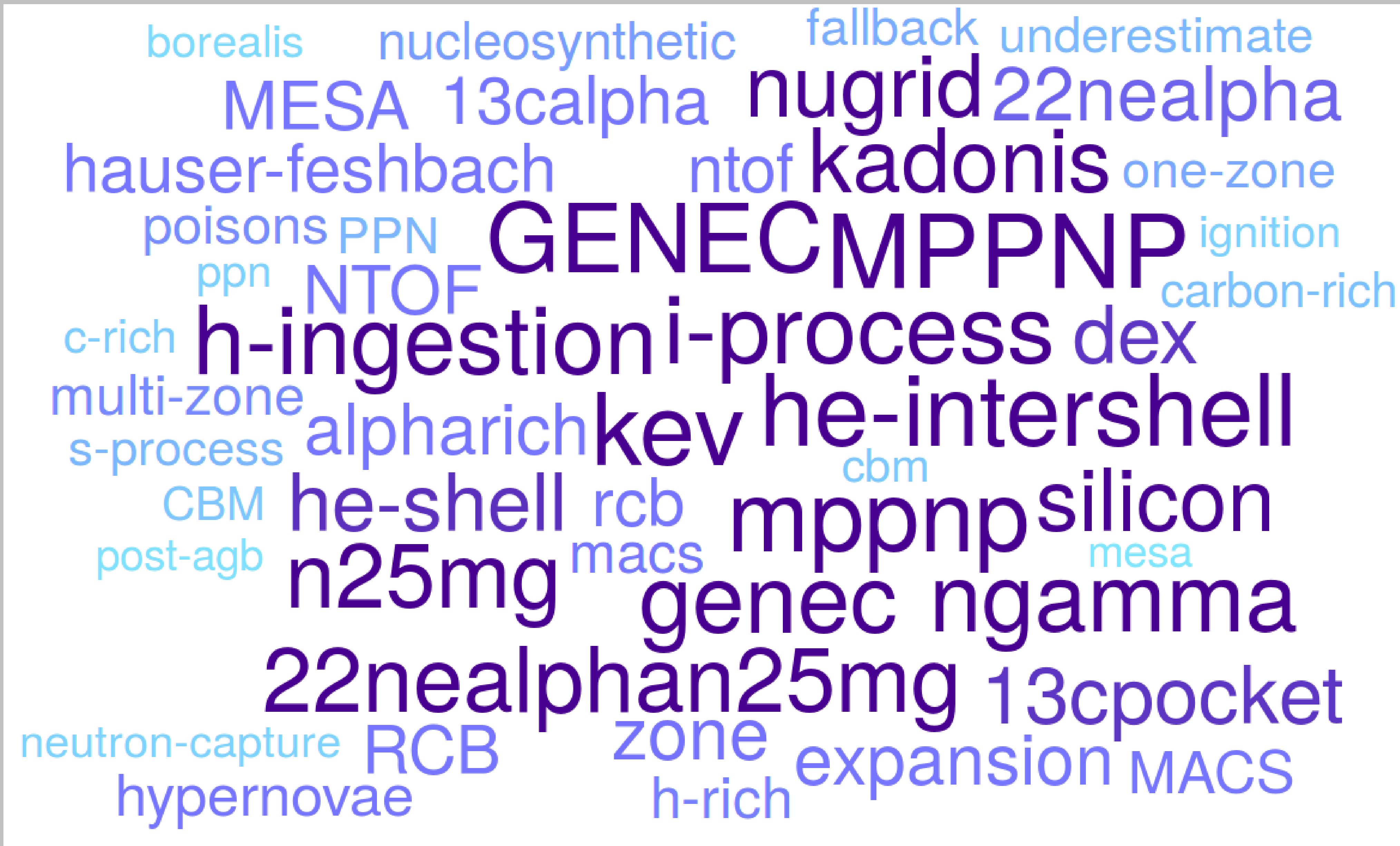
West Midlands:

Keele

Keele area

is famous for pottery: Wedgwood, ...

and football: Stoke city fc in ~~premier~~ league



Source: ADS Bumblebee

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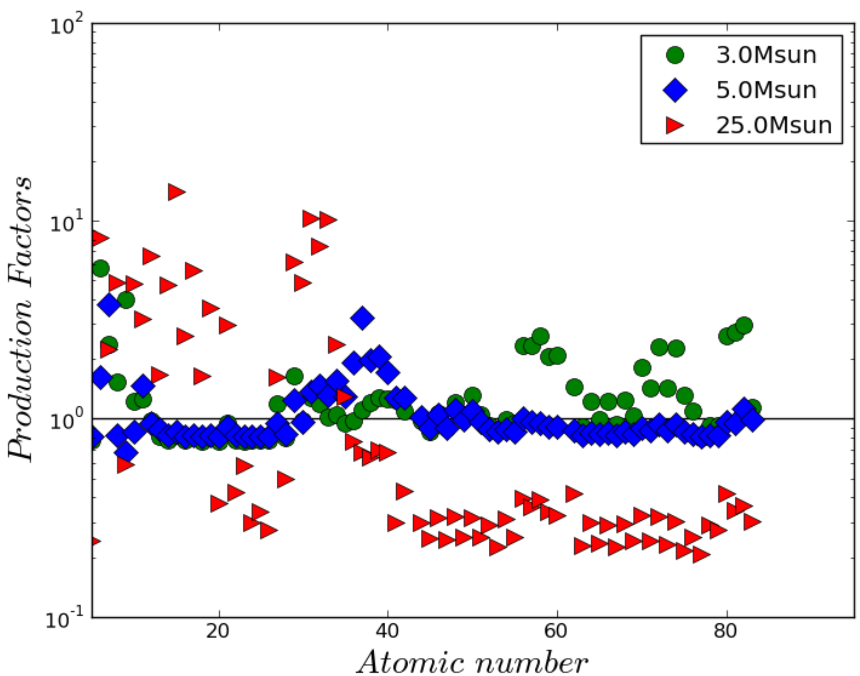
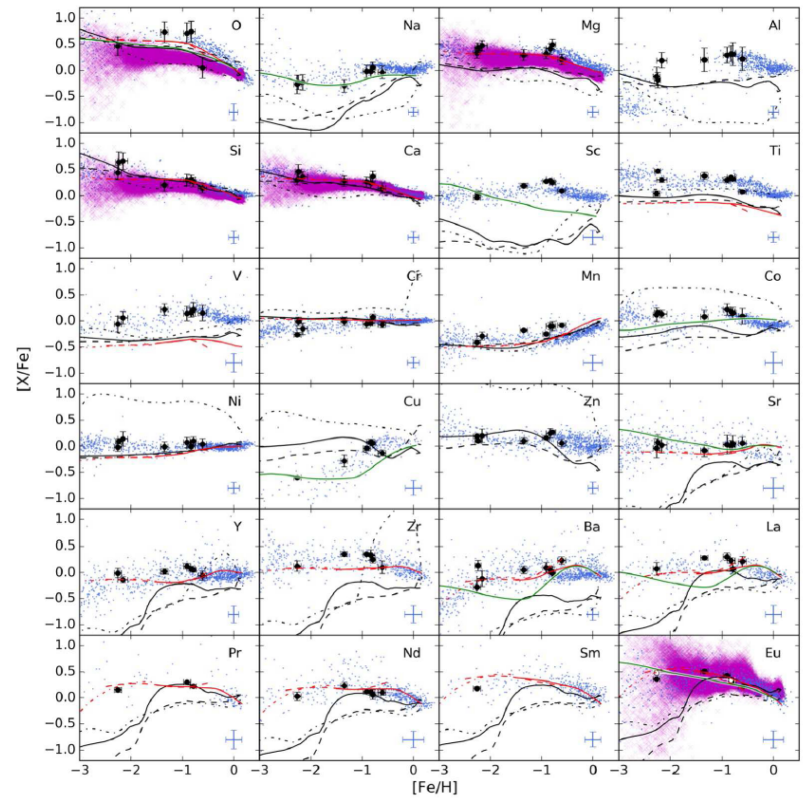
NuGrid :

- www.nugridstars.org
- data.nugridstars.org
- wendi.nugridstars.org

The Nucleosynthesis Grid (NuGrid) project mantains and develops tools for post-processing nucleosynthesis simulations, and applies these to produce complete sets of stellar yields.

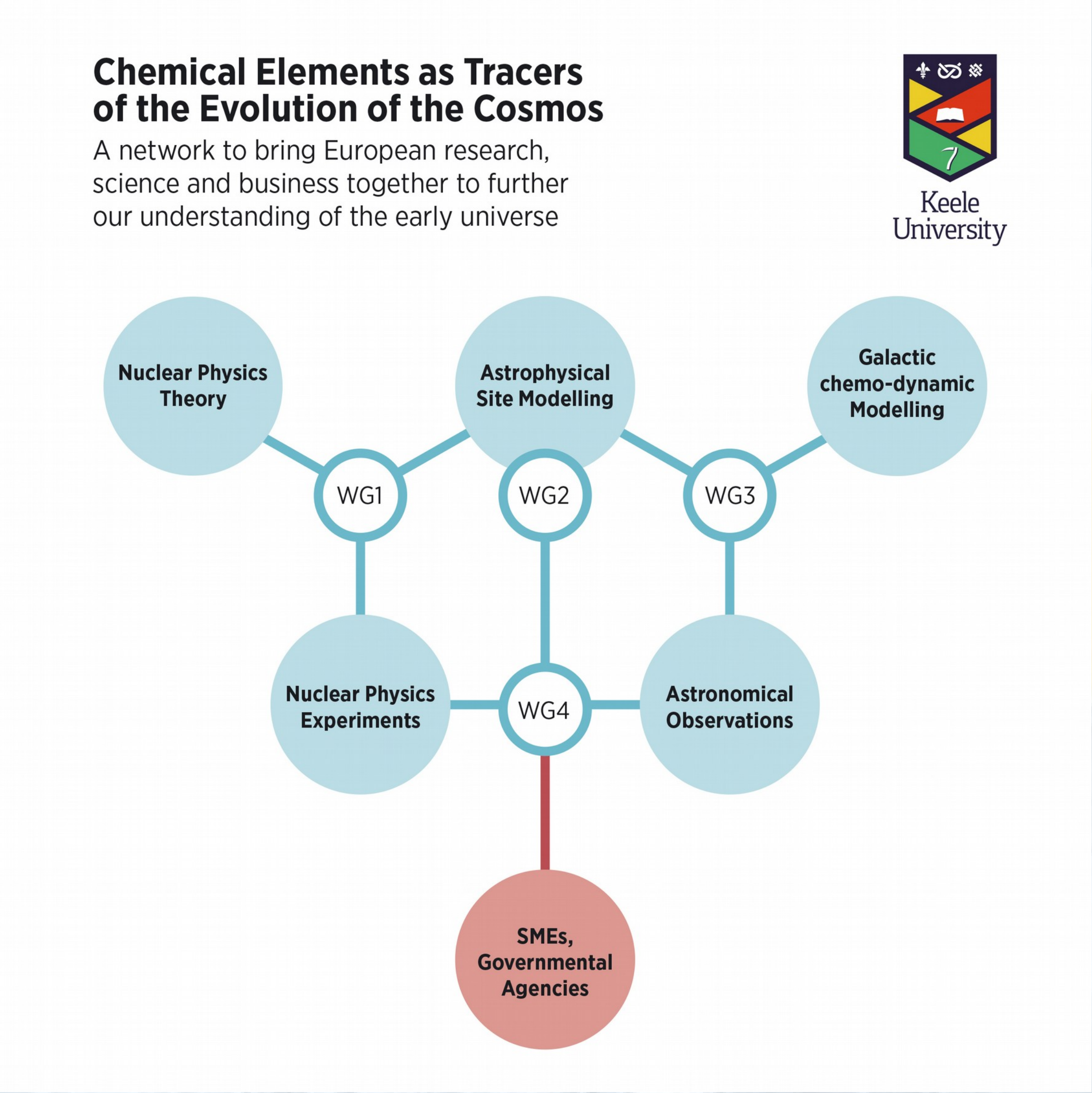


Final elemental production factors for a low mass AGB star (3 Msun), a massive AGB star (5 Msun), and a massive star (25 Msun) (MP+2016 ApJS, CR+18, MNRAS).



GCE simulations: OMEGA vs other codes, NuGrid yields vs other yields (BC+17, ...).

ChETEC COST Action (2017-2021) www.chetec.eu



Funding for collaboration visits: STSMs!!

Formal cooperation with JINA-CEE underway!!

30 countries have already joined ChETEC to coordinate research efforts in Nuclear Astrophysics: Austria, Belgium, Bulgaria, Czech Rep., Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom

Nucleosynthesis Components for GCE

Sites & processes:

https://docs.google.com/document/d/18VKFZqtwbyjD6GK2nDiU7UImiuOrJ-_zkh_lj35mY2Q/edit

I need You!

Plan

- Sites, processes, elements produced

- Massive stars & the (not always) weak s process

- Low-mass stars & the main s process

- i process in various sites

- Explosive nucleosynthesis summary

… including a few key stellar & nuclear uncertainties along the way.

Sites

- Secular evolution:

Low-mass stars, intermediate, Massive, VMS, SMS?

- Recurring events:

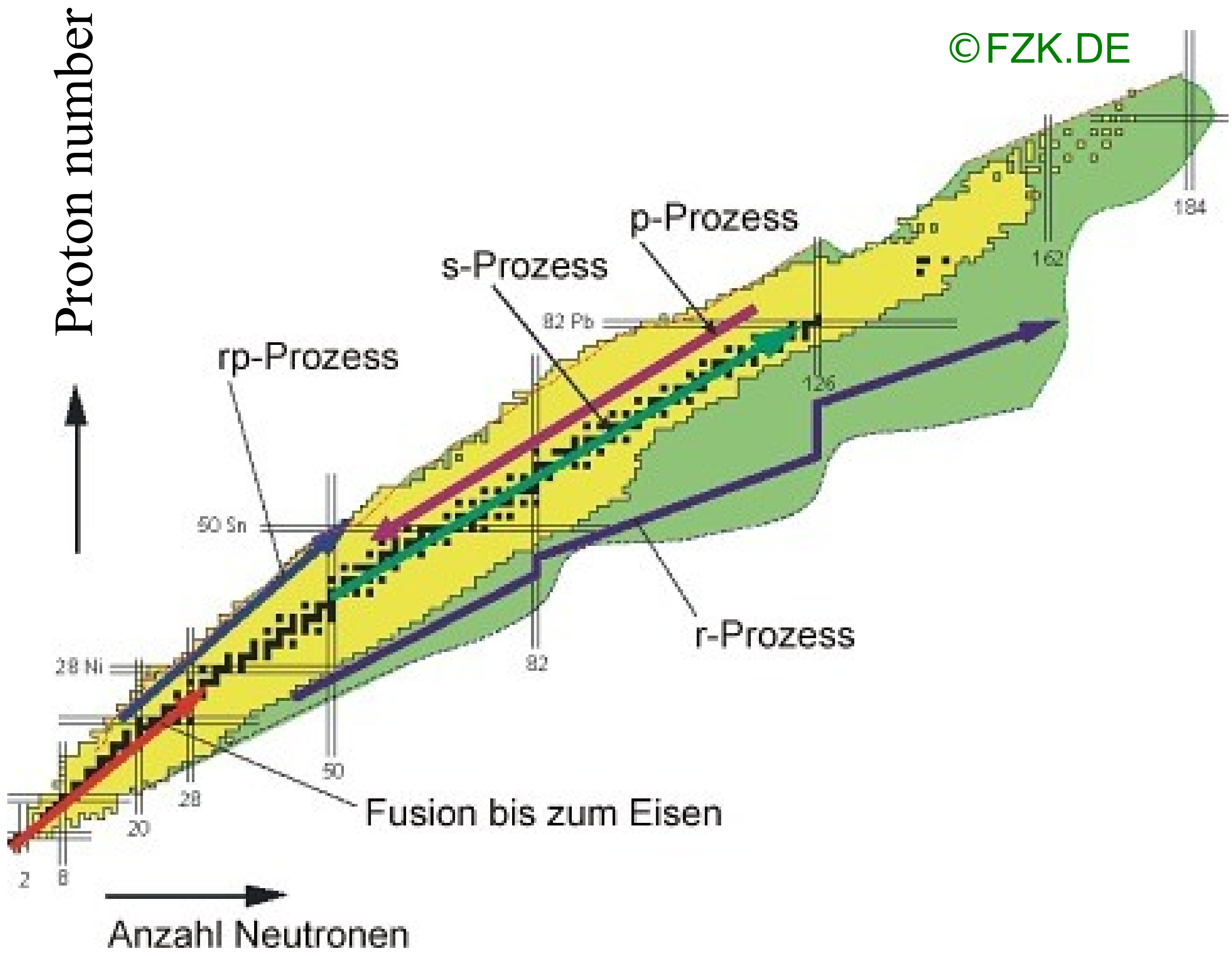
Novae/RAWD, X-ray burst

- Single events:

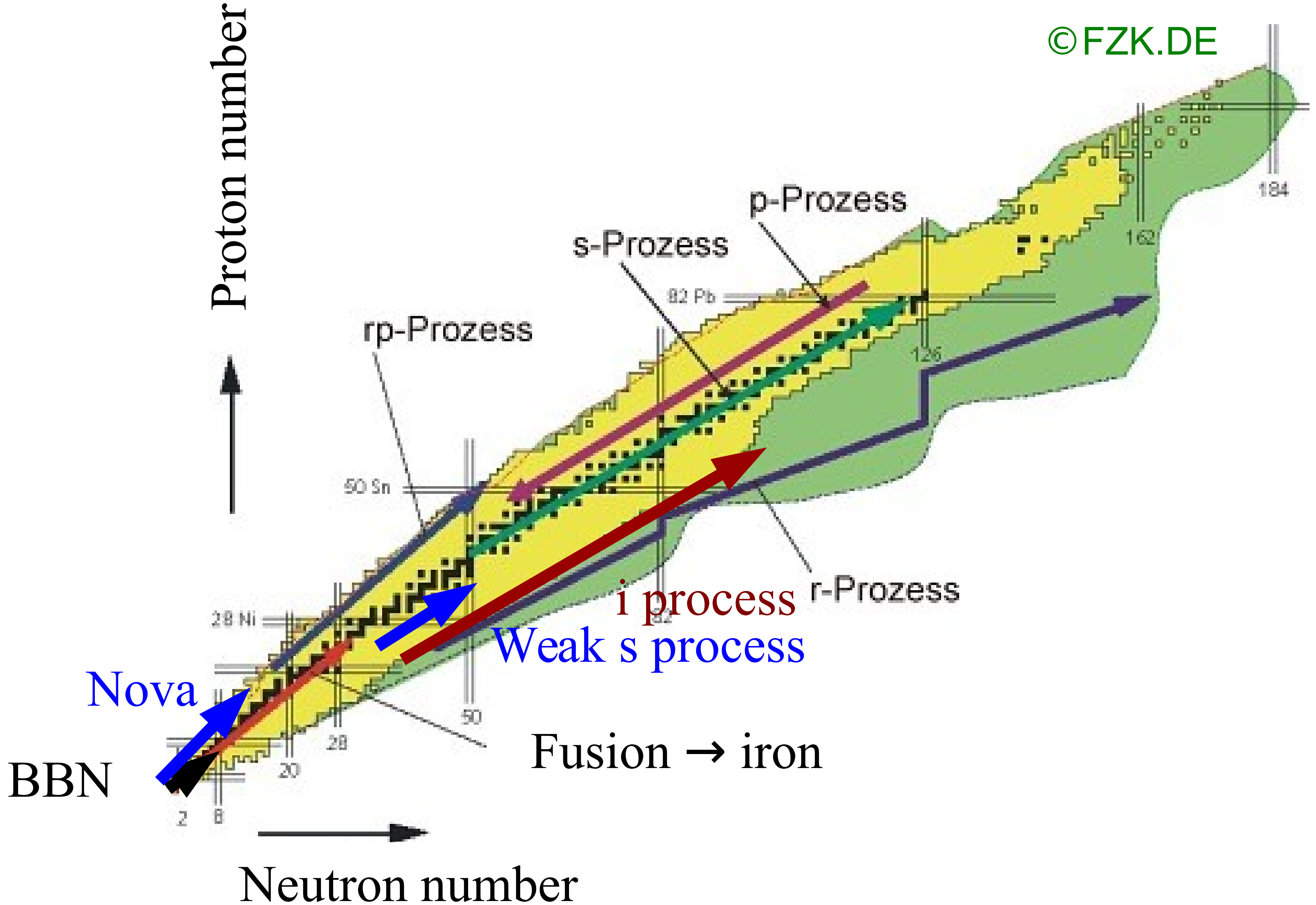
- CCSNe, SNIa, MHD-SNe, NS-mergers

…?

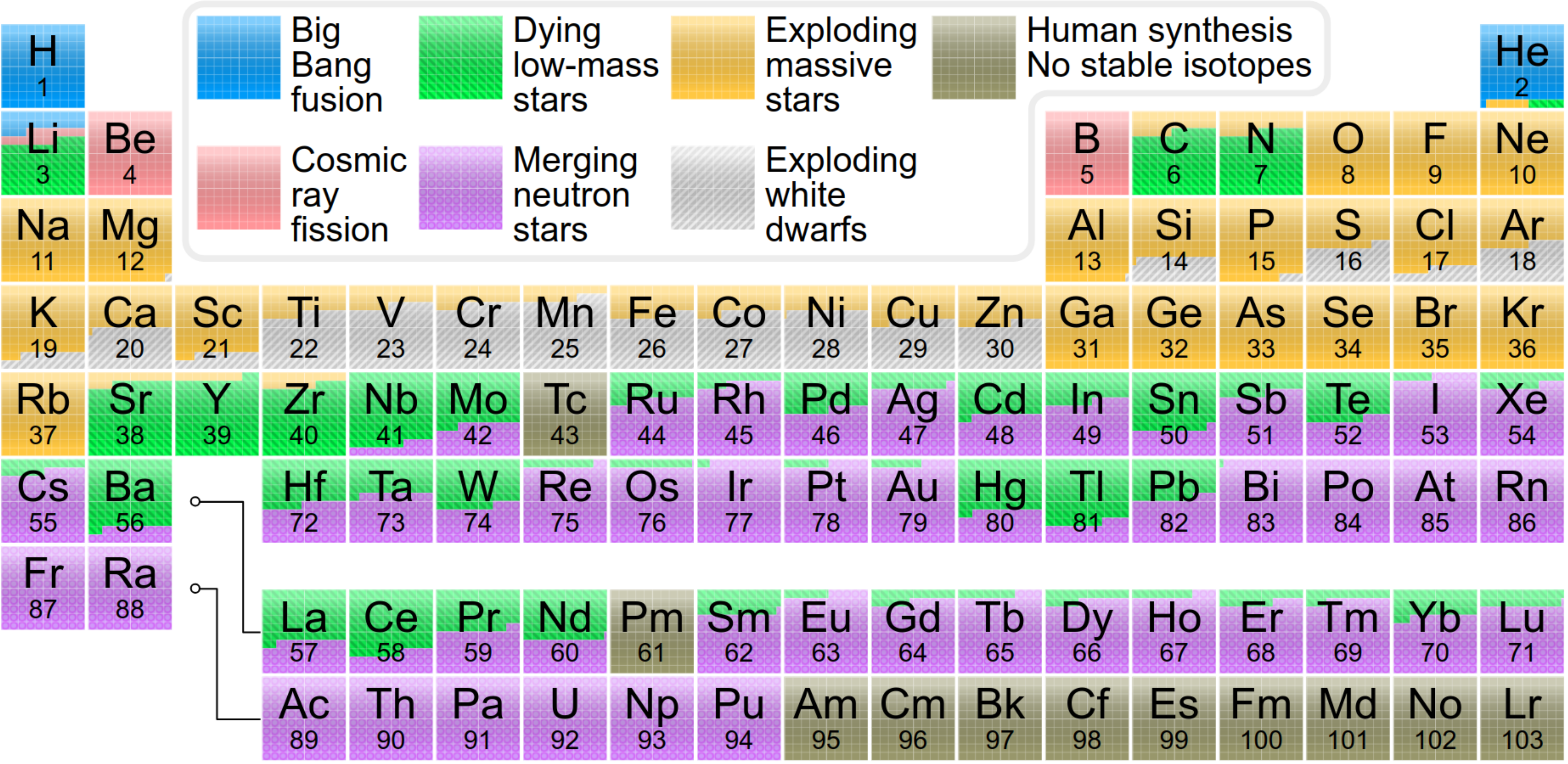
Nucleosynthesis Processes



Nucleosynthesis Processes



Which "Stars" Are We Made Of?



https://en.wikipedia.org/wiki/File:Nucleosynthesis_periodic_table.svg

Woosley, Heger & Weaver, 2002 RvMP Vol. 74. p. 1015

TABLE III. The origin of the light and intermediate-mass elements.

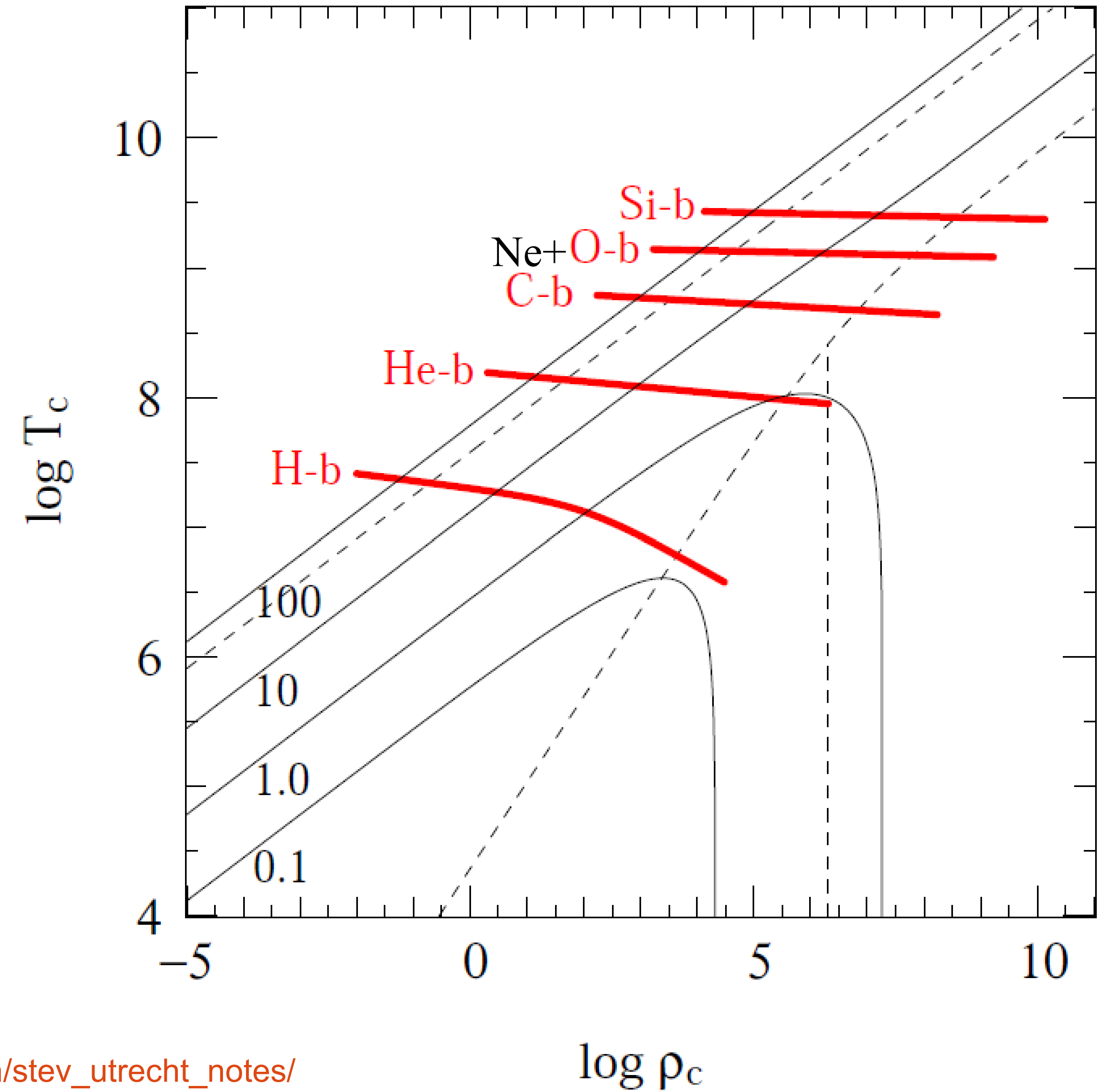
Species	Origin	Species	Origin	Species	Origin
^{1}H	BB	^{30}Si	C,Ne	^{51}V	α,Ia-det,xSi,xO,ν
^{2}H	BB	^{31}P	C,Ne	^{50}Cr	xSi,xO,α,Ia-det
^{3}He	BB,L*	^{32}S	xO,O	^{52}Cr	xSi,α,Ia-det
^{4}He	BB,L*,H	^{33}S	xO,xNe	^{53}Cr	xO,xSi
^{6}Li	CR	^{34}S	xO,O	^{54}Cr	nse-IaMCh
^{7}Li	BB,ν,L*,CR	^{36}S	He(s),C,Ne	^{55}Mn	Ia,xSi,ν
^{9}Be	CR	^{35}Cl	xO,xNe,ν	^{54}Fe	Ia,xSi
^{10}B	CR	^{37}Cl	He(s),xO,xNe	^{56}Fe	xSi,Ia
^{11}B	ν	^{36}Ar	xO,O	^{57}Fe	xSi,Ia
^{12}C	L*,He	^{38}Ar	xO,O	^{58}Fe	He(s),nse-IaMCh
^{13}C	L*,H	^{40}Ar	He(s),C,Ne	^{59}Co	He(s),α,Ia,ν
^{14}N	L*,H	^{39}K	xO,O.ν	^{58}Ni	α
^{15}N	novae,ν	^{40}K	He(s),C,Ne	^{60}Ni	α, He(s)
^{16}O	He	^{41}K	xO	^{61}Ni	He(s),α,Ia-det
^{17}O	novae, L*	^{40}Ca	xO,O	^{62}Ni	He(s),α
^{18}O	He	^{42}Ca	xO	^{64}Ni	He(s)
^{19}F	ν,He,L*	^{43}Ca	C,Ne,α	^{63}Cu	He(s),C,Ne
^{20}Ne	C	^{44}Ca	α,Ia-det	^{65}Cu	He(s)
^{21}Ne	C	^{46}Ca	C,Ne	^{64}Zn	ν-wind,α,He(s)
^{22}Ne	He	^{48}Ca	nse-IaMCh	^{66}Zn	He(s),α,nse-IaMCh
^{23}Na	C,Ne,H	^{45}Sc	α,C,Ne,ν	^{67}Zn	He(s)
^{24}Mg	C,Ne	^{46}Ti	xO,Ia-det	^{68}Zn	He(s)
^{25}Mg	C,Ne	^{47}Ti	Ia-det,xO,xSi	r	ν-wind
^{26}Mg	C,Ne	^{48}Ti	xSi,Ia-det	p	xNe,O
^{27}Al	C,Ne	^{49}Ti	xSi	$s(A<90)$	He(s)
^{28}Si	xO,O	^{50}Ti	nse-IaMCh,He(s)	$s(A>90)$	L*
^{29}Si	C,Ne	^{50}V	C,Ne,xNe,xO		

List of neutron capture processes (with products observed/measured)

- 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^{13} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n < 10^{13}$ n cm^{-3}.

Mass Domains

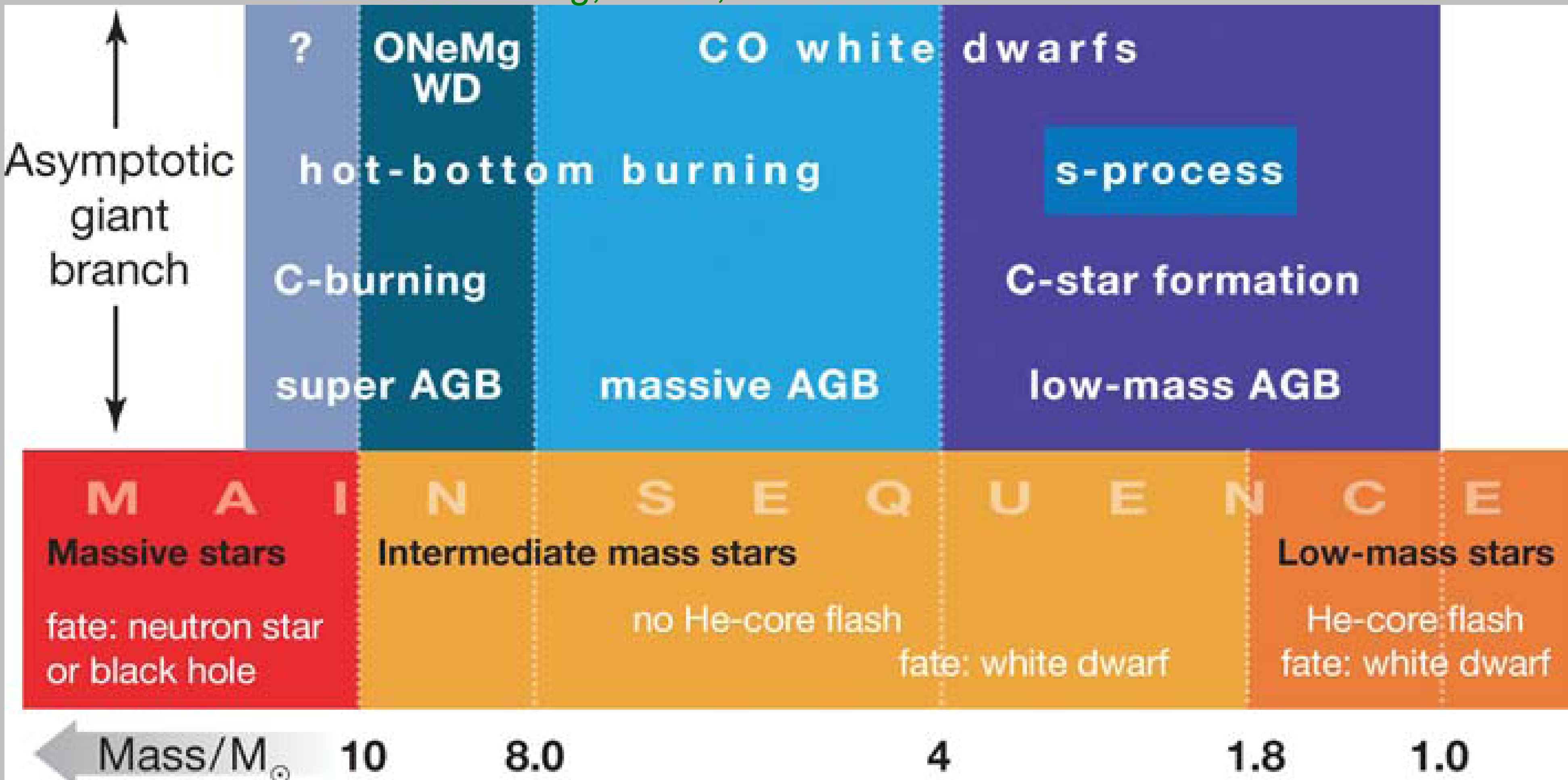
$$\epsilon_{\rm nuc} = \epsilon_0 \, \rho^{\lambda} \, T^{\nu}$$



Lecture notes from O. Pols taken from:
http://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/

Mass Domains

Herwig, ARAA, 2005



Massive stars: > 9 M_o : go through all burning stages

Intermediate-mass stars: 1.8 - 9 M_o do not ignite C-burning in centre (C-flash for SAGB stars)

Low-mass stars: <1.8M_o do not ignite He-burning in centre (He-flash)

Stellar Models:

Stellar structure equations +

- Nuclear reactions

- Mass loss

- Rotation

- Convection

- Magnetic fields

- Binarity

- Equation of state, opacities & neutrino losses

including metallicity dependence

Mass Loss: Types, Driving & Recipes

Mass loss driving mechanism and prescriptions at different stages:

- O-type & "LBV" stars (bi-stab.): line-driven Vink et al 2000, 2001
- WR stars (clumping effect): line-driven Nugis & Lamers 2000, Gräfener & Hamann (2008)
- RSG: Pulsation/dust? de Jager et al 1988
- RG: Pulsation/dust? Reimers 1975,78, with η=~0.5
- AGB: Super winds? Dust Bloecker et al 1995, with η=~0.05
- LBV eruptions: continuous driven winds? Owocki et al
- …

What changes at low Z?

- Stars are more compact: R~R(Z_o)/4 (lower opacities) at $Z=10^{-8}$

$$\dot{M}(Z)=\dot{M}(Z_0)(Z/Z_0)^{\alpha}$$

- α = 0.5-0.6 (Kudritzki & Puls 00, Ku02)

(Nugis & Lamers, Evans et al 05)

- α = 0.7-0.86 (Vink et al 00,01,05)

Z(LMC)~Z_o/2.3 => Mdot/1.5 – Mdot/2

Z(SMC)~Z_o/7 => Mdot/2.6 - Mdot/5

Mass loss at low Z still possible?

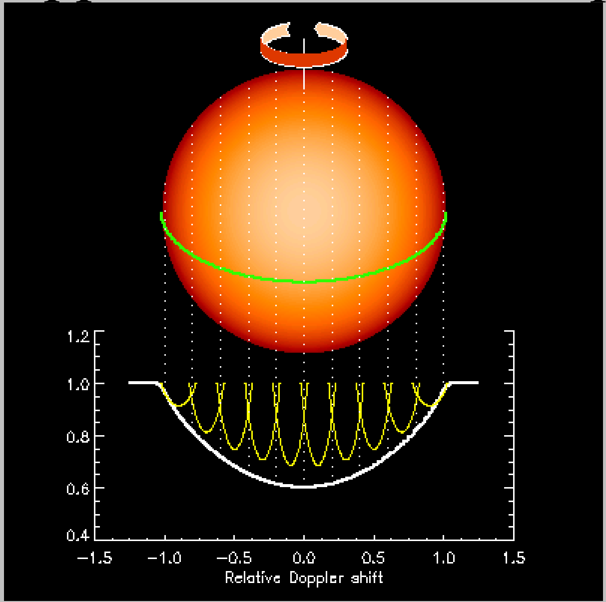
RSG (and LBV?): no Z-dep.; CNO? (Van Loon 05, Owocky et al)

Mechanical mass loss ← critical rotation

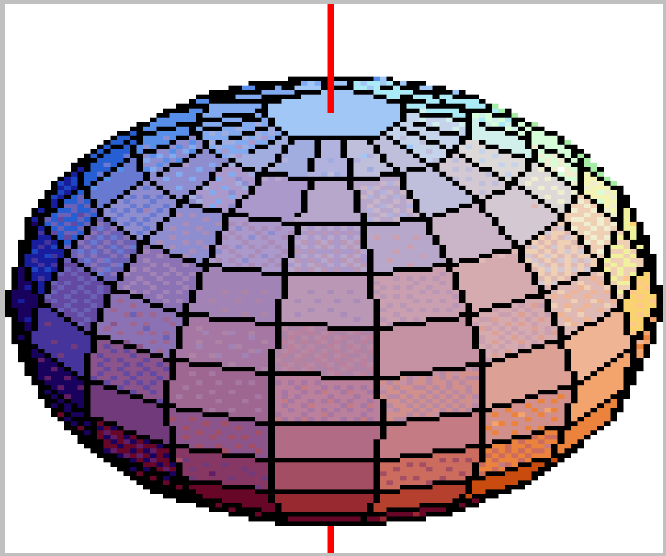
(e.g. Hirschi 2007, Ekstroem et al 2008, Yoon et al 2012)

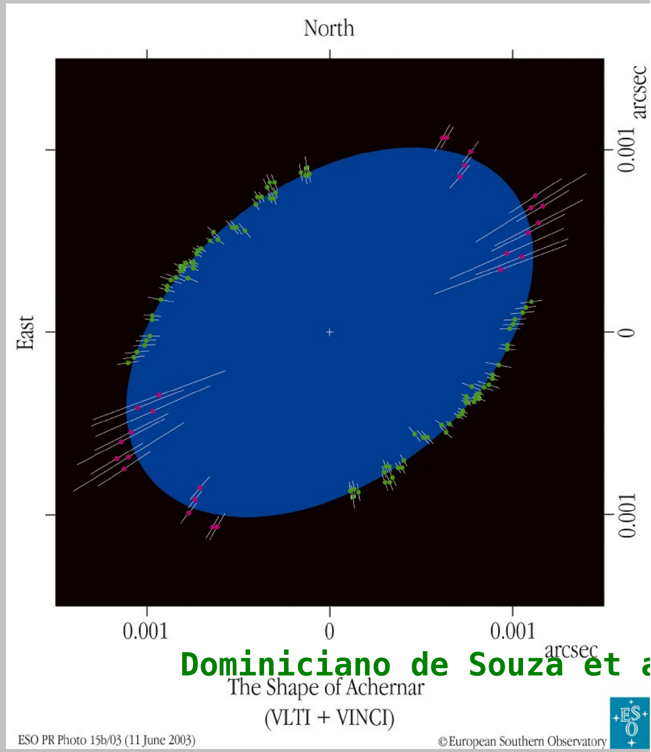
Rotational Effects on Surface

Doppler-broadened line profile



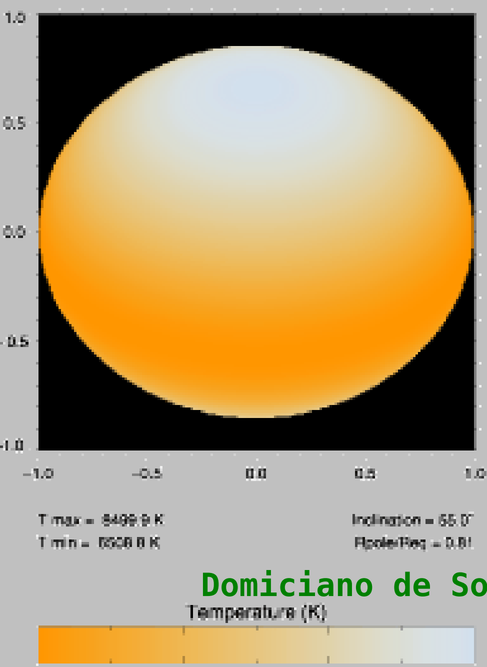
Fast rotators –> oblate shape:





Dominiciano de Souza et a

T_{eff} map (BMAD)



Domiciano de Souza et al. 2005

← Altair: pole brighter than equator: Effect compatible with von-Zeipel theorem (1924)

→ enhanced mass loss (+ anisotropic)

Stellar Evolution with Rotation: Geneva Code

1.5D hydrostatic code (Eggenberger et al 2008)

Rotation: (Maeder & Meynet 2008)

Centrifugal force: KEY FOR GRB prog.

$$\vec{g}_{\rm eff} = \vec{g}_{\rm eff}(\Omega,\theta) = \left(-\frac{GM}{r^2} + \Omega^2 r \sin^2\theta\right) \vec{e}_r + \Omega^2 r \sin\theta \cos\theta \, \vec{e}_\theta$$

Shellular rotation → still 1D: (Zahn 1992)

- Energy conservation:

$$\frac{\partial L_P}{\partial M_P} = \epsilon_{nucl} - \epsilon_\nu + \epsilon_{grav} = \epsilon_{nucl} - \epsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} \quad (2.9)$$

- Momentum equation:

$$\frac{\partial P}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \quad (2.10)$$

- Mass conservation (or continuity equation):

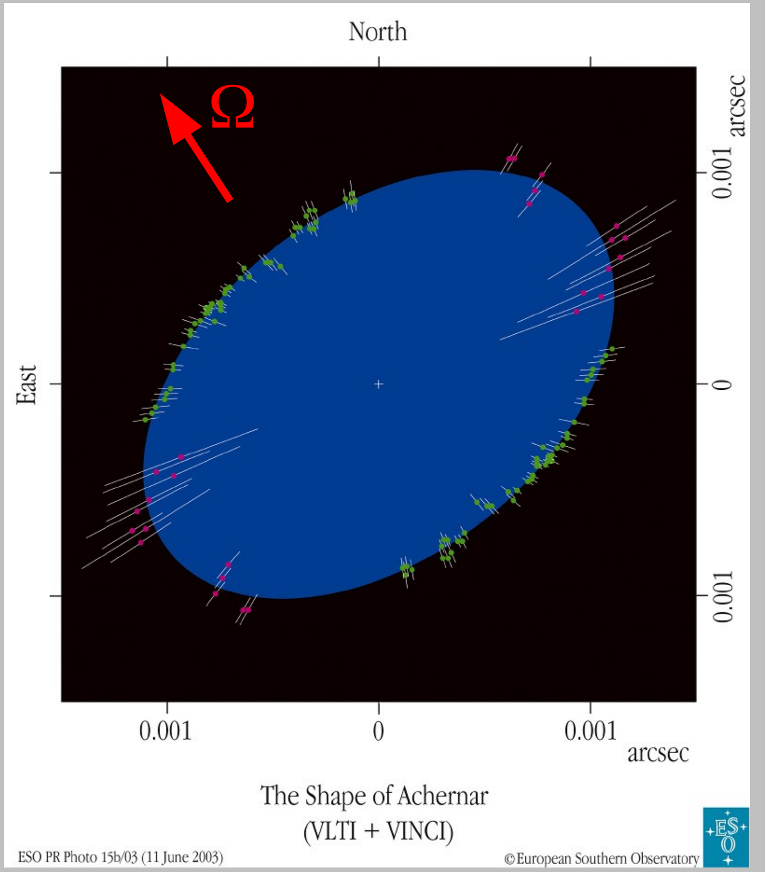
$$\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \overline{\rho}} \quad (2.11)$$

- Energy transport equation:

$$\frac{\partial \ln \overline{T}}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \min[\nabla_{\rm ad}, \nabla_{\rm rad}\frac{f_T}{f_P}] \quad (2.12)$$

where

$$\nabla_{\rm ad} = \frac{P\delta}{\overline{T}\overline{\rho} c_P} \quad \text{(convective zones)},$$
$$\nabla_{\rm rad} = \frac{3}{16\pi a c G}\frac{\kappa l P}{m \overline{T}^4} \quad \text{(radiative zones)},$$



$$f_P = \frac{4\pi r_P^4}{GM_P S_P}\frac{1}{<g^{-1}>},$$
$$f_T = \left(\frac{4\pi r_P^2}{S_P}\right)^2 \frac{1}{<g><g^{-1}>},$$

(Meynet and Meynet 97)

Rotation Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

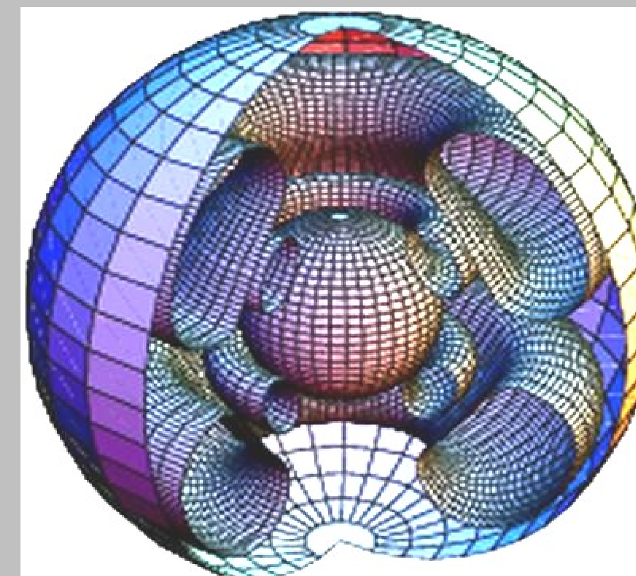
$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \bar{\Omega}}{\partial r}\right)}_{\text{diffusion term}}$$

Transport of chemical elements:

$$\rho \frac{\mathrm{d}X_i}{\mathrm{d}t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 \left[D + D_{eff}\right] \frac{\partial X_i}{\partial r}\right) + \left(\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\mathrm{nucl}}$$

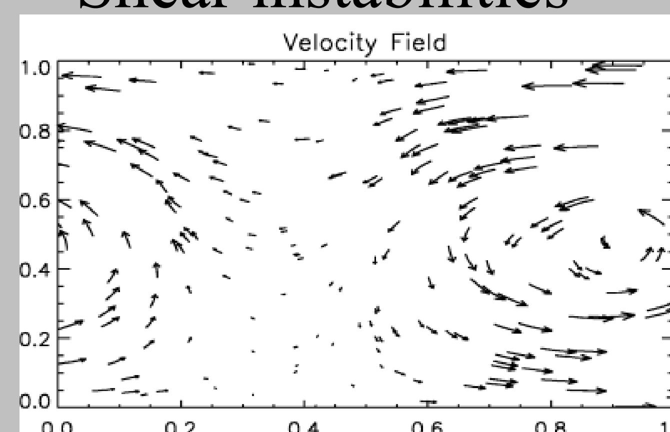
D: diffusion coeff. due to various transport mechanisms (convection, shear)

D_{eff}: diffusion coeff. due to meridional circulation + horizontal turbulence



Meynet & Maeder 2000

Shear instabilities



Brueggen & Hillebrandt 2000

Massive Stars: Evolution of the chemical composition

Burning stages (lifetime [yr]):

Hydrogen (10^{6-7}): $^{1}H \rightarrow {}^{4}He$

& ^{12}C, $^{16}O \rightarrow {}^{14}N$

Helium (10^{5-6}): $^{4}He \rightarrow {}^{12}C$, ^{16}O

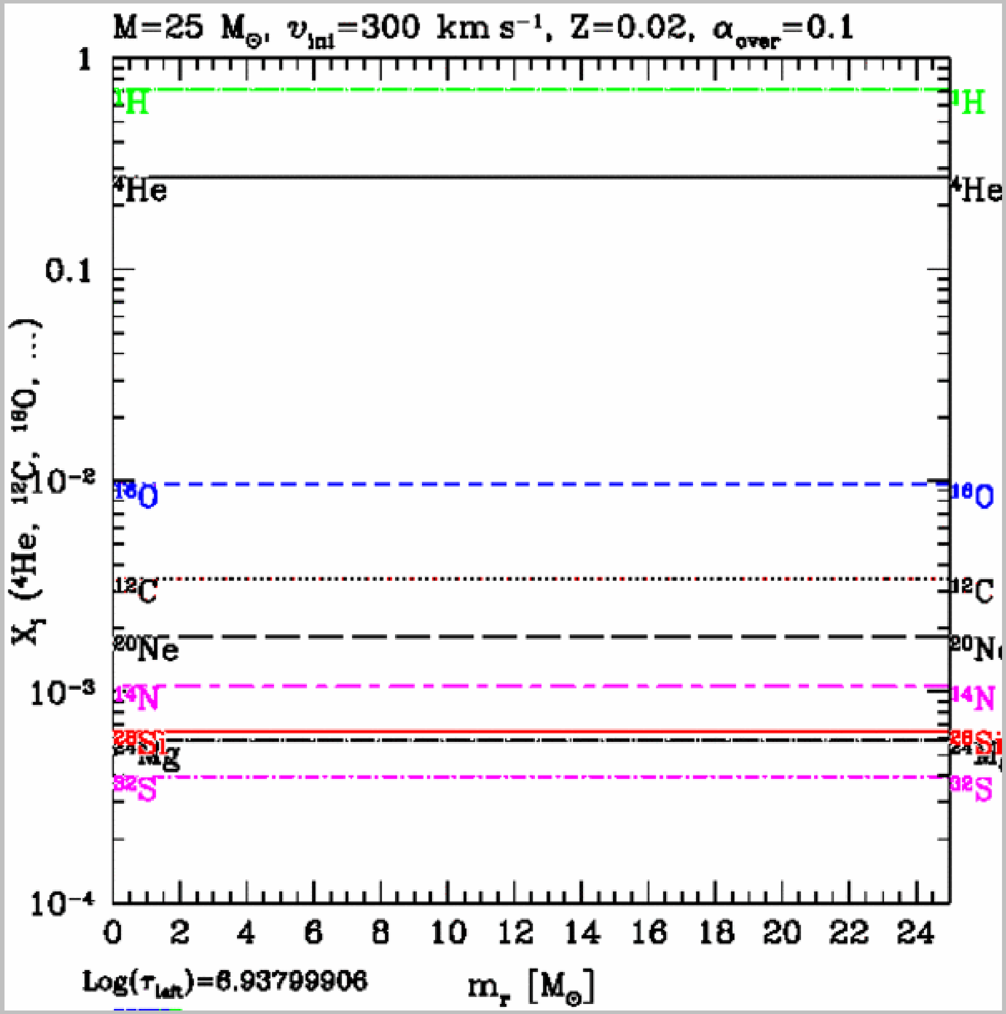
& $^{14}N \rightarrow {}^{18}O \rightarrow {}^{22}Ne$

Carbon (10^{2-3}): $^{12}C \rightarrow {}^{20}Ne$, ^{24}Mg

Neon (0.1-1): $^{20}Ne \rightarrow {}^{16}O$, ^{24}Mg

Oxygen (0.1-1): $^{16}O \rightarrow {}^{28}Si$, ^{32}S

Silicon (10^{-3}): ^{28}Si, $^{32}S \rightarrow {}^{56}Ni$

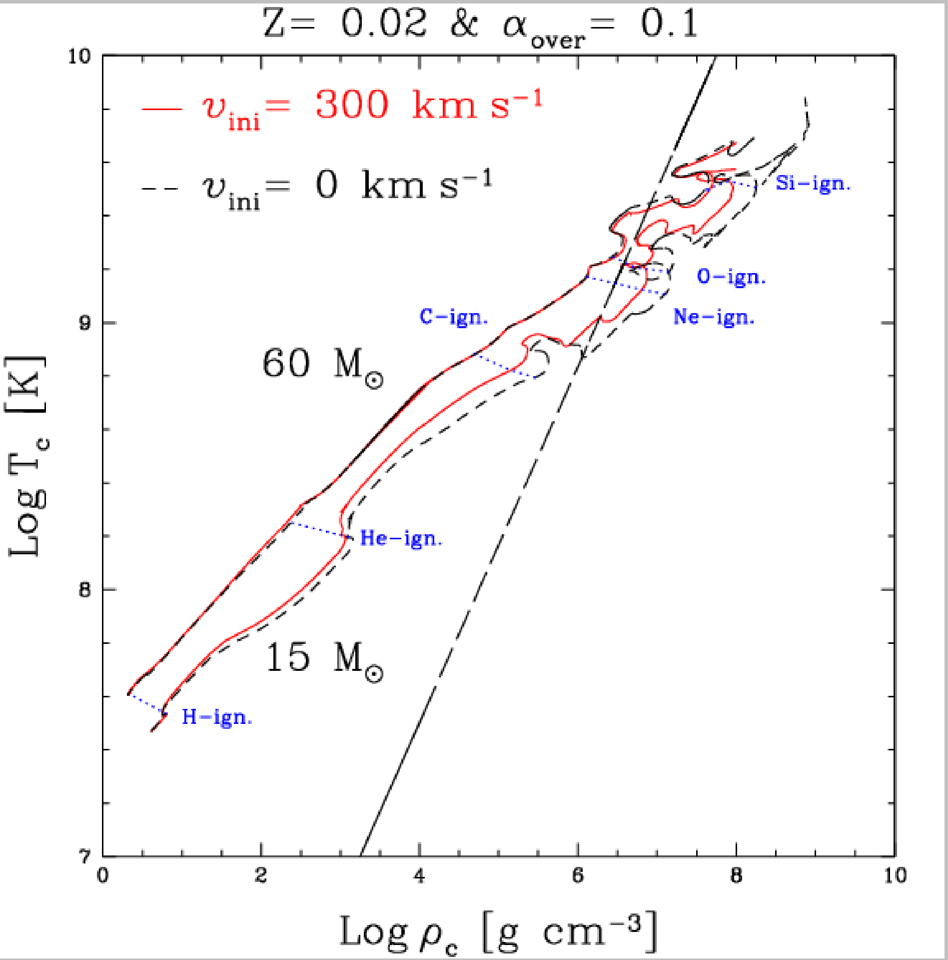


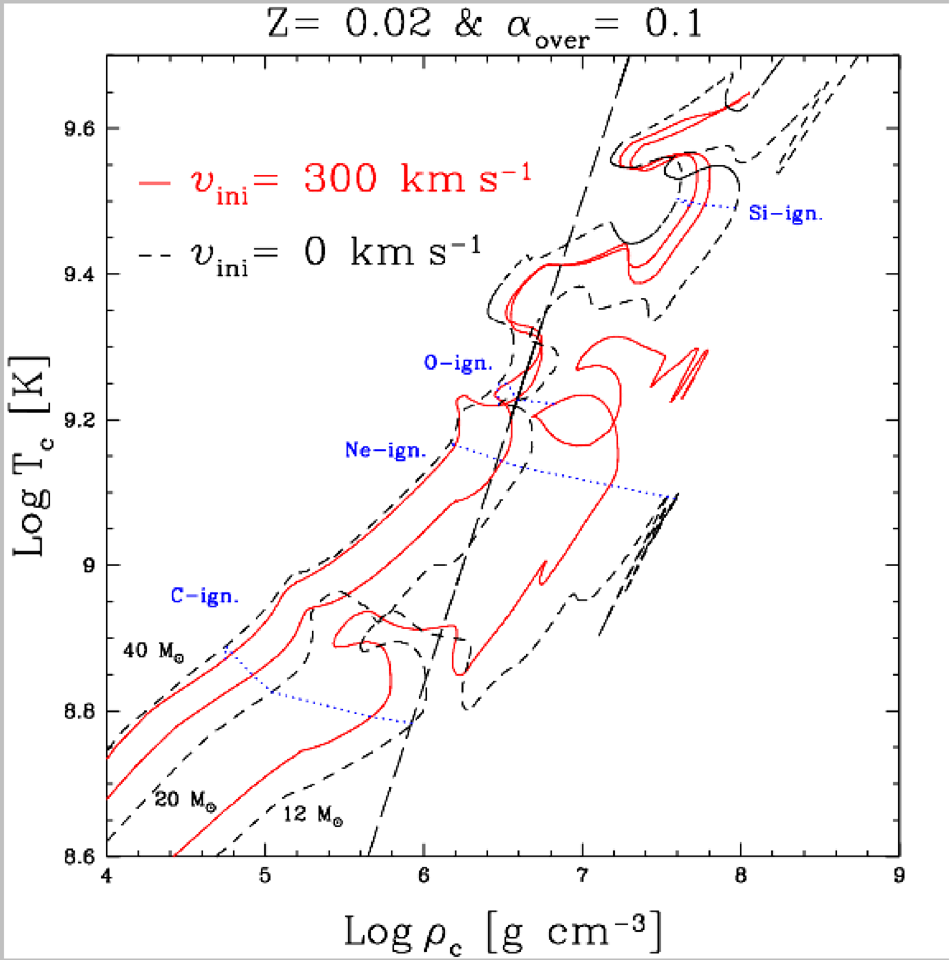
http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Massive Stars

M<~30 M_o : Rotational mixing dominates → bigger cores

M>~30 M_o : mass loss dominates → ~ or smaller cores





S Process in Massive Stars

Kaeppeler, et al, 2011, RvMP, 83, 157, ...

Weak s process: (slow neutron capture process) during core He- and shell C-burning

He: T > 0.25 GK

(~ 21.6keV)

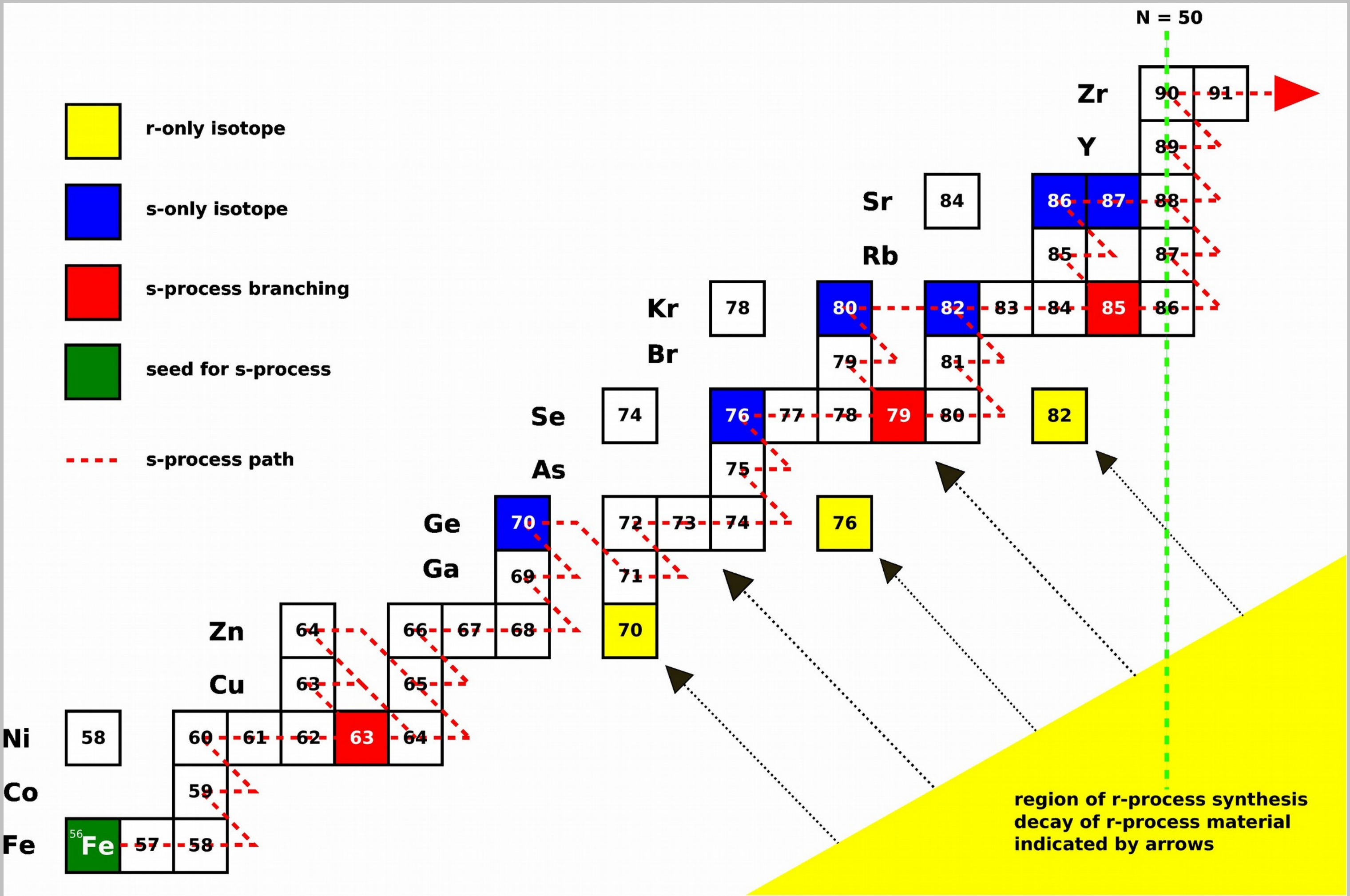
C: T ~ 1GK

N-source: $^{22}Ne(a,n)$

Seed: iron

Poisons:

- He-b.: ^{22}Ne, ^{25}Mg, ^{16}O, ^{12}C
- C-b.: ^{24}Mg, ^{25}Mg, ^{16}O, ^{20}Ne



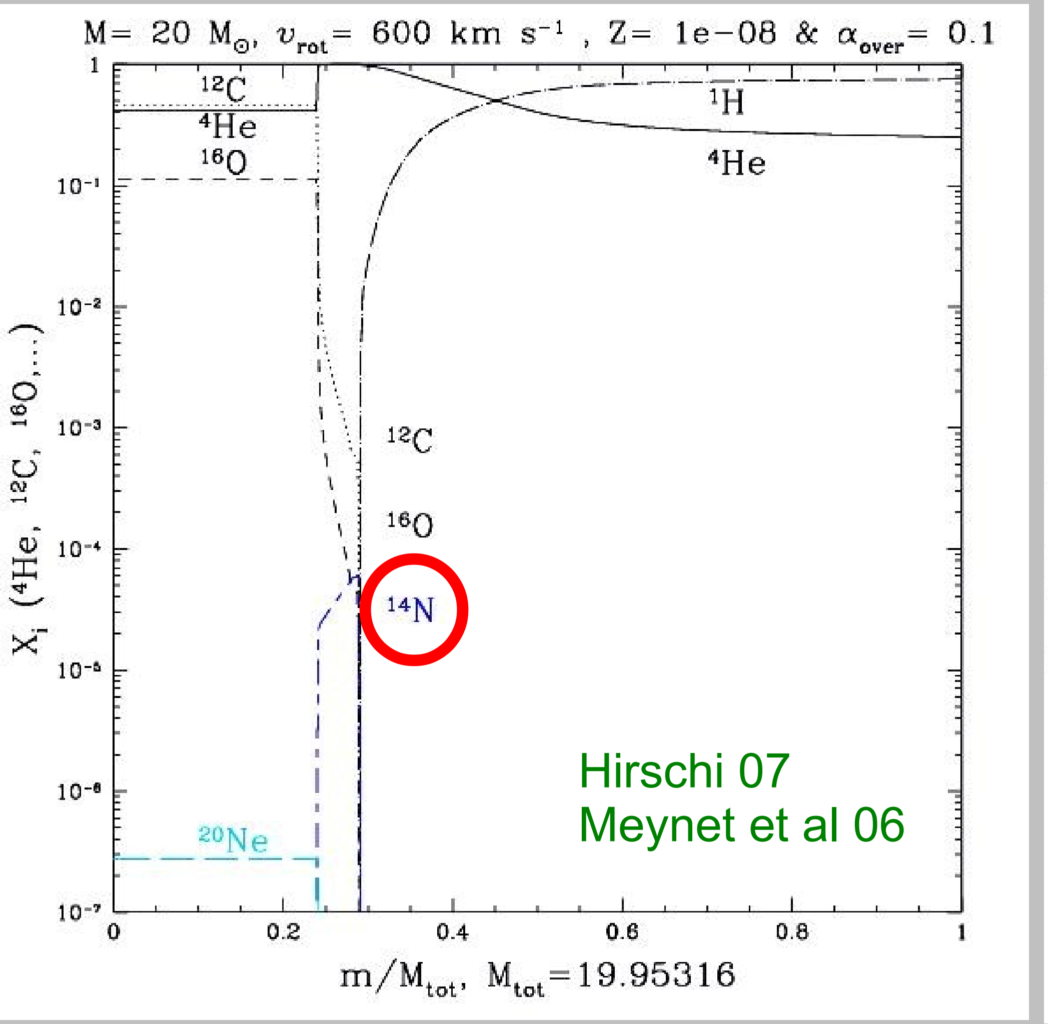
At solar Z: rotating models may produce up to 3x more s process

(See also Chieffi, Limongi, 2012ApJS..199...38L)

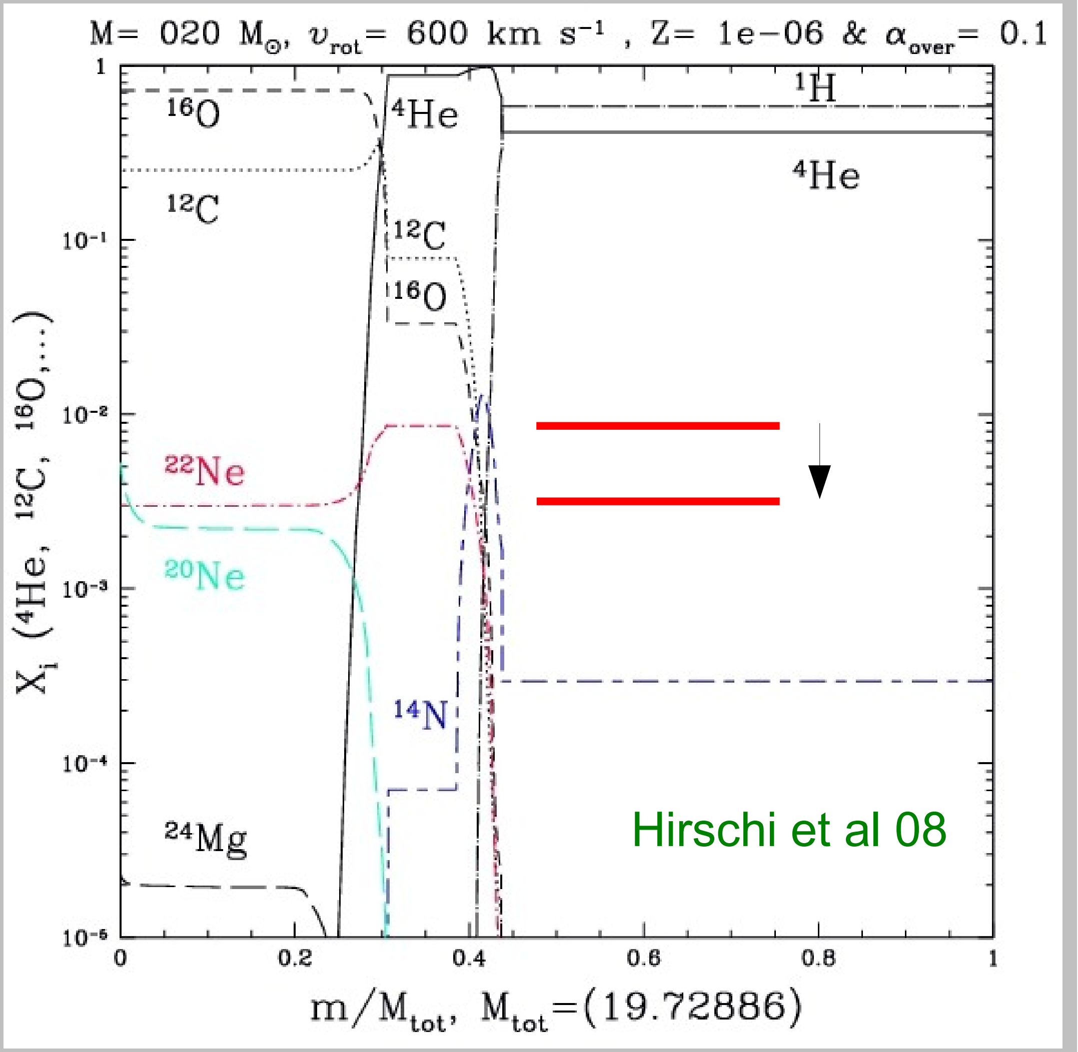
How much s process do massive rotating stars produce at low Z?

Rotation induced mixing @ low Z

Before H-shell boost



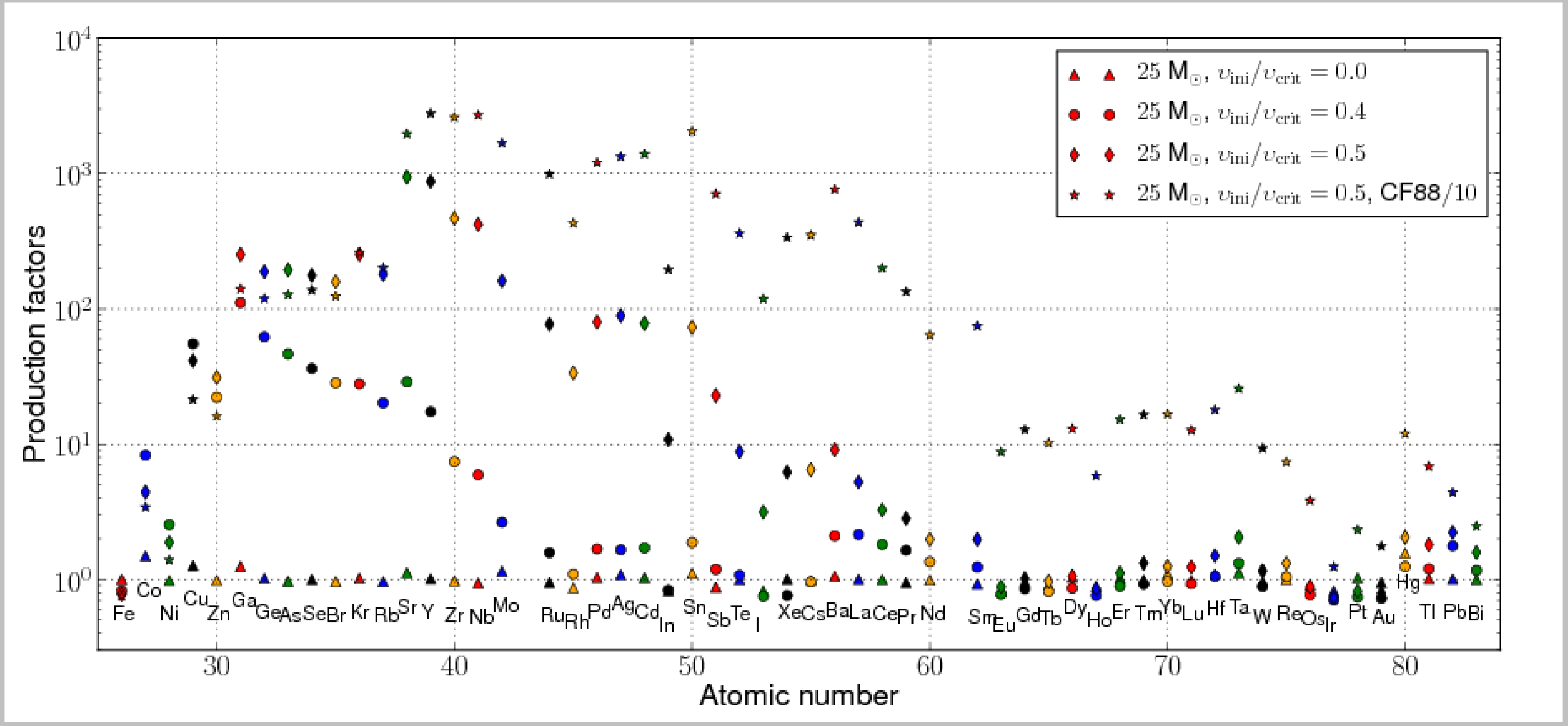
Xi @ end of He burning



--> s process ???

S-Process Models of Massive Rotating Stars

$Z=10^{-5}$, rotating models with different $^{17}O(a,g)$ rates; V_{ini}



Frischknecht et al, A&A letter 2011, 2014 in prep

- STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

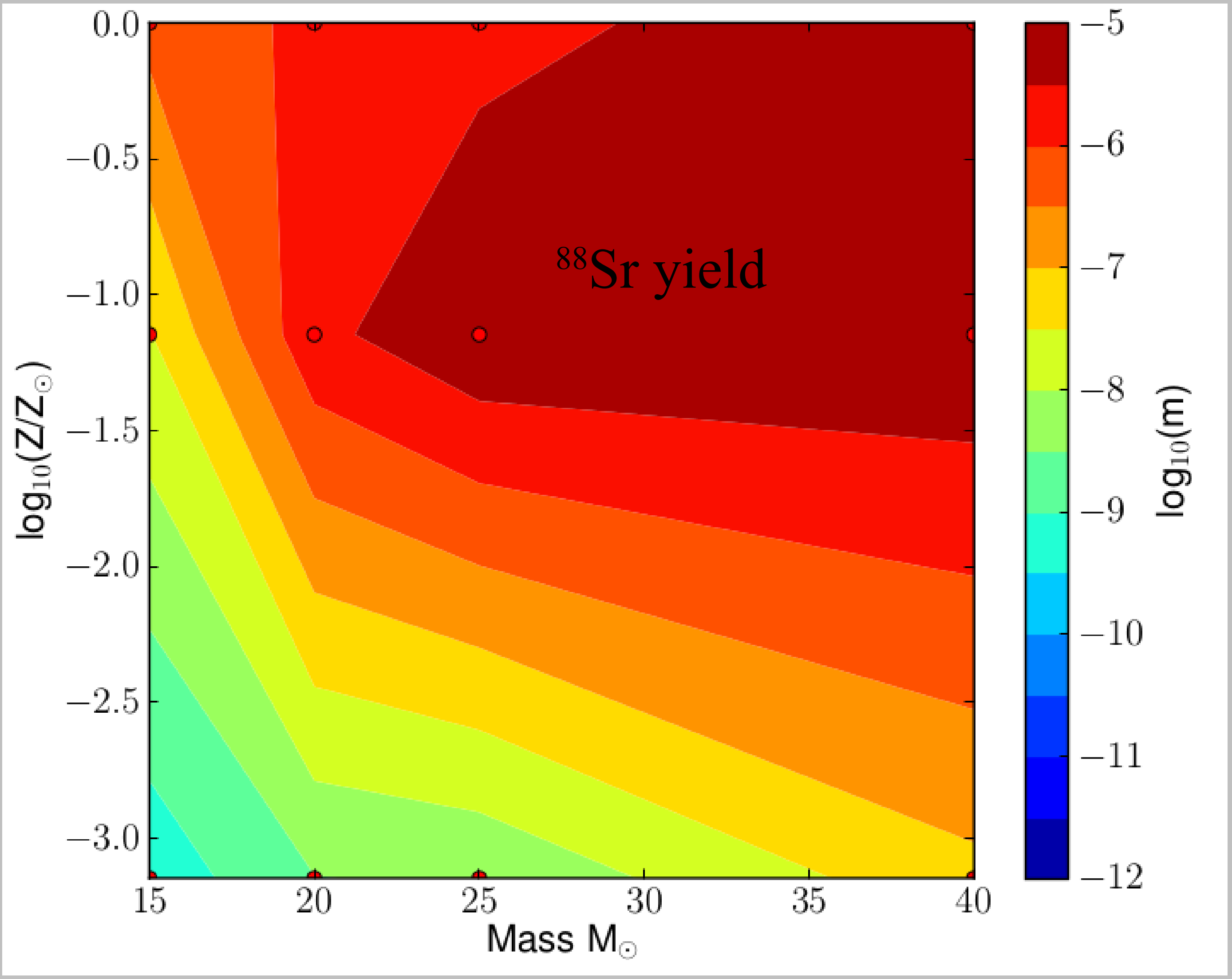
- **^{22}Ne production almost primary but still varies with Z & especially V_{ini}.** M_{ini}
- Secondary seeds (Fe) limit production (^{22}Ne cannot act as seed)
- Strong variations in [Sr,Y/Ba] up to 2 dex dep. on Z,V_{ini}, and $^{17}O(a,g)$

See also Limongi & Chieffi 2018

S-Process Models of Massive Rotating Stars

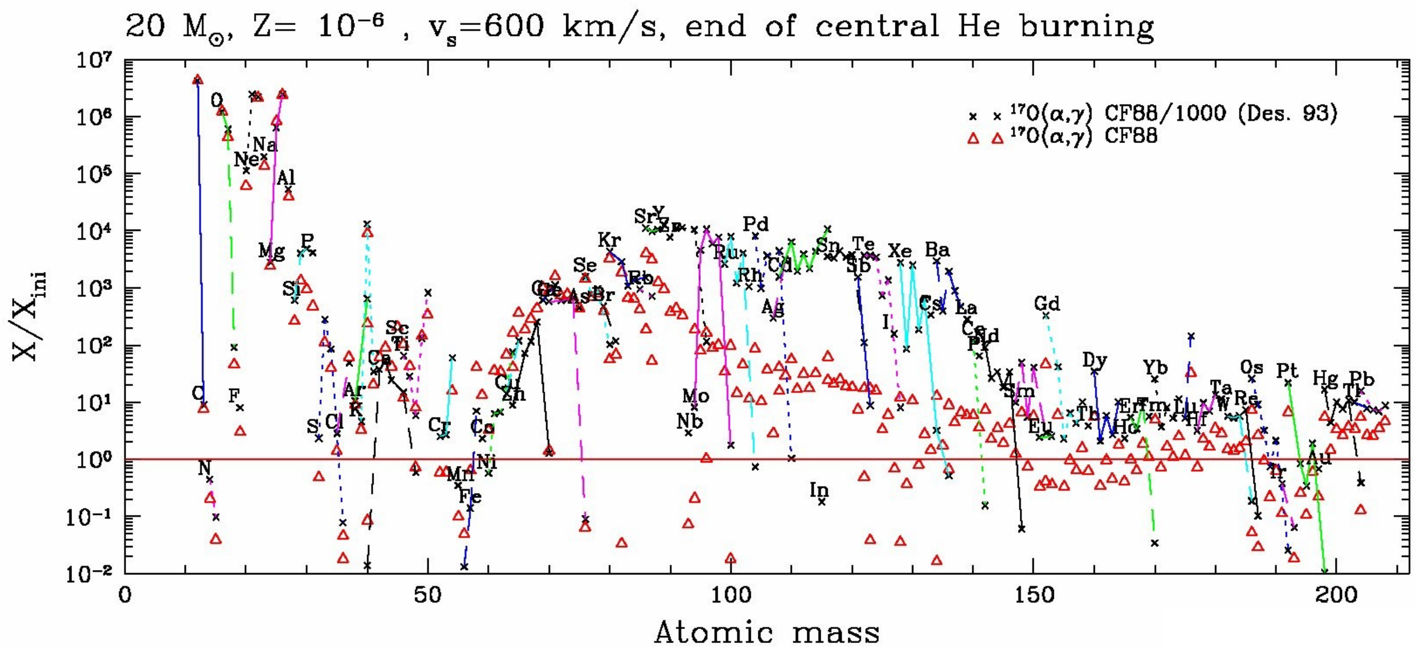
- FULL GRID NOW PUBLISHED!

Frischknecht, Hirschi et al, MNRAS, 2016, 456, 1803



STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

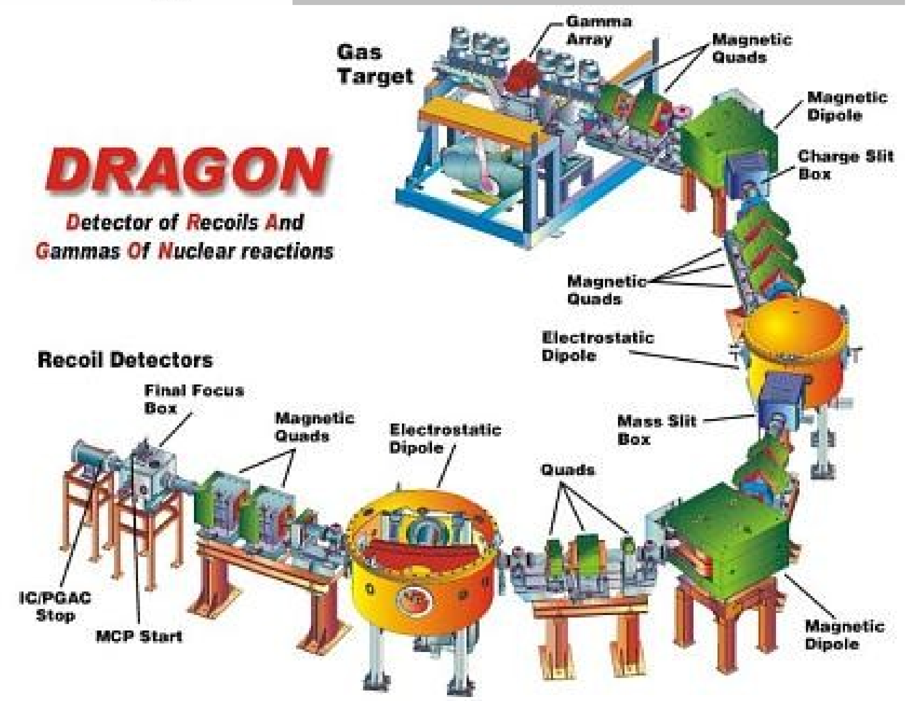
S Process in Massive Stars: Nuclear Physics Uncertainty



Hirschi et al 2008, NICX
Pignatari et al 08, ApJ letter, 687,95

$^{16}O(n,\gamma)^{17}O$:
- ^{16}O poison if $^{17}O(\alpha,\gamma)^{21}Ne$ dom.
- ^{16}O absorber if $^{17}O(\alpha,n)^{20}Ne$ dom.

Measurement of $^{17}O(a,g)^{21}Ne$ at TRIUMF
Taggart et al NICXI:
$^{17}O(a,g)$ lower than CF88!
Best et al 2011 (@ Notre Dame):
But much higher than Descouvemont 1993!



S Process in Massive Stars: Nuclear Uncertainty: $^{22}Ne+\alpha$

$^{22}Ne+\alpha$ are well known important reactions for s process, that are still uncertain.

see R. Longland, C. Iliadis, and A. I. Karakas, PRC, 065809, (2012) and references therein

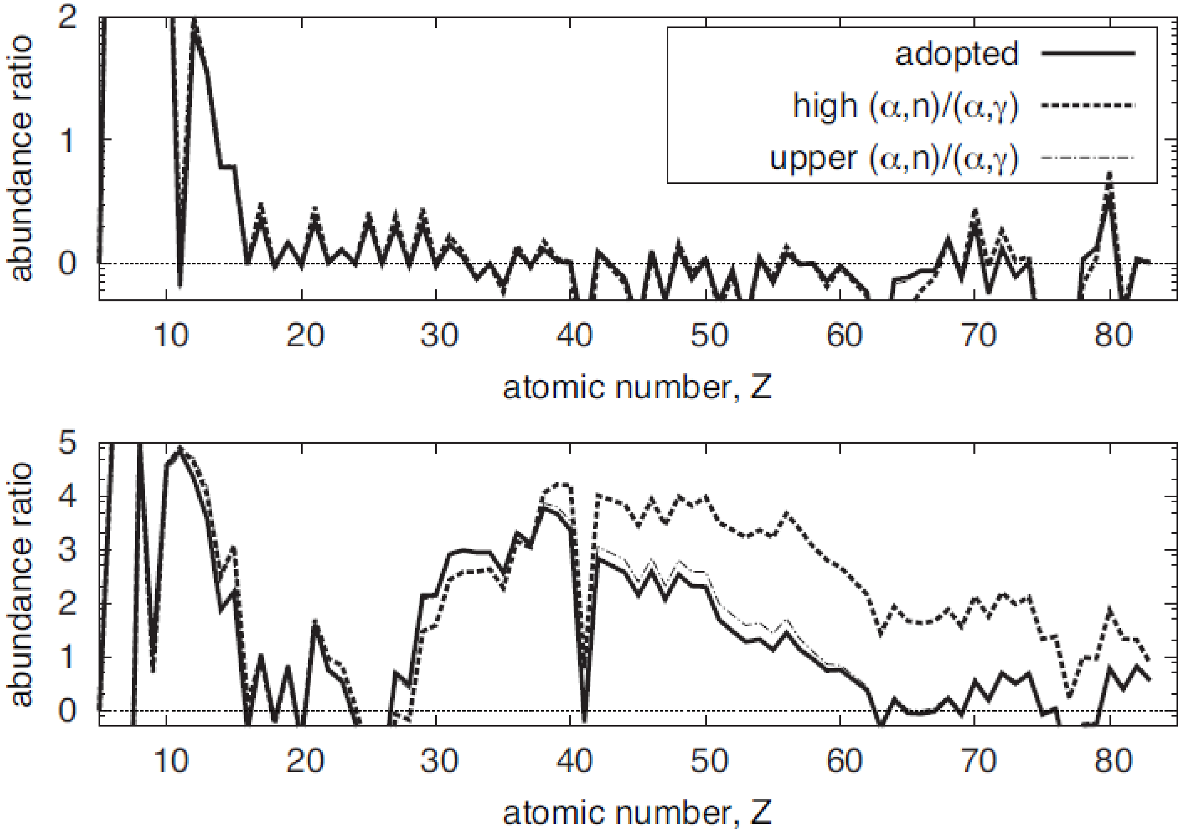


FIGURE 4. Abundance ratios of different reaction rates for α-captures by ^{22}Ne. All of the results are based on a one-zone trajectory mimicking the conditions in a 20 $M_\odot$ star of $Z = 10^{-6}$ (described in [10]) without rotation (upper) and with "effective rotation" via ^{14}N-enhancement (lower). Both panels show results using different reaction rate sets.

Nishimura et al 2013, OMEG12 proceedings

Reactions also strongly affect weak s process at low Z

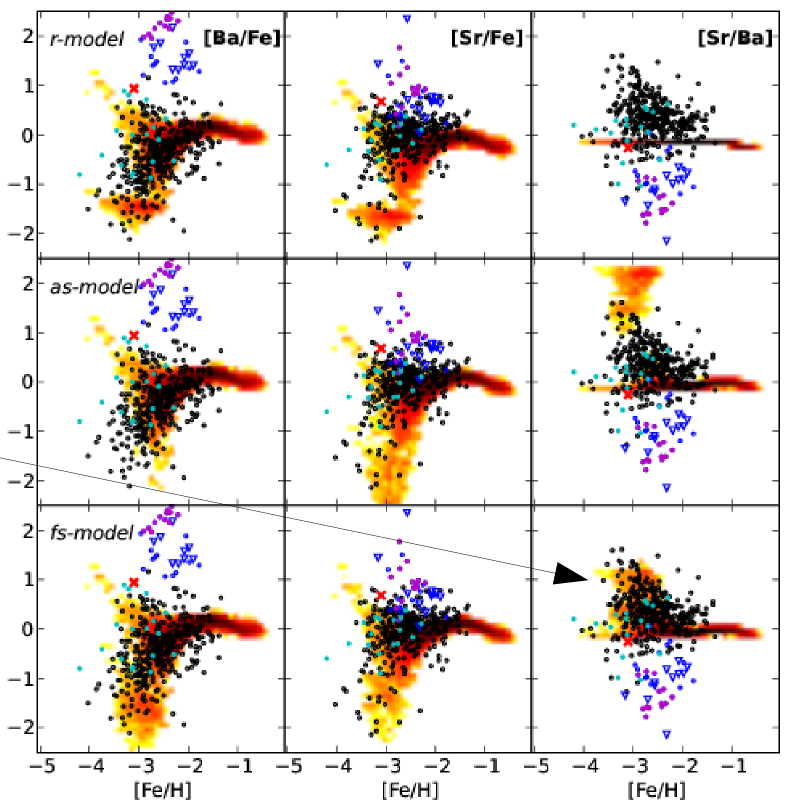
New S-Process Models Compared to EMP * & Bulge GC

* New models also explain abundances in one of the oldest clusters in galactic bulge Chiappini et al, Nature Letter, 2011

Inhomogeneous GCE models by
Cescutti et al 2013 A&A,553,51

- Strong variations in
  [Sr/Ba] > 1 dex
  matches well observed range
  for EMP stars (black circles)!

(no main s process included so cannot explain CEMP-s stars in blue)



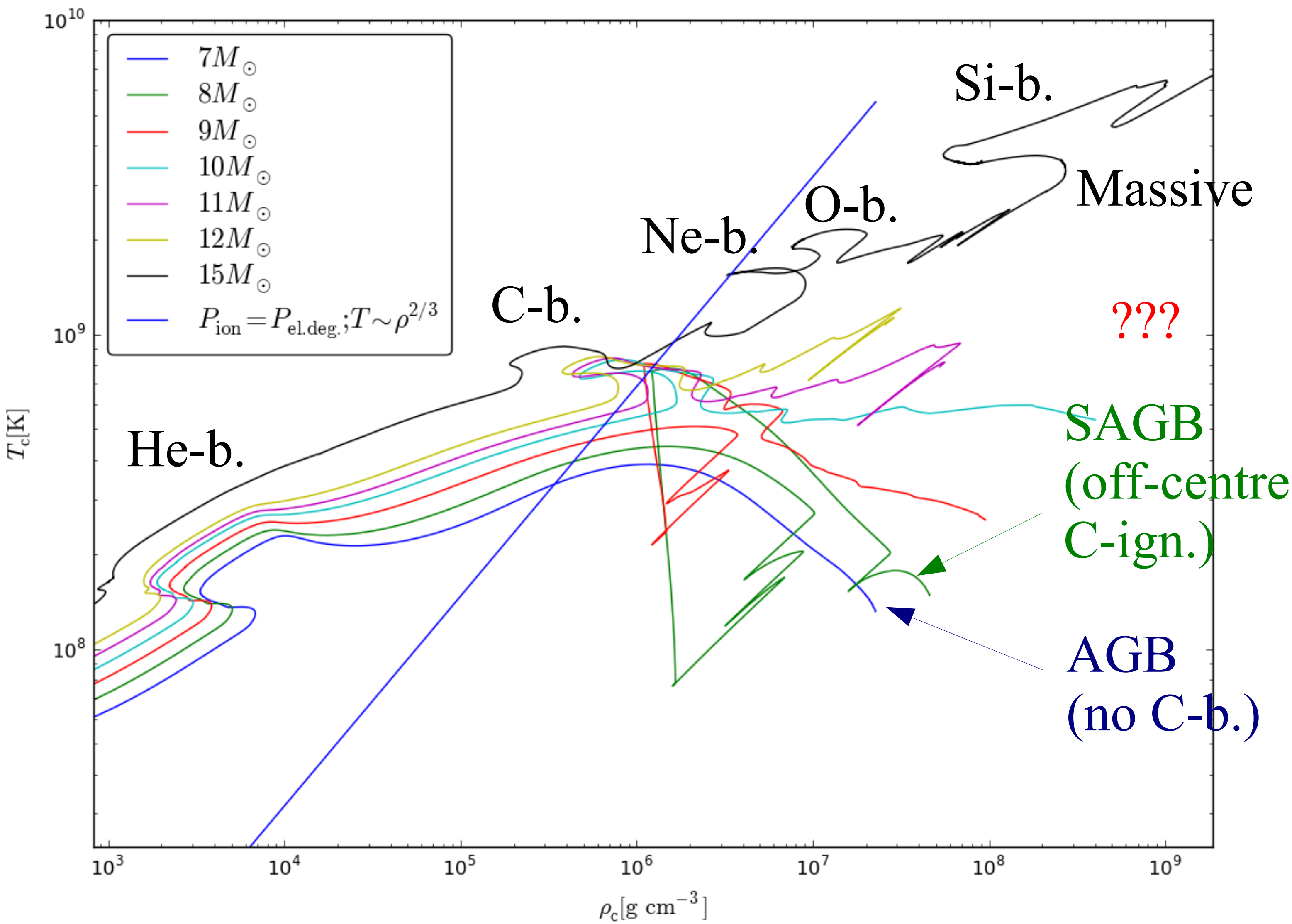
Model name	panels in Fig. 5	s-process	r-process
r-	Upper	No s-process from massive stars	standard + extended r-process site (8 - 30 $M_\odot$)
as-	middle	average rotators (v_{ini}/v_{critic} = 0.4)	standard r-process site (8 - 10 $M_\odot$)
fs-	lower	fast rotators (v_{ini}/v_{critic} = 0.5) and 1/10 for $^{17}O(\alpha,\gamma)$ reaction rate	standard r-process site (8 - 10 $M_\odot$)

(EMP *: Frebel et al 2010)

Massive/AGB Stars Transition

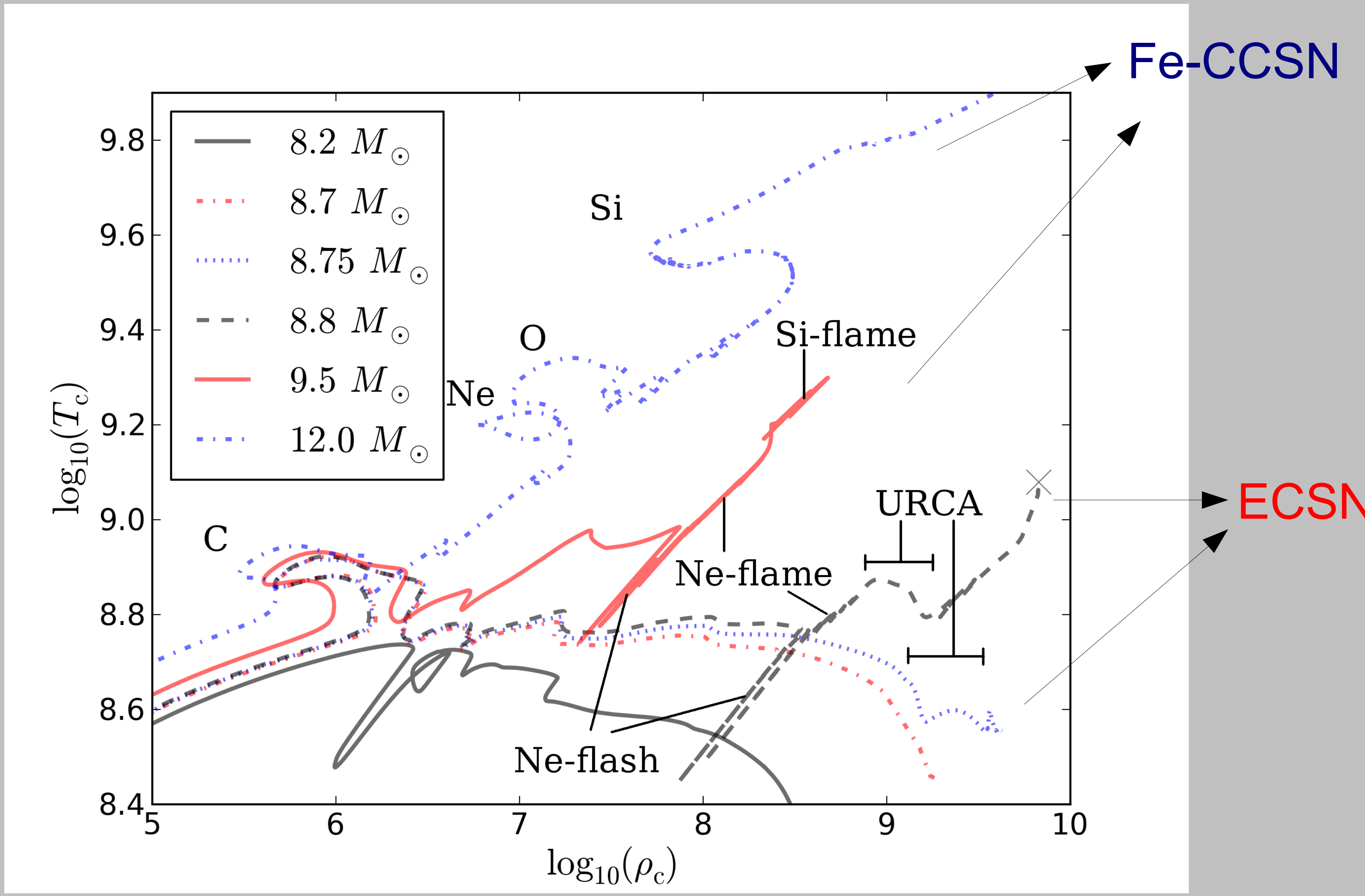
7-15 M_o models ← MESA stellar evolution code: http://mesa.sourceforge.net/

Paxton et al 10



Jones et al 2013; Takahashi et al 13;see also Mueller et al 12, Umeda et al 12

Fate of Least-Massive MS: ECSN/Fe-CCSN?

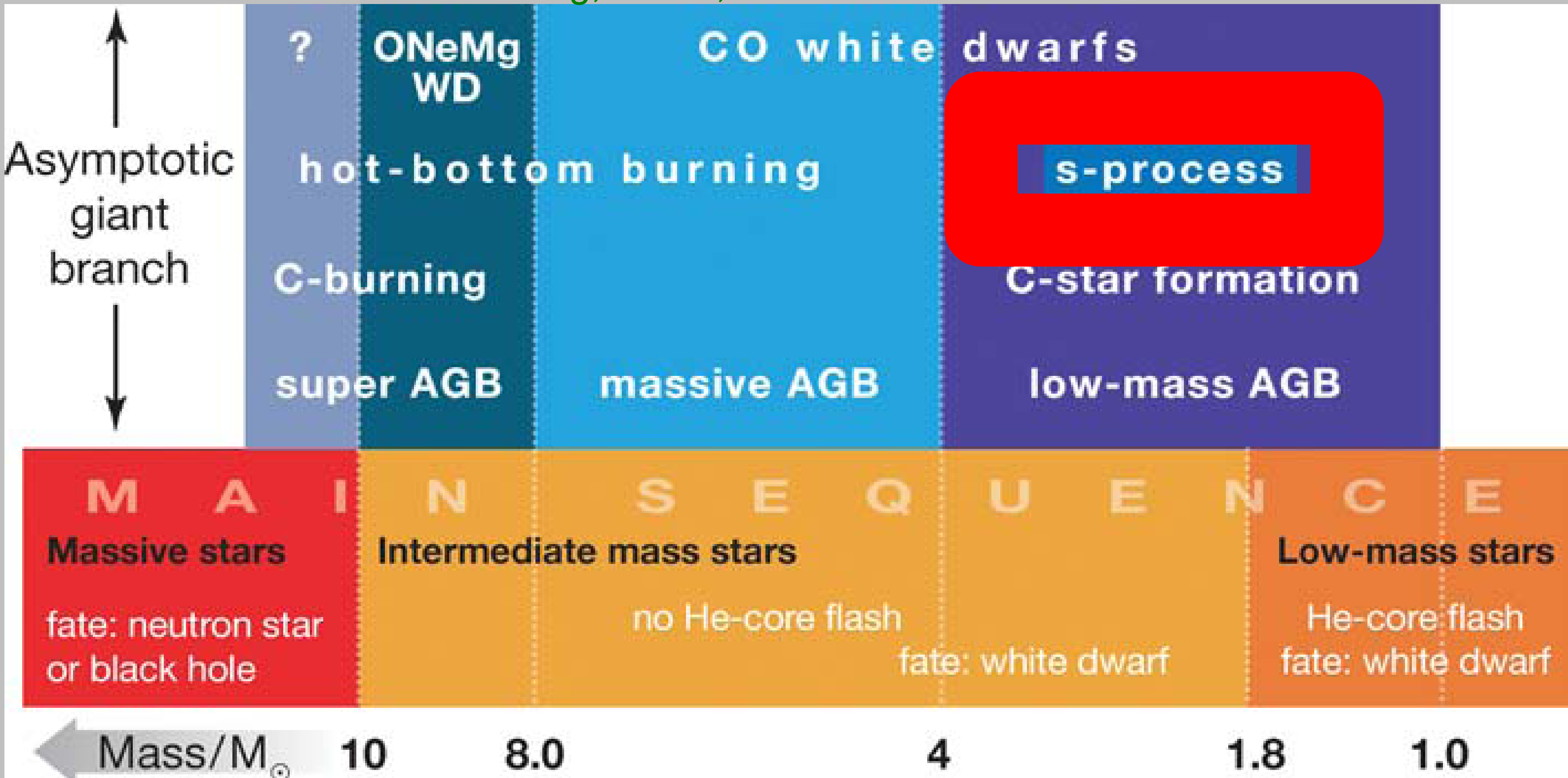


Both SAGB and failed massive stars may produce ECSN

Jones et al. (2013), ApJ 772, 150, Jones et al 2014-2017

Intermediate & Low-Mass Stars

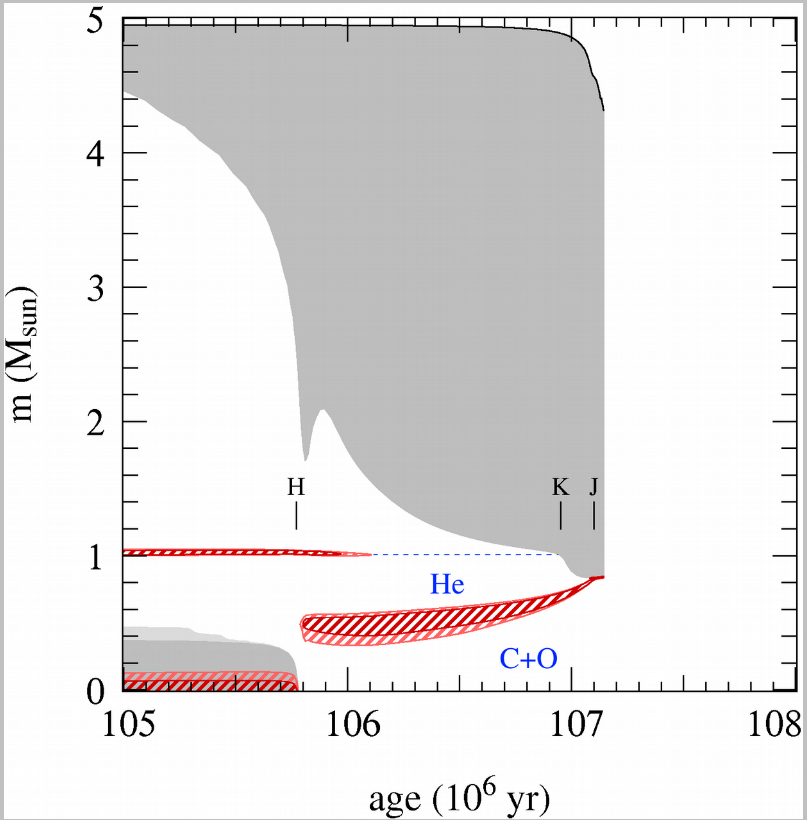
Herwig, ARAA, 2005



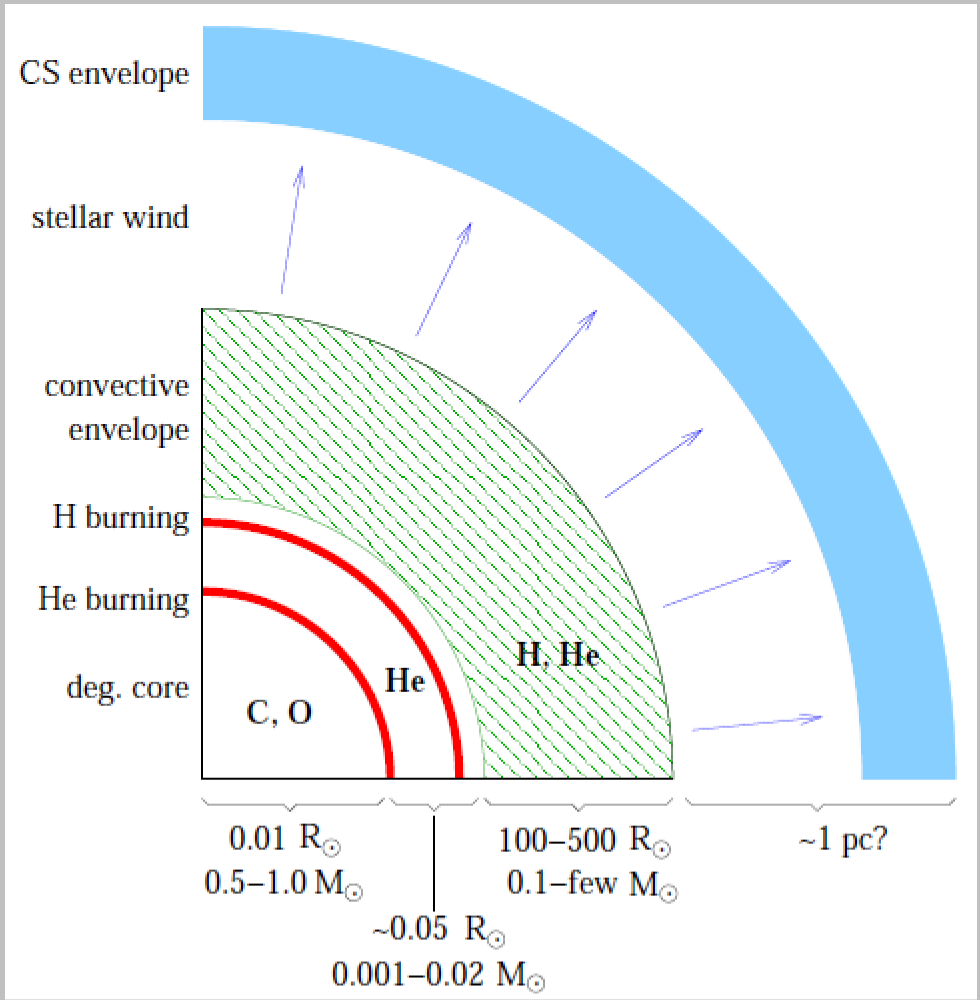
AGB phase & s process in both intermediate-mass stars and low-mass stars!

Intermediate & Low-Mass Stars

$5\ M_o$ star: AGB phase



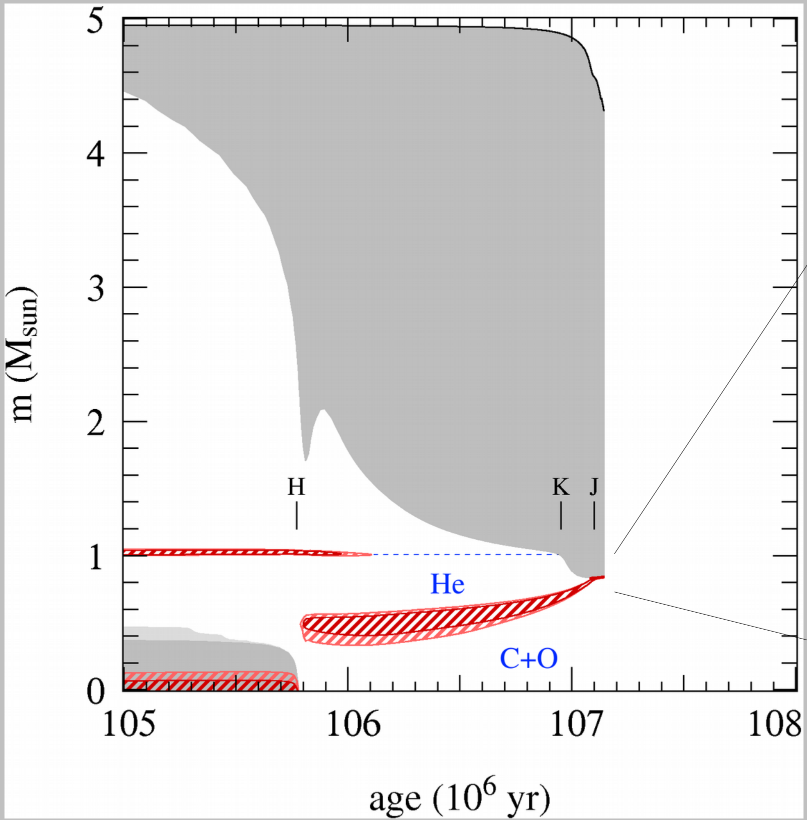
Structure in AGB phase



From SE notes, O. Pols (2009)

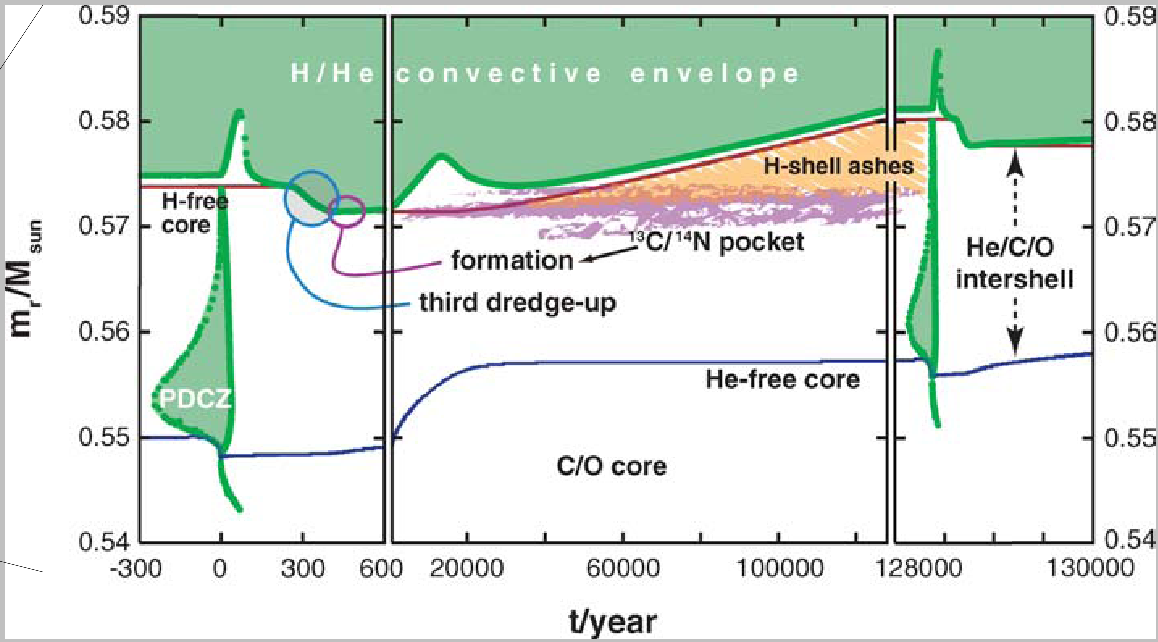
Intermediate & Low-Mass Stars

5 M_o star: AGB phase



From SE notes, O. Pols (2009)

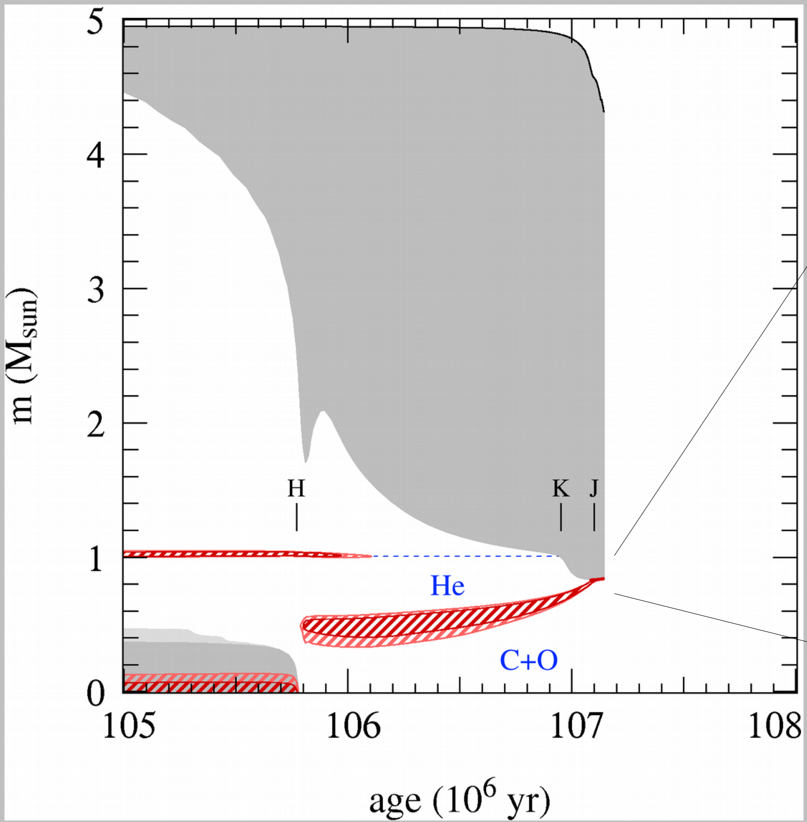
Structure in AGB phase



Herwig, ARAA, 2005

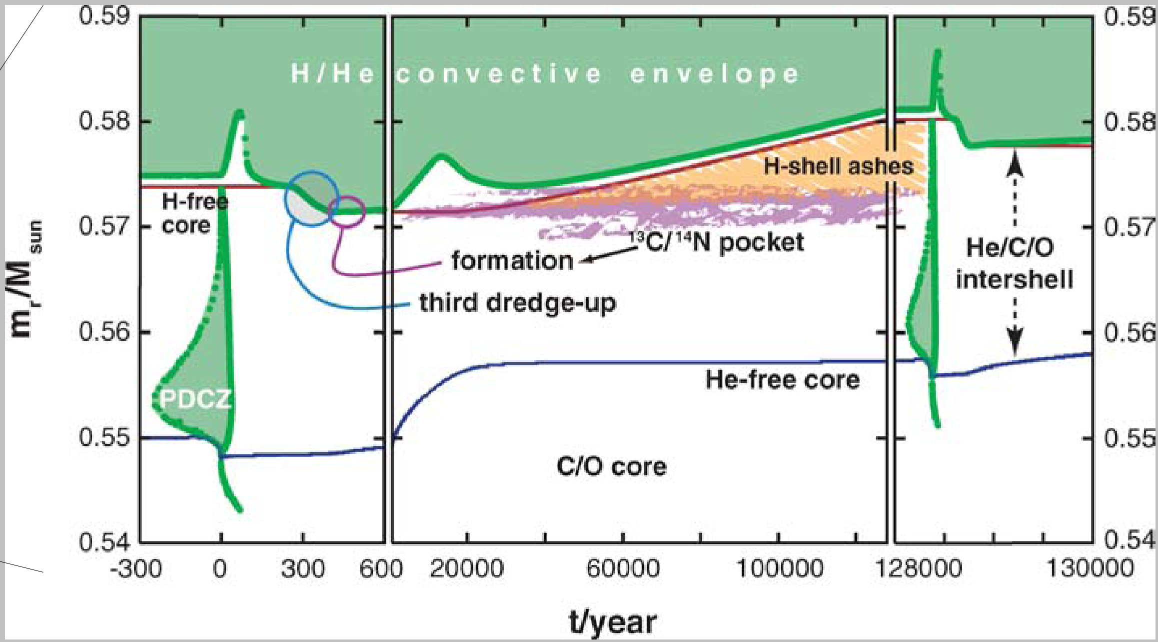
Intermediate & Low-Mass Stars

5 M_o star: AGB phase



From SE notes, O. Pols (2009)

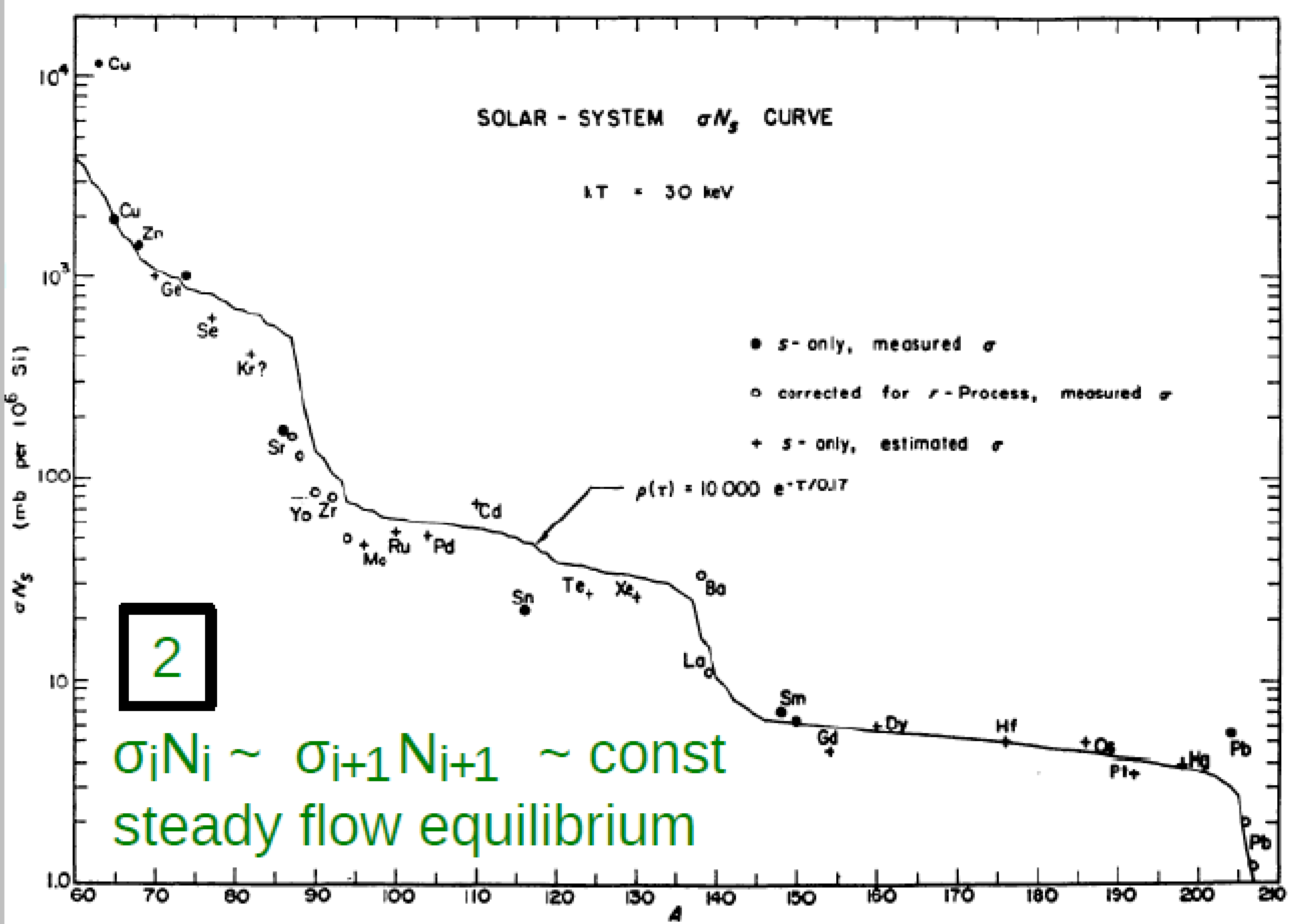
Structure in AGB phase



Herwig, ARAA, 2005

Main S Process

Kaeppeler, et al, 2011, RvMP, 83, 157, ...



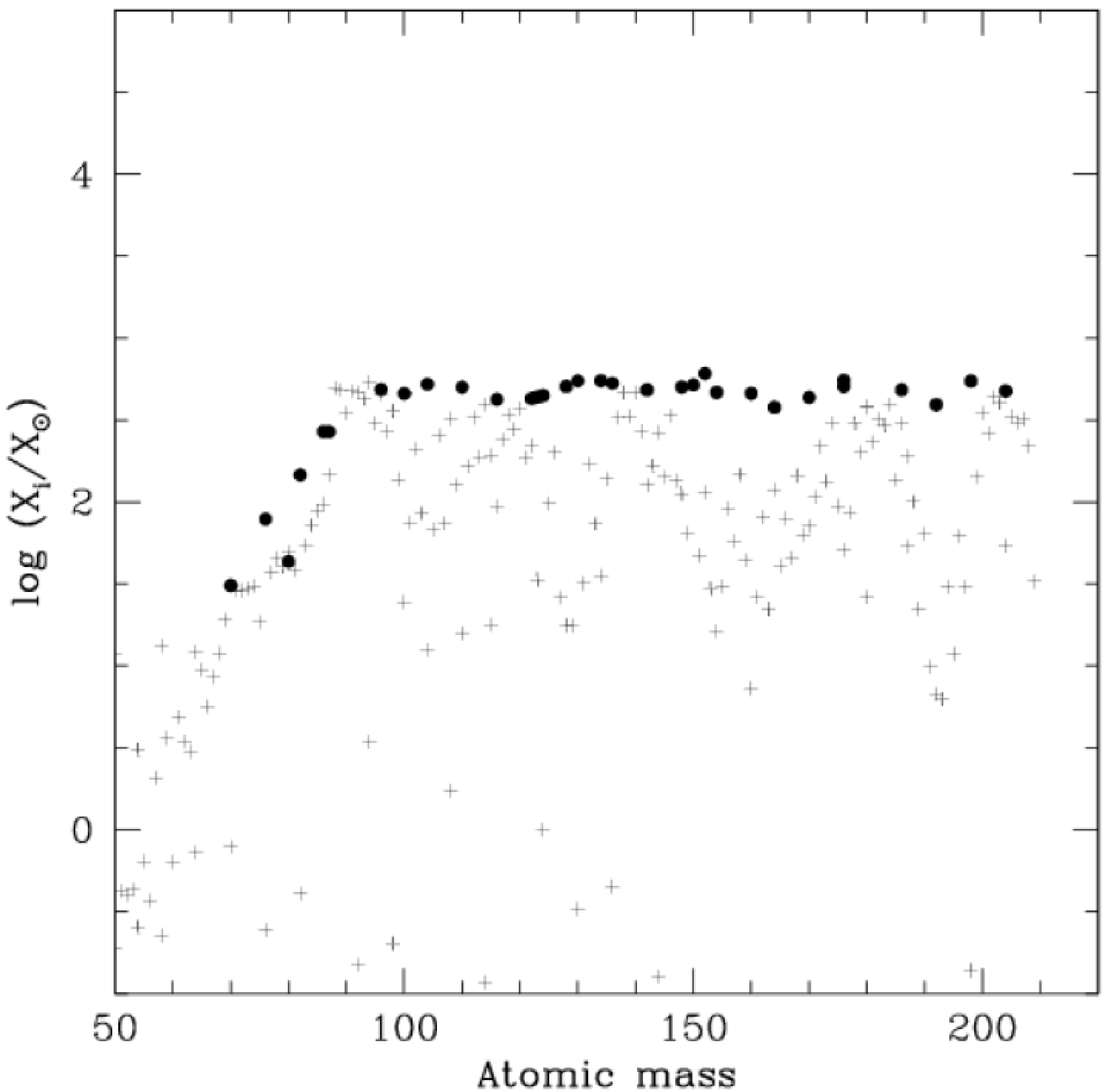
2

$\sigma_i N_i \sim \sigma_{i+1} N_{i+1} \sim \text{const}$

steady flow equilibrium

Seeger, Fowler & Clayton et al. 1965
(see also Clayton 1968 and references therein)

Parametrized C13-pocket
Reproduction of the main component by an AGB stellar model
(Gallino et al. 1998; Arlandini et al. 1999)



^{13}C-pocket choice:

- ad hoc modulated
- constant Pulse by Pulse

AND METALLICITY

$[Fe/H] = -0.3$

- artificially introduced in the third dredge up phases

AGB stars
s-process nucleosynthesis – uncertainties I

A radiative C13-pocket working in interpulse conditions is a well extablished scenario, but its mechanism of formation is still unclear (discussion in Herwig 2005, and references therein). Impact of overshooting, rotation, mixing prescriptions, multi-D effects, etc. Despite this limitation, it is able to explain with some approximation many independent observations, within a 'spread' of C13-pockets:

- main s component in the solar system (e.g., Arlandini et al. 1999);
- a relevant part of spectroscopic observations
(e.g., Busso et al. 2001 at solar metallicity, Bisterzo et al. 2010 at halo metallicity);
- presolar grains (e.g., Lugaro et al. 2004);
- GCE calculations compared to evolution of abundances observed in the Galaxy
(e.g., Travaglio et al. 2004)
- PNe abundances observations (e.g., Karakas et al. 2005, Pignatari et al., 2009)

Does Rotation Kill the S-process in AGB Stars?

YES: Herwig et al 2003 (see also Decressin etal 2004)

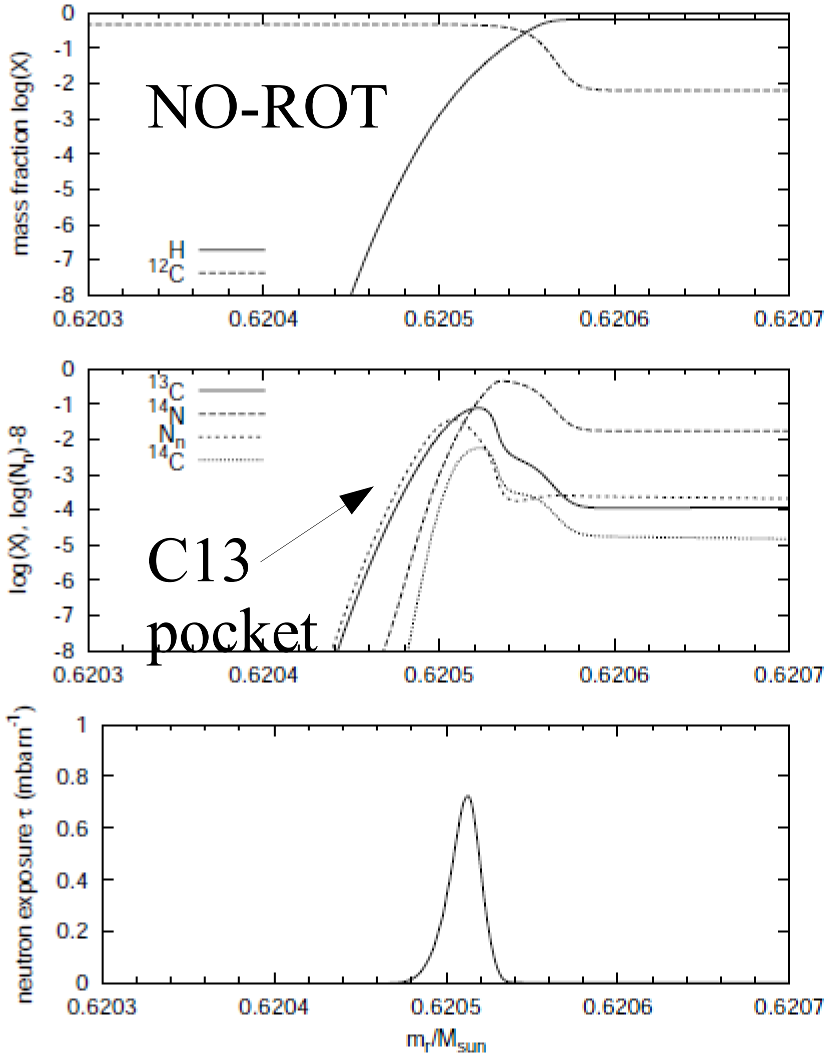


FIG. 6.—Abundance profiles in the partial mixing zone at three times during the seventh interpulse phase of the model with hydrodynamic overshoot and no rotation. *Top*: First postprocessing model after the end of the third dredge-up phase. *Middle*: 10% of ^{13}C is burned by $^{13}C(\alpha, n)^{16}O$. *Bottom*: Neutron exposure τ at end of the *s*-process in the partial mixing zone when the ^{13}C neutron source is exhausted.

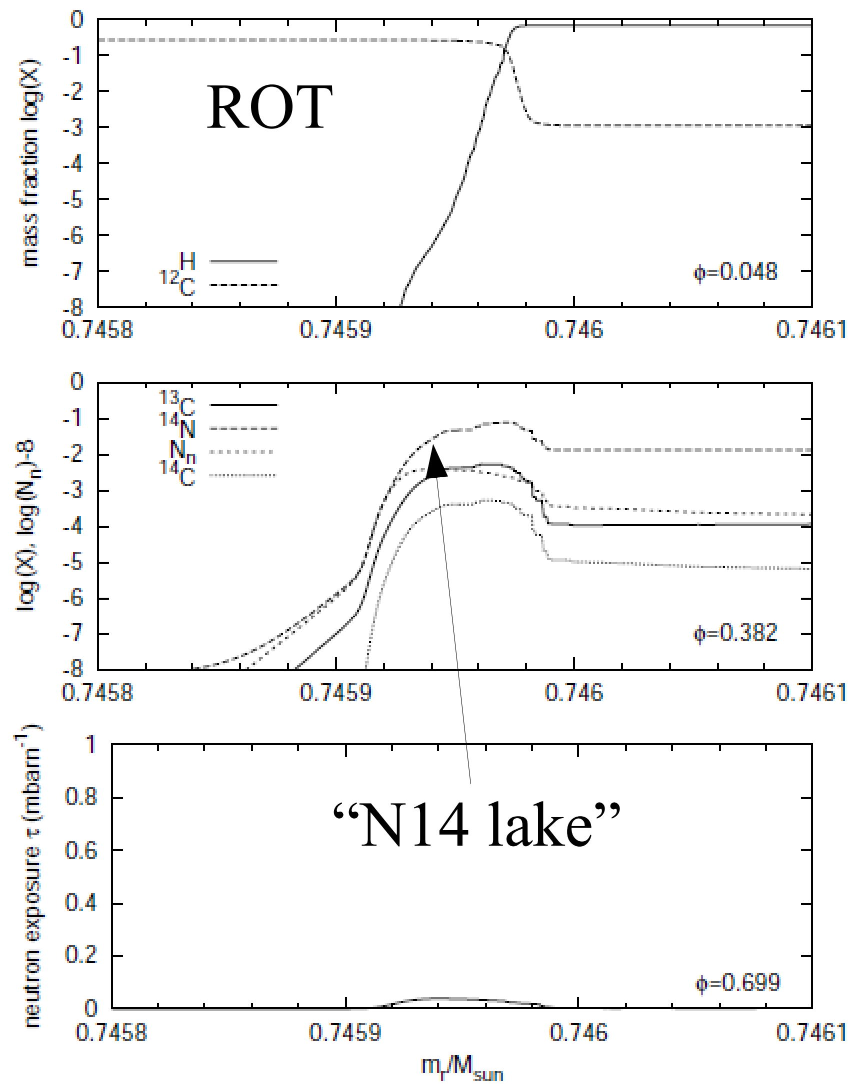


FIG. 9.—Same as Fig. 6 for the simulation at the 25th interpulse phase including rotation and no hydrodynamic overshoot. The middle panel shows the same interpulse phase as the middle panel in Fig. 6 with respect to the nuclear lifetime of ^{13}C against α-capture.

Does Rotation Kill the S-process in AGB Stars?

NO: Piersanti et al 2013
Cristallo et al

[hs/ls] and [Pb/hs] decrease by increasing the initial rotation velocity
But s process still active

Different implementations of rotation induced mixing lead to different conclusions.

What about magnetic fields?
Nucci, M. C.; Busso, M. 2014ApJ...787..141N

Models with B-fields behaviour is inbetween non-rotating and current rotating models. den Hartogh et al in prep.
MAYBE!

NO-ROT ROT

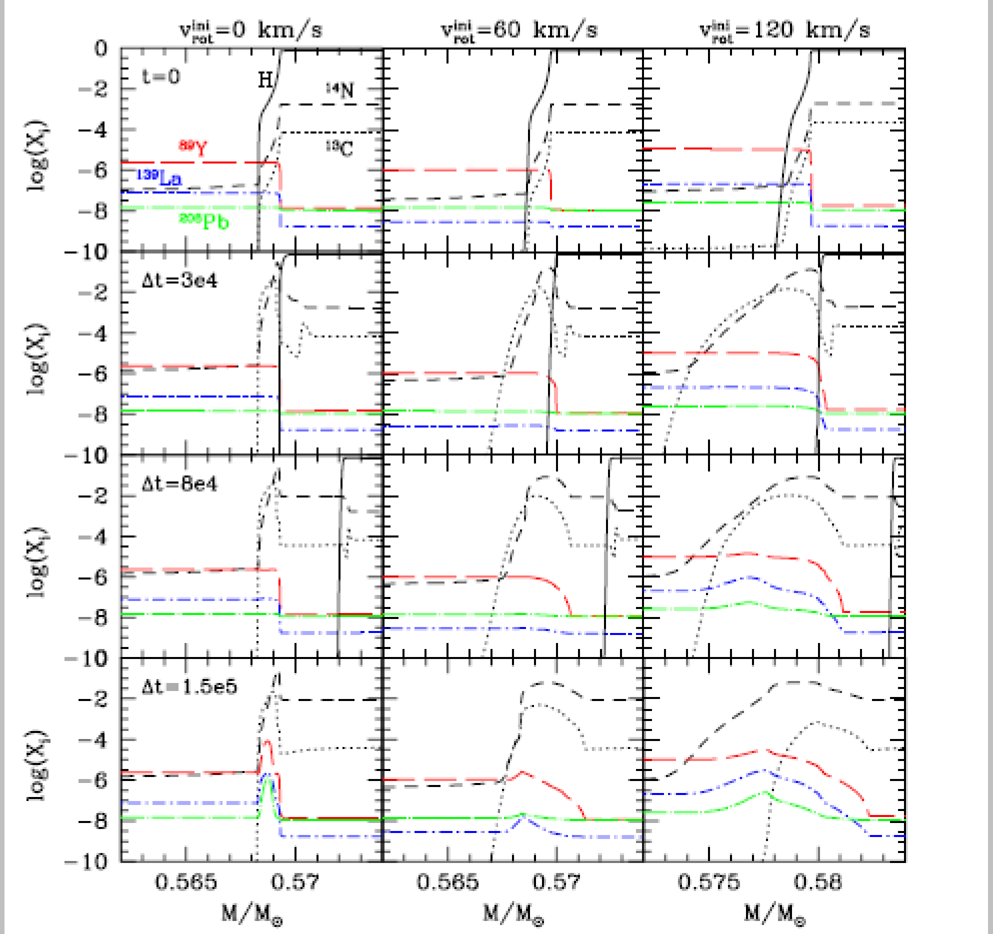
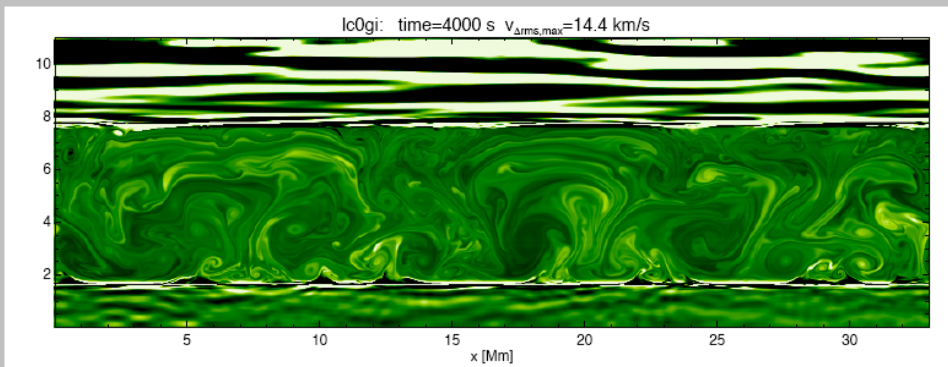


Fig. 3.— Evolution of key selected isotopes in the region where the ^{13}C pocket forms during the interpulse after the 2^{nd} TDU for the M=2 $M_\odot$, [Fe/H]=0 model with different initial rotation velocities: H (solid), ^{13}C (dotted), ^{14}N (short-dashed), ^{89}Y (long-dashed), ^{139}La (dot-short-dashed) and ^{208}Pb (dot-long-dashed) (see the on-line edition for a color version).

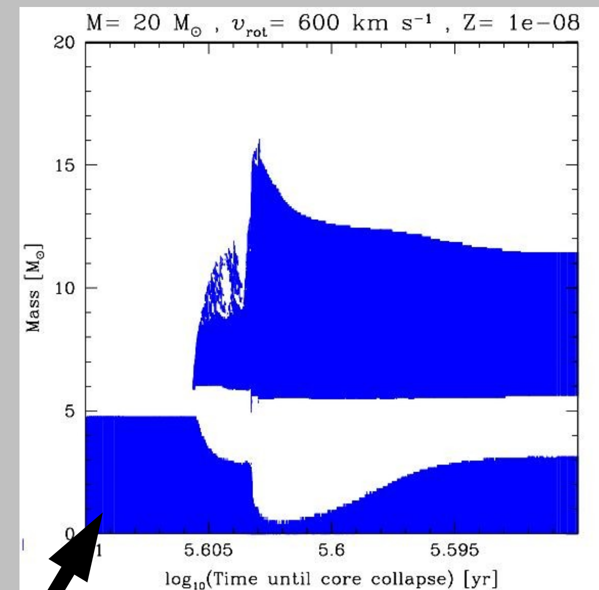
3to1D link for convection

3D simulations

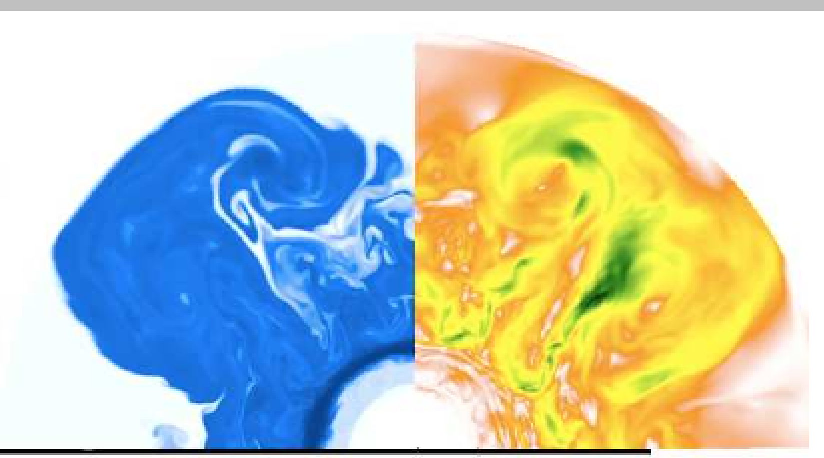


Herwig et al 06

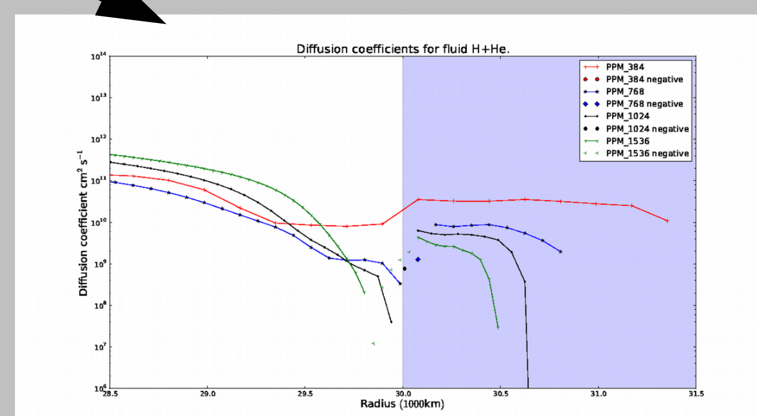
Uncertainties in 1D



e.g. Hirschi 07



e.g. Arnett & Meakin 2011
Mocak et al 2011,
Viallet et al 2013, ...



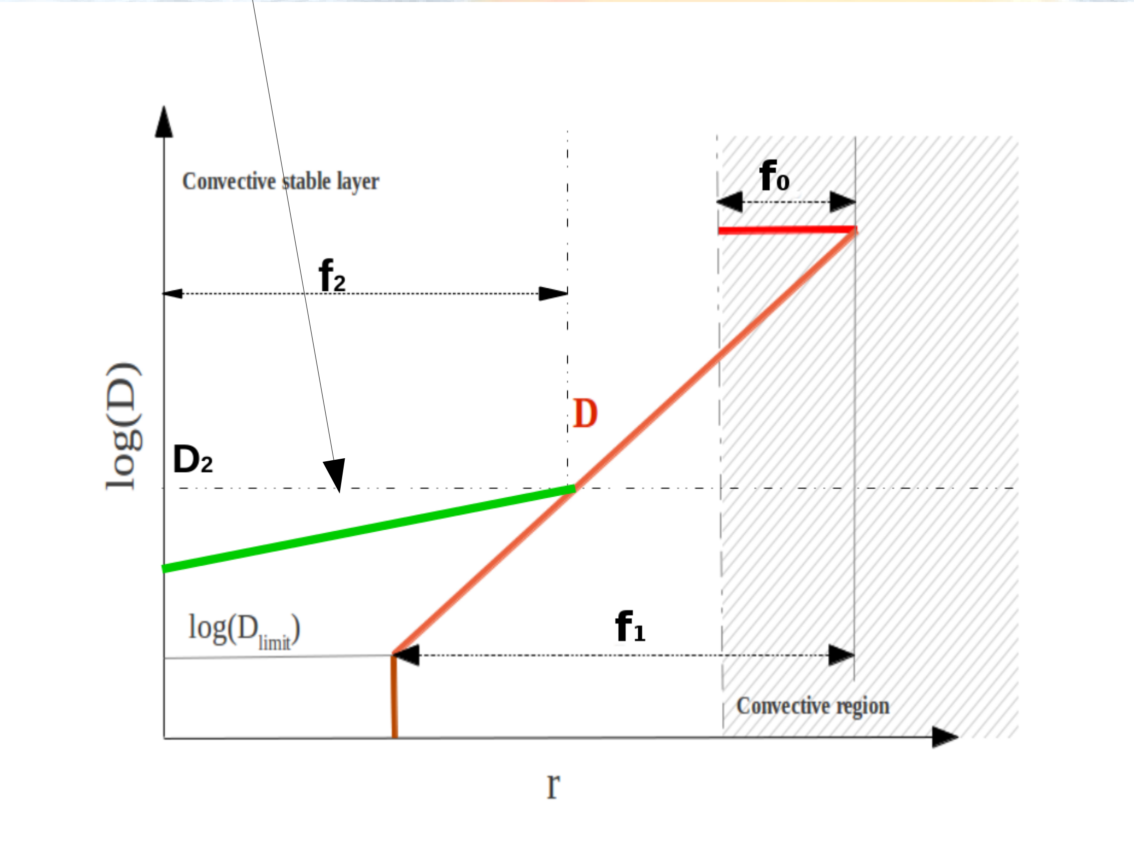
Meakin et al 2009 ; Bennett et al in prep

Determine effective diffusion (advection?) coefficient

Back to 1D: CBM in AGB Stars (NuGrid project)

Internal gravity wave (IGW) driven mixing

Battino+ ApJ 2016



1) CBM (first f) plays a key role both for the C13 pocket via CBM below CE (needed for TDU) and for the c12 & o16 abundances in the intershell via CBM below TPs

2) IGW (second f) plays a key role for the C13 pocket (not so much for mixing below the TPs)

Back to 1D: CBM in AGB Stars (NuGrid project)

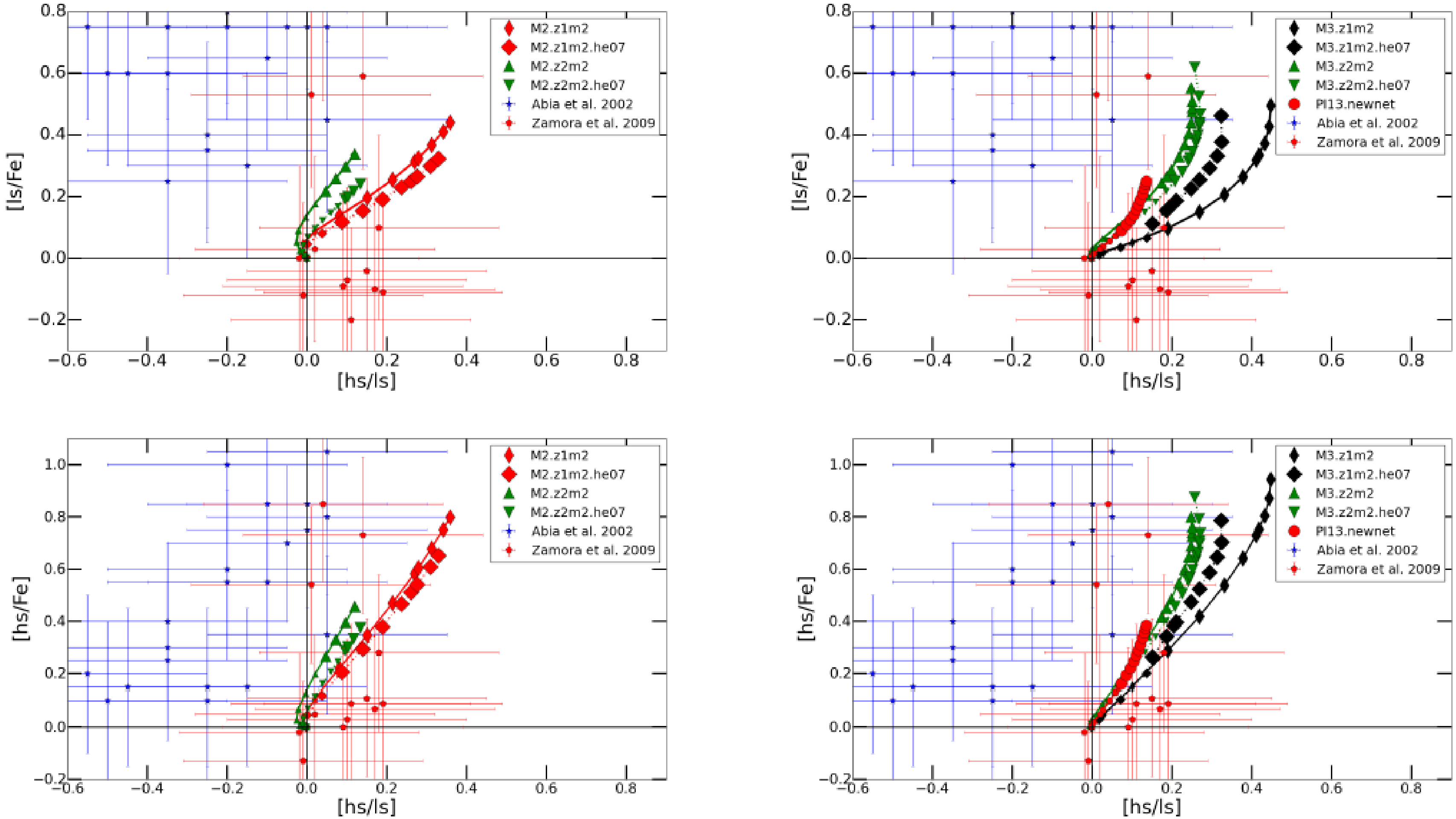
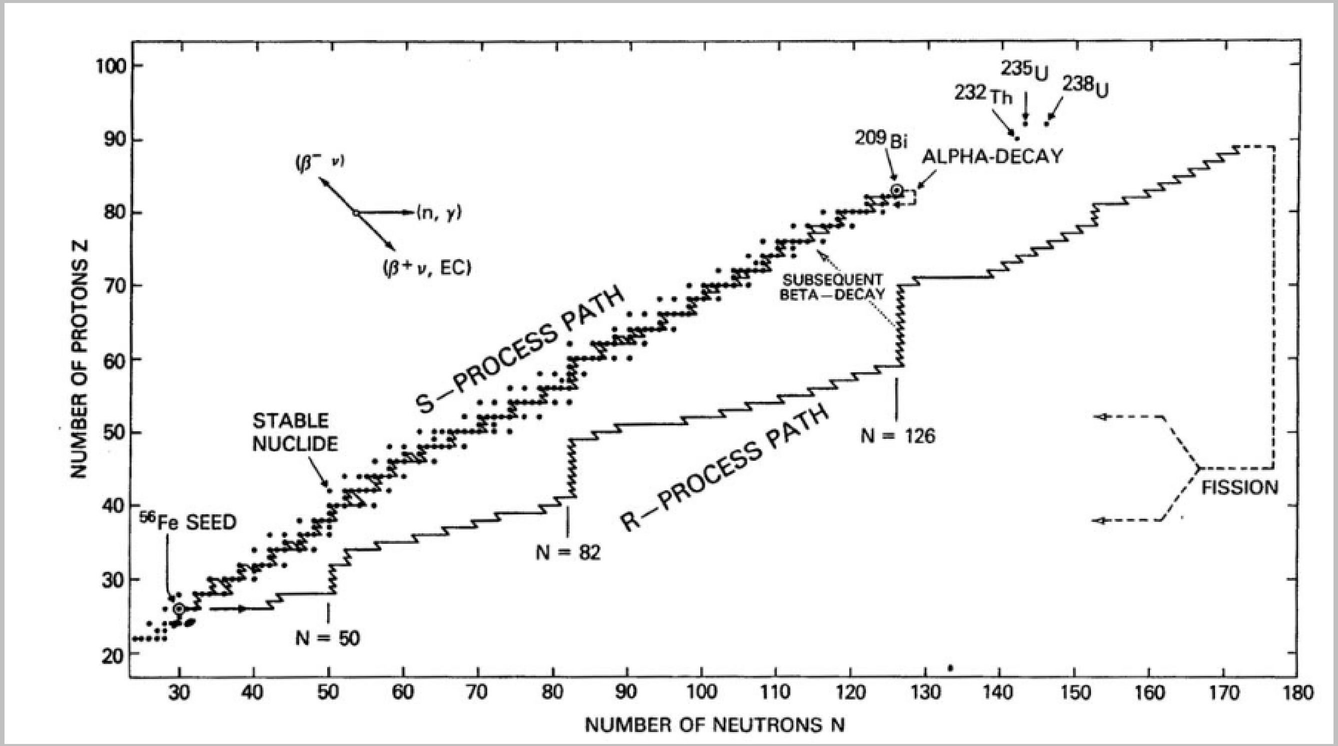


Fig. 8.— The evolution of the [ls/Fe], [hs/Fe] and [hs/ls] ratios during the AGB evolution are shown for the models M2.z1m2, M2.z2m2, M2.z1m2.he07 and M2.z2m2.he07 (left panels) and PI13.newnet, M3.z1m2 and M3.z2m2, M3.z1m2.he07 and M3.z2m2.he07 (right panel). Also the comparison with observational data from Abia et al. (2002) and Zamora et al. (2009) is provided.

List of neutron capture processes (with products observed/measured)

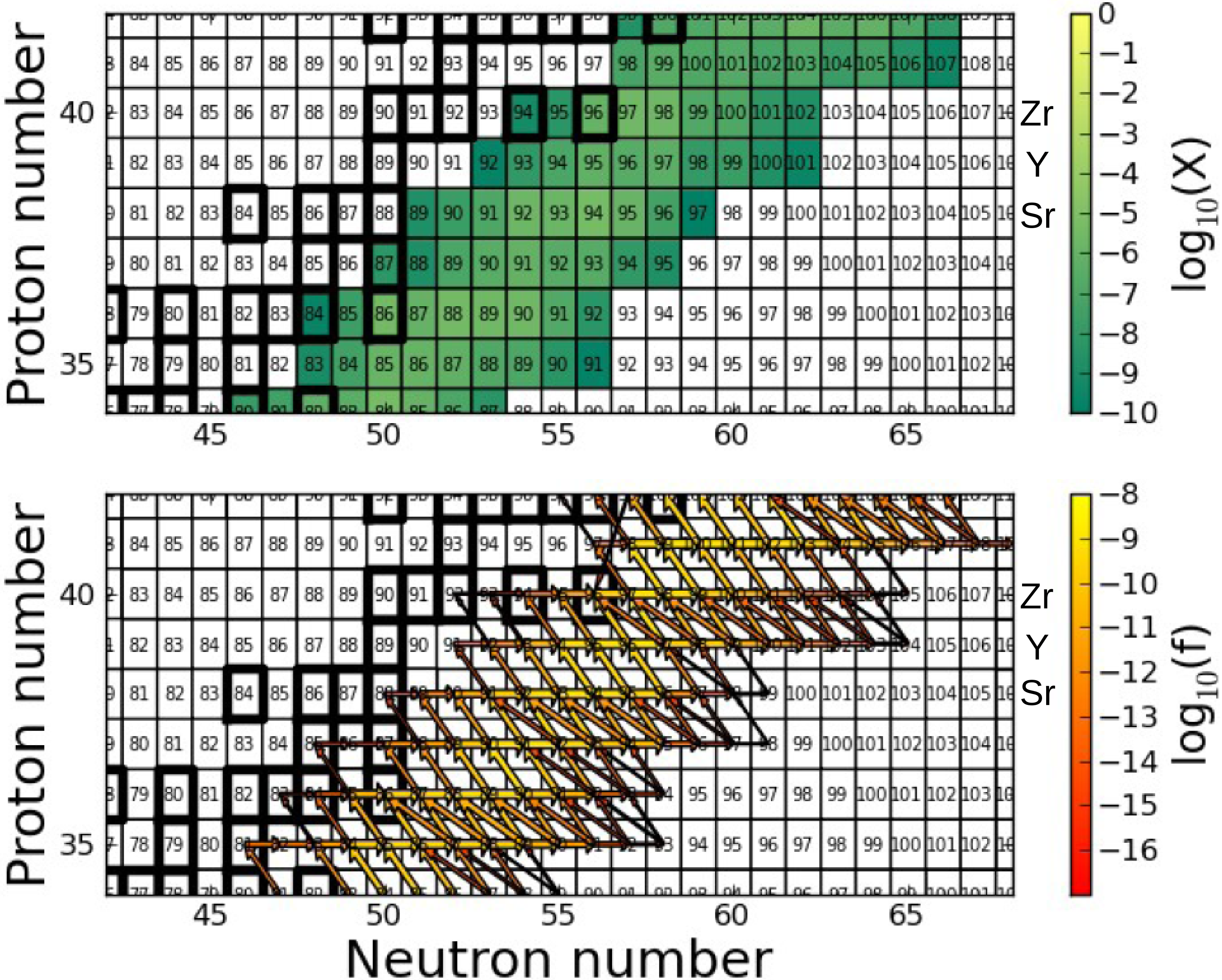
- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) - 10^{18} n cm$^{-3} < N_n < 10^{20}$ n cm^{-3};
- The i process - 10^{13} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n < 10^{13}$ n cm^{-3}.

Paths of neutron capture processes

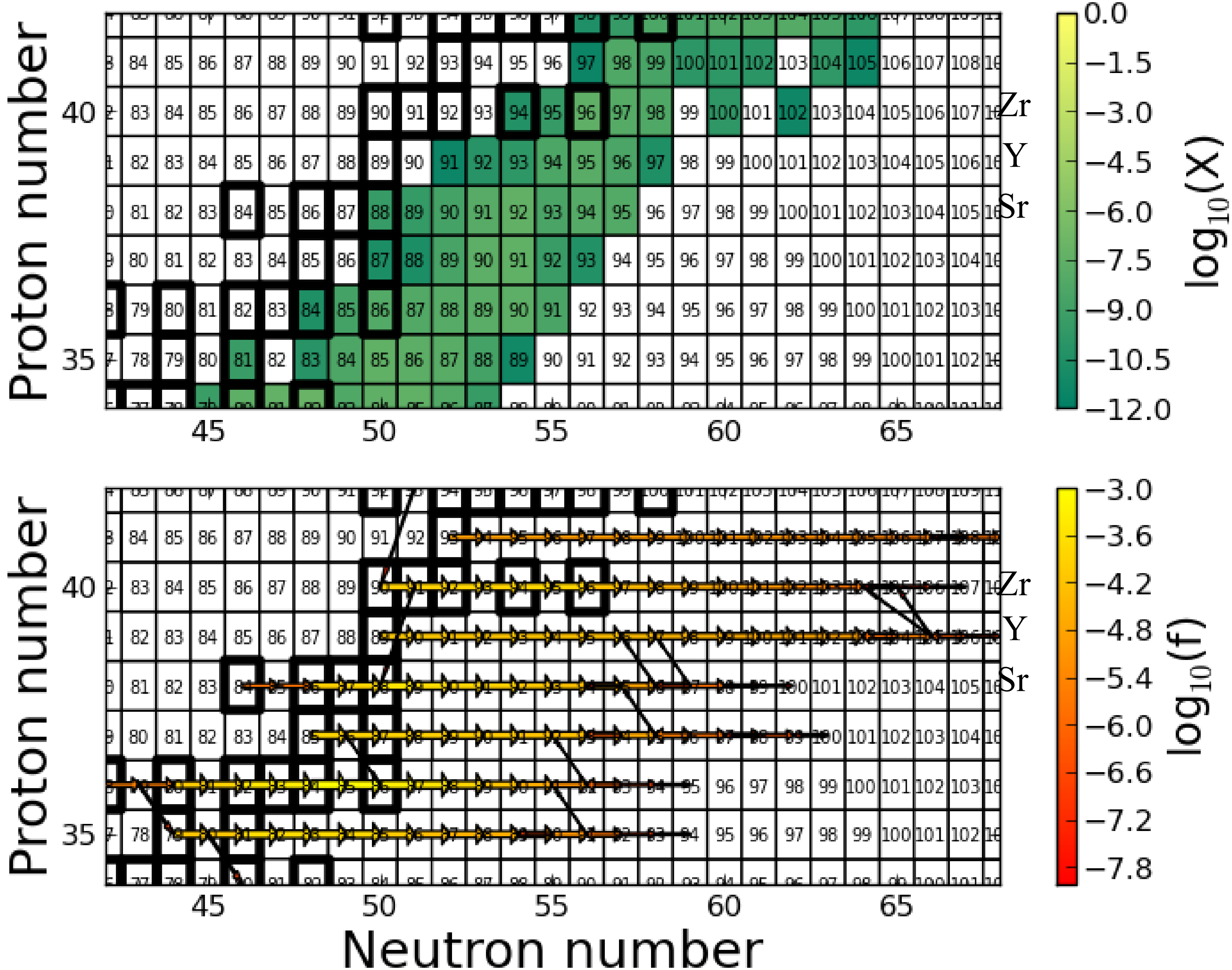


Cauldrons in the cosmos, 1988

Nucleosynthesis path of the i process: Se-Nb



Nucleosynthesis path of the n process: Se-Nb



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

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

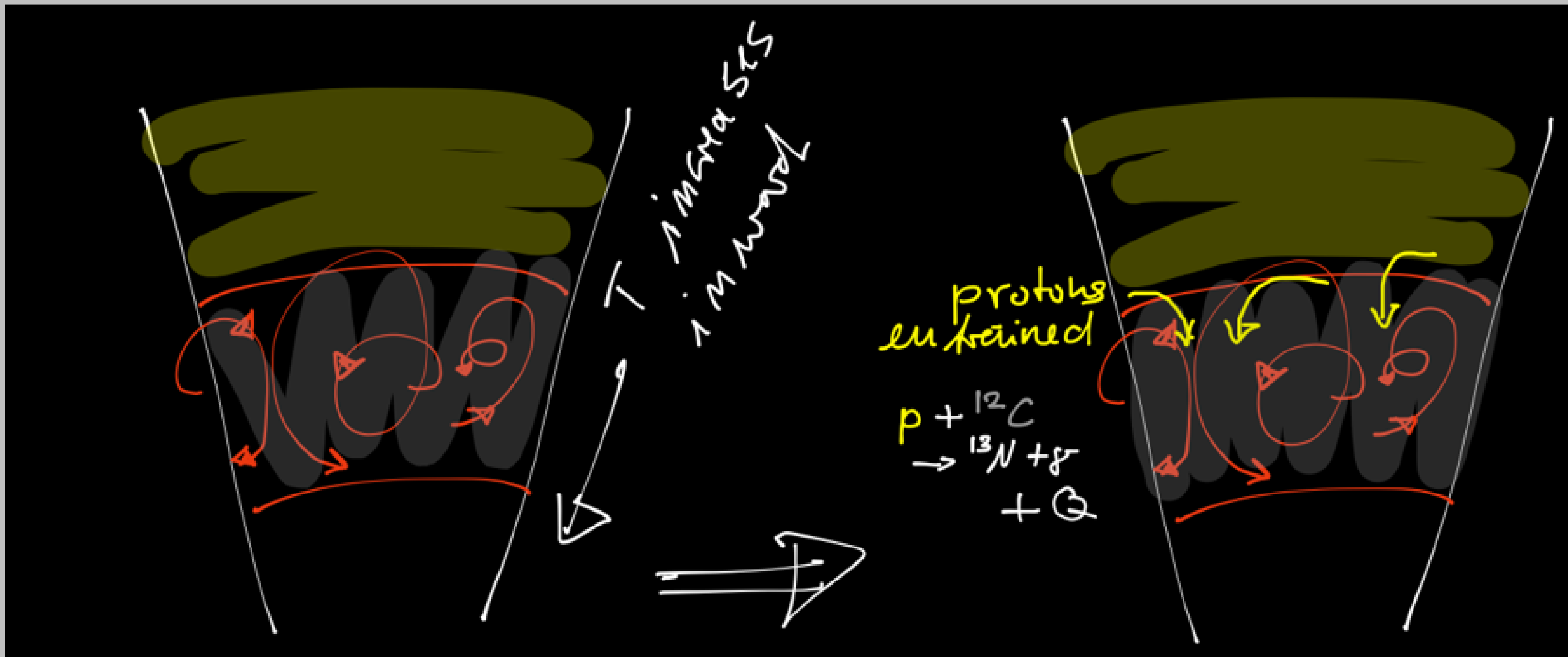
We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the $^{14}N(n, p)^{14}C$ reaction. If substantial portions of this intershell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

"Simulation" from F. Herwig



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

Possible sites: low-Z LMS & MS; RAWD

Challenge: requires multi-D hydro simulations

i process in RAWD

Denissenkov + 2018: ArXiV 1809.03666

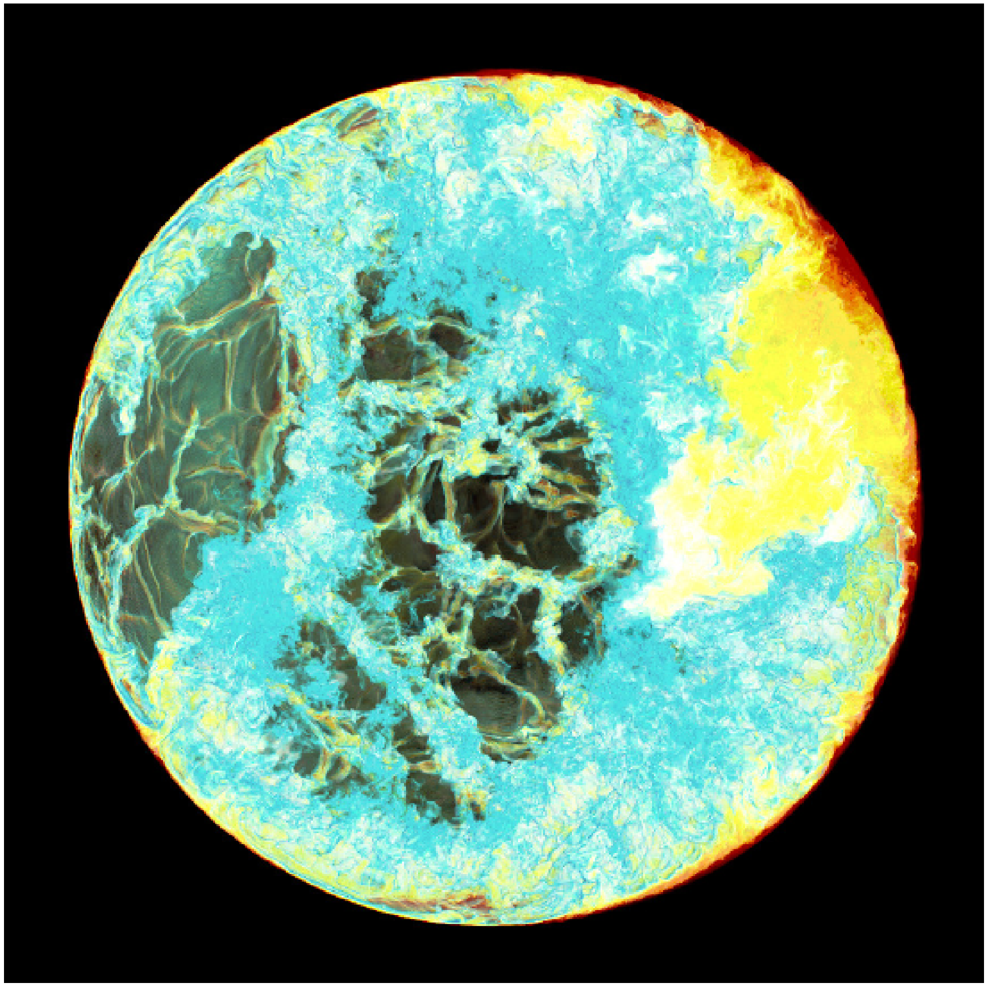


Figure 3. Fractional volume of the fluid ingested into the convection zone in run E10 at $t = 359.8\,\mathrm{min}$. The colour scale is logarithmic and very low concentrations are transparent. The front half of the sphere is not shown and the camera is looking into the back half of the sphere in this rendering.

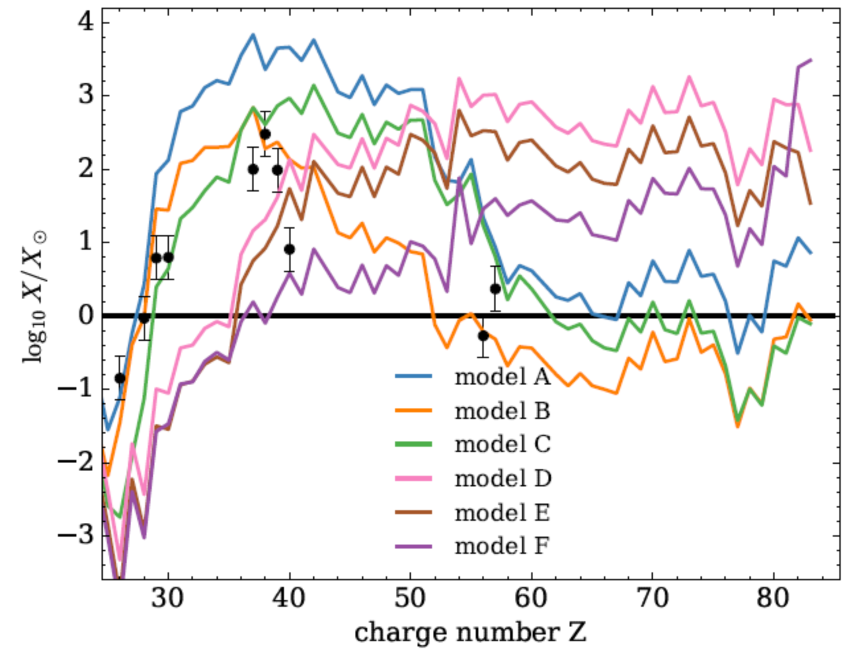


Figure 11. The elemental *i*-process yields (solar-scaled mass fractions) from our RAWD models. For comparison, the abundances of the first peak n-capture elements measured in Sakurai's object by Asplund et al. (1999) are shown as filled black circles with errorbars. They were interpreted by Herwig et al. (2011) as results of the *i*-process nucleosynthesis in the convective He shell during its very late thermal pulse in a model of Sakurai's object with a half-solar metallicity.

CEMP-i stars?

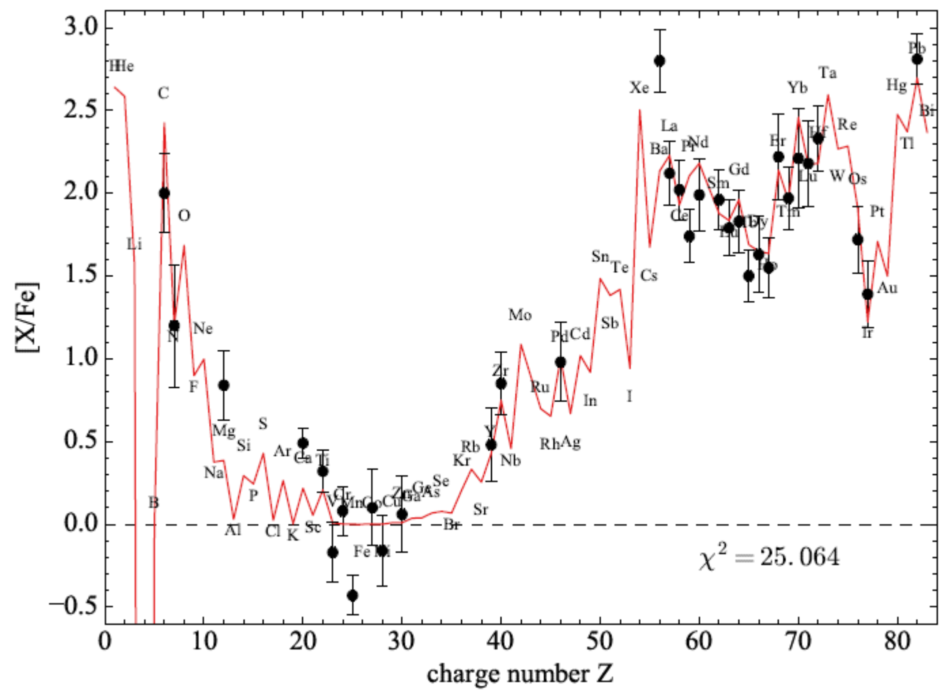
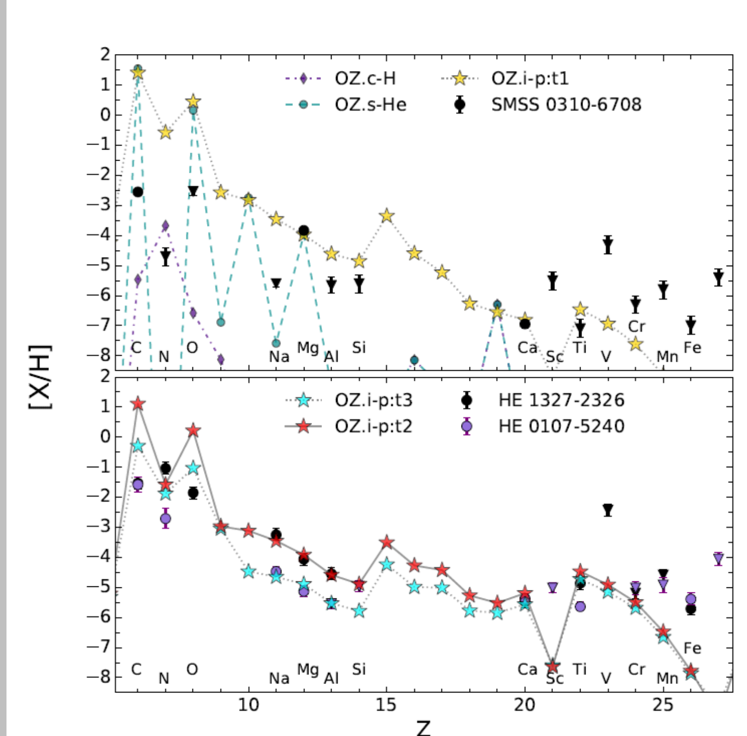


Figure 12. Abundances of heavy elements observed in the CEMP-r/s star CS31062-050 (Aoki et al. 2002; Johnson & Bolte 2004) and the best-fit abundance distribution from the time evolution of the RAWD model G diluted with 99.58% of the initial abundances.

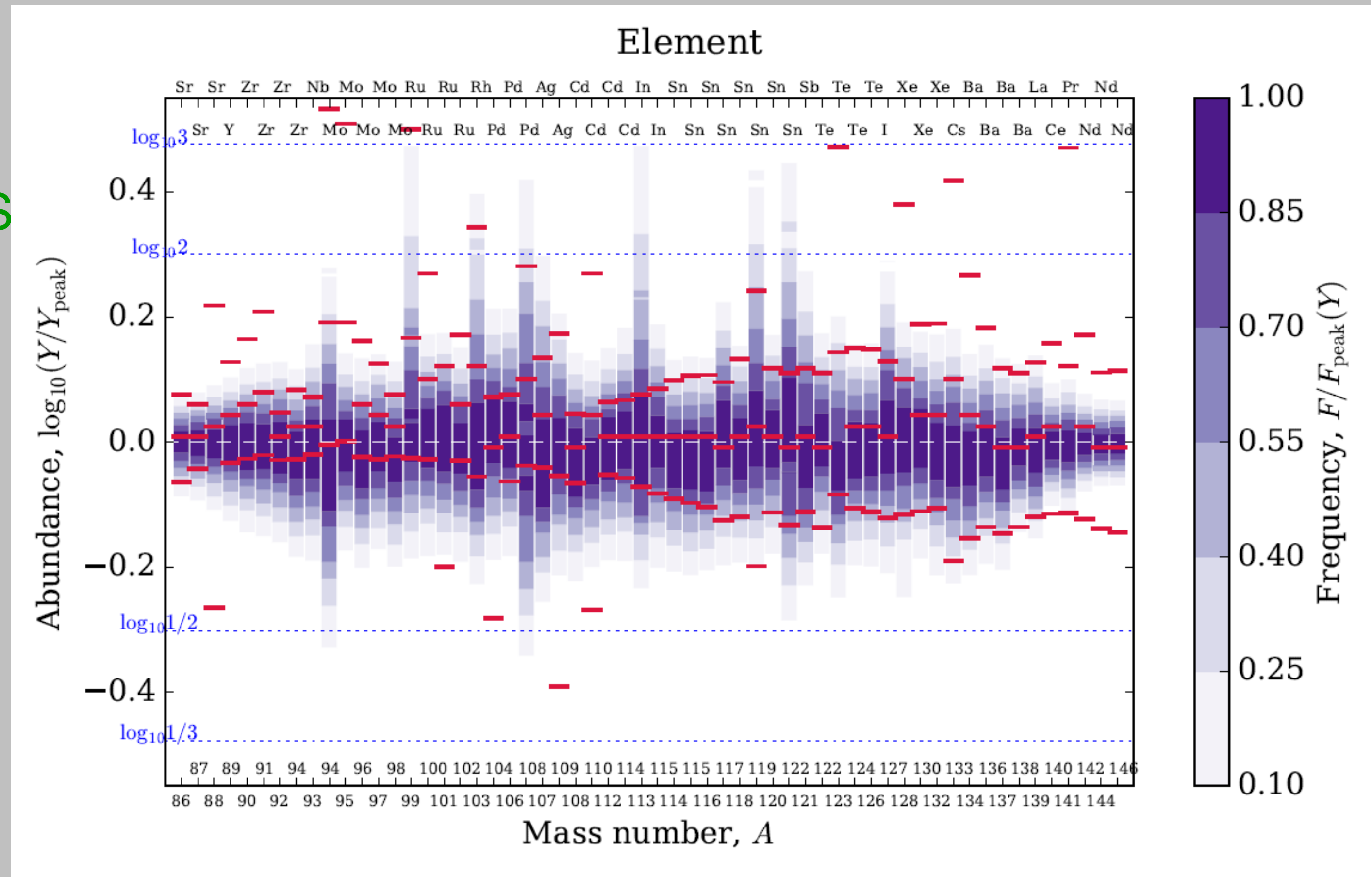


Clarkson+2018 MNRAS:
- H-ingestion in massive star at Z=0
- Neutron density ~ 10^{13} n cm^{-3}
- The i-process does not reach Fe

For GCE impact, see Cote + 2018ApJ...854..105C

Key Reaction Lists

Priority lists established for:
- Enhanced (weak) s proc. in low-Z fast rotating stars: N. Nishimura+ 2017 MNRAS



- i process: Denissenkov+

2018JPhG...45e5203D

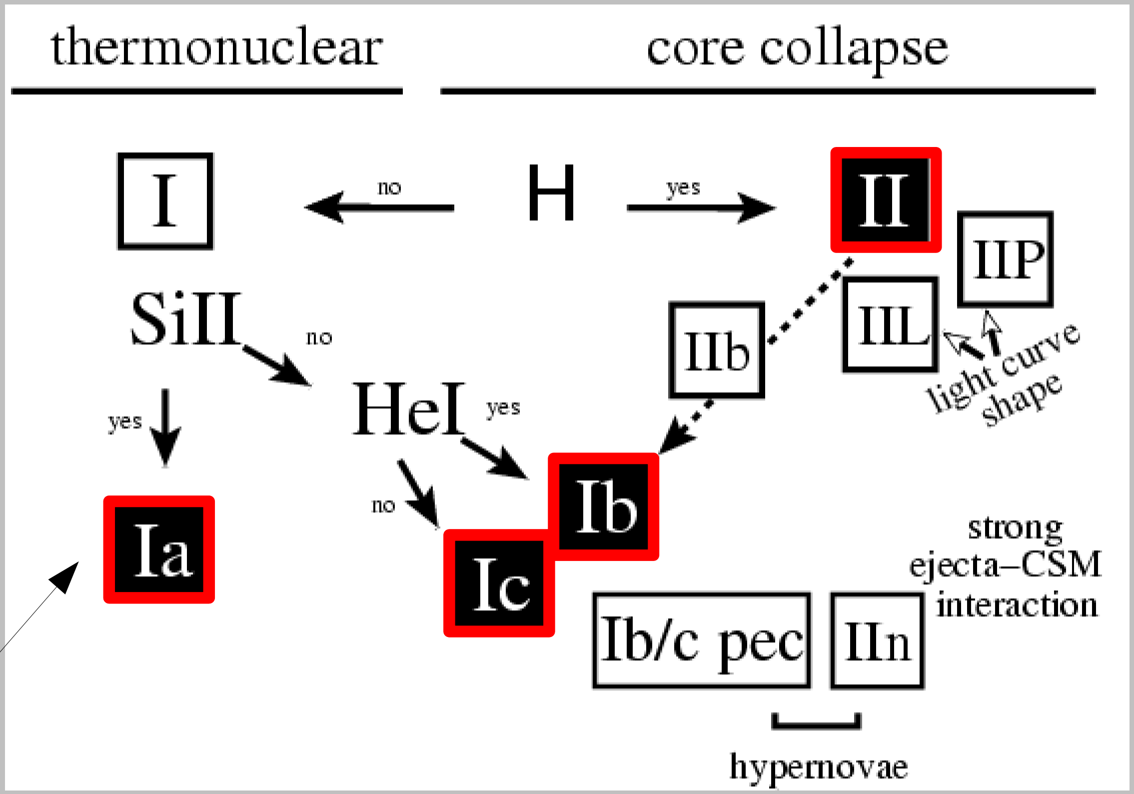
- Gamma (aka p) process in CCSNe: T. Rauscher+ 2016 http://adsabs.harvard.edu/abs/2016MNRAS.463.4153R

- Gamma (aka p) process in Sne Ia: Nishimura+ 2018, MNRAS

- Main s process (C13-pocket & TP) Cescutti + 2018, MNRAS

Supernova Explosion Types

Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR

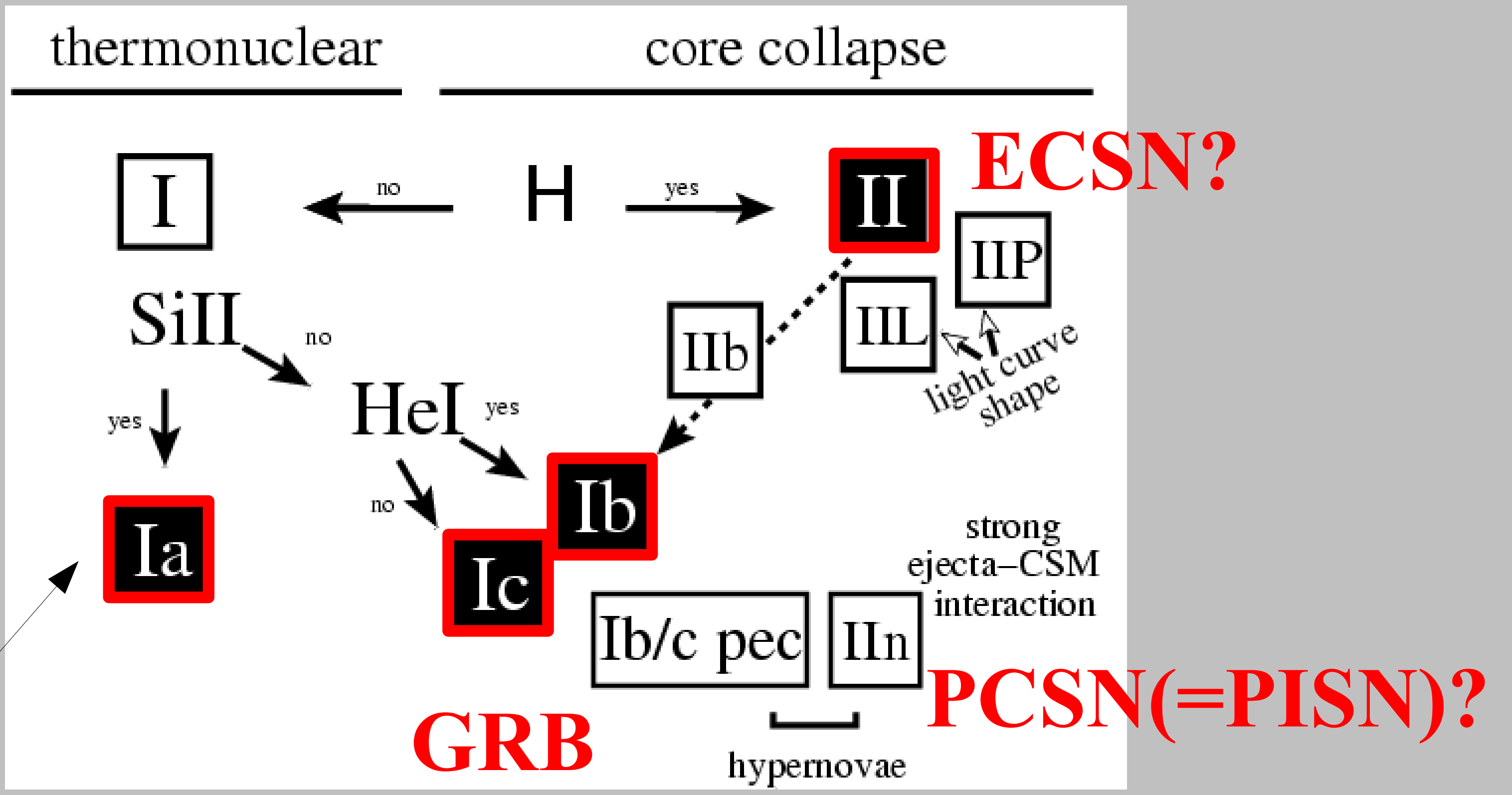


White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

(Turatto 03)

Supernova Explosion Types

Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR



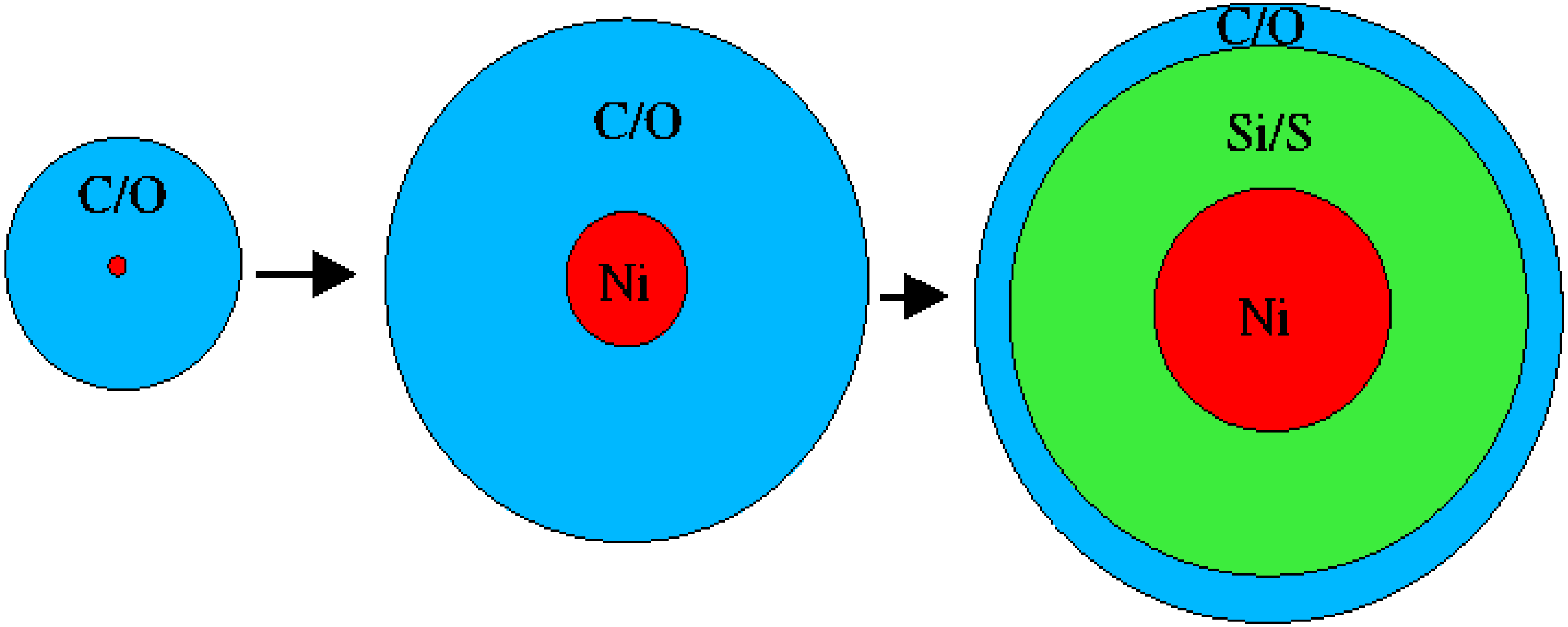
White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

(Hirschi+05
Woosley+06
Yoon+06, ...)

(Turatto 03)

Back of the Envelope (simple) SN Ia picture

e.g. W7 (Nomoto, Thielemann, Yokoi 1984); delayed detonations (Khokhlov, Höflich, Müller; Woosley et al.)



$M_{ch} \approx 1.4 M_\odot$ of $^{12}C/^{16}O$=1 WD $\rightarrow$ 1.398776 $M_\odot$ ^{56}Ni

$\rightarrow 2.19 \times 10^{51}$ erg - $E_{grav} \approx (5-6) \times 10^{50}$ erg

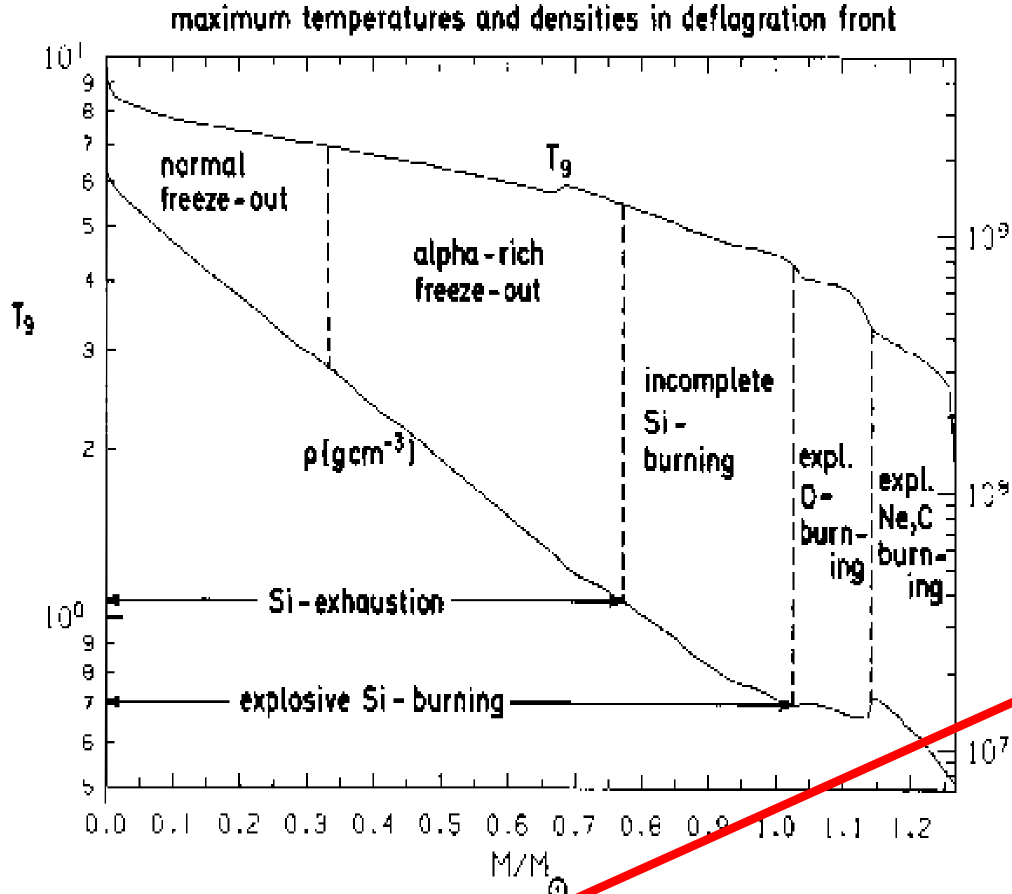
reduction due to intermediate elements like Mg, Si, S, Ca

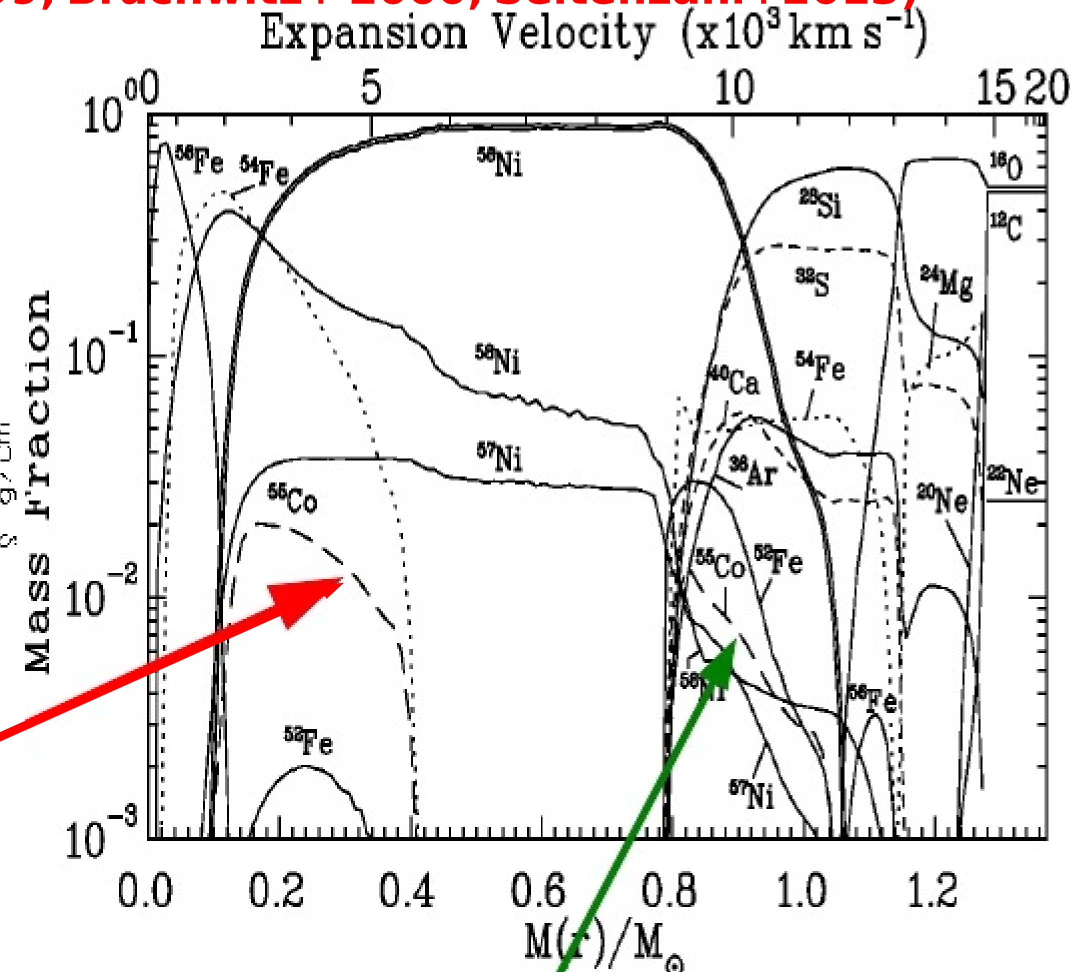
$\rightarrow 1.3 \times 10^{51}$ erg

in spherically symmetric models description of the burning front propagation (with hydrodynamic instabilities) determines outcome!

SNIA: spherically symm. Expl. with simplified approx. for the burning front propagation

Near Chandrasekhar Models (deflagrations W7, Nomoto, Thielemann, Yokoi et al. 1984), delayed detontaions (Iwamoto+ 1999, Brachwitz+ 2000, Seitenzahl+2013)



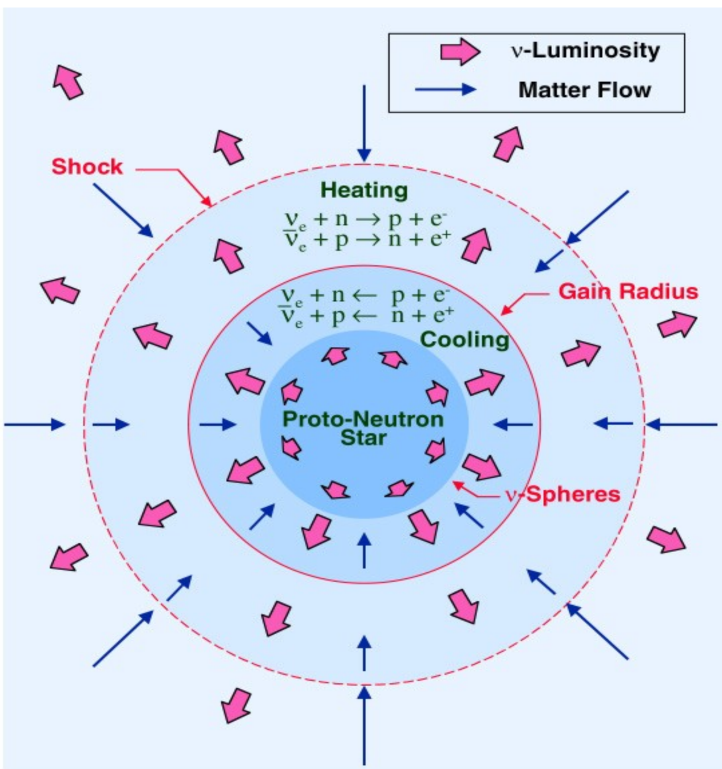


Mn comes in form of its only stable isotope ^{55}Mn, and is the decay product of ^{55}Co, produced in incomplete and complete Si-burning under ***optimal conditions with Ye=Z/A=0.491*** . In alpha-rich freeze-out, determined by entropy $S \propto T_9{}^3/\rho$, with values of T_9 and ρ_8 exceeding $T_9{}^3/\rho_8>180$, ^{55}Co is moved to ^{59}Cu (→ ^{59}Co).

In the inner zones of M_{ch}-models this Ye is attained via electron capture (electrons are degenerate with high Fermi energy) ,

in the outer zones it can be approached by metallicity CNO → ^{22}Ne, leading for [Fe/H]=- ∞ ,0,025,0.5 to Ye= 0.5, 0.499, 0.498, 0.496 (also characterized by the appearance of ^{54}Fe (moved to ^{58}Ni in alpha-rich freeze-out). See for more details Seitenzahl and Townsley (2016), Höflich et al. (2017),Leung & Nomoto (2017)

Neutrino-driven Core Collapse Supernovae



H.-T. Janka

$\nu_e + n \leftrightarrow p + e^-$ heating

$\bar{\nu}_e + p \leftrightarrow n + e^+$

$\nu_e + A' \leftrightarrow A + e^-$ opacity

$\nu + N \leftrightarrow \nu + N$

$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ thermalization

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\nu = \nu_e, \nu_\mu, \nu_\tau$ source terms

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

also

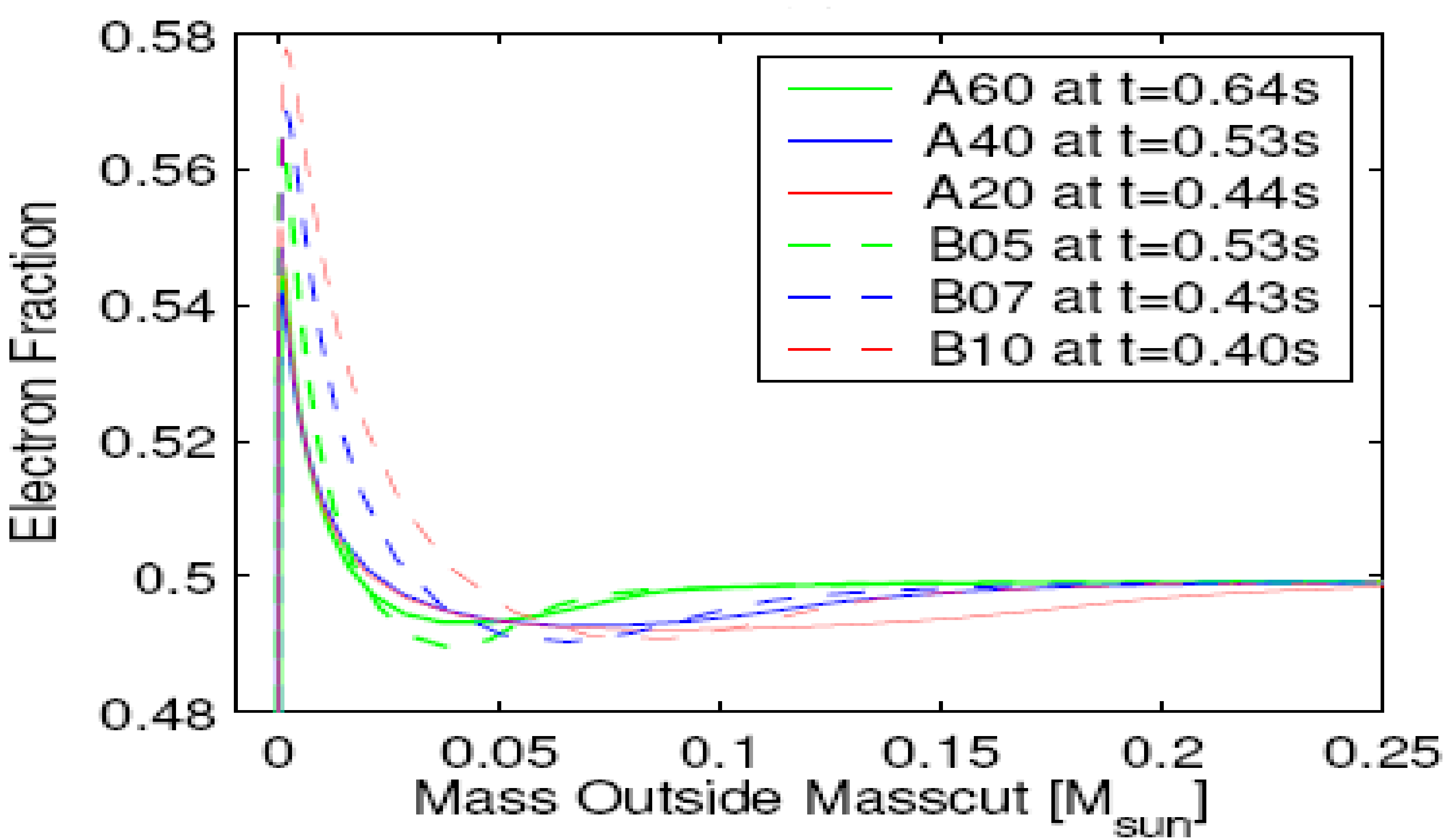
$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

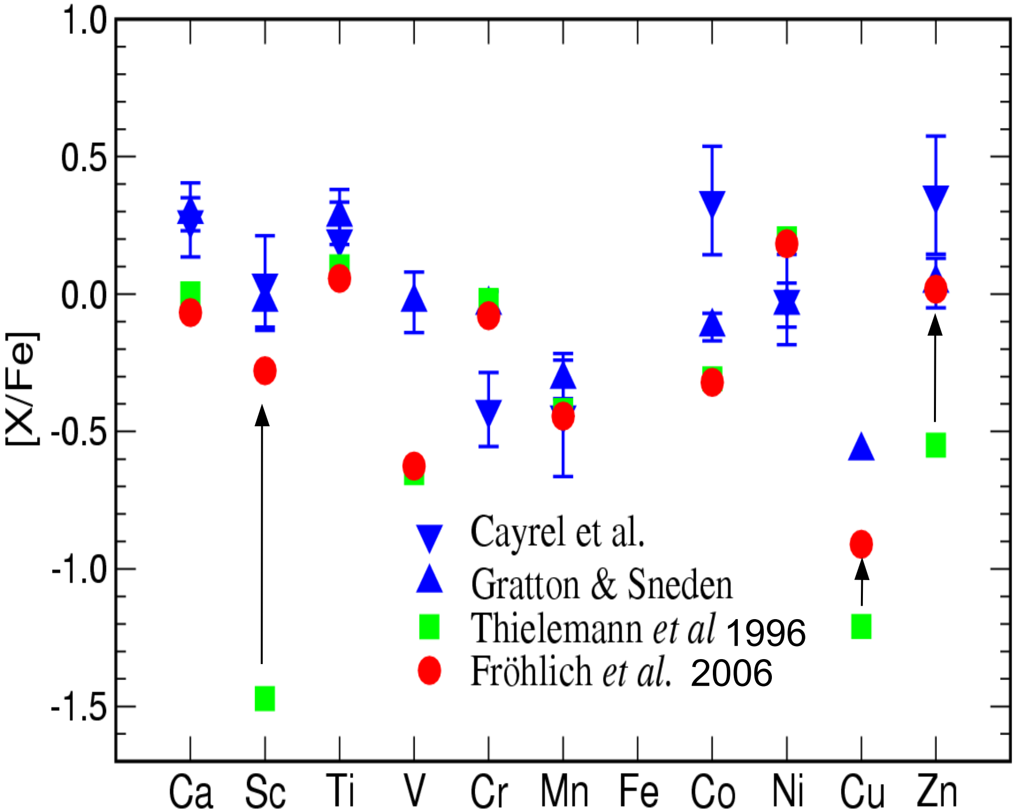
<u>CCSNe</u>: In exploding models matter in innermost ejected zones becomes proton-rich (Y_e>0.5)

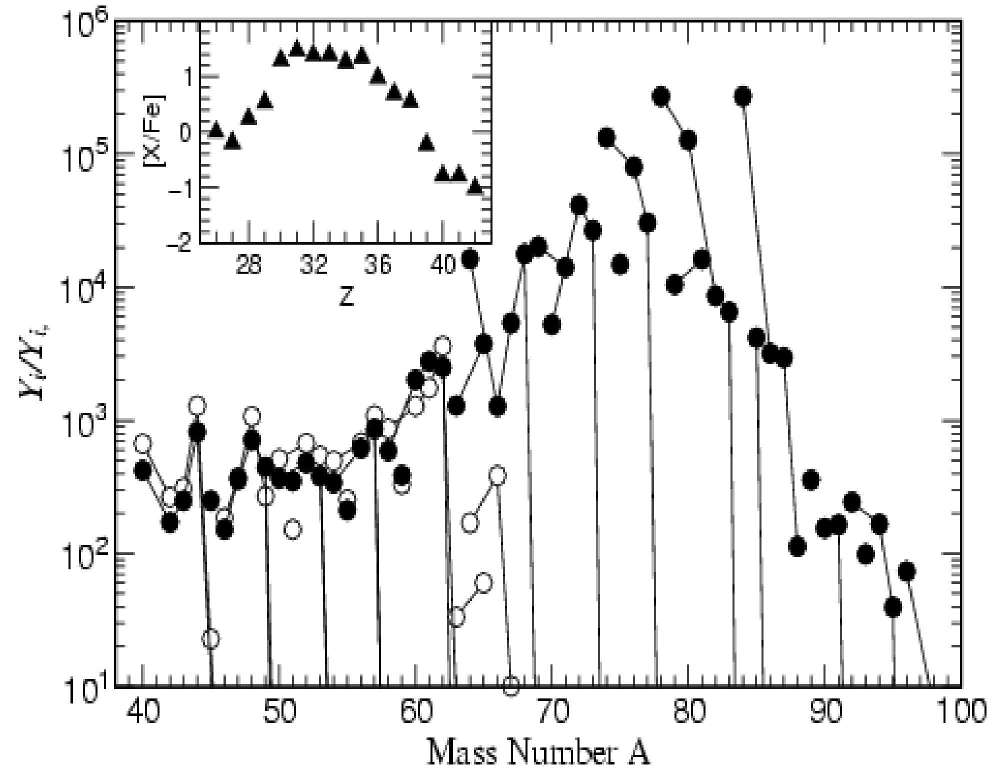
if the neutrino flux is sufficiant (scales with $1/r^2$)! :



A bit of history: Liebendörfer et al. (2003), Fröhlich et al. (2006a), Pruet et al. (2005)

Improved Fe-group composition and production beyond





Models with Y_e>0.5 lead to an alpha-rich freeze-out with remaining protons which can be captured similar to an rp-process. This ends at ^{64}Ge, due to (low) densities and a long beta-decay half-life (decaying to ^{64}Zn).

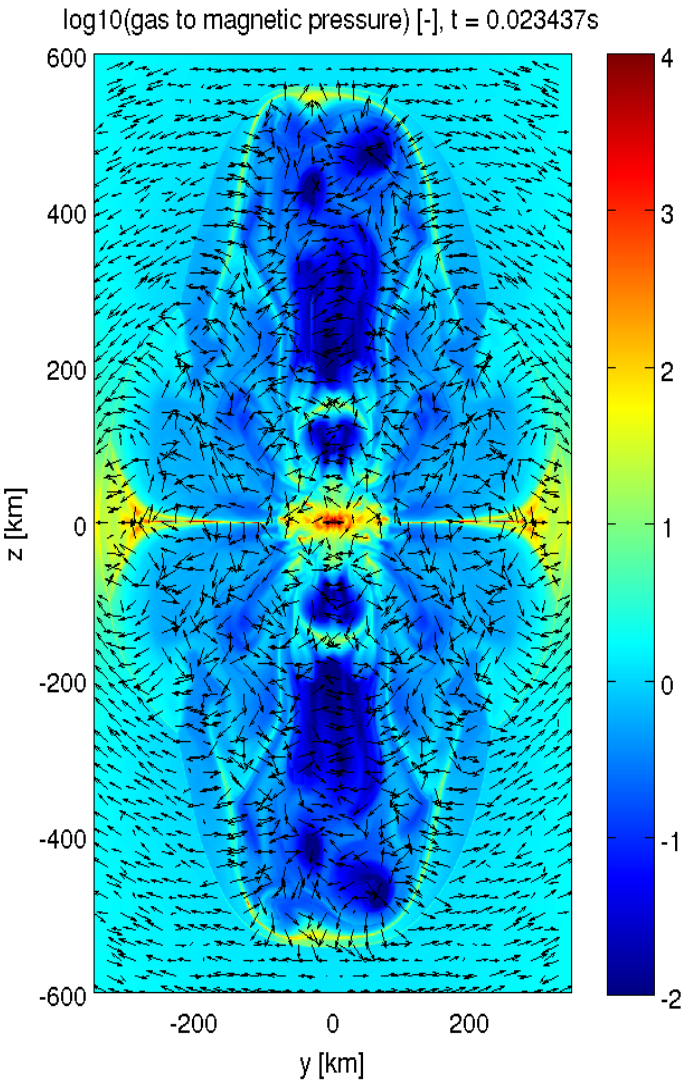
This effect improves the Fe-group composition in general (e.g. Sc) and extends it to Cu and Zn! (Fröhlich et al. 2006a, Pruet et al. 2005)

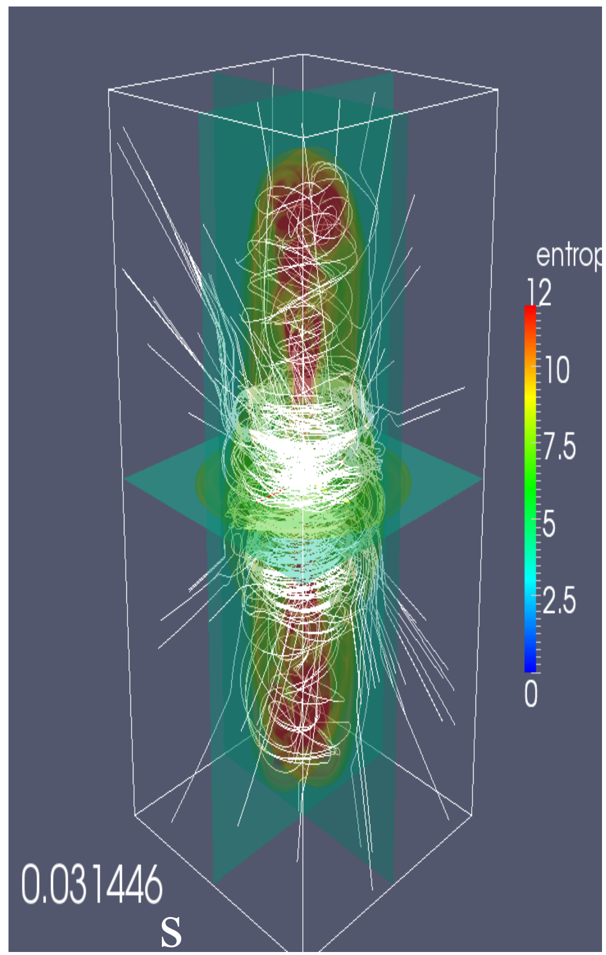
Anti-neutrino capture on protons provides always a small background of neutrons which can mimic beta-decay via (n,p)-reactions.(**Fröhlich et al. 2006b**, Pruet et al.2005, Wanajo 2007); also strong over-abundances can be obtained up to Sr and beyond (light p-process nuclei). ***Further analysis by Wanajo et al. (2010), Arcones et al. (2011).***

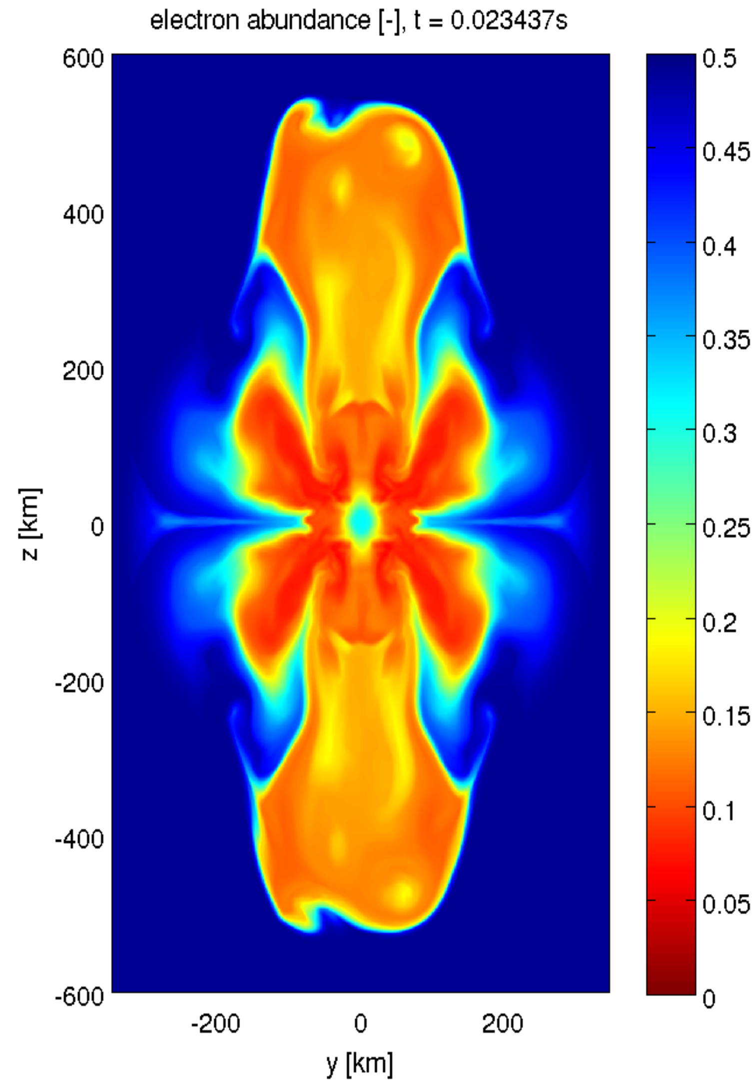
3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 $\times 10^{12}$ Gauss,

results in 10^{15} Gauss neutron star







3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2015

Other 3D Studies (Mösta et al. 2014, 2015)

25 M_{sol} progenitor (Heger+ 2000), magnetic field in z-direction of 10^{12} Gauss, kink instability develops

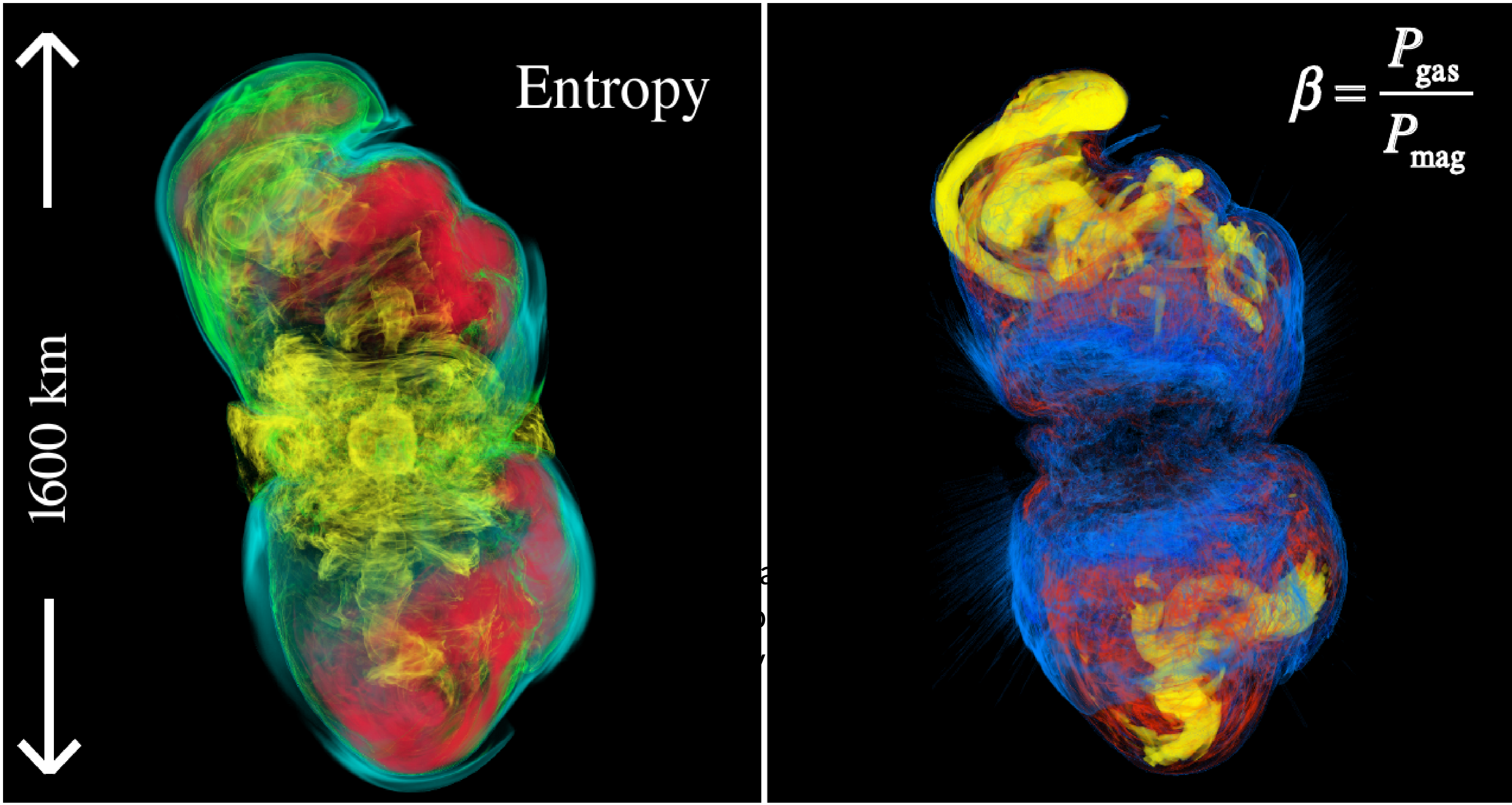


Figure 4. Volume renderings of entropy and β at $t - t_b = 161$ ms. The z-axis is the spin axis of the protoneutron star and we show 1600 km on a side. The colormap for entropy is chosen such that blue corresponds to $s = 3.7 k_b$ baryon^{-1}, cyan to $s = 4.8 k_b$ baryon^{-1} indicating the shock surface, green to $s = 5.8 k_b$ baryon^{-1}, yellow to $s = 7.4 k_b$ baryon^{-1}, and red to higher entropy material at $s = 10 k_b$ baryon^{-1}. For β we choose yellow to correspond to $\beta = 0.1$, red to $\beta = 0.6$, and blue to $\beta = 3.5$. Magnetically dominated material at $\beta < 1$ (yellow) is expelled from the protoneutron star and twisted in highly asymmetric tubes that drive the secular expansion of the polar lobes.

<u>MHD-SNe</u>: Eichler et al. (2018) (based on axis-symmetric simulations by Nakamura et al. 2015/16), see also other recent multi-D results by e.g. the Oak Ridge or Garching groups

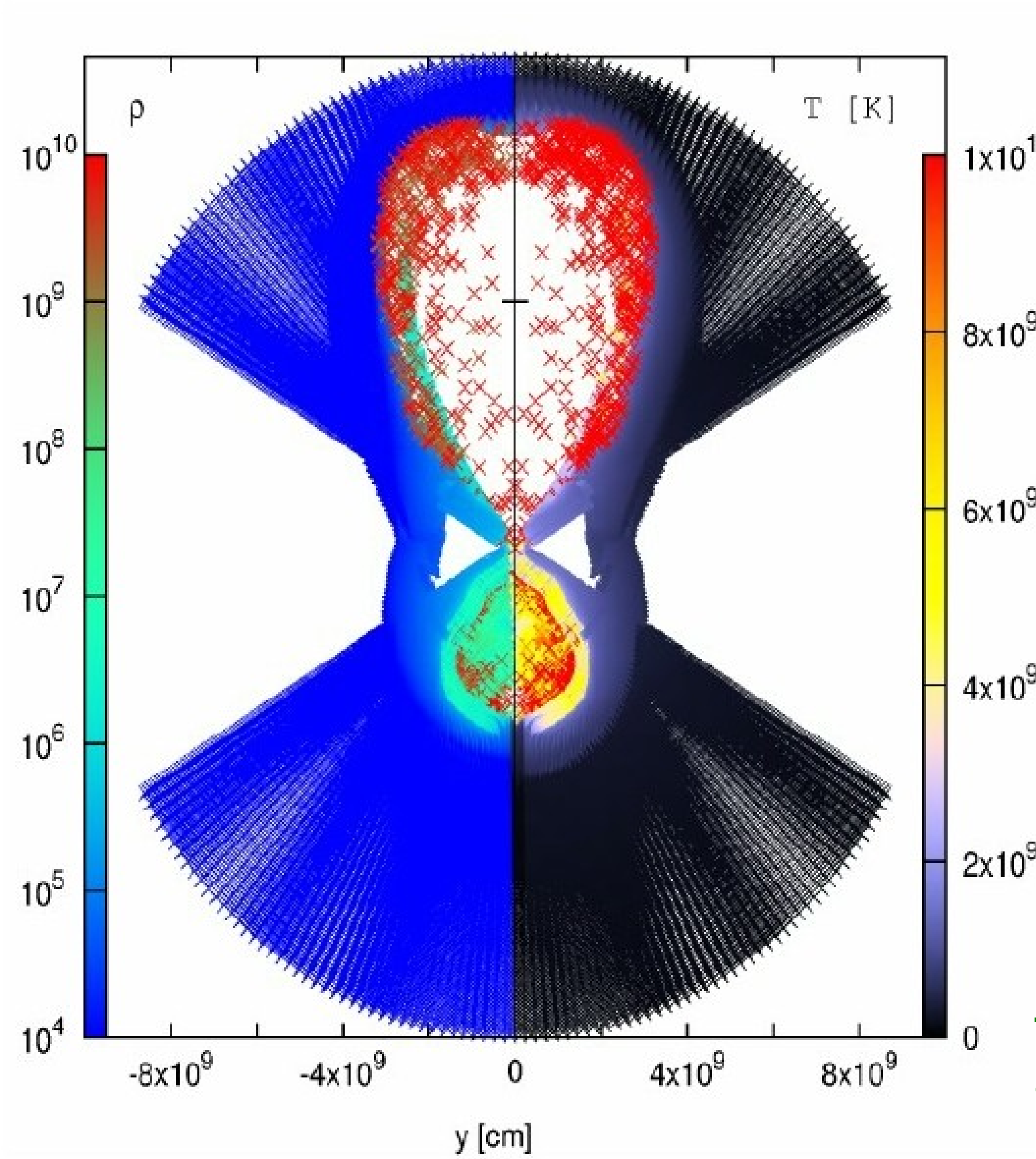
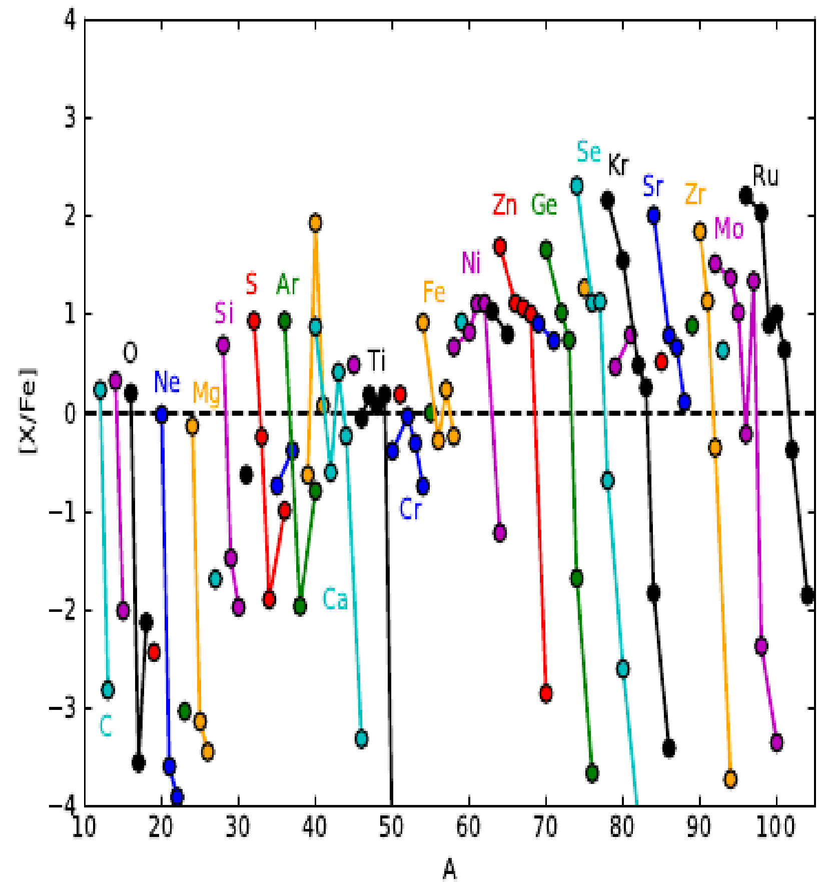
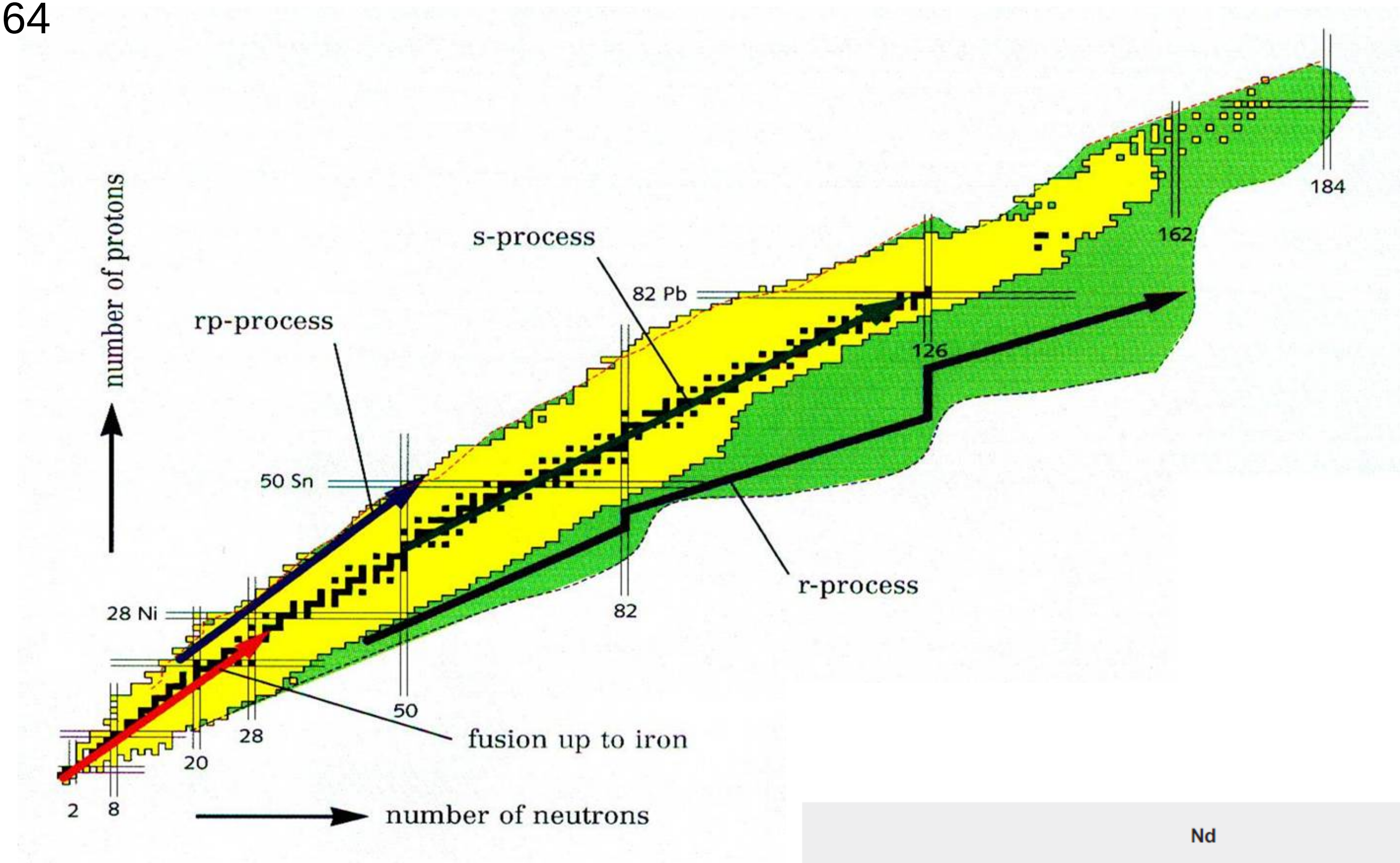
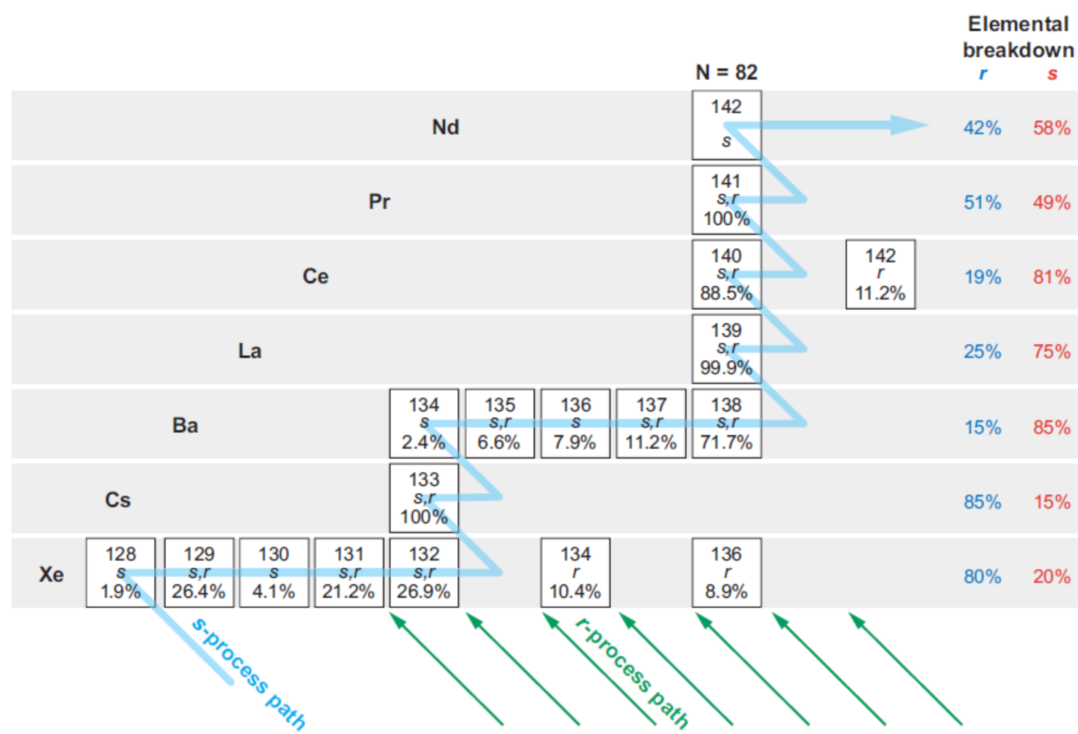


Figure 2: Peak Temperature (right) and corresponding density (left) of ejected tracers for the 17.0 $M_\odot$ progenitor.



This example features a nice/strong νp-process caused by Ye>0.5 conditions for an 11.2 Msol star (see Fröhlich+ 2006, Wanajo 2006),
but large-scale predictions are presently still made in induced spherical explosion models.

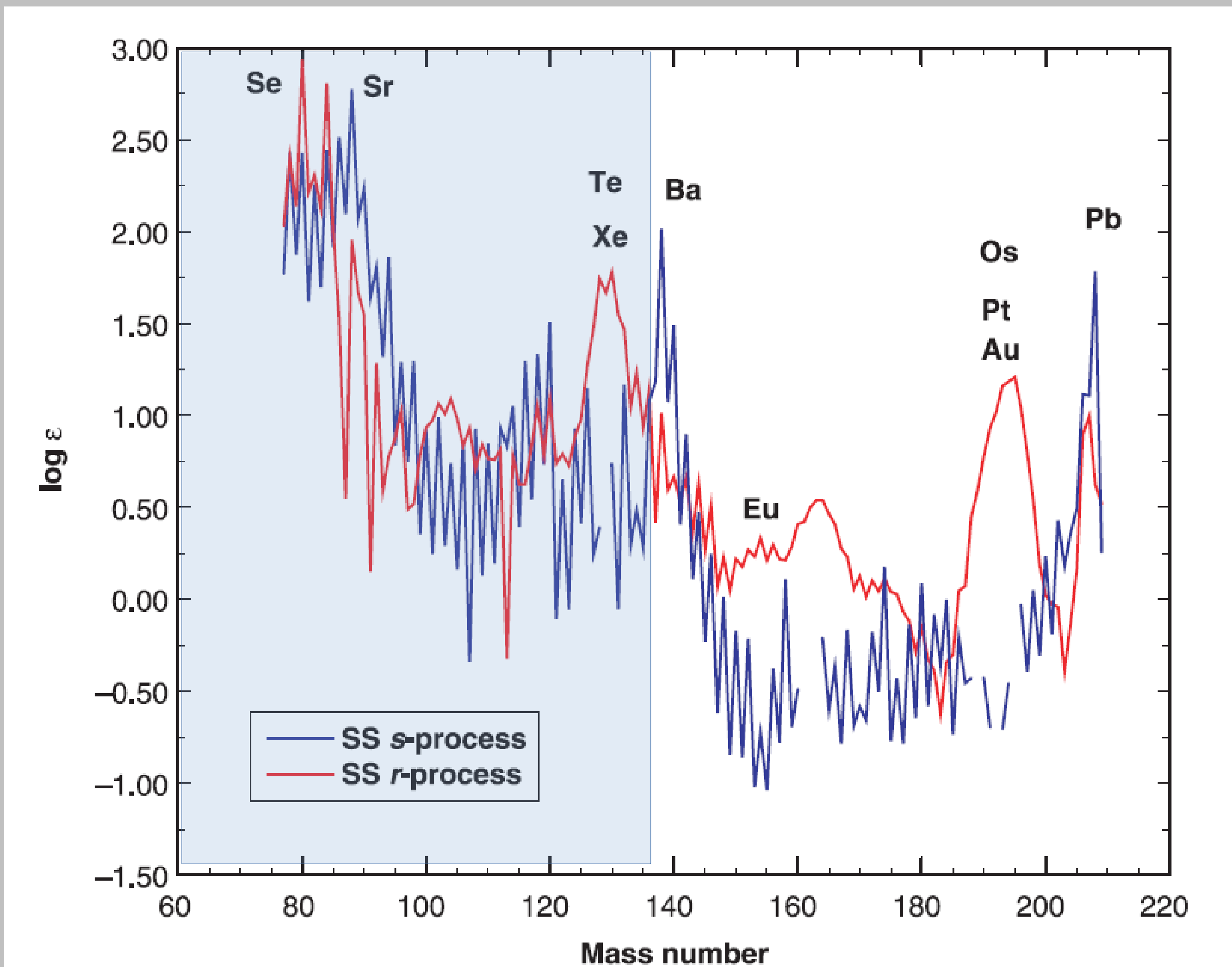




Where is the r-process (and gold!) made in the Universe?

Residual method: approach

Sneden & Cowan 2003



MACS from experiments

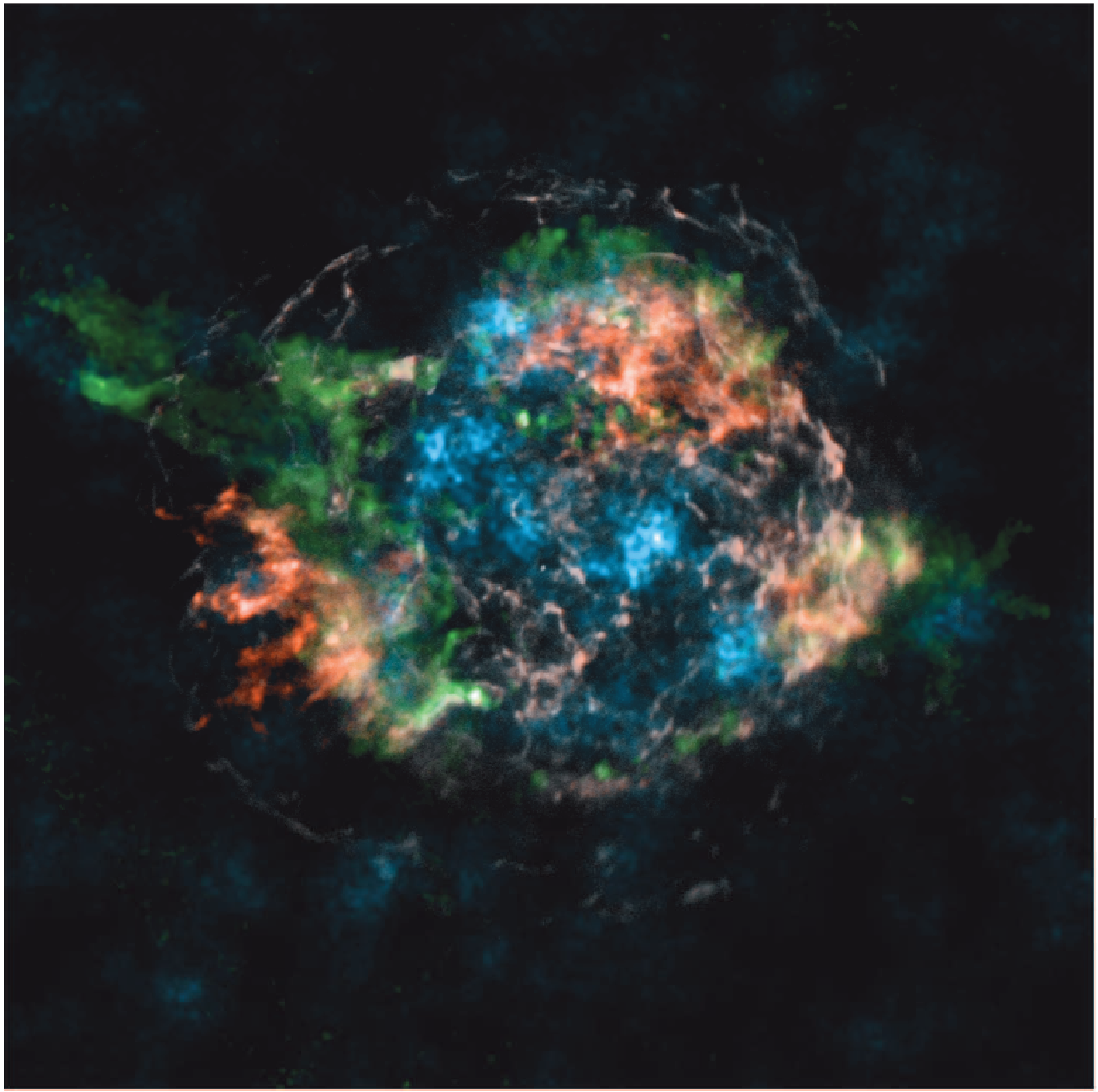
s-process pattern

r-process pattern in the Sun

r-process pattern in old stars

CCSN remnant

Cassiopea A
11000 ly
~ 300 years ago



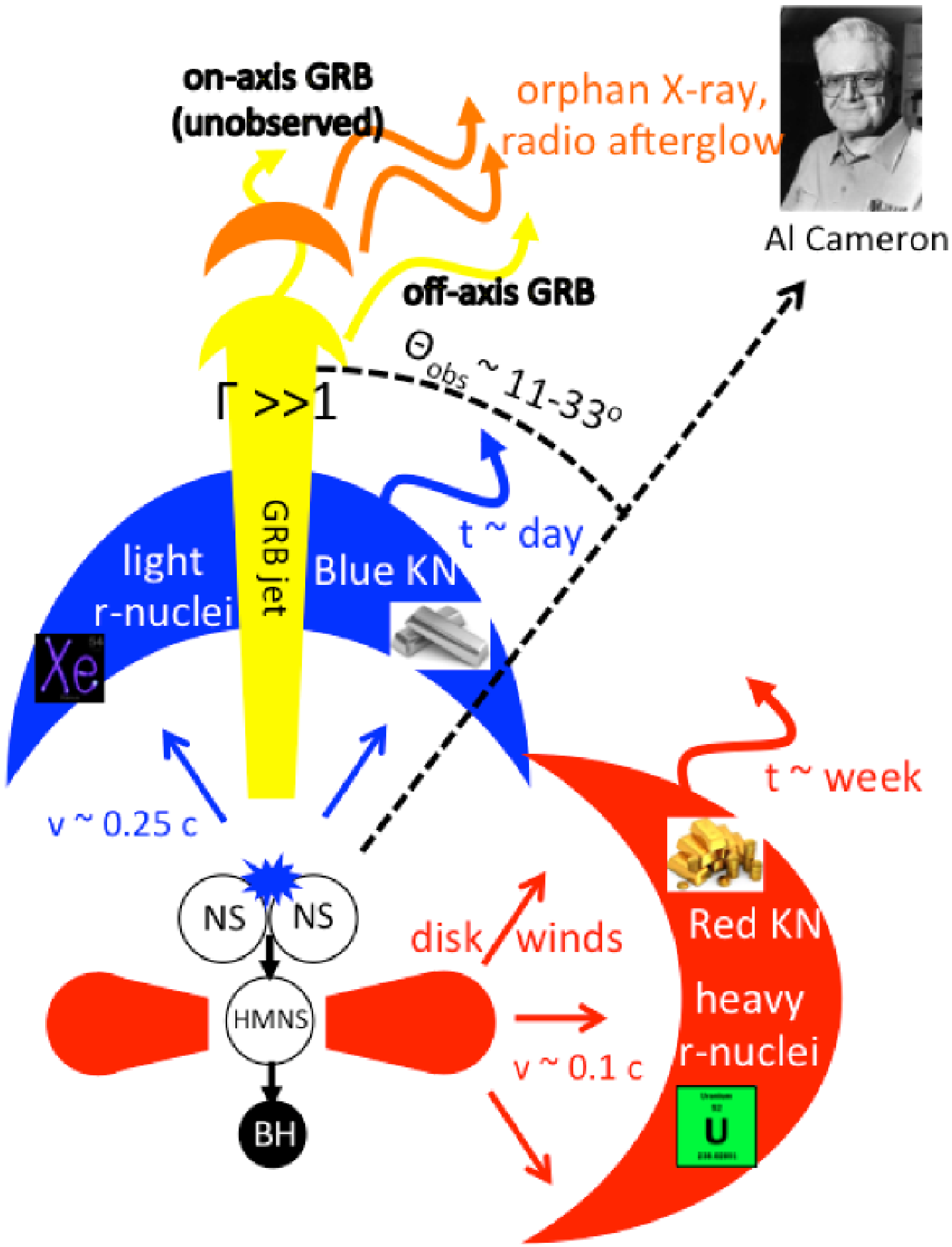
Grefenstette et al. 2014, Nature
(NuSTAR telescope data)

CCSN remnant

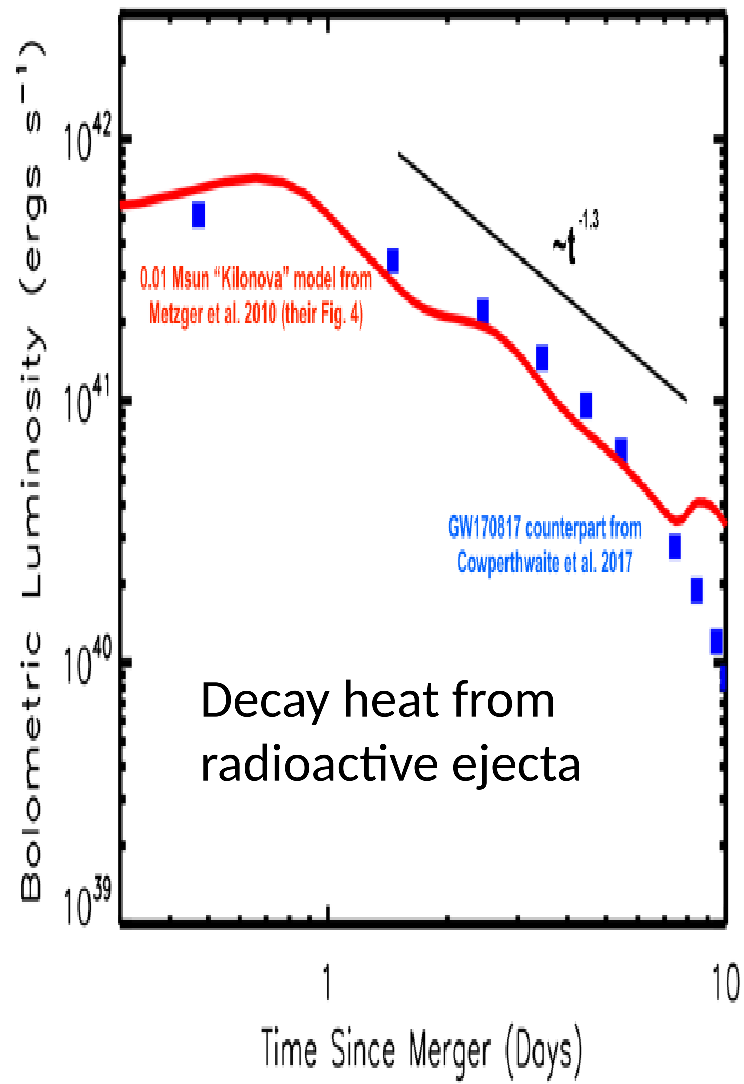
Cassiopea A
11000 ly
~ 300 years ago

The killer reaction:
2α(n,γ)Be9(α,n)C12
Woosley & Hoffman 1992, ApJ

Neither ECSNe but weak r process still possible in neutrino wind!
See e.g. Martinez-Pinedo+; Arcones +



Metzger, Martinez-Pinedo et al. (2010)

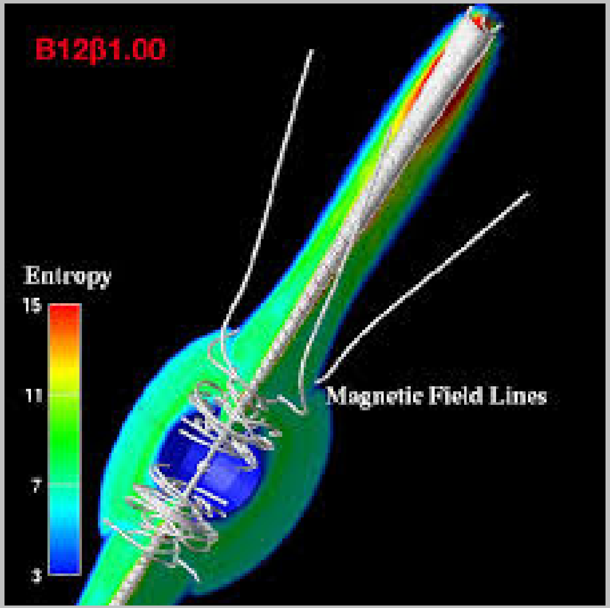


Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation

The r-process sources: short summary

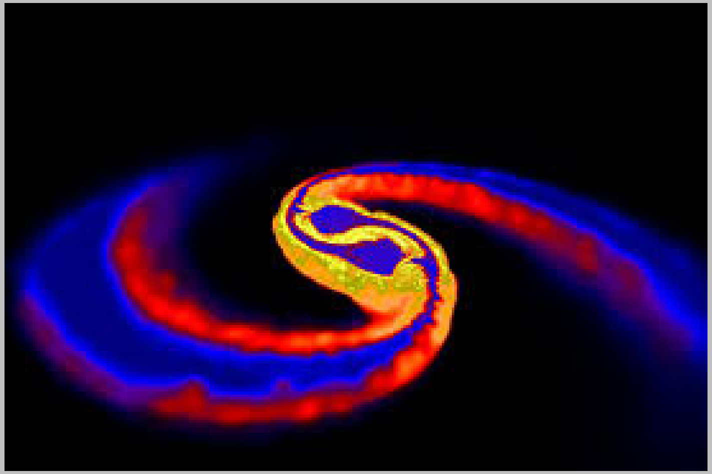
Huge effort ongoing! Far too many papers and work to cover in one talk

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



See e.g. Nishimura + 2015ApJ...810..109N

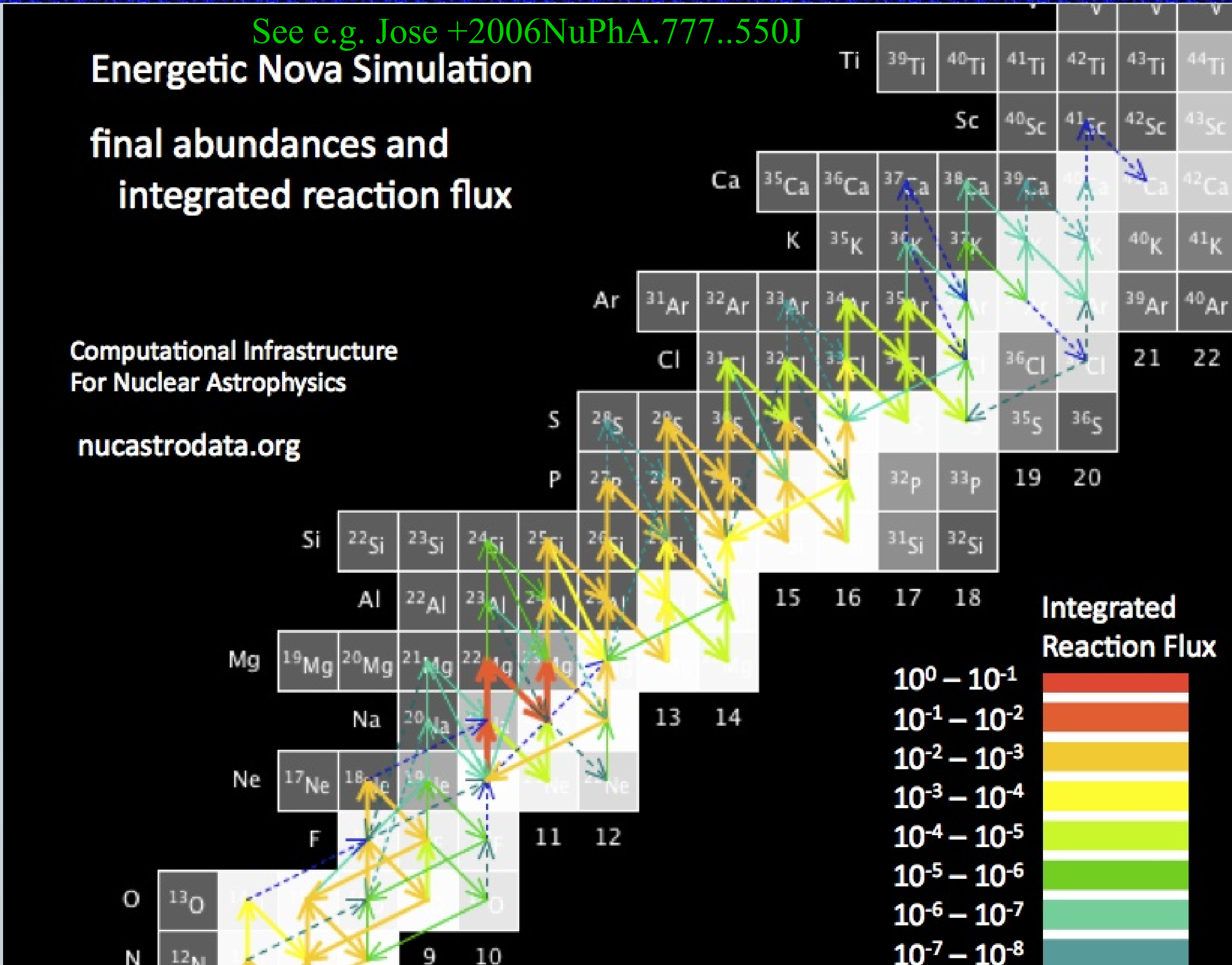
Neutron Star Mergers:
protons/neutrons ≤ 0.1



See e.g. Nishimura + 2016JPhCS.665a2059N

Novae

See e.g. Jose +2006NuPhA.777..550J



X-ray burst

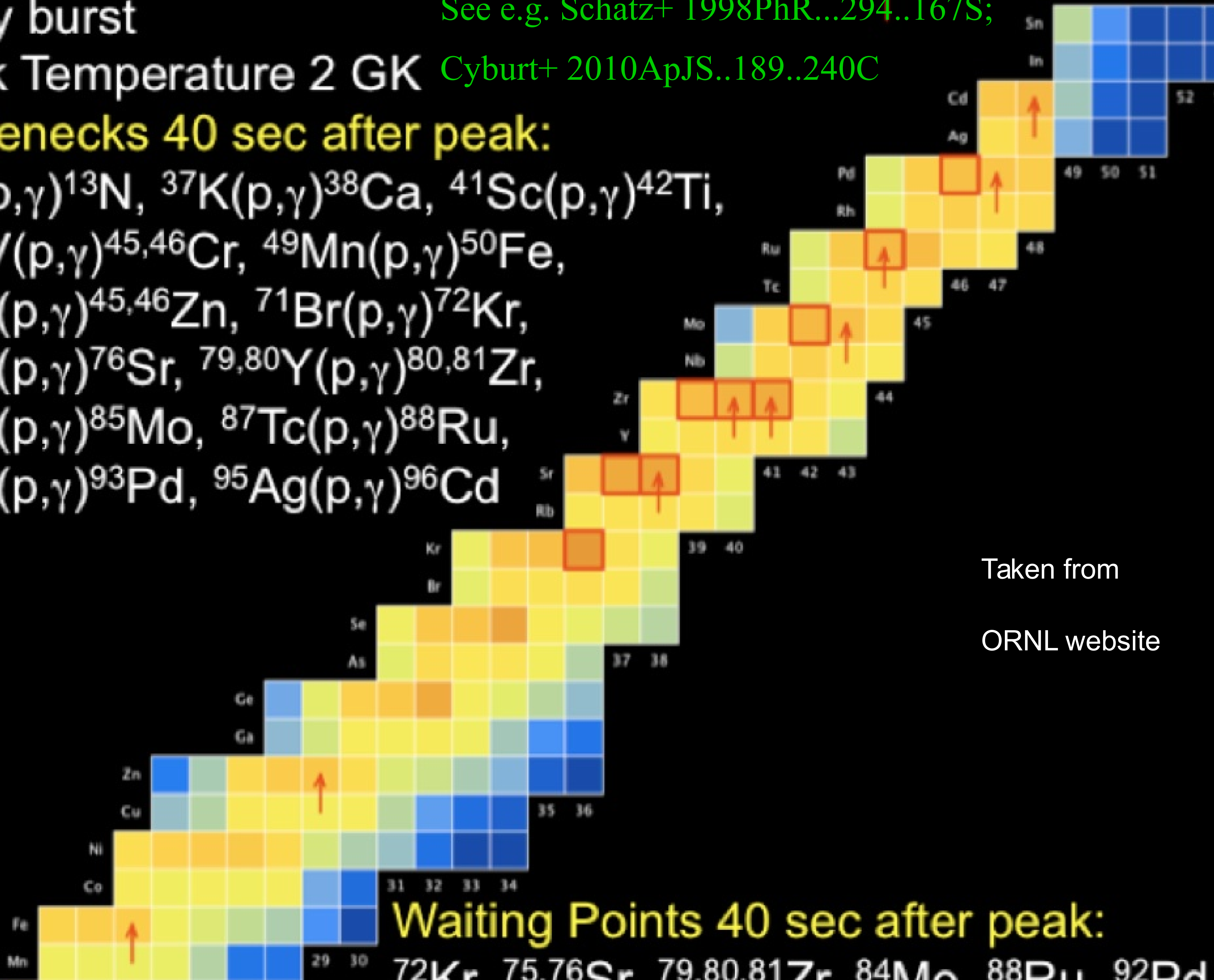
Peak Temperature 2 GK

See e.g. Schatz+ 1998PhR...294..167S;

Cyburt+ 2010ApJS..189..240C

Bottlenecks 40 sec after peak:

$^{12}C(p,\gamma)^{13}N$, $^{37}K(p,\gamma)^{38}Ca$, $^{41}Sc(p,\gamma)^{42}Ti$, $^{44,45}V(p,\gamma)^{45,46}Cr$, $^{49}Mn(p,\gamma)^{50}Fe$, $^{58}Cu(p,\gamma)^{45,46}Zn$, $^{71}Br(p,\gamma)^{72}Kr$, $^{75}Rb(p,\gamma)^{76}Sr$, $^{79,80}Y(p,\gamma)^{80,81}Zr$, $^{84}Nb(p,\gamma)^{85}Mo$, $^{87}Tc(p,\gamma)^{88}Ru$, $^{92}Rh(p,\gamma)^{93}Pd$, $^{95}Ag(p,\gamma)^{96}Cd$



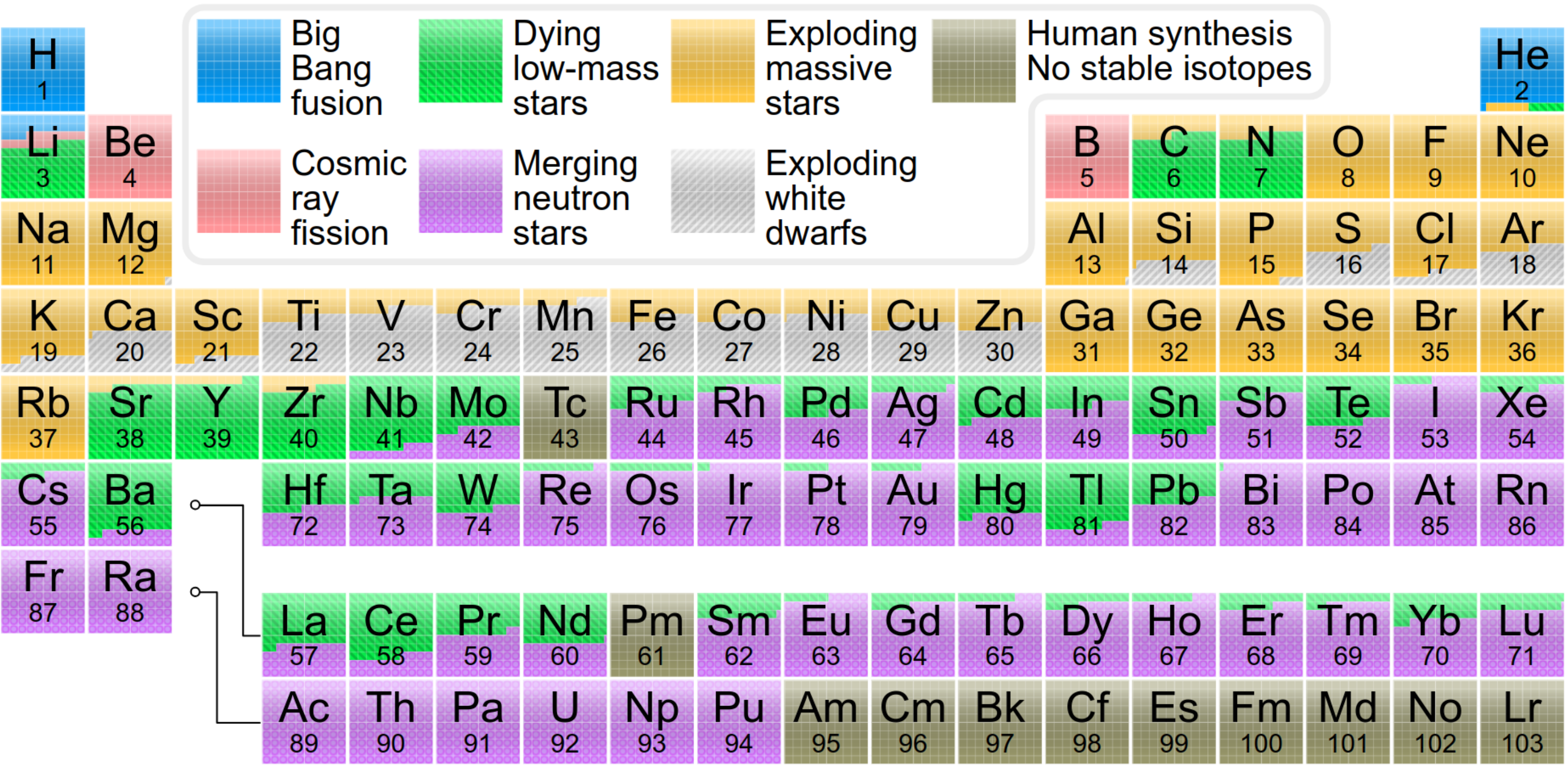
Taken from

ORNL website

Waiting Points 40 sec after peak:

^{72}Kr, $^{75,76}Sr$, $^{79,80,81}Zr$, ^{84}Mo, ^{88}Ru, ^{92}Pd

Which Stars Are We Made Of?



https://en.wikipedia.org/wiki/File:Nucleosynthesis_periodic_table.svg

Adverts for recent work

- Main & weak s processes:

Large grid of massive star models + weak s proc (Frischknecht+2016, MNRAS):

Nugrid: set 1 (Pignatari+2016, ApJ), set1extension (Ritter+in 2018),

s process with new convective boundary mixing (CBM): (Battino+ ApJ 2016)

- Nuclear uncertainties: MC-based sensitivity studies for gamma-process (Rauscher+2016, MNRAS), weak s process (Nishimura+2017, MNRAS), main s process (Cescutti+in prep)

- Stellar uncertainties:

Multi-D tests of convection (Cristini+ 2017, MNRAS) and rotation (Edelmann+2017, A&A)

- Reviews/book chapters: Springer Handbook of Supernovae

"Pre-supernova Evolution and Nucleosynthesis in Massive Stars and Their Stellar Wind Contribution" (doi:10.1007/978-3-319-20794-0_82-1)

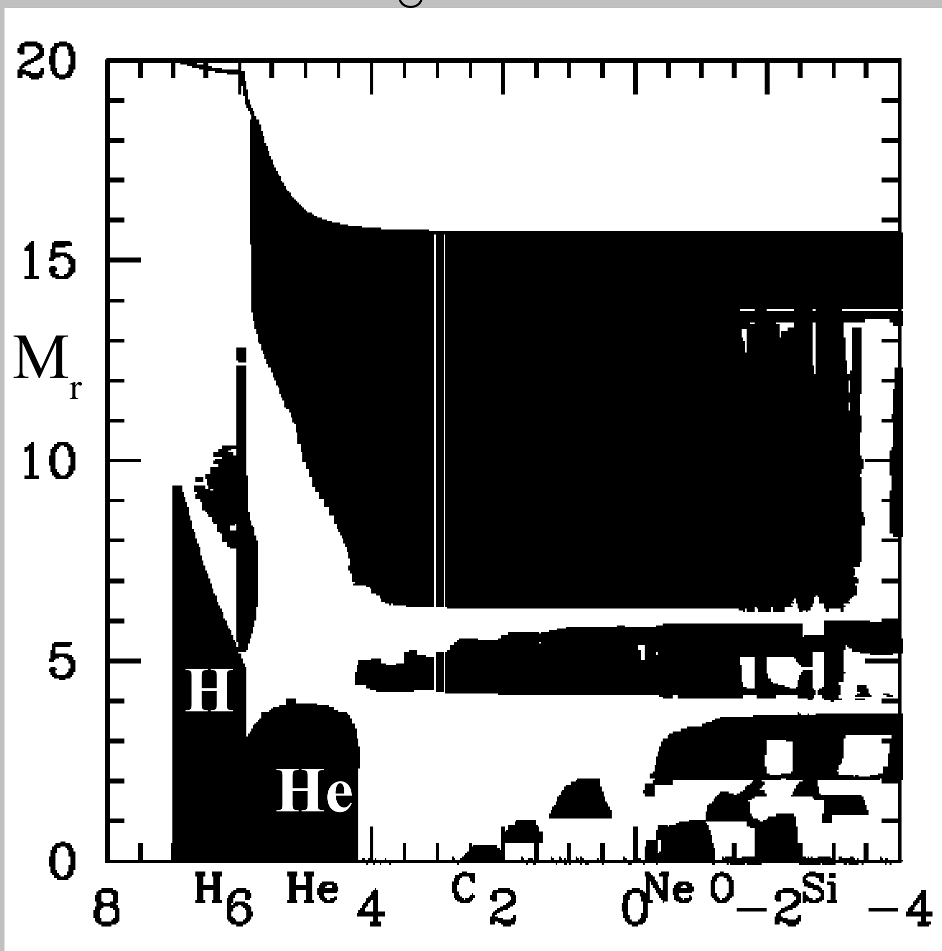
"Very Massive and Supermassive Stars: Evolution and Fate" (doi:10.1007/978-3-319-20794-0_120-1)

- ChETEC COST Action started in April 2017: see www.chetec.eu for details

The Evolution of VMS

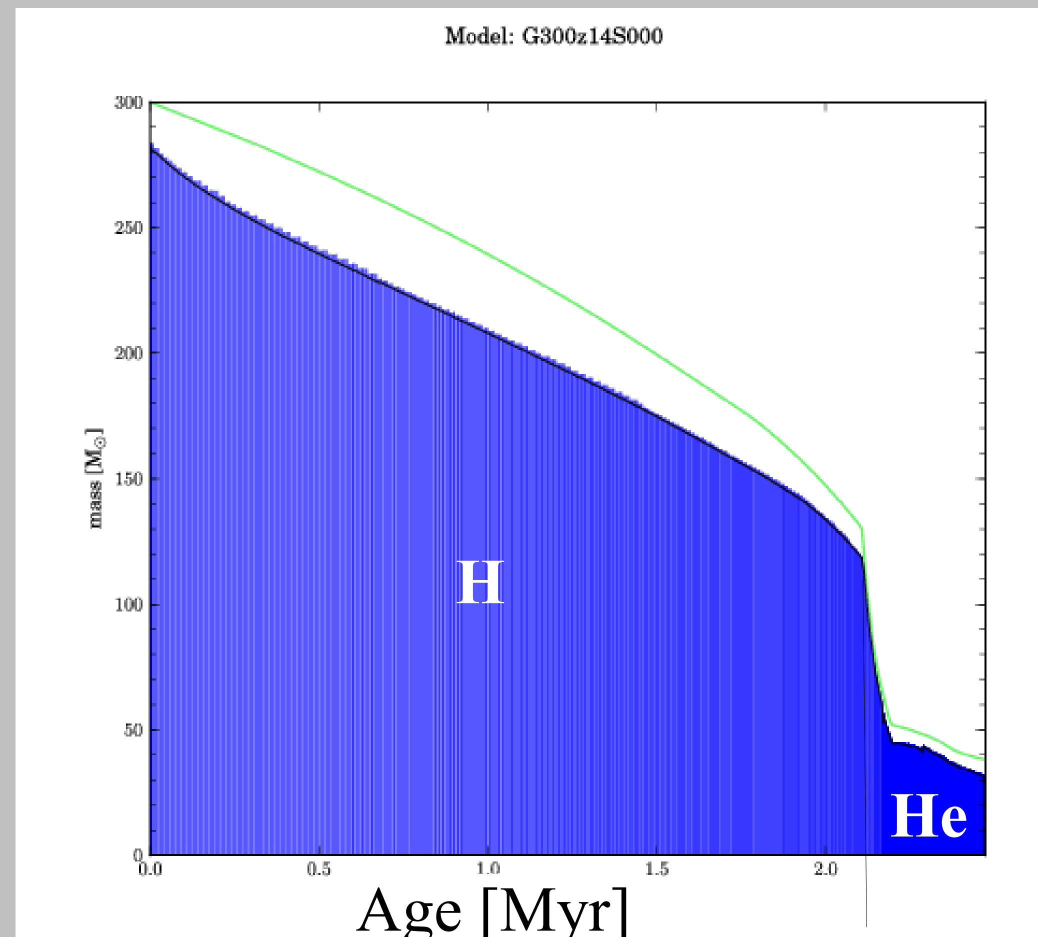
VMS = Very Massive Stars for M > 100 $M_\odot$

20 $M_\odot$



Log10(Time left until collapse)

300 $M_\odot$



(Yusof et al 13 MNRAS, aph1305.2099)

VMS: much larger convective core & mass loss!

The fate of VMS: PCSN/BH/CCSN?

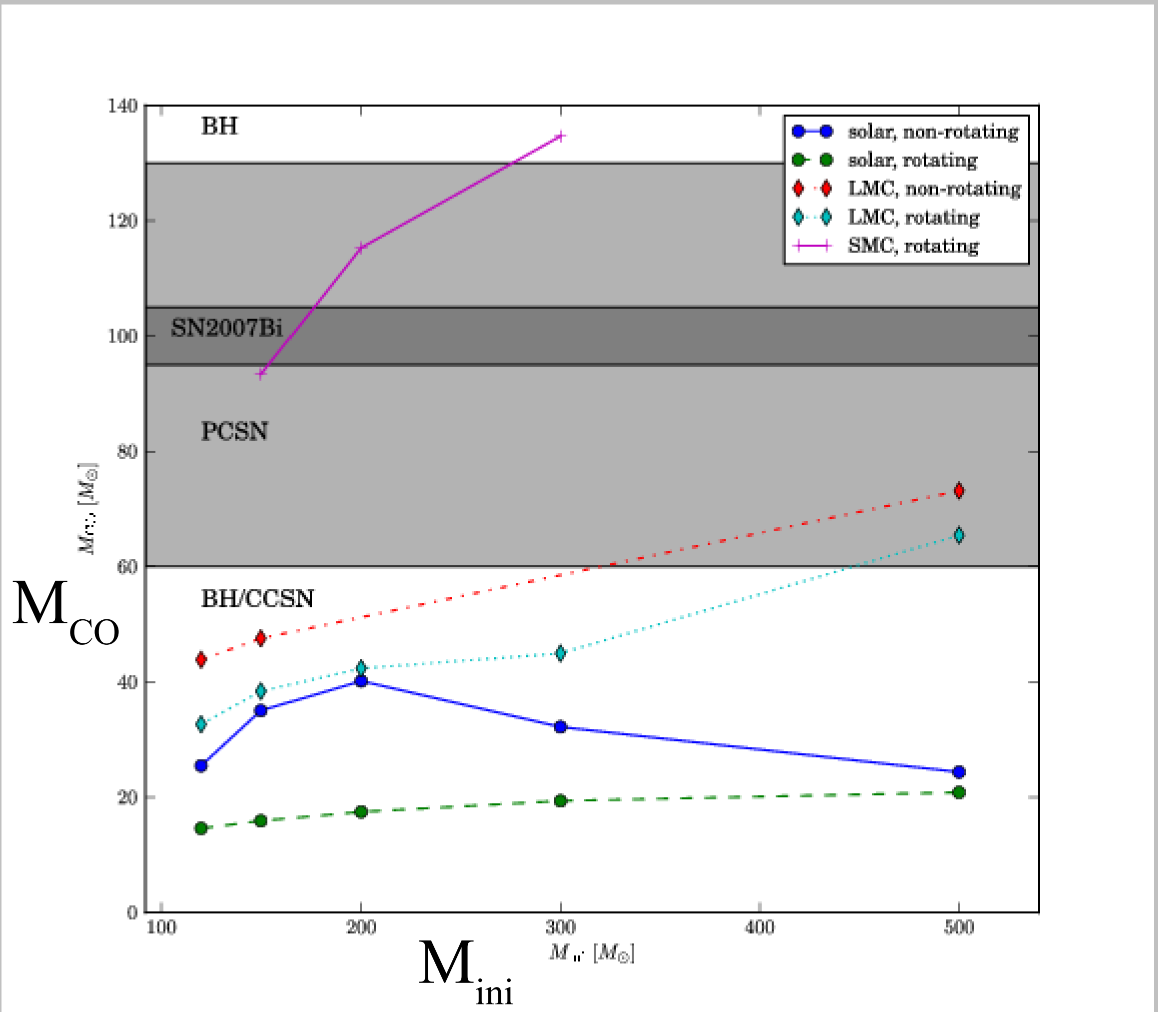
(Yusof et al 13 MNRAS, aph1305.2099)

Z_{solar}: no PCSN

(Rotating) models with Z<Z(LMC) lose less mass,

and enter the PCSN instability region!

BUT mass loss uncertain!



PCSN range from Heger & Woosley (2002)

Consistent with Langer et al (2007): PCSN for $Z<Z_{\odot}/3$

Main S Process: C13-pocket

Kaeppeler, et al, 2011, RvMP, 83, 157, ...

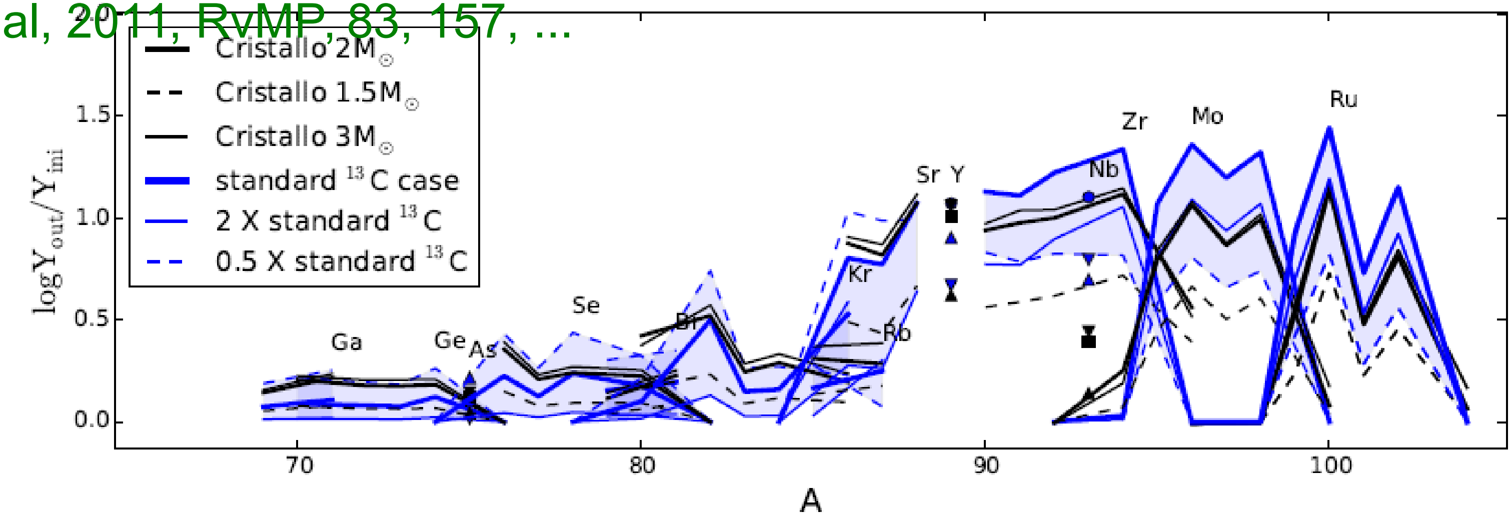
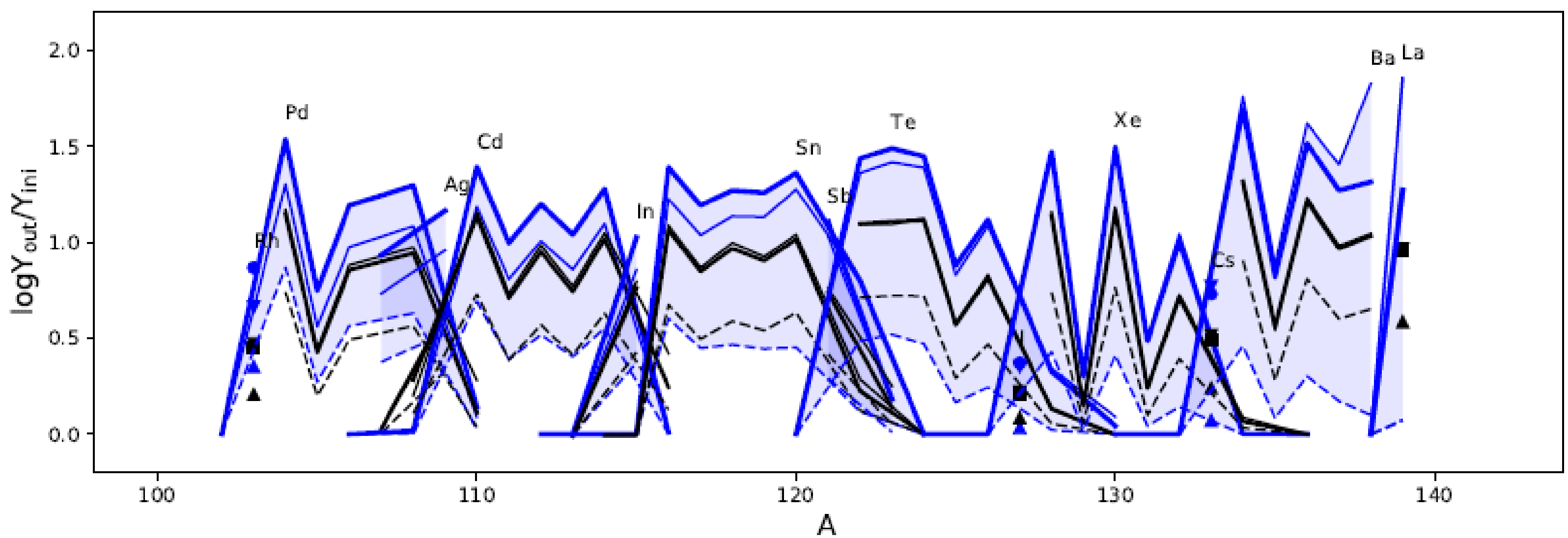
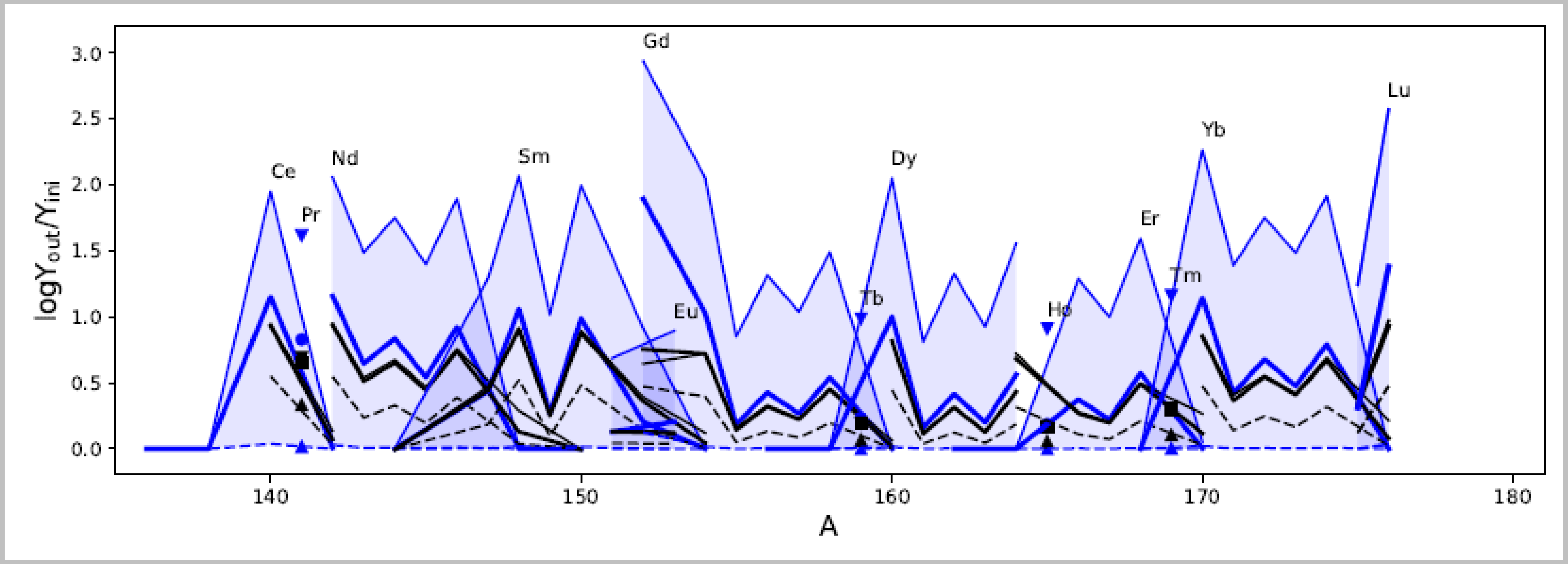
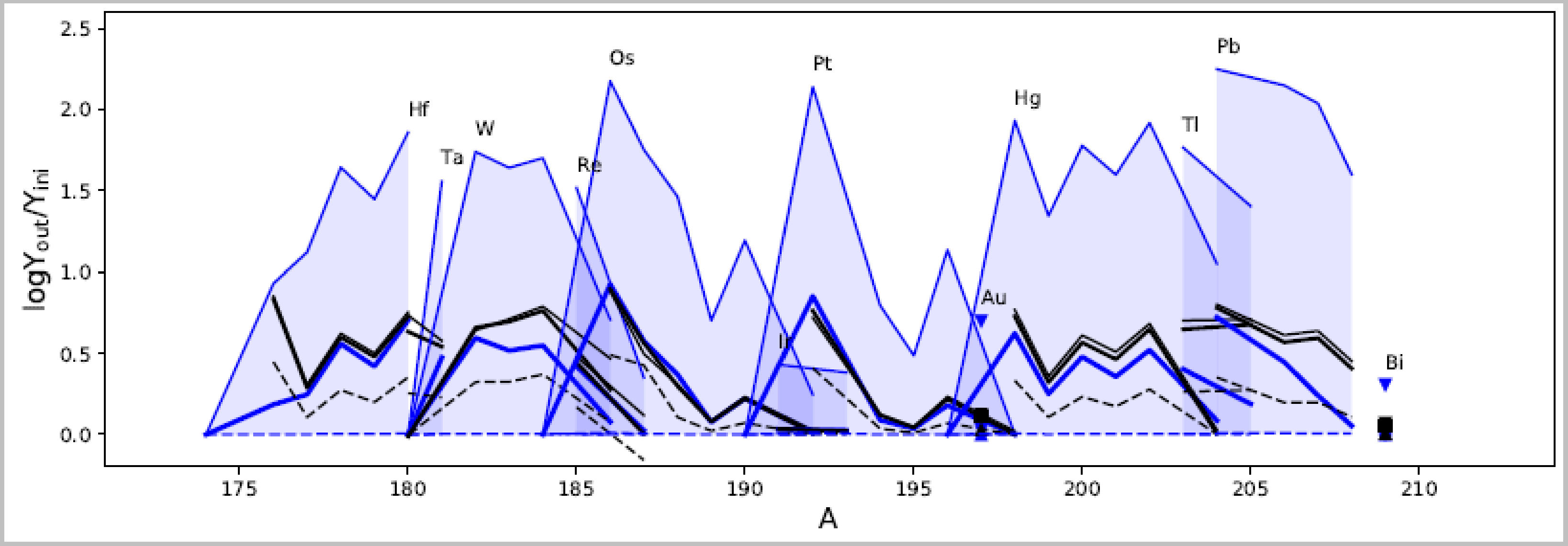


Figure 3. Production factors as a function of the atomic mass for elements from Ga to Ru during the ^{13}C pocket. Comparison between the results obtained for a 1.5 (dashed black line - black triangle for monoisotopic elements), 2 (thick solid black line - black square) and 3 $M_{\odot}$ (thin solid black line - upside down black triangle) by C11 and the trajectory considered in this study with the 3 different initial abundance for ^{13}C: standard case (thick solid blue line - blue dot), half (dashed blue line - blue triangle) and double (thin solid blue line - upside down blue triangle) the standard case. The blue area highlights the range of s-process production obtained using the three cases for the initial ^{13}C abundance. Note that we applied a dilution factor, f, to our results to compare them to production factors of C11 (see eq. 2.1.1).



Main S Process: C13-pocket





Main S Process: TP