宇宙最初のrプロセス天体は何か？

What is the first r-process event/star in the universe

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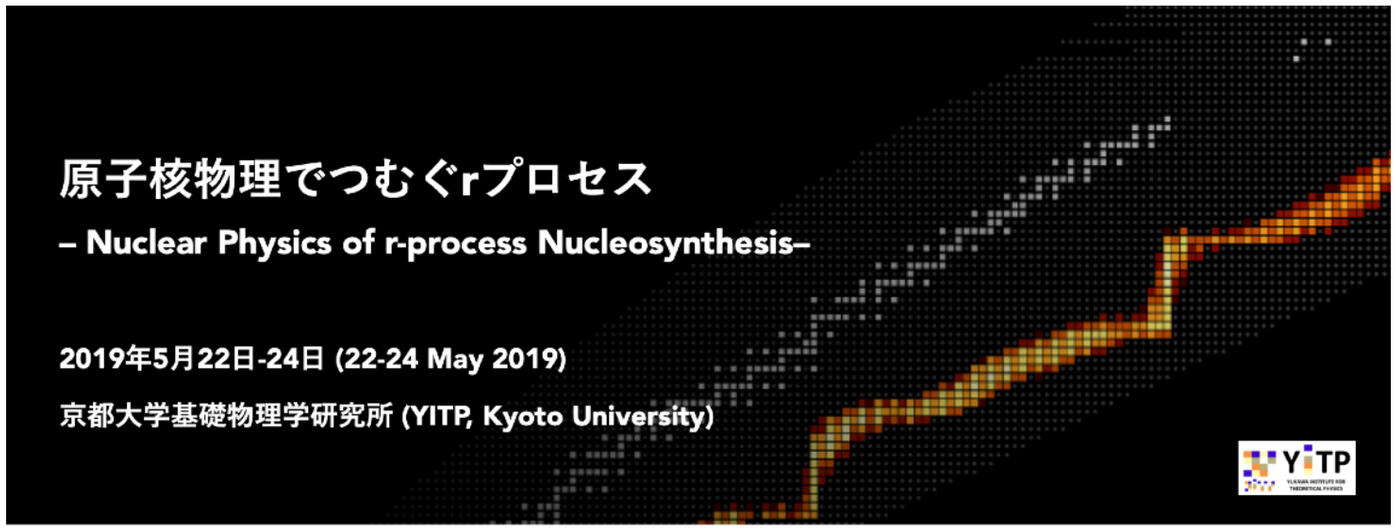
Reviews on r-process studies

- Review papers
  - Horowitz et al. (38 authors), JPhG, (2019)
  - Cowan et al., Rev of Mod. Phys., submitted (arXiv:1901.01410)
- Japanese WSs (in the era of post-GW170817); trilogy(?)

https://sites.google.com/view/rp2018

https://www2.yukawa.kyoto-u.ac.jp/~rp2019



Astrophysics × nuclear-physics

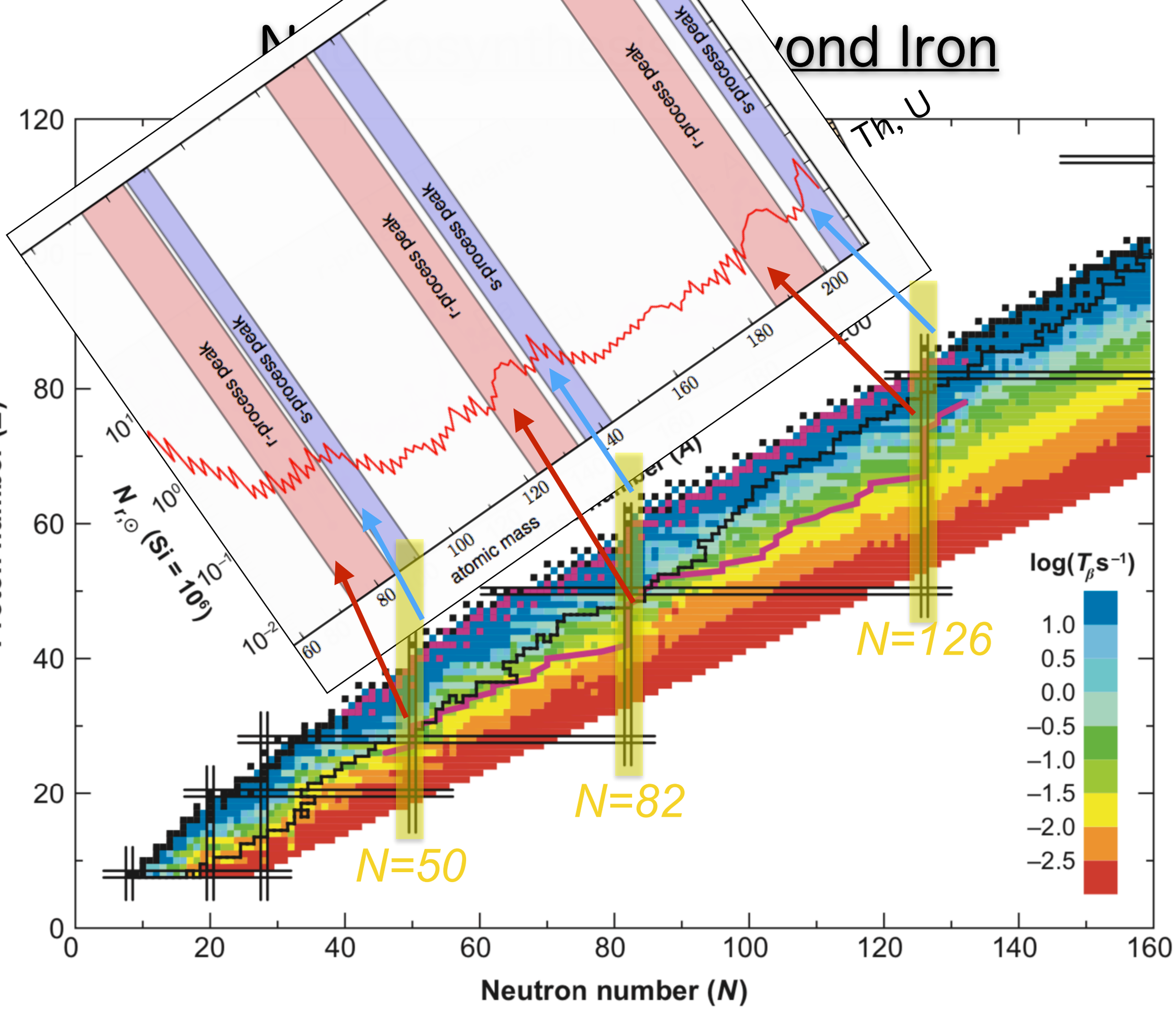
- GW170817
- RIBF experiments
- astrophysics
  - NS-NS mergers
  - kilonovae

Nuclear-physics theory

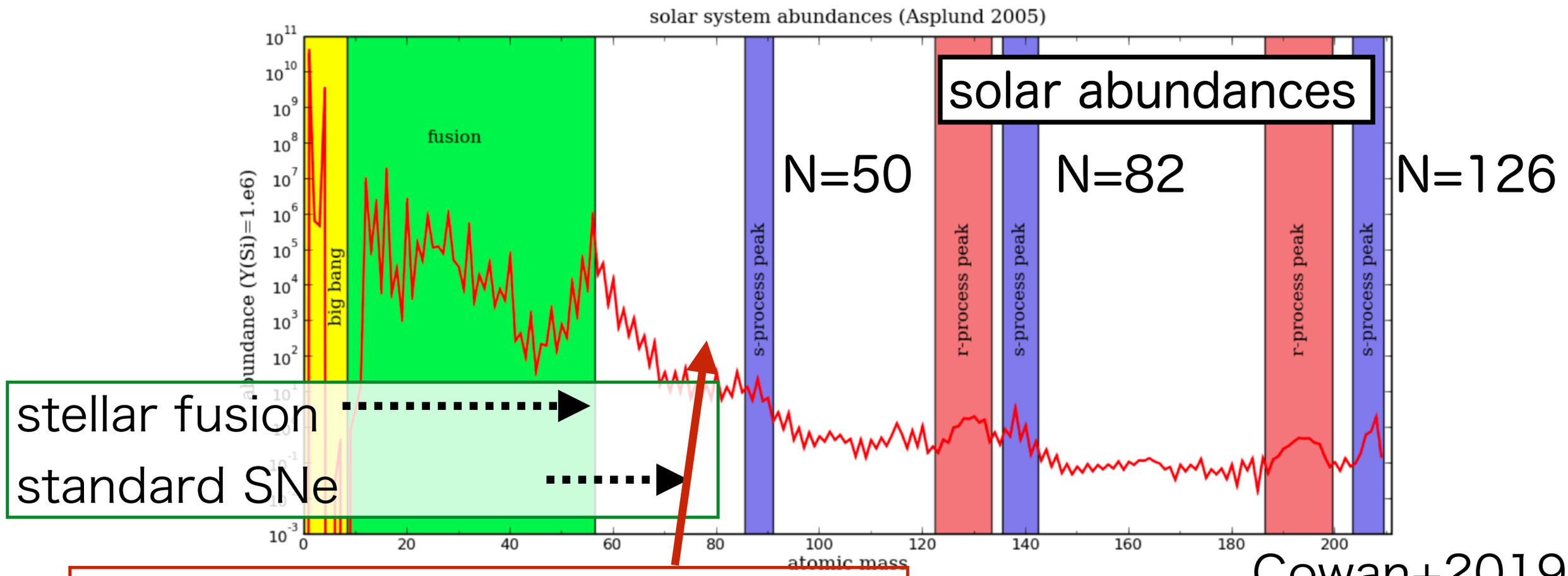
- mass formula
- neutron capture
- β-decay (and others)
- fission

N ond Iron

Th, U



Solar neutron-capture (s/r-process) elements



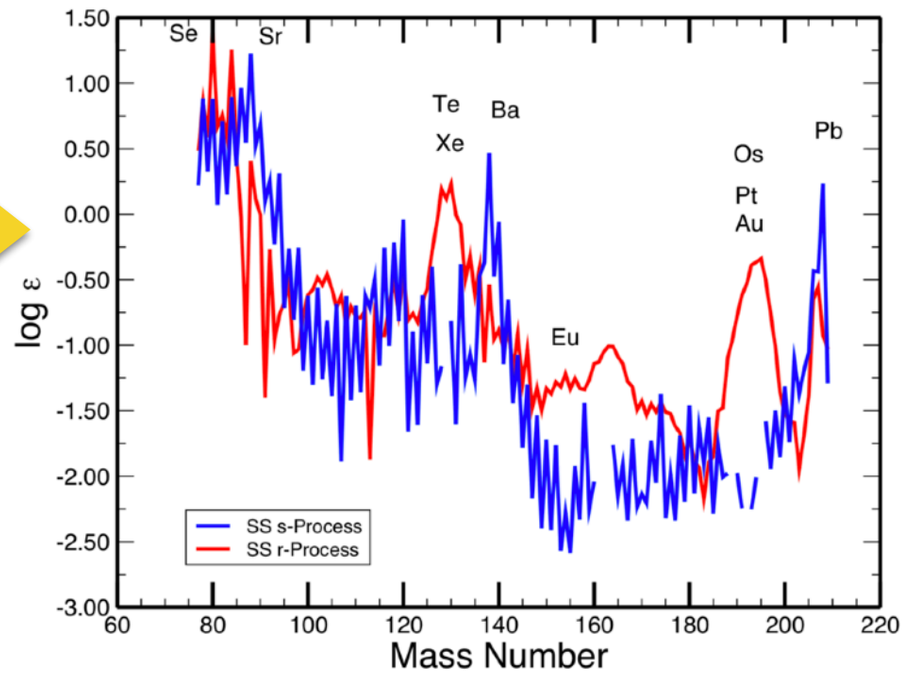
may be NO well defined r-process peak corresponding N = 50

classification of s & r process is based on s-process "theory"

uncertainty of the s-process is due to n-capture on stable nuclei (experimental) (see, NN+2017, Cescutti+NN+2018)

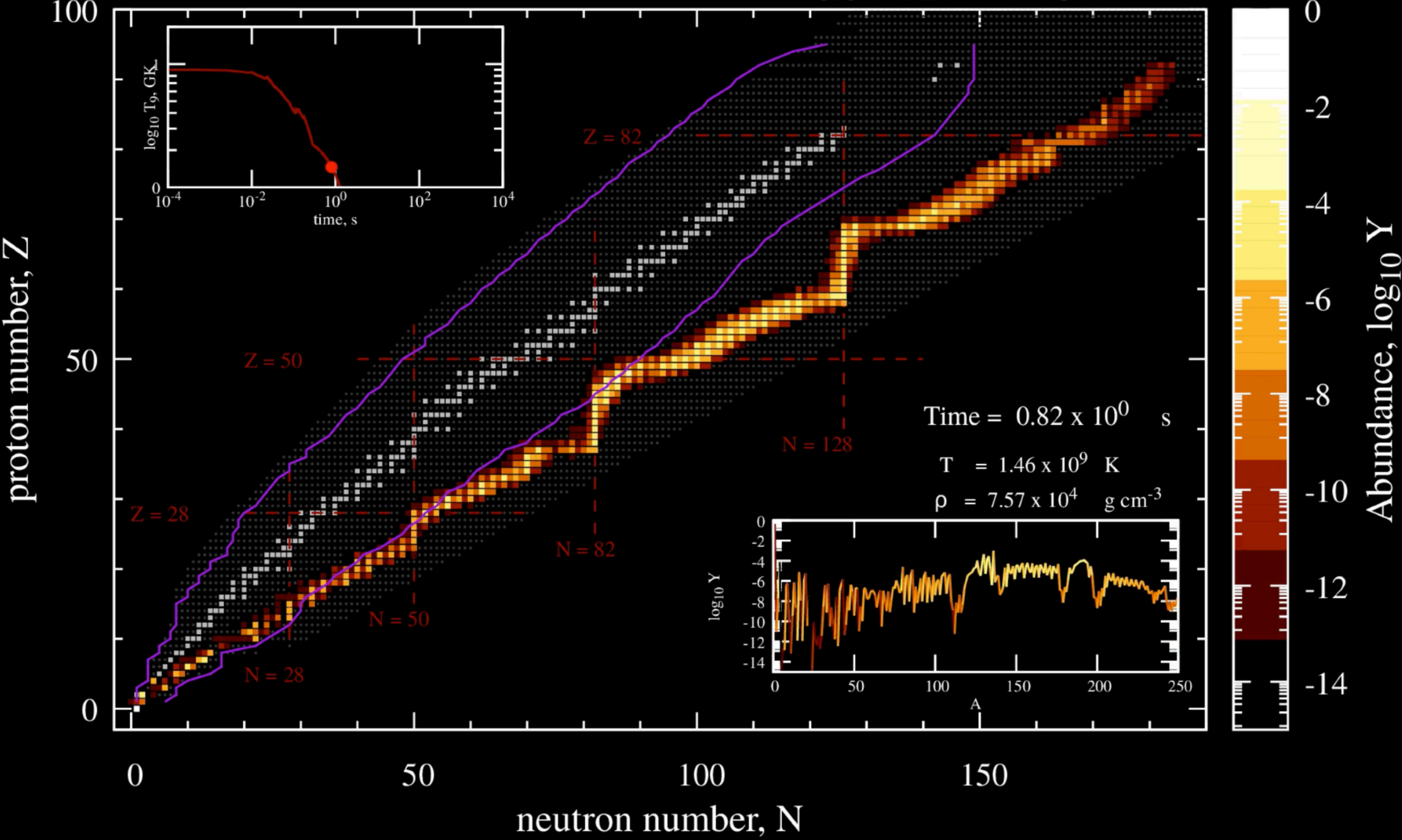
Cowan+2019

Cowan&Thieleman(2004)

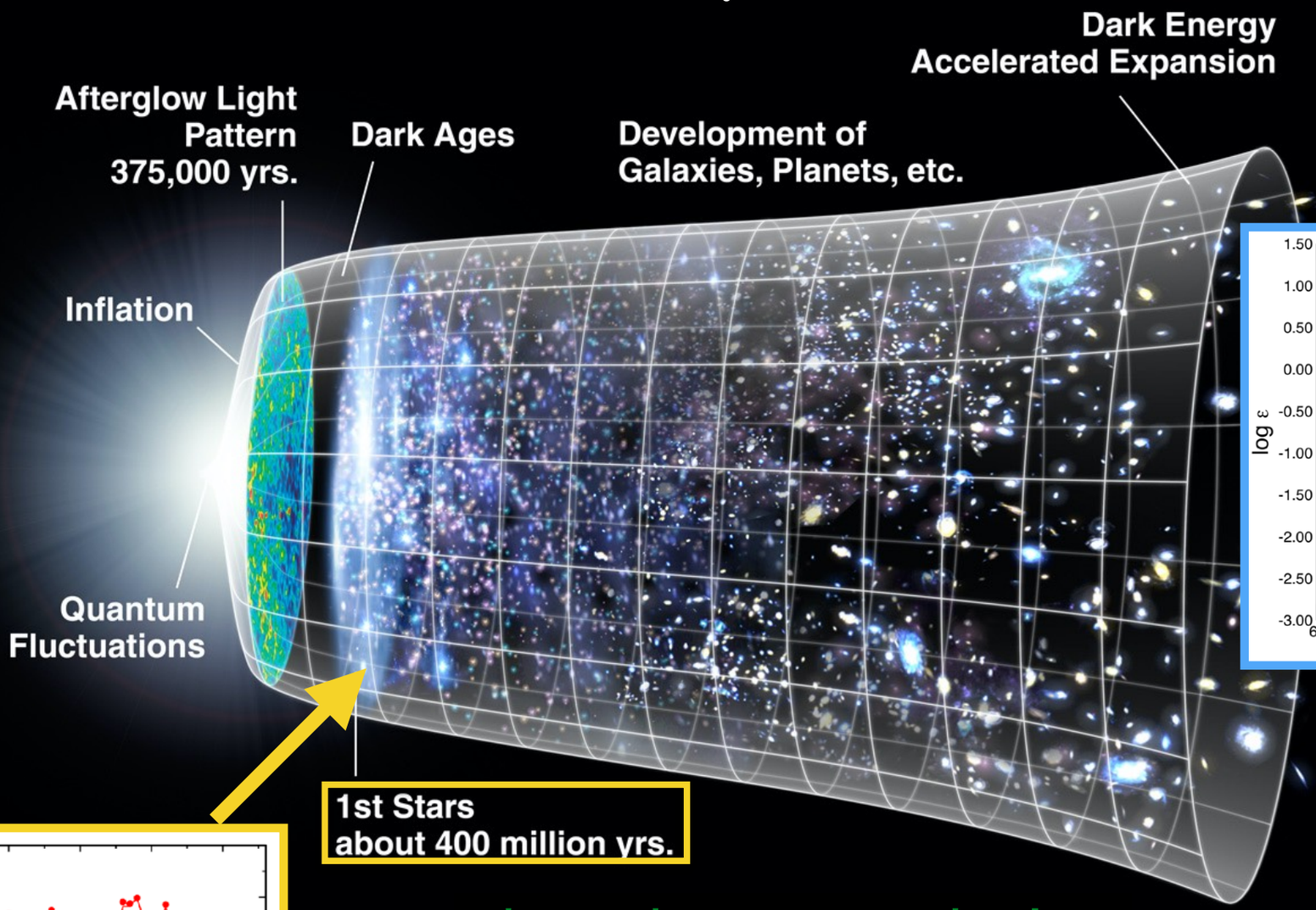


r-process nucleosynthesis “flow”

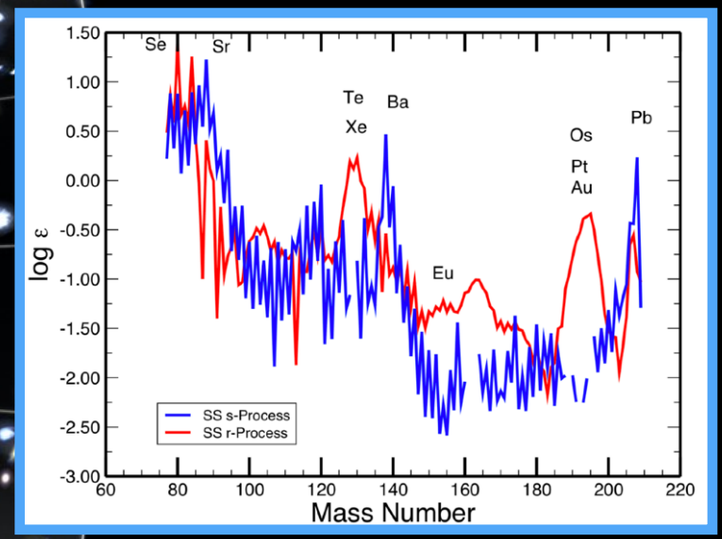
1e-4 pps limit
at RIBF Riken



Evolution of r-process elements

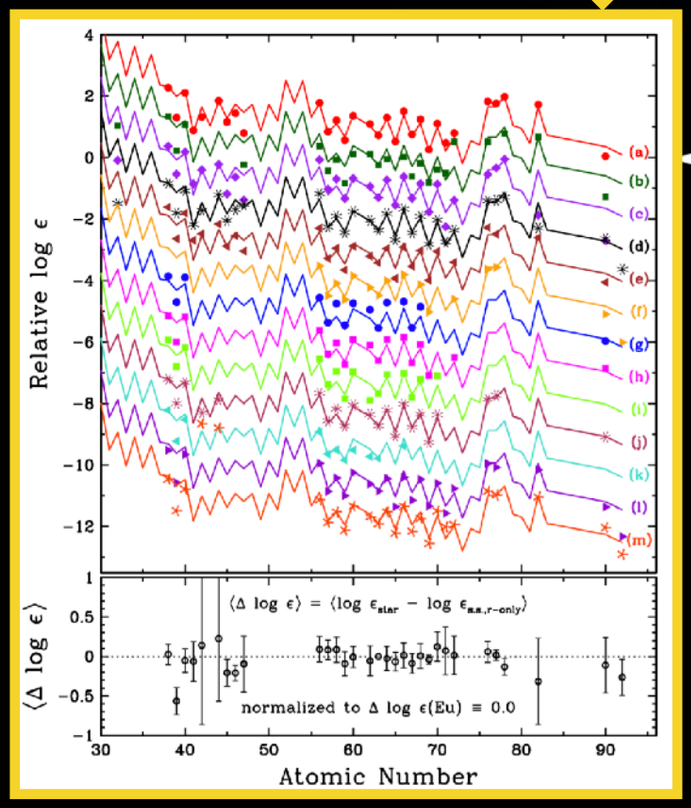


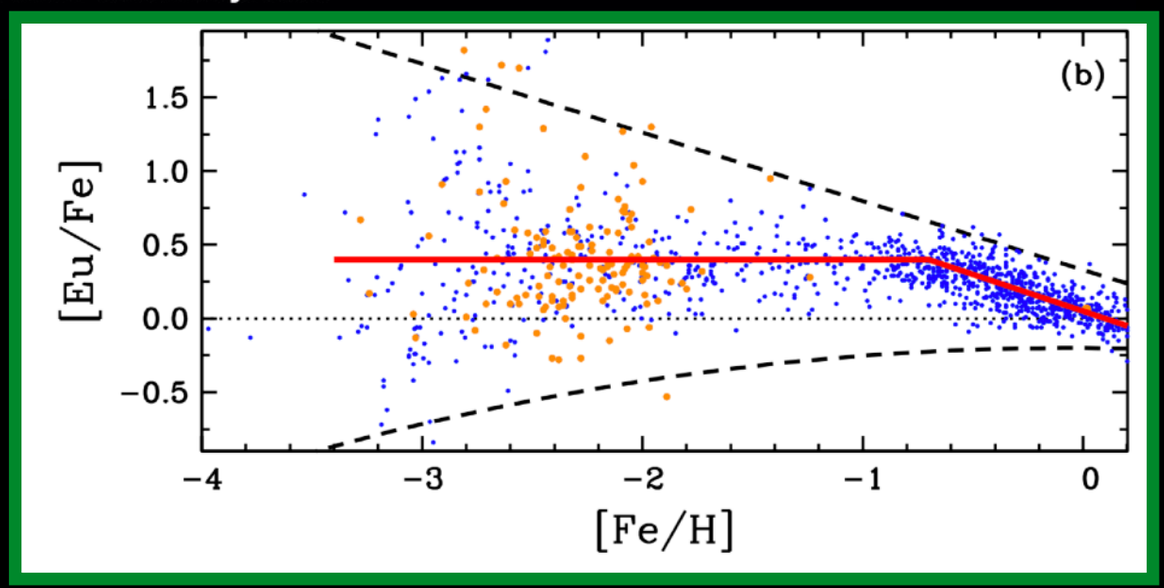
solar abundances



abundance evolution

13.77 billion years





Contents

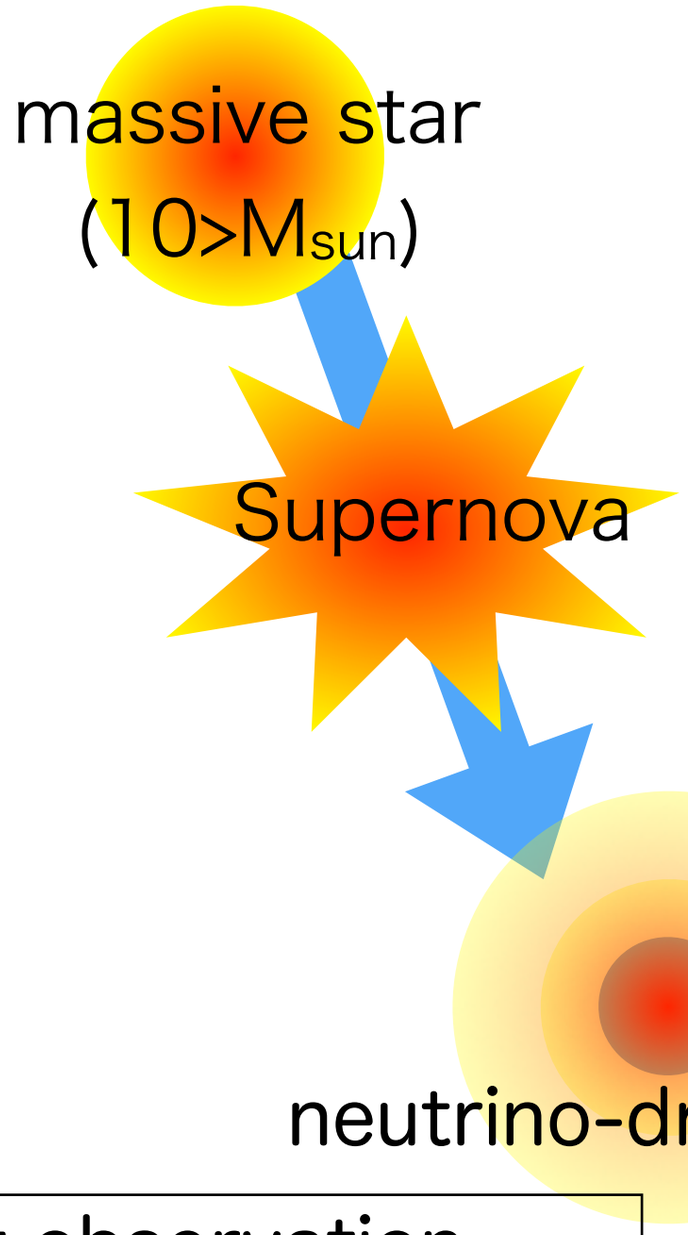
- **Introduction**
  - overview of r-process nucleosynthesis
- **NS mergers as the main r-process site**
  - a brief overview of r-process astrophysical sites
  - NS mergers, GW170817, kilonova/macronova, GCE etc.
- **MR-SNe as alternative r-process sites**
  - central engine of “r-process jet” cc-SNe
  - connection to observation
- **(Nuclear-physics uncertainties)**

Neutron-star mergers as the main r-process site

- Wanajo, Sekiguchi, NN+(2014), ApJL
- Fujibayashi, Kiuchi, NN+(2018), ApJ

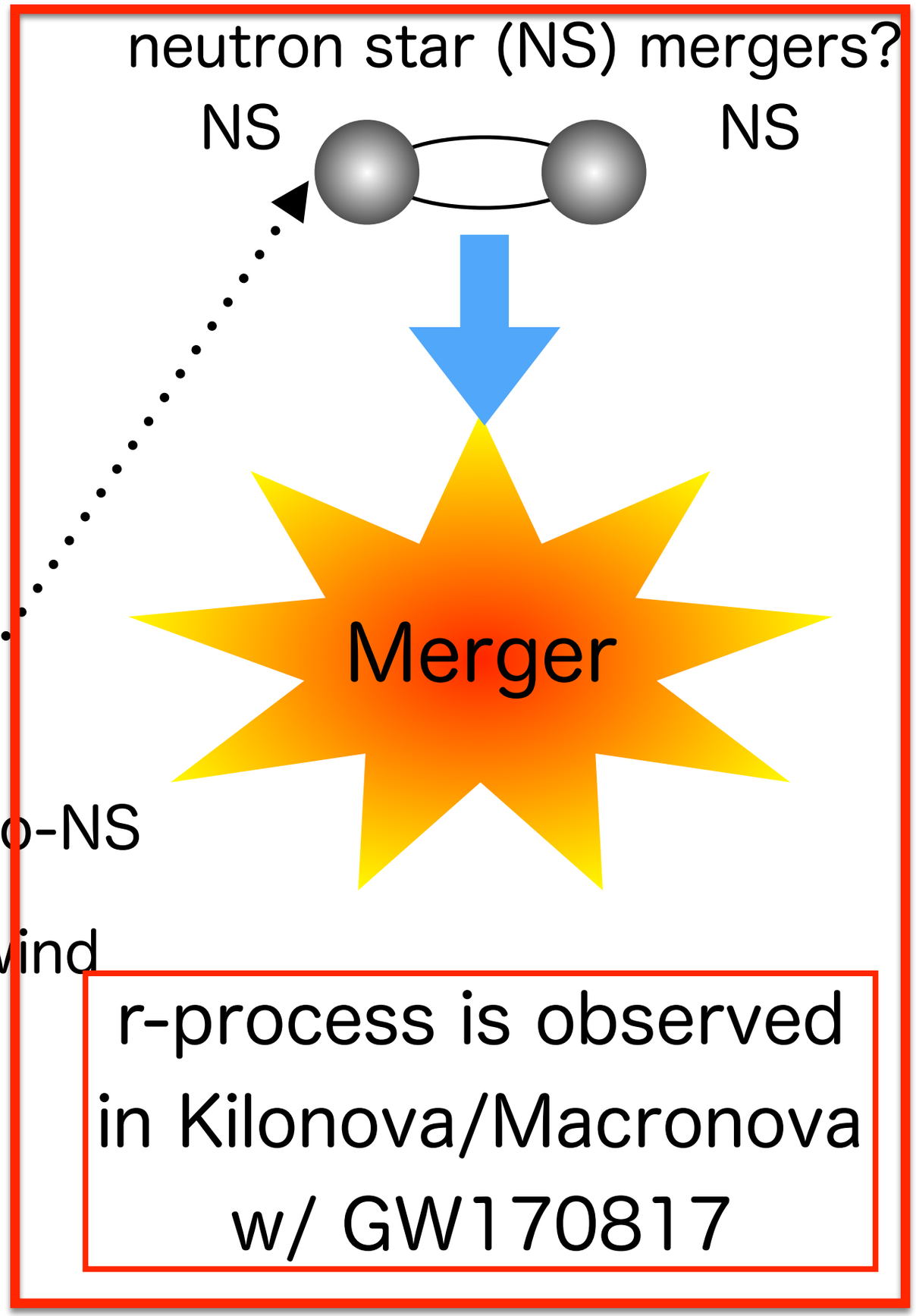
Astronomical site(s) of the r-process

Supernovae (cc-SNe)?



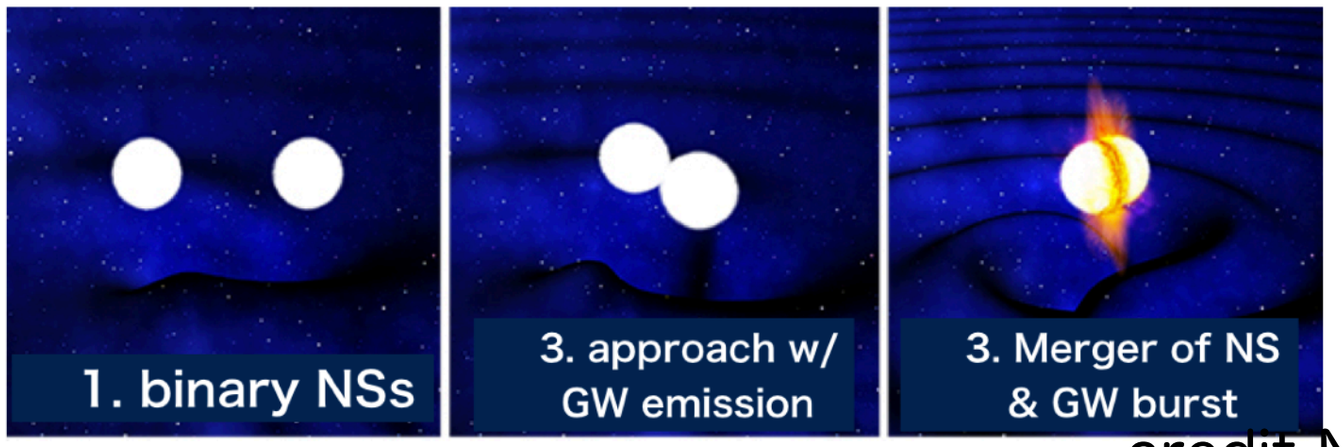
- no direct observation
- theoretical difficulty
  - (no very n-rich matter)

neutron star (NS) mergers?

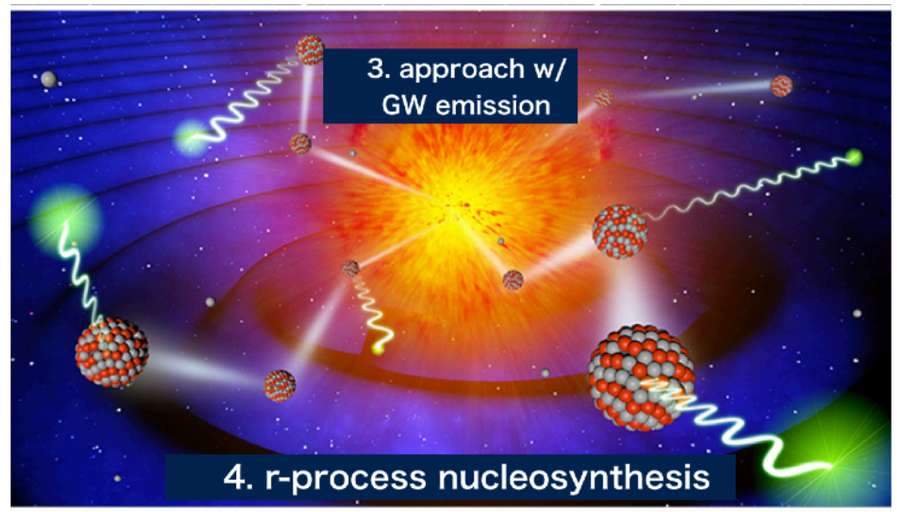


r-process is observed
in Kilonova/Macronova
w/ GW170817

The “kilonova/macronova” with GW

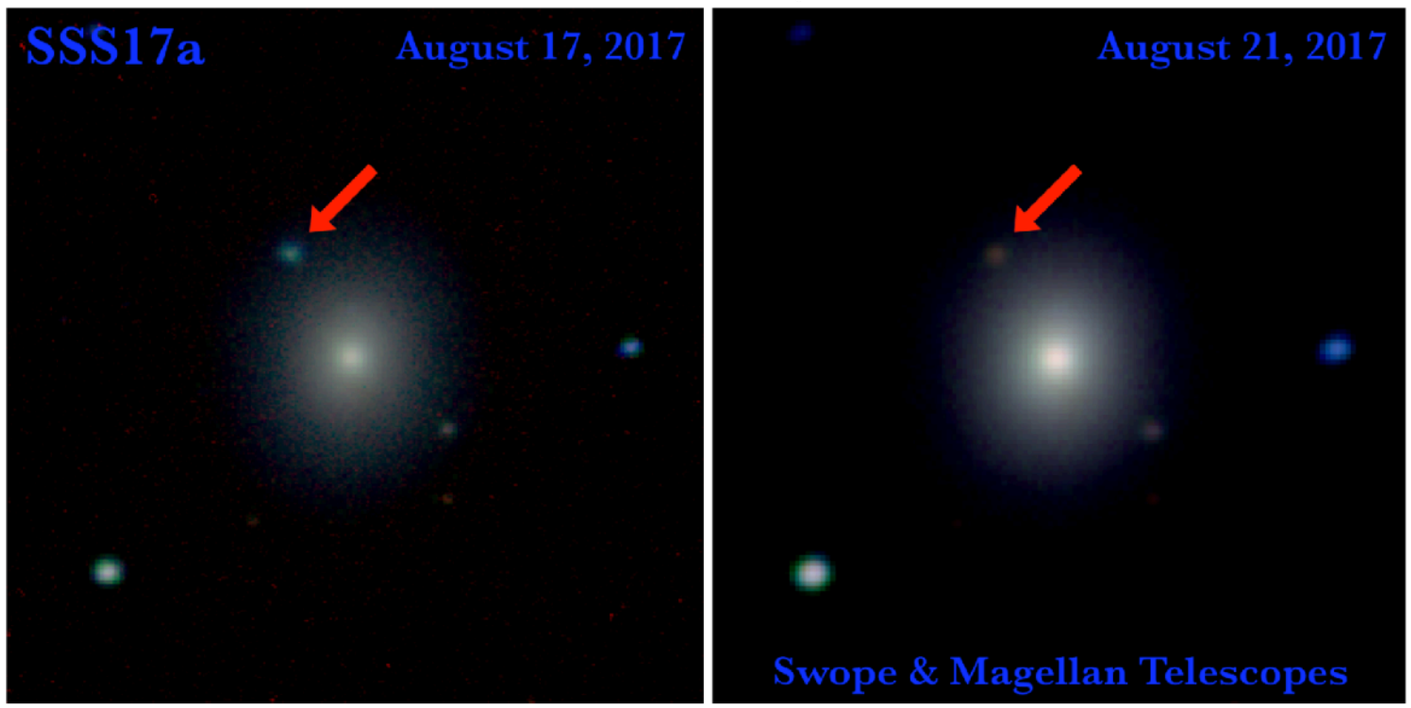


credit NAOJ



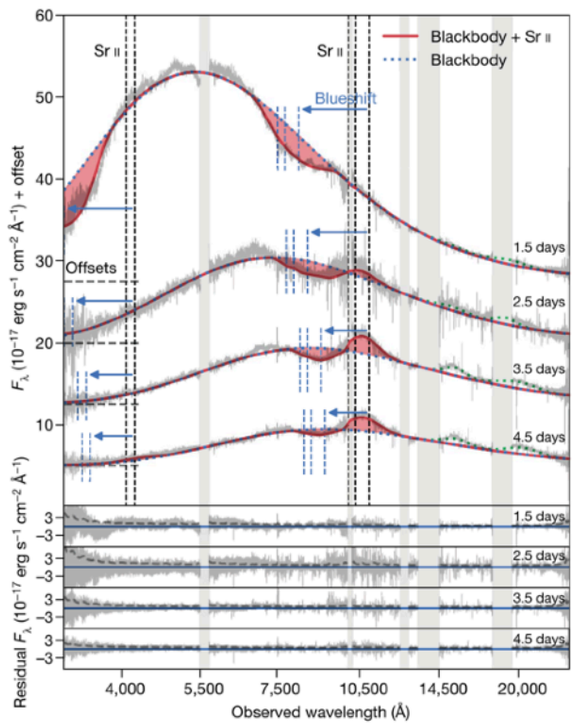
The electromagnetic counter part of GW170817 (17. Aug. 2017)
Energy source? —> radioactive decay (e.g, β, α & fission etc.) of neutron-rich matter during r-process nucleosynthesis

NGC4993 (39.5Mpc)



By Magellan telescope; Drout+2017, Science

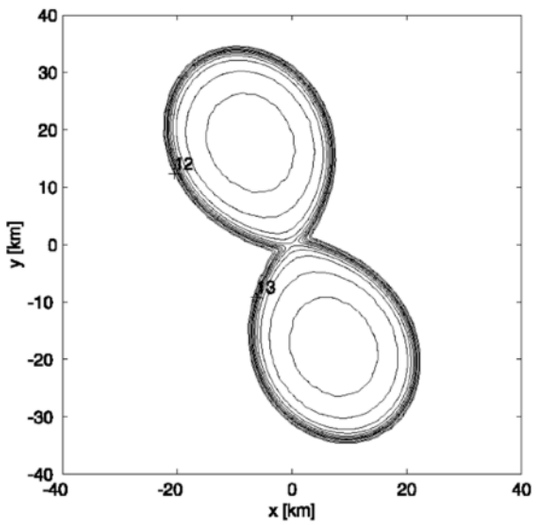
Sr in the remnant

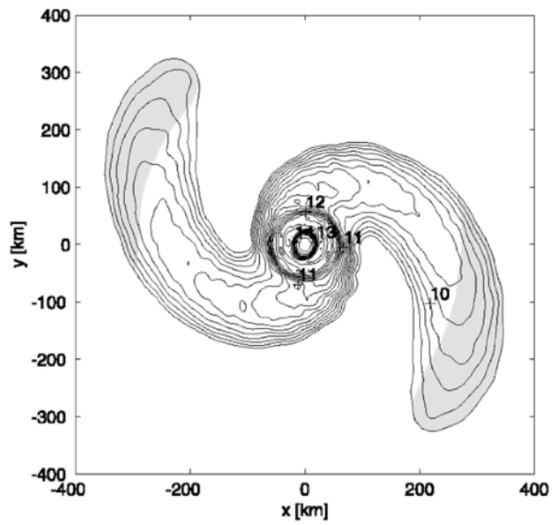


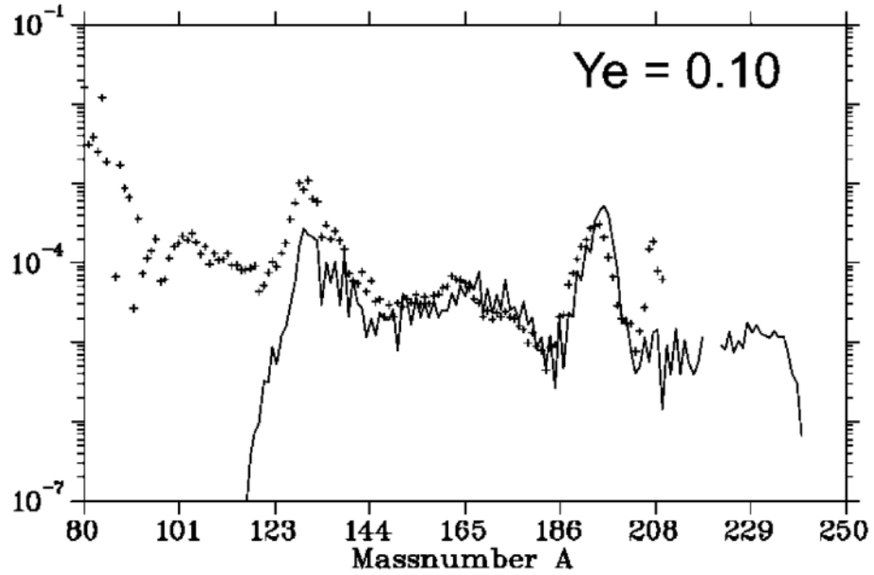
Watson+2019 Nature

“Classic” view: dynamical + post-merger

Freiburghaus, Rosswog & Thielemann (1999)

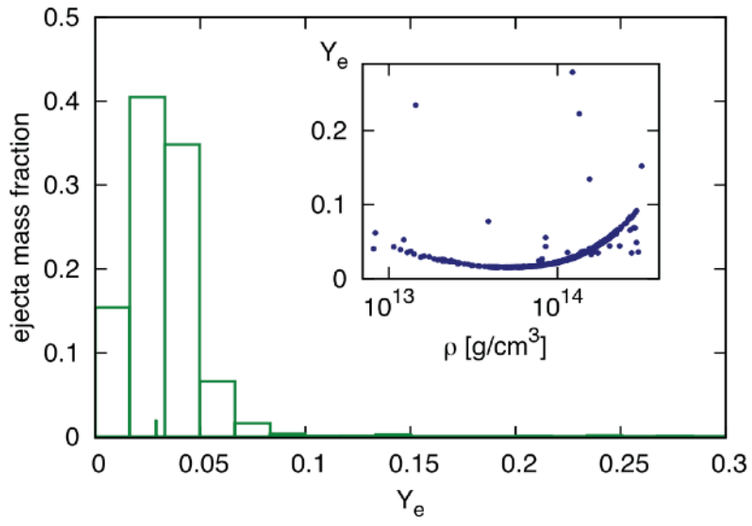


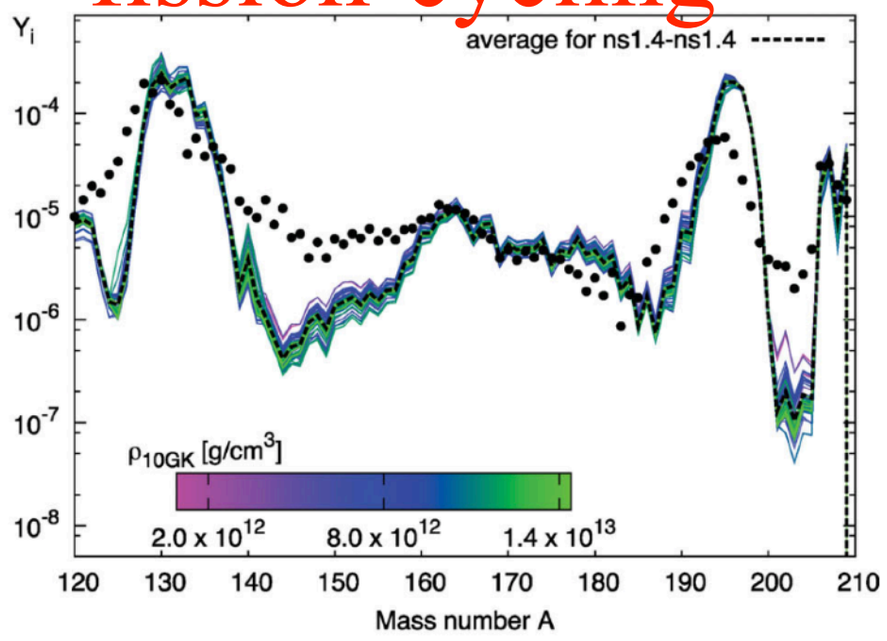




tidal ejection of “pure” n-rich matter with $Y_e << 0.1$

fission-cycling

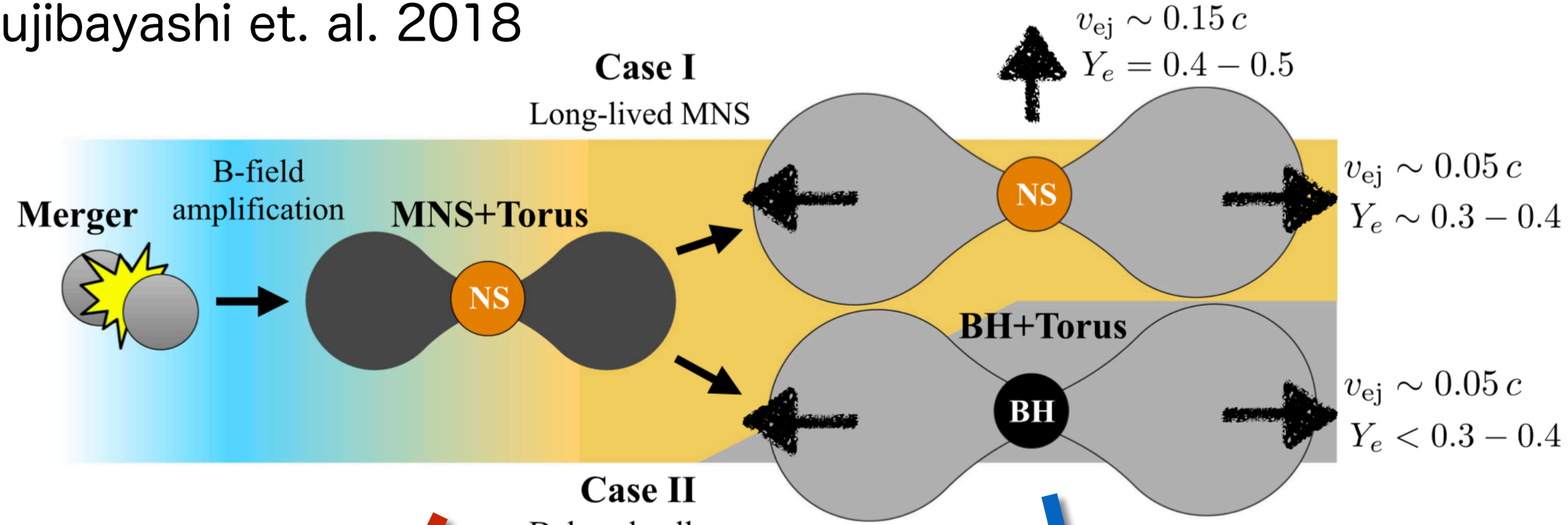




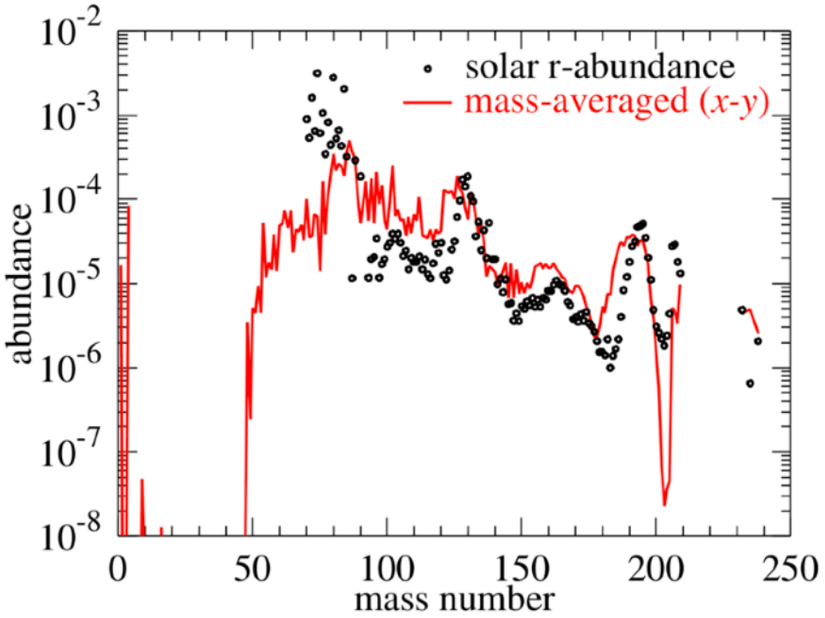
Korobkin+ 2012 (e.g., Goriely+ 2011, Rosswog+ 2013)

Modern view: dynamical + post-merger

Fujibayashi et. al. 2018



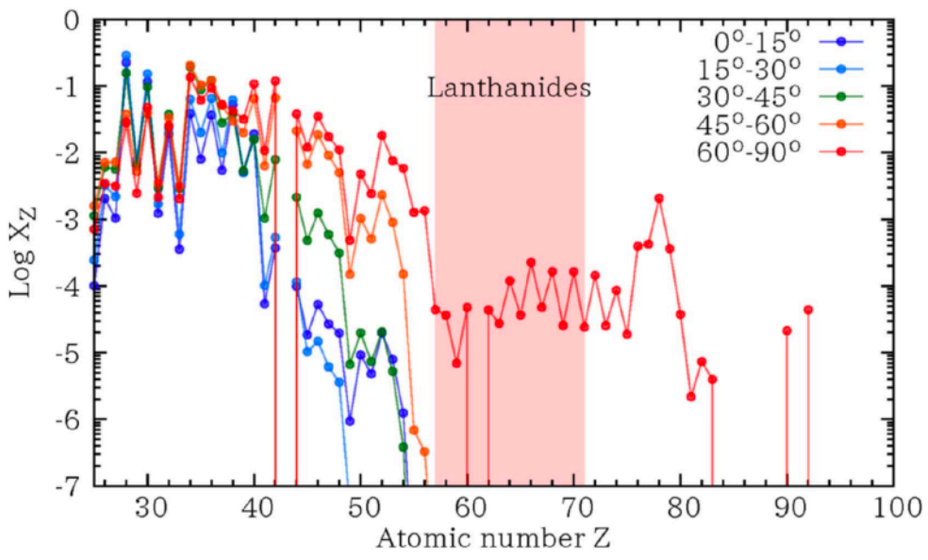
dynamical mass ejection



post-merger

lighter r-nuclei (lanthanide poor)

lanthanide
Z=5 7 – 7 1



r-proces mechanism

neutron-rich ejecta
in stellar explosion

high T & ρ

① NSE (> 1 MeV)
(only nucleon and α)

proton
neutron

③n-capture: A ↑
(A,Z) → (A+1,Z)

⑤ β-decay
+fission

② seed formation
(α + recombination)
A ～ 100

^{-}e

④ β-decay : Z ↑
(A,Z) → (A,Z+1)

Low T

r-proces mechanism

neutron-rich ejecta
in stellar explosio

① NSE (> 1 MeV)

d α)

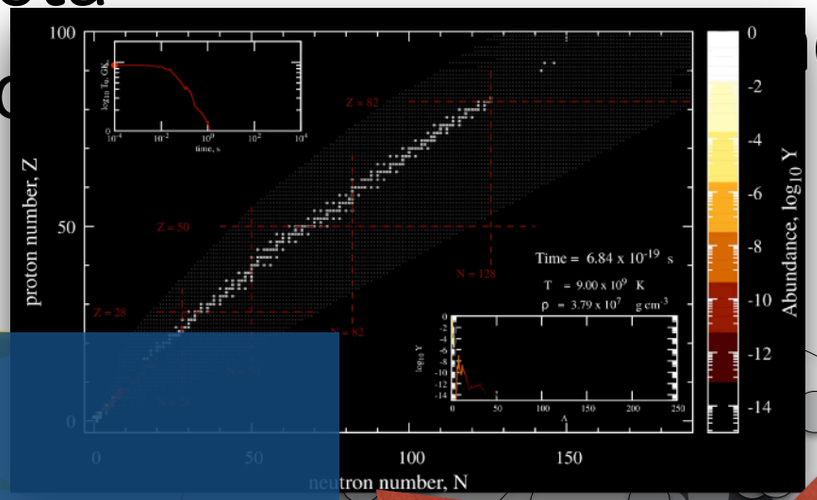
ton
neutron

capture: A ↑

A,Z) → (A+1,Z)

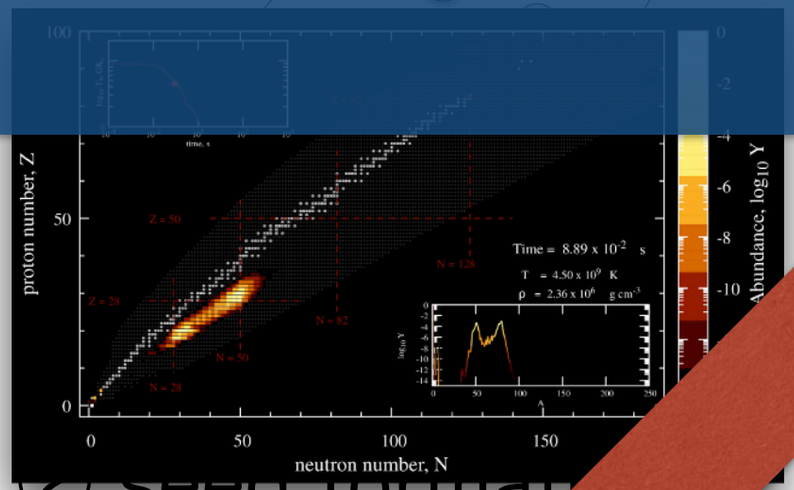
⑤ β-decay

+fission



high T & ρ

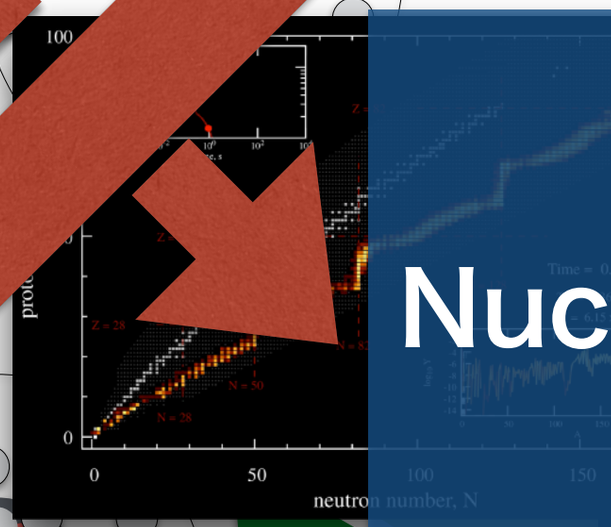
Astrophysics

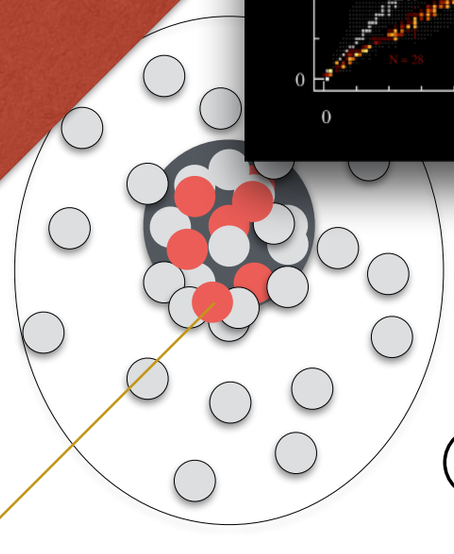


② seed formation

(α + recombination)

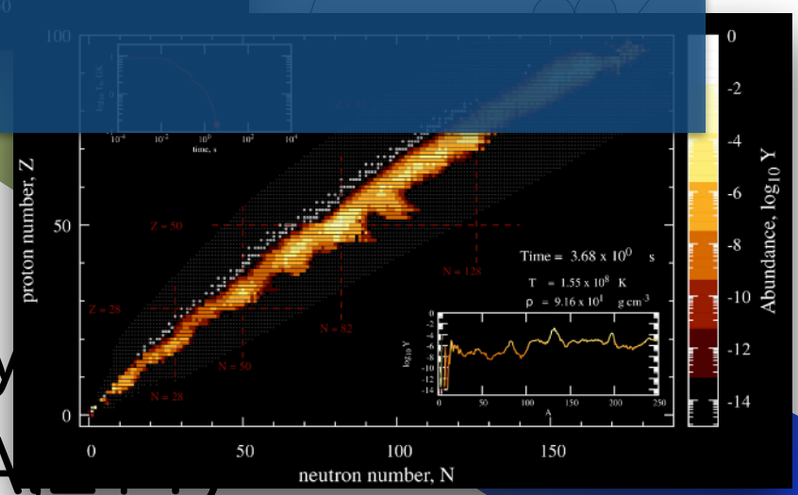
A ~





④ β-decay

(A,Z) → (A,



Nuclear physics

Physical conditions for r-process production

- neutronization （low Y_e） by e-cap. ($p + e^- \rightarrow n + \nu_e$) + ν-absorption

$$Y_e = Y_{"p"} = \Sigma(A_i/Z_i)X_i \sim N_p/(N_n + N_p)$$

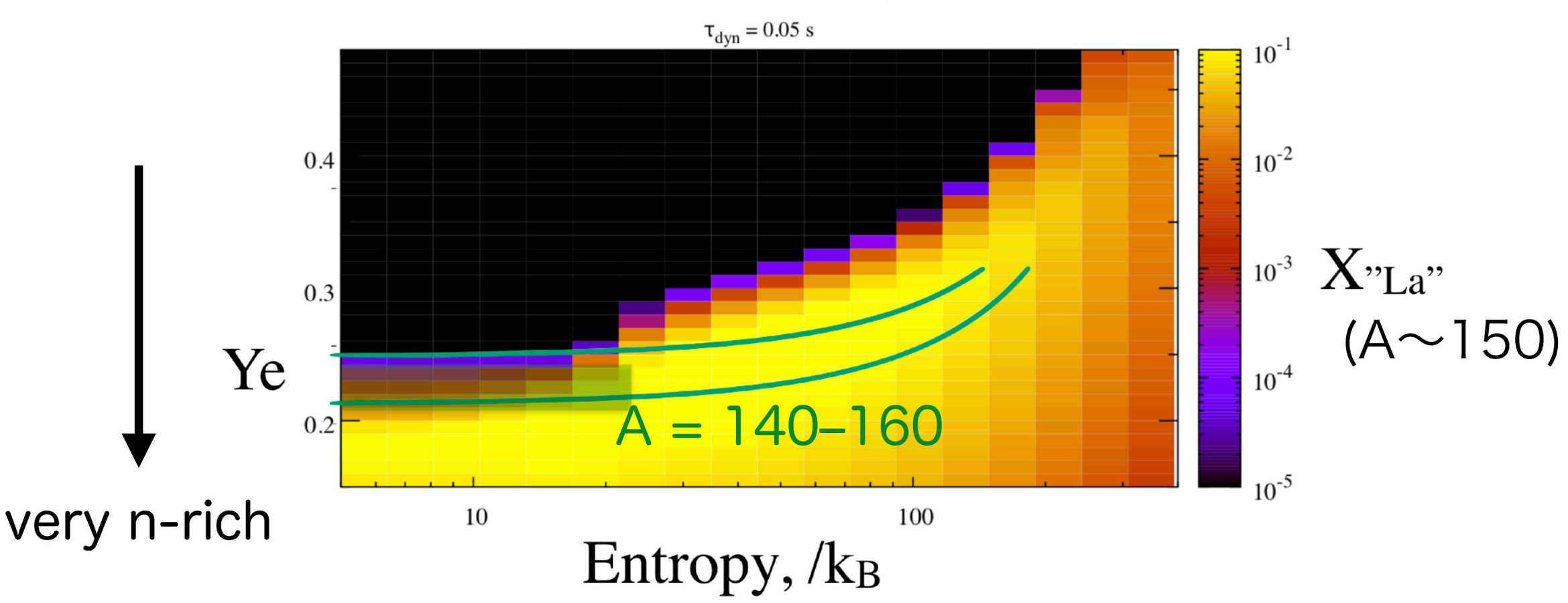
low Y_e = neutron-rich

- seed formation (see Hoffman et al. 1997)

n/seed > 100 for the 3rd peak production

($\alpha + \alpha + n \rightarrow {}^{9}Be$; ${}^{9}Be + \alpha \rightarrow {}^{12}C + n$)

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



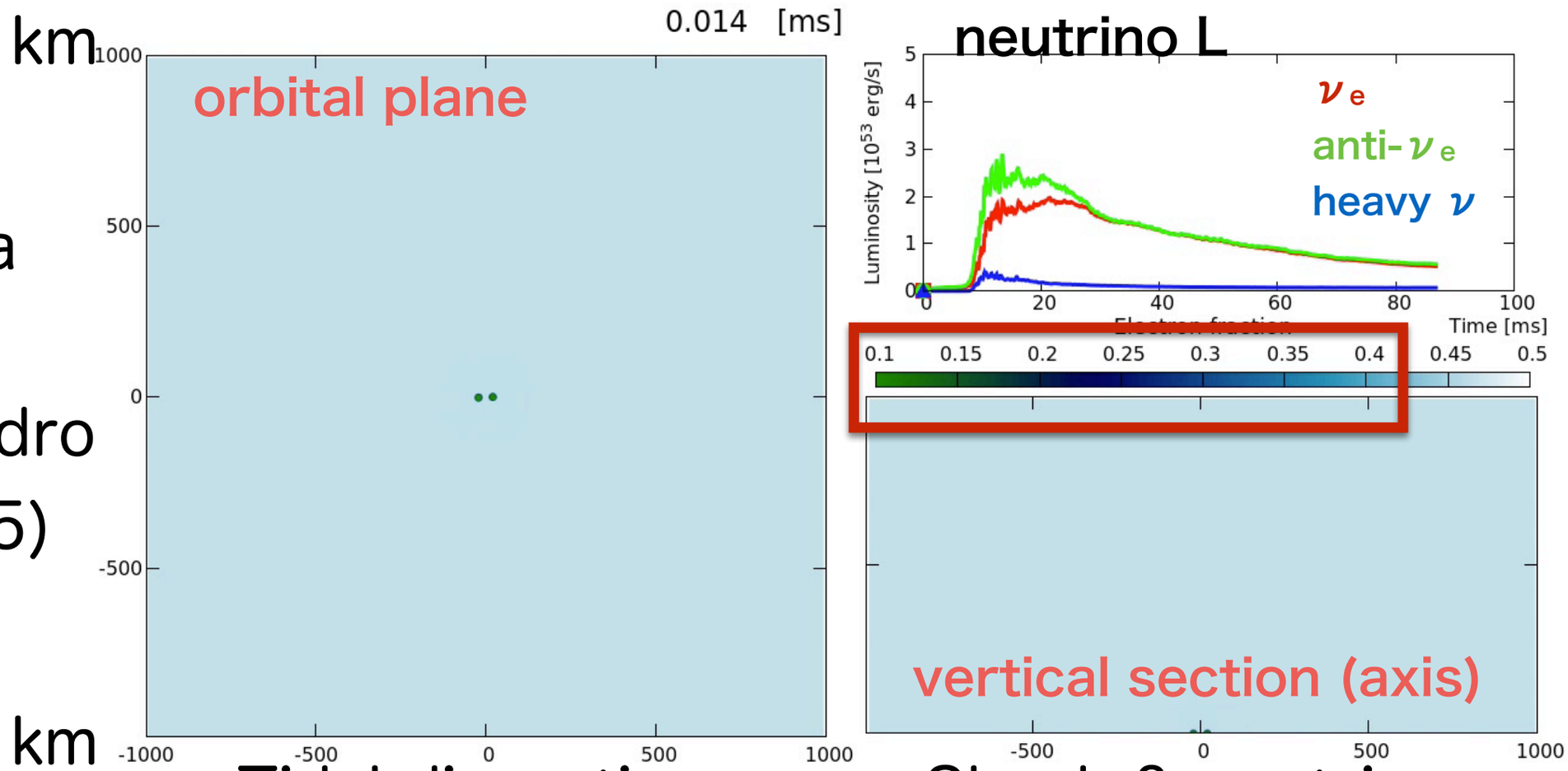
Details: NS masses & EoS in 3D hydro

dynamical ejecta

Y_e evolution

based on 3D hydro

(Sekiguchi+2015)

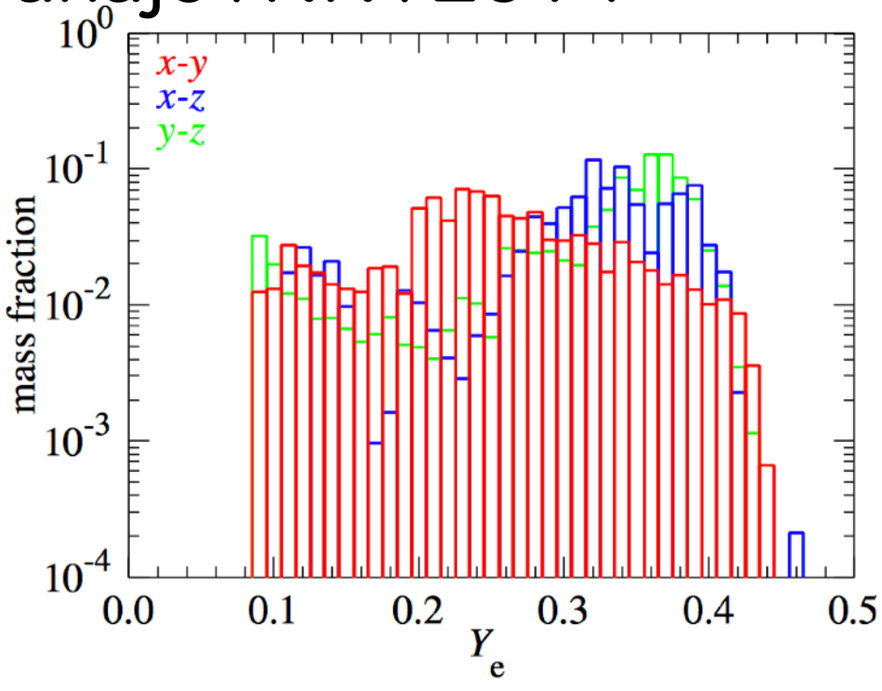


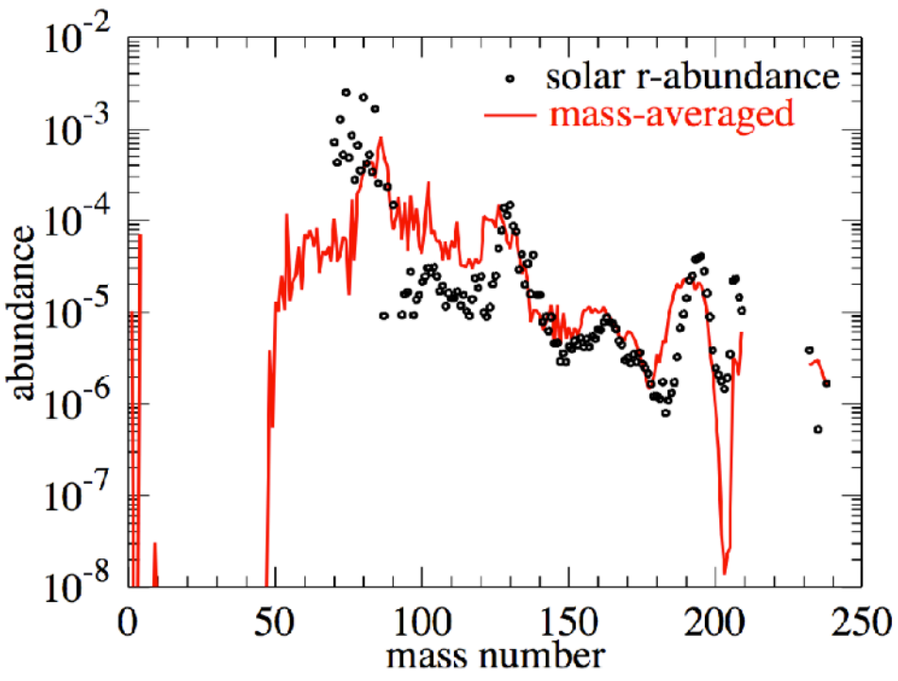
km

Tidal disruption

Shock & neutrino

Wanajo+NN+2014





NS-NS merger: post-merger evolution

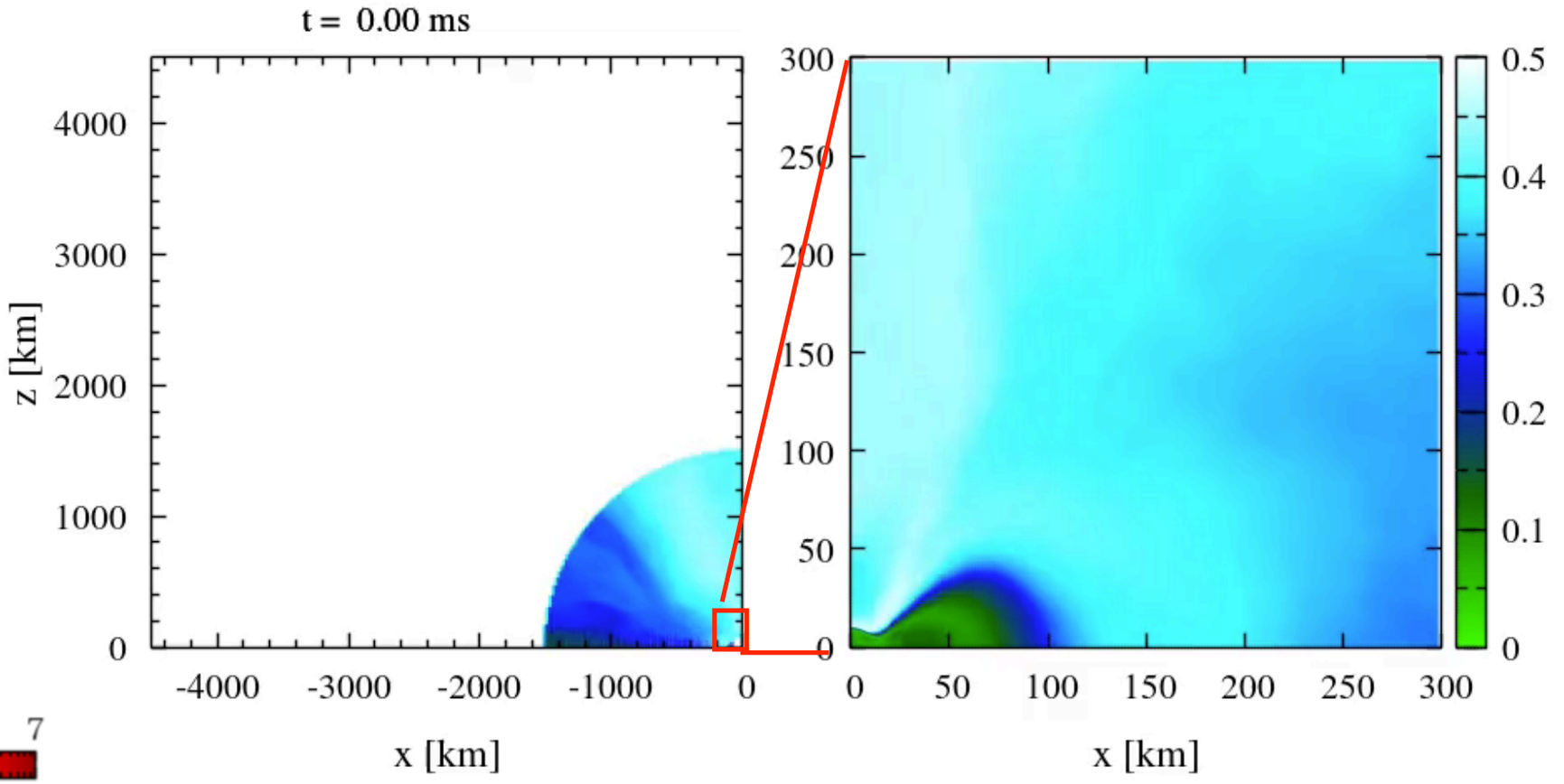
Ye: electron faction (green: heavy nuclei; blue : lighter nuclei)

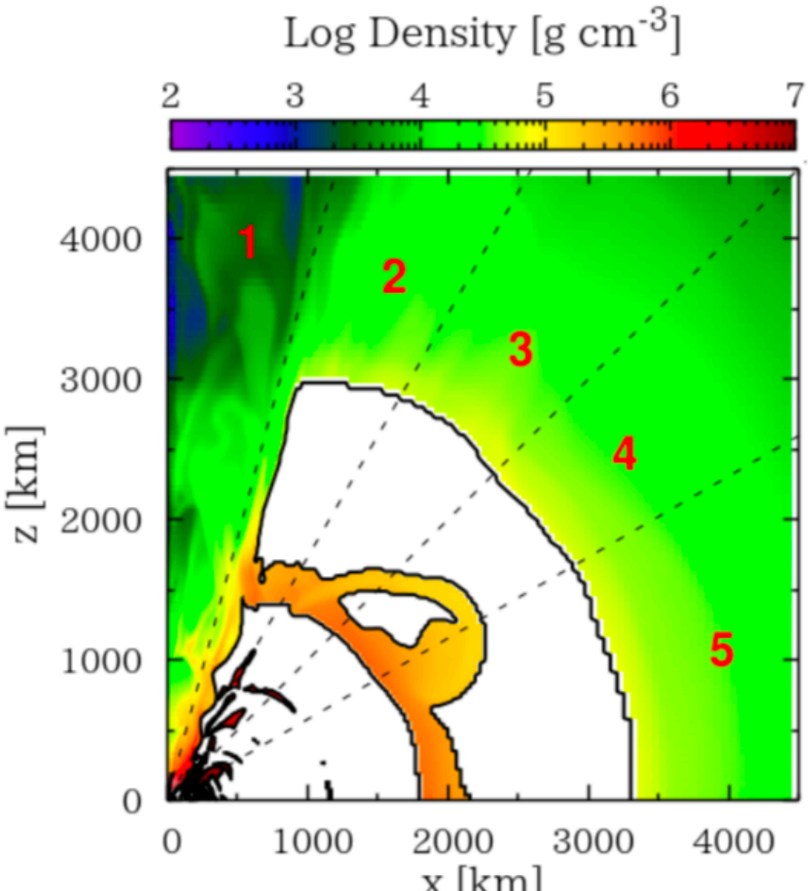
post-merger ejecta

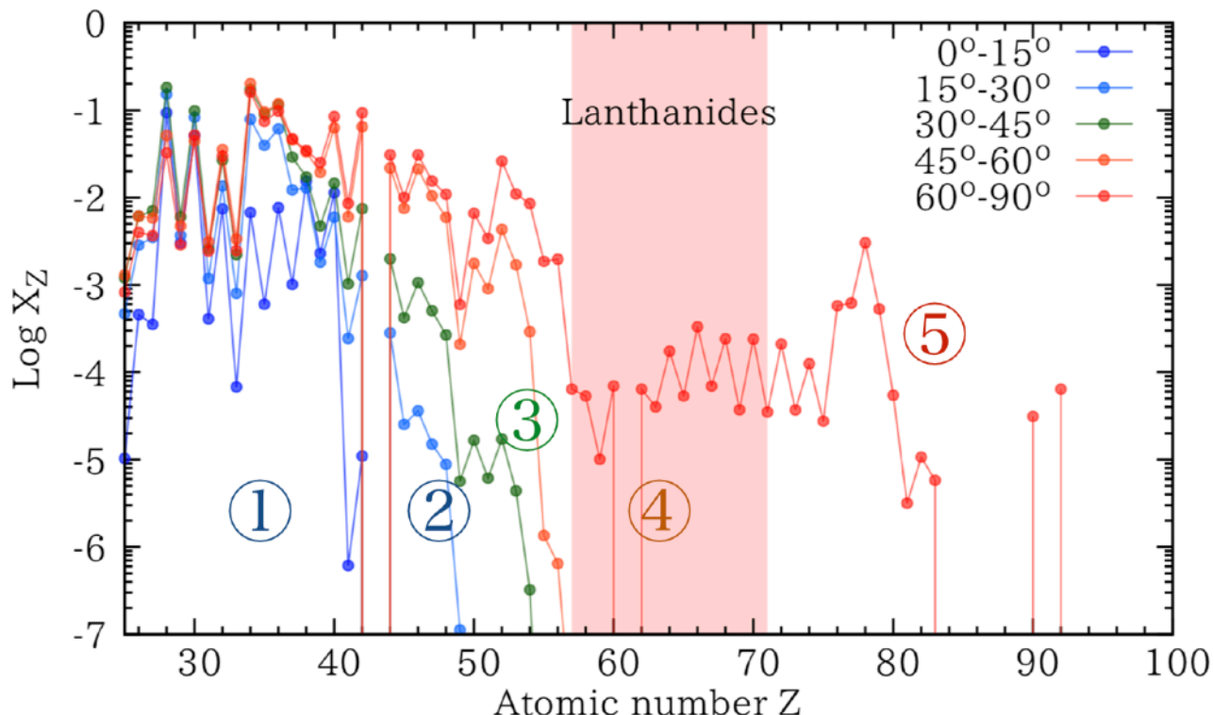
Y_e evolution

based on 2D hydro

(Fujibayashi+NN+2018)







Simulation models vs Kilonova

Indicated by the simulation is agree with kilonova observation

heavy r-process elements (= lanthanide-rich) w/ high opacity

→ peak temperature becomes low (in low density)

→ late IR peak

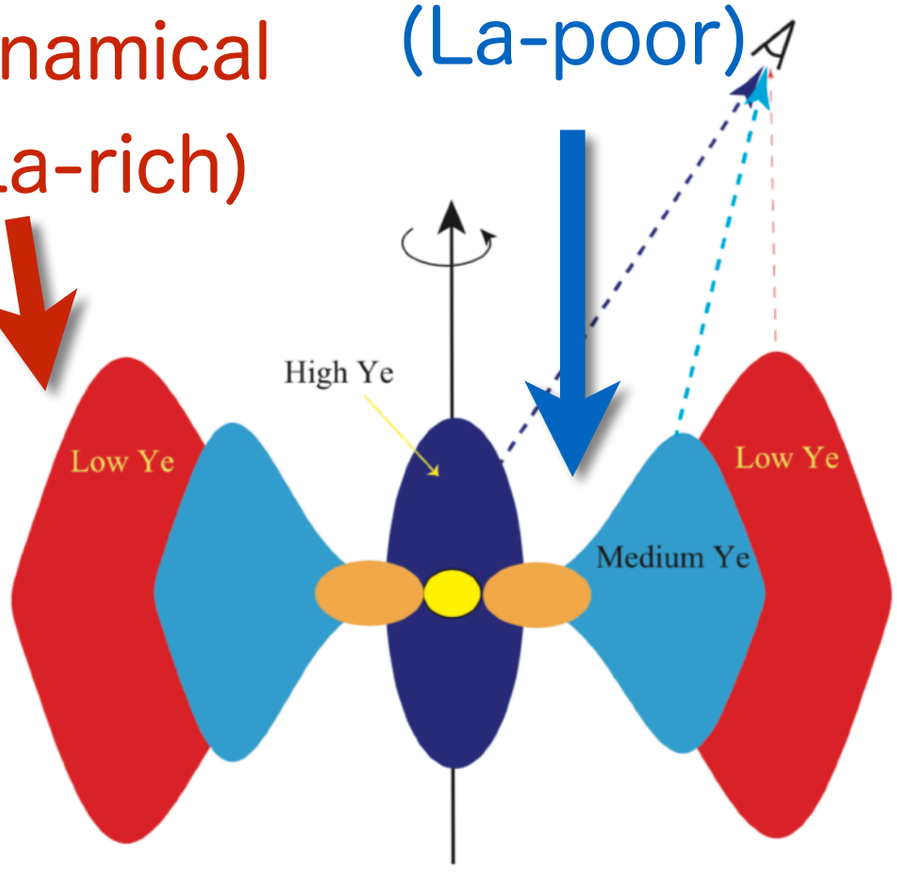
(⇆ La-poor -> early “blue” peak)

post-merger

(La-poor)

dynamical

(La-rich)

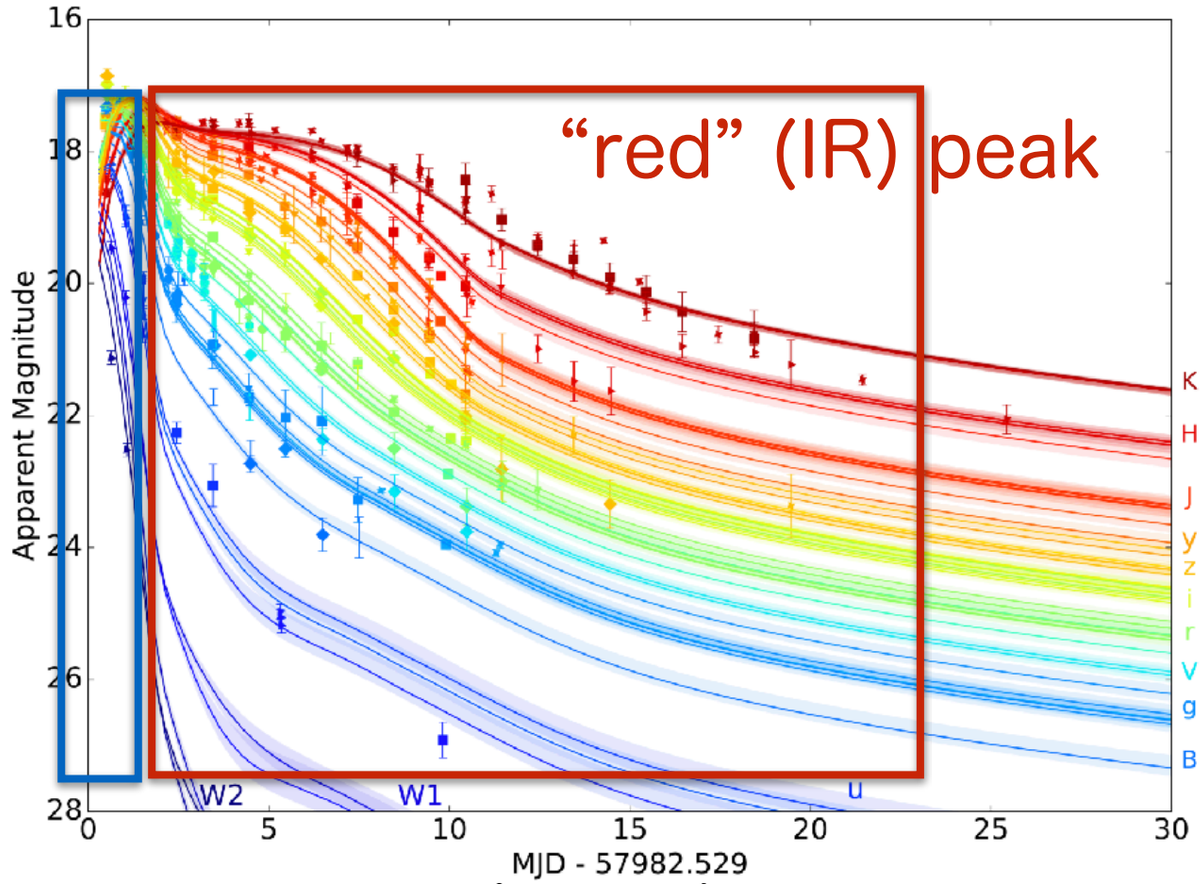


Shibata et al. 2018

bolometric luminosity

“blue” (UV) peak

Villar et al. 2018



time, day

Short Summary

- NS mergers can produce (all) r-process elements in
  - based on “Modern” hydrodynamical simulations
    - dynamical ejecta: lanthanide- and actinide-rich
    - post-merger ejecta: lanthanide poor

- observations confirmed theoretical models
  - kilonova w/ GW170817
    - the light curve: blue -> red
    - detection of Sr in the remnant?
      (indicate “weak” r-process components)

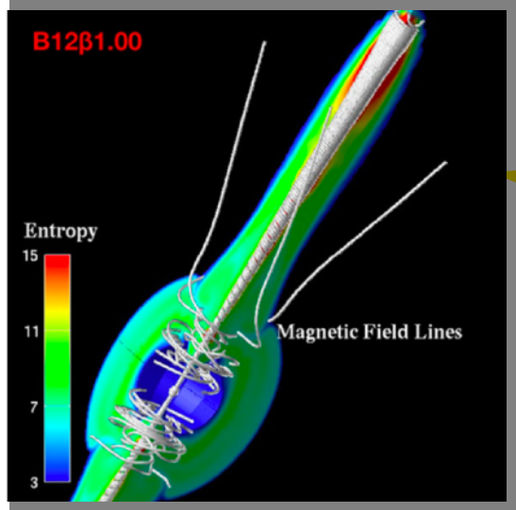
Magneto-rotational SNe as alternative r-process sites

- Winteler+NN+ (2012) ApJL
- NN, Takiwaki & Thielemann (2015) ApJ
- NN, Sawai, Takiwaki+(2017) ApJL

Astronomical site(s) of the r-process

Supernovae (cc-SNe)?

massive star
($10>M_{sun}$)



another mechanism
magneto-driven jet?

proto-NS

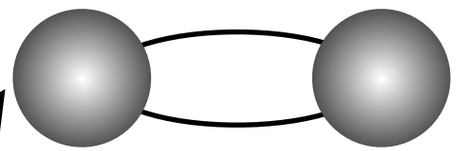
utrino-driven wind


magnetar

・no direct on
・theoretic
・(no ver atter)

neutron star (NS) mergers?

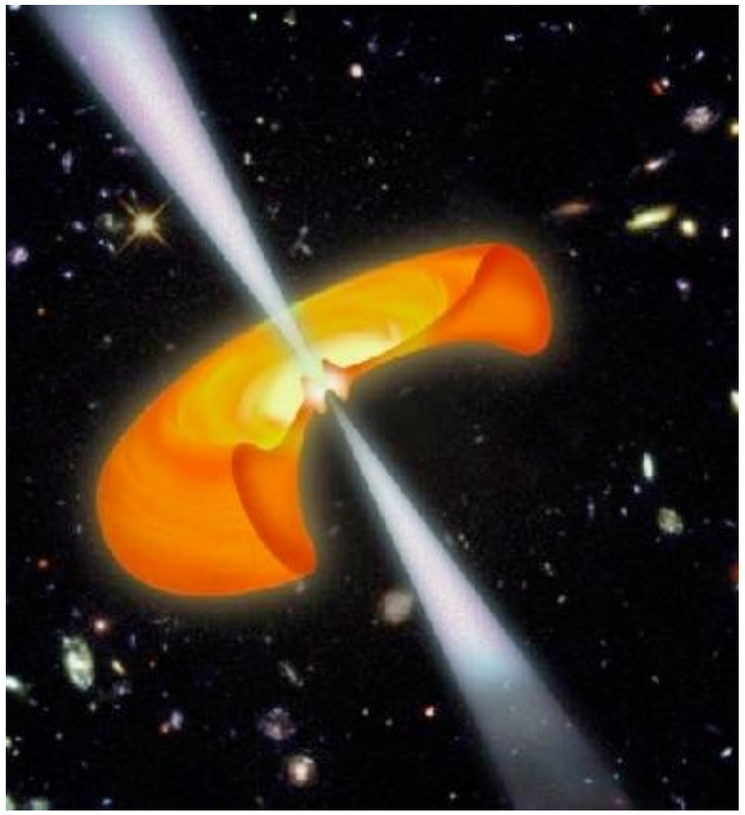
NS NS



Merger

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

r-Process in magneto-rotational supernovae



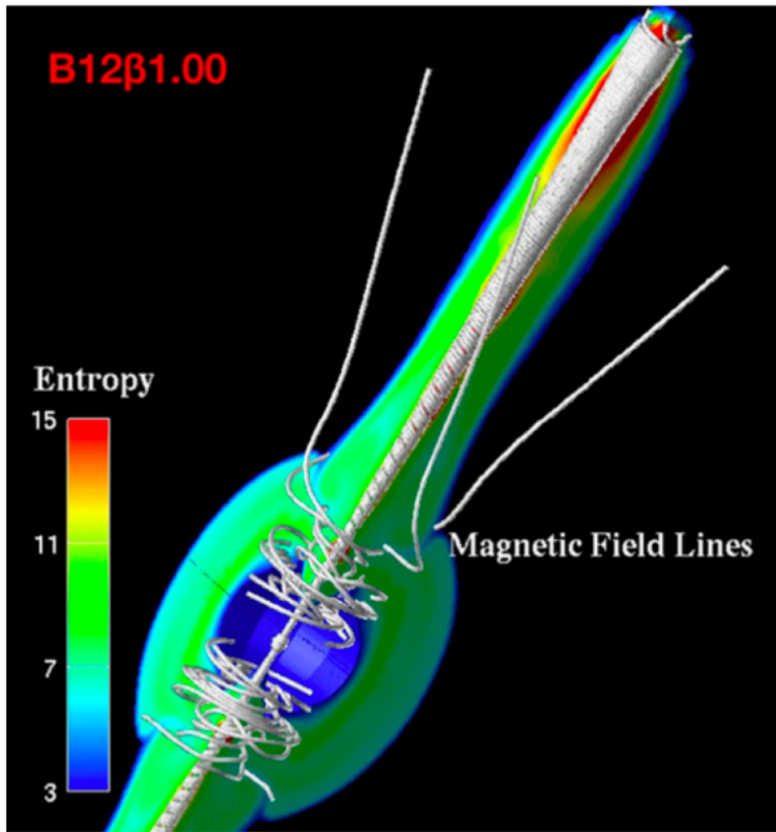
- Magnetar
  - strong magnetic field ～10^{15} G

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

hypernova/jet-like SN

NN+2015

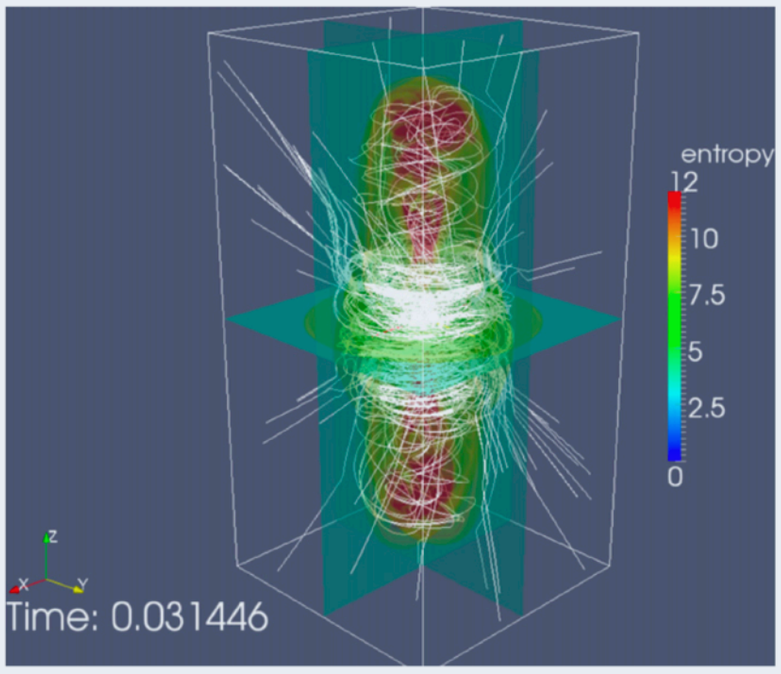
- MR-SNe (magnetar formation)
  - “the classics”: Symbalisty(1984), Cameron(2003)
  - 2D: Nishimura+NN+(2006); NN+(2012,2015,2017)
  - 3D: Winteler+NN+(2012); Mösta+(2014,2018), Halevi&Mösta(2018)
- “Collapsar model” (BH + disk + jet)
  - 2D: Fujimoto+(2007); Fujimoto, NN, Hashimoto(2009);
  - Ono+(2009, 2012)

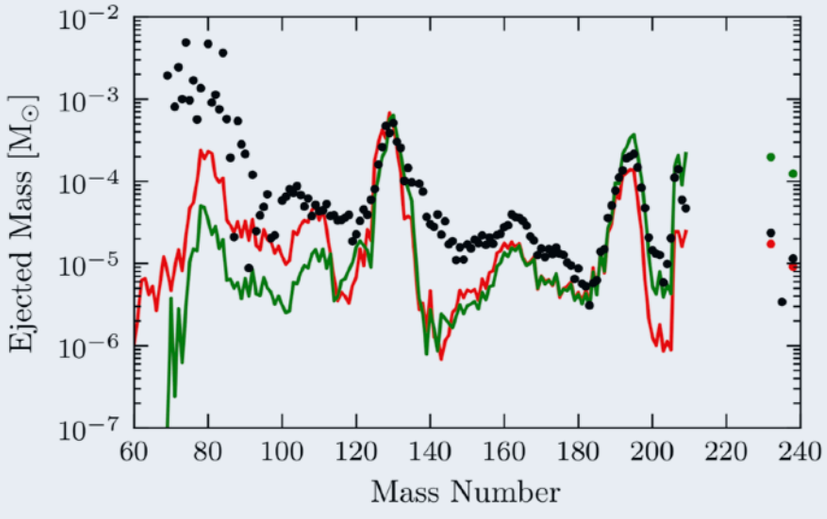


3D effects on jet-propagation

strong jet in 3D

Winteler+NN+(2012)

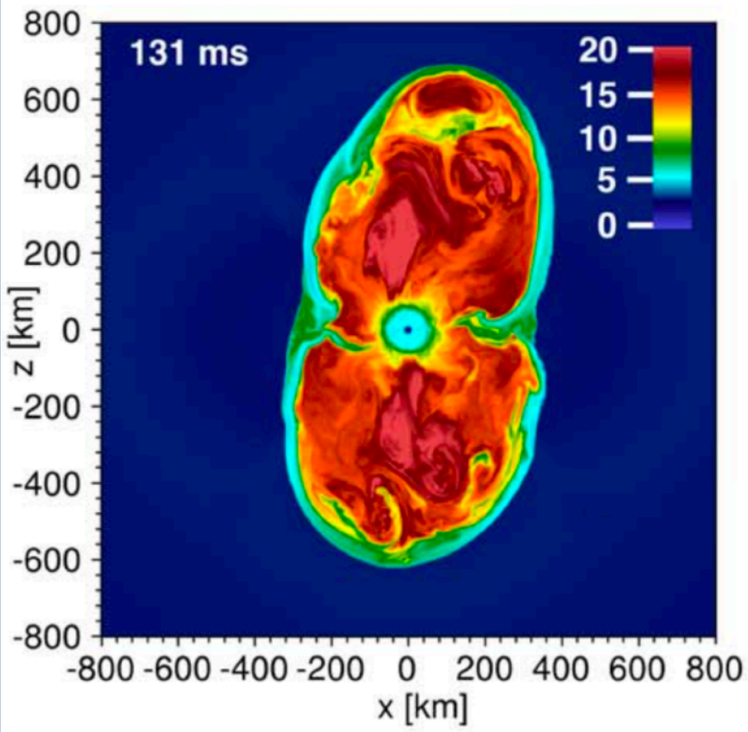


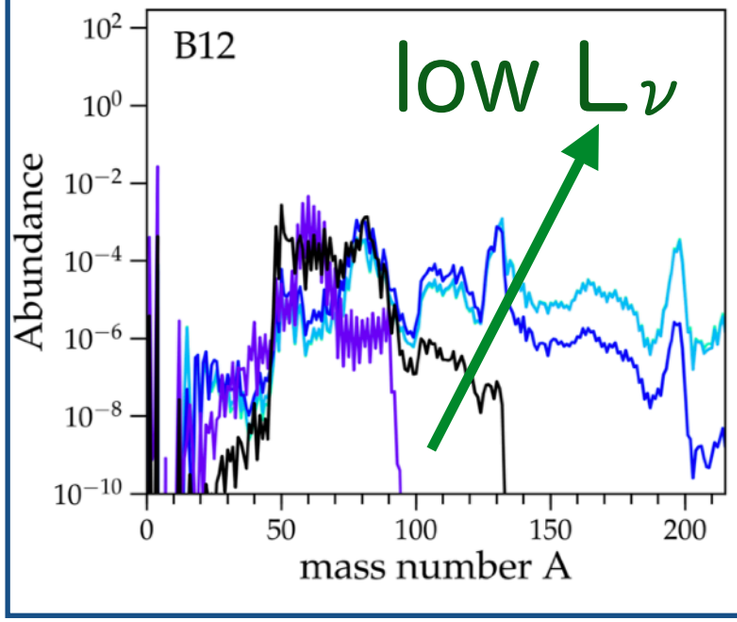


*difference is due to uncertainty

deformation by hydro-instability

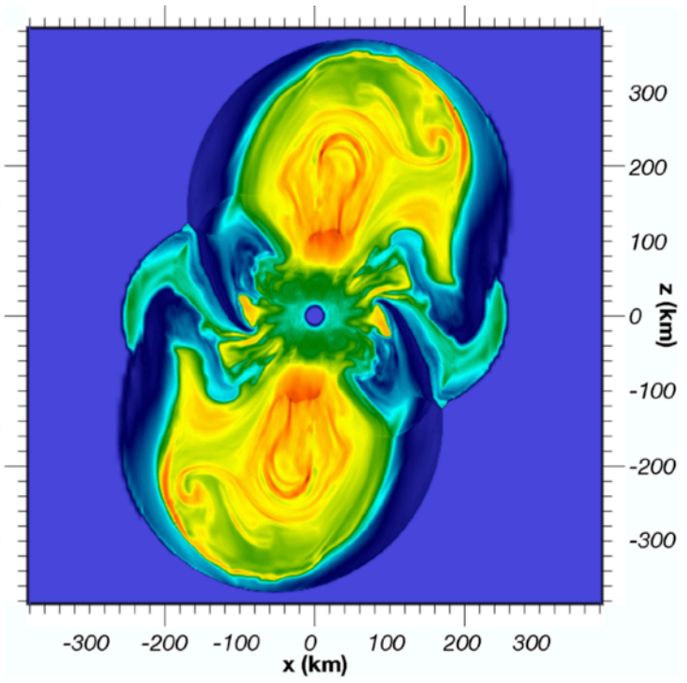
Mösta+(2018)

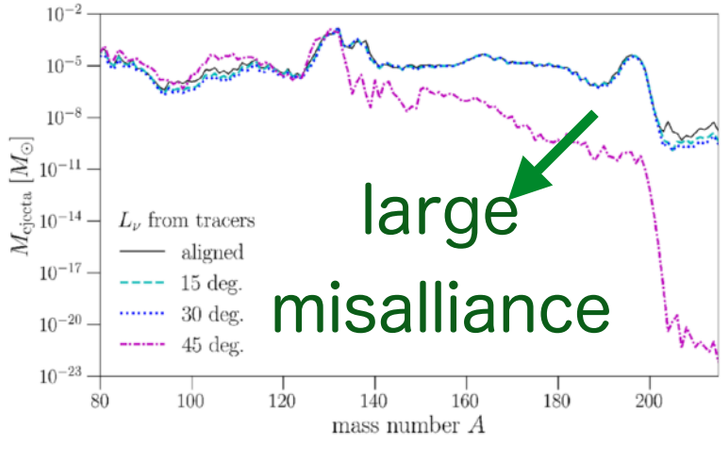




misalliance of B-filed and rotation

Halevi&Mösta(2018)

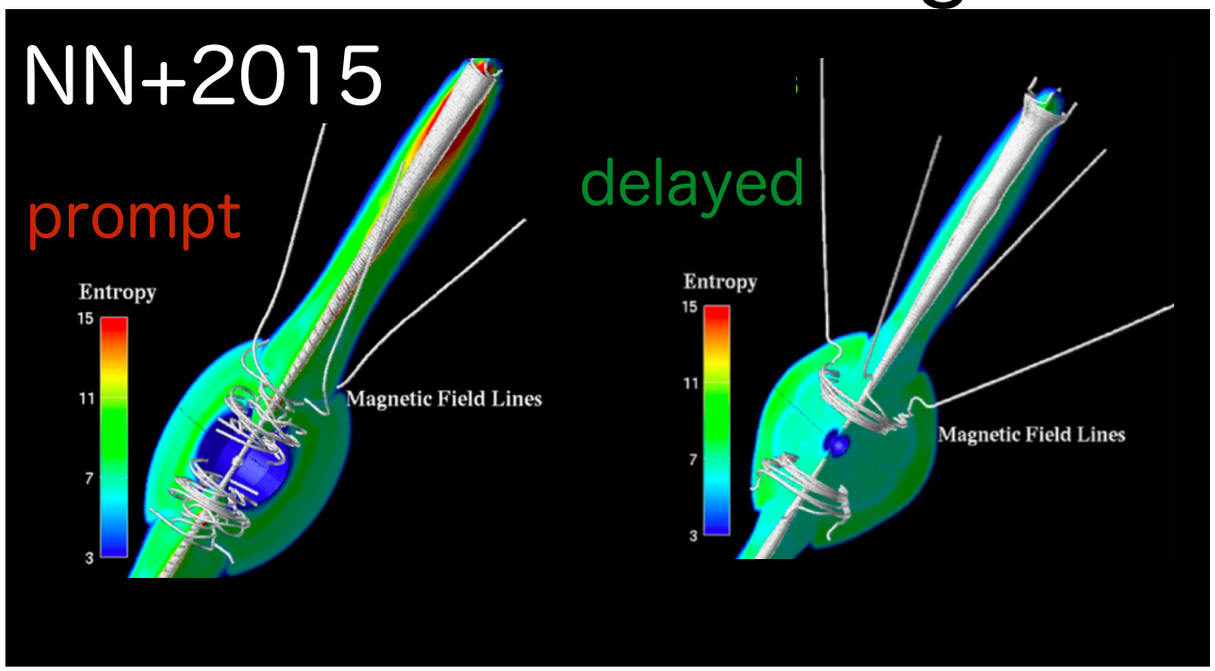


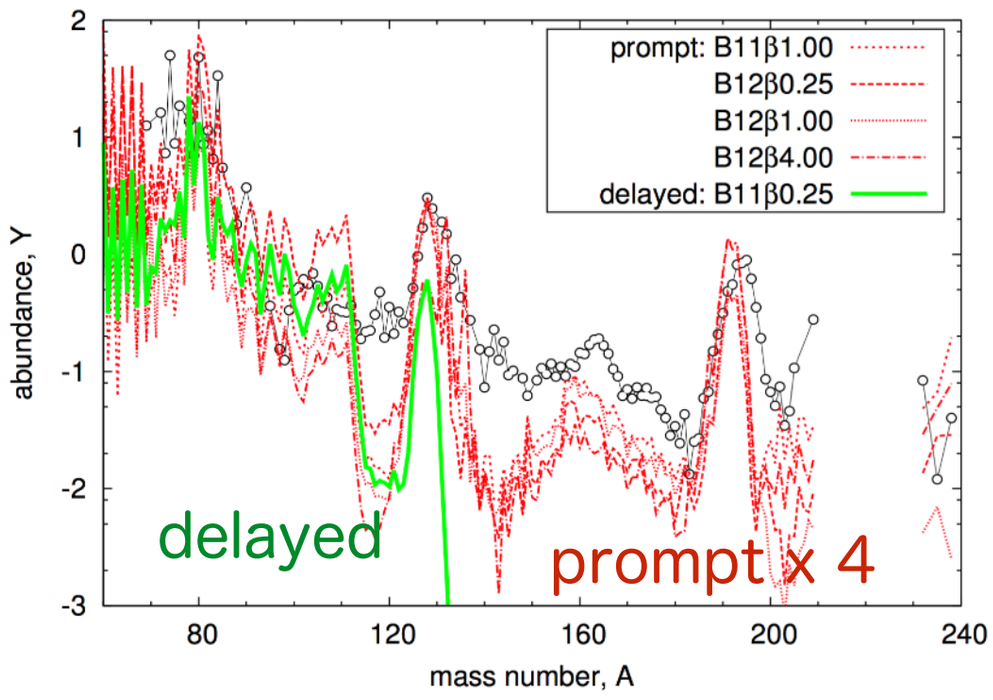


magnetic-field enhancement process?

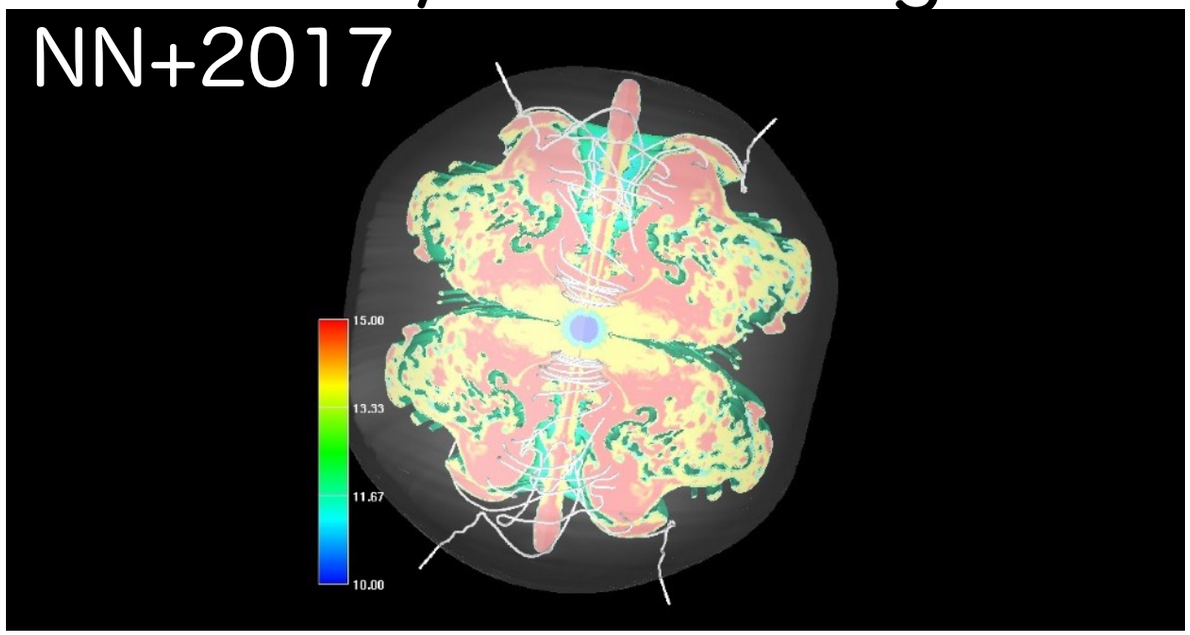
axi-symmetric (2D); long-term, high-resolution

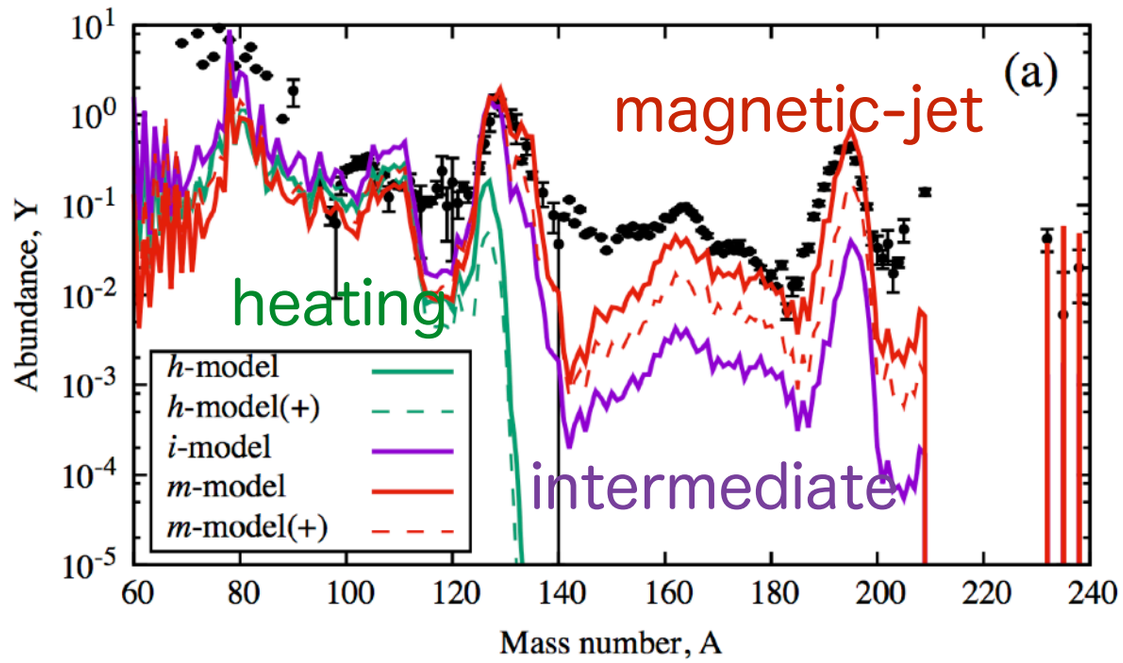
B-field winding





MRI w/ ν-heating

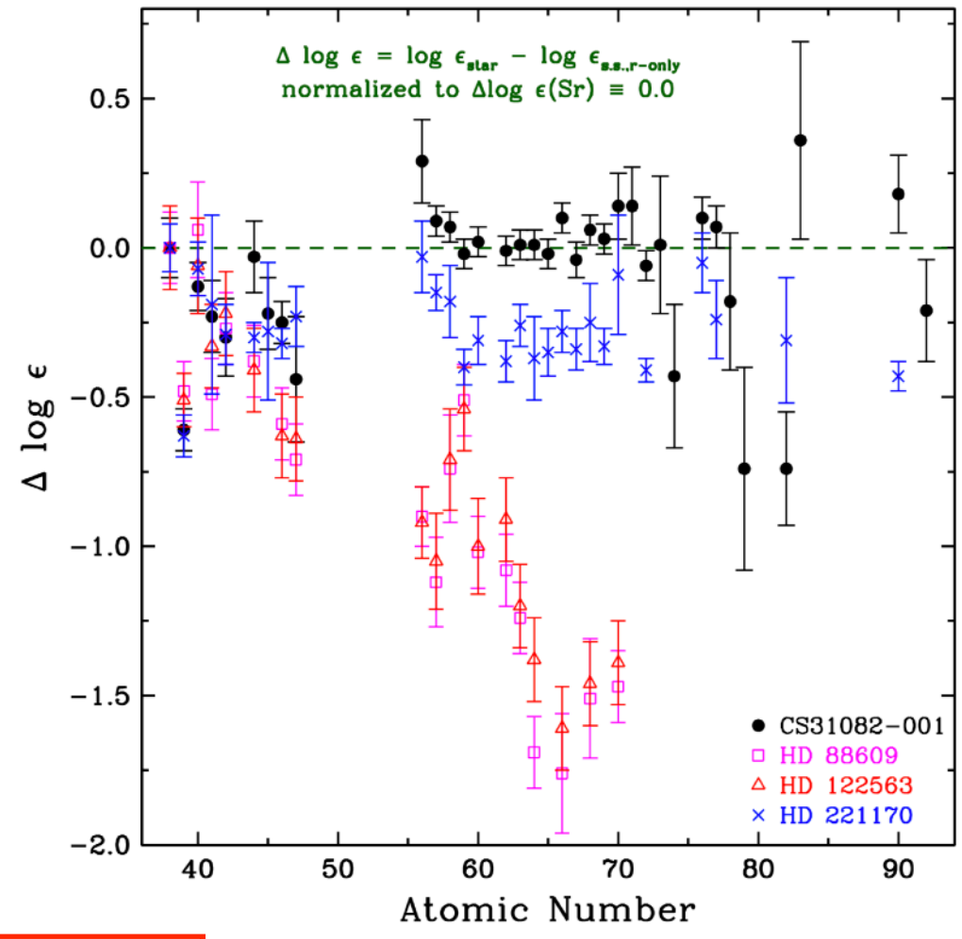




Diversity in metal-poor star abundances?

- 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



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

metal-poor stars contain very fast rotator?

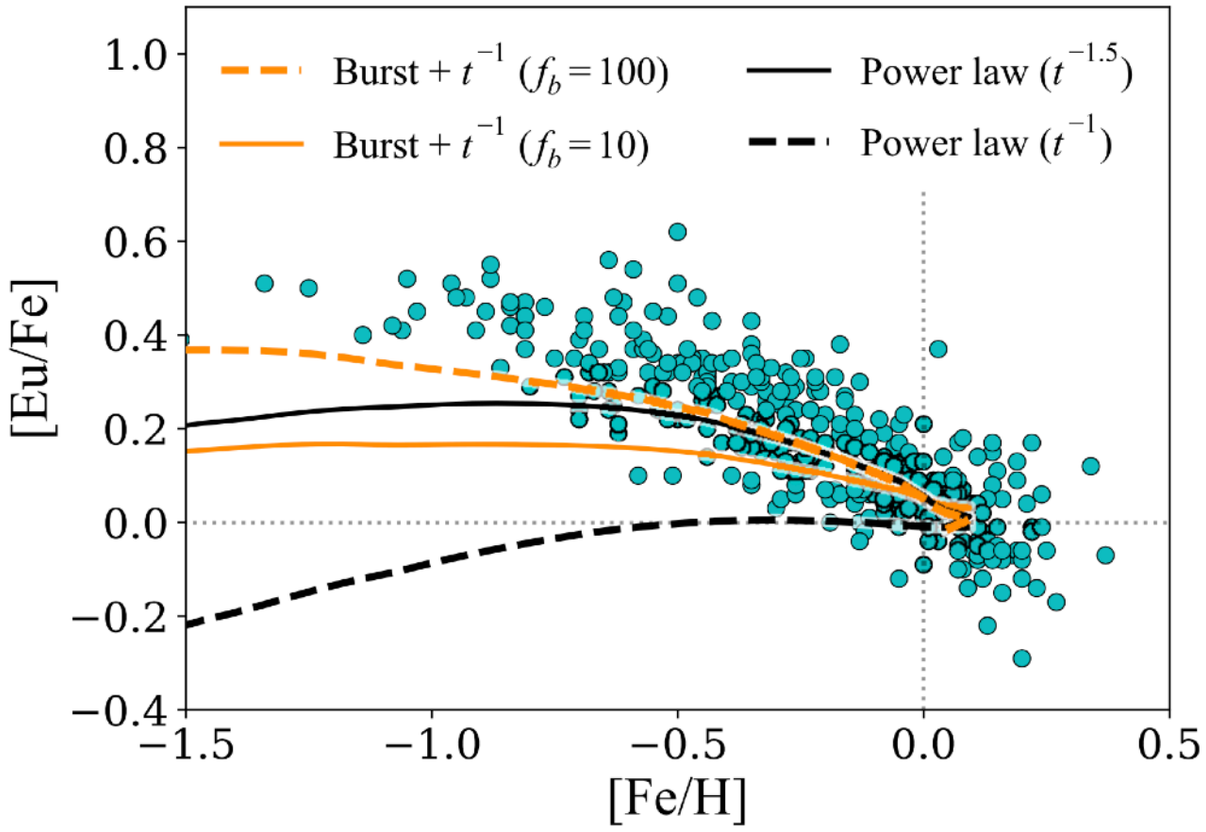
(Talk by A. Choplin: s-process in fast rotating massive star)

Multiple r-process sources in GCE?

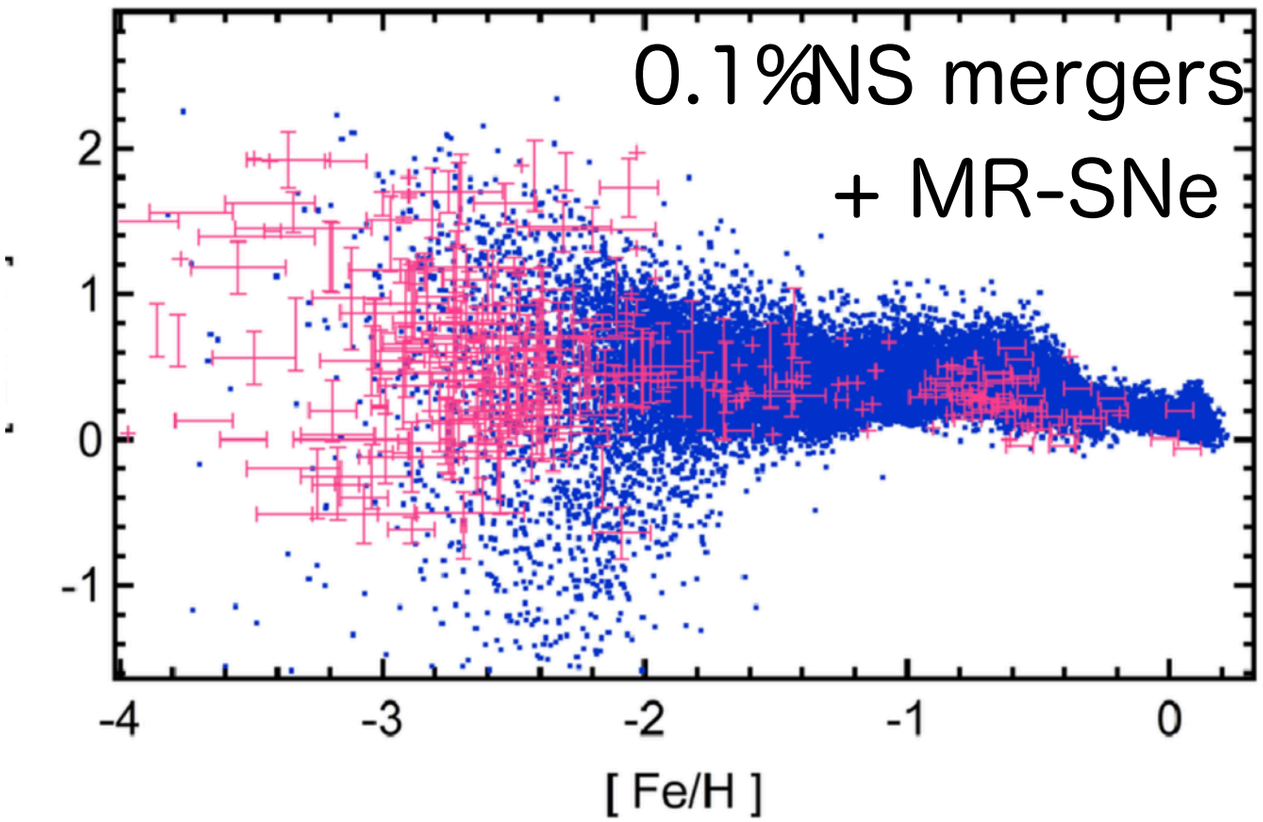
NS mergers cannot explain early chemical evolution
of r-process elements, e.g., Eu?
→ shorter delay time or another source

comprehensive GCE analysis after GW170817 (e.g., Côté+2018)

standard DTD cannot explain
Eu evolution? (Côté+2018)
→ single r-process source scenario fails to explain



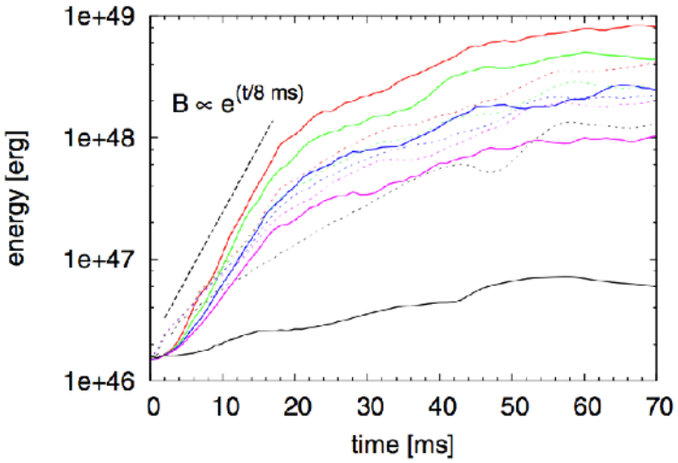
Wehmeyer+(2015,2019): different event rates for MR-SNe



Need those strong initial B-fields?

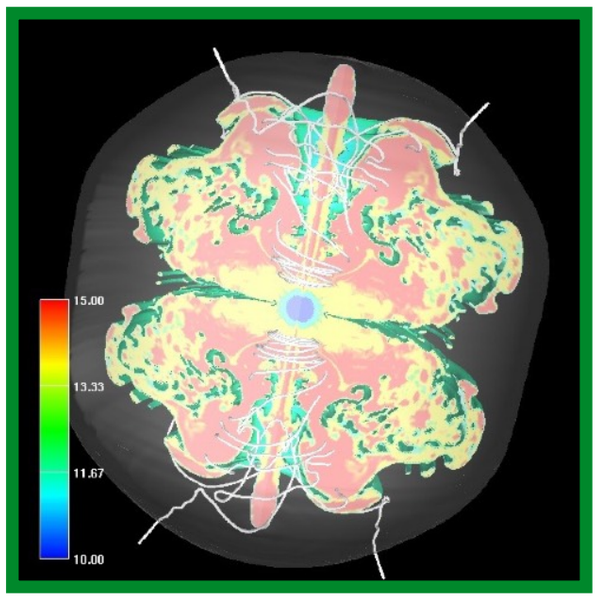
CC-SNe with B-field amplification by MRI

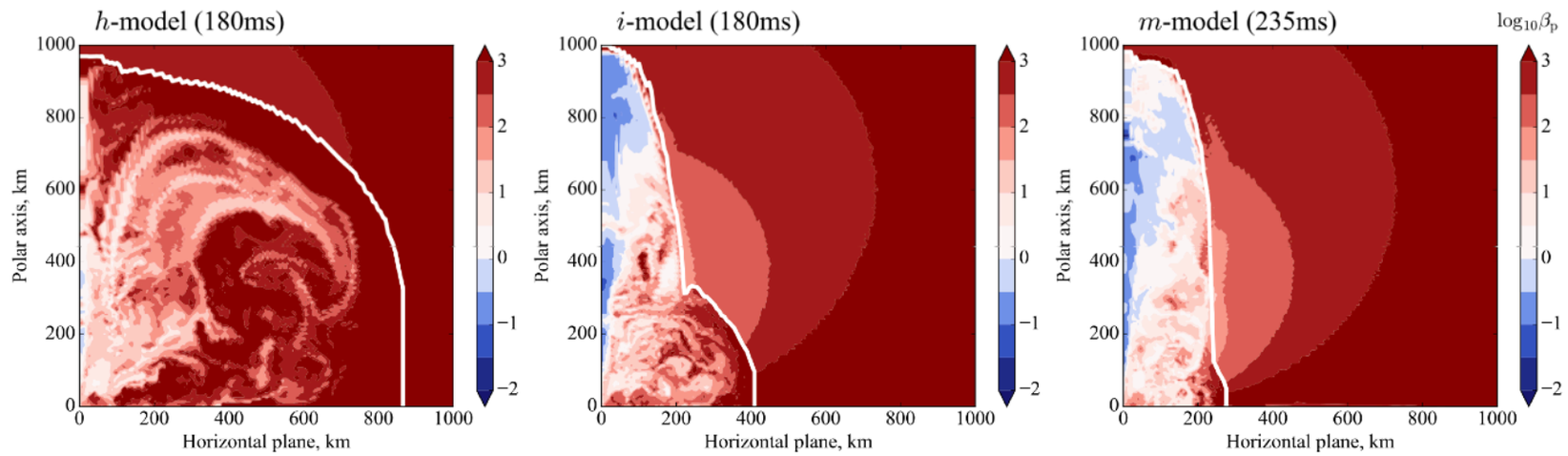
Sawai & Yamada (2014, 2016)



Δr_{min} = 100, 50, 25, 12.5 m

Entropy + B-fields(3D)





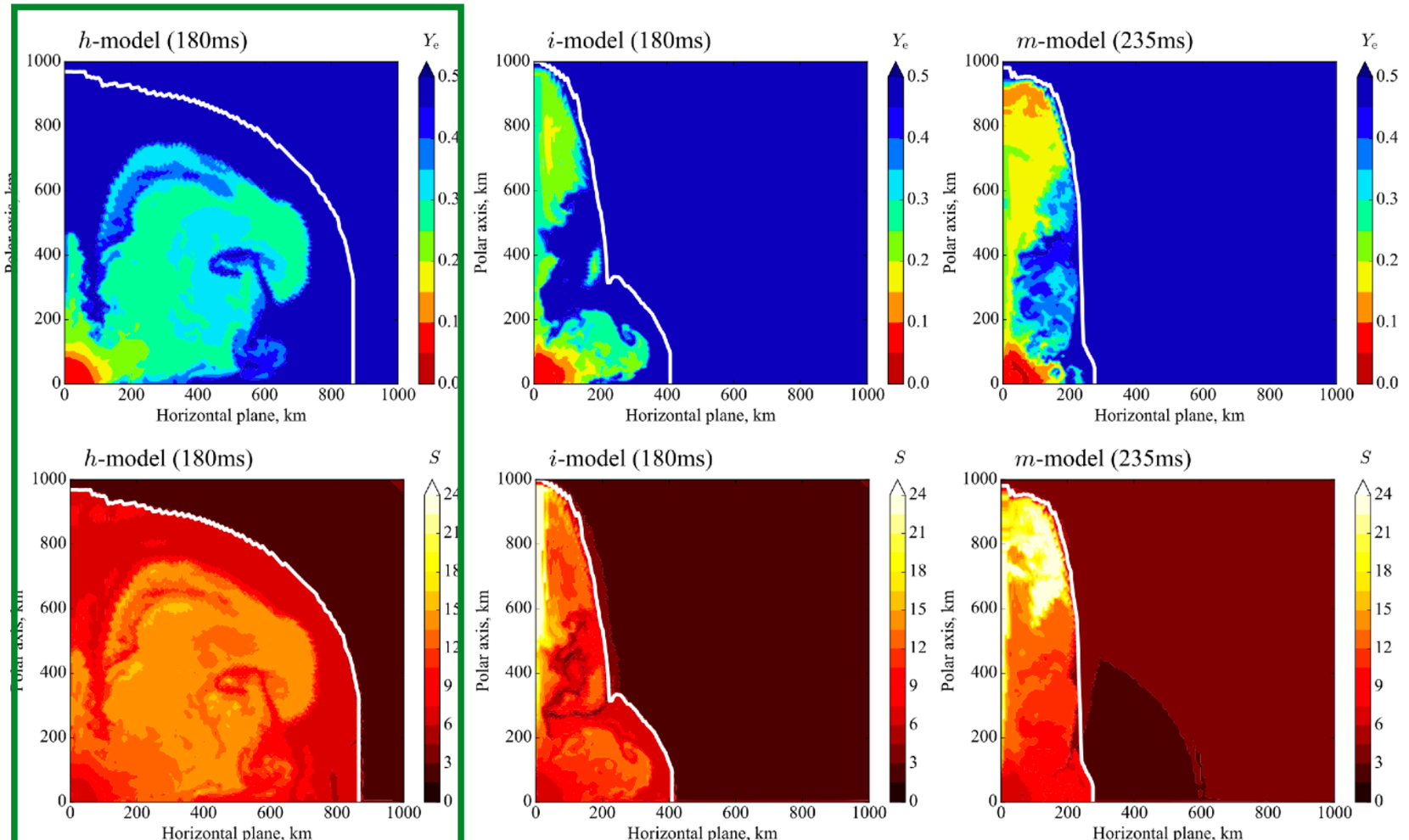
heating-dominated

intermediate

magnetically-dominated

Y_e

entropy

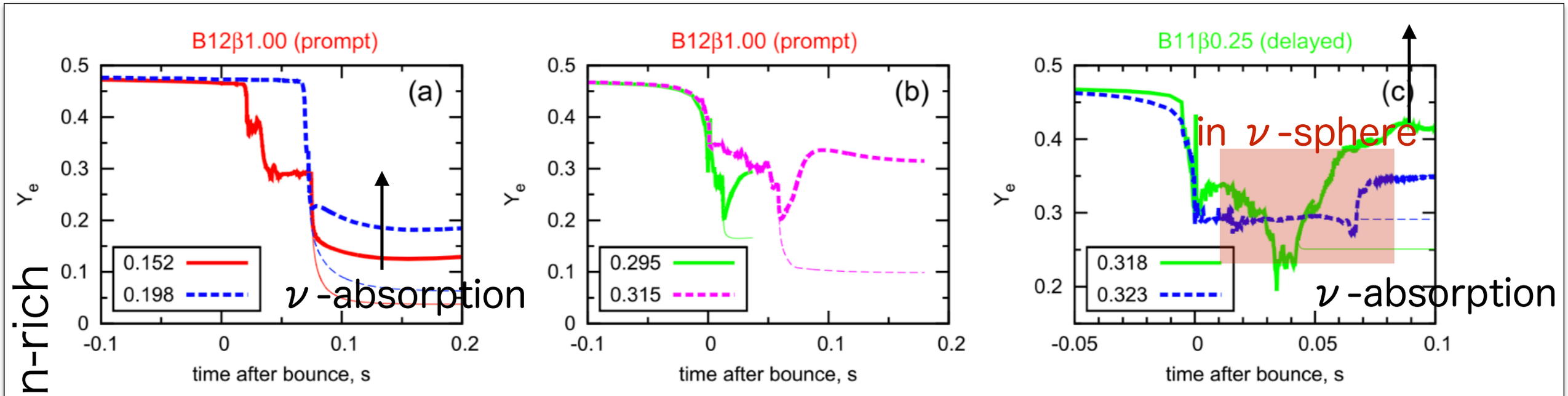


Various r-process in several jet SNe

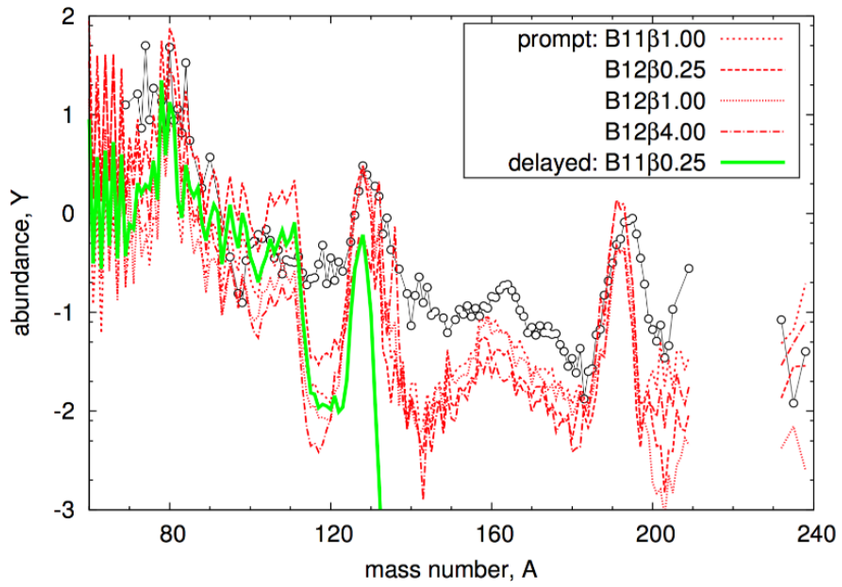
very neutron-rich matter in SN core (“proto-magnetar”)

significant effect of e^--capture (off β-equilibrium)

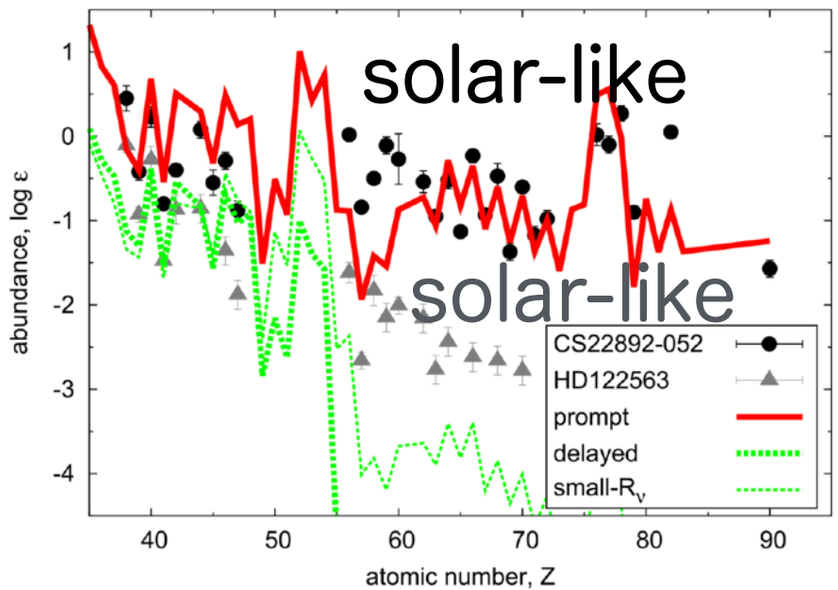
$$Y_e = Y_{\text{“p”}} = \Sigma(A_i/Z_i)X_i \sim N_p/(N_n + N_p)$$



solar r

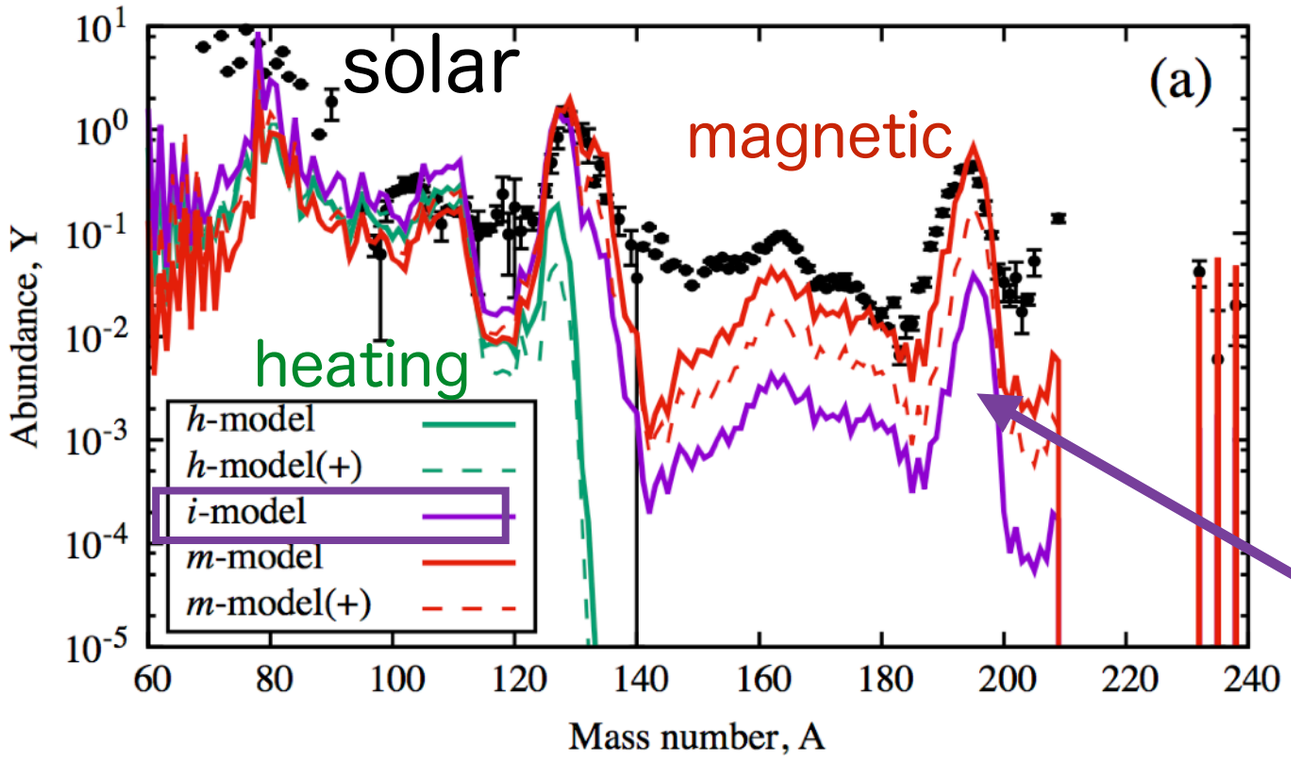


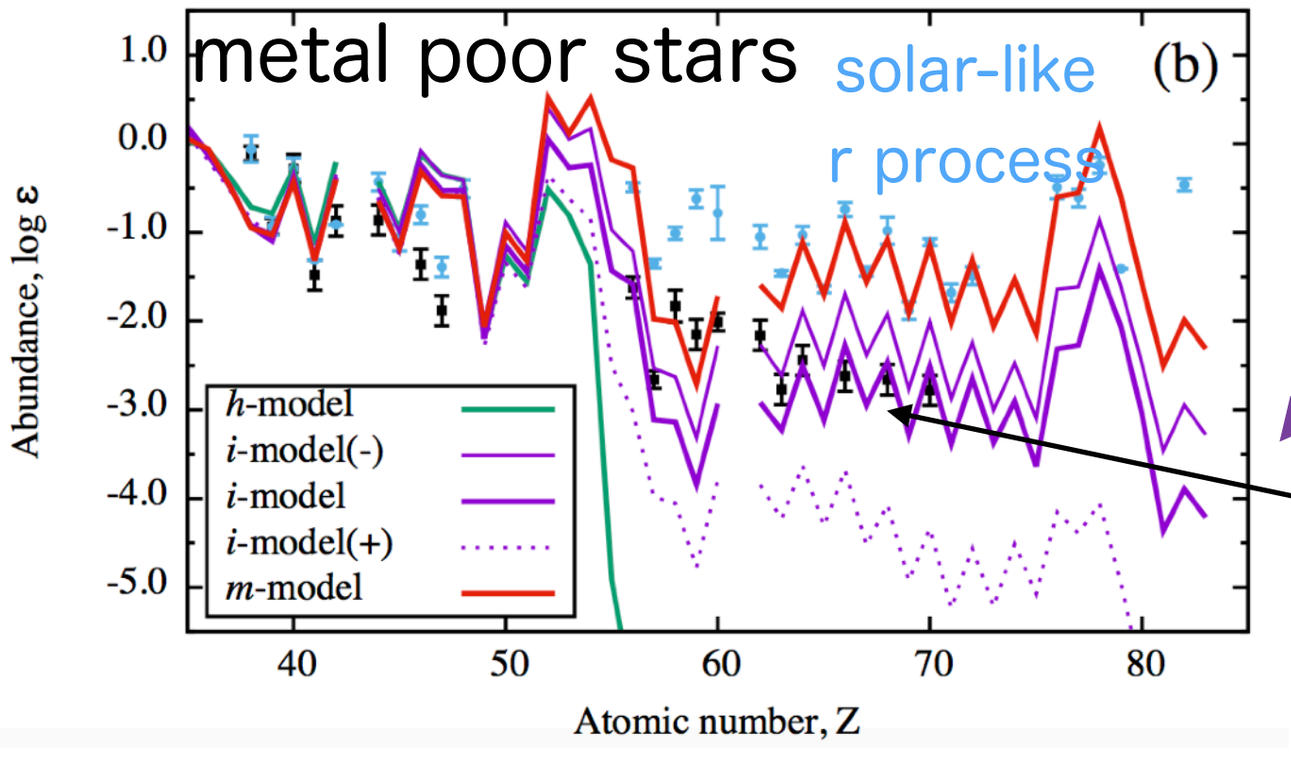
metal-poor stars

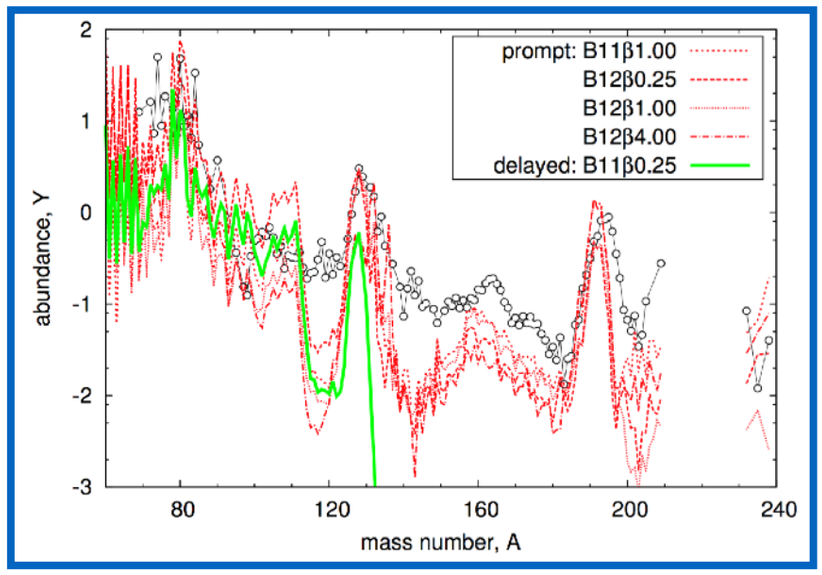


r-process abundances

NN+(2017), based on Sawai models







prompt vs delayed

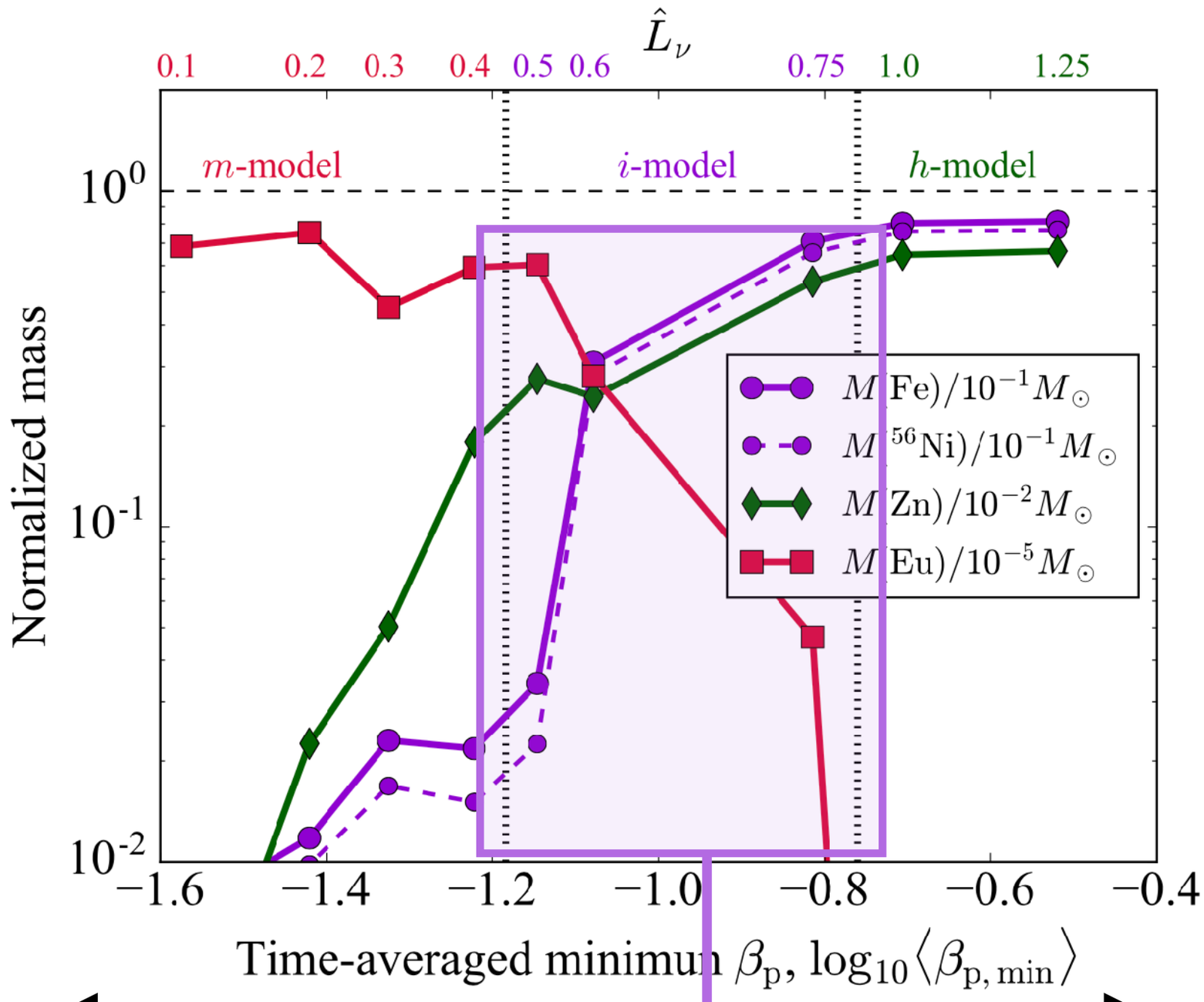
(NN+2015, Takiwaki models)

“intermediate” r-process?

“weak” heavy r pattern

HD122563 (Honda+2006)

Alternative r-process sources in early galaxy?



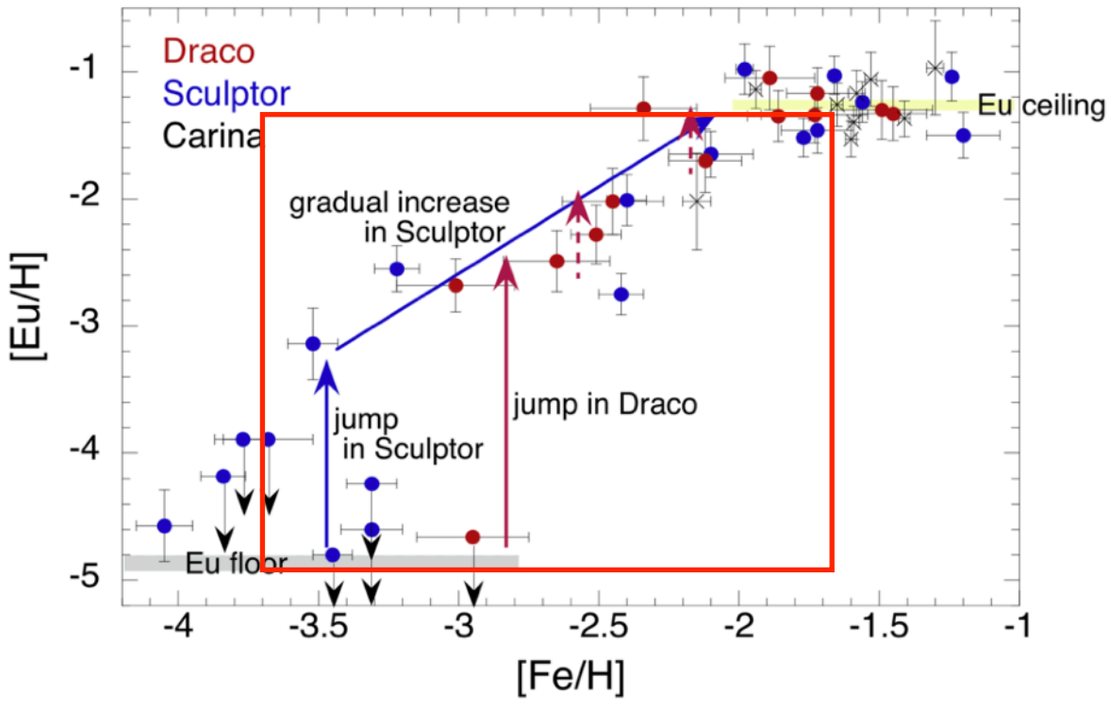
strong jet ⟵ ⟶ weak jet

“intermediate” r-process?

nucleosynthesis yields:

github.com/nnobuya/mrsn

Eu evolution by MR-SNe in dSph galaxies



Chemical evolution models

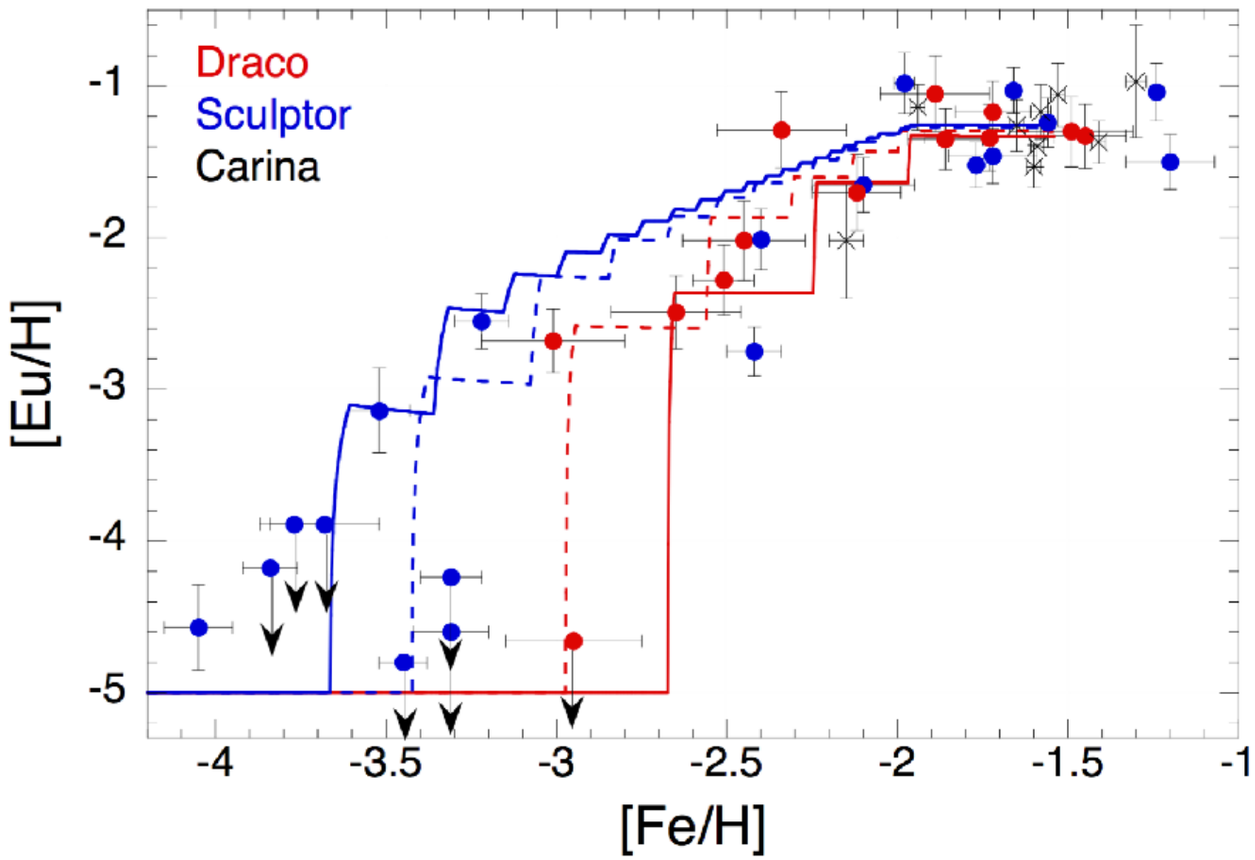
Tsujimoto & NN (2015)

GCE models suggest:

- event rate: 0.5 % of CC-SNe
- large Eu ejection: $\sim 10^{-5}\ M_{sun}$

agree with our MR-SN models

(e.g. NN+2015, 2017)



increase of Eu,
which are not explained
by NS-NS mergers

Short Summary

- MR-SNe are still possible sites for the r-process
- However, strong-magnetic jets are needed to produce heavier r-nuclei: unavailable so far in “realistic” progenitor/MHD set-up

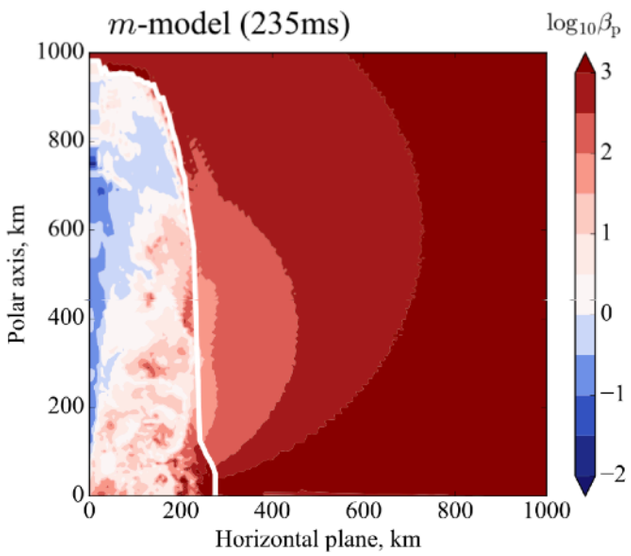
We want to discuss possible “observational” properties of such events: r-process-jet supernovae.

long-term evolution of r-process ejection

(propagation of r-process-rich jet in the progenitor)

Strong-magnetic jet: (strong r)

NN, Sawai+2017



10^8 cm

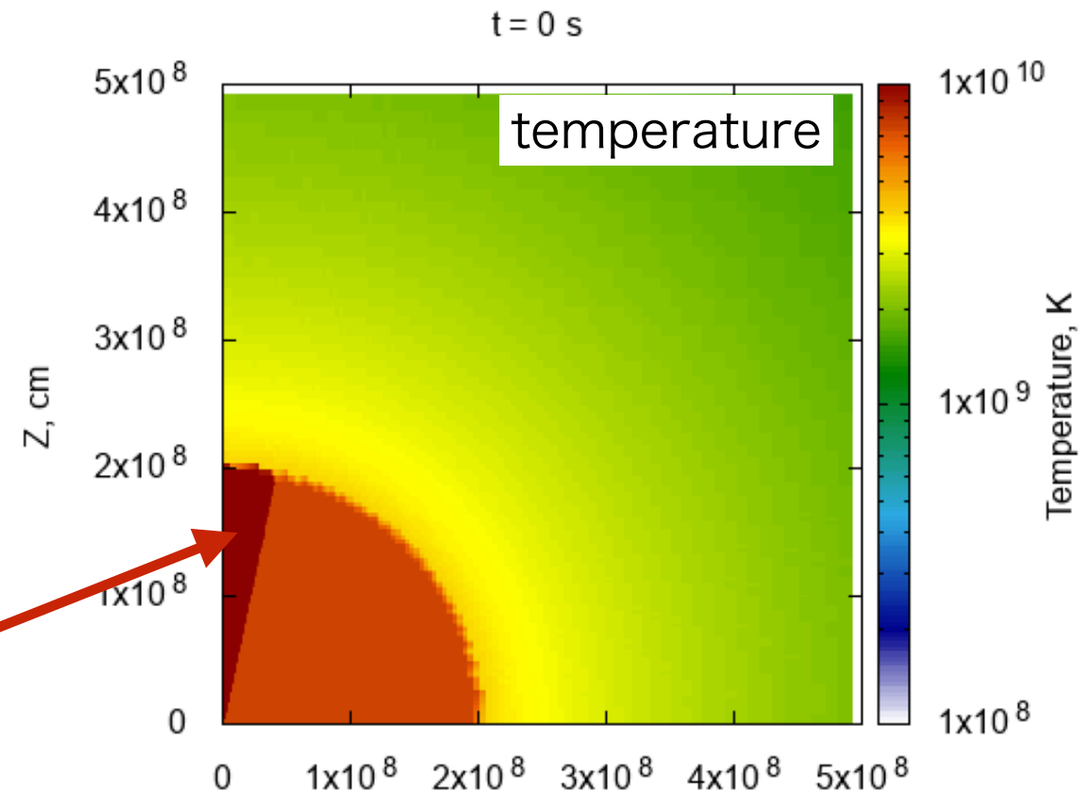
- hydrodynamics w/o B-fields
- “jet” injection
- Wolf-Rayet (no H-layer)

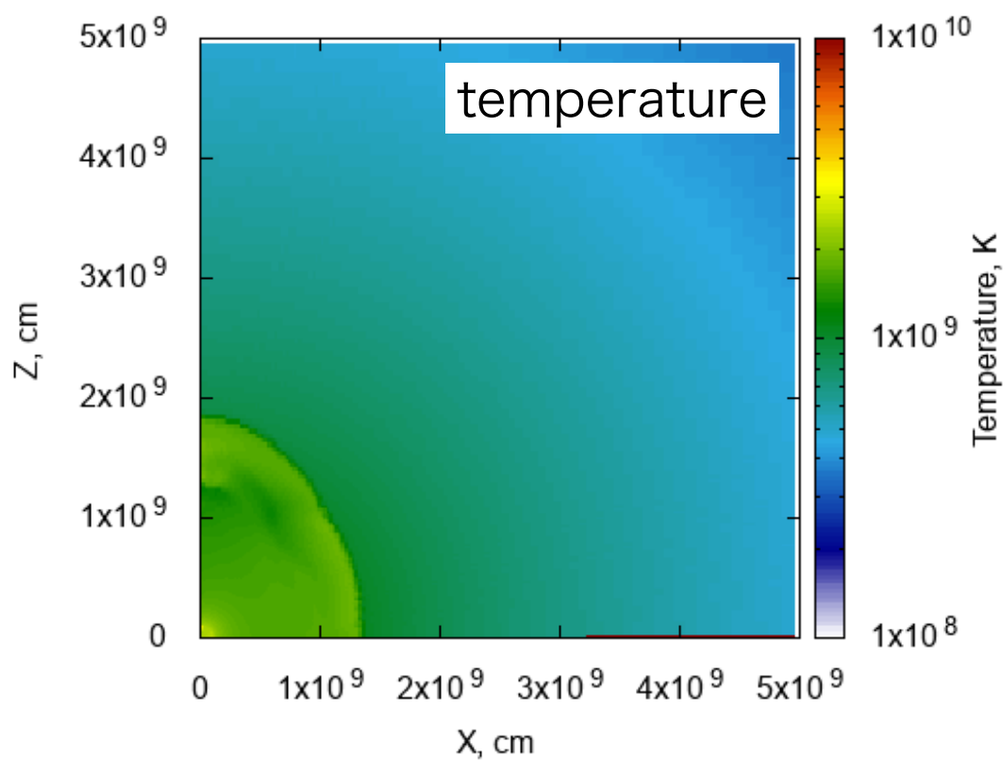
hydrodynamical simulation by J. Matsumoto

x 5

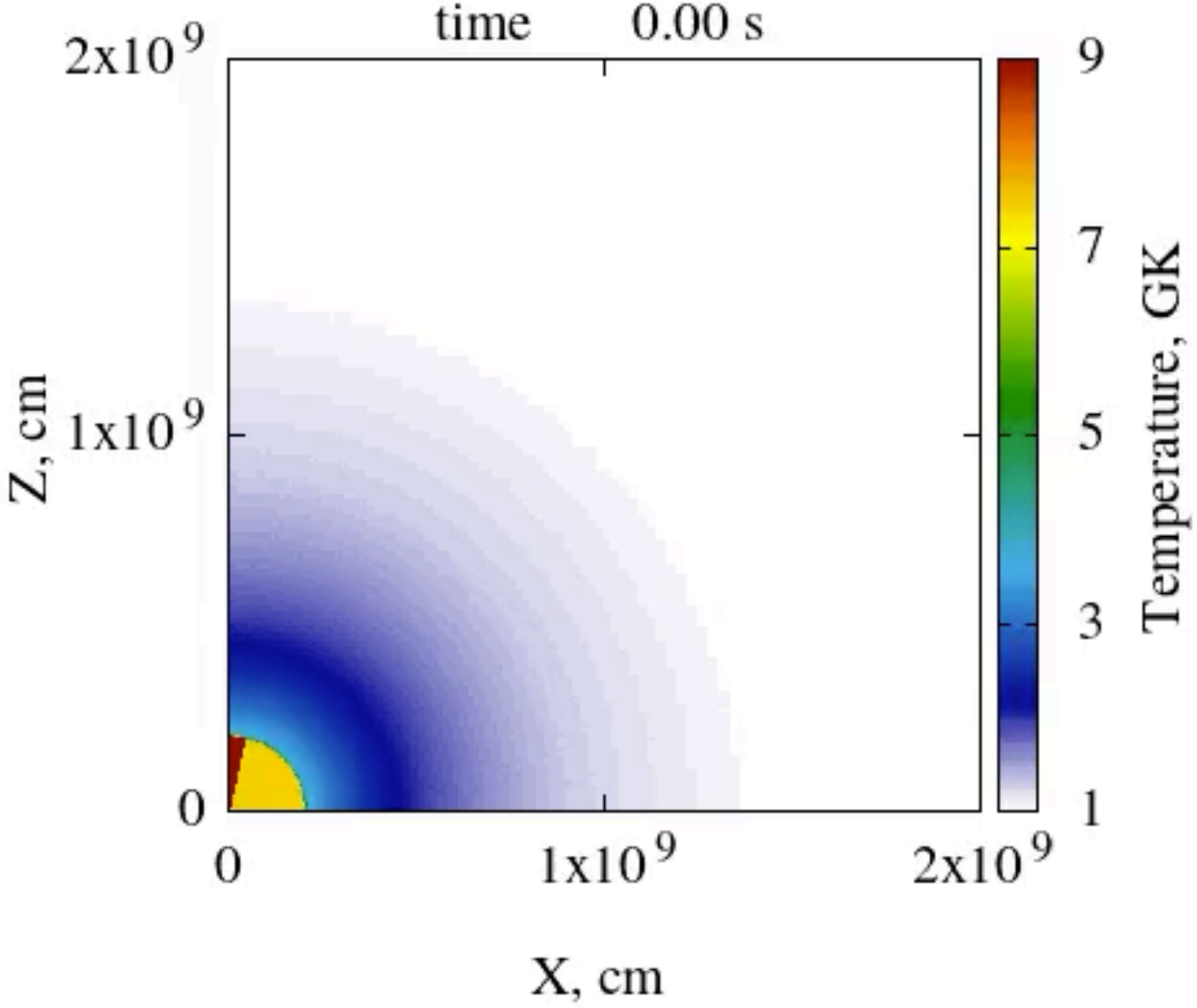
$E_{jet} = 10^{51}$ erg

x 10

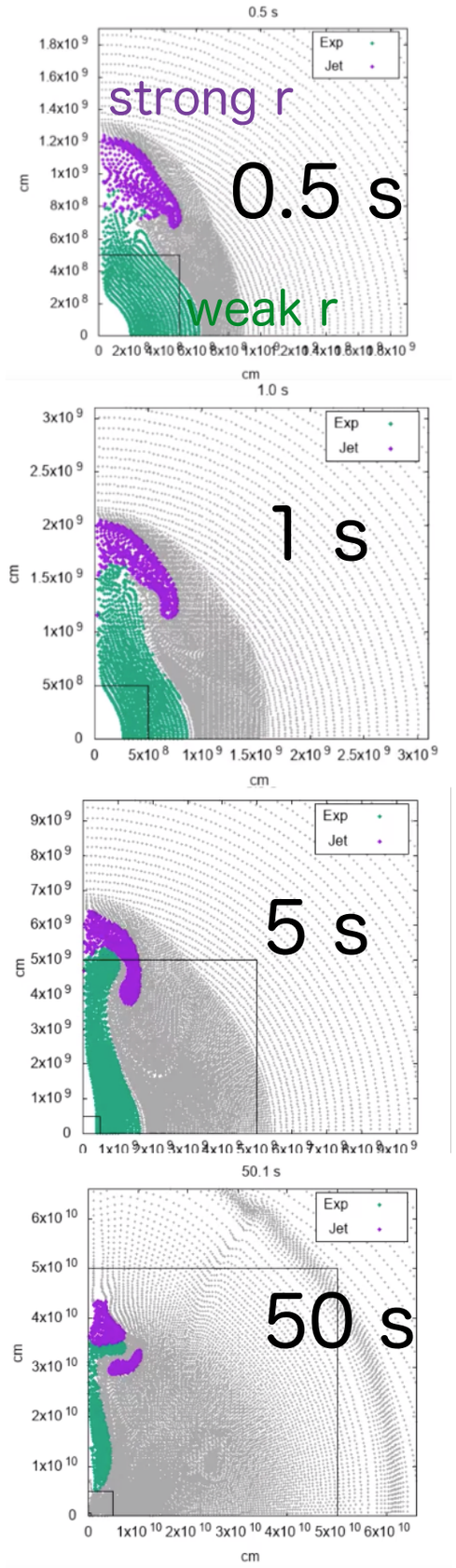




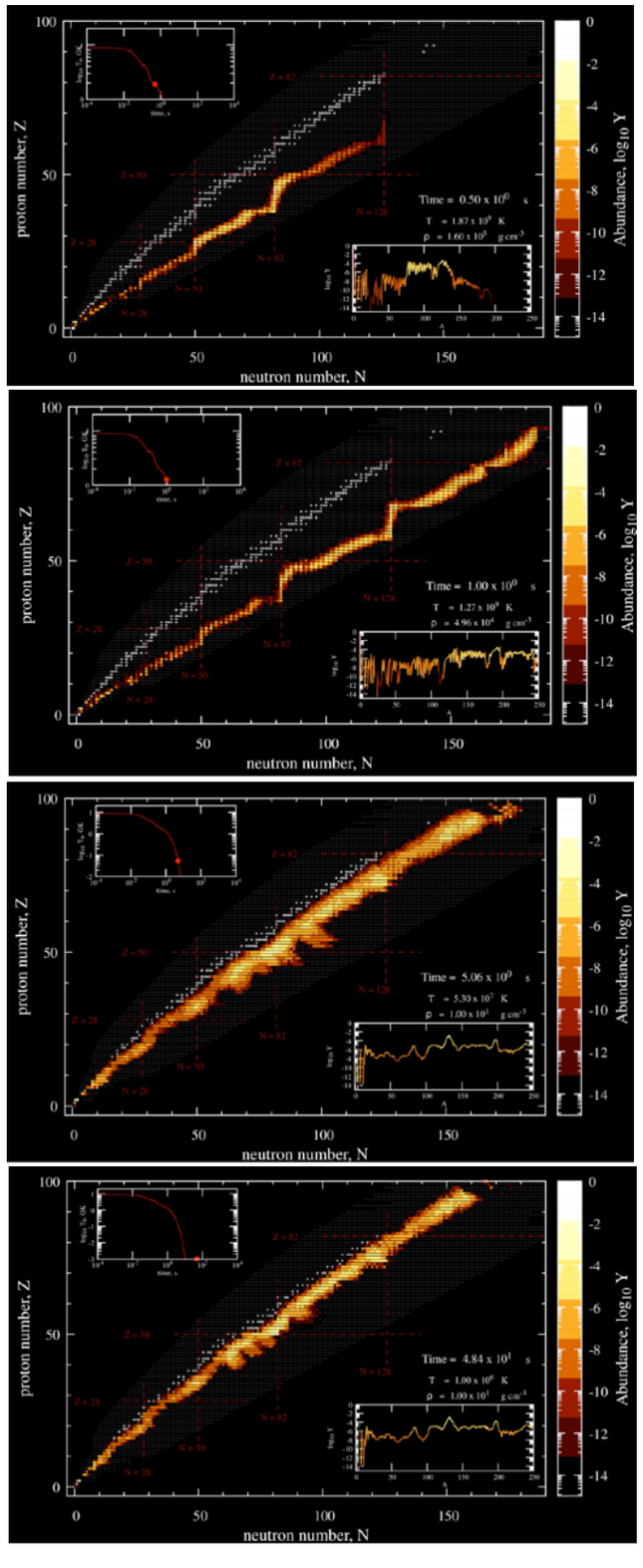
Strong-magnetic jet: (strong r)



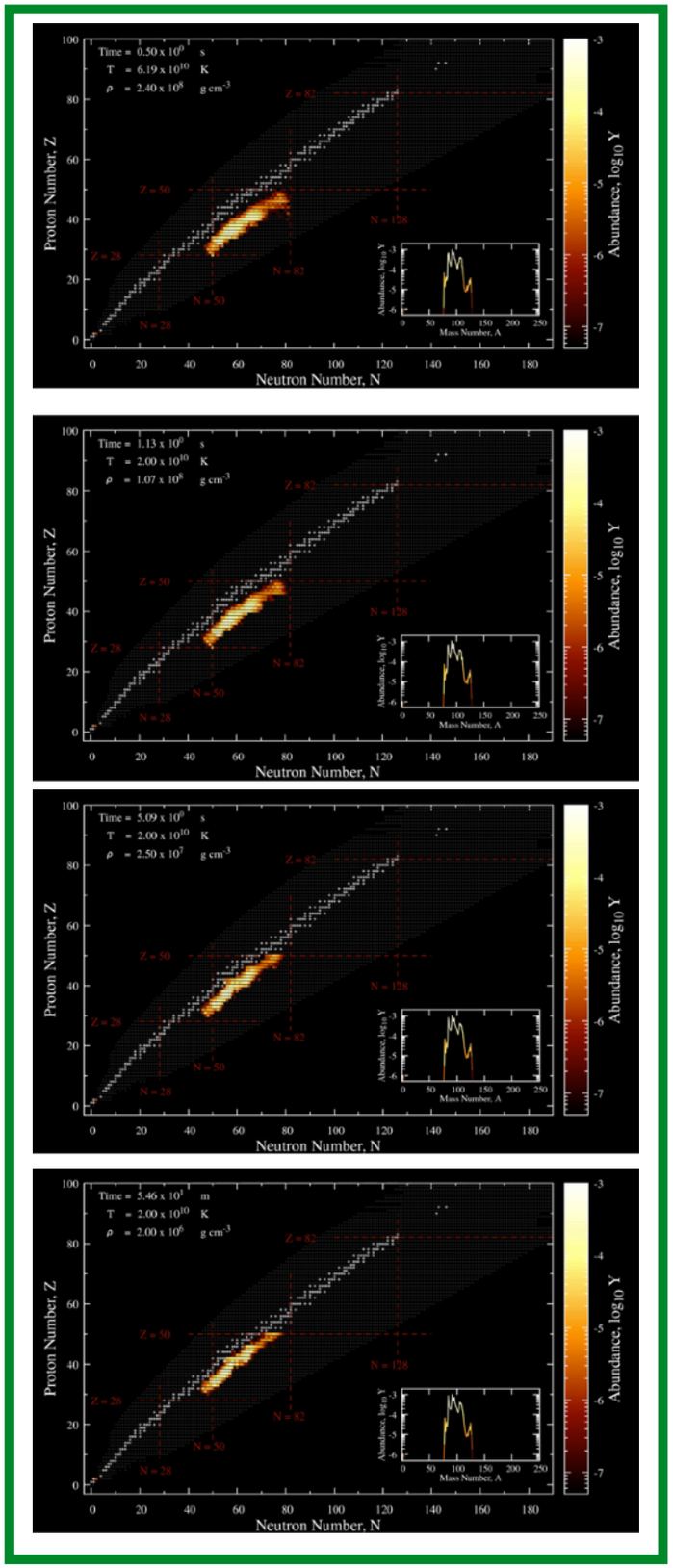
Evolution of hydro vs r-process



strong r



weak r



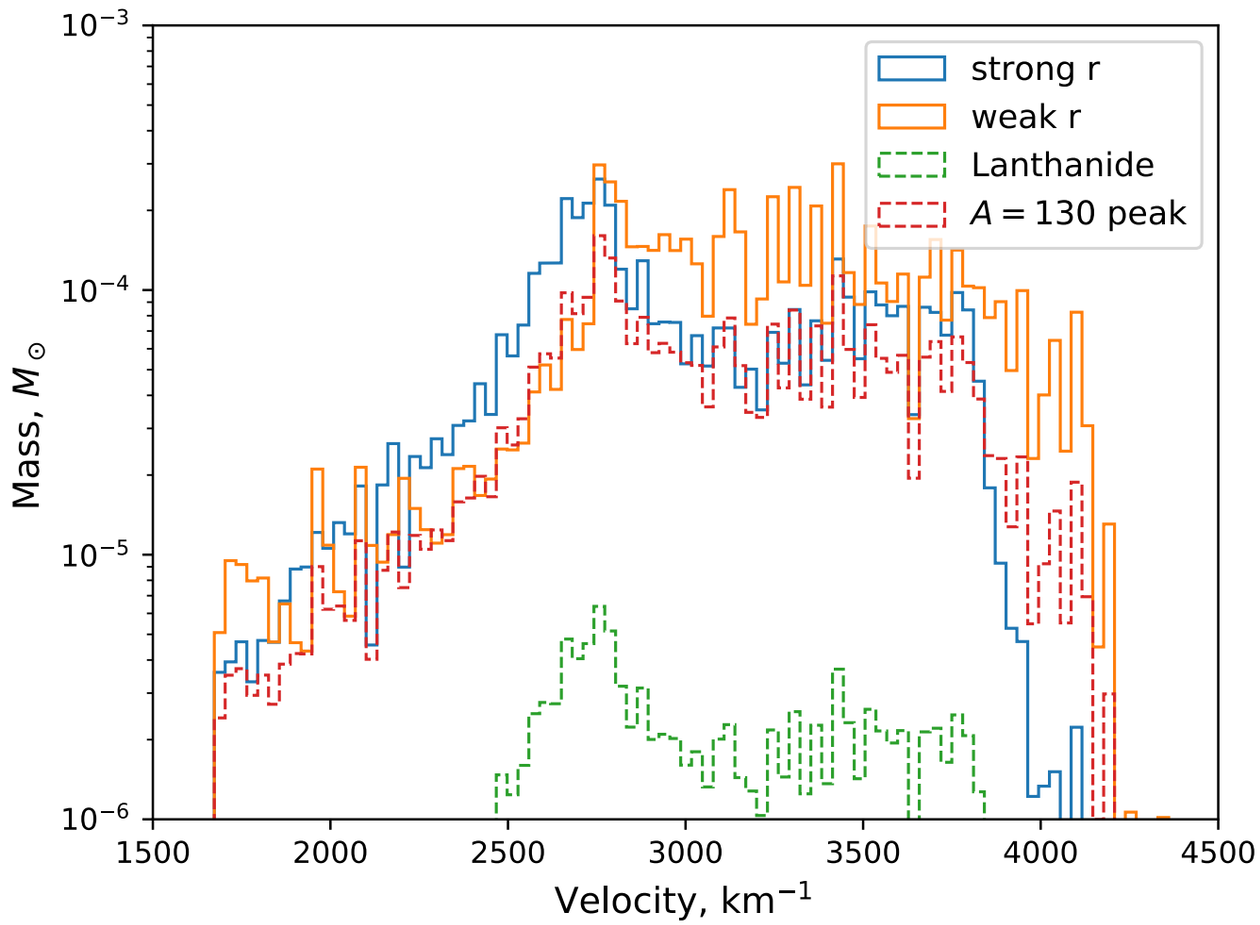
Elemental distribution in ejecta

based on the nucleosynthesis condition of NN+2017:

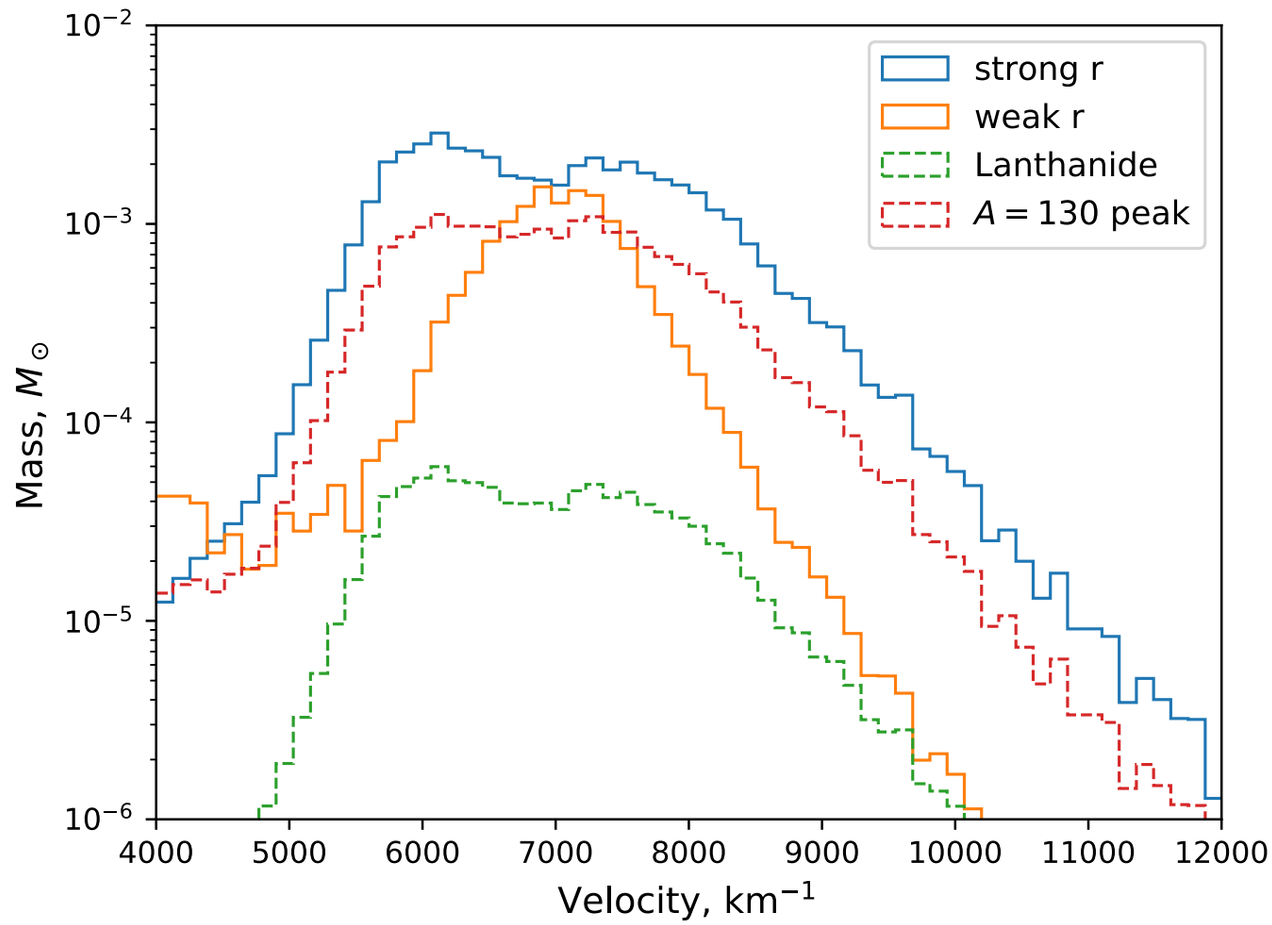
very n-rich —> strong r

medium n-rich —> “intermediate r”

weak magnetic jet



stronger magnetic jet



—> Future observation will provide new insights?

“kilonova” due to r-process decay?? (still, just idea …)

Summary

- NS-NS scenario has no severe problems in GCE
  - dispersion and event rates agree with Eu evolution
- But, some difficulties in the early galaxies
  - several “variations”:
    weak r-process and actinide-boost stars
- Multiple r-process sources in GCE
  - rate types of SNe with r-process rich yields
    - detection of Sr in the remnant?

theoretical interpretation ⇆ observational constraint

- merger, SN models
- Galactic evolution
- abundances
- kilonova

Perspective

What is the first r-process event/star in the universe?

- Neutron star mergers?
  - difficult?
    - large delay time
    - can have variation in r-process?
- CC-SNe (but, rare SNe, e.g., MR-SNe)
  - possible?
    - metallicity dependence; active in the early galaxies
    - variation in the r-process pattern
    - can be related to “POP III SNe” ?