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

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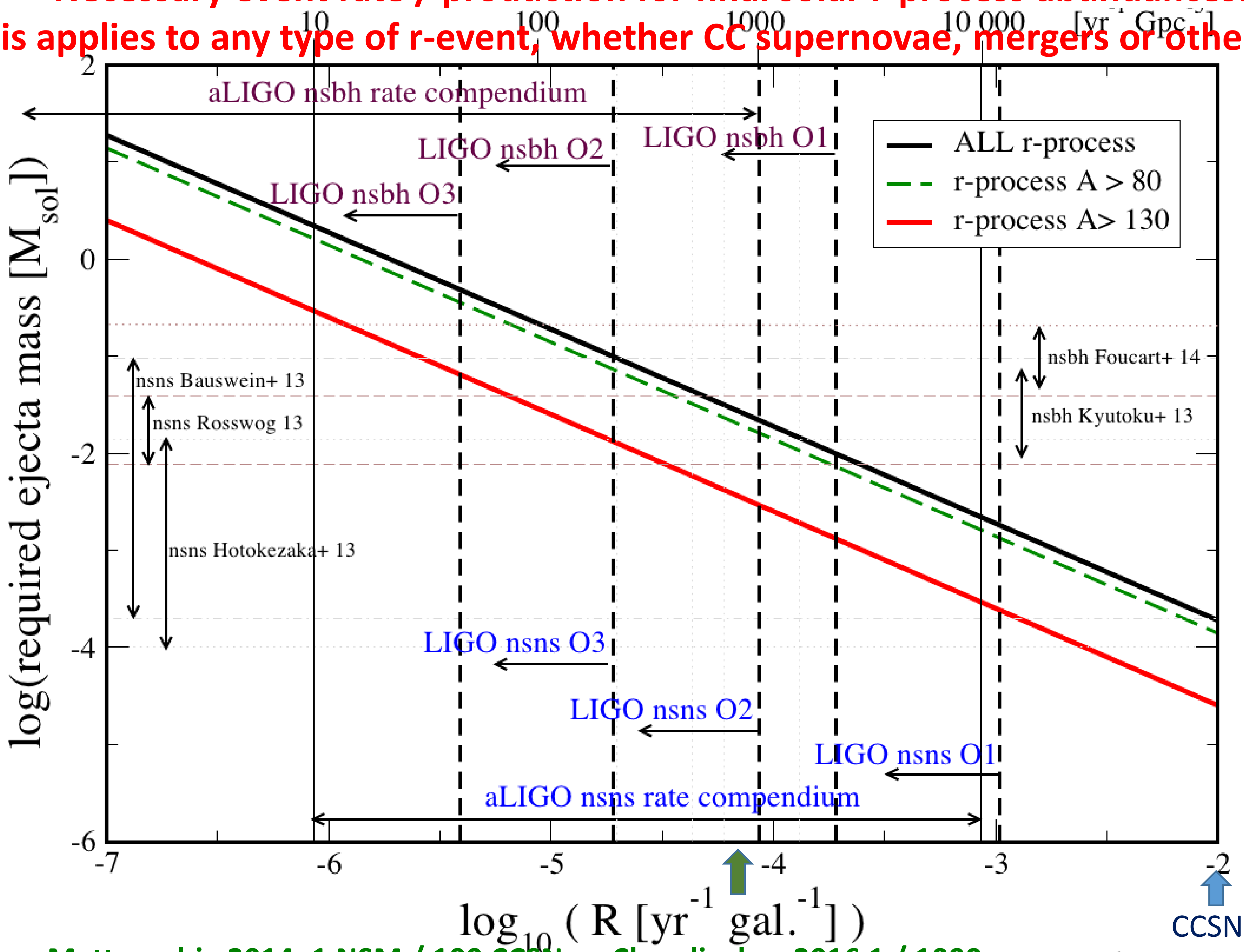
See also our recent r-process review for Rev. Mod. Phys. 2019arXiv190101410C, soon to be updated, including more recent publications and incorporating changes due to referee comments.

1. Observational Constraints

Necessary event rate / production for final solar r-process abundances:
This applies to any type of r-event, whether CC supernovae, mergers or other sites

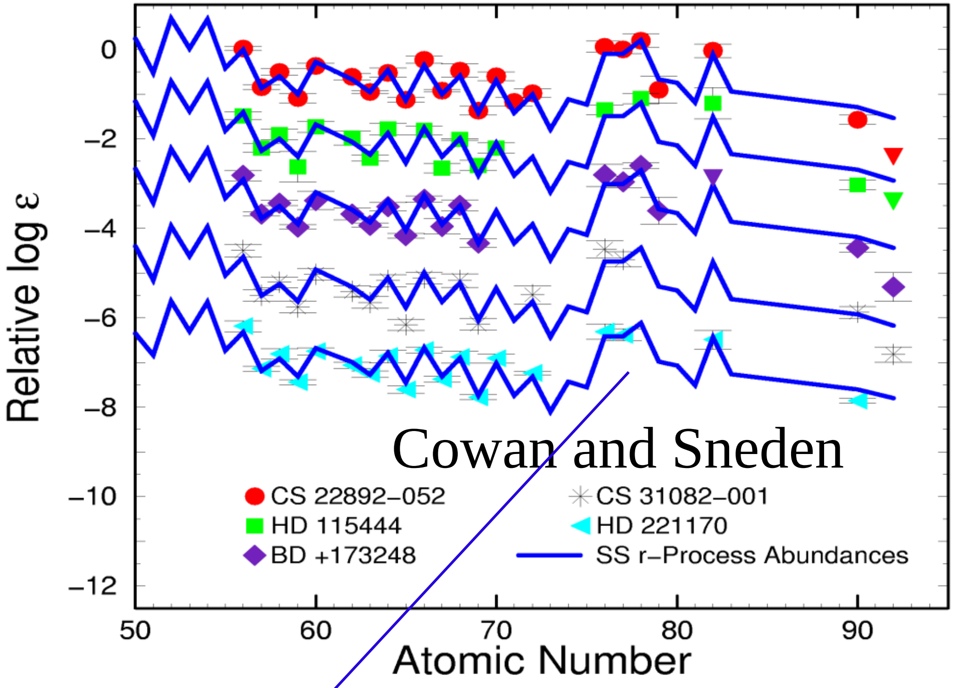


CCSNe

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

from Rosswog+ 18

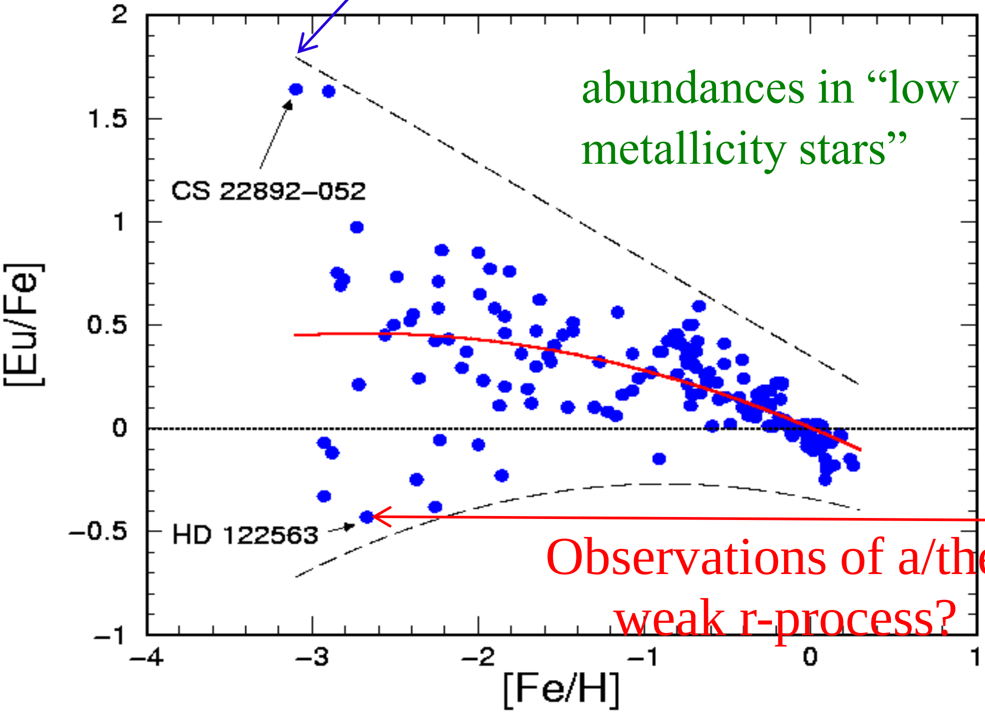
Observational Constraints on r-Process Sites



Cowan and Sneden

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

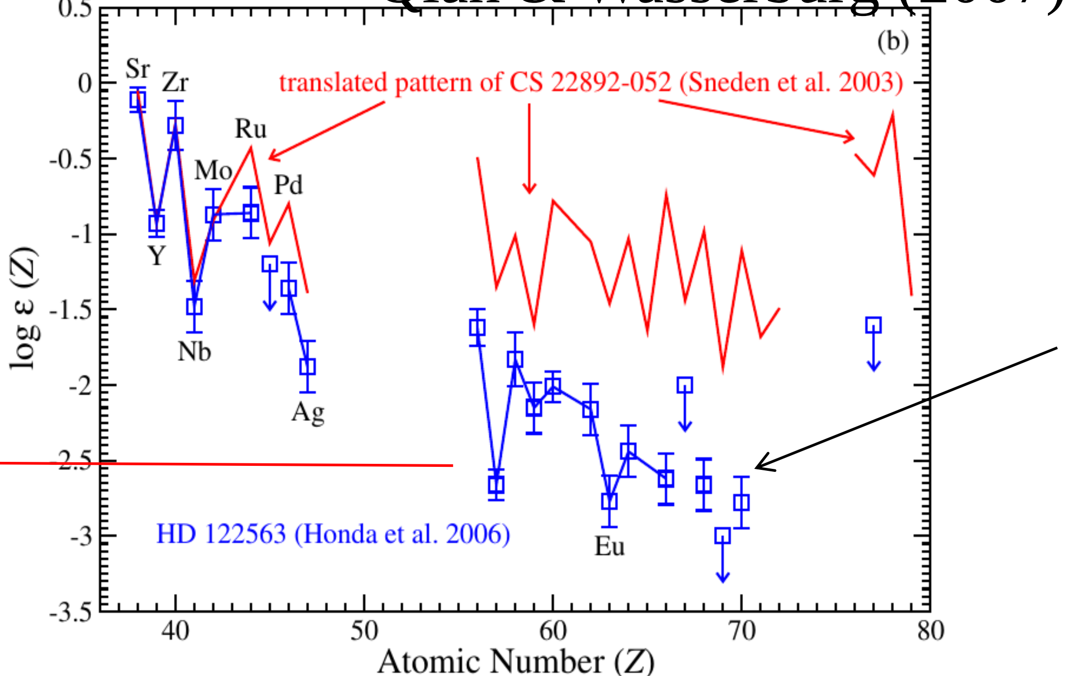
On “average” similar to CCSNe products like O, but with extreme scatter. Does the large scatter point to rare events, or different sites (Honda vs. Sneden, weak vs. strong r-process) or a combination of both?



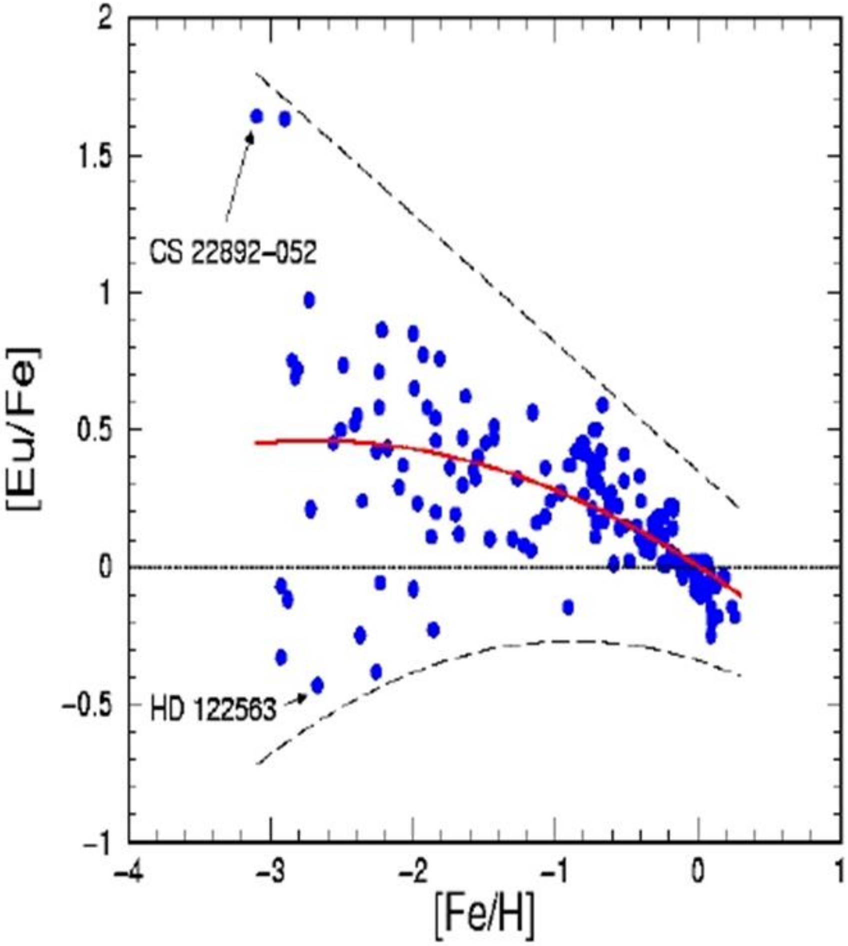
abundances in “low metallicity stars”

Observations of a/the? weak r-process?

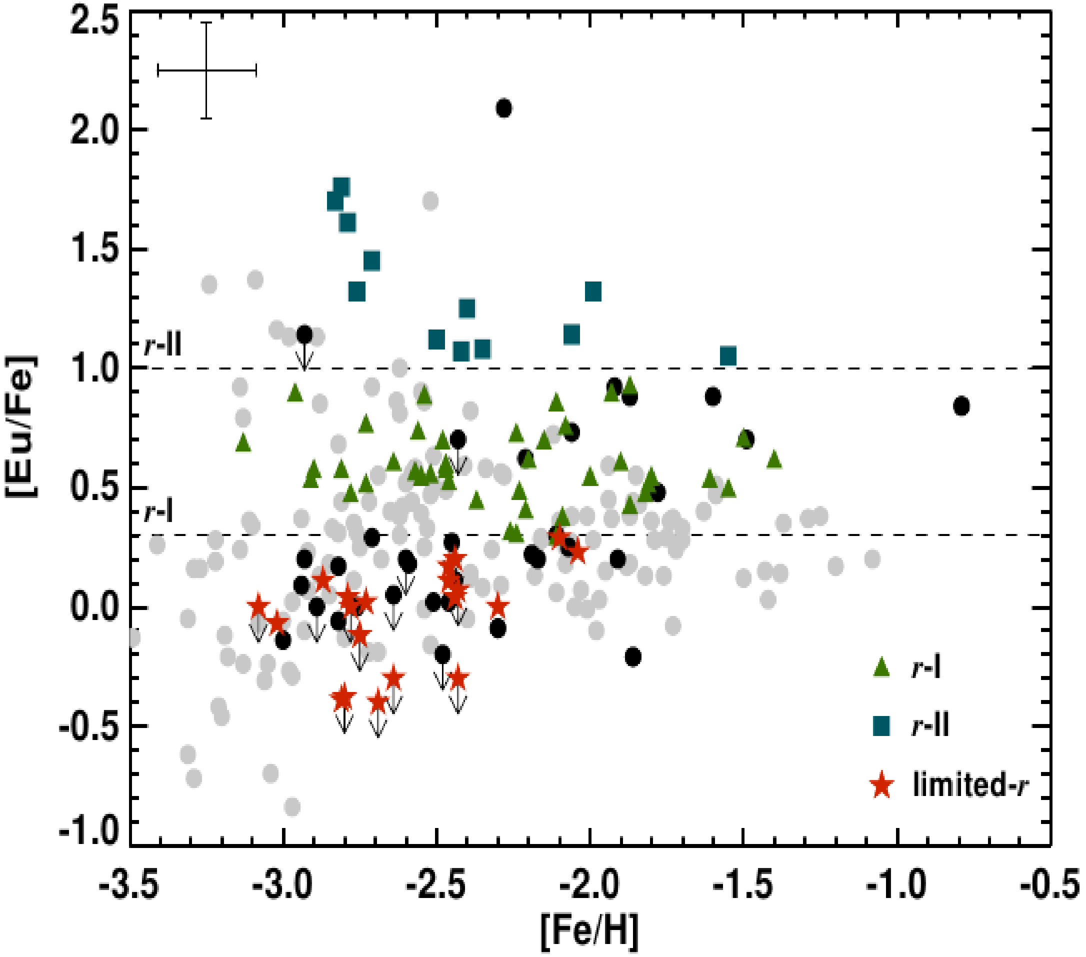
Qian & Wasserburg (2007)



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, hypernovae/collapsars)?
But does not exclude a very low base value from regular core-collapse supernovae (limited-r)?



Cowan & Thielemann (2004)



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

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

^{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.

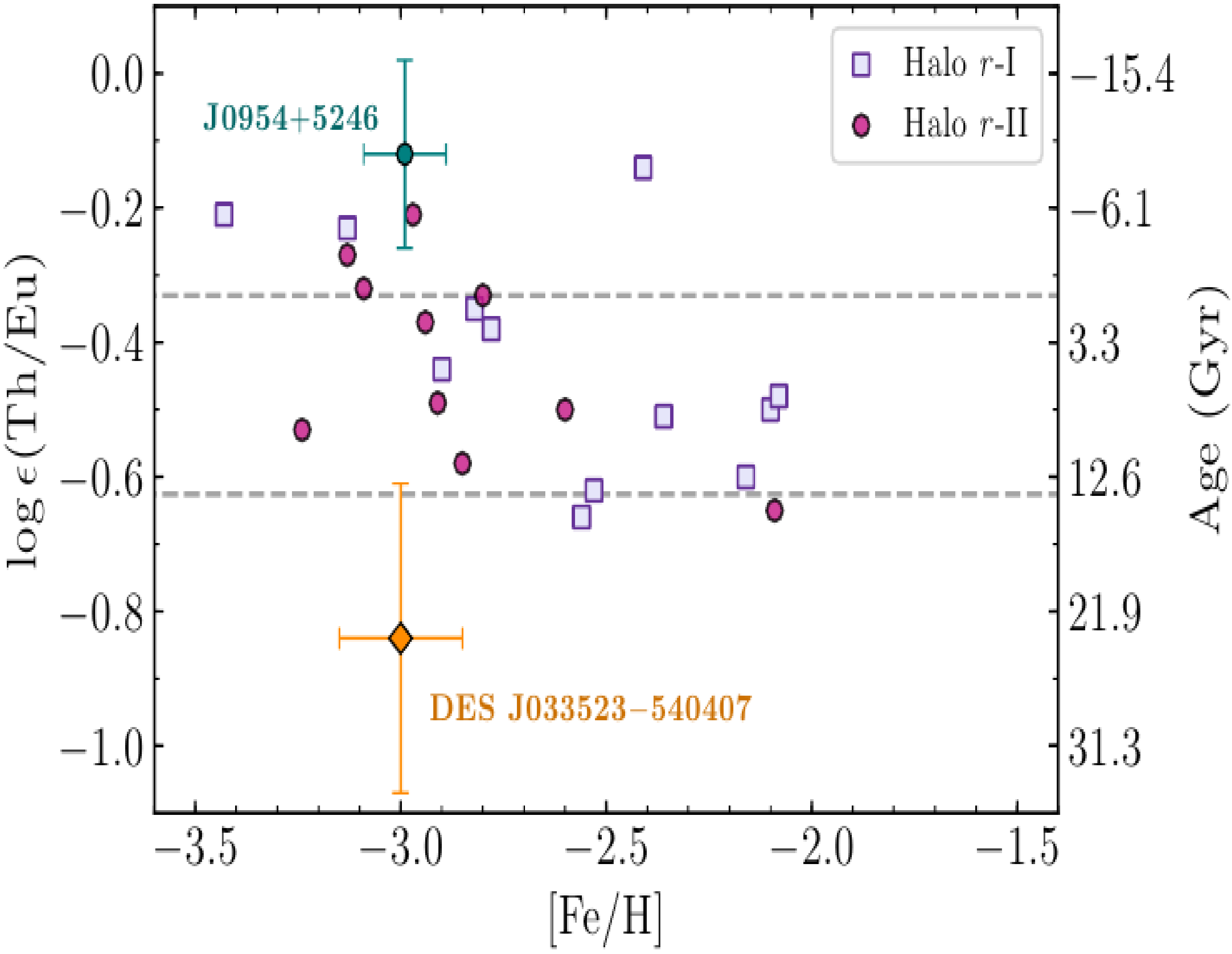
Two distinct influxes of ^{60}Fe, centered at 2.5 Myr before present and between 5.5 and 7 Myr.

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}Pu/^{60}Fe atom ratio of (3–5)×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.

Holmbeck+ (2018)

Actinide-Boost Stars



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

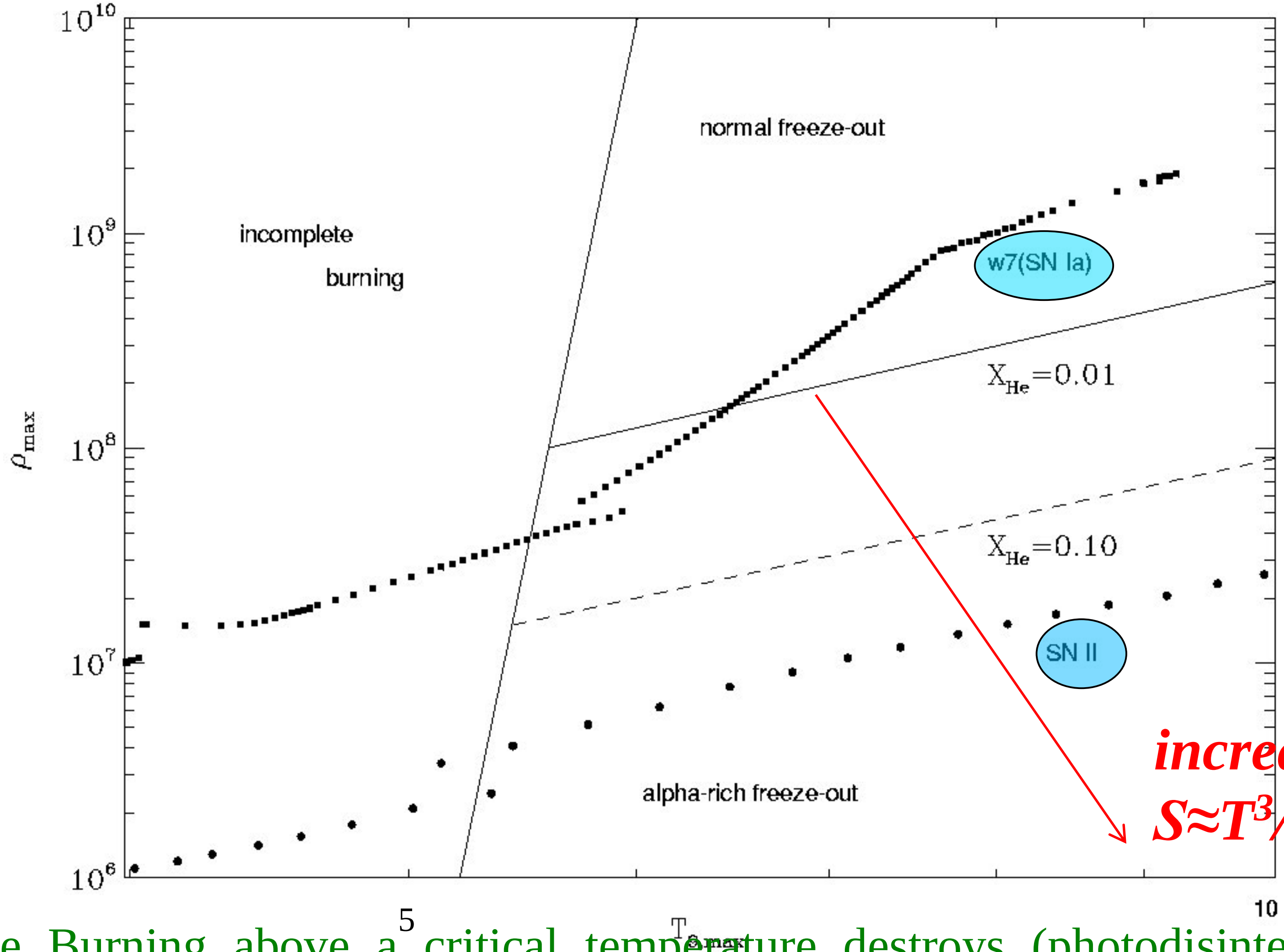
Apparently one finds different production of Eu, U, Th for different r-process enviroments/ conditions.

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?

2. General r-process Modeling:

Explosive Si-Burning



for Y_e=0.498

increasing entropy

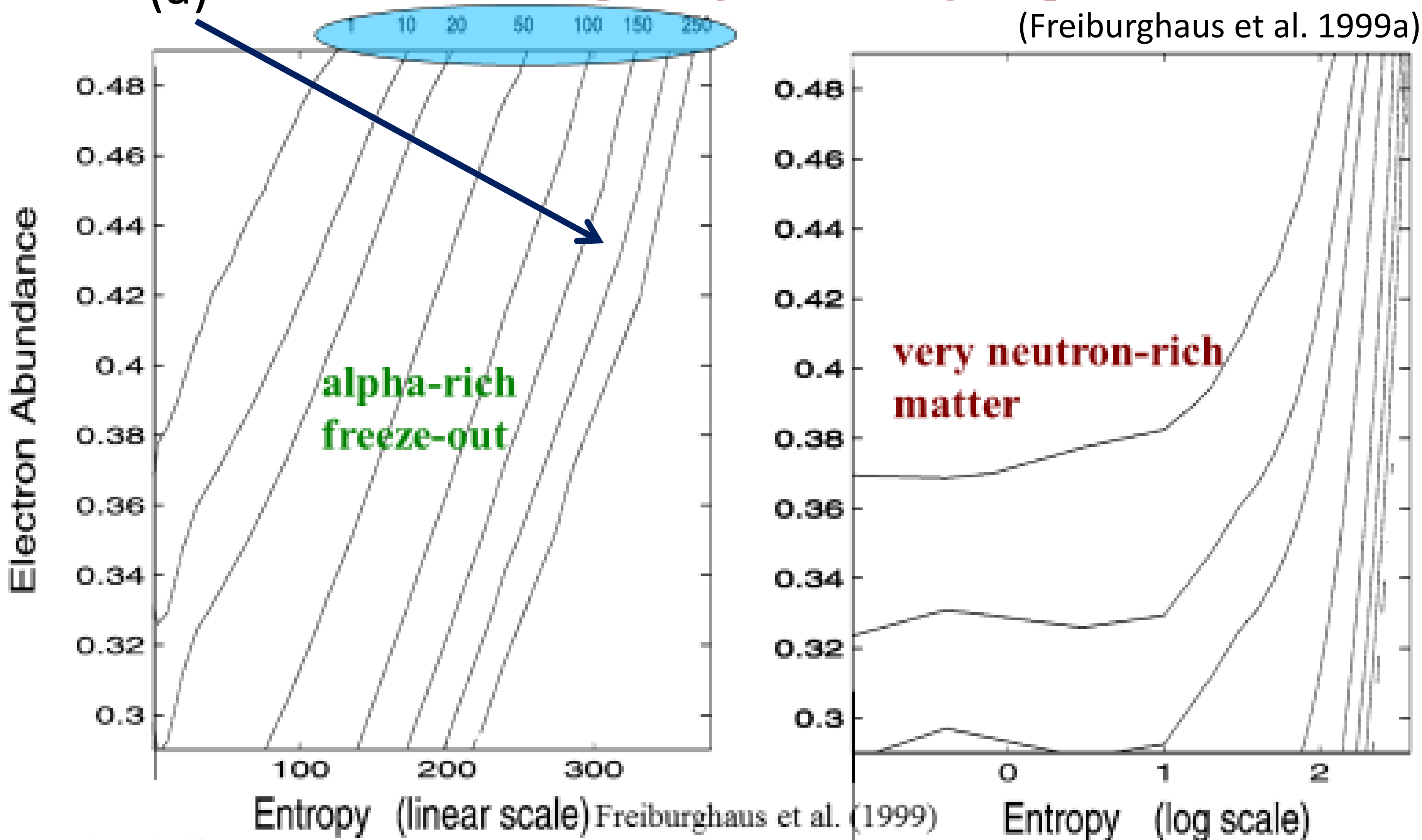
$S \approx T^3/\rho$

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).

n/seed ratios as function of S and Y_e

Two options for a successful r-process

(Freiburghaus et al. 1999a)



Freiburghaus et al. (1999)

neutrino wind?

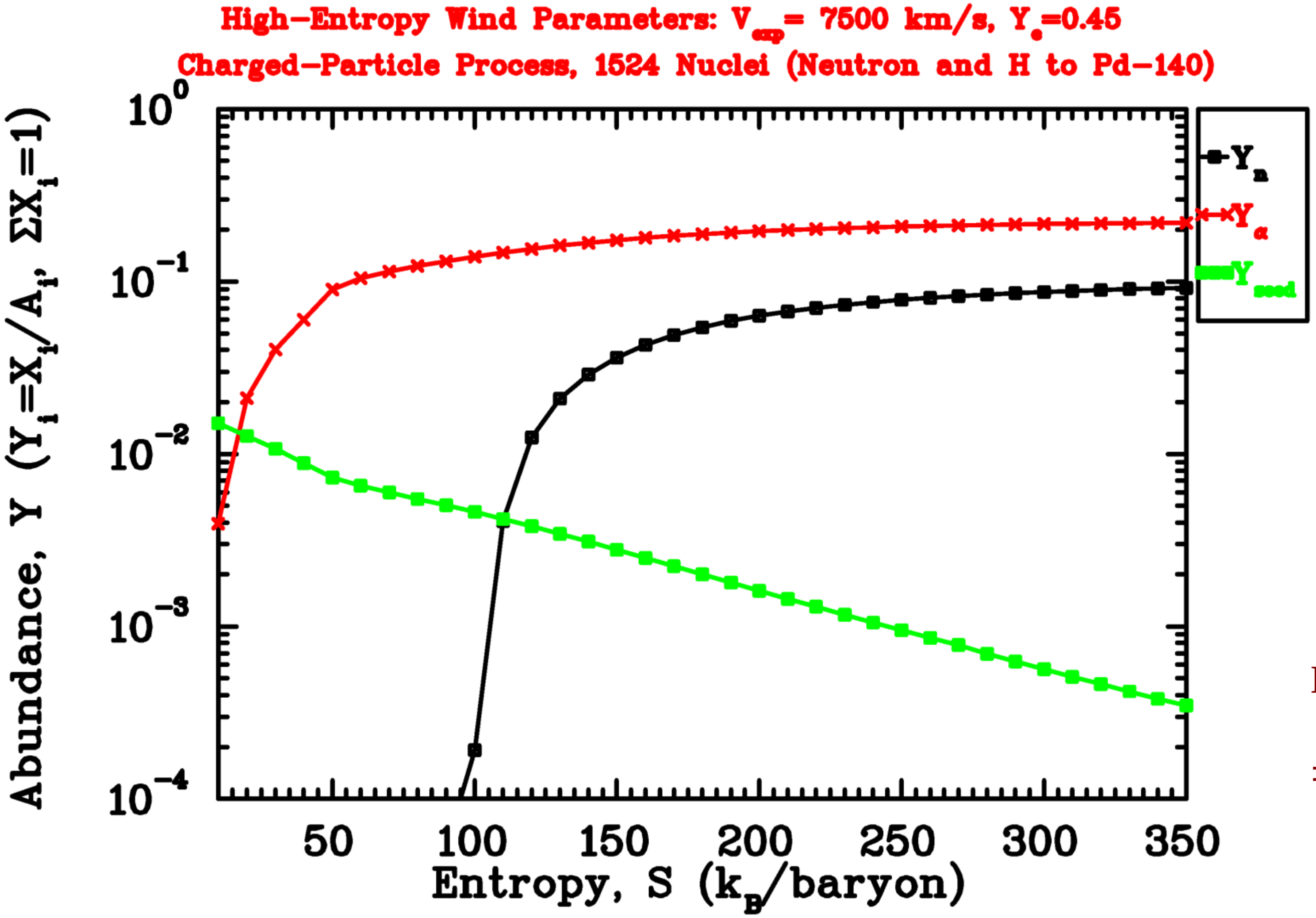
Neutron star mergers and polar jets?

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

n/seed ratios for high entropy conditions are are function of entropy

Farouqi et al. (2010)

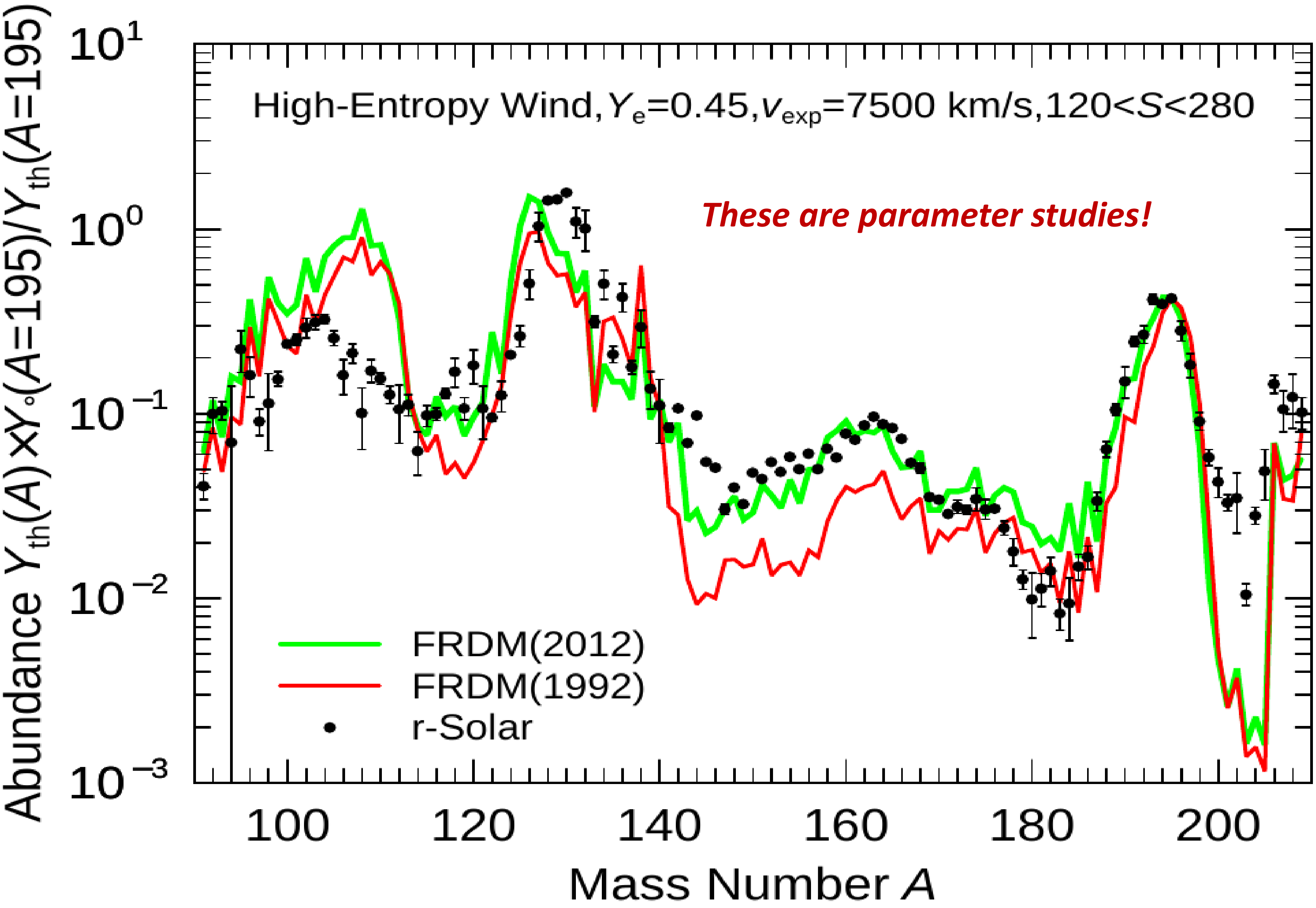
Case (a)



n/seed

$=Y_n/Y_{seed}$

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



High-Entropy Wind, $Y_e=0.45$, $v_{exp}=7500$ km/s, $120<S<280$

These are parameter studies!

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

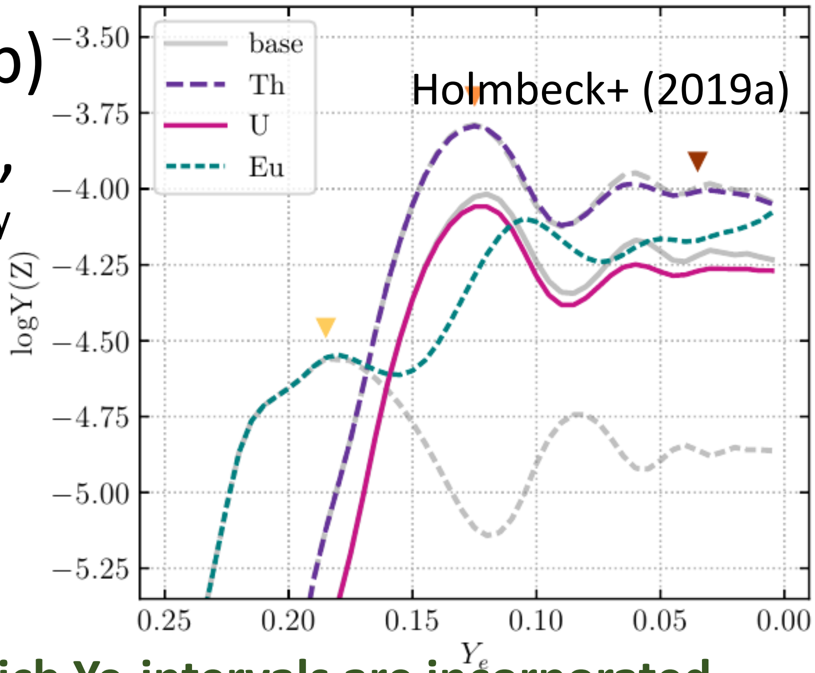
But the innermost ejecta of CCSNe are proton-rich and/or the entropies are not sufficient!

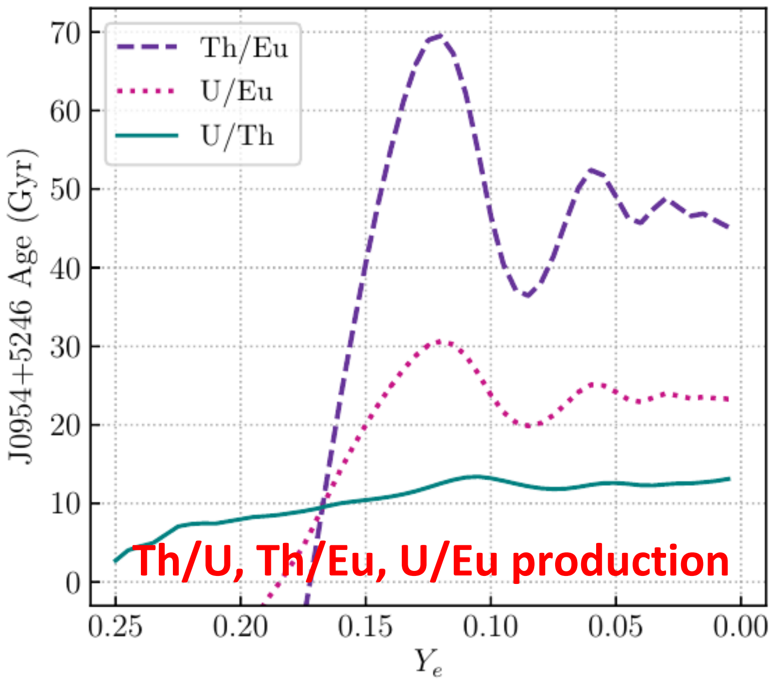
One finds different production of Eu, U, Th for different Ye conditions in r-process enviroments.

Case (b)

low Ye,

low entropy

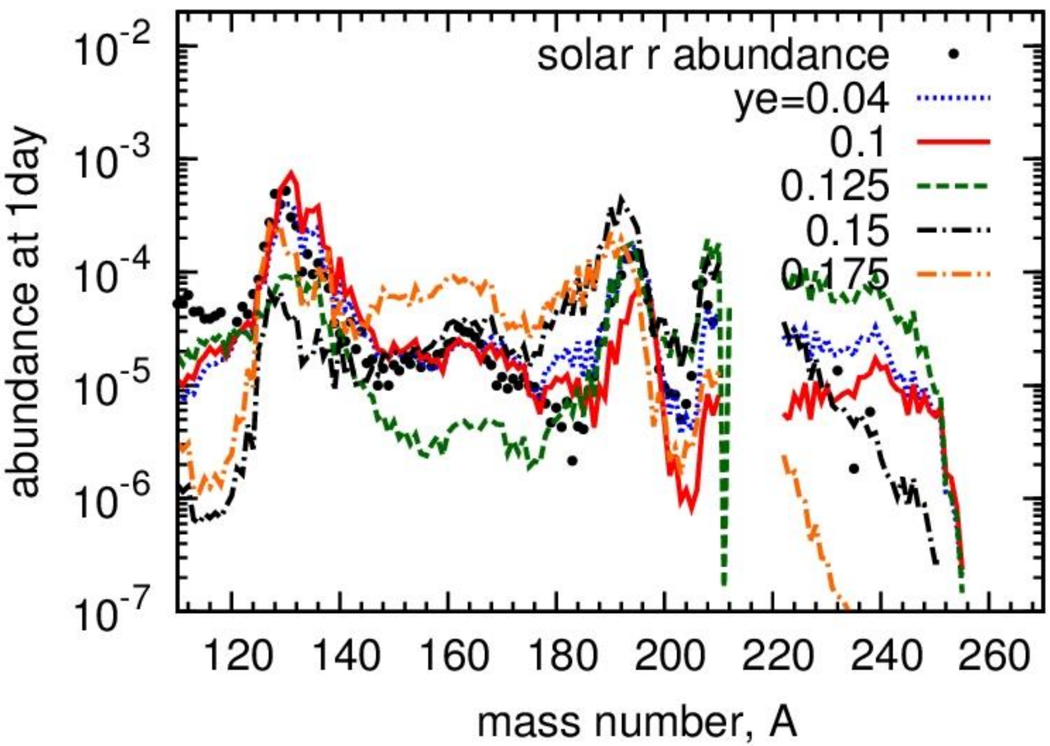




Th/U, Th/Eu, U/Eu production

Which Ye-intervals are incorporated astrophysical scenarios? ***Maximum actinide to Eu ratio in Ye-interval 0.1-0.15 (lower values below and above!)***

From Wu+ 2017:
Also the DZ mass model permits large variations of actinide production, even at low Ye's.
Do we have different Ye-superpositions in the same type of event, or do certain types of events include lowest Ye's like in NS matter and others go just down to Ye=0.15 or 0.125?



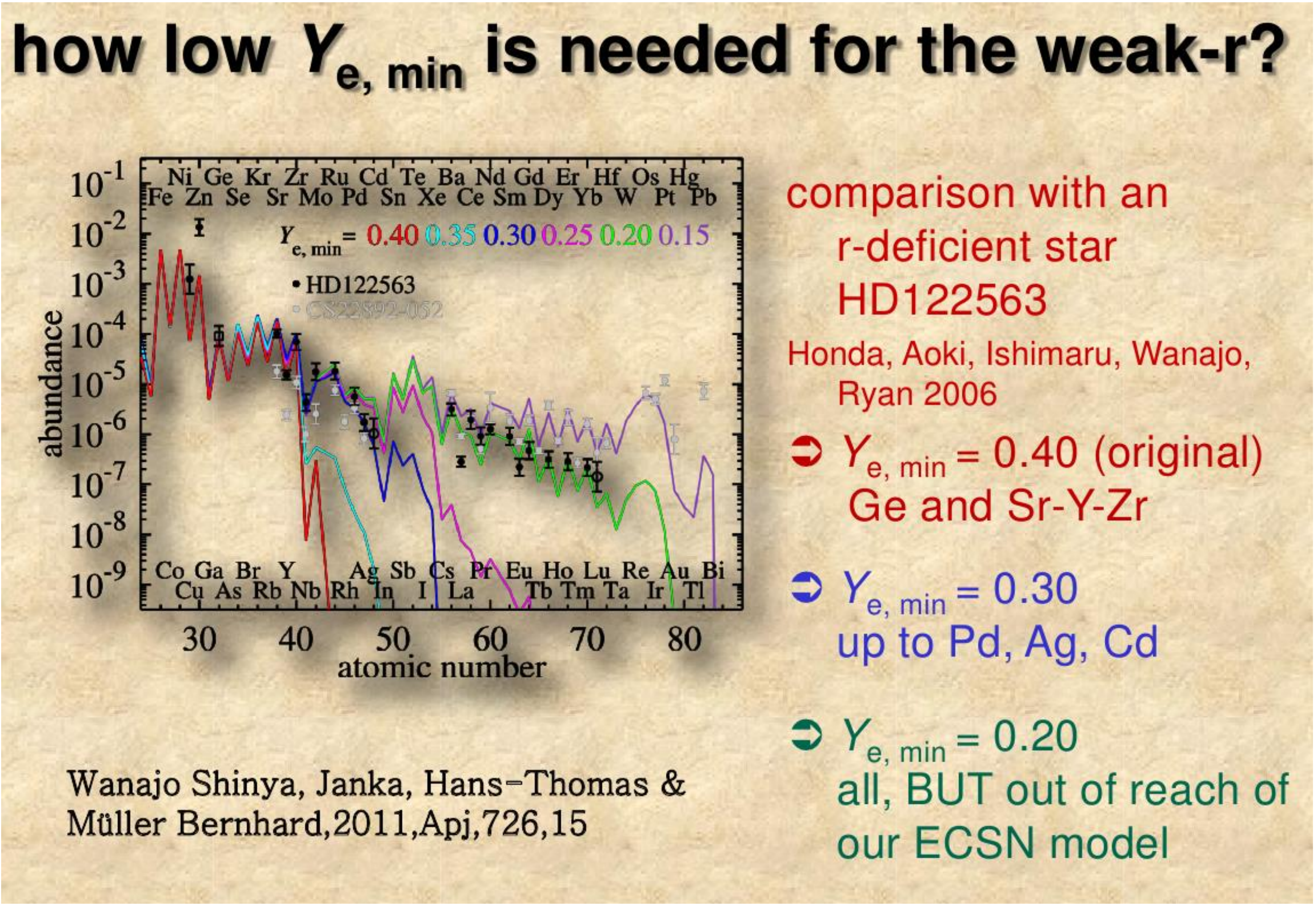
3. Astrophysical Sites

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) can be strong, dependent on initial magn. field
A.4 QCD-driven Supernova Explosions of Massive Stars (Fischer) weak
A.5 Collapsars (Siegel, Metzger, Surman et al.) possibly 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

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)

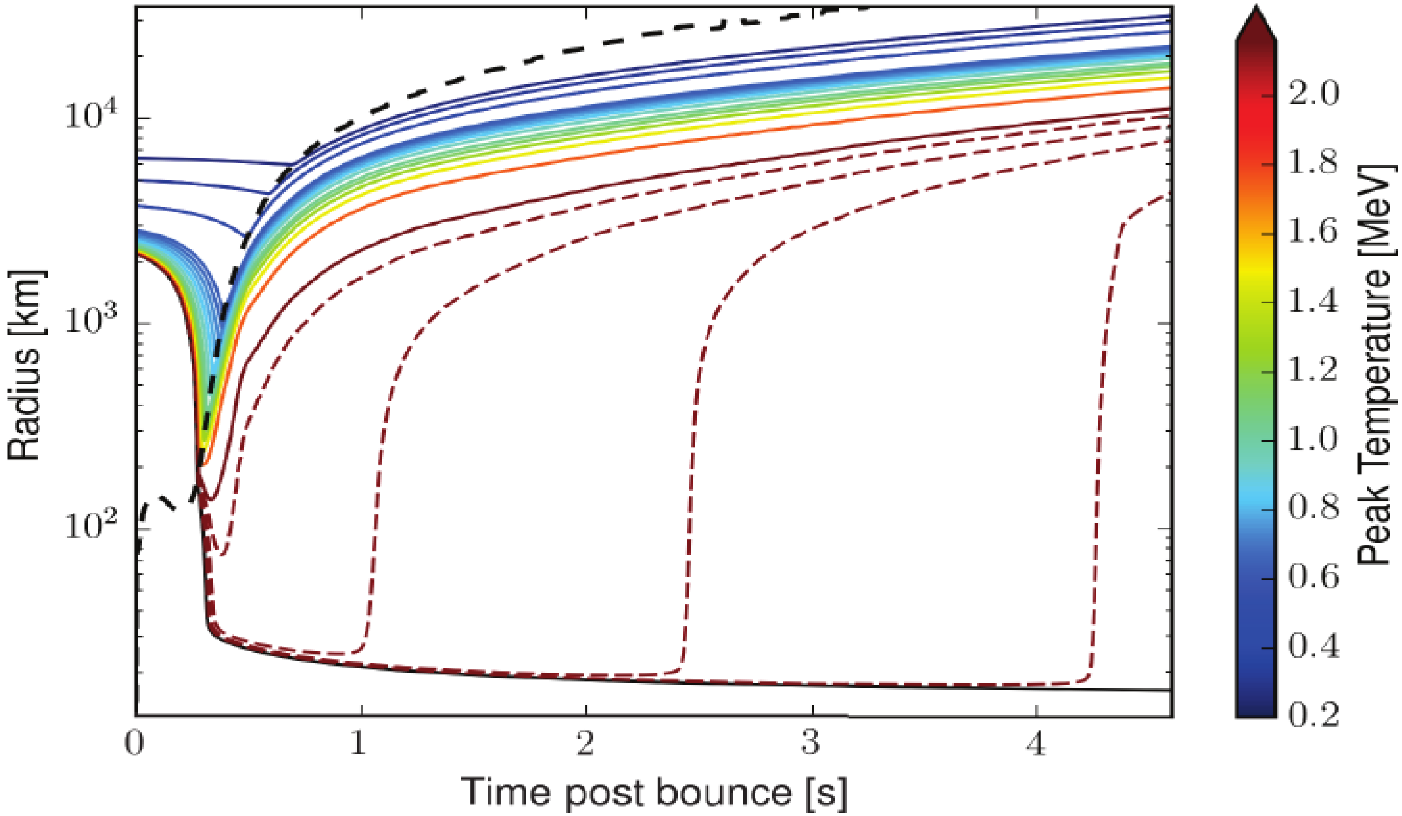


Fig. 3.8.: We show the mass tracers for a PUSH model (progenitor: 15 $M_\odot$ [47], k_{PUSH} =3.5, t_{rise} =200). The black line denotes the PNS surface, the dashed tracer lines (increasing in mass with steps of 10^{-3} $M_\odot$) are delayed ejecta (wind) that reach temperatures around 4 MeV before they are ejected. The colors of the remaining tracers denote their peak temperatures (the first six colored lines are separated by 5×10^{-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=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 → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → 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 $E_{\overline{\mathrm{av,v}}} - E_{\overline{\mathrm{av}},\mathrm{v}} > 4(m_n - m_p)c^2$ 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 (→ ^{64}Zn!), and the vp-process, which can produce nuclei up to Sr, Y, Zr and Mo. (Fröhlich, Martinez-Pinedo, Pruet, Wanajo .. Eichler)

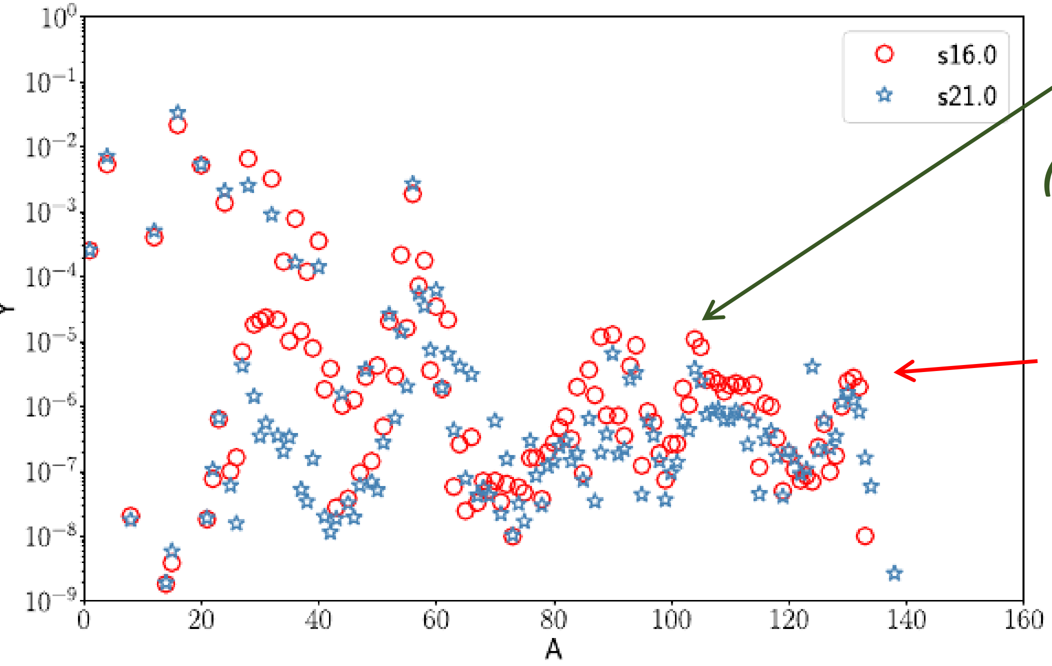
Types of explosive Si-burning: all explosive Si-burning zones in CCSNe lead to an alpha-rich freeze-out.

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

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

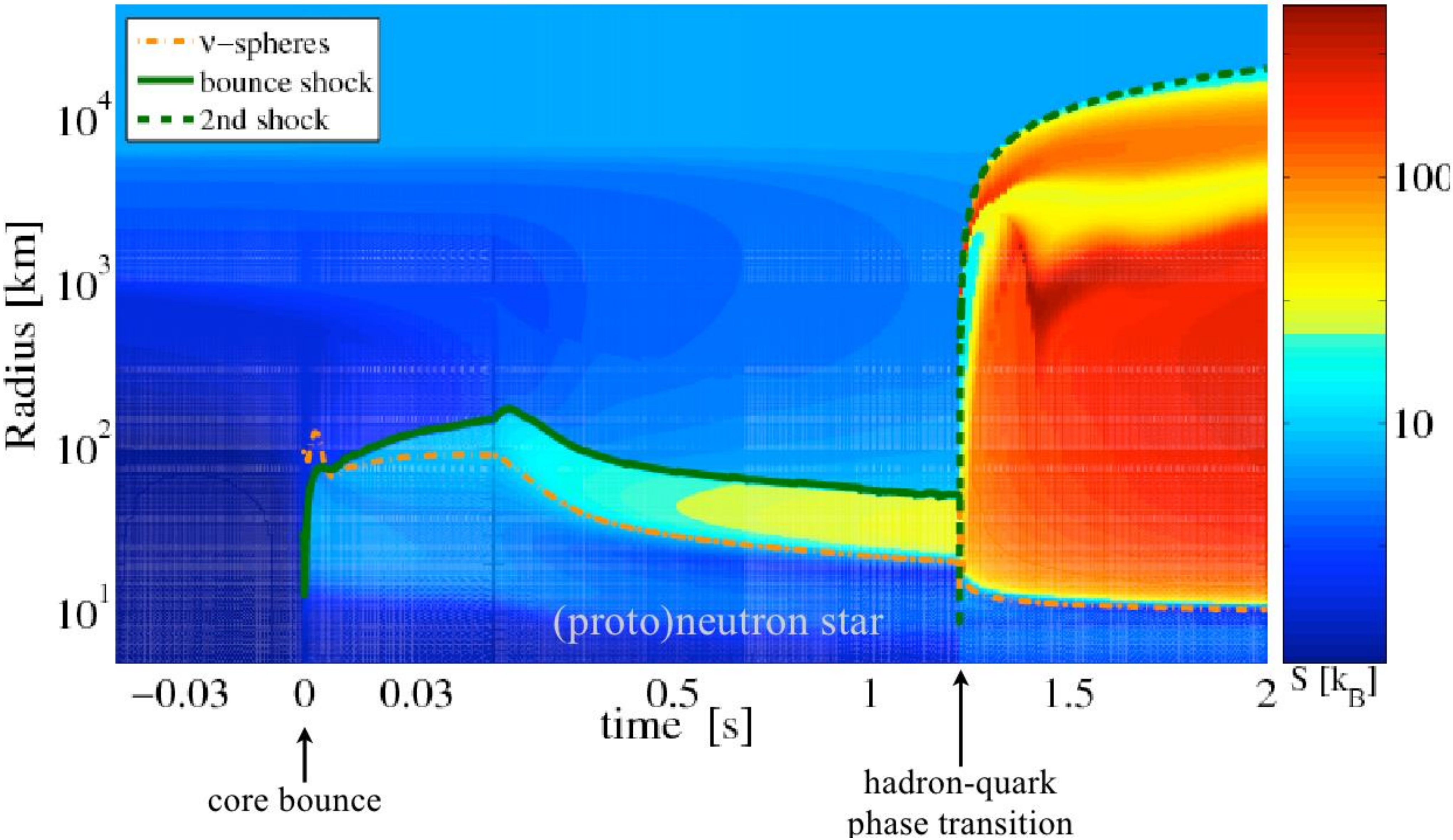
(2) Then follows a region where explosive Si-burning led to unstable nuclei which experience beta$^+$-decay. In a similar way electron captures can lower Ye slightly below 0.5.

(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 vp-process with abundance produced up to A=100.

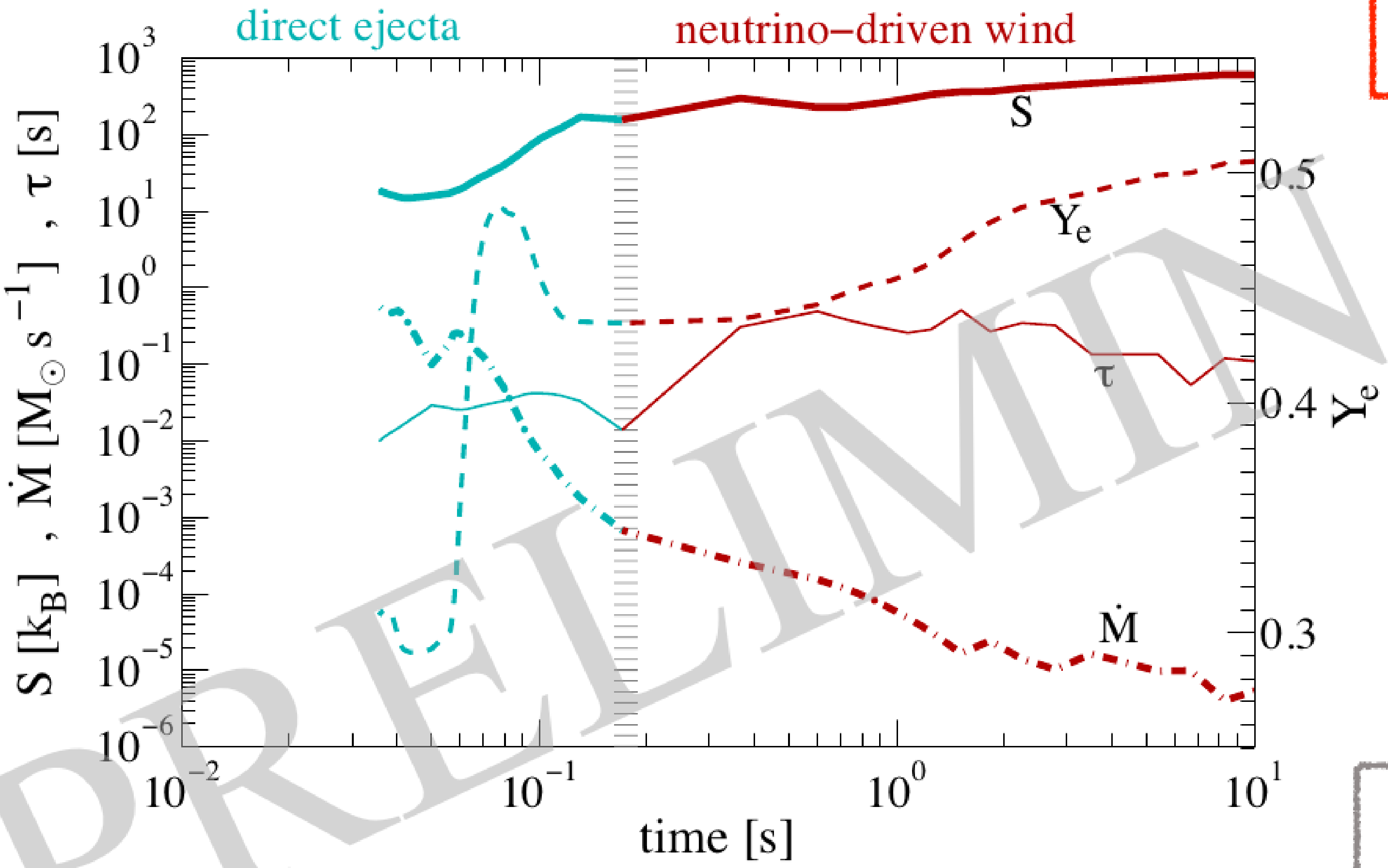


(4) The very innermost ejected layers come late, originate from regions deeper in the collapsed core which had become very neutron-rich via e-captures during core collapse, and neutrino interactions were not sufficient to turn them proton-rich. Ye's encountered here range from 0.32 to 0.42. These zone 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 from T. Fischer (2019), SN explosions due to QCD phase transition



T. Fischer (2019)



$$S \simeq 100 - 300\ k_B$$

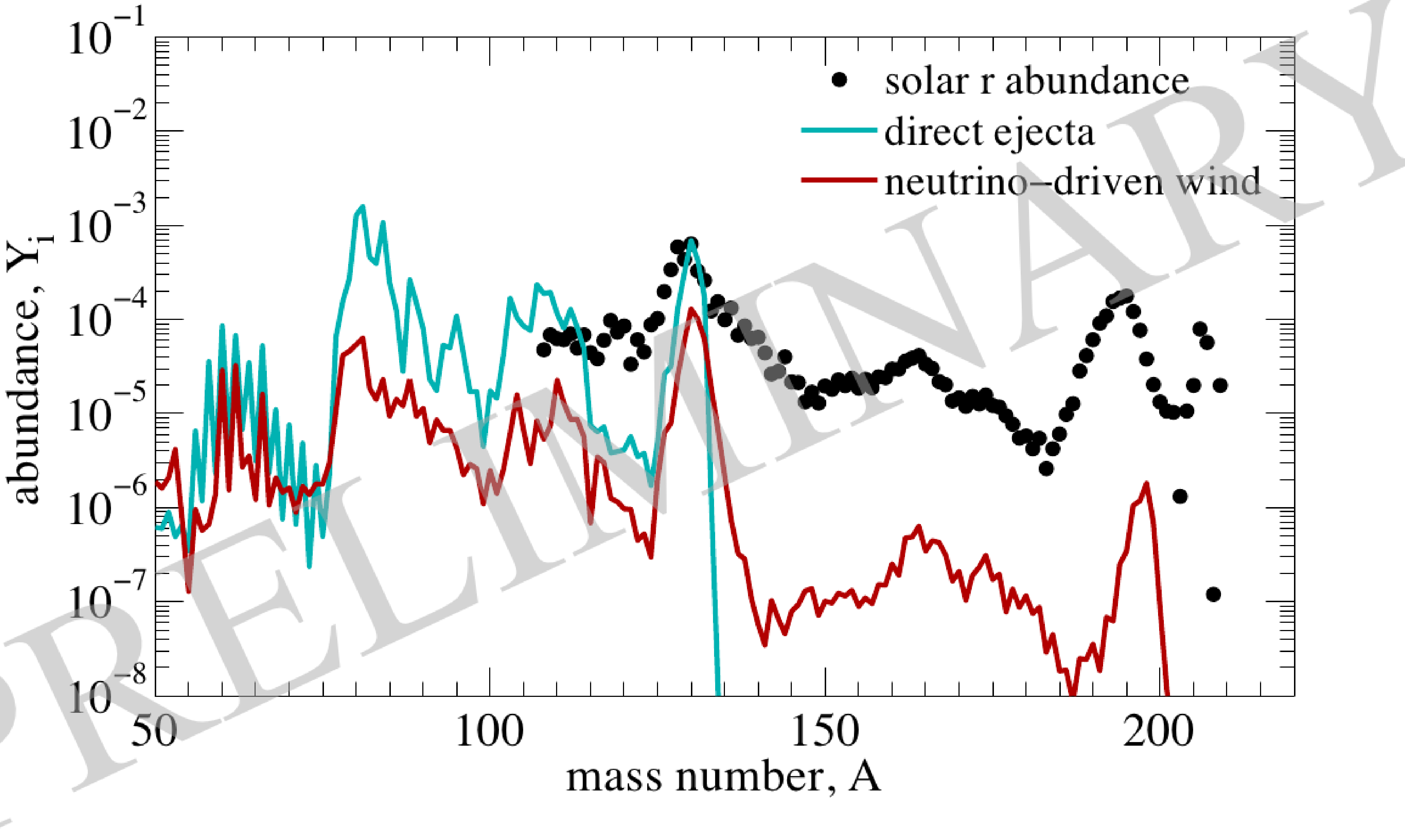
$$Y_e \simeq 0.3 - 0.5$$

'normal' ν-driven wind

$$S \simeq 50\ k_B$$

$$Y_e \simeq 0.49 - 0.55$$

T. Fischer (2019)



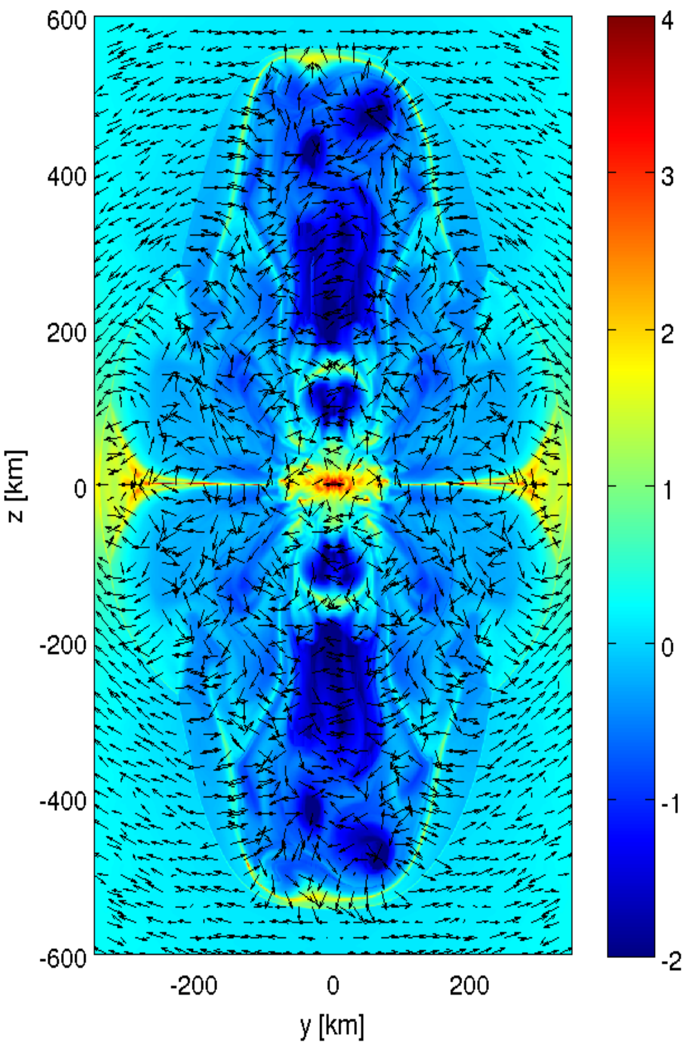
Magneto-Rotational Supernovae

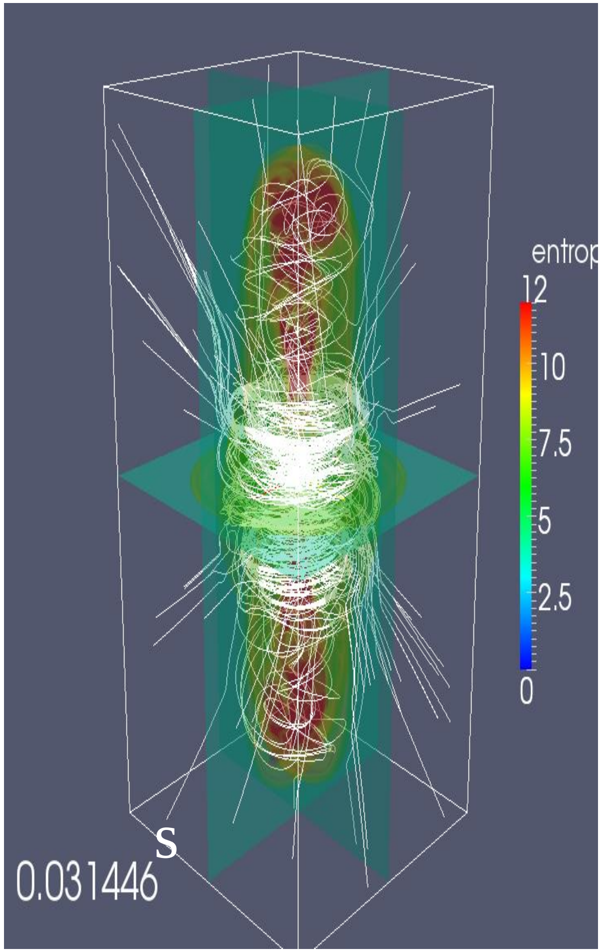
3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 x10^{12} Gauss,

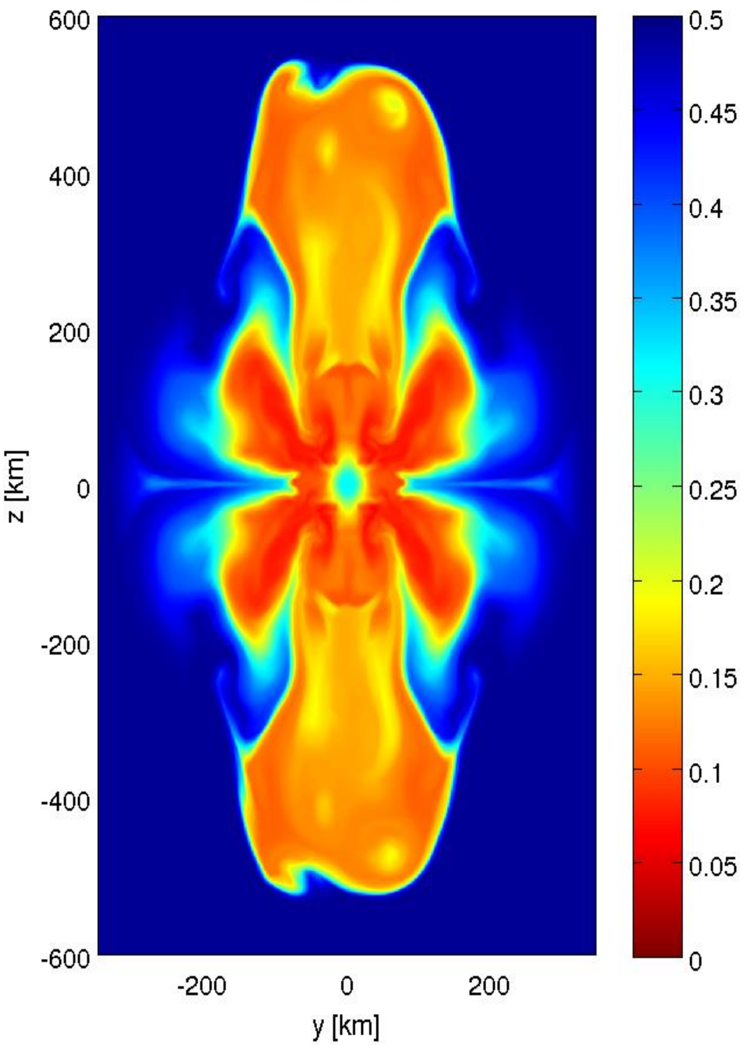
results in 10^{15} Gauss neutron star (magnetar)

log10(gas to magnetic pressure) [-], t = 0.023437s





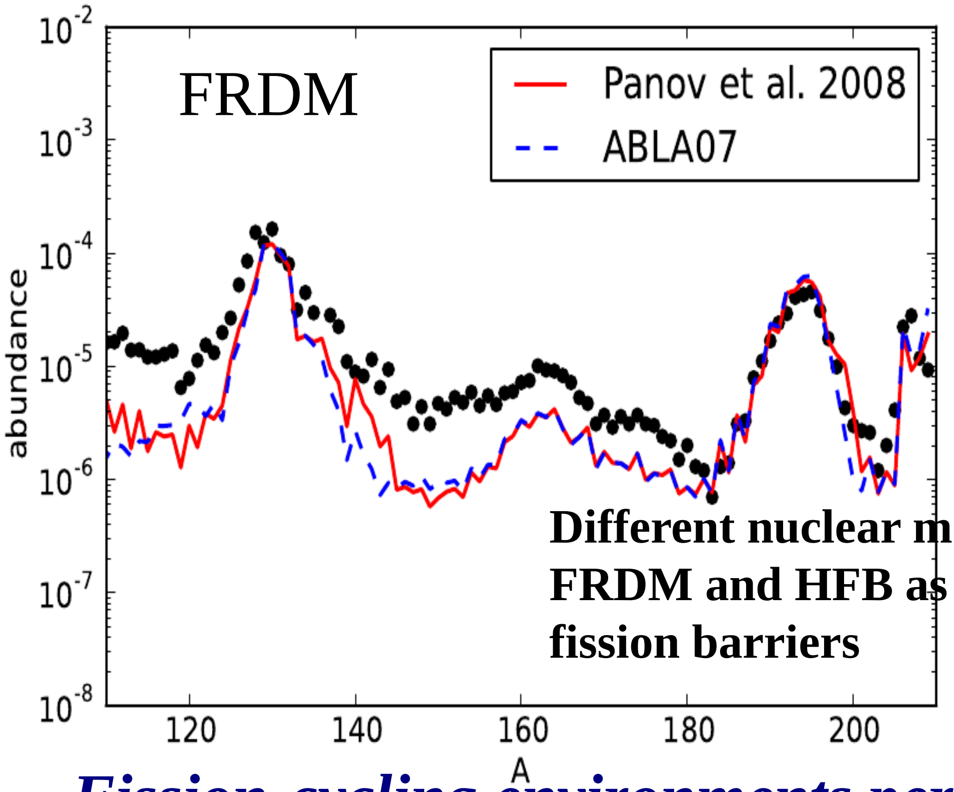
electron abundance [-], t = 0.023437s

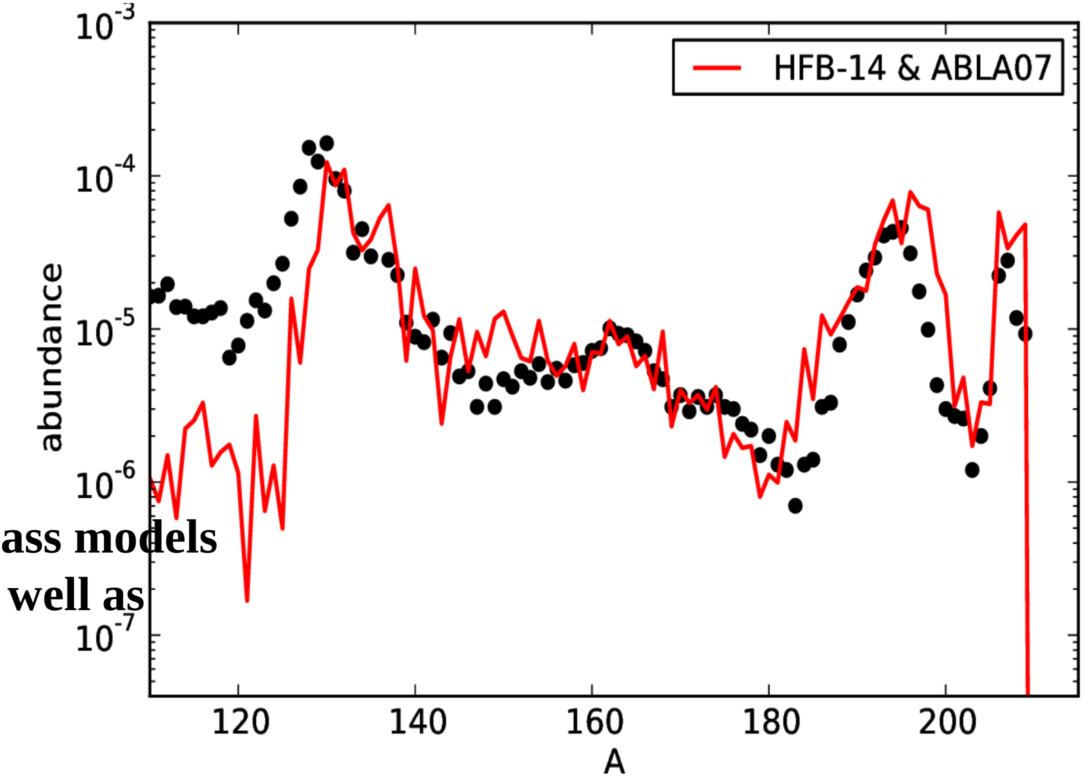


3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2015

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

(Eichler et al. 2015)





Different nuclear mass models FRDM and HFB as well as fission barriers

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

Mösta et al. (2017)

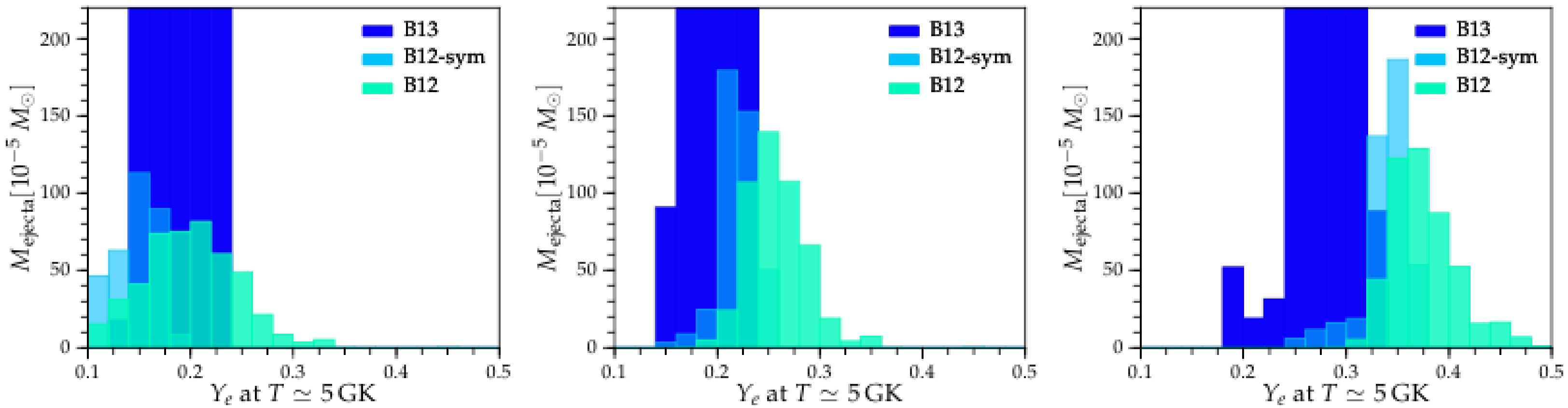


Figure 7. Y_e histograms when the particles are above a temperature of T=5 GK for the last time. We show simulation B13 (dark blue), B12-sym (cyan), and B12 (green). The left panel shows results obtained without taking neutrino luminosities into account for the network calculation. The center panel shows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

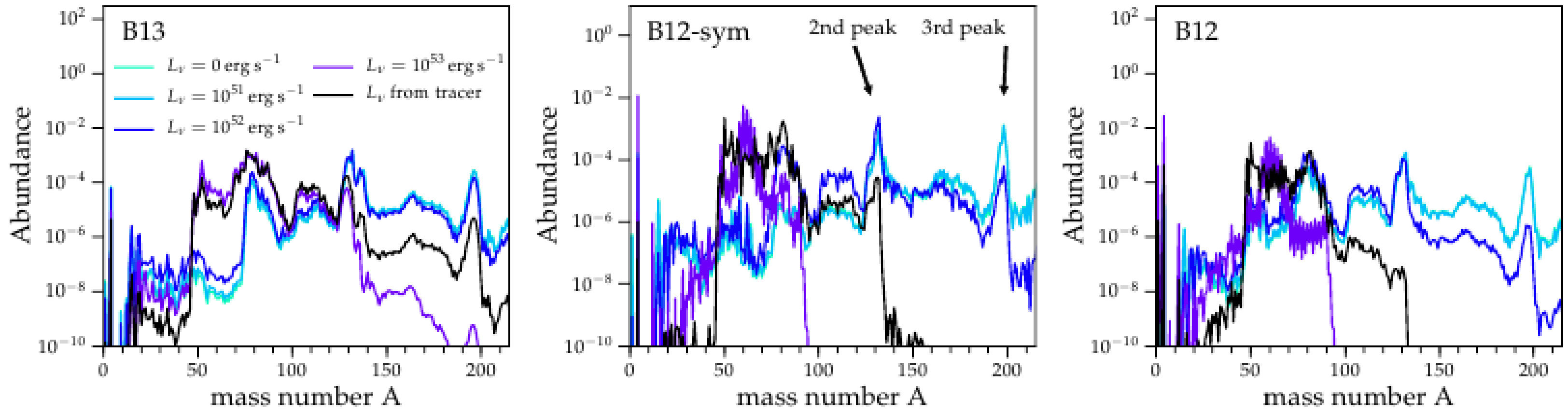
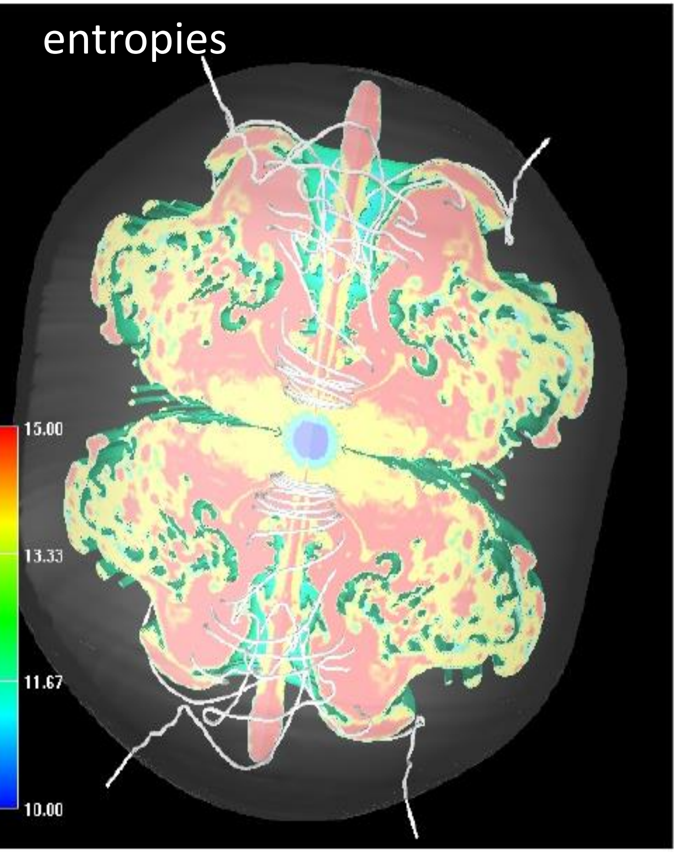
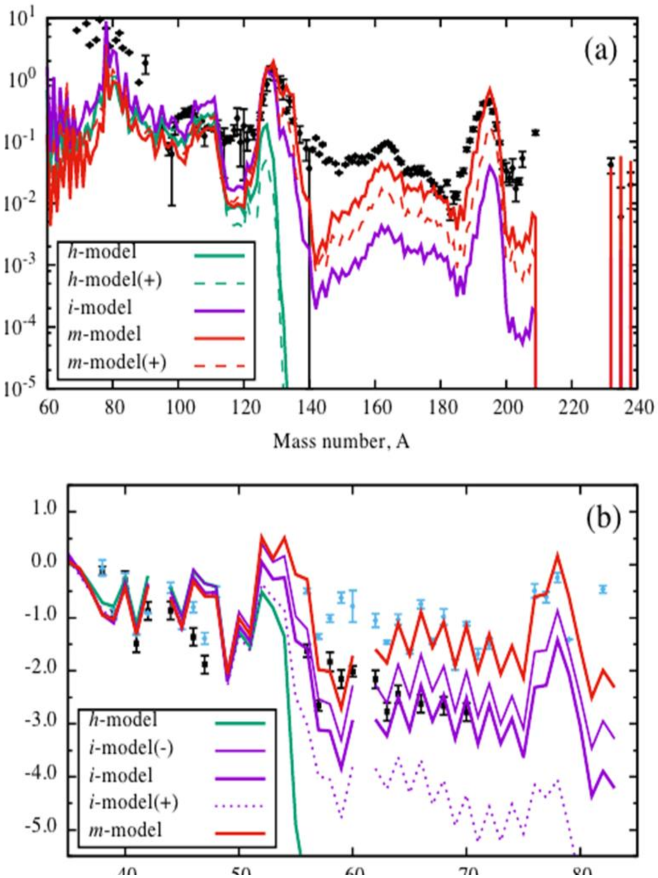


Figure 8. Fractional abundance as a function of mass number A for models B13 (left), B12-sym (center), and B12 (right). Differently colored lines indicate results obtained with different constant neutrino luminosities in the nuclear reaction network calculation. Black lines show the results obtained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

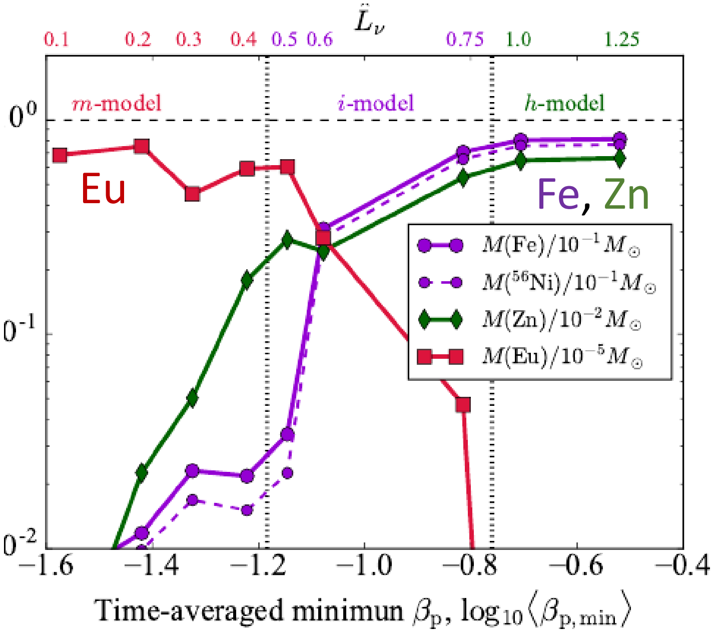
high magnetic fields required for low Ye's and a strong r-process
(close to 10^{13} Gauss for massive progenitors, see also Nishimura, Takiwaki, FKT 2015)
Halevi et al. (2018) test influence of alignment of rotation axies with magnetic fields.

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



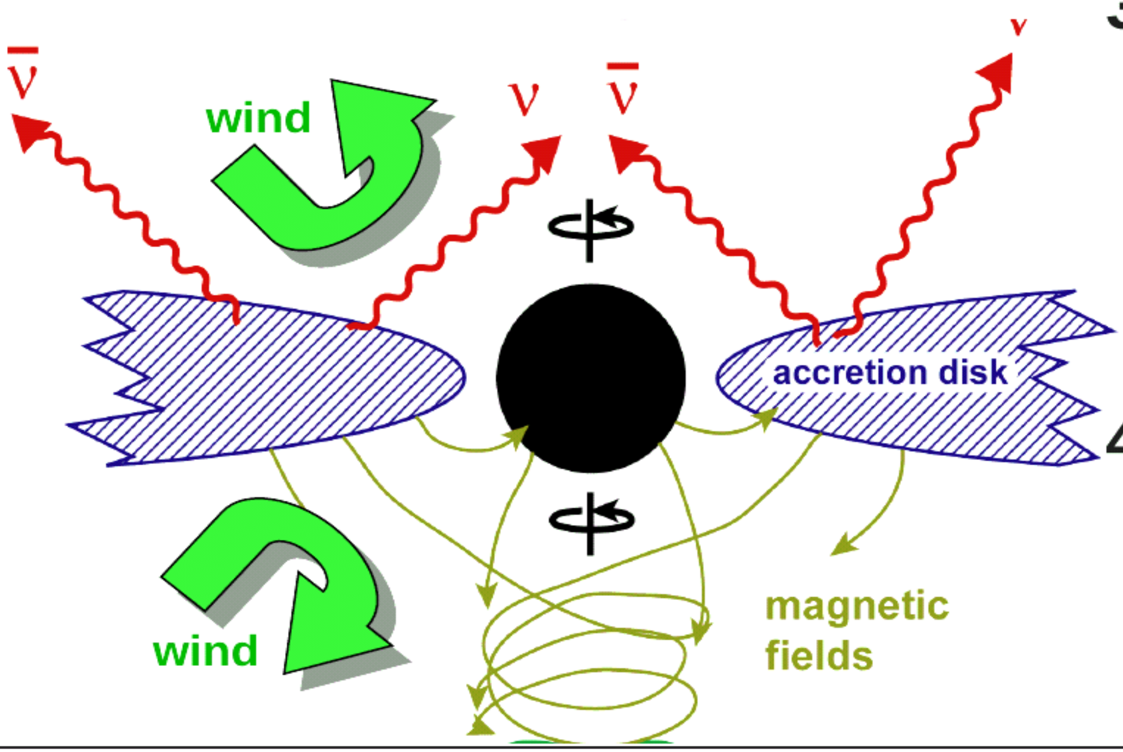
Dependent on the relation between neutrino luminosity and magnetic fields the nucleosynthesis behavior changes from regular CCSNe to neutron-rich jets with strong r-process.

Collapsars: Long Duration Gamma-Ray Bursts

How else can massive stars explode?

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

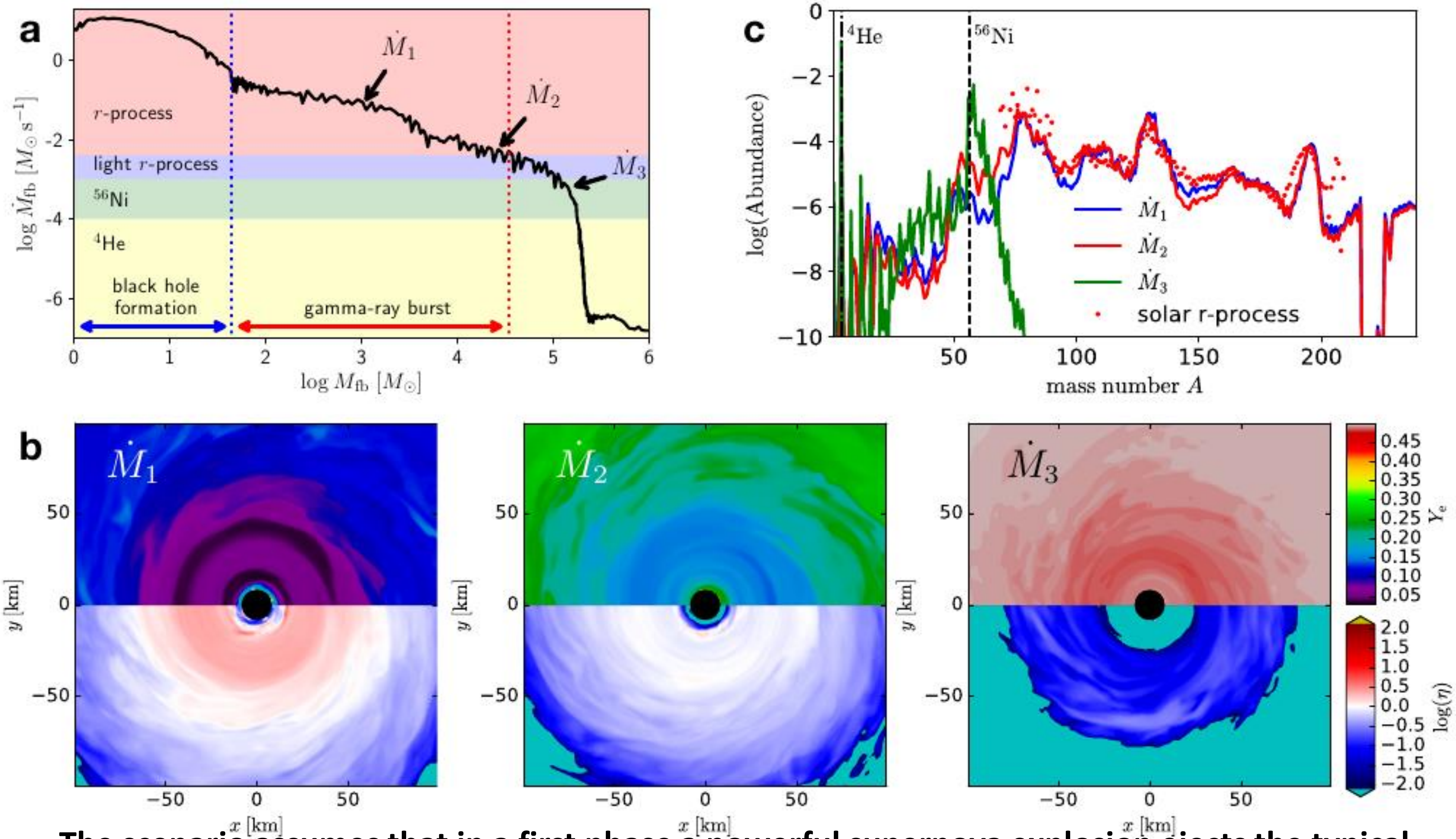
The “Collapsar Engine”



1. black hole forms inside the collapsing star
after failure or neutrino-powered explosion
2. The infalling matter forms and accretion disk ≃0.1 $M_\odot$/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 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).



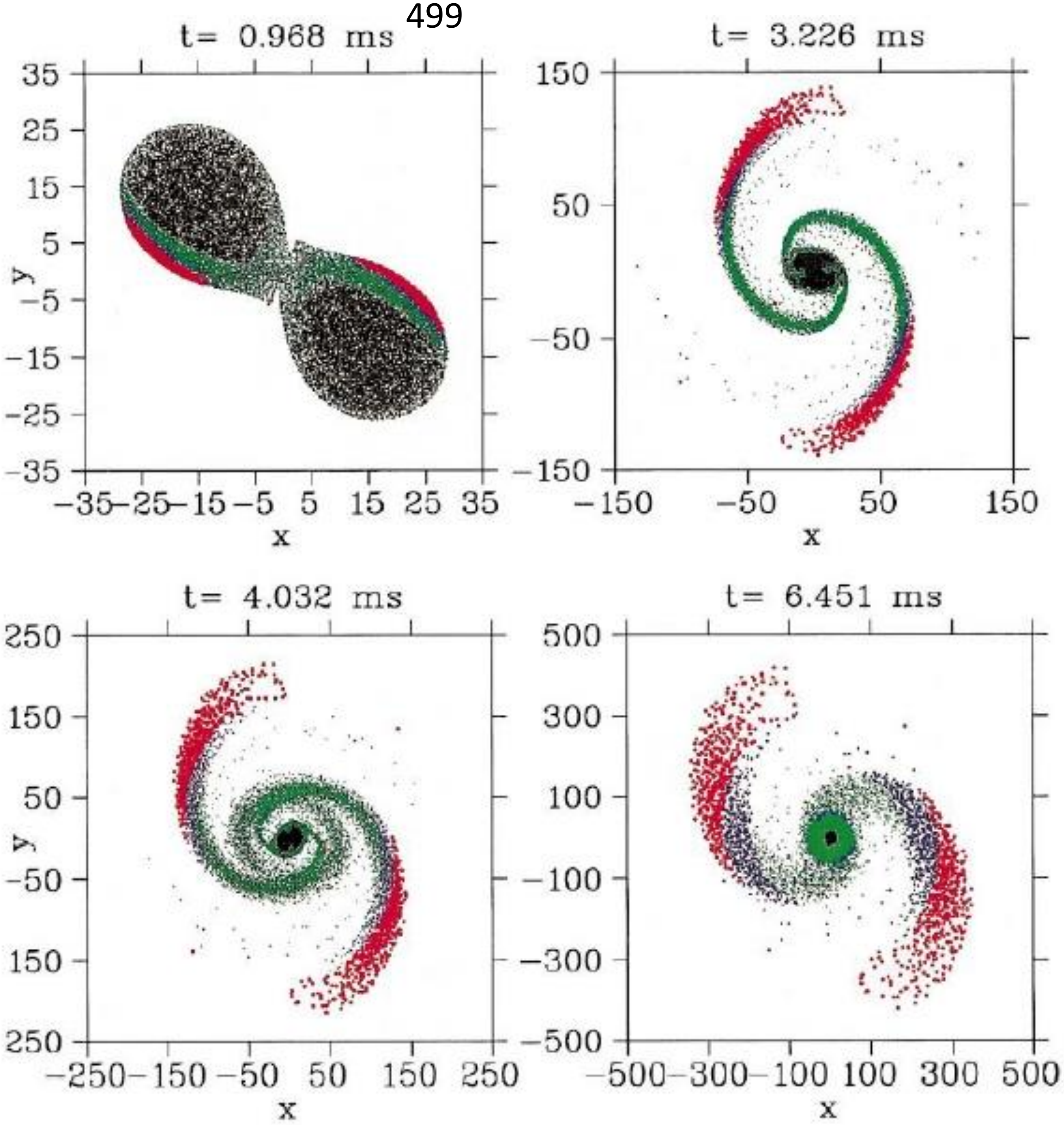
The scenario assumes that in a first phase a powerful supernova explosion ejects the typical up to $0.5M_\odot$ of ^{56}Ni (if these events are supposed to be identical with hypernovae) and further accretion leads to a black hole plus a BH accretion disk. somewhat fine-tuned scenario??

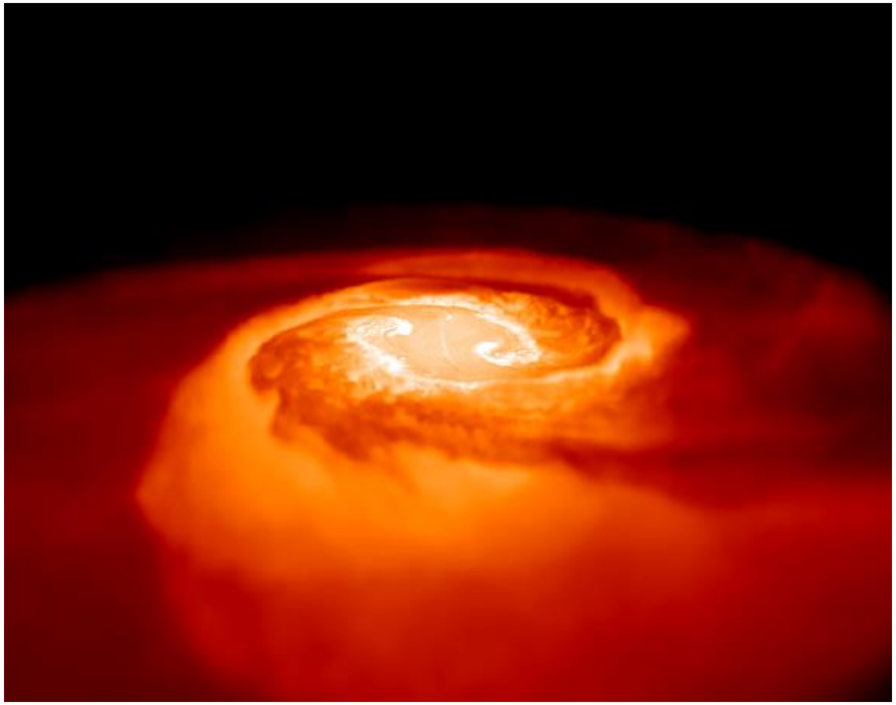
Early and later SPH simulations

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

only tidal arms in early approaches

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





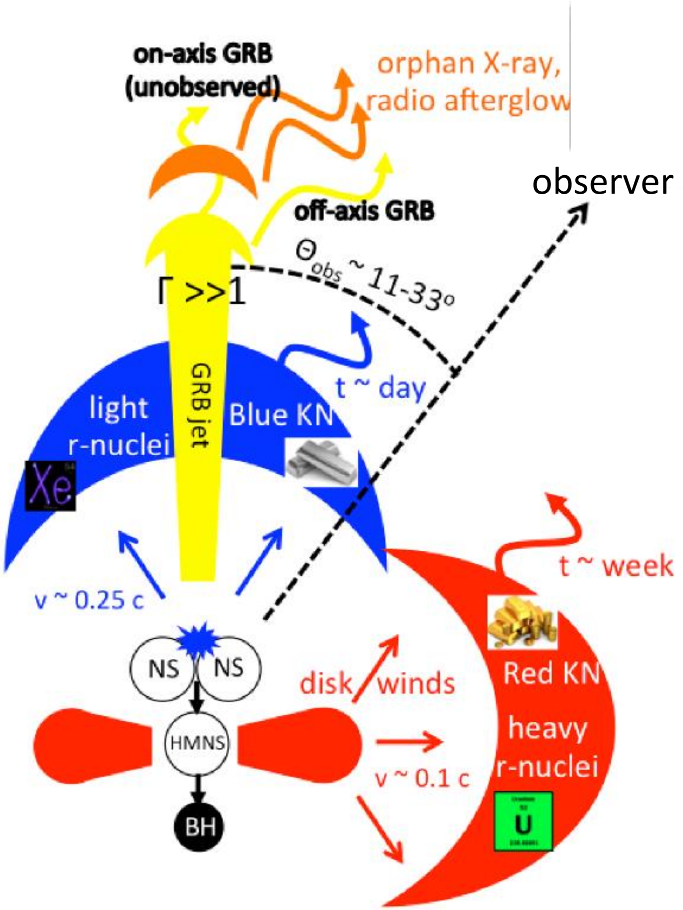
Rosswog et al. 2014

Compact binary mergers and BH accretion disks have recently developed into an exploding field, related also to electromagnetic afterglows/counterparts and gravitational wave emission

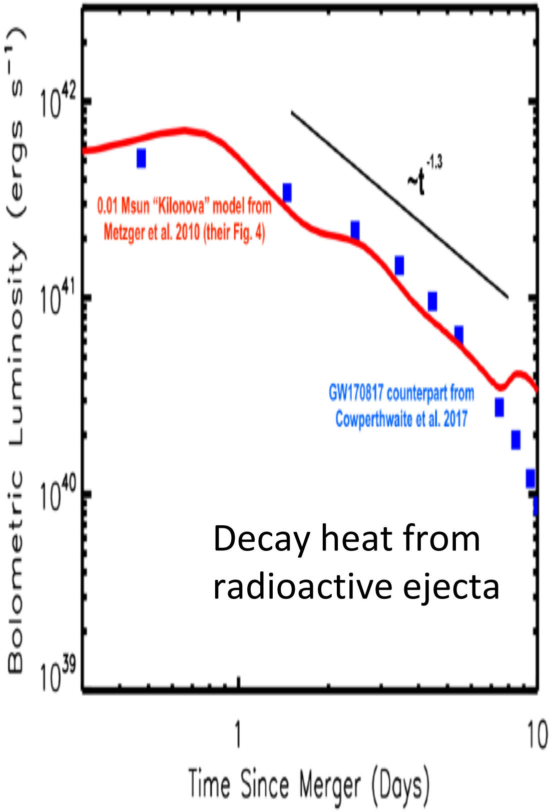
(Lattimer, Schramm, Symbalisty, Meyer, Eichler, Piran, Davies, FKT, Benz, Panov, Eichler, Ruffert, Janka, Rosswog, Oechslin, Bauswein, Korobkin, Goriely, Just, Wu, Arcones, Martin, Perego, Martinez-Pinedo, Hotokezaka, Sekiguchi, Kiuchu, Wanajo, Shibata, Nishimura, Fryer, Fernandez, Metzger, Kasen, Quaetert, Ramirez-Ruiz, Radice, Siegel, Pannarale, Giacomazzo, Lippuner, Barnes, Rezolla, Bovard, Most, … Malkus, McLaughlin, Surman, Zhu, Frensel…..)
Main features: (a) dynamic ejecta (tidal and due to collision, (b) neutrino-wind from hypermassive neutron star, (c) BH accretion disk outflow; (b) and (c) produce also A<130

see e.g. also reviews (just) before GW170817
(Fernandez & Metzger, ARNPS 2016, Metzger, Living Rev. Relativity 2017, Baiotti & Rezzolla, Rep. Prog. Phys. 2017, Thielemann+, ARNPS 2017), ***and after*** (e.g. Frebel 2018, Horowitz+ 2018, Cowan et al. 2019 ..)

and an uncountable number of publications afterwards
Observarions: Abott …., Berger …., ….
Theory: Tanaka, Rosswog, Metzger, Fryer, Mumpower, Wollaeger, Hotokezaka, Coté, Nishimura, Wu/Martinez-Pinedo, Holmbeck, Surman, Eichler, Wehmeyer …….

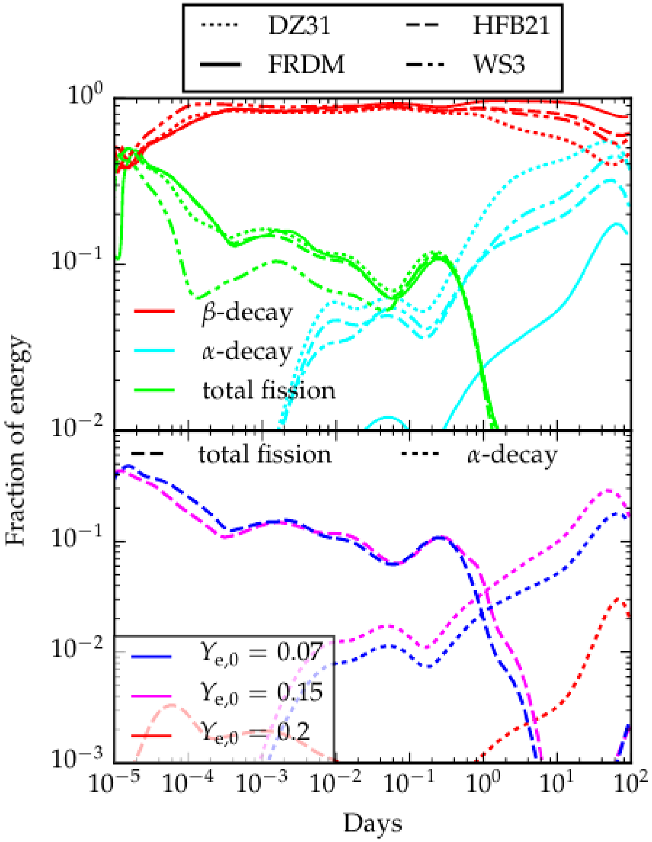


Metzger, Martinez-Pinedo
et al. (2010)



Decay heat from
radioactive ejecta

Barnes et al. (2016)

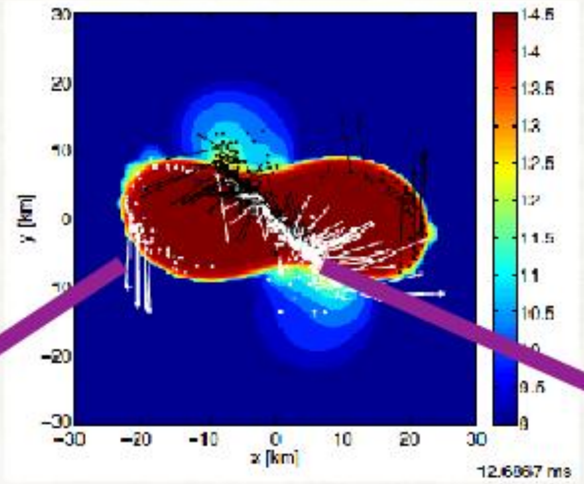


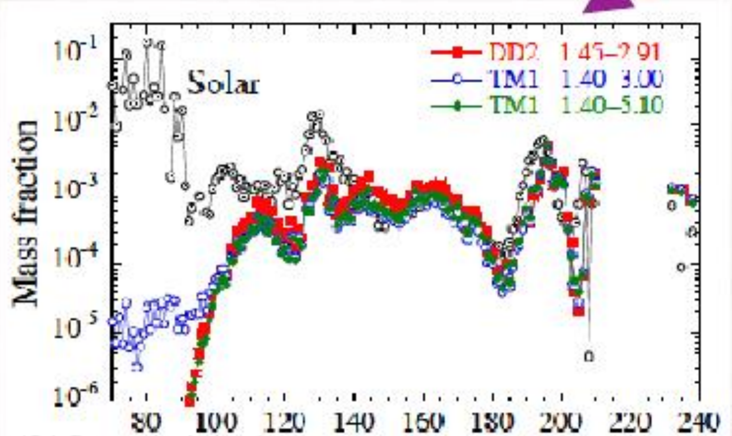
Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation

Prompt / dynamical Ejecta

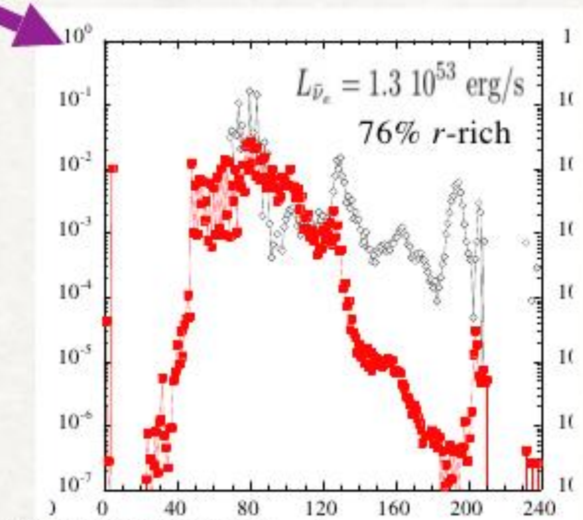
(qualitatively consistent
with works by, e.g.,
Hotokezaka '13,
Wanajo+Sekiguchi '14,'16,
Radice '16, Foucart '16)

from Just (2018)
Shanghai talk





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

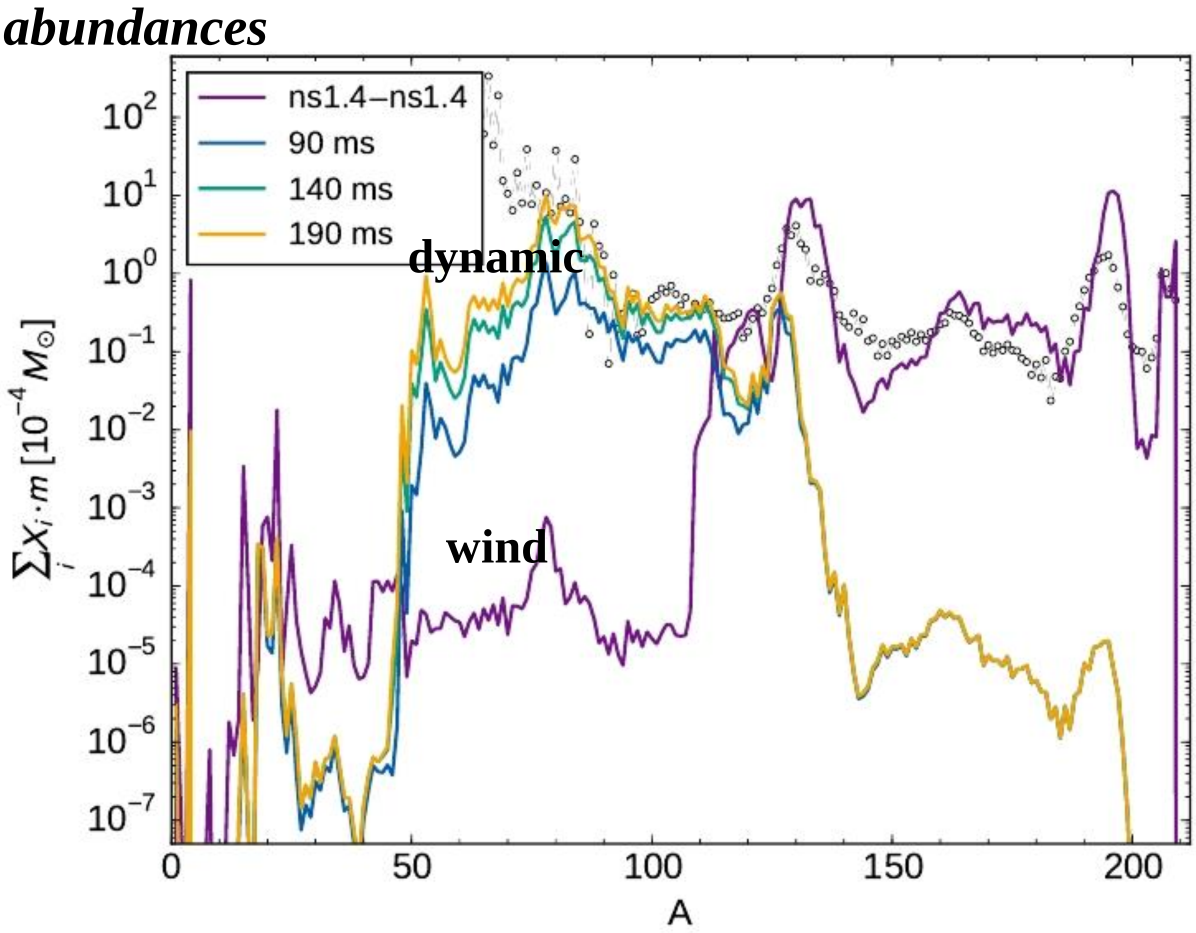


(Goriely et al '15+'18)

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)

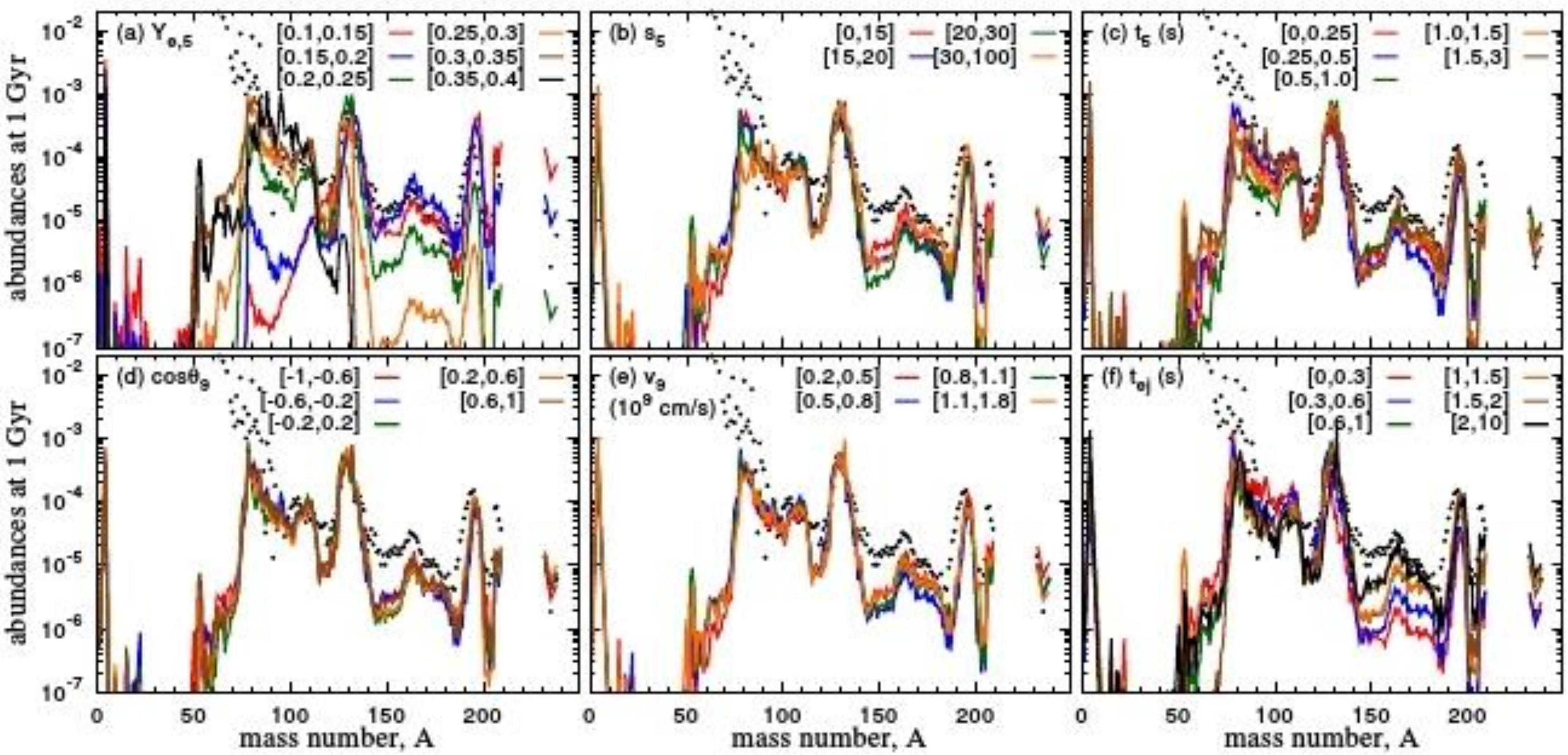
After dynamic ejection of matter, the hot, hypermassive neutron star (before – possibly and with which delay - **collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014), Martin et al. (2015)**



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

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 lanthinides and actinides *can* be produced.



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

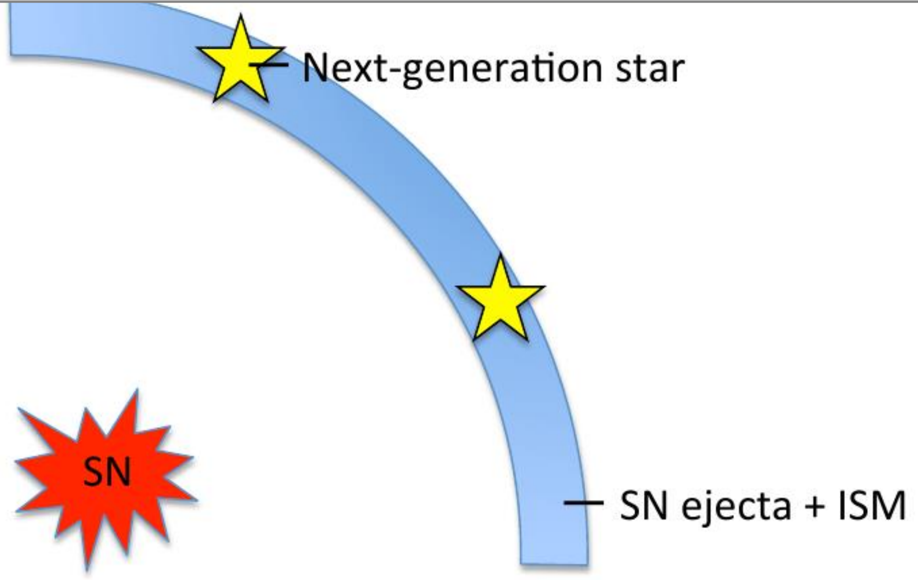
4. Chemical Evolution

A. ***Models utilzing 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).***

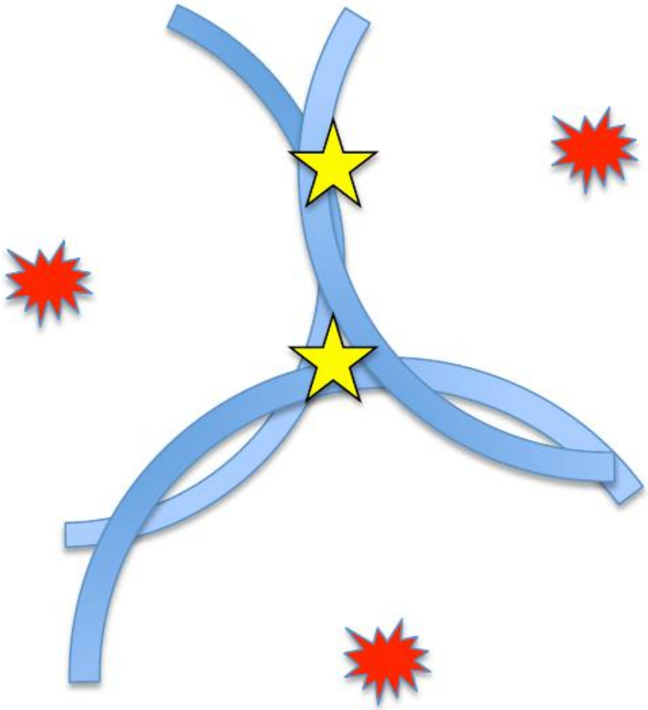
Stellar Abundances

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



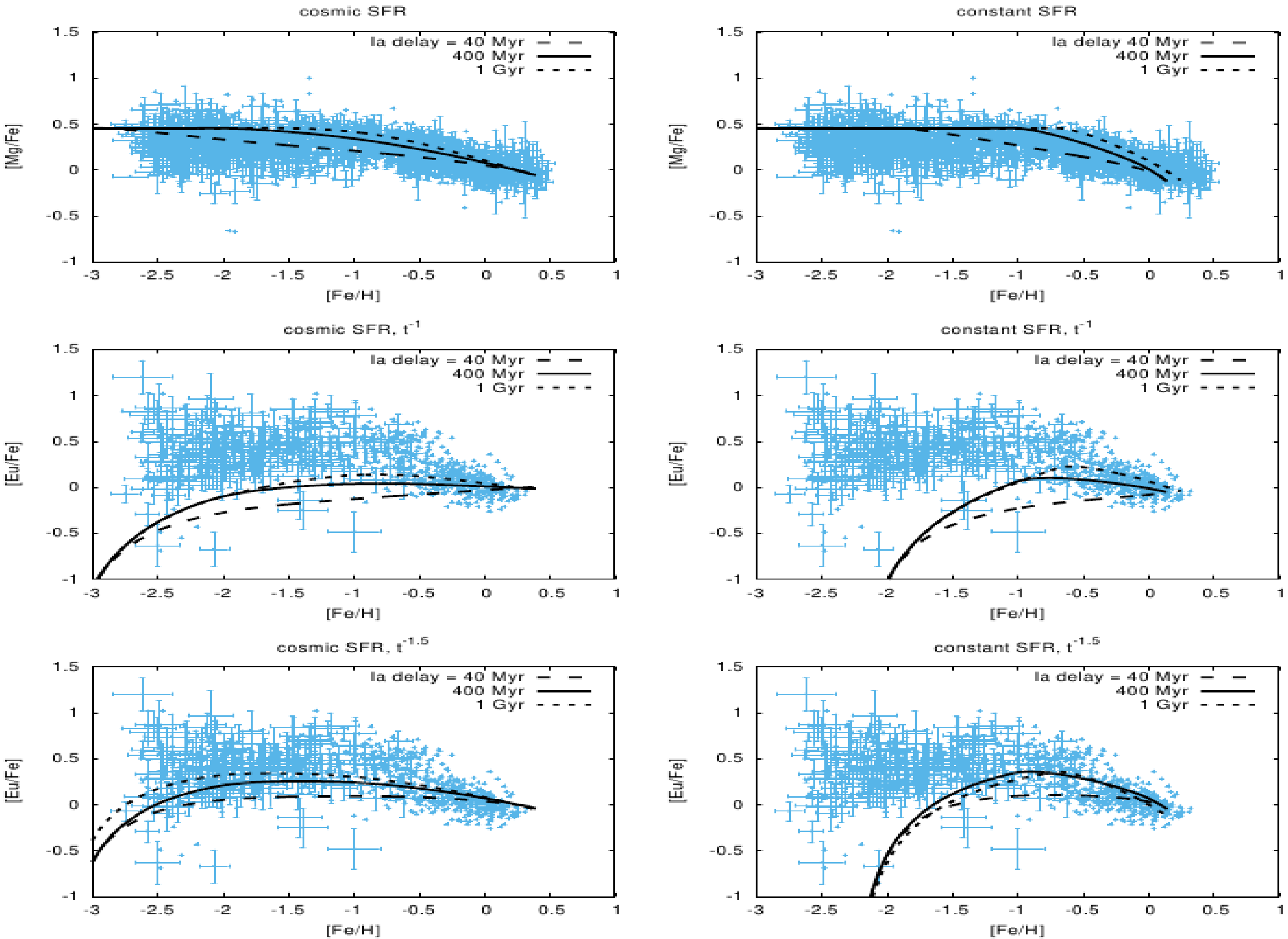
In the later phase

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



adopted from K. Nakamura

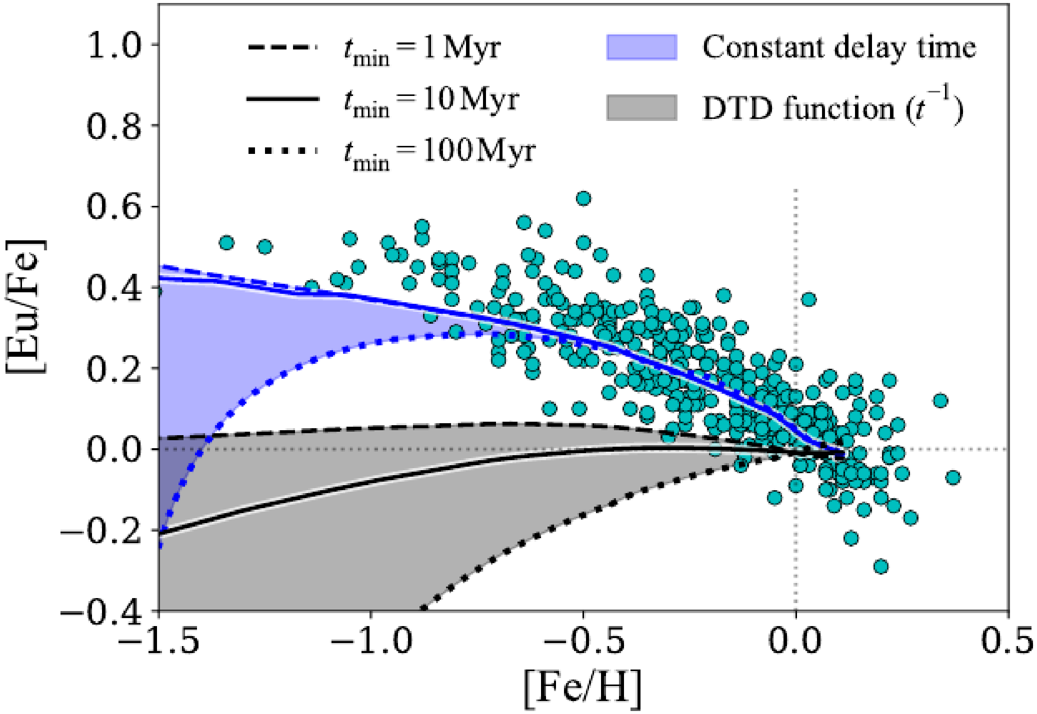
Hotokezaka et al. (2018), GCE with CCSNe, SNe Ia and NS-mergers, see also Coté et al. (2017,2019), Siegel (2019)

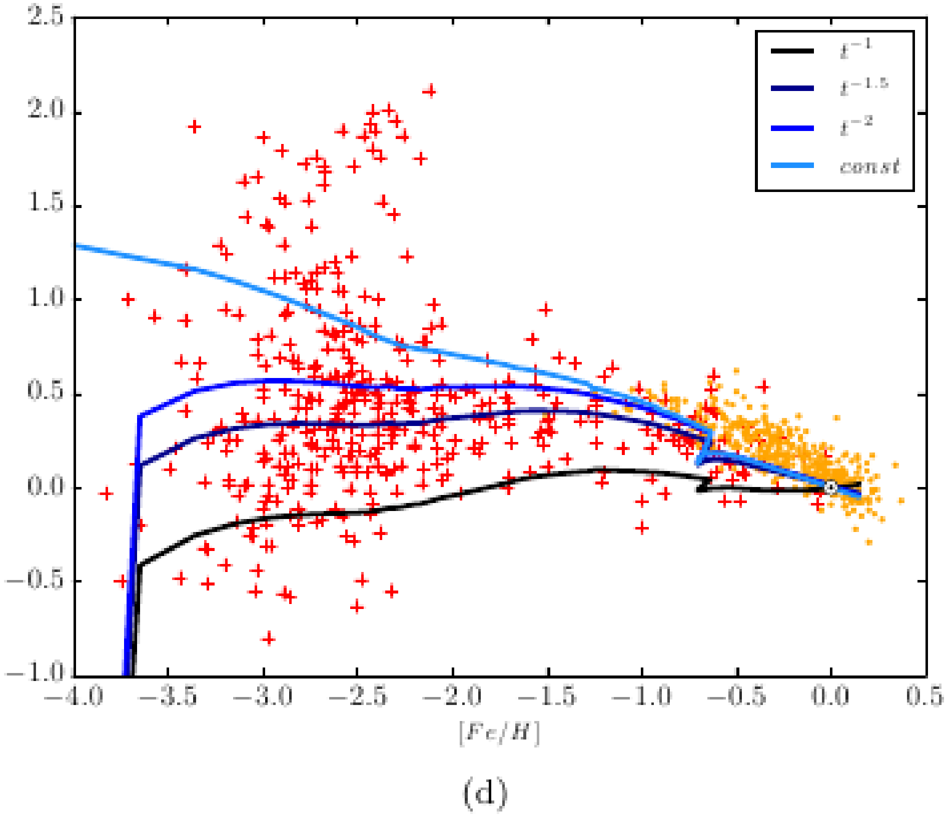


The delay time is not constant but follows a distribution. Population synthesis studies, consistant with short GRBs, indicate a t^{-1} behavior. Then problems would remain to explain the strong r-process by NS-mergers alone! But other options like (i) the mass, ejecta, and explosion energy of the second supernoa 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)

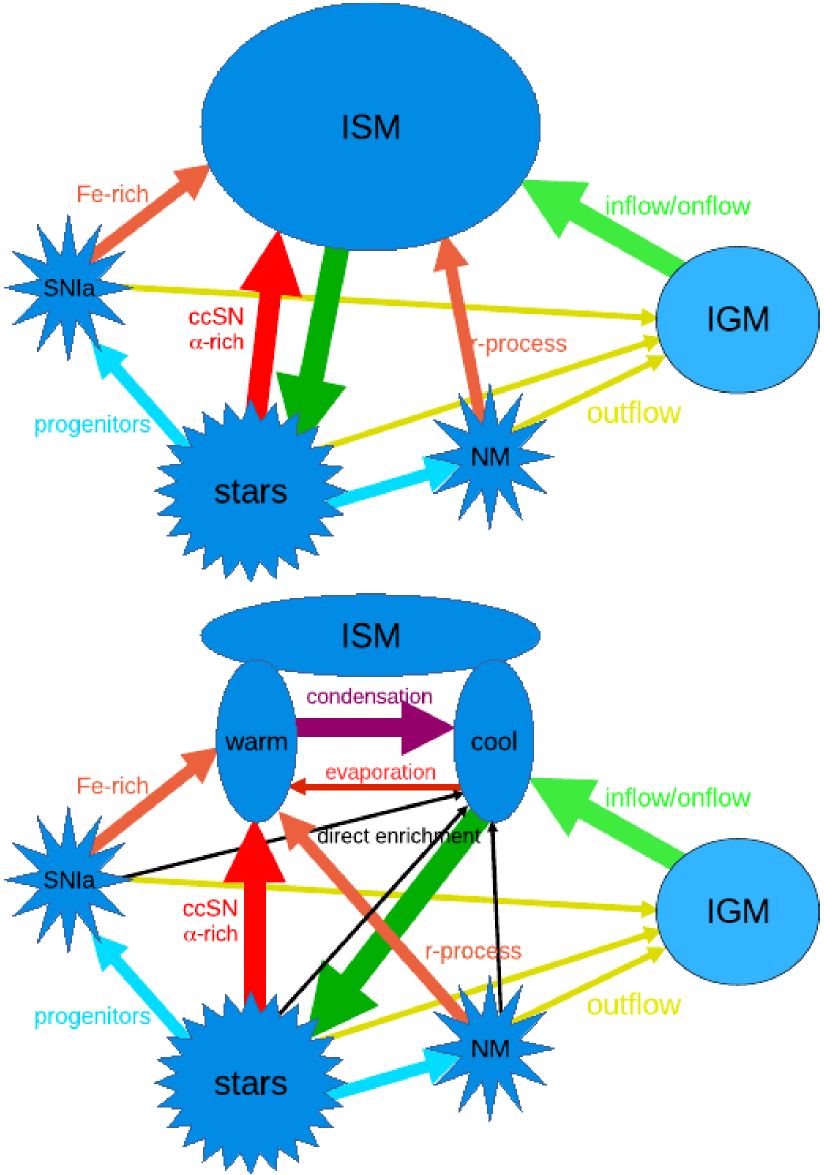




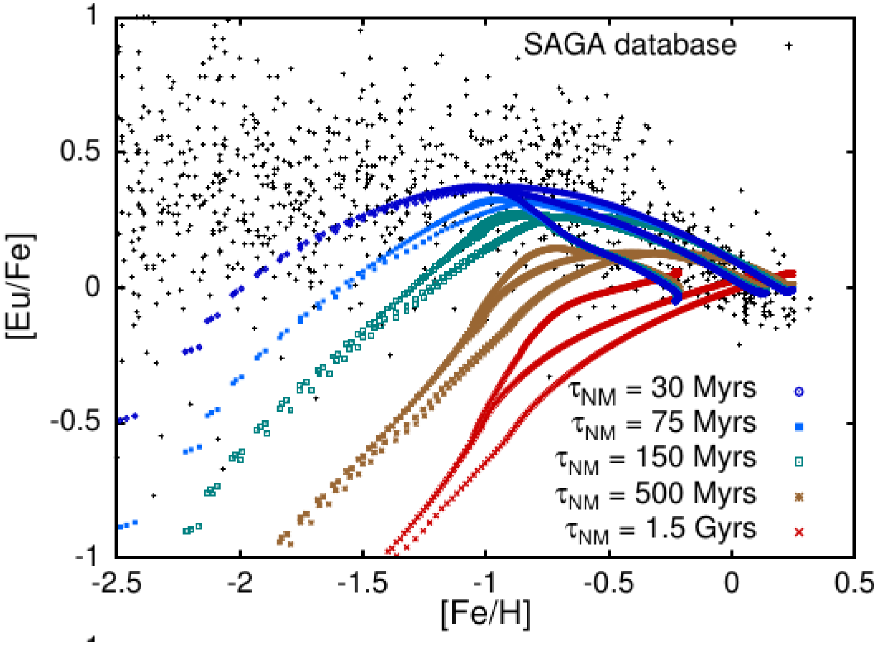
Coté et al. (2019)

Simonetta et al. (2019)

Schönrich et al. (2019)



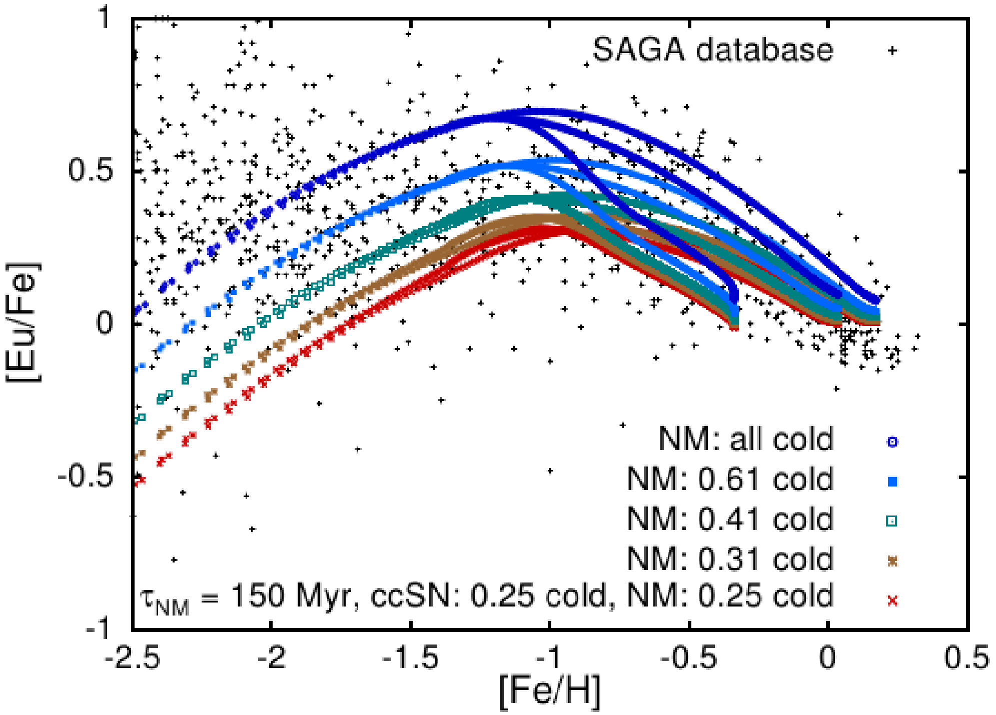
Star formation takes only place in cooled regions of the ISM, i.e. not all recently ejected matter can already be incorporated and stars contain lower metallicities ([Fe/H]) then the «present» ISM (shifts e.g. [Eu/Fe] ratios to lower [Fe/H]).

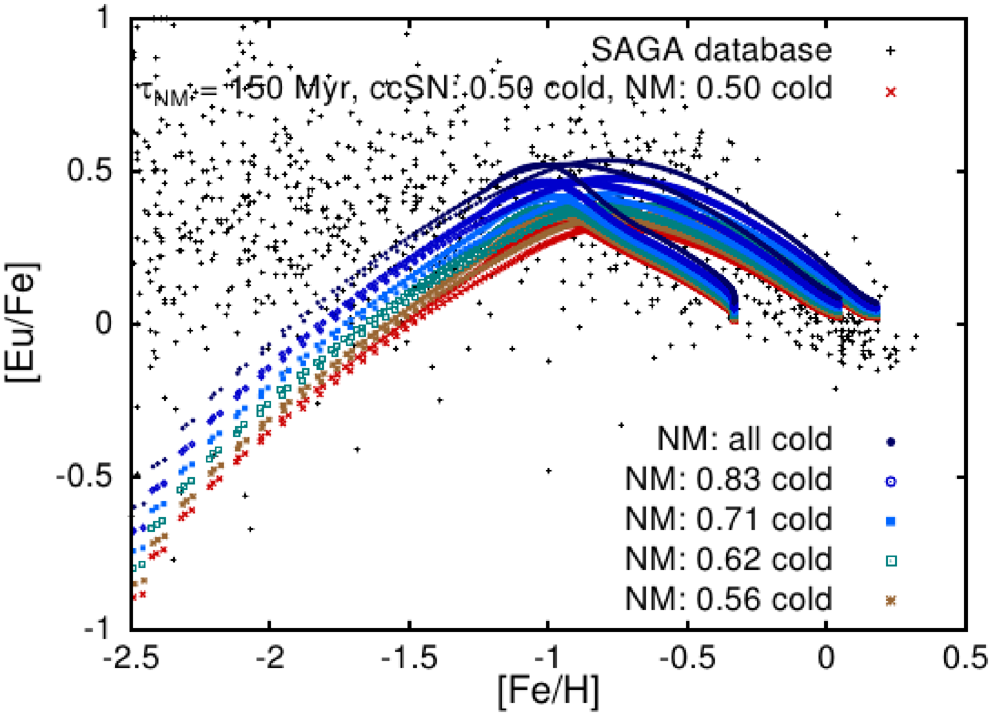


Schönrich et al. (2019)

1. ***as a function of (constant) delay time***
2. ***with varying degrees of star formation from only cooled reagions***

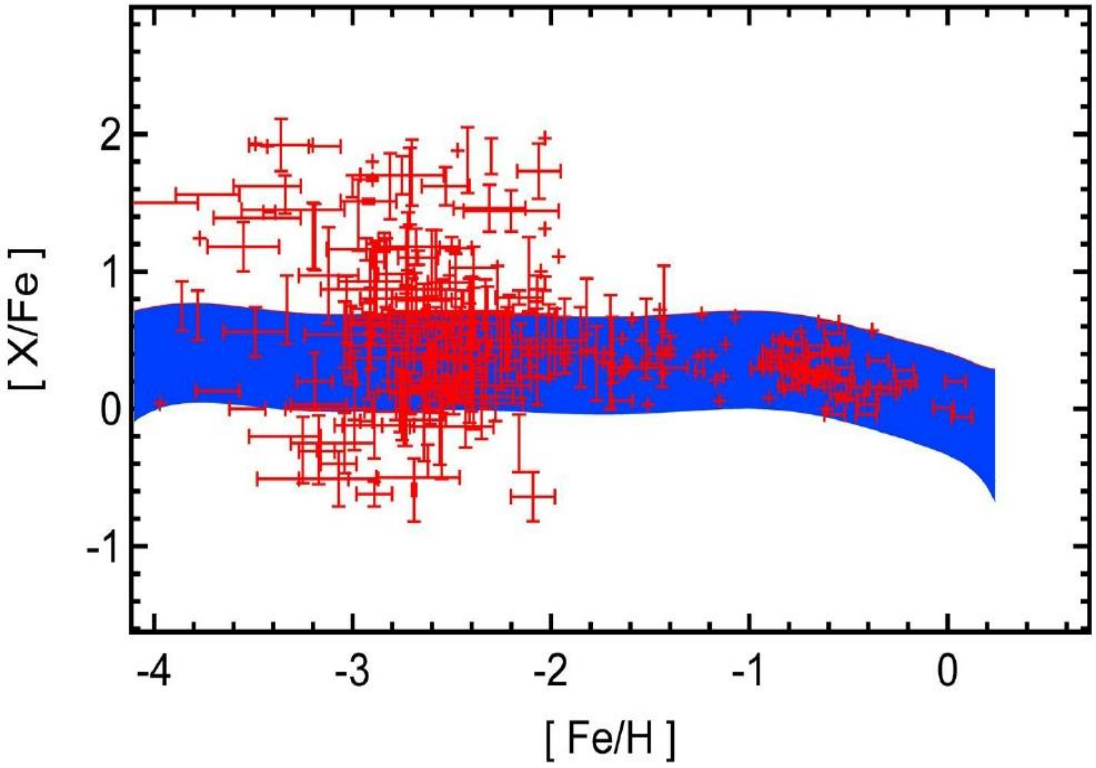
This has a similar effect as a steeper delay-time distribution, but can not solve problems as low metallicities.



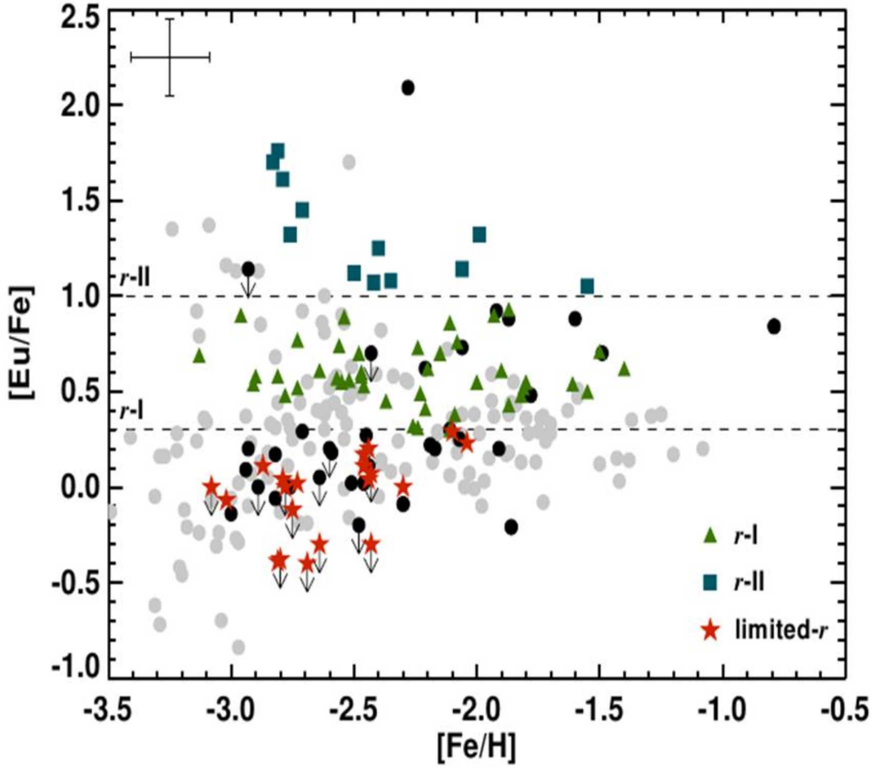


Rare events **lead initially to large scatter before an average is attained in galactic evolution! Need for inhomogeneous modeling!**

Data from SAGA database



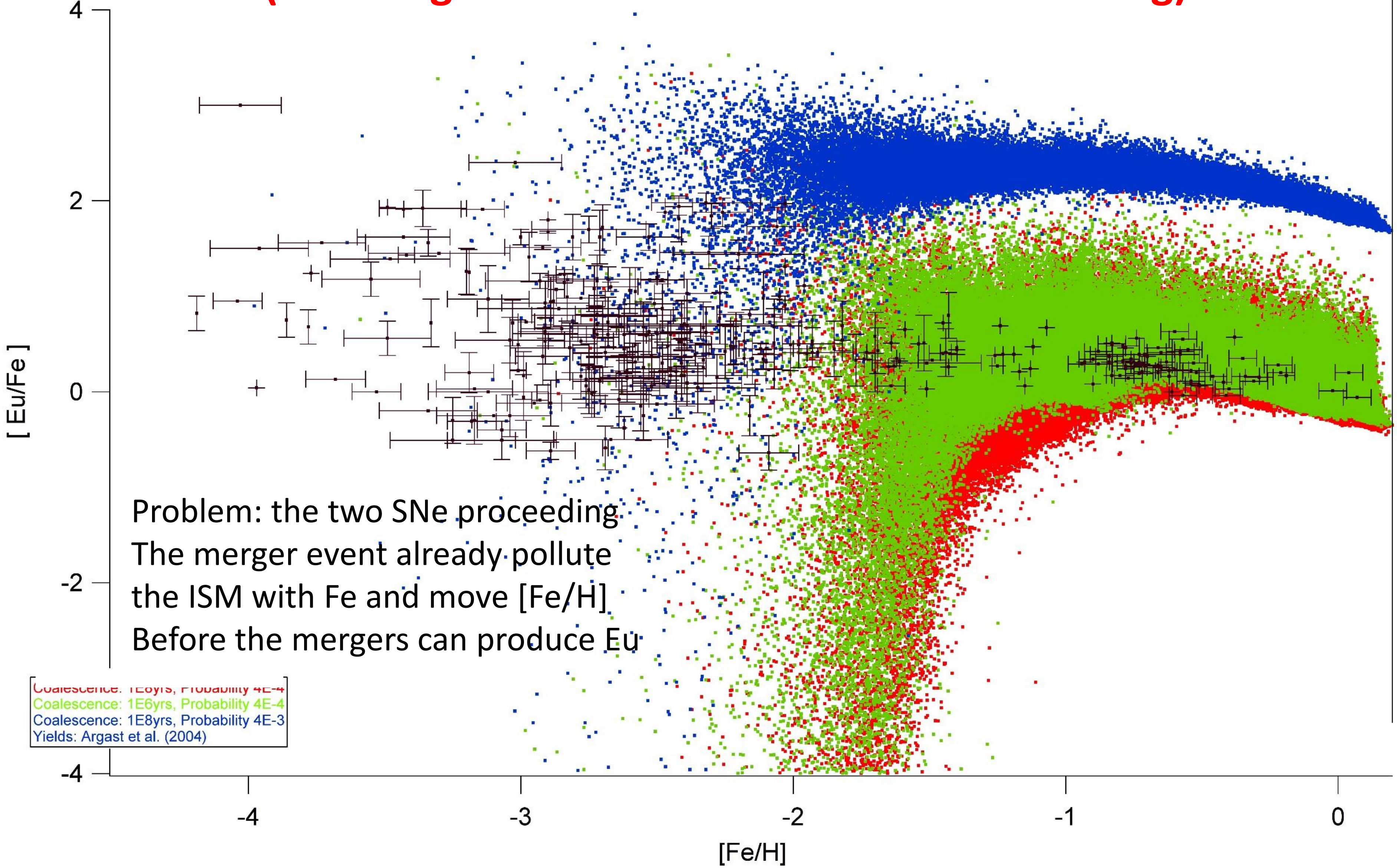
«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)



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 comparsion to CCSNe!

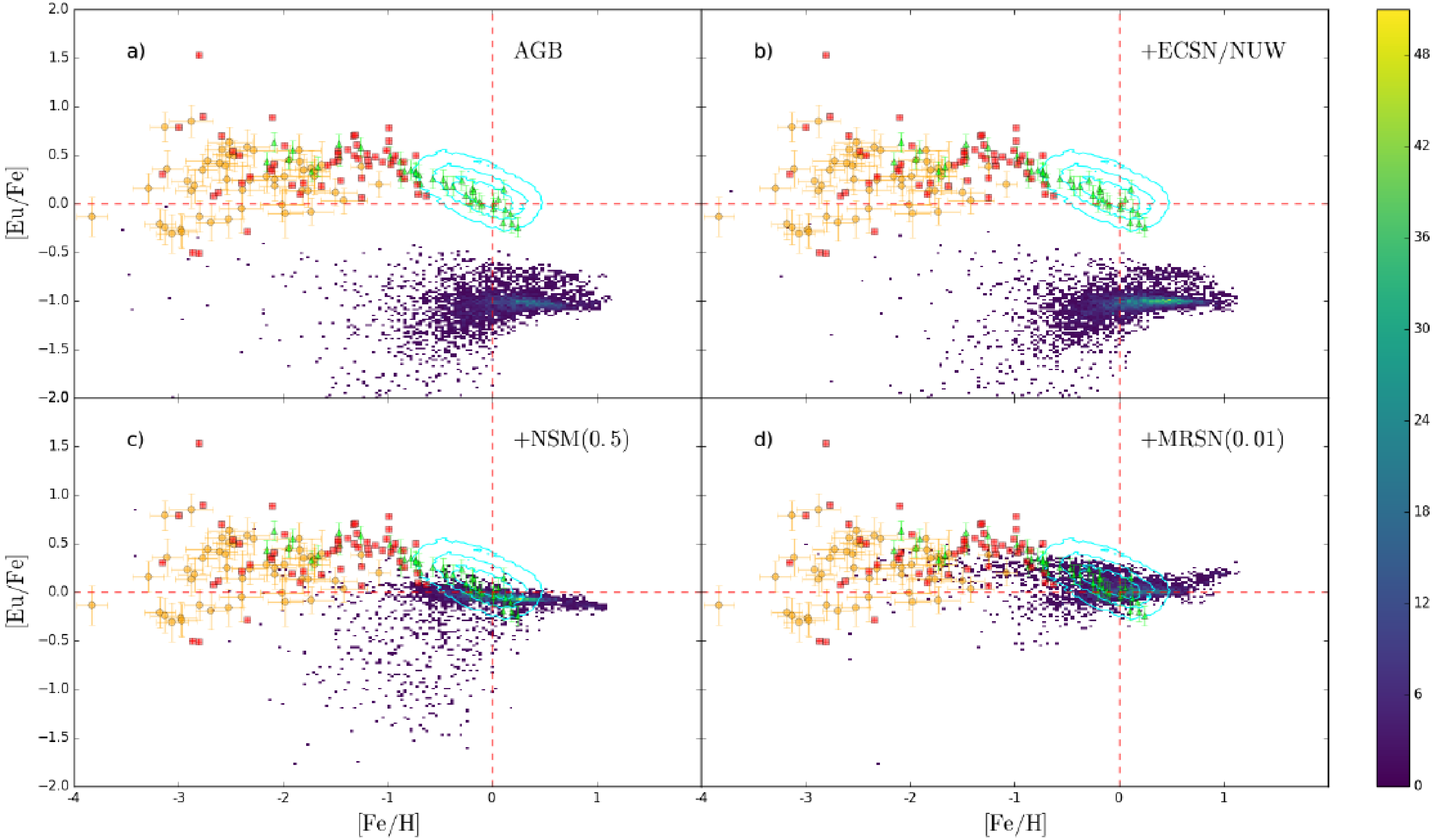
Can NS-mergers alone solve the problems at low metallicities?? (inhomogeneous chemical evolution modeling)



Problem: the two SNe proceeding
The merger event already pollute
the ISM with Fe and move [Fe/H]
Before the mergers can produce Eu

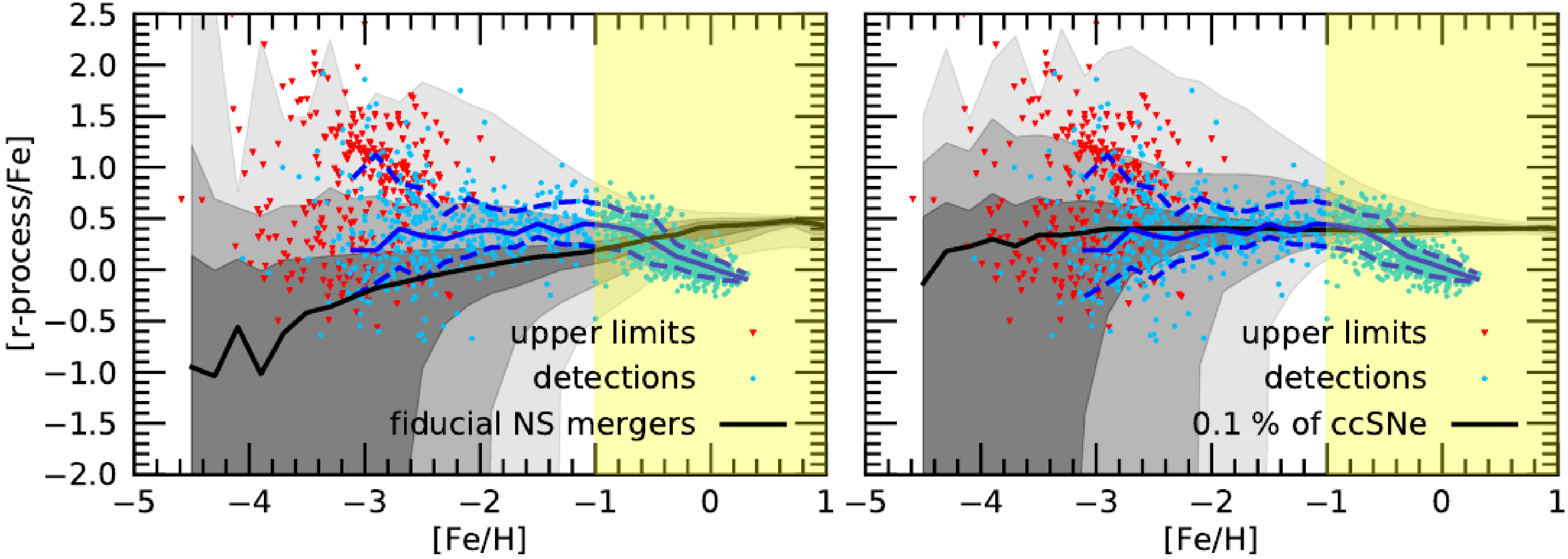
Wehmeyer et al. (2015, following Argast+ 2004 description), utilizing only NS merger: green/red different (constant) merging delay times, blue higher merger rate (not a solution, but turbulent mixing would shift the onset to lower metallicities)

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)*,*
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.



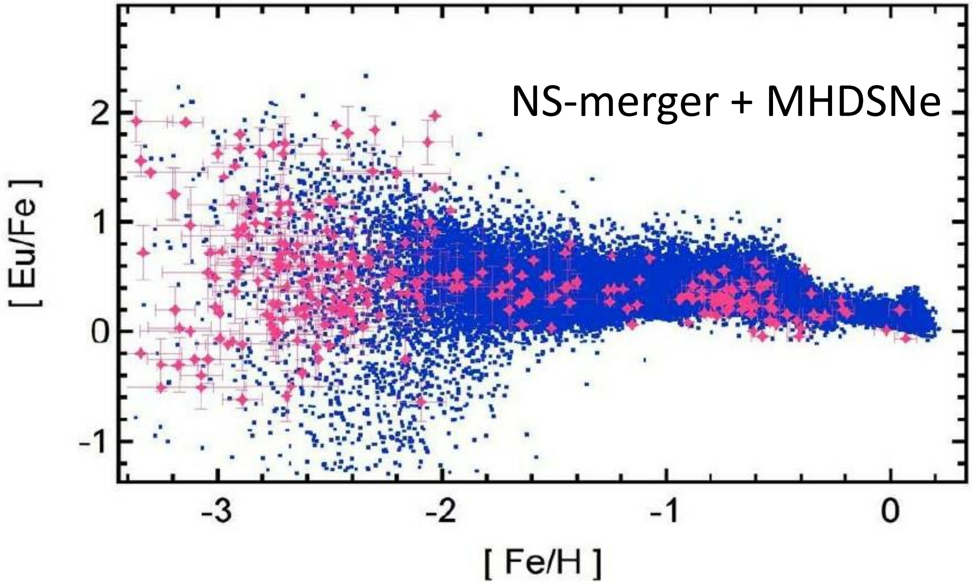
Combination of (a) NS mergers and magneto-rotational jets or (b) NS-BH and NS-mergers mergers (occuring earlier/at lower metallicity in galactic evolution, either

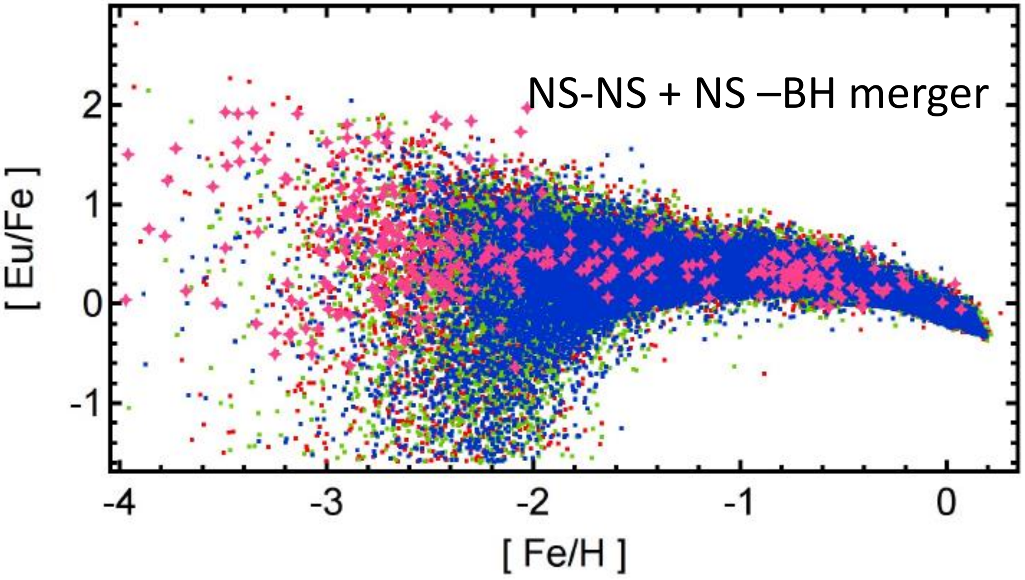
(a) because BH of more massive star origin or

(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,

5. Summary

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)
can be strong, dependent on initial magn. field

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

A.5 Collapsars (Siegel, Metzger, Surman et al.) possibly 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
A.3, A.5, B.1, B.2 qualify for rare, strong r-process events, A.3, A.5 and B.2 could match the low metallicity observations. Which of A.1, A.2 (low magn. field A.3), A.4 match the limited-r (Honda) observations needs still to be determined