6 Sep. 2017, 高エネルギー宇宙物理学研究会@Kyoto

rプロセス元素の起源と高エネルギー天体現象：Origin of r-process nuclei in high-energy astrophysical phenomenon

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Talk plan

- Astronomical origin of the r-process
  - Basics
  - The r-process in NS-NS mergers

- The r-process in peculiar Supernovae?
  - Magneto-driven Supernovae
  - Indication to other observables

- Summary

https://www.quantamagazine.org/

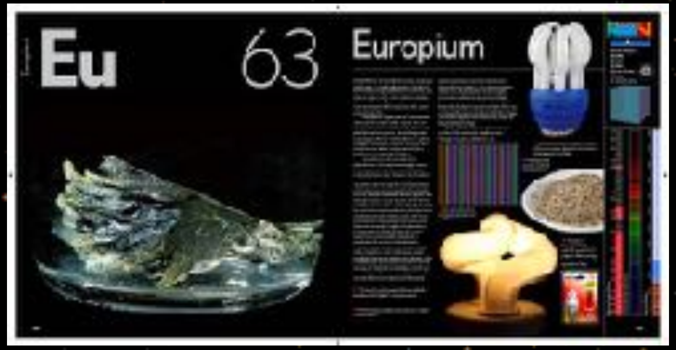
Astronomical Origin of the r-process

Collaboration with
S. Wanajo (Sophia U), Y. Sekiguchi (Toho U), S. Fujibayashi, K. Kiuchi, M. Shibata (Kyoto U), K. Kyutoku (KEK); H. Sawai (RIST), T. Takiwaki, T. Tsujimoto(NAOJ), S. Yamada (Waseda), F.-K. Thielemann (Basel)

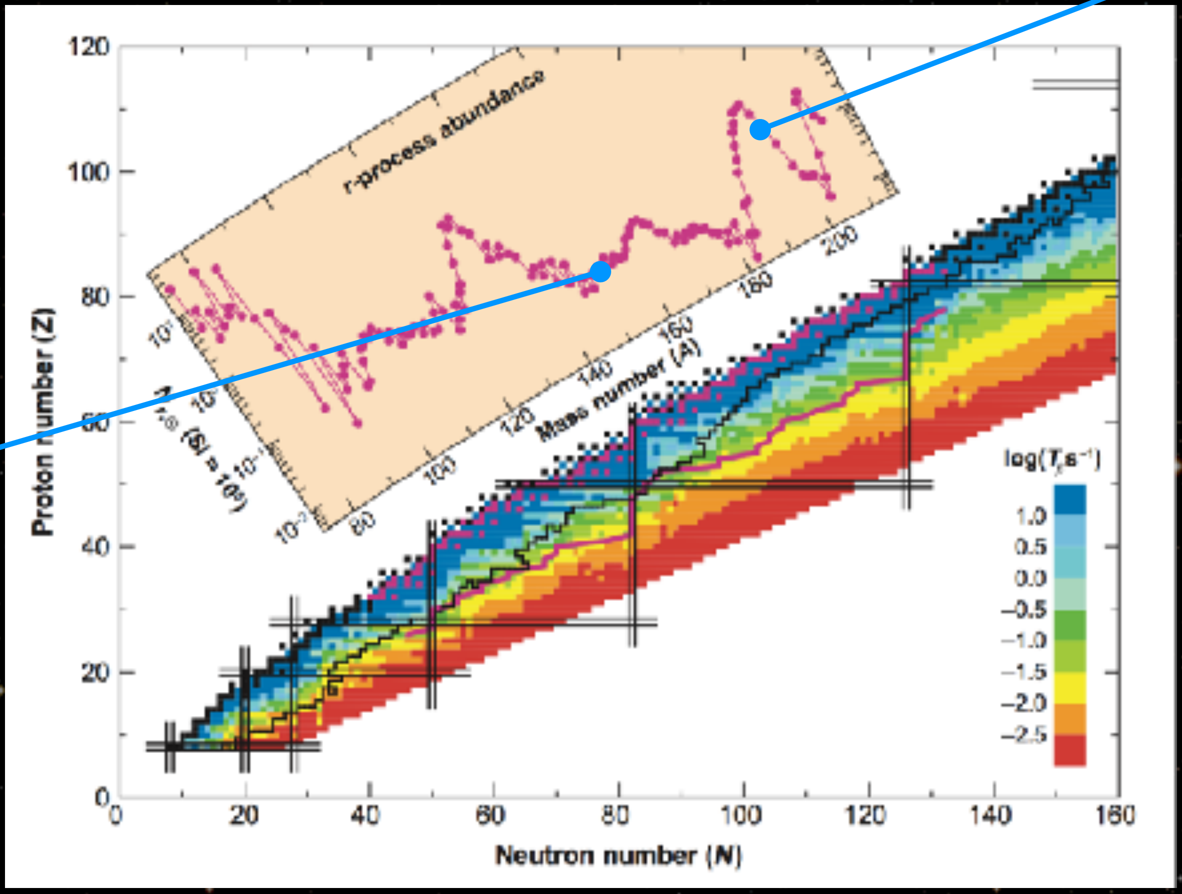
Origin of gold (beyond iron)

- Nuclear Physics
  - n-capture and β-decay; produces Eu, Pt, Au, U etc.
- Astronomical Observation
  - Solar/metal-poor stars; Galactic chemical evolution;
- Astronomical Origin (undetermined)
  - core-collapse SN or NS-NS/BH-NS mergers?

EU?



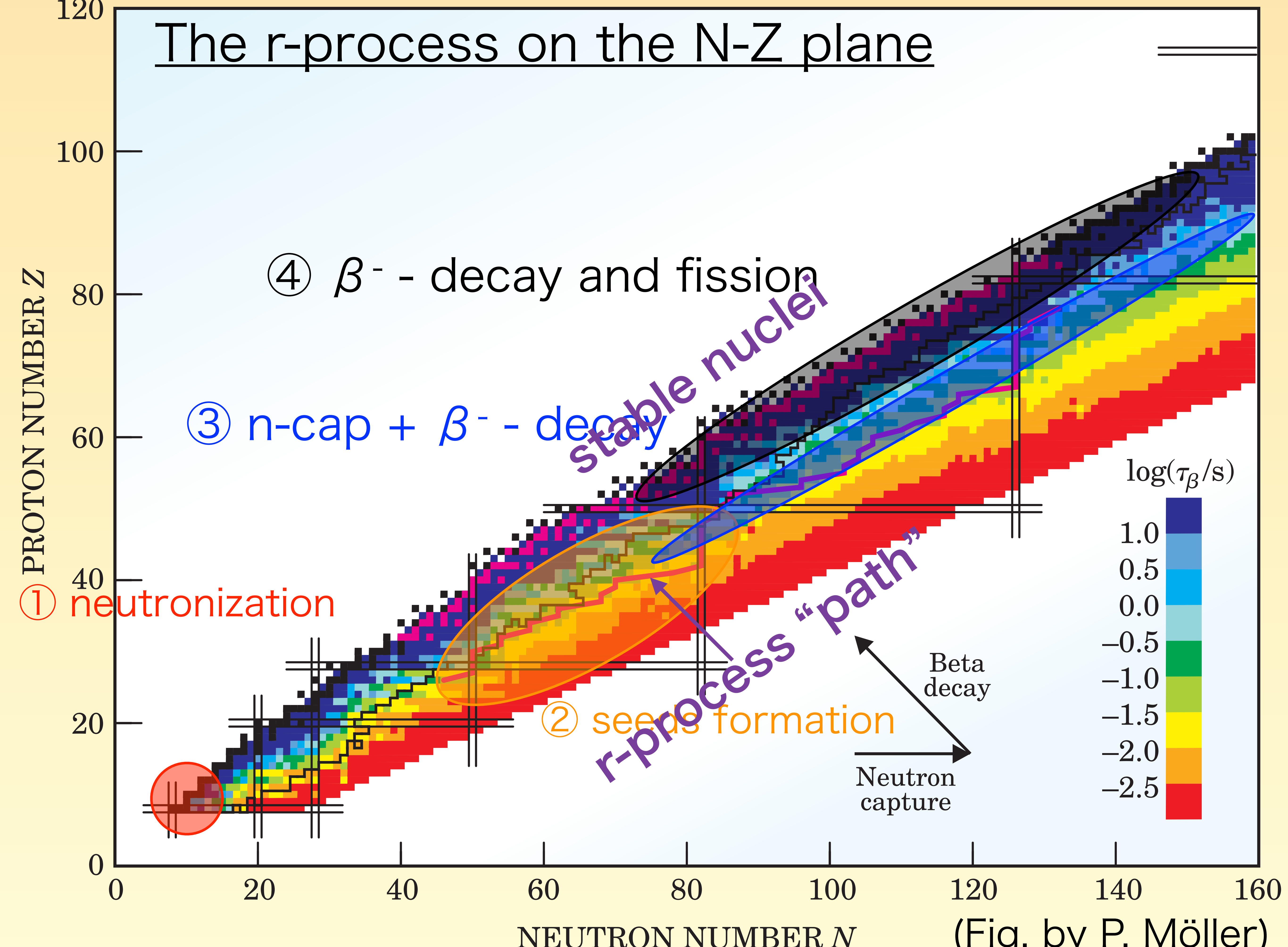
"The Elements" T. Gray



"The Elements" T. Gray

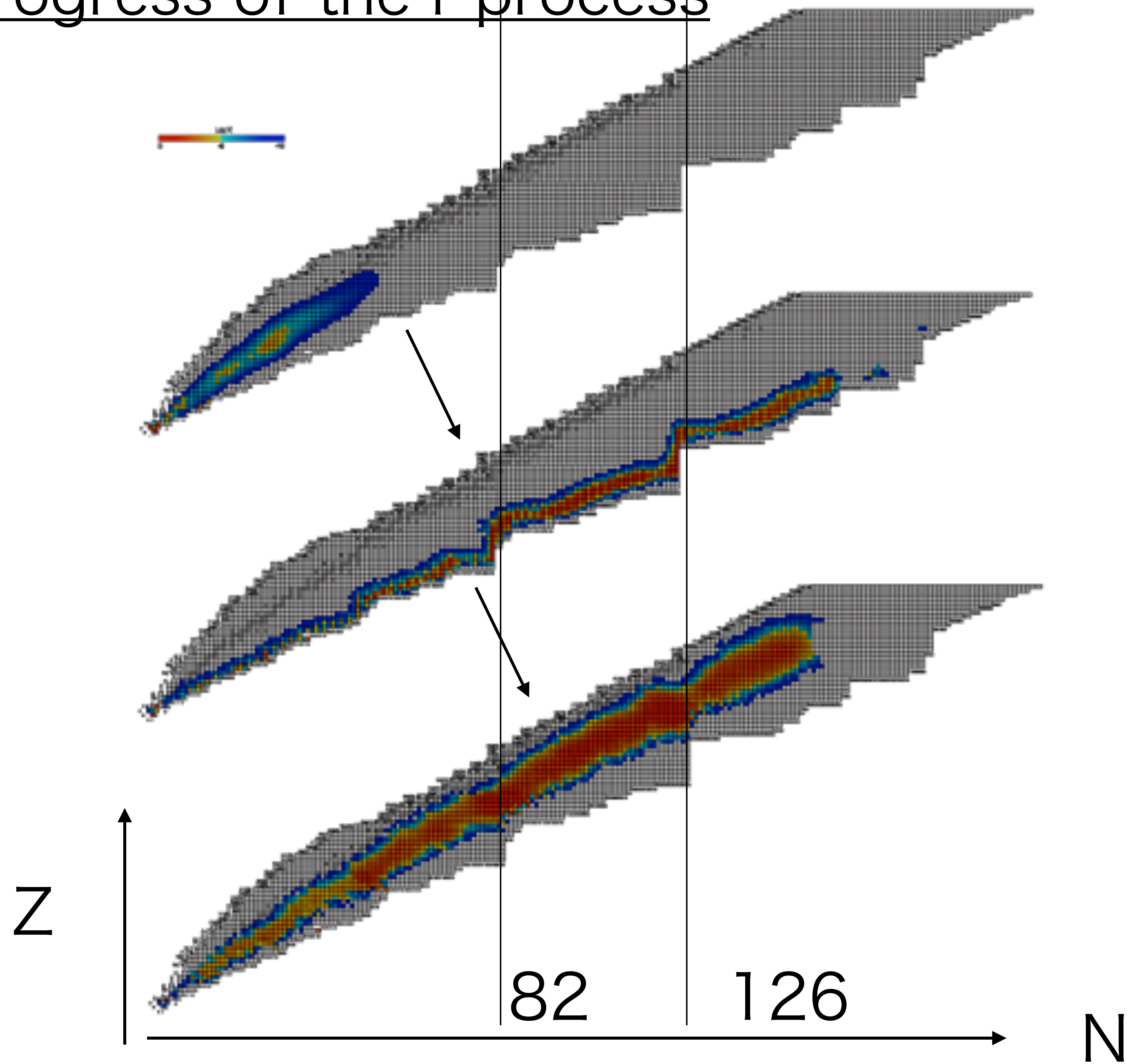
Sneden+ (2008)
(Möller+ 1997)

The r-process on the N-Z plane



(Fig. by P. Möller)

The progress of the r-process

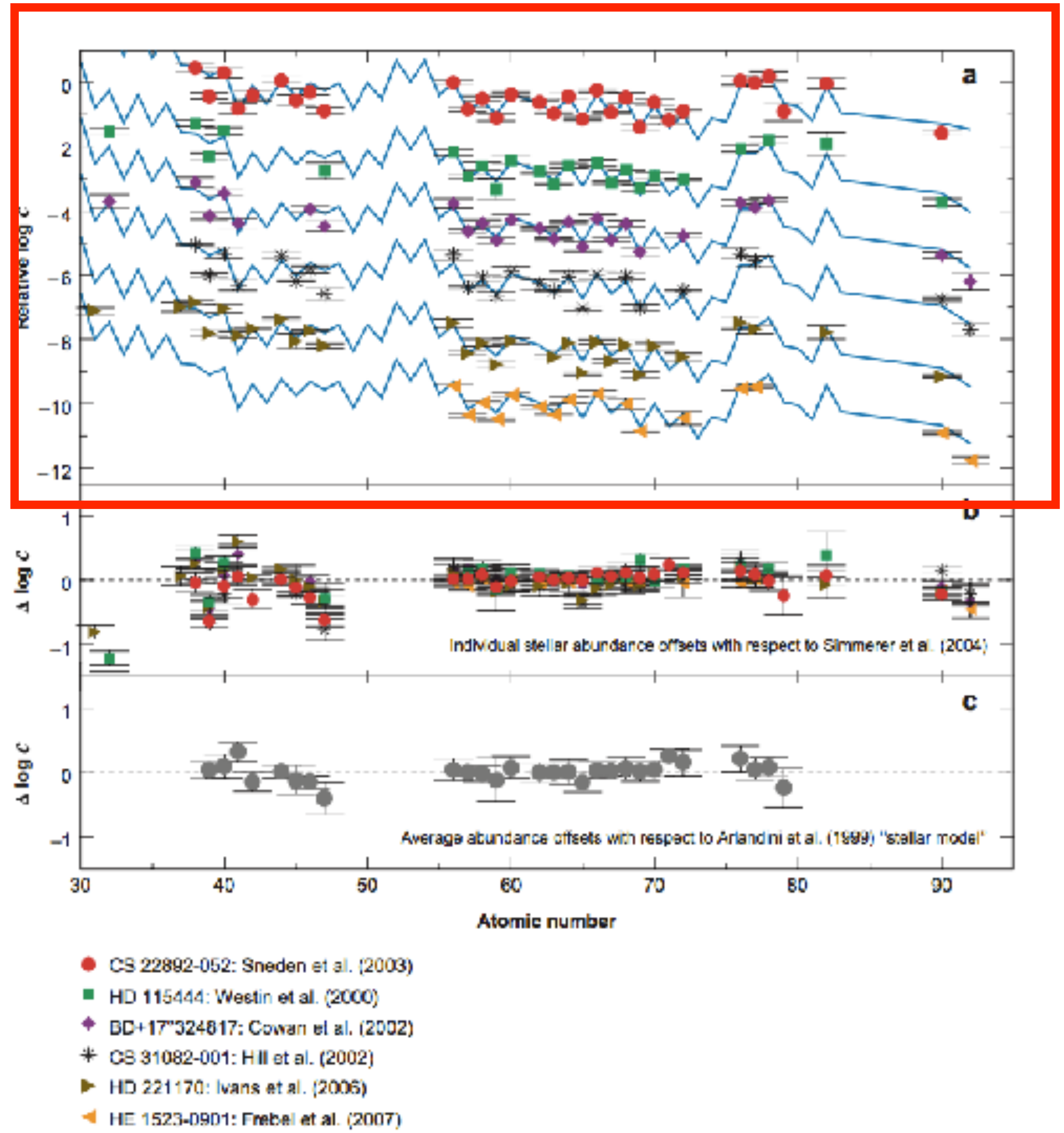


Similar pattern in r-process observation

Sneden+ (2008) ARAA

- many r-rich Galactic halo stars show agreement with solar pattern
- r-process has happened from the early Galaxy
- astrophysical models reproduce this common pattern (Z>40; A>90)

→ suggests existence of "main" r-process sites produces between 2nd and 3rd peak



but not for ALL metal-poor stars; e.g. Honda stars

Physical condition for r-process

high T and ρ

Y_e: electron fraction

$Y_e = Y_p$

$\sim N_p / (N_n + N_p)$

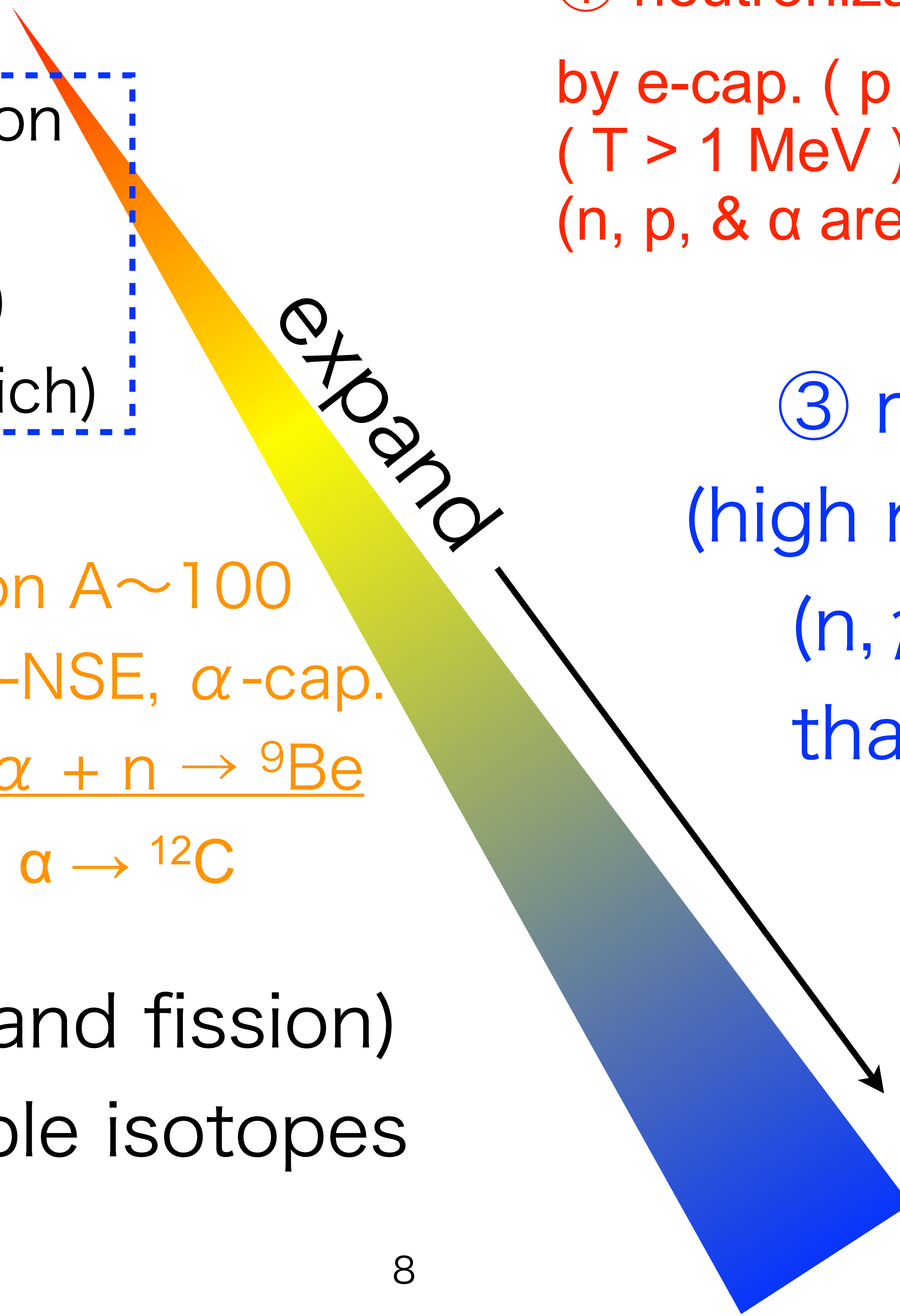
(low Y_e = neutron rich)

① neutronization (low Y_e)

by e-cap. ($p + e^- \rightarrow n + \nu_e$)

(T > 1 MeV) NSE

(n, p, & α are predominant)



② seed formation A∼100

(T > 0.5 MeV) quasi-NSE, α-cap.

"α-process": $\underline{\alpha + \alpha + n \rightarrow {}^{9}Be}$

${}^{9}Be + \alpha \rightarrow {}^{12}C$

③ rapid-n cap.

(high n/Seed > 100)

(n, γ) is faster

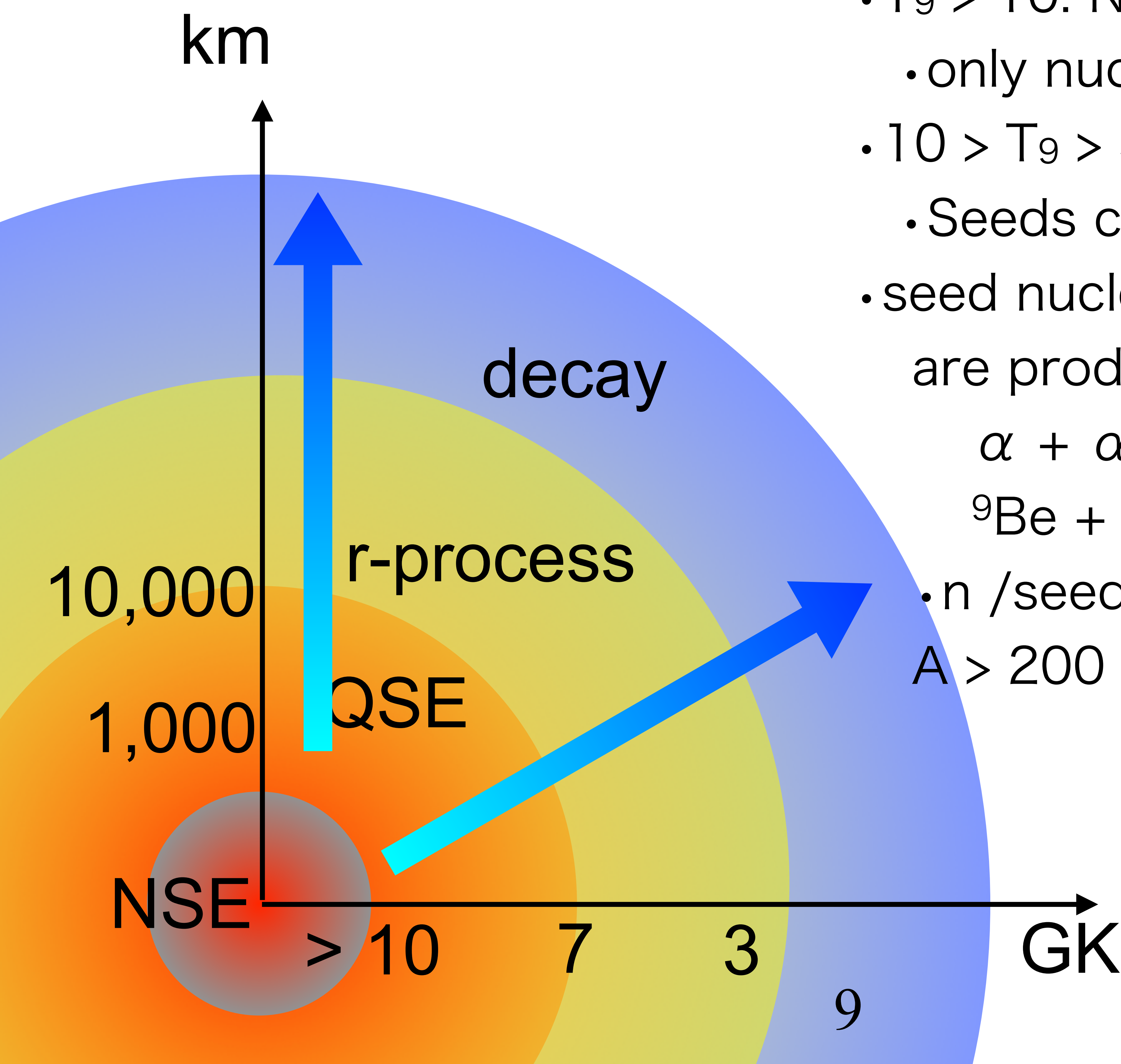
than β-decay

④ decay (β and fission)

decay to stable isotopes

low T and ρ

SNe and PNS winds



- $T_9 > 10$: NSE
  - only nucleon + α
- $10 > T_9 > 3$: QSE ("α-process")
  - Seeds creation
- seed nuclei (A = 80 - 90) are produced via

  $\alpha + \alpha + n \rightarrow {}^{9}Be$

  ${}^{9}Be + \alpha \rightarrow {}^{12}C$
- n /seed > 100 is required for m

A > 200

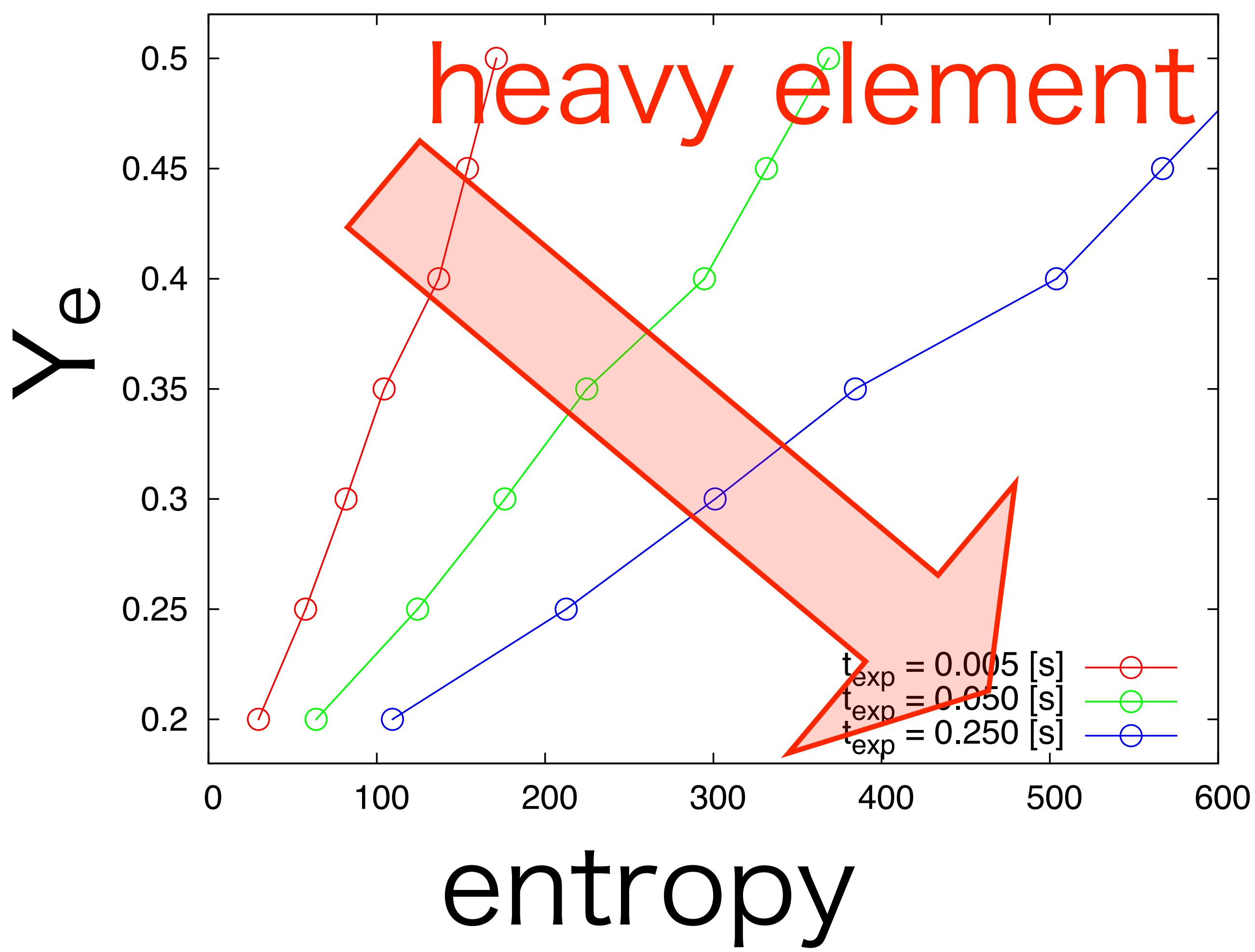
Physical condition for r-process

condition for r-process nuclei (A=200), 3rd peak:

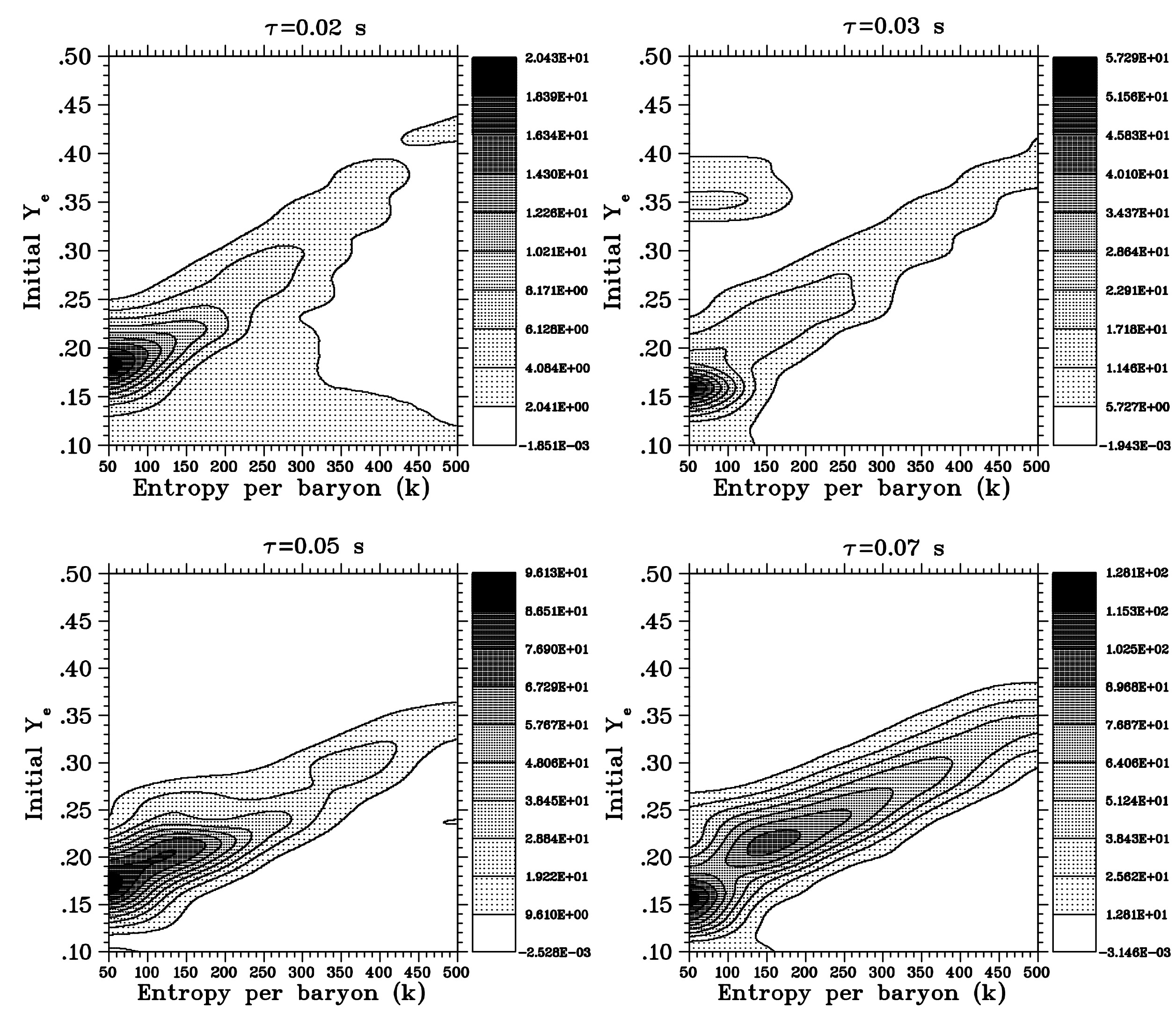
n/seed > 100 in appropriate time scale

($\alpha + \alpha + n \rightarrow {}^{9}Be$)

Meyer 1997



based on Hoffman et al. (1997)

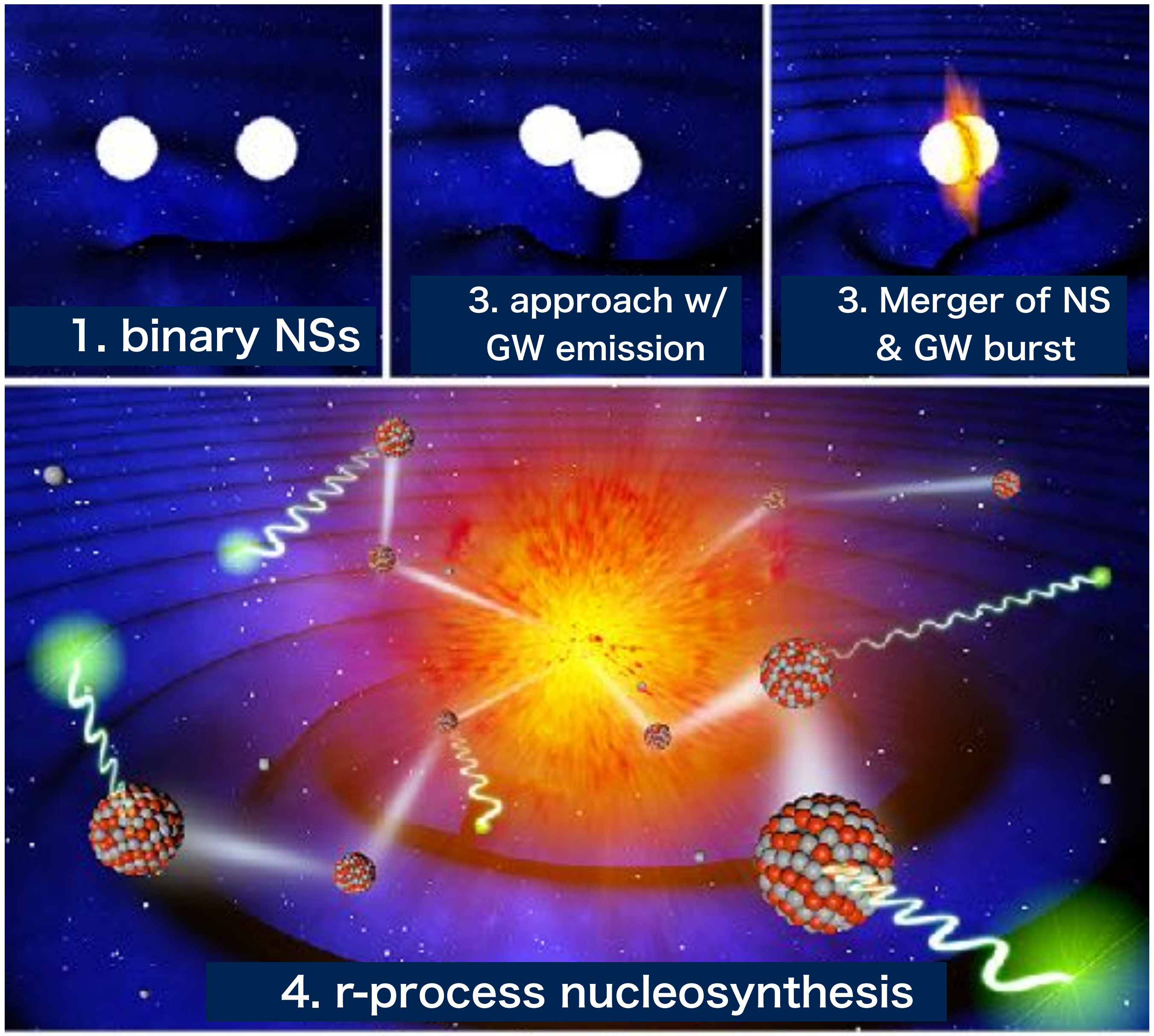


$$f_{200} = \frac{(S/230\,k_B\,\mathrm{nucleon}^{-1})}{(Y_e/0.40)(\tau/20\,\mathrm{ms})^{1/3}} \gtrsim 1, \quad 0.38 \lesssim Y_e \lesssim 0.46$$

Wanajo 2013

(Hoffman 1997)

Neutron-star mergers as r-process sites



from NAOJ Website
(Tsujimoto & Shigeyama)

Coalescence of two NSs

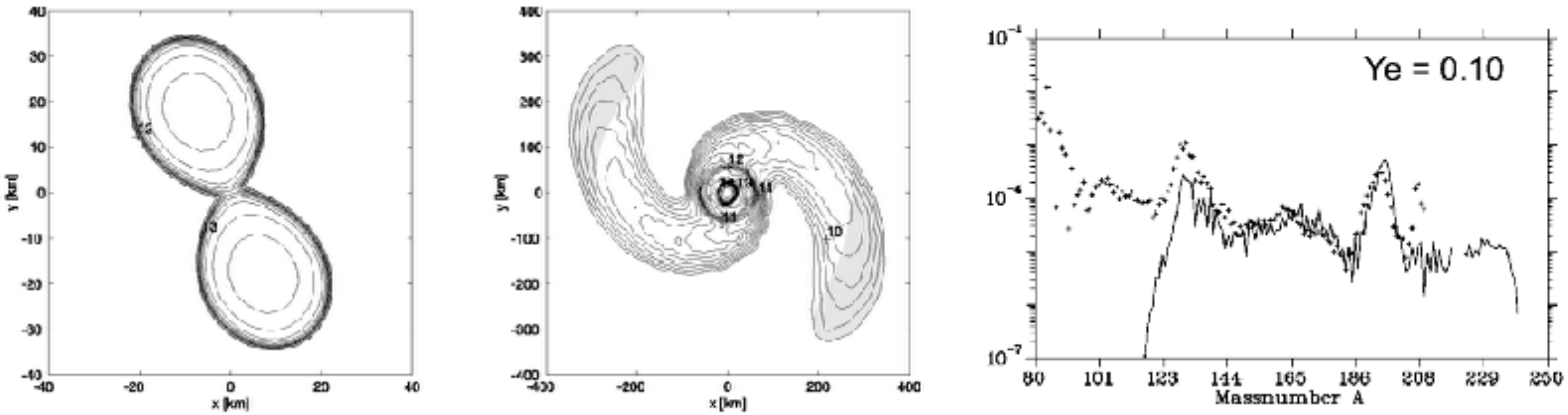
- eject neutron-rich matter
- sources of
  - GWs
  - Kilonovae/Macronovae
  - (short) GRBs

Galactic chemical evolution

- lower event rate, a large amount r-process nuclei
- problem: can explain r-process enrichment in early galaxies?

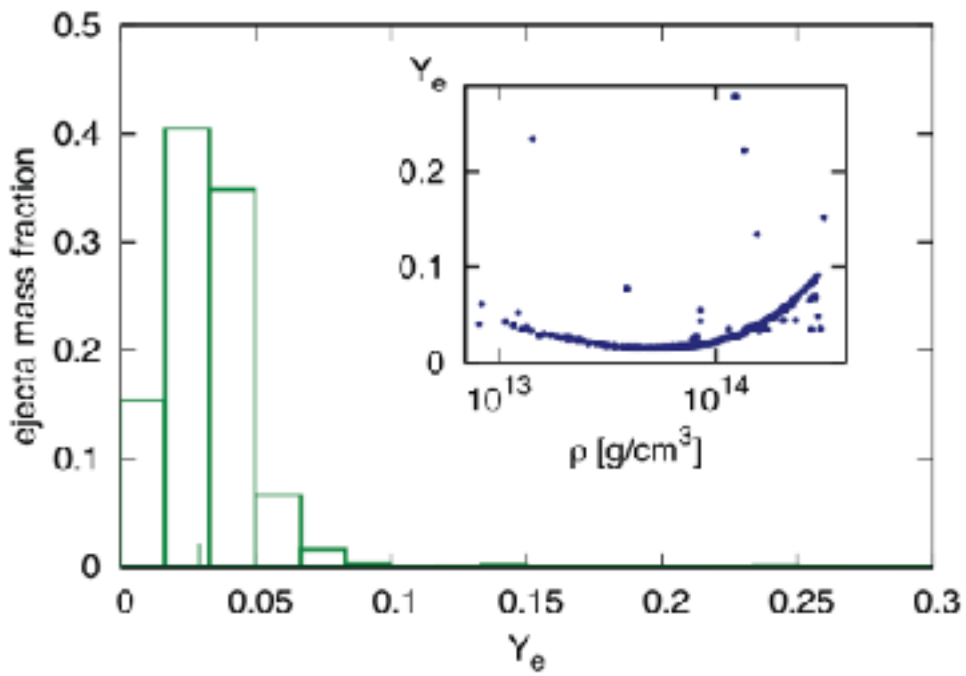
“Classical” model: only heavy r-process nuclei?

Freiburghaus, Rosswog & Thielemann (1999)

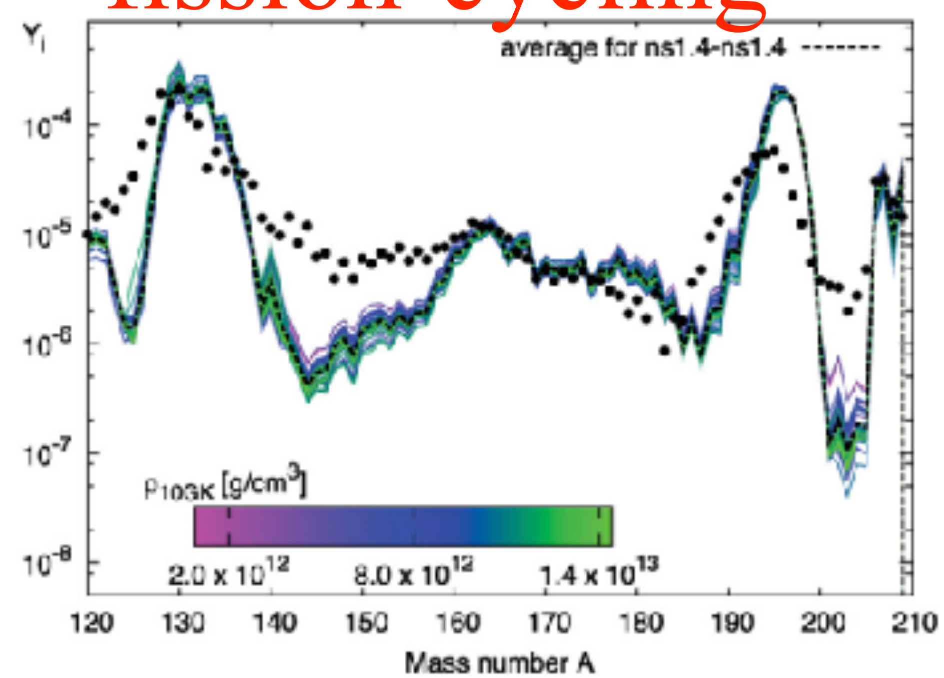


tidal ejection of “pure” n-rich matter with $Y_e \ll 0.1$

$Y_e \approx N_p/(N_n + N_p)$ if only nucleon



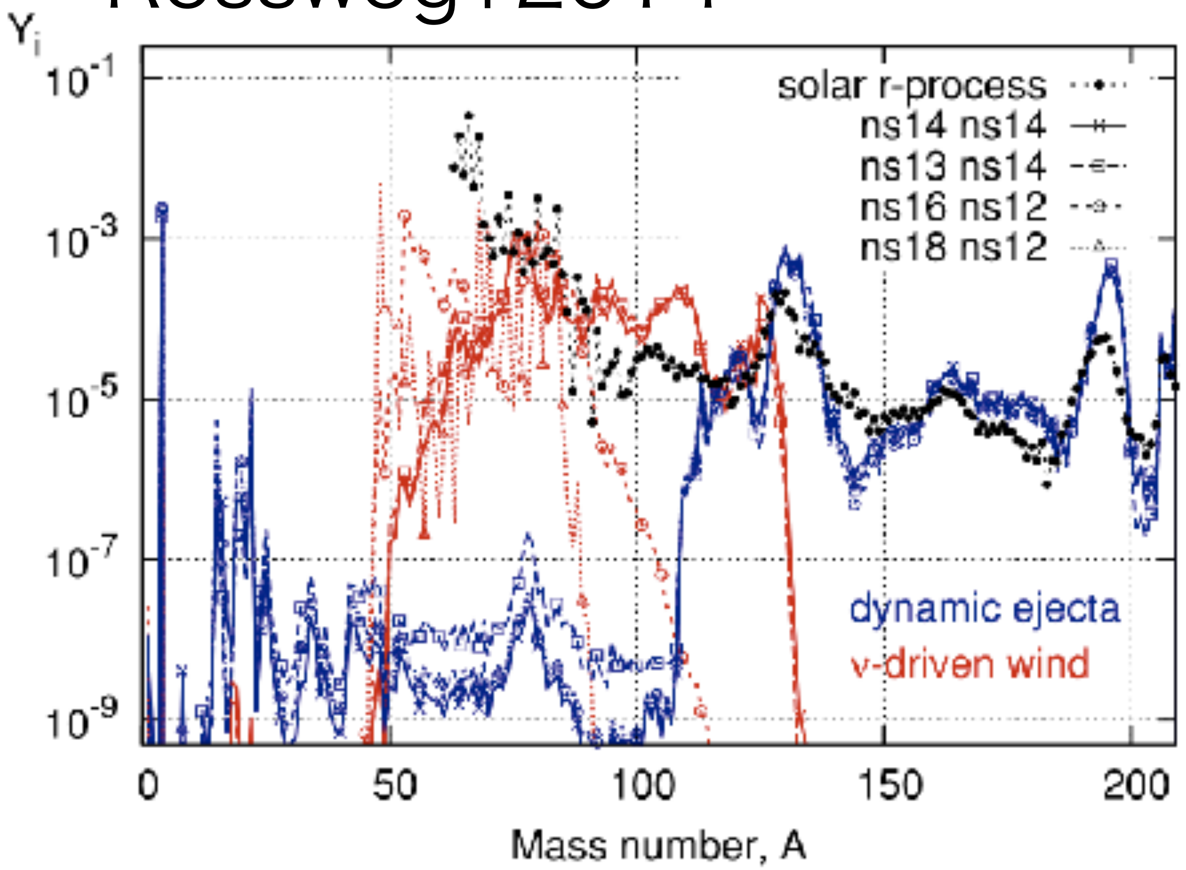
fission-cycling



Korobkin+ 2012 (e.g., Goriely+ 2011, Rosswog+ 2013)

r-process mass ejection scenario

Rosswog+2014



dynamical ejecta

(Ye < 0.1–0.2)

+

neutrino-driven ejecta

(Ye > 0.3)

However, there are still problems must be solved.

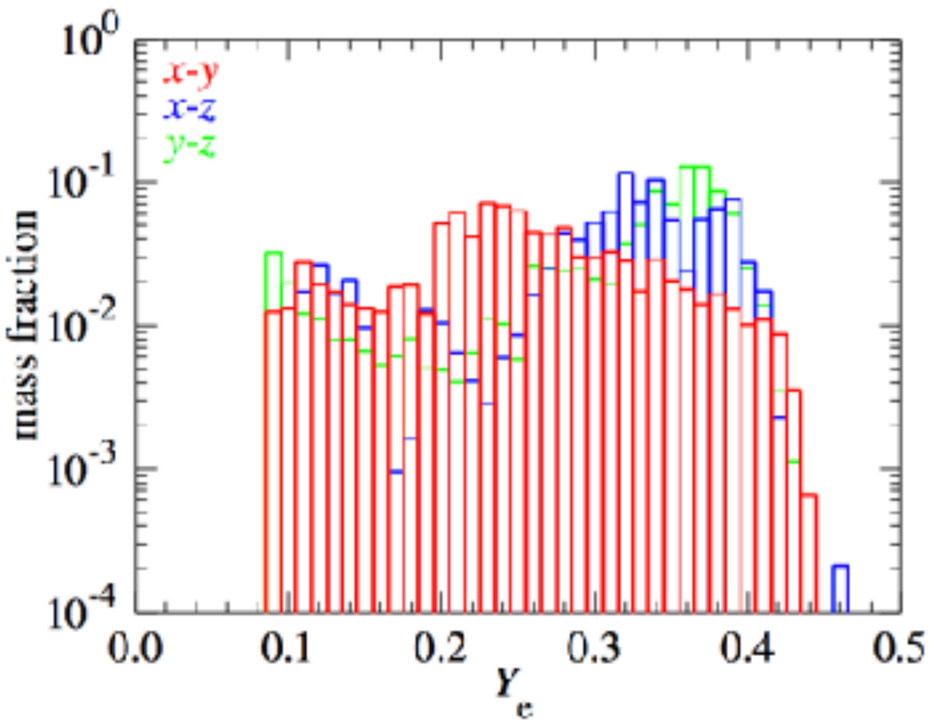
- more sophisticated hydro simulations
- dependence on EoS (physical uncertainty) and the NS mass ratio (astronomical properties)

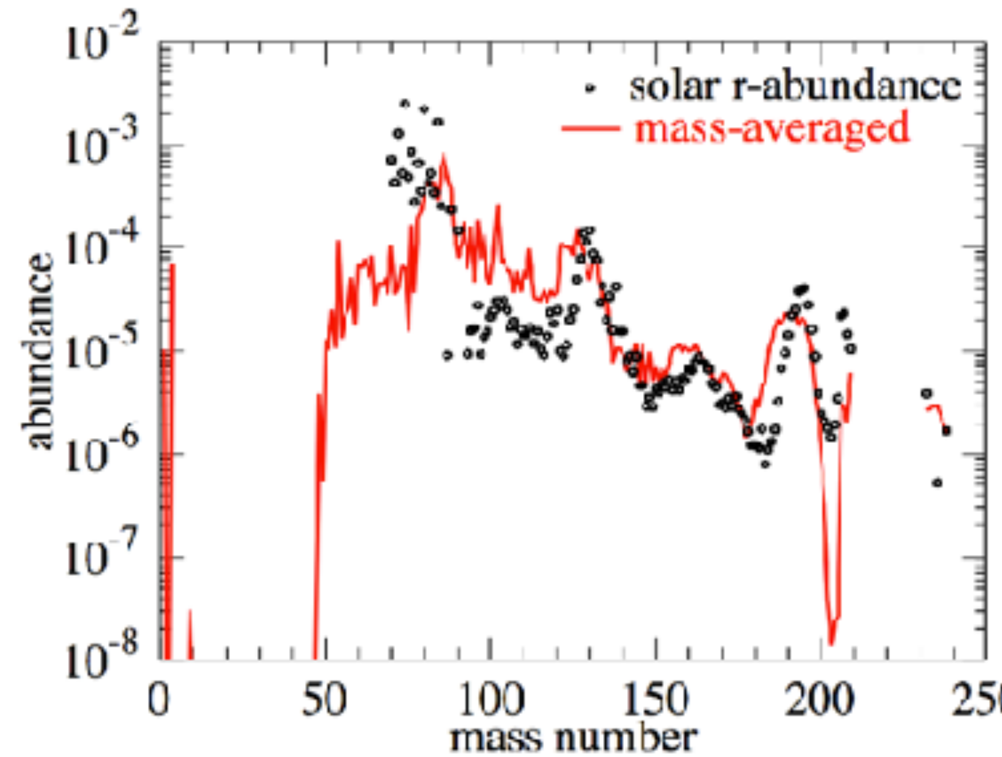
or nuclear physics uncertainty, e.g. fission play a role?

(see, Goriely+2013, Eichler+ 2015, Shibagaki+ 2016)

A new mechanism of dynamical ejecta

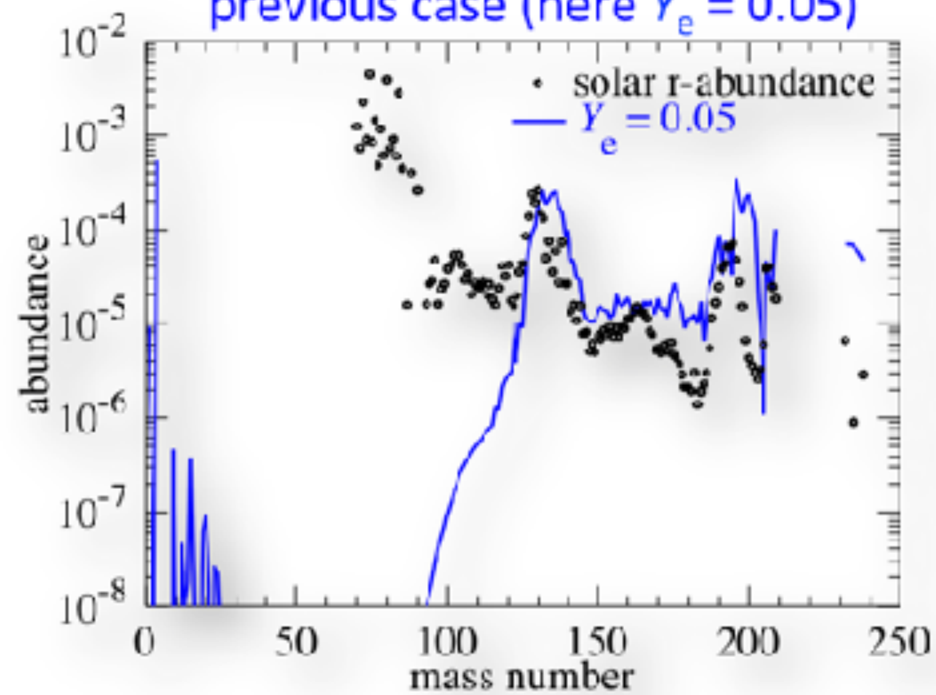
Wanajo, Sekiguchi, NN+2014 (w/ Kyoto GR-hydro Group)





Stronger shock heating, activating weak-reactions i.e., $e^{\pm}$ and neutrino absorption

previous case (here $Y_e = 0.05$)

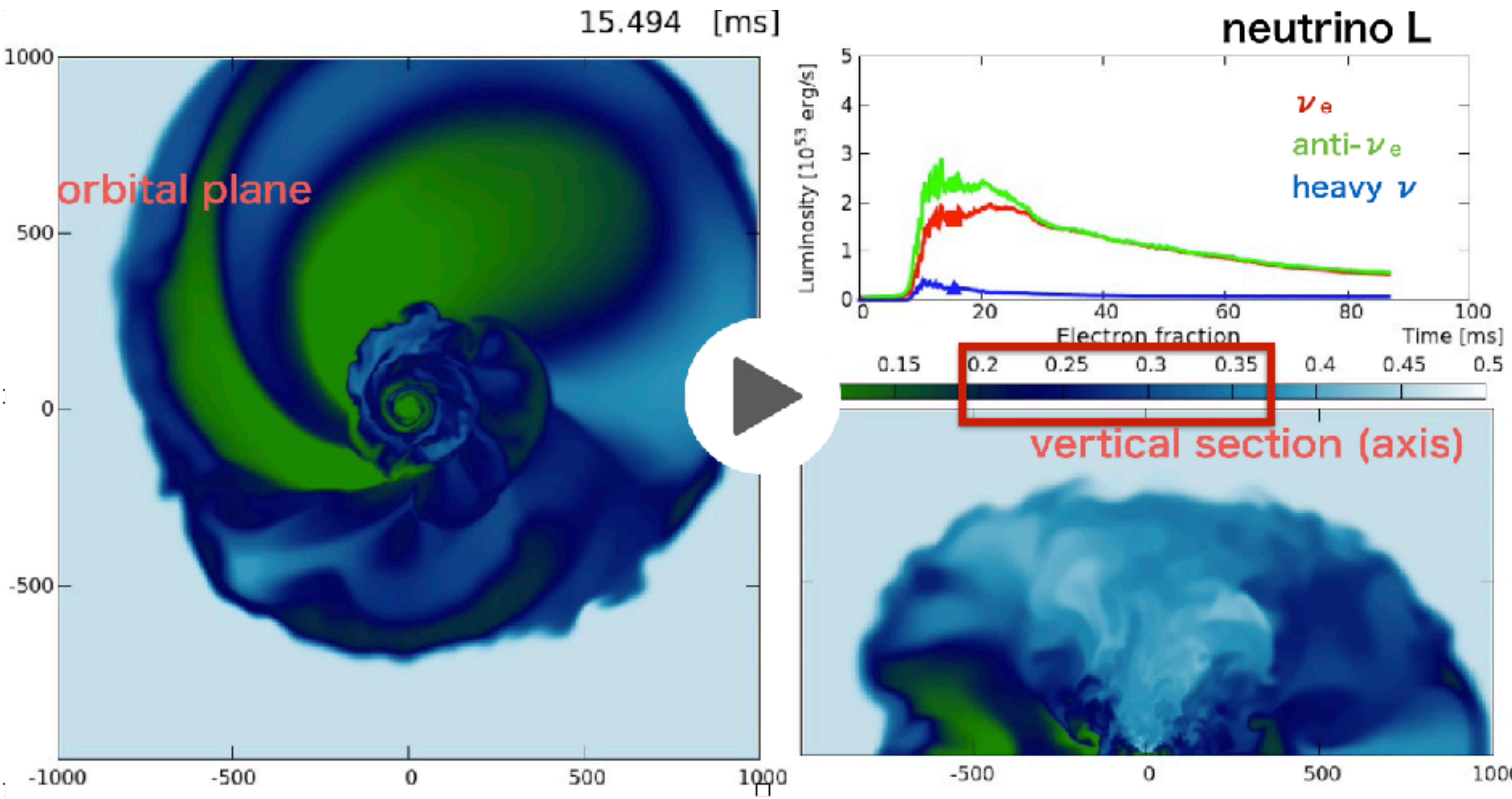


(see, also, Goriely+2015 by MPA group)

Details: NS masses & EoS in 3D hydro

r-process study using simplified model (Wanajo+2014)

Y_e evolution, based on 3D hydro (Sekiguchi+2015)



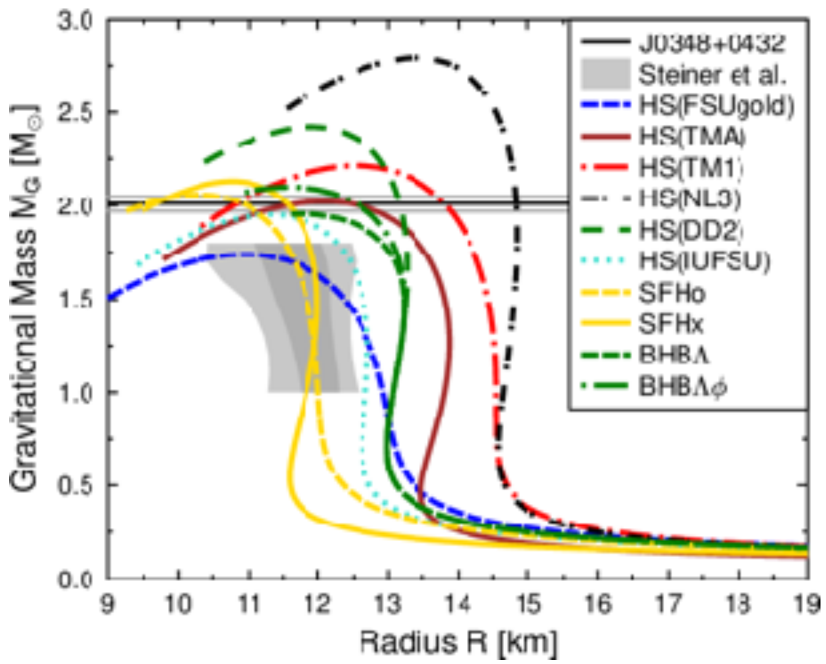
Tidal disruption

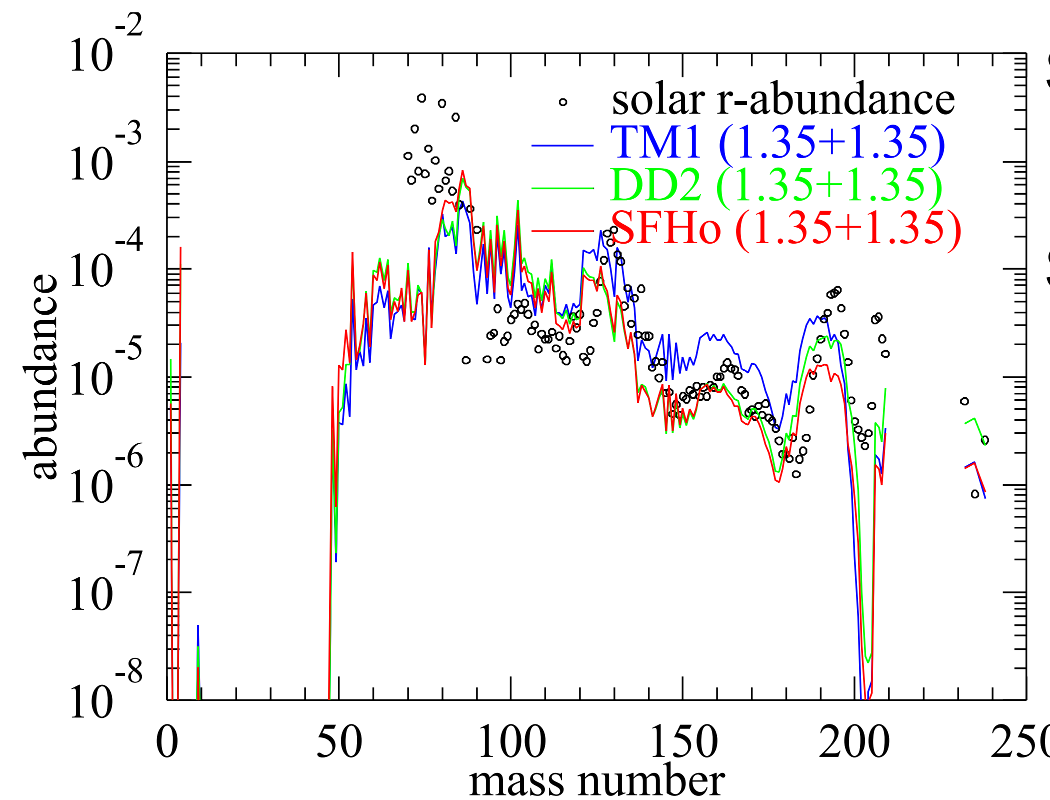
Shock & neutrino

Details: NS masses & EoS in 3D hydro

Wanajo, NN+ in prep.; NN+ in prep.

nuclear EOS (by M. Hempel)



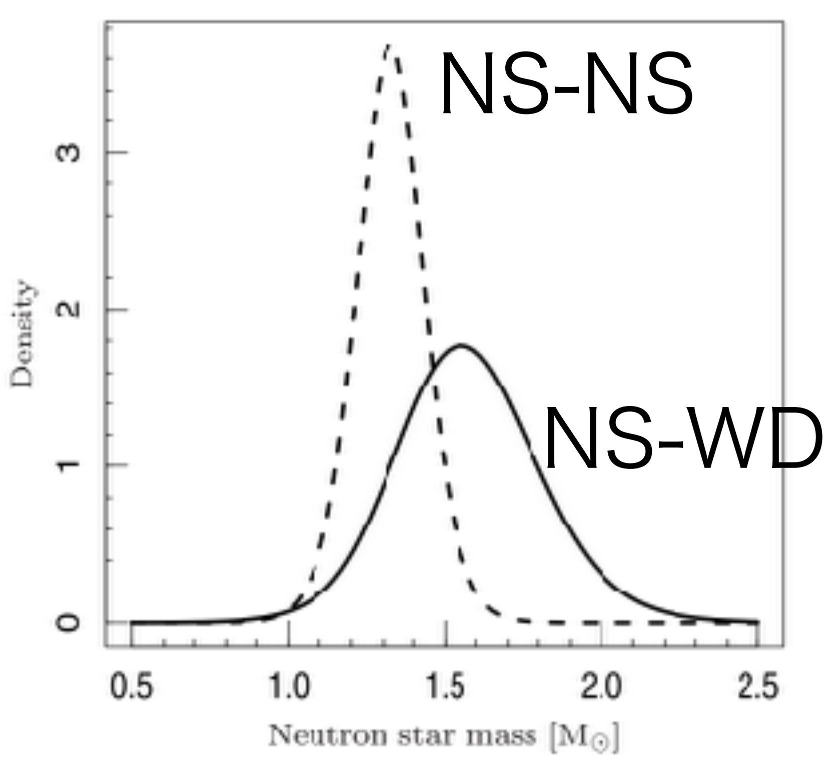


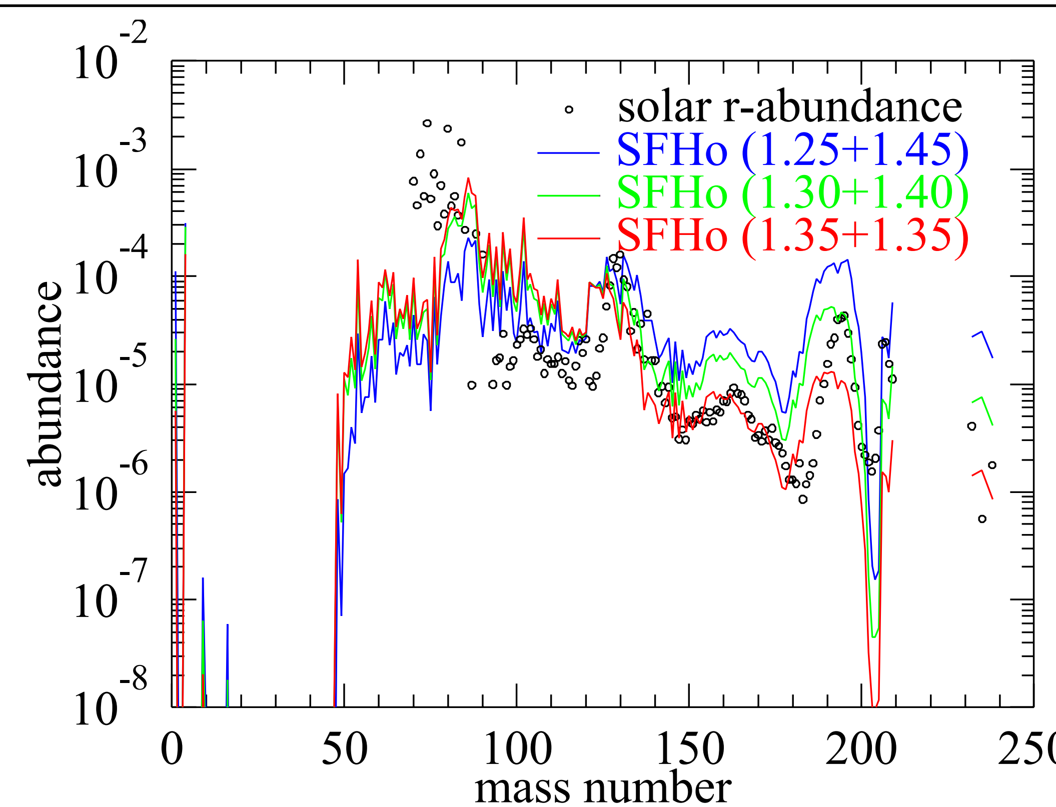
stiff

↑

soft

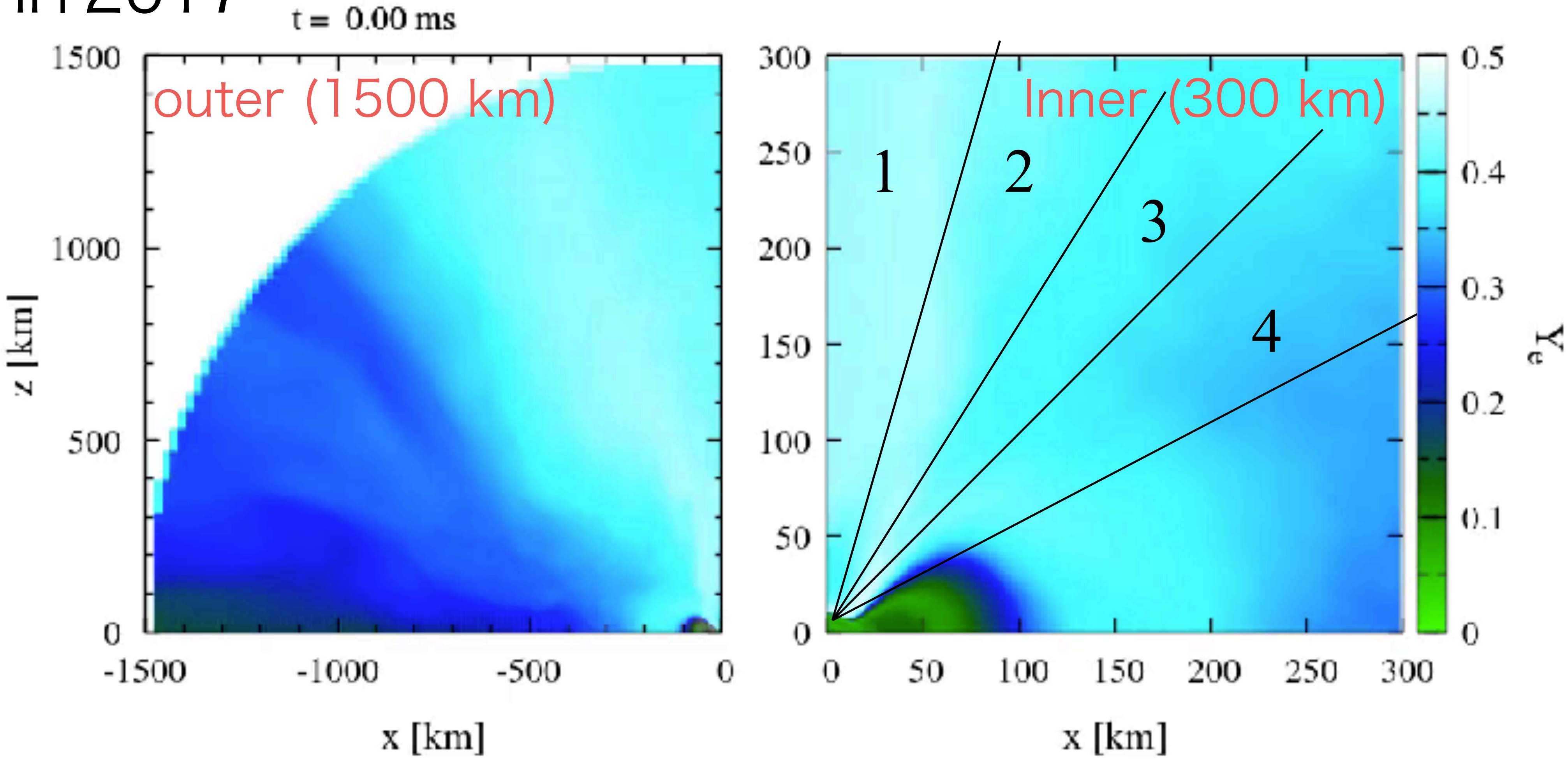
NS mass ratio (Kiziltan+ 2013)





Late-phase evolution: nu-driven ejecta

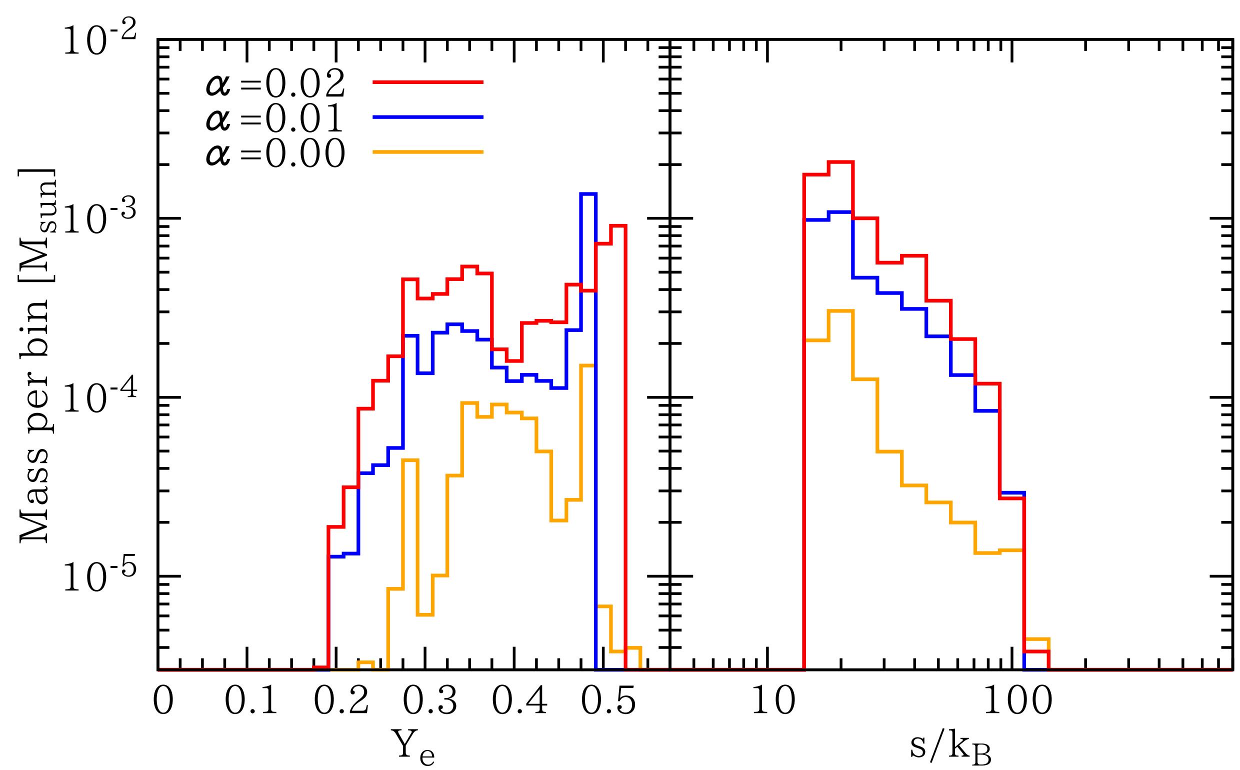
Fujibayashi+2017



neutrino-heating

+ pair annihilation

+ viscosity



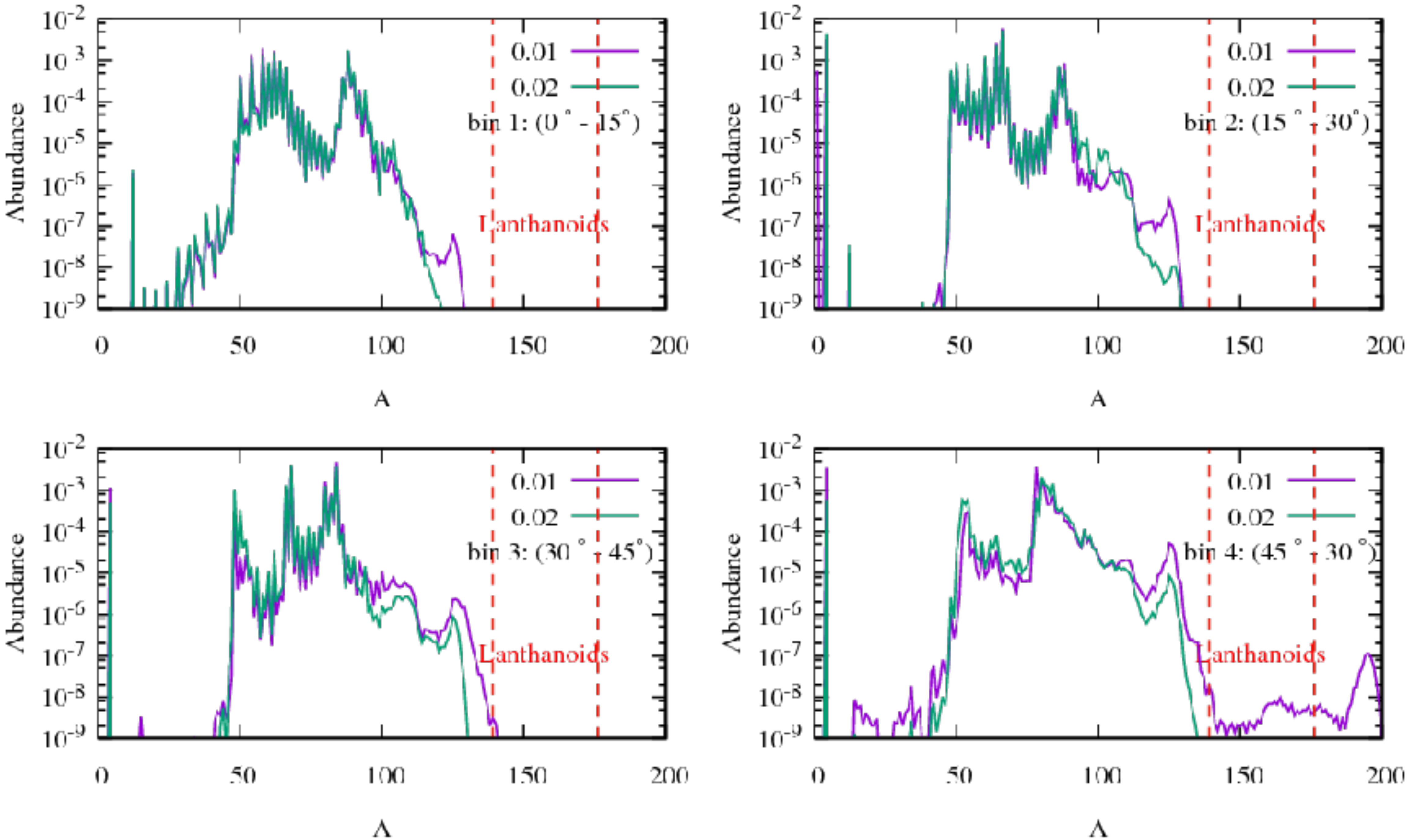
Late-phase evolution: nu-driven ejecta

Fujibayashi et al. in prep 2017

Lanthanide-free ejecta shows higher luminosity.

(e.g. Tanaka+2017)

M_{ej}: 3.0e-4 —> 3.5e-4 M_{sun}



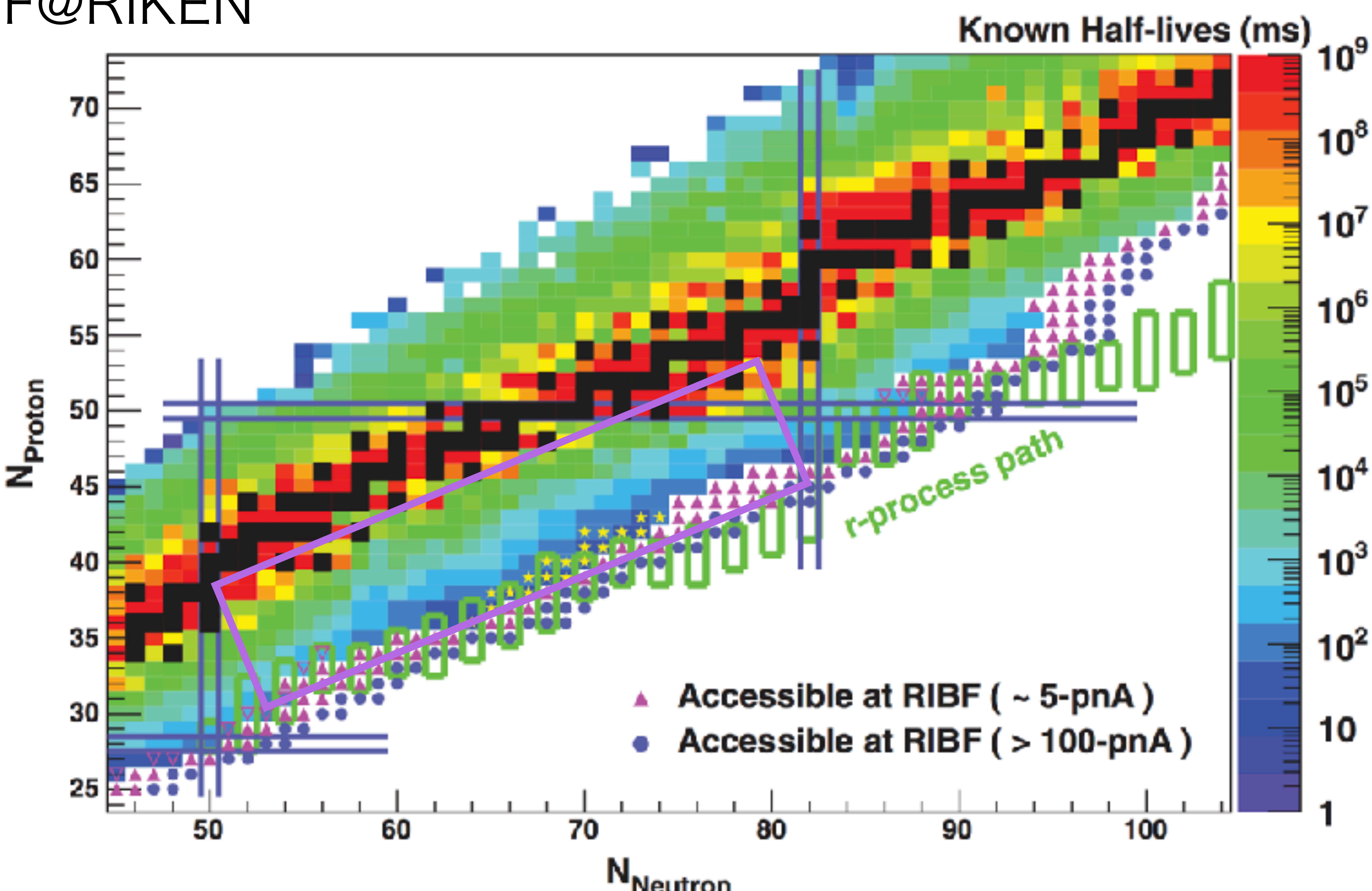
See also, D. Martin et al., ApJ, 2015

Highlight importance of RI-isotopes

International symposium on RI beam physics in the 21st century: 10th anniversary of RIBF

4-5 December 2017 *RIKEN*

RIBF@RIKEN



S. Nishimura PTEP 2012

Magneto-rotational Supernovae


rプロセス特集

磁気駆動型超新星での元素合成：
rプロセスと高エネルギー
天文学

西村

滝脇

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S. Yamada (Waseda)
F.-K. Thielemann (Basel U)
T. Tsujimoto (NAOJ)

Based on

- NN, Takiwaki & Thielemann, ApJ 810 (2015) 109
- Tsujimoto & NN, ApJL 811 (2015) L10
- NN, Podolyák, Fang & Suzuki, PLB 756 (2016) 273
- NN, Sawai, Takiwaki et al., ApJL 836 (2017) L21

cc-SNe as a long-expecting r-process site

Since B2FH (1957), core-collapse supernovae have been expected as the r-process sites. However, …

> temperature for the r-process to proceed. Perhaps ejection by a jet (LeBlanc and Wilson 1970) could alter these results but that remains to be demonstrated. It may even be that the r-process, if indeed there is a single 'r-process', does not occur predominantly in supernovae! Recent work by Cowan, Cameron and Truran (1981) suggests that the r-process may occur during an off-centre helium core flash in a low mass star (following the mixing of hydrogen into the helium core by 2-dimensional instability). These interesting speculations point out just how uncertain the true nature of the r-process really is.

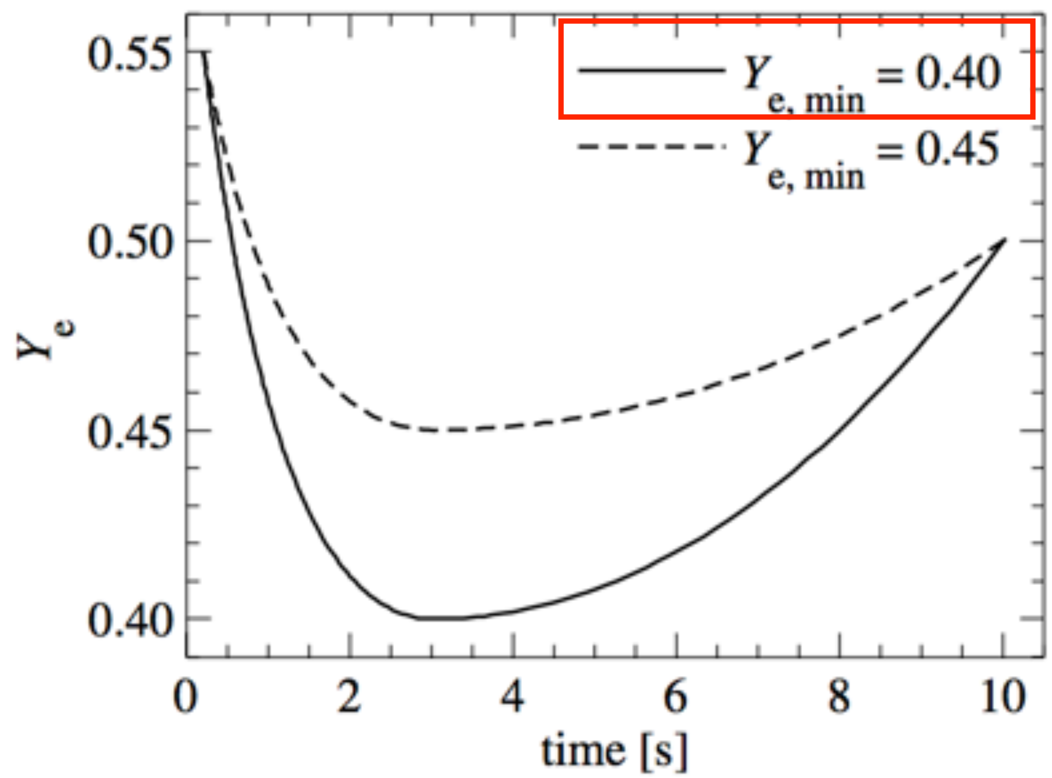
Proceedings of "Supernovae: A Survey of Current Research"
"Theoretical models for Supernovae" Woosely & Weaver 1981

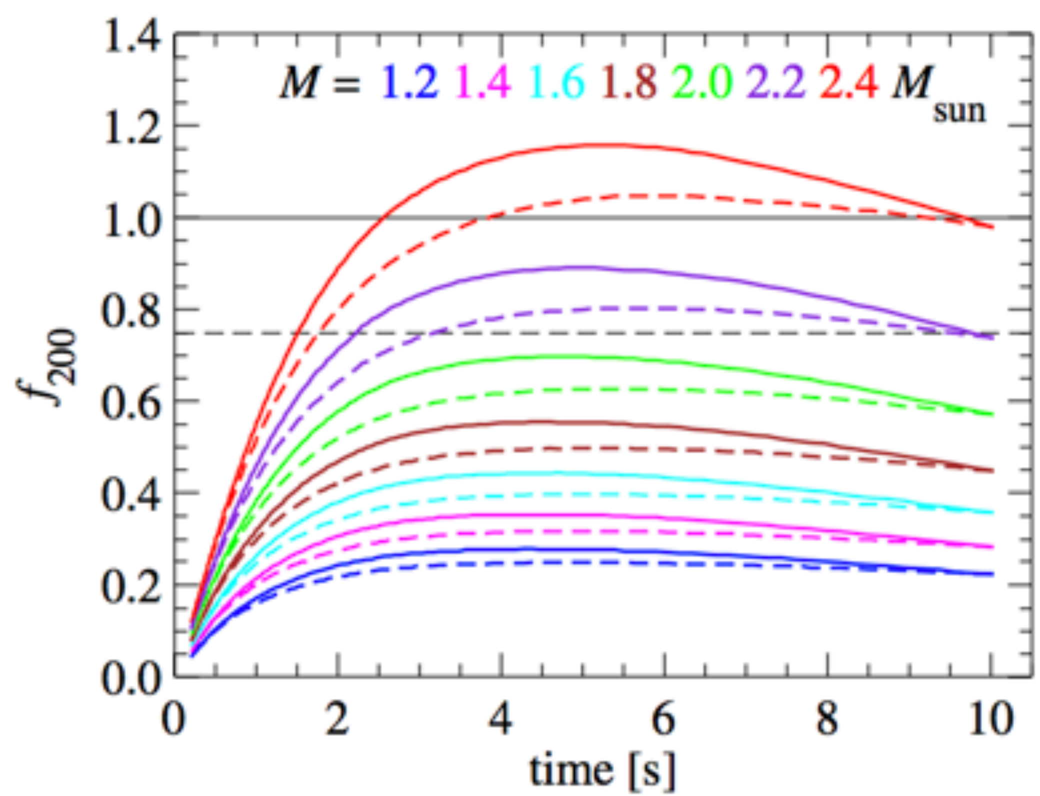
- "Prompt explosion" (e.g., Hillebrandt+1987; Sumiyoshi+2001)
  —> ONeMg SNe of 8-9Msun stars (with less neutrino heating)
- Neutrino-driven proto-neutron star wind
  (e.g. Woosley&Hoffman 1992; Meyer+1992; Howard+1993)

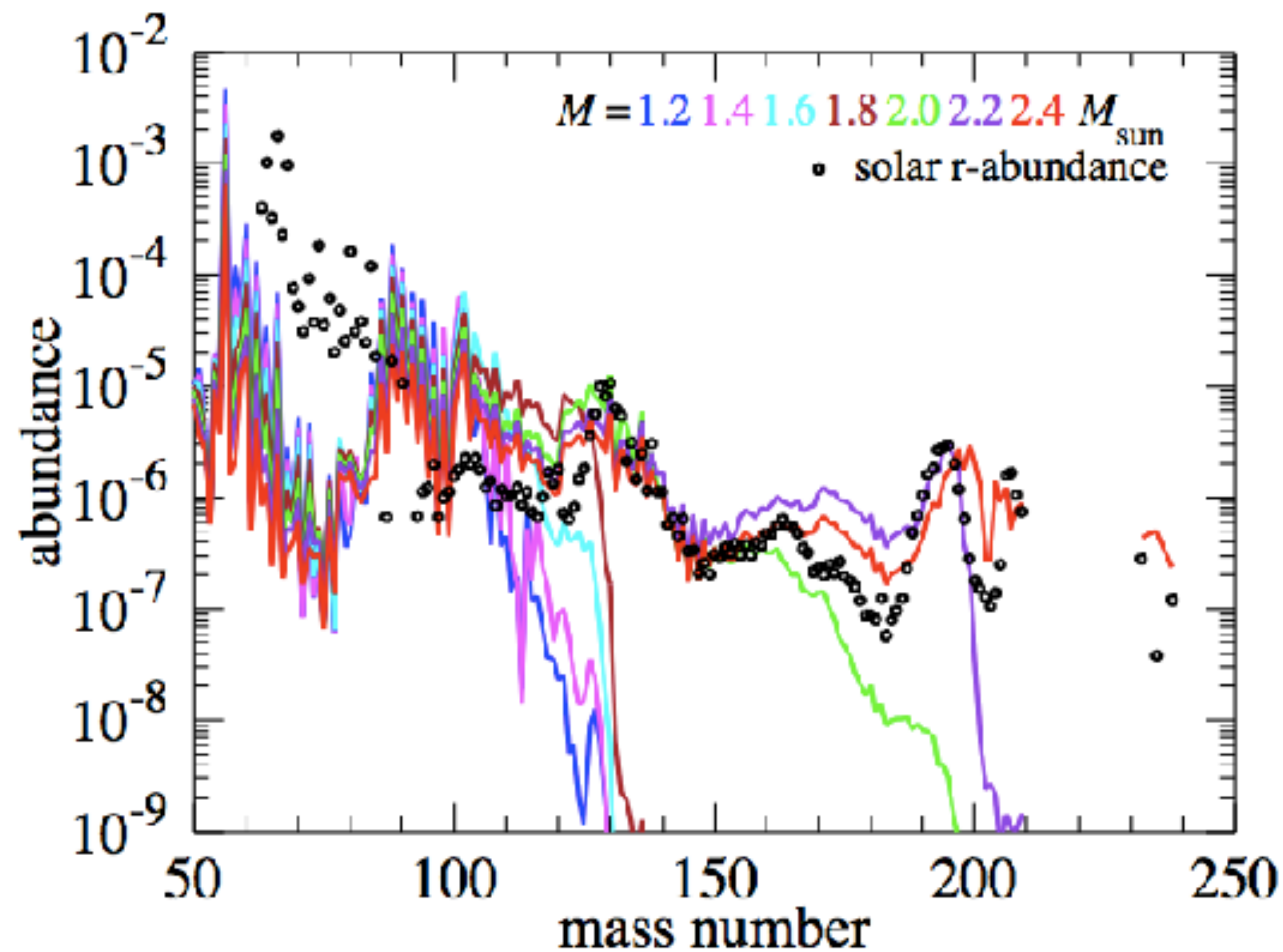
cc-SNe as a long-expecting r-process site

Wanajo 2013

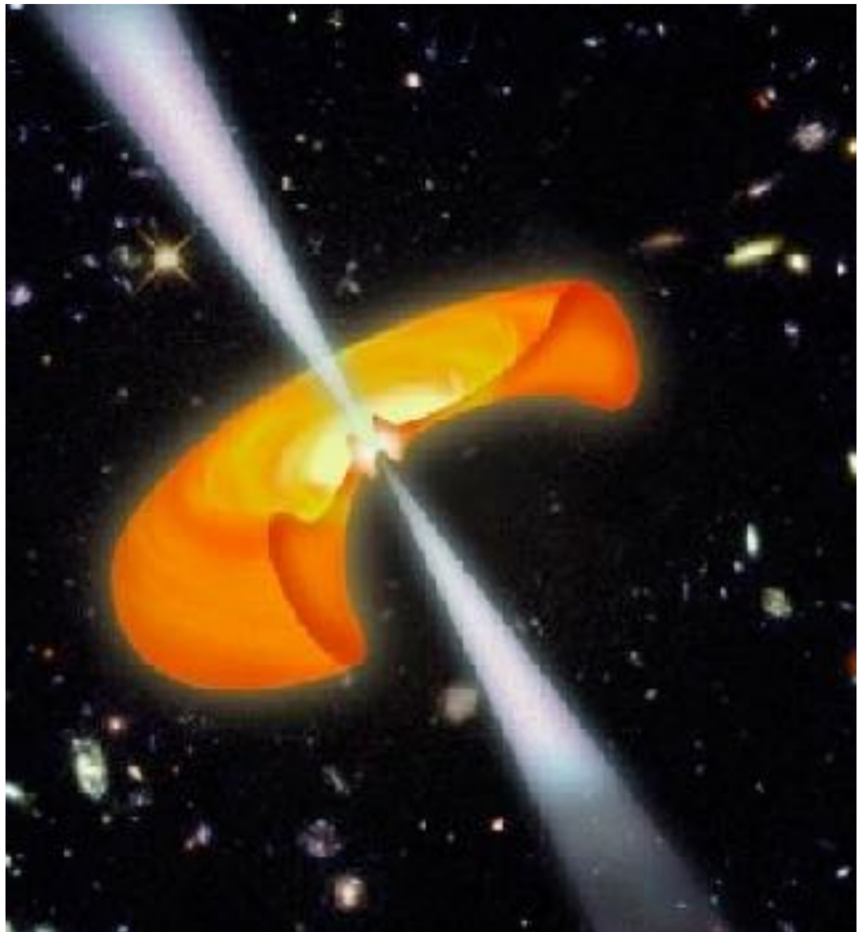
only > 2.2 Msun NSs
produce heavy
r-process nuclei







Magneto-rotationally driven (MR) SNe and magnetars



hypernova/jet-like SN

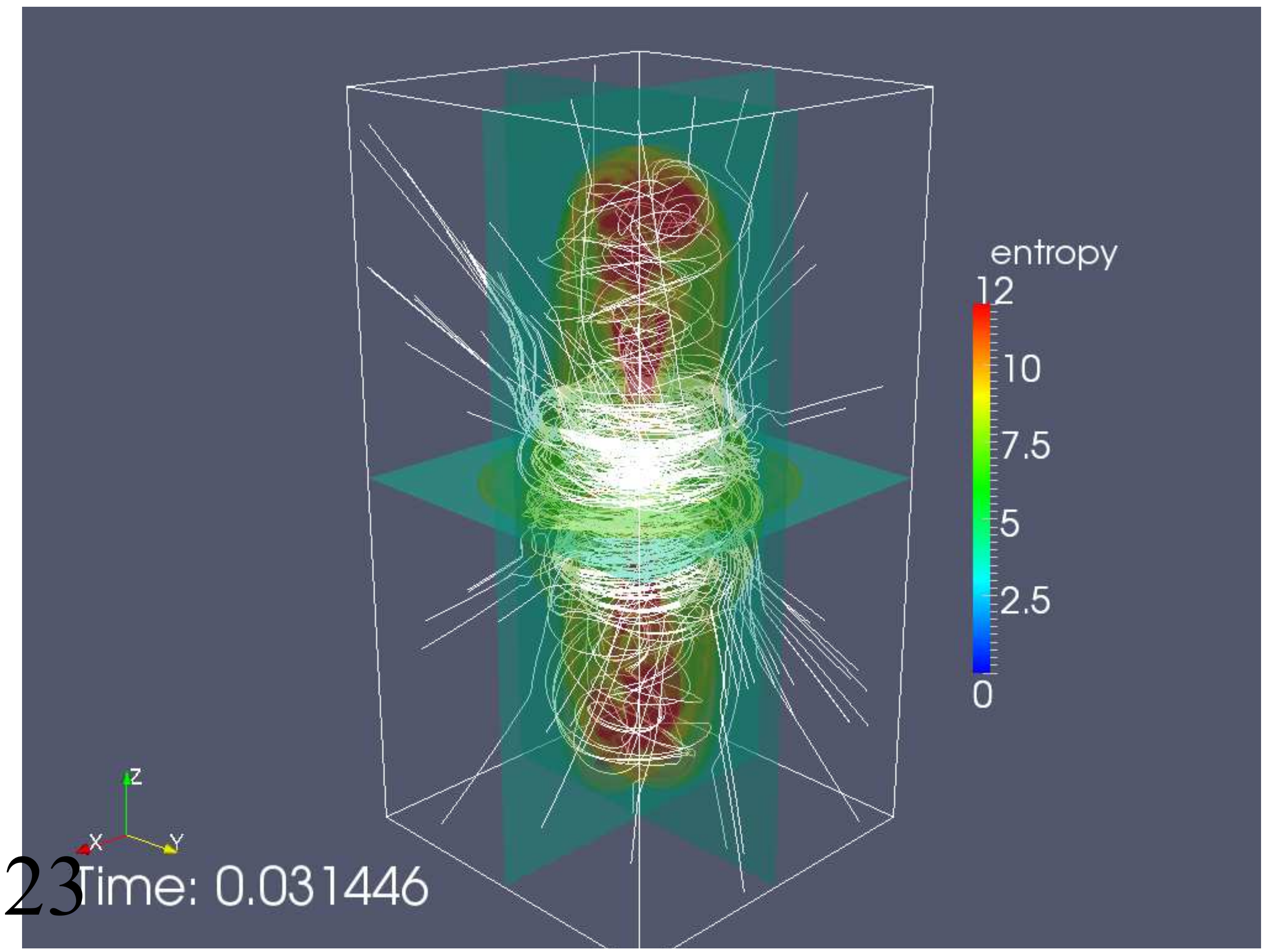
- Magnetar
  - strong magnetic field ～10^{15} G

  (～1 % of all neutron stars)
- Magneto-driven Supernovae?
  - GRB central engine
  - Hypernovae
  - Super luminous SNe

r-process studies

- 2D MHD-SNe
  - NN et al. (2009, 2012)
  - Fujimoto, NN and Hashimoto 2008
  (Collapsar: central Black-Hole and disk)
- 3D MHD-SNe with neutrino
  - Winteler et al. 2012

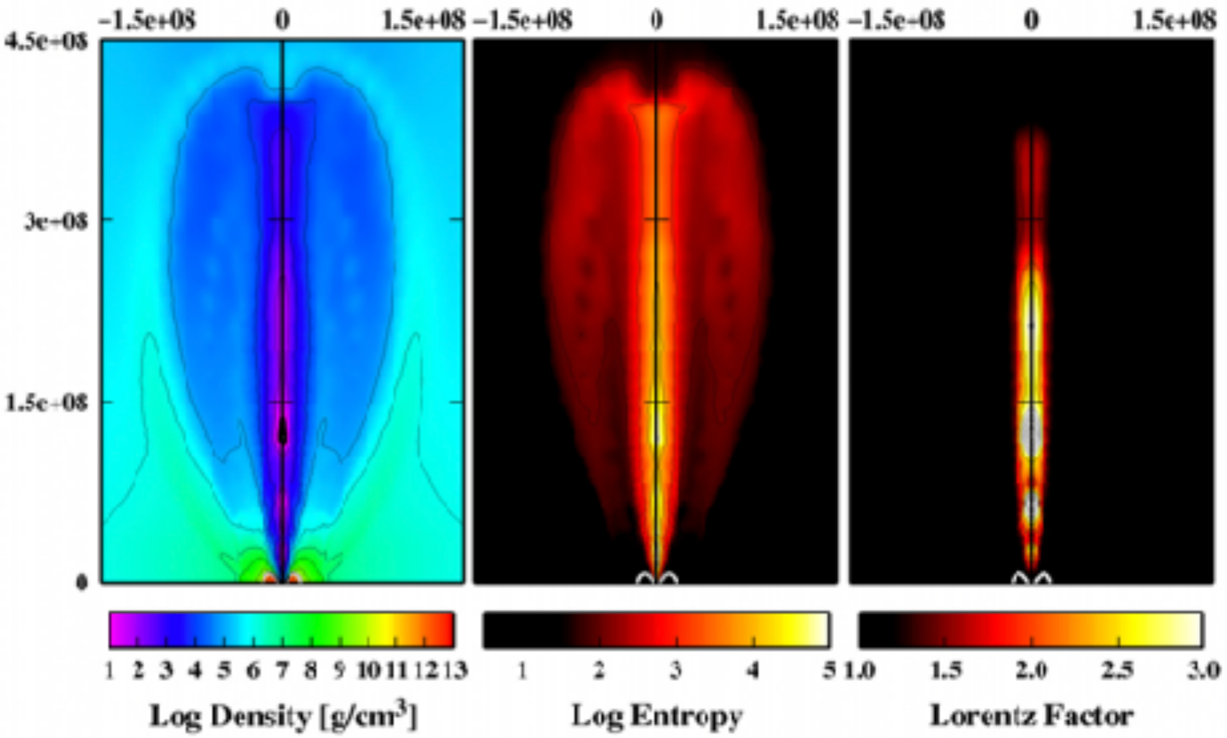
3D MHD simulation
Winteler et al. (2012)

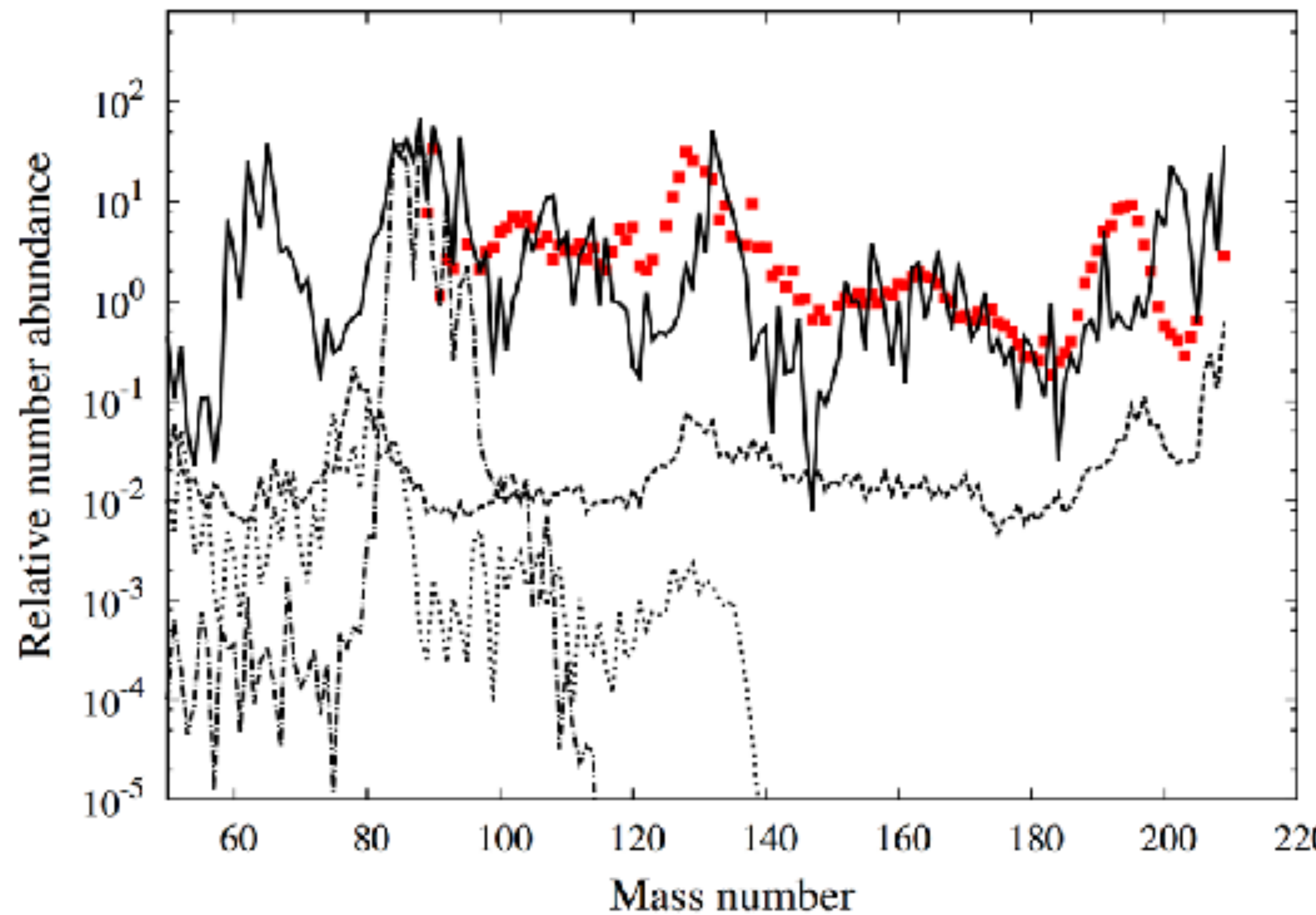


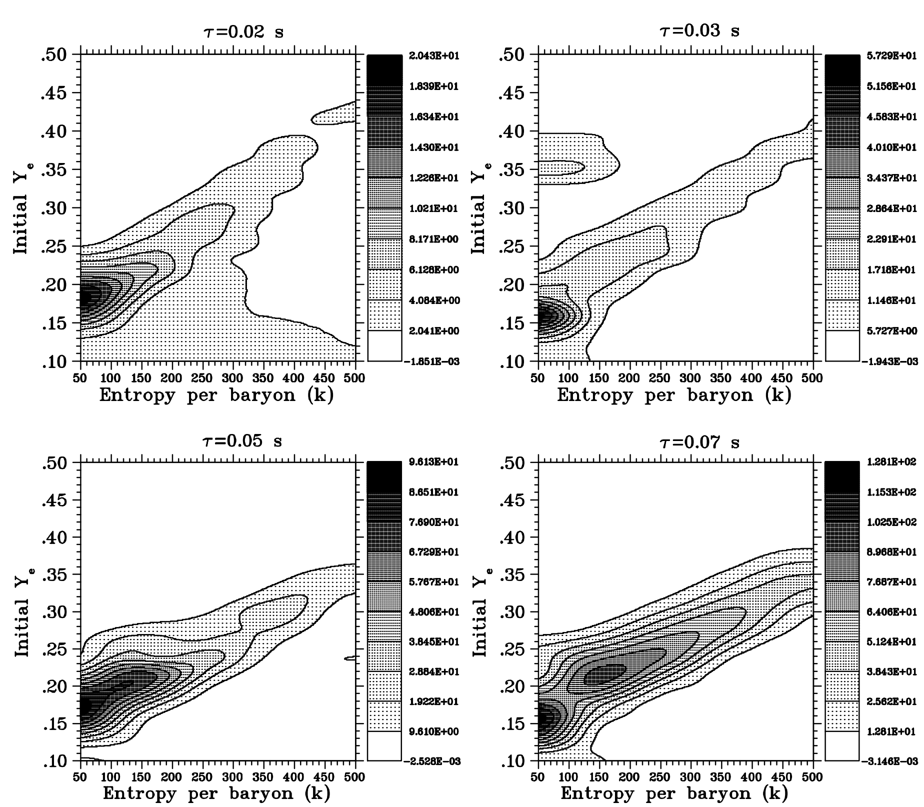
r-process in high entropy GRB jets??

MHD + neutrino heating jets; S > 1000 k_B/baryon

(e.g., Nakamura, Kajino, Mathews et al. 2015 A&A)







Meyer 1997

not the r-process

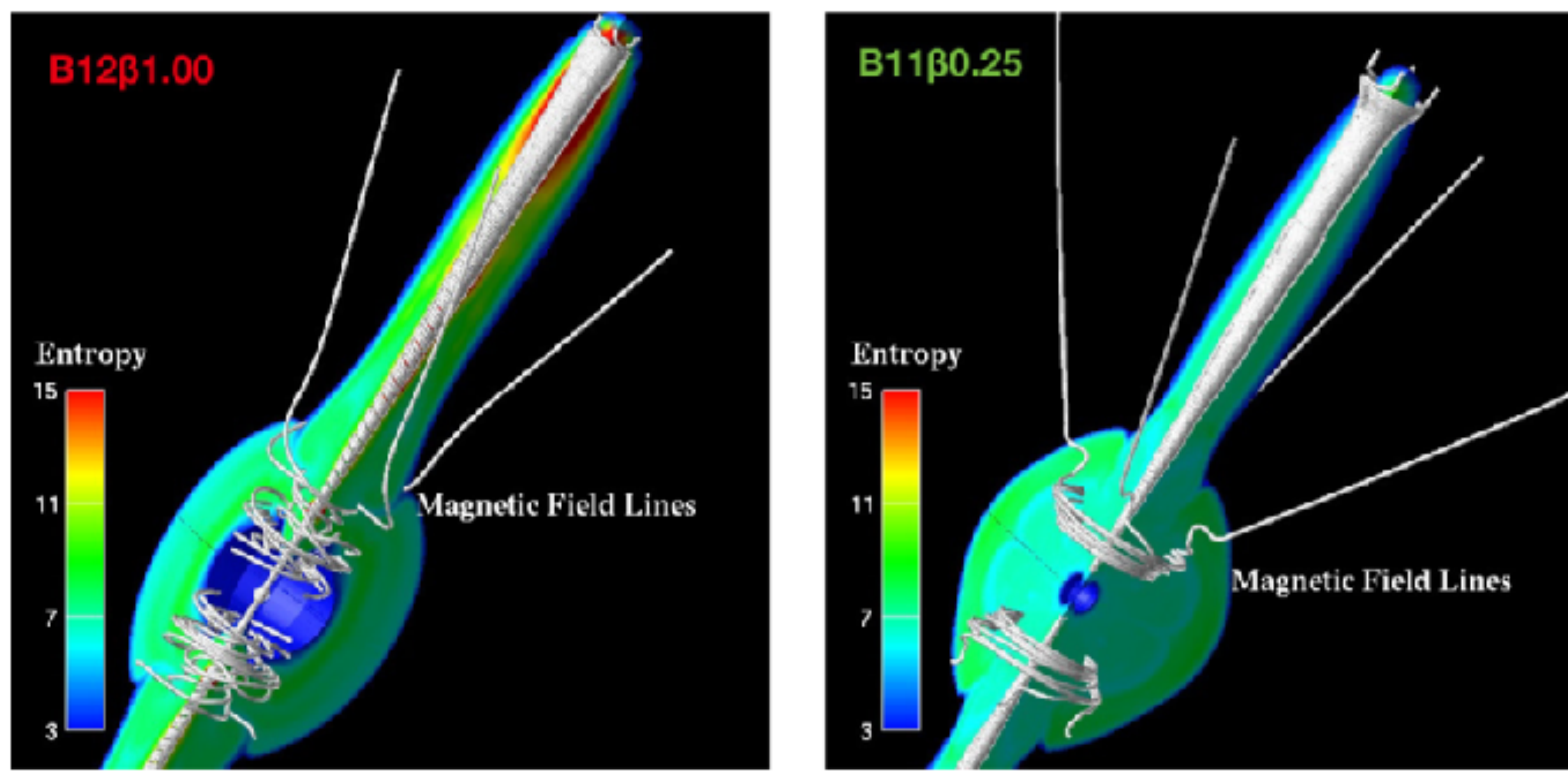
(possibly the i-process in CEMP-i stars, Hampel et al. ApJ 2016)

MR-SNe as origin of r-process elements

NTT15: NN, Takiwaki & Thielemann, ApJ (2015)

- explosion models (Takiwaki+ 2009; 2011):
  - strong magnetic-fields & jet
  - relevant to GRBs, hypernovae, magnetars
- nucleosynthesis
  - can eject very neutron-rich matter

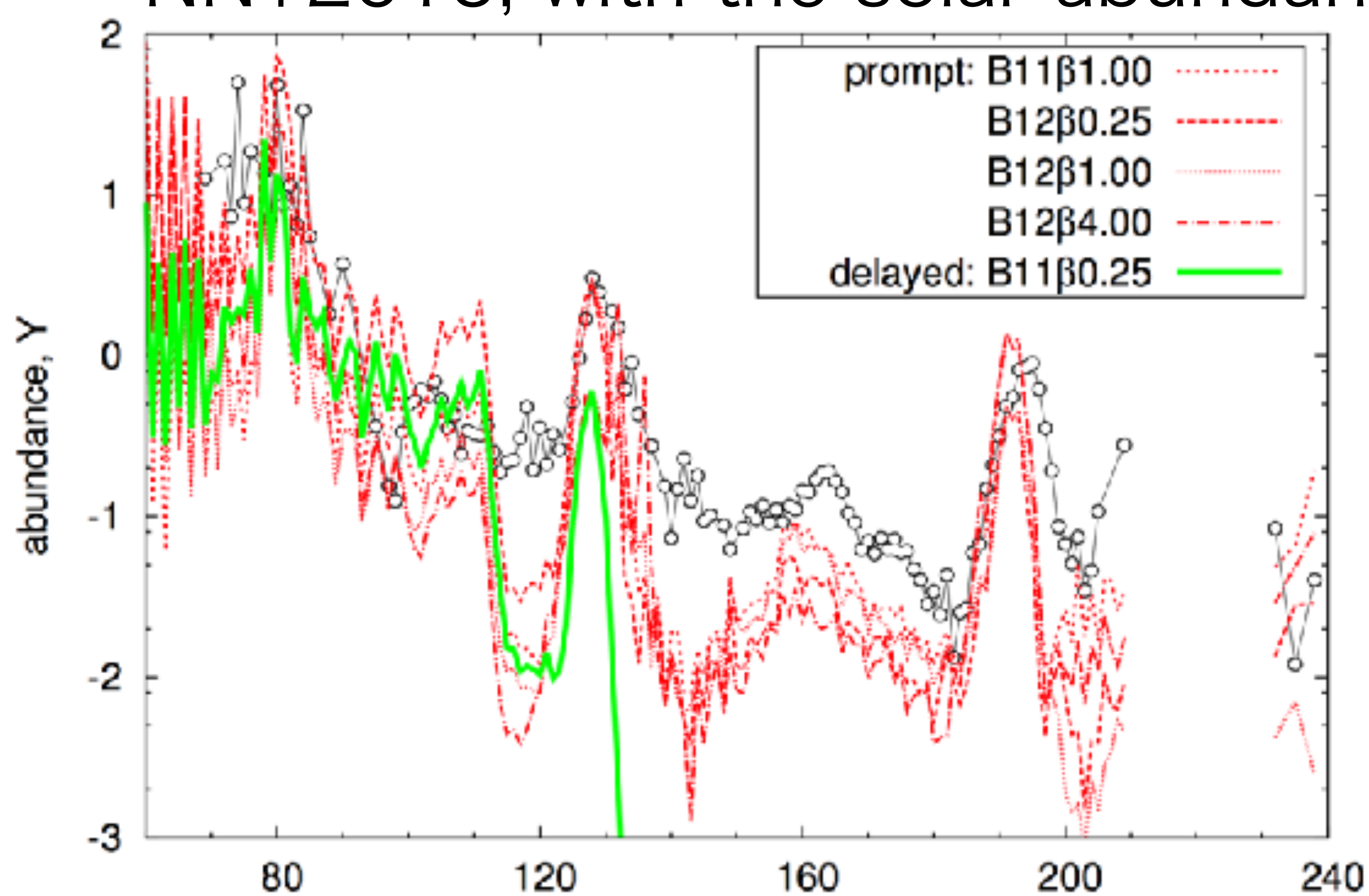
Jet-like explosions, driven by the strong magnetic pressure



Diversity of MR-SNe and r-process

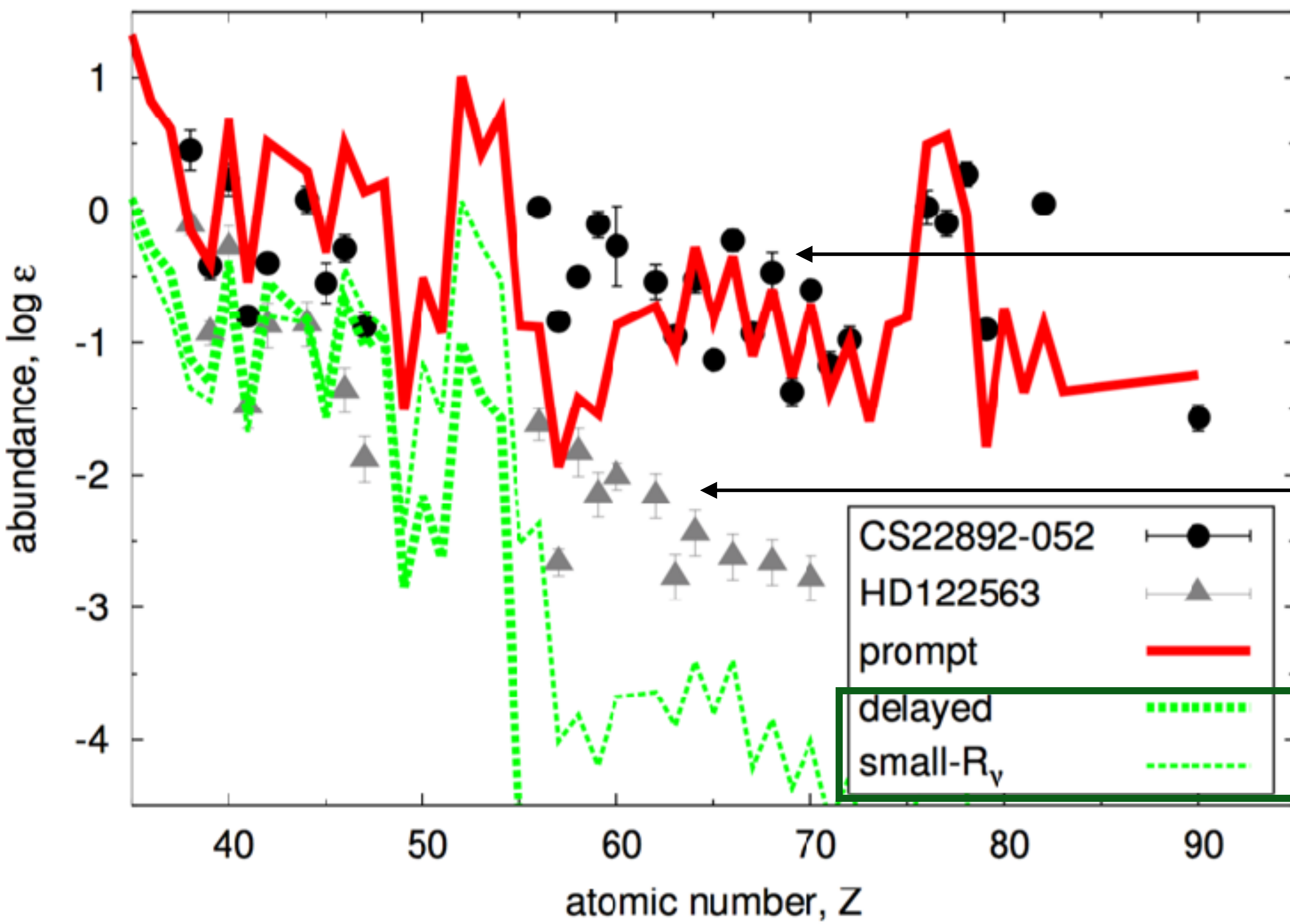
- **Strong (prompt)-jet**
  - immediately ejects very n-rich (low Y_e) matter dredged from the SN core (strong e^--capture)
- **Weaker (delayed) jet**
  - only ejects surface of the PNS and suffers Y_e increase by neutrino absorption

NN+2015; with the solar abundances



Diversity of MR-SNe and r-process

NN+ 2015; with r-process in metal-poor stars



solar-like

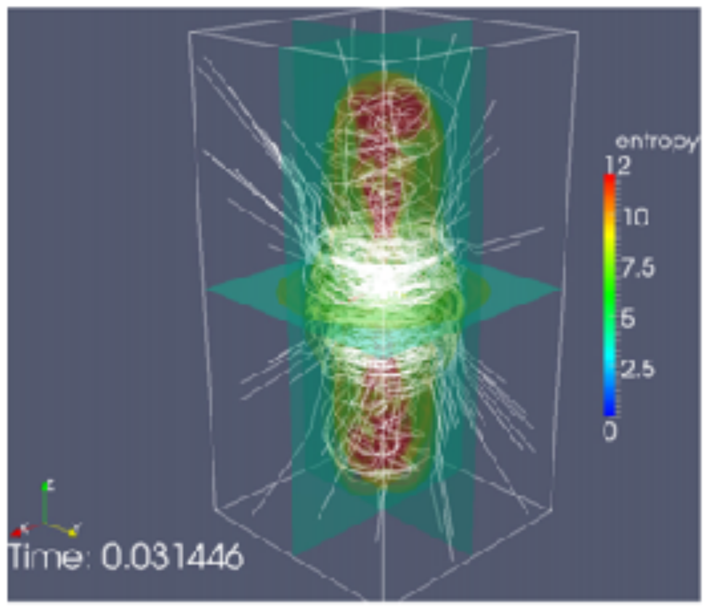
(Sneden's star)

Honda type

uncertainty of
explosion model

dimensionality: 2D or not 2D?

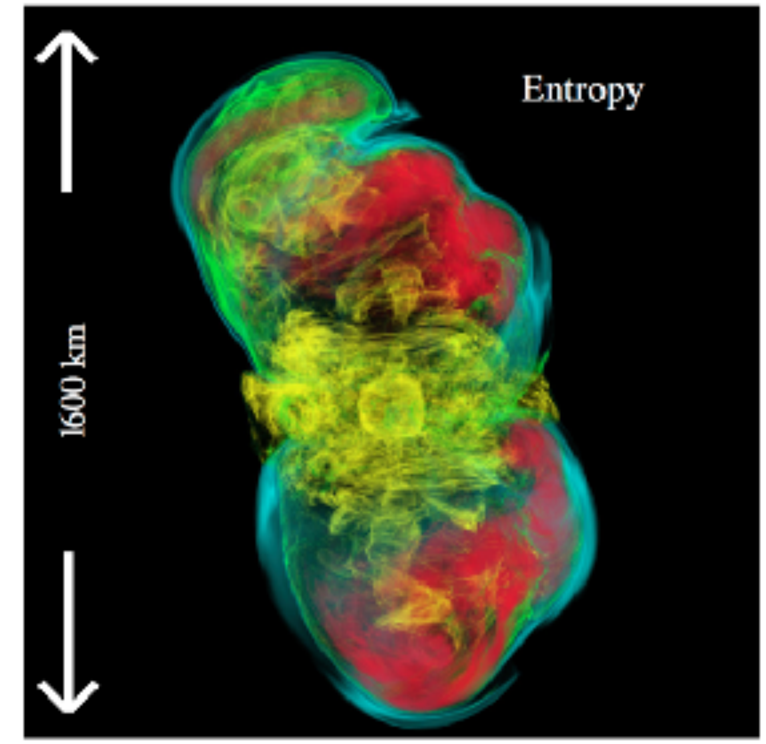
in 3D but polar-like jet



Winteler+ (2012)

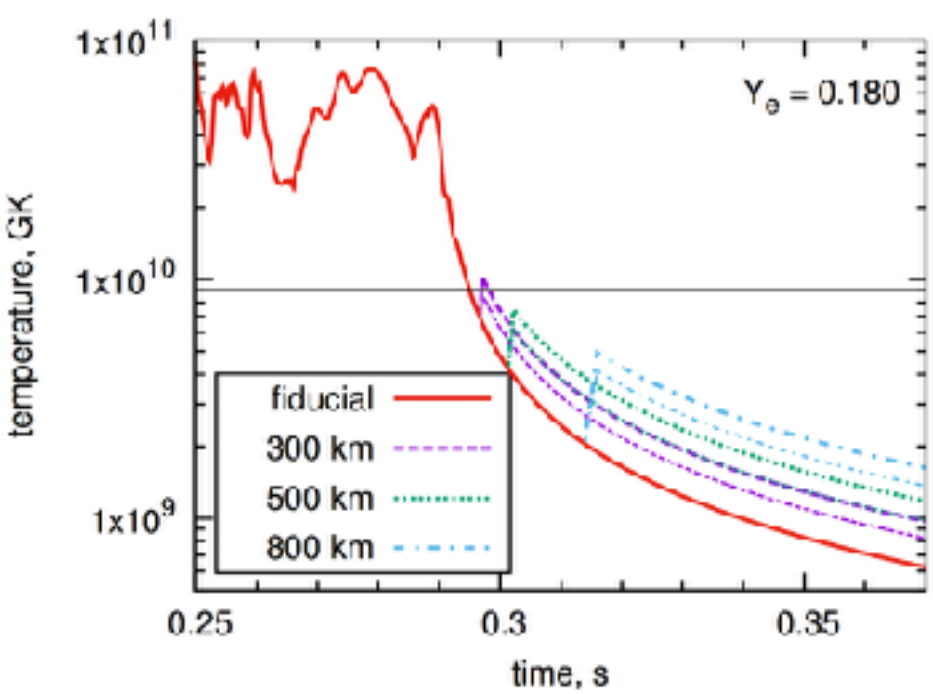
deformed jet by
the Kink-instability

Mösta+ (2014)



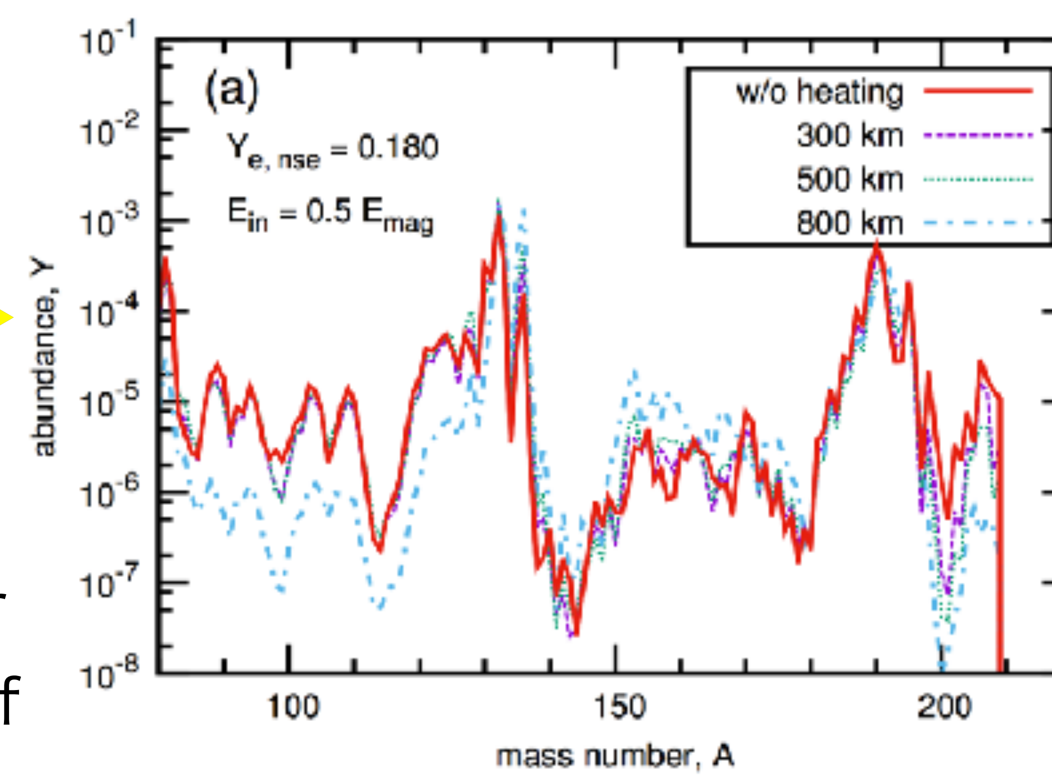
Question: How does it change r-process?

NN+ (2015)



energy injection
by reconnection

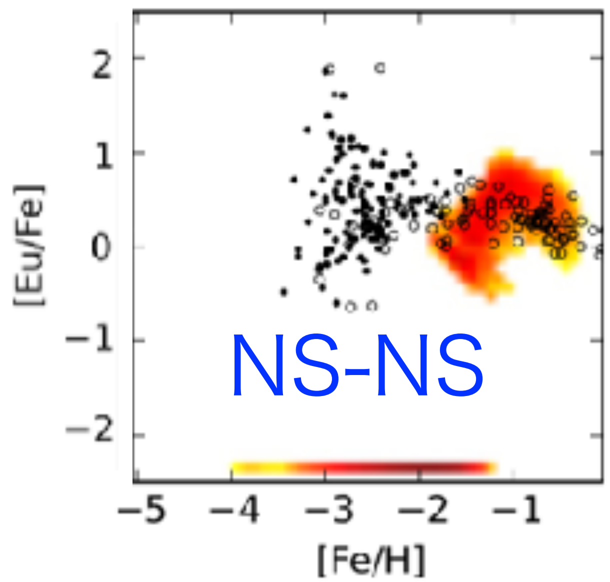
minor effects
on r-process
(But important for
ejection process of
n-rich matter)

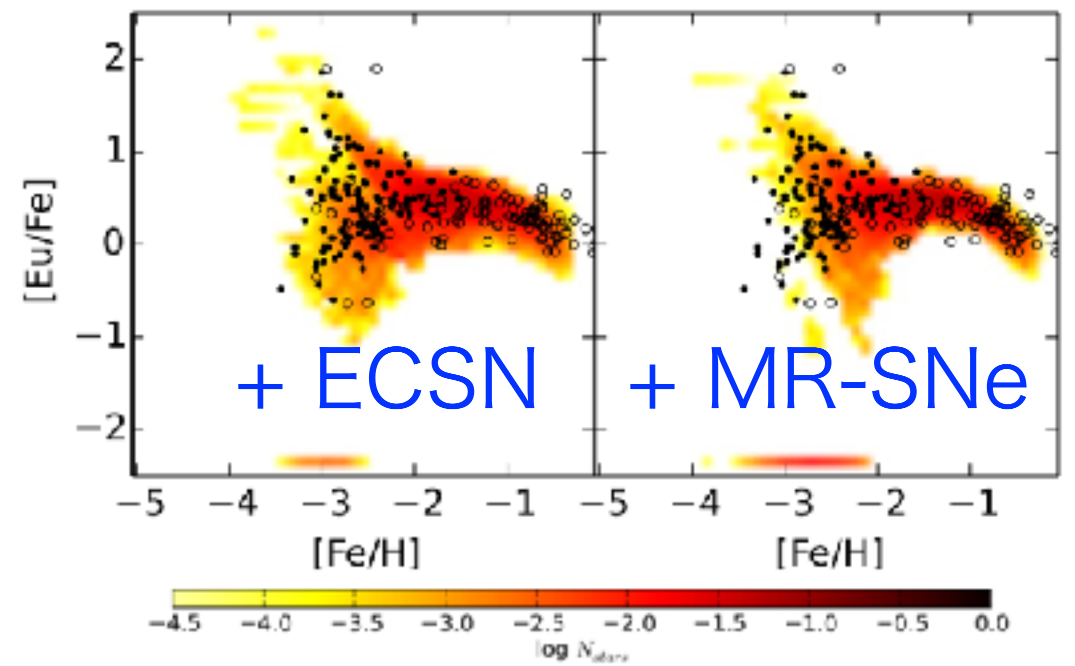


Multiple r-process sources in GCE?

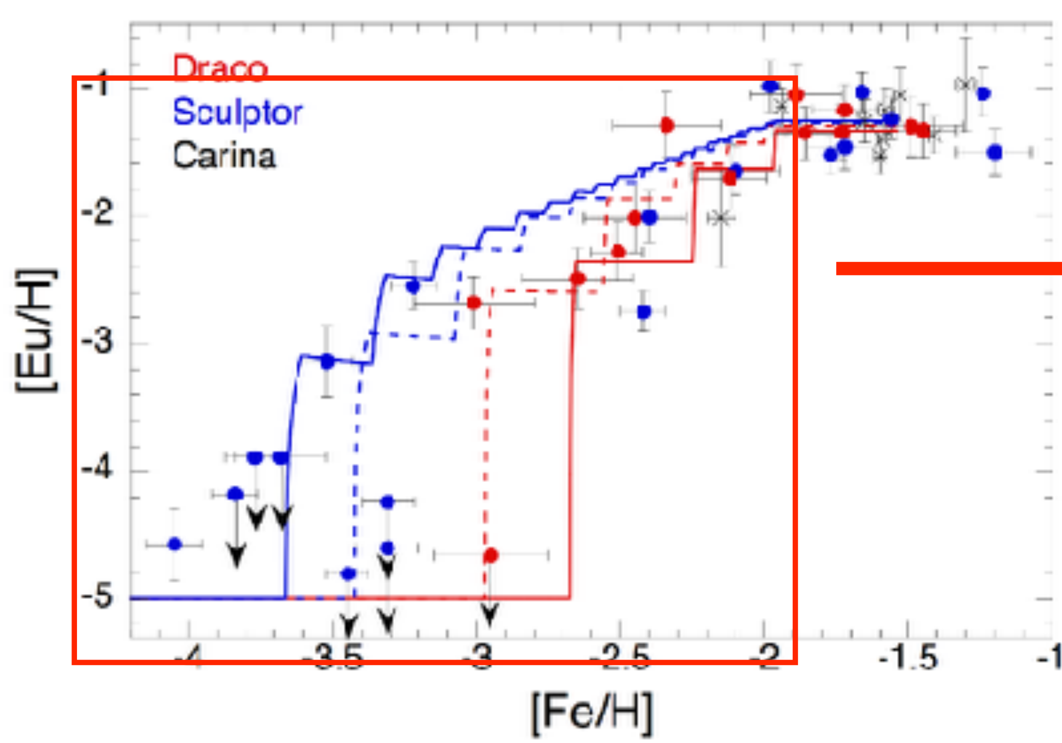
Cescutti+ 2015, A&A 577

see also, B. Wehmeyer+ 2015: different event rates for MR-SNe





Tsujimoto & NN, ApJL (2015)



Chemical evolution models

GCE models suggest:

- rate event: 1/200 CC-SNe
- large Eu ejection: ∼10^{-5} Msun

agree with our MR-SN models (e.g. Nishimura+ 2015)

by Wehmeyer+2017, based on inhomogeneous model (private communication)

Open questions

see, Winteler+2012; NN+(2015); Tsujimoto&NN (2015)

✔Magnetically-driven polar-jets ("prompt jets") produce produce heavy r-process elements

✔while weaker explosions ("delayed-jets") show weaker r-process ($A < 130$)

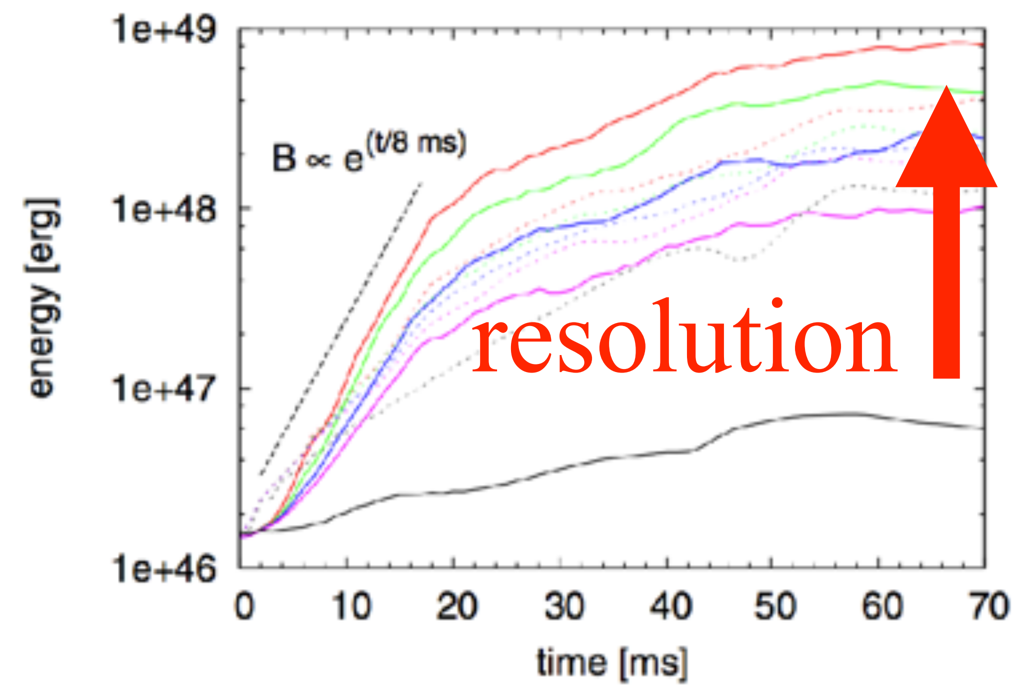
✔mostly active in early galaxies (metal-poor stars); and no contribution to the (total) solar-abundances?

- Really need/exist such strong initial magnetic fields?
- the MRI (magneto-rotational instability) is key?
- MRI induced explosion models must have different nucleosynthesis signatures from canonical CC-SNe

Magneto-rotational instability in CC-SN

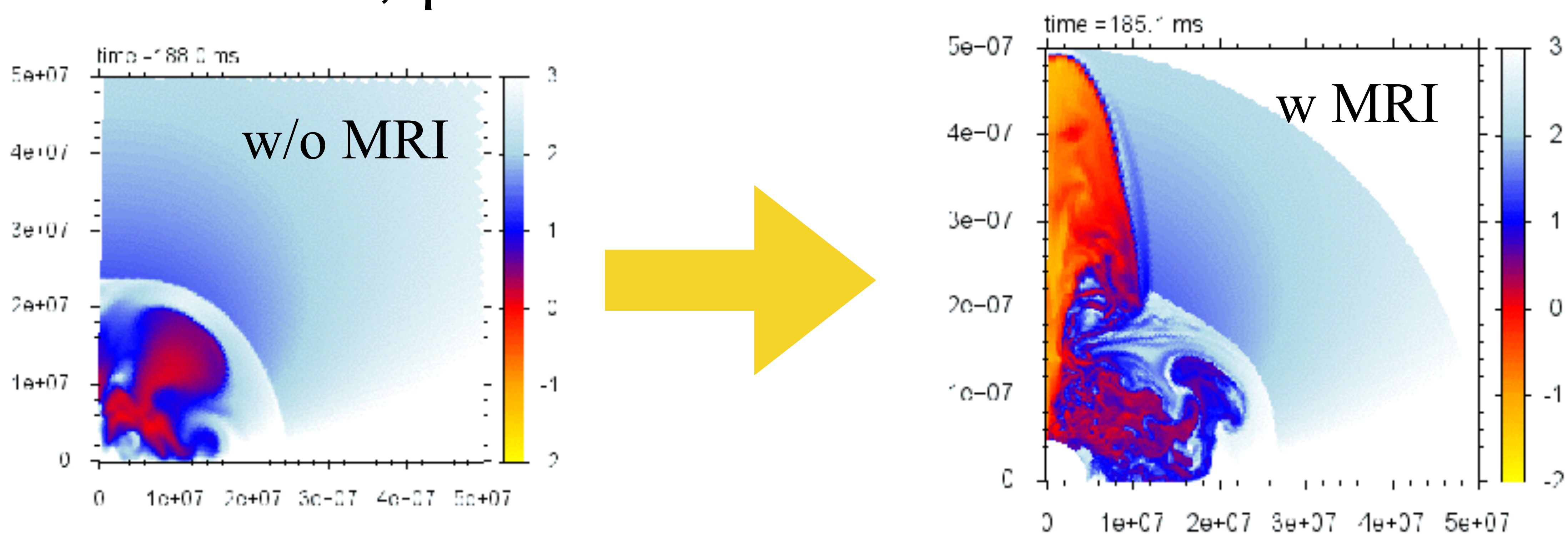
Sawai & Yamada (2014, 2016)

- **MRI enhance B-fields** of the core
- **neutrino-heating** also affects explosion



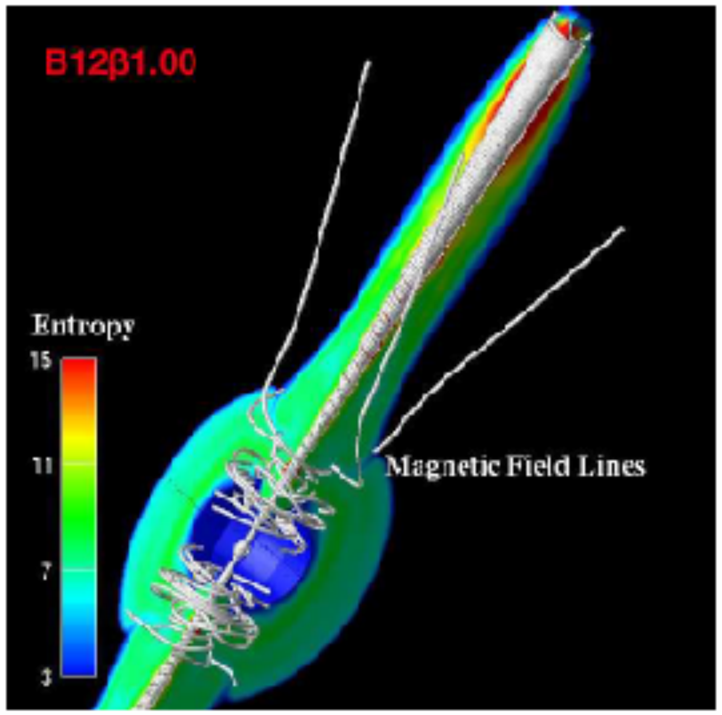
Δr_{min} = 100, 50, 25, 12.5 m

MRI-driven Jet; plasma-beta

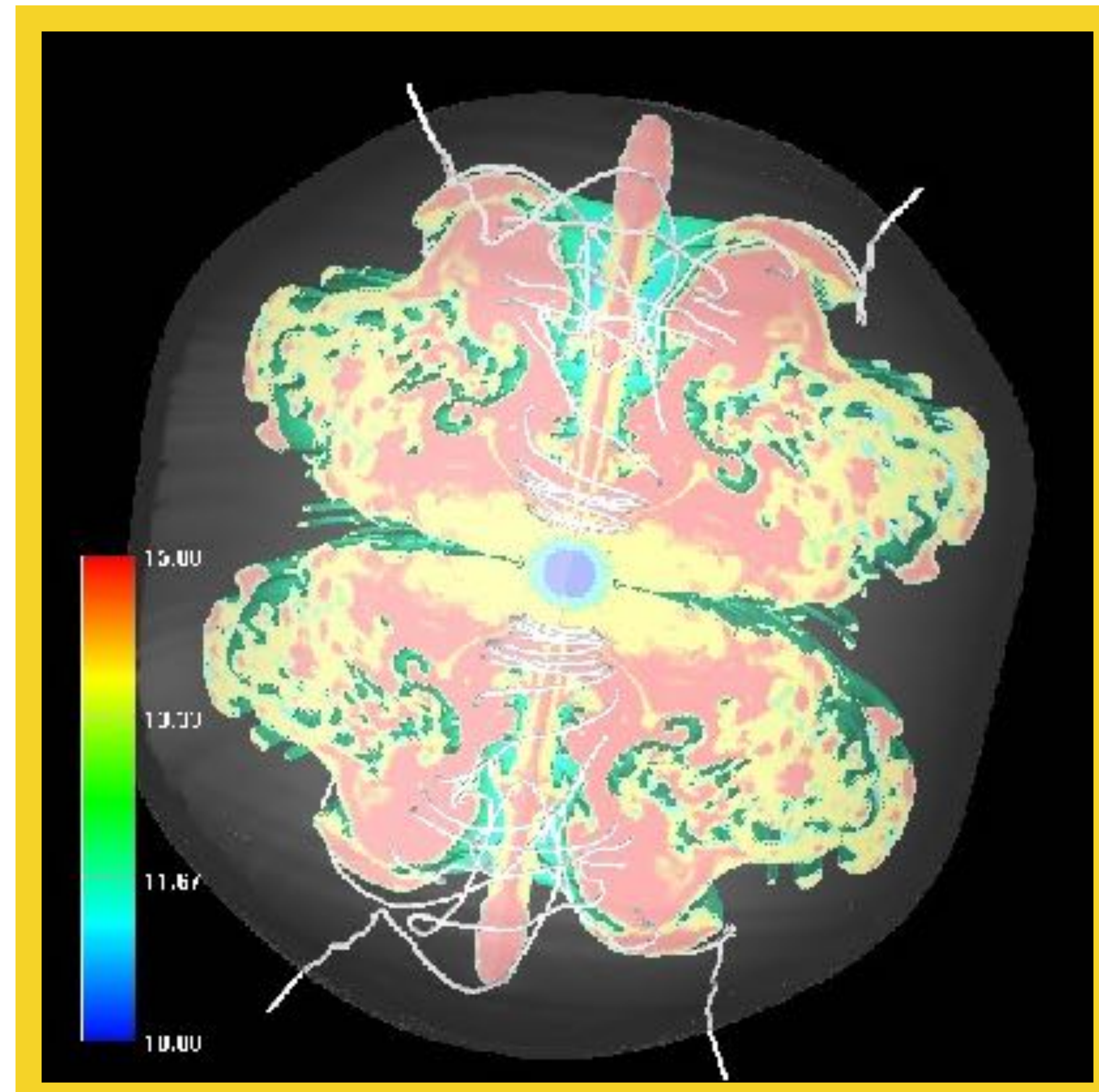


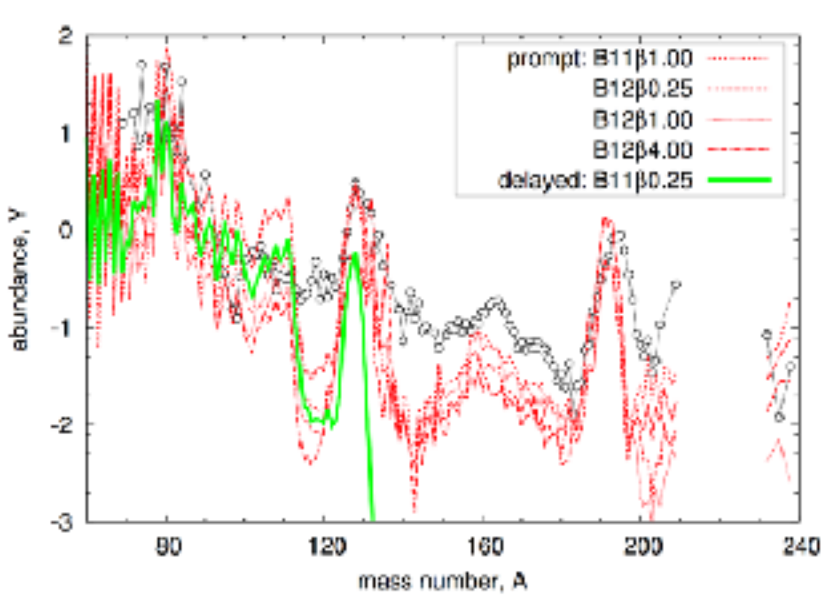
MR-SNe driven by the MRI

Nishimura+ (2015)
simulated by T. Takiwaki



Nishimura+ (2017)
simulated by H. Sawai





?

Need those strong initial B-fields?

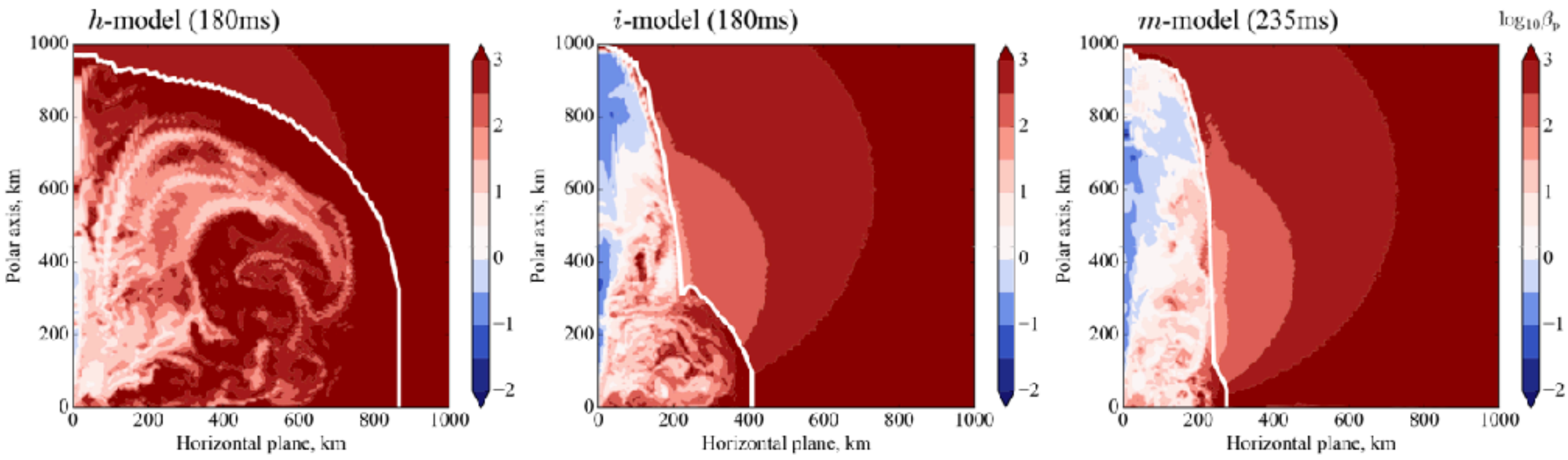
Problem: varying B-fields/rotation

—> requires MRI convergence for each case and comparison among models are difficult

Adopt: varying L_ν —> effective strength of B-fields in explosion dynamics

heating-dominated ⟷ intermediate ⟷ magnetically-dominated

plasma-β

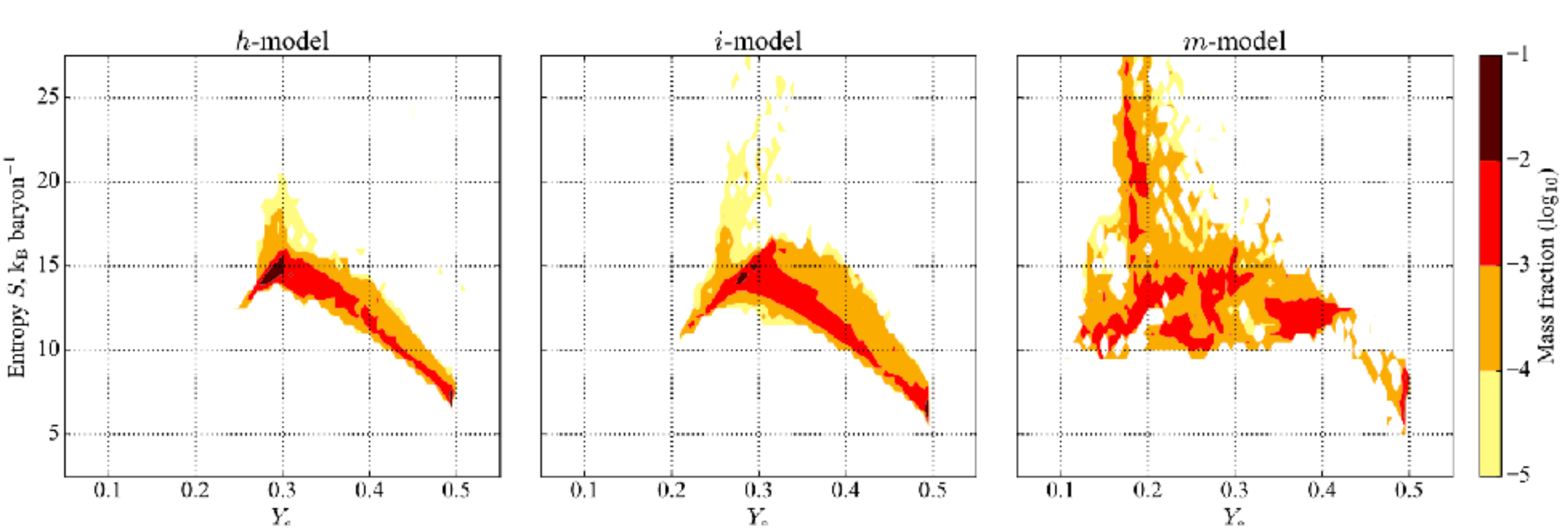


Ye vs S of ejecta

heating-dominated

magnetically-dominated

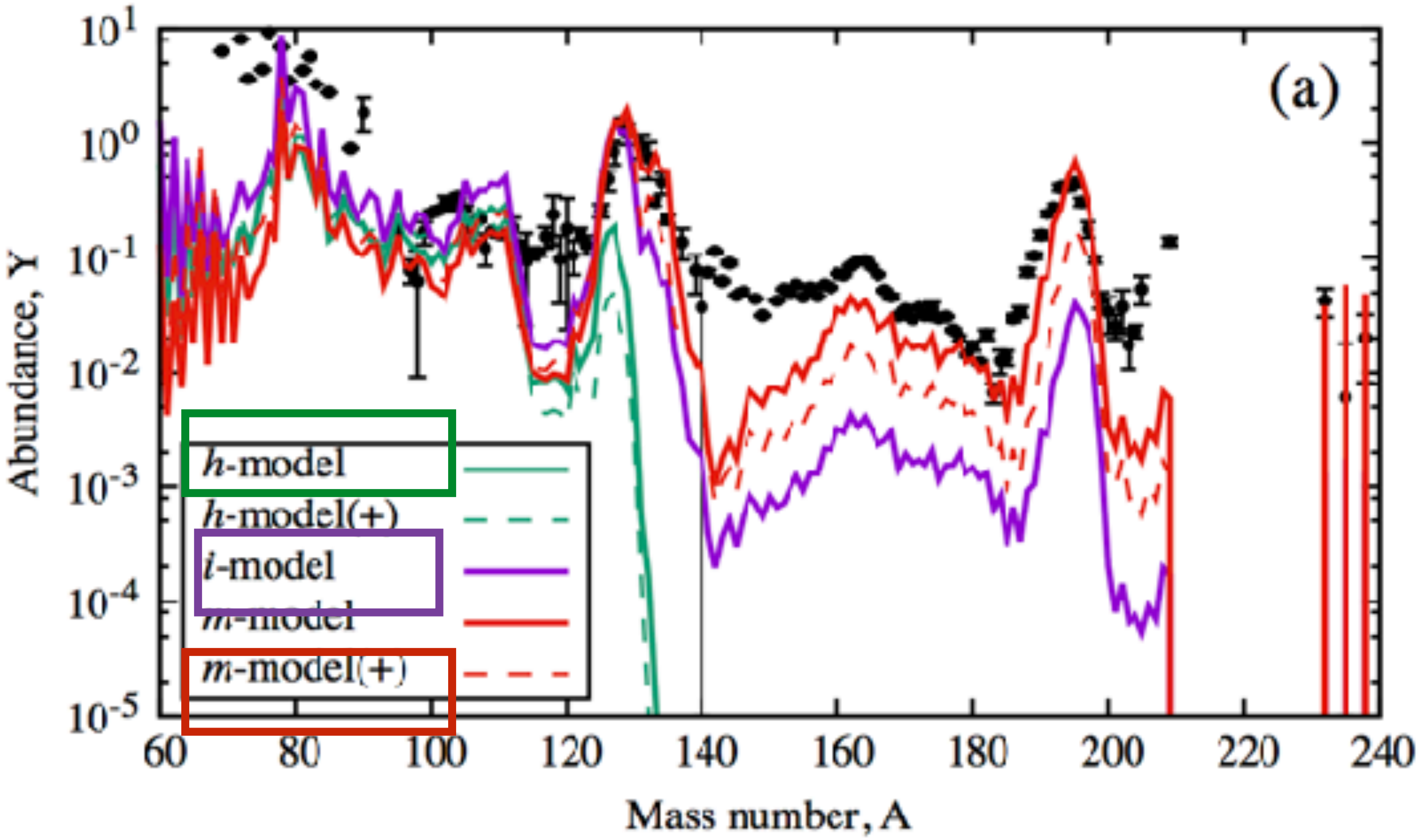
L_ν $\quad$ $L_\nu \times 0.6$ $\quad$ $L_\nu \times 0.2$

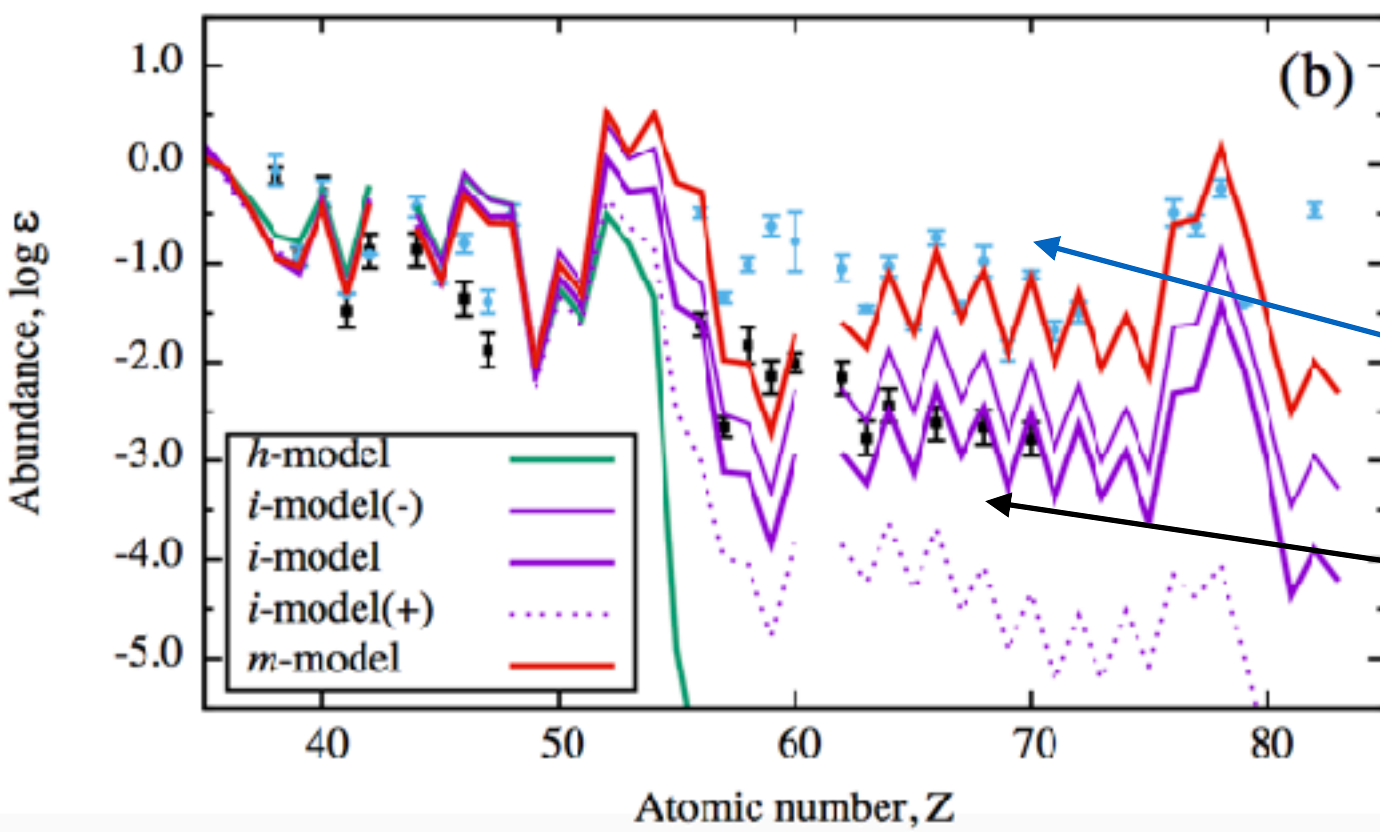


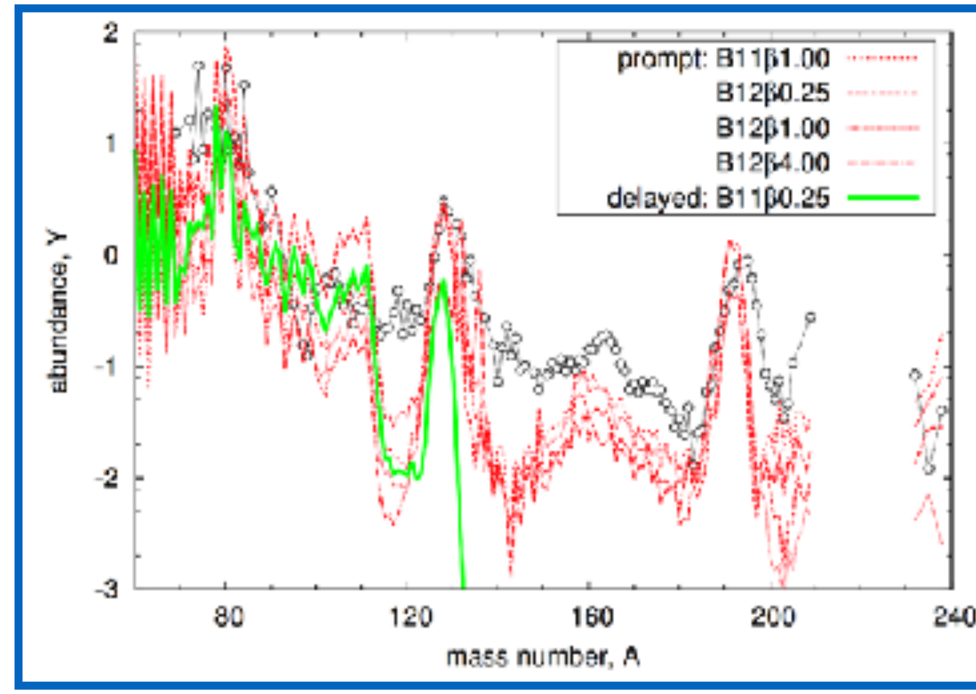
Y_e - S

Nucleosynthesis results

Nishimura+2017 (Sawai model)







Nishimura+ 2015

Takiwaki model

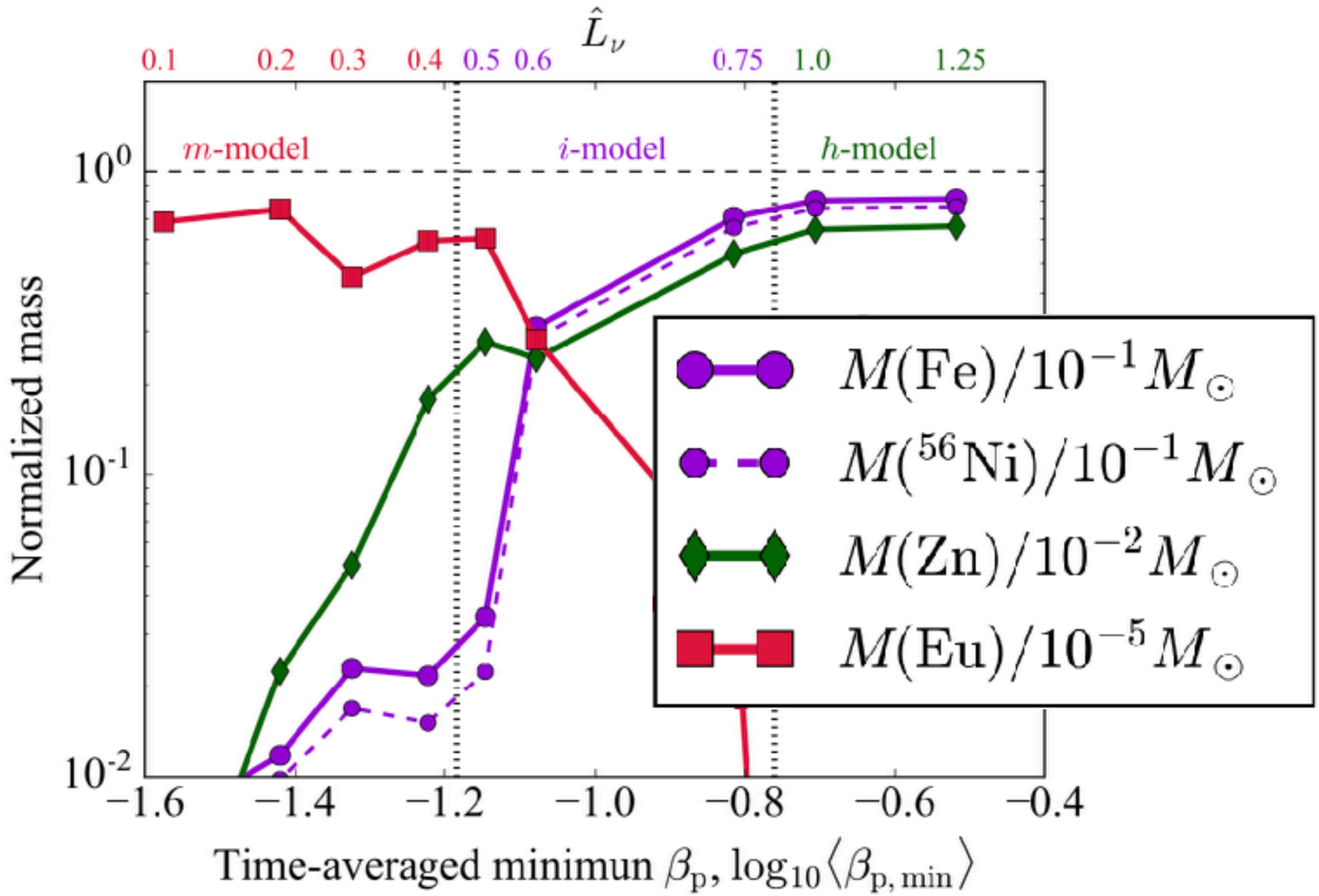
prompt vs delayed

solar-like

“weak” heavy r pattern

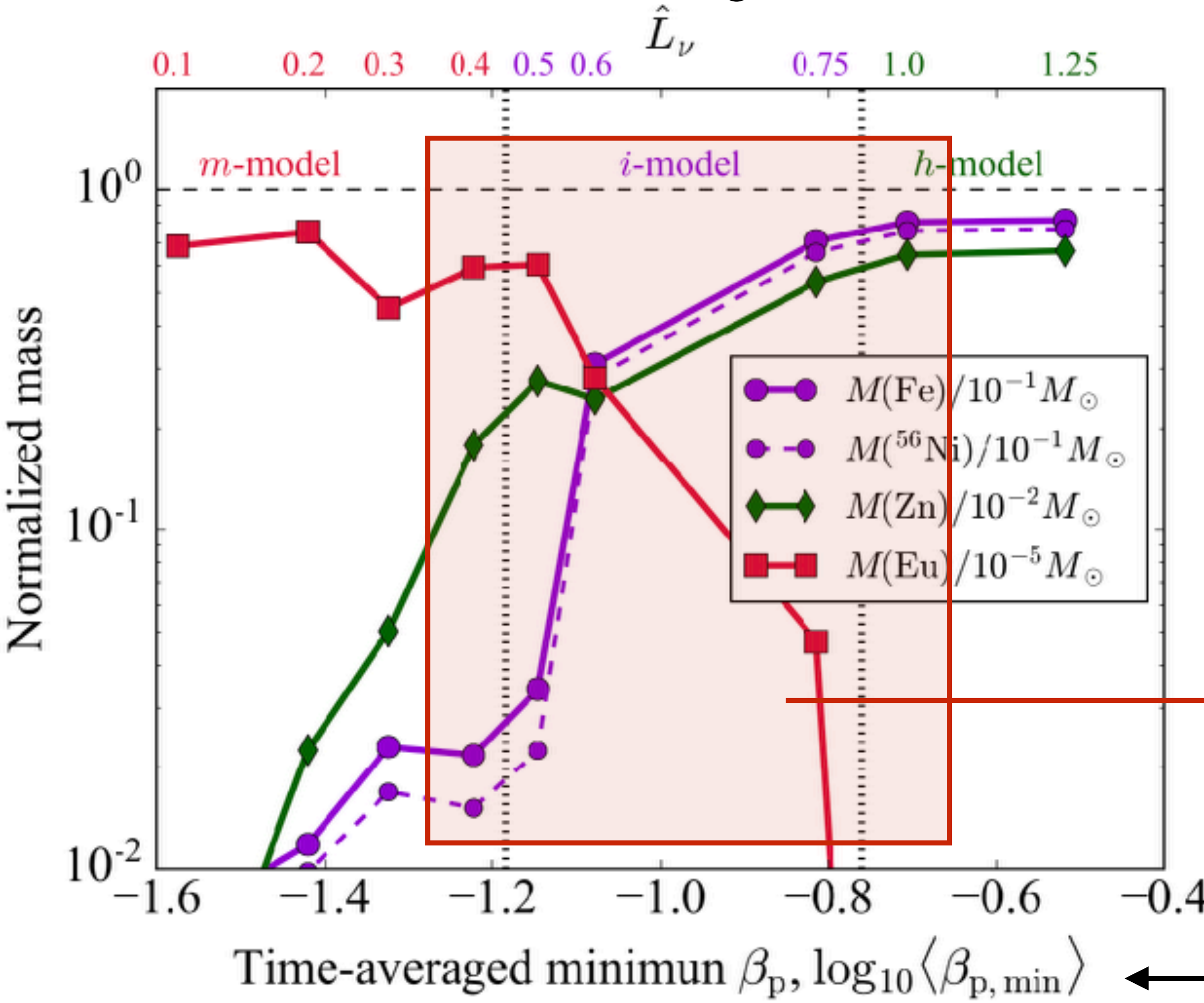
HD122563 (Honda+2006)

Origin of diversity in metal-poor stars?



- produces a wide range of nuclei (from Fe to r-process)
- final abundances vary due to the effect of magnetic fields in explosion models

How the reality should be?



Nucleosynthesis results should be confirmed varying the initial B-fields and rotation.

"intermediate" r-process?

B-fields and/or rotation of progenitors

1. does not exist (or quite few)?
2. has some observables/role in GCE?

e.g., high [Zn/Fe] >1.5 than regular ccSNe

—> source of Zn in early-galaxies?

nucleosynthesis yields: **github.com/nnobuya/mrsn**

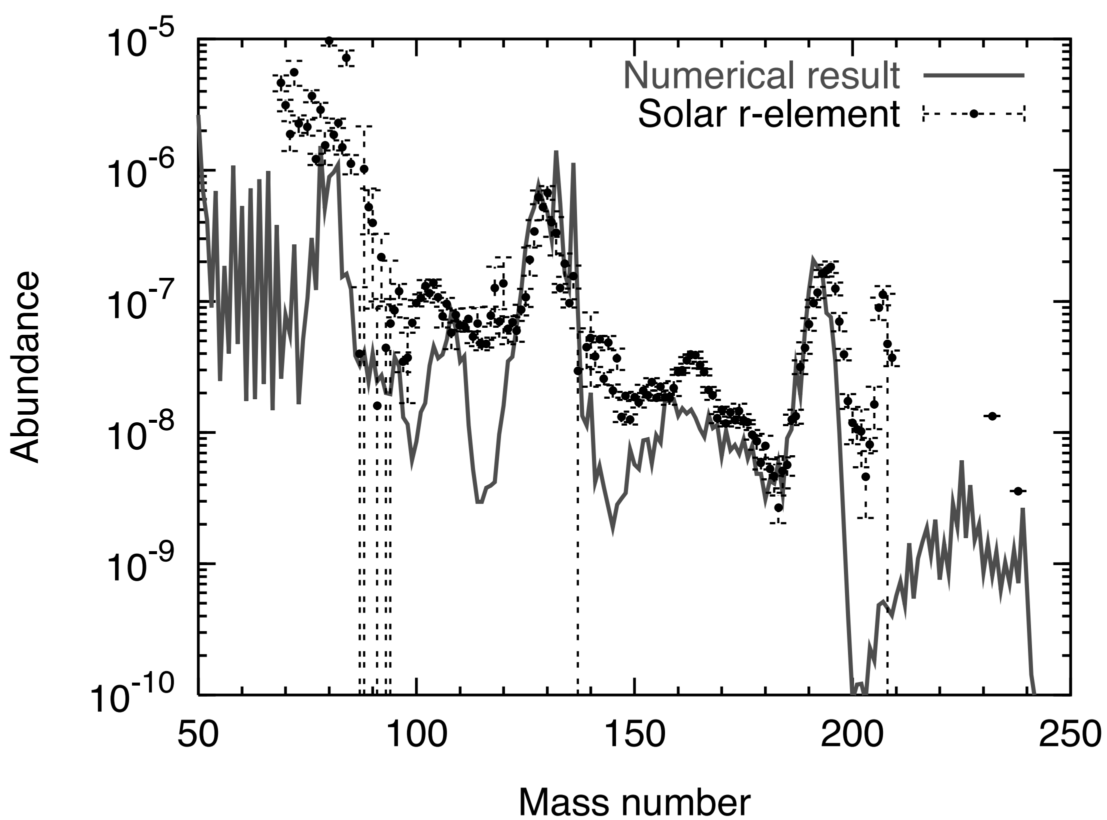
or **www2.yukawa.kyoto-u.ac.jp/~nobuya.nishimura/mrsn/**

r-process: nuclear physics inputs

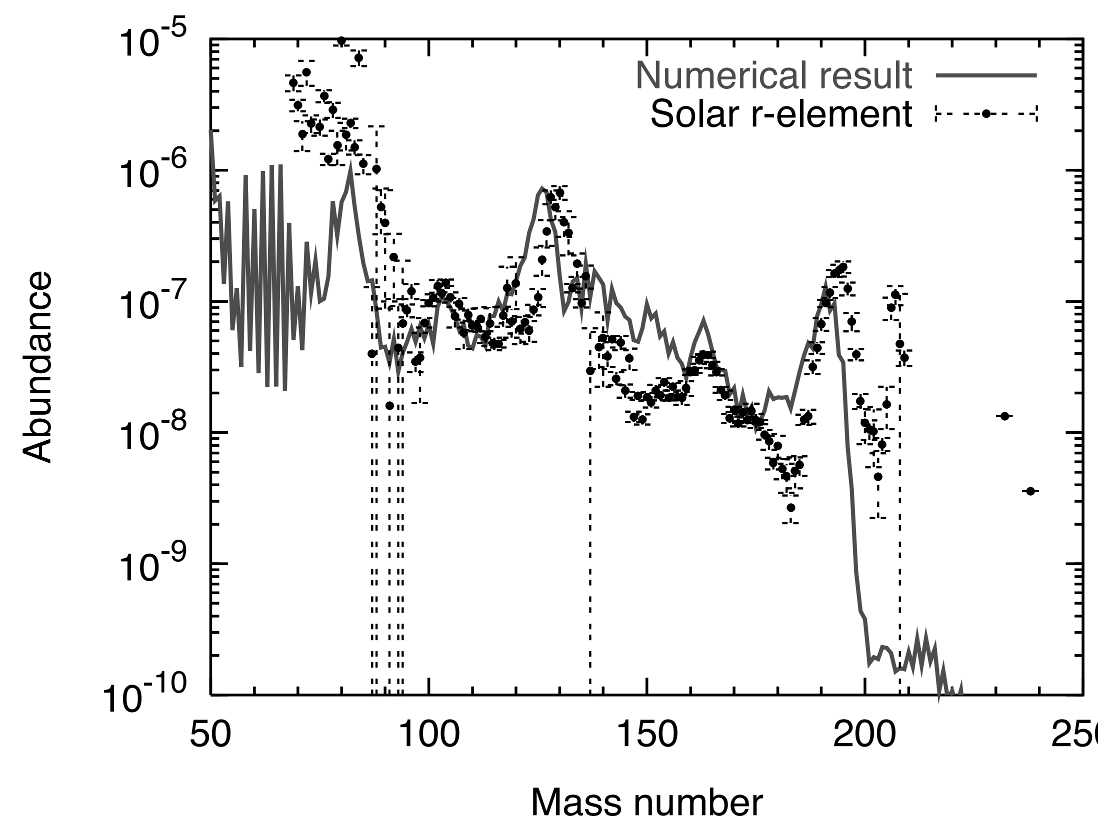
β-decay half-life, (γ,n), and (γ,n) are dominant

different nuclear physics theories (by MHD-SN)

mass model: FRDM



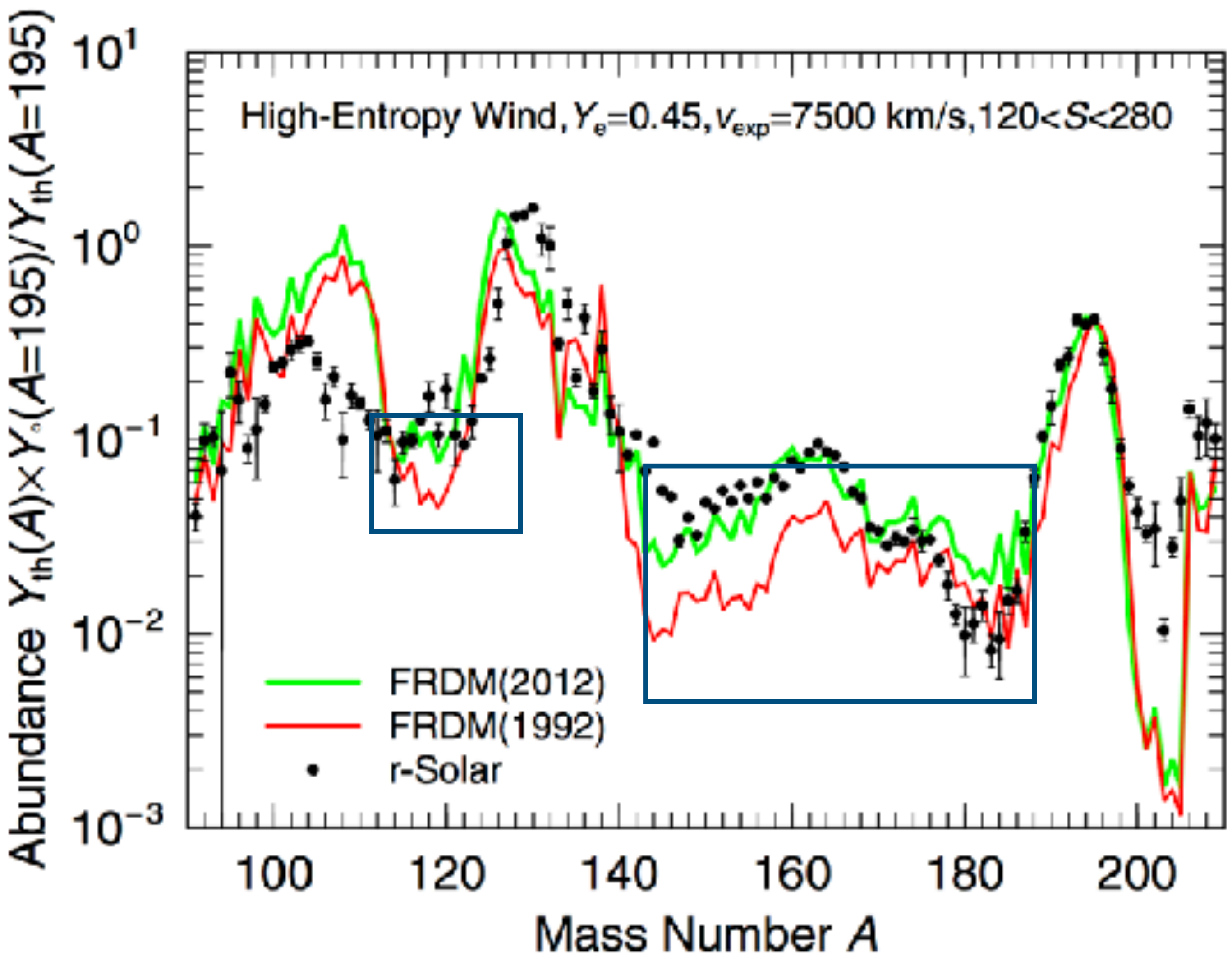
mass model: ETFSI



Nishimura et al., ApJ (2006)

Nuclear physics uncertainty (beta-decay)

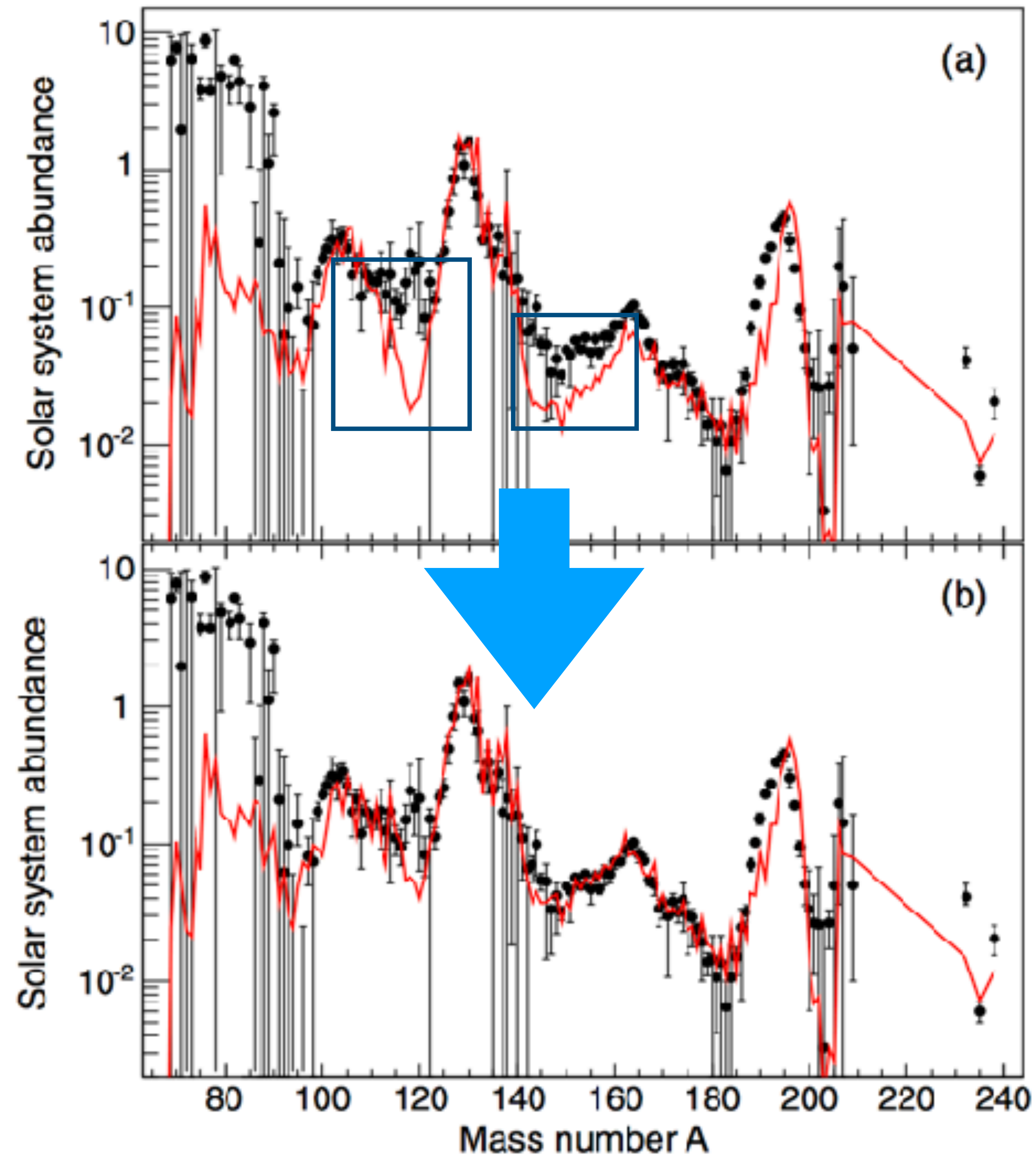
nuclear mass prediction
(FRDM)



Kratz+2014

Improvement of FRDM
(using high-entropy winds)

New Half-live
measurements @RIKEN



Lorusso+2015

Summary

- NS-NS mergers
  - no serious difficulty to produce heavy r-process nuclei
  - more detailed analysis, based on different initial/input parameters (NS mass, EoS)
  - but assuming only single r-process source has difficult to explain chemical evolution in early galaxies?
- MR-SNe
  - Several uncertainties and problems remain: hydro-simulations, initial rotation and B-fields etc.
  - a variety of “r-process” abundance patterns. How do we interpret in the GCE?; main source in early galaxies?
  - We can make some constraint on MR-SNe models by the comparison of several astronomical observation