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Nucleosynthesis of trans-iron elements in magneto-rotational core-collapse supernovae

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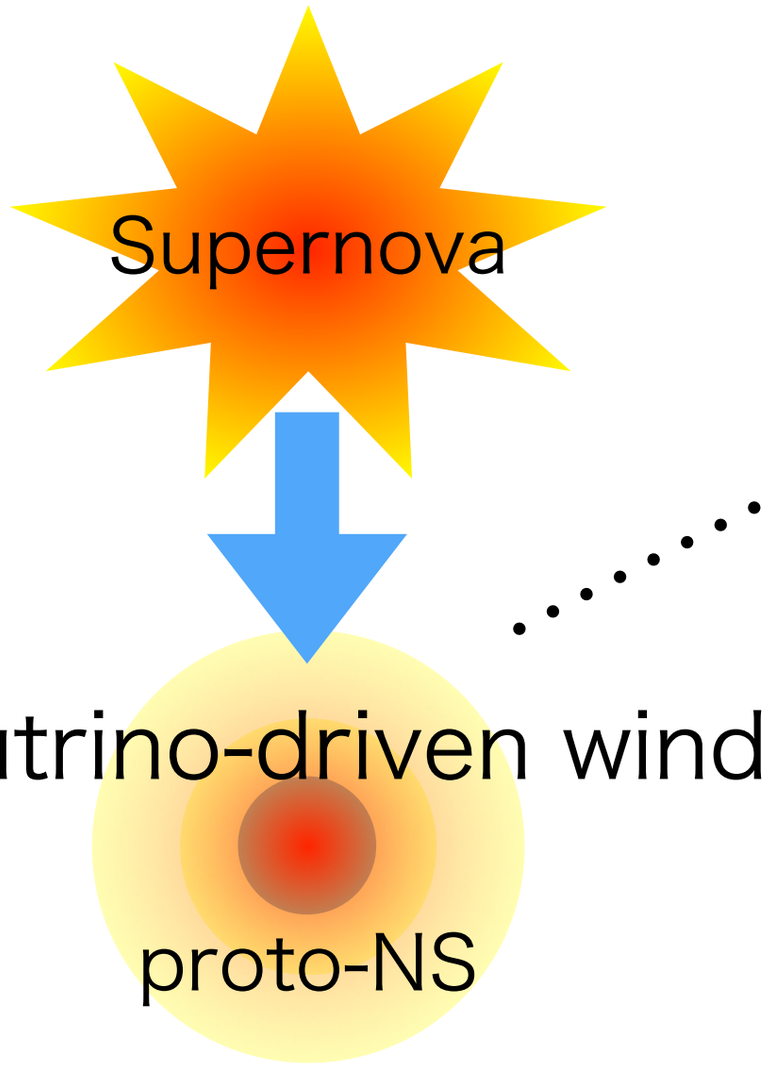
K computer

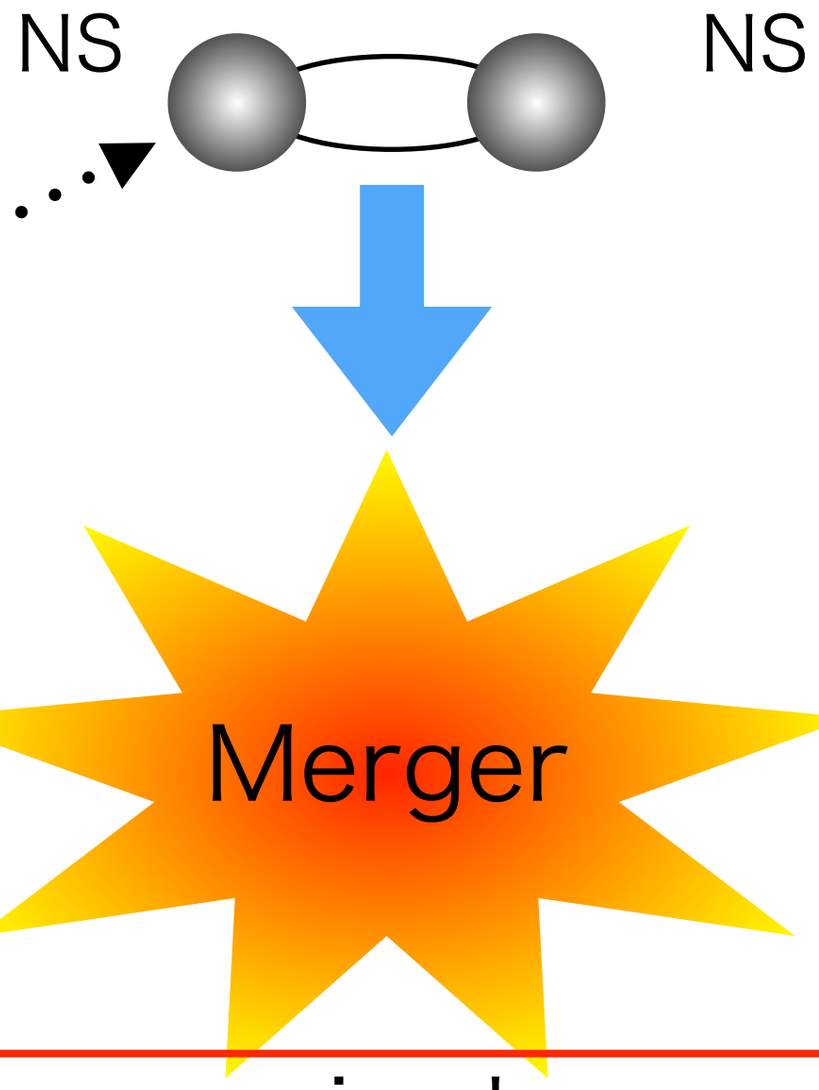
Astronomical origin of the r-process

Core-collapse Supernova (CC-SNe)?



- no direct observation
- theoretical difficulty
  - (no very n-rich matter)

neutron star (NS) mergers?



r-process is observed?
in Kilonova/Macronova
w/ GW170817

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

Since B²FH (1957), cc-SNe have been expected as the r-process sites. However, …

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

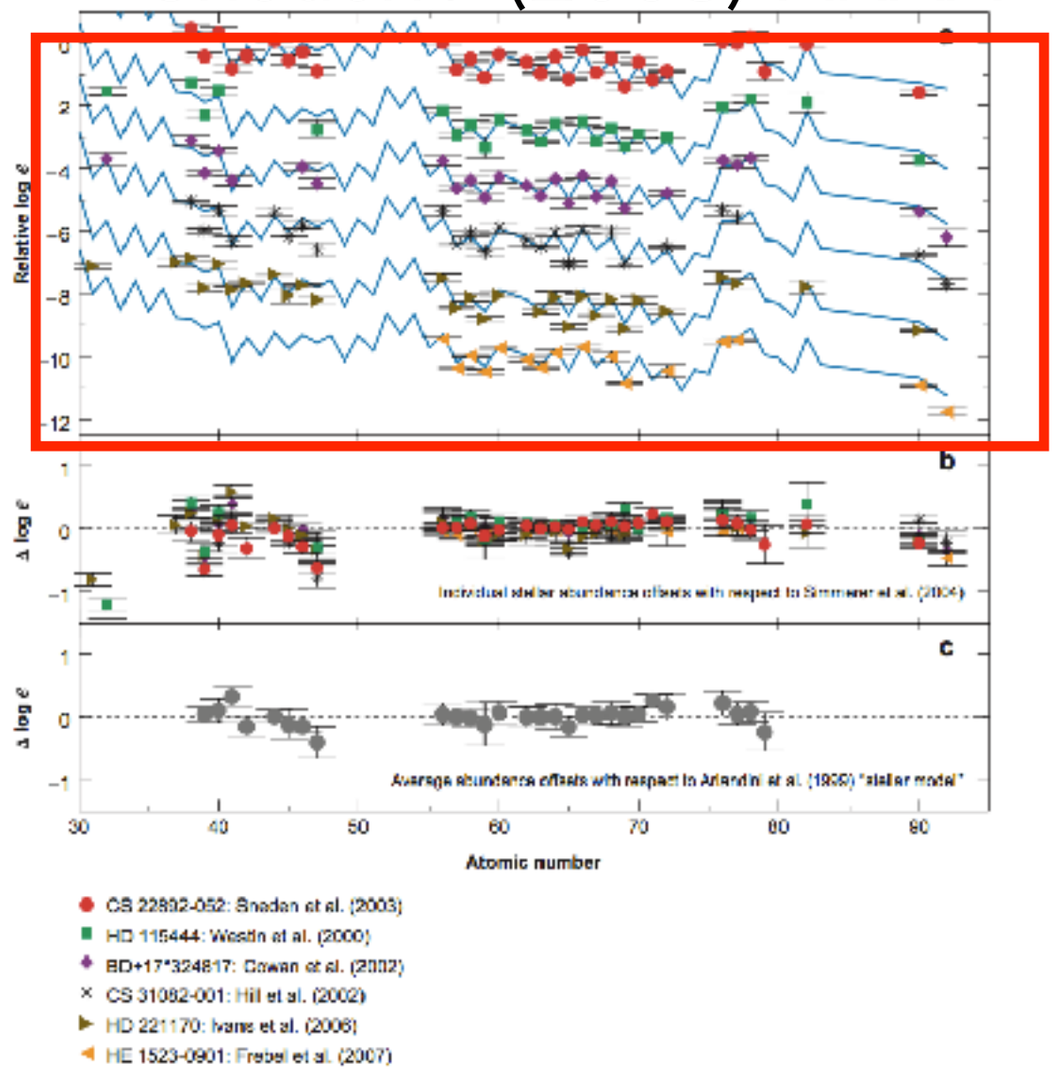
temperature for the r-process to proceed. Perhaps ejection by a jet (LeBlanc and Wilson 1970) could alter these results but that remains to be demonstrated. It may even be that the r-process, if indeed there is a single 'r-process', does not occur predominantly in supernovae! Recent work by Cowan, Cameron 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.

- “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)

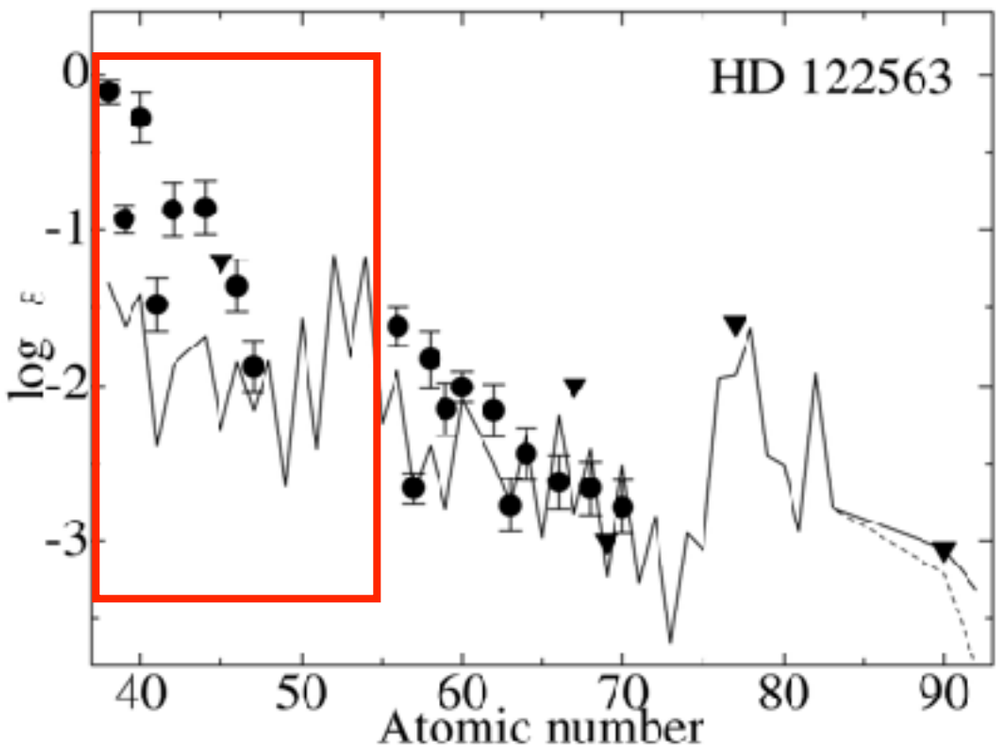
Origin of diversity in metal-poor stars?

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

Sneden+ (2008) ARAA



weak r (Honda+2006)



- medium r nuclei overproduced
- or heavy r nuclei underproduced

more examples
e.g., M. Aoki+(2017)

Contents

- Introduction
  - origin of r-process nucleosynthesis
  - “jet” supernovae?
- r-process in MR-SNe
  - prompt vs. delayed scenario
  - “intermediate” r-process?
- GCE
  - Eu: r-process elements
  - (Zn: lighter trans-iron element)

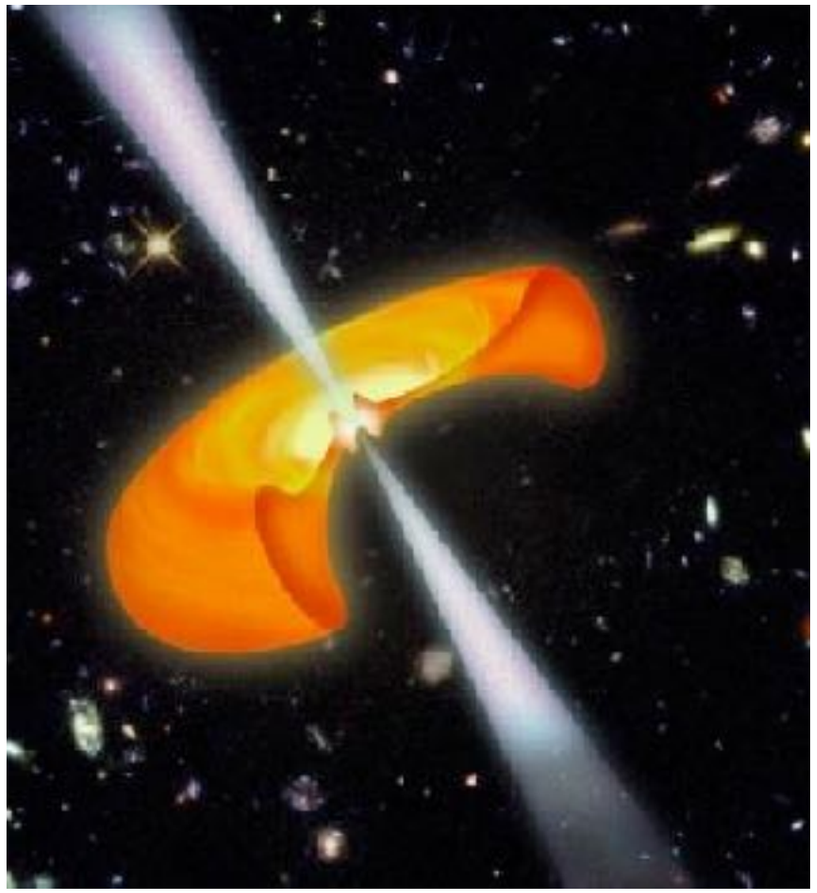
References

- Winteler+NN+(2012)
- NN, Takiwaki, Thielemann (2015) ApJ 810:109
- Tsujimoto & NN (2015) ApJL 810:L10
- NN, Sawai, Takiwaki+(2017) ApJL 836:L21
- Tsujimoto & NN (2018, in prep)

The r-process in MR-SNe

- NN, Takiwaki, Thielemann (2015) ApJ 810:109
- NN, Sawai, Takiwaki+(2017) ApJL 836:L21

r-Process nucleosynthesis in MR-SNe

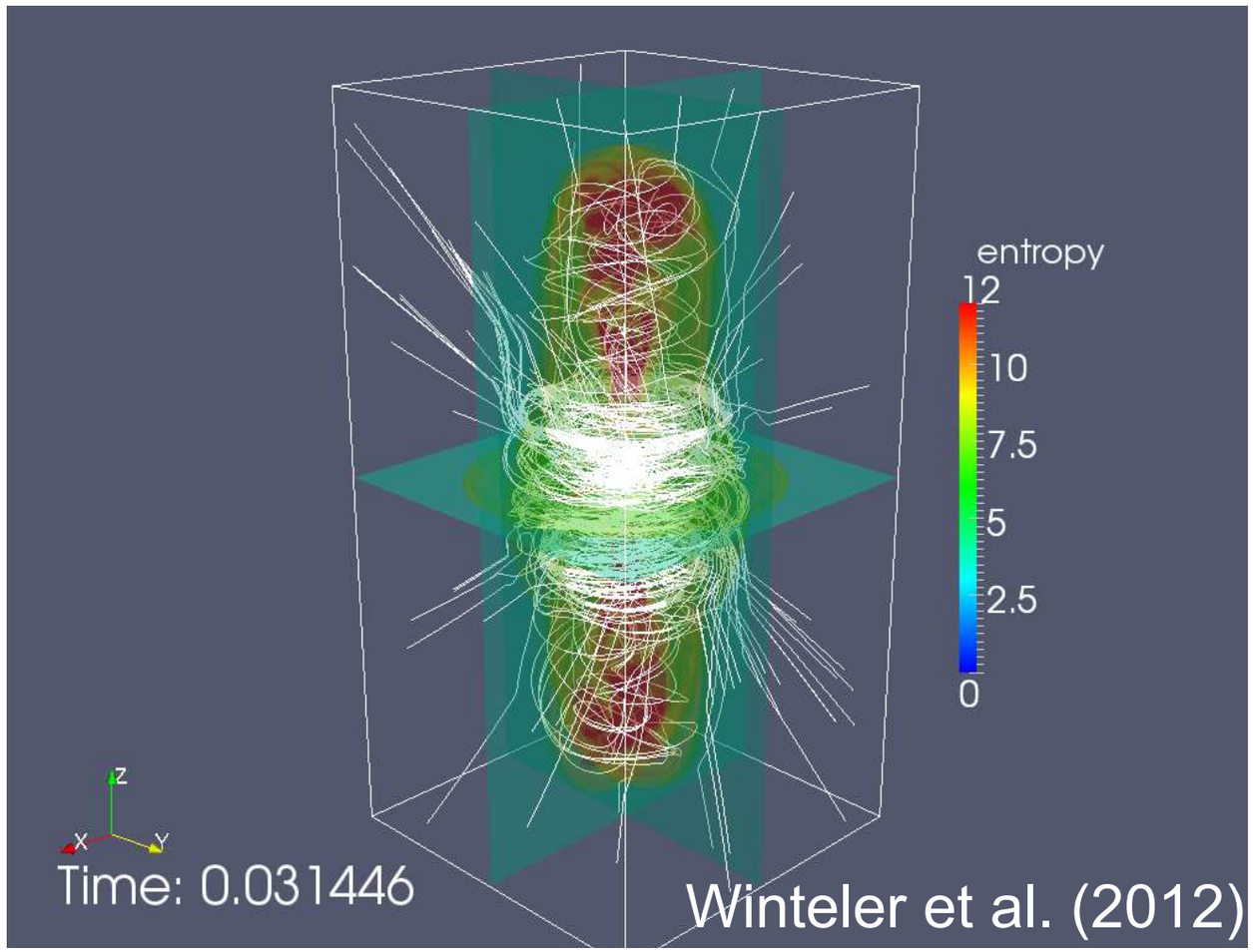


hypernova/jet-like SN

- MR-SNe (magnetar formation)
  - 2D: S.Nishimura+NN+(2006); NN+(2012)
  - 3D: Winteler+NN+(2012)
- "Collapsar model" (BH + disk + jet)
  - 2D: Fujimoto+(2007); Fujimoto, NN, Hashimoto(2009); Ono+(2009, 2012)

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

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

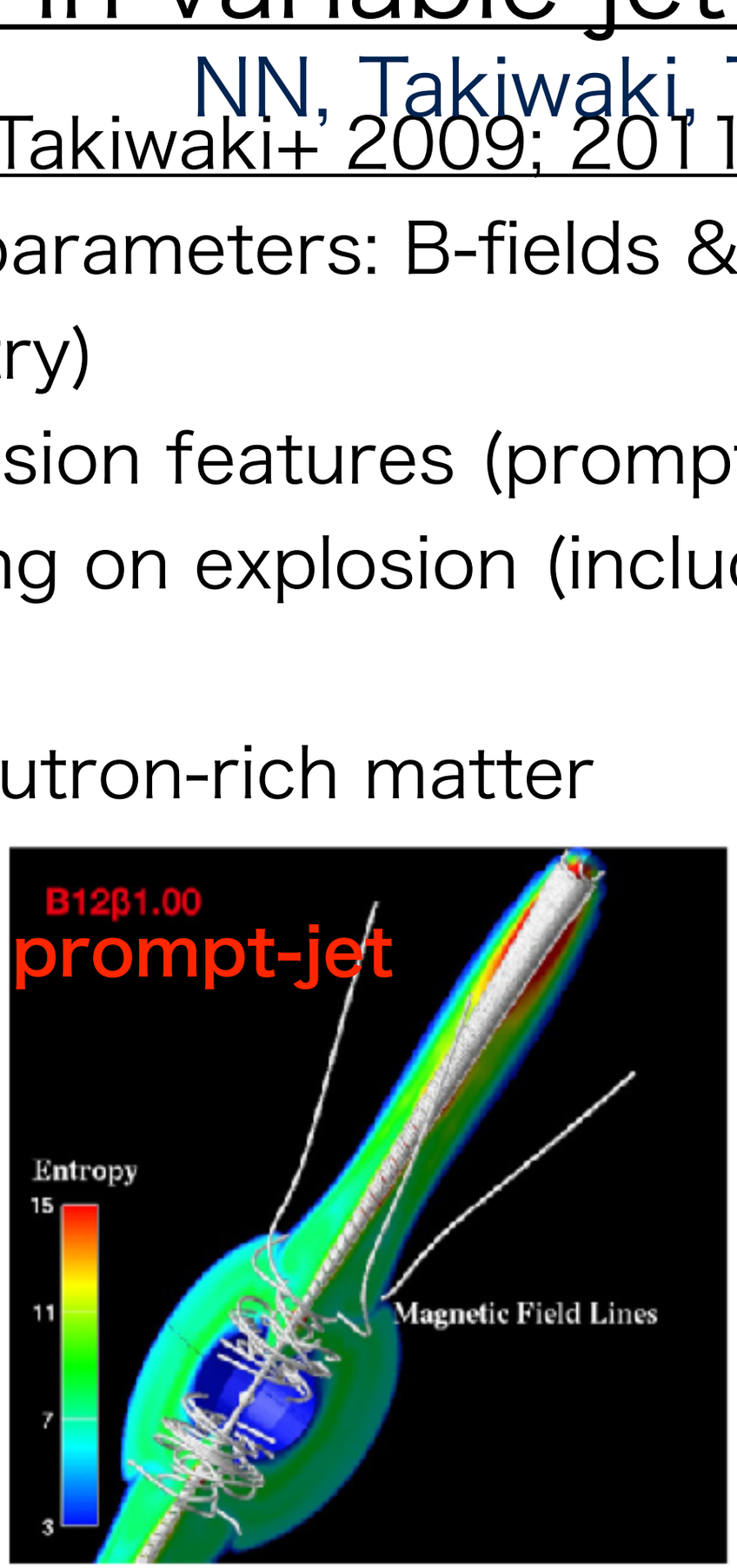


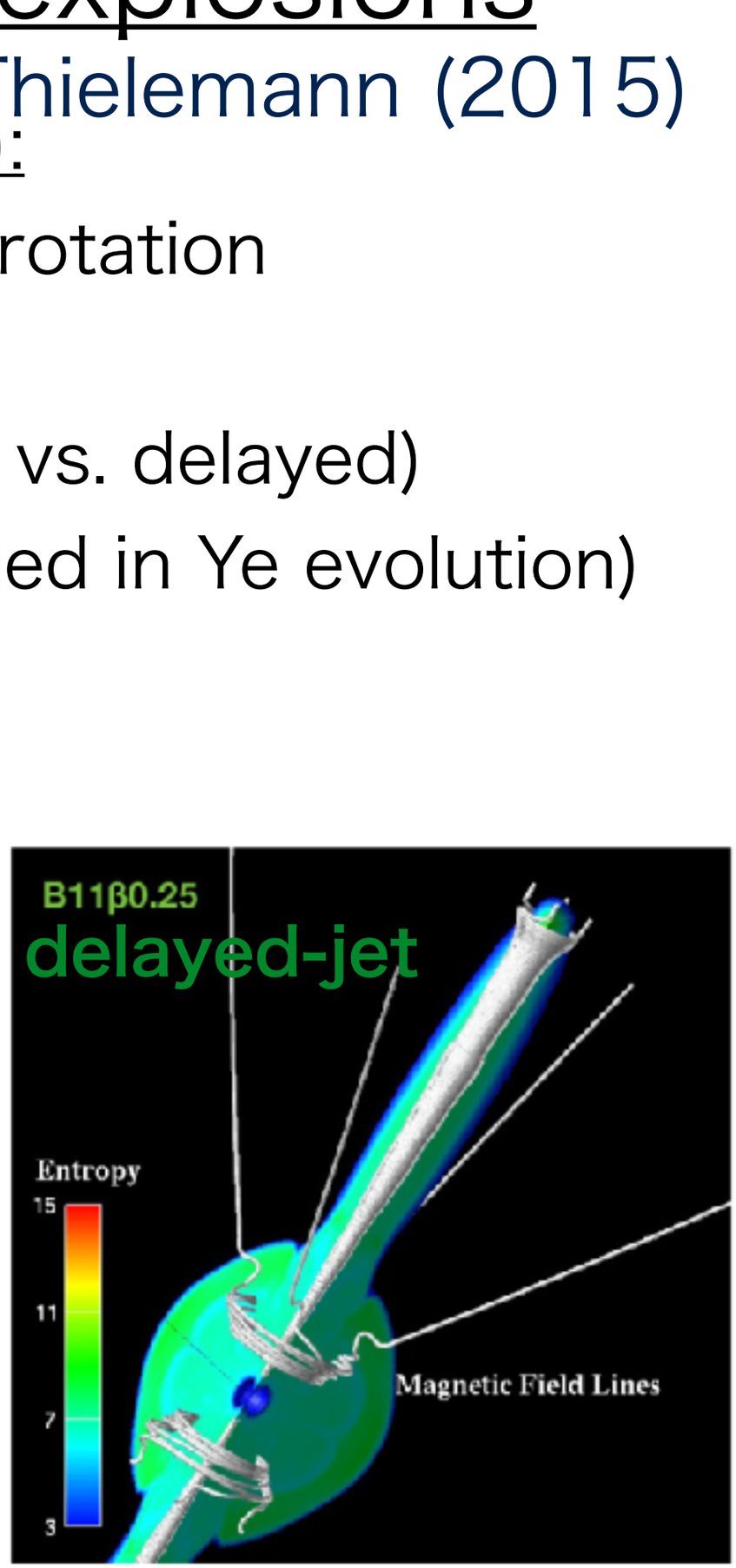
The r-process in variable jet explosions

NN, Takiwaki, Thielemann (2015)

- explosion models (Takiwaki+ 2009; 2011):
  - a wide range of parameters: B-fields & rotation
  - in 2D (axisymmetry)
  - a variety of explosion features (prompt vs. delayed)
  - ignoring ν-heating on explosion (included in Ye evolution)
- nucleosynthesis
  - can eject very neutron-rich matter

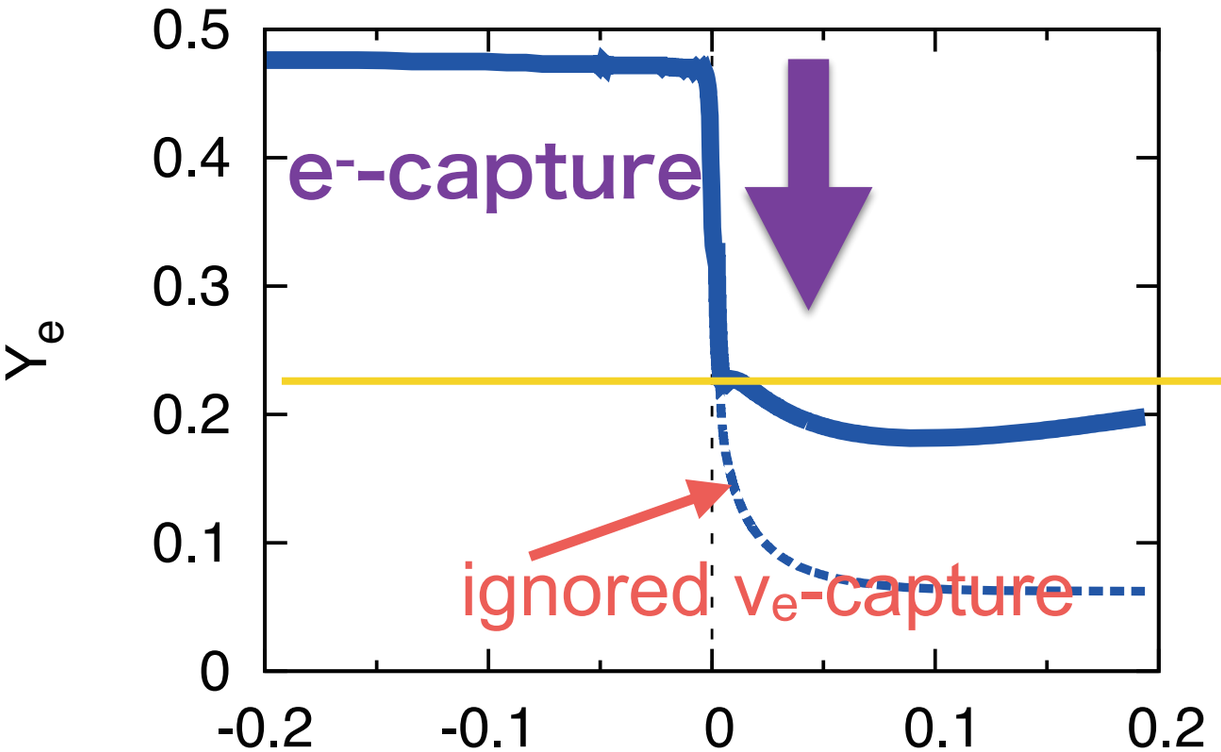
Jet-like explosions, driven by the strong magnetic pressure



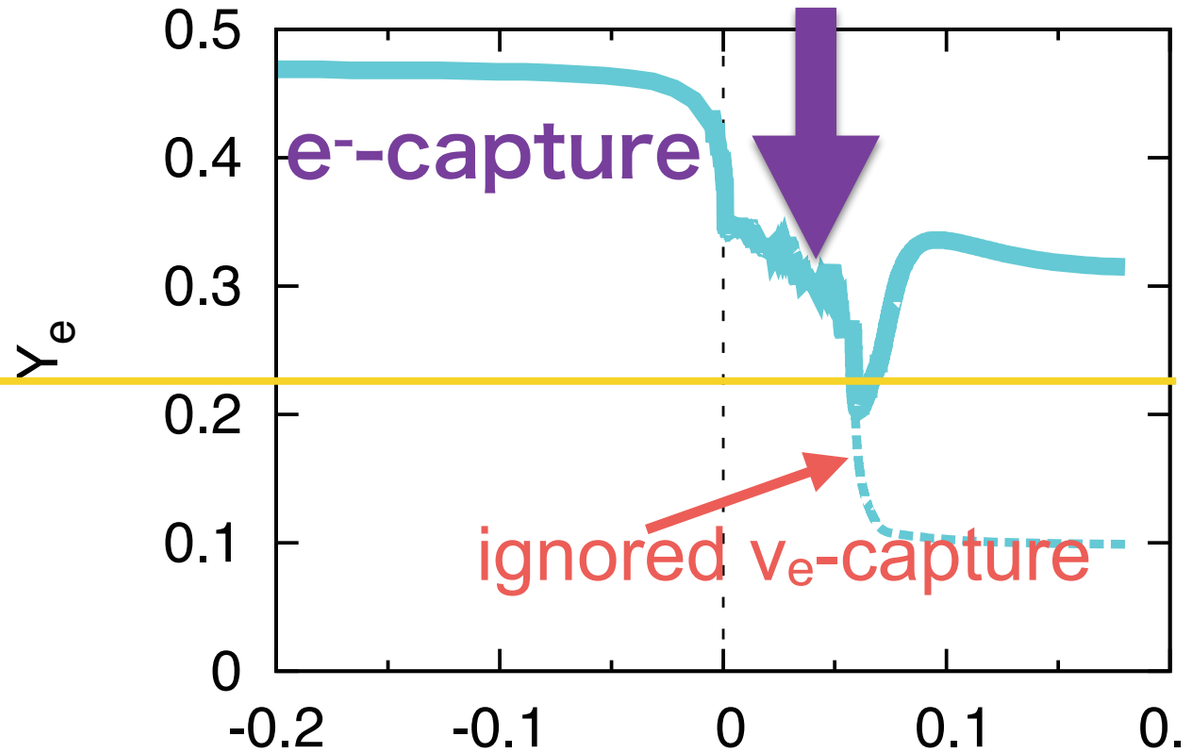


Y_e (or neutron-richness) for different ejecta

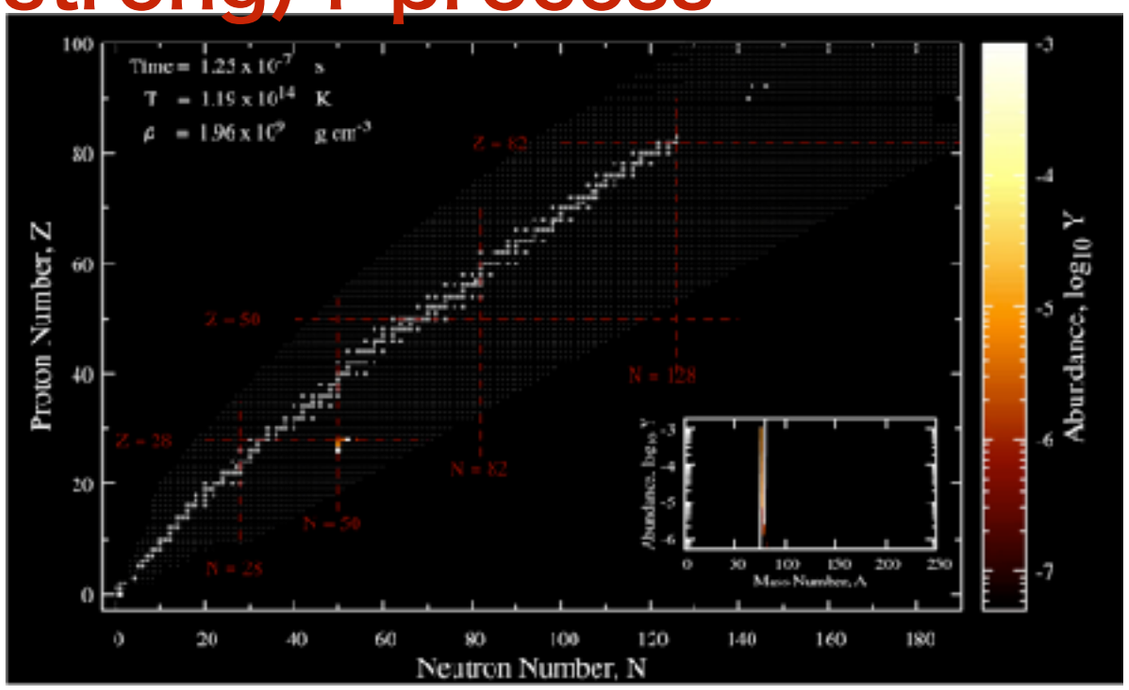
strong-mag. jet



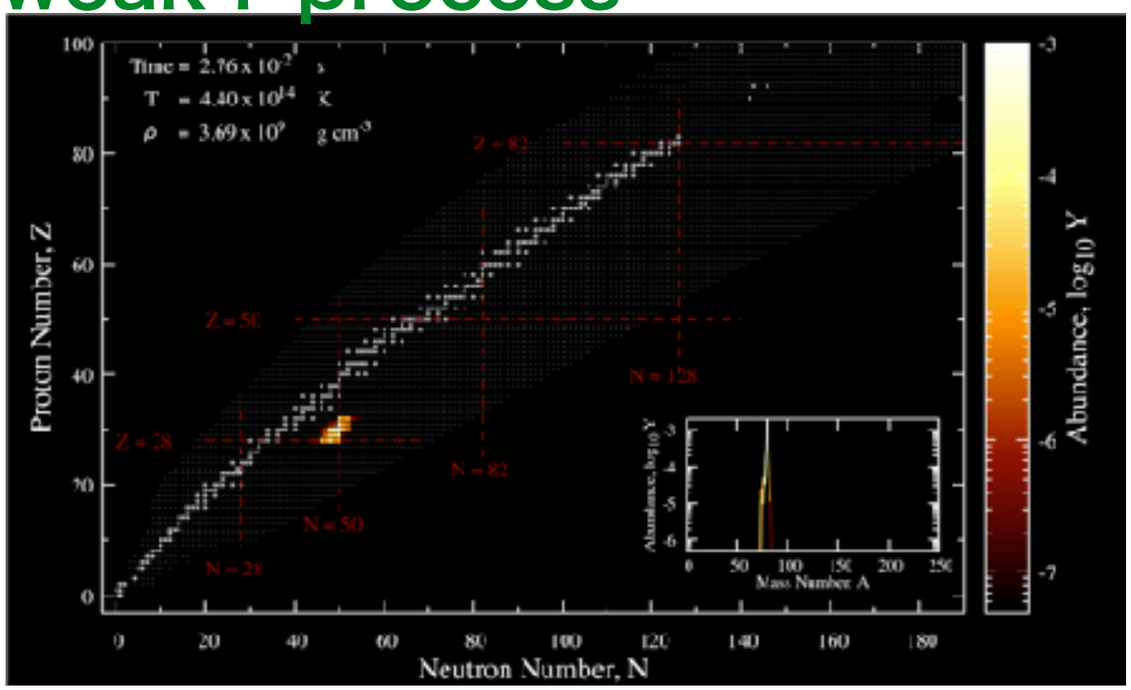
weaker-mag. jet



(strong) r-process



weak r-process

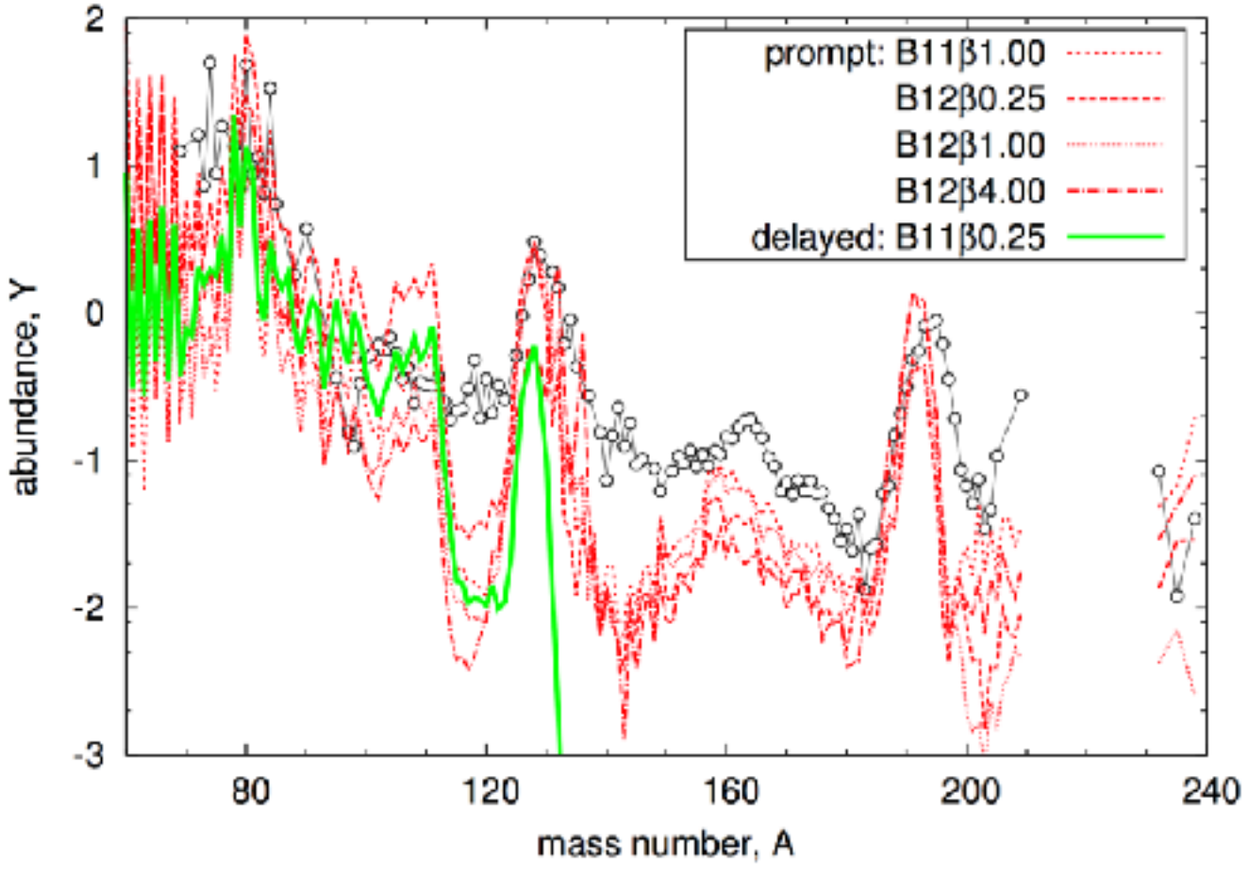


Diversity of MR-SNe and r-process

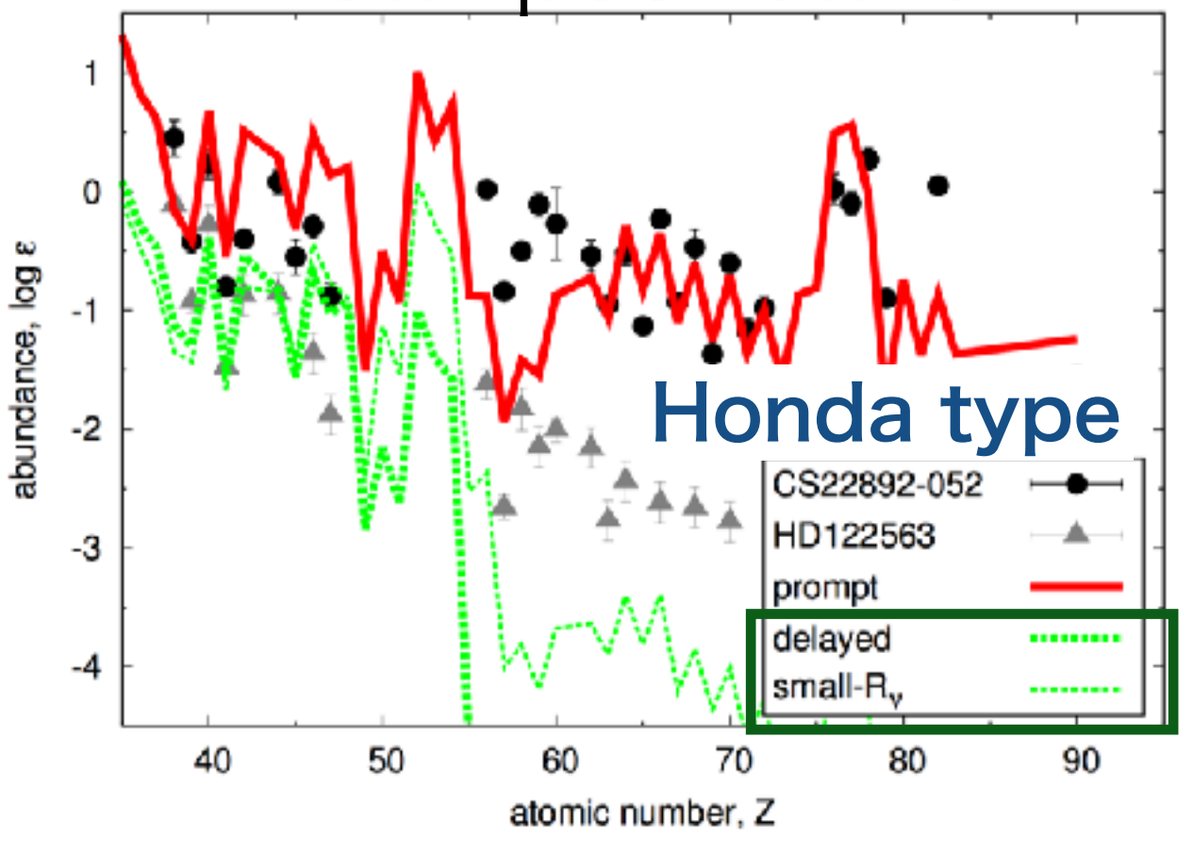
NN, Takiwaki, Thielemann (2015)

- **Strong (prompt)-jets**
  - very n-rich from the inside of the PSN (strong e−capture)
- **Weaker (delayed) jets**
  - less neutron-rich form PNS surface (strong neutrino absorption)

solar r



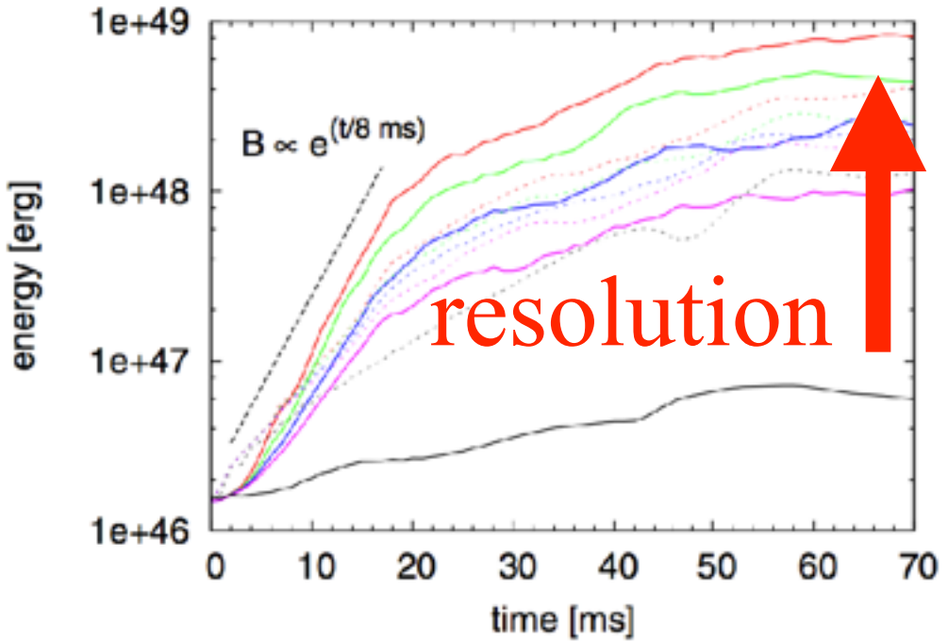
metal-poor stars



Magneto-rotational instability in CC-SN

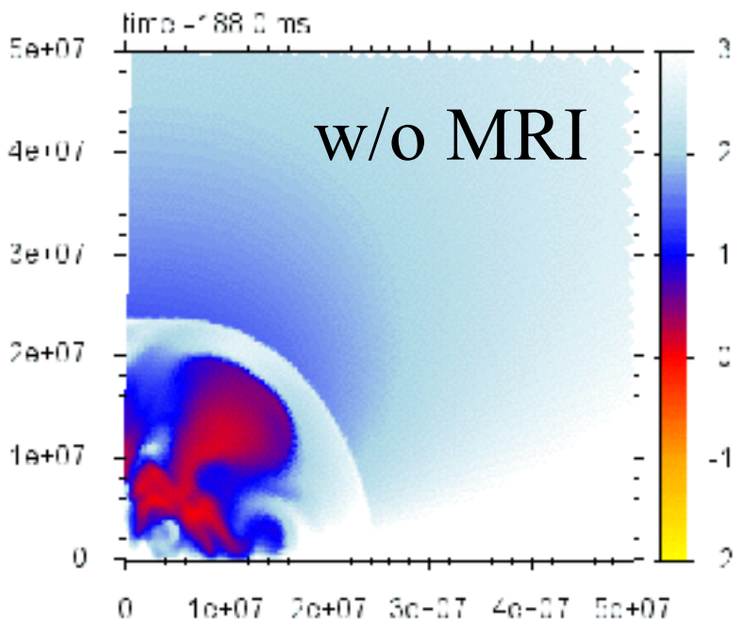
Sawai & Yamada (2014, 2016)

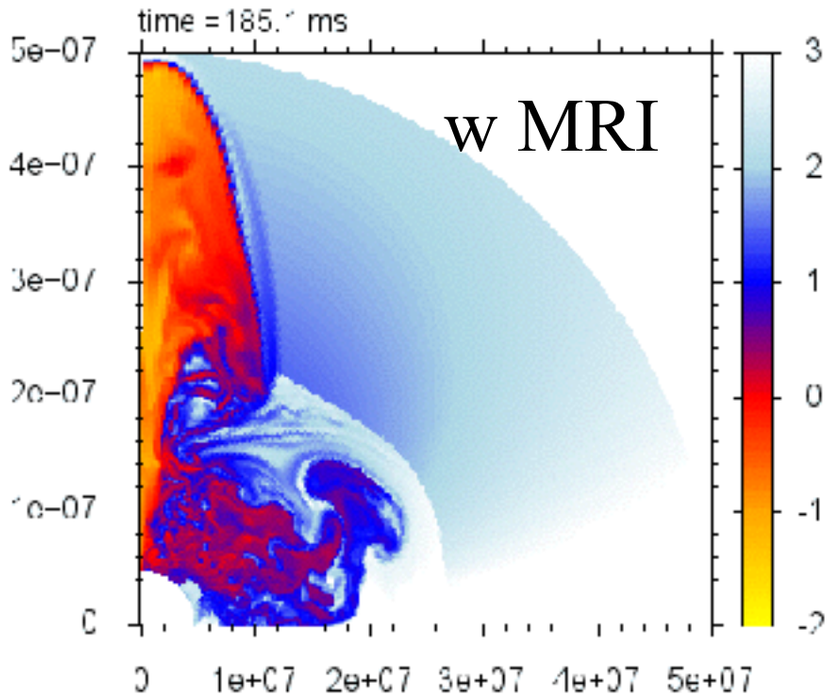
- **MRI enhance B-fields** of the core
- **neutrino-heating** also affects explosion
- 2D axisymmetric



Δr_{min} = 100, 50, 25, 12.5 m

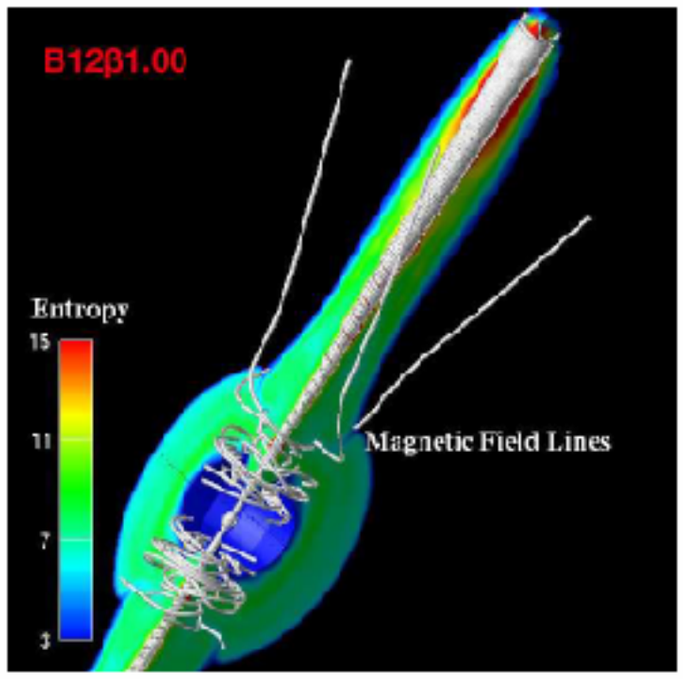
MRI-driven Jet; plasma-beta



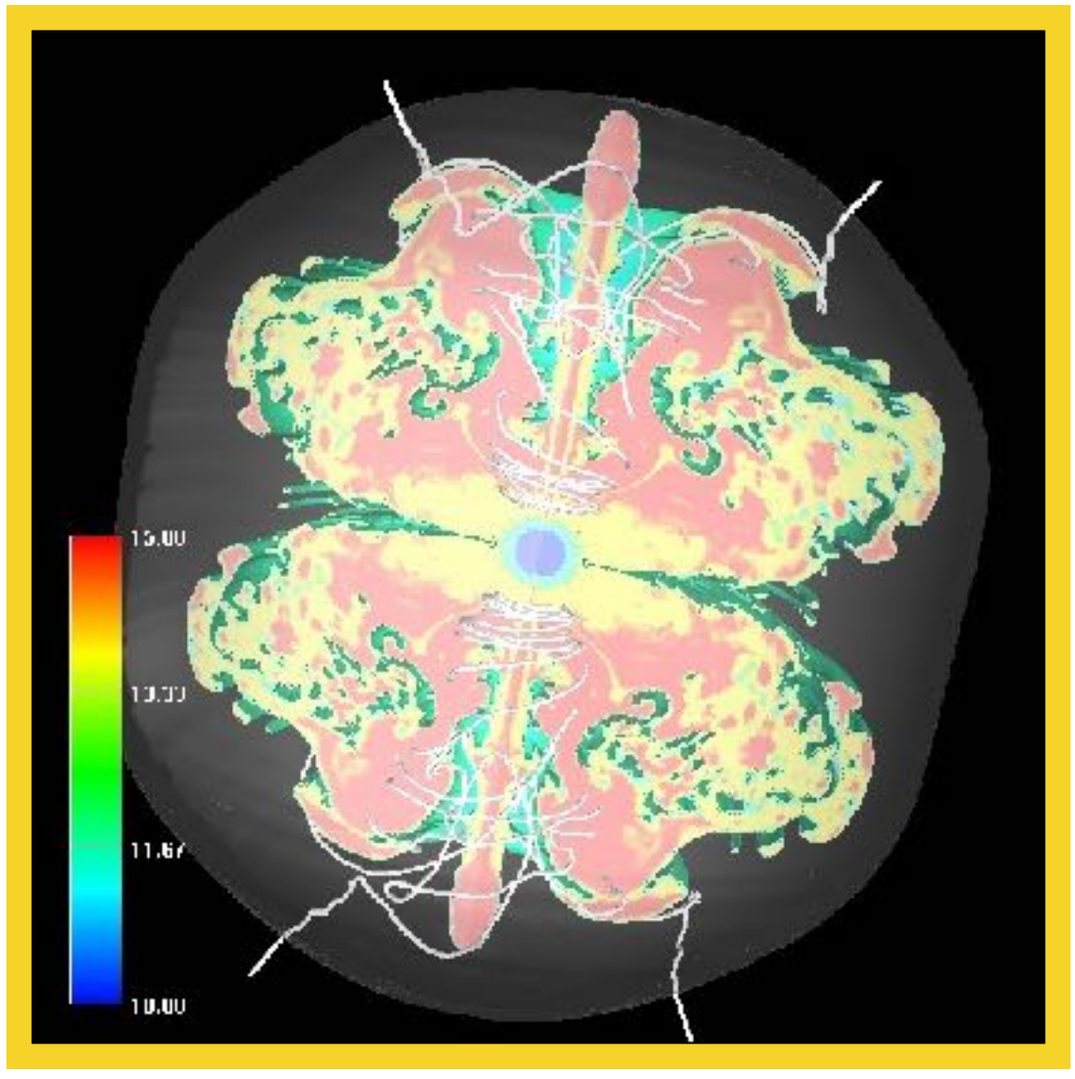


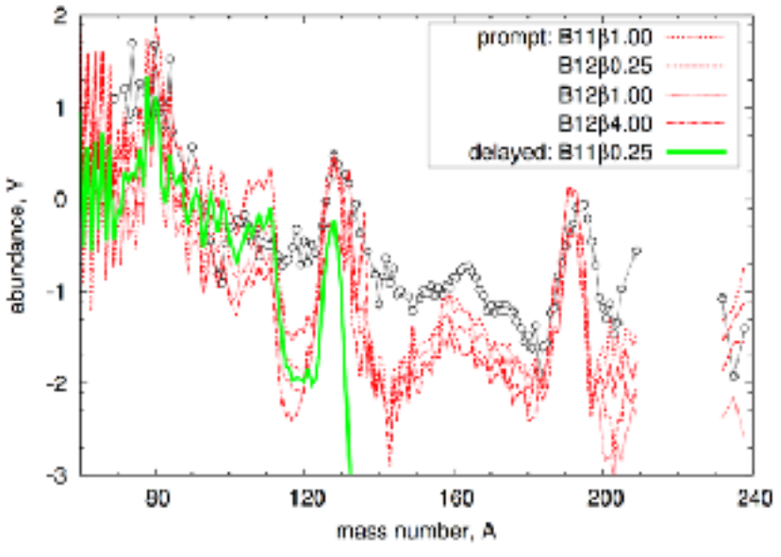
MR-SNe driven by the MRI

Nishimura+ (2015)
simulated by T. Takiwaki



Nishimura+ (2017)
simulated by H. Sawai





?

Need those strong initial B-fields?

Problem: varying B-fields/rotation

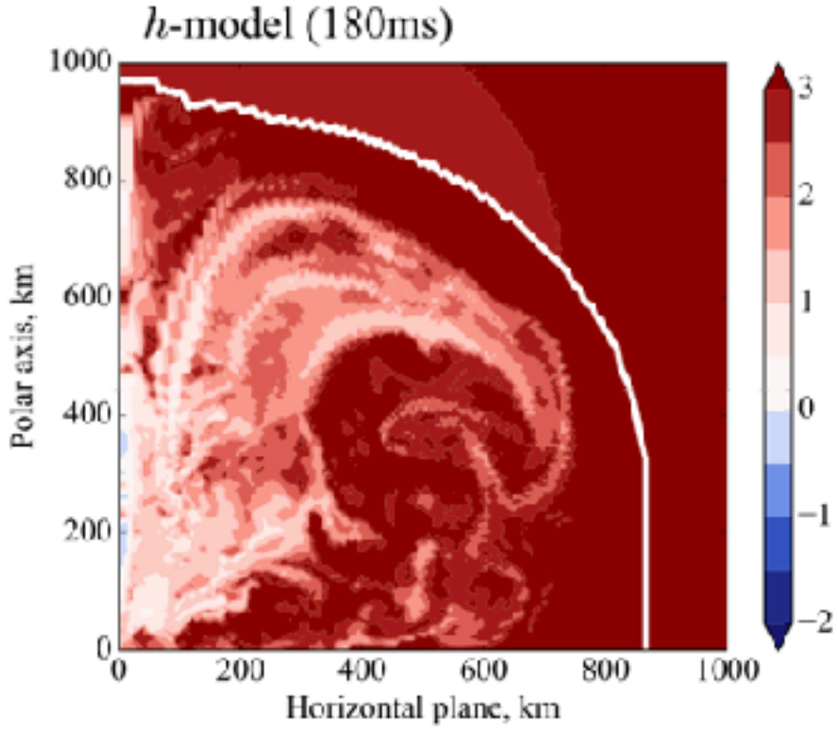
—> requires MRI convergence for each case

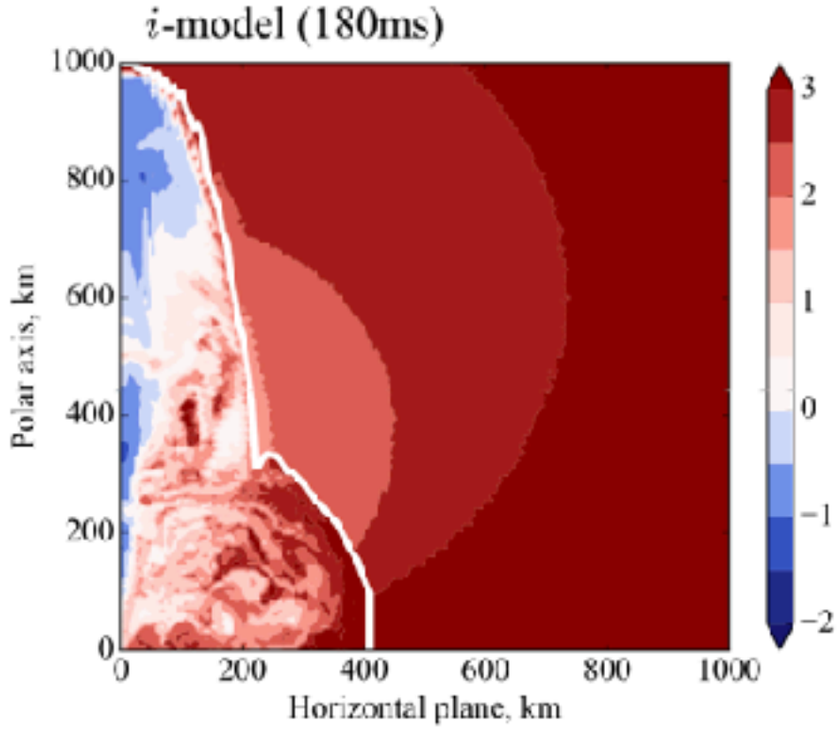
and comparison among models are difficult

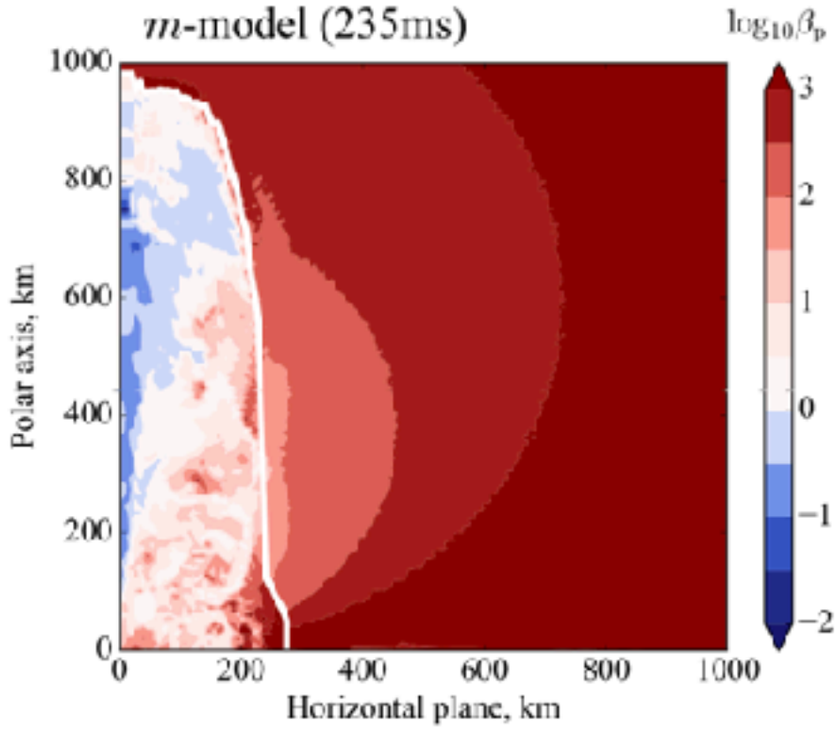
Adopt: varying L_ν —> effective strength of B-fields in explosion dynamics

heating-dominated ⟷ intermediate ⟷ magnetically-dominated

plasma-β







Ye vs S of ejecta

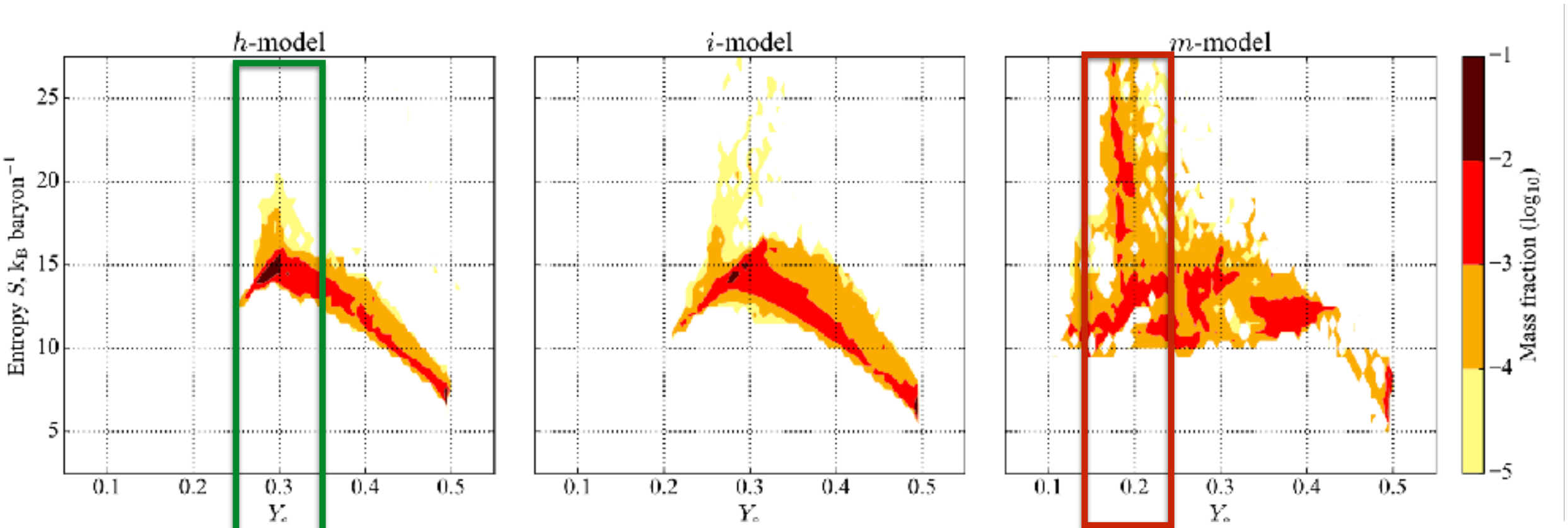
heating-dominated

magnetically-dominated

L_ν

$L_\nu \times 0.6$

$L_\nu \times 0.2$



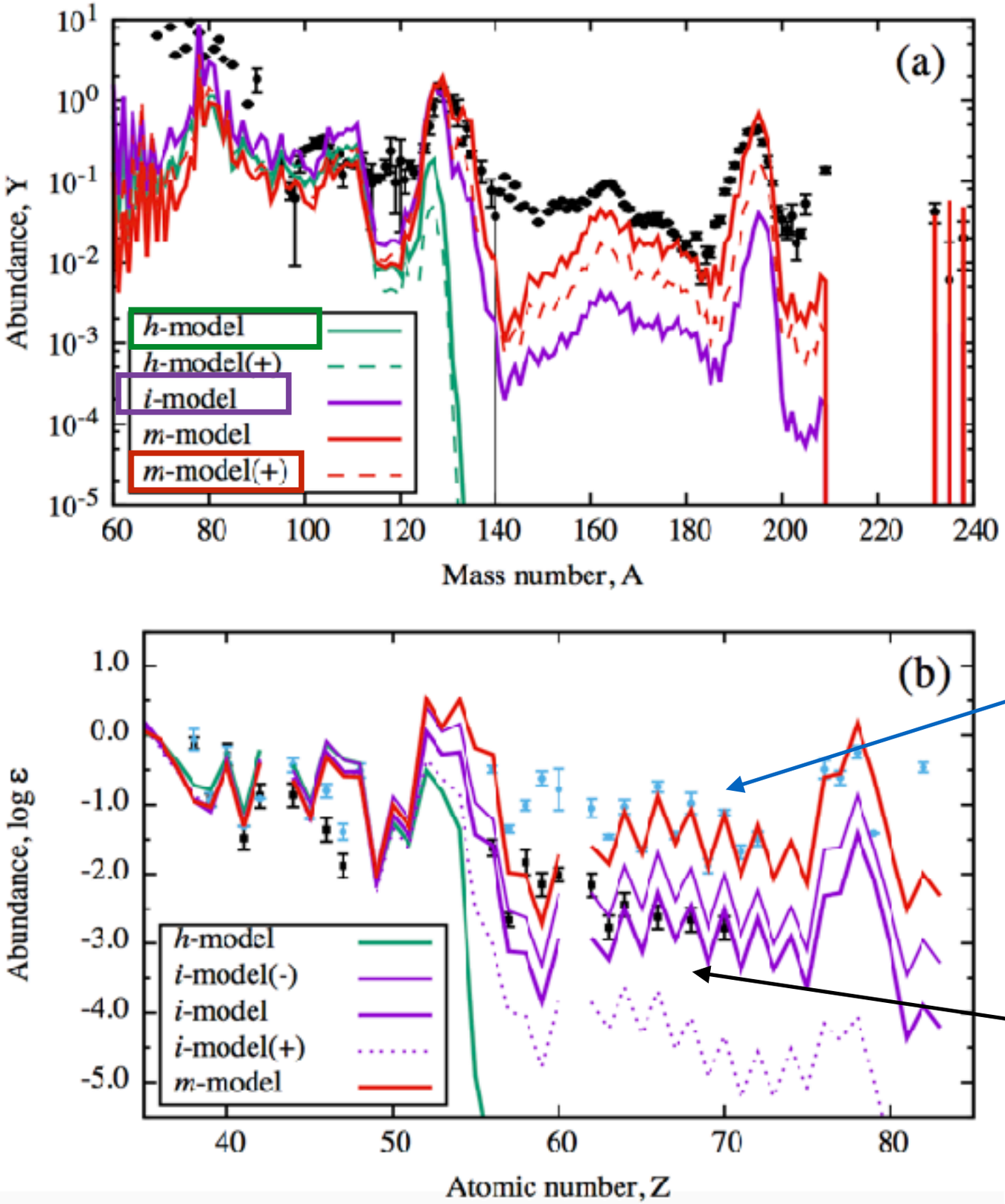
$Y_e = 0.3$

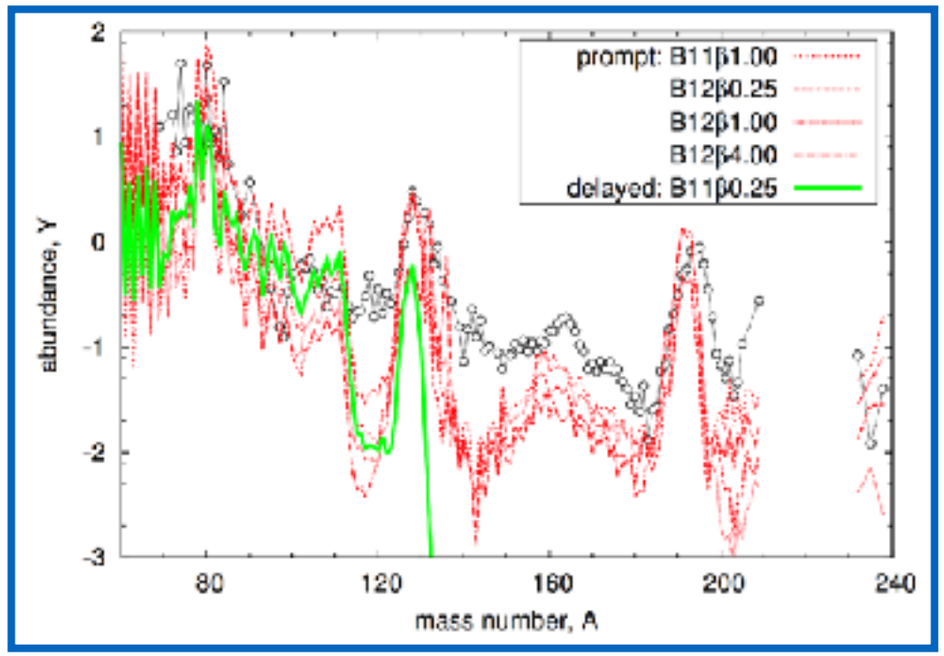
Y_e - S

$Y_e = 0.2$

Nucleosynthesis results

Nishimura+(2017) by Sawai models





Nishimura+ 2015

Takiwaki model

prompt vs delayed

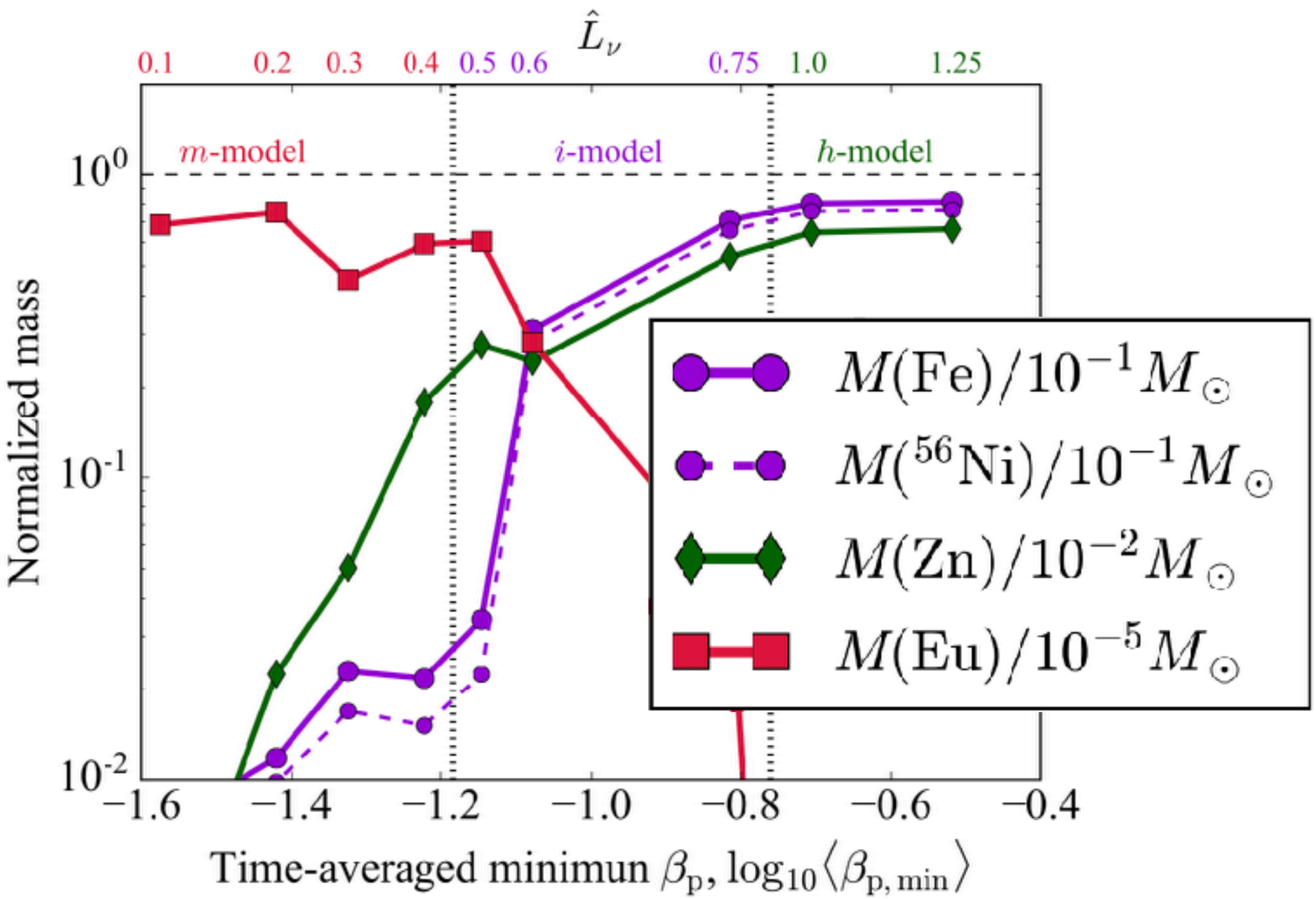
solar-like

“intermediate” r-process?

“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

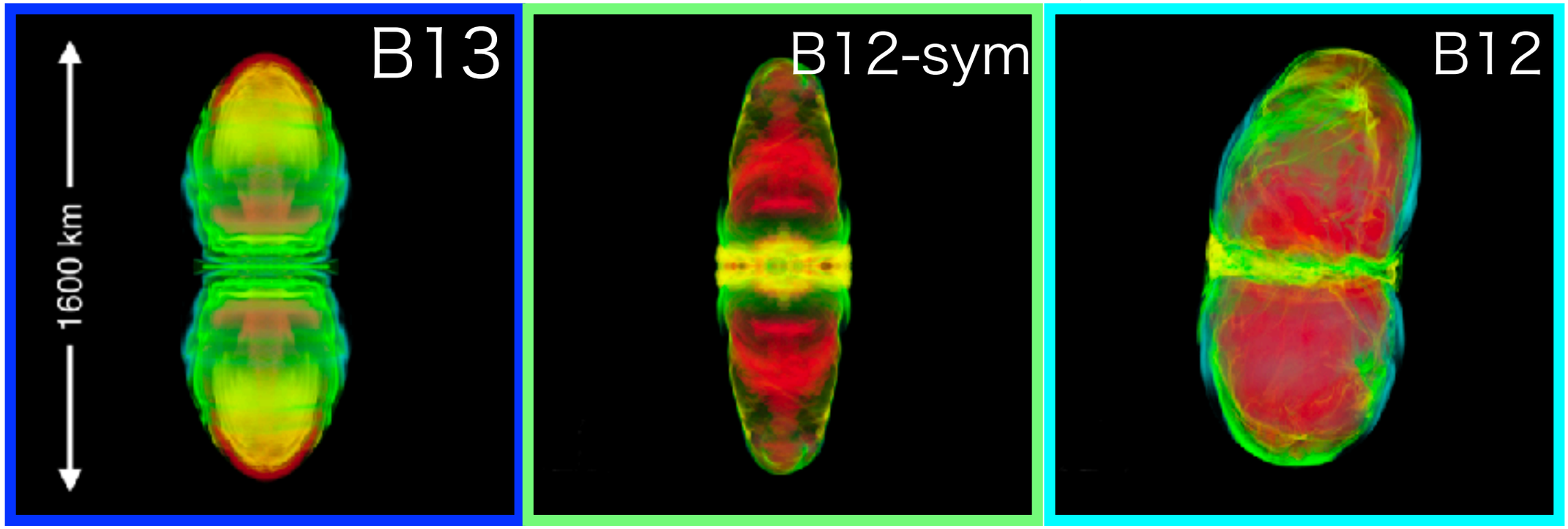
Summary & open questions

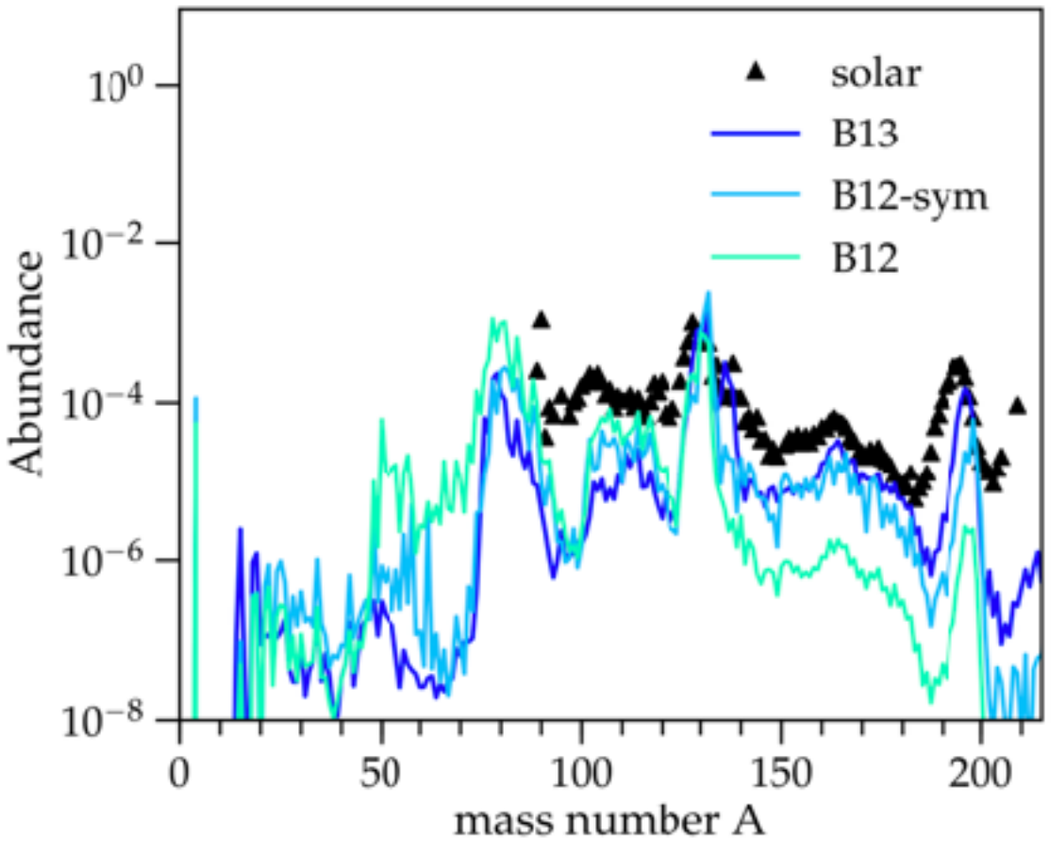
- ✔ Magnetically-driven polar-jets (“prompt jets”) produce produce heavy r-process elements
- ✔ while weaker explosions (“delayed-jets”) show weaker r-process (A < 130)
- ✔ more “realistic” (mild B-fields) prefer weaker r-processes?
- ✔ “intermediate” pattern can be reproduced by proper stellar parameters

- Really need/exist such strong initial magnetic fields?
- 3D effects
  - jet propagation
  - MRI in full 3D

3D effects on the r-process

Mösta+2017(arXiv:1712.09370)





- B12: weaker r: is more realistic
- B12-sym: artificially enhance jets —> prompt-jet of Nishimura+(2015)
- B13: unrealistically strong mag. fields—> Winteler+2012

see, also, Halevi&Mösta(2017); arXiv:1801.08943

MR-SNe in GCE

- Tsuijmoto & NN (2015) ApJL 811: L10
- Tsujimoto, NN, Thielemann (2018 in prep)

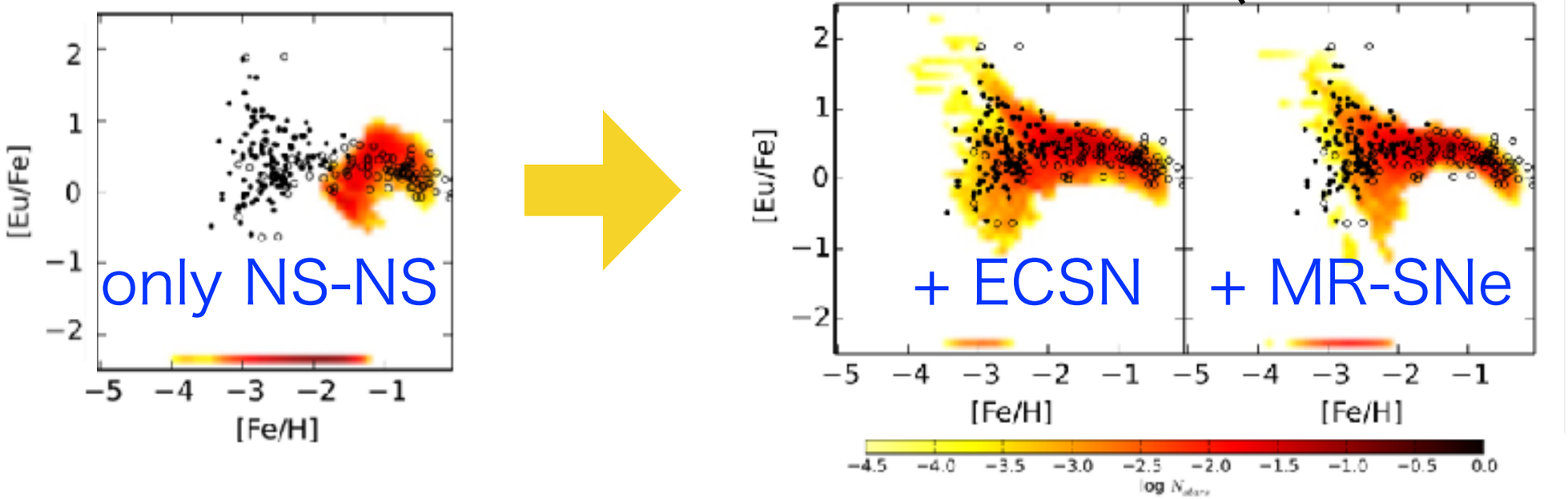
Multiple r-process sources in GCE?

shorter delay time or another source

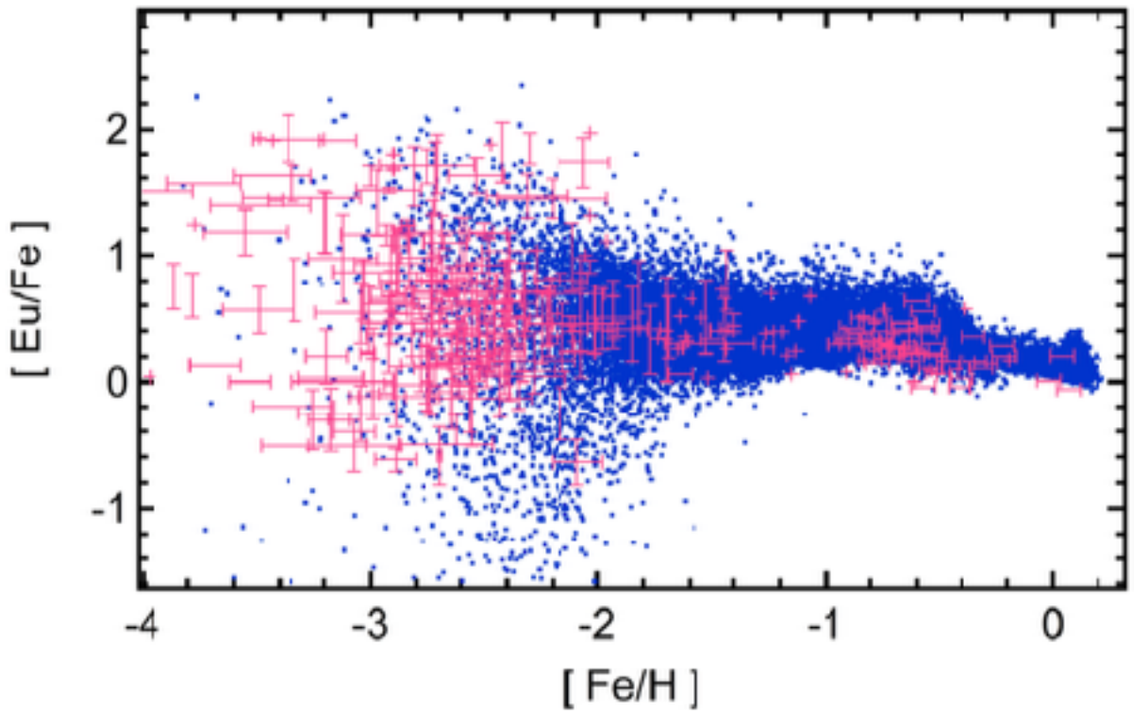
Cescutti+ 2015, A&A 577

10% of all CC-SN

(in $Z < 10^{-3}$)



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



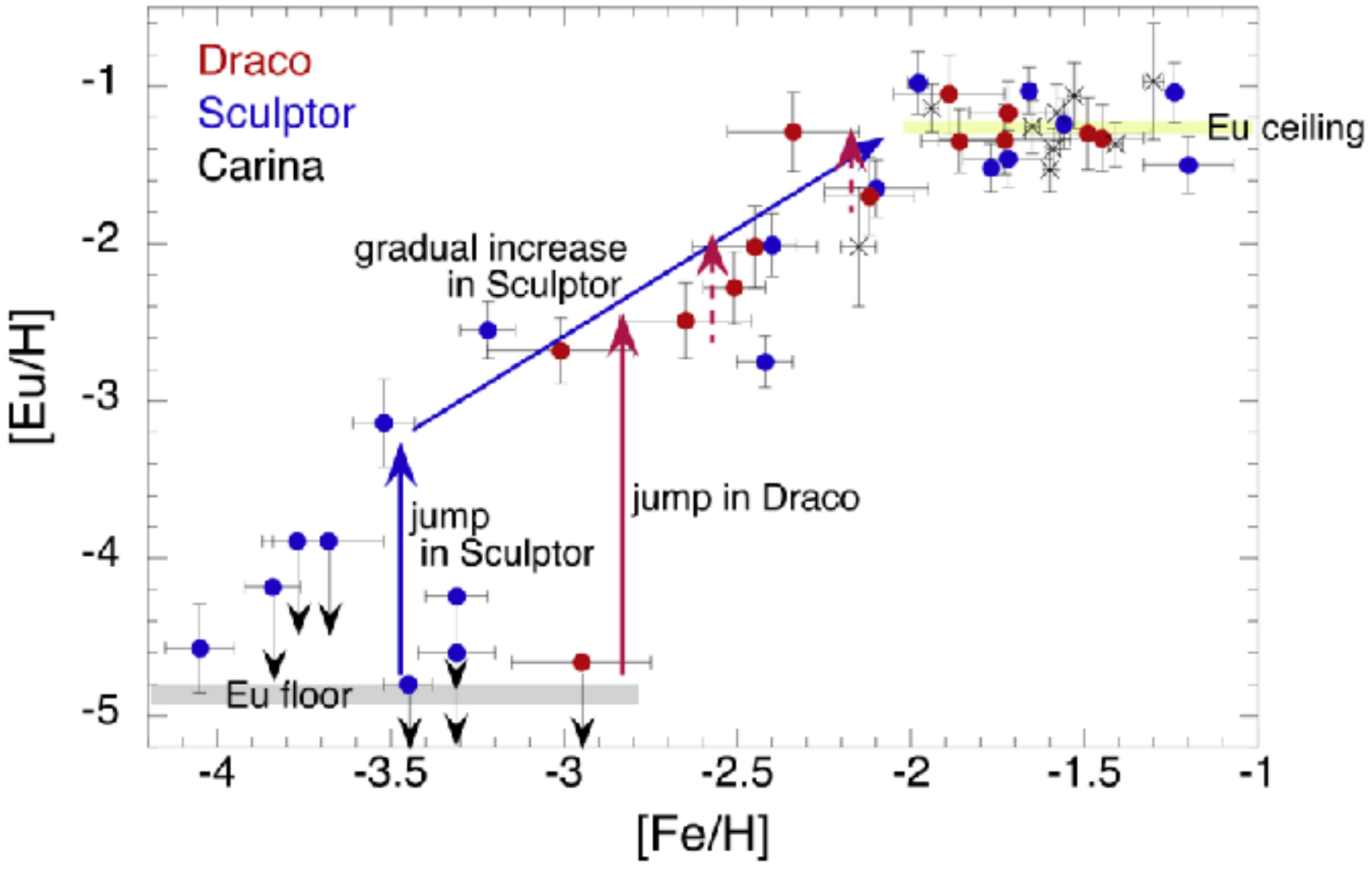
NS mergers

+ MR-SNe

0.1%

Eu evolution in Dwarf Galaxies

Tsujimoto&NN (2015)

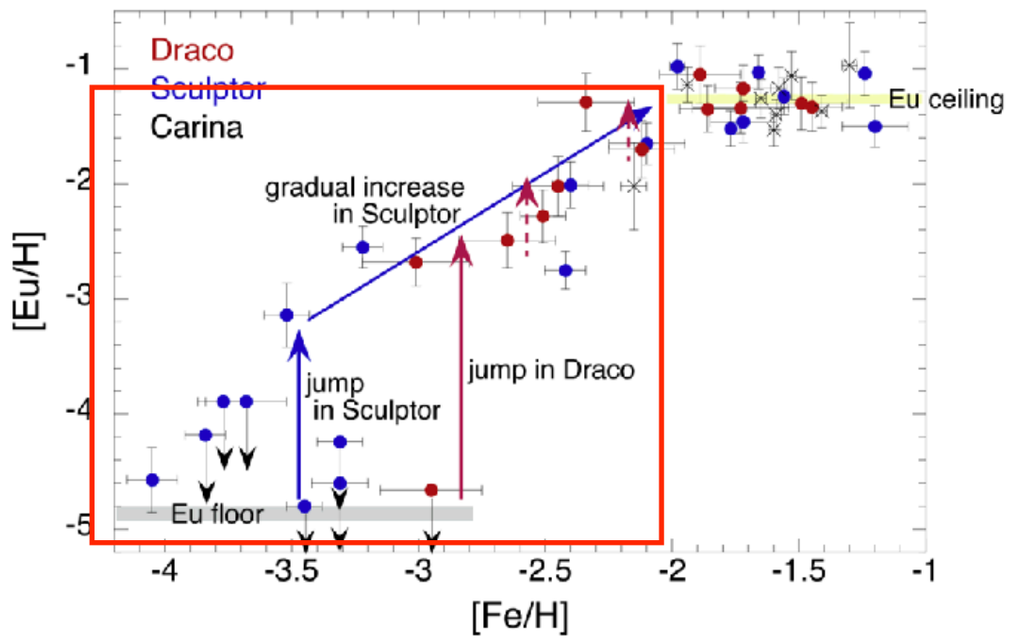


- more frequent than NS-mergers and much less than regular cc-SNe
- limited in low metallicity stars

→ MR-SNe?

Eu evolution by MR-SNe in dSph galaxies

Tsujimoto & NN, ApJL (2015)



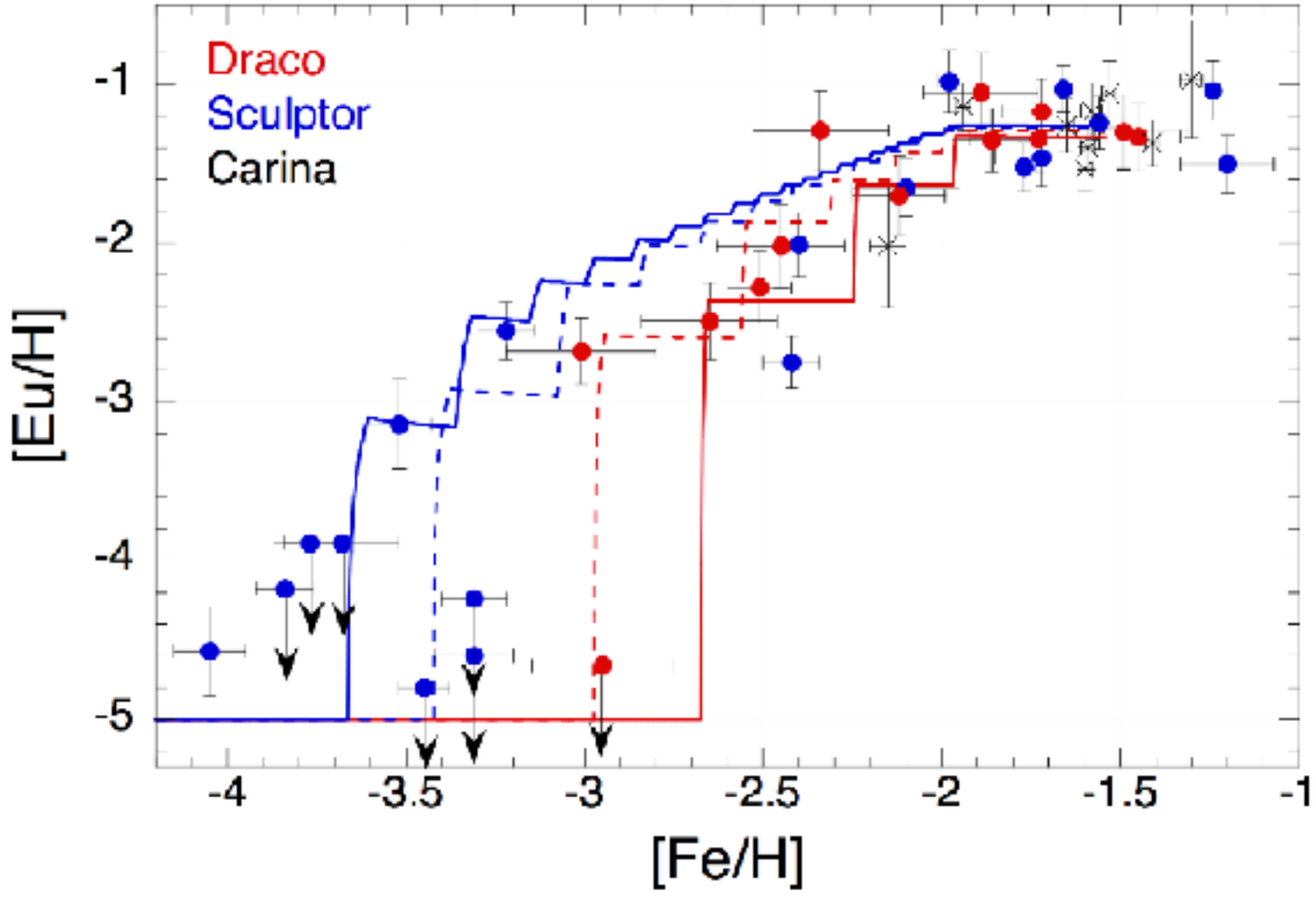
Chemical evolution models

GCE models suggest:

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

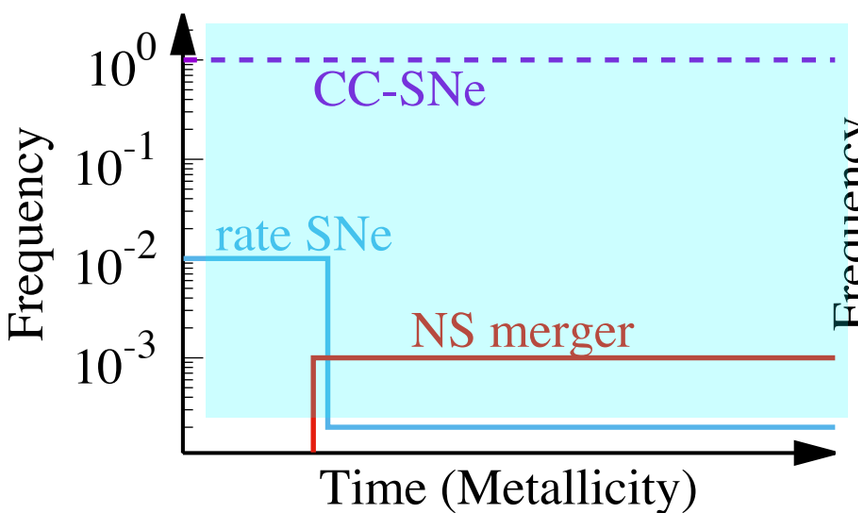
agree with our MR-SN models

(e.g. Nishimura+ 2015)

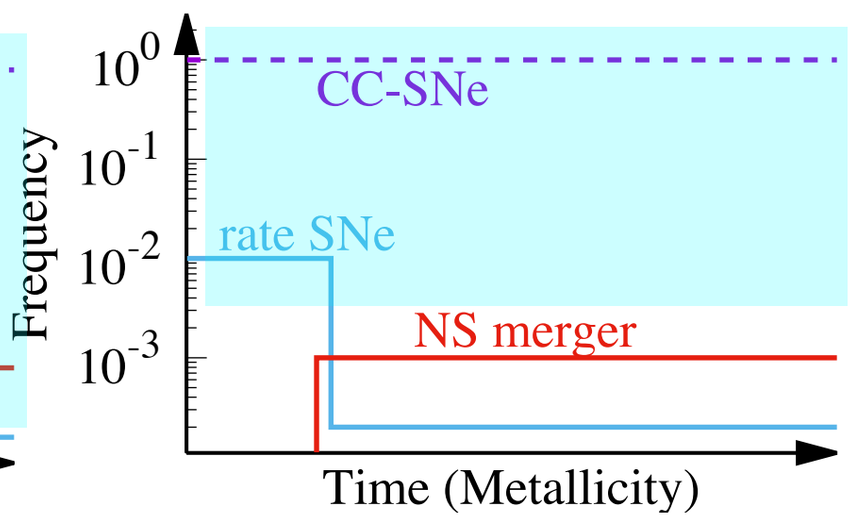


What we learned from faint dwarf galaxies

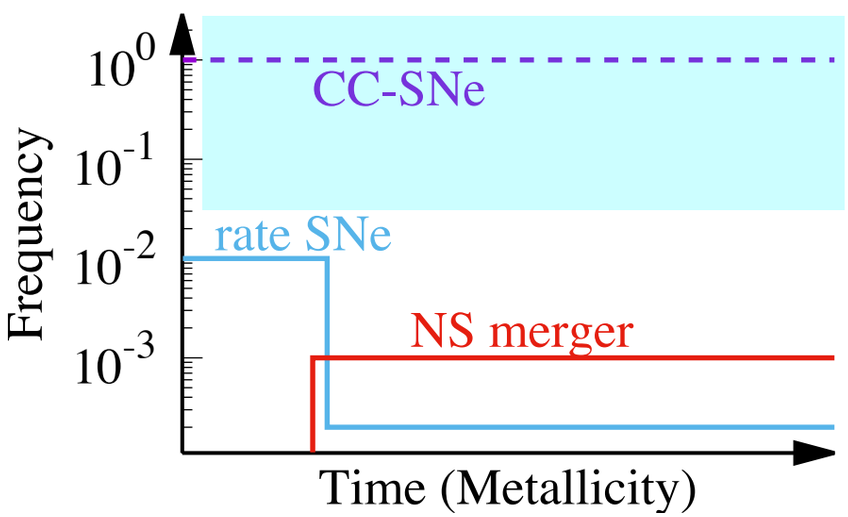
massive



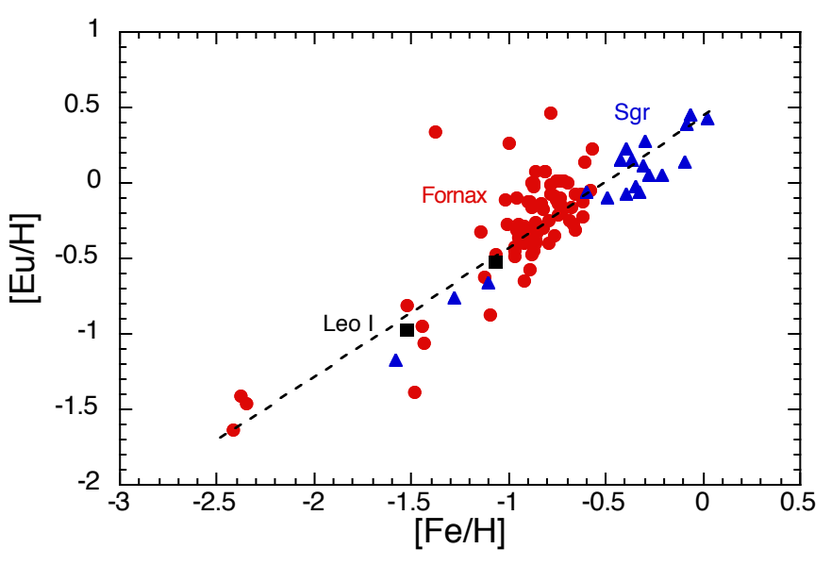
faint

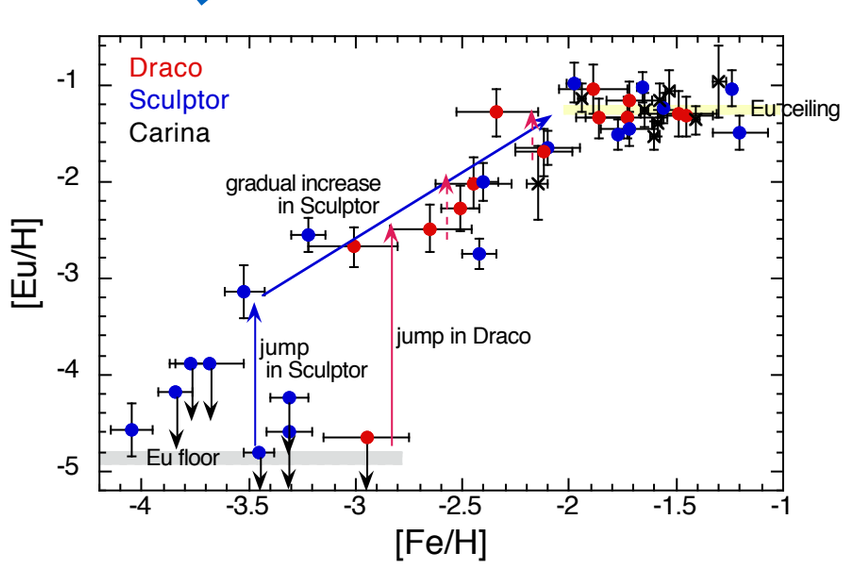


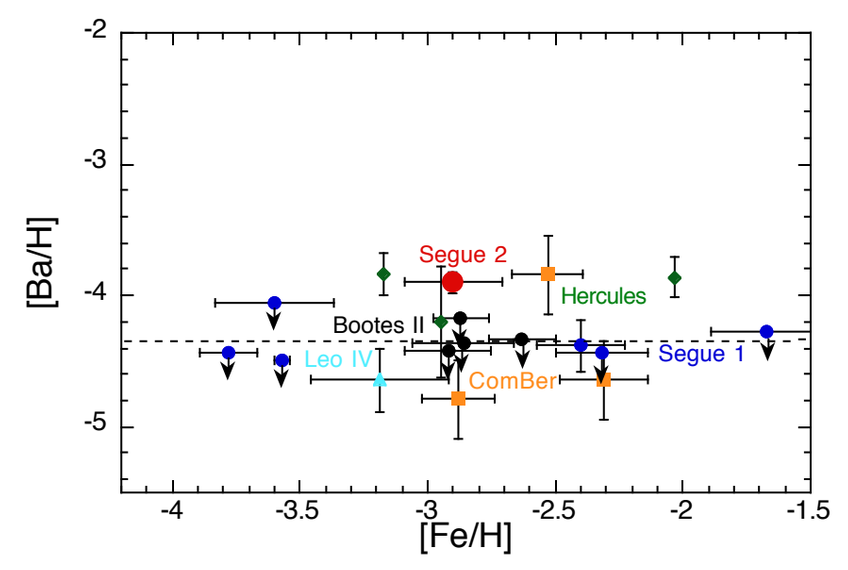
ultra faint



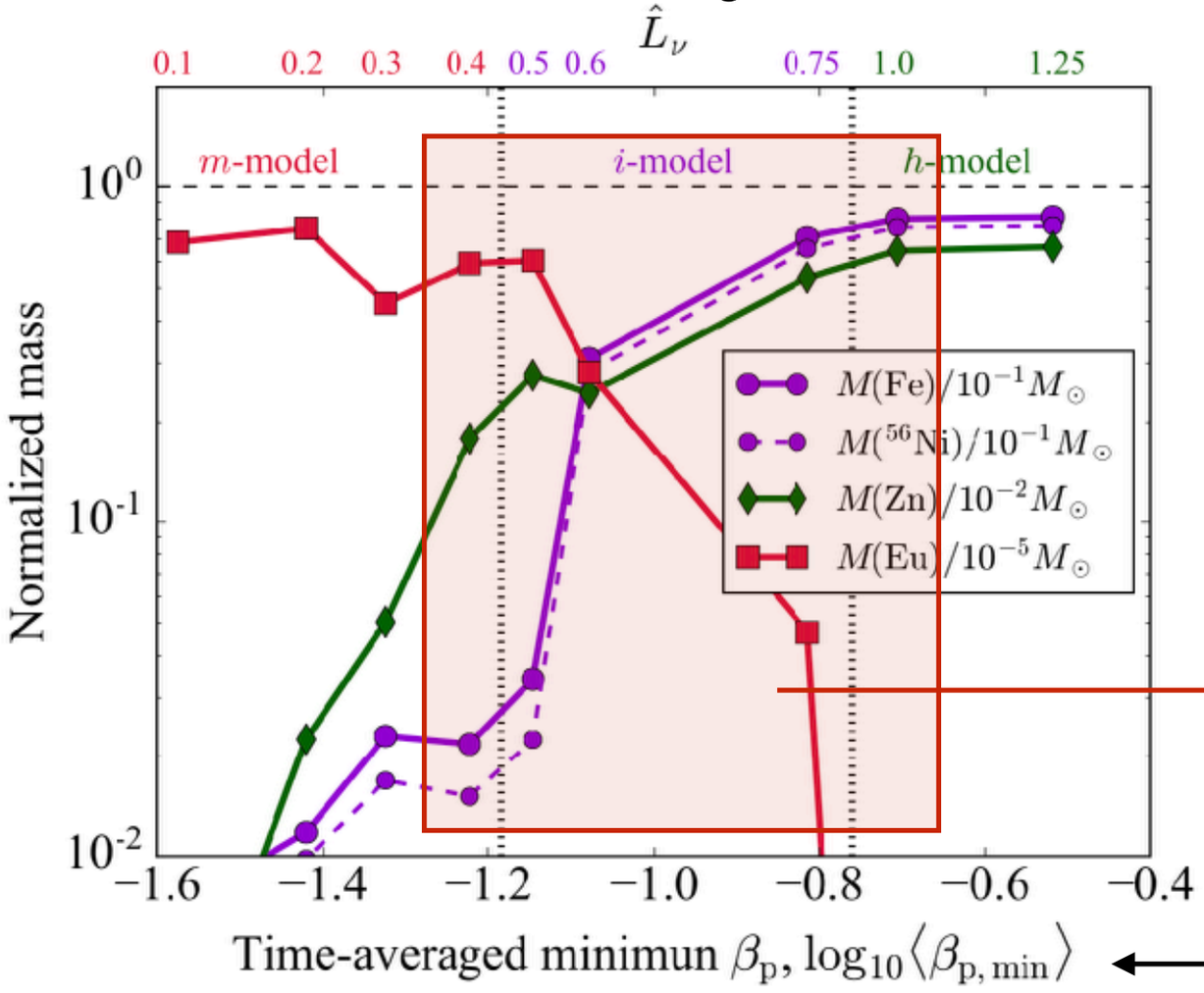
r-process abundance feature







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**

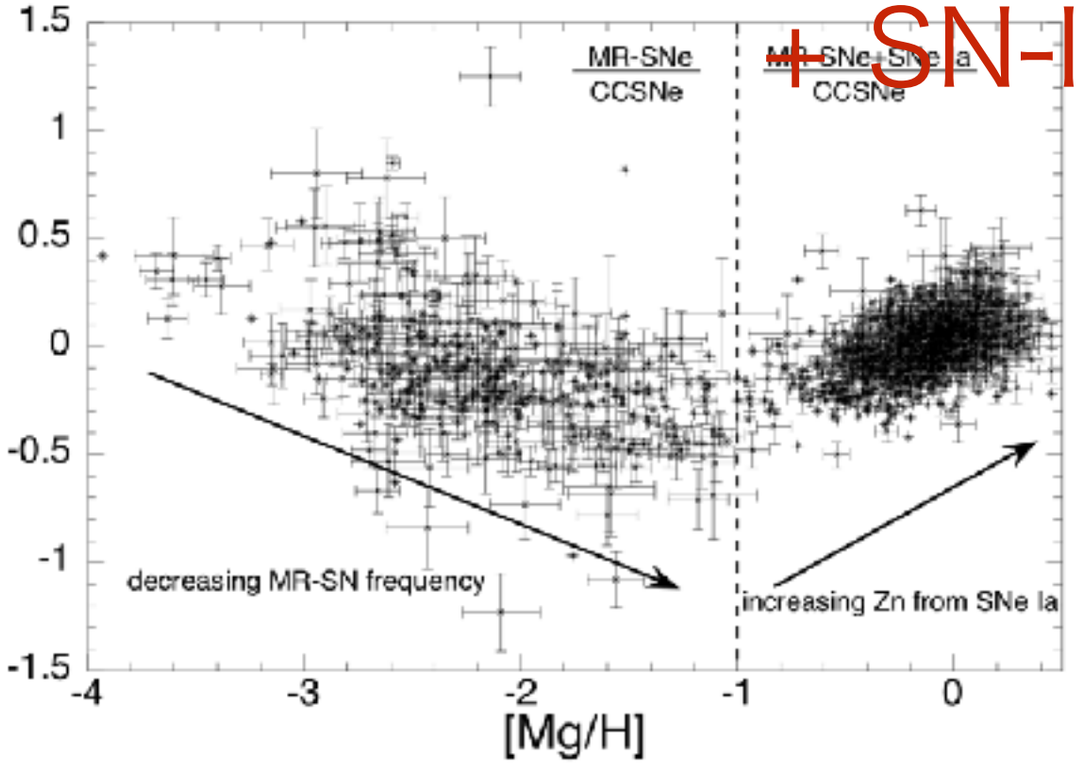
or **www2.yukawa.kyoto-u.ac.jp/~nobuya.nishimura/mrsn/**

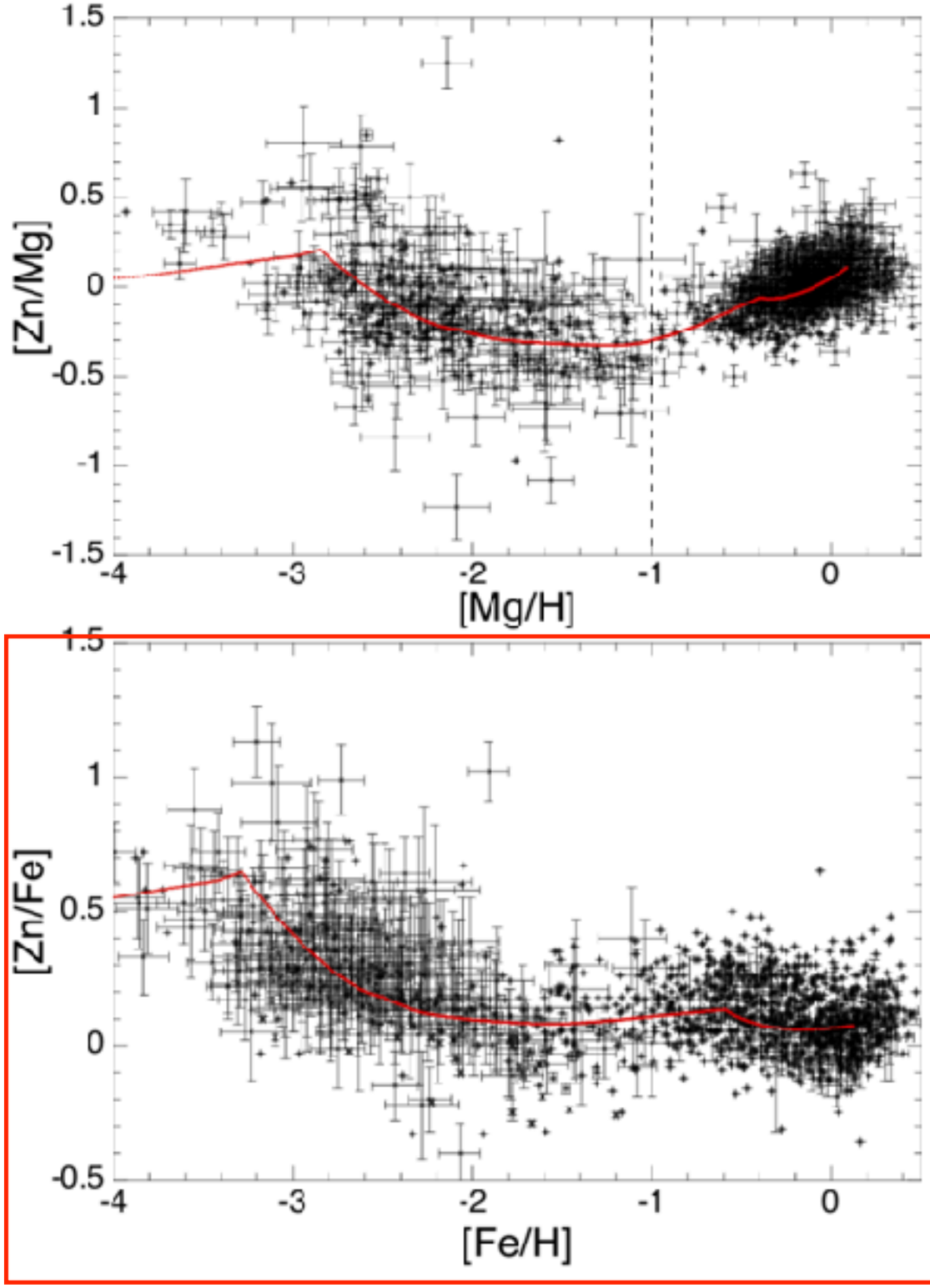
“Zn-problem”

Tsujimoto, NN, Thielemann (in prep)

MR-SNe

CC-SN + SN-Ia





see, Hirai+(2018)

- EC-SNe
- “hypernovae”