千葉工業大学セミナー

様々な天体環境下でのrプロセス元素合成とβ崩壊率がピーク生成に与える影響

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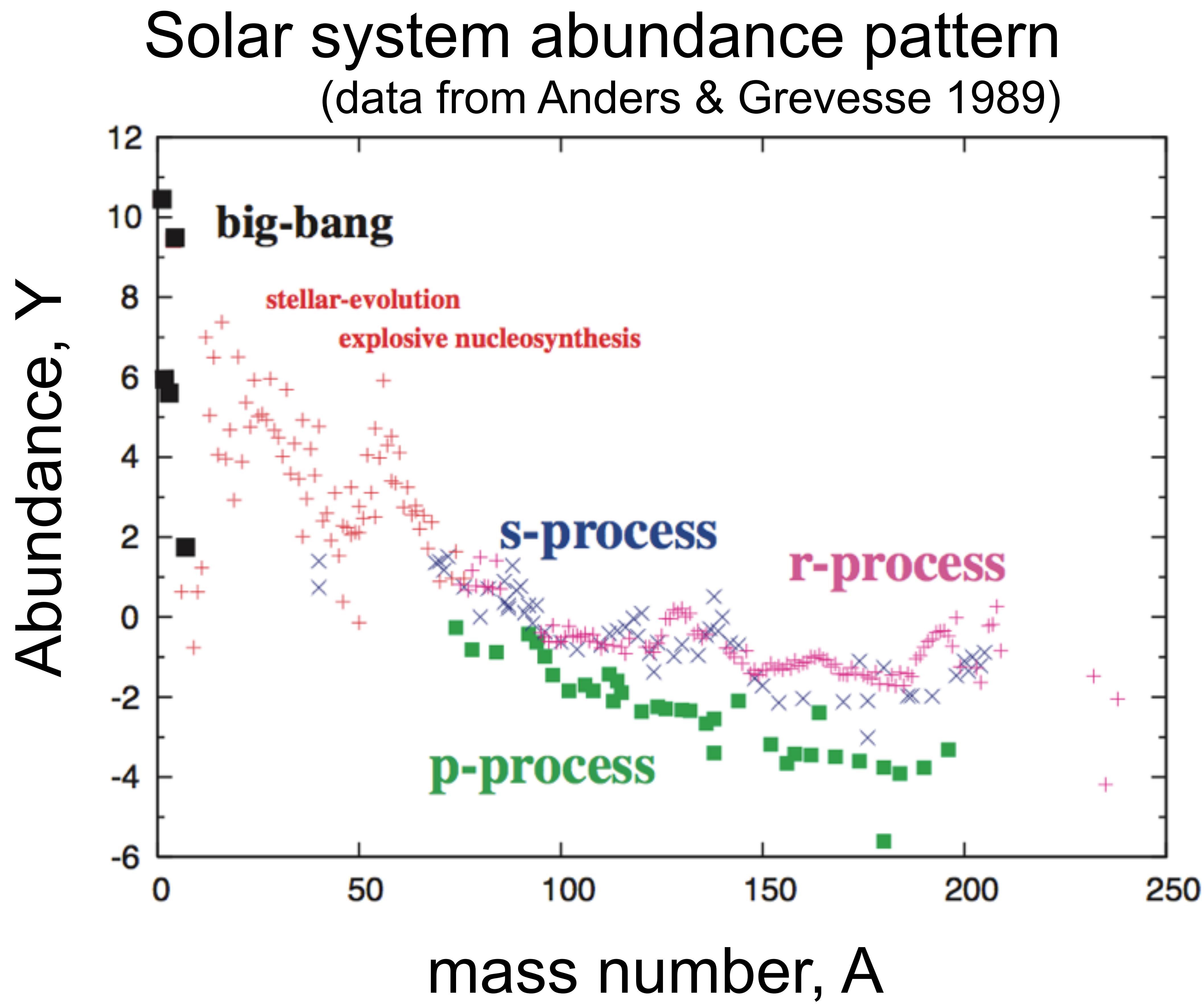
Origin of elements (beyond iron)

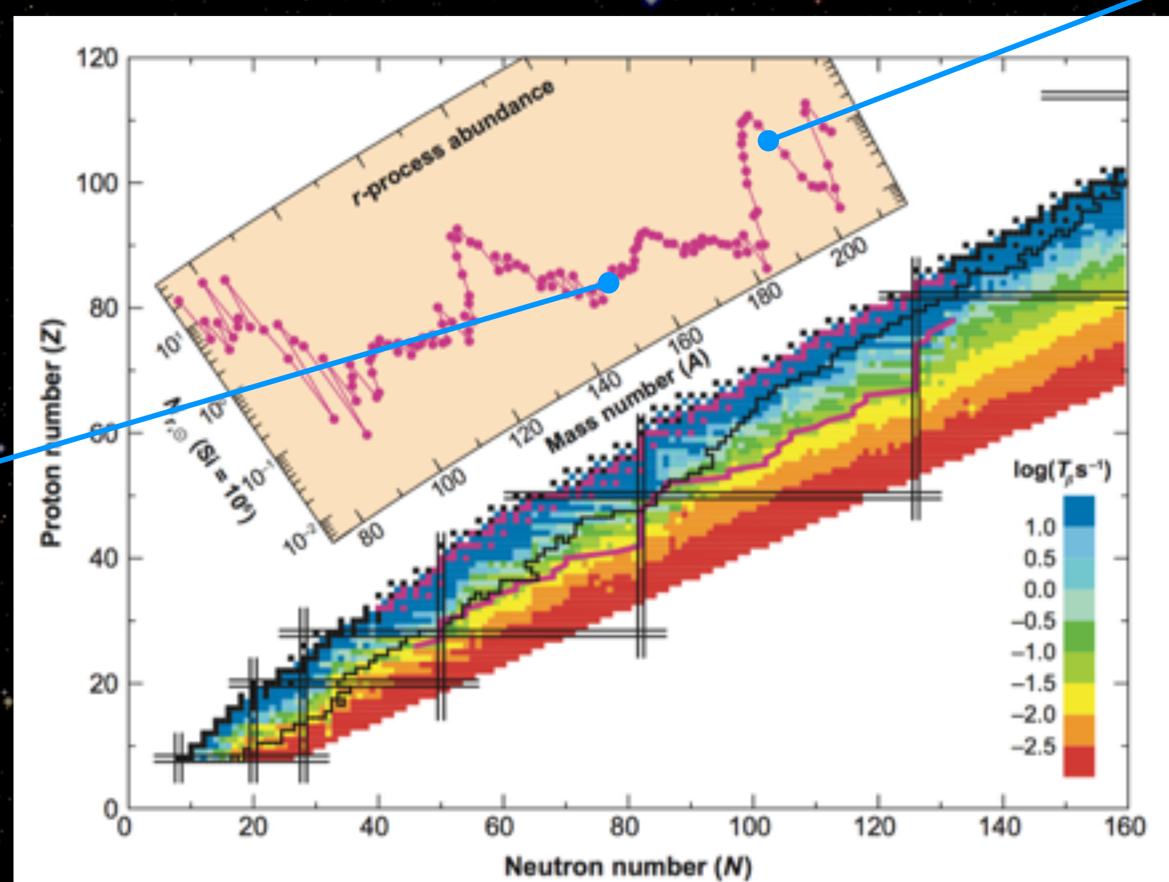


Origin of gold (beyond iron)

- 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?

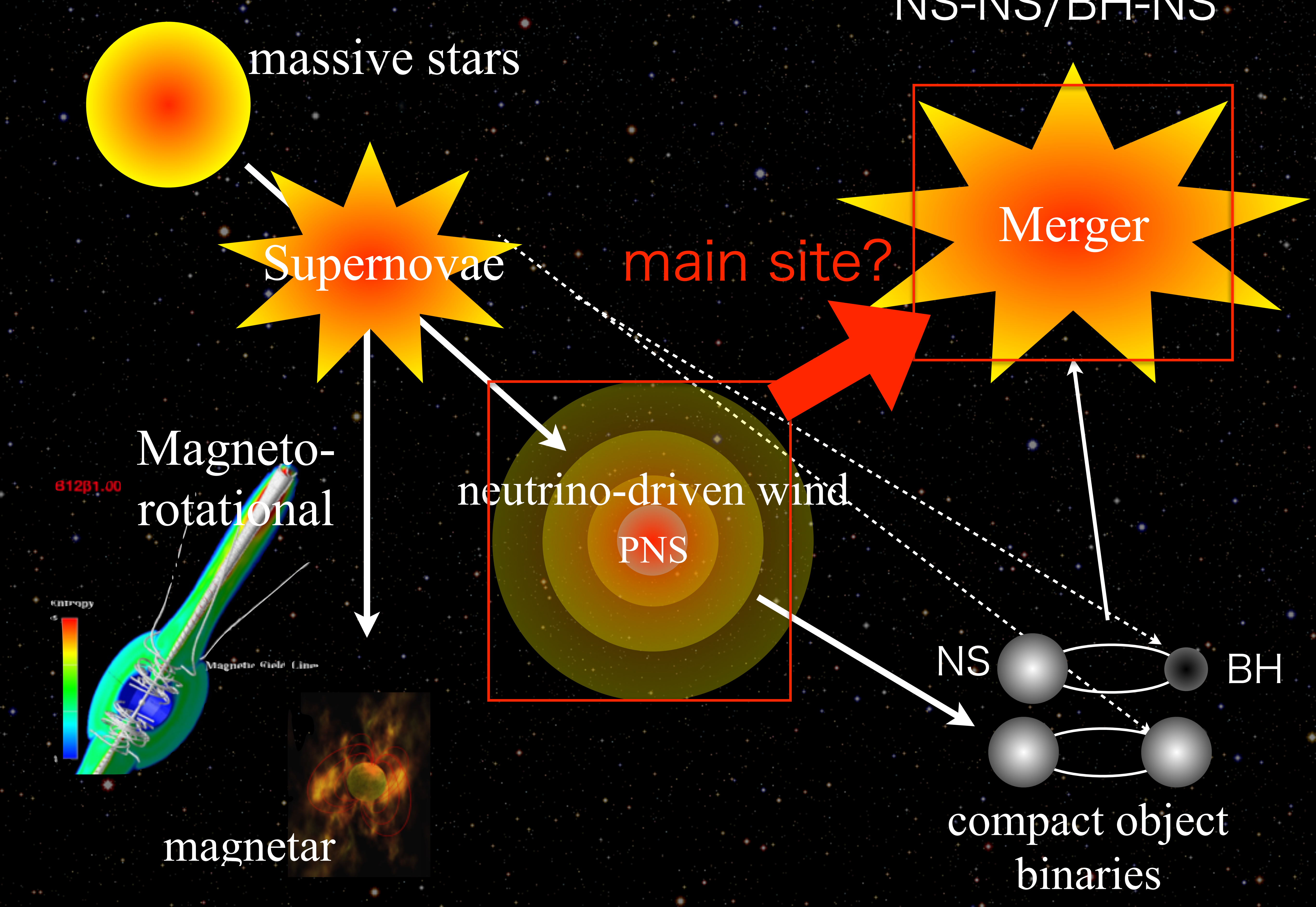
“The Elements” T. Gray



“The Elements” T. Gray

Sneden+ (2008)
(Möller+ 1997)

Astronomical sites/scenarios



Contents

- Astrophysical models for the r-process
  (a brief summary of r-process in NS merger)
- MRD-SNe as r-process
  - as alternative source in early galaxies
- β-decay
  - as alternative source in early galaxies
- conclusion

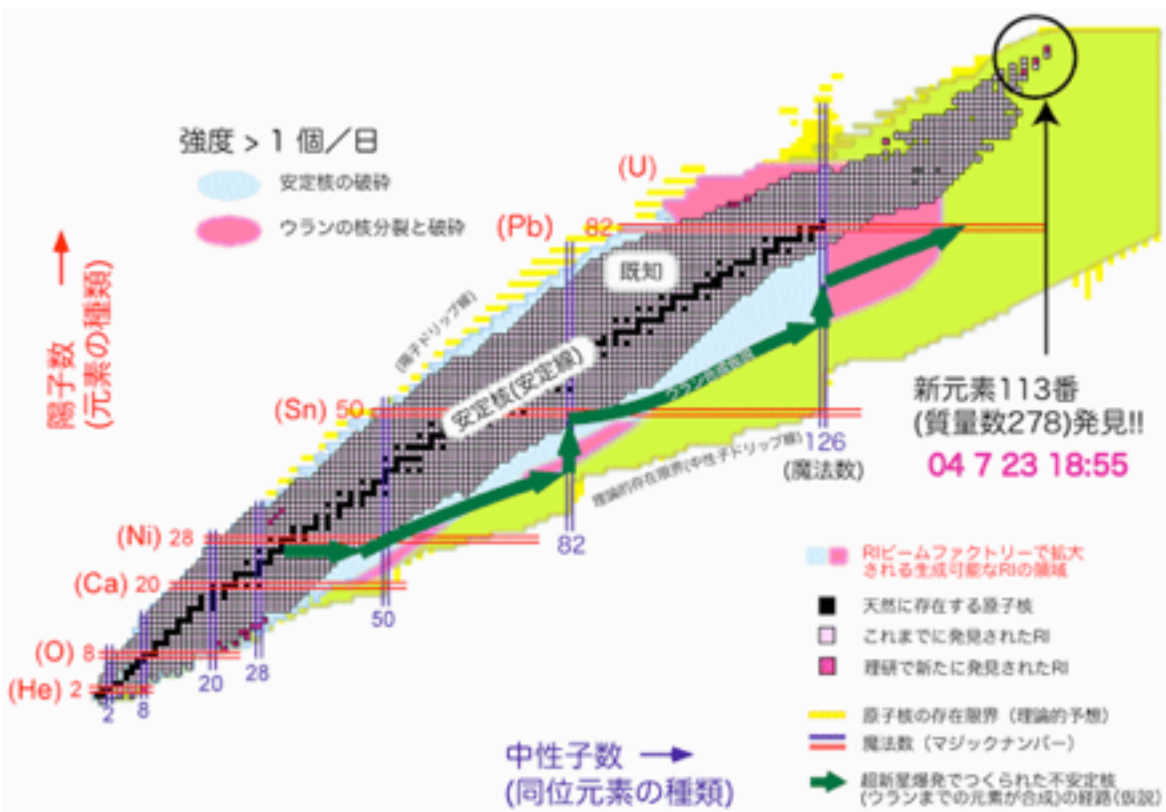
references (of our work)

- Wanajo, Sekiguchi, NN et al., ApJL 789 (2014) L39
- NN, Takiwaki & Thielemann, ApJ 810 (2015) 109
- Tsujimoto & NN, ApJL 811 (2015) L10
- NN, Podolyák, Fang & Suzuki, PLB 756 (2016) 273

Astronomical sites of the r-process: NS mergers as a main cosmic source

The r-process: beyond iron

r-process: rapid($\tau_{(n,\gamma)} < \tau_{\beta\text{-decay}}$) n-captures
"explosive event" related to neutron stars



RIKEN RIBF Website

proton neutron

Movie by T. Wada (RIKEN)

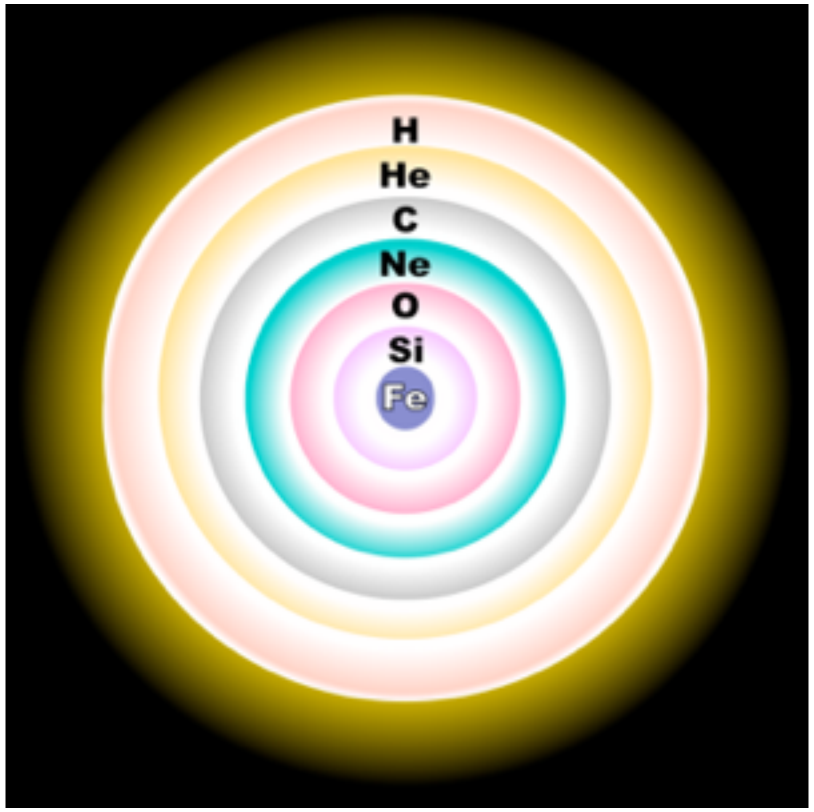
Massive star's evolution : > 10 M☉

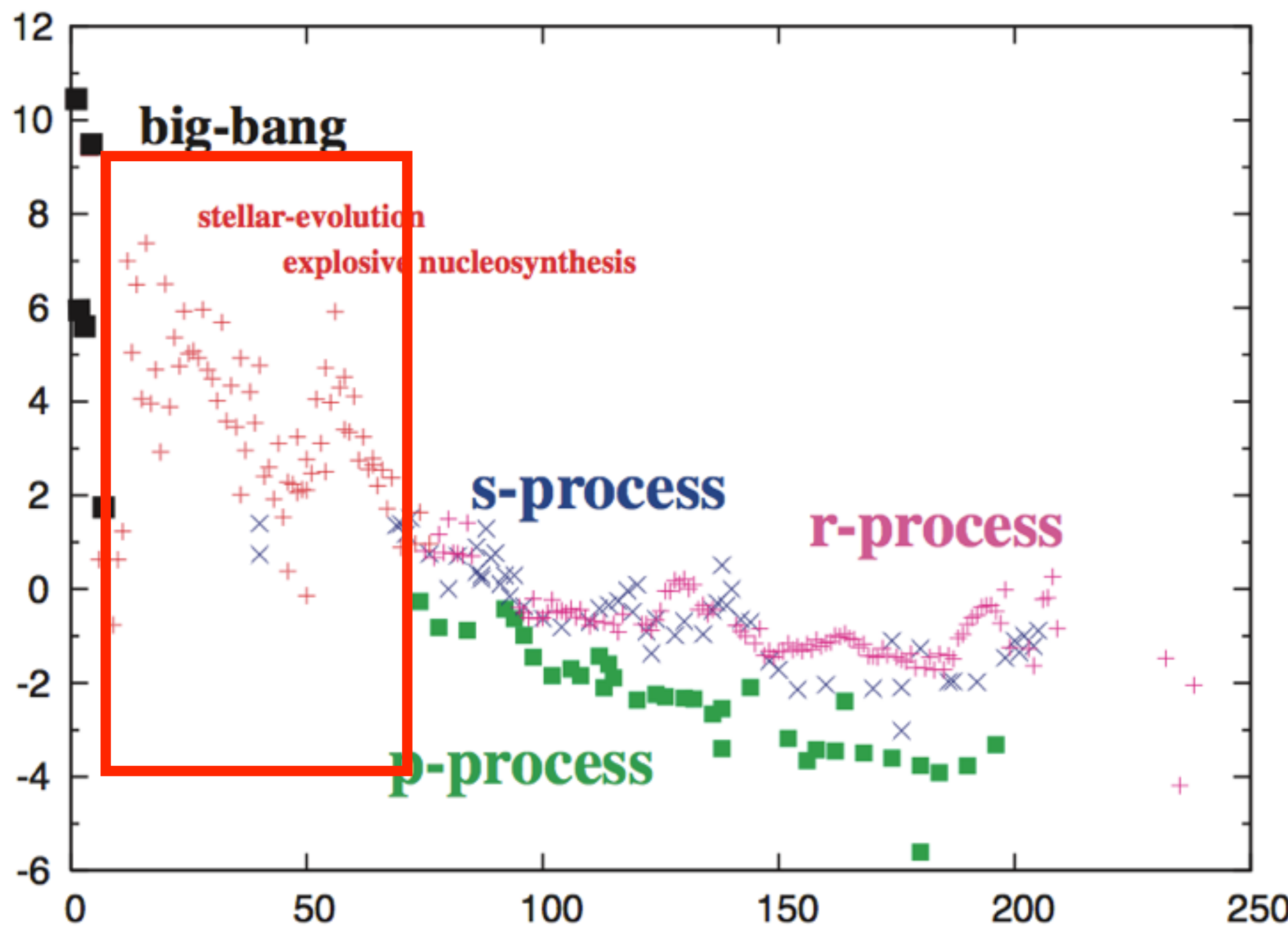
- H-burning
  H → He
- He-burning
  He → C, O
- C-burning
  C → Ne, Mg, Na, Al
- Ne-burning
  Ne → O, Mg
- O-burning
  O → Si, P, S, Cl, Ar, Ca
- Si-burning
  Si → Fe, Ni (iron Group)

→ core-collapse

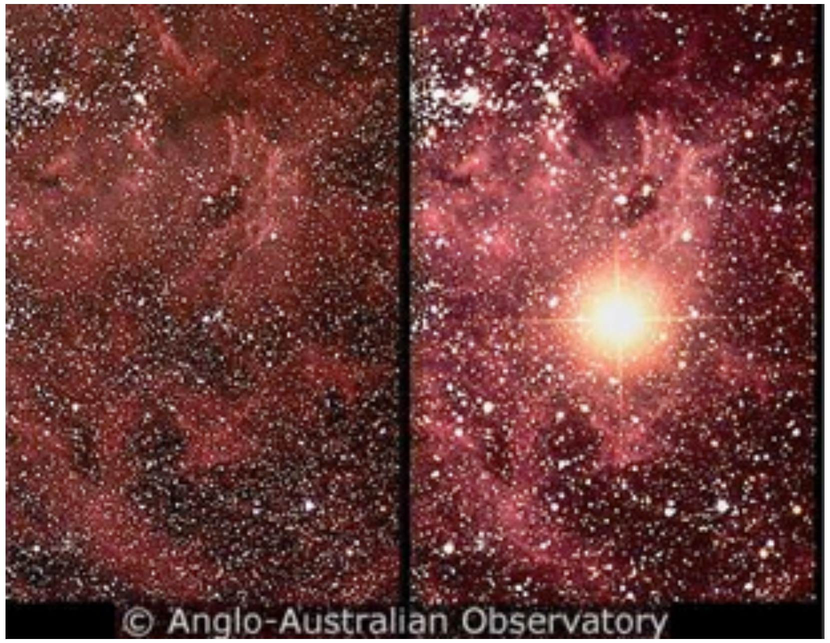
$Fe + \gamma \rightarrow 13\ {}^{4}He + 4n$

(photo-disintegration)





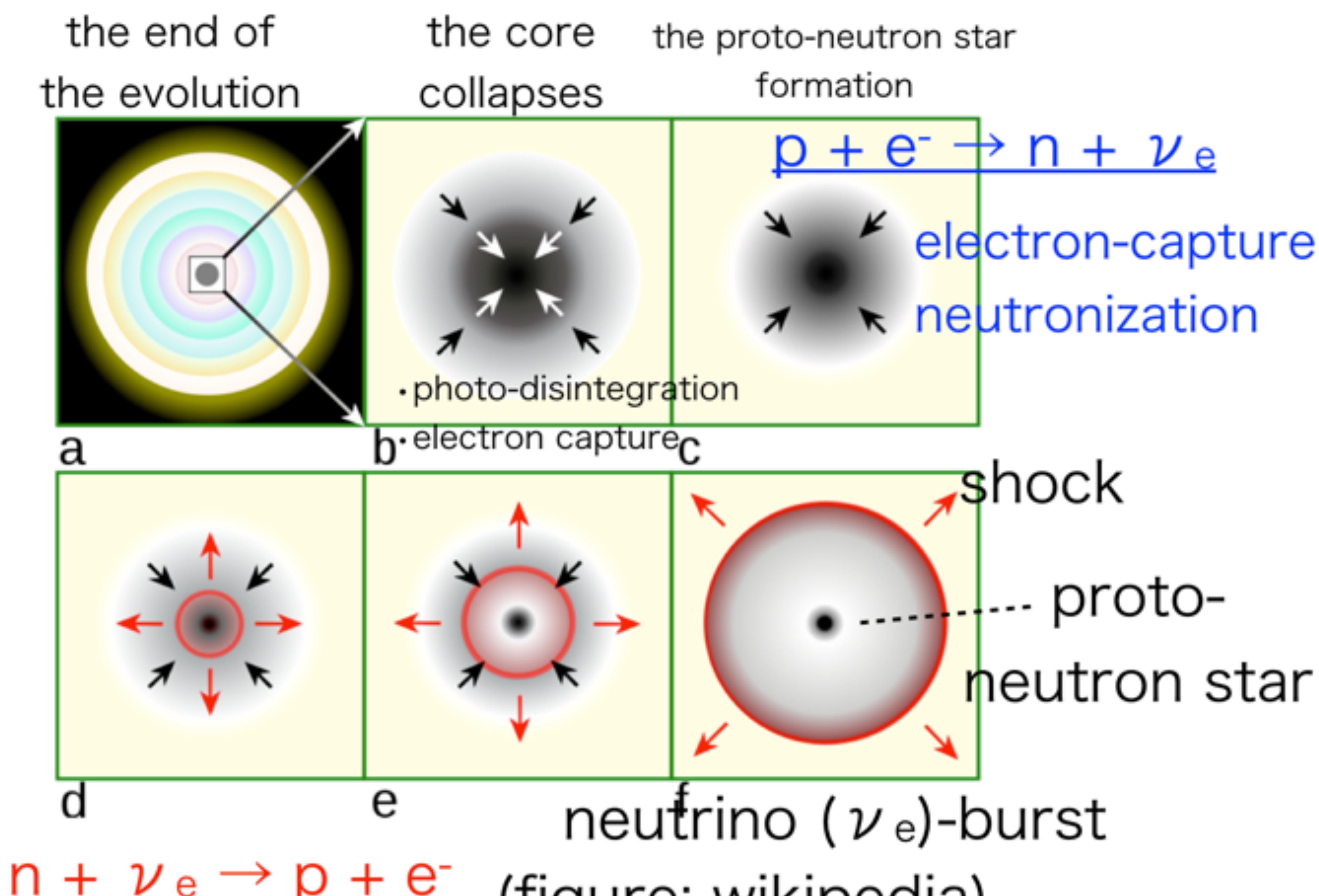
Core-Collapse Supernovae: > 10 M⊙



- SN1987A
- detection of neutrino

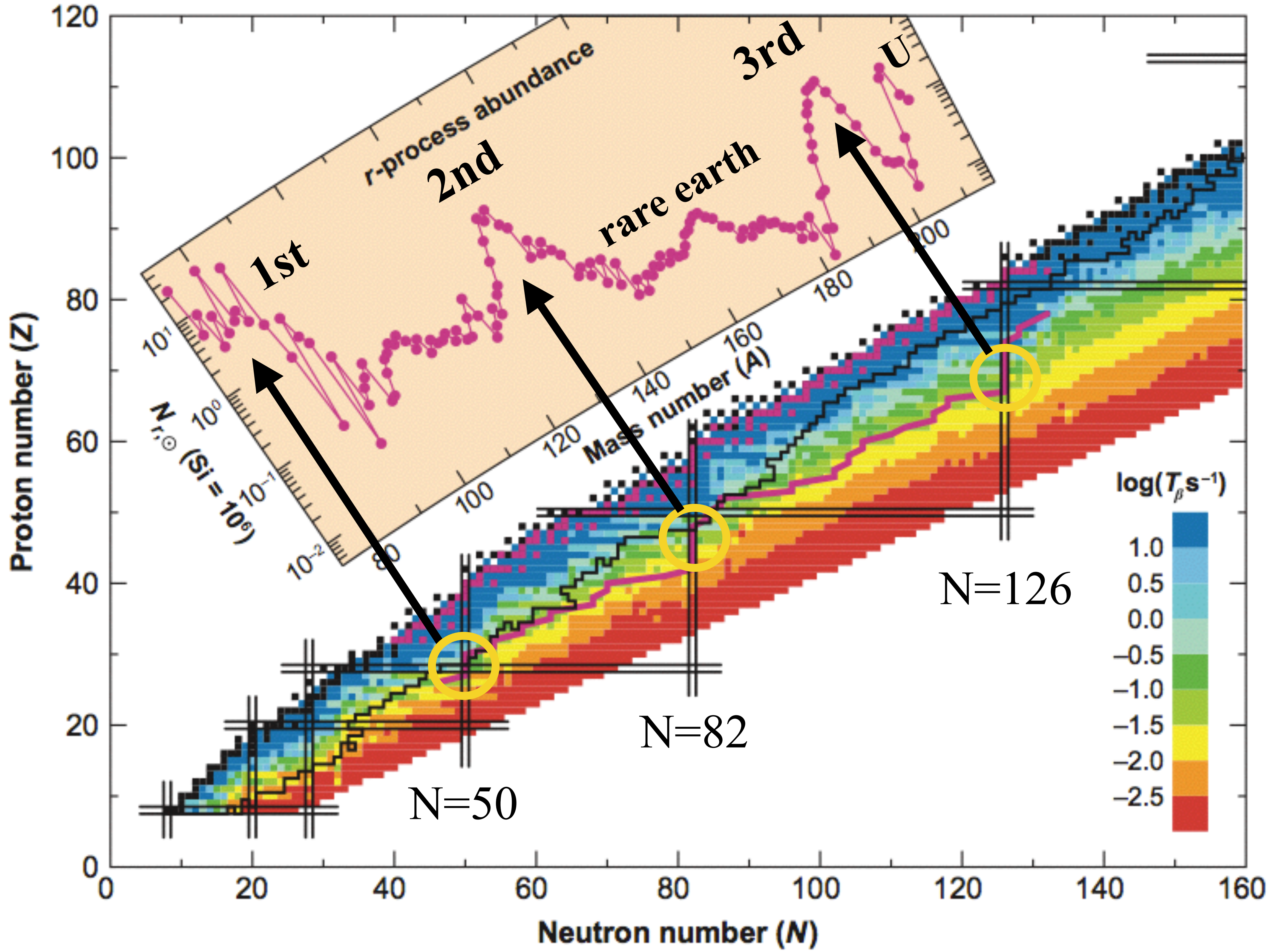
<u>observations</u>

- •optical
- •neutrino
- •cosmic ray
- •GW ?
- •nucleosynthesi



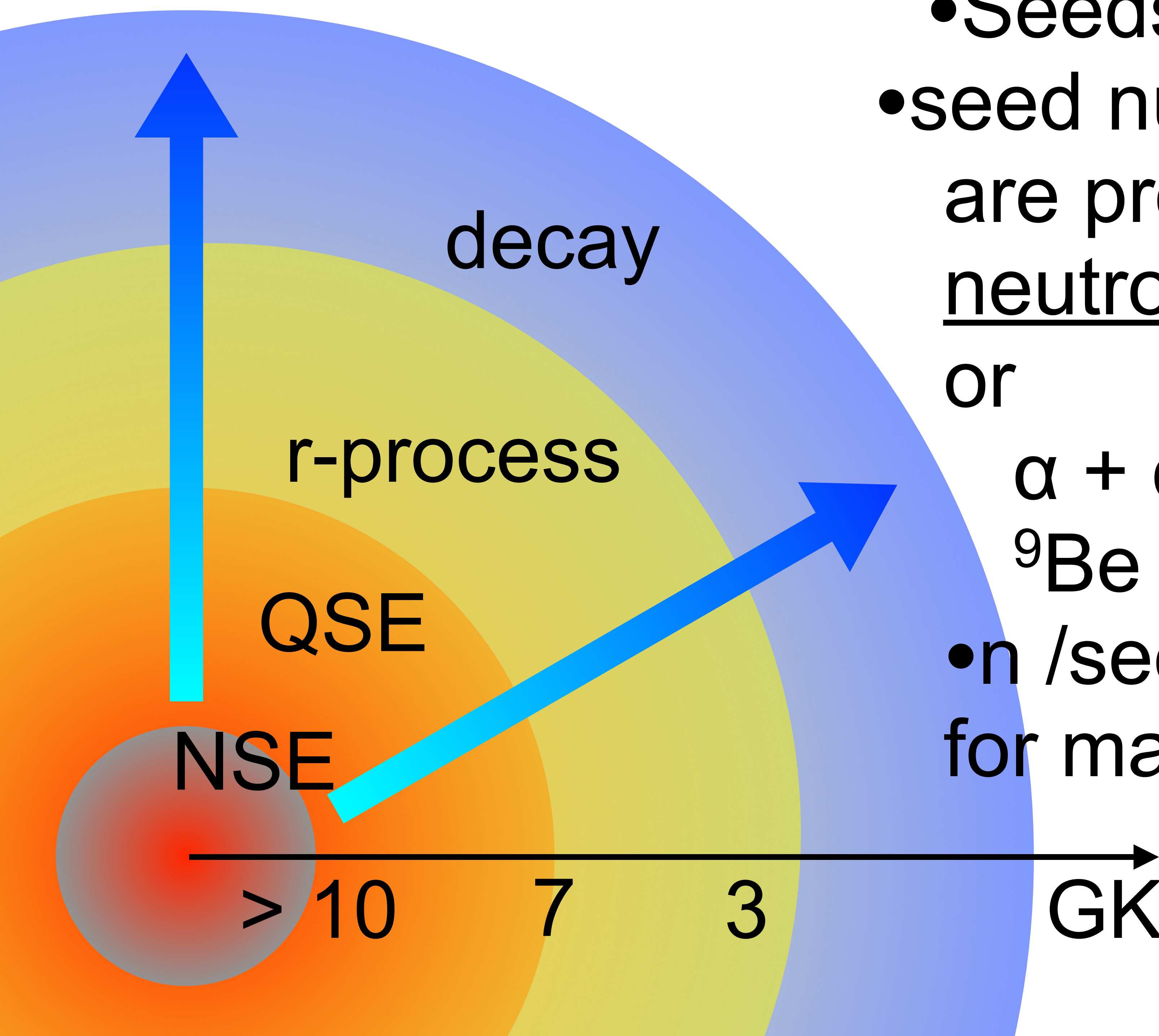
(figure: wikipedia)

The *r*-process: “origin of gold"



based on Sneden+ (2008) ARAA

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 in <u>neutron-rich equilibrium</u> or

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

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

  - n /seed > 100 is required for making A > 200

See, Fujibayashi+ 2015 for n-rich NSE

Physical condition for r-process

high T and ρ

Y_e: electron fraction

$Y_e = Y_p$

$\sim N_p / (N_n + N_p)$

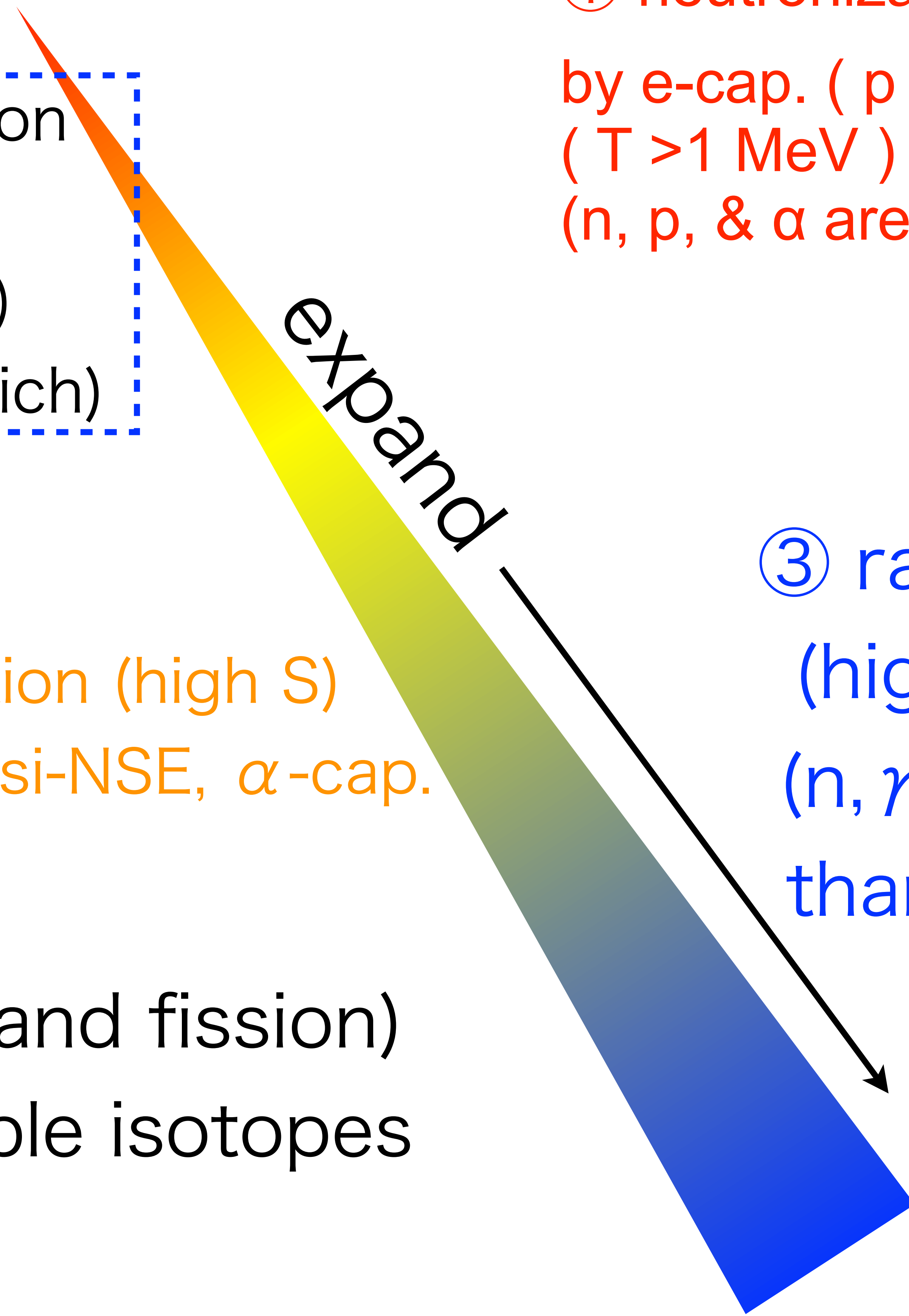
(low Y_e = neutron rich)

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 (high S)

(T > 0.5 MeV) quasi-NSE, α-cap.

③ rapid-n cap.

(high n/Seed)

(n, γ) is faster

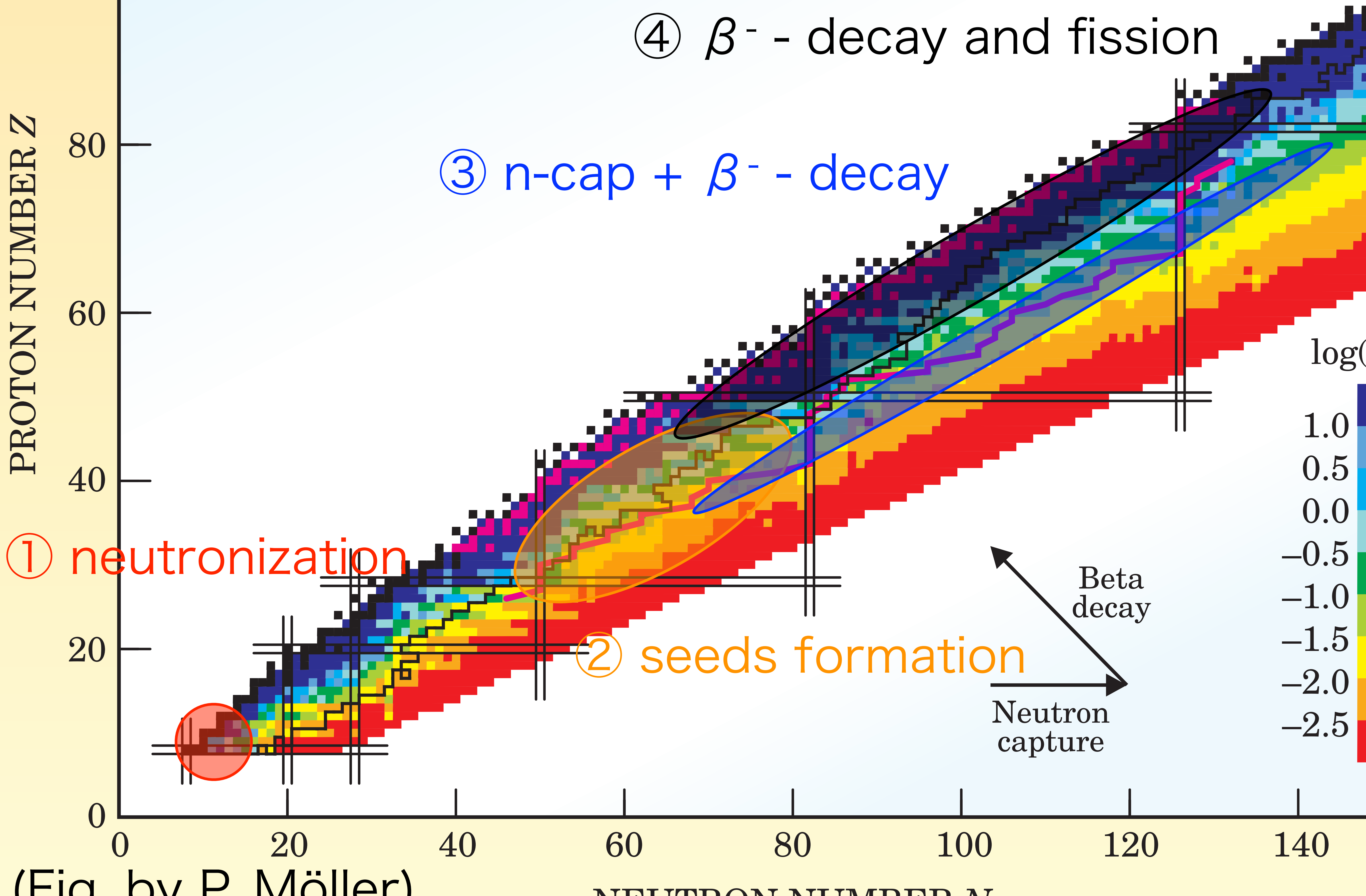
than β-decay

④ decay (β and fission)

decay to stable isotopes

low T and ρ

r-process nucleosynthesis

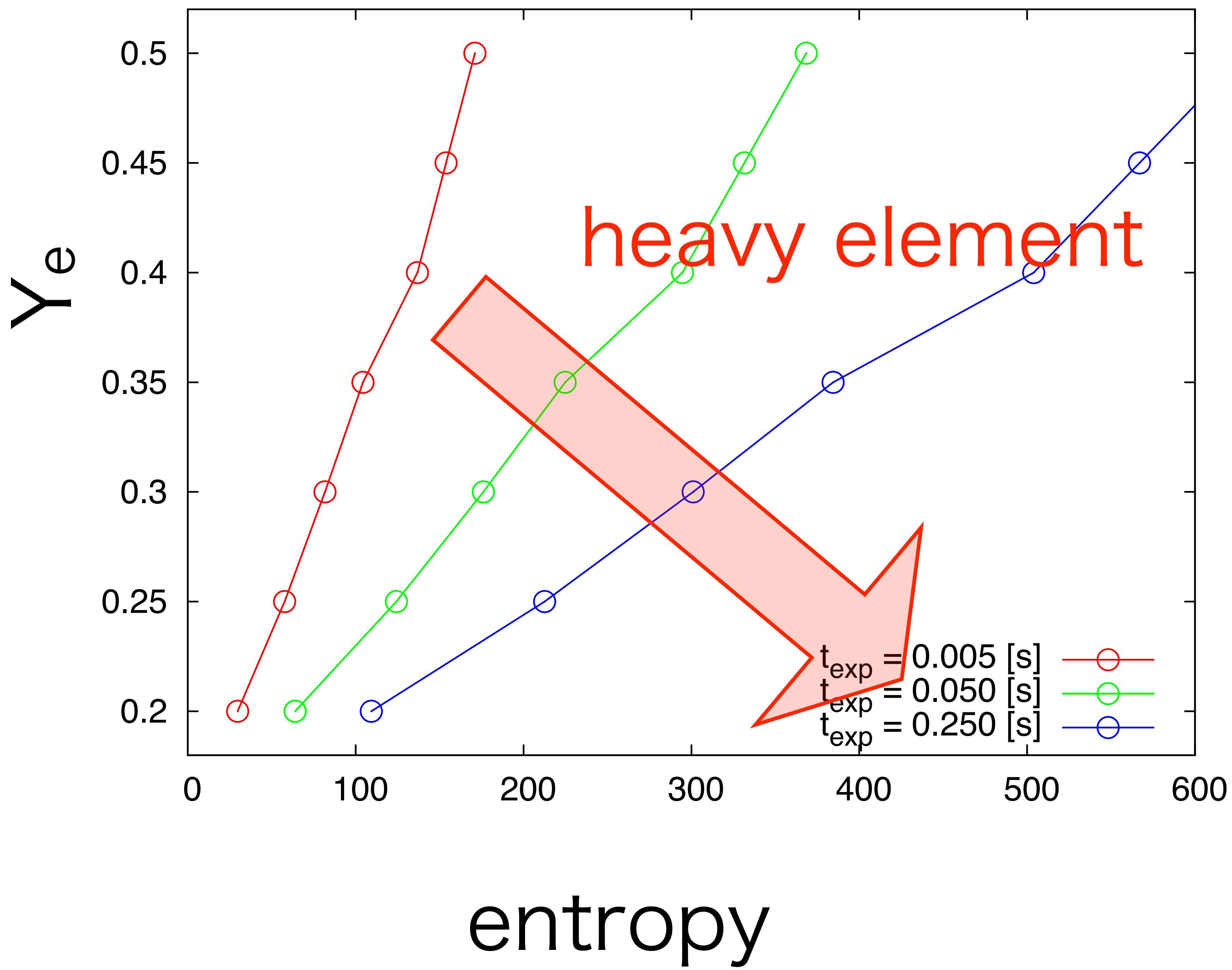


(Fig. by P. Möller)

Physical condition for r-process

condition for r-process 3rd peak

based on Hoffman et al. (1997)



hight entropy

→ high T

→ low seed

→ high n /seed

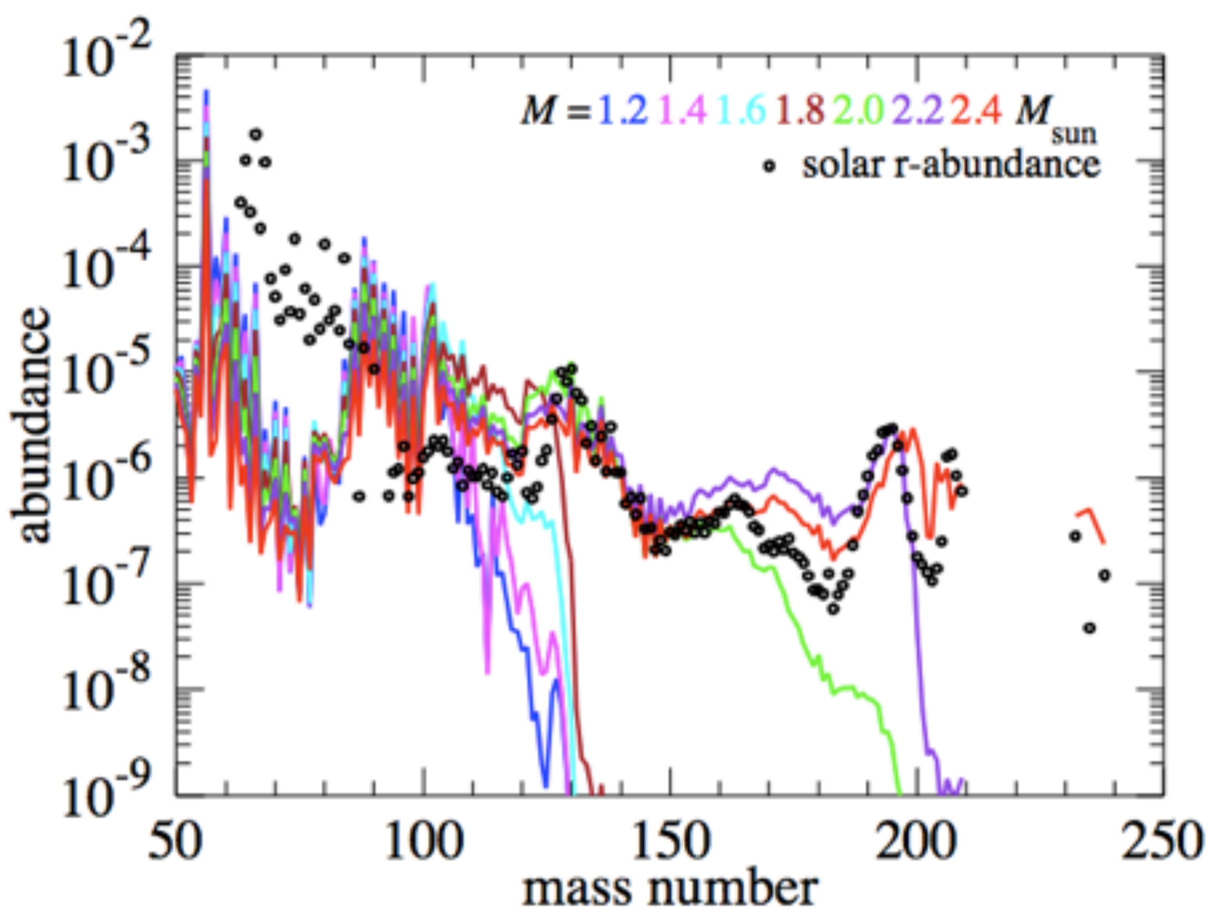
Difficulty of Core-collapse Supernovae

Dynamical ejecta of explosion

- mostly produce iron-group (A<100)
- exception: EC-SNe (Wanajo et al. 2012)

- PNS-wind (neutrino-driven)
  - requires very high entropy
  - Y_e is not low enough

    →the νp-process (proton-rich nuclei)



Latest results
of nucleosynthesis
for NDW scenario
Wanajo 2013

Why matter in PNS winds is not neutron-rich?

Y_e is determined by

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

equilibrium value is

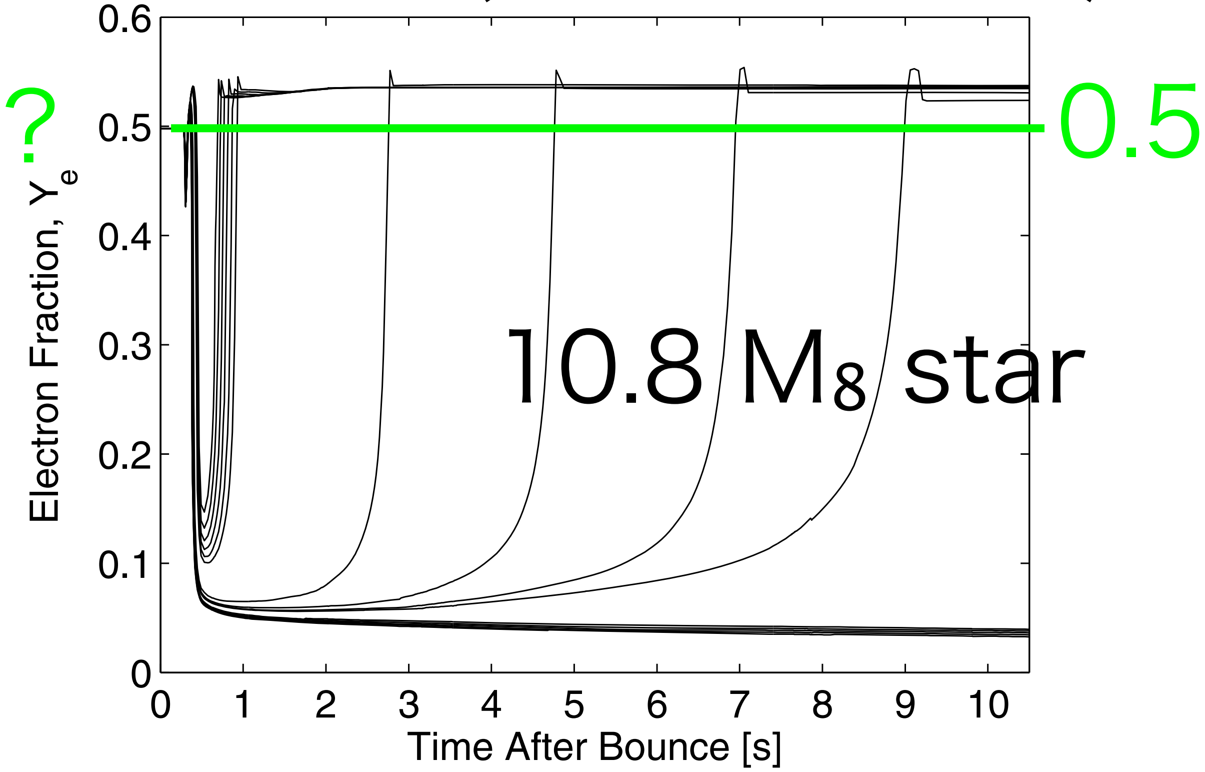
$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta} \right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

for $Y_e < 0.5$ (i.e., n-rich)

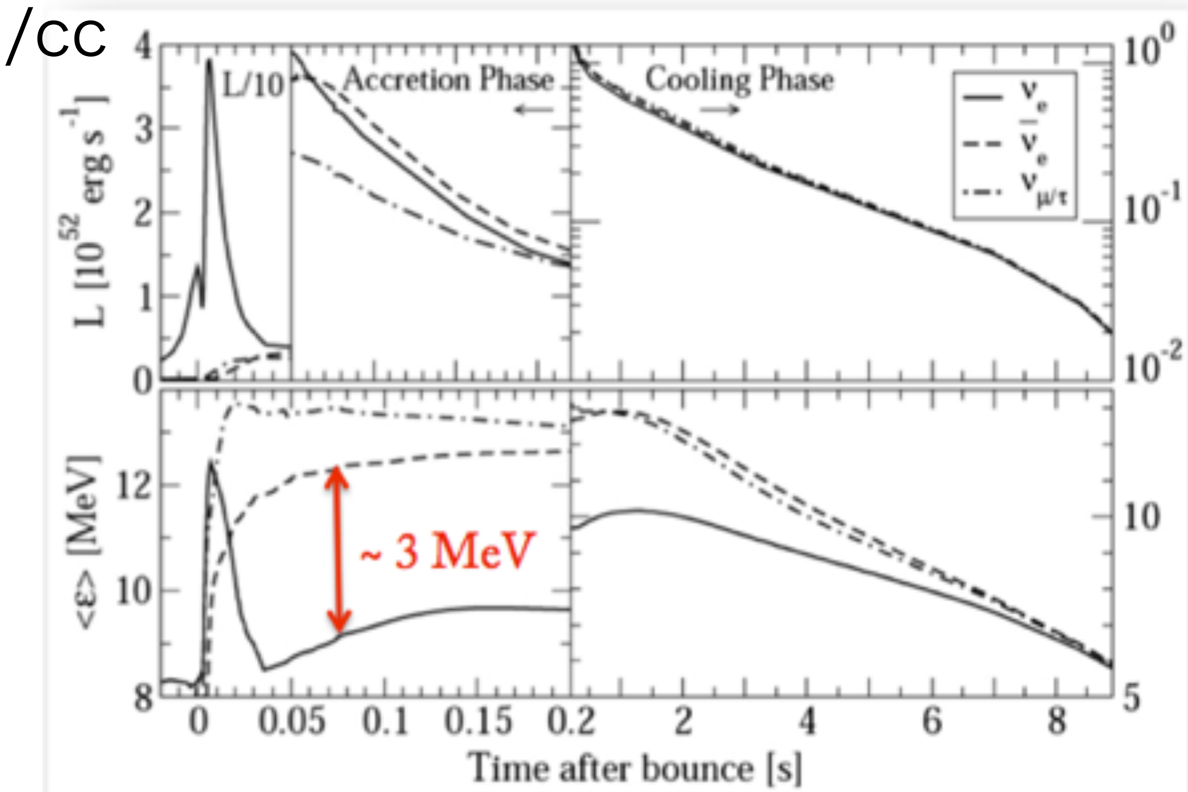
$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
if $L_{\bar{\nu}e} \approx L_{\nu e}$

(Fischer et al. 2009)

proton-rich?



nucleon-potential correction (Reddy et al. 1998)
for $\rho > 10^{13}$ g/cc



self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl+2009

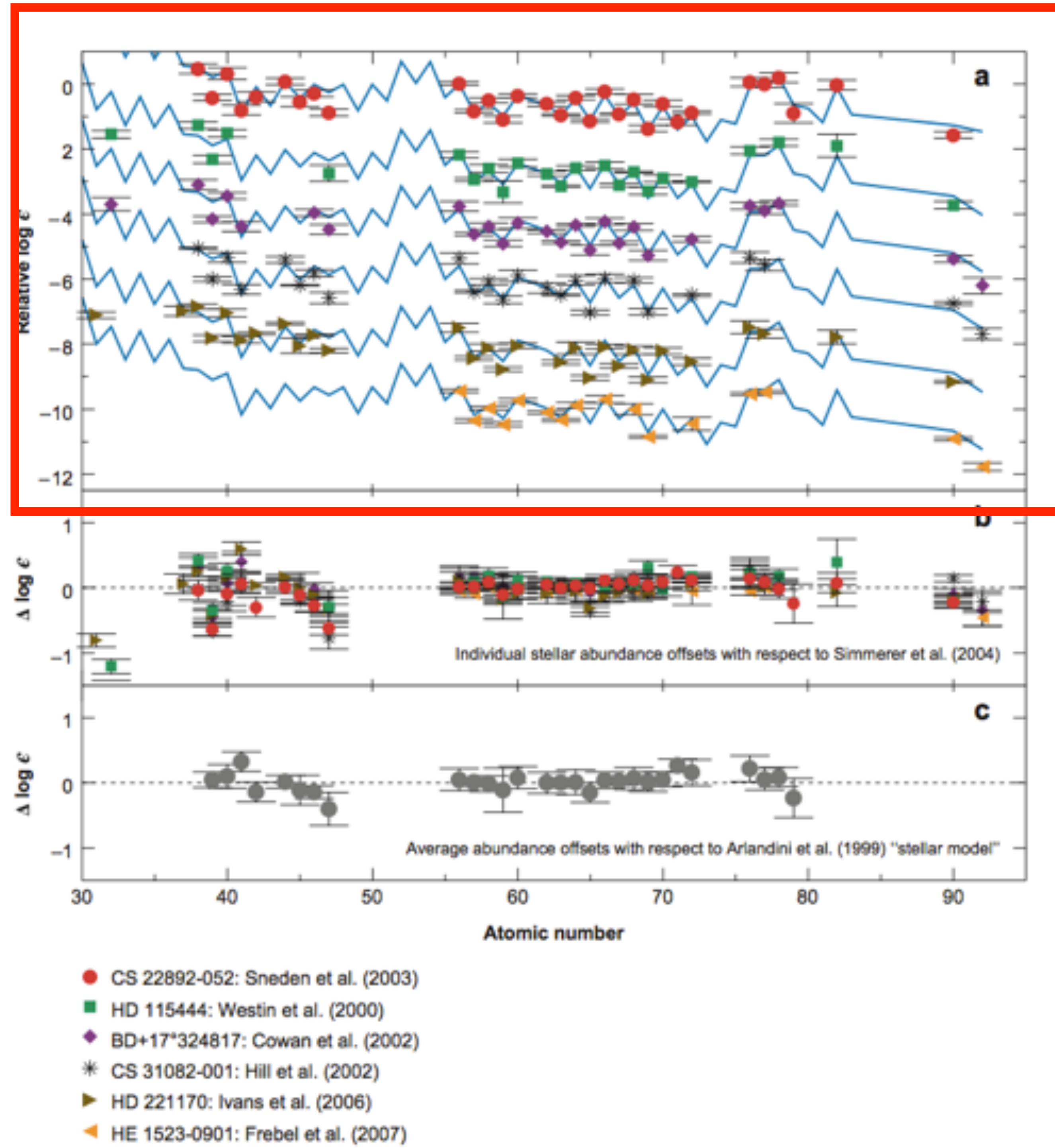
Similar pattern in r-process observation

Sneden+ (2008) ARAA

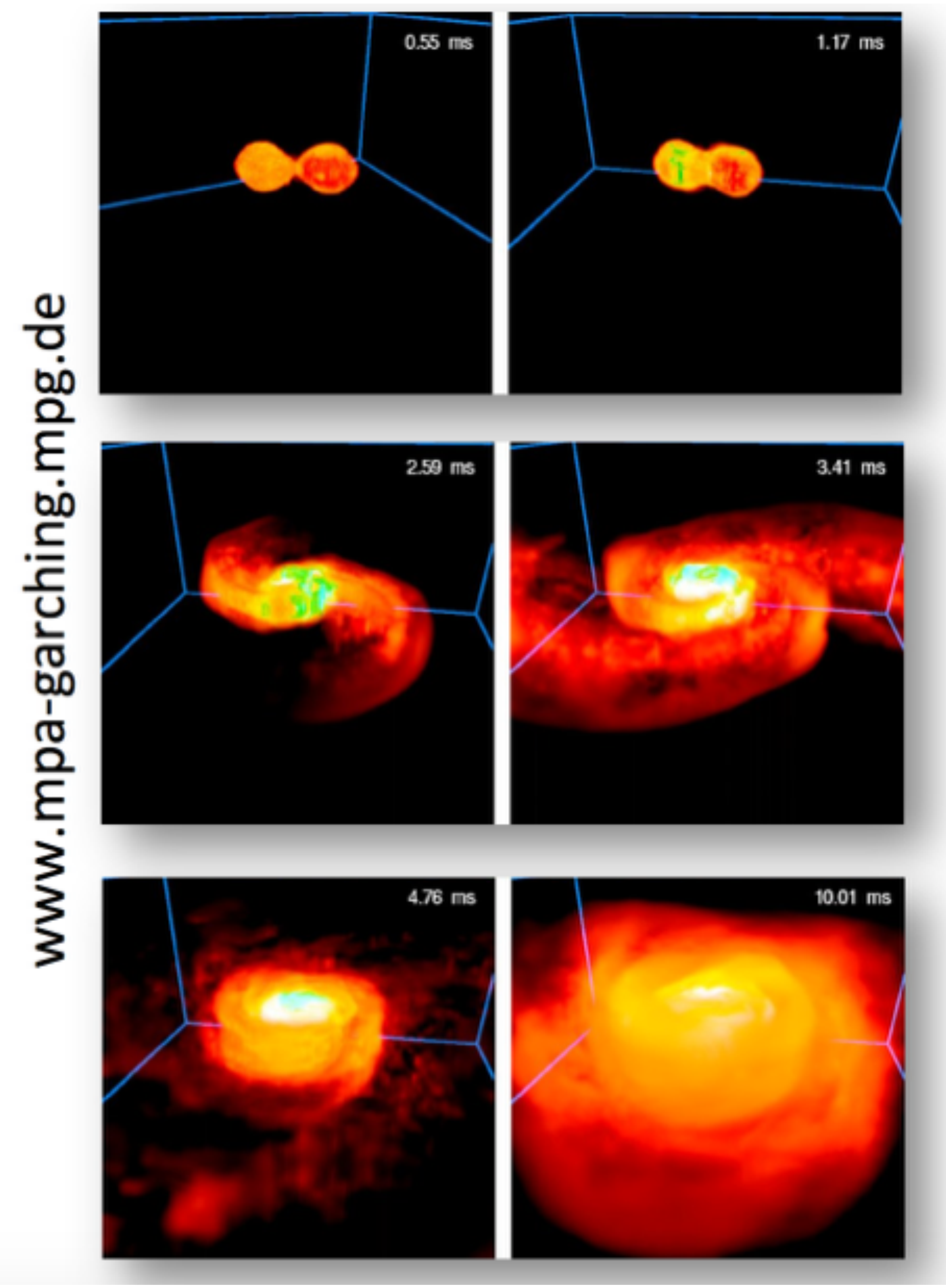
- many r-rich Galactic halo stars show agreement with solar pattern
- r-process has happened from the early Galaxy
- astrophysical models reproduce this common pattern (Z>40; A>90)

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

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



Neutron star mergers



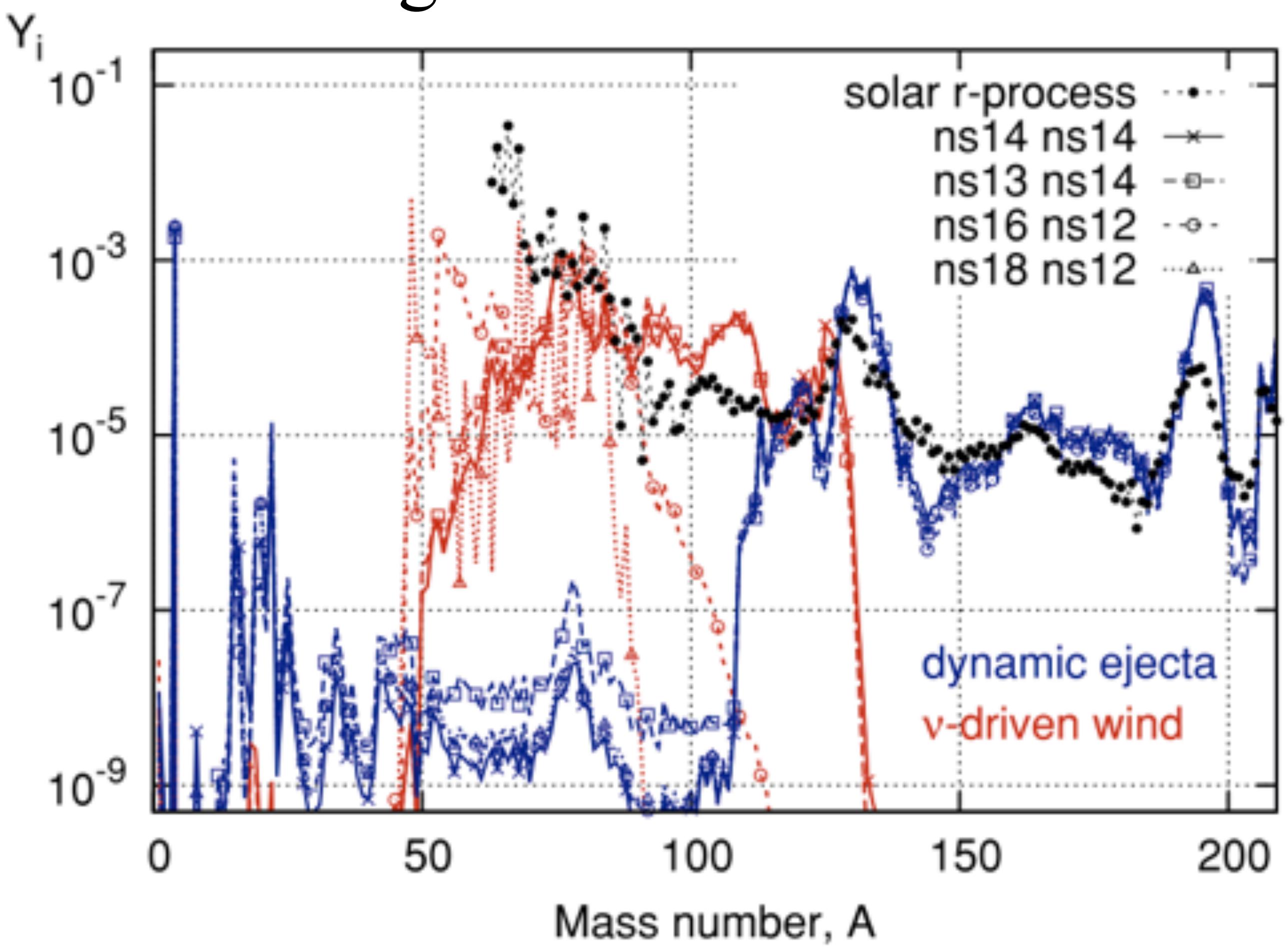
collision of neutron stars

- easily eject neutron-rich matter
- expected as sources of
  Gravitational wave,
  (short) GRBs
  Kilonova/macronova

- But, event rates and role in galactic chemical evolution are poorly known compared to SNe

Solution?: wind ejecta driven by neutrino

Rosswog 2014+



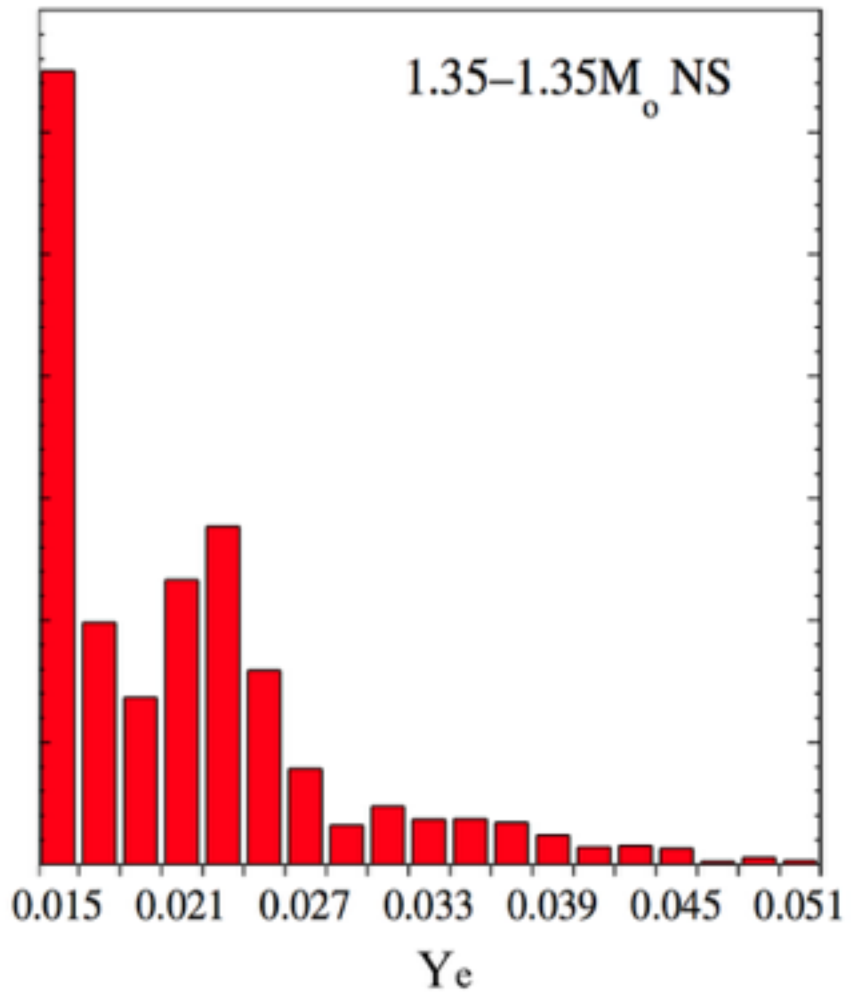
dynamical ejecta
(Ye < 0.1)
+
neutrino-driven ejecta
(Ye > 0.3)

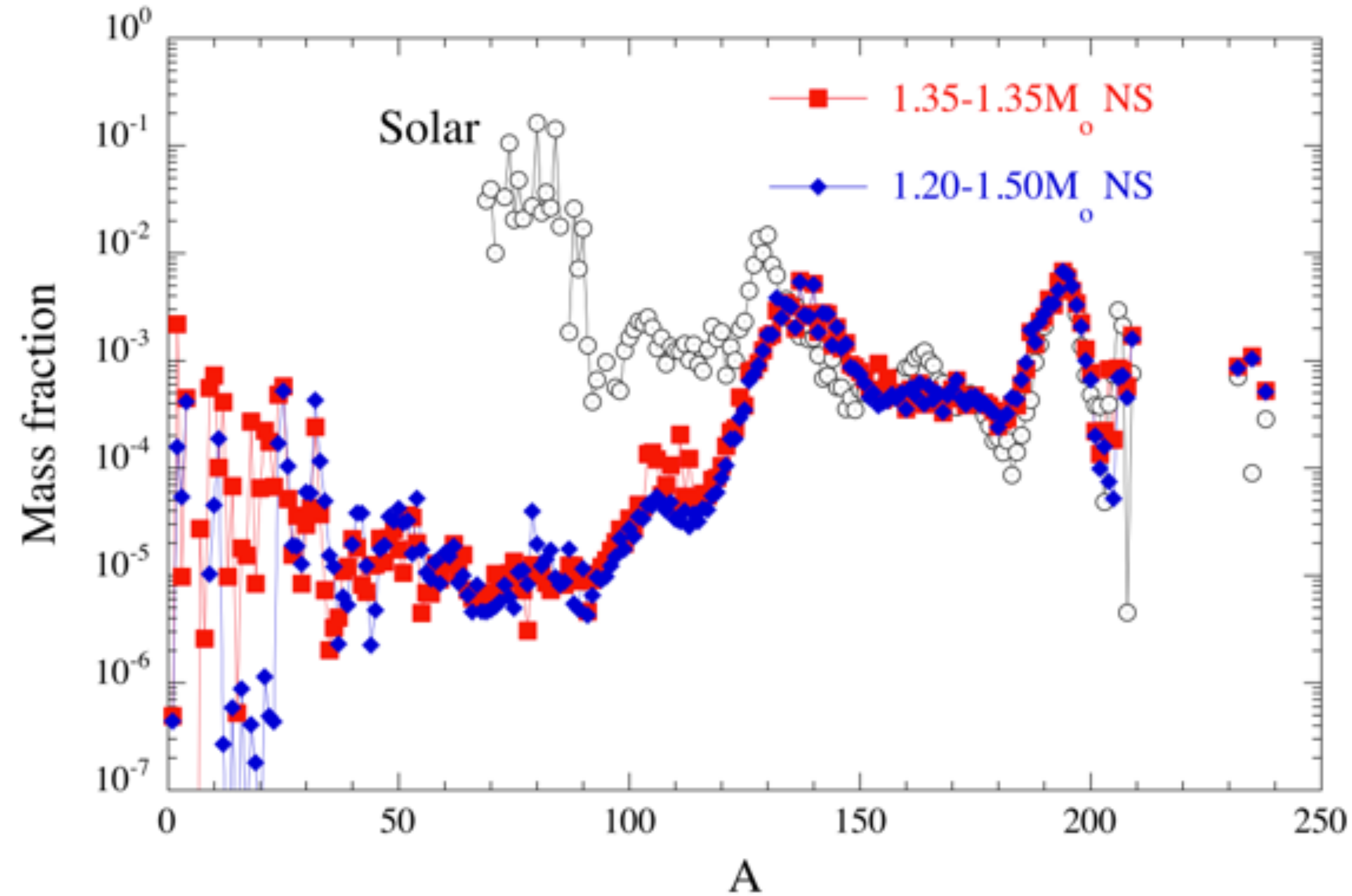
- Two different components can explain “universality” ?
- The property of dynamical ejecta is not well known

Can dynamical ejecta produce
the entire r-process pattern?

A long-standing problem: too neutron-rich

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





mass number

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

$(Y_e = Y_p = 1 - Y_n)$

r-process with fission-cycling

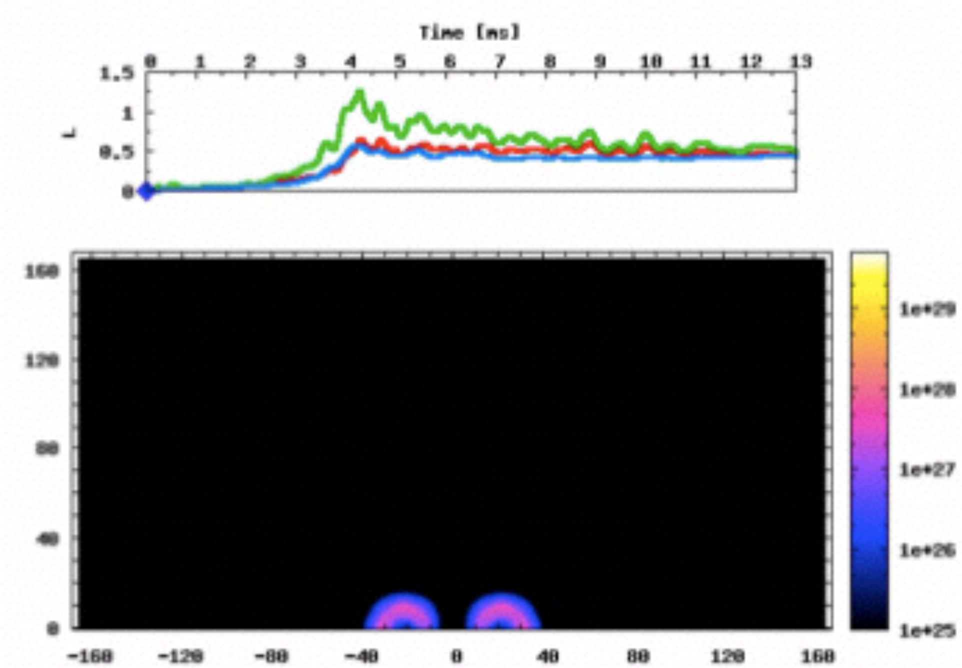
severe problem: only A > 130 with fission recycling

(see, Eichler+ 2015; Shibagaki+ 2016)

new challenge: GR-hydro model

slide by Y.Sekiguchi

- Einstein's equations: Puncture-BSSN/Z4c formalism
- GR radiation-hydrodynamics (Sekiguchi + 2013)
  - **Advection terms :** Truncated **Moment scheme** (based on Shibata et al. 2011)
    - Fully covariant and relativistic
    - gray or multi-energy but advection in energy is not included
    - M-1 closure
    - EOS : any tabulated EOS with 3D smooth connection to Timmes EOS
  - **Source terms :** two options
    - Implicit treatment : Bruenn's prescription
    - Explicit treatment : trapped /streaming ν's
      - e-captures: thermal unblocking/weak magnetism; NSE rate
      - Iso-energy scattering : recoil, Coulomb, finite size
      - e±annihilation, plasmon decay, bremsstrahlung
      - diffusion rate (Rosswog & Liebendoerfer 2004)
      - two (beta- and non-beta) EOS method



New NS merger models by Kyoto Group

See, Wanajo, Sekiguchi, NN, Kiuchi, Kyutoku & Shibata
ApJL 789 (2014) L39

- Setup for simulation
    - (first principle) full GR hydrodynamics
    - neutrino transport
    - micro physics: EoS, weak interaction

- Physics determining ejecta (neutron-richness / Ye)
    - more-compact neutron stars
    - Strong Gravity

      => Strong collision (less tidal disruption)

      => Strong shock heating

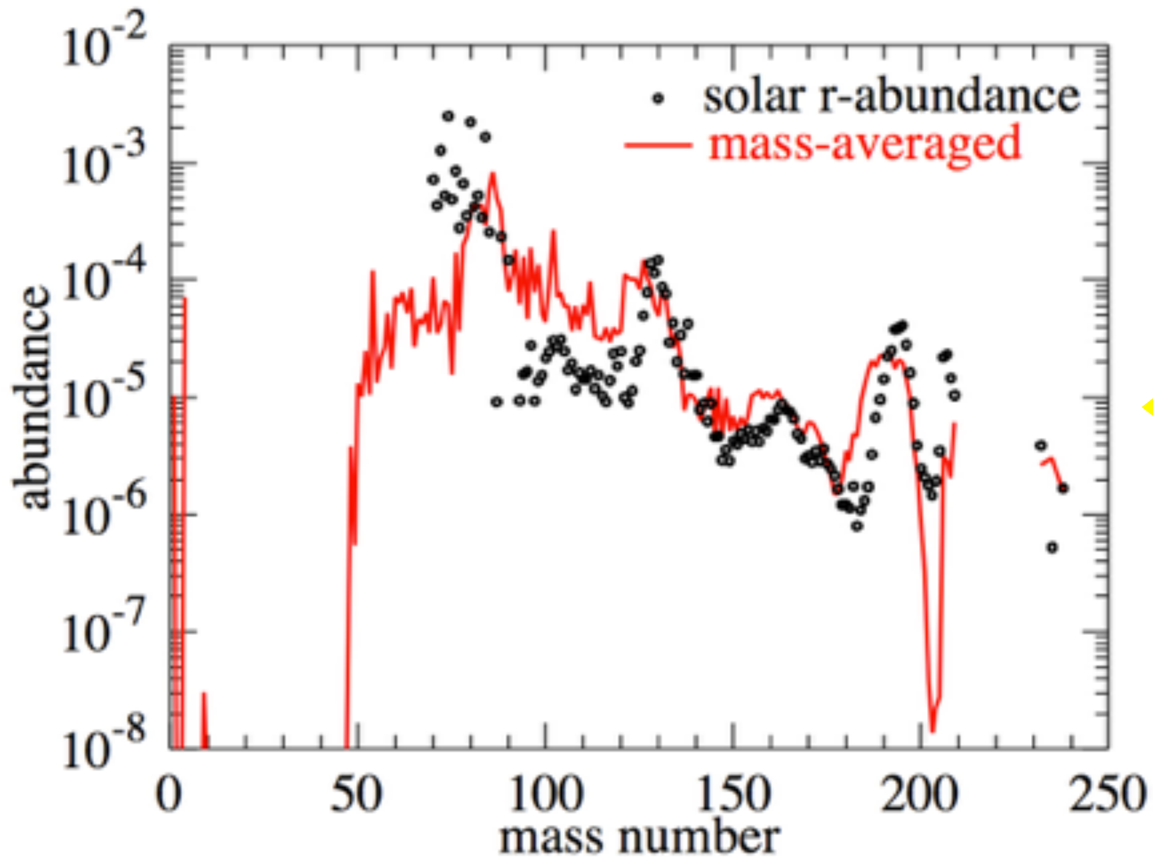
      => high temperature

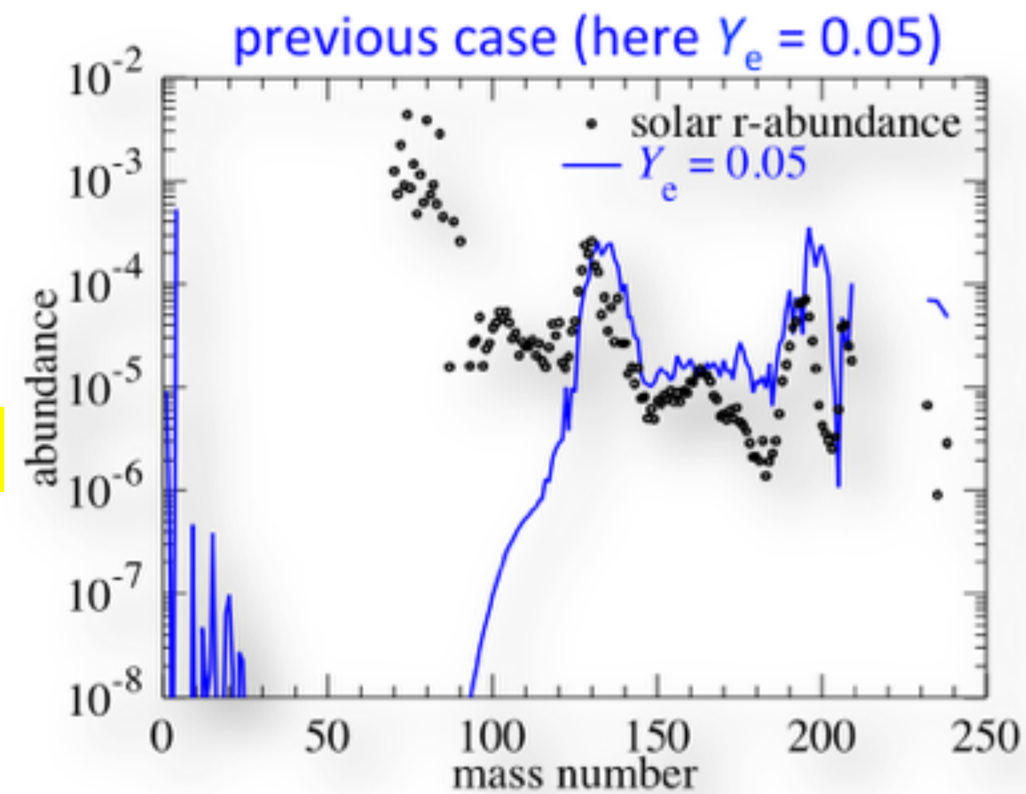
      => weak interactions are activated

      matter is ejected by tidal disruption + shock heating

A paradigm shift? (since 2014)

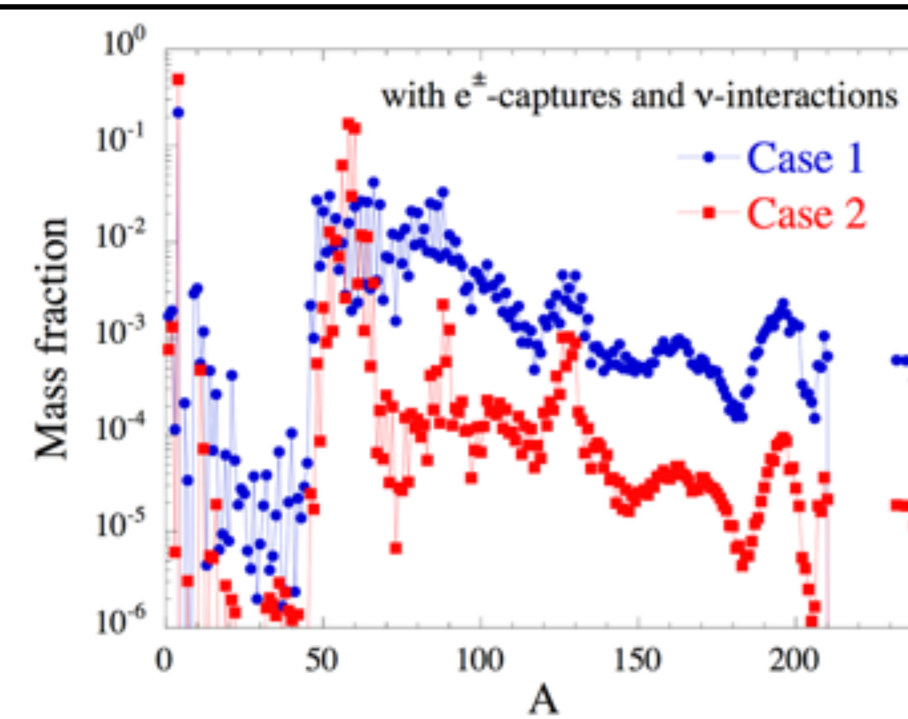
Wanajo+ 2014





Goriely et al. 2015
NS-NS merger models
by MPA Group

with different neutrino models



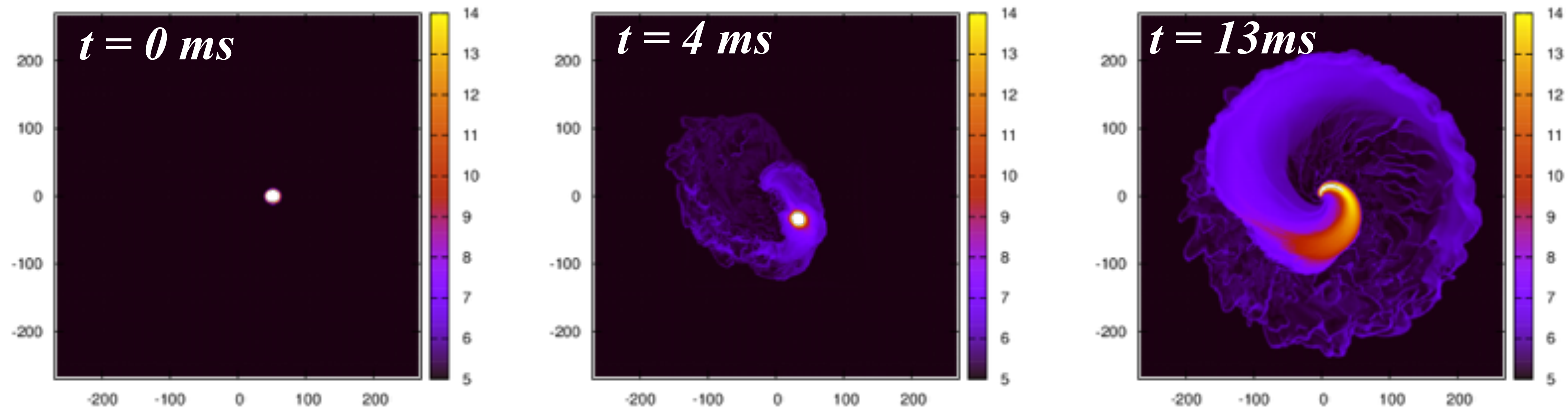
BH-NS merger

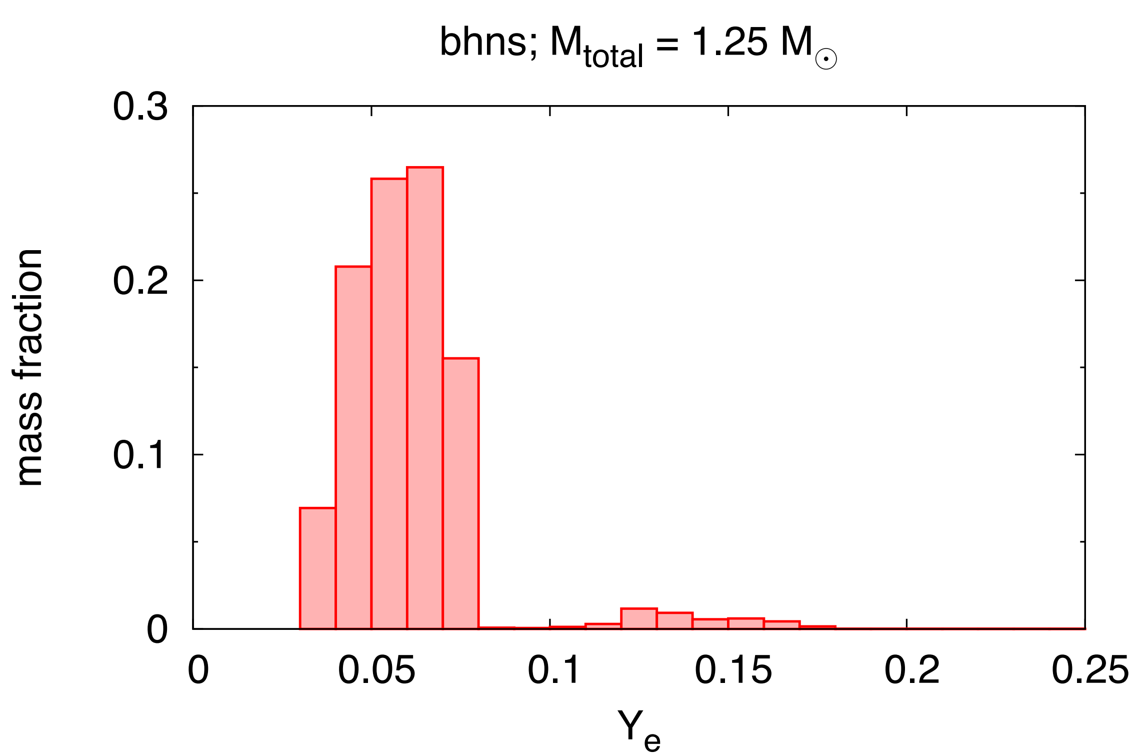
NN, Wanajo, Sekicuchi+ (2016); JPh conf. 665

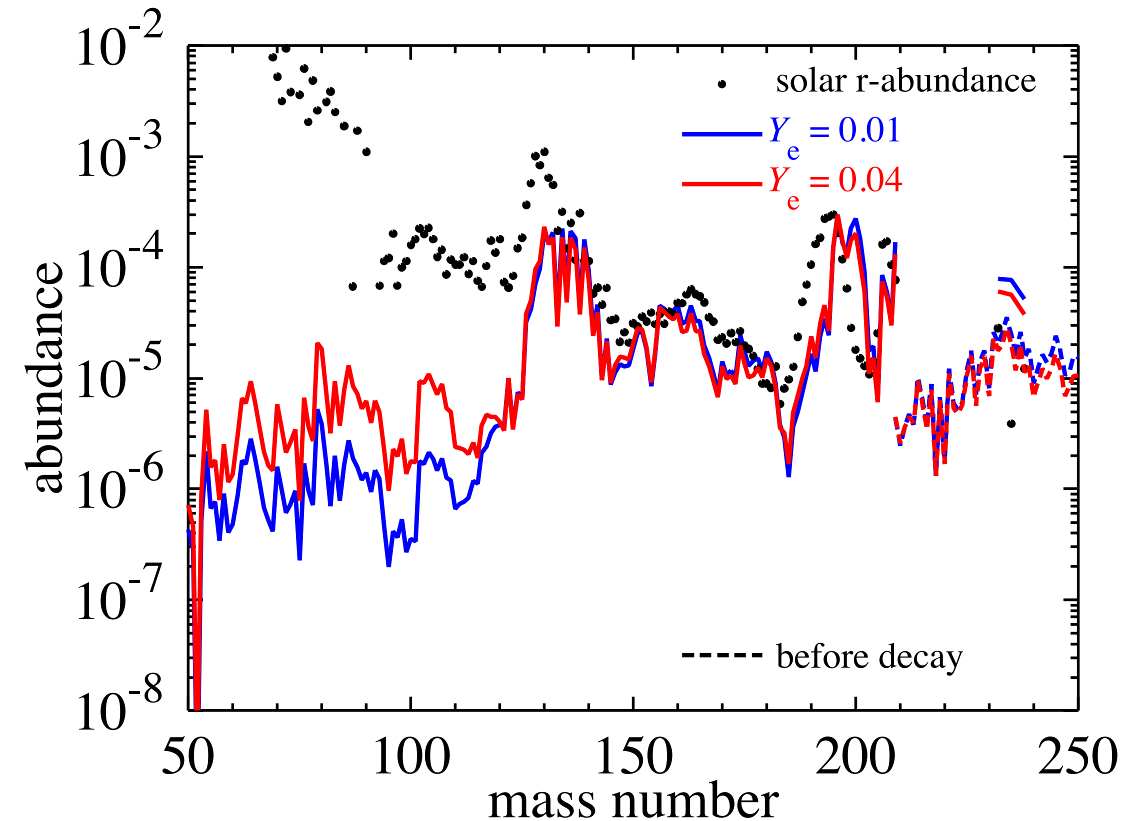
ejected matter by strong tidal disruption:

BH ($4M_\odot$) — NS ($1.25M_\odot$)

→ maintaining initial very low Y_e (neutron rich)

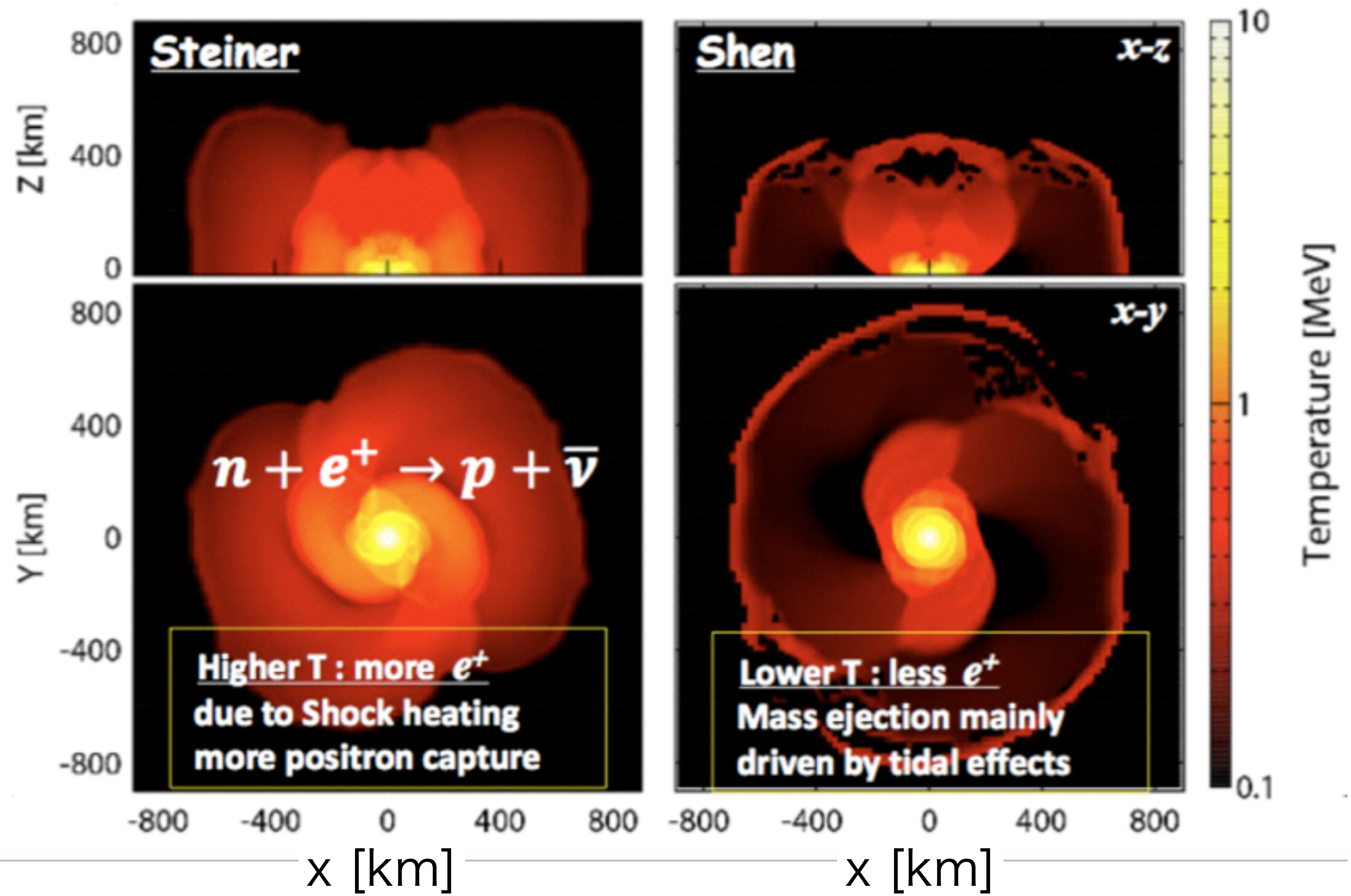




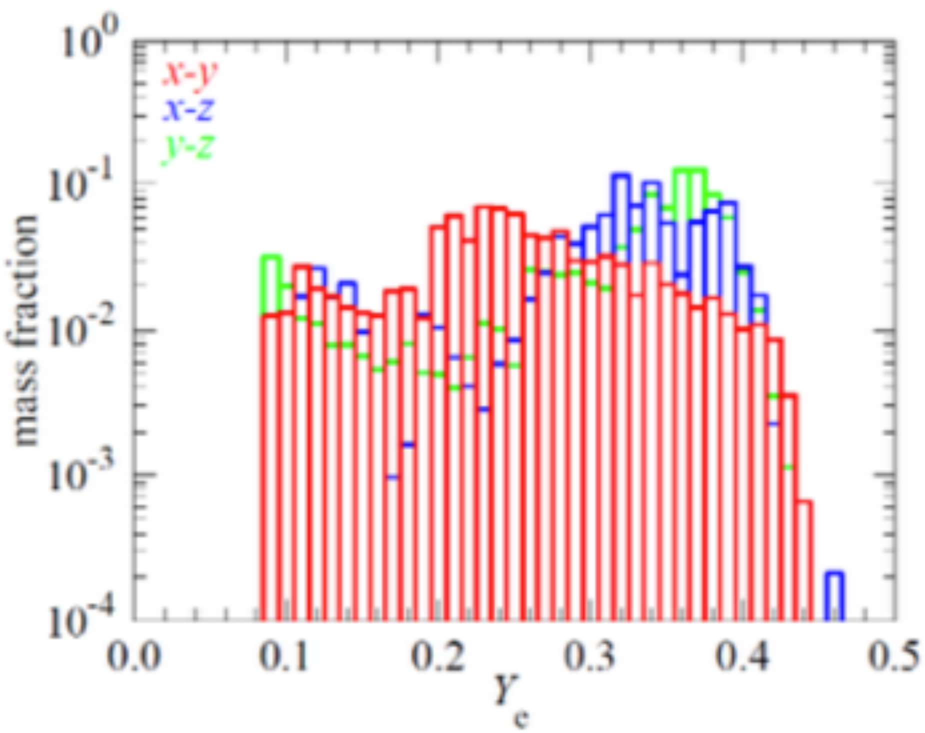


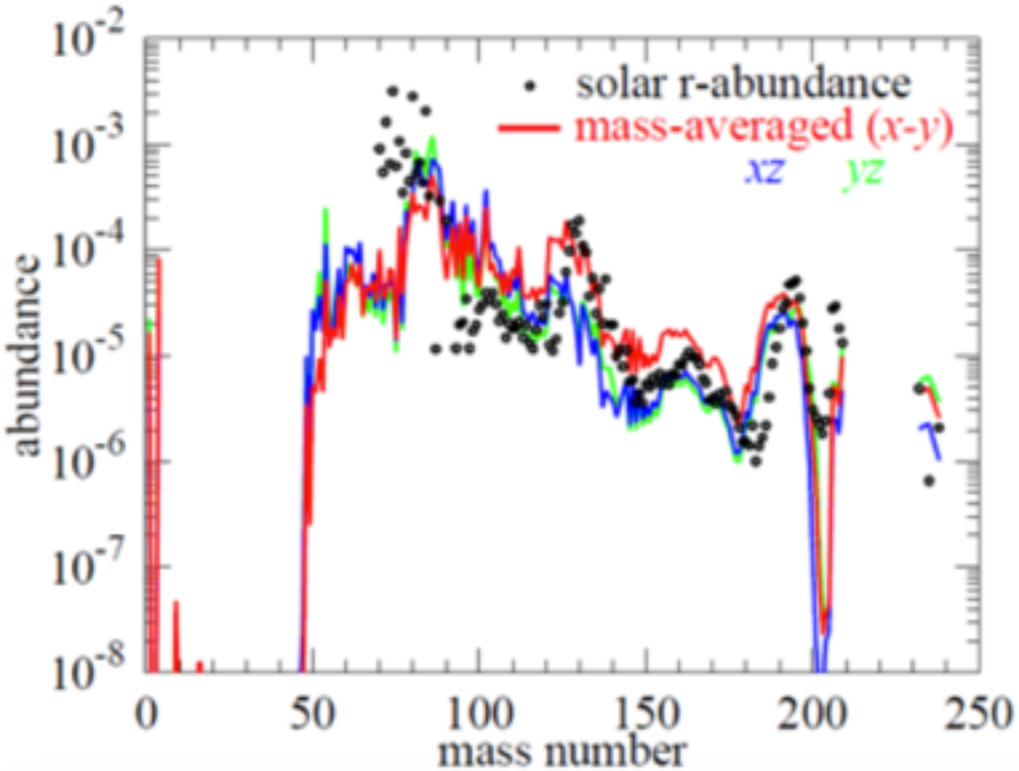
Temperature structure

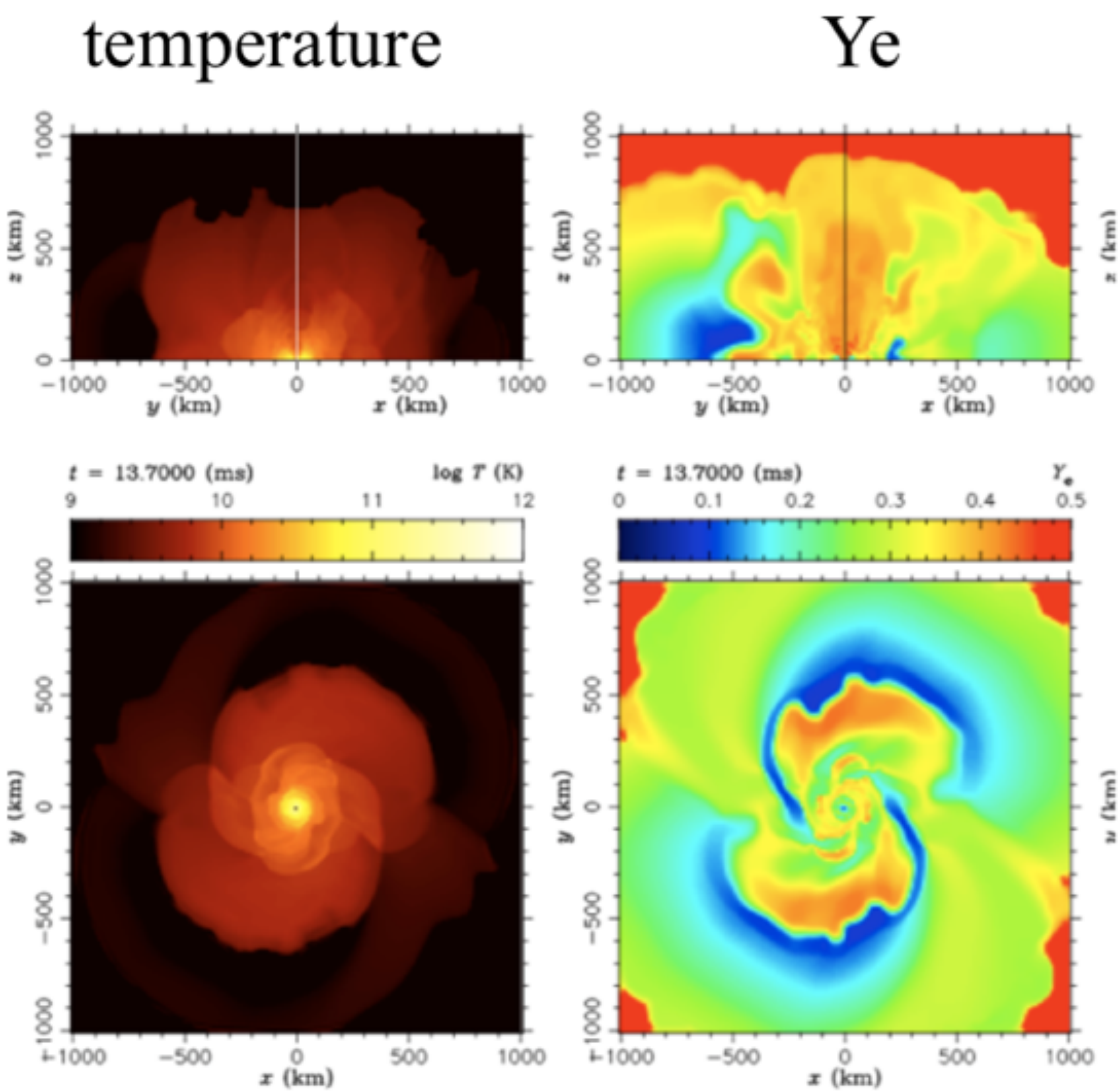
- Steiner's EOS makes compact NS
- compact NS
  → less tidal disruption + strong collision



3D geometry of ejecta



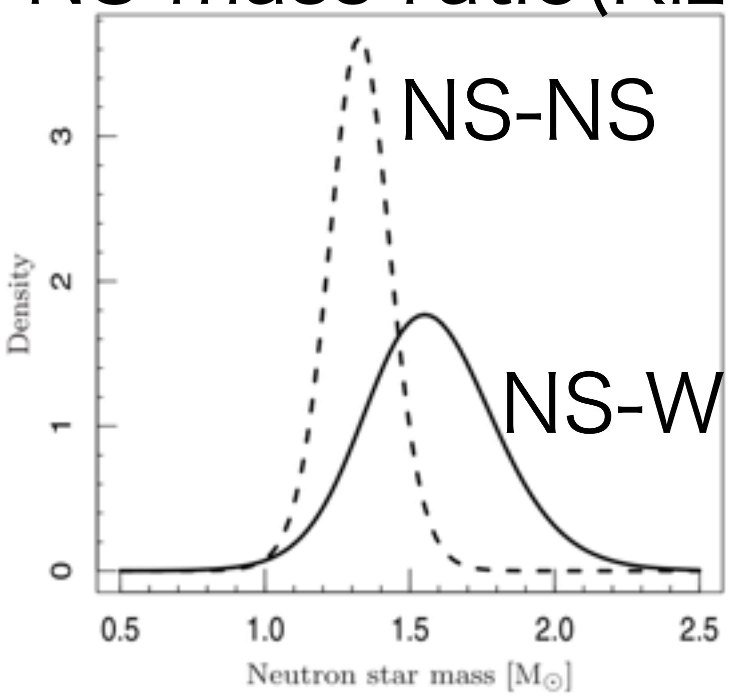


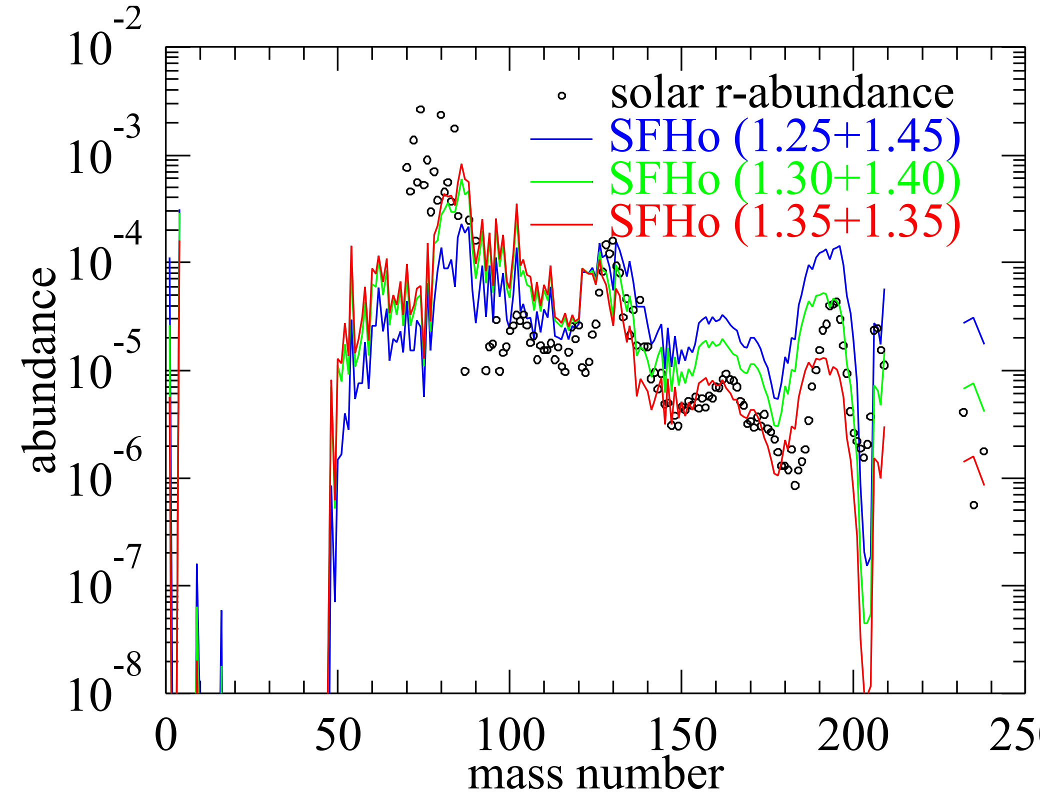


Details: NS masses & EoS in 3D hydro

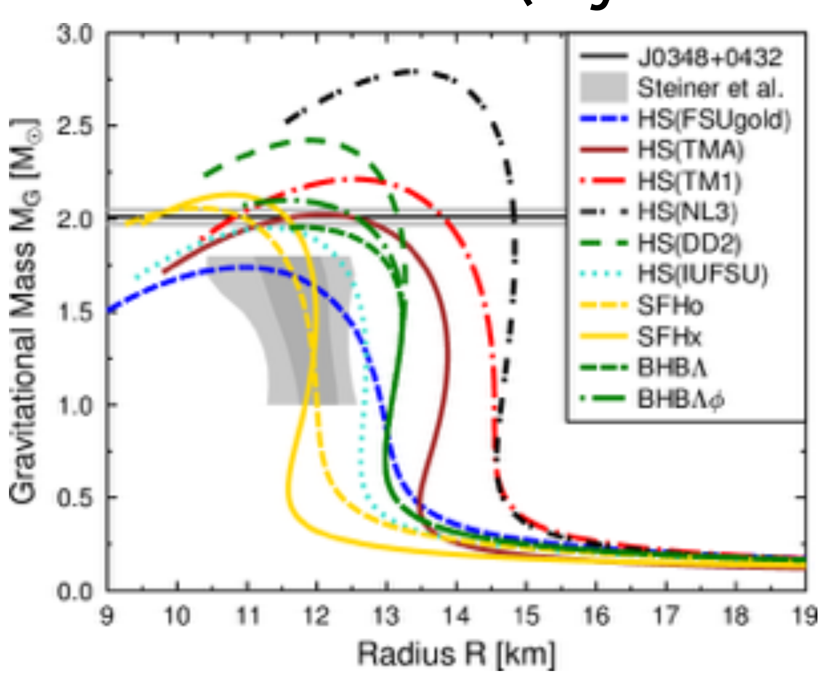
Wanajo+ in prep.(2016?); NN+ in prep. (2017?)

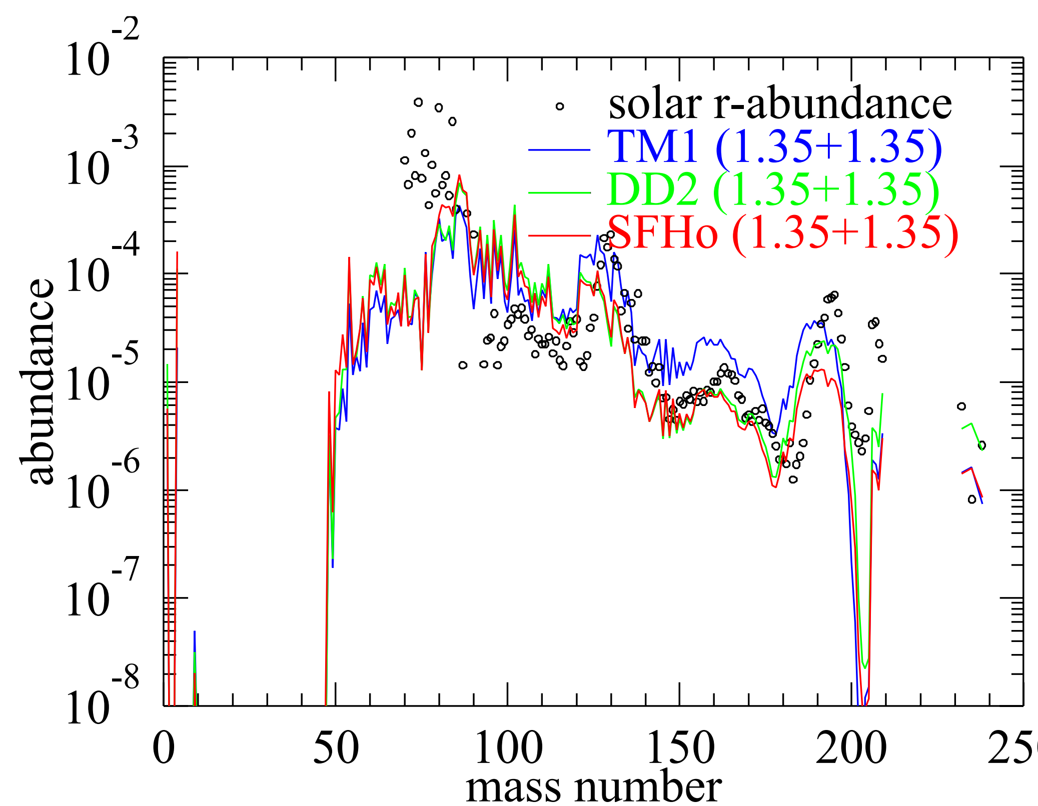
NS mass ratio(Kiziltan+ 2013)





nuclear EOS (by Hempel)





CC-SNe must be excluded?

CC-SNe must leave from production site of Eu?

NO

- GCE (Eu evolution) can be explained only by NS mergers
- if SN core has strong magnetic fields?

SNe vs NS mergers: exiting discussion (in last two weeks)

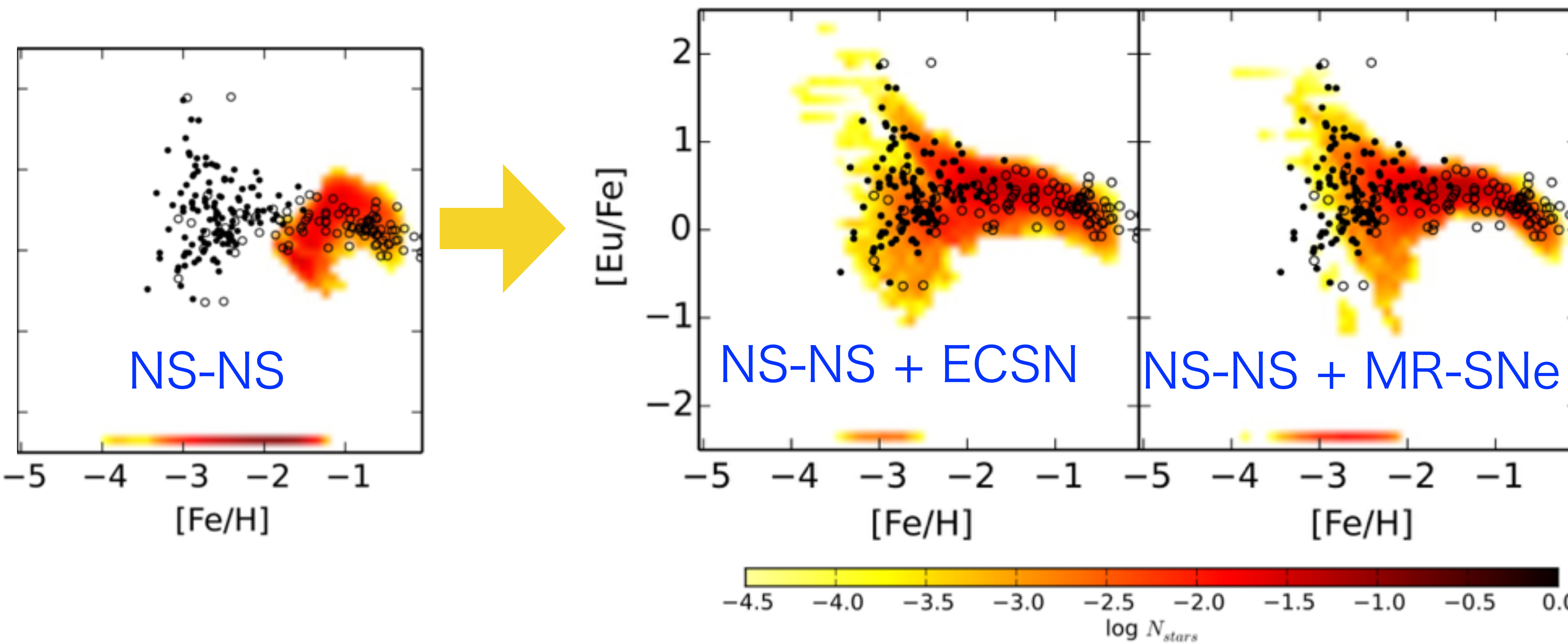
NIC14 (Niigata) and NAOJ-ECT* workshop

Galactic Chemical Evolution: merger + MR-SN?

Cescutti+ 2015, A&A 577

- NS mergers need shorter duration 1 Myr
- 100 Myr NS merger

+ MR-SNe (10% of all CCSN for $Z < 10^{-3}$)

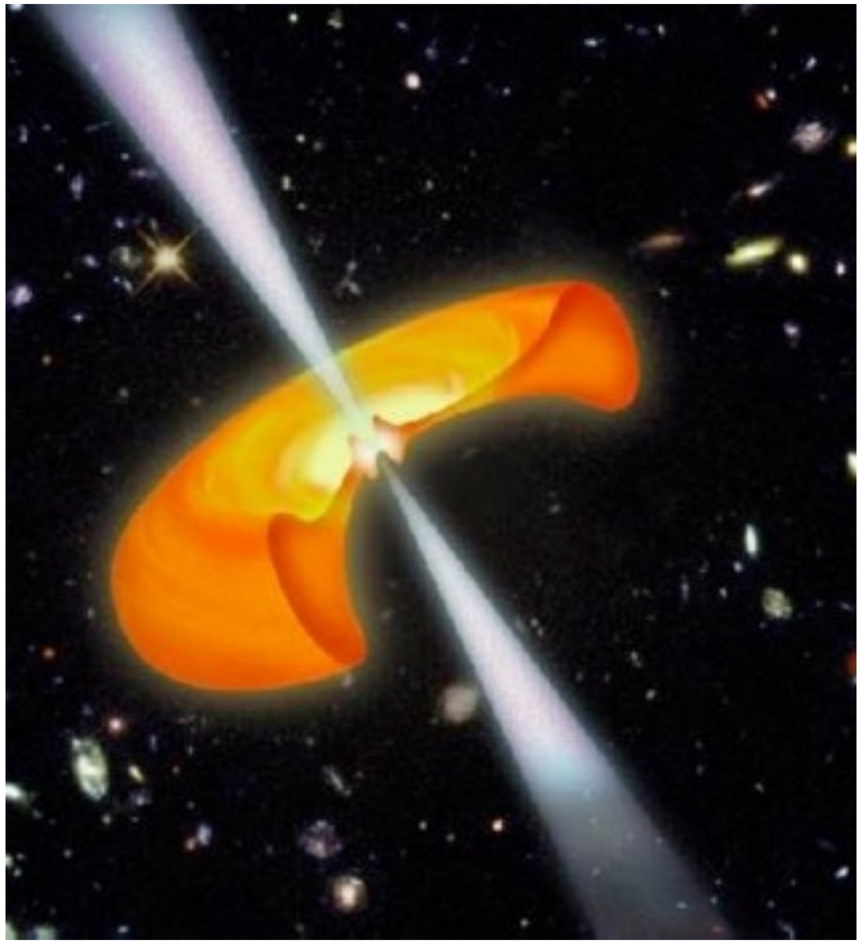


see also, B. Wehmeyer+ 2015, MNRAS 452

detailed study in different event rates for MR-SNe

r-Process nucleosynthesis
by Magneto-rotational Supernovae
(MR-SNe)

Magneto-rotationally driven (MR) SNe and magnetars

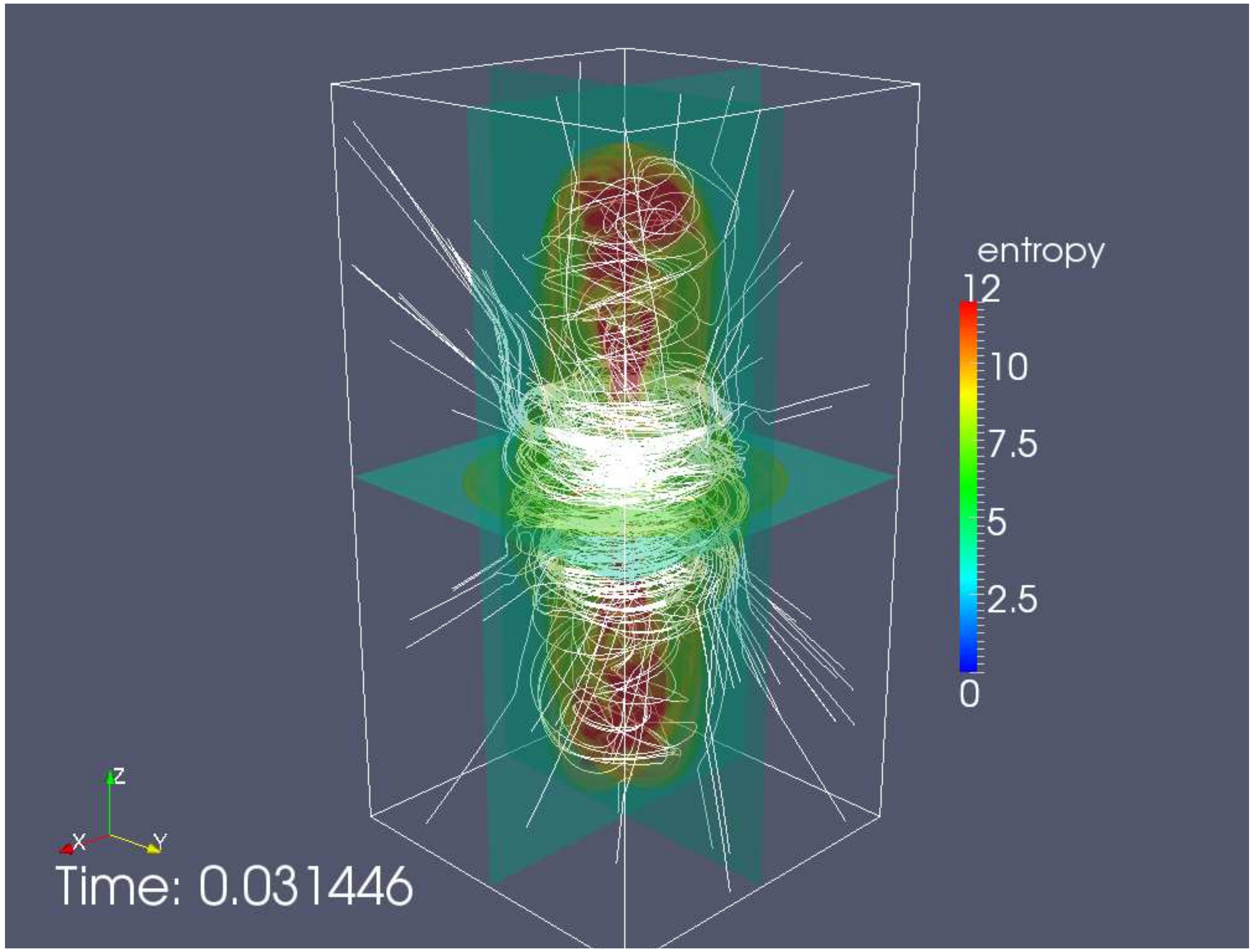


hypernova/jet-like SN

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)



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

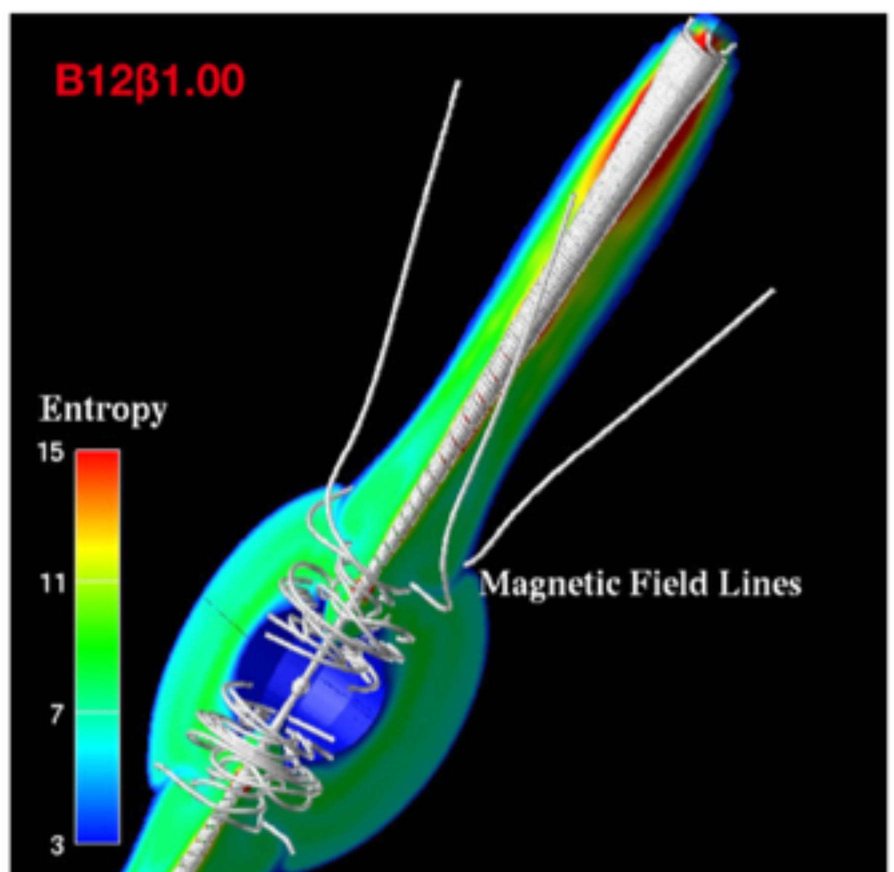
  (～1 % of all neutron stars)
- Magneto-driven Supernovae?
  - GRB central engine
  - Hypernovae

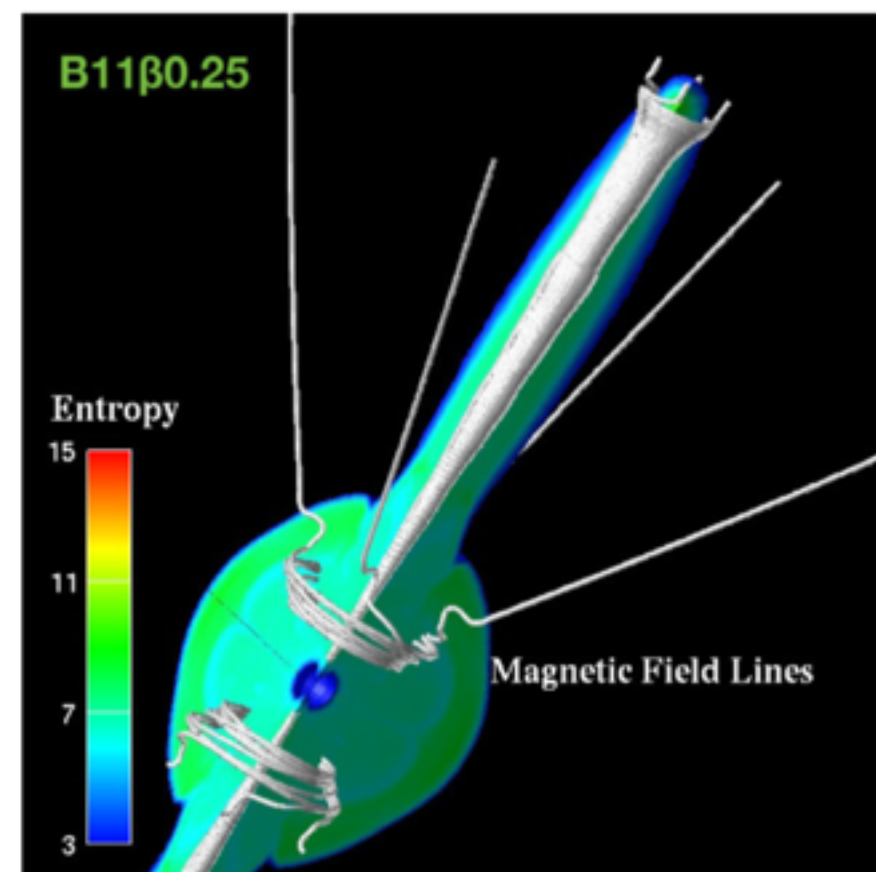
MR-SNe as origin of r-process elements

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

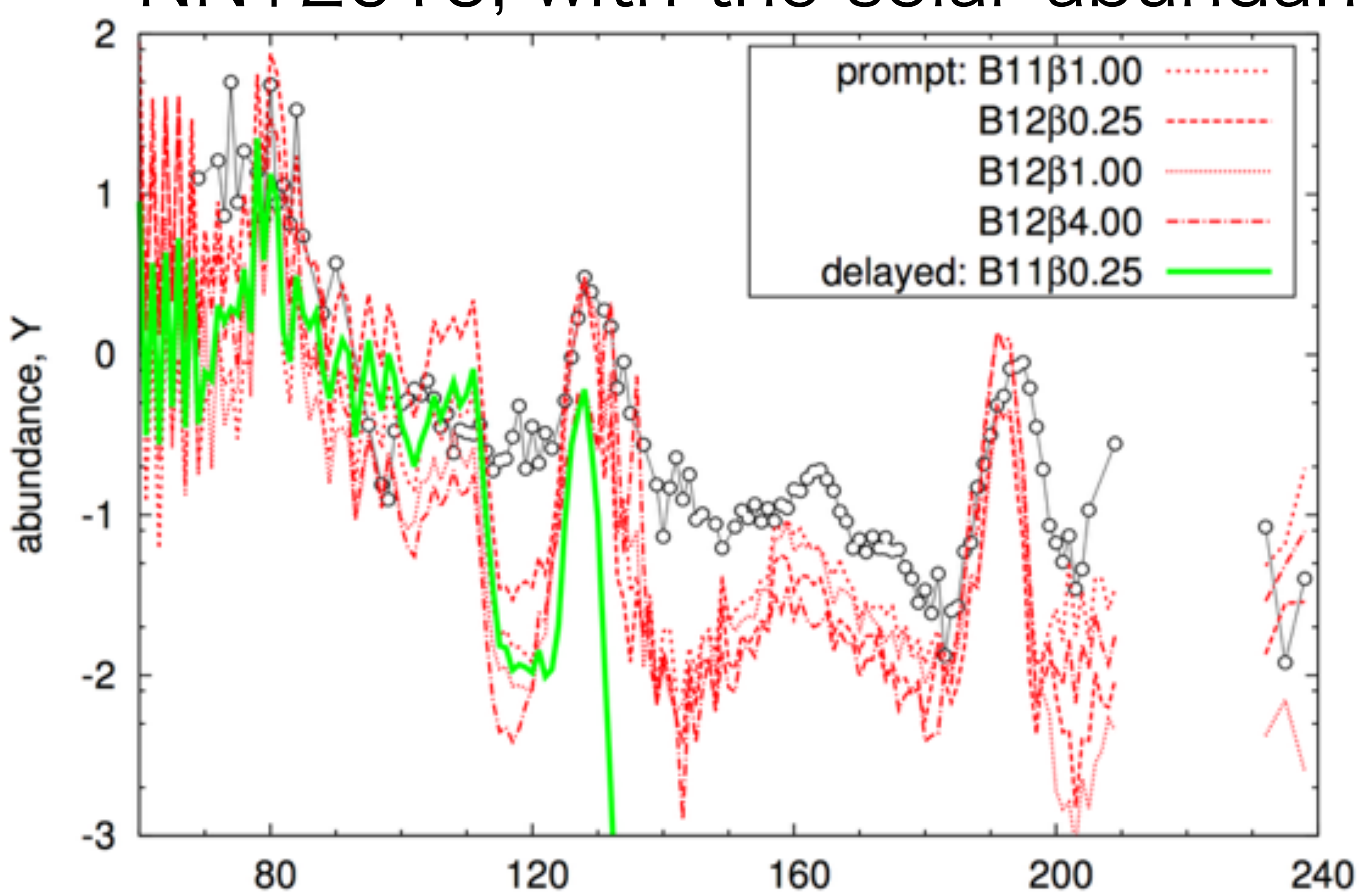




Diversity of MR-SNe and r-process

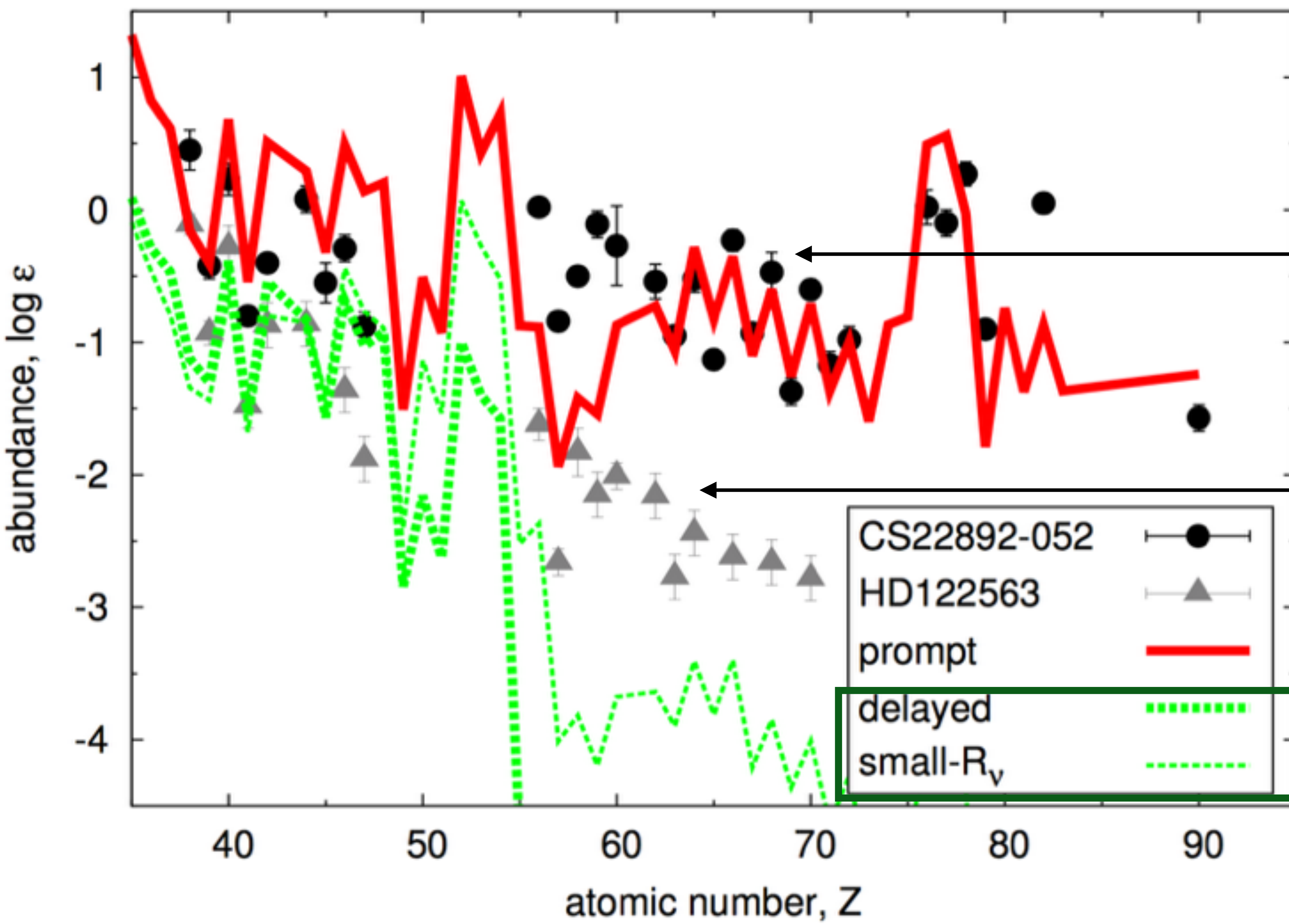
- **Strong (prompt)-jet**
  - immediately ejects very n-rich (low Y_e) matter dredged from the SN core (strong e^--capture)
- **Weaker (delayed) jet**
  - only ejects surface of the PNS and suffers Y_e increase by neutrino absorption

NN+2015; with the solar abundances



Diversity of MR-SNe and r-process

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



solar-like

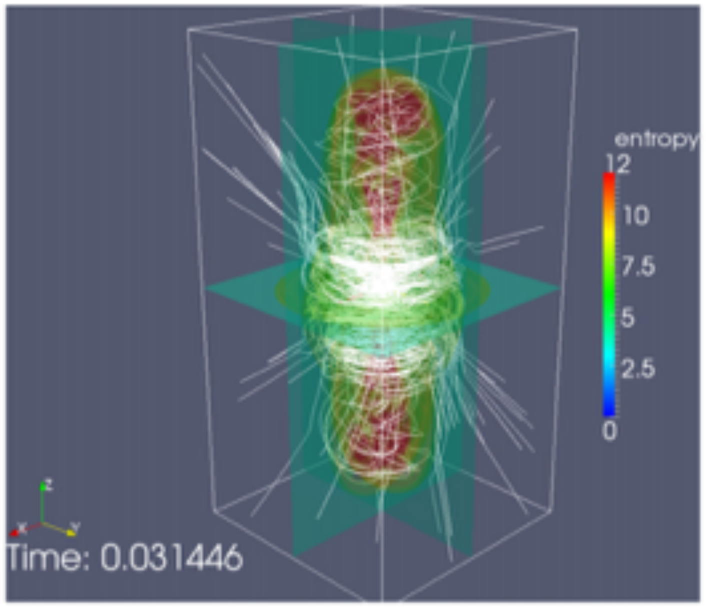
(Sneden's star)

Honda type

uncertainty of explosion model

dimensionality: 2D or not 2D?

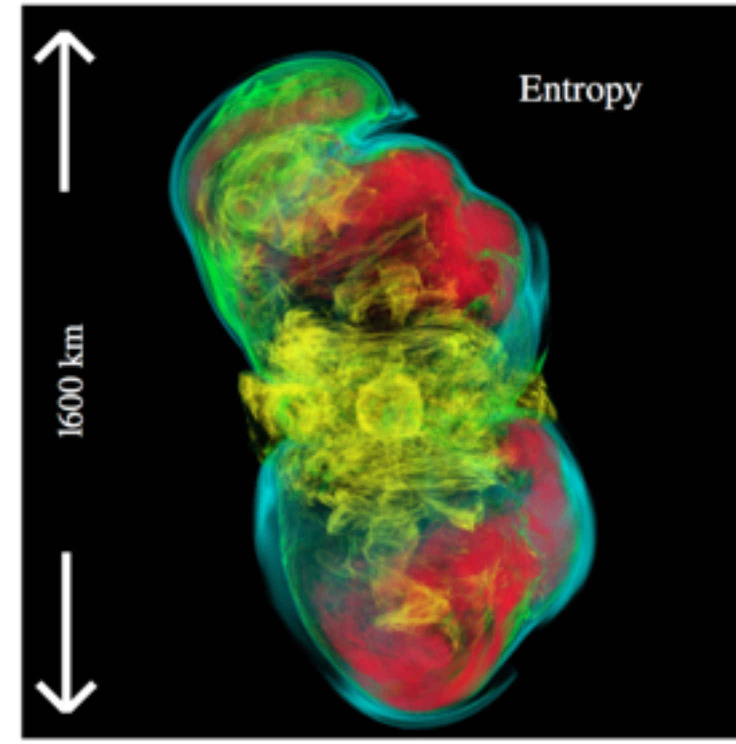
in 3D but polar-like jet



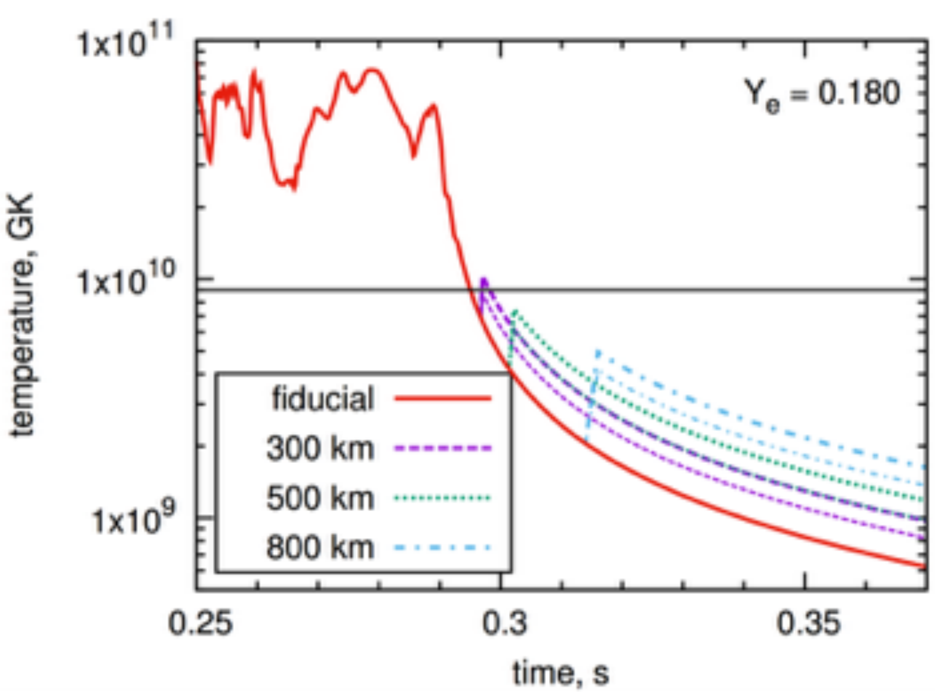
Winteler+ (2012)

deformed jet by
the Kink-instability

Mösta+ (2014)



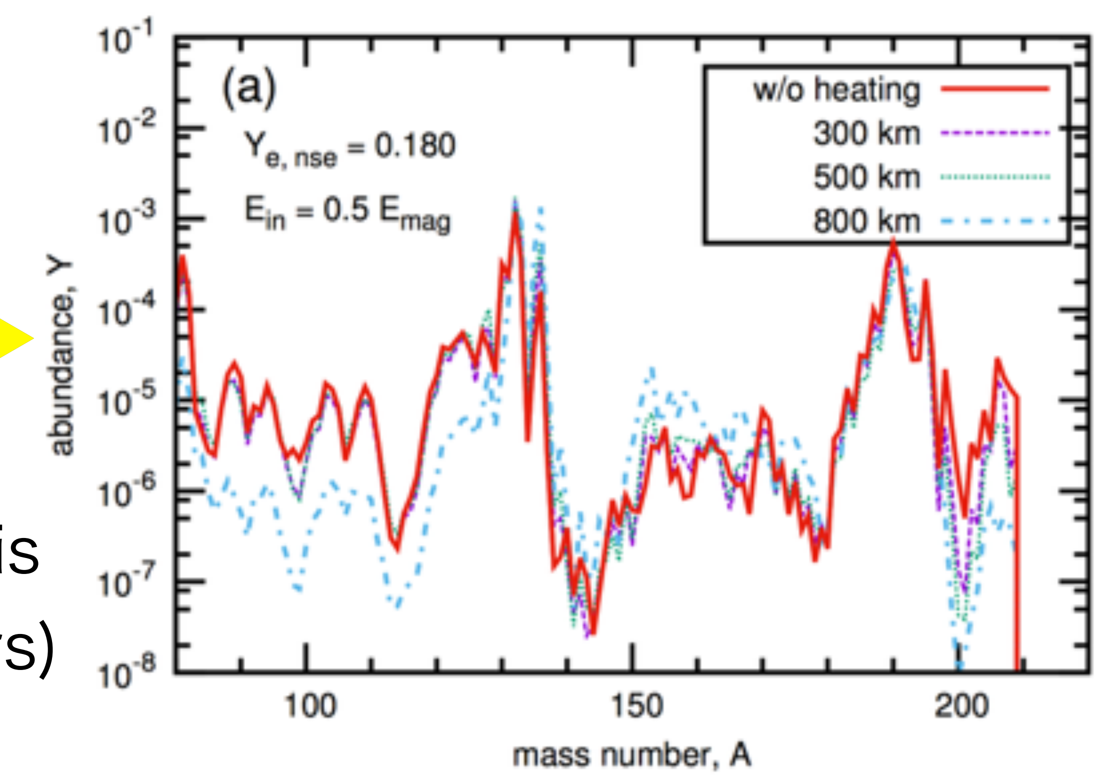
Question: How does it change r-process?



energy injection
by reconnection

minor effects
on nucleosynthesis
(if explosion occurs)

NN+ (2015)



Need those strong initial B-fields?

✔Magnetic driven SNe associated with strong polar-jets produce (heavy) r-process elements,

✔while weaker explosions show lower production of heavier r-process nuclei (i.e. weak r-process?).

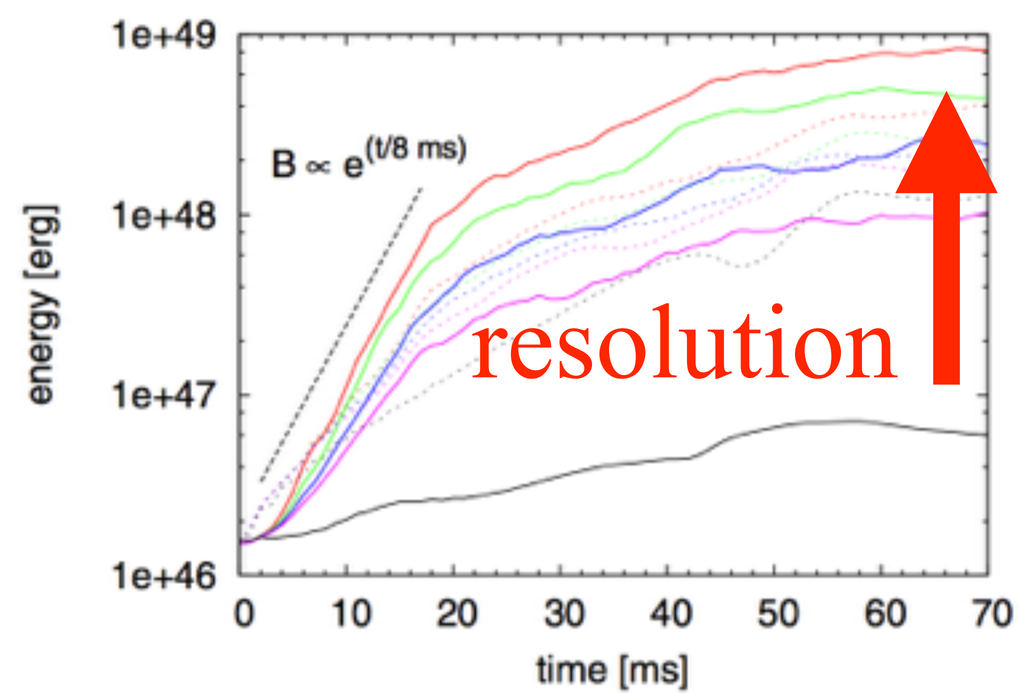
Next questions:

- 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. (see, Sawai's talk)

Magneto-rotational instability in CC-SN

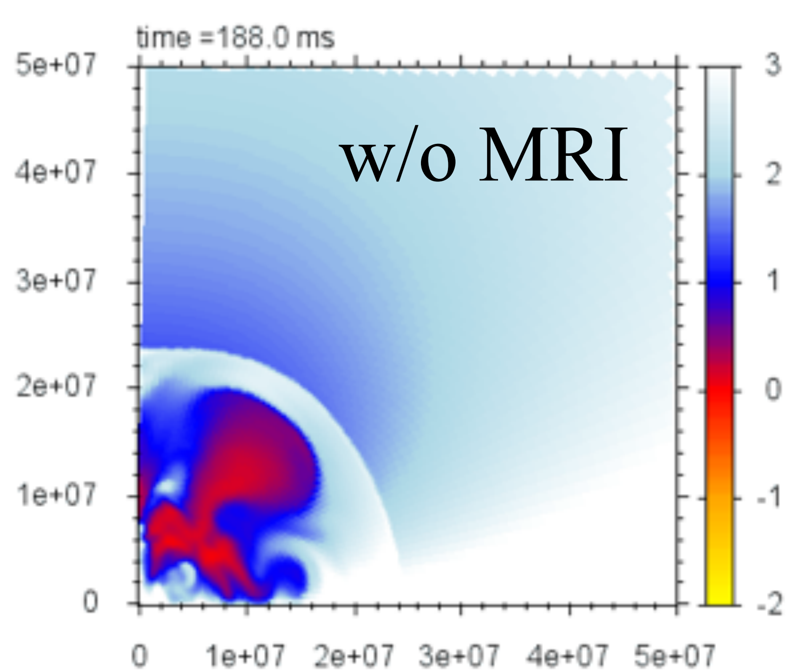
Sawai & Yamada (2014, 2016)

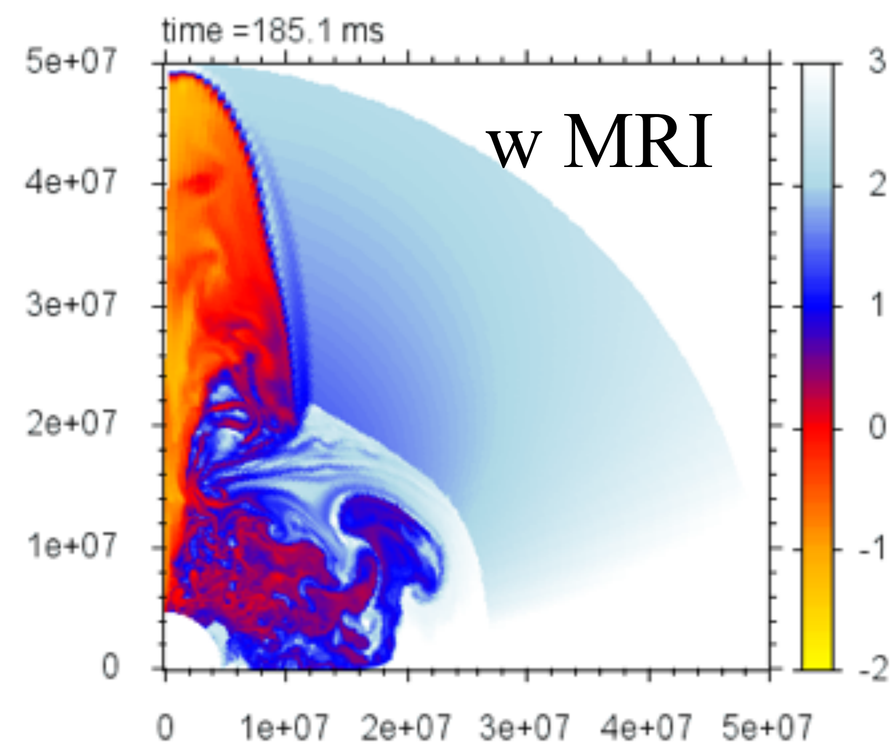
- MRI enhance B-fields of the core
- neutrino-heating also affects explosion
- see Talk by H. Sawai for more detail



Δr_{min} = 100, 50, 25, 12.5 m

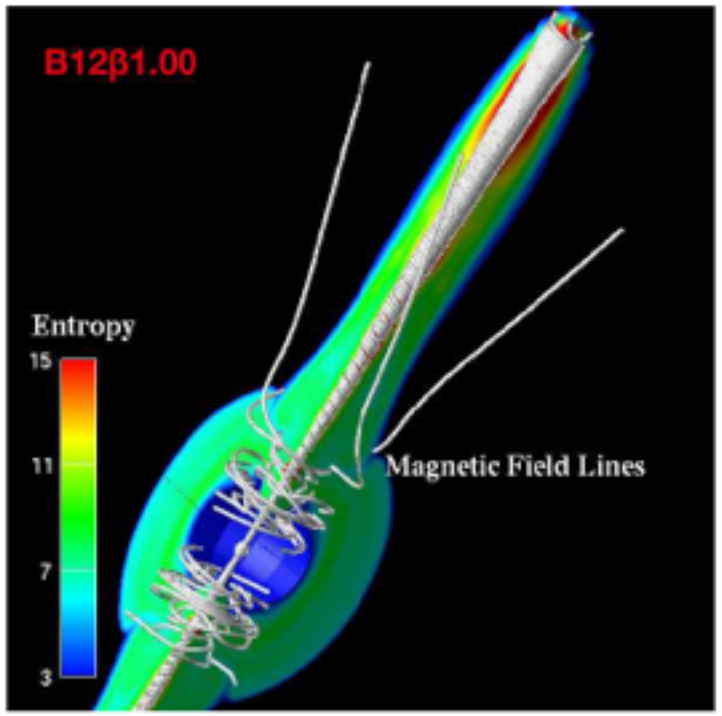
MRI-driven Jet; plasma-beta

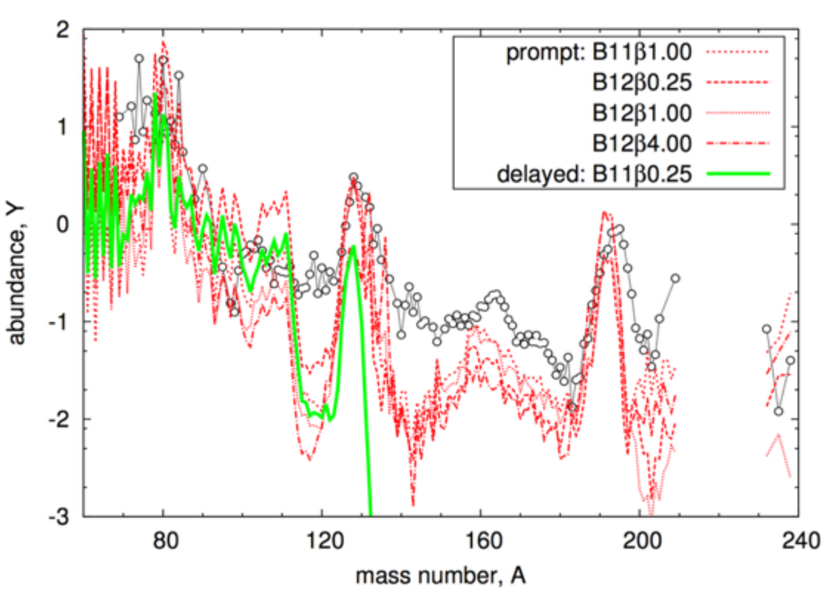




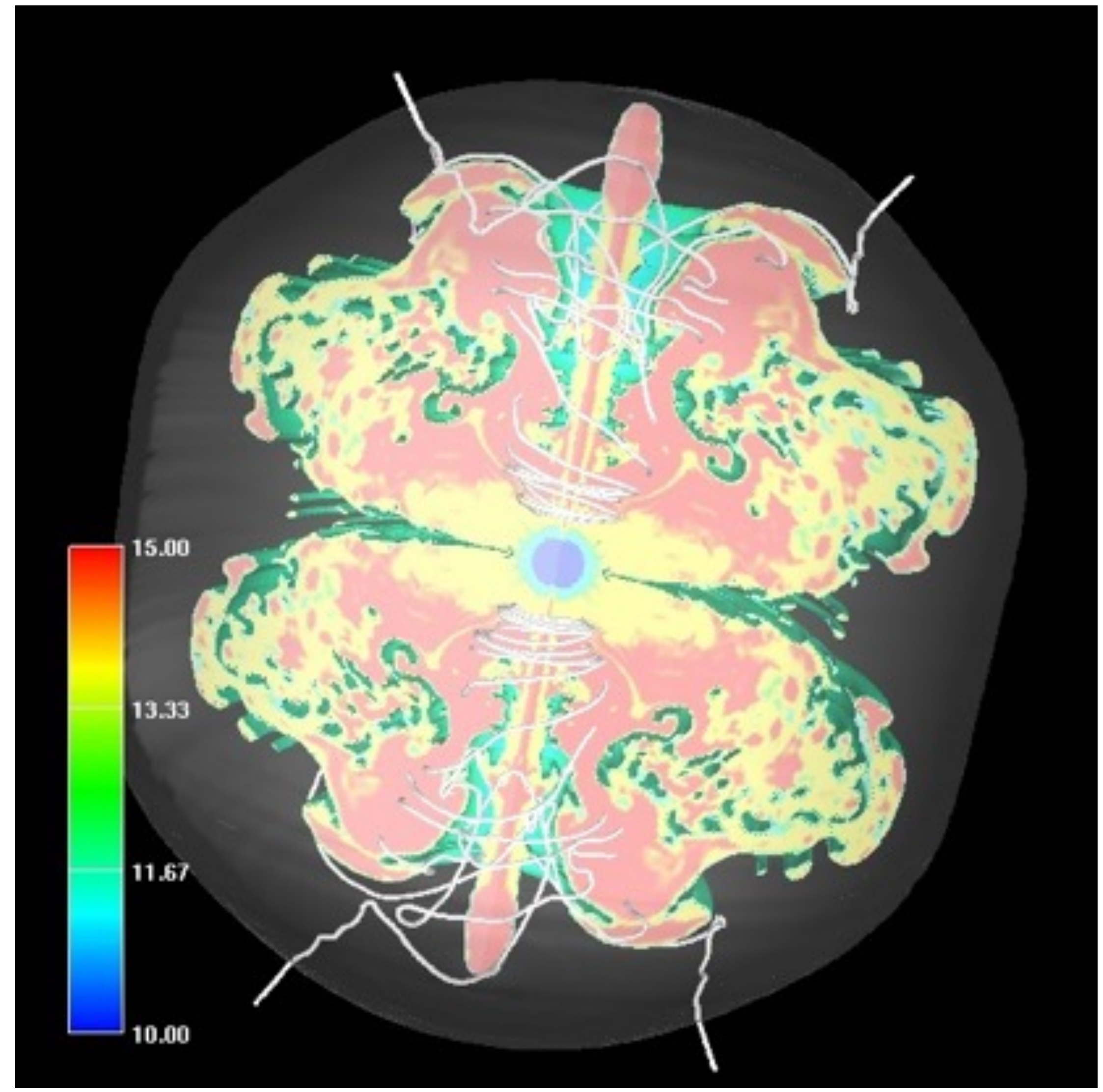
MR-SNe driven by the MRI

Nishimura+ (2015)
simulated by T. Takiwaki





Nishimura+ (2016 in prep.)
simulated by H. Sawai



?

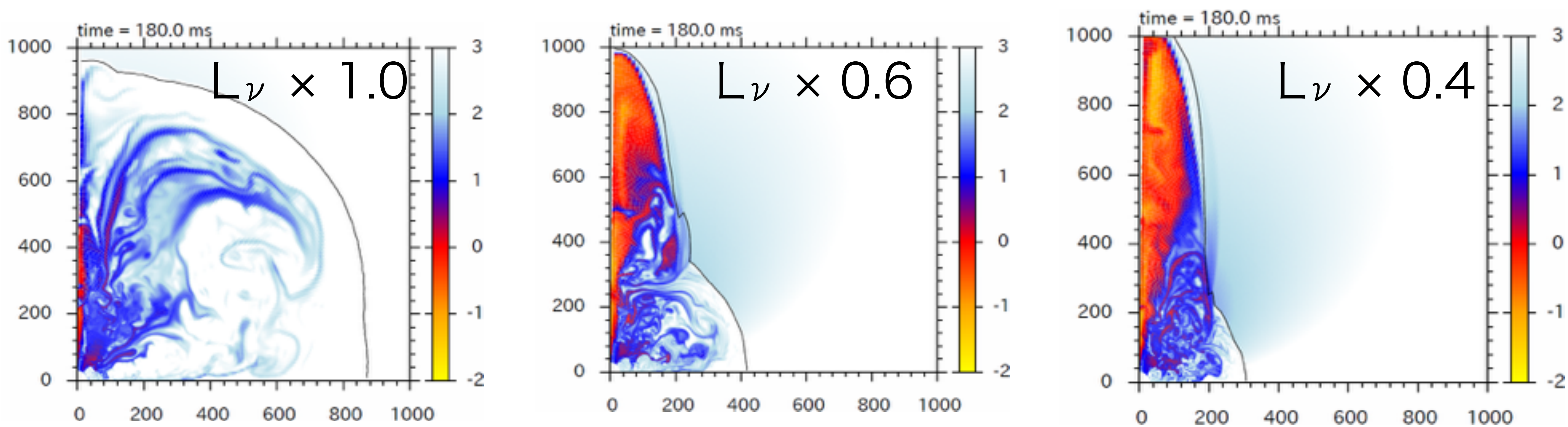
Need those strong initial B-fields?

- adopts one representative model
  - initial magnetic fields: 10^{11} G and rotation: 2.5 rad/s
  - neutrino-heating by “light-bulb” with the evolution of neutrino luminosity by IDSA (by Takiwaki)
- changes the neutrino luminosity
- (correspond to different rotation and B-fields in progenitors)

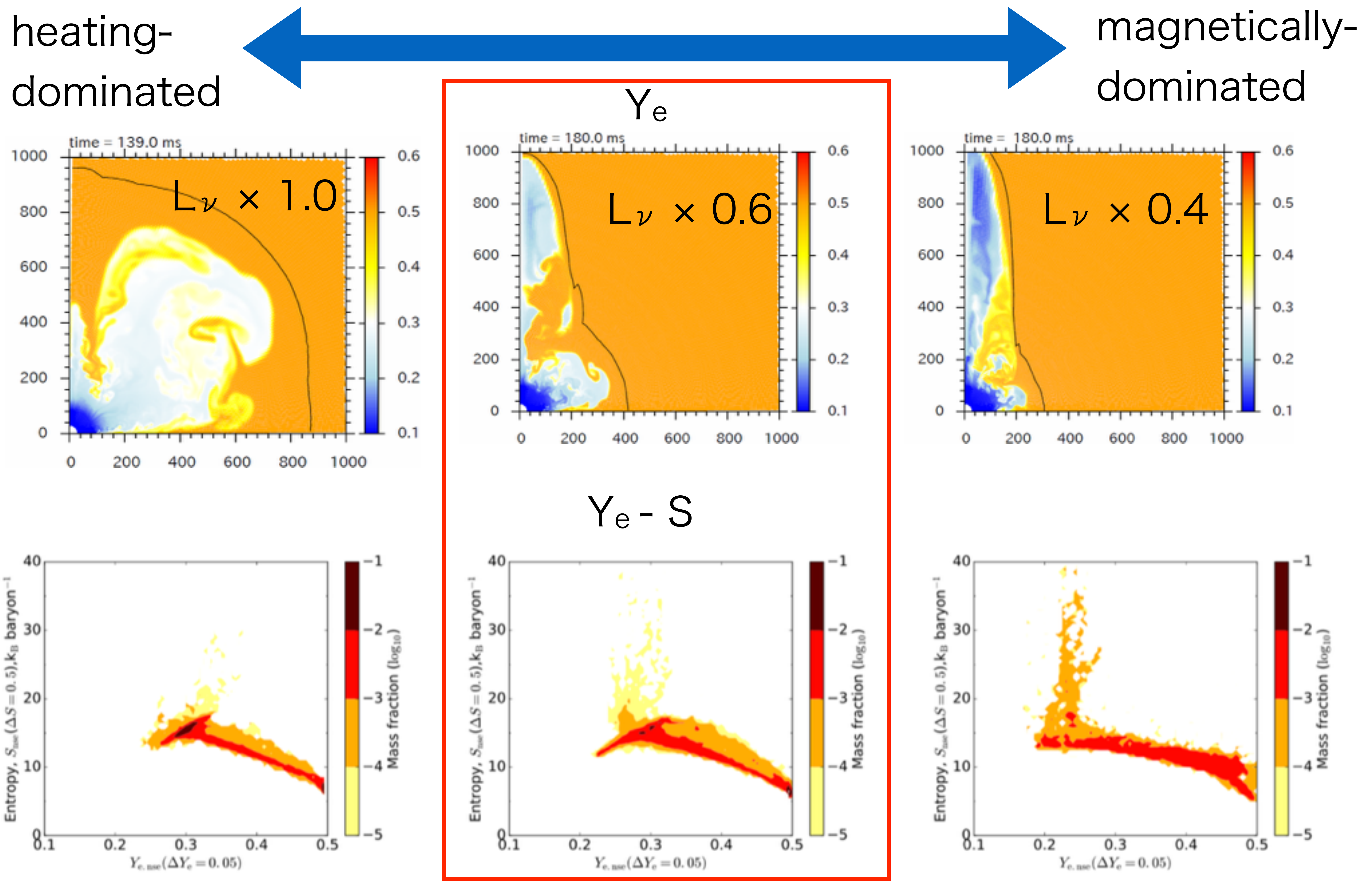
heating-dominated

magnetically-dominated

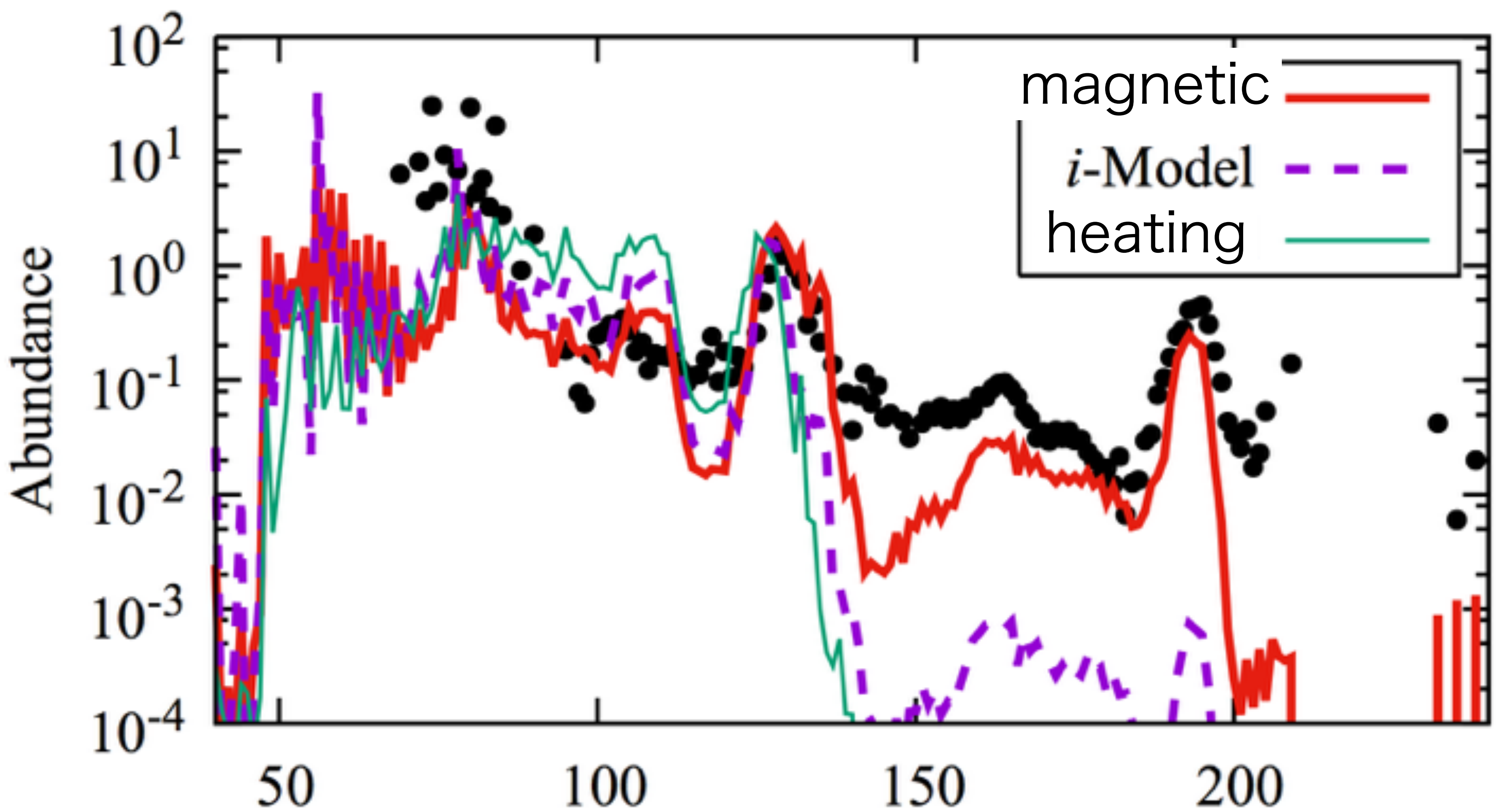
plasma-β



Need those strong initial B-fields?

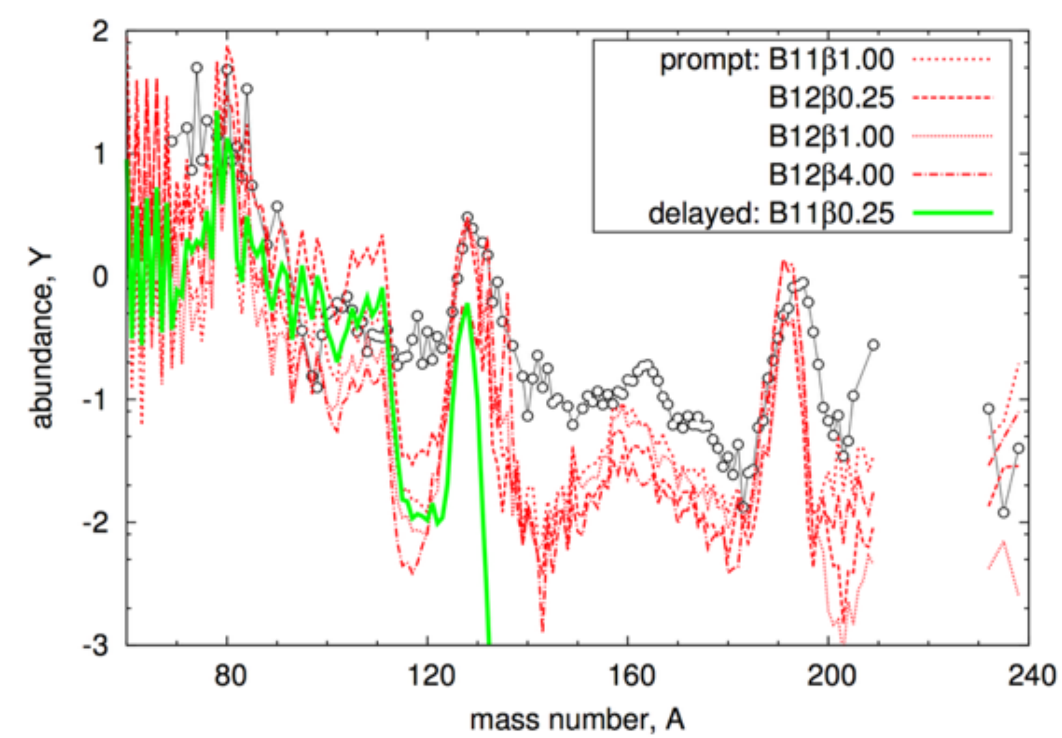


Need those strong initial B-fields?

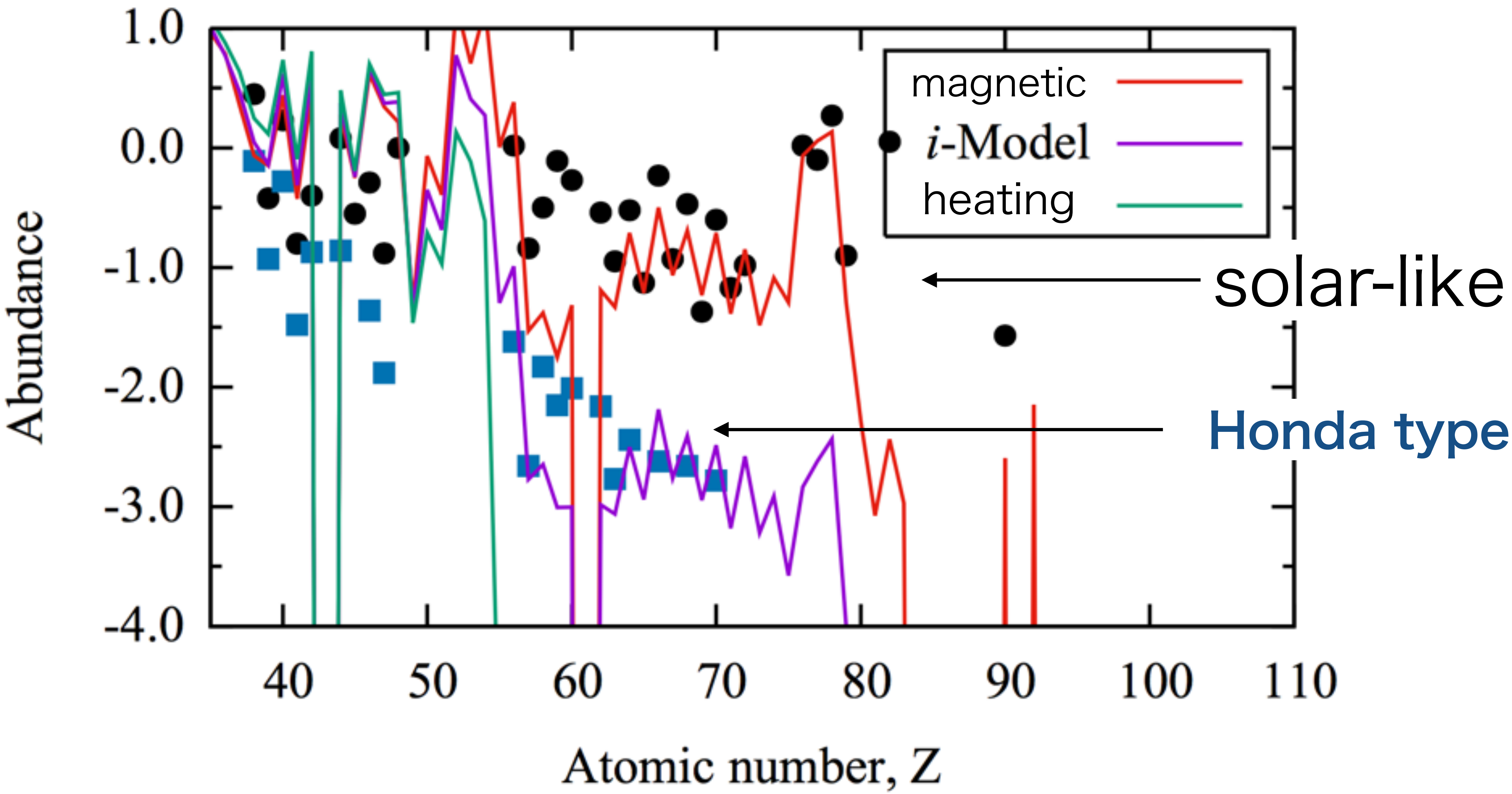


variation in the final abundances

Nishimura+ 2015
Takiwaki model
prompt vs delayed



Origin of diversity in metal-poor stars?



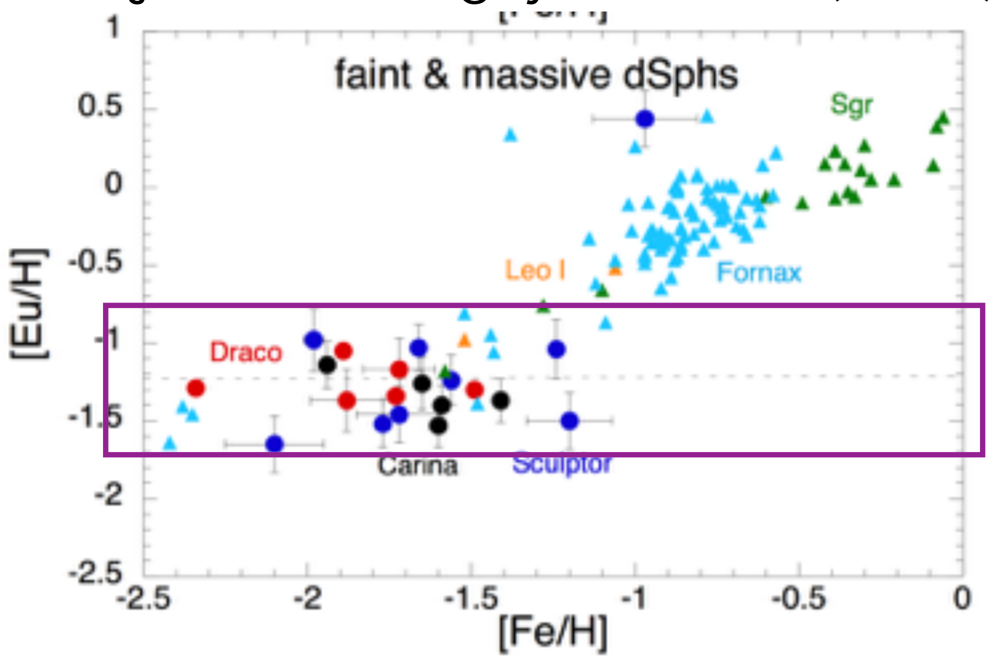
Magnetic-fields (MRI + heating models) can be origin of diversity in r-process in metal-poor stars

More observation of Honda-type stars?

e.g., M. Aoki, Ishimaru, W. Aoki & Wanajo 2016; presentation at NIC14

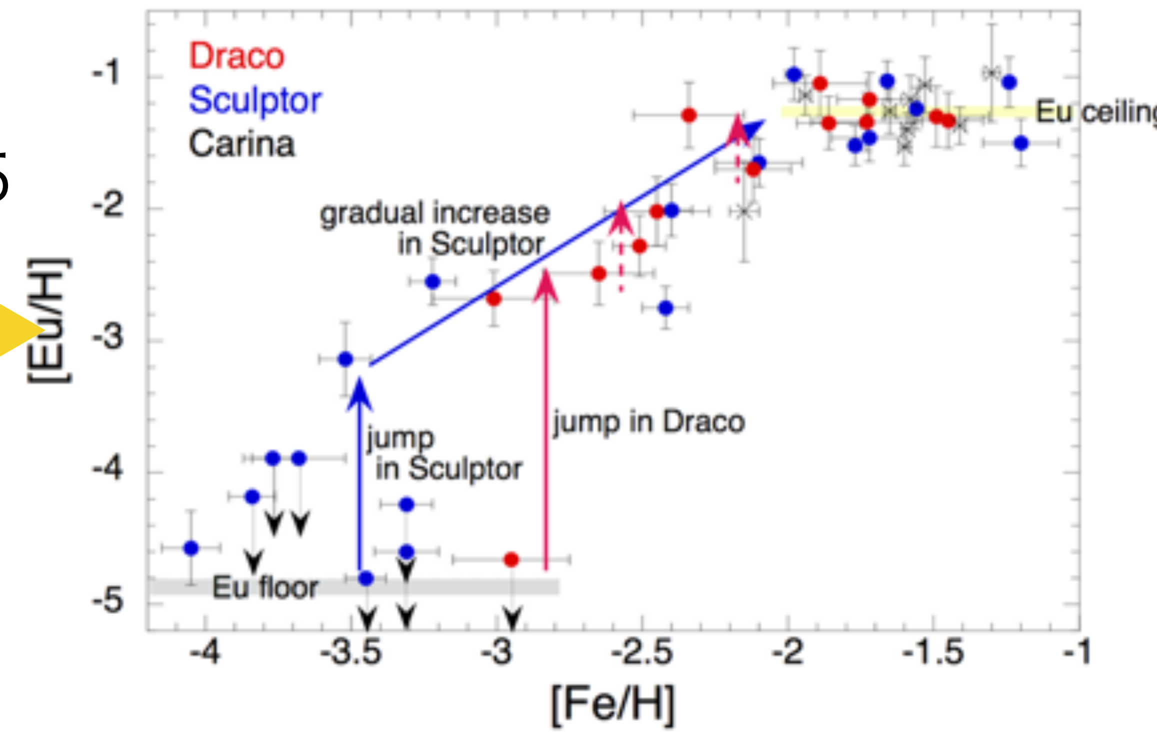
GCE: early dwarf spheroidal galaxies

Tsujimoto & Shigeyama A&A (2014)

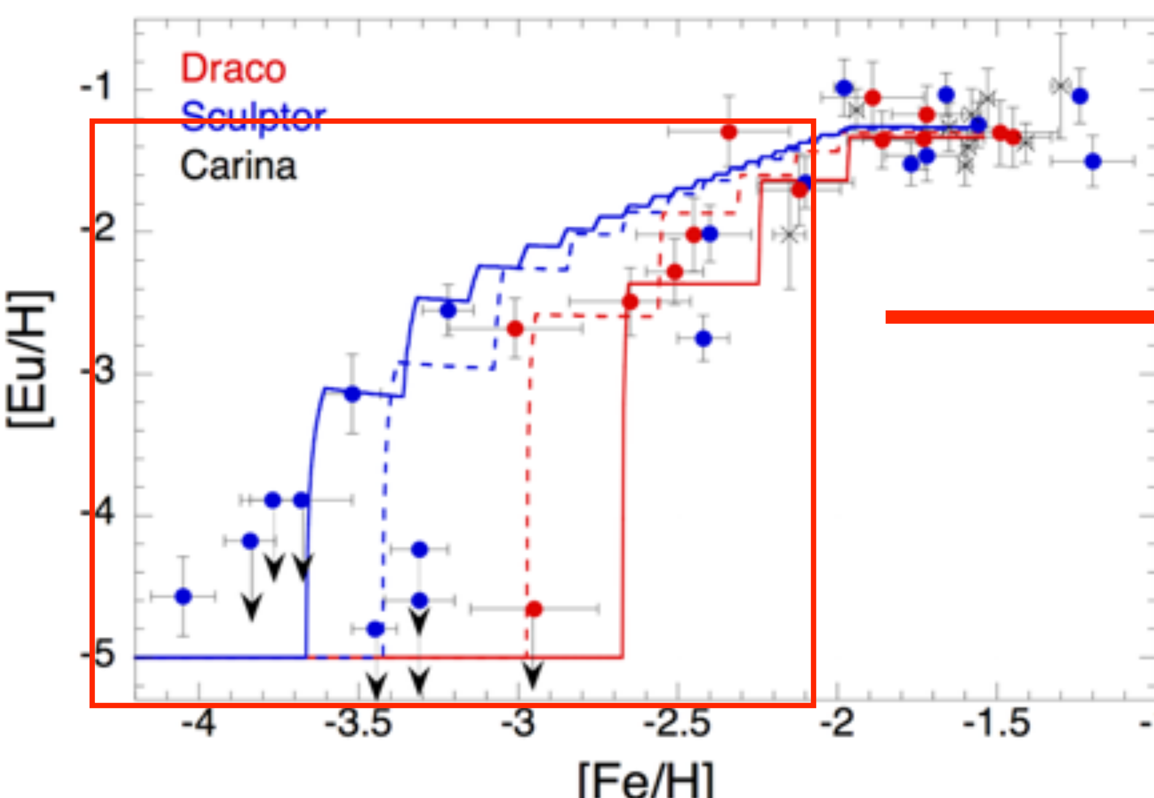


[Fe/H] < -2.5

Tsujimoto & NN ApJL (2015)
(see also, Tsujimoto+ PASJ 2015)



Tsujimoto & NN, ApJL (2015)



Chemical evolution models

<u>GCE models suggest:</u>

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

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

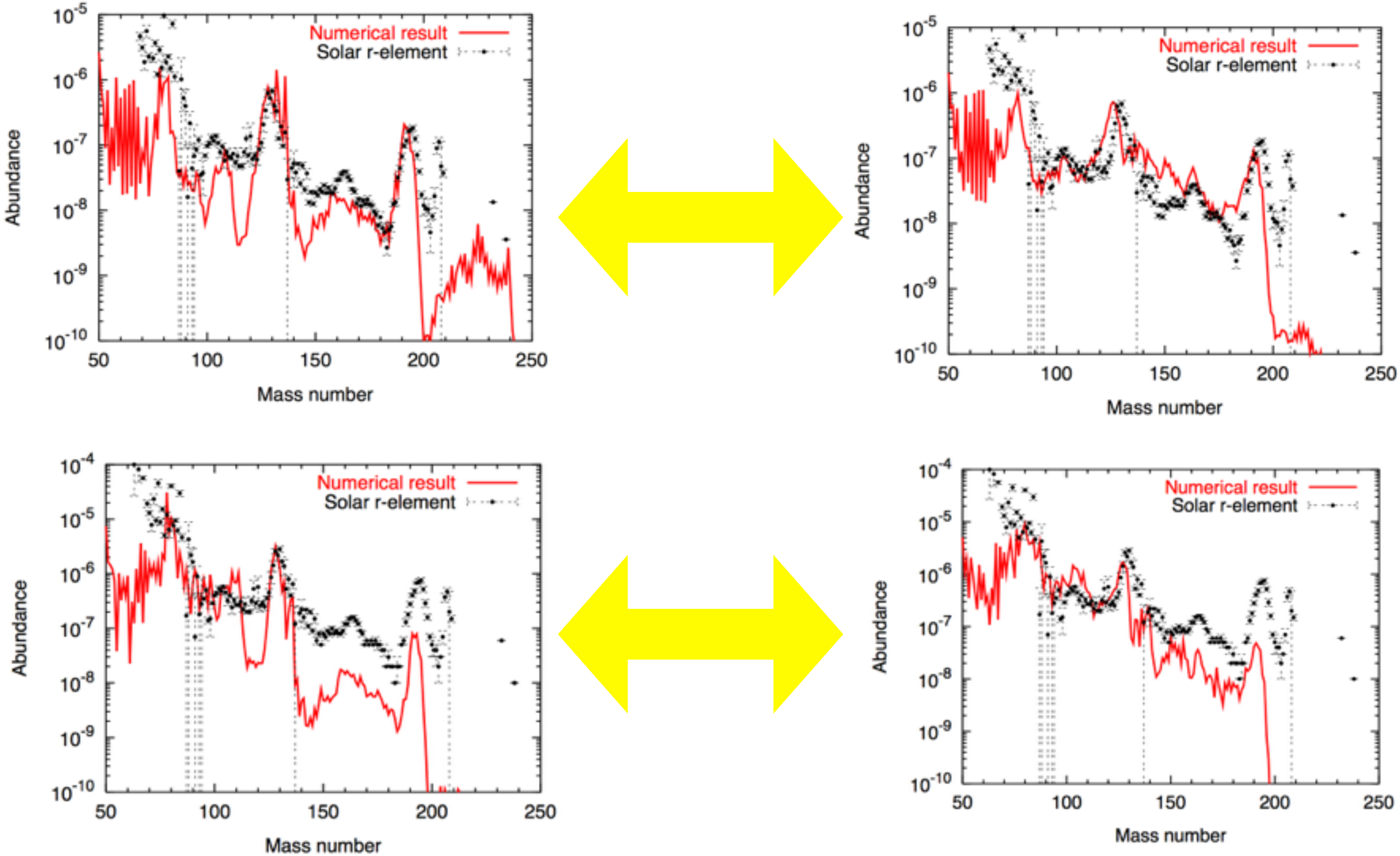
Impacts of Beta-decay on production of r-process peaks

r-process: nuclear physics inputs

β-decay half-life, (γ,n), and (γ,n) are dominant; different nuclear physics inputs change the results: see Koura's talk

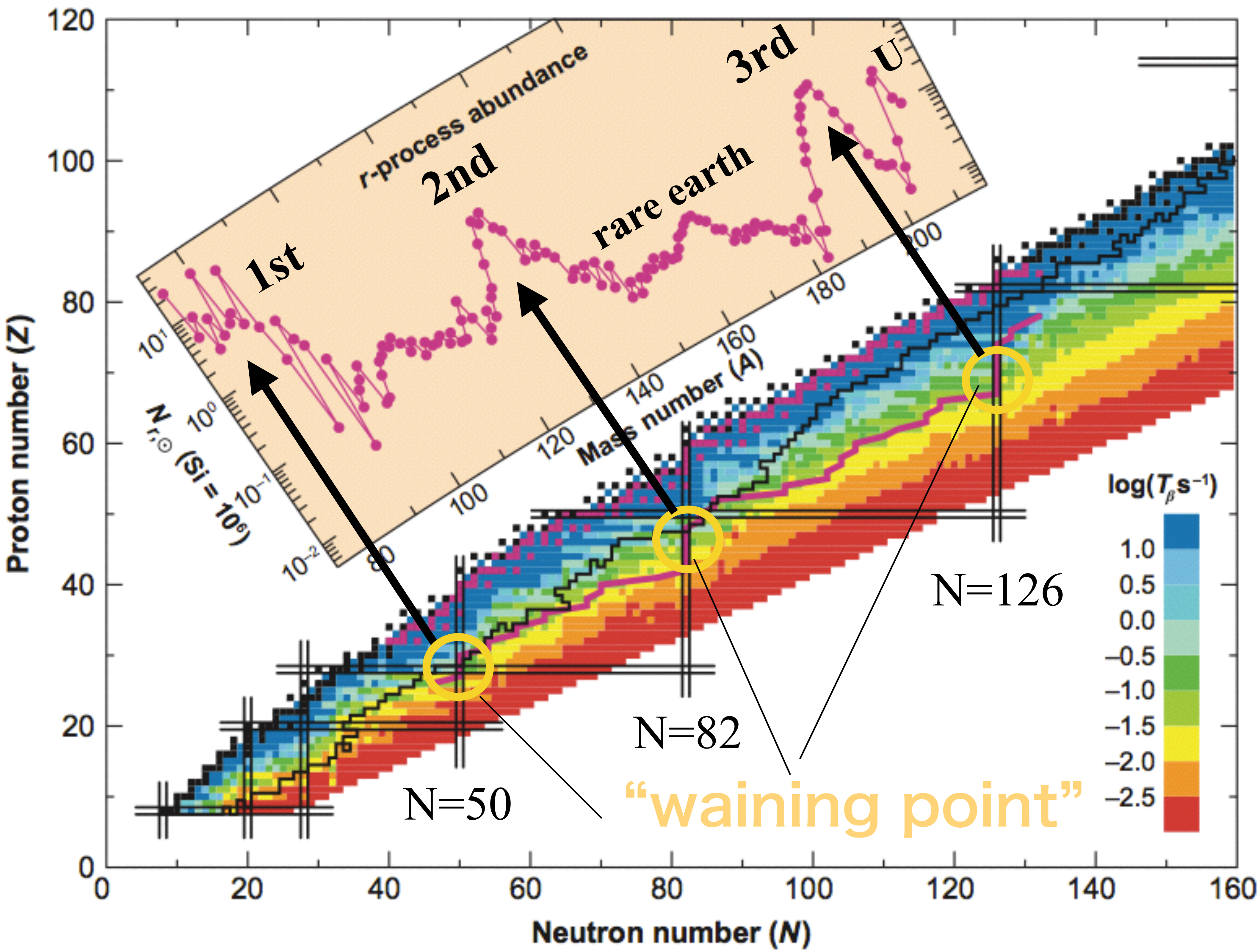
mass model: FRDM

mass model: ETFSI



Nishimura et al., ApJ (2006)

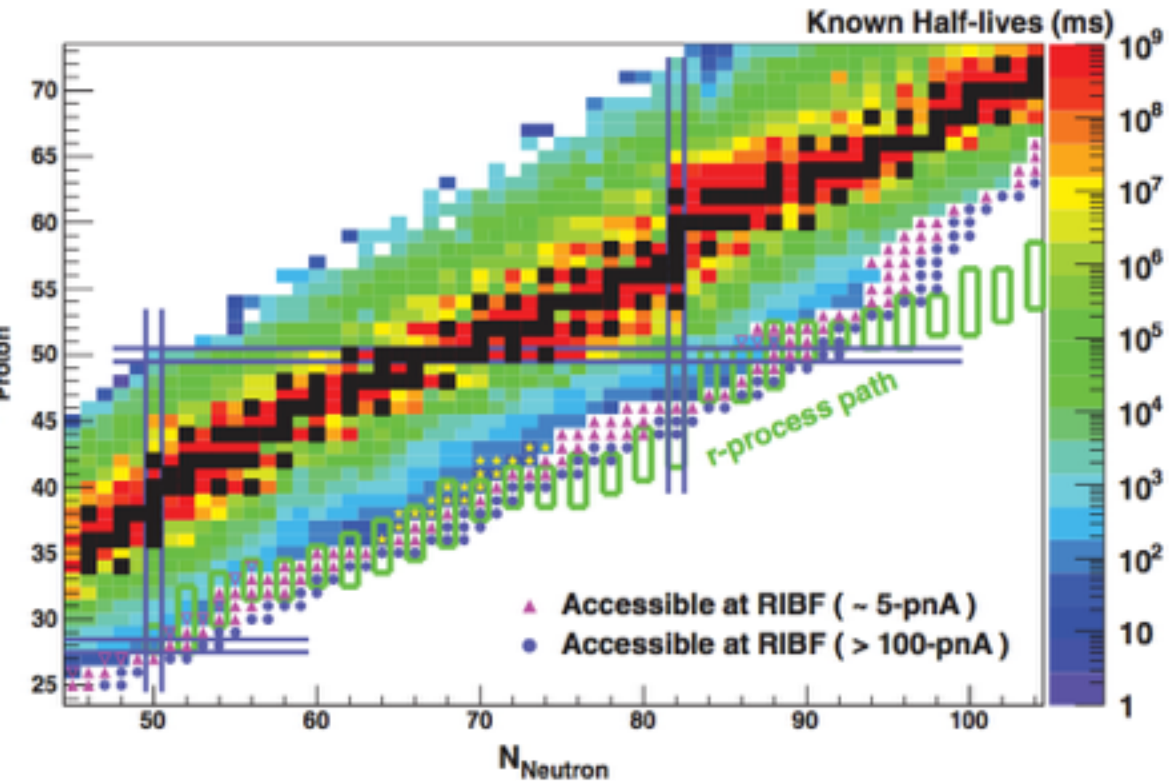
beta-decay half-lives and the r-process



based on Sneden+ (2008) ARAA

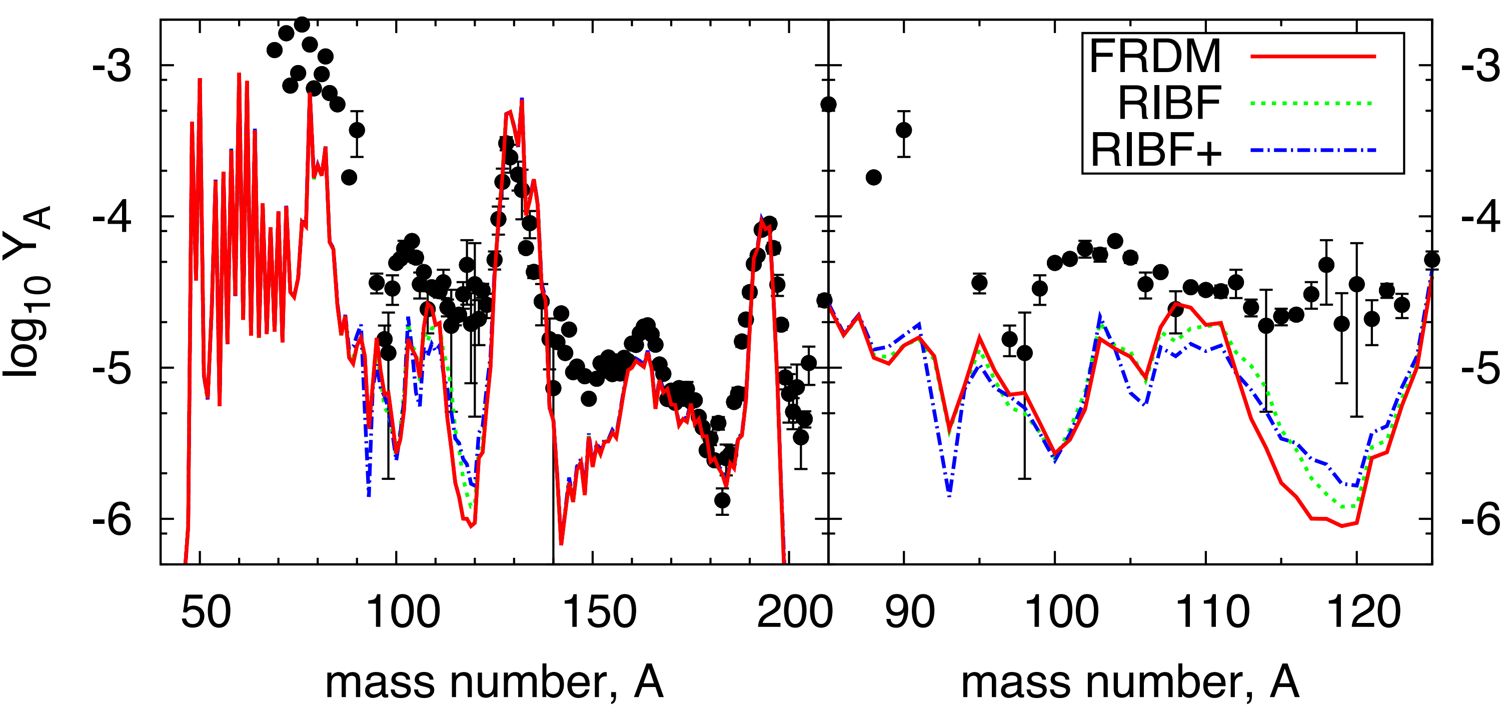
2nd peak (N=82): RIBF@RIKEN experiment

S. Nishimura, PTEP, 2012



new measured half-lives
S. Nishimura+, PRL 106, 2011
G. Lorusso+, PRL 114, 2015

NN+, PRC (2012)



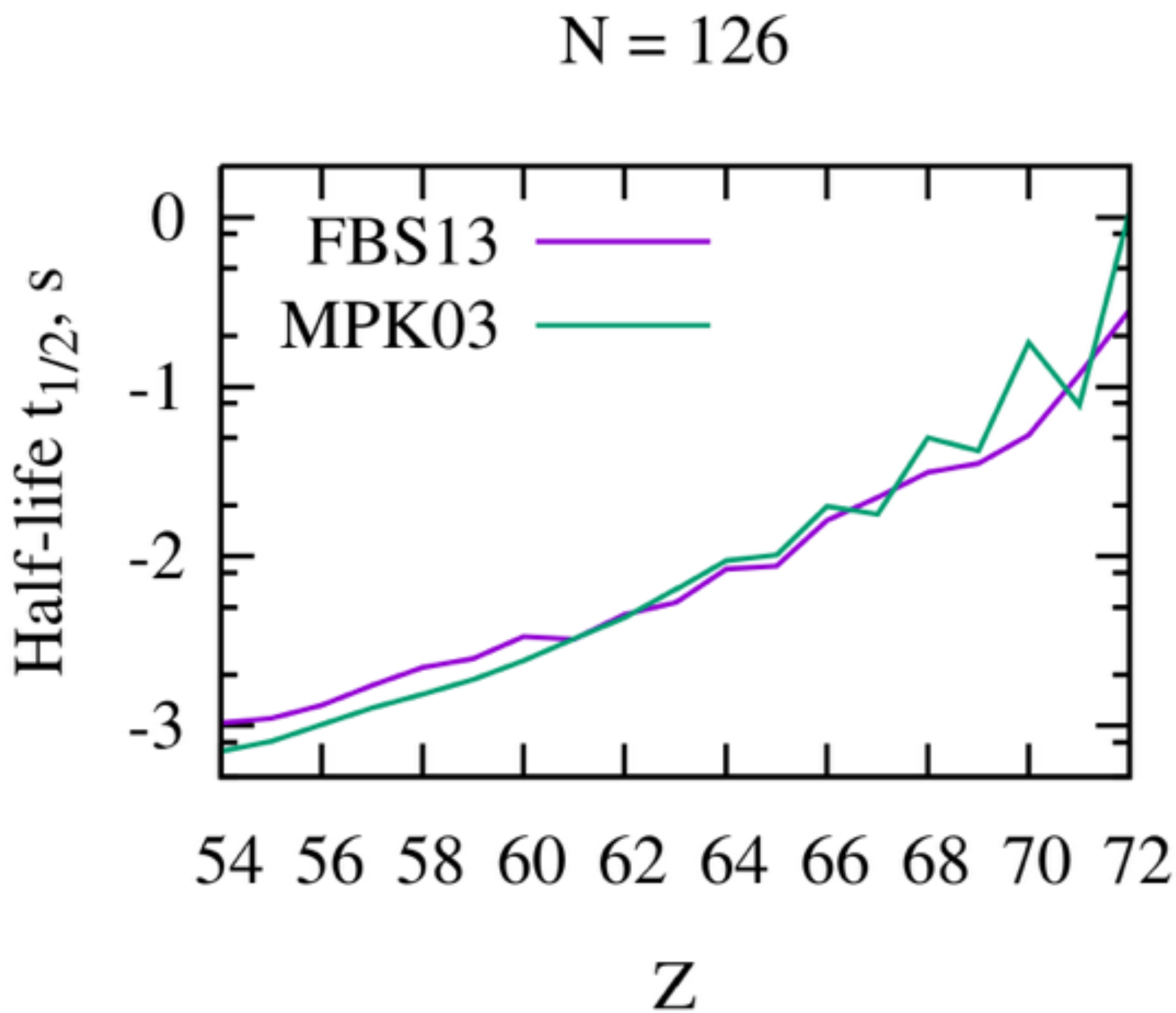
applied new experimental data by RIBF (RIKEN)

Nuclear physics uncertainty affects?

Problem: The first-forbidden (FF) transition changes β decay

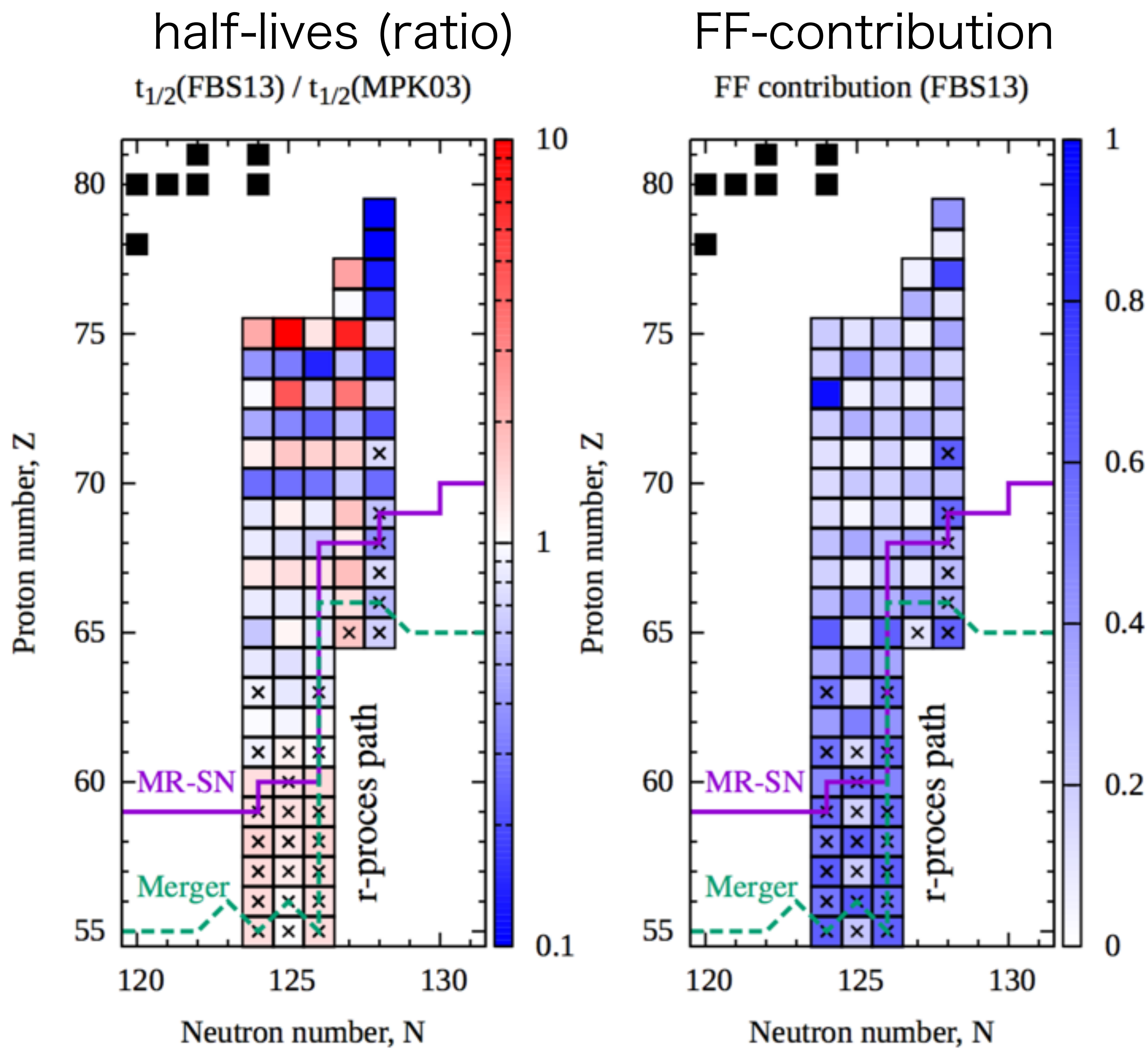
new rates based on QRPA calculations

FBS13: Fang, Brown, Suzuki, PRC88 (2013)



vs. MPK03: Gross theory (Möller, Pfeiffer, Kratz 2003)

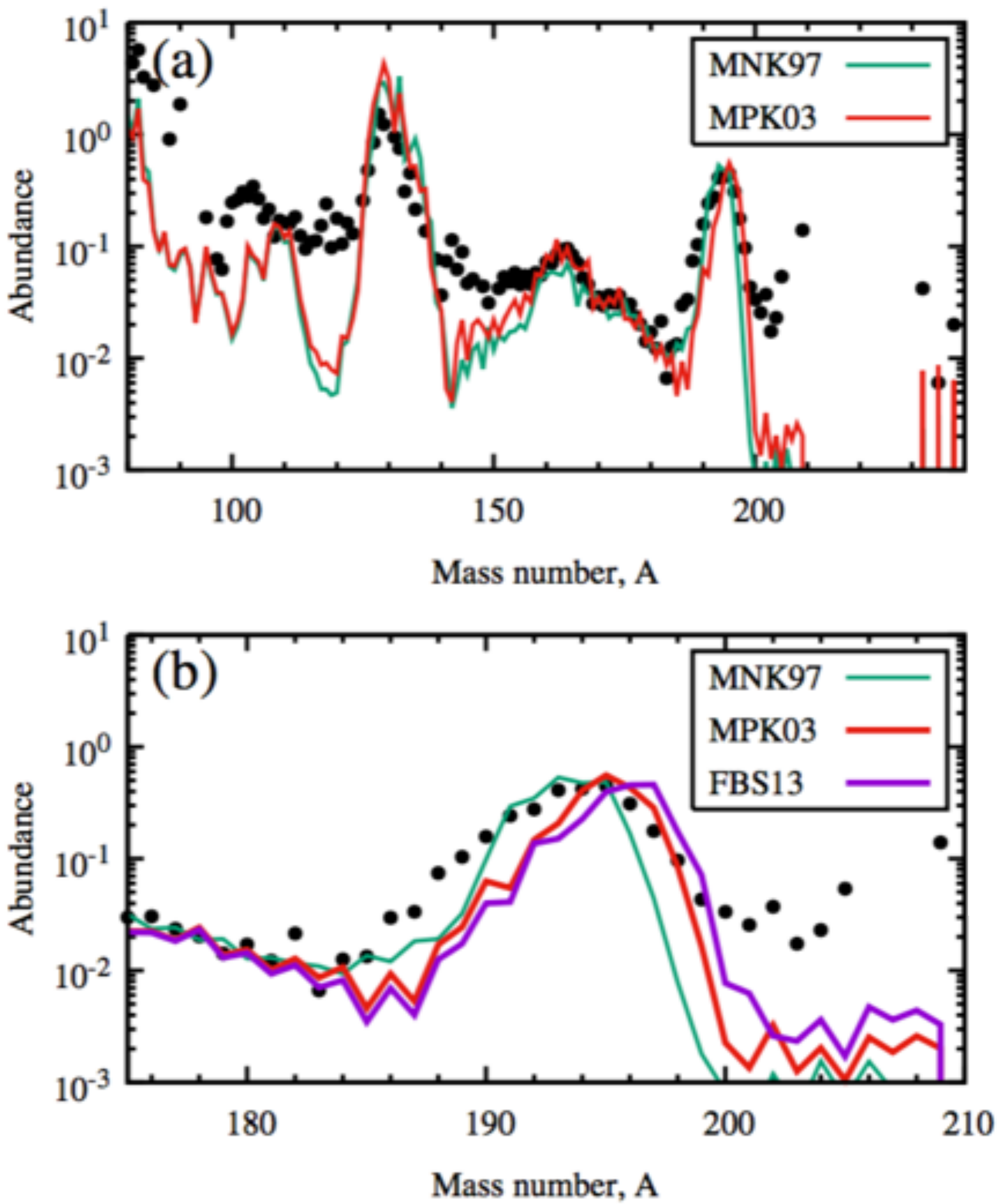
beta-decay with first forbidden and n-emission

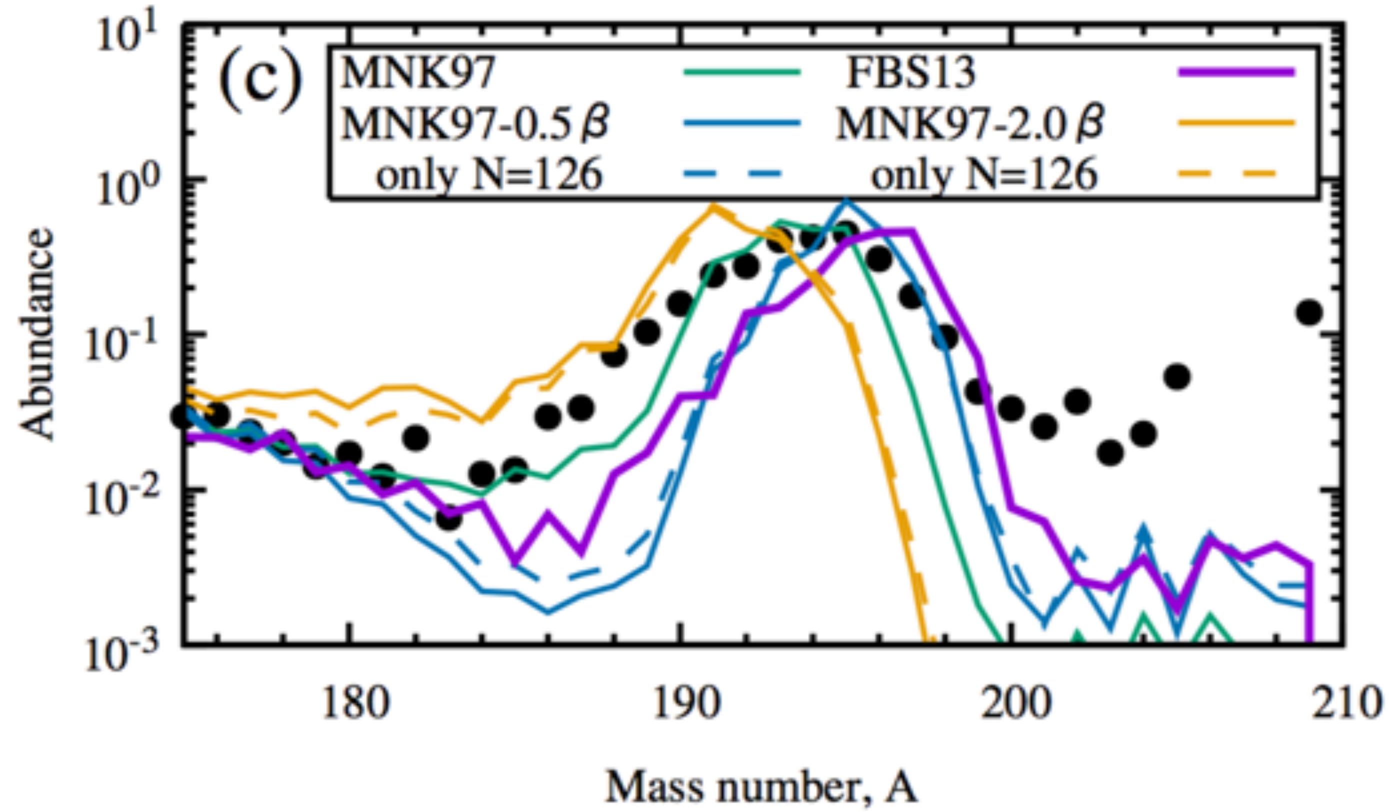


✖ strong n-emission

Nuclear physics uncertainty affects?

faster decay enhances
3rd peak production

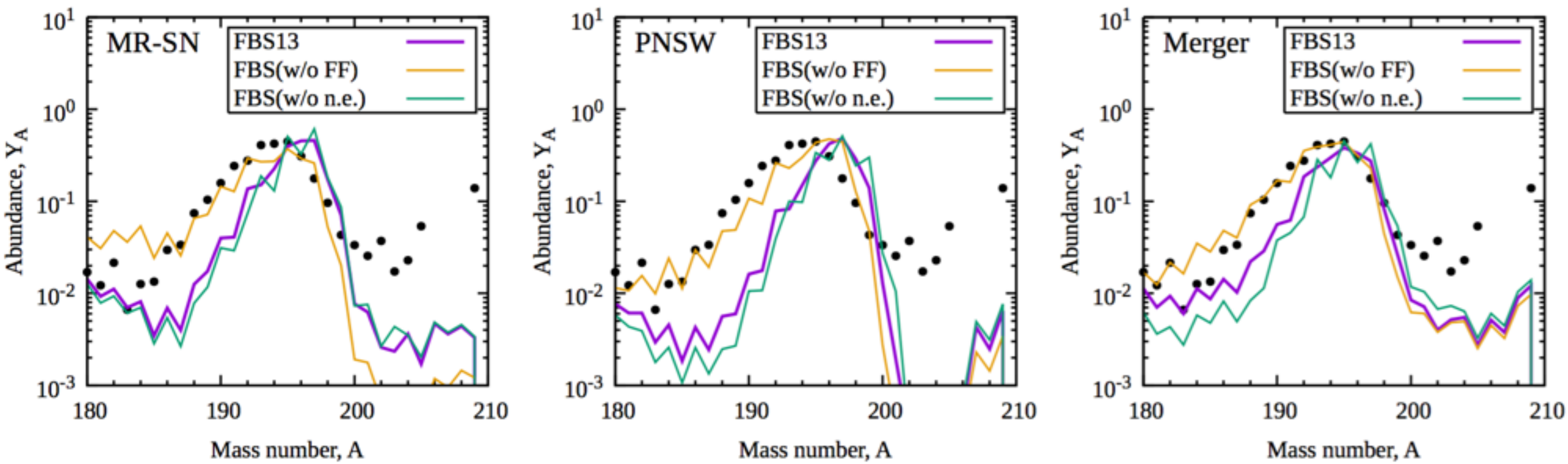




mostly N=126 isotones
cause the impacts

Impacts of each component in different models

- MR-SN (NN+ 2015)
- Proto-NS wind (Arocnes 2009)
- NS-NS merger (Freiburghouse 1999)

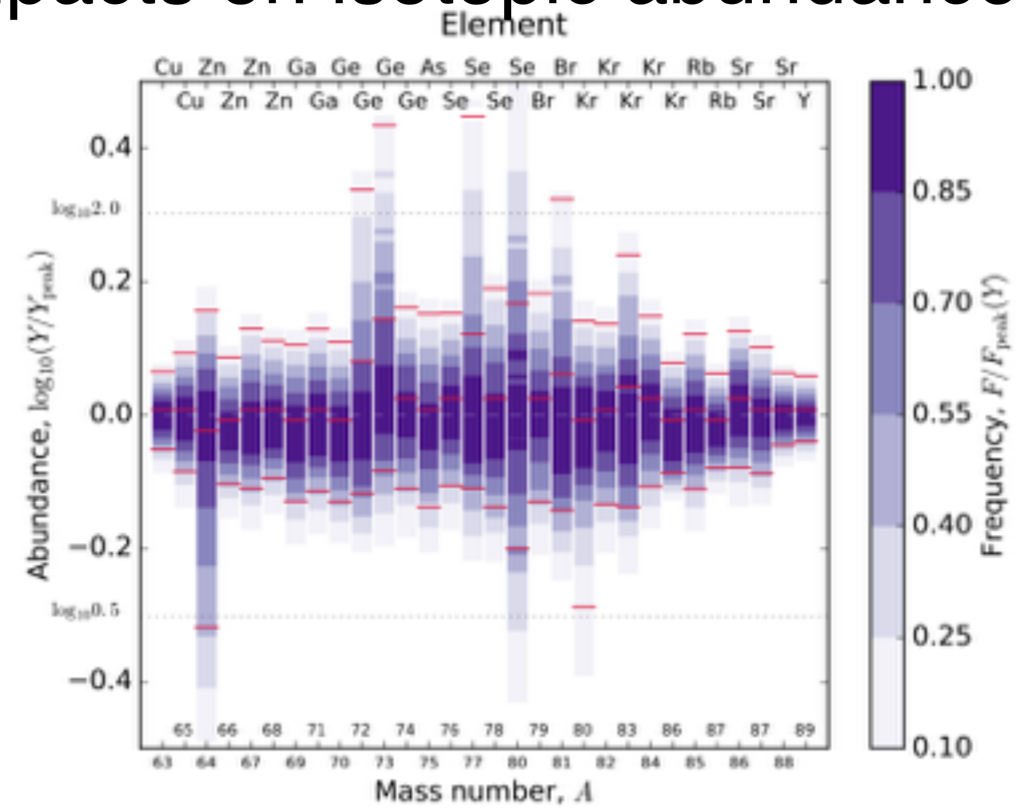


What is the next?: to find “important” reactions

We have fast super computers. Let’s go to more comprehensive studies! (project with T. Rauscher, R.Hirschi)

Example for the s-process
(smaller computational scales)

impacts on isotopic abundances



evaluate uncertainty for relevant reactions → Monte-Carlo

for detail, see My presentation at NIC14 (Niigata); Rauscher+ 2016 arXiv: 1606.05671

UK Supercomputer facility

DiRAC

Science & Technology Facilities Council

COSMOS at Cambridge

Key reactions: weak s-proc.

all Lv1 reaction are fixed

all Lv1+Lv2 reaction are fixed

Nuclide	$r_{\mathrm{cor},0}$	$r_{\mathrm{cor},1}$	$r_{\mathrm{cor},2}$	Key reaction Level 1	Key reaction Level 2	Key reaction level 3
Zn64	0.76			^{64}Cu(+β)^{64}Zn		
	-0.47	-0.73			^{64}Cu(ec)^{64}Ni	
Zn67	-0.67			^{67}Zn(n,γ)^{68}Zn		
Ge72	-0.85			^{72}Ge(n,γ)^{73}Ge		
Ge73	-0.84			^{73}Ge(n,γ)^{74}Ge		
Ge74	-0.44	-0.53	-0.67			^{74}Ge(n,γ)^{75}Ge
As75	-0.50	-0.58	-0.70			^{75}As(n,γ)^{76}As
Se77	-0.86			^{77}Se(n,γ)^{78}Se		
Se78	-0.71			^{78}Se(n,γ)^{79}Se		
	0.37	0.68			^{68}Zn(n,γ)^{69}Zn	
Se80	-0.76			^{80}Br(+β)^{80}Kr		
	0.27	0.73			^{80}Br($-\beta$)^{80}Se	
	0.16	0.44	0.88			^{80}Br(ec)^{80}Se
Br79	-0.63	-0.73			^{79}Br(n,γ)^{80}Br	
Br81	-0.80			^{81}Kr(n,γ)^{82}Kr		
Kr83	-0.76			^{83}Kr(n,γ)^{84}Kr		
Kr84	-0.49	-0.64	-0.76			^{84}Kr(n,γ)^{85}Kr
Kr86	0.84			^{85}Kr(n,γ)^{86}Kr		
	-0.31	-0.71			^{86}Kr(n,γ)^{87}Kr	
	-0.33	-0.62	-0.90			^{85}Kr(+β)^{85}Rb
Rb87	-0.57	-0.64	-0.95			^{87}Rb(n,γ)^{88}Rb

Summary

- Astronomical origin of r-process nucleosynthesis
  - NS-NS mergers
    - main contributor in GCE
    - but need other components in early galaxies?
  - MHD-Supernovae
    - can be origin (of e.g. Eu) in early galaxies
    - the differences in rotation and magnetic fields change final r-process abundances; “intermediate” pattern?
- nuclear physics uncertainty
  - beta-decay and r-process peak formation
    - first-forbidden effects accelerate production of heavy r-process peak (3rd)
  - more comprehensive studies in multiple astro-modes (MC approach in future)