Stellar Nucleosynthesis

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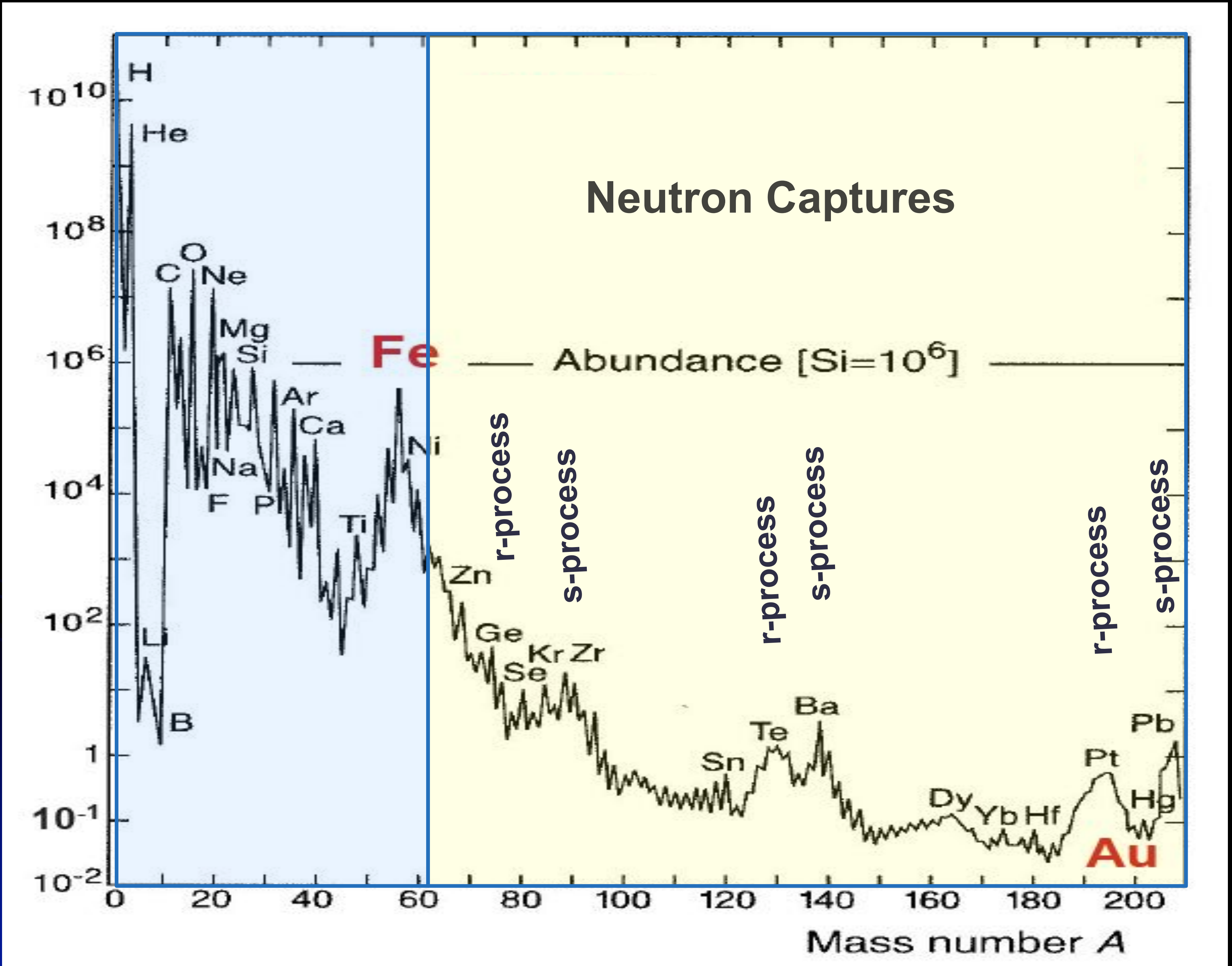
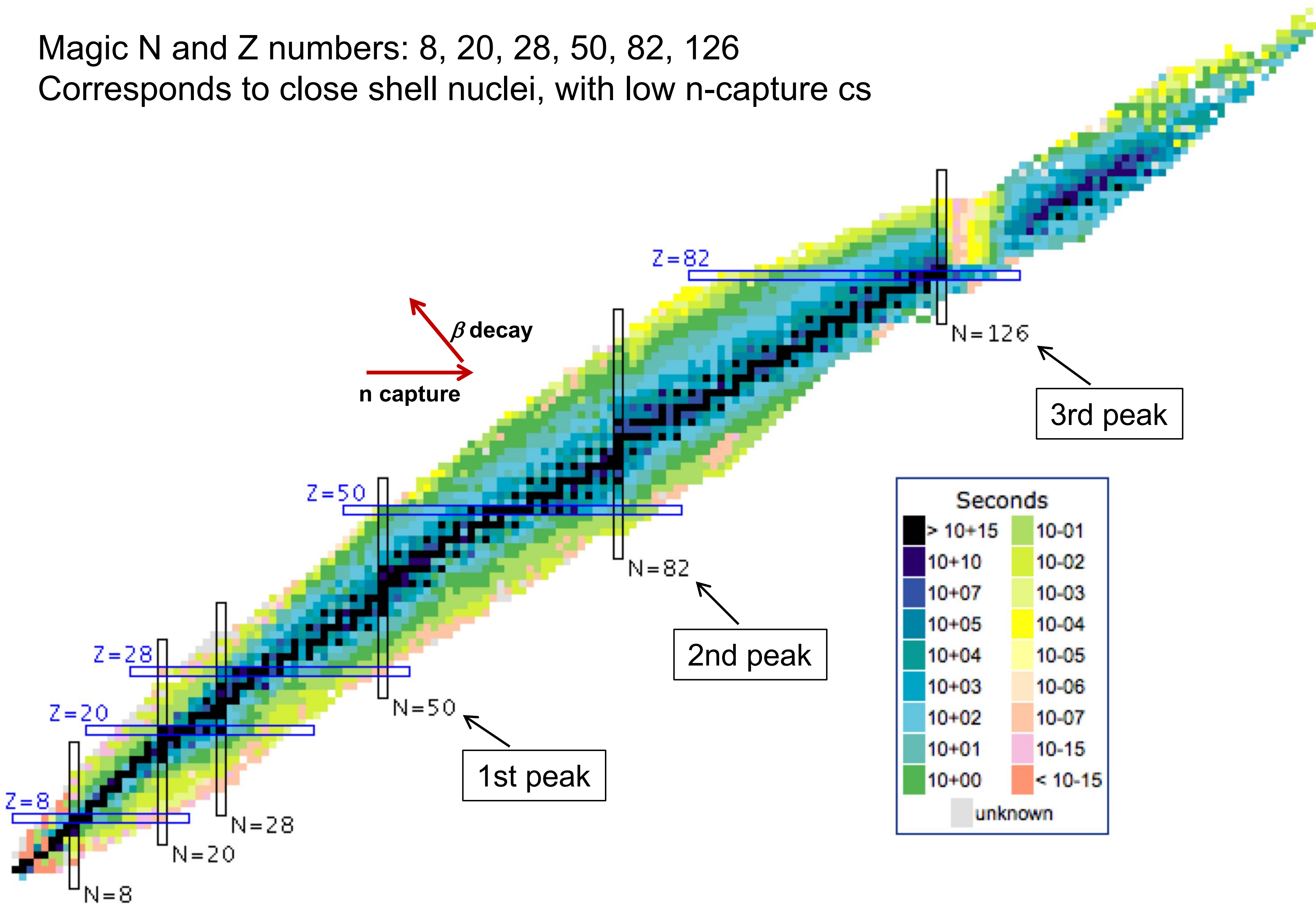


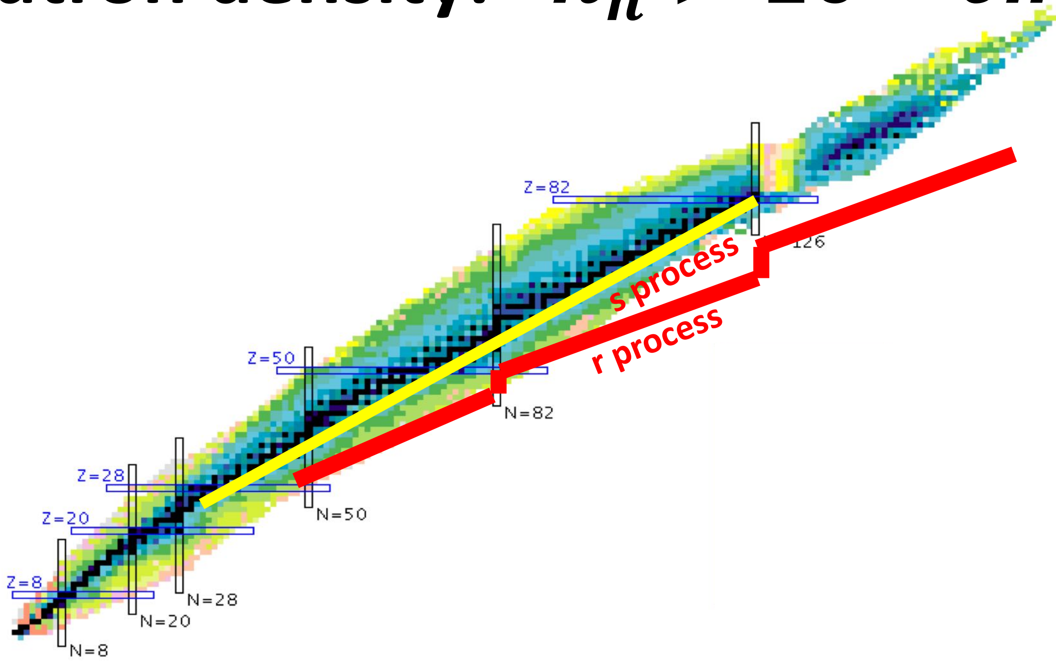
Neutron Captures
Abundance [Si=10^6]
Fe
Au
r-process
s-process
r-process
s-process
r-process
s-process
H
He
Li
B
C
O
Ne
Mg
Si
Na
F
P
Ar
Ca
Ti
Ni
Zn
Ge
Se
Kr Zr
Sn
Te
Ba
Dy
Yb Hf
Pt
Hg
Pb
Mass number A

Magic N and Z numbers: 8, 20, 28, 50, 82, 126
Corresponds to close shell nuclei, with low n-capture cs

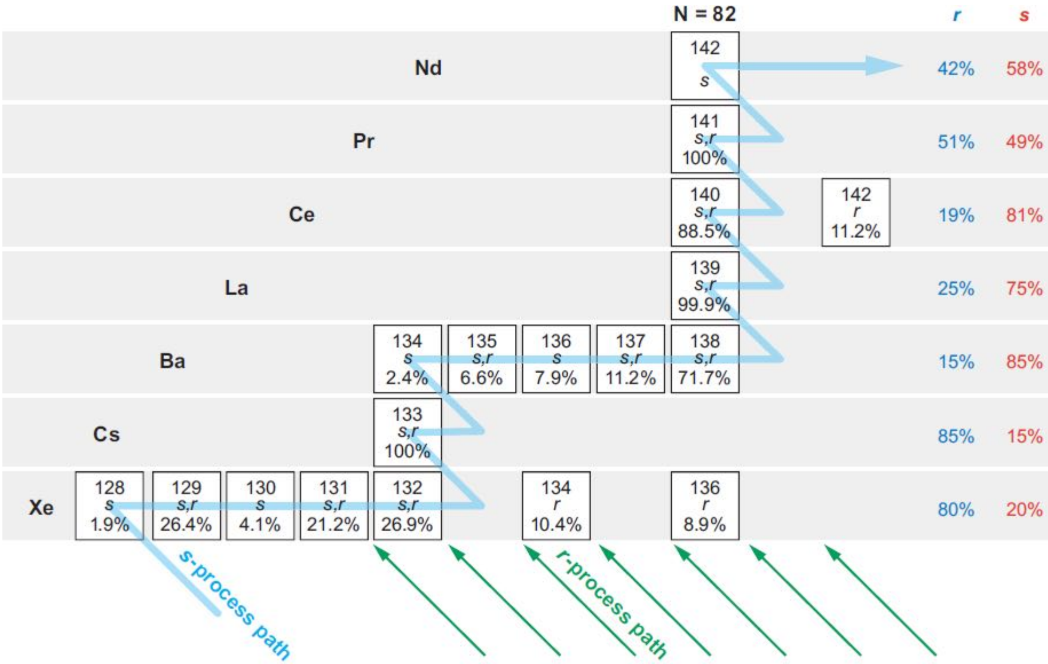


s process, always close to the β-stability line. It implies low neutron density: $n_n \approx 10^7\ cm^{-3}$

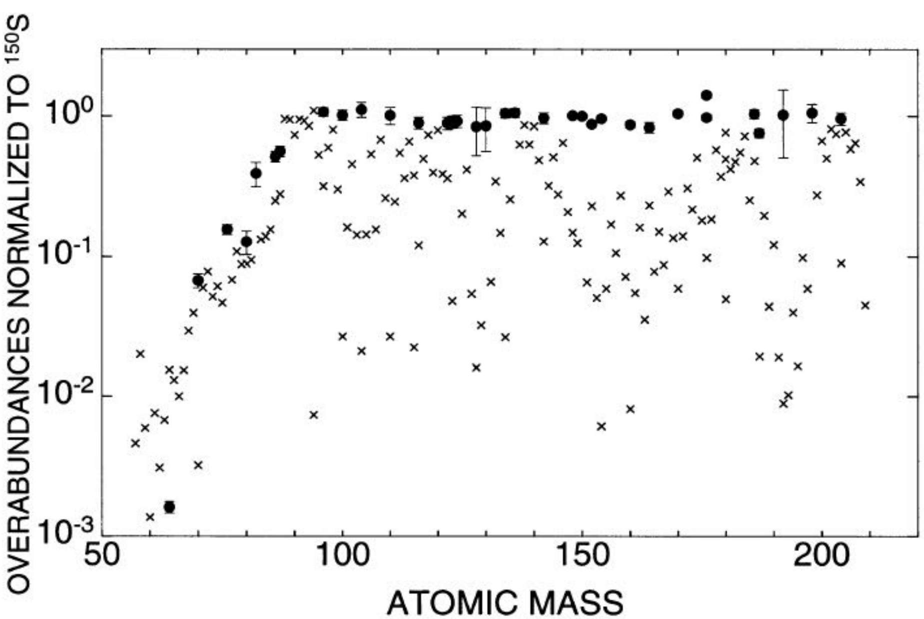
r process, involves nuclei far from the stability and close to the neutron drip line. It implies higher neutron density: $n_n > 10^{20}\ cm^{-3}$



*** It has been recently speculated about the existence of an i-process (intermediate) for which $n_n \approx 10^{15}\ cm^{-3}$ (late thermal pulses in post-AGB stars).**



s,r-only nuclei



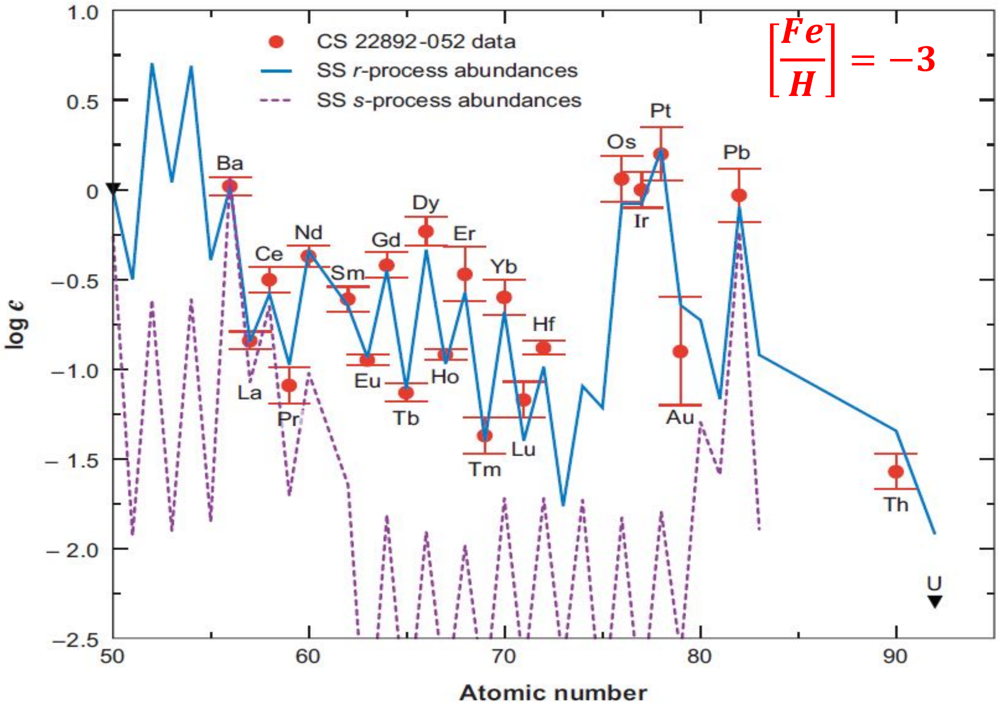
Arlandini et al. 1999, Bisterzo et al. 2014

$$overabundance = \frac{x_{s\ process}}{x_{\odot}}$$

ov = 1 for the s-only isotopes (filled circles). Fr the others (crosses), the r-process abundances can be obtained by subtracting the s-process contribution.:

$$\frac{x_{r\ process}}{x_{\odot}} = 1 - \frac{x_{s\ process}}{x_{\odot}}$$

Sneden et al. 2008

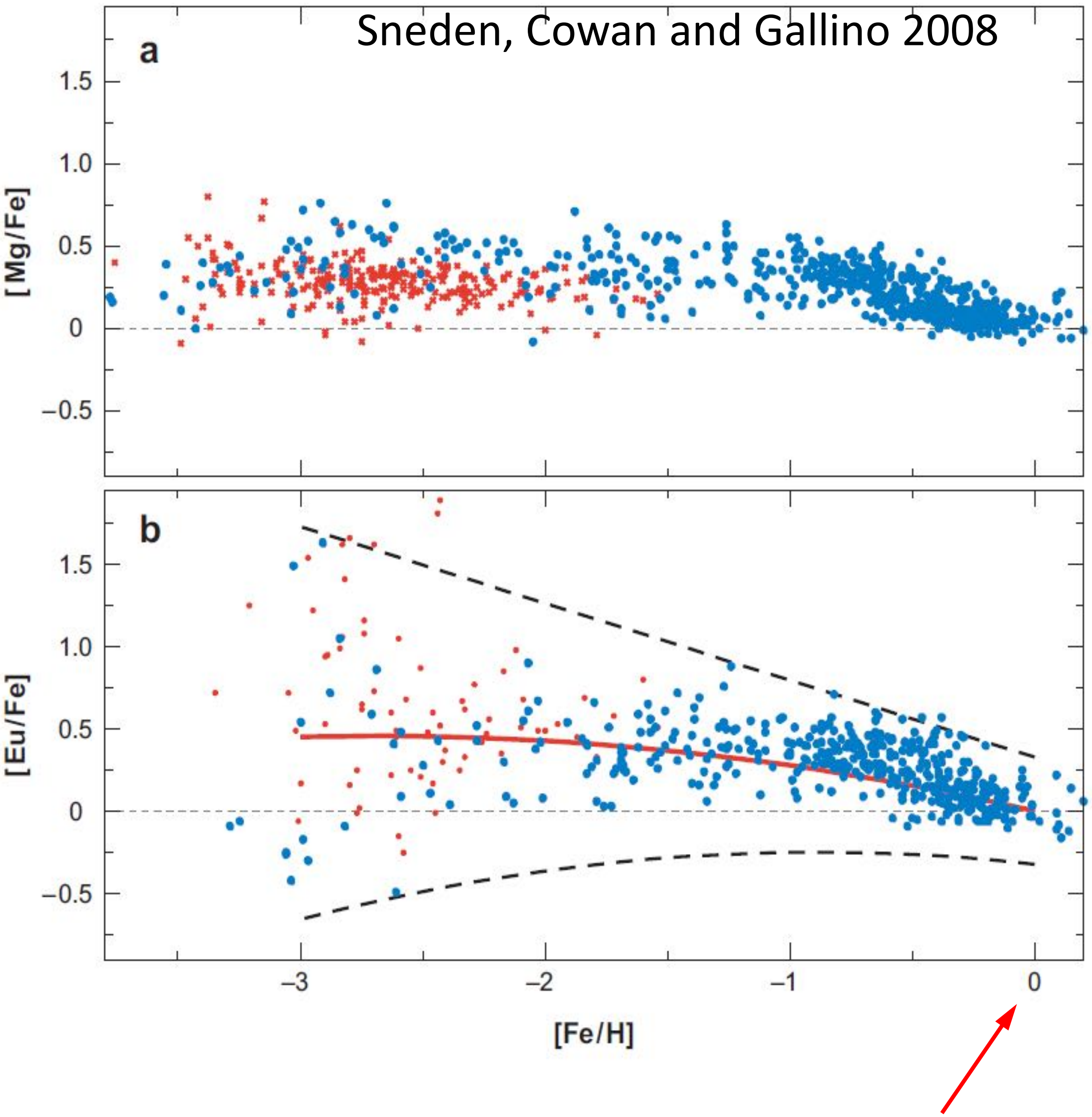


r-process pollution is found everywhere, since the most metal poor stars. No variation with metallicity (for A>13). The polluters lifetime must be very short → CCSNe or BNS. The smoking gun was sGRB, GRB130603B, (Melandri et al. 2013) for which the HST (Tanvir et al. 2013; Berger et al. 2013) detected a nIR point source, 9 days after the burst: the associated Knova.

In contrast, no s-process pollution in halo stars*. The polluters must have a relatively long lifetime (more than 1 Gyr) → low-mass stars. Indeed, there are clear evidences that the source of the main component are Asymptotic Giant Branch stars (AGB) with mass between 1.5 and 3. The smoking gun was the detection of Technetium (^{99}Tc half life 2x10^{5} yr) in the spectra of M, S and C giants (Merrill 1952).

* exceptions are CEMPs and a few Globular Clusters, in both cases the origin of the s-process is a self-pollution, (see Straniero et al. 2014)!

Galactic evolution: r process

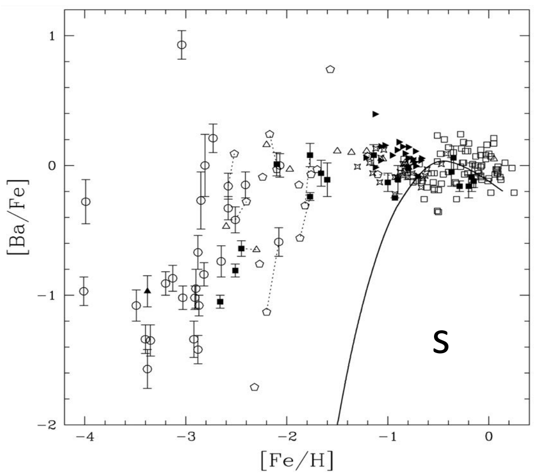


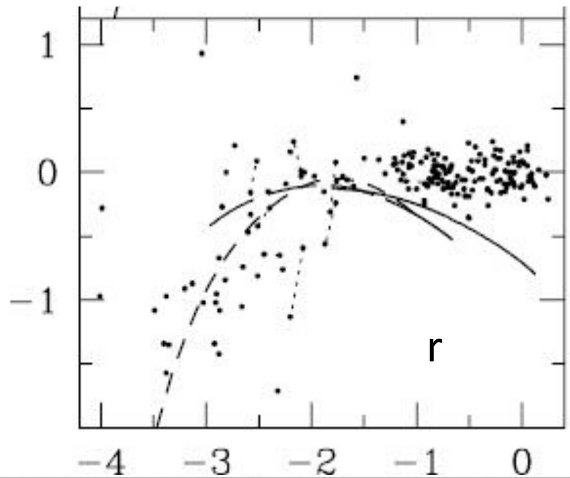
- [Ba/Fe] similar to [α/Fe] and α elements are from CCSNe.
- However, larger spread for [Eu/Fe]. Evidence for a low event rate (lower than that of normal CCSNe), but high r-process yields.
- Current paradigm: the main sources of the r process are NS-NS or NS-BH mergers.
- However, it has been argue that the coalescence timescale is not so short (10^8 yr). Possible contribution of a peculiar class of CCSNe at low metallicity (e.g., explosion driven by huge magnetic field).

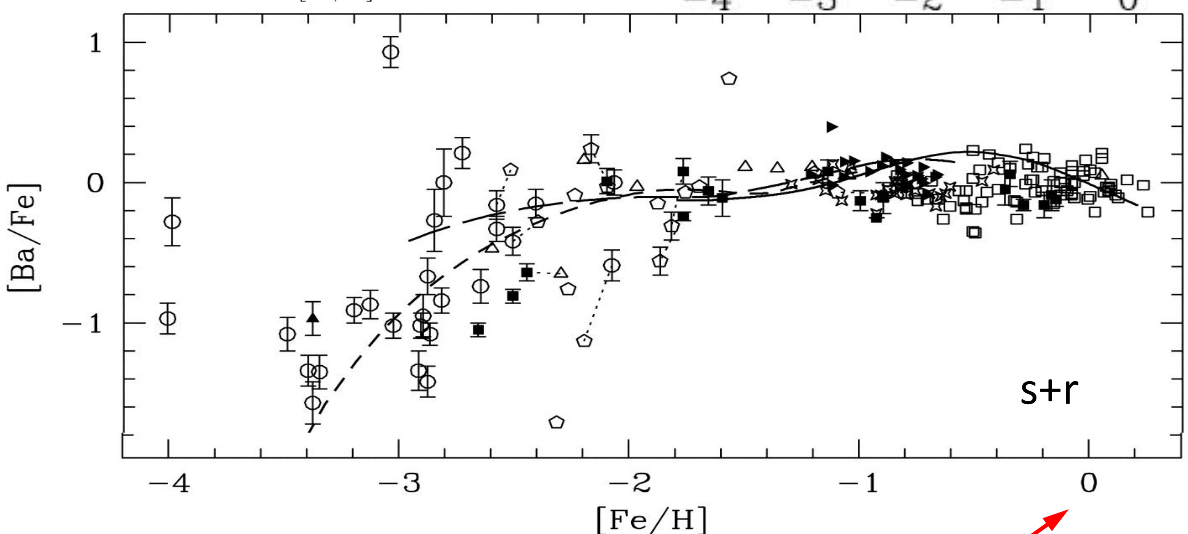
Eu in the Solar System, Eu 92% r process 8% s process.

Galactic evolution: s process

Lines are GCE models from Travaglio et al. 2001:
Halo (dashed), Thick Disk (long-dashed), Thin Disk (solid)







- **[Ba/Fe] nearly solar in the Galactic Disk ([Fe/H]>-1.5).**
- **[Ba/Fe] deficiency in halo stars ([Fe/H]<-1.5)**
- **Current paradigm: in the Disk, Ba produced by s-process in low mass AGB stars (1.5<M<3).**
- **In the Halo, Ba from r process.**

Ba in the Solar System, 15% r process and 85% s process.

The 3 components of the s process

- **WEAK: 30<Z<38**

  astrophysical site: MASSIVE STARS, Core-He burning (marginal),
  and shell-C burning (dominant).

  neutron source: $^{22}Ne(\alpha,n)^{25}Mg$ *

* ***^{22}Ne is secondary, the process depends on the initial C+N+O.***

- **MAIN (38<Z<80)**

  astrophysical site: LOW-MASS AGB STARS, $\mathbf{1.5-2.5}\ \boldsymbol{M_{\odot}}$
  He/C rich mantel.

  neutron source: $^{13}C(\alpha,n)^{16}O$ (dominant), $^{22}Ne(\alpha,n)^{25}Mg$ (marginal)*

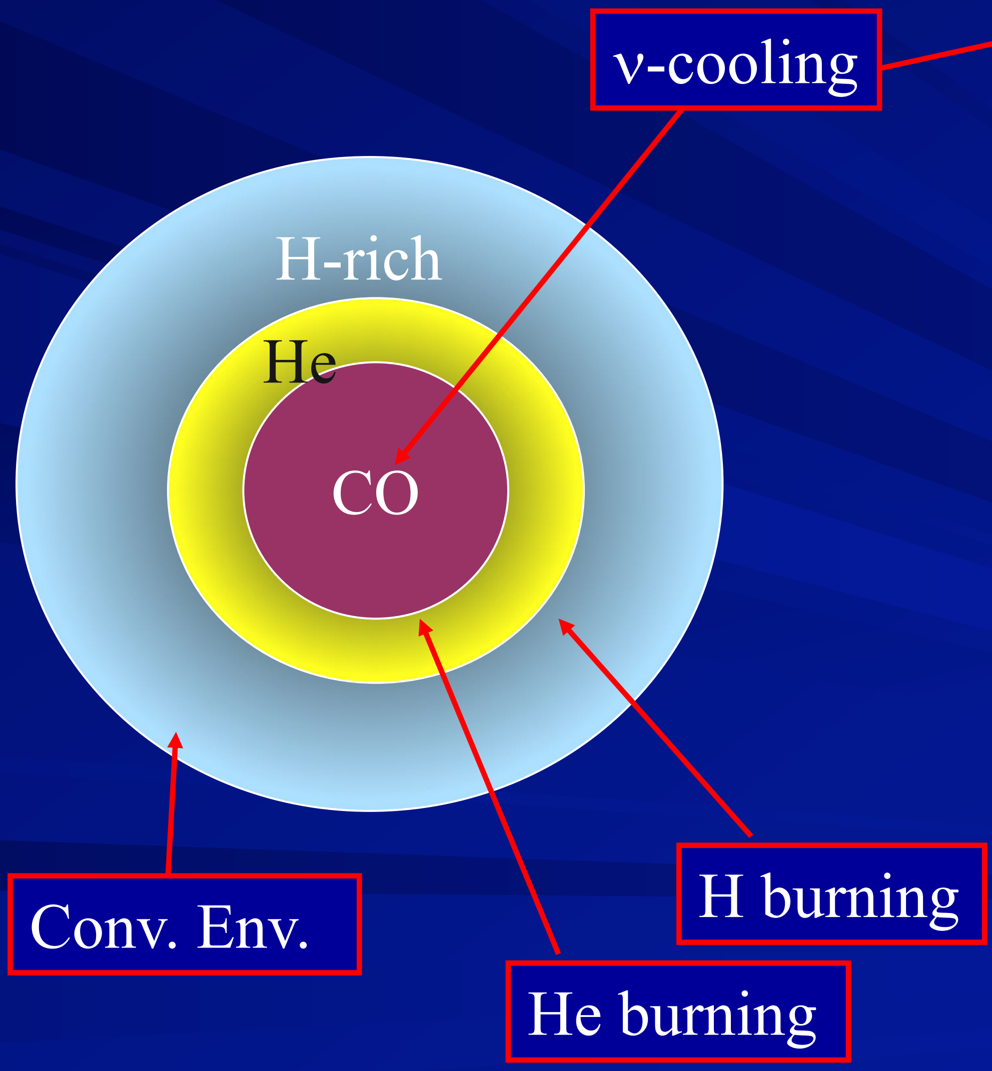
* ***Both ^{13}C and ^{22}Ne are primary, because of the third dredge up, which moves fresh C in the envelope.***

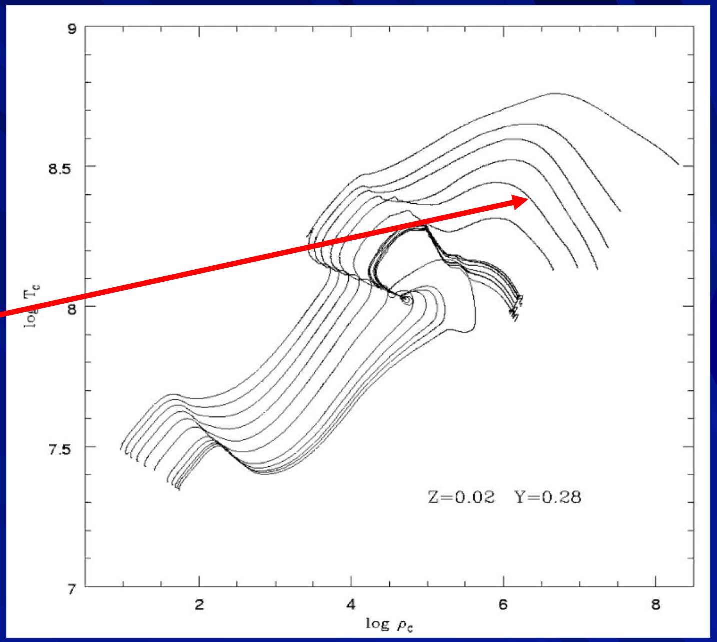
- **STRONG (Pb/Bi).**

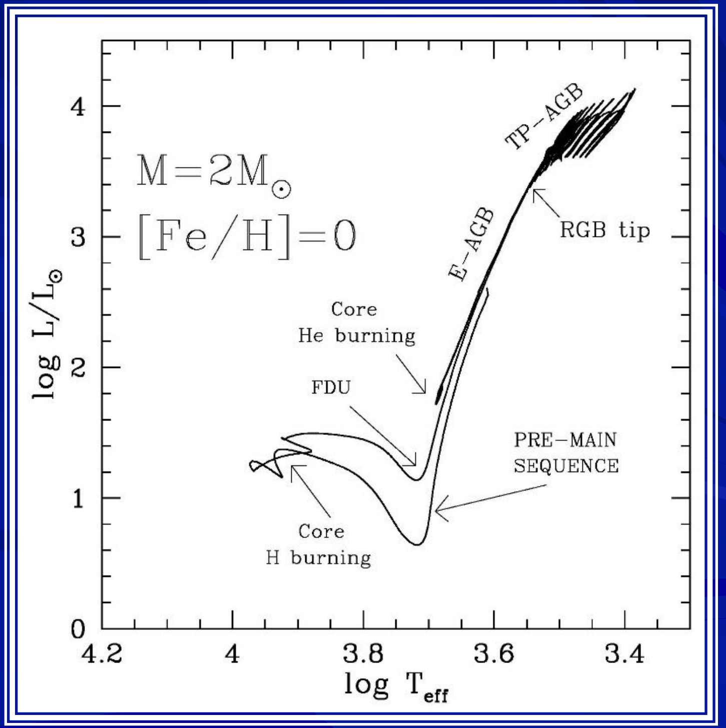
  astrophysical site: LOW-MASS AGB STARS, $\mathbf{1.5-2.5}\ \boldsymbol{M_{\odot}}$, but ***[Fe/H]<-0.6***

s process in low-mass AGB stars

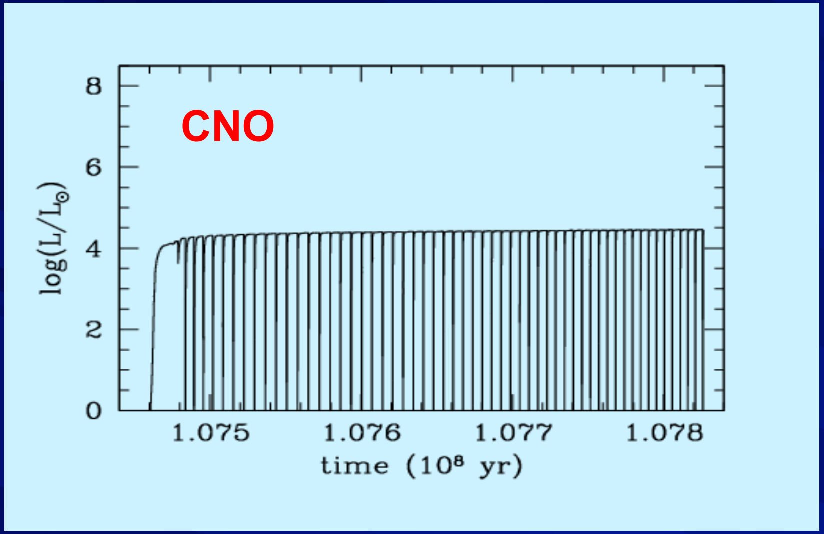
Beyond the core He burning: the AGB

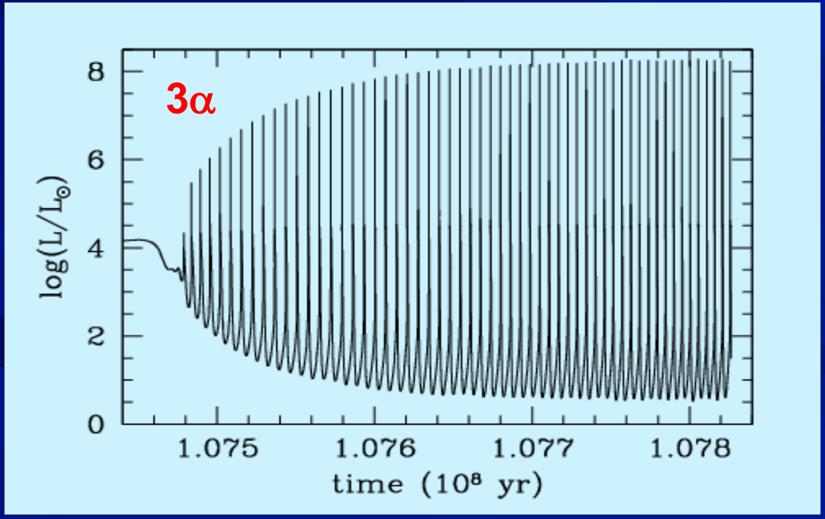


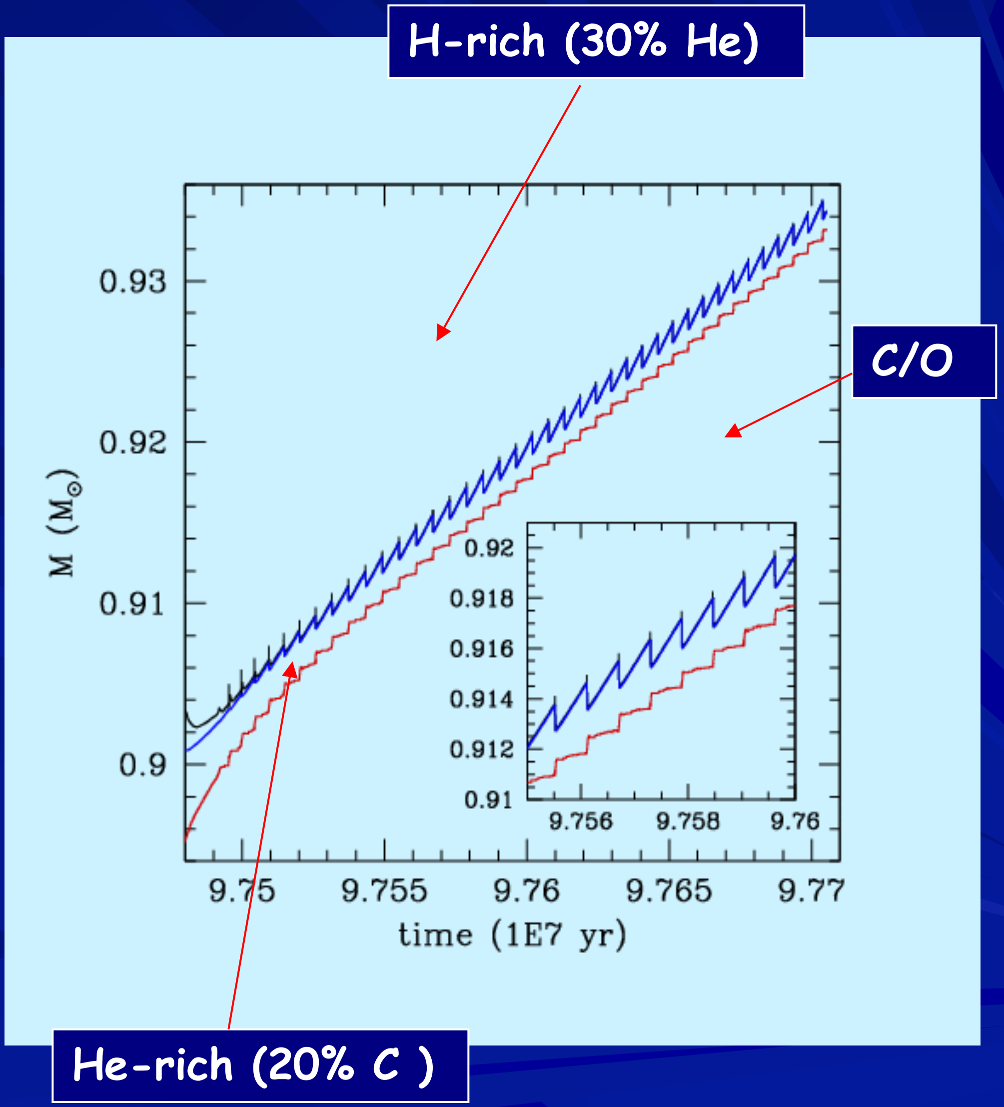




Thermally Pulsing AGB stars

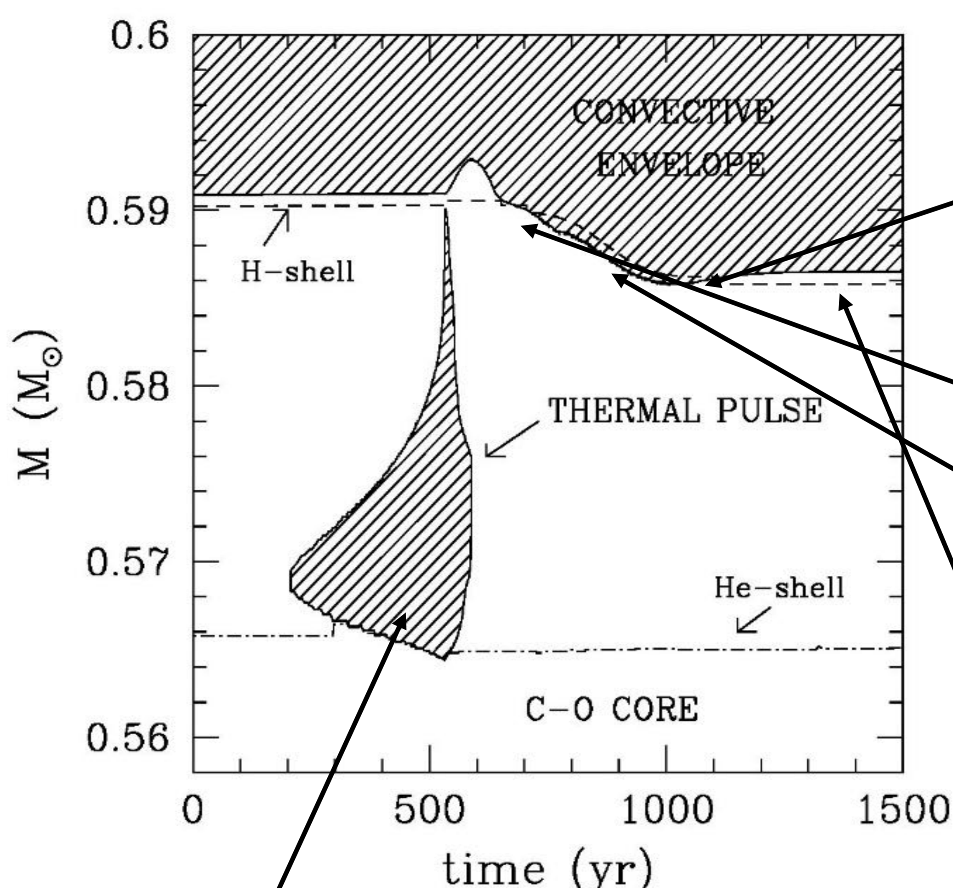






The main s-process site

Straniero et al. 1995, Gallino et al. 1998, Straniero et al. 2006



Receding convection leaves a proton tail in a region where C is enhanced because of the previous mixing due to the thermal pulse.

As a consequence of the He flash, the H-shell expands and cools, until H burning stops

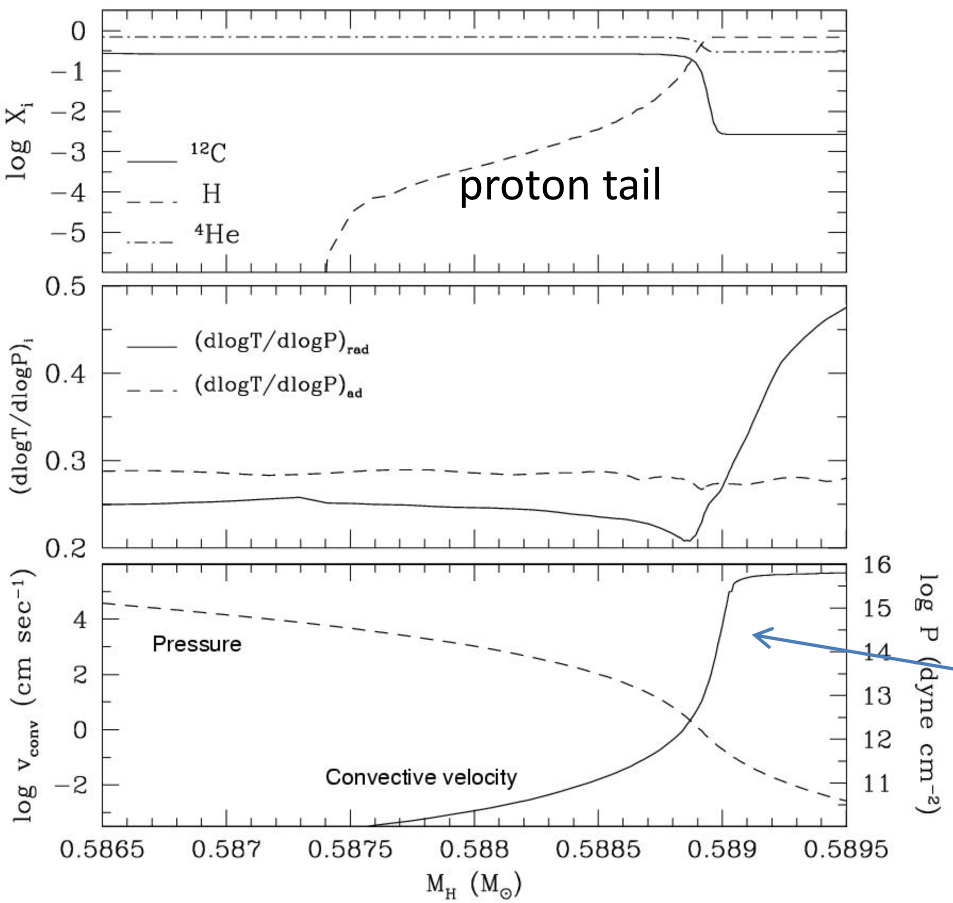
The convective envelope penetrates the H-exhausted core: the Third Dredge Up

When the He burning stops, the H burning rises up and a ^{13}C pocket forms:
$^{12}C(p,\gamma)^{13}N \rightarrow {}^{13}C$

Later on, when T≈90 MK
$^{13}C(\alpha,n)^{16}O \rightarrow$ s process

Eventually, *if T>300 MK: $^{22}Ne(\alpha,n)^{25}Mg$*
Massive AGB only (M>4 $M_\odot$)

When the convective envelope attains the maximum penetration into the H-exhausted core



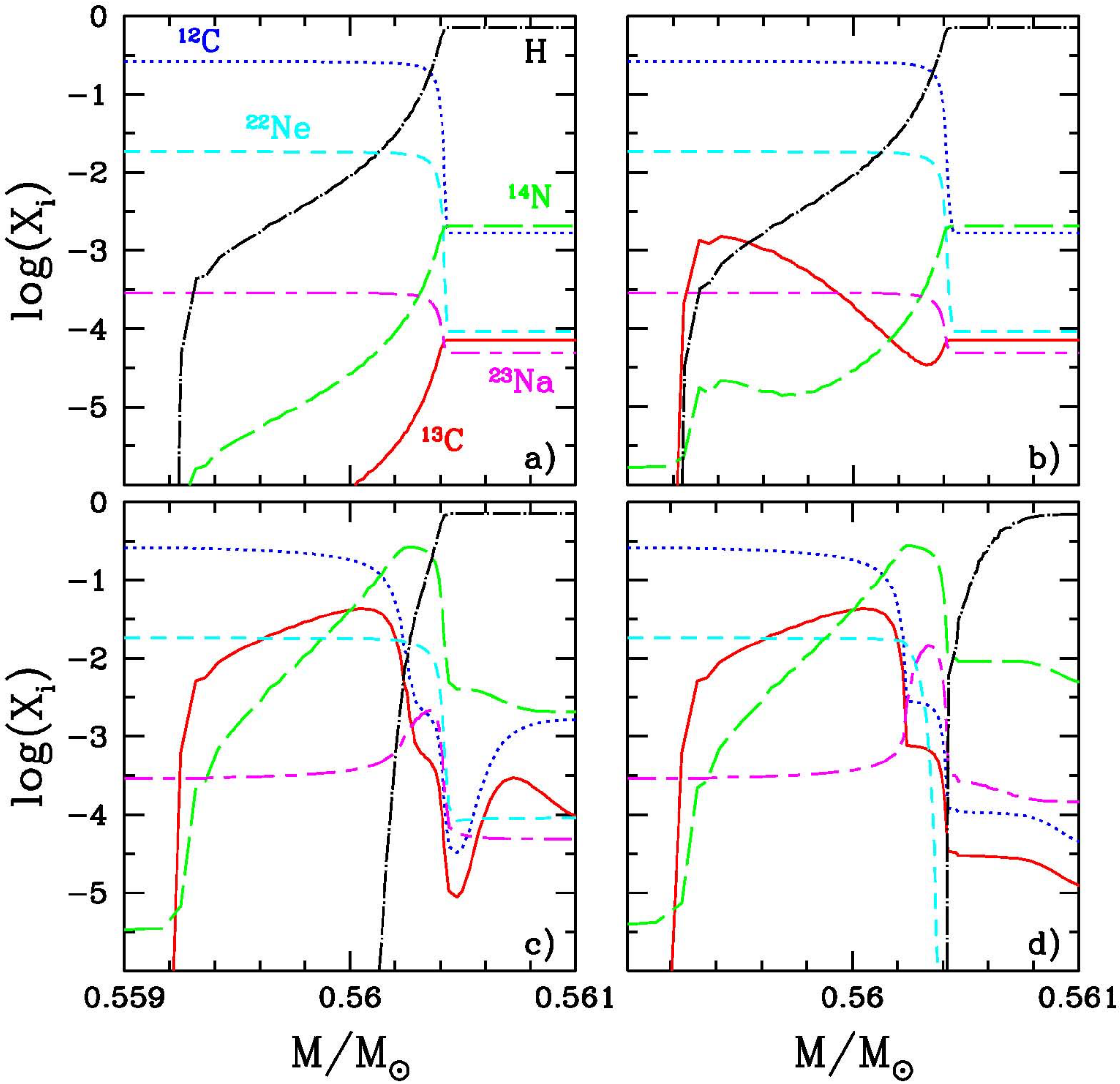
Chemical profiles

Temperature gradient

$$V = V_o \exp\left(-\frac{\delta r}{\beta H_p} \right)$$

Radiative core	Transition zone	Convective envelope

The formation of the ^{13}C pocket.

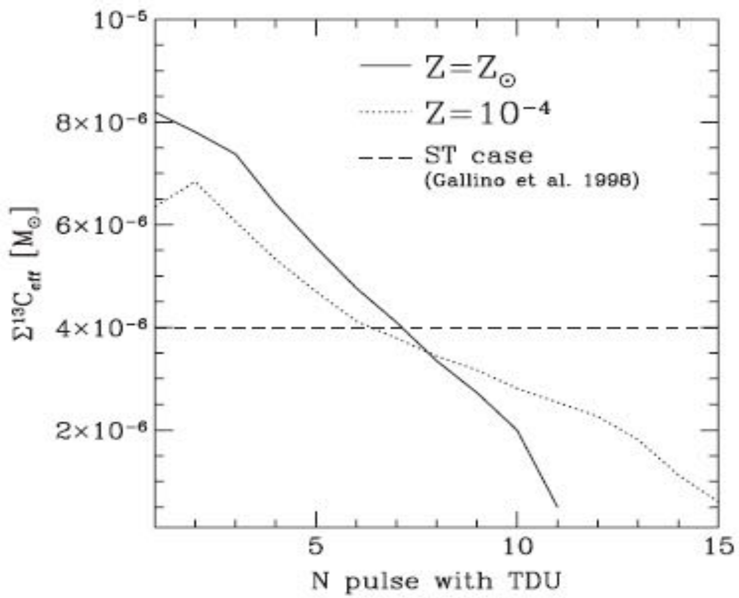


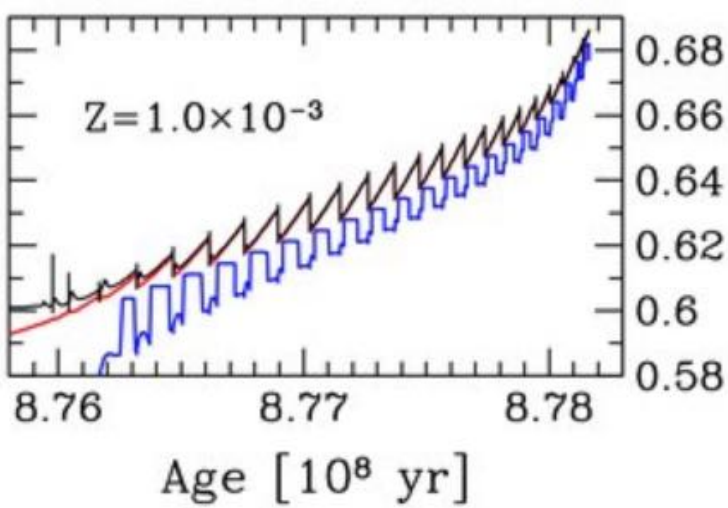
a)
Maximum envelope penetration (TDU);

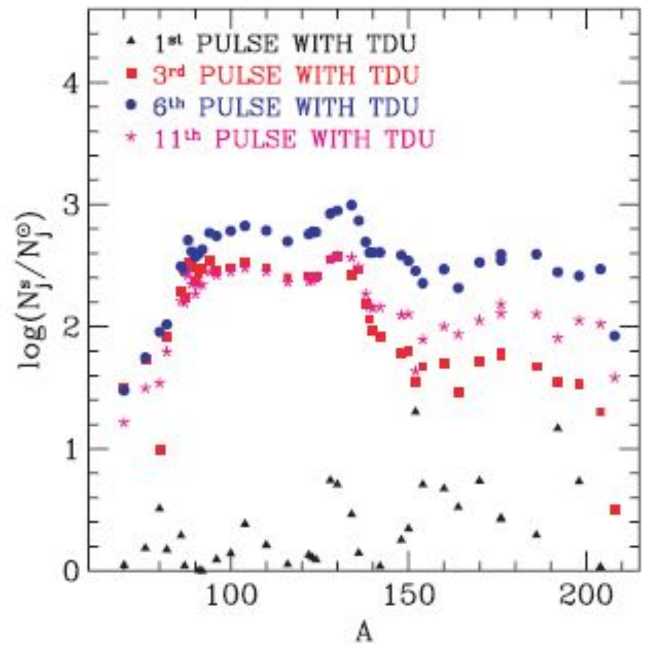
b) & c)
$^{12}C(p,\gamma)^{13}N(\beta^-)^{13}C$ followed by $^{13}C(p,\gamma)^{14}N$;

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

Nucleosynthesis in the He-rich mantel of AGB stars

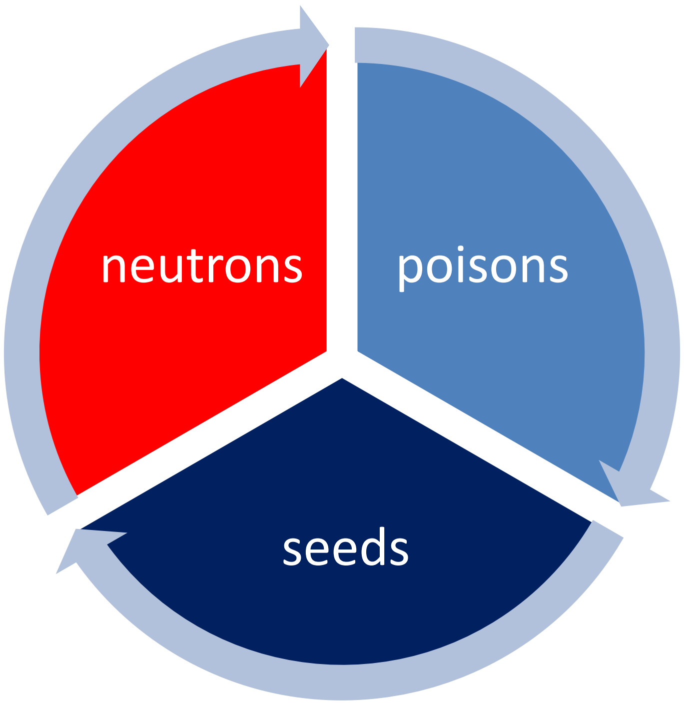


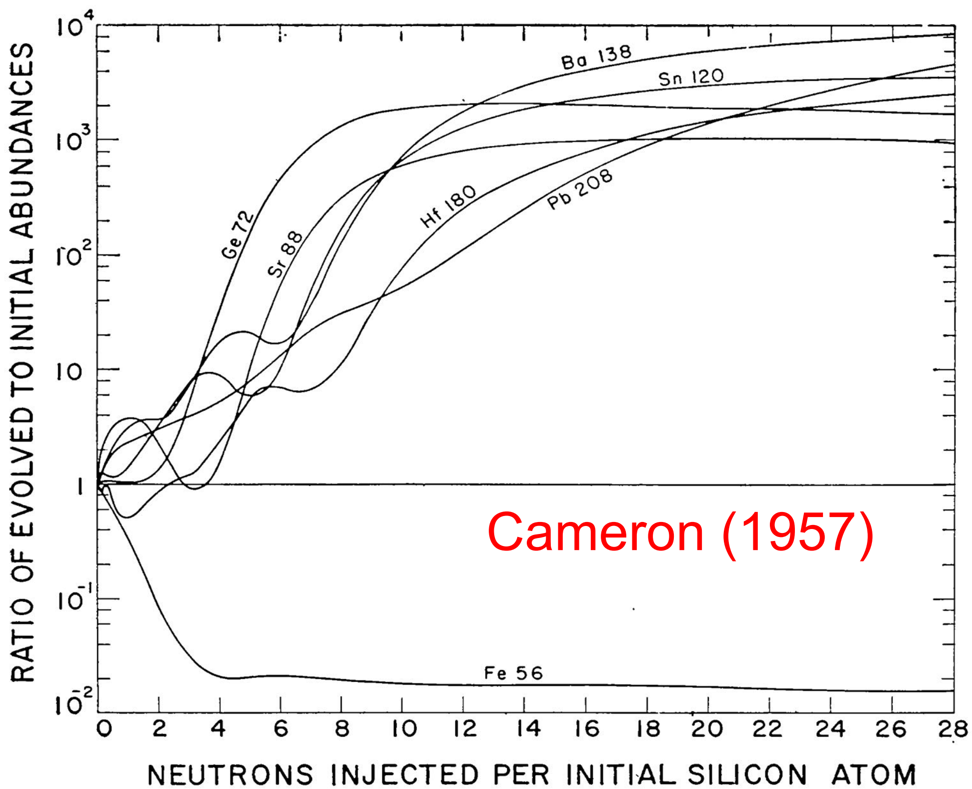




After each TDU, a new ^{13}C pocket forms, and the final s-process yield is the cumulative contribution of all these pockets

The 3 players of the s-process

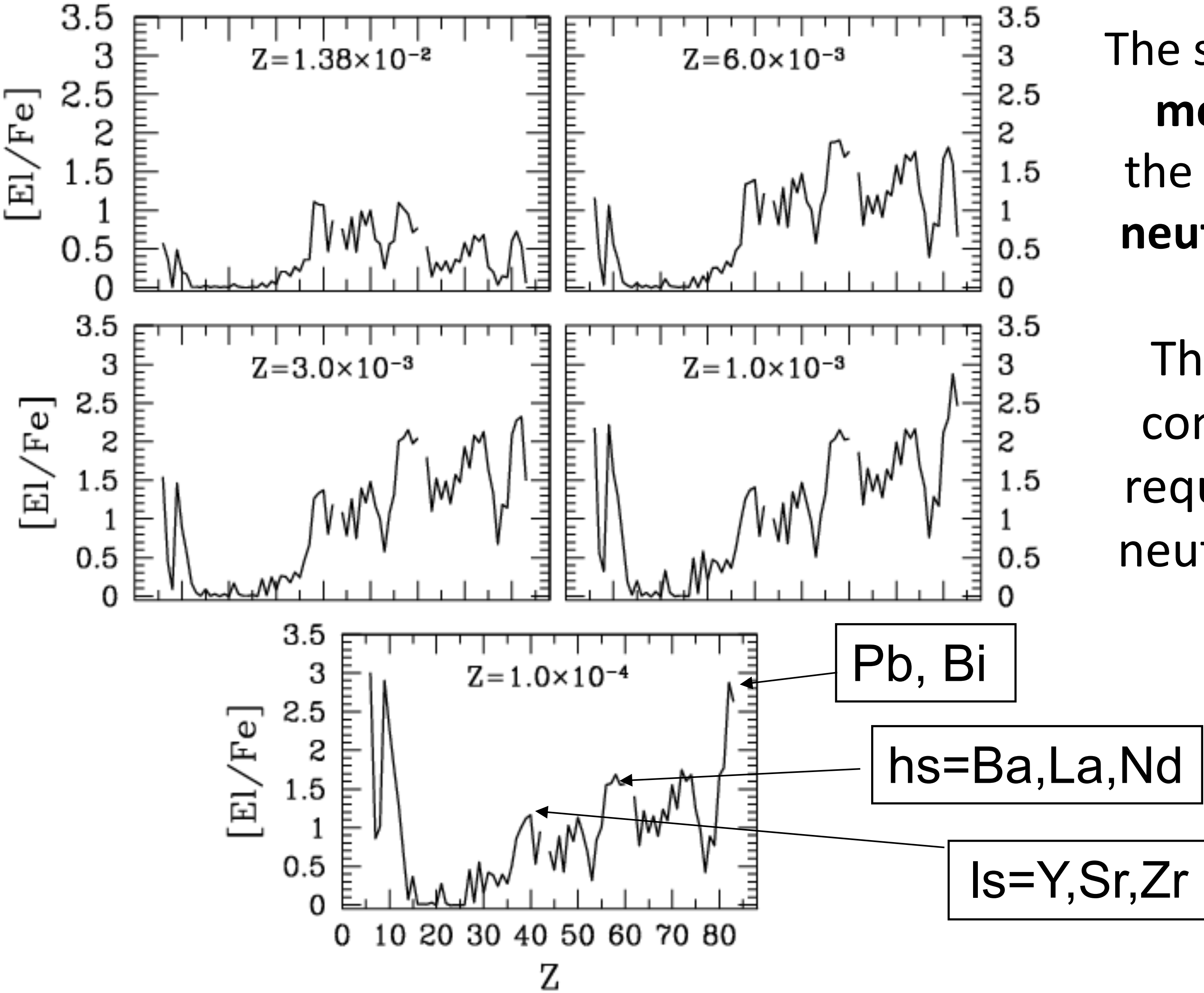




$$\frac{neutrons - poisons}{seeds} = \frac{Y_{13C} - Y_{14N}}{Y_{56Fe}}$$

Ratios of the 3 s-process peaks ls, hs, Pb

FUNS results Cristallo et al. 2009 & 2011: 0.0001<Z<Z$_\odot$



The smaller the **metallicty,** the larger the **neutron/seed**

The strong component requires high neutron/seed

Additional processes….

- Instabilities induced by rotation may modify the H profile left by the third dredge up and, later on, the ^{13}C and the ^{14}N profile into the pocket (Piersanti et al. 2013).
- The bulk motion in the convective envelope generates gravity waves propagating inward . Turbulence may be generated by non-linear effects (Denussenkov 2003) or by interaction with rotation (Talon 2007). The consequent mixing may affect nucleosynthesis and angular momentum transport
- Magnetic field dissipates angular momentum (magnetic breaking, Sujis 2008), but may also induce magnetic buoyancy operating in the He-rich intershell (Trippella et al. 2015).

r process and stellar collapse

The first evidence of heavy elements produced via rapid neutron captures was obtained by analysing data of an American H-bomb test on the Bikini Atoll in 1950.

The connection with stellar explosions immediately became obvious (B^2HF 1957, Cameron 1957)

Basic ingredients for explosive r-process nucleosynthesis

The leading parameters of the r process are:

- The specific entropy, in a radiation dominated environment: $\boldsymbol{S} \propto \boldsymbol{T^3/\rho}$.
- The degree of neutronization, often measured by the electron fraction:

$$Y_e = \sum \frac{x_i}{A_i} Z_i = \sum Y_i Z_i = \frac{1}{1 + \frac{Y_n}{Y_p}}$$

- The timescale $\boldsymbol{\tau}$.

Combinations of $\boldsymbol{S}$ and $\boldsymbol{\tau}$ determine to **neutron-to-seed ratio.**

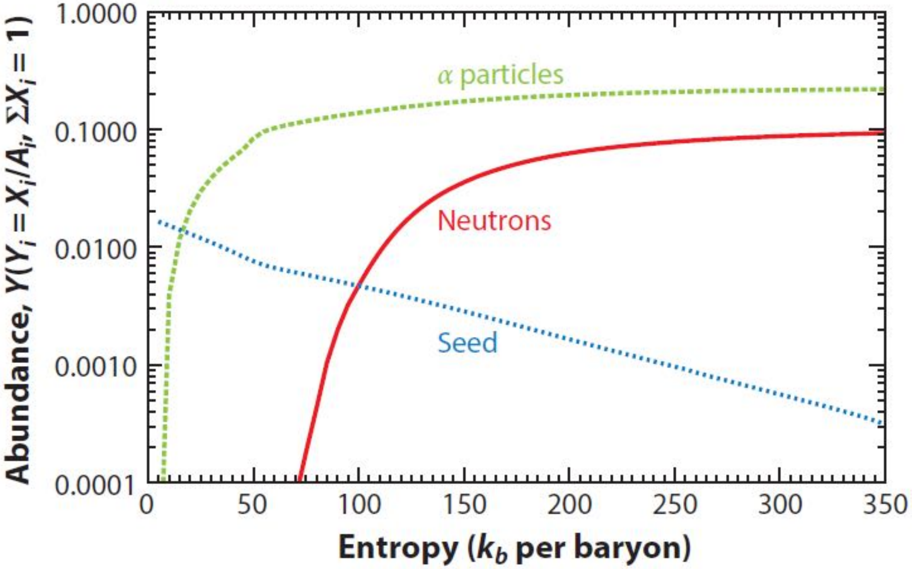
Seeds are relatively heavy nuclei (50<A<90) from which the neutron captures chain stars.

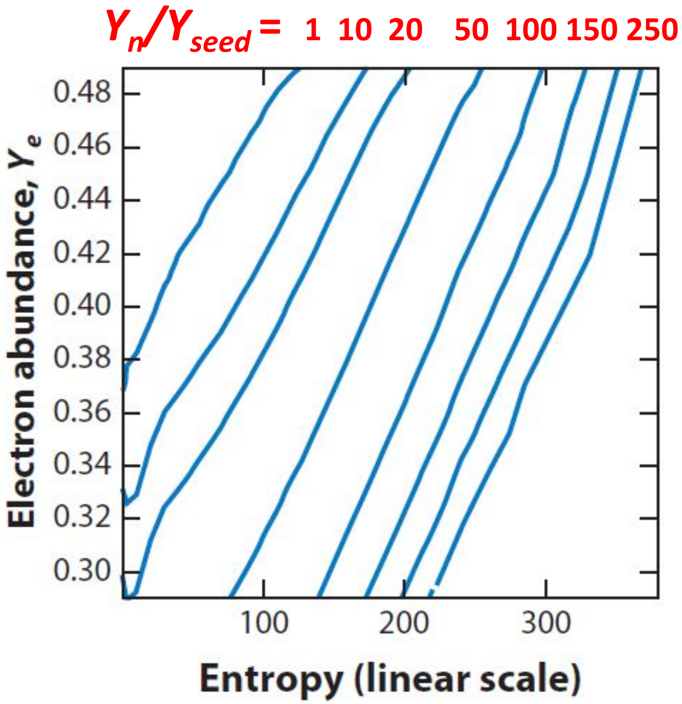
General rule: the larger the $\boldsymbol{\frac{neutron}{seed}}$, the heavier the products of the nucleosynthesis. Transuranian nuclei are produced when $\boldsymbol{\frac{Y_n}{Y_{seed}} > 150}$.

Basic ingredients for the explosive r-process nucleosynthesis

- Initially, **high T** causes nuclei to photo-disintegrate into neutrons, protons, and α particles (NSE).
- Then, matter expands and cools, until charge particles reactions begins to produce heavier isotopes. This process is hampered by the well-known gap of stable nuclei with A=5,8:

  $$\boldsymbol{{}^{4}He + {}^{4}He \leftrightarrow {}^{8}Be + {}^{4}He \rightarrow {}^{12}C}.$$
- Depending on density and timescale, only a little amount of matter can pass through the gap, thus producing heavy seeds. Therefore, **the higher the entropy the lower the amount of seeds.** On the other hand, **the lower the electron fraction the higher the number of neutrons** available for the r-process:





α-rich freeze-out

(from Thielemann et al. 2017)

Large entropy implies high number of neutrons per seeds. Seeds are heavy nuclei with 50<A<90.

After the charge particles freeze-out, only neutron captures remain alive.

Large neutron–to-seed ratio ***(Y_n/Y_{seed} > 150)*** is required to produce a robust r process, which produces second and third peaks, i.e., ***Lanthanides*** and ***Actinides***

$Y_e \approx 0.45 \rightarrow S \geq 300\ K_b$ **per baryon**

In contrast, much lower S is required in case of lower $Y_e \approx 0.10 - 0.30$.

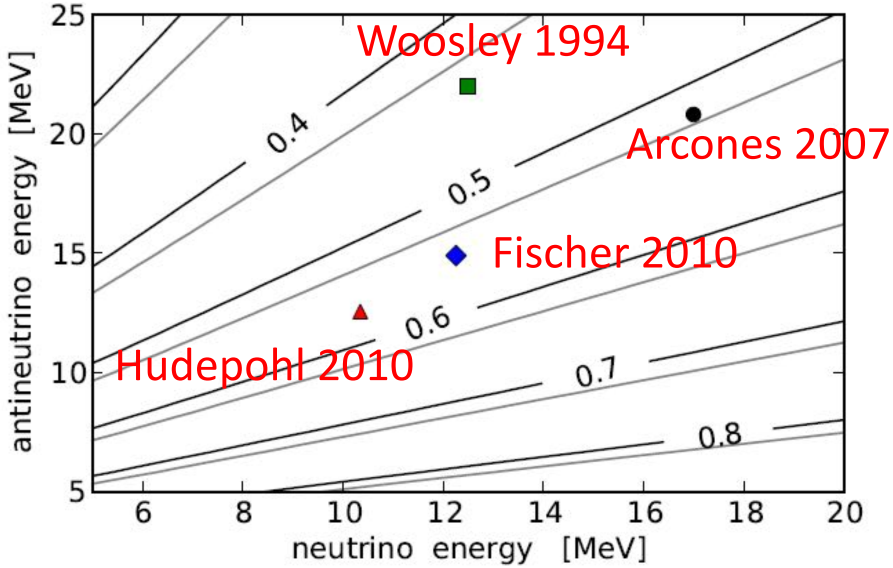
Core-collapse SNe and neutrino wind

- As a result of the deleptonization, about **10^{53} erg** (the released gravitational energy) are **converted into neutrinos**. The **neutrinosphere** is the region from where neutrinos escape.
- Escaping neutrinos/anti-neutrinos deposit energy at the neutrinosphere mainly via:

$$\nu_e + n \rightarrow p + e^-$$

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

- The injection of energy causes that the outer layers of the proto-neutron star are blown by a so-called **neutrino-driven-wind**.
- Due to the high entropy, the neutrino wind was early considered a promising site for the r-process nucleosynthesis. However a neutron-rich environment is needed ($Y_e < 0.5$).



$$Y_e \approx \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e})}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e})}\right]^{-1}$$

L and ε are the electron neutrino and antineutrino luminosities and mean energies, respectively, while $\Delta = m_n - m_p = 1.293$ MeV (see Arcones et al. 2012). Dots: neutrinos/antineutrinos energies at 10 s after the bounce.

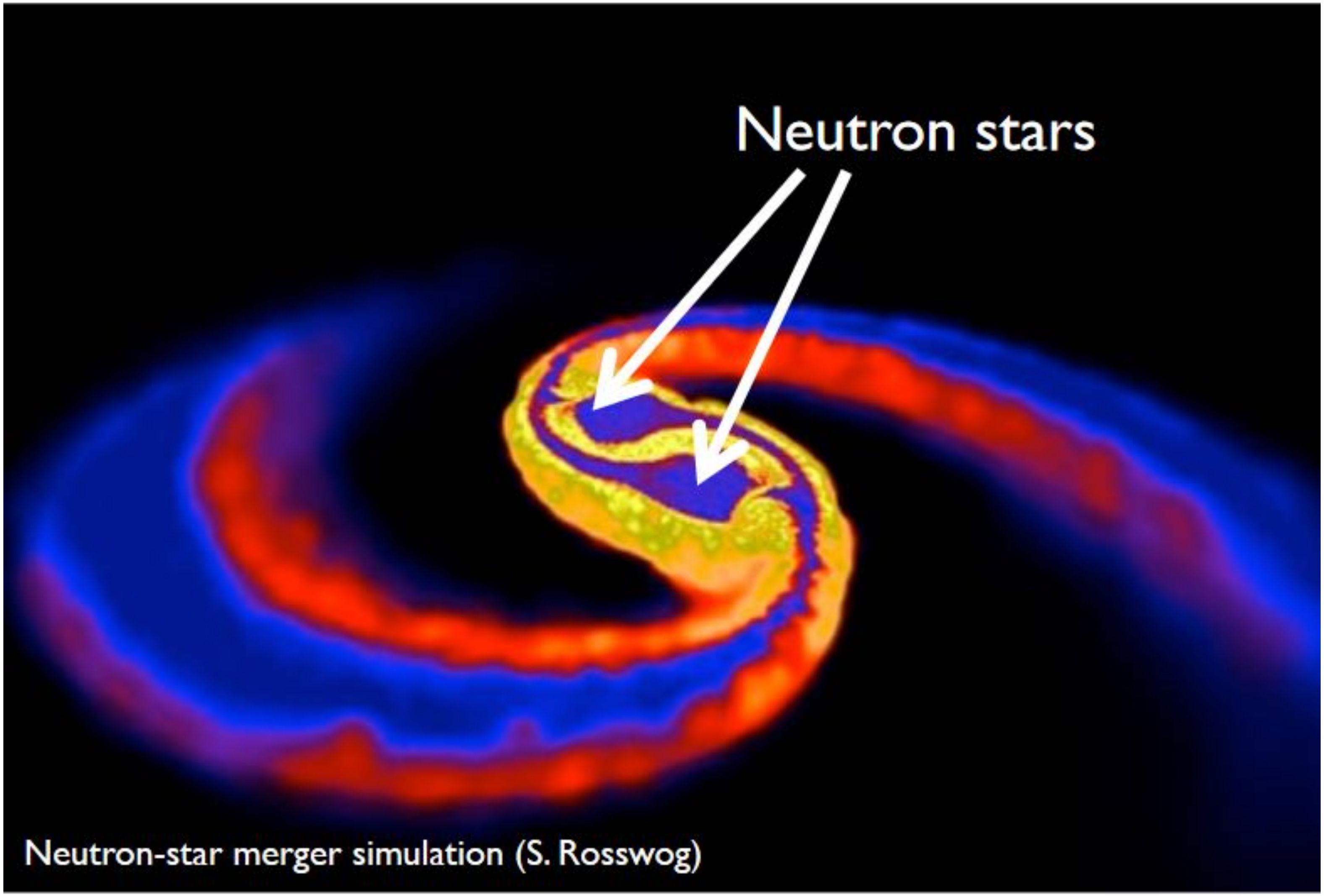
Black and Grey Y_e contours correspond to $\frac{L_{\bar{\nu}}}{L_{\nu}} = 1 \; and \; 1.1$, respectively.

$Y_e \geq 0.5$ is found in more recent models with update microphysics.

CCSN are ruled out as main source of the r-process elements.

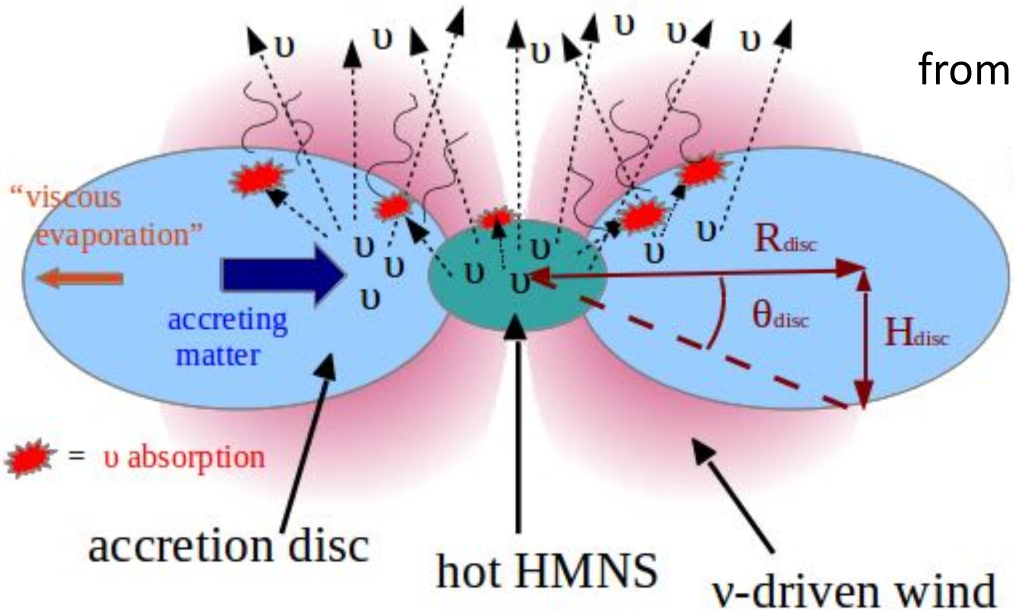
However, it has been argued that in fast-rotating massive stars, undergoing a collapse driven by a strong magnetic field (perhaps progenitors of magnetars, about 1% of the CCSNe) a robust r-process may take place. Possibly, these objects were more frequent at very low metallicity.

Binary Mergers: NS-NS or NS-BH

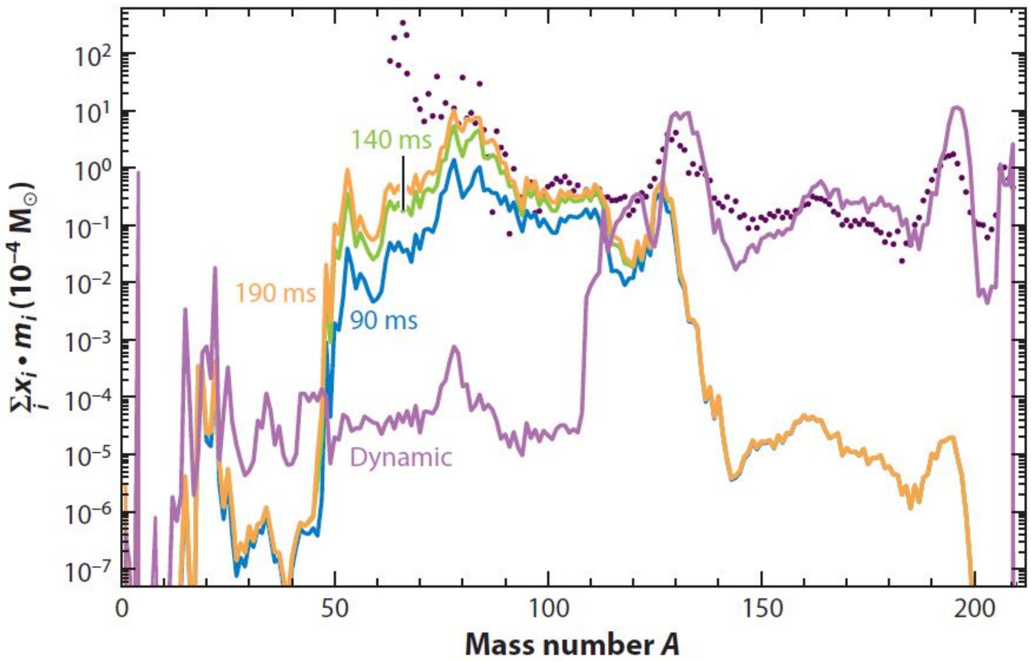


r-process in BNS/NS-BH mergers

- Dynamic ejecta ($Y_e \approx 0.1$).
- Neutrino driven wind from the hot-massive-neutron-star ($Y_e \approx 0.45$).
- Viscous heating and evaporation from the accretion disc of the new-born BH ($0.2 \leq Y_e \leq 0.3$).

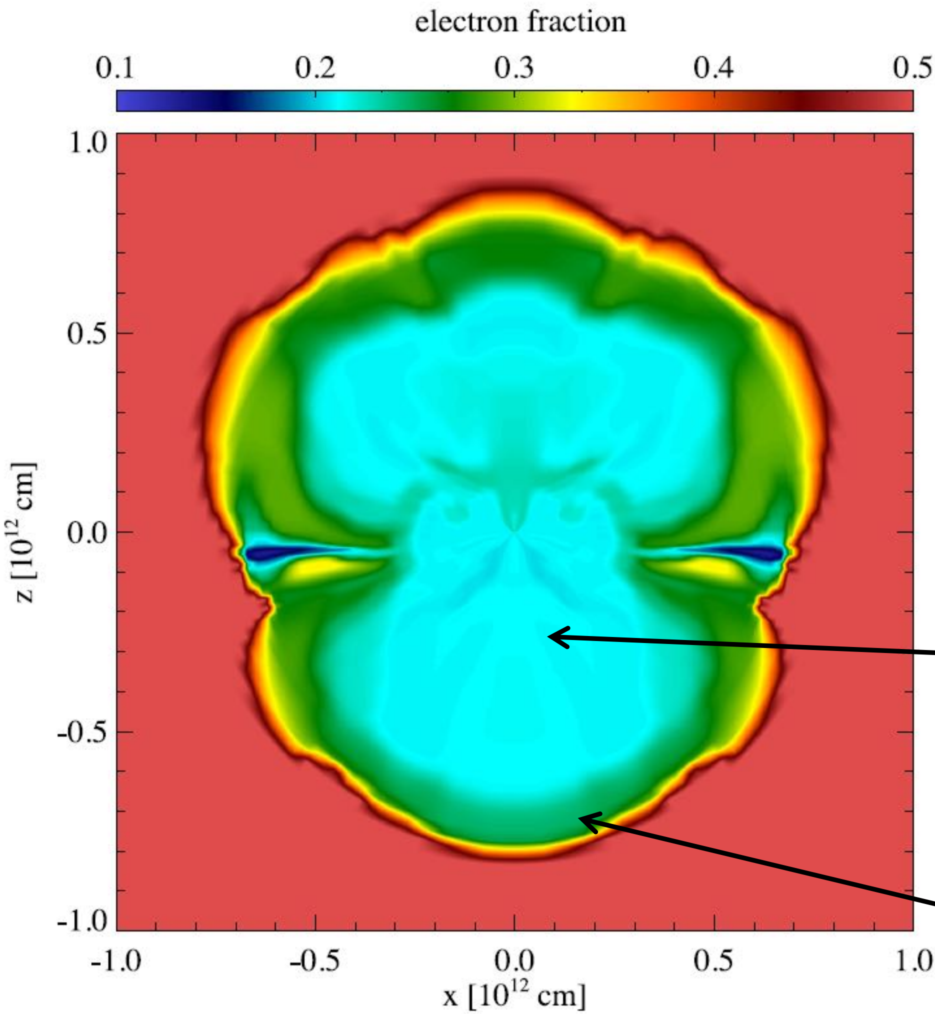


from Perego et al. 2014



- Dynamic ejecta contribute to the main/strong component of the r process (A>130).
- Neutrino driven wind may account for a large fraction of the weak component of the r-process. Depends on the time elapsed between the merger and the BH formation.

From Martin et al. 2015



Electron fraction after 300 s, ejecta from viscous evaporation (2D model from Fernandez et al. 2015)

High neutron-to-seed → strong component. High opacity from Actinides

Lower neutron-to-seed → weak and main components. Also lower opacity

Kilonova, from ultraviolet to near IR. A prompt blue bump is predicted after 1 day, followed by a long-lasting near-IR transient

r-process conclusions

- The Kilonova is the smoking gun connecting a robust r-process nucleosynthesis to short γ-ray bursts and, coupled with GW signals, to BNS/NS-BH mergers.
- Merger frequency and predicted nucleosynthesis are compatible with being the source of the bulk of the galactic r process.
- However the coalescence timescale ($\approx 10^8$ years) appears incompatible with the observed prompt galactic pollution. Additional contributions from rare CCSNe, as driven by strong magnetic fields, may solve this problem.
- The scenario above described is also compatible with the observed Eu/Fe vs Fe/H.