150 Years Periodic Table of the Elements

Stellar Explosions and the Heavy Elements

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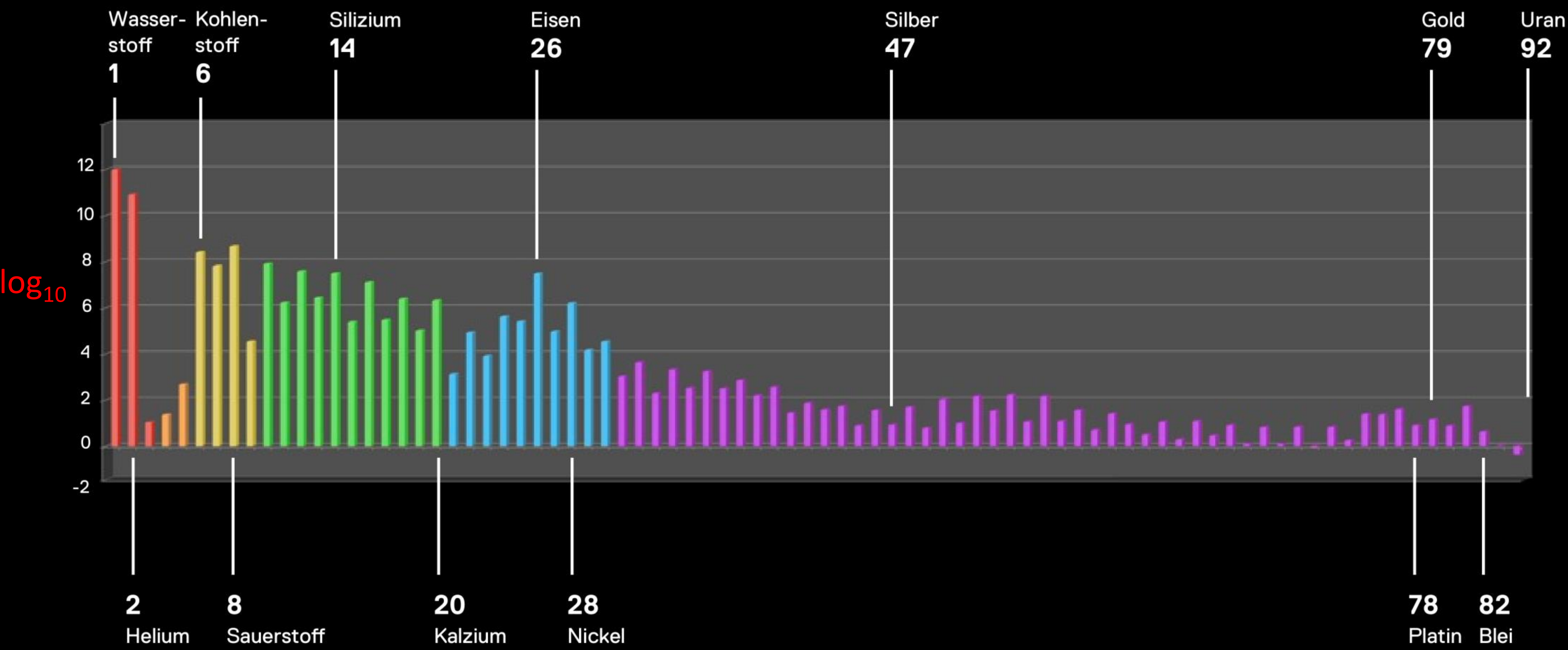
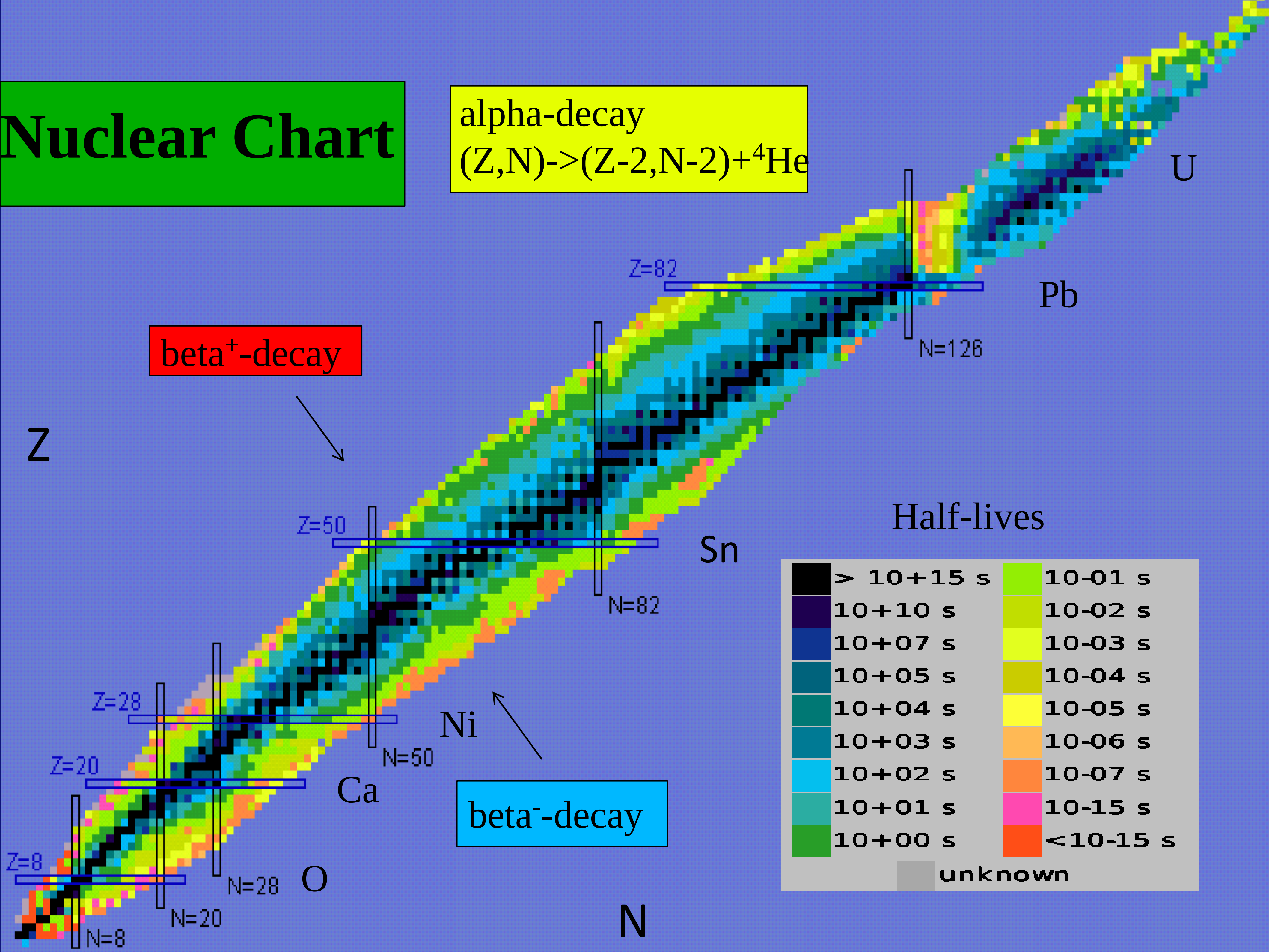
See recent reviews on nucleosynthesis in supernovae: http://adsabs.harvard.edu/abs/2018ASSL..453...91L, http://adsabs.harvard.edu/abs/2018SSRv..214...62T, http://adsabs.harvard.edu/abs/2017hsn..book.1843T, and the r-process: http://adsabs.harvard.edu/abs/2017ARNPS..67..253T, as well as for Rev. Mod. Phys. 2019arXiv190101410C, presently under (minor) revisions after receiving the referee reports

Abundances in the Solar System

HÄUFIGKEITSVERTEILUNG IM SONNENSYSTEM
(AUS KOHLIGEN CHONDRITEN UND SOLAREN ABSORPTIONSSPEKTREN)

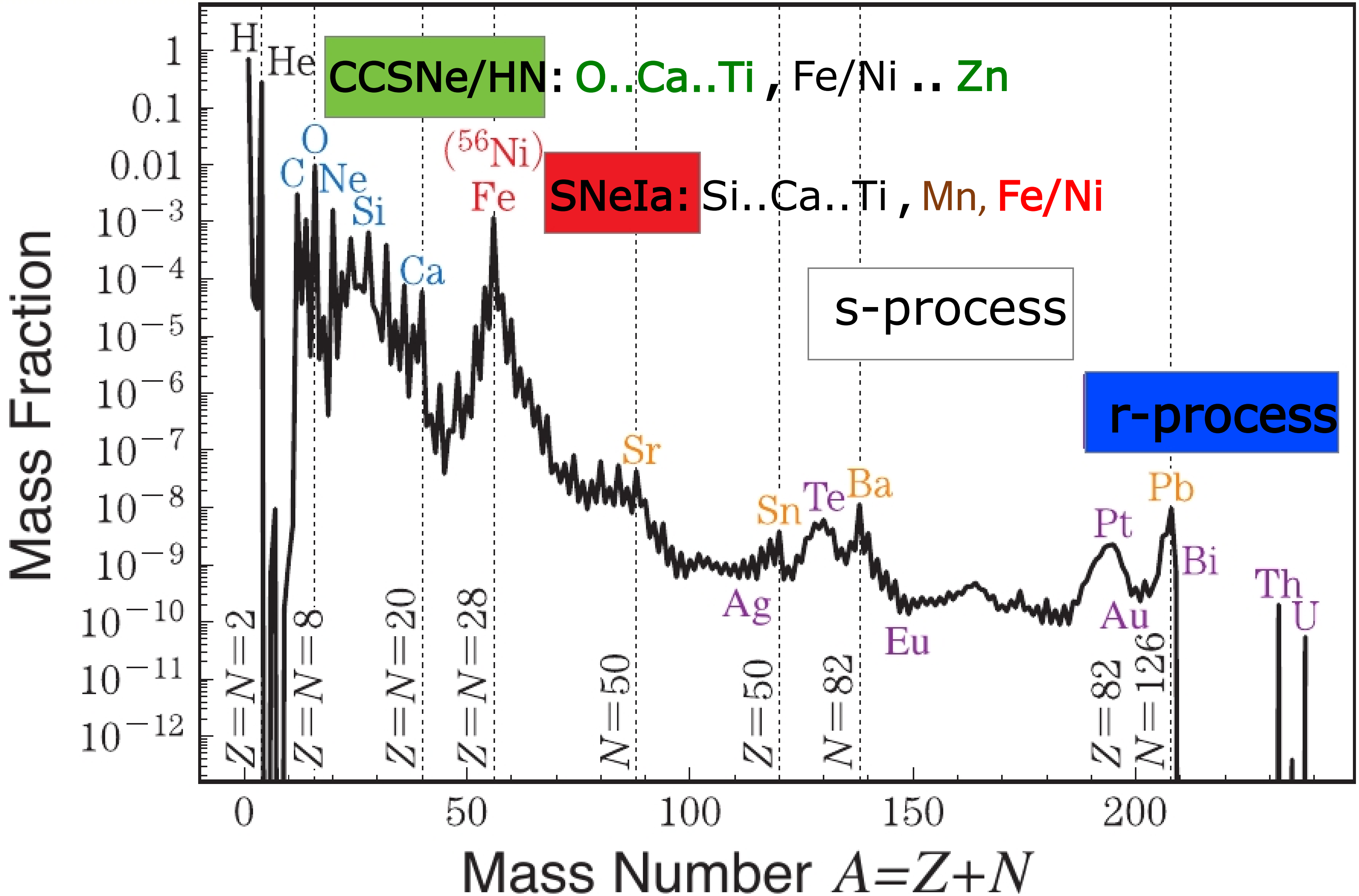


Nuclear Chart



BBN makes ^{1,2}H, ^{3,4}He, ^{7}Li

A preview of stellar origins to solar abundances



adopted from
C. Kobayashi

Introduction to nuclear reaction rates

$$\sigma = \frac{\text{number of reactions target}^{-1}\text{sec}^{-1}}{\text{flux of incoming projectiles}} = \frac{r/n_i}{n_j v}$$

$$r = \sigma v n_i n_j$$

reaction rate r (per volume and sec) for a fixed bombarding velocity/energy (like in an accelerator)

$$r_{i;j} = \int \sigma \cdot |\vec{v}_i - \vec{v}_j| dn_i dn_j$$

for thermal distributions in a hot plasma

e.g. Maxwell-Boltzmann (nuclei/nucleons) or Planck (photons)

$$dn_j = n_j \frac{4\pi p_j^2}{(2\pi m_j kT)^{3/2}} \exp(-\frac{p_j^2}{2m_j kT}) dp_j$$

$$dn_\gamma = \frac{8\pi}{c^3} \frac{\nu^2 d\nu}{\exp(h\nu/kT) - 1} = \frac{1}{\pi^2 (c\hbar)^3} \frac{E_\gamma^2 dE_\gamma}{\exp(E_\gamma/kT) - 1}$$

for two MB-distributions for i and j one obtains after variable transformations

$$r_{i;j} = n_i n_j \langle \sigma v \rangle_{i;j}$$

$$\langle \sigma v \rangle (T) = \left(\frac{8}{\mu\pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E) \, \exp(-E/kT) dE$$

Highly (exponentially) dependent on T for charged-particle reactions due to Coulomb repulsion, close to constant (slightly decreasing with T) for neutron induced reations. Also highly temperature-dependent for photo-disintegrations (inverse to capture reactions), they win typically when 30kT>Q (reaction gain for capture reaction), but high densities (entering only linearly) can enhance capture.

Brief Summary of Stellar Burning Stages (Major Reactions)

1. Hydrogen Burning — $T = (1\text{-}4)\times10^7$K
   - pp-cycles -> $^{1}H(p,e^{+}\nu)^{2}H$
   - CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$
2. Helium Burning — $T=(1\text{-}2)\times10^8$K
   - $^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $\quad$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   - $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C(\alpha,n)^{16}O$)
3. Carbon Burning — $T=(6\text{-}8)\times10^8$K
   - $^{12}C(^{12}C,\alpha)^{20}Ne$ $\quad$ $^{23}Na(p,\alpha)^{20}Ne$
   - $^{12}C(^{12}C,p)^{23}Na$ $\quad$ $^{23}Na(p,\gamma)^{24}Mg$
4. Neon Burning — $T=(1.2\text{-}1.4)\times10^9$K
   - $^{20}Ne(\gamma,\alpha)^{16}O$
   - $^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$

30kT = 4MeV

5. Oxygen Burning — $T=(1.5\text{-}2.2)\times10^9$K
   - $^{16}O(^{16}O,\alpha)^{28}Si$ $\quad$ $^{31}P(p,\alpha)^{28}Si$
   - $......,p)^{31}P$ $\quad ...,n)^{31}S(\beta^{+})^{31}P$ $\quad$ $^{31}P(p,\gamma)^{32}S$
6. "Silicon" Burning — $T=(3\text{-}4)\times10^9$K

(all) photodisintegrations and capture reactions possible

⇒ thermal (chemical) equilibrium

ongoing measurements of key fusion reactions at low energies

proton/nucleon ratio Ye decreases with enrichment of "metals"!!

Global Chemical (=Nuclear Statistical) Equilibrium (NSE)

$$\bar{\mu}(Z,N) + \bar{\mu}_n = \bar{\mu}(Z,N+1)$$
$$\bar{\mu}(Z,N) + \bar{\mu}_p = \bar{\mu}(Z+1,N)$$

Neutron and proton captures as well as their inverse photo-disintegrattions are in equilibrium

$$\bar{\mu}_i = kT \ln\left(\frac{\rho N_A Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right) + m_i c^2$$

Chemical potential (including rest mass) for particles following Maxwell-Boltzmann statistics

$$N\text{neutrons} + Z \ \text{ protons} \rightleftharpoons (Z,N)$$

$$N\bar{\mu}_n + Z\bar{\mu}_p = \bar{\mu}_{Z,N}.$$

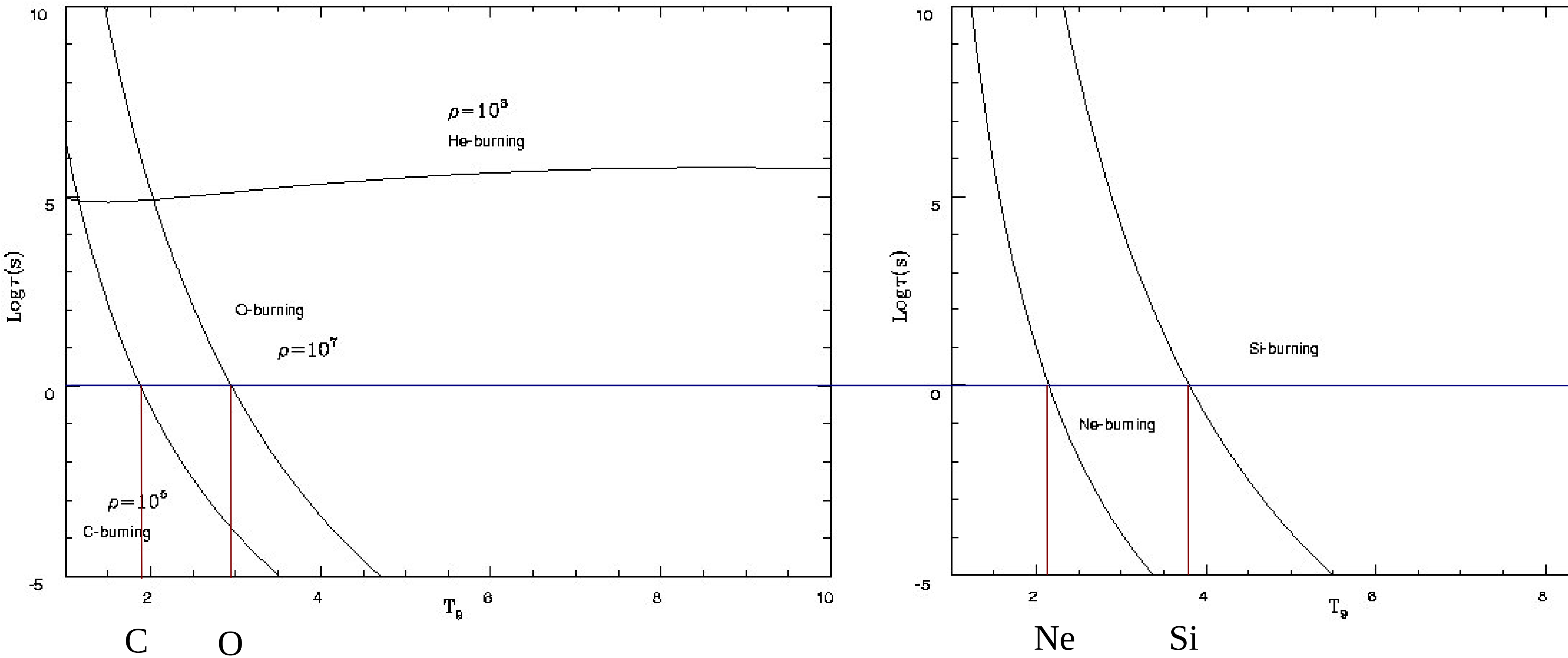
$$Y(Z,N) = G_{Z,N}(\rho N_A)^{A-1}\frac{A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{\frac{3}{2}(A-1)} \exp(B_{Z,N}/kT) Y_n^N Y_p^Z$$

$$\sum_i A_i Y_i = 1$$
$$\sum_i Z_i Y_i = Y_e$$

For temperatures T being sufficiently high to enable all capture as well as photo-disintegration reactions an equilibrium sets in, favoring for moderate denities and temperatures nuclei with the highest binding energies (around Fe and Ni). For extremly high temperatures (>5-6 10^9 K) everything is disintegrated into neutrons and protons. Extremely high densities (still below nuclear matter density) can lead to nuclei as heavy as A=500.

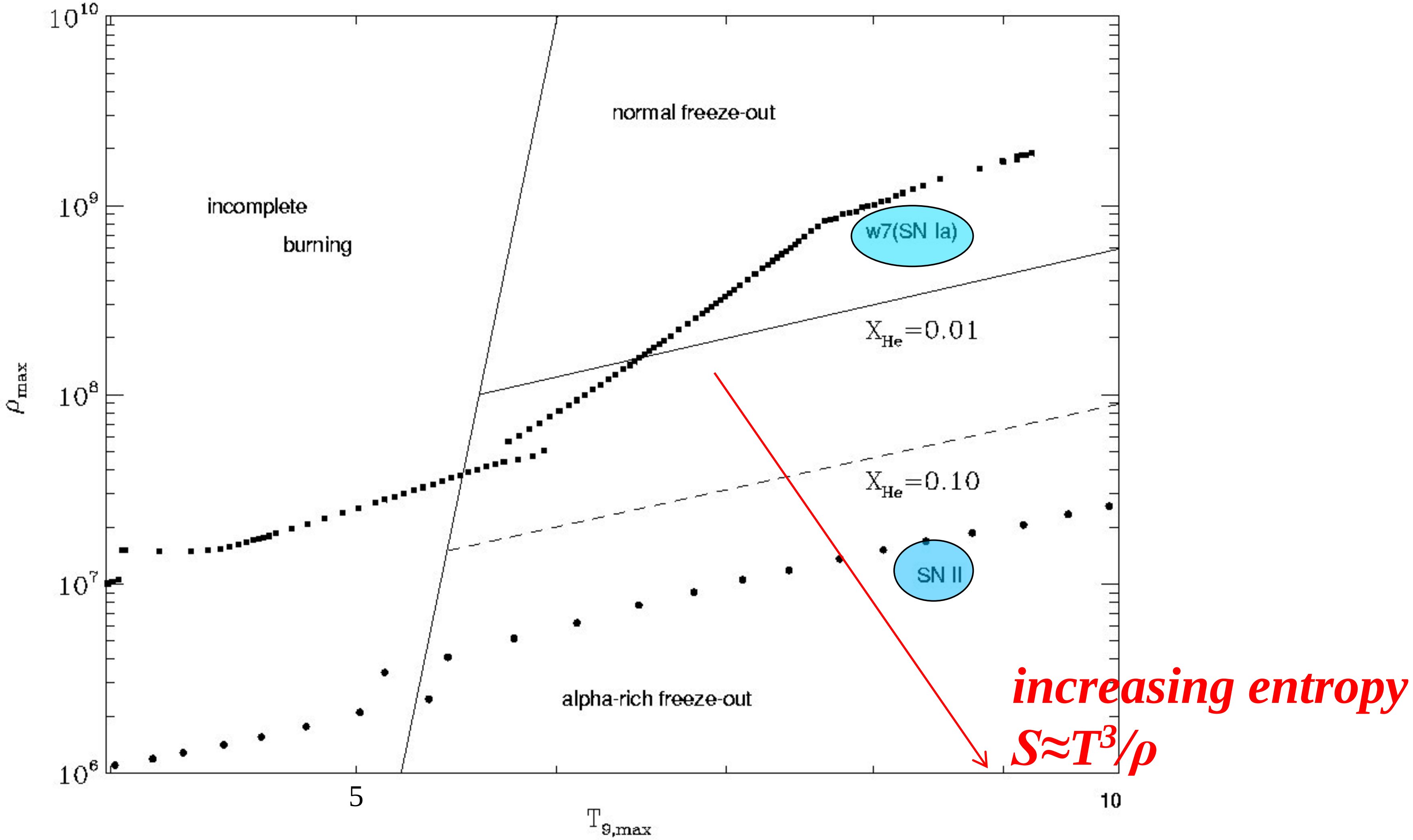
Explosive Burning

Time scales decrease exponentially with increasing temperature, in comparison with the long time scales at low temperatures in stellar evolution



typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent

Explosive Si-Burning



Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^{4}He to C and beyond freeze out earlier (alpha-rich freeze-out).

How can the heavy elements be made?

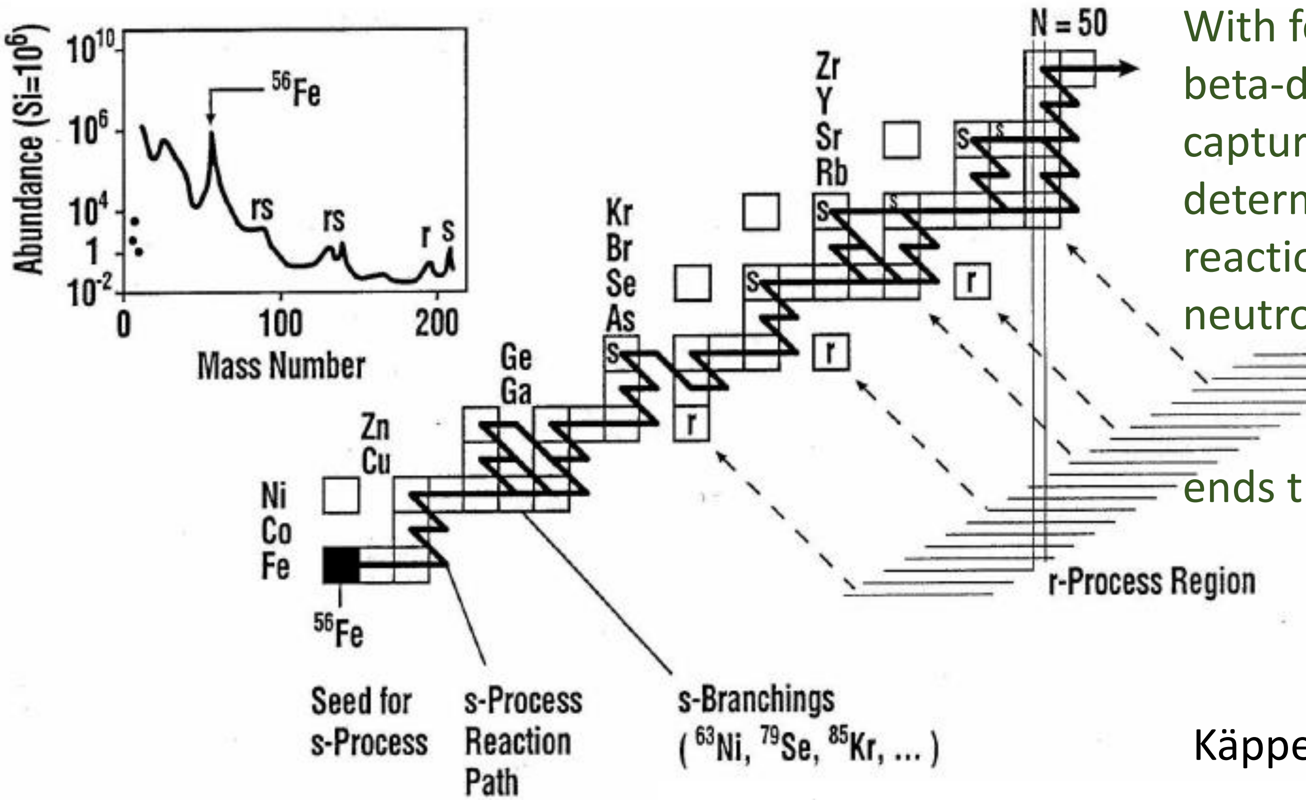
Fusion with charged particles (protons, alphas, nuclei) required increasing temperatures with the increasing charge of heavier nuclei. To enable such reactions above the Fe-group (which formed in a nuclear statistical (chemical) equilibrium) would need tempeartures above 5 10^9 K, where the reverse photodisintegrations win and no built-up of heavier nuclei is possible with charged-particle reactions (minor exceptions are only possible for very high densities, which can be found on the surface of neutron stars.

The only way to produce heavier nuclei/elements is via the capture of neutrons which do not experience Coulomb repulsion and which is possible at low temperatures. The only caveat is that neutrons have a half-life of about 10min, i.e. they need to be produced locally via reactions.

In stellar evolution the neutron sources are $^{22}Ne(\alpha,n)^{25}Mg$ and $^{13}C(\alpha,n)^{16}O$ (the latter being much stronger). This leads to a low abundance of neutrons, i.e. in most cases the beta-decay of unstable nuclei is much faster than the next neutron capture and the reaction path of this slow process (*s-process*) passes close to stable nuclei.

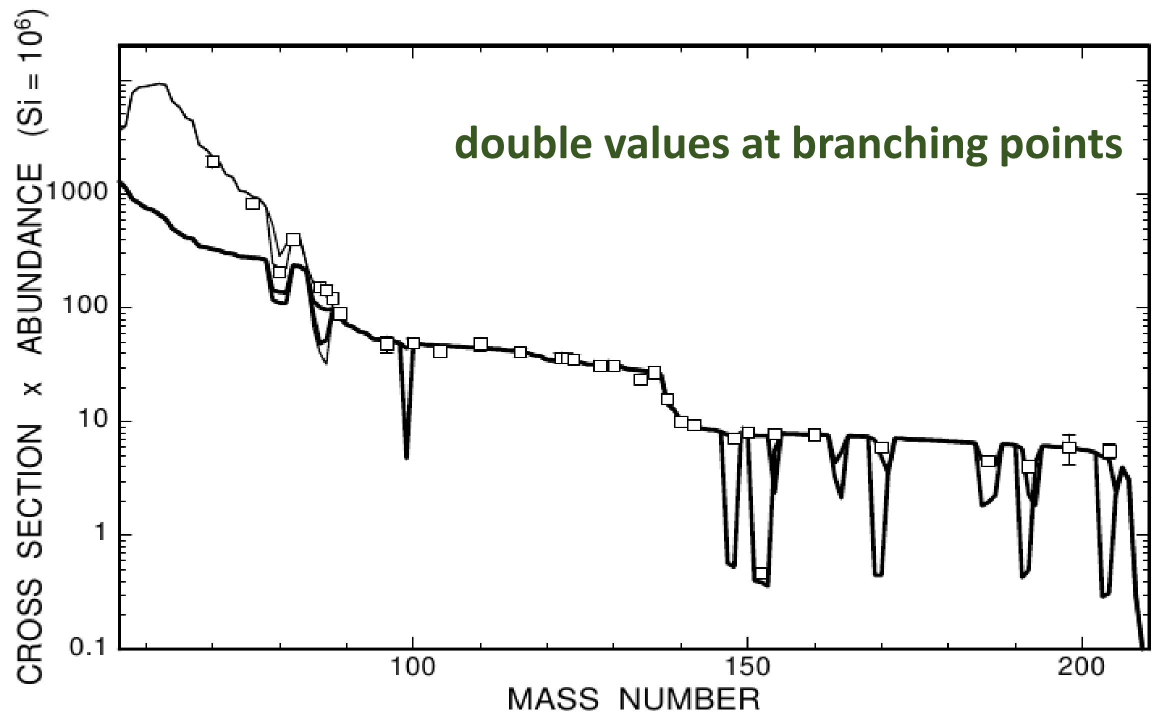
If in an explosive environment huge amounts of neutrons are released, neutron captures can be much faster than beta-decays (i.e. this happens rapid), leading to an *r-process* up to 20 neutron numbers away from stable nuclei.

With few exceptions (so-called branchings) beta-decays are much faster than neutron captures and the speed of the process is determined by the neutron capture reaction cross sections. Above Pd and Bi neutron captures lead to alpha unstable nuclei, i.e. (n,α) reactions form nuclei with Z-2 and the process ends there to produce heavîer nuclei.

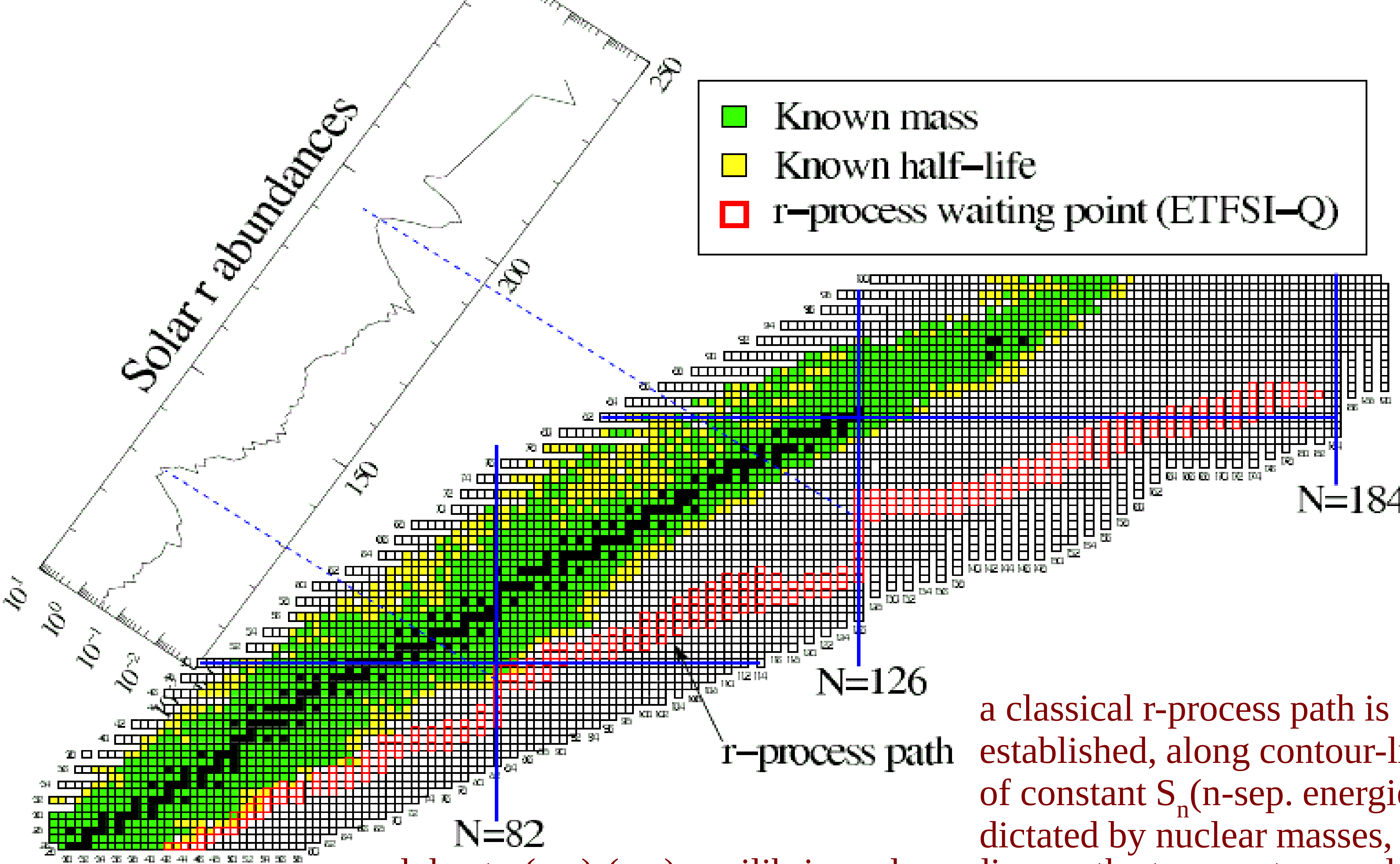


Käppeler et al. (2011)

In a steady-flow equilibrium the neutron capture on nucleus (Z,N) is as fast as its production via neutron capture on nucleus (Z,N-1).
This leads to a steady-flow equilibrium, causing the product of the abundance of a nucleus and its neutron-capture cross section to be constant. The adjacent figure shows that this is the case with the exception of neutron shell closures, where reaction Q-values and reaction rates are small, i.e. they cause a barrier in the flow.



r-Process Path



a classical r-process path is established, along contour-lines of constant S_n(n-sep. energies), dictated by nuclear masses, and due to (n,γ)-(γ,n) equilibrium, depending on the temperature and density. As in the r-process neutron captures and their reverse are fast, the process is controlled by beta-decay half-lives of "waiting points" in each isotopic chain, the longest encountered at closed shells close to stability.

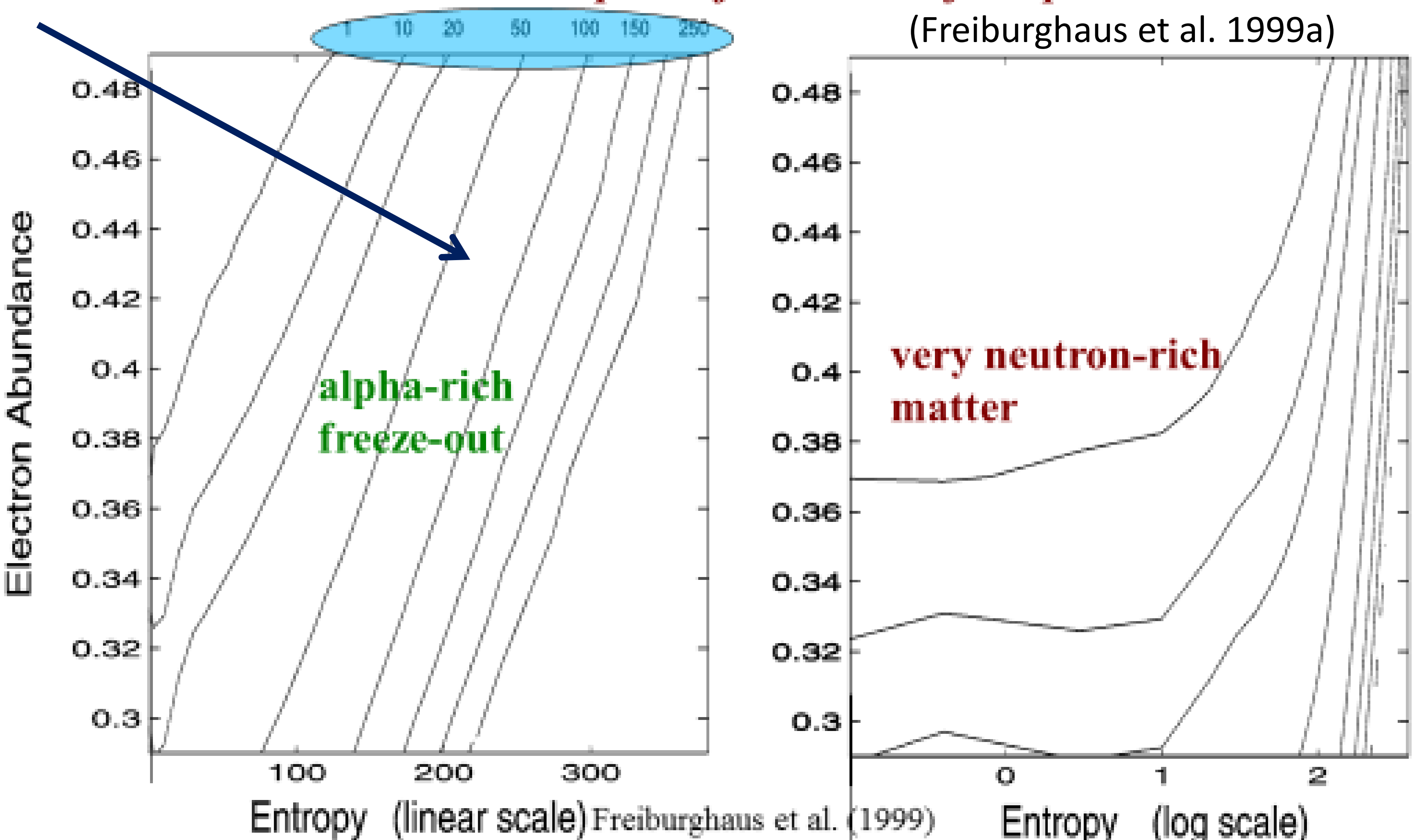
Pfeiffer/Kratz

n/seed ratios as function of S and Y_e

Two options for a successful r-process

(Freiburghaus et al. 1999a)

Ye=proton to nucleon ratio



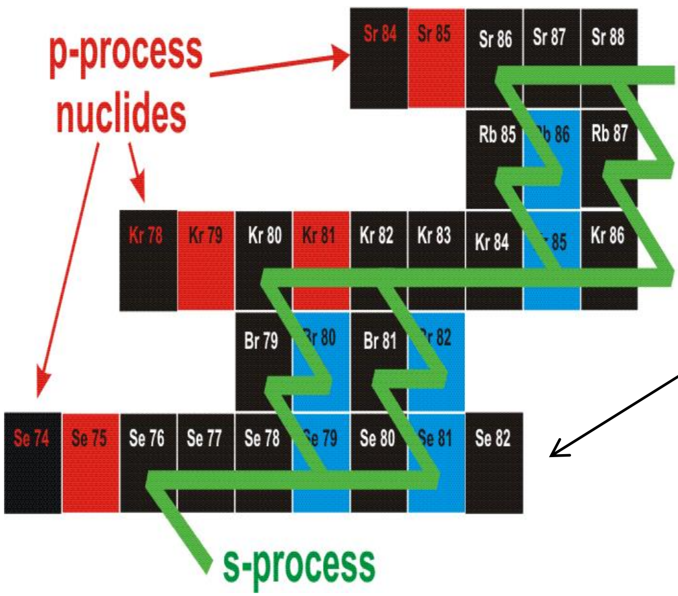
Freiburghaus et al. (1999)

neutrino wind?

Neutron star mergers and polar jets?

The essential quantity for a successful r-process to occur is to have an n/seed ratio so that A_{seed}+n/seed=$A_{actinides}$!

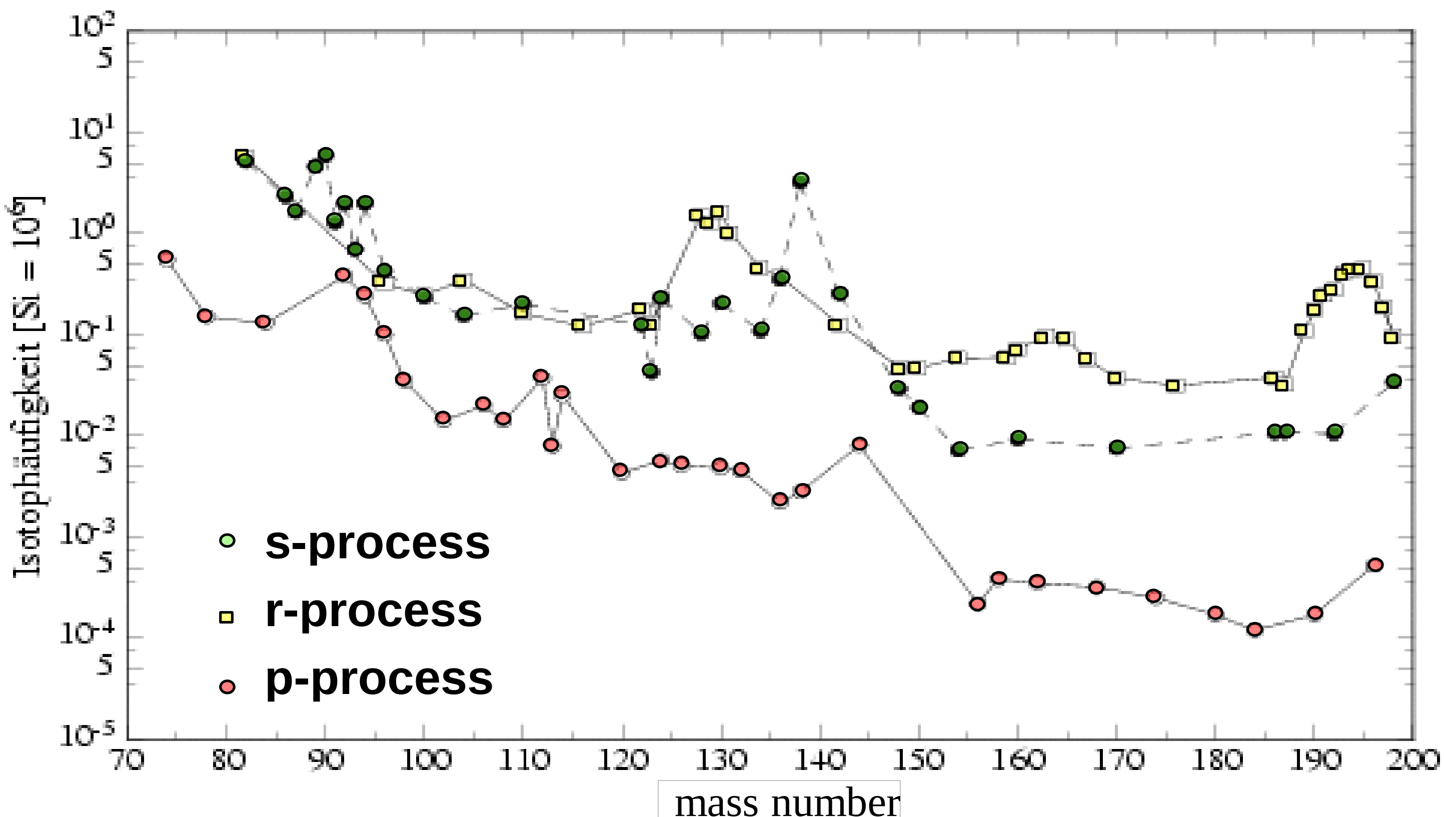
s-, r-, and p-decomposition of heavy elements above Fe-group



of pure s-, r-, or p-nuclei

r-process

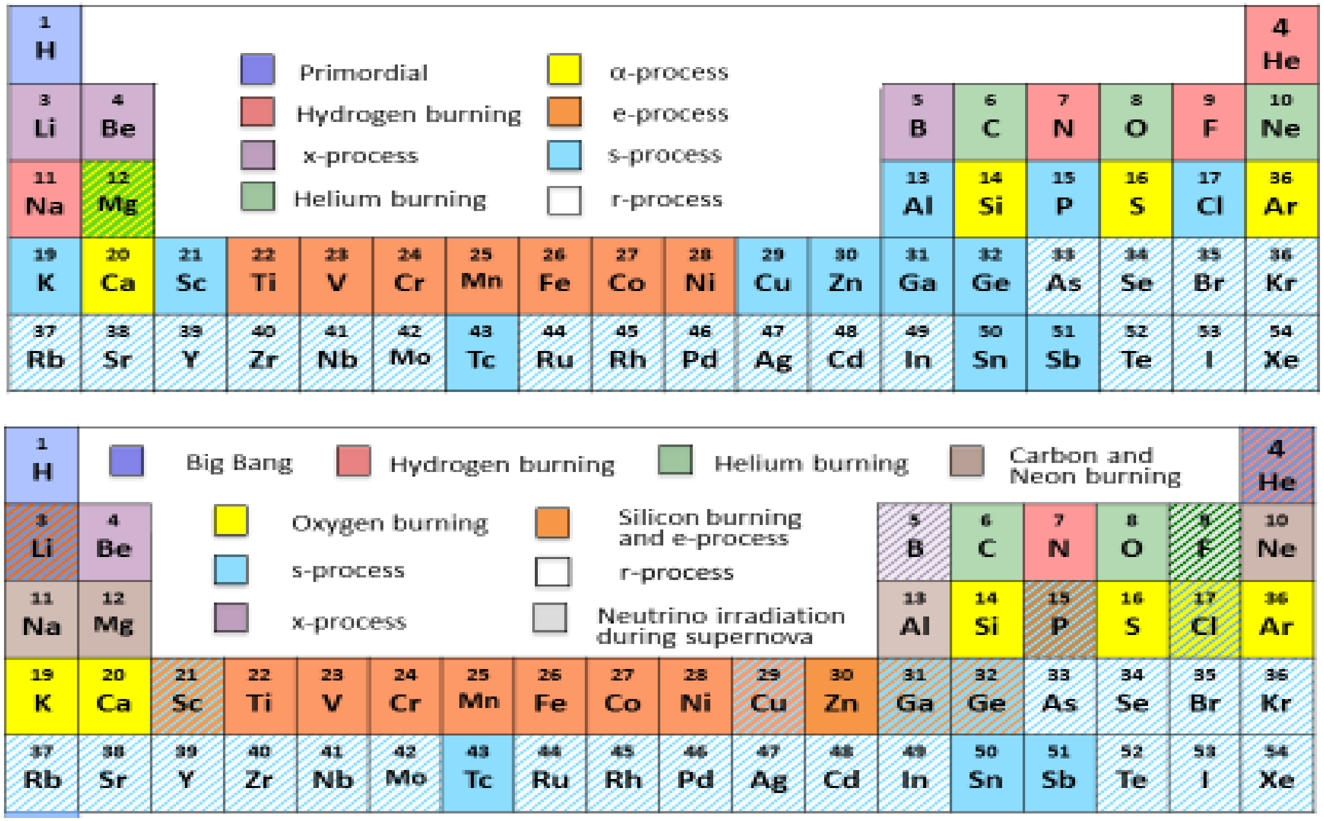
Solar abundances (Anders & Grevesse)



Abundance, normalized to Si = 10^6

1

2



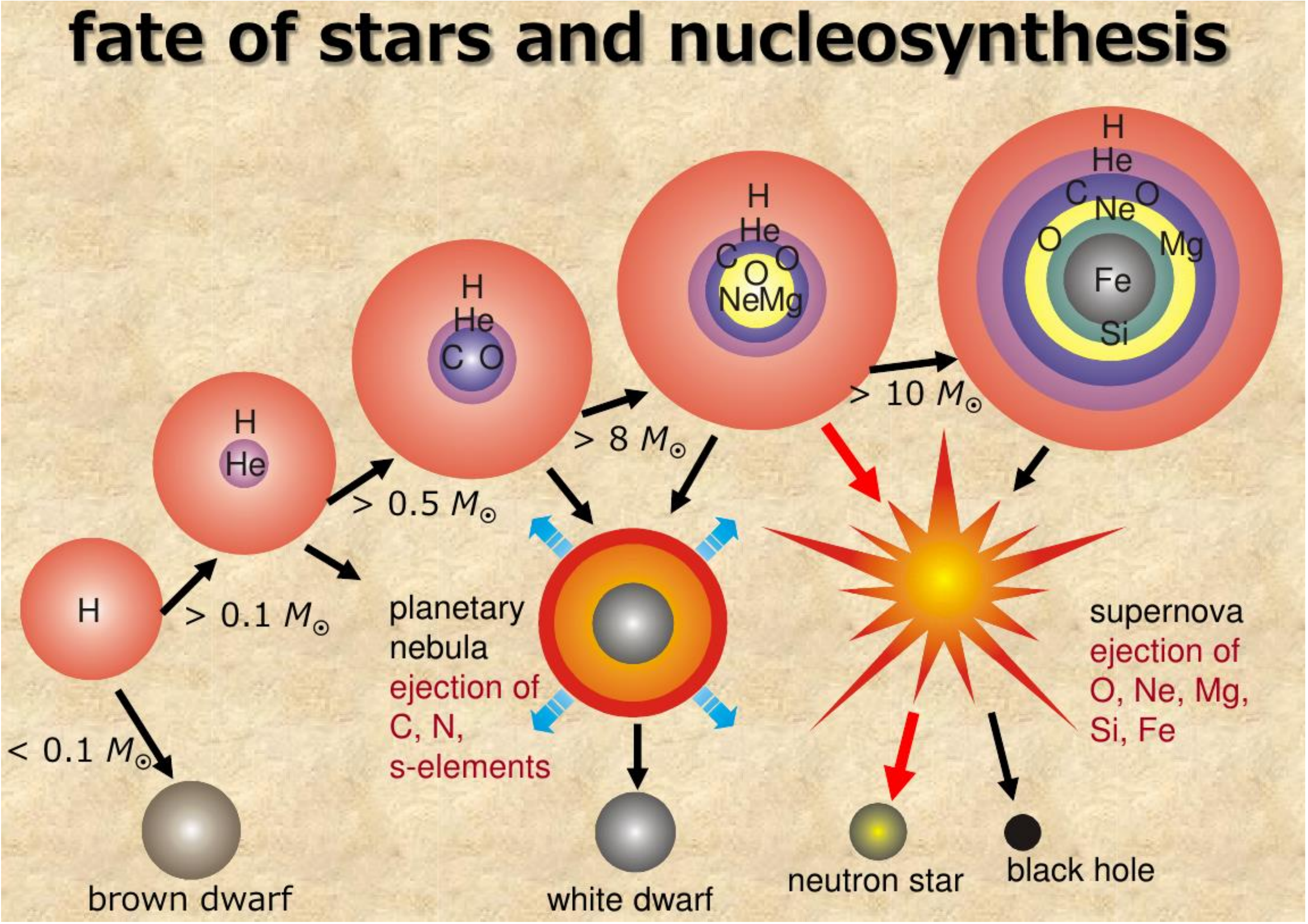
What is the origin of the elements in the solar system?

1. B^{2}FH (Burbidge, Burbidge, Fowler, Hoyle, 1957): the first attempt of a complete strategy to explain solar abundances in terms of processes
2. Woosley, Trimble, Thielemann (2019) also via processes within present understanding

Nucleosynthesis then and now. *The top panel shows the periodic chart of the elements color coded according to the eight processes assigned* ***by B^{2}FH****. The bottom panel shows the* ***current assignments****, dropping the alpha-process and indicating the new fusion processes carbon, neon, and oxygen burning. Cross hatching indicates more than one process involved. Boron and fluorine are at least partly made by neutrino interactions in the explosion.*

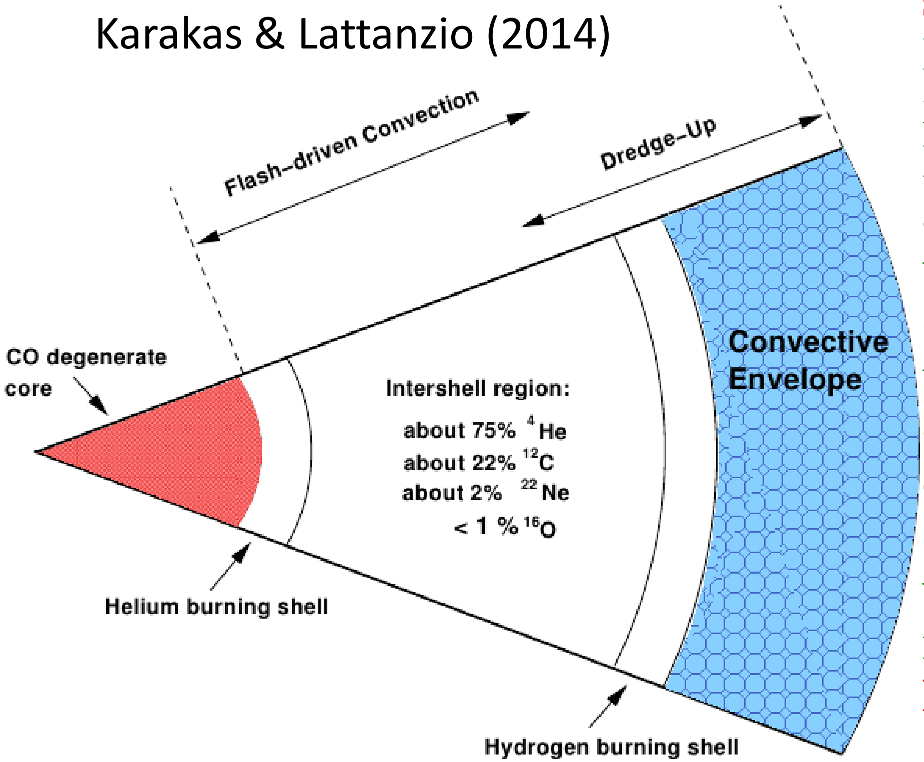
For clarity, elements above xenon, generally due to combinations of the r- and s-processes, have been omitted. Unshaded r- and s-process squares indicate that more than 80(60)% of the element is due to that process. *Above Xe these are for the s-process Sr, Y, Zr, Nb; Ba, (La, Ce); (Hg, Tl), for the r-process Ag, (In, Sb),Te, Xe, Cs; (Sm), Eu, Gd, Tb, Dy, Ho, Er, Tm, (Yb, Lu), Re, Os, Ir, Pt, Au, Bi, and all heavier elements. Up to Sr, Y, Zr, and still slighty beyond, other non-neutron capture processes in explosive environments might also contribute.*

After having an idea about the contributing types of nucleosynthesis processes, we have to look for the **stellar sites** where they take place!

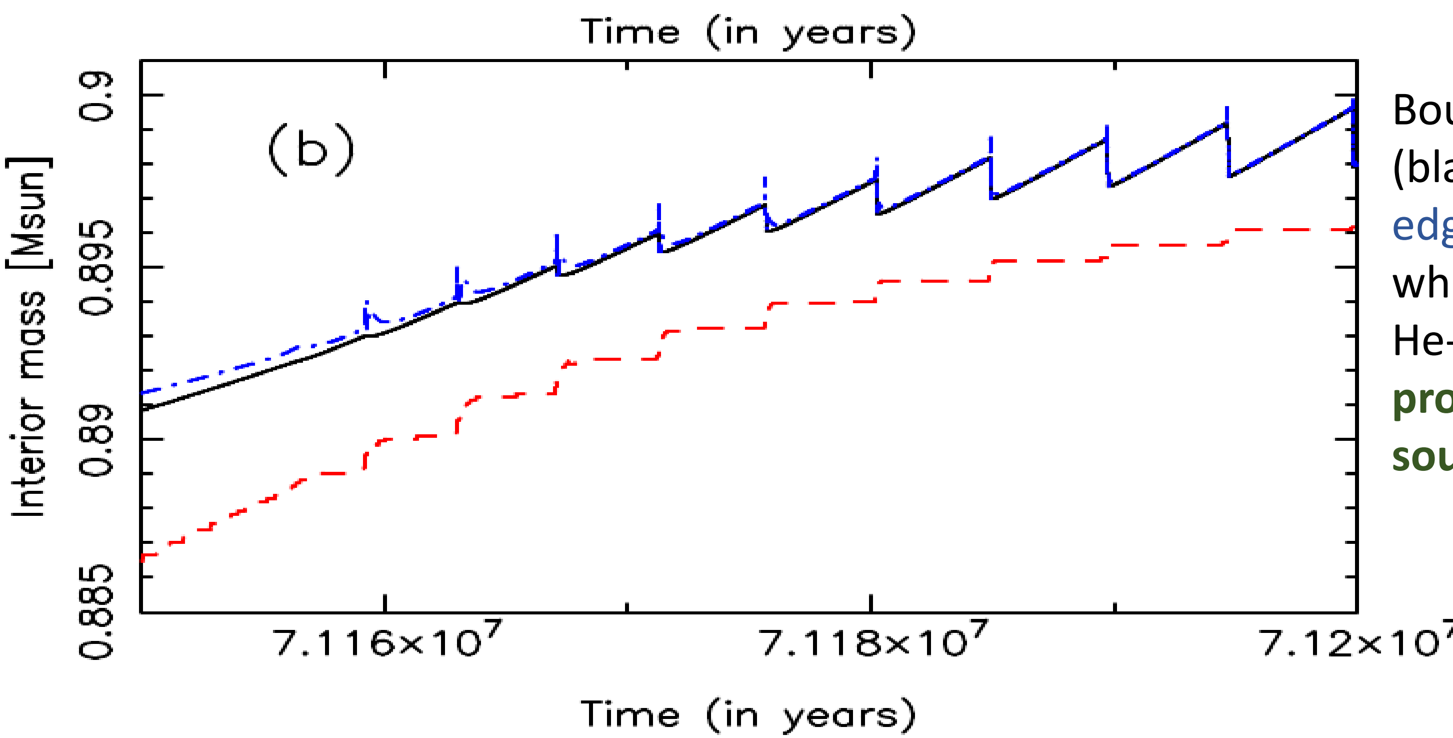


adopted from Wanajo

Karakas & Lattanzio (2014)

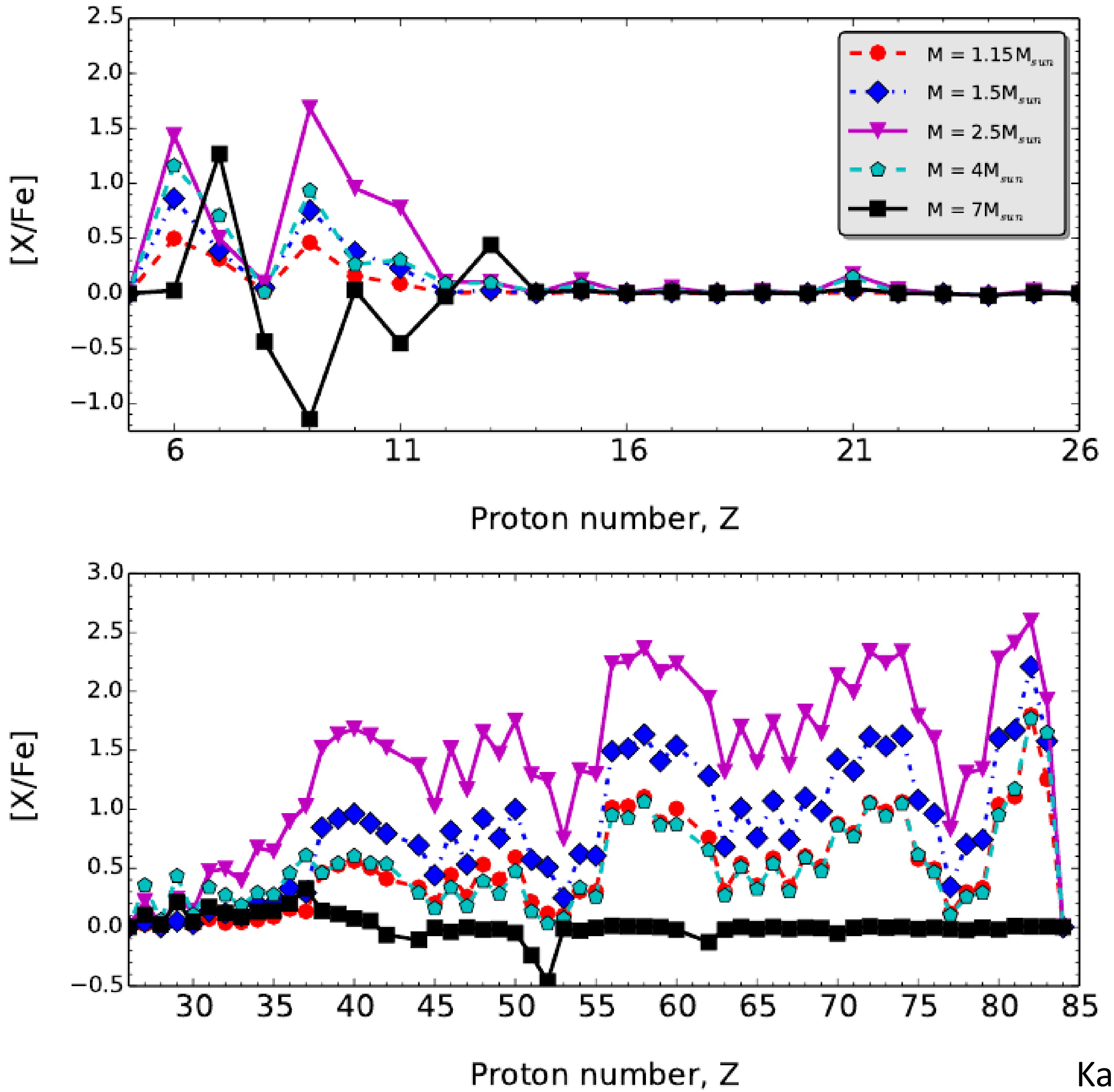


s-process in low and intermediate mass stars: the H- and He-shells are located at small distances. They do not burn in a constant fashion. If the H-burning zone is on, it creates He fuel. After sufficient He is produced, He is ignited in an unburned He-rich zone (at sufficient densities and temperatures). The burning is not stable, the amount of energy created in a shallow zone is not sufficient to lift the overlaying H-shell which would cause expansion + cooling, i.e. steady burning. Instead He-burning, being dependent on the density squared, burns almost explosively (flash), causing then a stronger expansion which even stops H-burning in the H-shell. This behavior repeats in recurrent flashes. **H is mixed into the unburned He fuel, causing $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$ and the production of neutrons.**



Boundary of H-free core (black), He-free core (red), edge of convective zone (blue), which mixes H (protons) into He-burning, **leading to the production of the neutron source ^{13}C.**

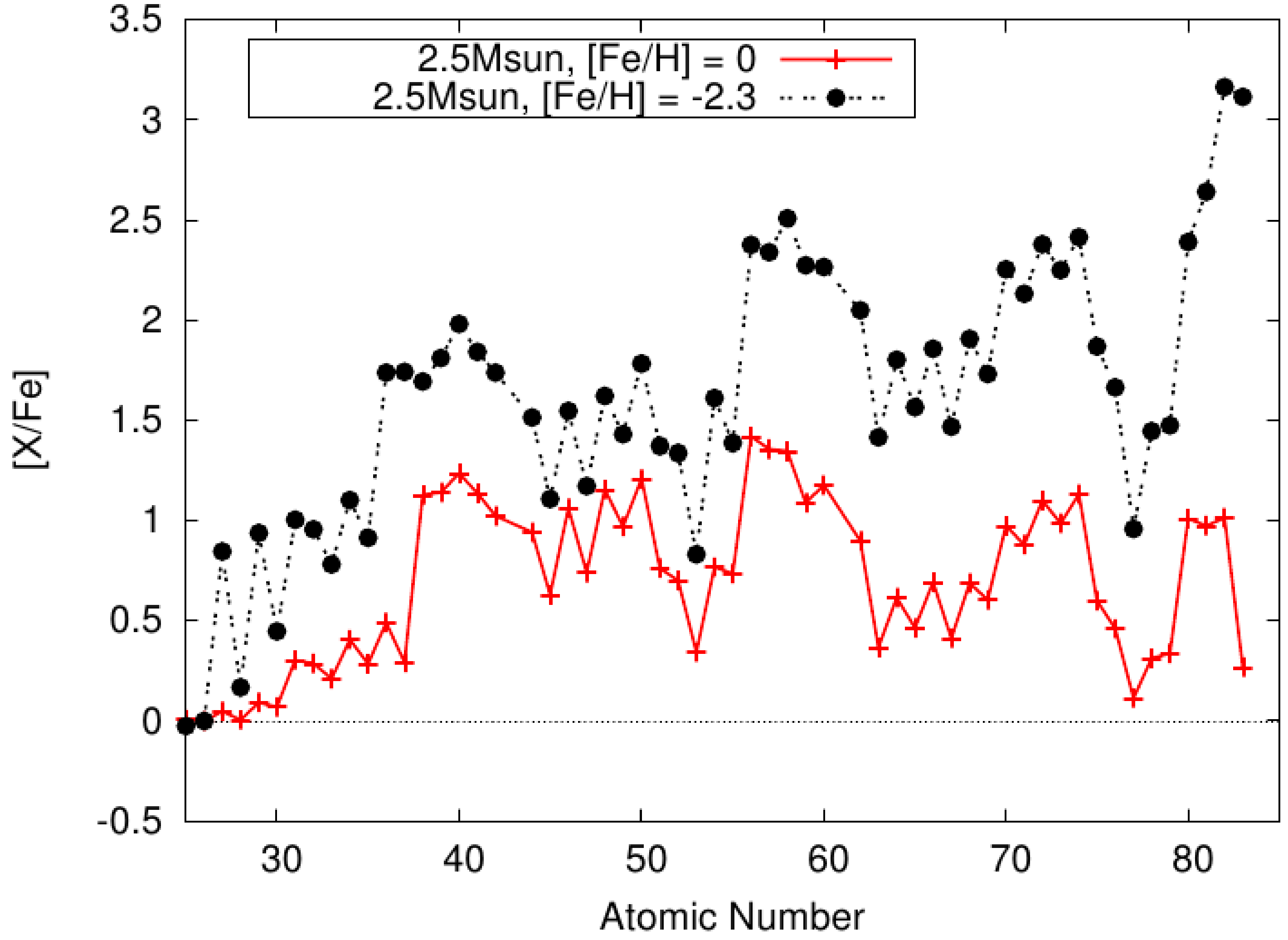
Results differ for varying stellar masses



Karakas & Lattanzio (2014)

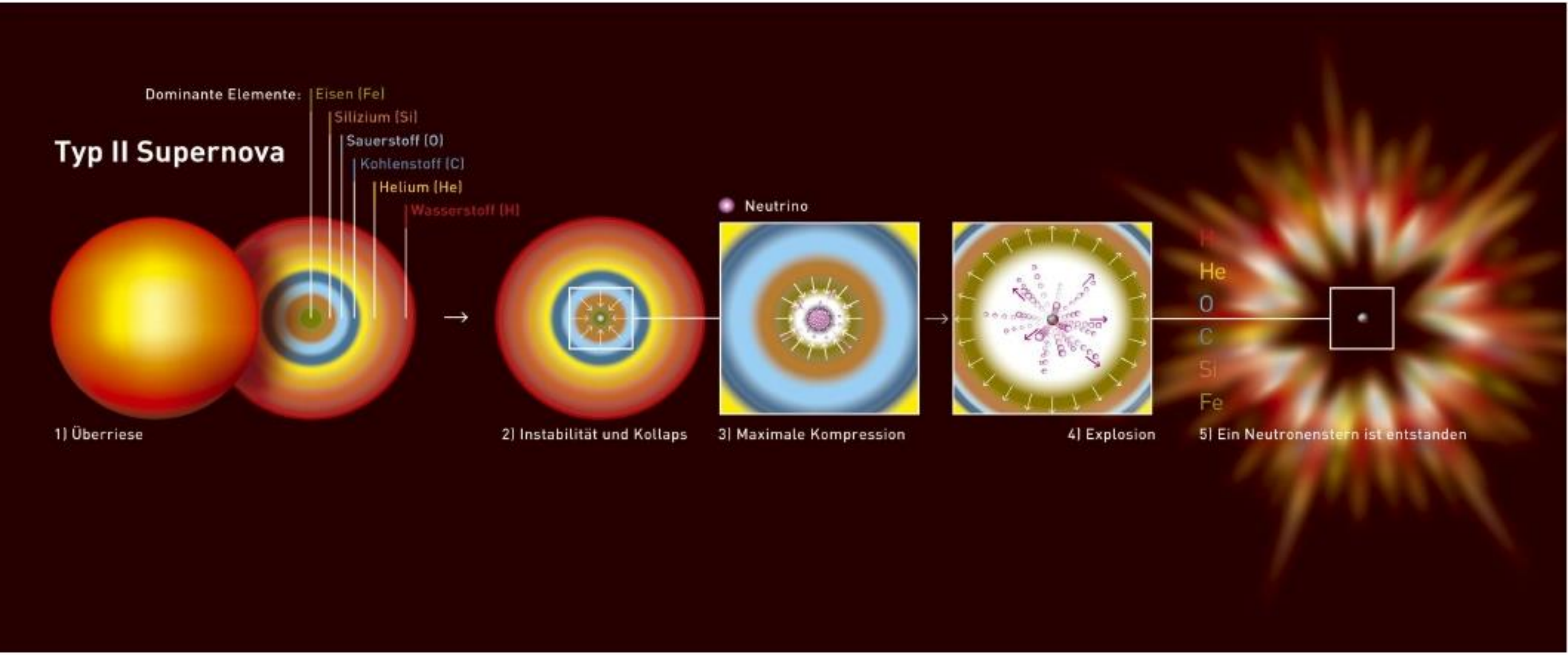
The s-process is secondary process (capturing neutrons on pre-existing Fe-group nuclei).

A similar neutron exposure on smaller amounts of Fe-seeds leads to stronger production of the heaviest s-nuclei (so-called lead stars).



each star shows a specific stage of s-processing, i.e. we have no overall agreement with ”solar“ s-process abundances in a single star. **Solar s-abundances are only obtained via integrating over an IMF distribution of stellar masses and over galactic evolution with increasing “metallicity” [Fe/H].**

Core-Collapse Supernovae and Neutron Stars as End Stages of Massive Stars in Neutrino-Driven Explosion

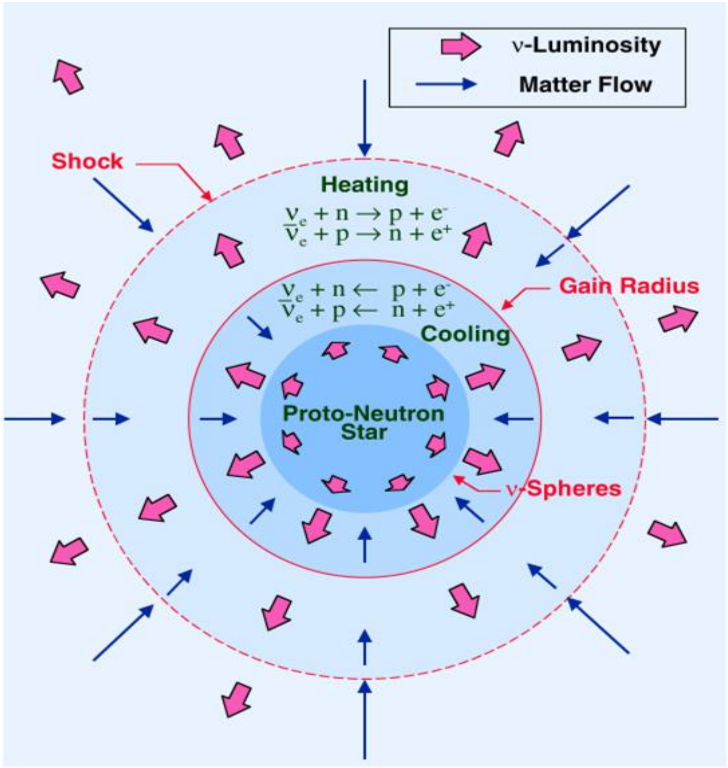


Main products: O, Ne, Mg, S, Ar, Ca, Ti and Fe/Ni

How about heavier nuclei (Zn .. Sr, Y, Zr)

and the r-process ?????

Neutrino-driven Core Collapse Supernovae



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

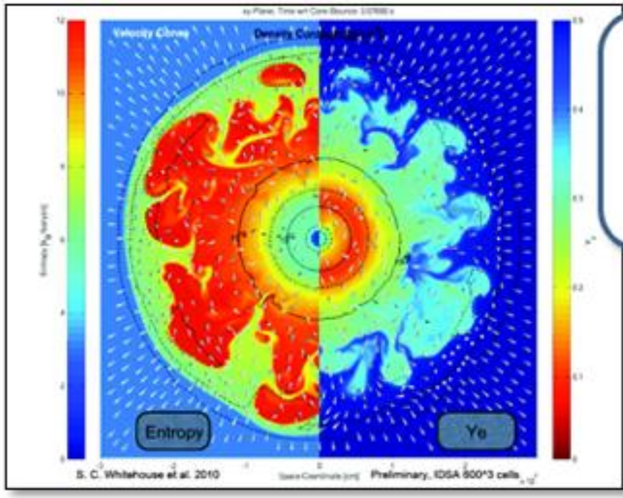
$\nu_e + A' \leftrightarrow A + e^-$ opacity
$\nu + N \leftrightarrow \nu + N$
$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ 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
$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

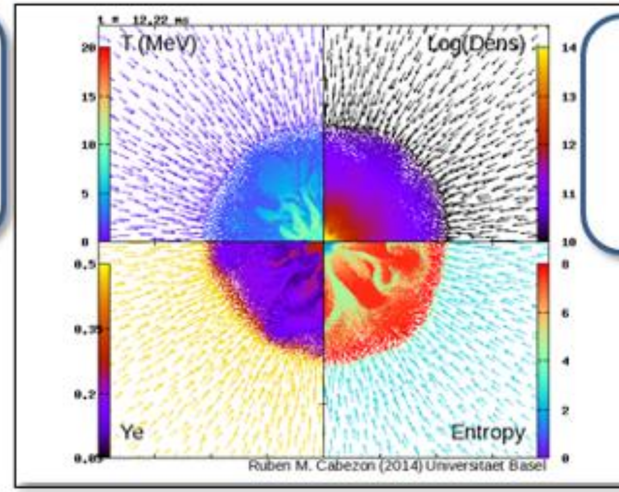
Basel activities with IDSA (Isotropic Diffusions Source Approximation) in Multi-D



Elephant

3D IDSA
Cartesian mesh
1D GR potential

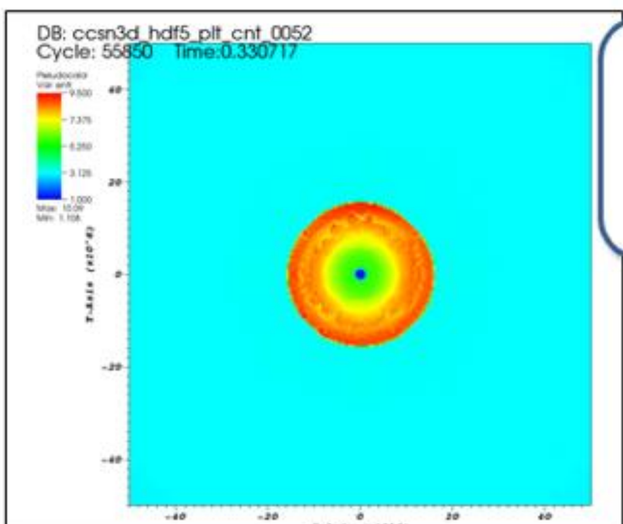
M. Liebendörfer
S. C. Whitehouse
R. Käppeli



SPHYNX

ASL
SPH
3D Newtonian

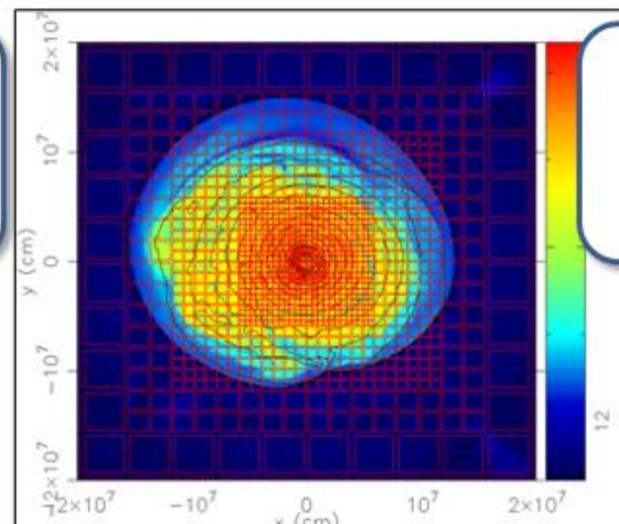
R. M. Cabezón



FLASH

3D IDSA
AMR
3D Newtonian

K.-C. Pan



fGR_M1

M1
Nested meshes
3D GR

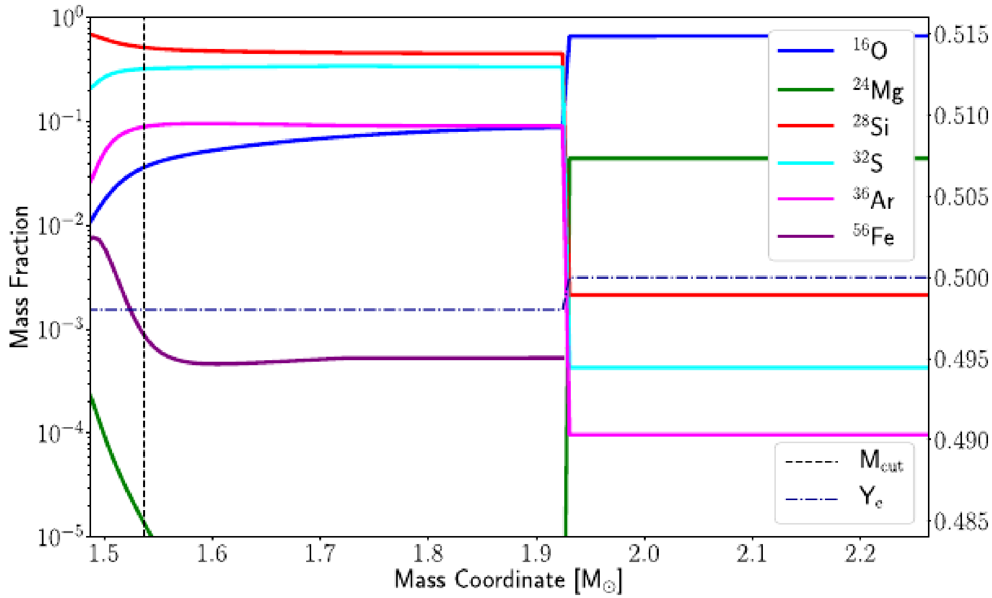
T. Kuroda

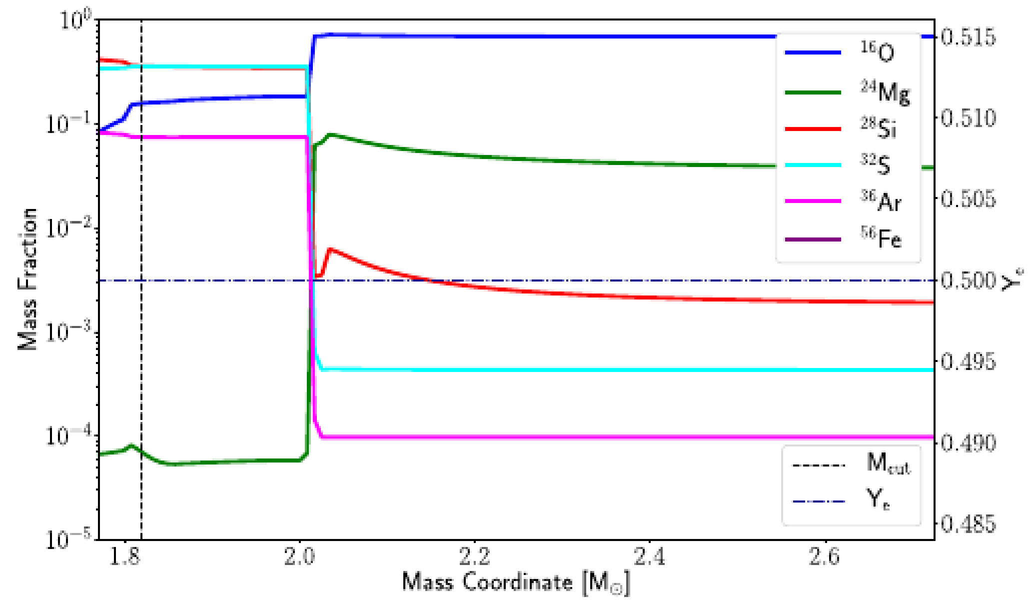
Cabezon et al. (2018): a three-dimensional code-comparison project

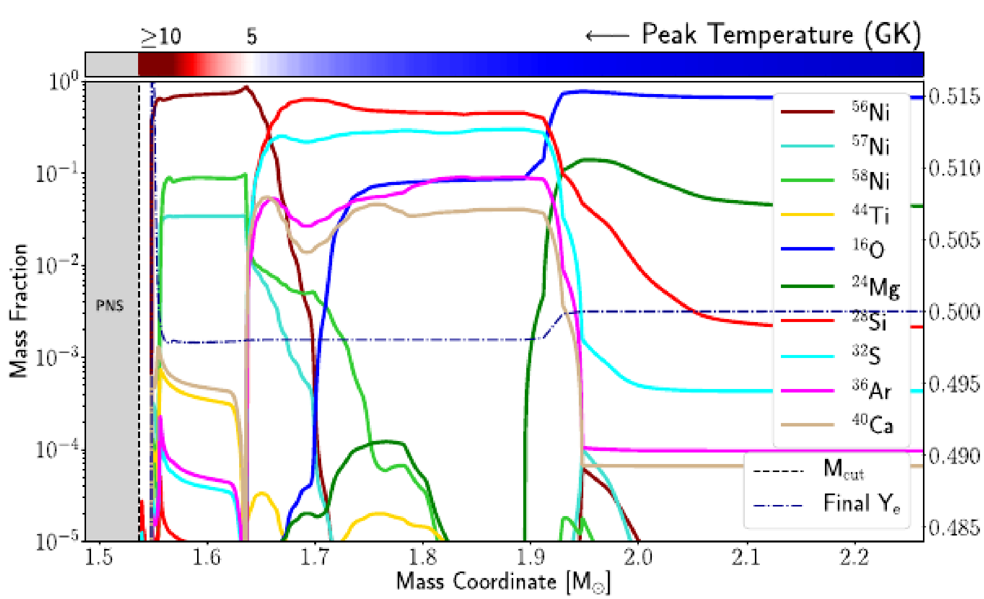
For futher comparison projects see also Just et al. (2018), 1D and 2D, O’Connor et al. (2018), 1D, but for more extended times after bounce!

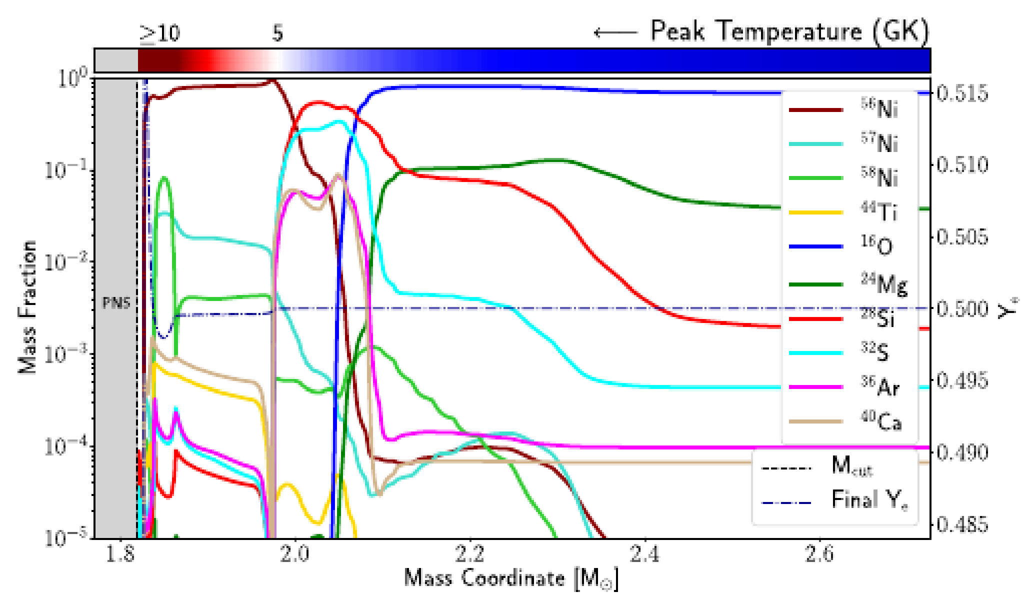
Composition in Pre-Explosion Model and Explosive Ejecta (Curtis et al. 2019)

for 16 and 21 Msol progenitors (based on PUSH approach)



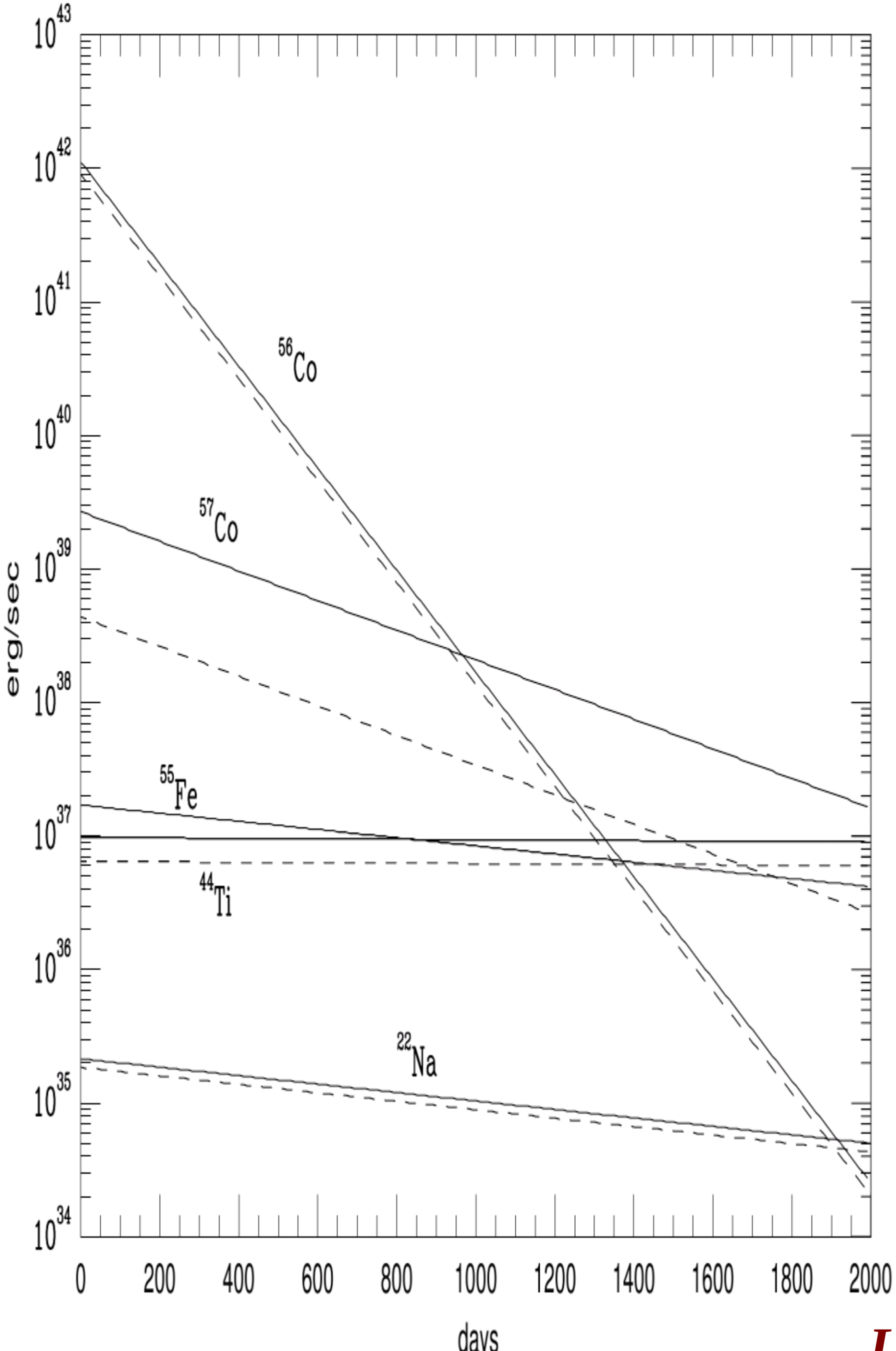




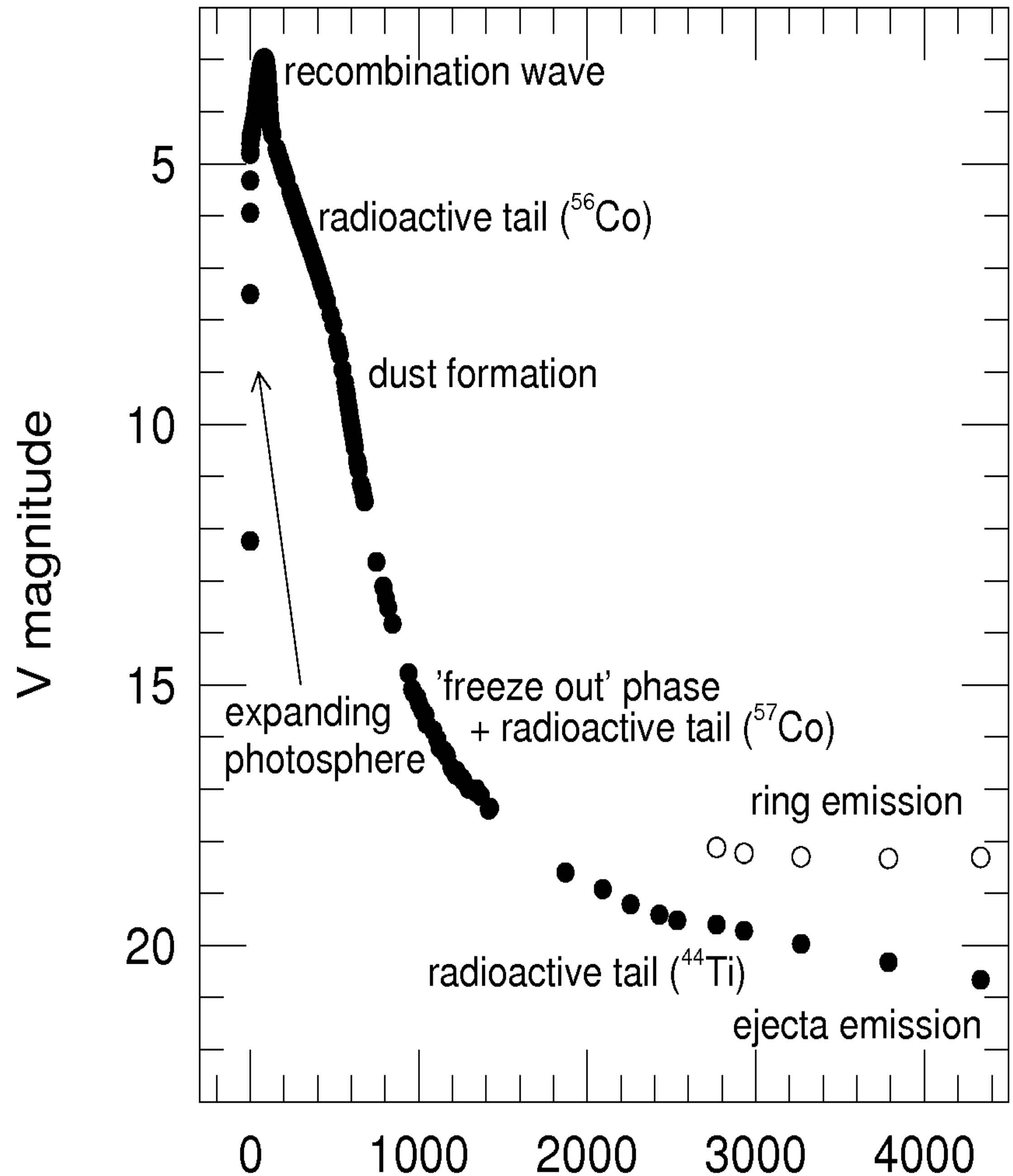


Ye on right abzissa (dashed), being in the outer layers unchanged from the initial (hydrostatic) Ye close to 0.5, decreased due to (beta$^+$-decays and e-captures) in explosive Si-burning, and enhanced via neutrino interactions with matter in inner layers at small radii. Innermost layers not well visible here, see next transparency

Radioactivity Diagnostics of SN1987A: ^{56}Ni/Co, ^{57}Ni/Co, ^{44}Ti



total/photon decay energy input from models



Leibundgut** (ESO) & Suntzeff 2003, **other determinations (e.g. ^{44}Ti undertaken by Fransson+ Stockholm)

What determines the neutron/proton or proton/nucleon=Ye ratio in ejecta?

Y_e dominantly determined by $e^{\pm}$ and ν_e, $\bar{\nu}_e$ captures on neutrons and protons

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

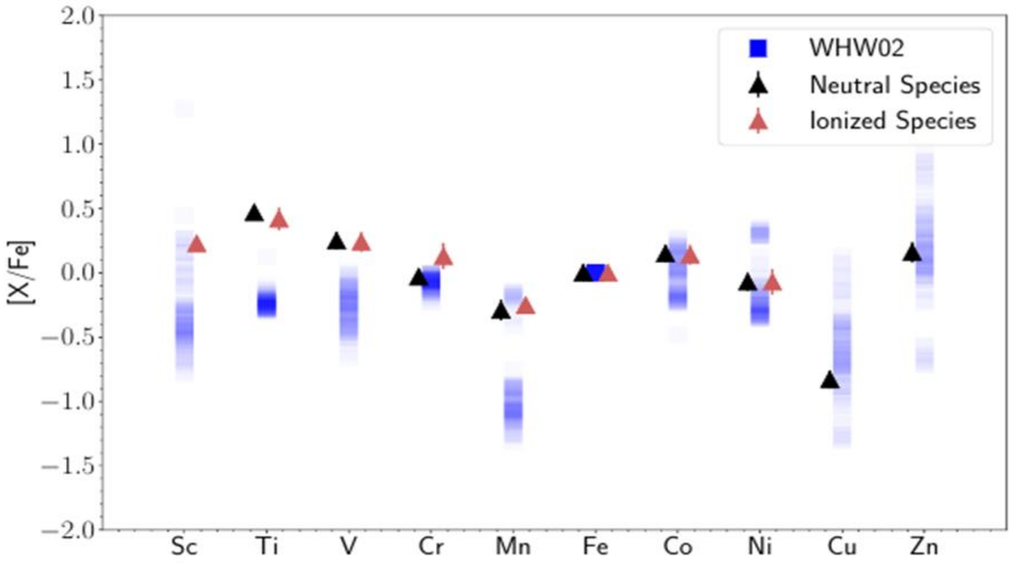
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

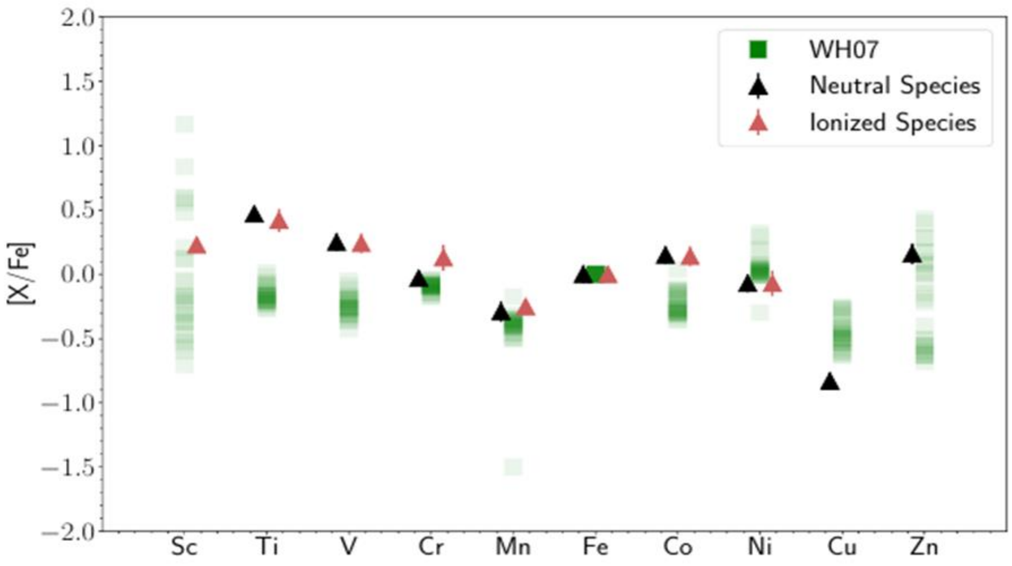
- high density / low temperature $\longrightarrow$ high E_F for electrons $\longrightarrow$ e-captures dominate $\longrightarrow$ n-rich composition
- if el.-degeneracy lifted for high T $\longrightarrow$ ν_e-capture dominates $\longrightarrow$ due to n-p mass difference, p-rich composition

If neutrino flux sufficient to have an effect (scales with $1/r^2$), and total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with $E_{\overline{av,\nu}} - E_{av,\nu} > 4(m_n - m_p)c^2$ lead to $Y_e < 0.5$!

Otherwise the interaction with neutrinos leads to proton-rich conditions. The latter favors improvements in the Fe-group composition Sc, Ti, Co, including the production of ^{64}Ge ($\rightarrow$ ^{64}Zn!), and the *vp-process*, which can produce nuclei up to Sr, Y, Zr and Mo. (Fröhlich, Martinez-Pinedo, Pruet, Wanajo .. Eichler)

Comparison of low metallicity star HD 84937 (Sneden et al. 2016)
with predicted CCSN yields





Good fit to Fe-group composition of low metallicity stars which is dominated by core-collapse supernovae and essentially due to introducing the Ye-variations caused by neutrino interactions during core-collapse and explosion (first suggested by Fröhlich et al. 2006a).

The shaded boxes pass through the whole mass sequence of the two progenitor sets.

Curtis et al. (2019)

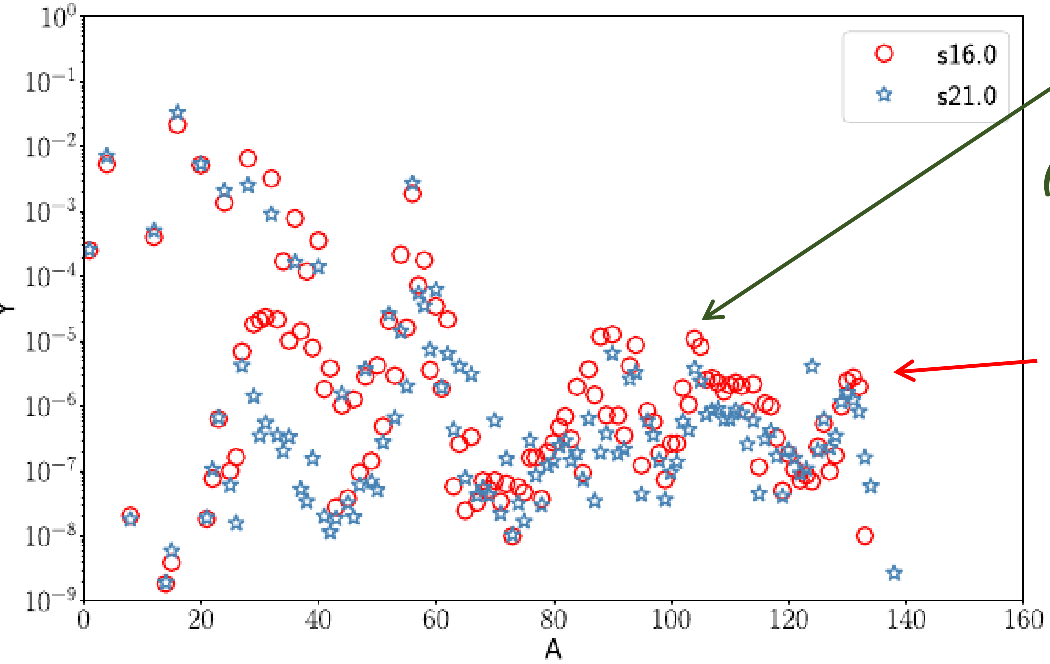
Types of explosive Si-burning: all explosive Si-burning zones in CCSNe lead to an alpha-rich freeze-out.

Other features are due to the Ye or neutron-richness encountered (Curtis et al. 2019)

(1) In outer layers, Ye is essentially given by pre-explosive (hydrostatic) values.

(2) Then follows a region where explosive Si-burning led to unstable nuclei which experience beta$^+$-decay. In a similar way electron captures can lower Ye slightly below 0.5.

(3) Neutrino interactions with nucleons and nuclei can enhance Ye, for similar luminosities of neutrinos and antineutrinos the latter win, making Ye proton-rich >0.5. This, together with the less proton-rich layers of explosive Si-burning (see 2) provides a good fit to the Fe-group composition and also permits a νp-process with abundance produced up to A=100.



(4) The very innermost ejected layers come late, originate from regions deeper in the collapsed core which had become very neutron-rich via e-captures during core collapse, and neutrino interactions were not sufficient to turn them proton-rich. Ye's encountered here range from 0.32 to 0.42. These zone are responsible for a weak r-process and abundances up to A=140 (see also Wanajo 2013 for proto-neutron star, < 2Msol, neutrino winds, possibly permitting a weak r-process up to Lanthanides - subsolar by a factor 10-100) .

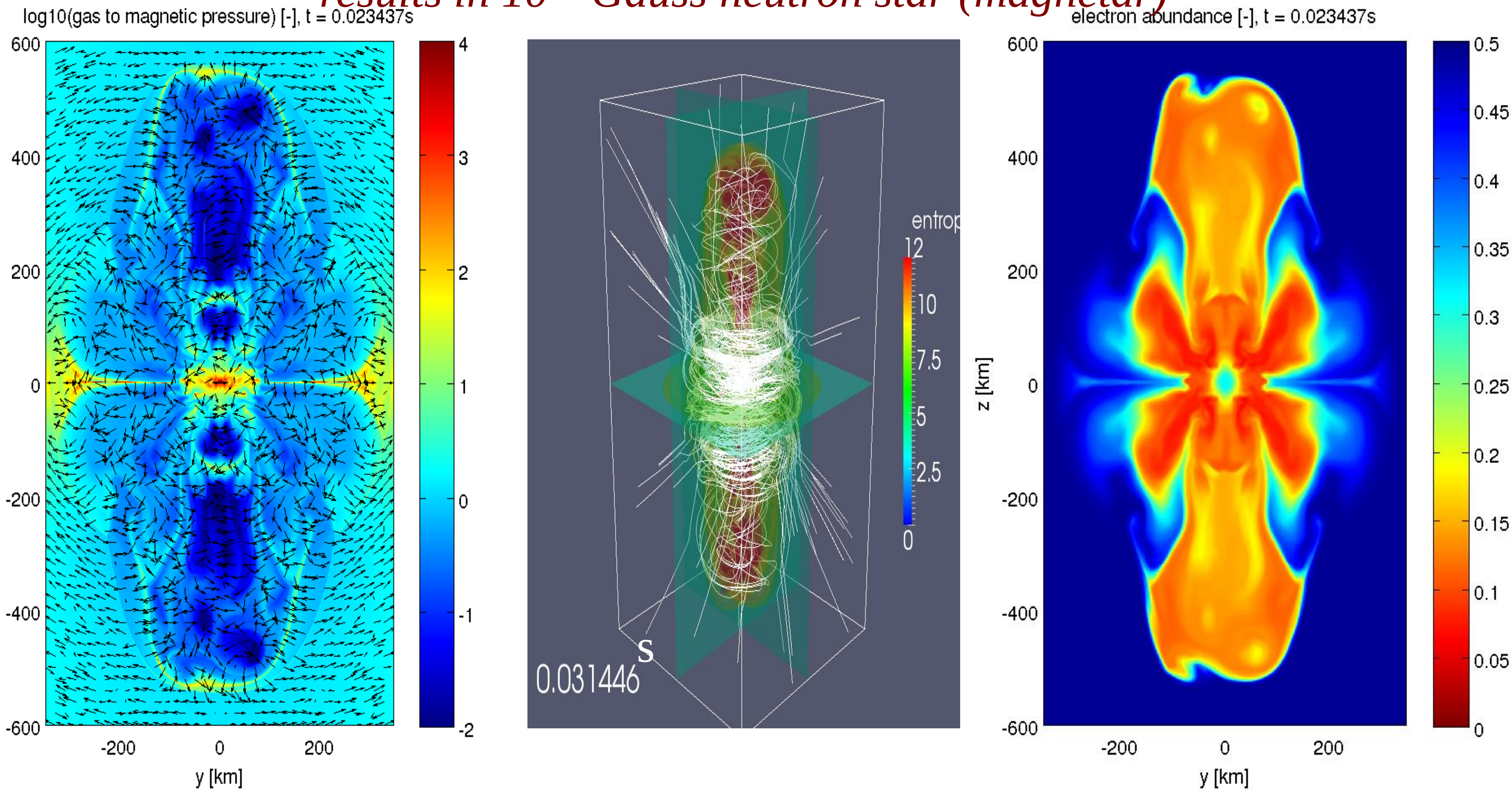
Abundances of explosive ejecta for two progenitors

A rare class of Magneto-Rotational Supernovae

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 $x10^{12}$ Gauss,

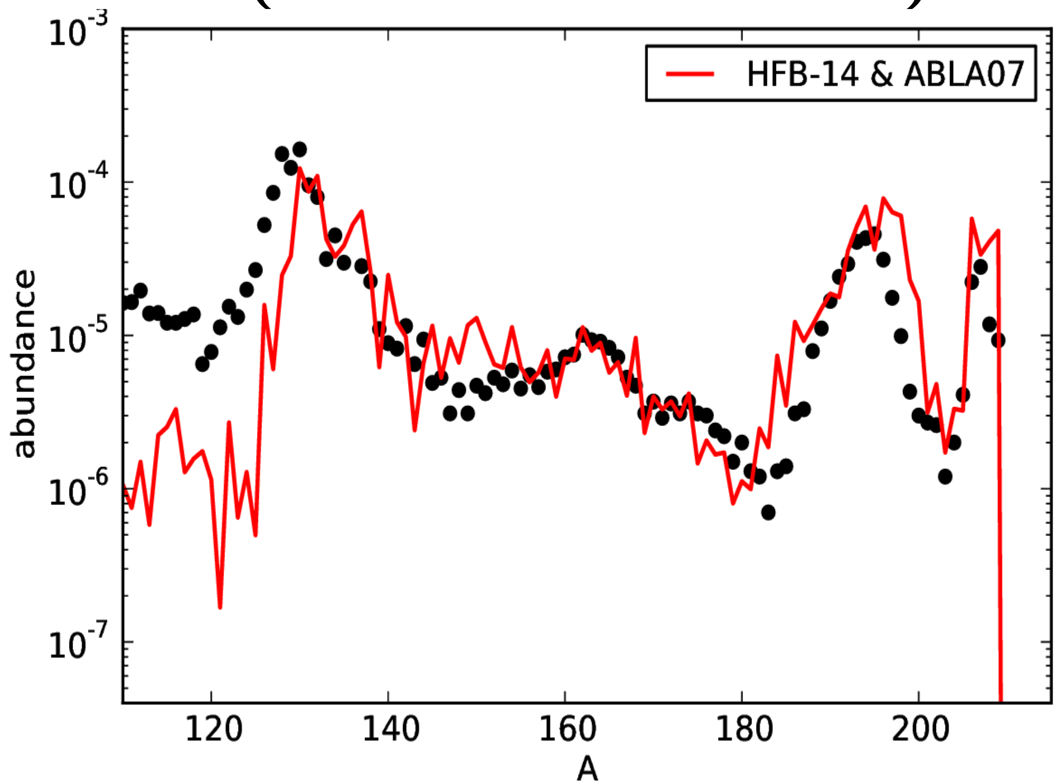
results in 10^{15} Gauss neutron star (magnetar)



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

Nucleosynthesis results, utilizing Winteler et al. (2012) model with variations in nuclear Mass Model and Fission Yield Distribution

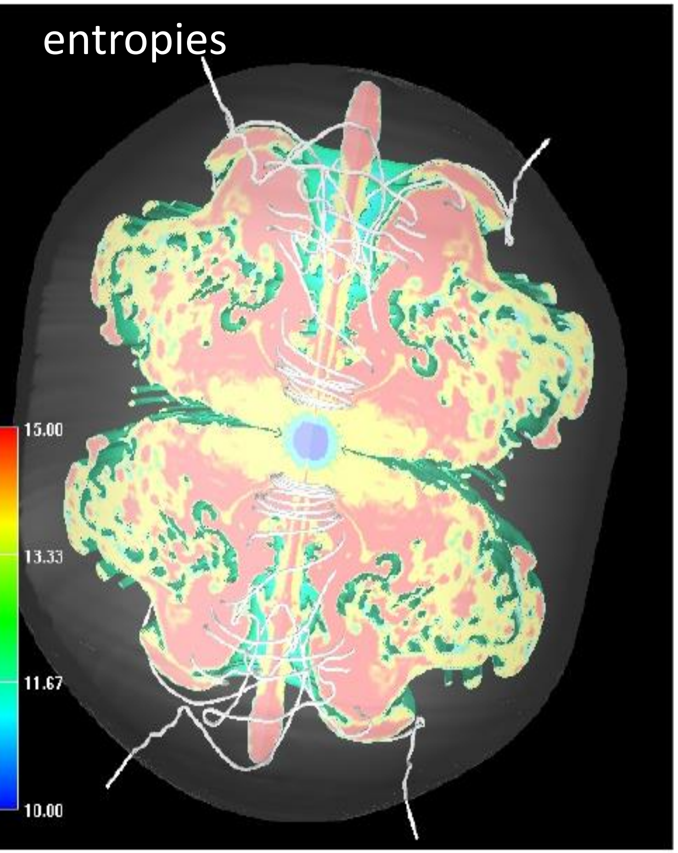
(Eichler et al. 2015)

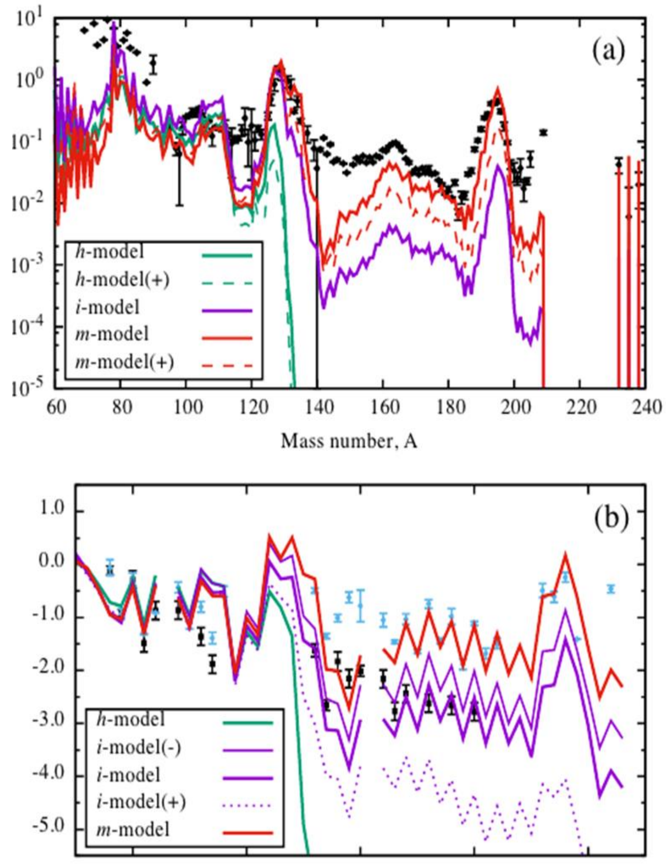


Fission-cycling environments permit n-capture due to fission neutrons in the late freeze-out phase and shifts peaks, but effect generally not strong and overall good fit in such "weak" fission-cycling environments!

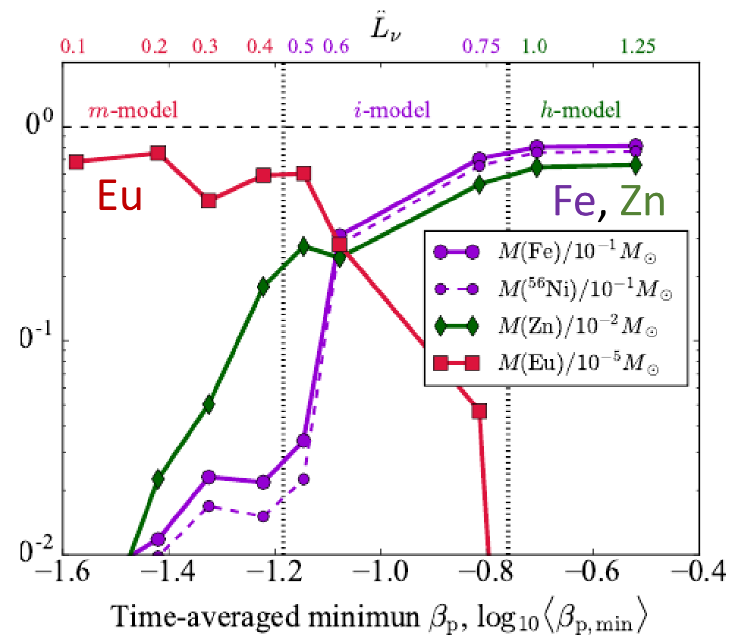
Ejected matter with A>62 $M_{\mathrm{r,ej}} \approx 6 \times 10^{-3}\ M_{\odot}$

Full MHD calculations resolving the magneto-rotational instability MRI (Nishimura, Sawai, Takiwaki, Yamada, Thielemann, 2017)





Measuring the ratio of magnetic field strength in comparison to neutrino heating



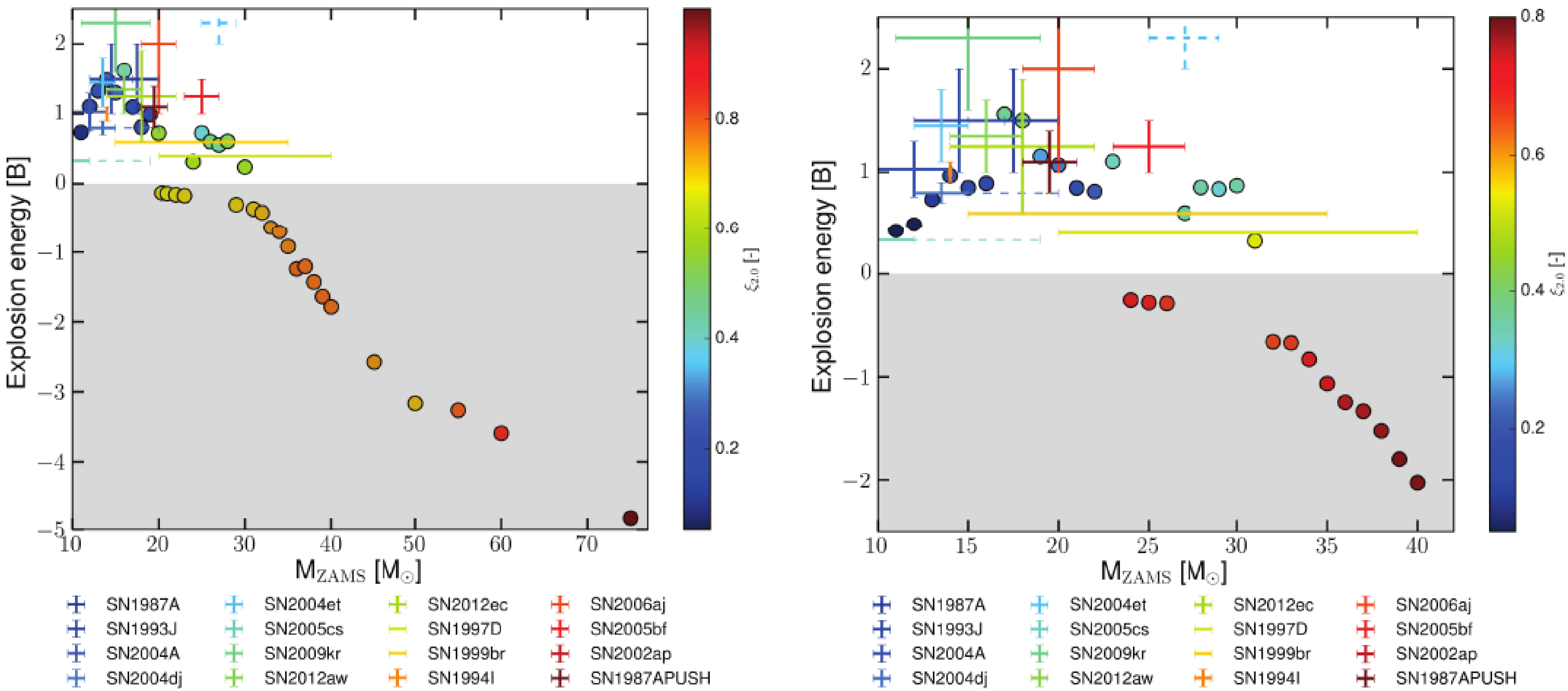
Dependent on the relation between neutrino luminosity and magnetic fields the nucleosynthesis behavior changes from regular CCSNe to neutron-rich jets with strong r-process.

high magnetic fields required for low Ye's and a strong r-process

(close to 10^{13} Gauss for massive progenitors, see also Mösta et al. 2017)

Halevi et al. (2018) test influence of alignment of rotation axies with magnetic fields.

Results of the PUSH Approach (Ebinger et al. 2019): Black hole formation beyond about 30 Msol

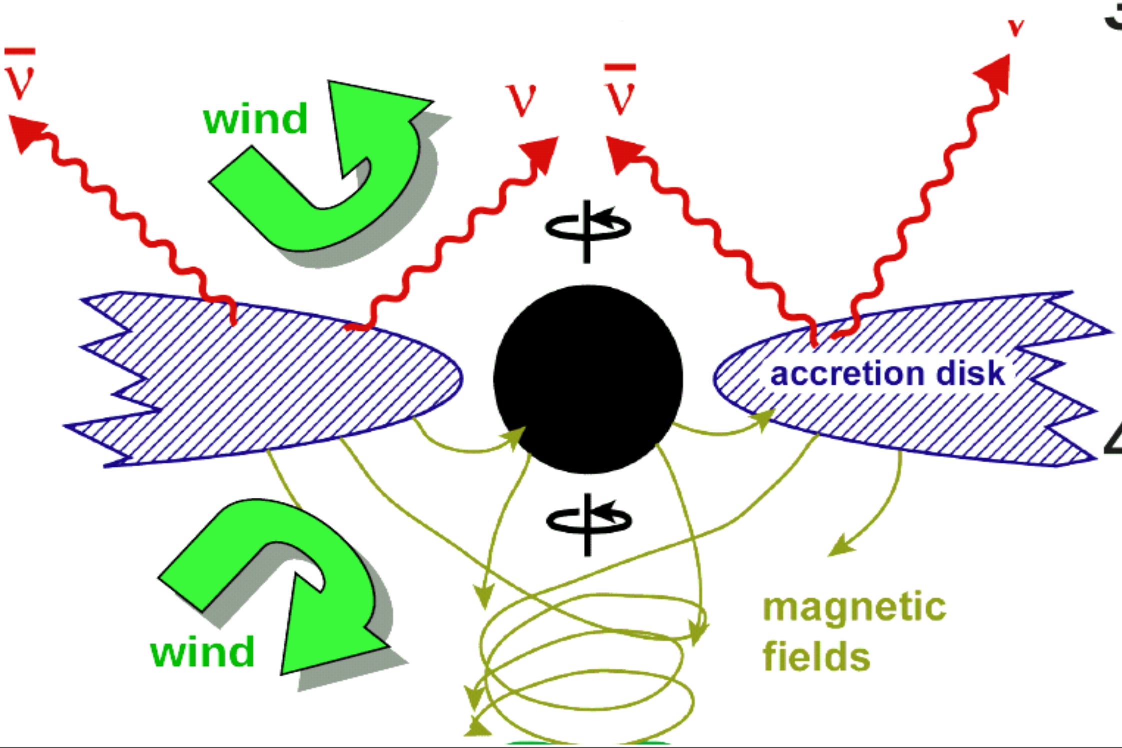


For 2 sets of stellar progenitor models (Woosley et al. 2002, Woosler & Heger 2007), Results clearly depend on the compactness of the central stellar core!!!!!!

How else can massive stars explode?

$25M_\odot < M < 100M_\odot$,
$M > 250M_\odot$

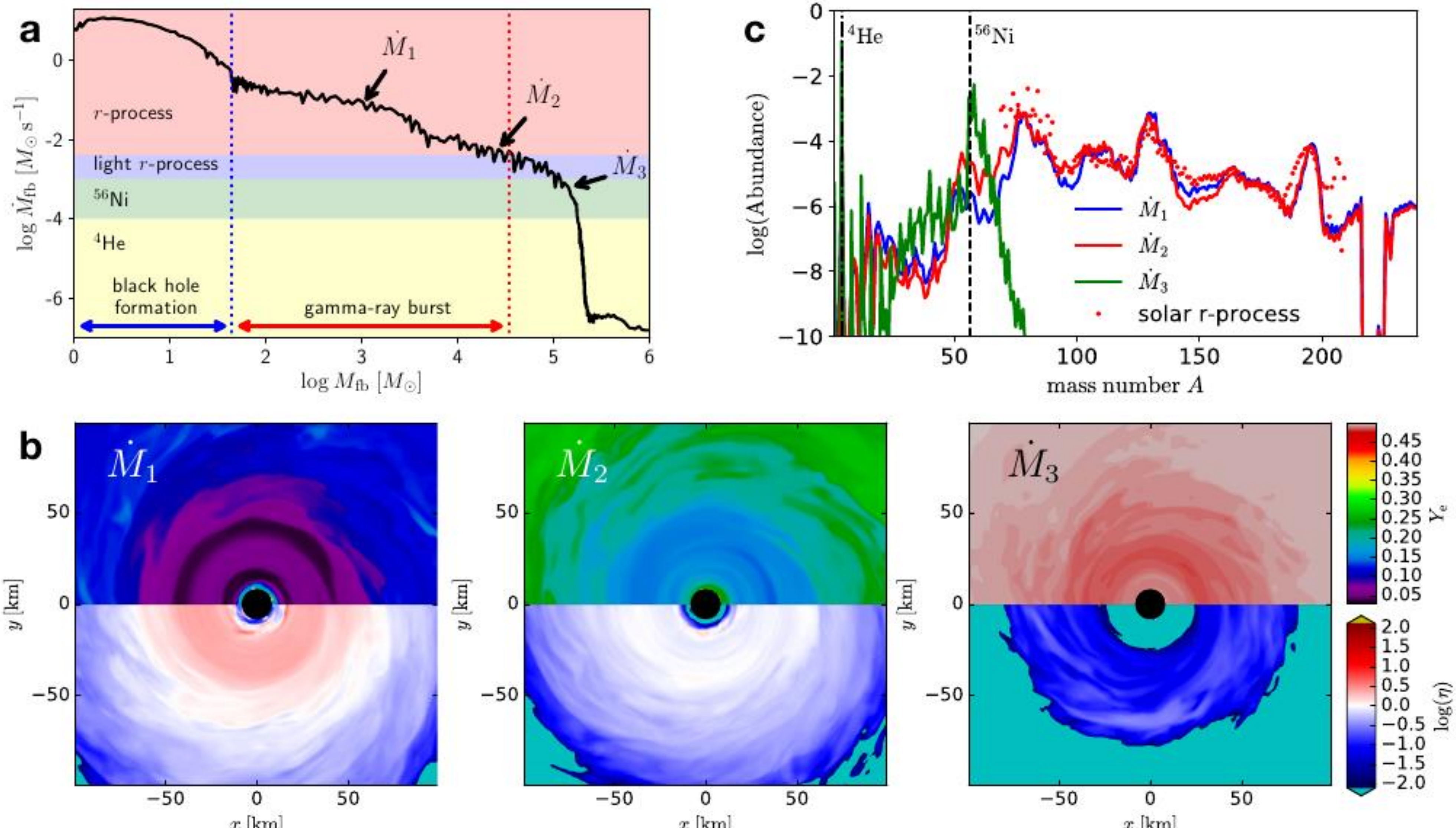
The “Collapsar Engine”



1. black hole forms inside the collapsing star
after failure of neutrino-powered explosion
2. The infallin_ matter forms and accretion disk $\simeq 0.1\ M_\odot/\mathrm{sec}$
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

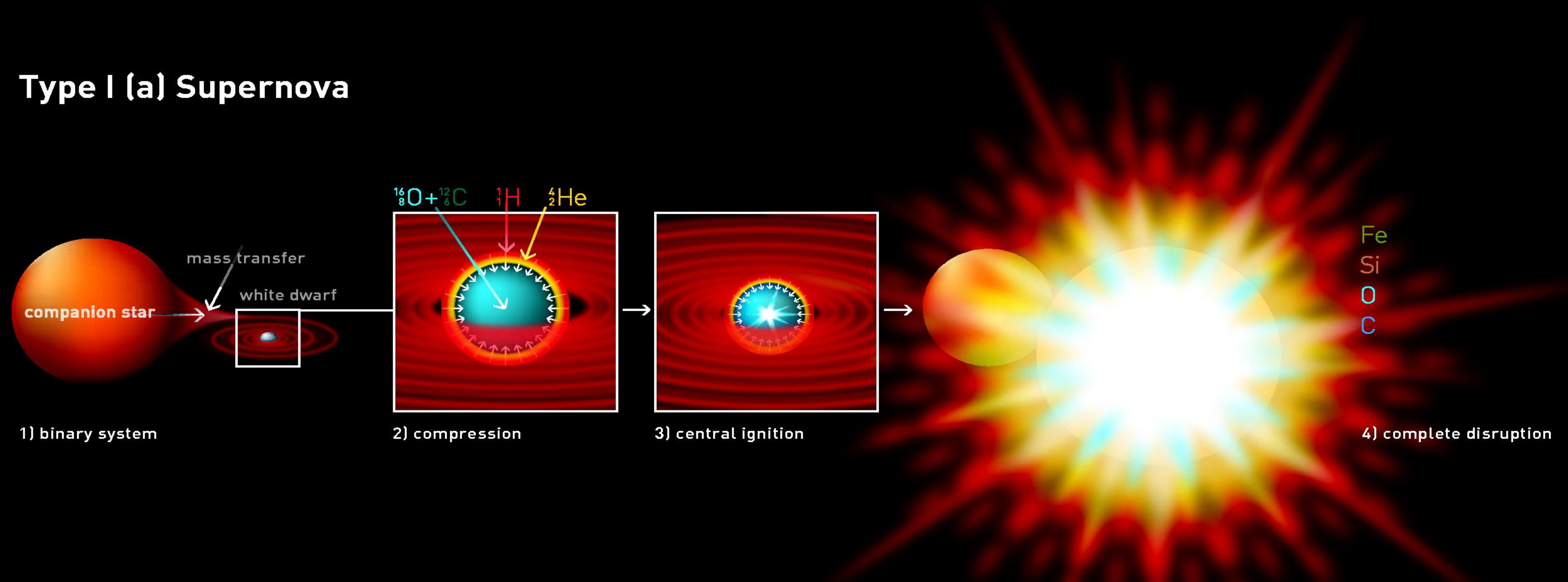
Adopted from MacFadyen (requiring black hole formation and rotation)

Siegel+ (2019) find in in general relativistic MHD simulations, making use of weak interactions (including also electron degeneracy and electron capture on protons) and approximate neutrino transport (leakage scheme) in total the ejection of up to $1M_\odot$ of r-process ejecta (Janiuk, private communication, seems to obtain similar results).



The scenario assumes that in a first phase a powerful supernova explosion ejects the typical up to $0.5M_\odot$ of ^{56}Ni (if these events are supposed to be identical with hypernovae) and further accretion leads to a black hole plus a BH accretion disk. somewhat fine-tuned scenario??

Explosions caused by accretion in *binary stellar systems*

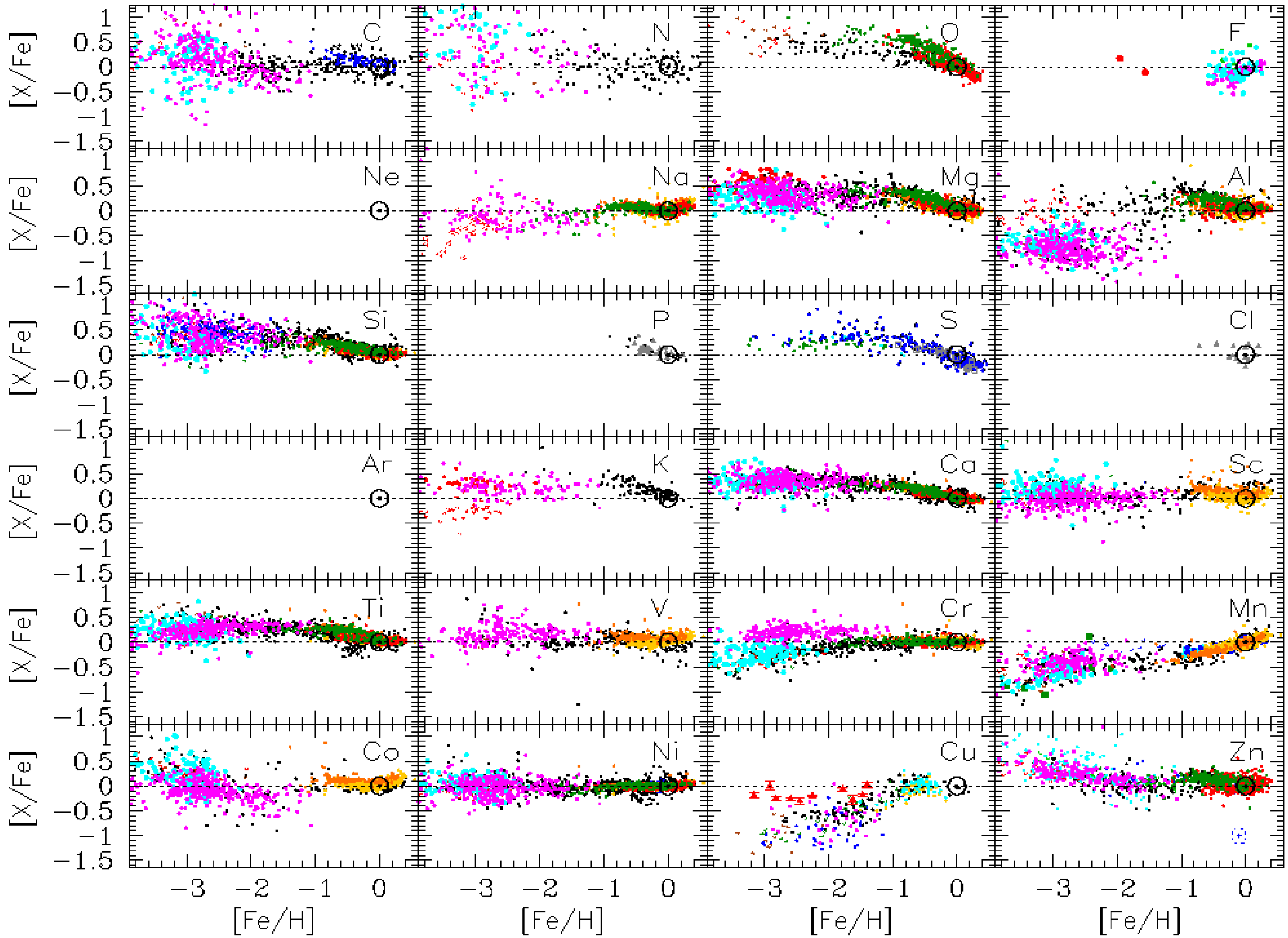


binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- white dwarfs (novae, type Ia supernovae)
- neutron stars (type I X-ray bursts, superbursts?)

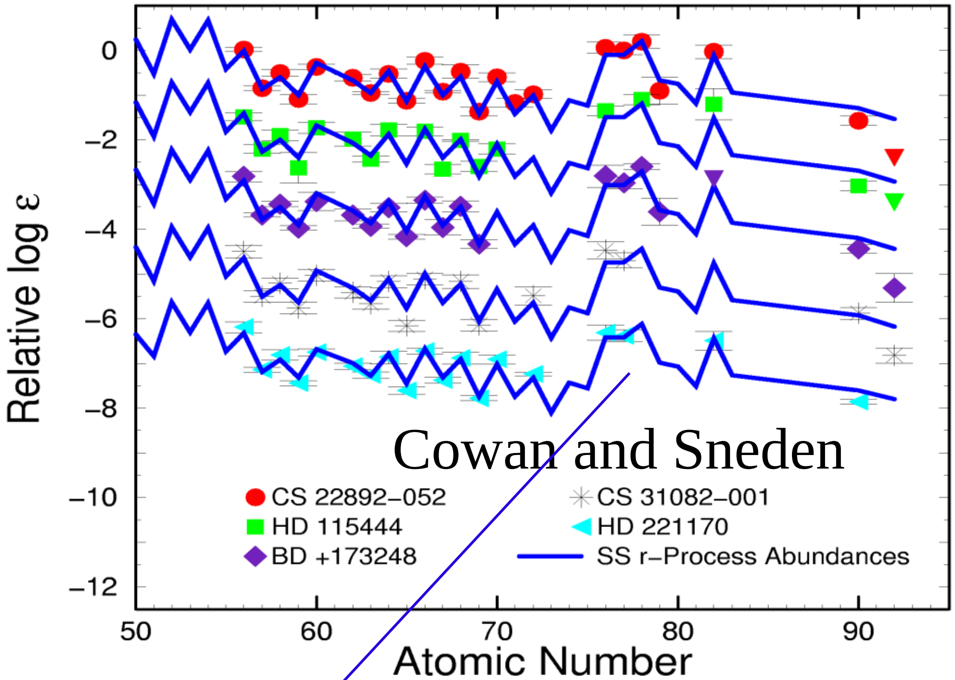
Other options:
White Dwarf Mergers (super-Chandrasekhar)
He-accretion on WD (sub-Chandra)

Stellar Surface Abundances (inherited from the gas of the interstellar medium when they formed) give a clue to the abundance evolution in the Galaxy as a function of time or «metallicity», adopted from Prantzos (2019). [Fe/H] measures logarthmically the Fe/H ratio (0=solar, -1 = 1/10, -2 = 1/100 ...). Fast evolving massive stars (their winds and core-sollapse supernovae) contribute dominantly up to [Fe/H]=-1 and overproduce the alpha-elements O, Mg, Si, S, Ca, Ti by a factor 2-3 in comparison to solar.



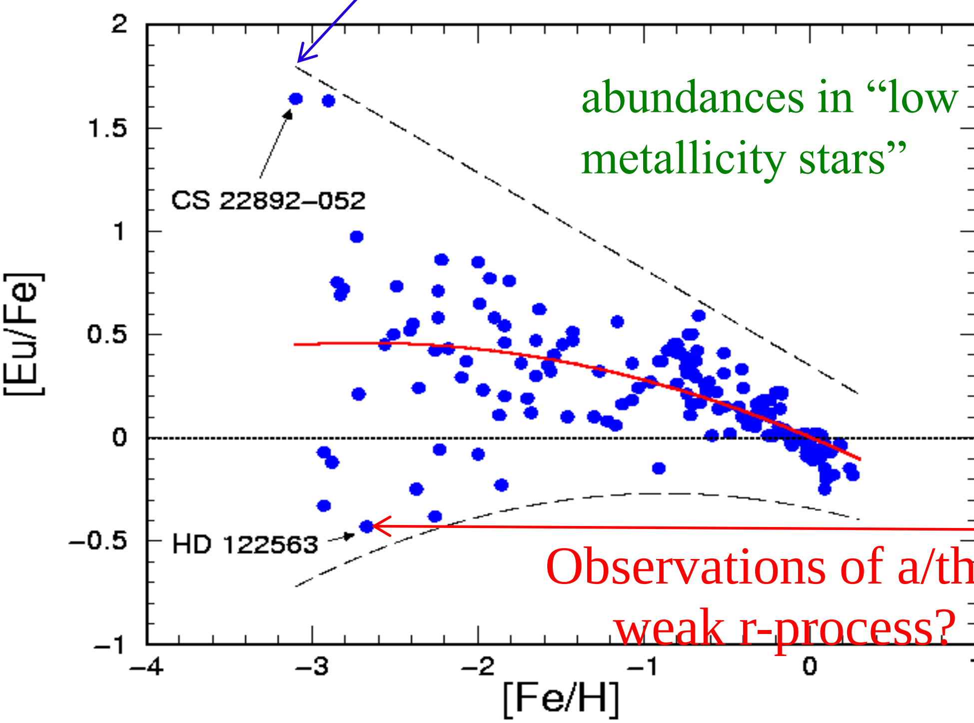
The contribution of type Ia supernovae (with larger amounts of Fe and a delayed formation time in binary systems) becomes apparent at [Fe/H]=-1. Many elements of the Fe-group (Sc, V, Cr, Co, Ni, Zn) are co-produced in similar portions in both types of SNe. Mn and Cu are dominantly produced in SNe Ia, Co and Zn need an early input from hypernovae/collapsars.

Low-metallicity observations of r-process abundances

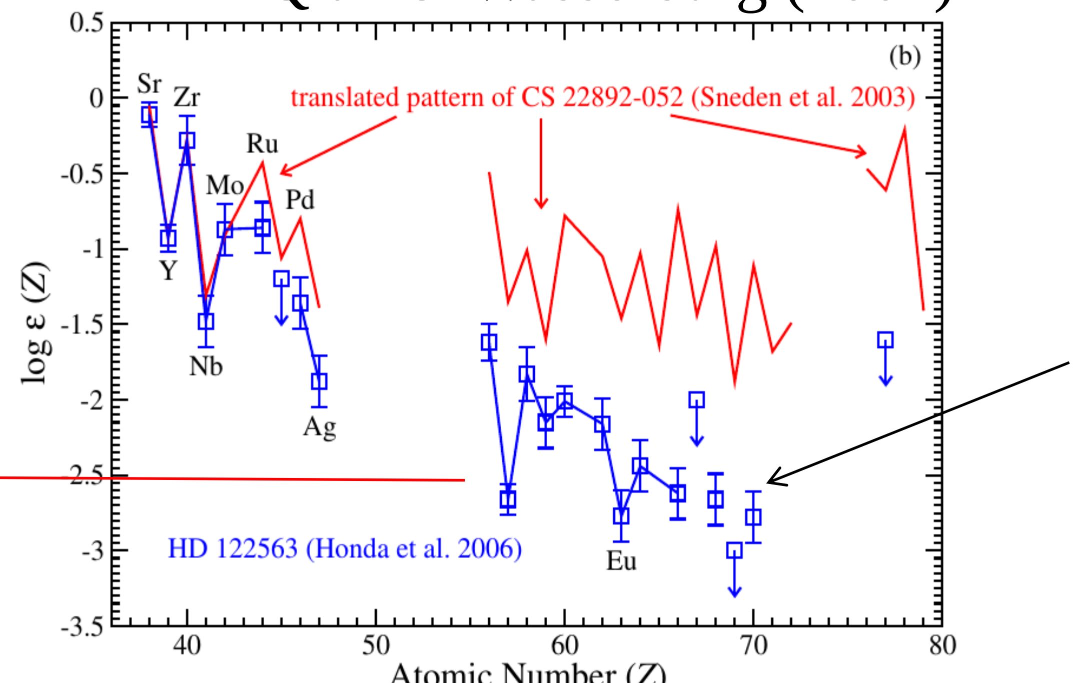


apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

Weak (non-solar) r-process in Honda-type stars

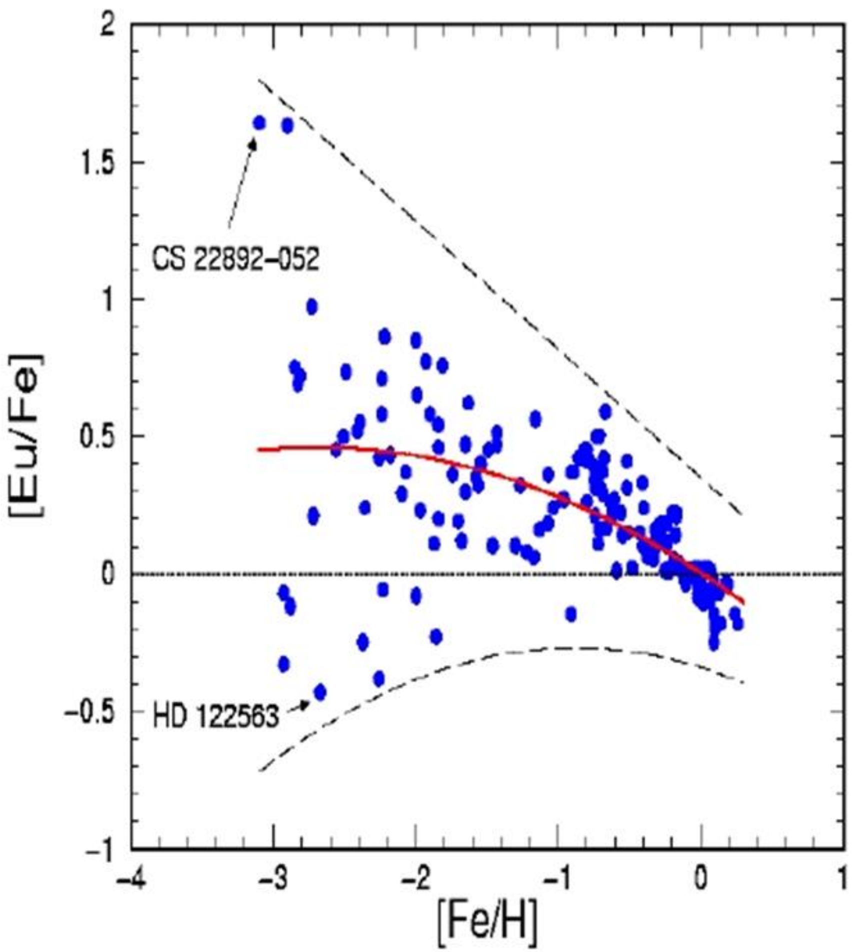


Qian & Wasserburg (2007)

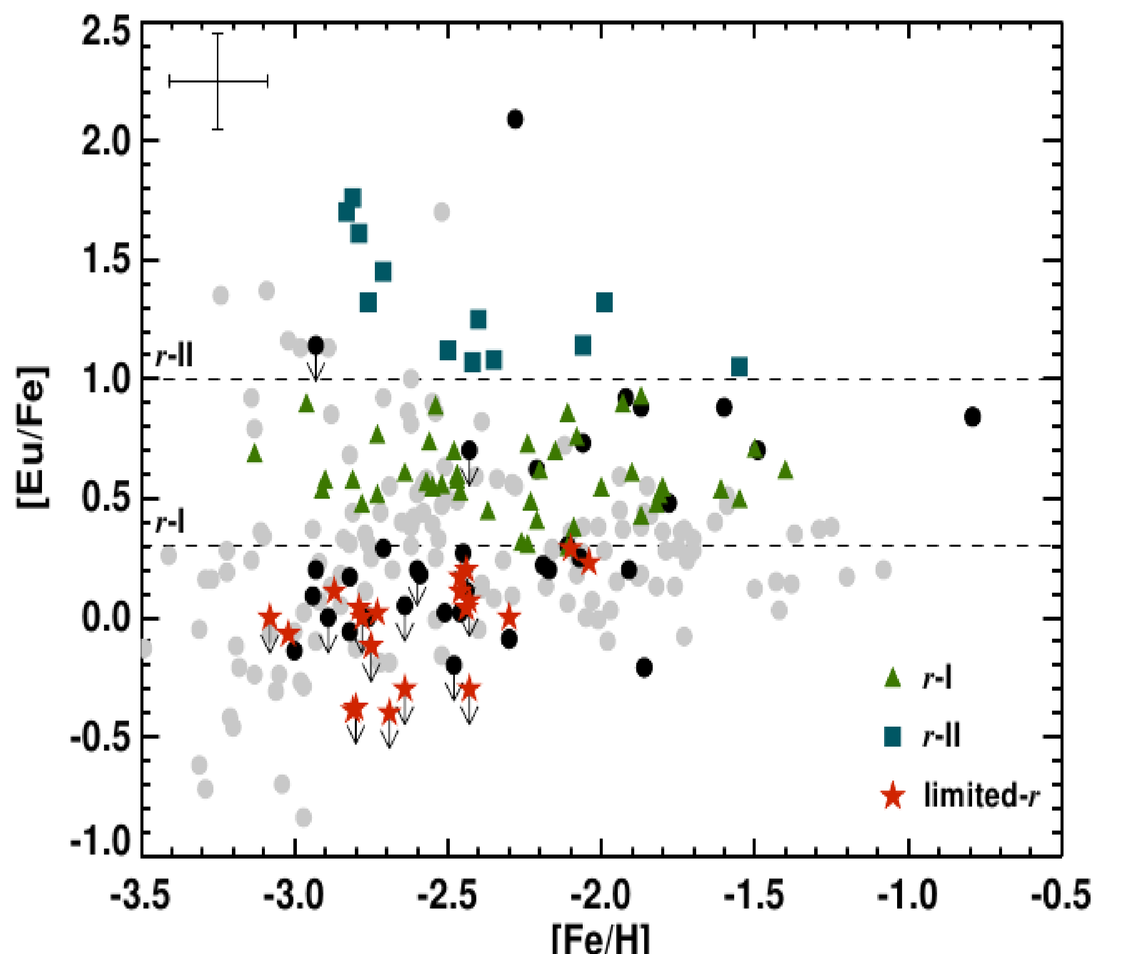


Average *r-process (Eu) behavior resembles CCSN contribution of alpha elements (O, Mg, SI, S, Ca, Ti), but large scatter at low metallicities!!*

The scatter of [Eu/Fe] at low metallicities by more than two orders of magnitude indicates rare events (compact binary mergers and/or a rare class of supernovae/hypernoae/collapsars)?
But does not exclude a very low base value from regular core-collapse supernovae?

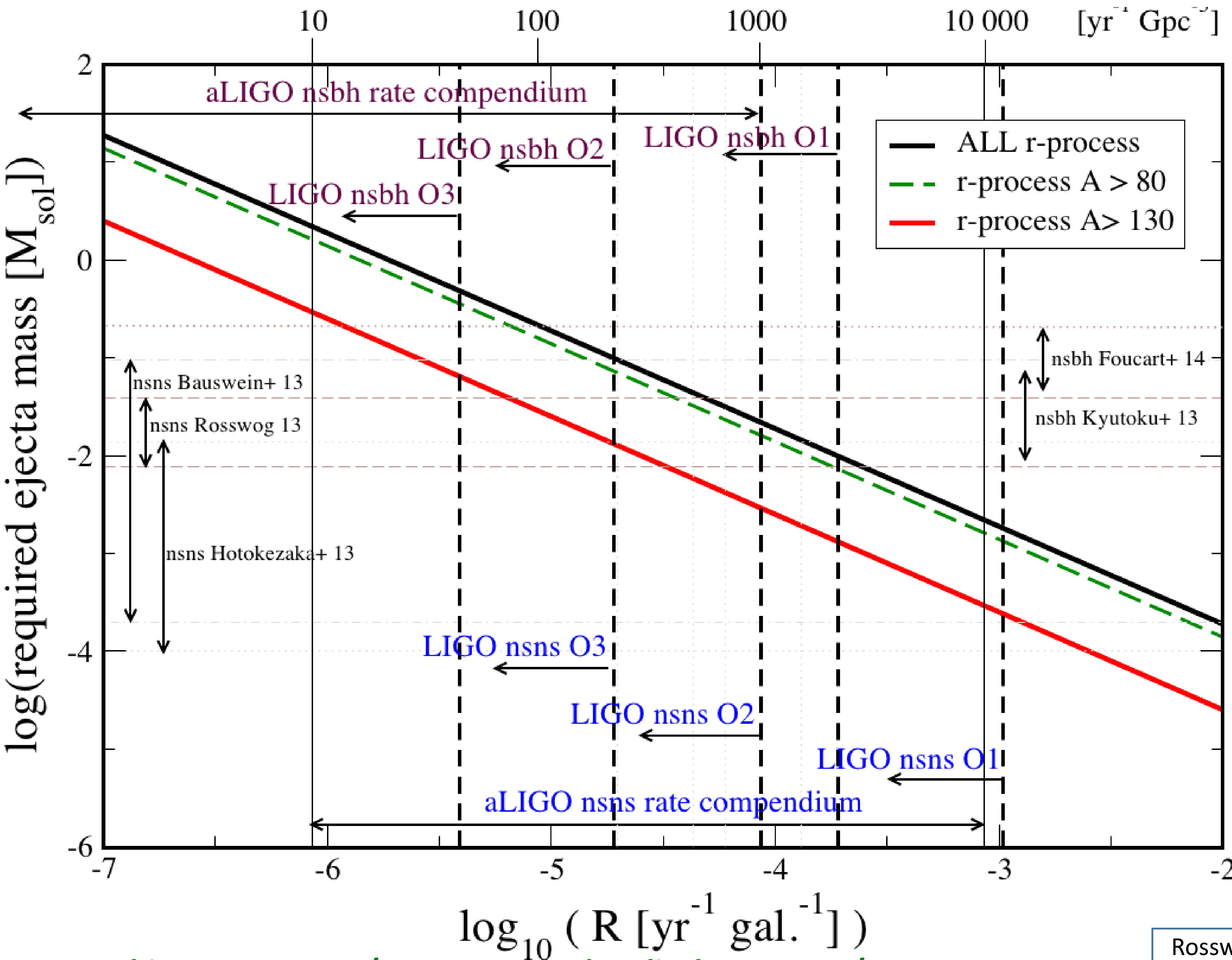


Cowan & Thielemann (2004)



«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)

Necessary event rate / production for final solar r-process abundances:
This applies to any type of rare r-event, whether CC supernova or NS or NS-BH merger



Rosswog+ 2018

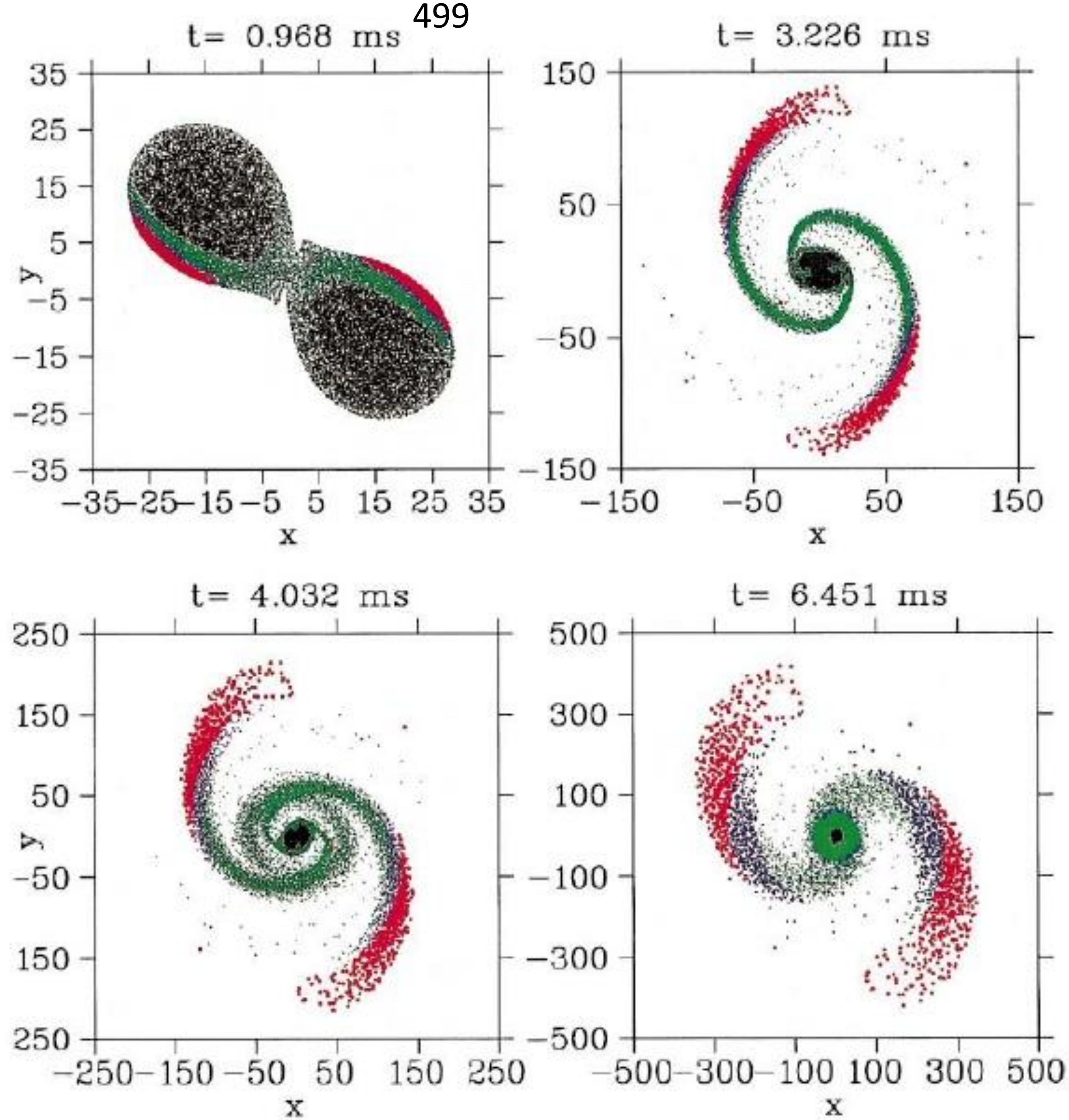
Matteucchi+ 2014: 1 NSM / 100 CCSNe – Chruslinska+ 2016 1 / 1000

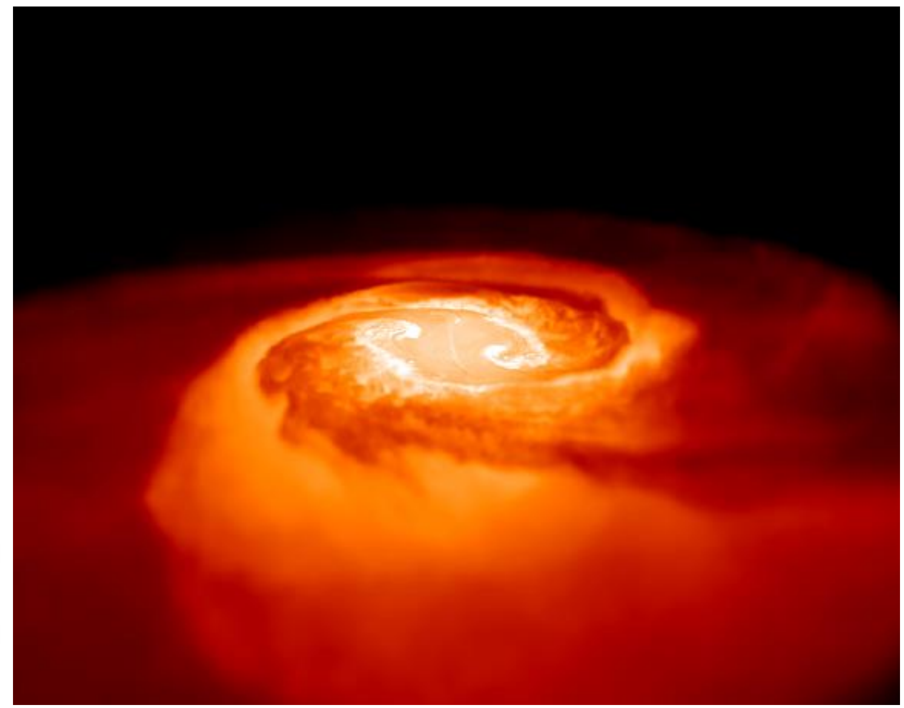
Early and later simulations of neutron star mergers

„Classical“ r -process site: NSMs and their «dynamic ejecta»

Rosswog et al.
A&A 341 (1999)
499

only tidal arms in early approaches



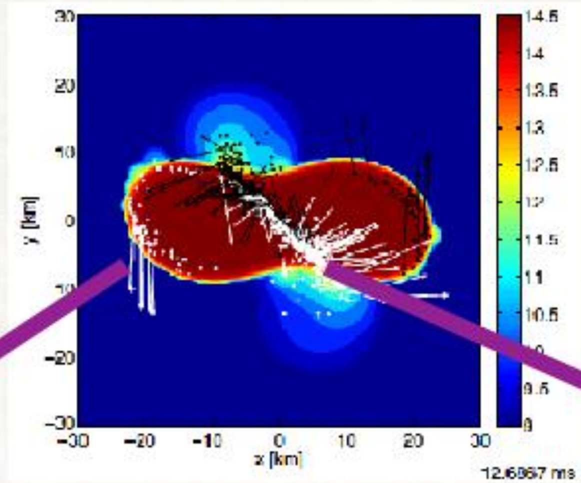


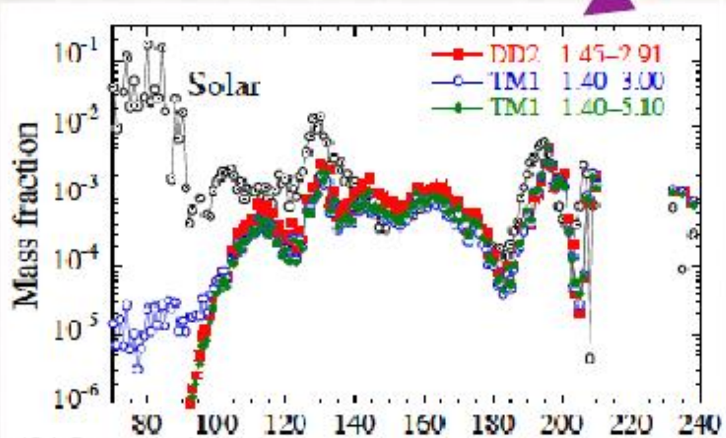
Rosswog et al. 2014

Prompt / dynamical Ejecta

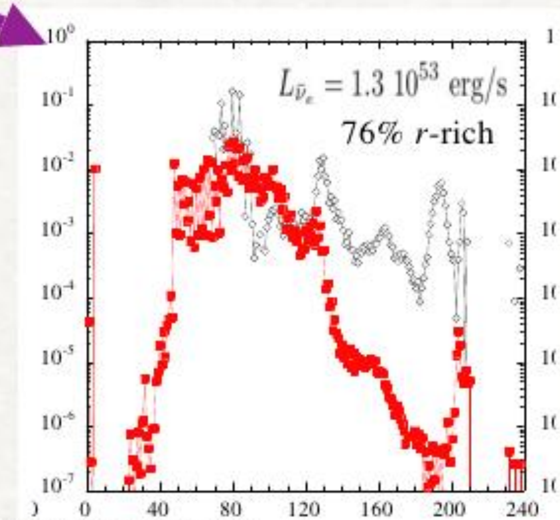
(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16)

from Just (2018)
Shanghai talk





(OJ, Bauswein, Ardevol, Goriely, Janka '15)

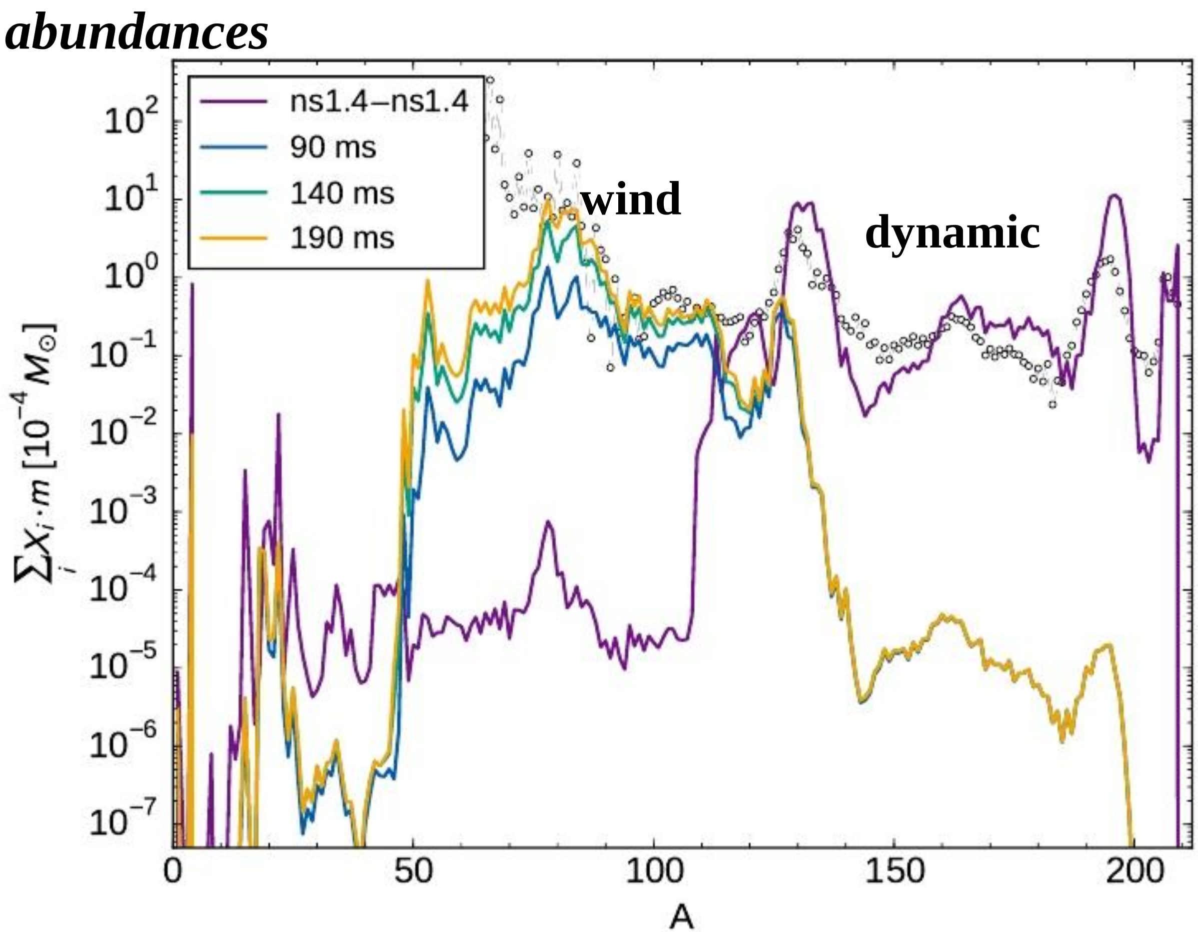


(Goriely et al '15+'18)

from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

from collision shock
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

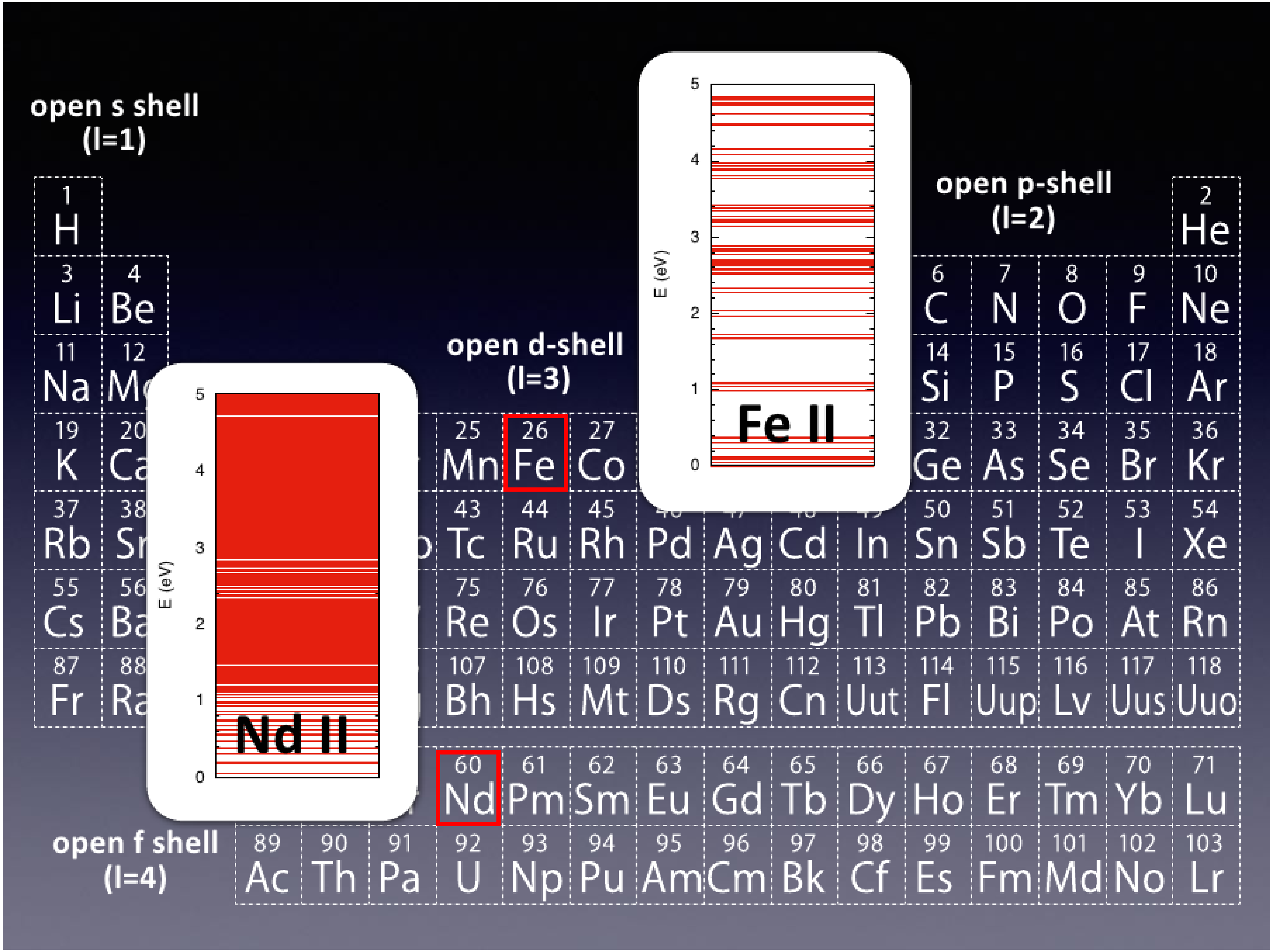
After dynamic ejection of matter, the hot, hypermassive neutron star (before – possibly and with which delay - **collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014), Martin et al. (2015)**

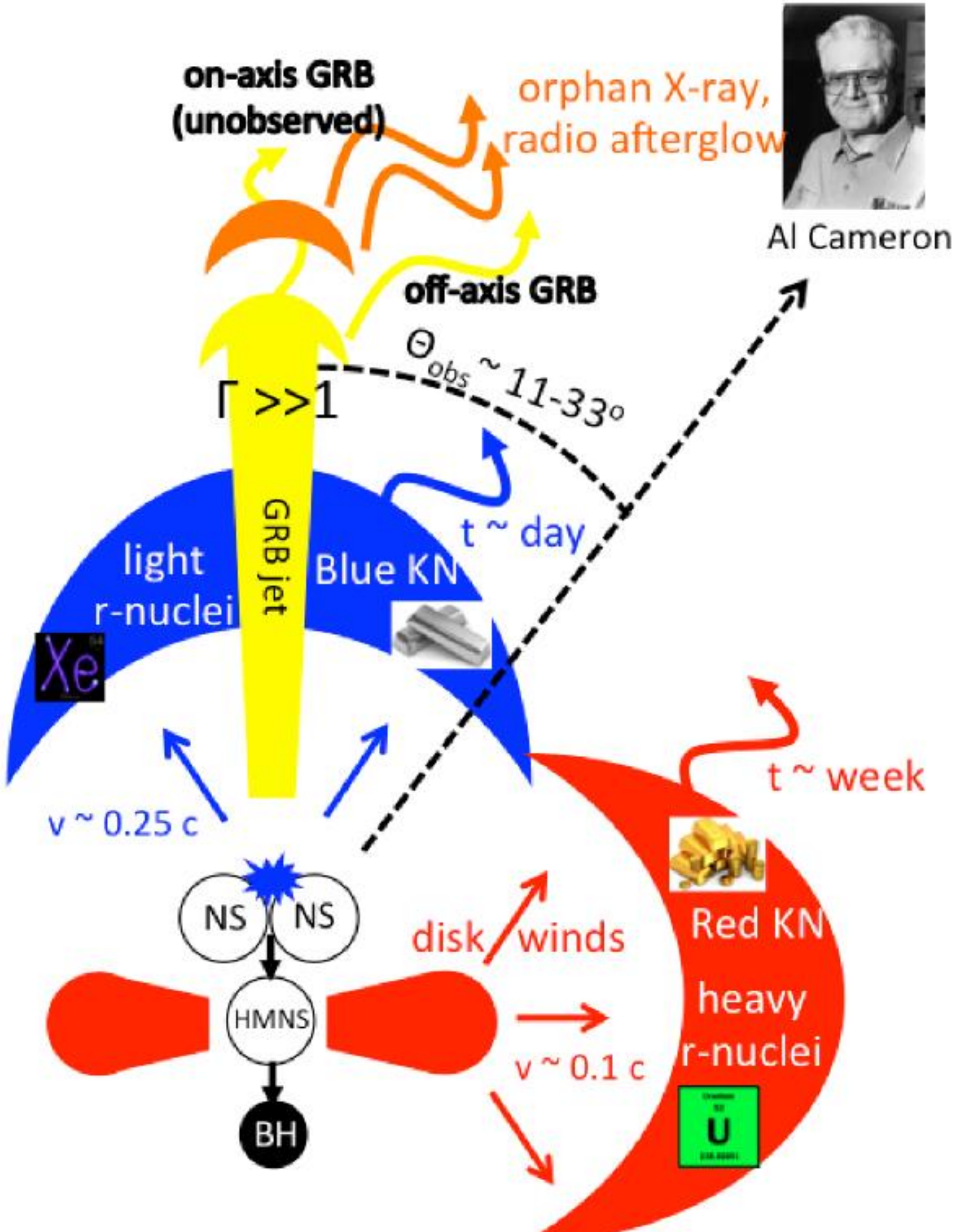


Martin et al. (2015) with neutrino wind contributions, here still combined with composition of dynamic ejecta of Korobkin+ (2012) with their known deficiences.

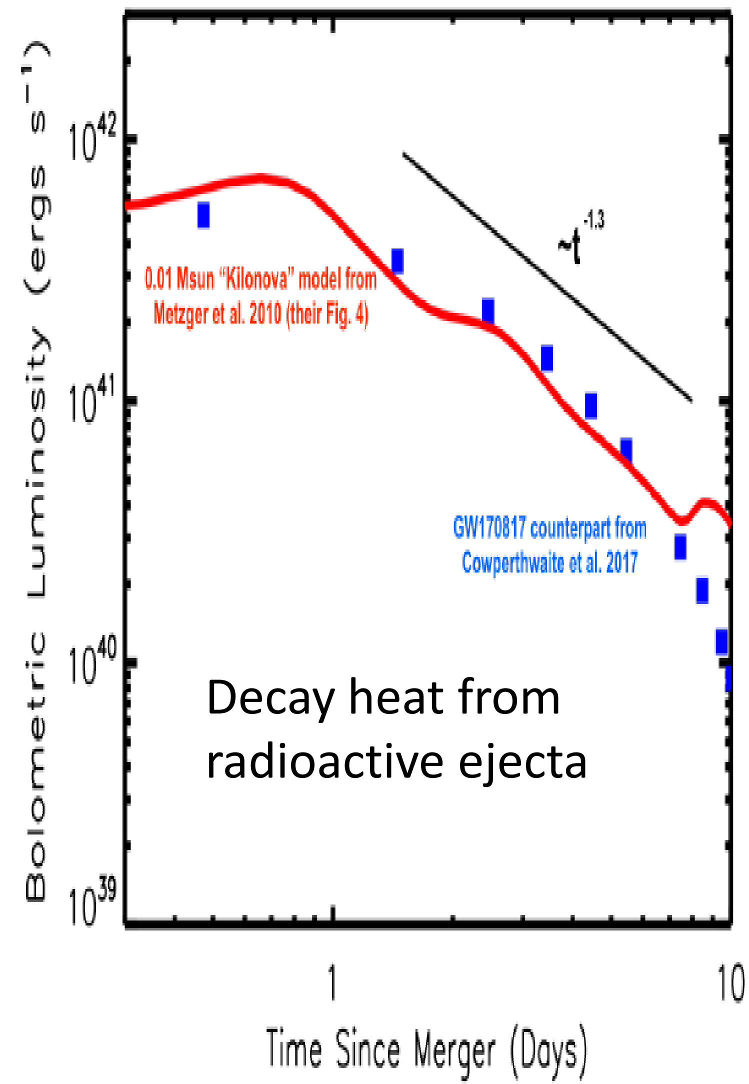
Different opacities of matter due to density of atomic states

(from M. Tanaka 2017)





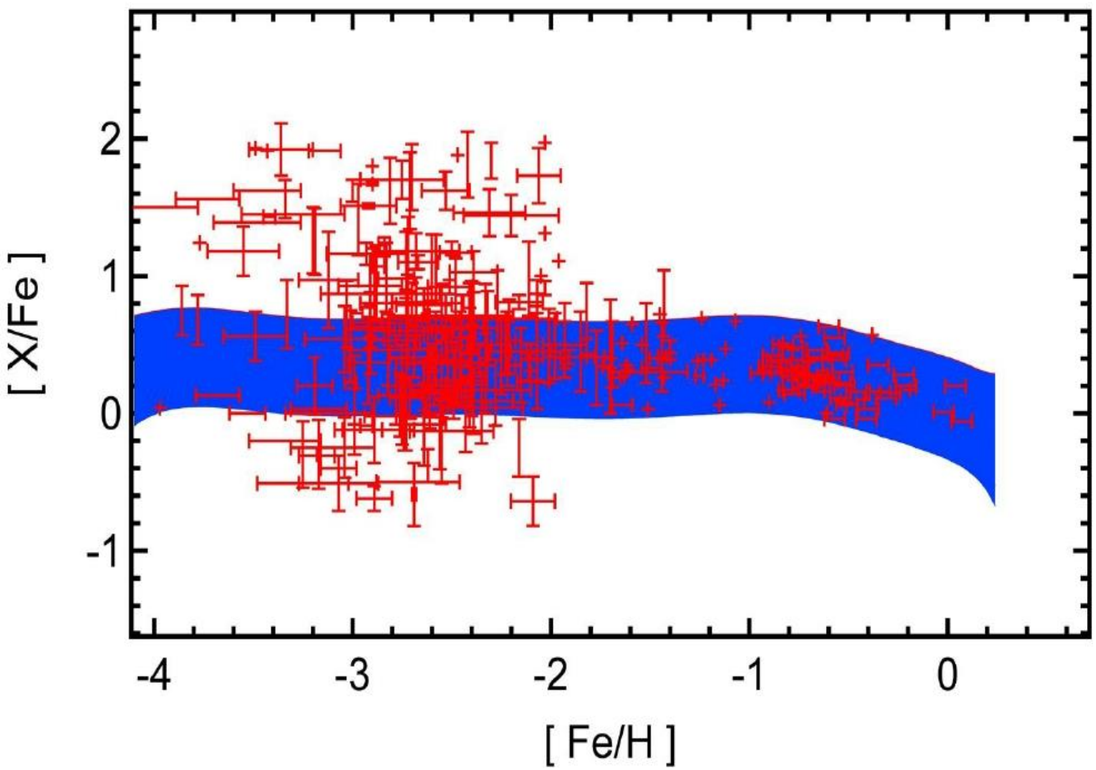
Metzger, Martinez-Pinedo
et al. (2010)



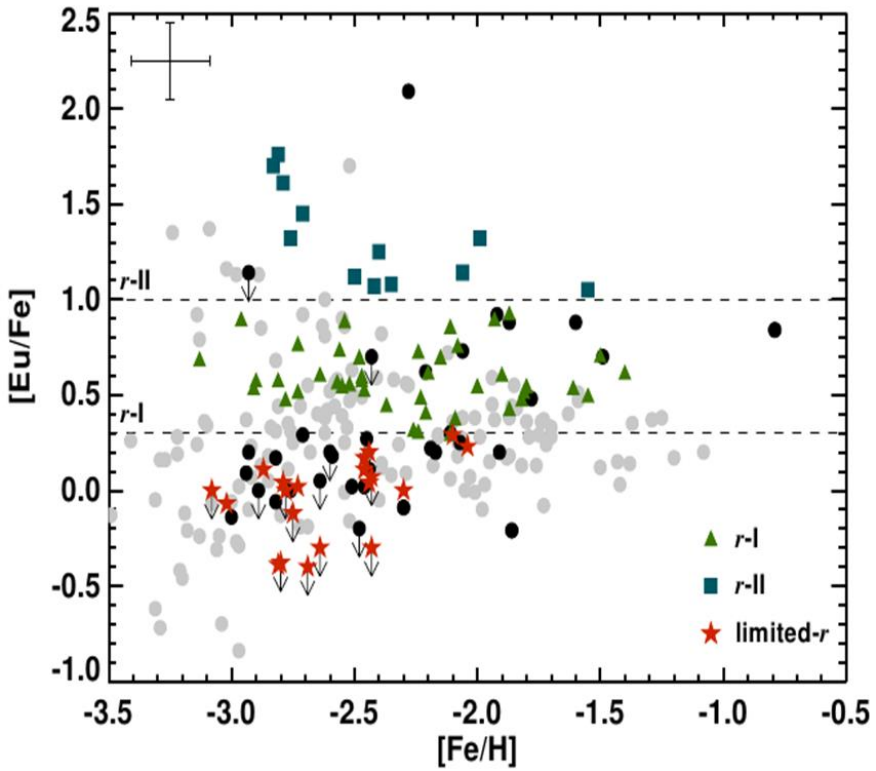
Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation

Rare events lead initially to large scatter before an average is attained in galactic evolution!
Need for inhomogeneous modeling!

Data from SAGA database



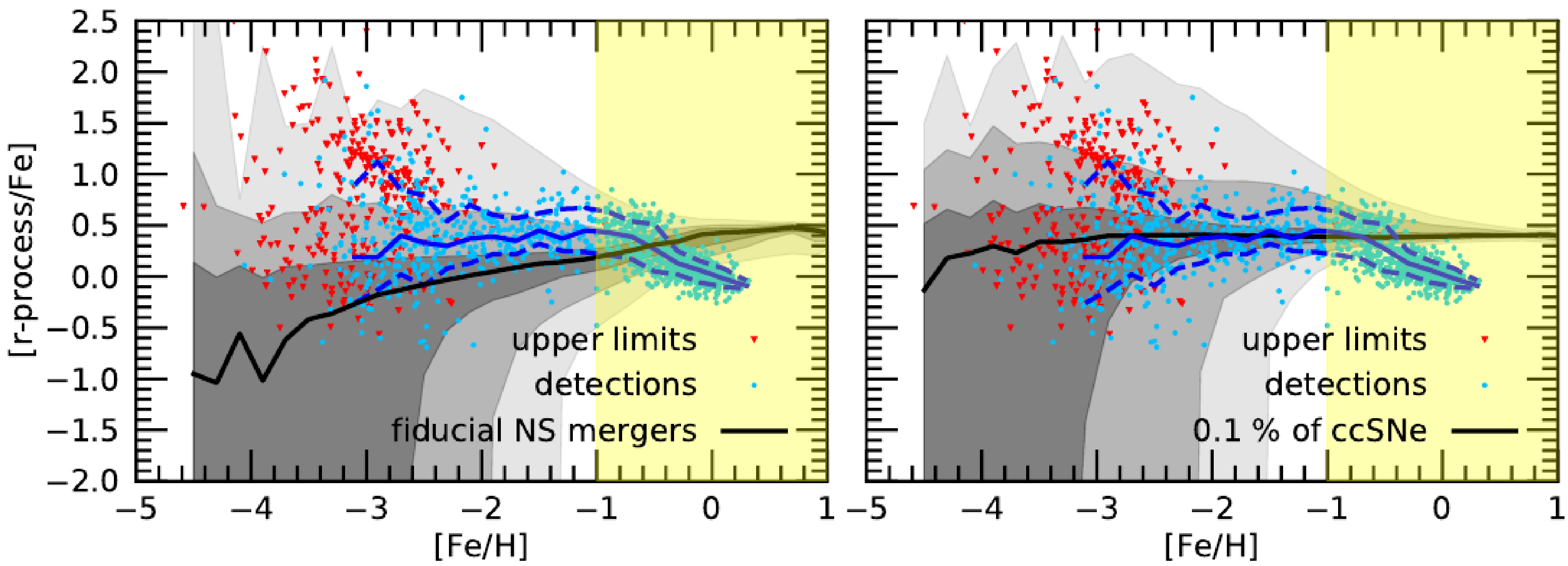
«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)



Blue band: Mg/Fe observations (95%), explained from _frequent_ CCSNe, red crosses: individual Eu/Fe obs.

^{60}Fe and ^{244}Pu measurements in deep sea sediments also indicate that the strong r-process is rare in comparsion to CCSNe!

Cosmological simulation by F. van de Voort et al. (2019)*,*
including mixing processes, which also move [Eu/Fe] to lower metallicities. But also in this case NS-mergers alone cannot explain the full spread/scatter at low metallicities, still produce a rising rather than flat median trend.
Only the inclusion of rare single massive star events (1 permille of CCSNe) leads to a flat median and a consistent scatter.



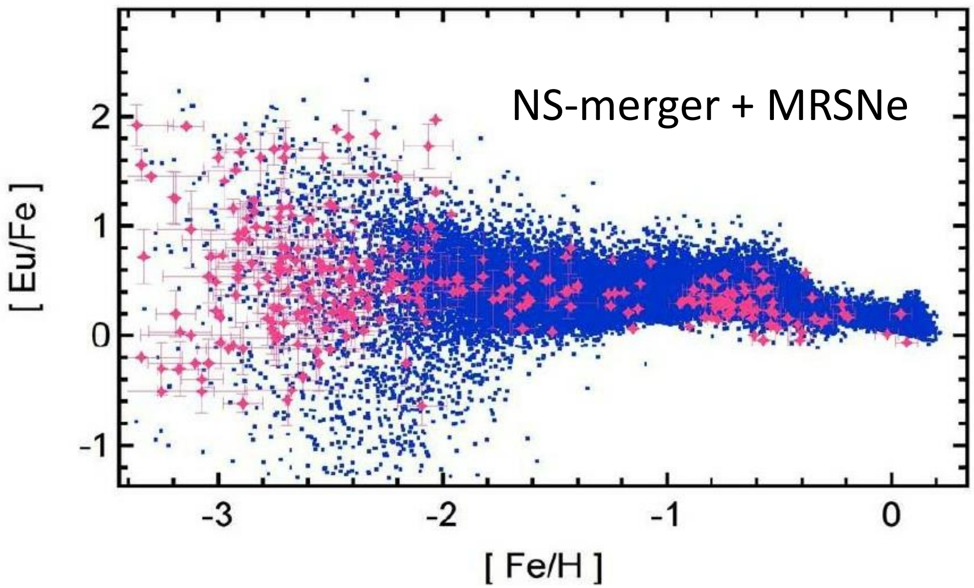
Combination of (a) NS mergers and magneto-rotational jets or (b) NS-BH and NS-mergers mergers (occuring earlier/at lower metallicity in galactic evolution, either

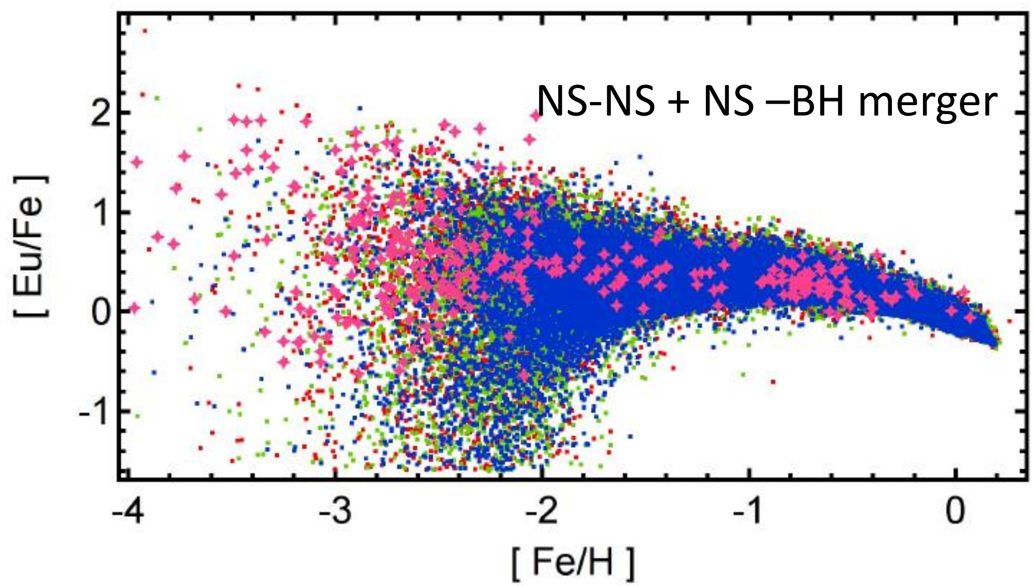
(a) because of massive star origin or

(b) because only one SN explosion of the binary system ejects Fe, less SNe occur due to BH formation, and shorter delay times because of more massive BHs)

in (stochastic) inhomogeneous GCE

Wehmeyer, Pignatari, Thielemann (2015), Wehmeyer et al. (2019)





variations in minimum mass for BH formations

$\Rightarrow$ Options to solve the low metallicity problem,

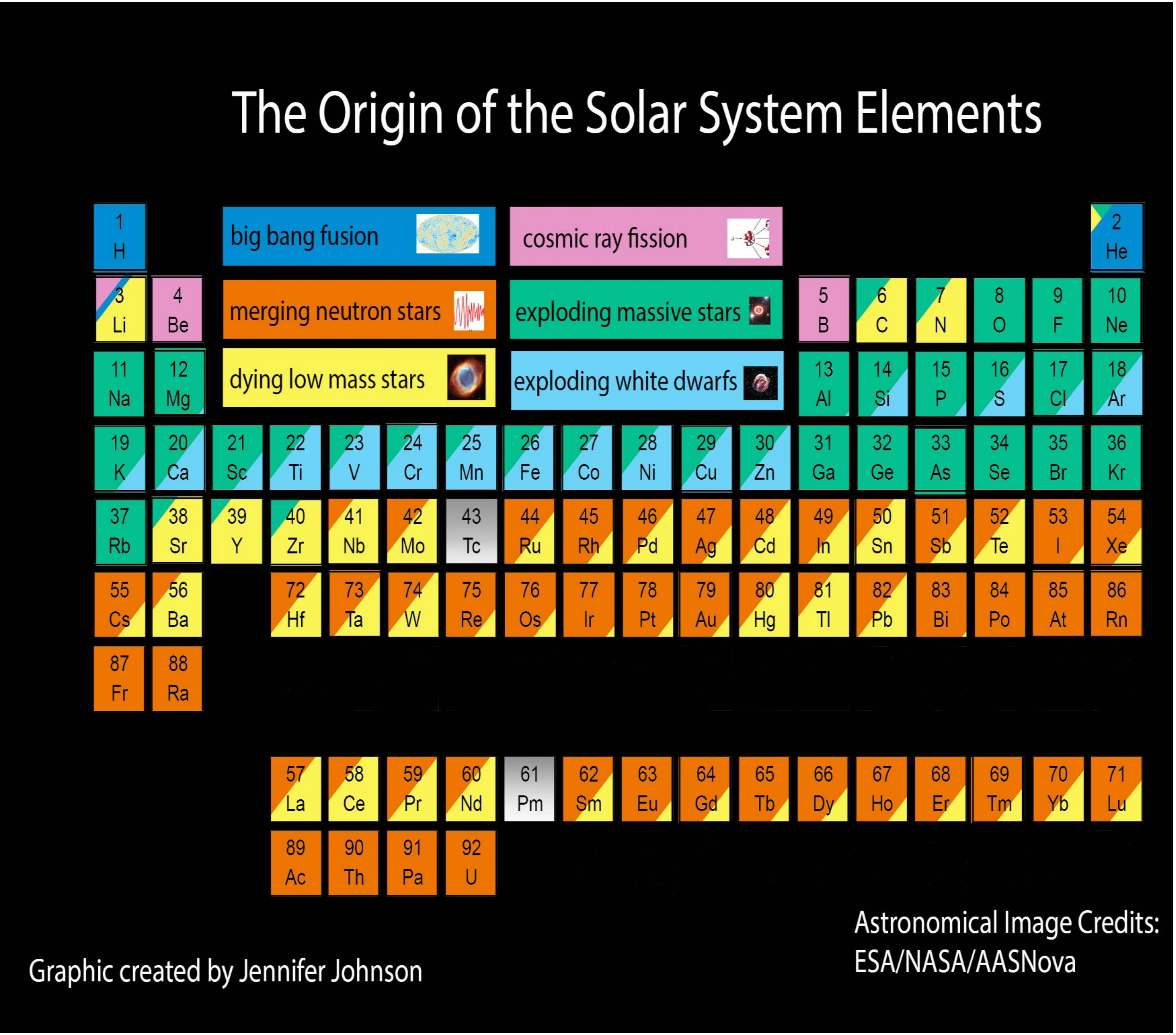
Astrophysical s- and r-Process Sites

I. s-Process Sites
A. Low and intermediate mass stars (<4Msol) are responsibe for the main s-process up to Pb and Bi (mostly ^{13}C-driven) in thermal pulses (He-shell flashes)
B. Massive stars do not experience these pulses, here a weak s-process (^{22}Ne-driven) produces nuclei up to about A=100 in core He-burning

II. r-Process Sites
A. Single Stars
A.1 EC-Supernovae (e.g. Wanajo) weak
A.2 Regular Core-Collapse Supernovae (e.g. Curties et al.) weak
A.3 Magneto-Rotational Supernovae (e.g. Winteler, Mösta, Nishimura) strong
A.4 QCD-driven Supernova Explosions of Massive Stars (Fischer) weak
A.5 Collapsars/Hypernovae (Siegel, Metzger, Surman et al.) strong

B. Compact Binary Mergers
B.1 NS-NS Mergers strong
B.2 NS-BH Mergers strong

A.5 as well as B.1 and B.2 lead to BH accretion disks and their outflows
All the strong r-process sites mentioned here are rare events, in frequency about a factor of 100 to 1000 below that of regular CCSNe



links the individual sites and their occurrence frequency to the temporal evolution of the Galaxy.

J. Johnson (2019): in terms of stellar origins (still a bit ambiguous, as there are weak and strong s-processes and r-processes, and possibly even multiple strong r-process sites, and additional processes like the vp-process)