OMEG15@YITP Kyoto

Observational signatures of magneto-rotational supernovae associated with r-process jets

Nobuya Nishimura

YITP, Kyoto University

collaboration with

J. Matsumoto (Fukuoka U), T. Takiwaki (NAOJ), H.Sawai (RIST)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP

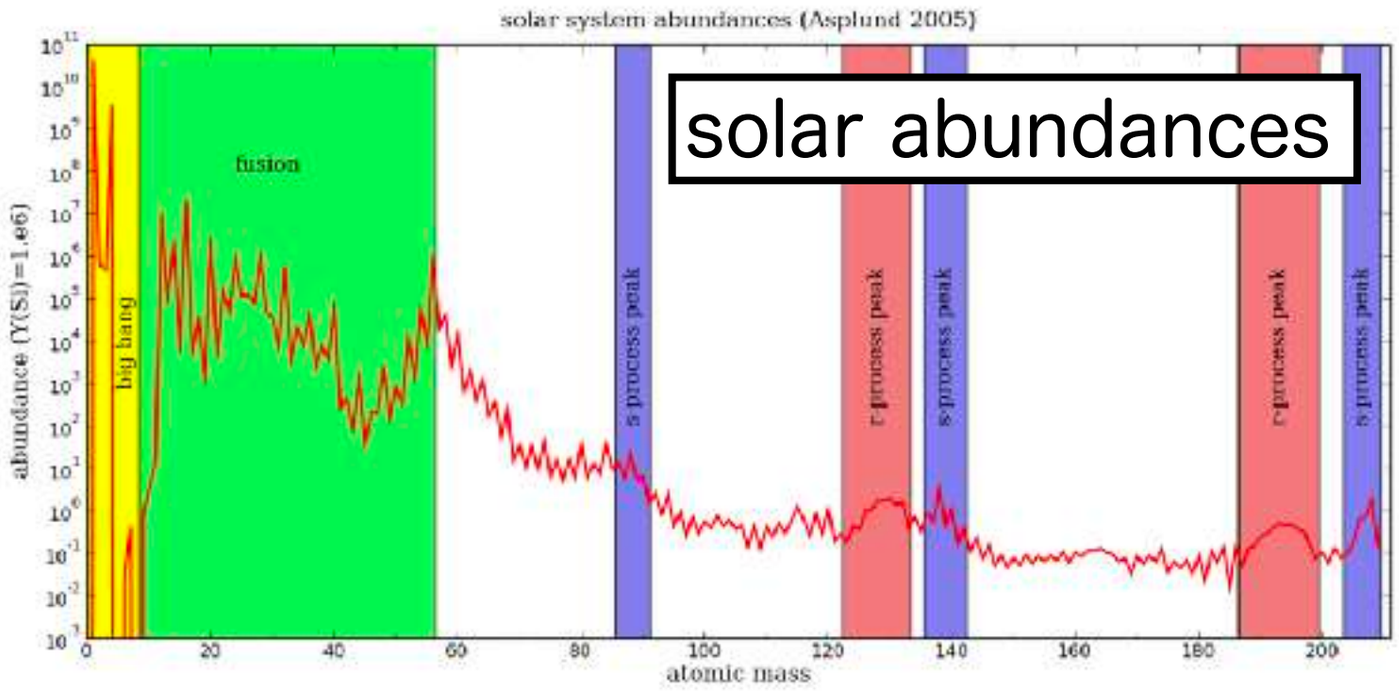
京都大学 KYOTO UNIVERSITY

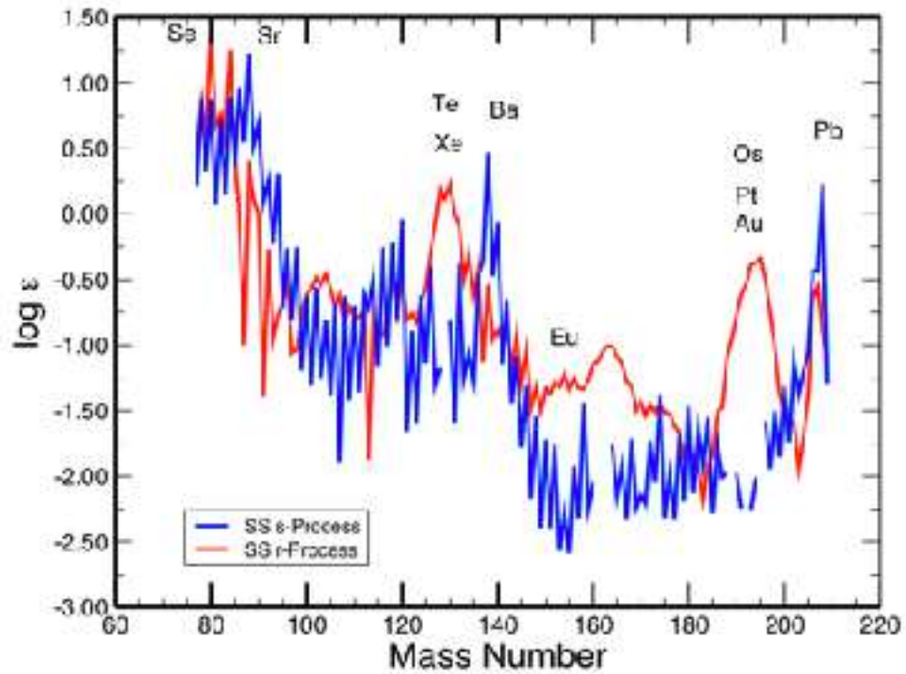
JICFuS 計算基礎科学連携拠点 Joint Institute for Computational Fundamental Science

K computer

r-Process elements in nature (solar system)

Cowan+2019





classification of s & r processes is based on the s-process calculation

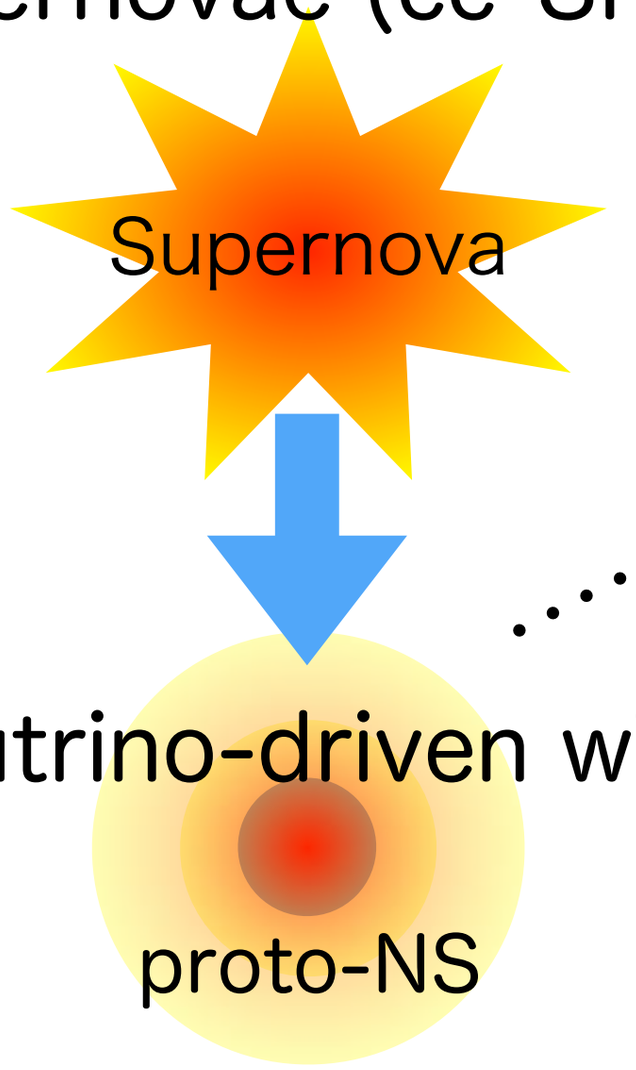
"solar r" = [solar abundances] - "solar s"(=theory)

- "r-process by NS mergers"

= 0 ? or + other sources?

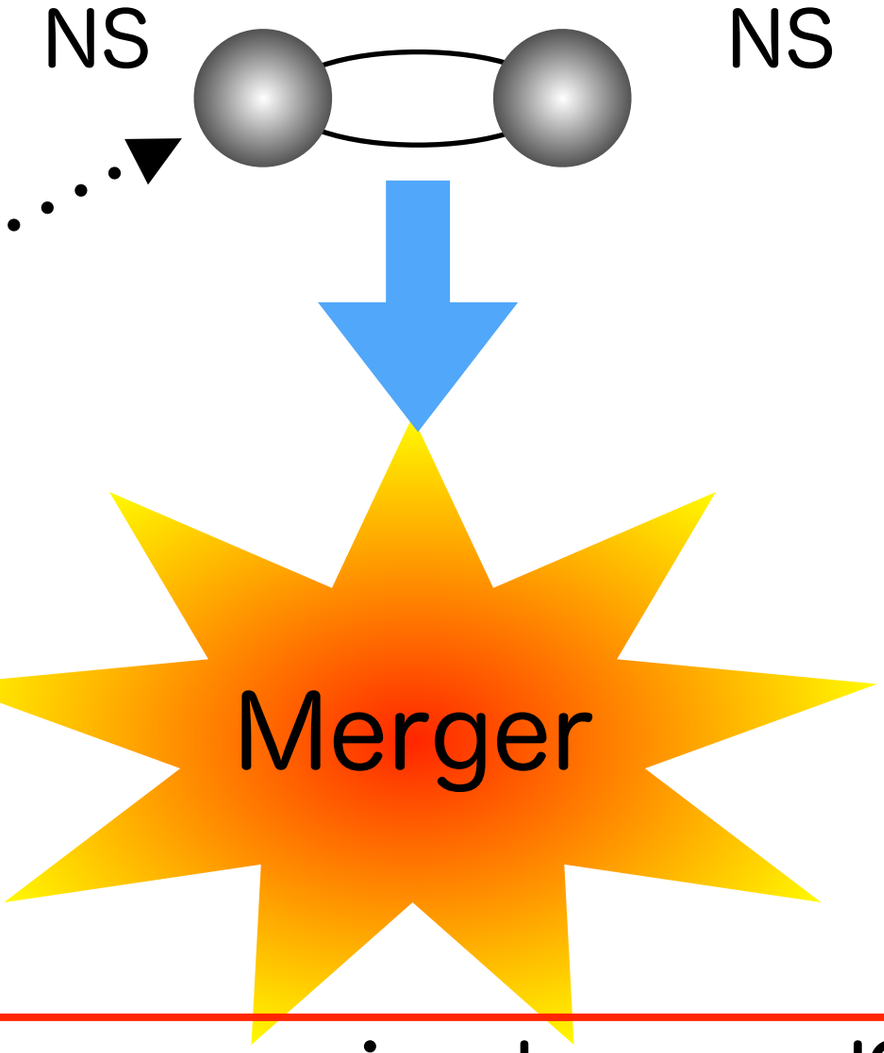
Astronomical site(s) of the r-process

Supernovae (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

Astronomical site(s) of the r-process

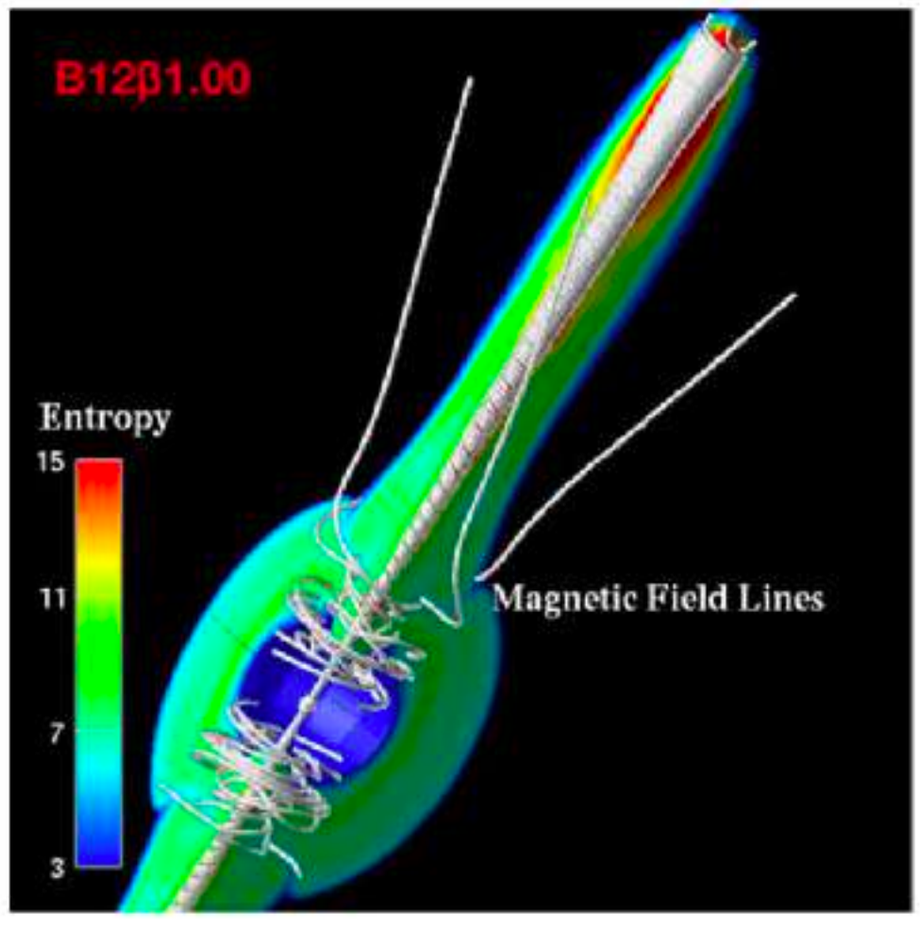
Supernovae (cc-SNe)?

neutrino-driven wind

proto-NS

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

other explosion mechanism
(“extotic” supernovae)
by strong magnetic fields
(so-called jet SNe)



Contents

References

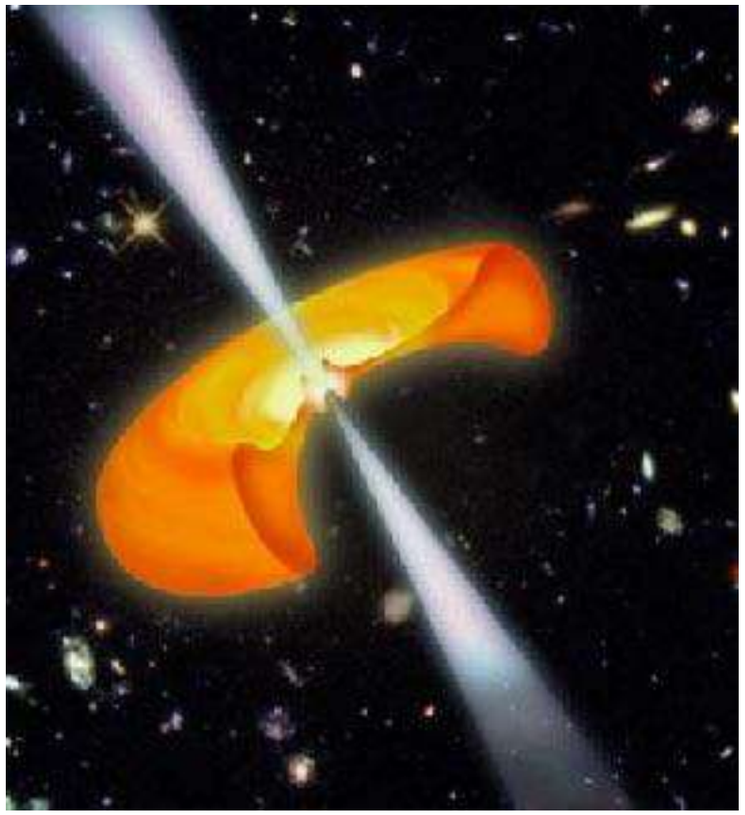
- Winteler+NN+(2012) ApJL 750:L22
- NN, Takiwaki, Thielemann (2015) ApJ 810:109
- Tsujimoto & NN (2015) ApJL 810:L10
- NN, Sawai, Takiwaki+(2017) ApJL 836:L21
- Tsujimoto & NN (2018) ApJL 863:L27

The r-process in MR-SNe

from the central engine to the ejection of r-process matter

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

r-Process in magneto-rotational supernovae

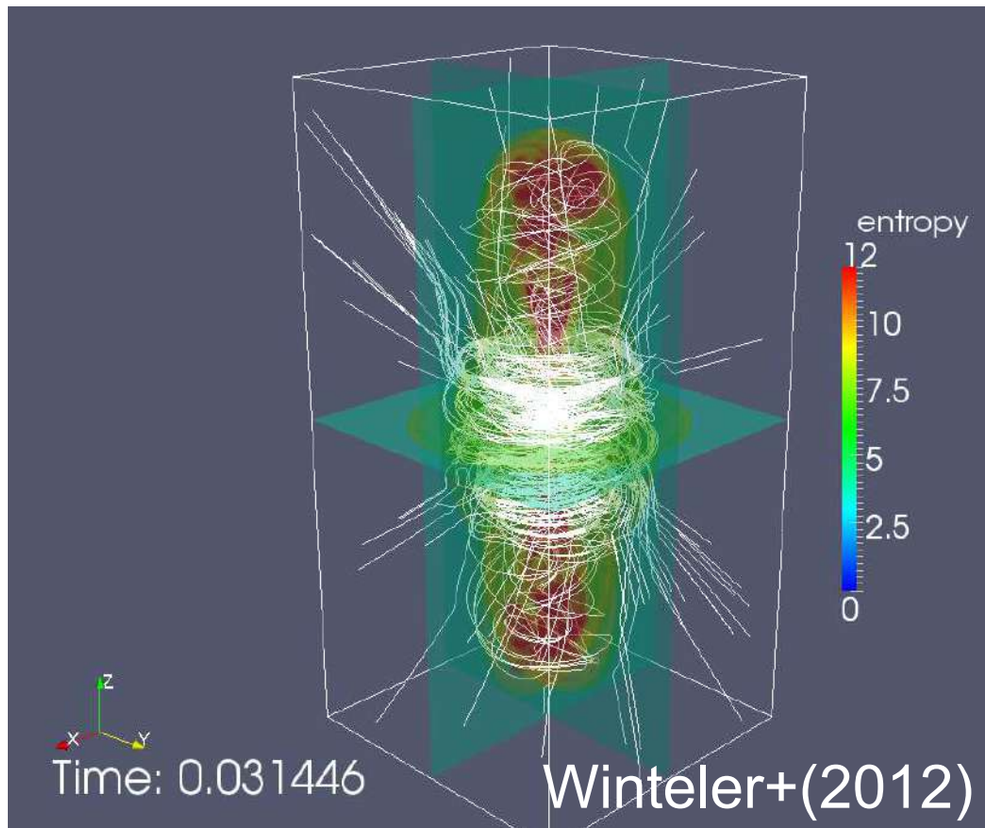


- Magnetar
  - strong magnetic field $\sim 10^{15}$ G

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

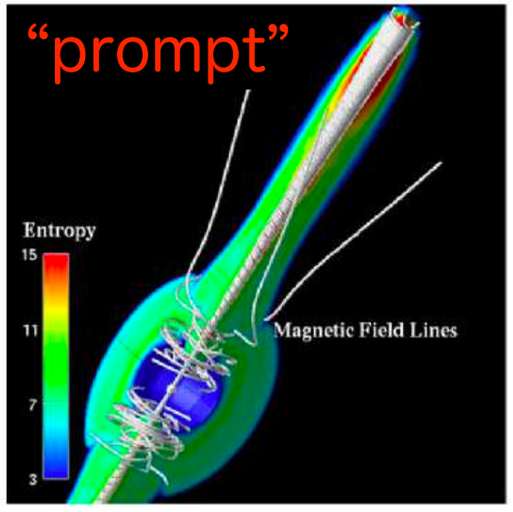


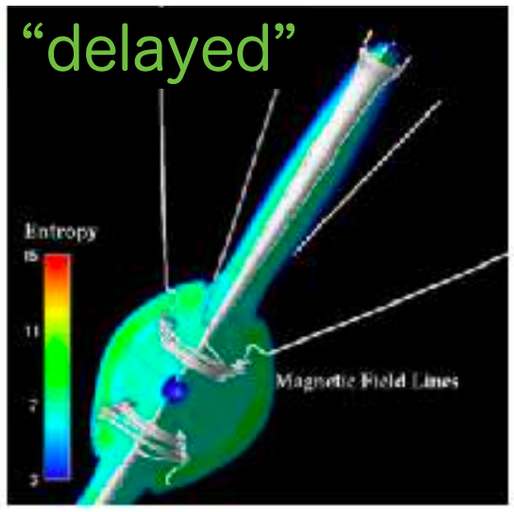
Various r-process in several jet SNe

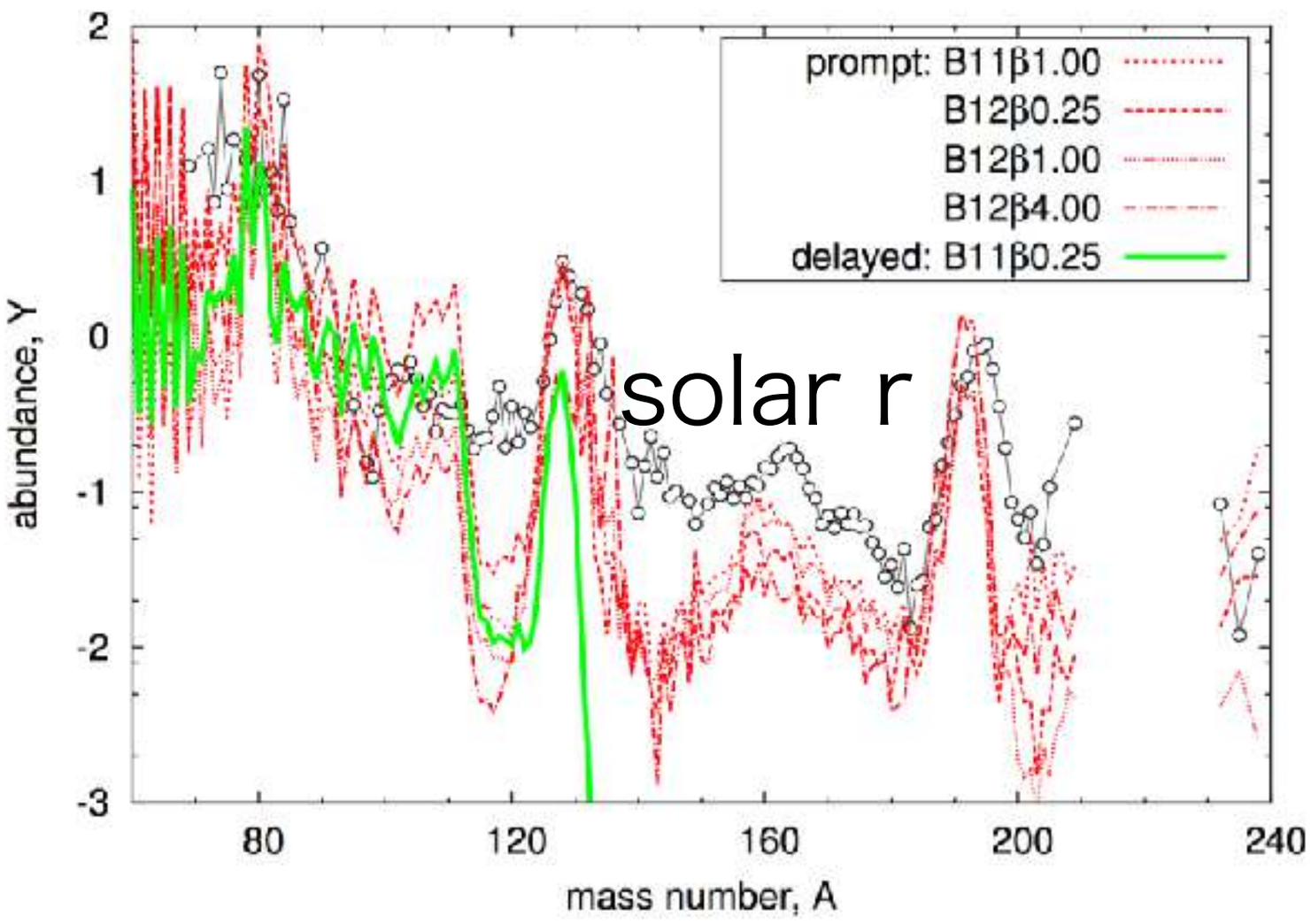
2D-hydro w/ parametric rotation & B-fields

(NN+2015, based on Takiwaki+2009)

- **Strong (prompt)-jets**
  - very n-rich from the inside of the PSN (strong e^--capture)
- **Weaker (delayed) jets**
  - less neutron-rich due to strong neutrino absorption



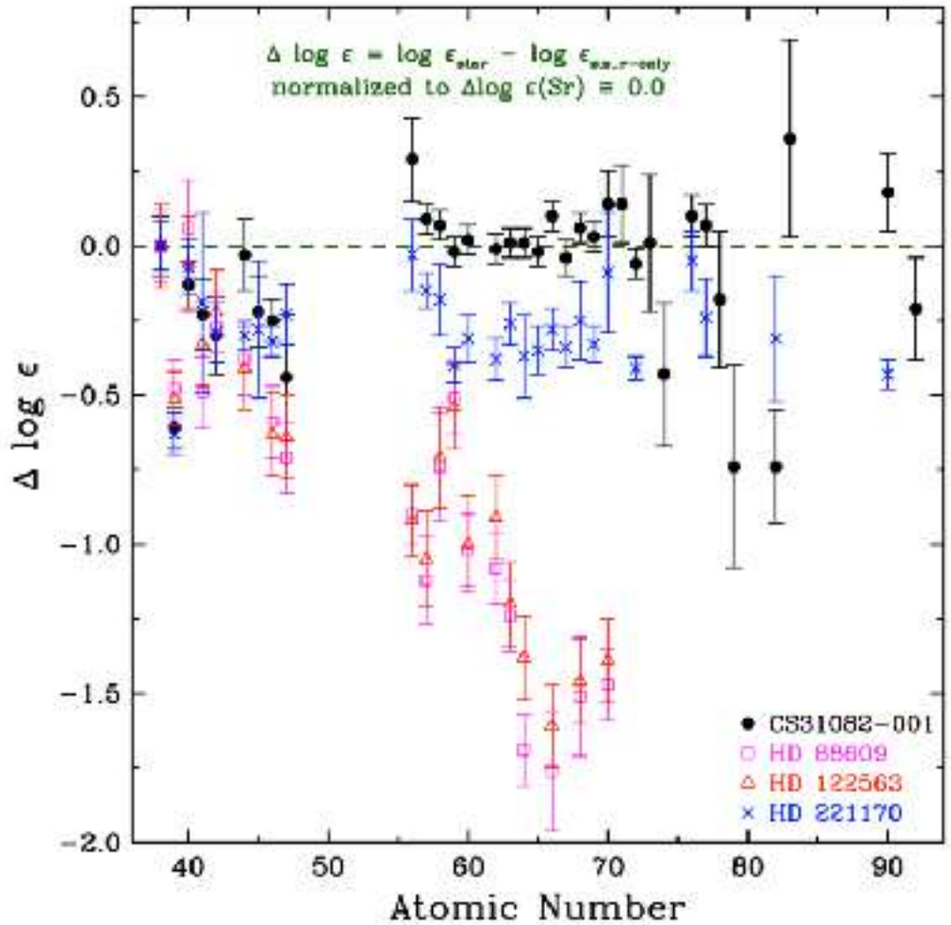




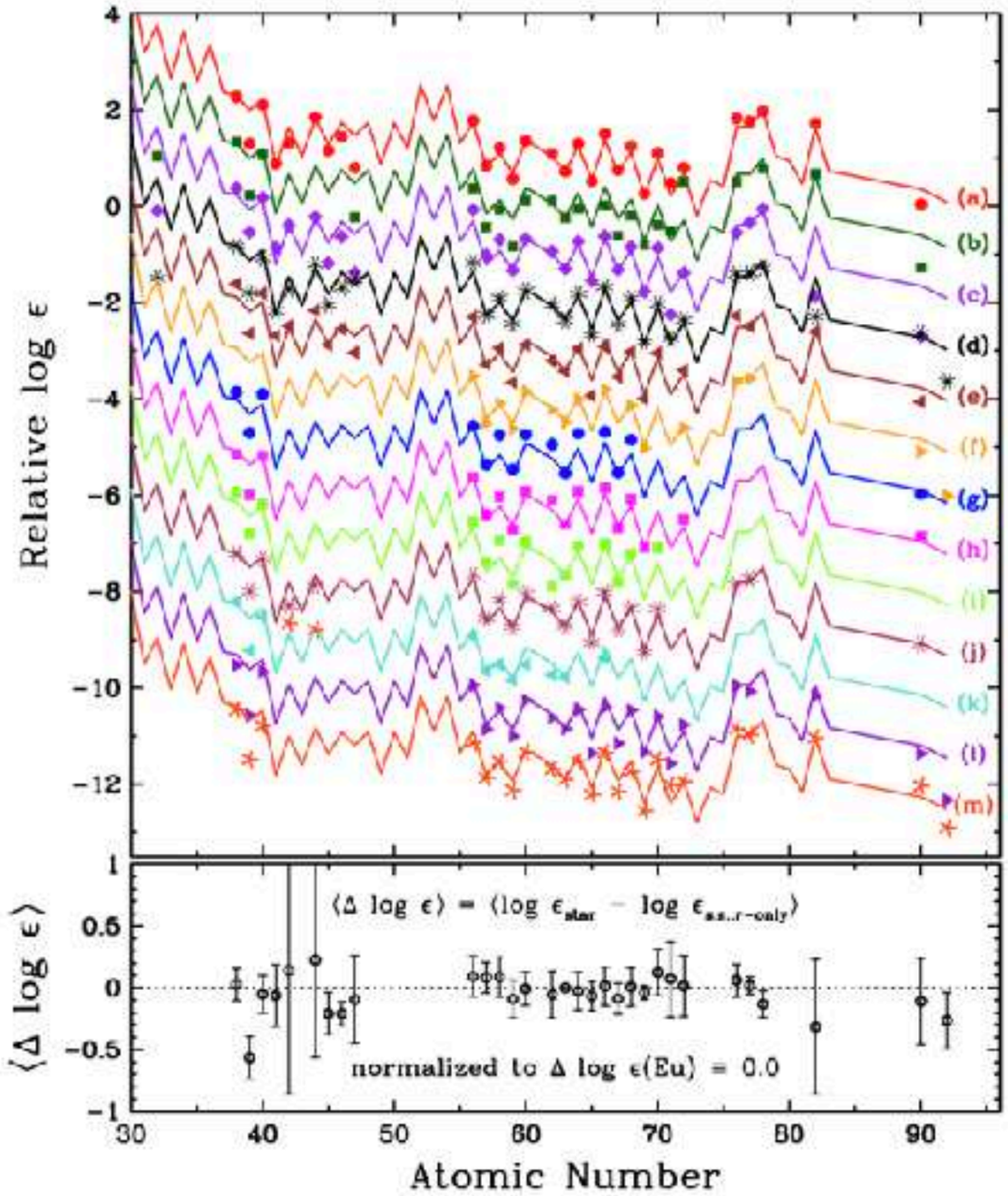
Diversity in metal-poor star abundances?

- 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)

Cowan+2019



Cowan+2019



- However, growing evidence for "weak" r-process patterns (e.g., Honda+2006)

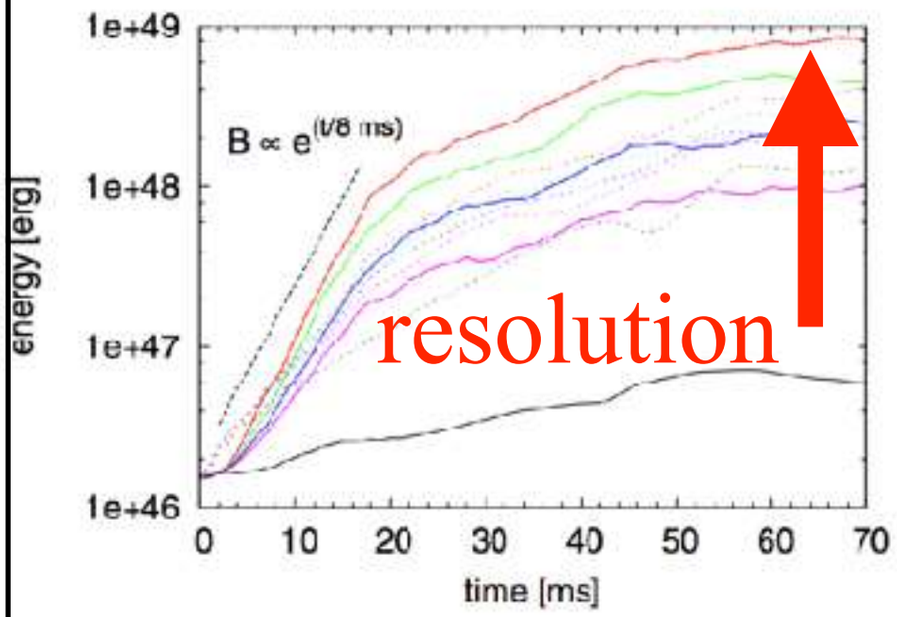
Magneto-rotational instability in CC-SN

Sawai & Yamada (2014, 2016)

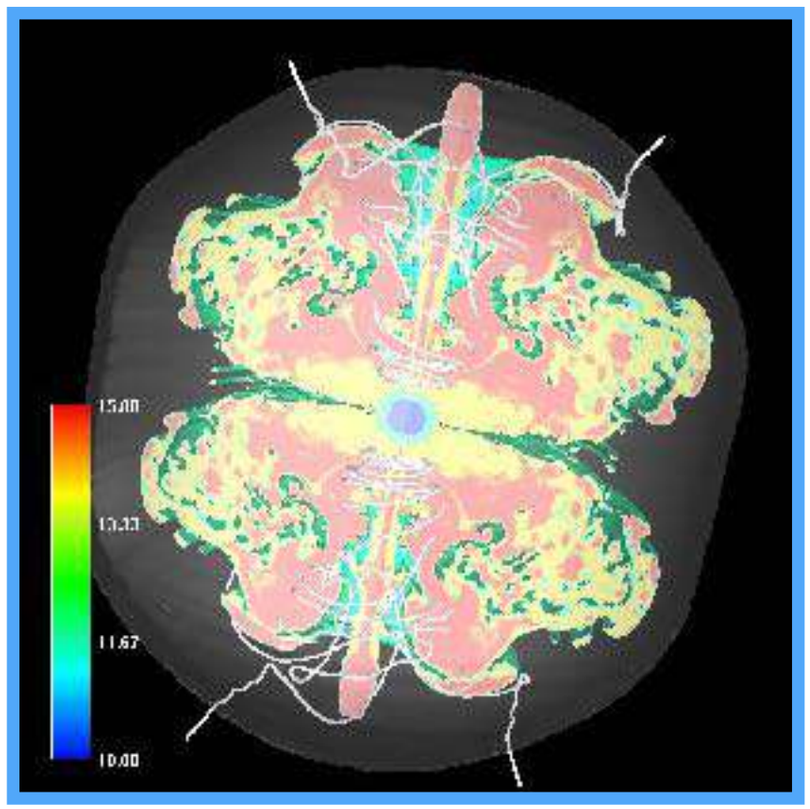
Δr_{min} = 100, 50, 25, 12.5 m

- MR-hydro code (山桜: “YAMAZAKURA”)
- MRI enhance B-fields of the core
- neutrino-heating also affects explosion
- 2D axisymmetric
- initial condition:
  - $15M_{sun}$ (Fe: $1.4M_{sun}$) (Woosley&Heger1995)
  - rotation (core): 2.7 rad/s
  - B-fields: 2×10^{11} G (B flux: 7×10^{27} cm^{2}G)

—> magnetar candidate



Entropy + B-fields(3D)



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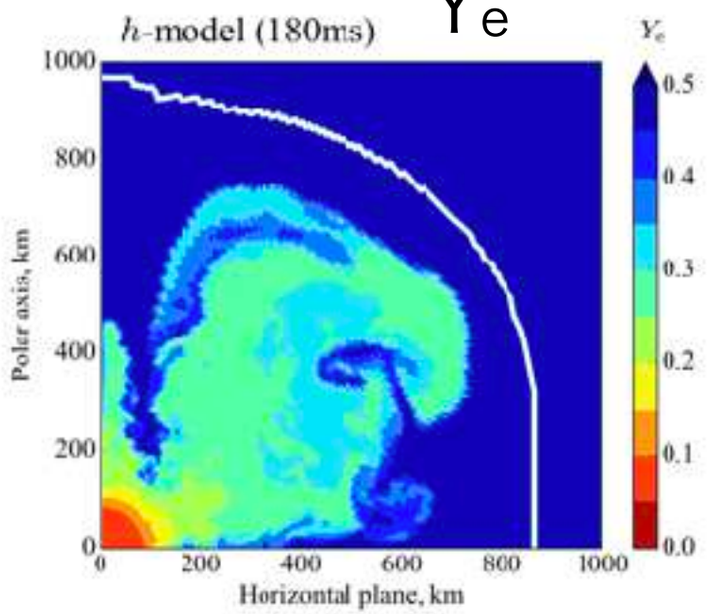
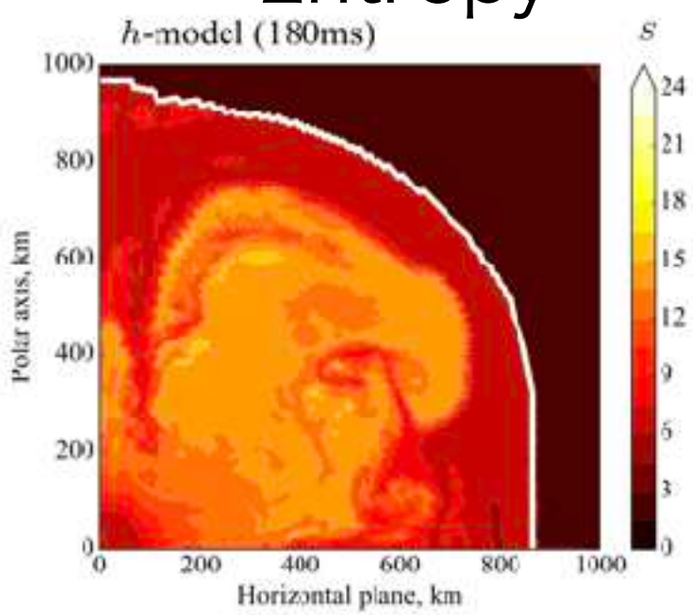


Entropy



Need those strong initial B-fields?

Problem: varying B-fields/rotation

—> requires MRI convergence for each case

and comparison among models are difficult

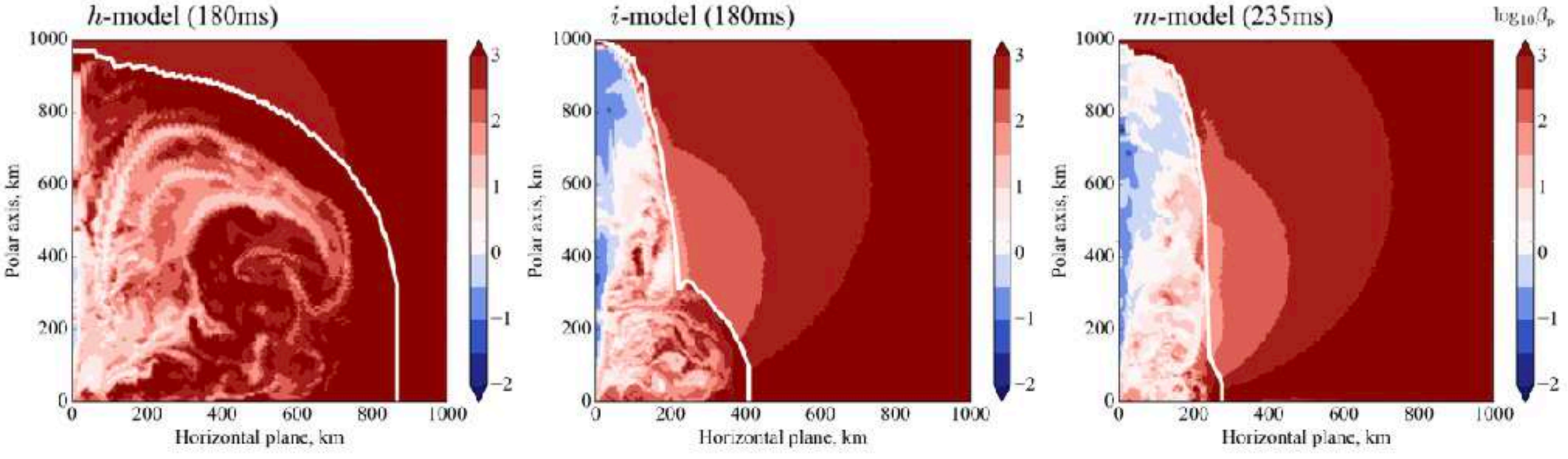
Adopt: varying L_ν —> effective strength of B-fields in explosion dynamics

heating-dominated

intermediate

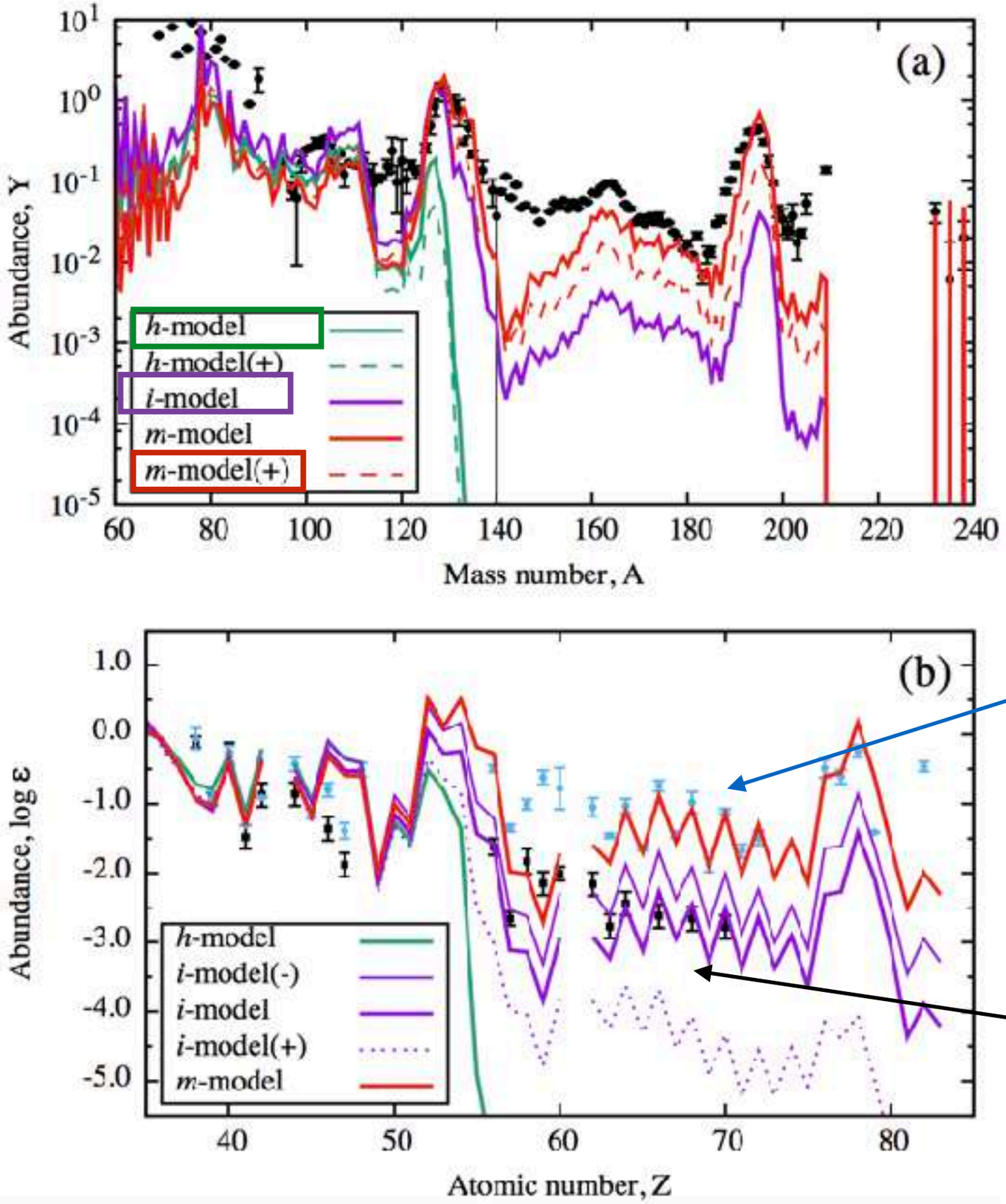
magnetically-dominated

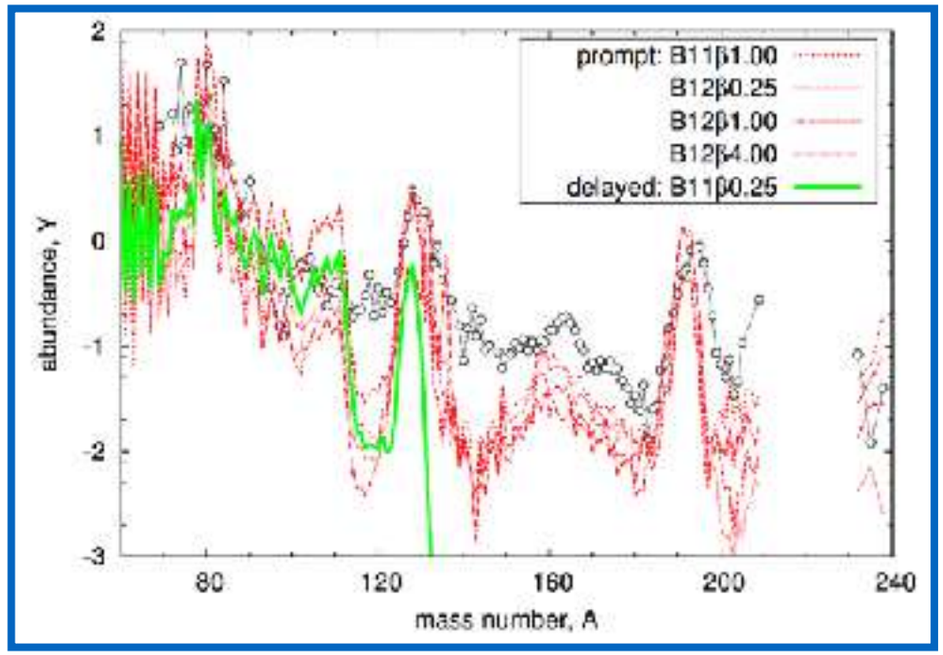
plasma-β



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)

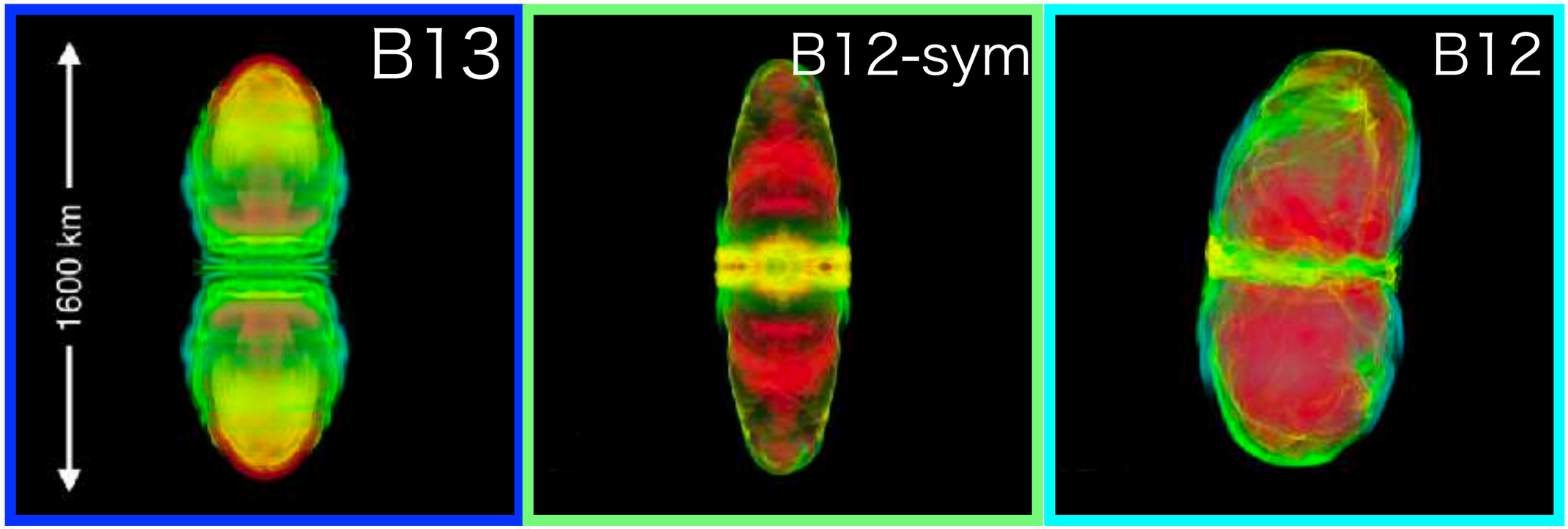
What we have done and need to next?

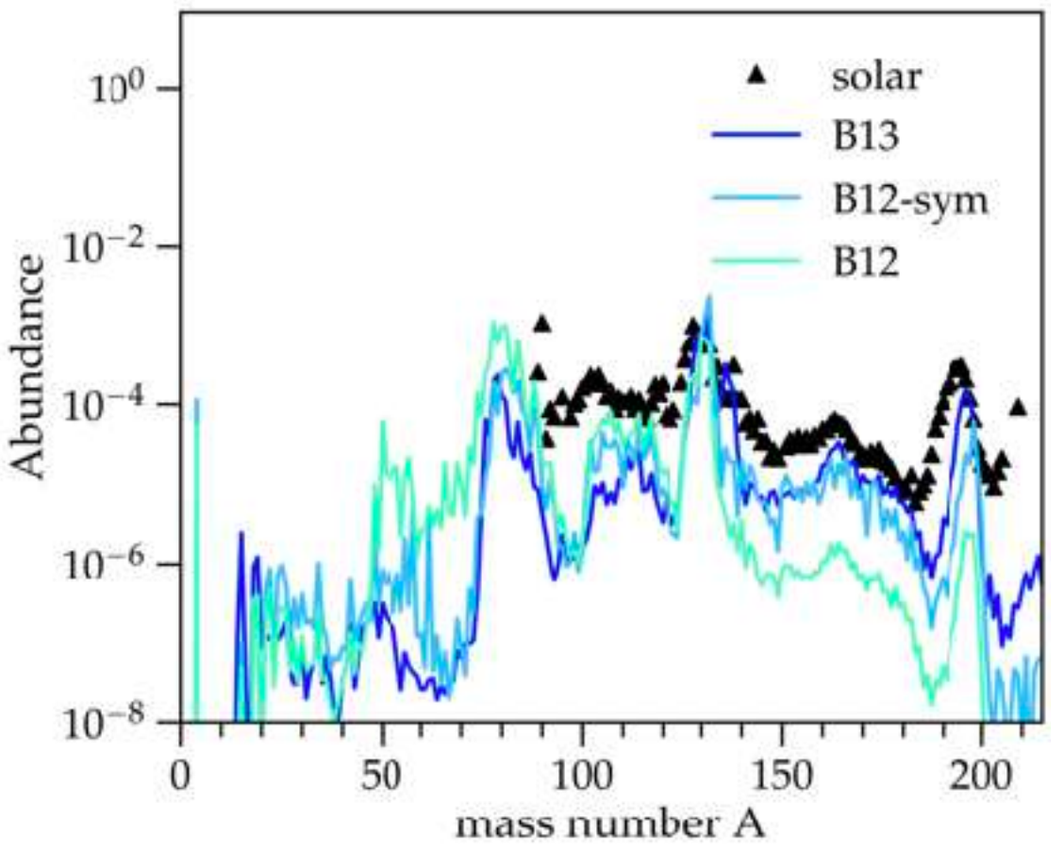
- ✔ Magnetically-driven polar-jets (“prompt jets”) produce produce heavy r-process elements
- ✔ while weaker explosions (“delayed-jets”) show weaker r-process (A < 130)
- ✔ more “realistic” (mild B-fields) prefer weaker r-processes?
- ✔ “intermediate” pattern can be reproduced by proper stellar parameters

- Really need/exist such strong initial magnetic fields?
  → stellar evolution w/ rotation & B-fields
- 3D effects
  - jet propagation
  - MRI in full 3D
- Longer-term (time and space) simulation

3D effects on the r-process

by Mösta+(2018)





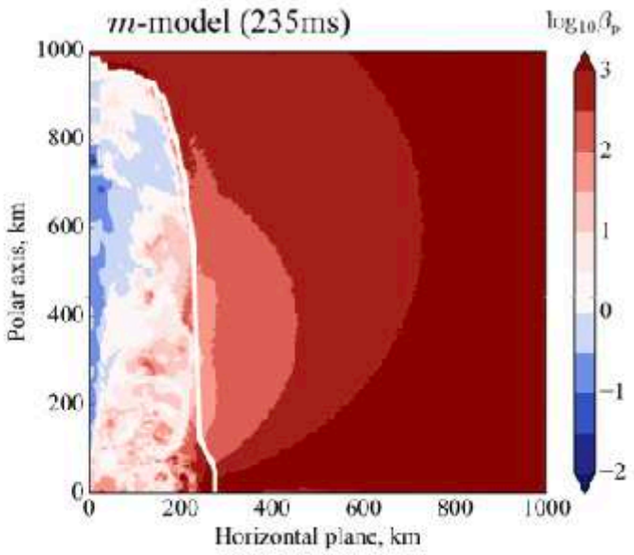
- B12: weaker r: is more realistic
- B12-sym: artificially enhance jets
  —> prompt-jet of Nishimura+(2015)
- B13: unrealistically strong mag. fields
  —> Winteler+2012

misaligning rotation and B-field axises:
Halevi & Mösta (2018)

Strong-magnetic jet: (strong r)

hydrodynamical simulation
by J. Matsumoto

NN, Sawai+2017

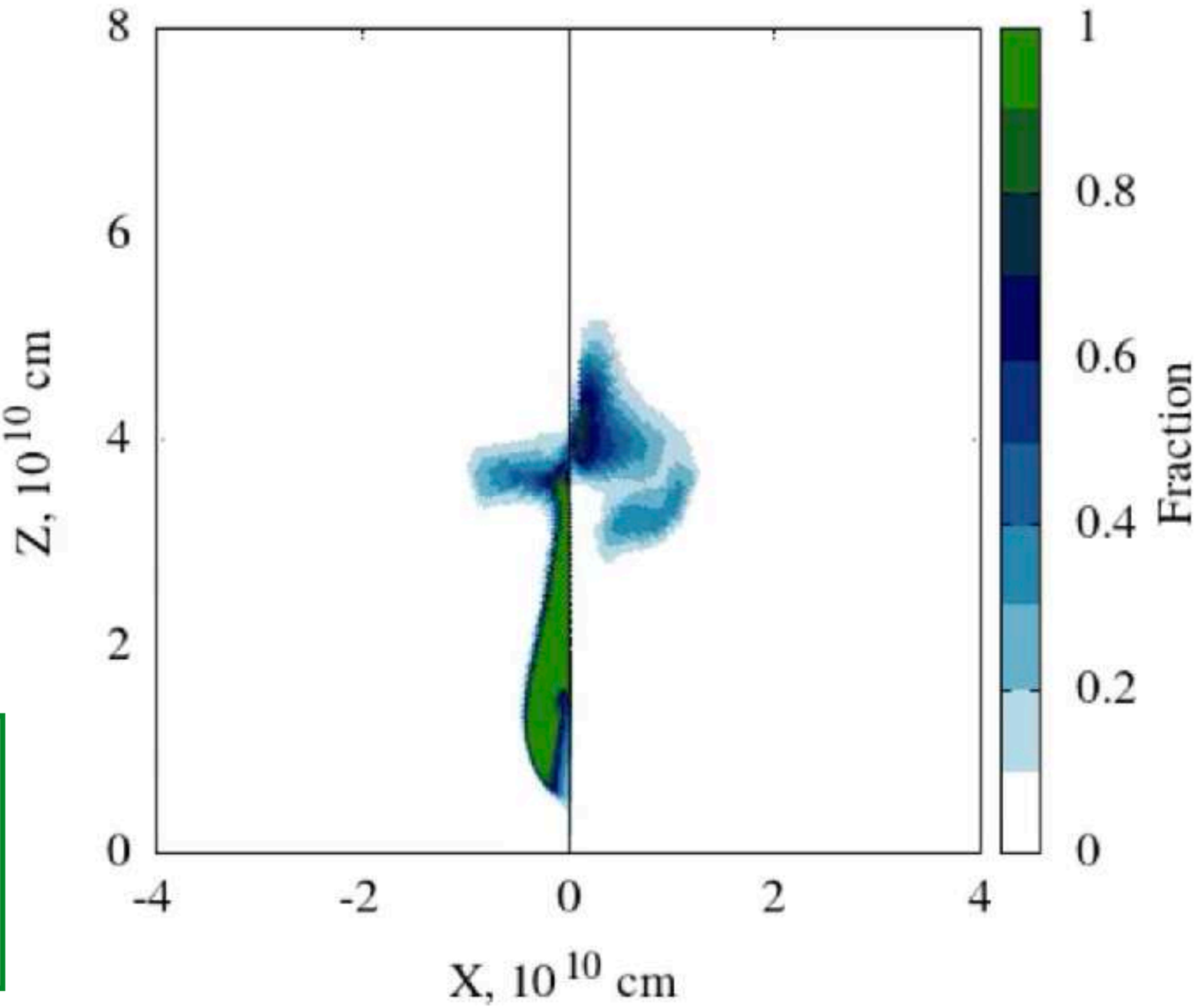


10^8 cm

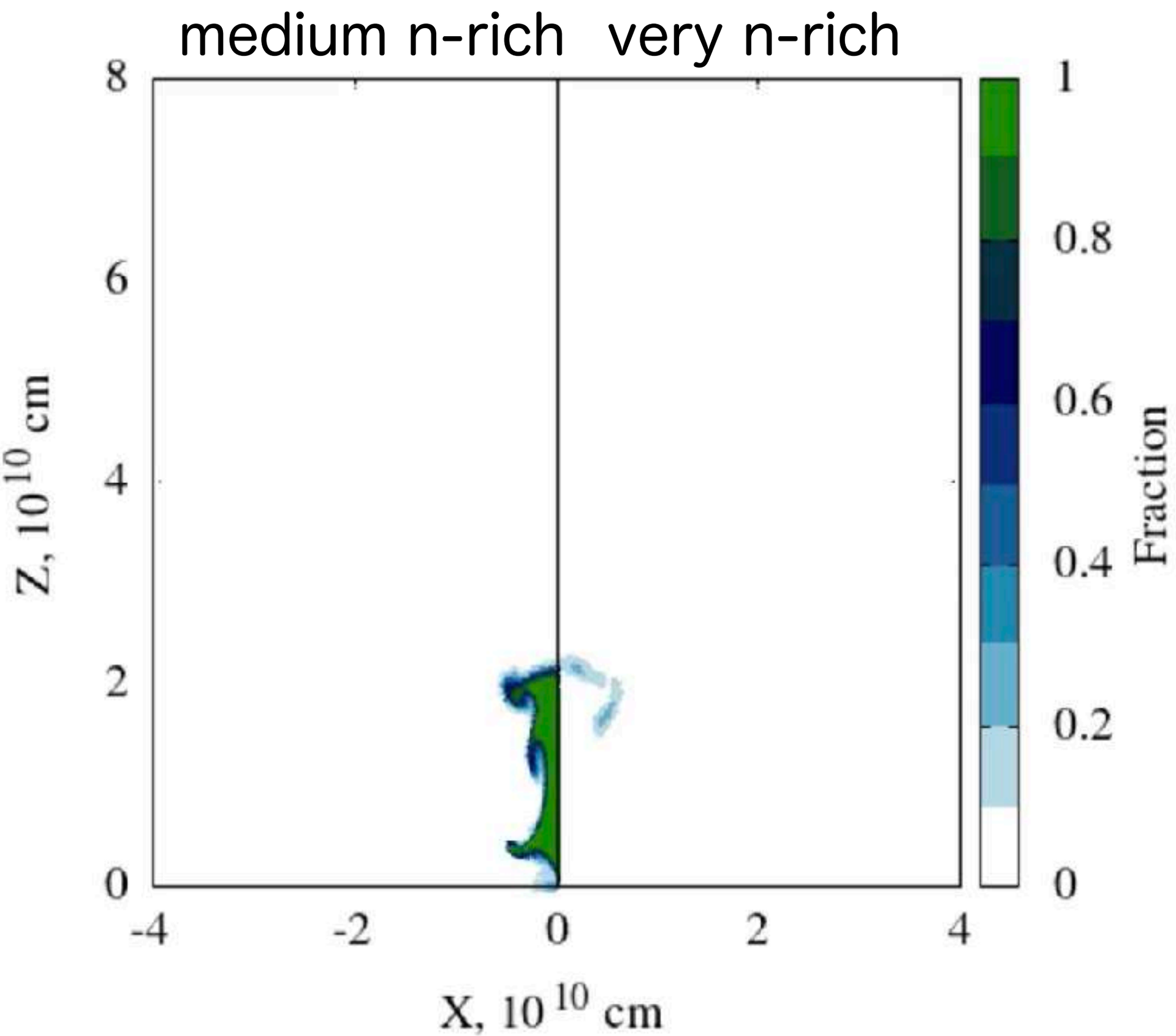
x 100

- hydrodynamics w/o B-fields
- “jet” injection

medium n-rich very n-rich



Weker magnetic-jet: intermediate r



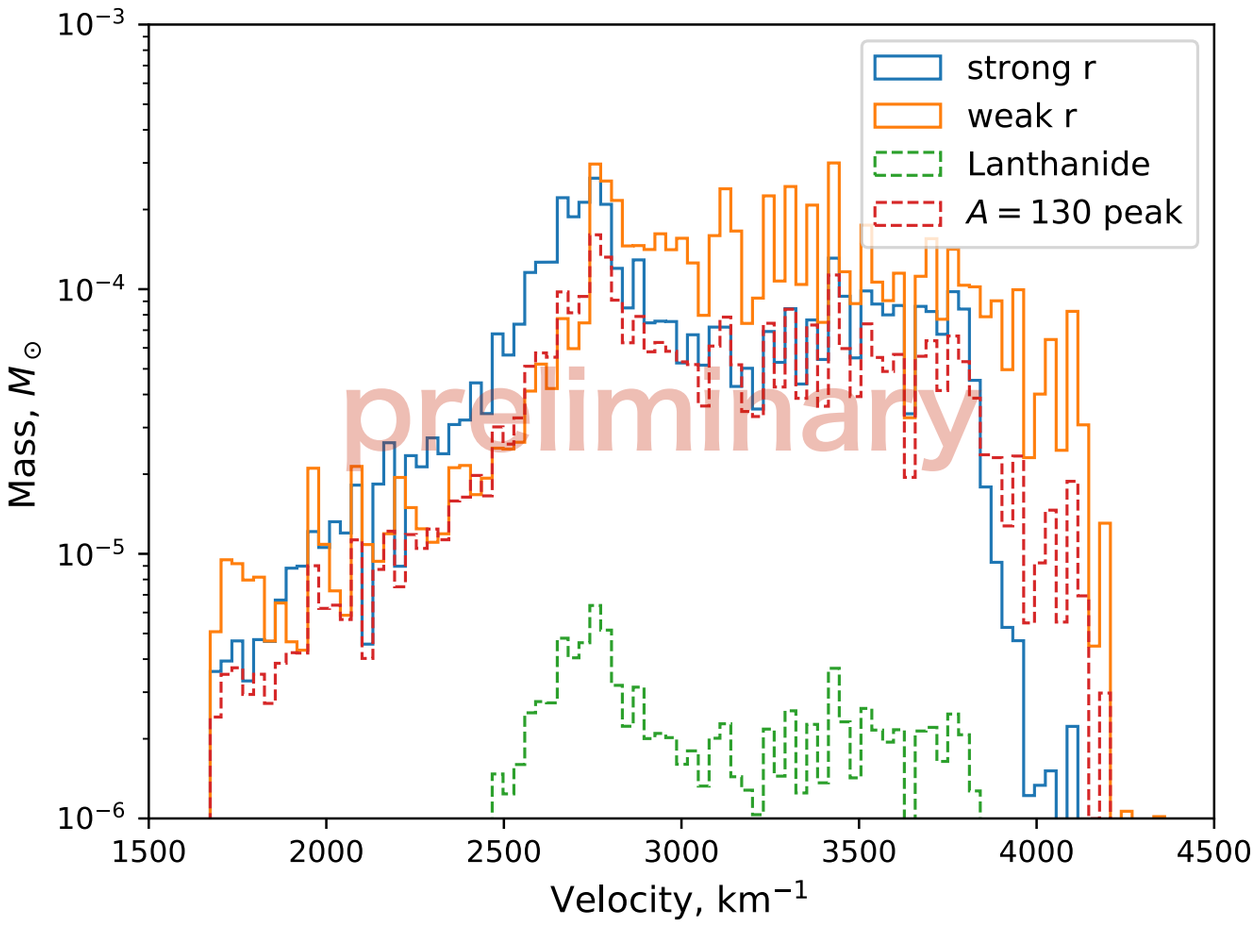
Elemental distribution in ejecta

based on the nucleosynthesis condition of NN+2017:

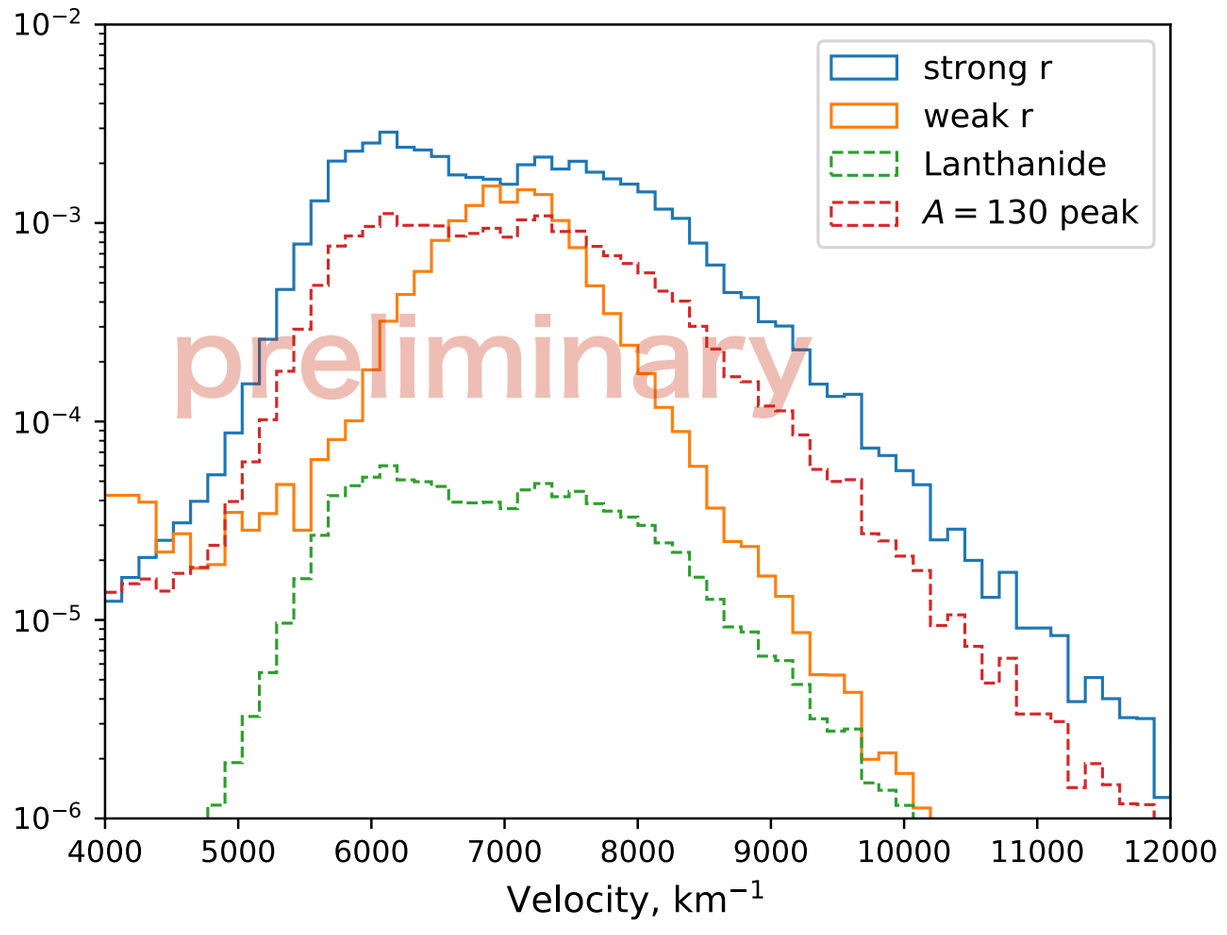
very n-rich —> strong r

medium n-rich —> “intermediate r”

weak magnetic jet



stronger magnetic jet



—> future observation will provide new insights?

Summary: r-process in MR-Supernovae

- Central engine
  - MR-SNe can produce a variety of r-process patterns depending on explosion models (rotation & B-fields)
  - Several uncertainties and problems remain: hydro-simulations, initial rotation and B-fields etc.
  - Shock launch by MRI and shock deformation appear to result in suppress the neutron-rich condition
- Ejection phase
  - We apply simplified jet propagation model to follow ejection process of r-process elements
  - different explosion mechanism (magnetic jet?) provide different elemental distribution in ejecta