

r-Process Sites, their Ejecta Composition, and their Imprint in Galactic Chemical Evolution

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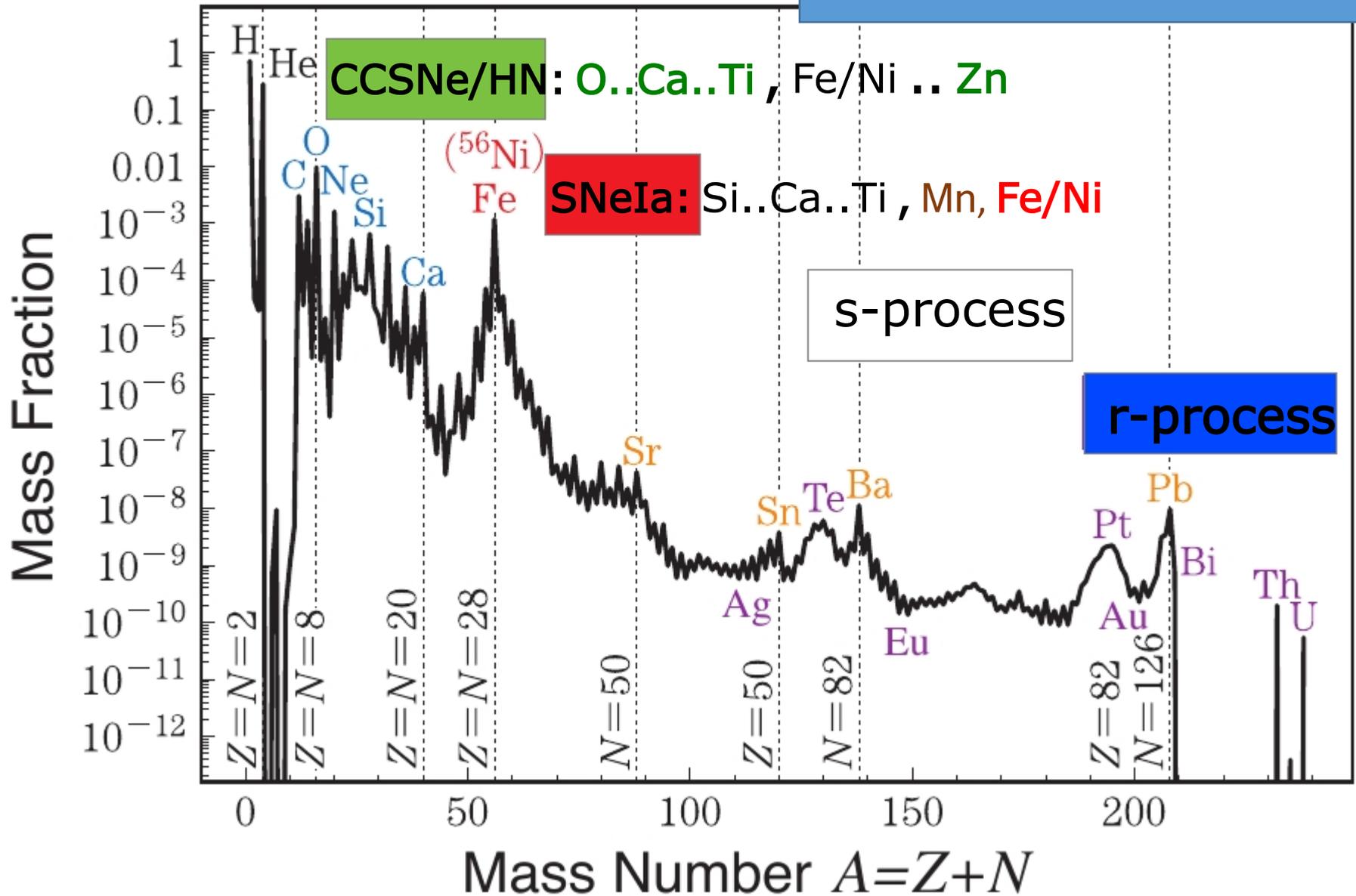
**University of Basel
Switzerland**

**Darmstadt
Germany**

See also our recent r-process review for Rev. Mod. Phys. [2019arXiv190101410C](https://arxiv.org/abs/20190101410C), presently under (minor) revisions after receiving the referee reports

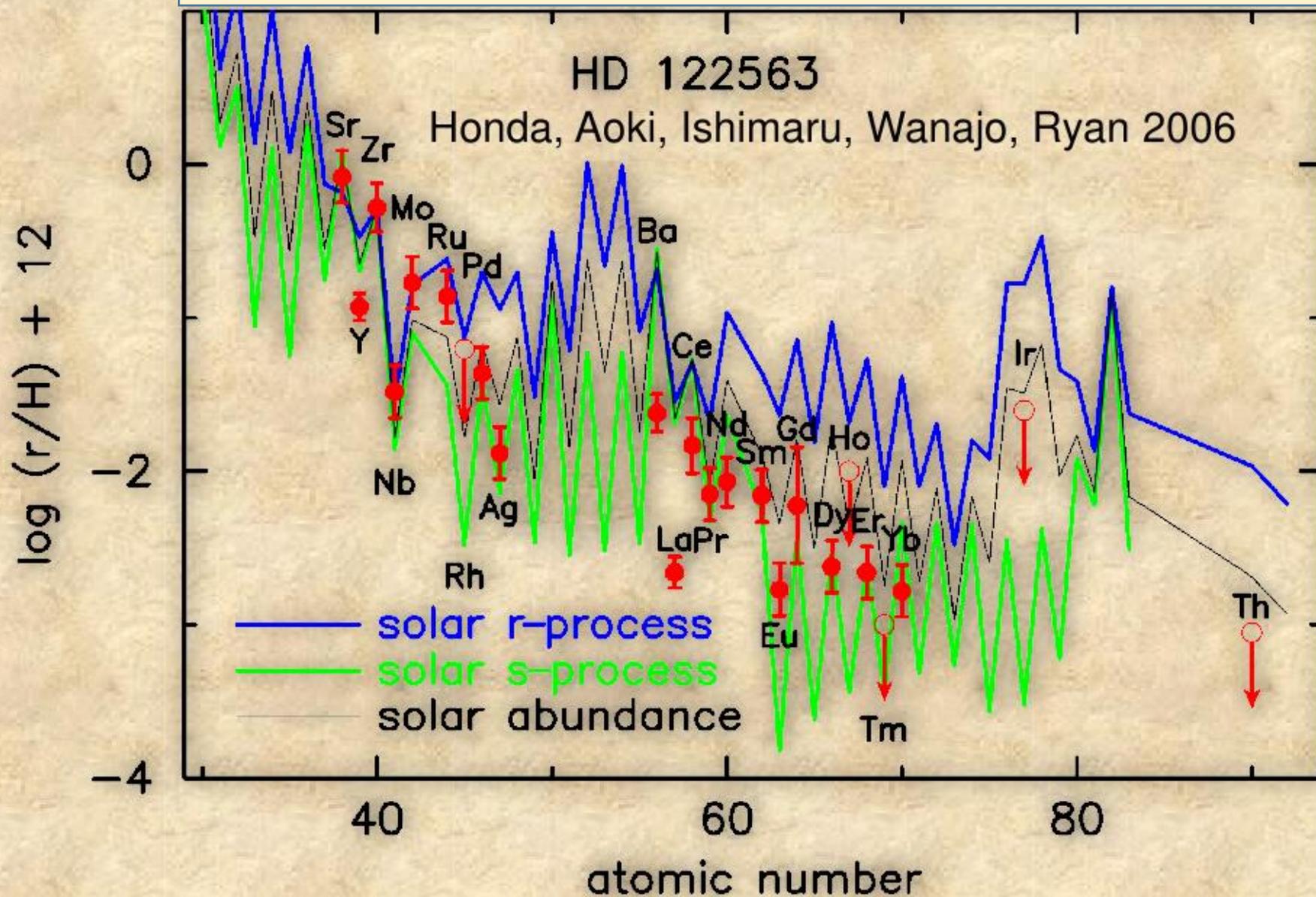
BBN makes ^1_1H , ^3_2He , ^4_2He , ^7_3Li

1. Observations:
Solar Abundances



adopted from
C. Kobayashi

solar r-process and s-process abundances

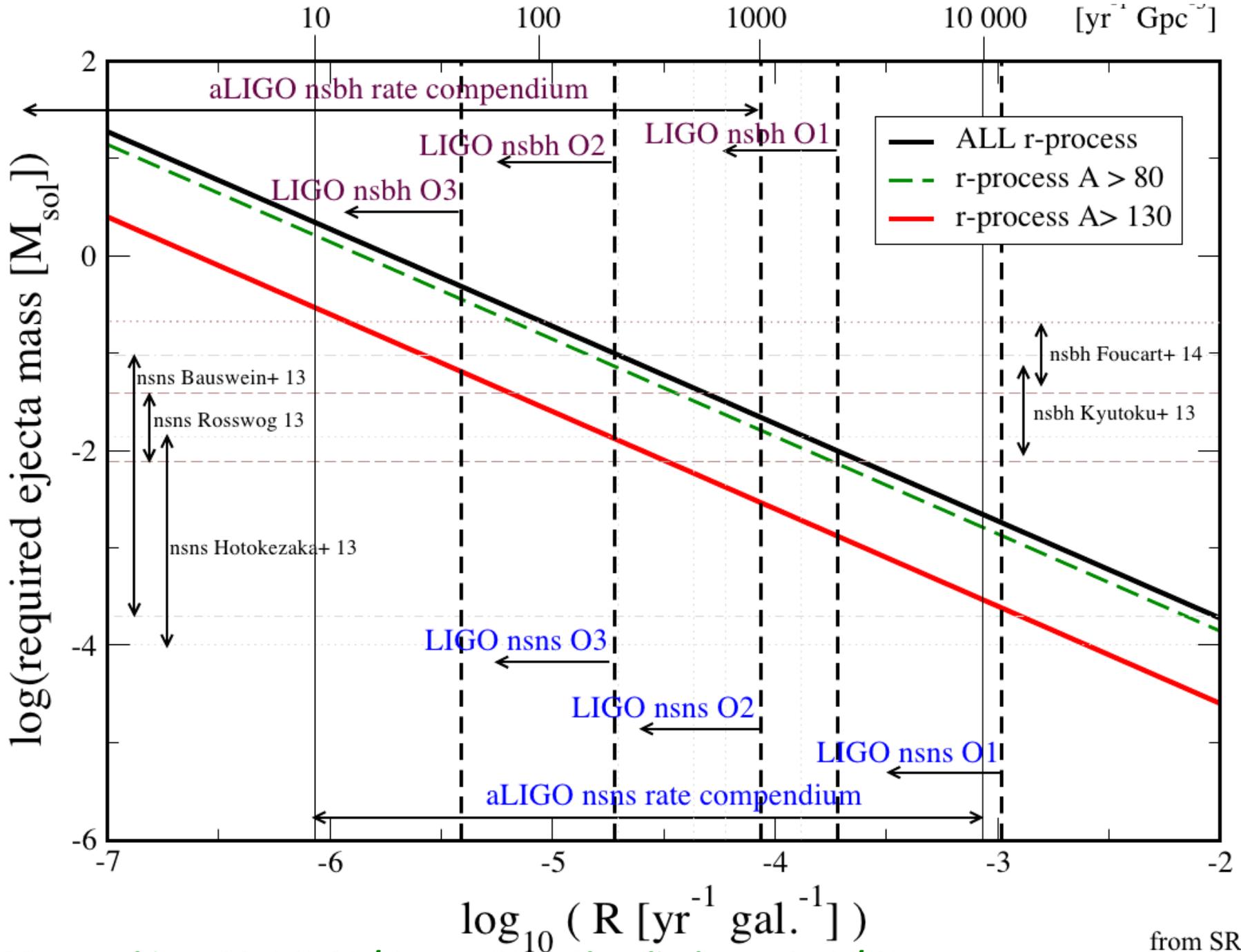


Blue: standard solar r-process, as found in «Snedden-type» stars

Red dots: weak r-process as found (more rarely) in «Honda-type» stars

(Eu underproduced more than an order of magnitude in comparison to Sr) (adapted from Wanajo)

**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**



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

from SR++ (2017)

Wallner et al. (2019): measurement in deep-sea sediments, corresponding to ages in the range 0-9 Myr (private communication)

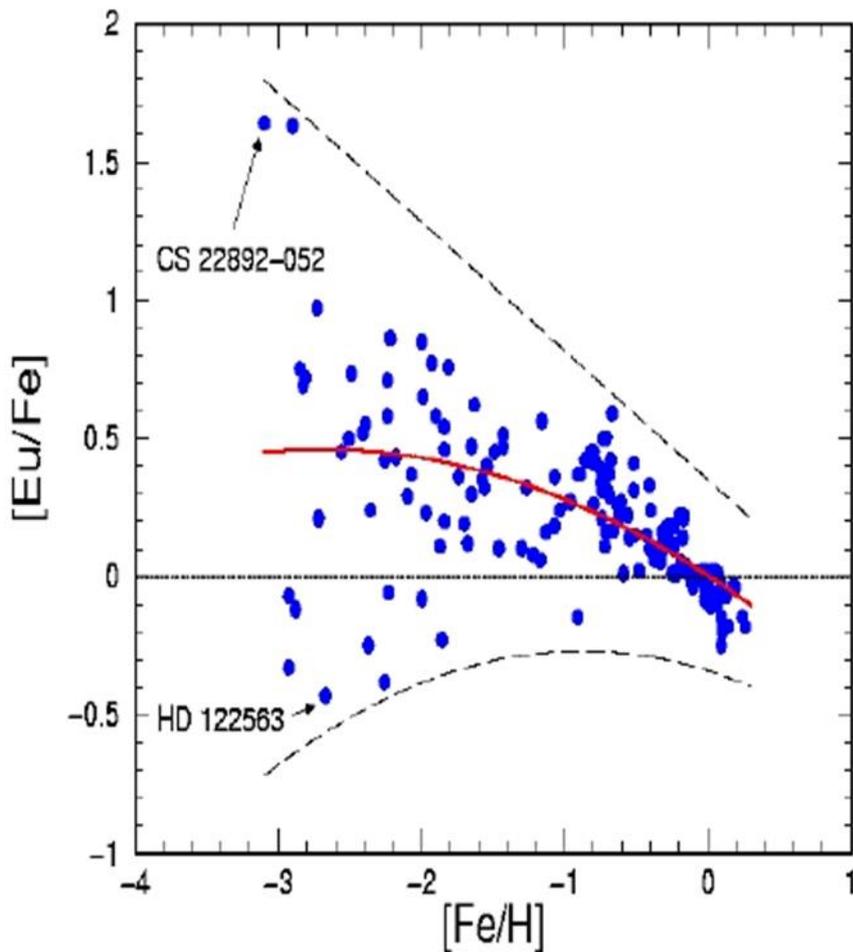
*^{60}Fe ($t_{1/2}=2.6$ Myr), ejected dominantly in SN explosions,
 ^{244}Pu ($t_{1/2}=80.6$ Myr), solely produced in the r-process.*

Two distinct influxes of ^{60}Fe , centered at 2.5 Myr before present and between 5.5 and 7 Myr.

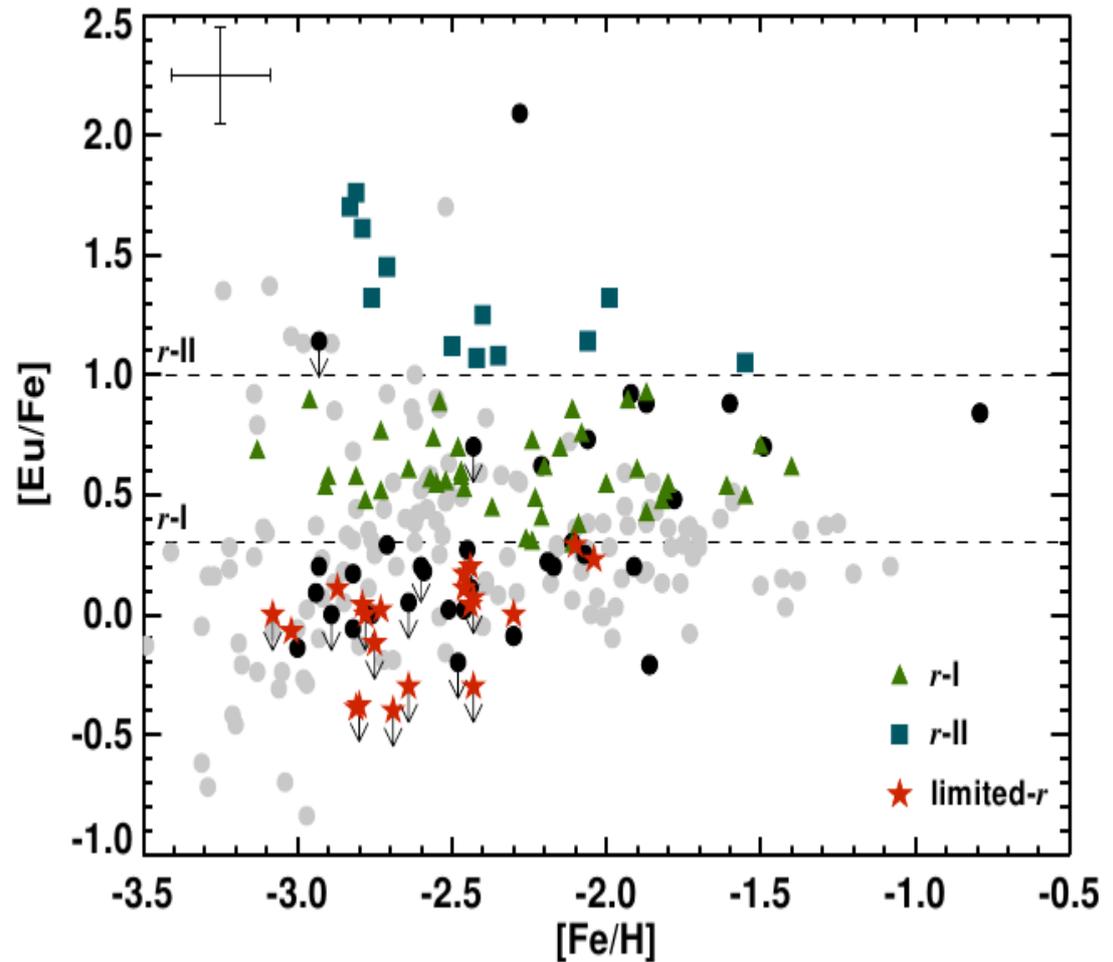
First clear signal of interstellar ^{244}Pu , suggesting an influx concomitant with ^{60}Fe during the last 10 Myr. ^{244}Pu may originate from recent SNe or from an old rare event.

The measured $^{244}\text{Pu}/^{60}\text{Fe}$ atom ratio of $(3-5)\times 10^{-5}$ is constant and lower by a factor of 10–100 than expected from CCSNe, if being the main site for heavy r-process nucleosynthesis. The presence of ^{244}Pu suggests, however, a regular minor production of actinides in CCSNe. The dominant production must come from rare events, whose ejected matter has decayed already.

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)?
 But does not exclude a very low base value from regular core-collapse supernovae?



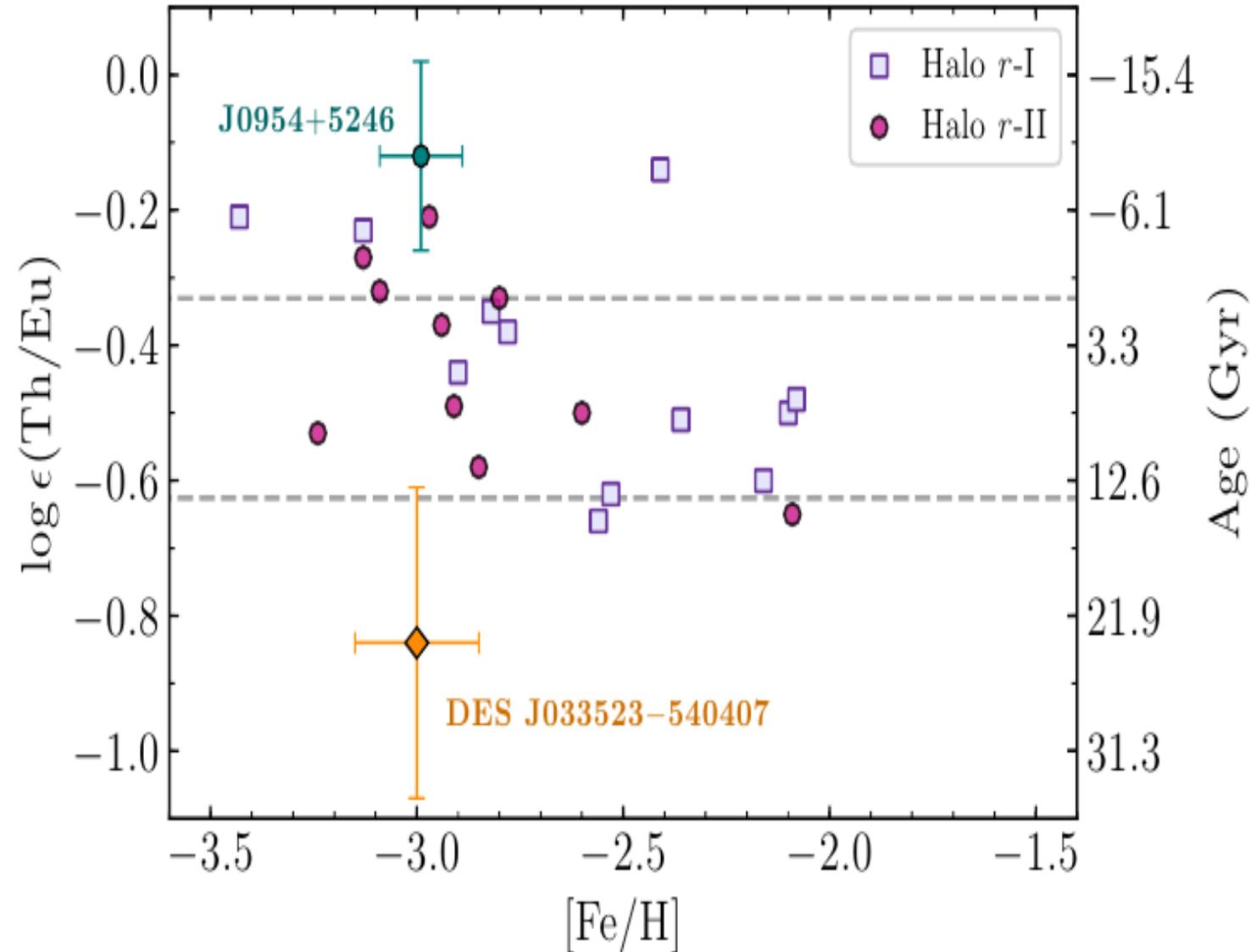
Cowan & Thielemann (2004)



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

Holmbeck+ (2018)

Actinide-Boost Stars



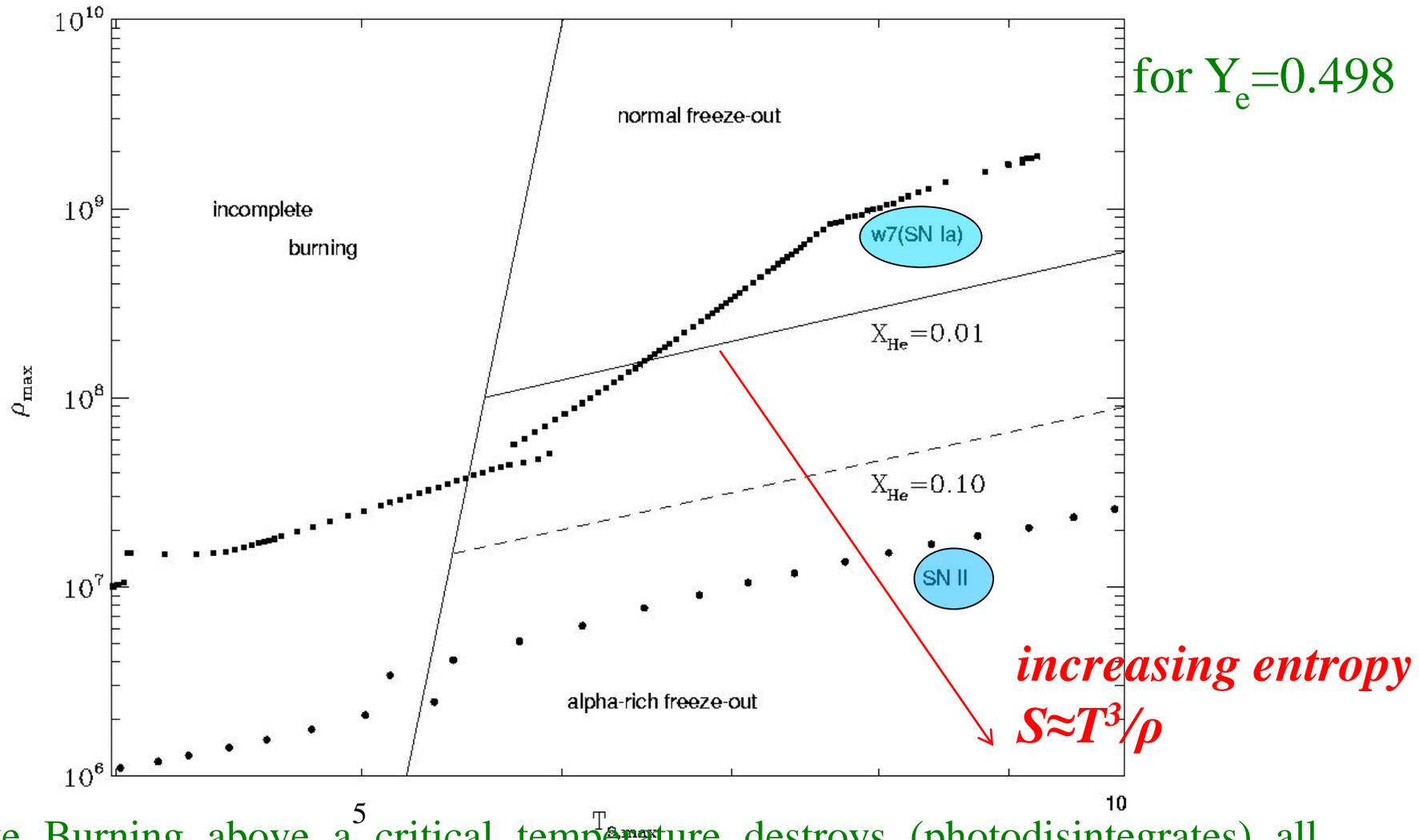
Are there any features which point to a variety of events at lowest metallicities (actinide boost stars at about $[\text{Fe}/\text{H}] \approx -3$)?

Apparently one finds different production of Eu, U, Th for different r -process environments/conditions.

When utilizing element production ratios which would fit well the solar r -abundances, unreasonable ages for these stars result when making use of Th/Eu and U/Eu chronometers.

*Different events or different variations in the same type of event?
(see also Eichler's and Surman's talks!)*

2. General r-process Modeling: Explosive Si-Burning

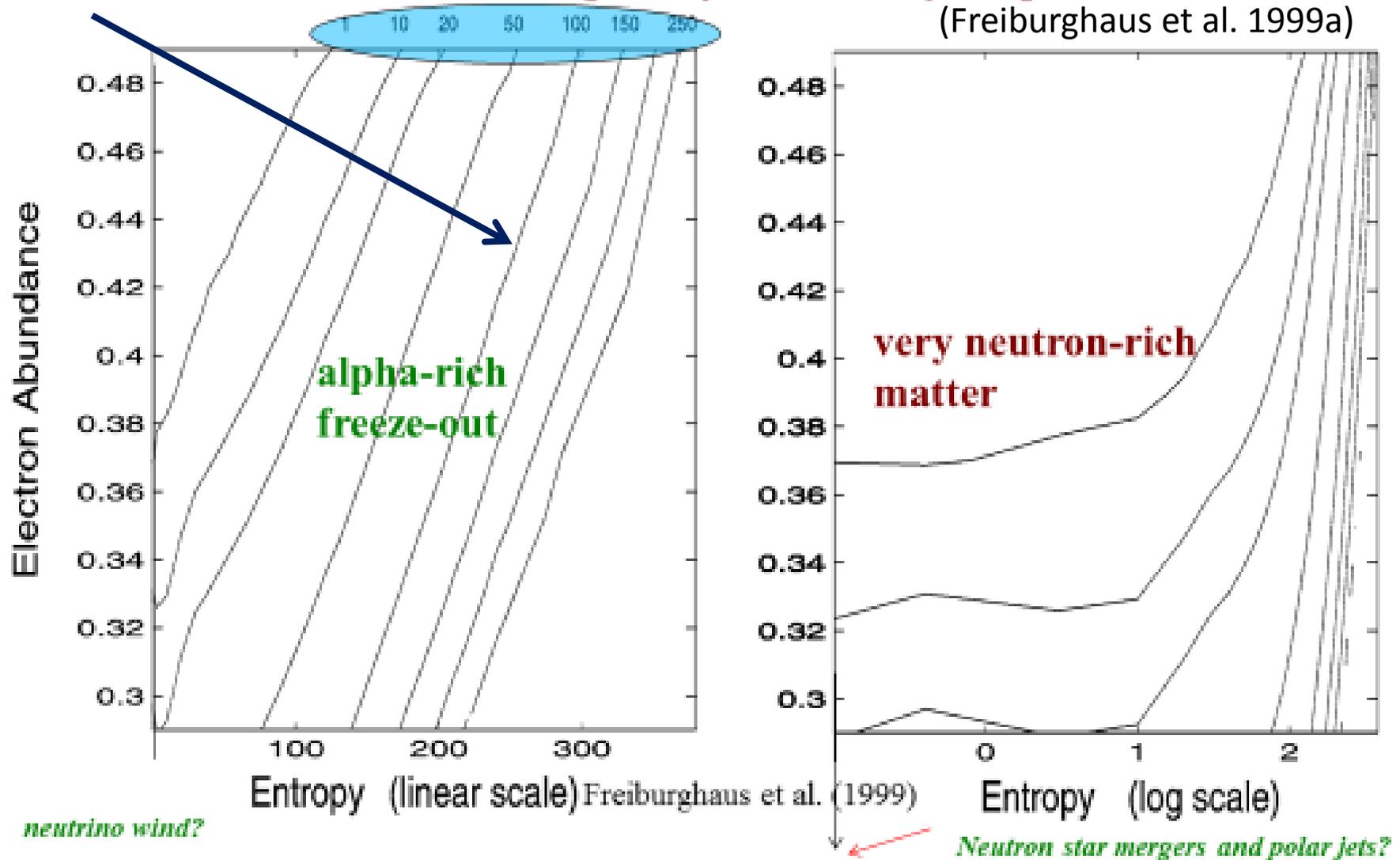


Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ${}^4\text{He}$ to C and beyond freeze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

n/seed ratios as function of S and Y_e

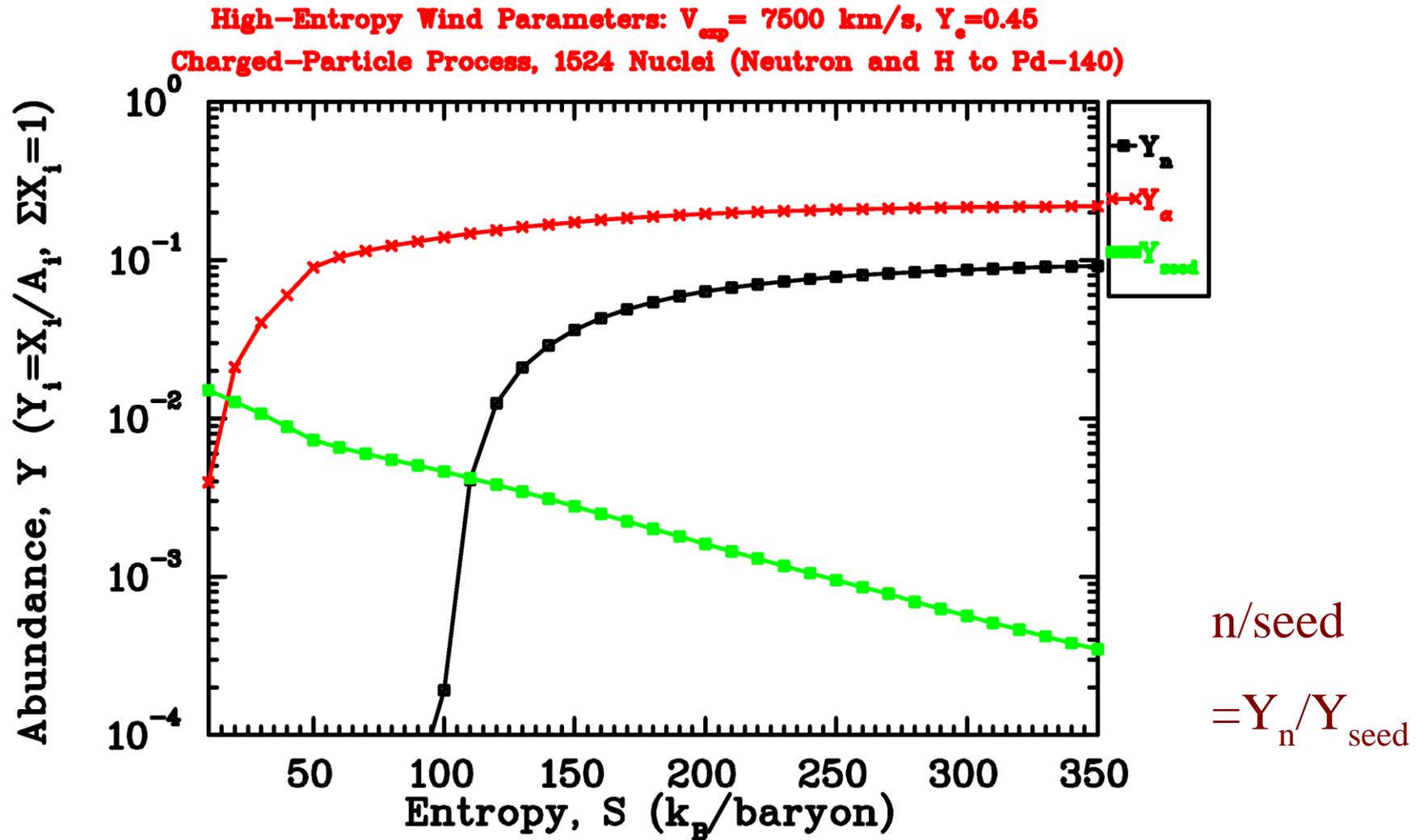
Two options for a successful r-process

(Freiburghaus et al. 1999a)

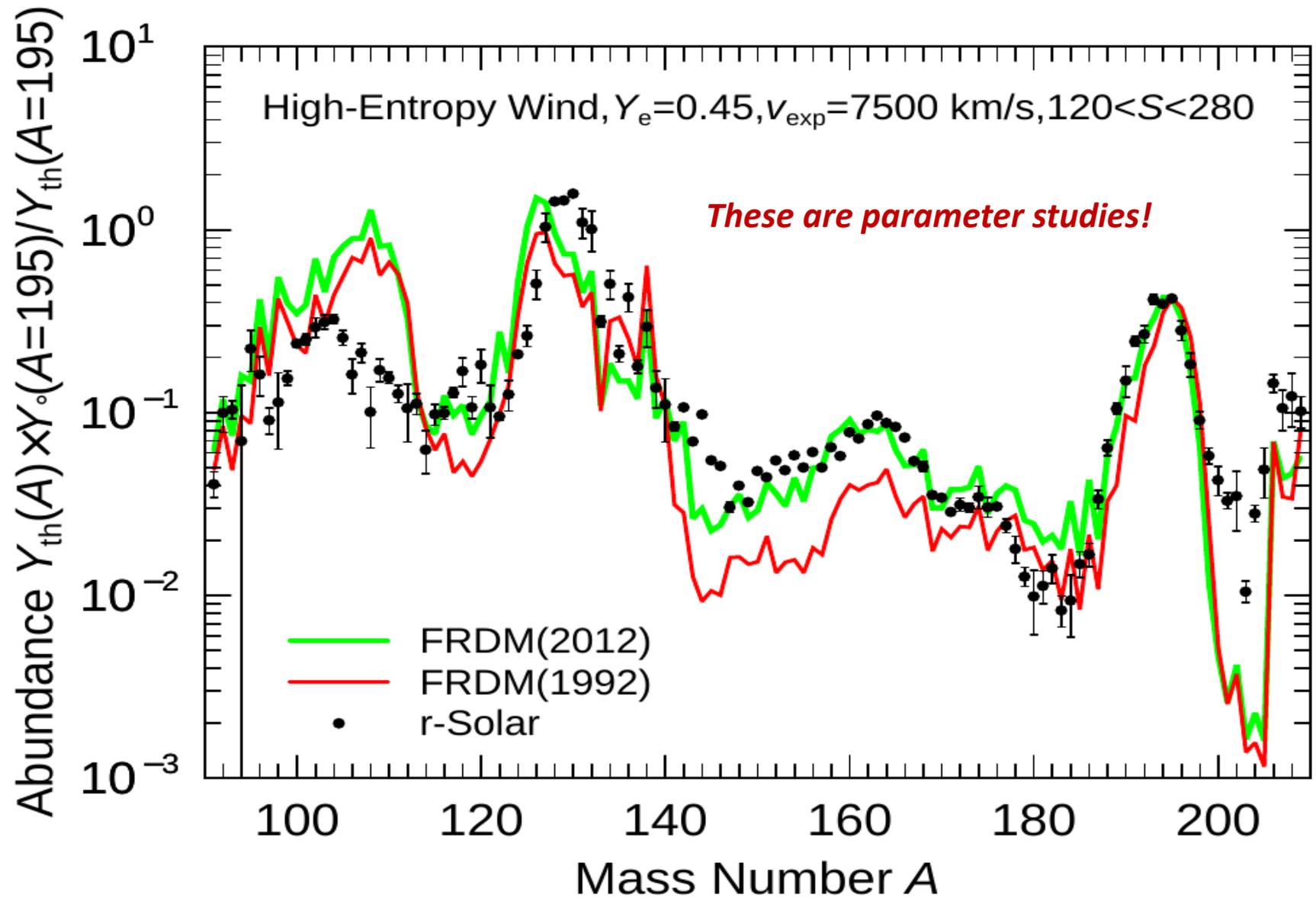


The essential quantity for a successful r-process to occur is to have an n/seed ratio so that $A_{\text{seed}} + n/\text{seed} = A_{\text{actinides}}$!

n/seed ratios for high entropy conditions are are function of entropy
 Farouqi et al. (2010)



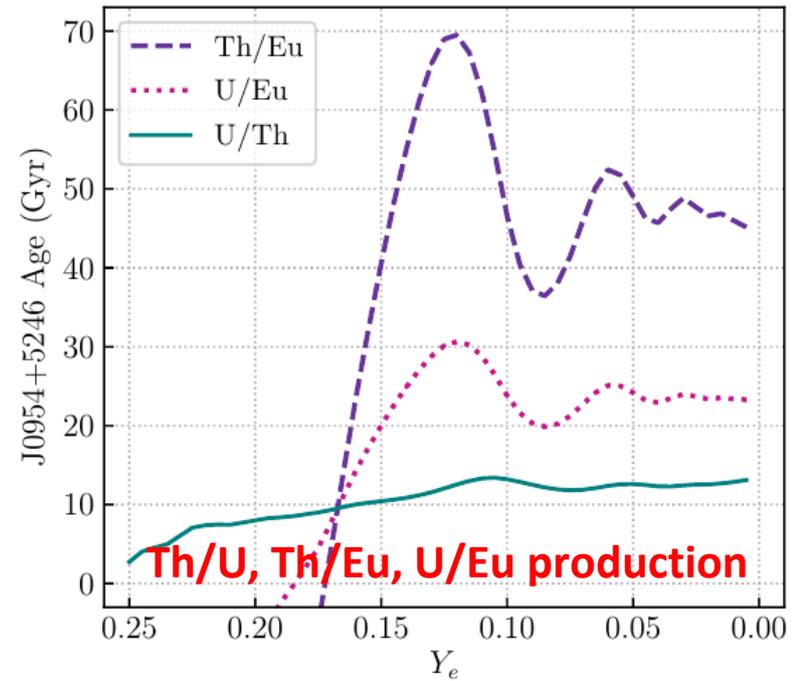
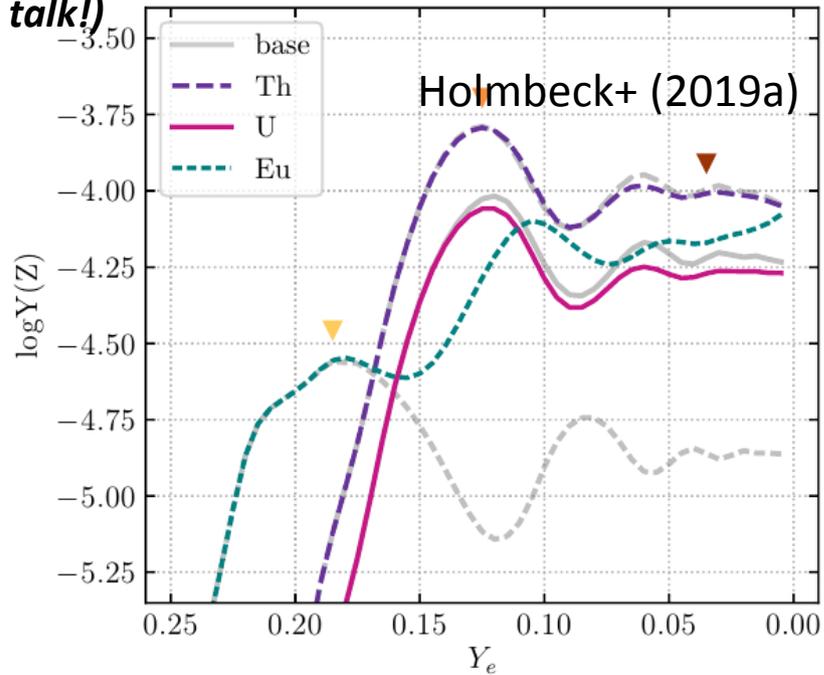
The essential quantity for a successful r-process to occur is to have a n/seed ratio so that $A_{\text{seed}} + n/\text{seed} = A_{\text{actinides}}$!



Kratz et al. (2014): Update from FRDM (1995) to FRDM (2012).

But the innermost ejecta of CCSNe are proton-rich and/or the entropies are not sufficient!

One finds different production of Eu, U, Th for different Y_e conditions in r-process environments. (see also Eichler's talk!)

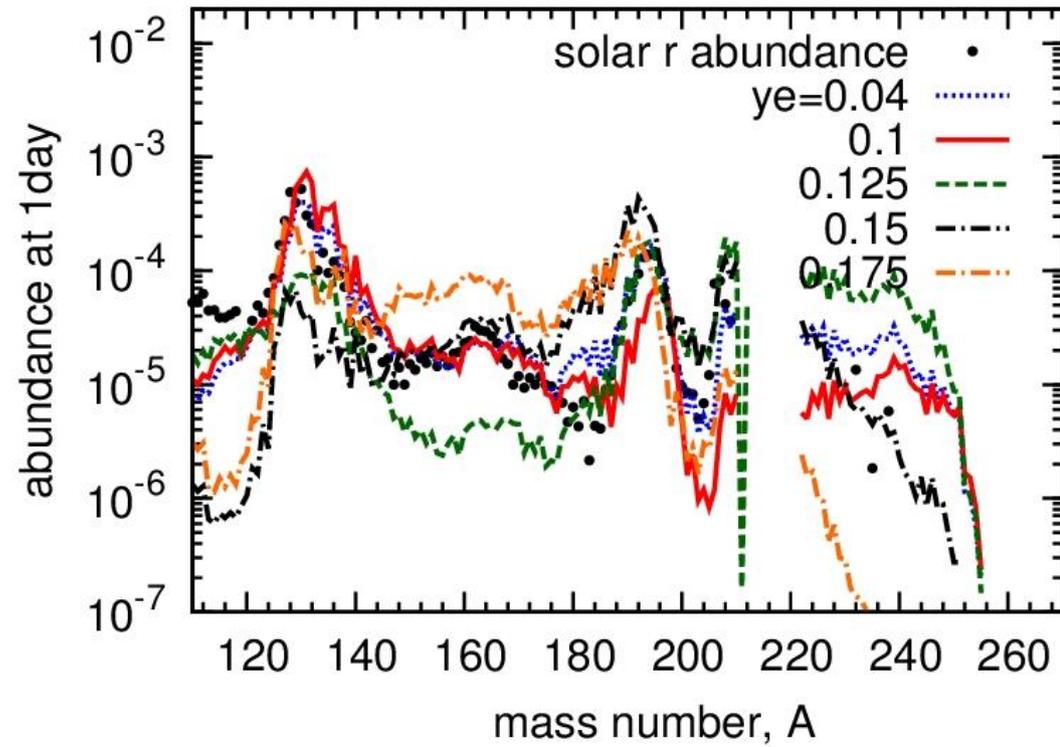


Which Y_e -intervals are incorporated astrophysical scenarios?

From Wu+ 2017:

Also the DZ mass model permits large variations of actinide production, even at low Y_e 's.

Do we have different Y_e -superpositions in the same type of event, or do certain types of events include lowest Y_e 's like in NS matter and others go just down to $Y_e=0.15$ or 0.125 ?



3. Astrophysical Sites

A. Single Stars

A.1 EC-Supernovae (e.g. Wanajo)

A.2 Regular Core-Collapse Supernovae (e.g. Curties et al.)

A.3 Magneto-Rotational Supernovae (e.g. Winteler, Mösta, Nishimura)

A.4 QCD-driven Supernova Explosions of Massive Stars (Fischer)

A.5 Collapsars (Siegel, Metzger, Surman et al.)

B. Compact Binary Mergers

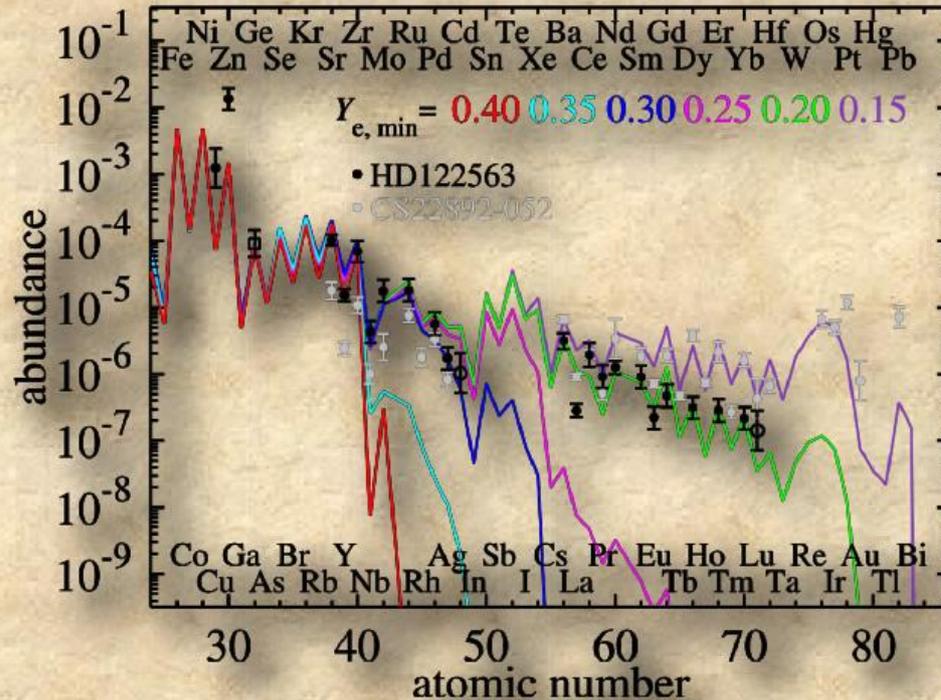
B.1 NS-NS Mergers

B.2 NS-BH Mergers

A.5 as well as B.1 and B.2 lead to BH accretion disks and their outflows

EC-Supernovae (Wanajo)

how low $Y_{e, \min}$ is needed for the weak-r?



Wanajo Shinya, Janka, Hans=Thomas & Müller Bernhard, 2011, Apj, 726, 15

comparison with an
r-deficient star
HD122563

Honda, Aoki, Ishimaru, Wanajo,
Ryan 2006

➔ $Y_{e, \min} = 0.40$ (original)
Ge and Sr-Y-Zr

➔ $Y_{e, \min} = 0.30$
up to Pd, Ag, Cd

➔ $Y_{e, \min} = 0.20$
all, BUT out of reach of
our ECSN model

Results with PUSH (Ebinger et al. 2017/18/19)

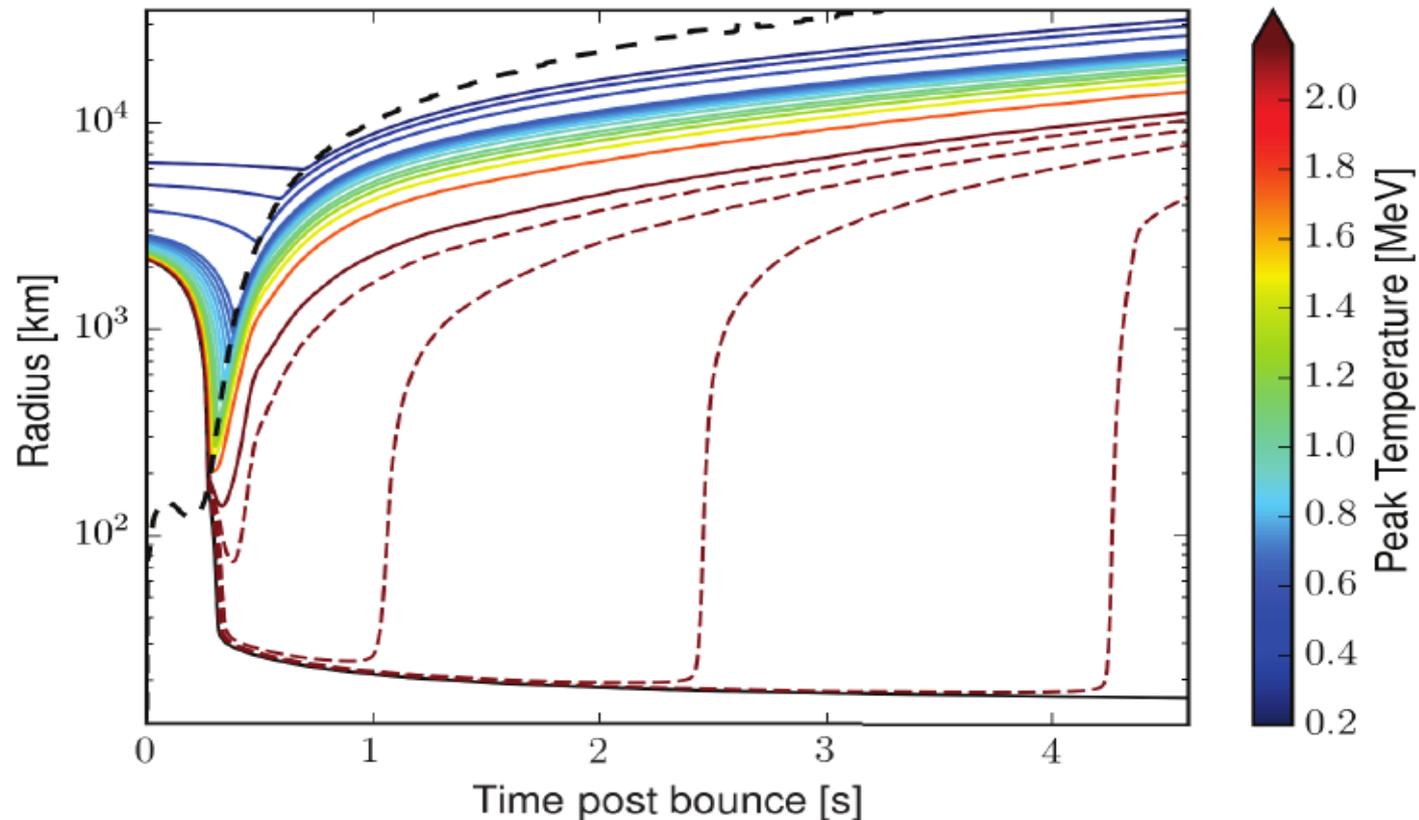
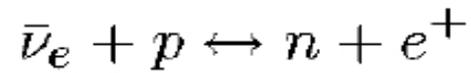
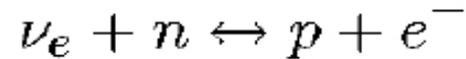


Fig. 3.8.: We show the mass tracers for a PUSH model (progenitor: $15 M_{\odot}$ [47], $k_{\text{PUSH}} = 3.5$, $t_{\text{rise}} = 200$). The black line denotes the PNS surface, the dashed tracer lines (increasing in mass with steps of $10^{-3} M_{\odot}$) are delayed ejecta (wind) that reach temperatures around 4 MeV before they are ejected. The colors of the remaining tracers denote their peak temperatures (the first six colored lines are separated by $5 \times 10^{-3} M_{\odot}$, then the next six by $10^{-2} M_{\odot}$, and the last three tracers are separated by $0.1 M_{\odot}$). The black dashed line denotes the shock front.

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

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



- high density / low temperature \rightarrow high E_F for electrons \rightarrow e-captures dominate \rightarrow n-rich composition
- if el.-degeneracy lifted for high $T \rightarrow \nu_e$ -capture dominates \rightarrow 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 $E_{\bar{\nu}_e} - E_{\nu_e} > 4(m_n - m_p)c^2$ 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)

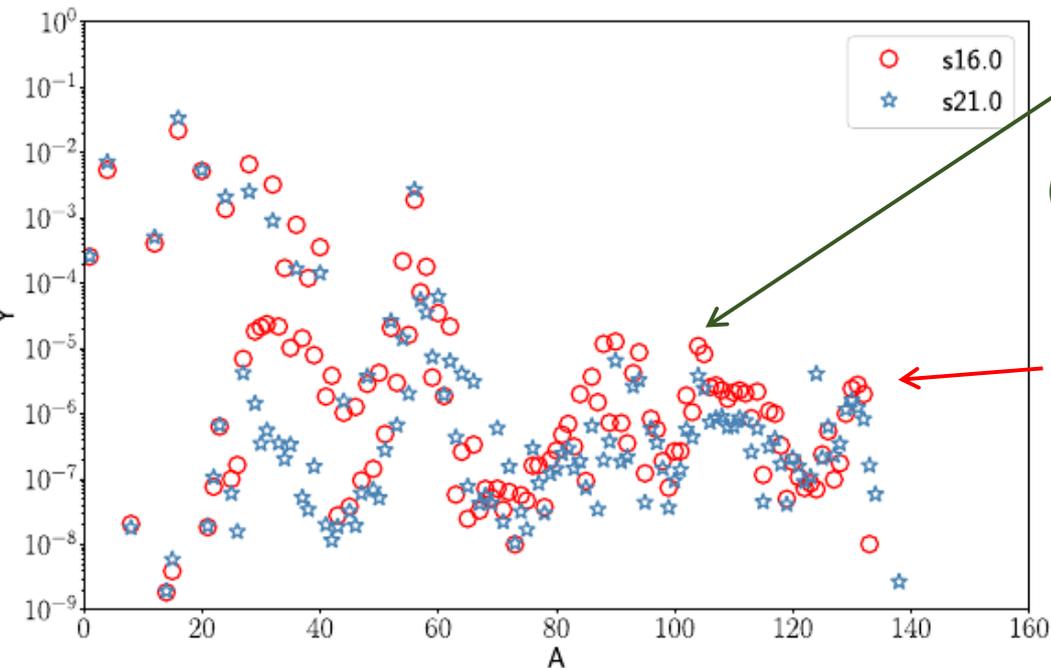
Types of explosive Si-burning: all explosive Si-burning zones in CCSNe lead to an alpha-rich freeze-out.

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

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

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

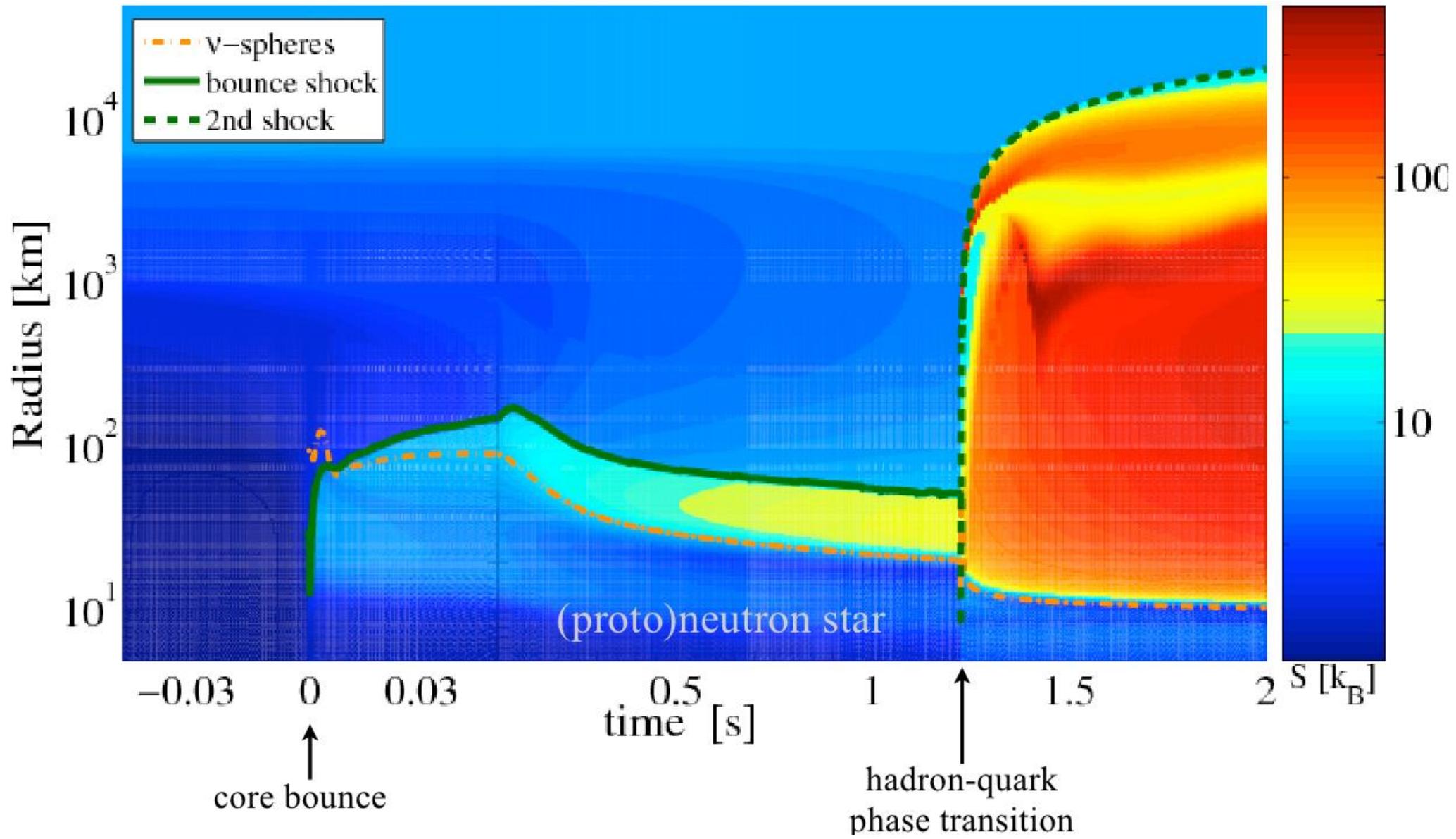
(3) Neutrino interactions with nucleons and nuclei can enhance Y_e , for similar luminosities of neutrinos and antineutrinos the latter win, making Y_e proton-rich >0.5 . This, together with the less proton-rich layers of explosive Si-burning (see 2) provides a good fit to the Fe-group composition and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



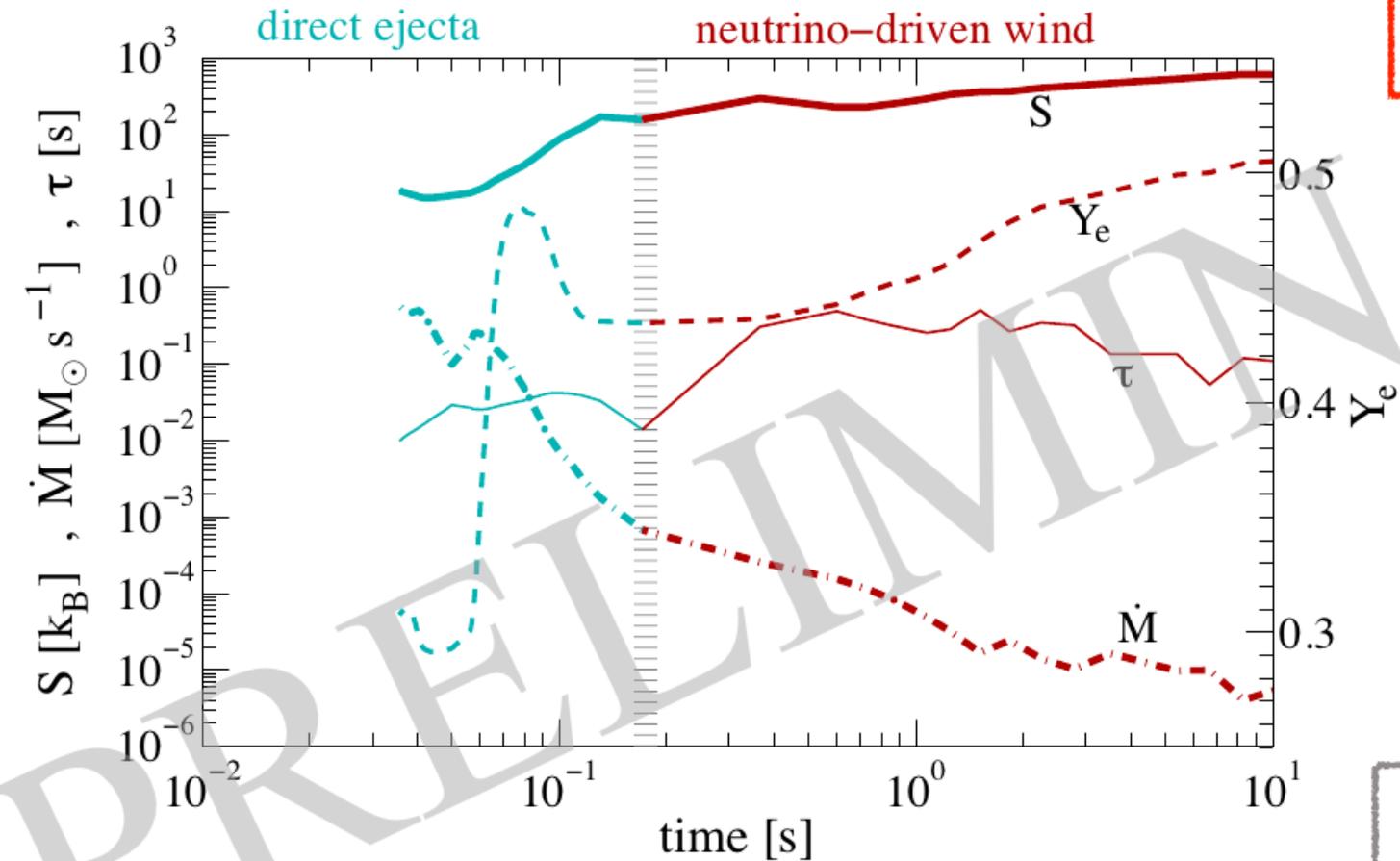
(4) The very innermost ejected layers come late, originate from regions deeper in the collapsed core which had become very neutron-rich via e -captures during core collapse, and neutrino interactions were not sufficient to turn them proton-rich. Y_e 's encountered here range from 0.32 to 0.42. These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

Abundances of explosive ejecta for two progenitors

from T. Fischer (2019), SN explosions due to QCD phase transition



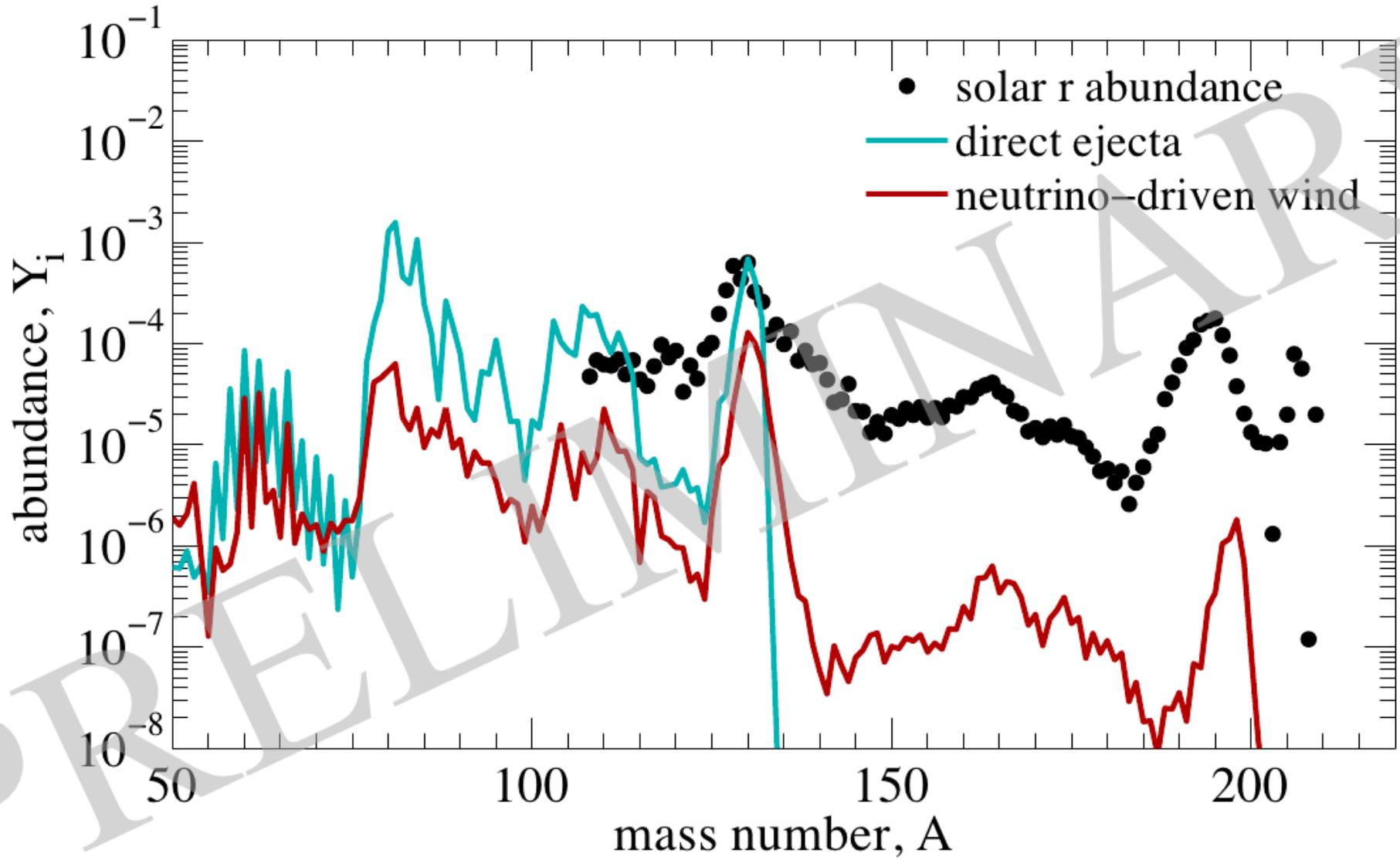
T. Fischer (2019)



$S \simeq 100 - 300 k_B$
 $Y_e \simeq 0.3 - 0.5$

'normal' ν -driven wind
 $S \simeq 50 k_B$
 $Y_e \simeq 0.49 - 0.55$

T. Fischer (2019)

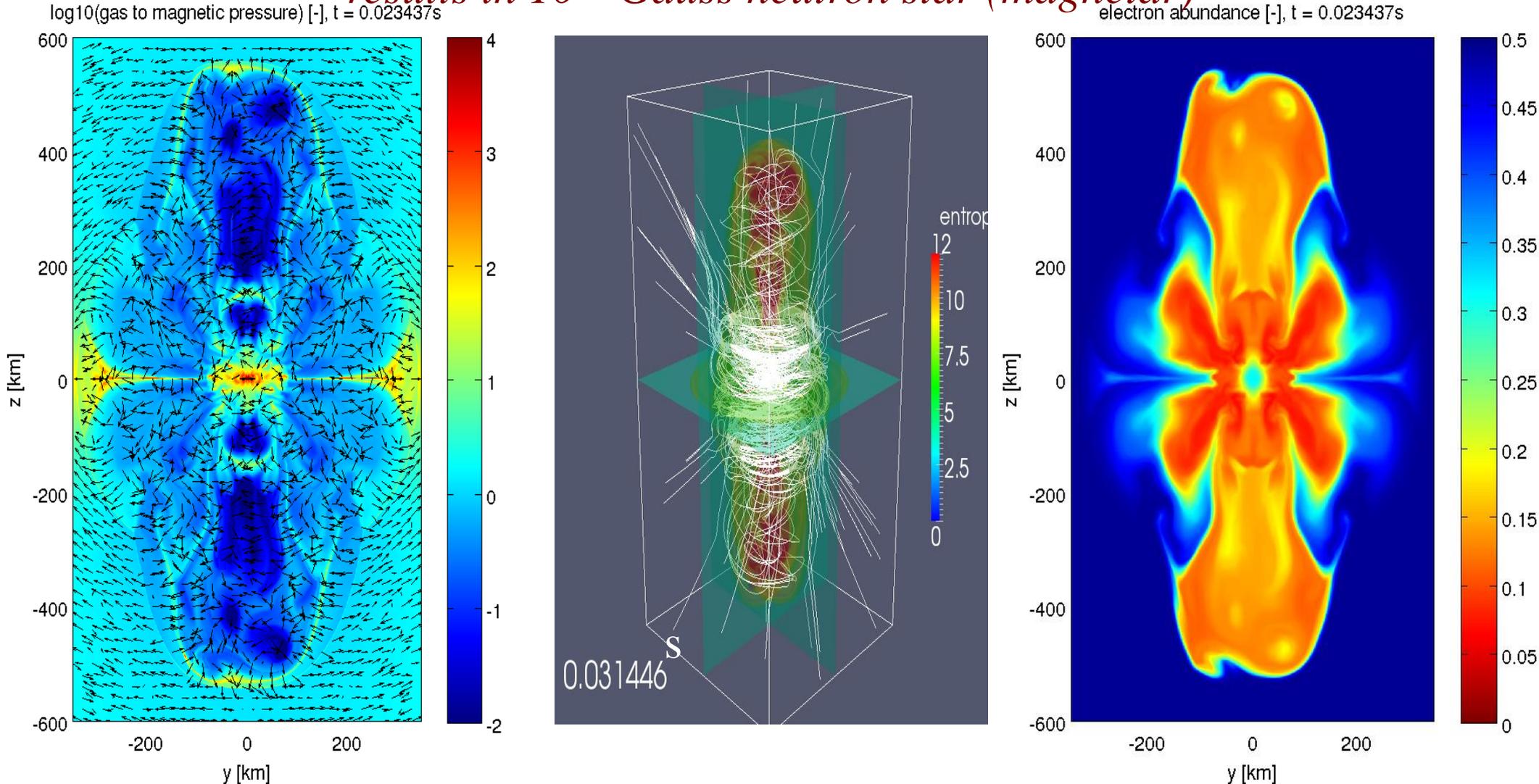


Magneto-Rotational Supernovae

3D Collapse of Fast Rotator with Strong Magnetic Fields:

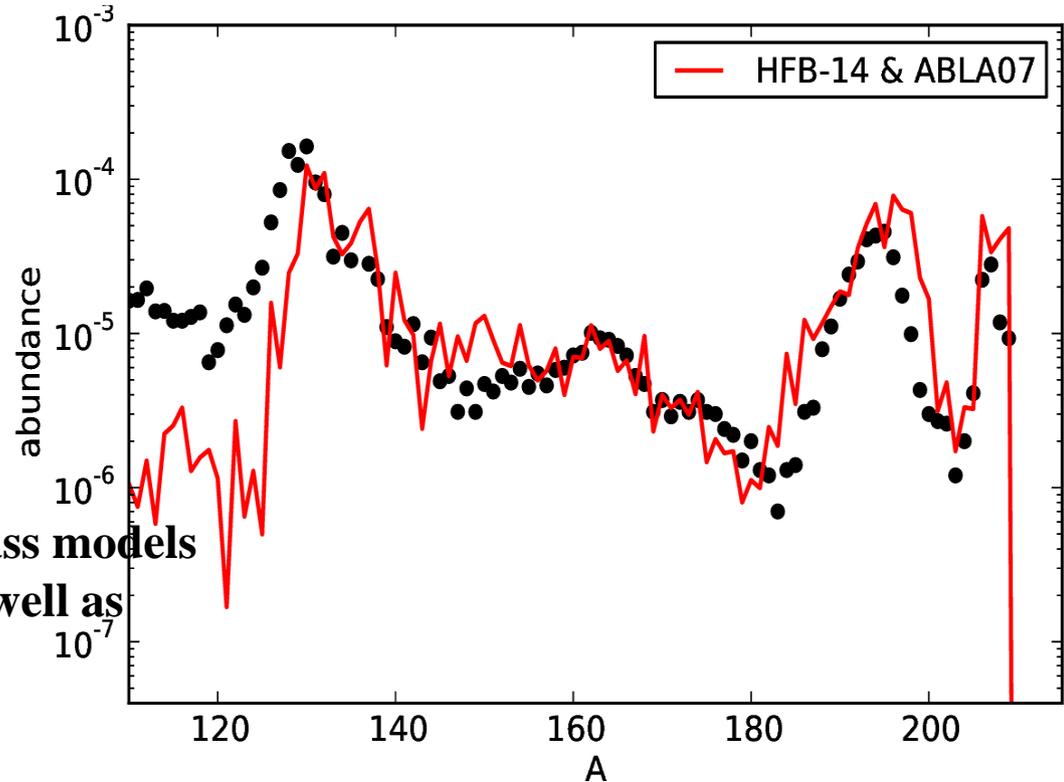
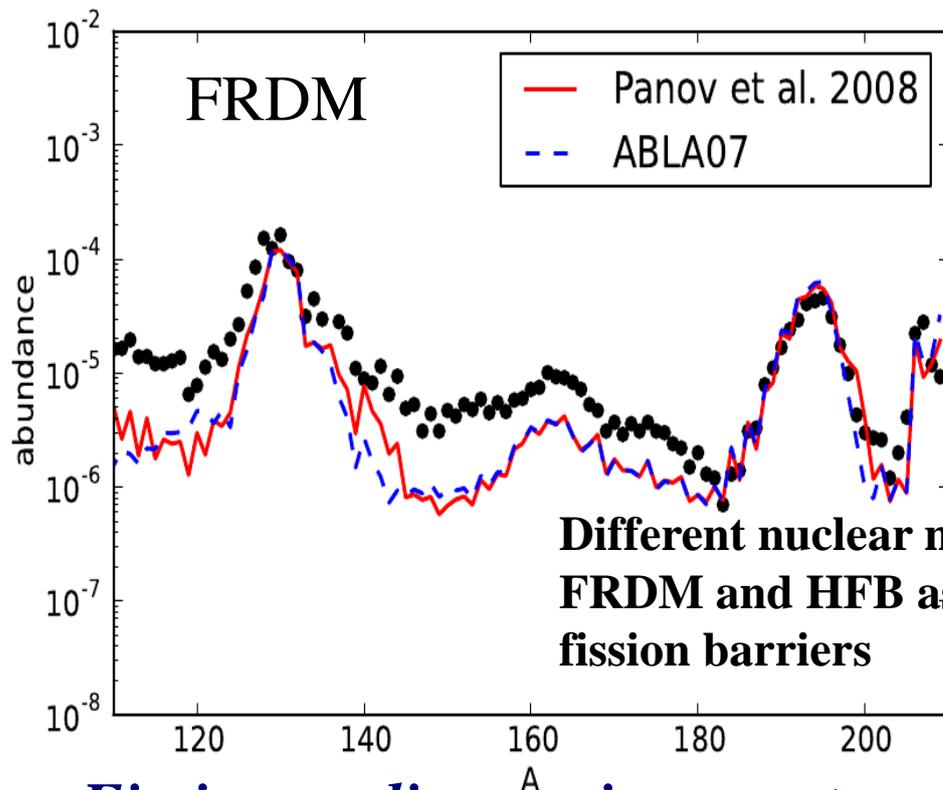
15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5×10^{12} Gauss,

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

Mösta et al. (2017)

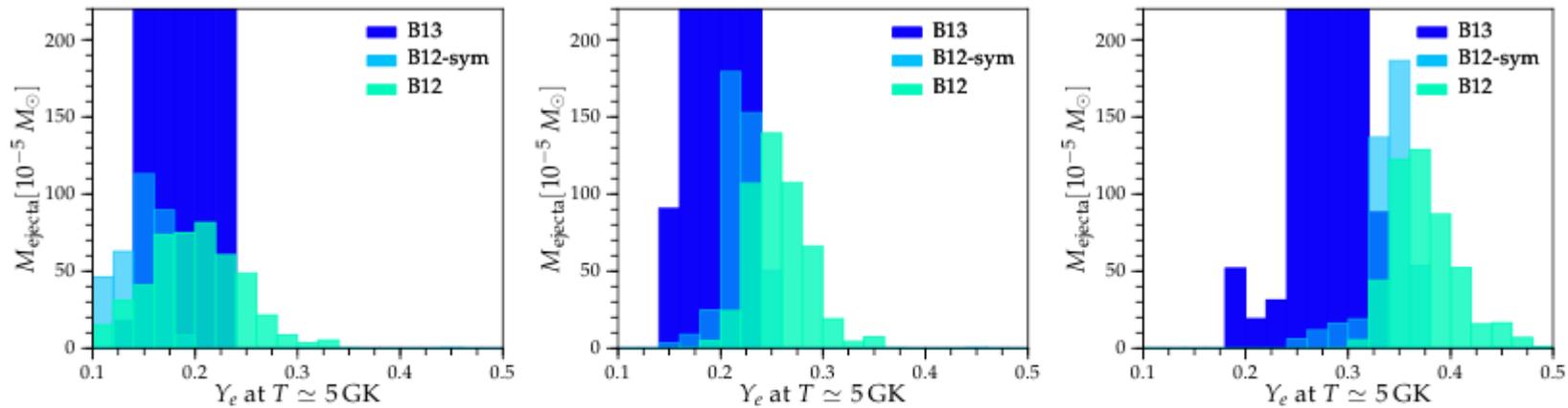


Figure 7. Y_e histograms when the particles are above a temperature of $T=5$ GK for the last time. We show simulation B13 (dark blue), B12-sym (cyan), and B12 (green). The left panel shows results obtained without taking neutrino luminosities into account for the network calculation. The center panel shows results obtained with constant neutrino luminosities $L_{\nu_e} = L_{\bar{\nu}_e} = 10^{52} \text{ erg s}^{-1}$, and the right panel shows results obtained using the luminosities recorded from the tracer particles. We bin Y_e in intervals of 0.02 and weigh the Y_e statistics with the mass of the ejected particles.

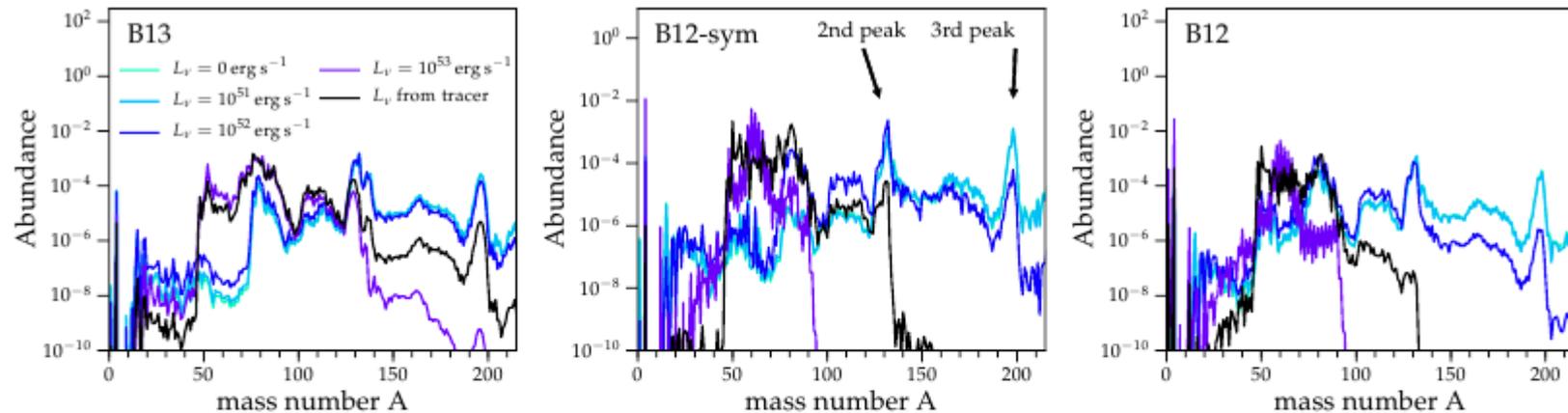


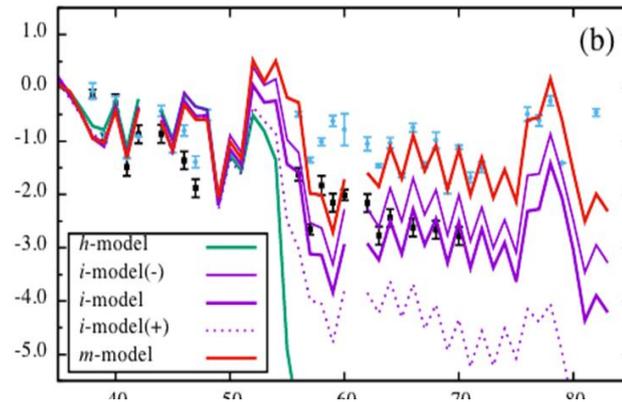
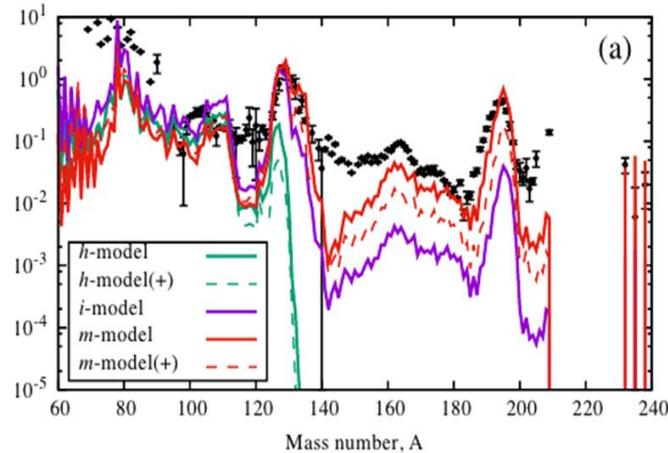
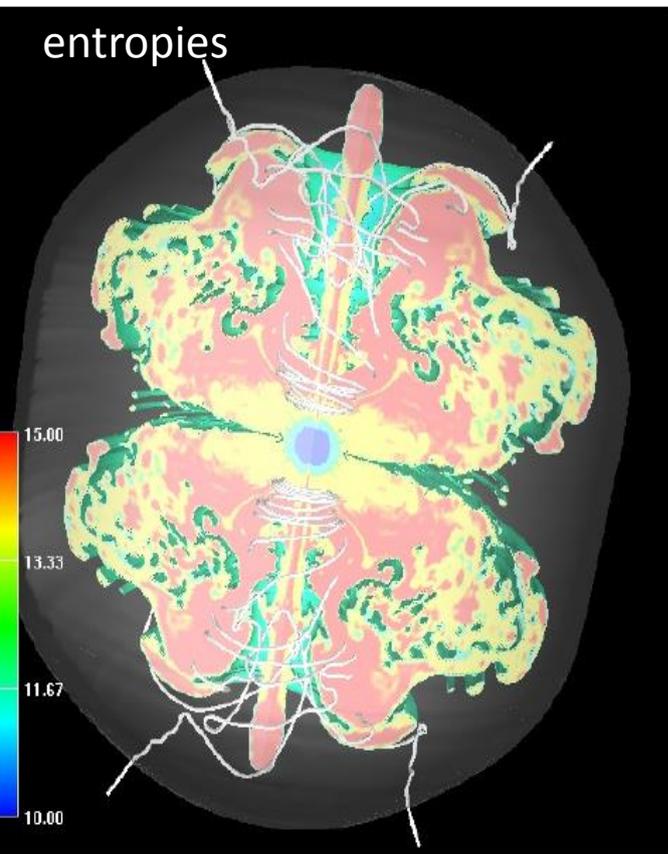
Figure 8. Fractional abundance as a function of mass number A for models B13 (left), B12-sym (center), and B12 (right). Differently colored lines indicate results obtained with different constant neutrino luminosities in the nuclear reaction network calculation. Black lines show the results obtained when using the neutrino luminosities as recorded from the tracer particles in the simulations. For model B13, neutrino luminosities up to $L_{\nu_e} = L_{\bar{\nu}_e} = 10^{52} \text{ erg s}^{-1}$ produce a robust second and third peak r -process pattern. Starting from a neutrino luminosity of $L_{\nu_e} = L_{\bar{\nu}_e} = 10^{53} \text{ erg s}^{-1}$ and the neutrino luminosity from the tracer particles material beyond the second peak is reduced in abundance. This trend is continued in models B12-sym and B12, but with a reduction in abundance of nuclei beyond the second peak starting at lower and lower neutrino luminosities. For model B12, only $L_{\nu_e} = L_{\bar{\nu}_e} = 10^{51} \text{ erg s}^{-1}$ still produces a robust r -process abundance pattern.

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

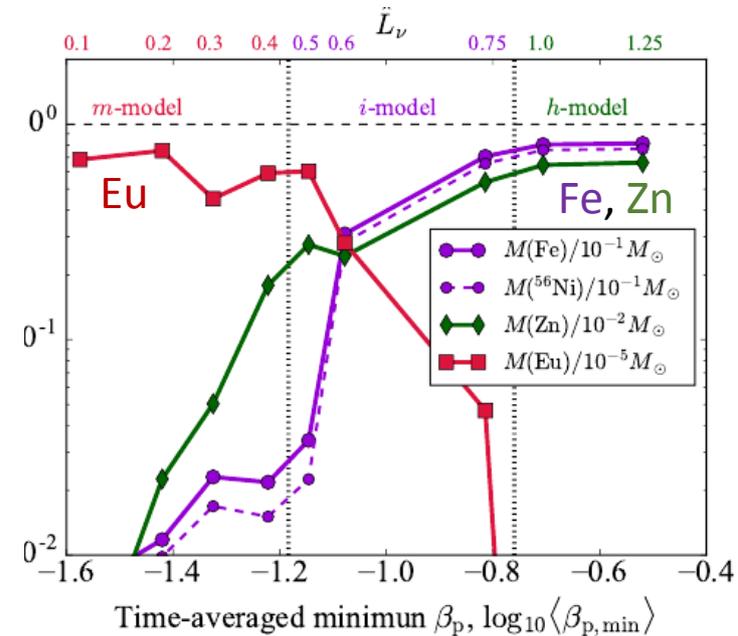
(close to 10^{13} Gauss for massive progenitors, see also Nishimura, Takiwaki, FKT 2015)

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

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



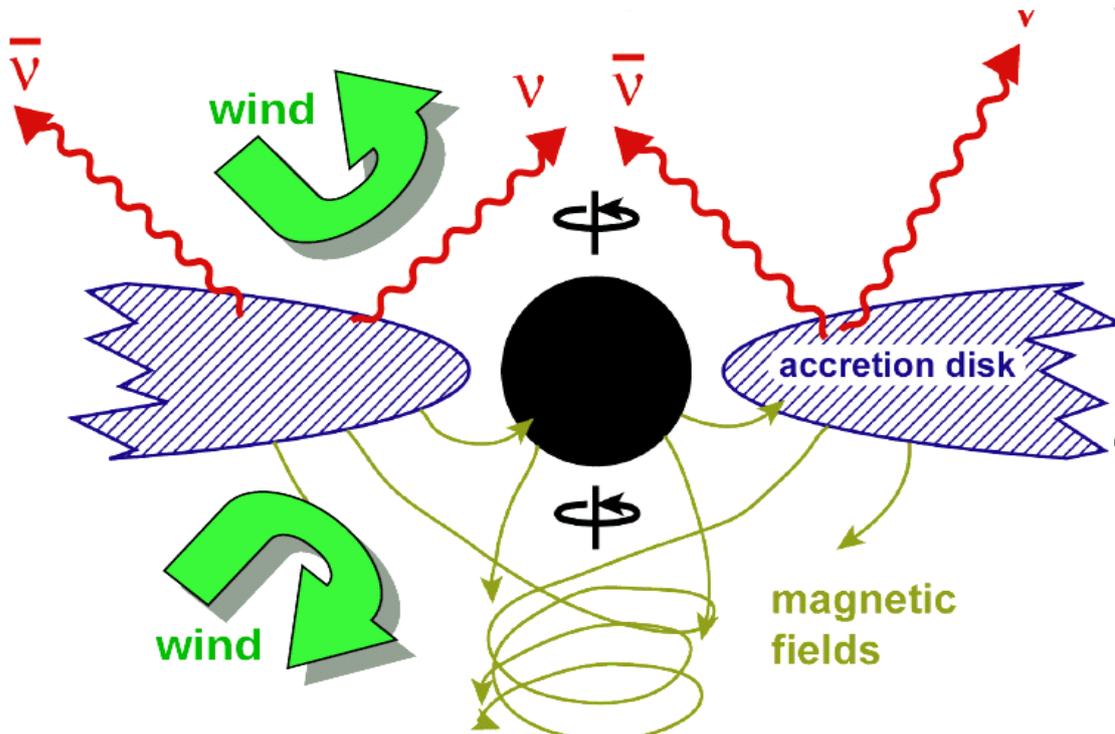
Dependent on the relation between neutrino luminosity and magnetic fields the nucleosynthesis behavior changes from regular CCSNe to neutron-rich jets with strong r-process.

Collapsars: Long Duration Gamma-Ray Bursts

How else can massive stars explode?

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

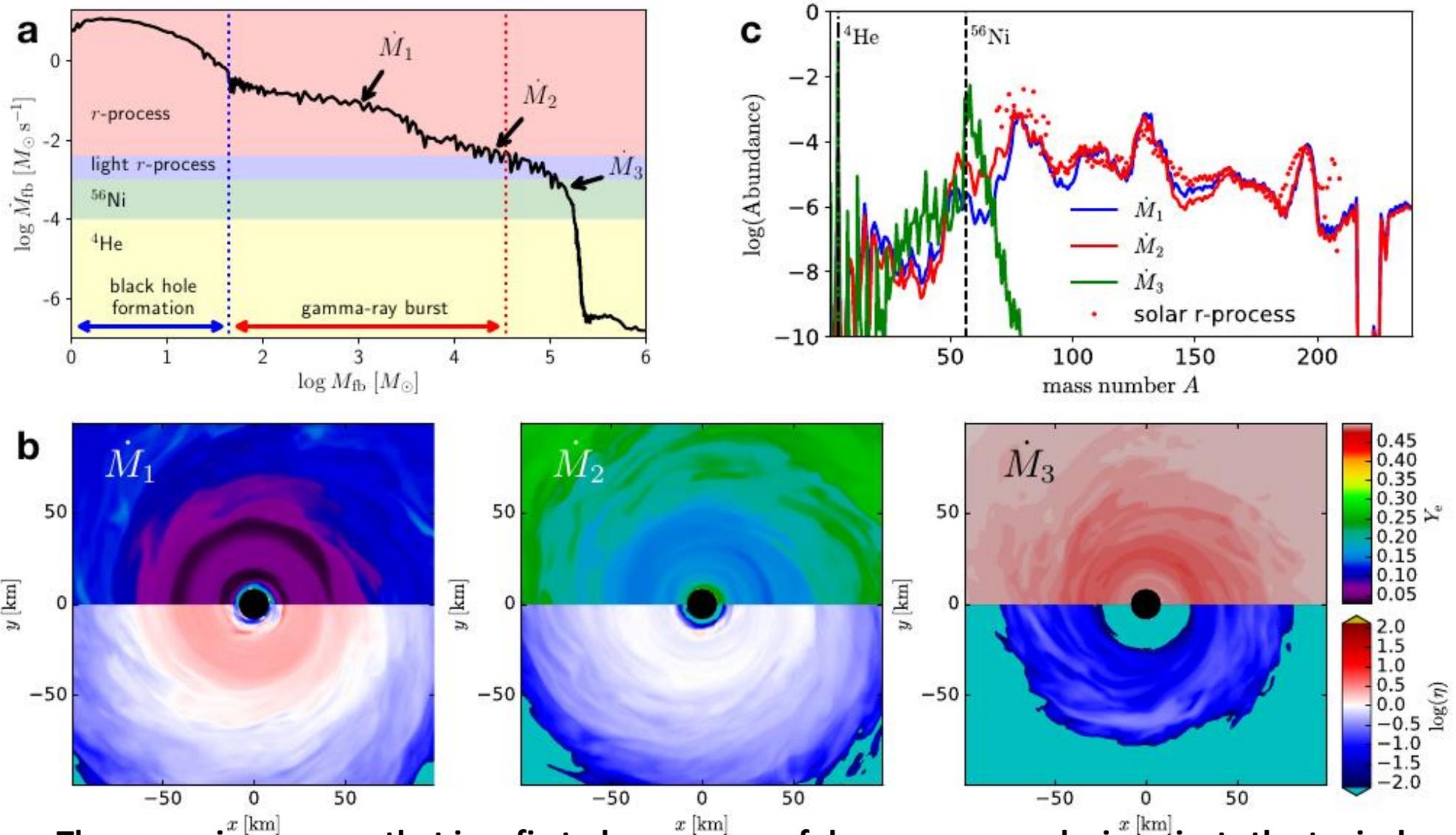
The “Collapsar Engine”



1. black hole forms inside the collapsing star after failure or neutrino-powered explosion
2. The infalling matter forms an accretion disk $\approx 0.1 M_{\odot}/\text{sec}$
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).



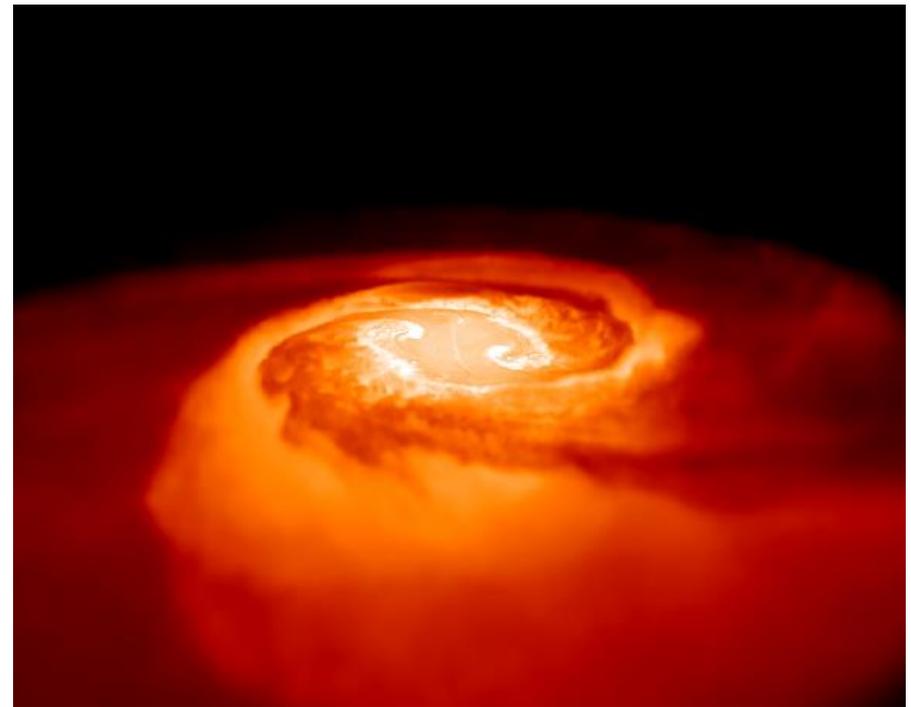
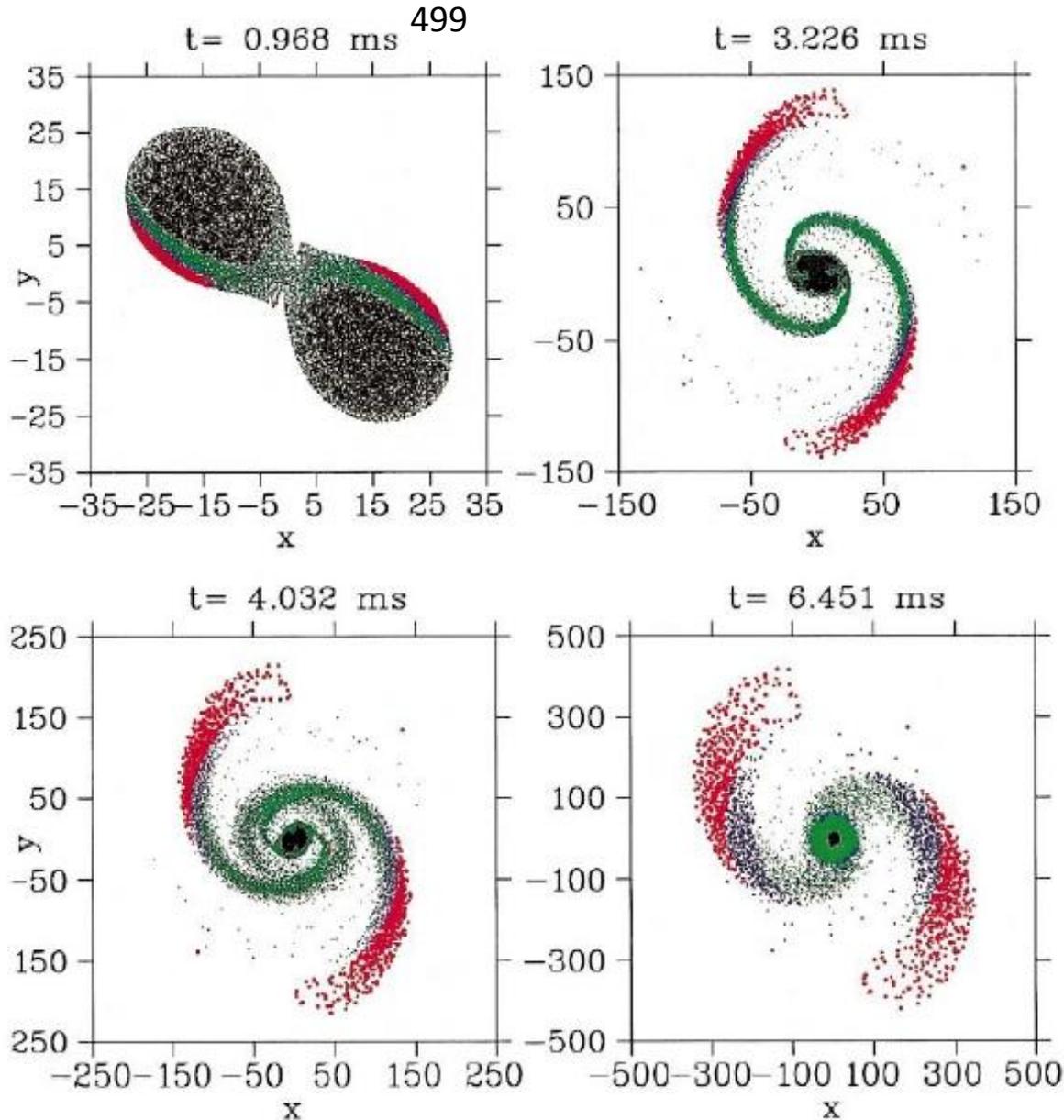
The scenario assumes that in a first phase a powerful supernova explosion ejects the typical up to $0.5M_{\odot}$ of ^{56}Ni (if these events are supposed to be identical with hypernovae) and further accretion leads to a black hole plus a BH accretion disk. somewhat fine-tuned scenario??

Early and later SPH simulations

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

Rosswog et al.
A&A 341 (1999)

only tidal arms in early approaches

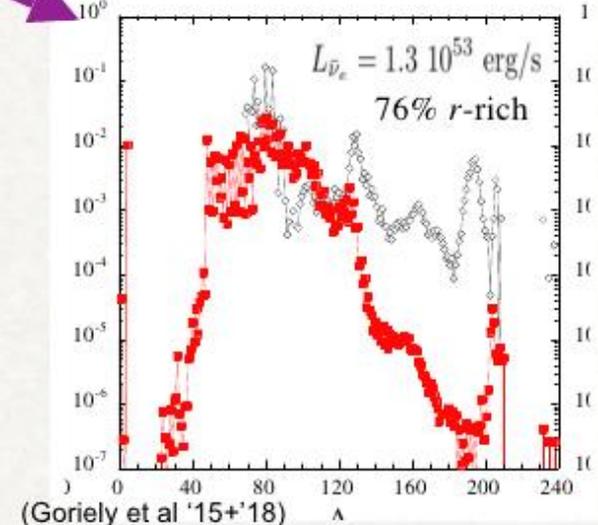
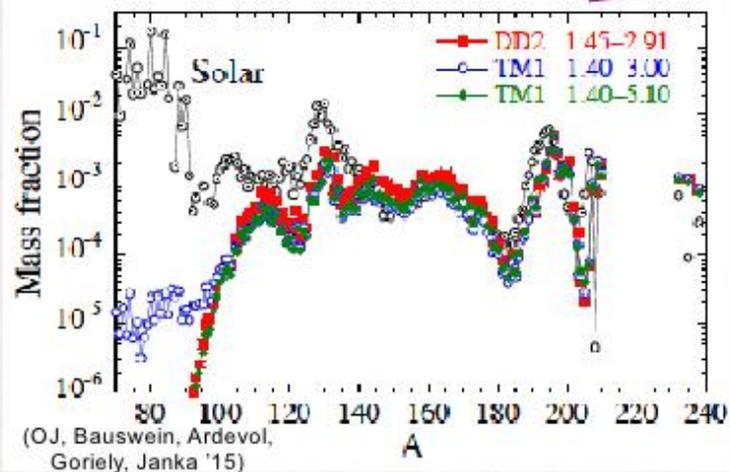
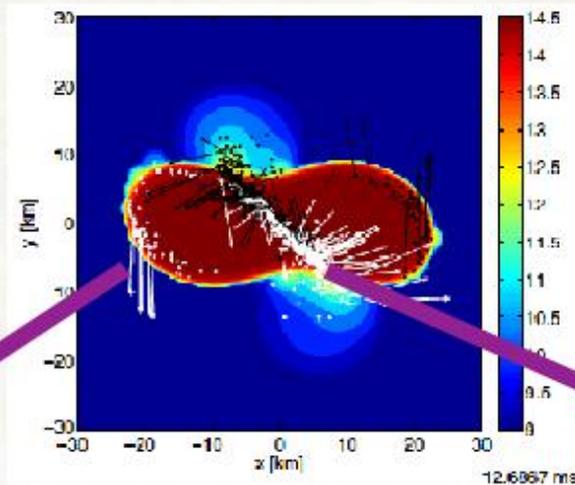


Rosswog et al. 2014

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



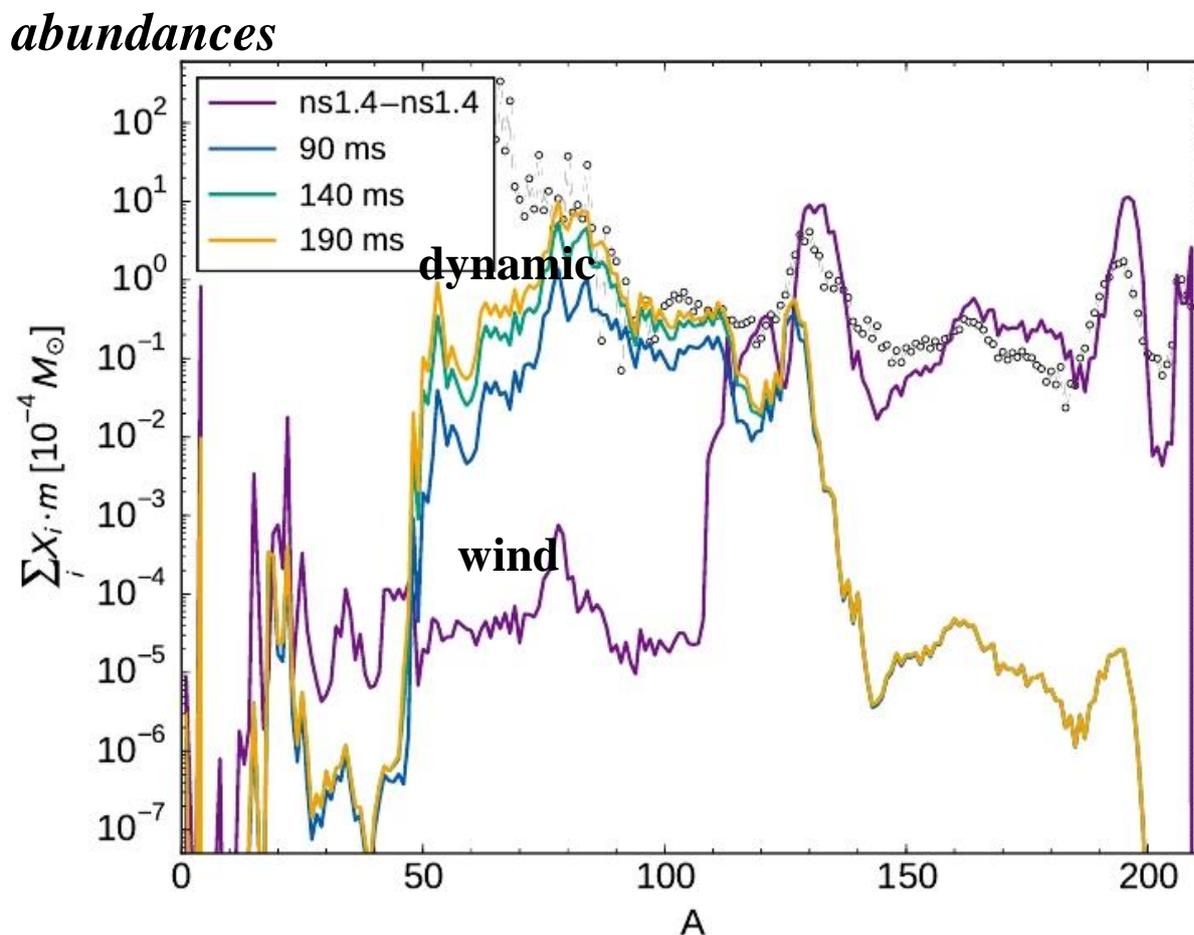
from tidal tails

- > low Y_e
- > more lanthanides
- > higher opacity
- > **red Kilonova**
(if observed independently)

from collision shock

- > high Y_e
- > less lanthanides
- > lower opacity
- > **blue Kilonova**
(if observed independently)

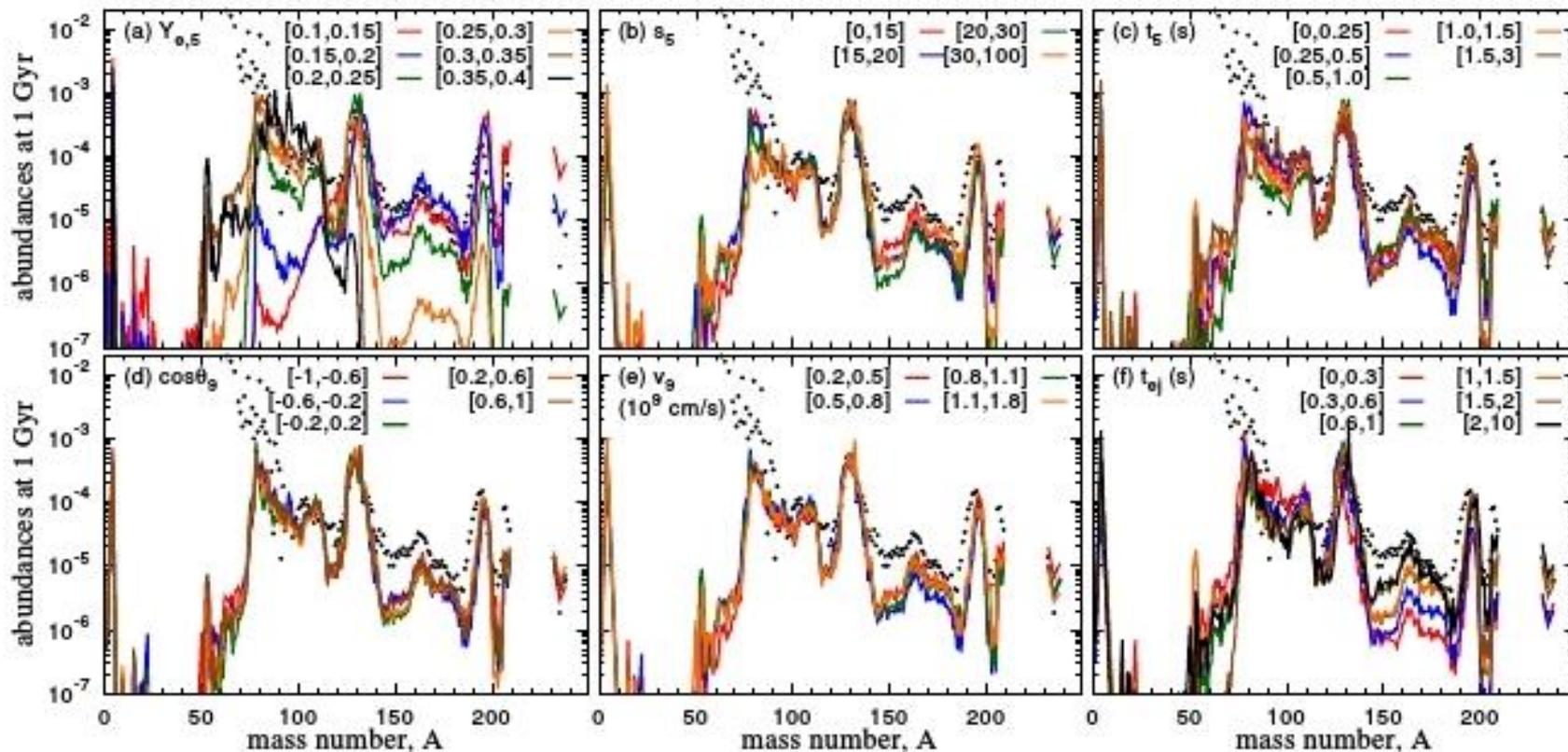
After dynamic ejection of matter, the hot, hypermassive neutron star (before – possibly and with which delay - collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014), Martin et al. (2015)



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

Another Substructure of Ejecta: Nucleosynthesis from BH accretion disks (after merger and BH formation, but without dynamical ejecta)

Variations in BH mass, spin, disk mass, viscosity, entropy in alpha-disk models: r-process nuclides up to lanthanides and actinides *can* be produced.



Wu, Fernandez, Martinez-Pinedo, Metzger (2016)

4. Chemical Evolution

- A. Models utilizing the instantaneous mixing approximation (IMA) assuming instantaneous mixing of ejecta with interstellar medium. Applicable for a metallicity range $[Fe/H] > -1.5$?, when an averaging over IMF obtained and also many compact binary mergers reached already averaged values.***

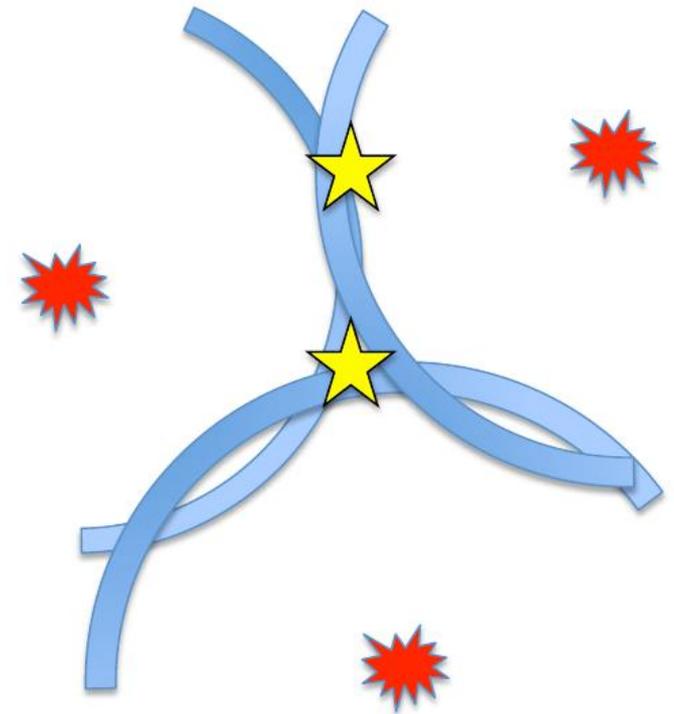
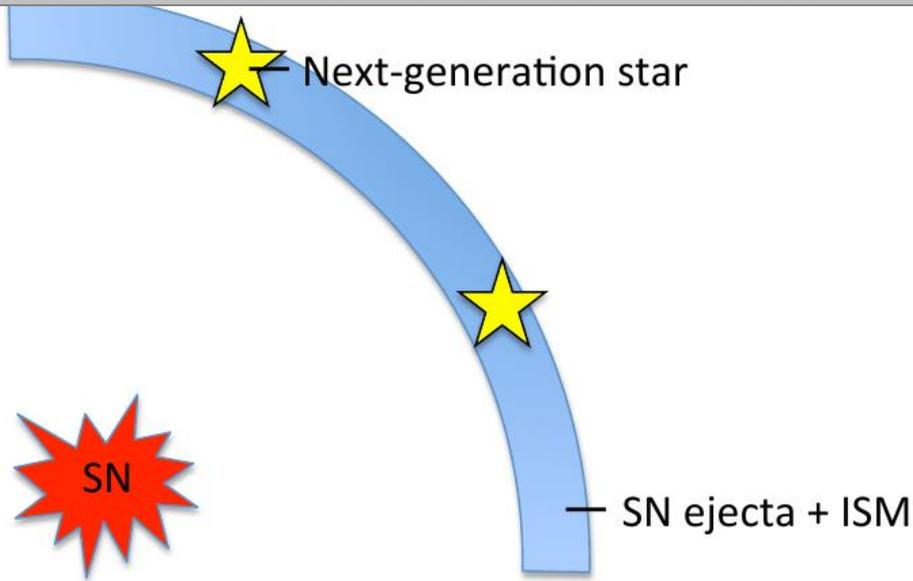
- B. Models utilizing inhomogeneous approach, which can treat individual? contributions (from stochastic simplified models up to cosmological models).***

Stellar Abundances

Inhomogeneous „chemical evolution“ models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about $5 \cdot 10^4 M_{\text{sol}}$ (Sedov-Taylor blast wave).
After many events an averaging of ejecta composition is attained.

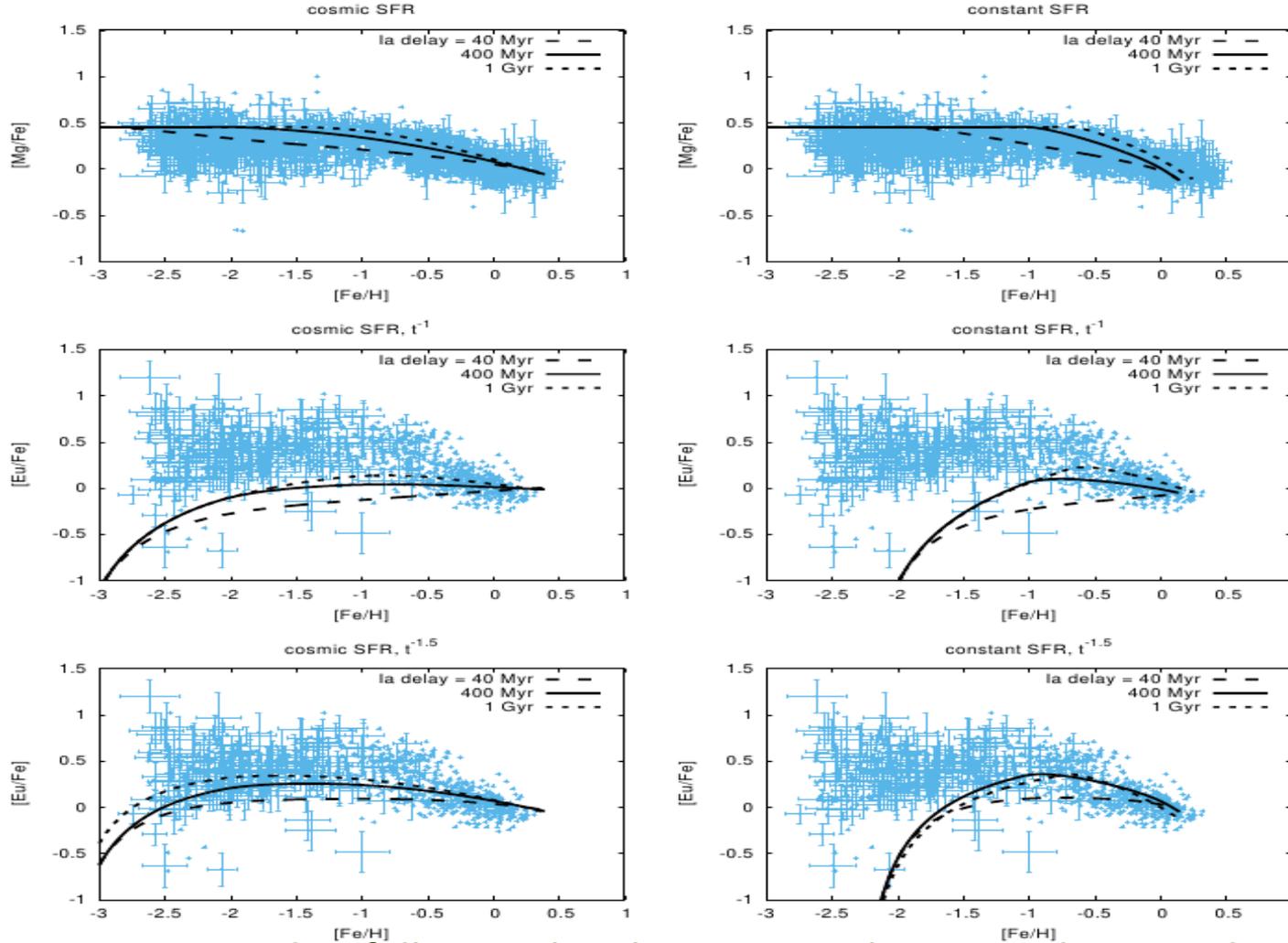
In the later phase

Contribution from multiple CCSNe
(unknown → average weighted by IMF)



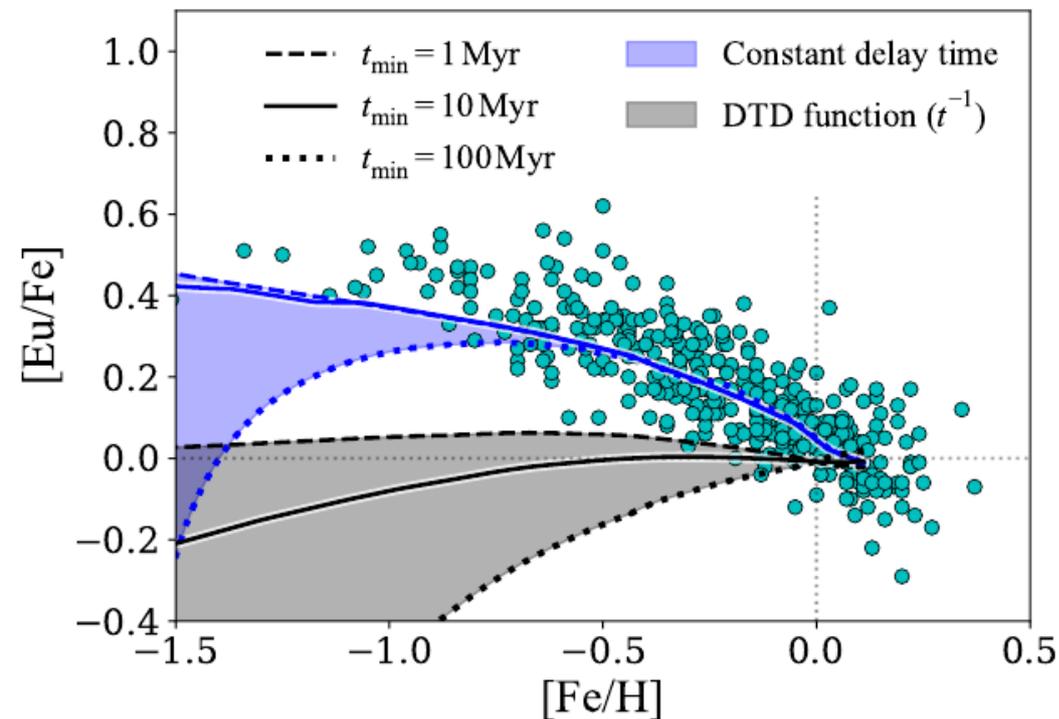
adopted from K. Nakamura

Hotokezaka et al. (2018), GCE with CCSNe, SNe Ia and NS-mergers, see also Coté et al. (2017,2019)

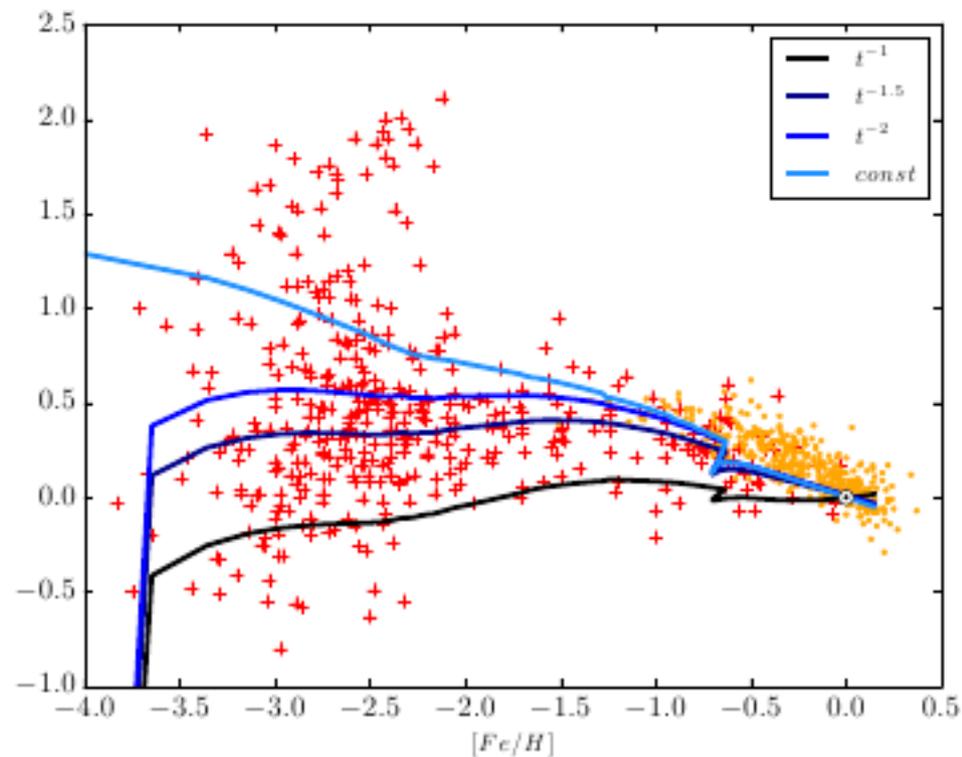


The delay time is not constant but follows a distribution. Population synthesis studies, consistent with short GRBs, indicate a t^{-1} behavior. Then problems would remain to explain the strong r-process by NS-mergers alone! But other options like (i) the mass, ejecta, and explosion energy of the second supernova in a binary system have to be addressed as well (Müller et al. 2018), (ii) turbulent mixing would shift the onset to lower metallicities, (iii) different SFR in initial substructures can also do so, (iv) neutron star kicks can lead to r-process ejecta in regions unpolluted by prior SNe

Probing the Delay-Time Distribution (DTD)



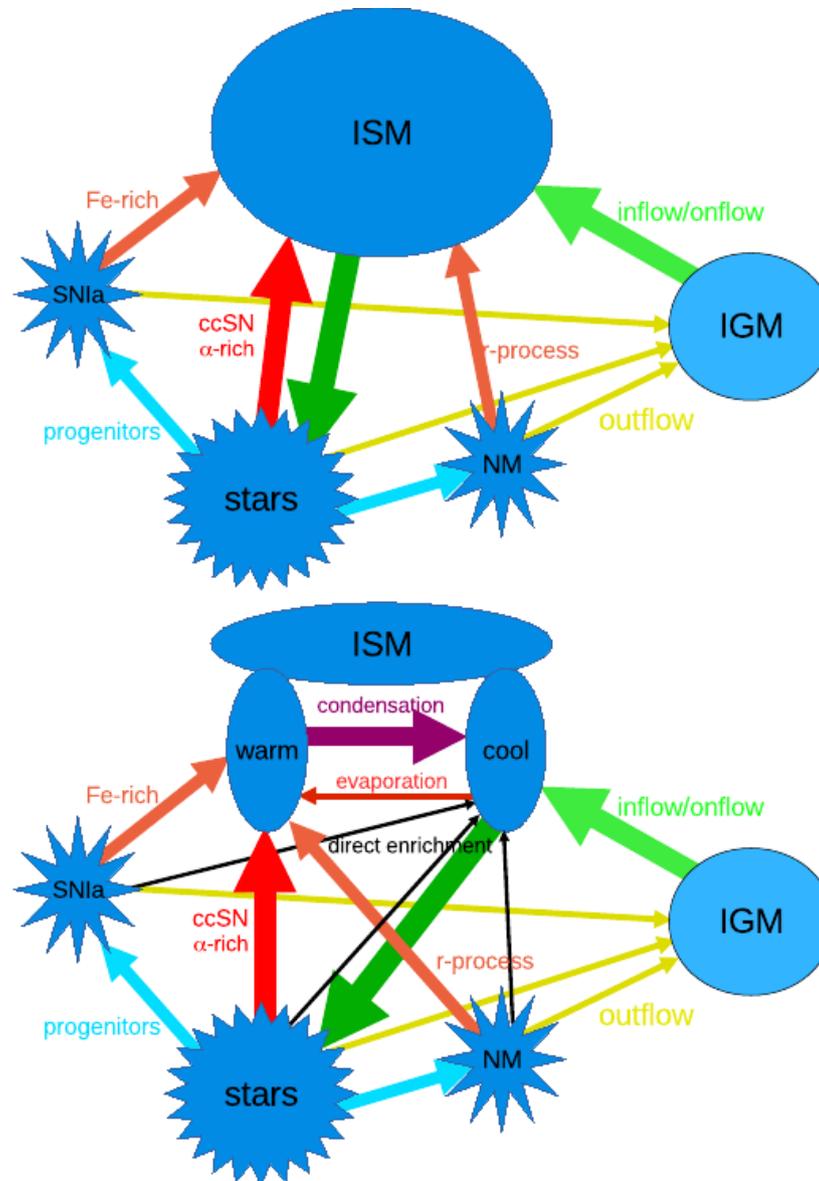
Coté et al. (2019)



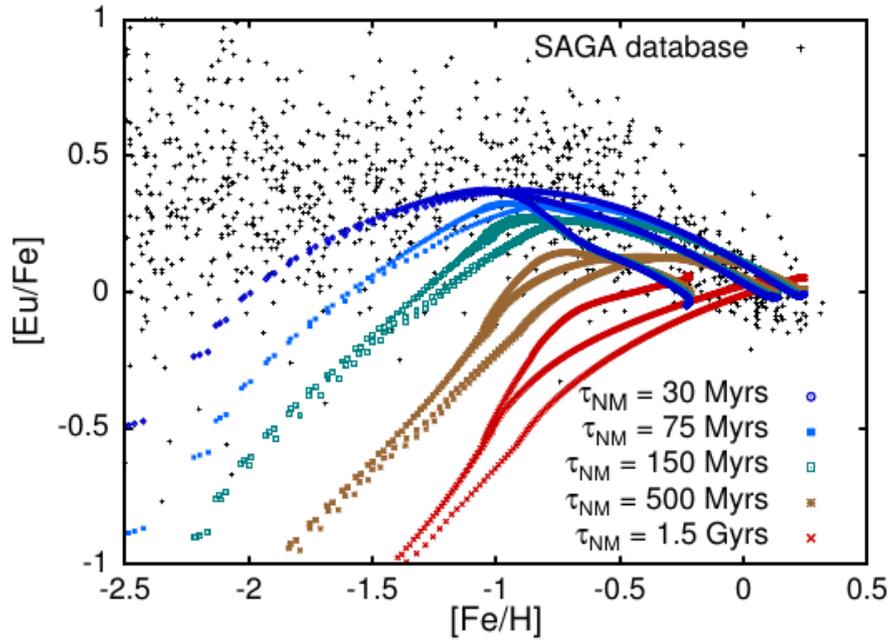
(d)

Simonetta et al. (2019)

Schönrich et al. (2019)



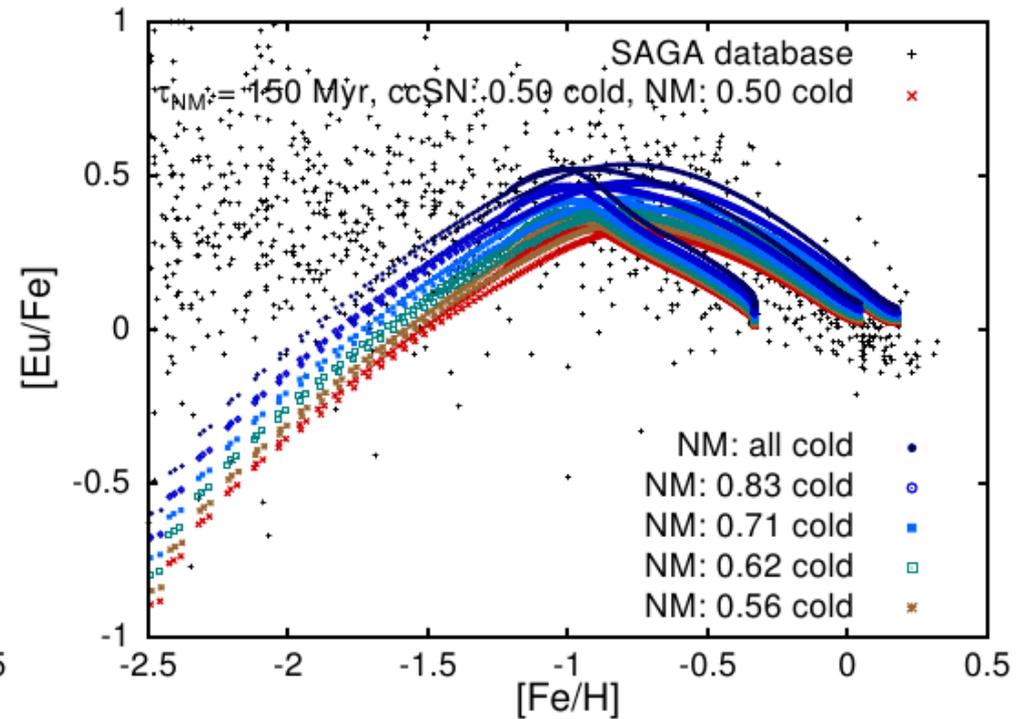
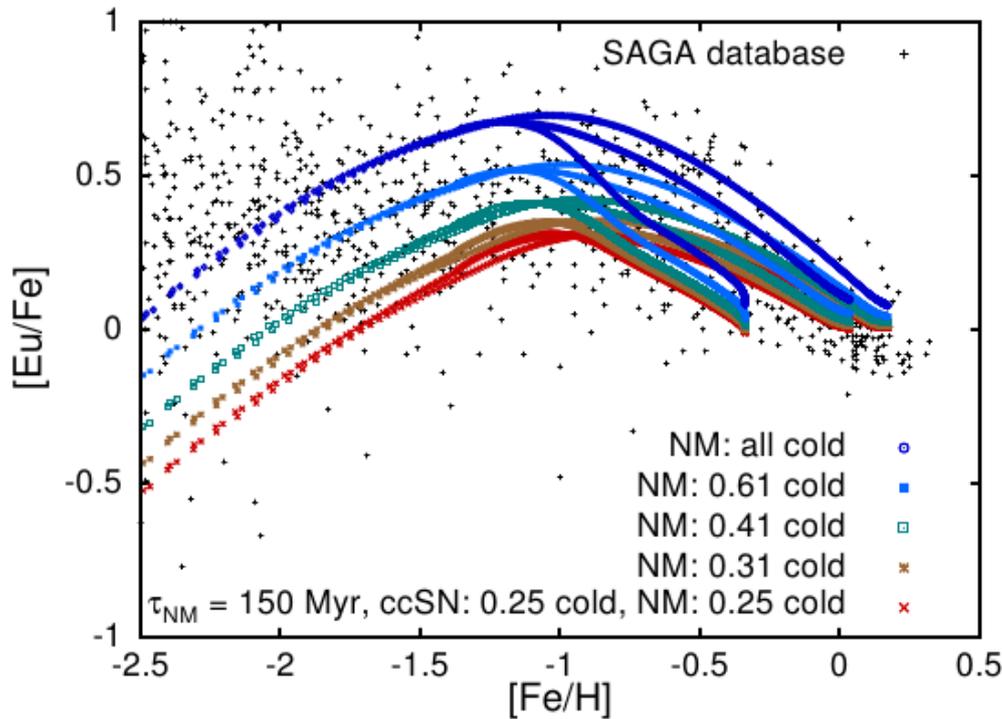
Star formation takes only place in cooled regions of the ISM, i.e. not all recently ejected matter can already be incorporated and stars contain lower metallicities ($[Fe/H]$) than the «present» ISM (shifts e.g. $[Eu/Fe]$ ratios to lower $[Fe/H]$).



Schönrich et al. (2019)

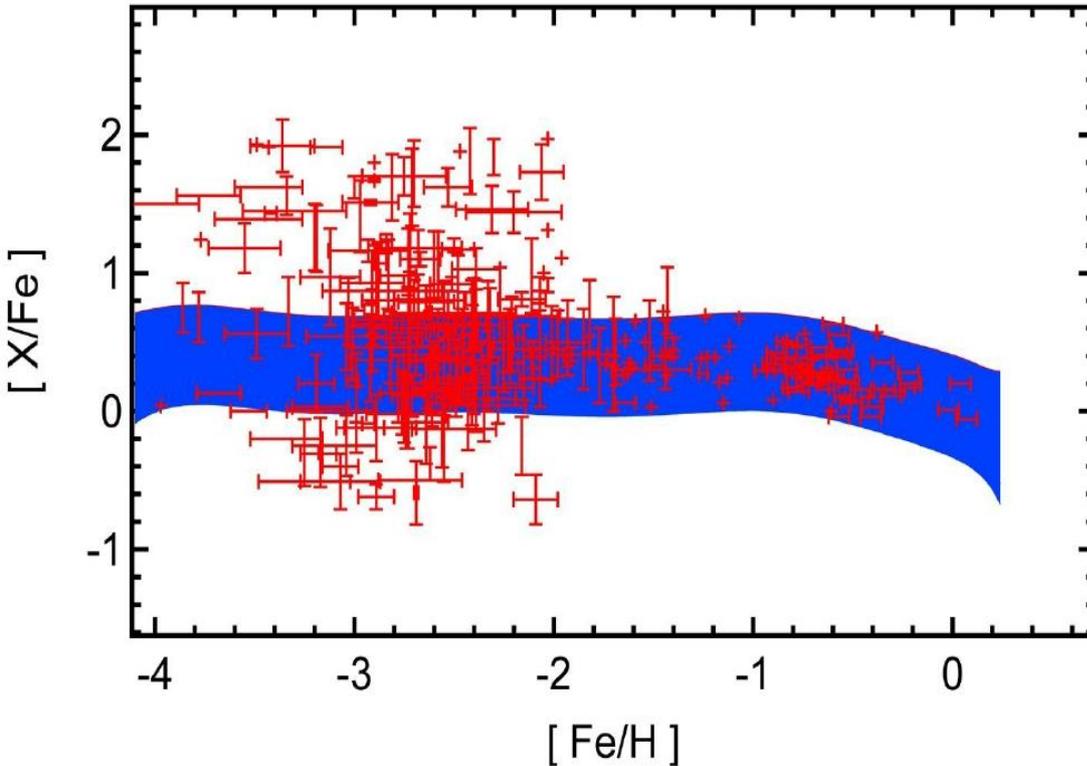
- a) as a function of (constant) delay time
 b) with varying degrees of star formation from only cooled regions

This has a similar effect as a steeper delay-time distribution, but can not solve problems as low metallicities.

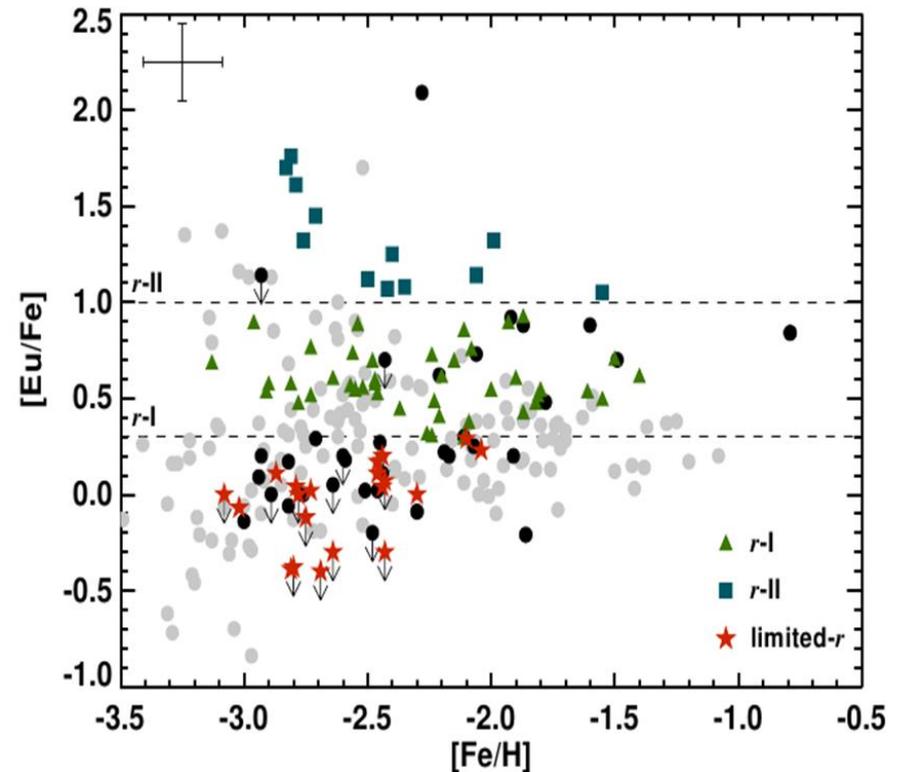


Rare events lead initially to large scatter before an average is attained in galactic evolution!
Need for inhomogeneous modeling!

Data from SAGA database



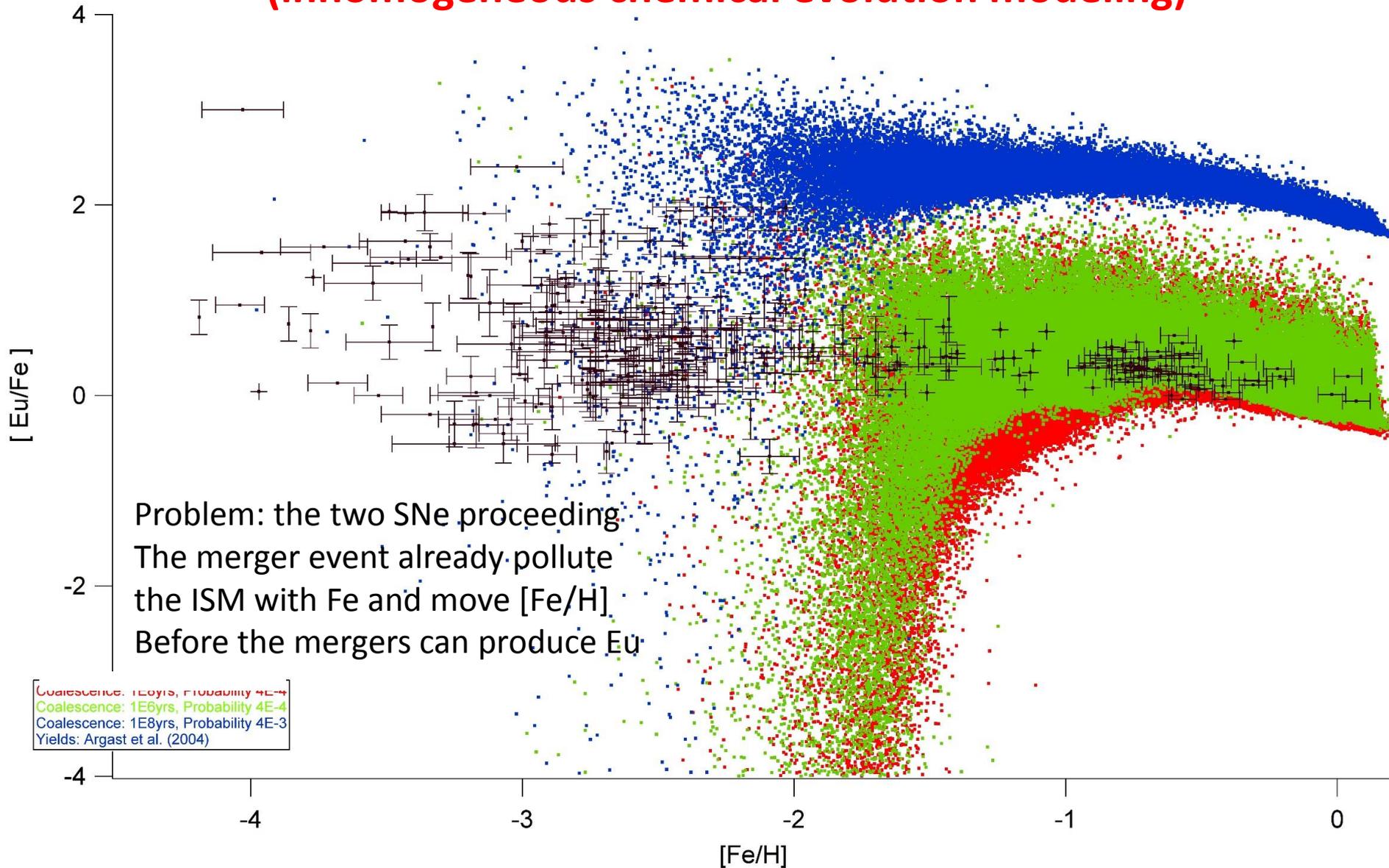
«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)



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

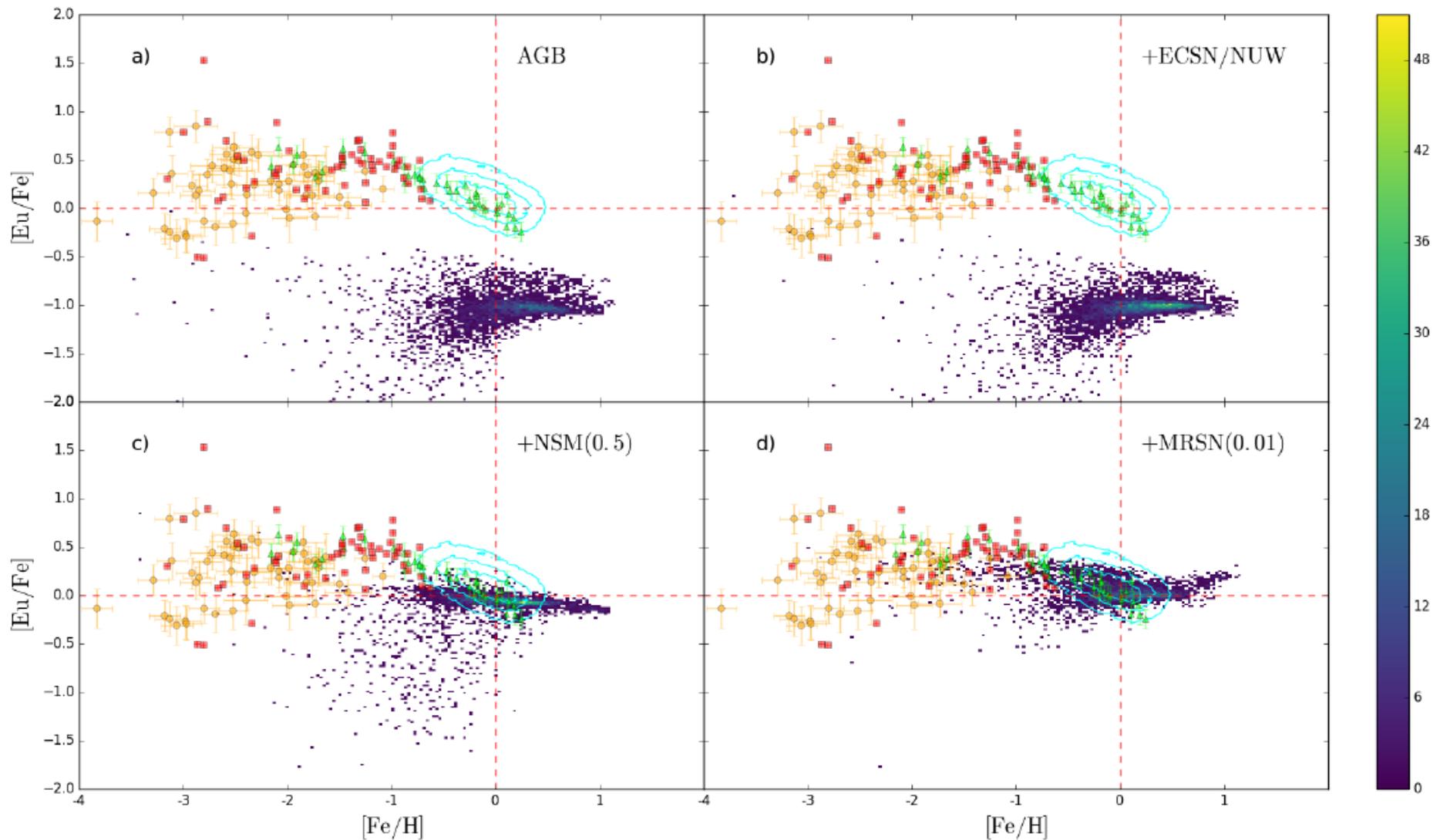
^{60}Fe and ^{244}Pu measurements in deep sea sediments also indicate that the strong r-process is rare in comparison to CCSNe!

Can NS-mergers alone solve the problems at low metallicities?? (inhomogeneous chemical evolution modeling)



Wehmeyer et al. (2015, following Argast+ 2004 description), utilizing only NS merger: green/red different (constant) merging delay times, blue higher merger rate (not a solution, but turbulent mixing would shift the onset to lower metallicities)

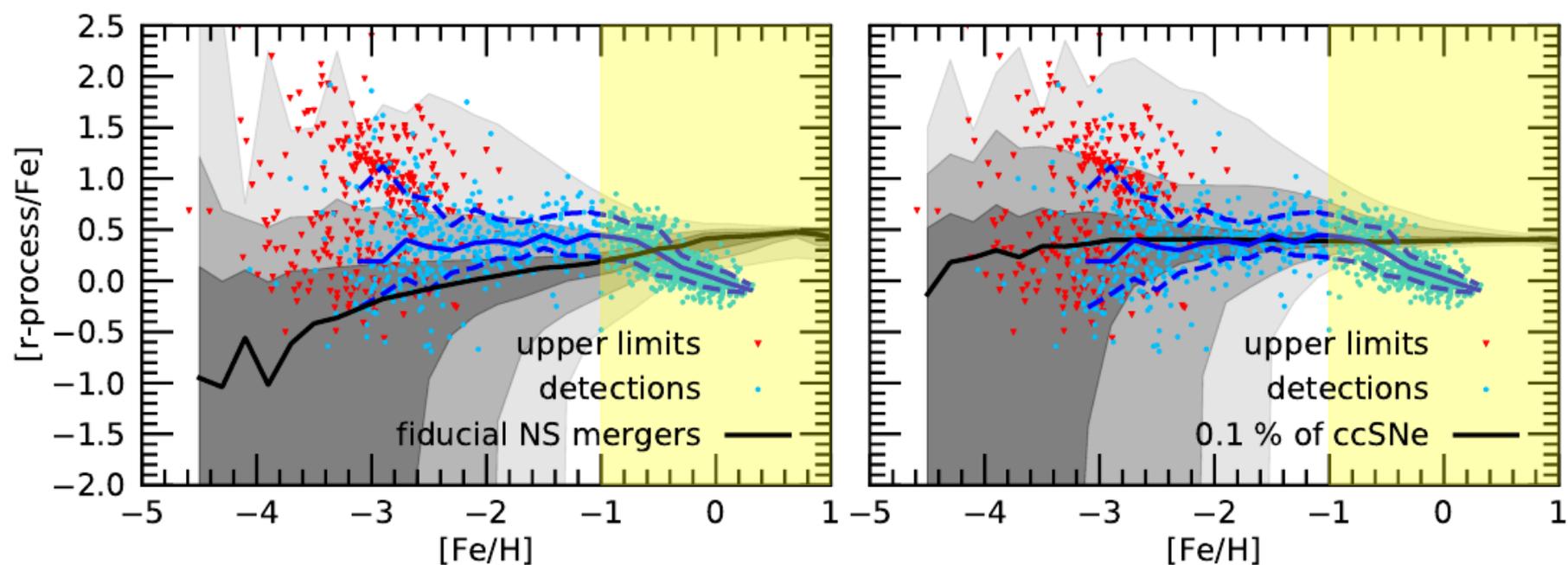
Predicted [Eu/Fe] distribution, when utilizing the contribution of:
a) AGB stars, b) EC supernovae and neutrino wind from massive stars (regular CCSNe),
c) neutron star mergers, and also magneto-rotational supernovae.
It seems that other (earlier) inputs than NS-mergers are required!



Haynes & Kobayashi (2019)

Cosmological simulation by F. van de Voort et al. (2019, in preparation, private communication), 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.

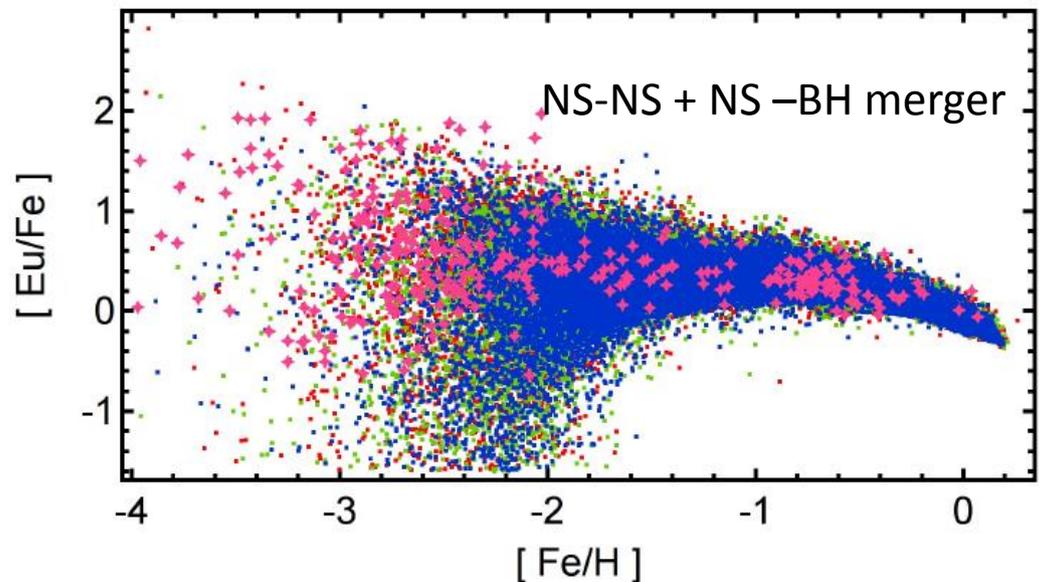
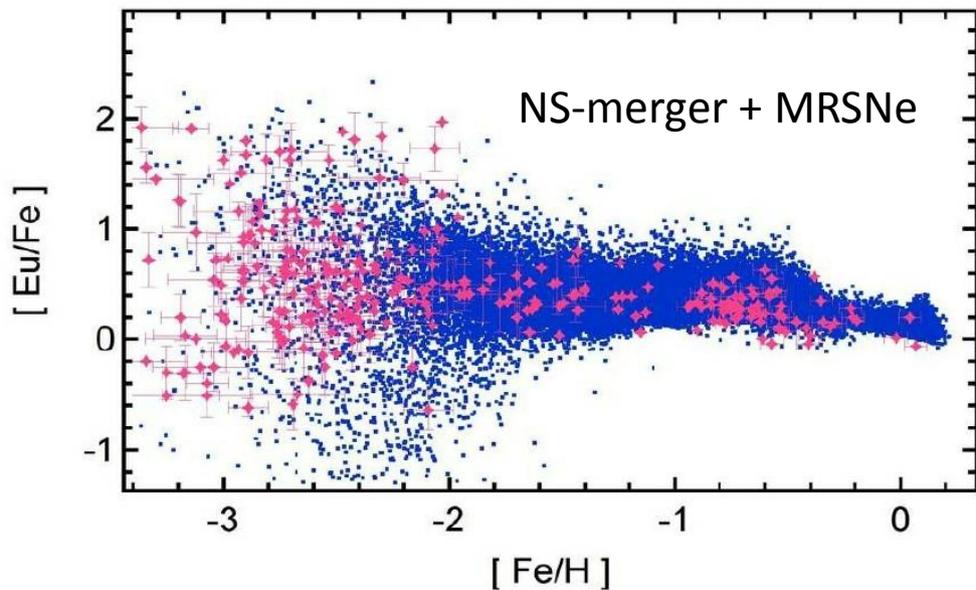
Only the inclusion of rare single massive star events (1 permille of CCSNe) leads to a flat median and a consistent scatter.



Combination of (a) NS mergers and magneto-rotational jets or (b) NS-BH and NS-mergers (occurring 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

⇒ Options to solve the low metallicity problem,