RIBF Nuclear Physics Seminar
05. 06. 2012

“Current Status of r-process studies in Core-Collapse Supernovae”

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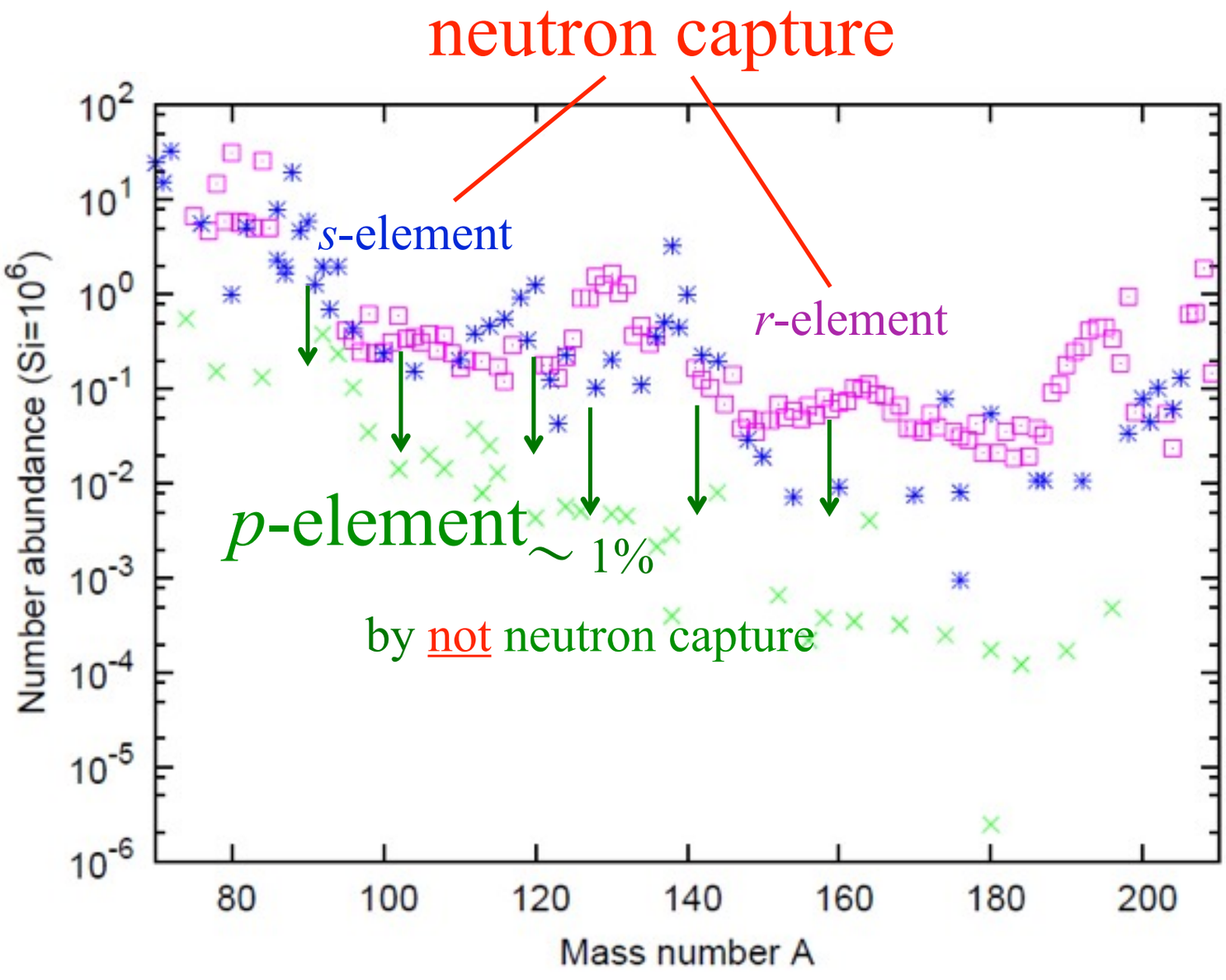
（西村 信哉）

Introduction:
Core-Collapse supernovae as the origin of r-process

heavy element nucleosynthesis beyond iron

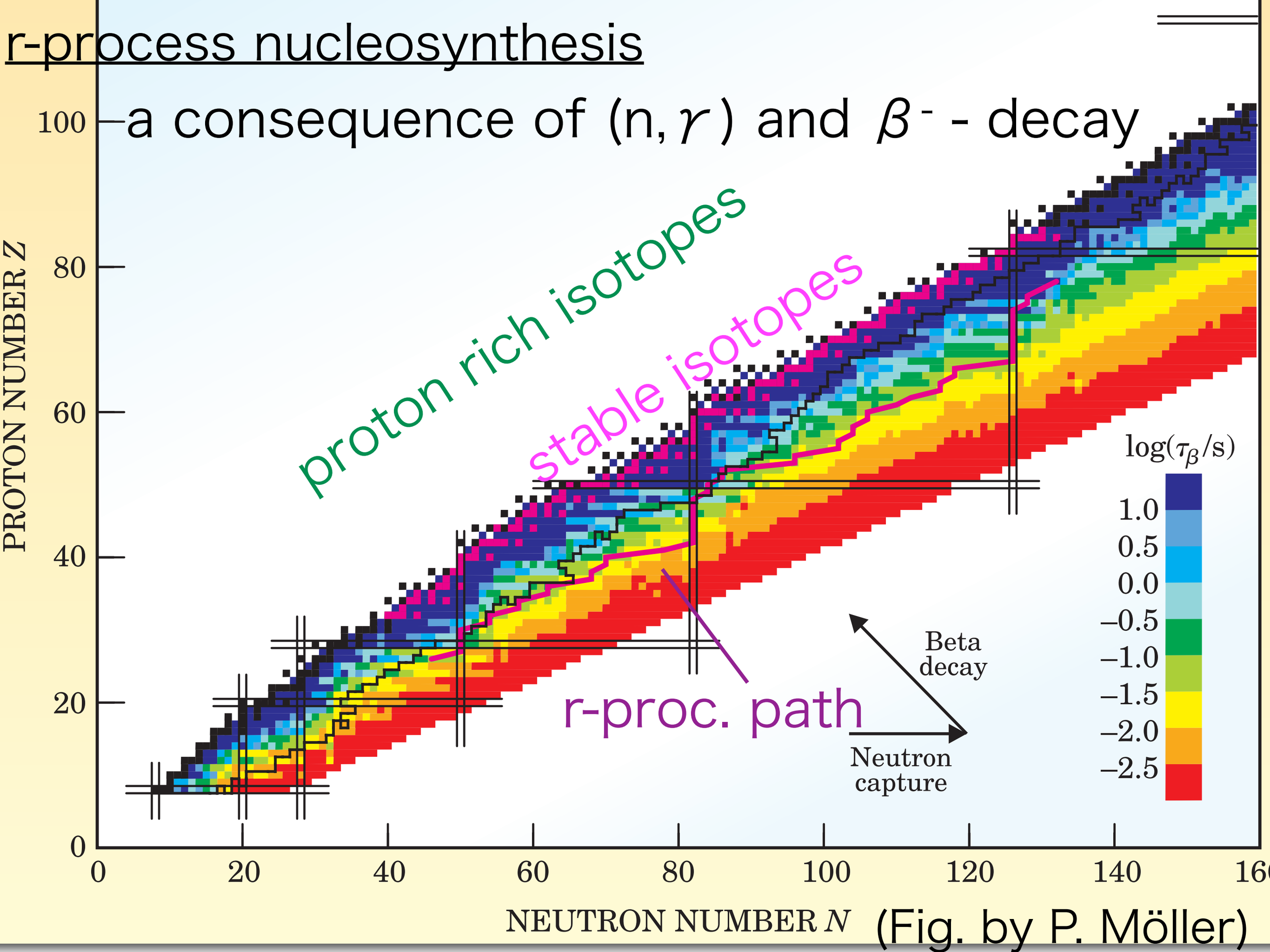
Solar system abundances



data by (Anders & Grevesse 1989)

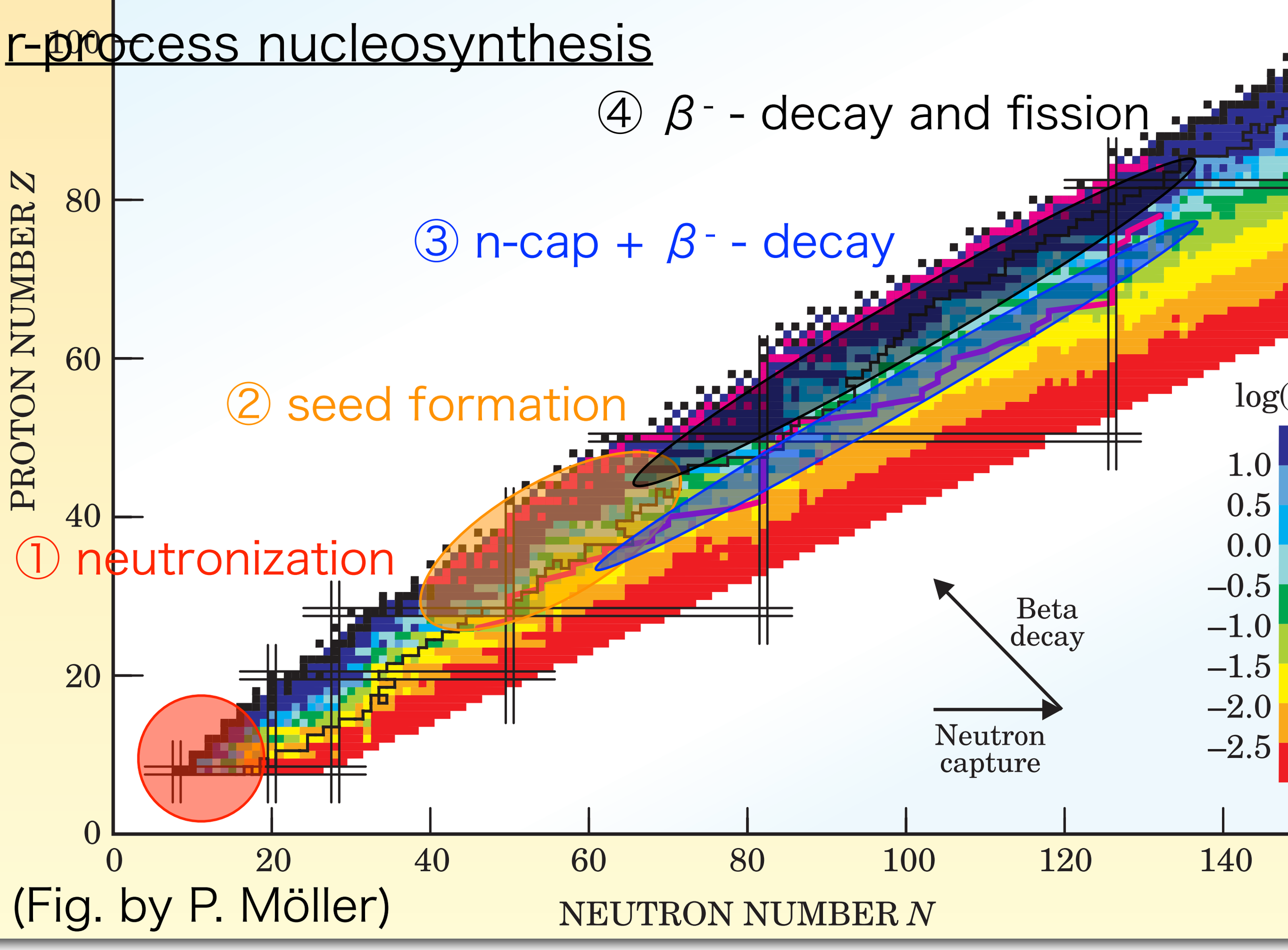
r-process nucleosynthesis

– a consequence of (n, γ) and β^- - decay



(Fig. by P. Möller)

r-process nucleosynthesis



(Fig. by P. Möller)

Physical condition for r-process

high T and ρ

① neutronization (low Y_e)
by e-cap. ($p + e^- \rightarrow n + \nu_e$)
(T >10 MeV) NSE
(n, p, & α are predominant)

Y_e: electron fraction
$Y_e = Y_p$
$\sim N_p / (N_n + N_p)$
(low Y_e = neutron rich)

② seed formation (high S)
quasi-NSE (α-process)

expand

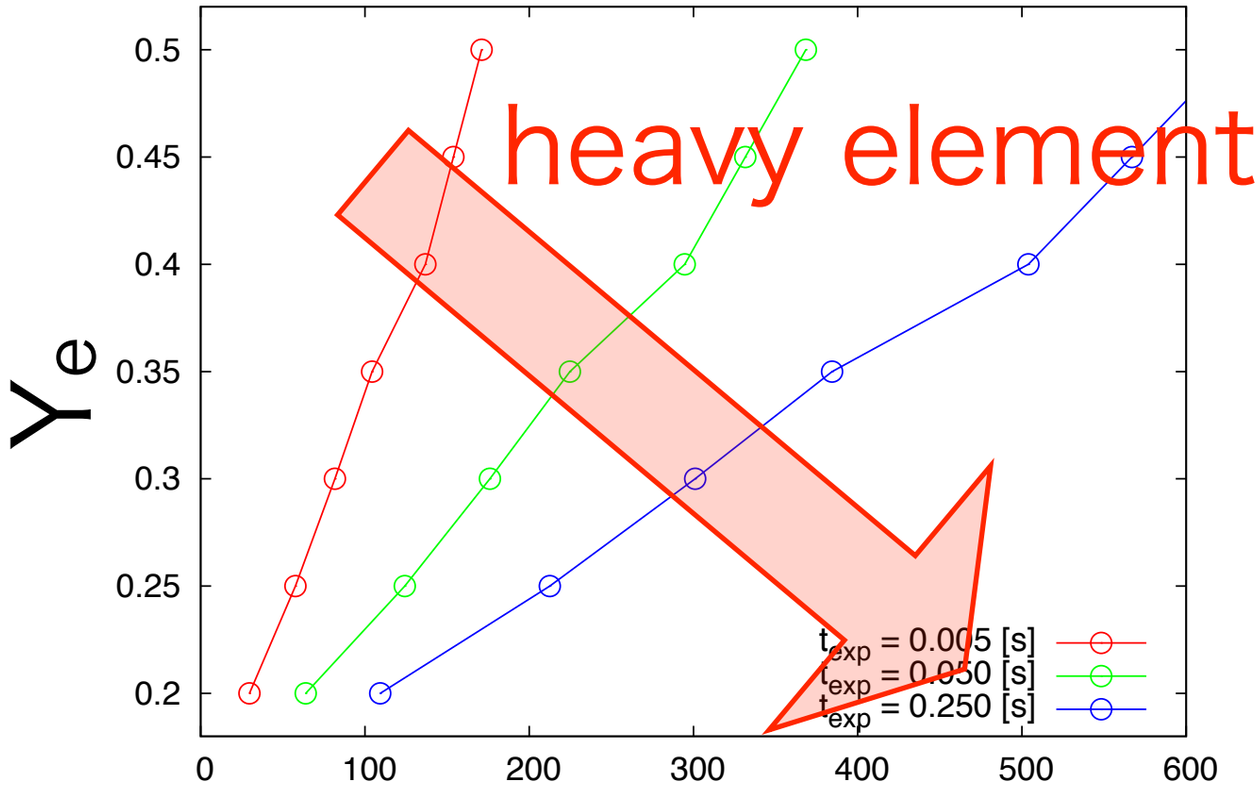
③ rapid-n cap.
(high n/Seed)
(n, γ) is faster
than β-decay

④ decay (β and fission)
decay to stable isotopes

low T and ρ

Physical condition for r-process

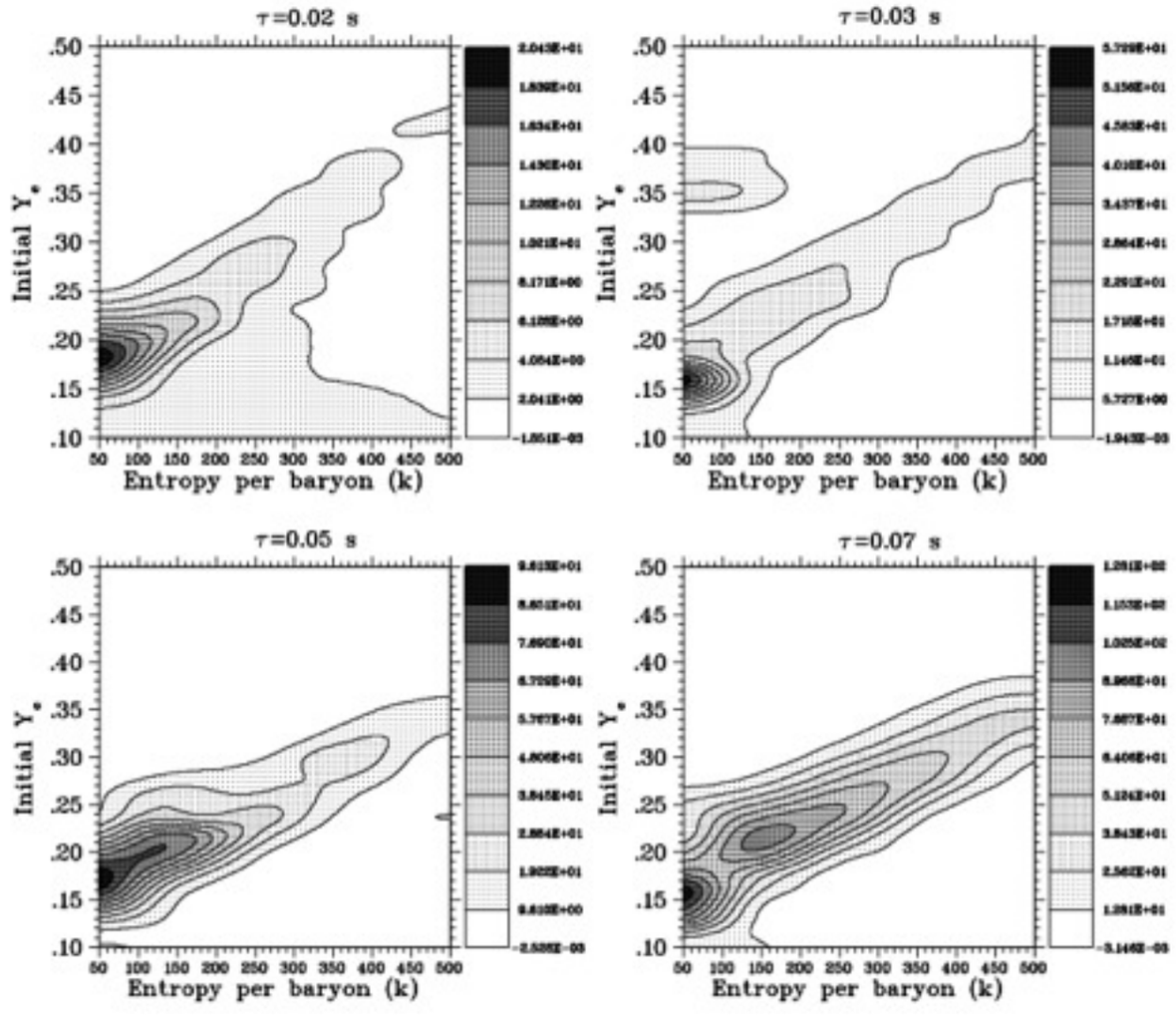
condition for r-process 3rd peak



entropy

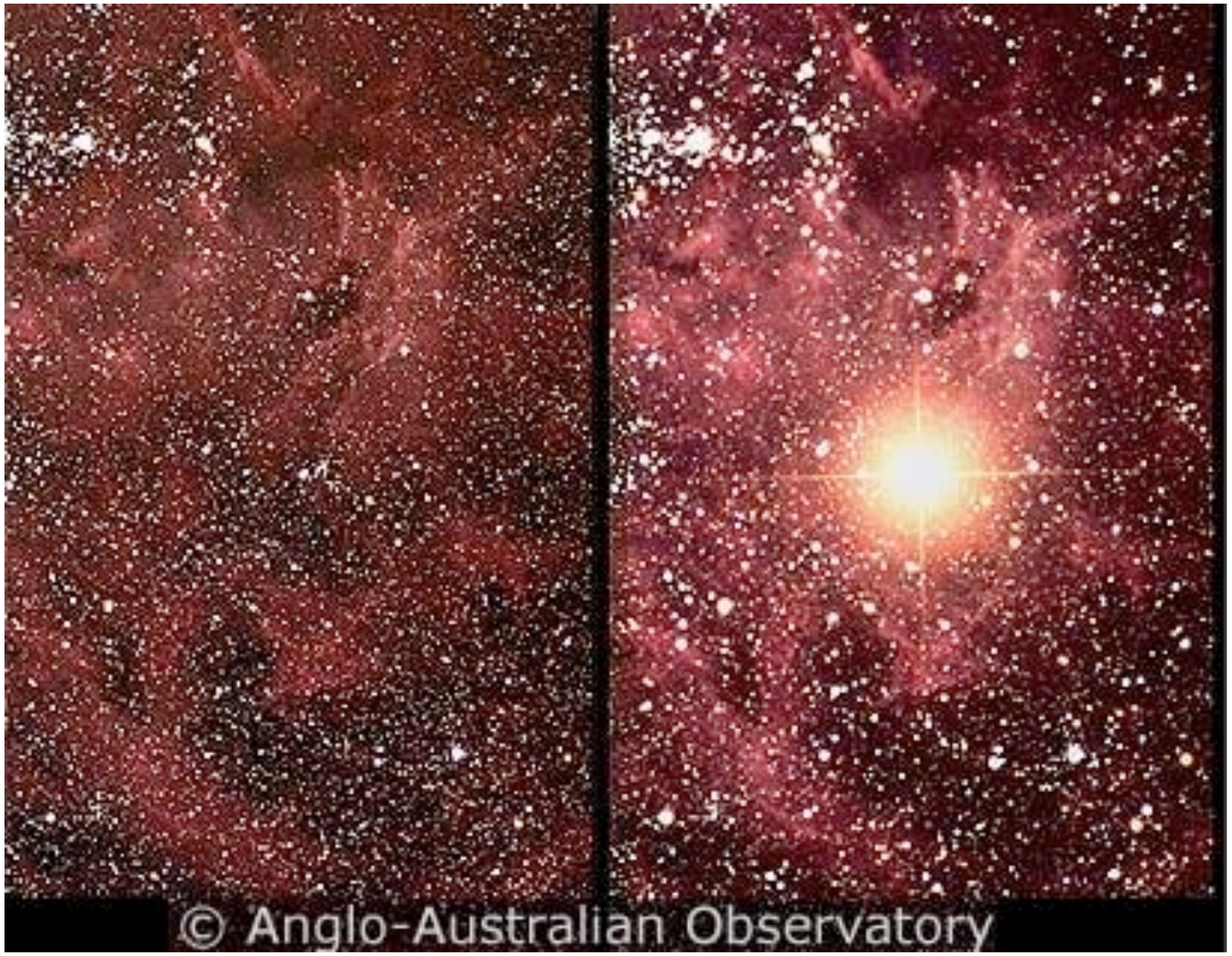
based on Hoffman et al. (1997)

Meyer 1997



Core-Collapse Supernovae: > 10 $M_\odot$

SN1987A



observations

- optical
- neutrino
- cosmic ray
- GW ?
- nucleosynthesis

the formation process of compact object
(neutron stars, and black holes, etc.)

Core-Collapse Supernovae: > 10 $M_\odot$

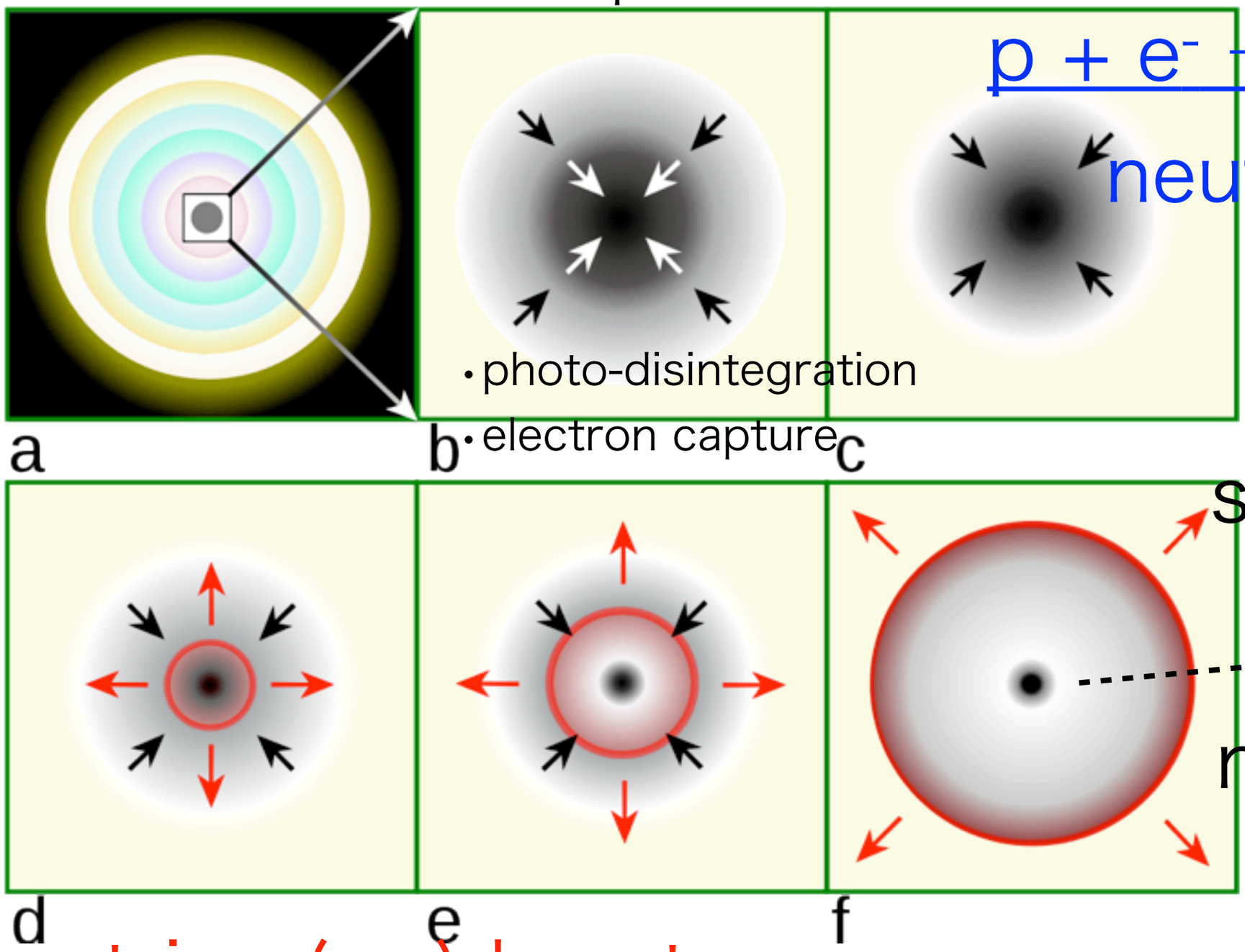
the end of the evolution

the core collapses

a proto-neutron star is formed

$p + e^- \rightarrow n + \nu_e$

neutronization



shock

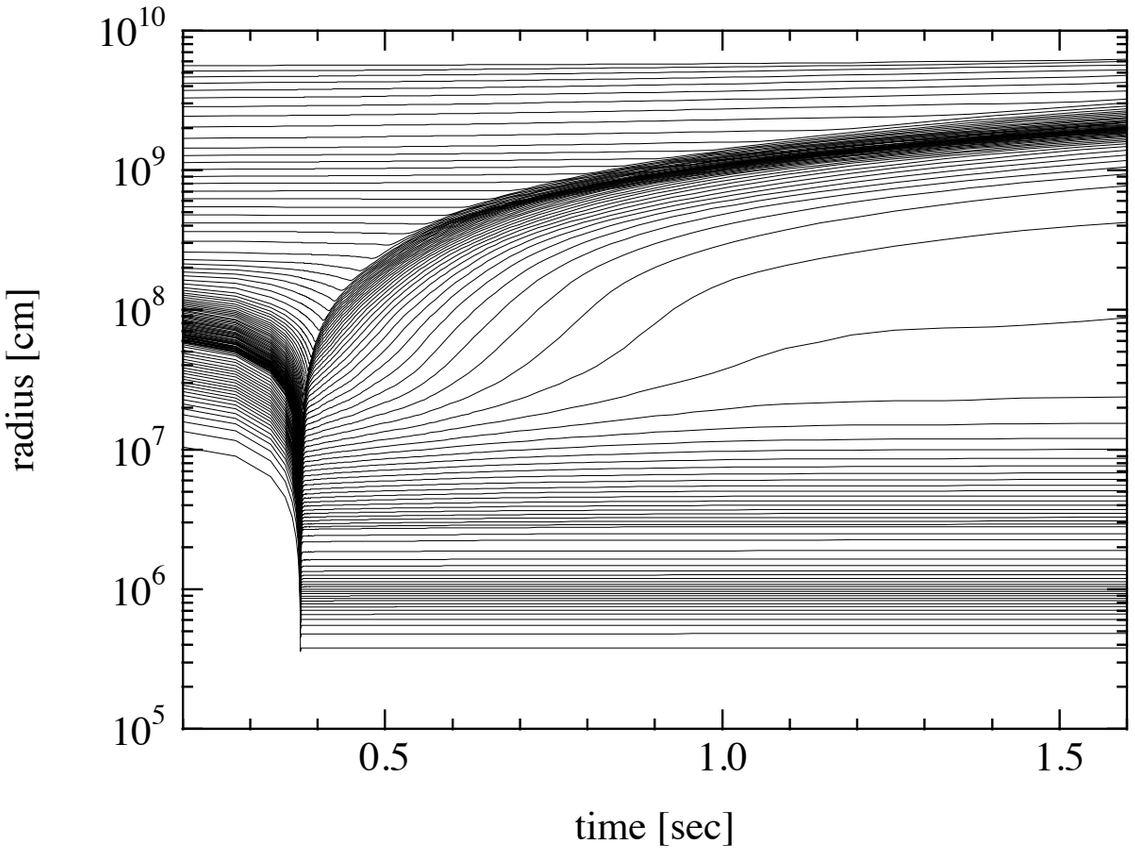
---------- proto-neutron star

neutrino (ν_e)-burst

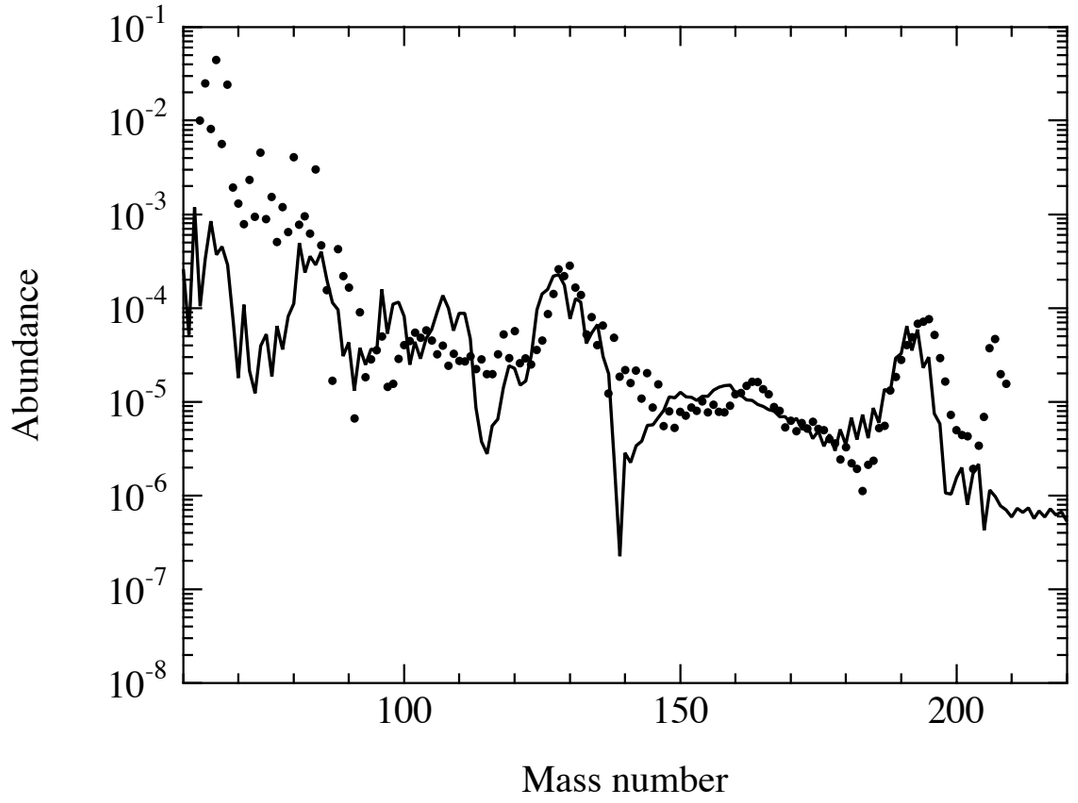
figure: wikipedia

Core-collapse SNe

prompt explosion scenario



Sumiyoshi et al. 2001



problem of this scenario

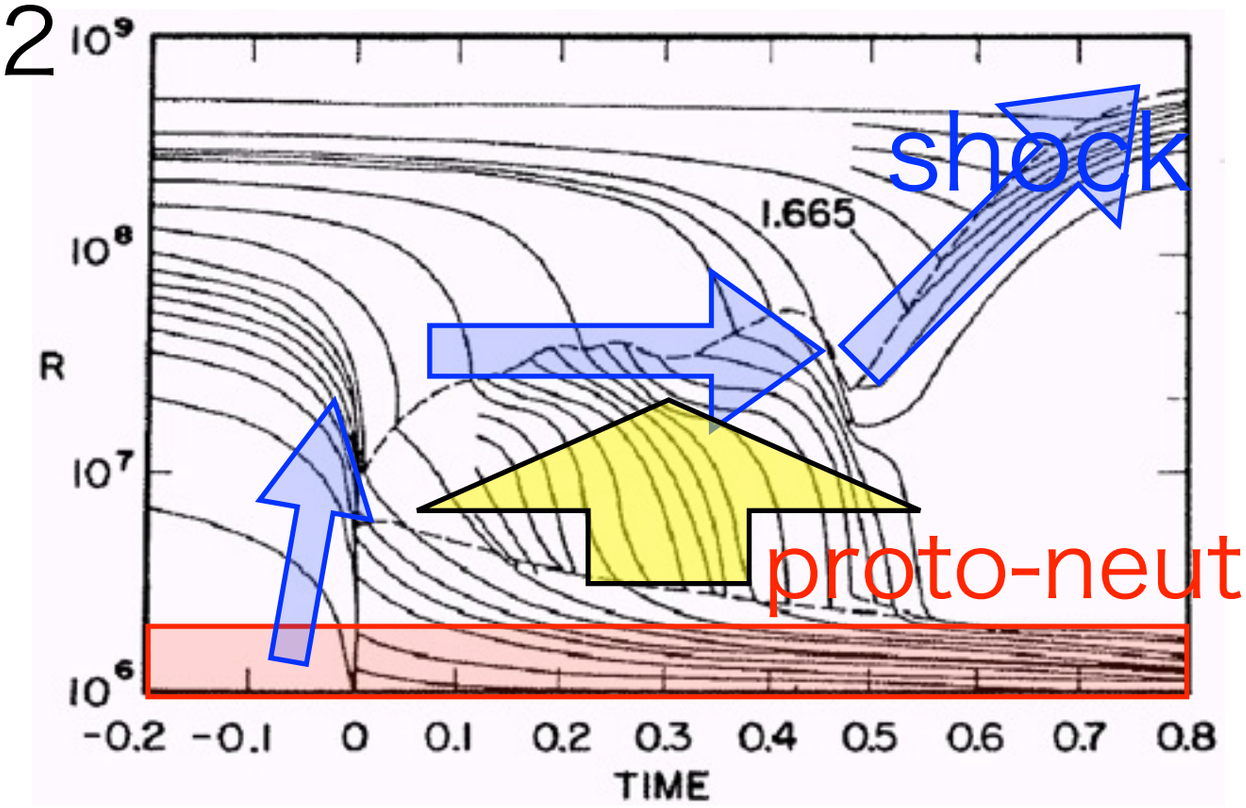
- too much ejection of r-element mass ($\sim 10^{-3}\ M_\odot$)
- ignores neutrino absorption ($\nu_e + n \rightarrow e^- + p$)
  - both of explosion dynamics and Y_e
- was completely ruled out explosion scenario

Core-collapse SNe

delayed (neutrino heating) explosion scenario

Wilson 1982

the stalled shock
is revived by
neutrino heating
(n + ν_e → p + e^-)



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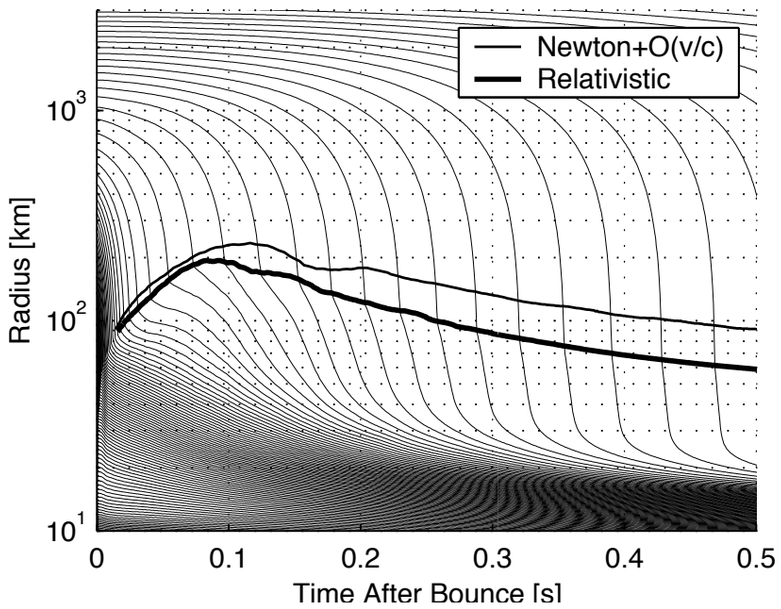


Liebendörfer 2000

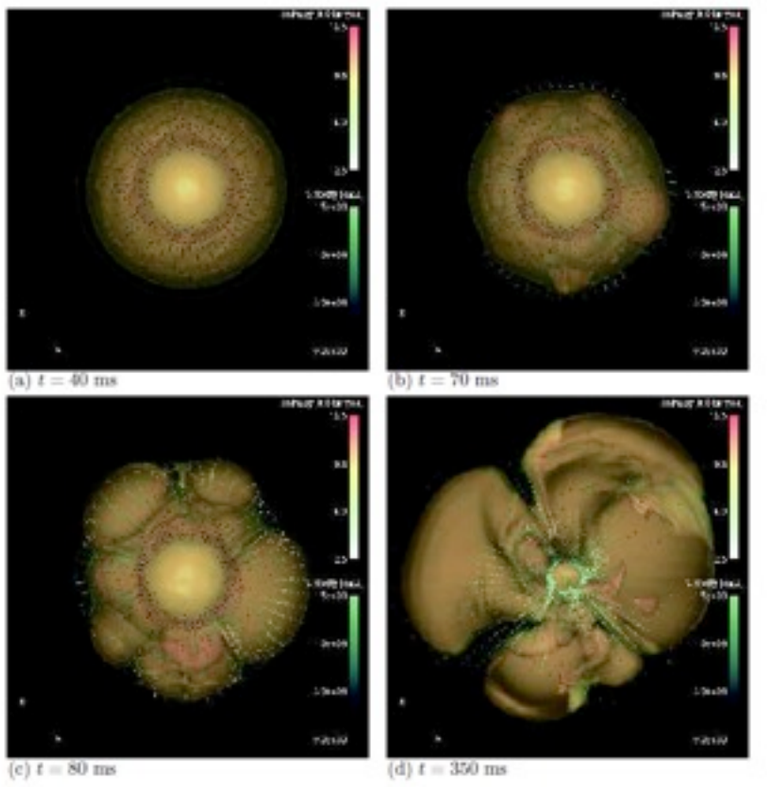
State of the art simulation (EOS, GR hydro, neutrino transport, etc.) have shown no successful explosion in spherical symmetry simulation

→ needs multi-dimension

Core-collapse SNe

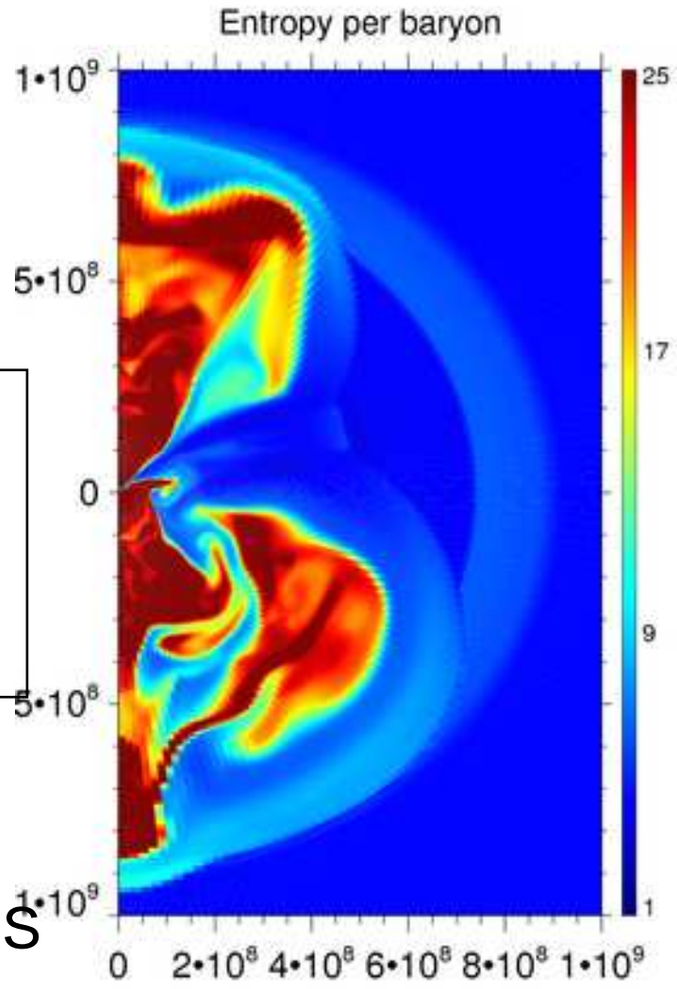
neutrino heating rates are enhanced by SASI (Standing Accretion shock instability)

Iwakami et al. 2008

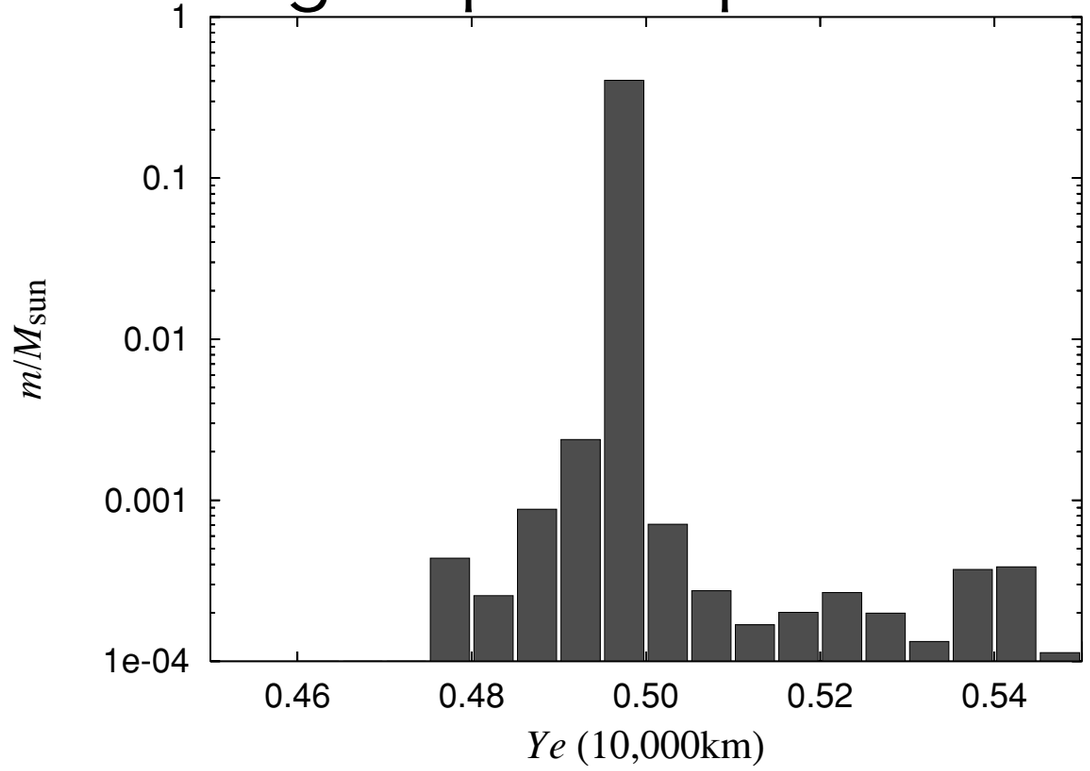


3D simulation

nucleosynthesis study (2D hydro. simulations) (Fujimoto et al. 2011)



explosive nucleosynthesis mainly produce iron group isotopes

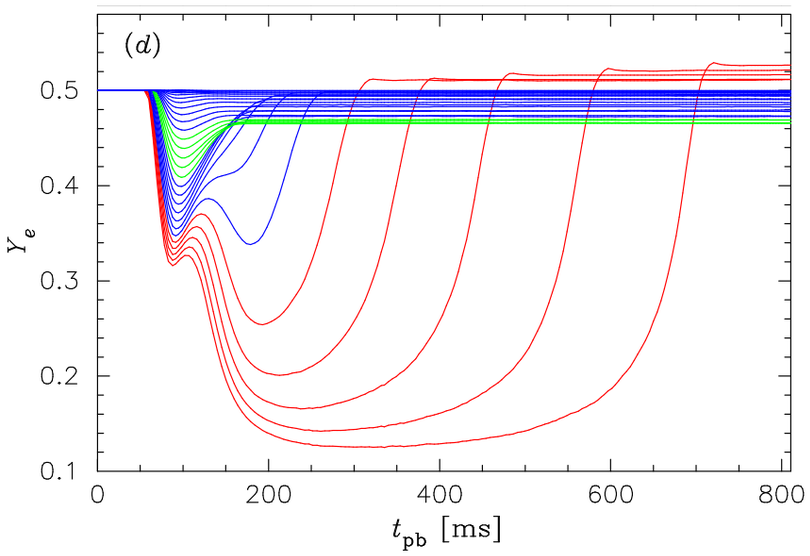


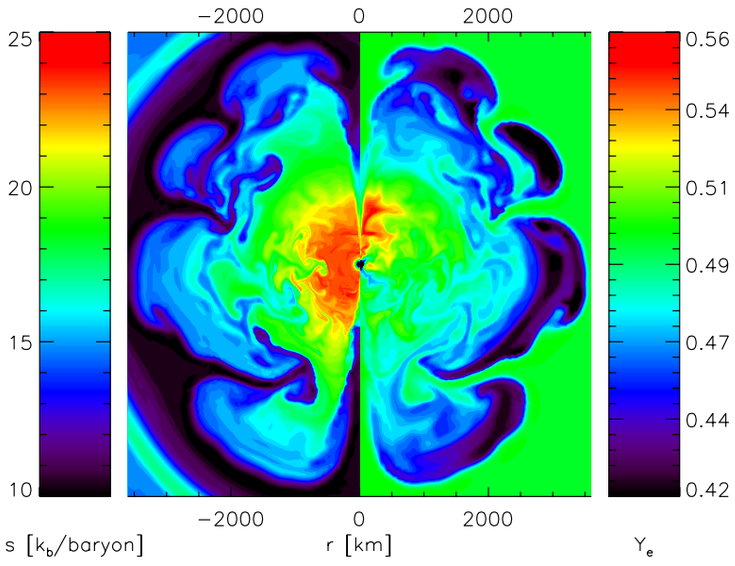
Core-collapse SNe: AGB/ONeMg supernova

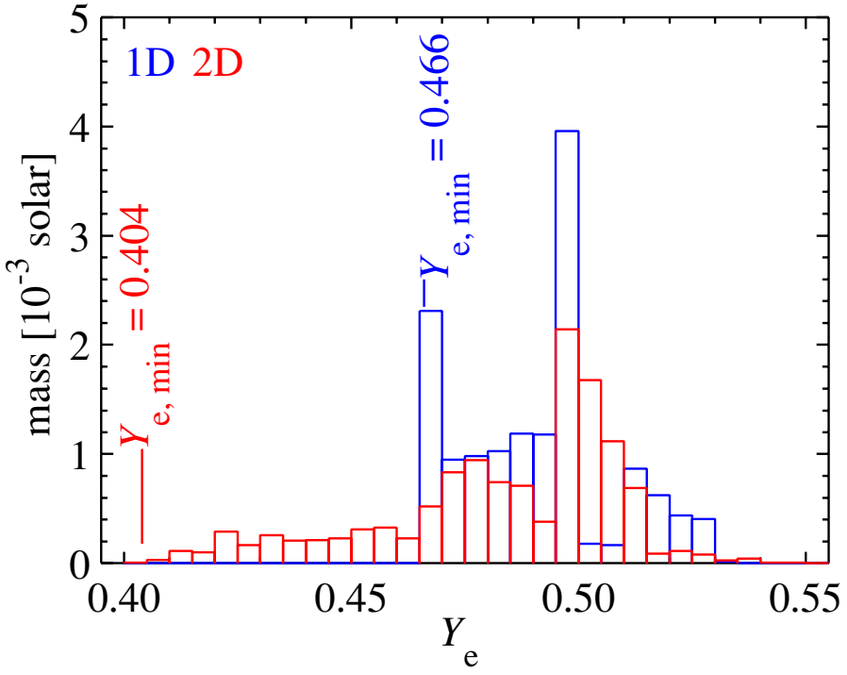
successful explosion models (both 1D and 2D)

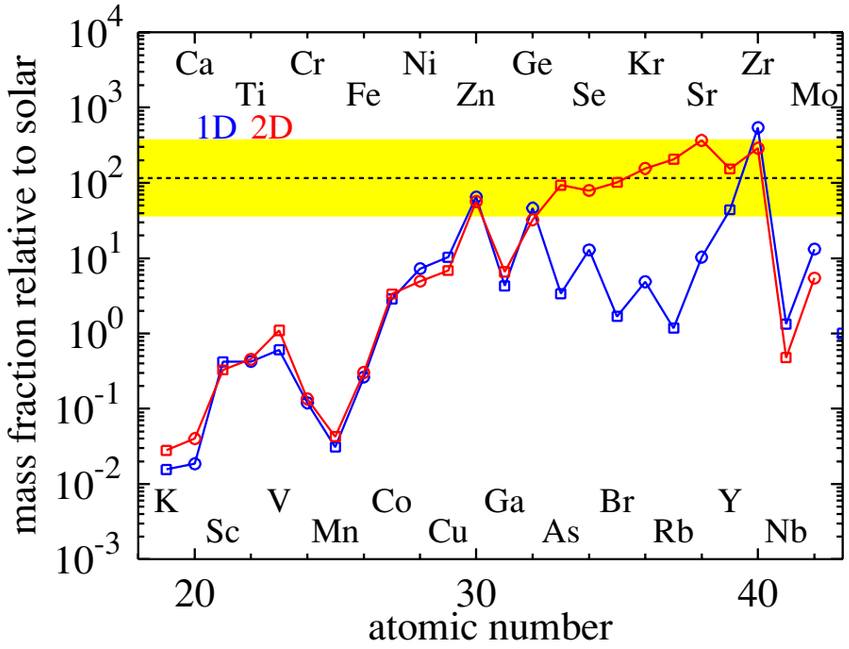
$Y_e > 0.4$ (2D model); weak r-process

(Wanajo 2009, 2011)









Neutrino Driven Wind

relativistic winds from the hot (newly born)

proto- neutron star accompanying CC-SNe

some extremely case

(parameters) reproduce

solar system r-process elements

physical condition

- entropy S > 100
- Ye ～ 0.4

Otsuki et al. 2001

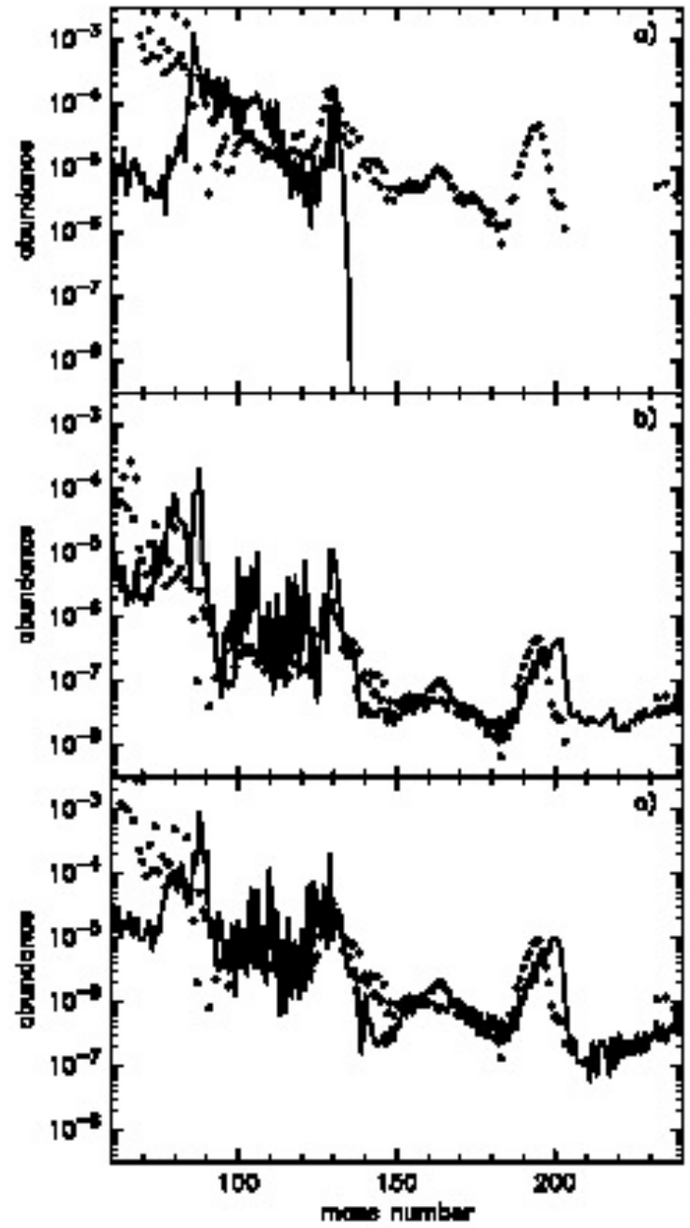
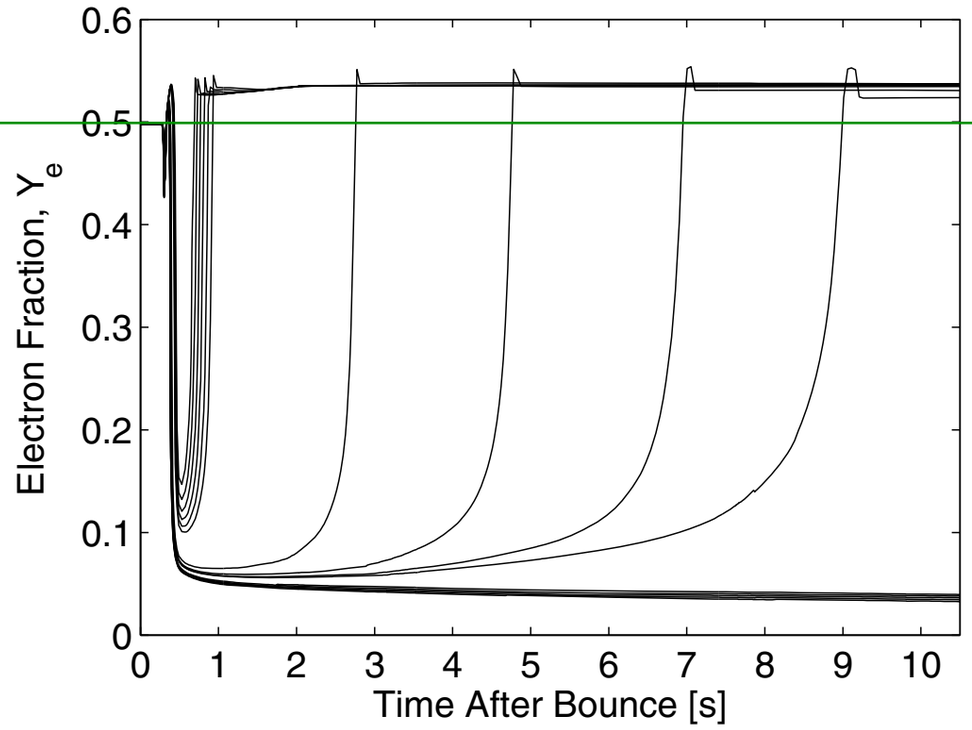


FIG. 4.—Mass-weighted integrated yields for models (*a*) A, (*b*) B, and (*c*) C as functions of mass number (*lines*). Also denoted are the scaled solar *r*-abundances (*filled circles*).

Newtrino Driven Wind

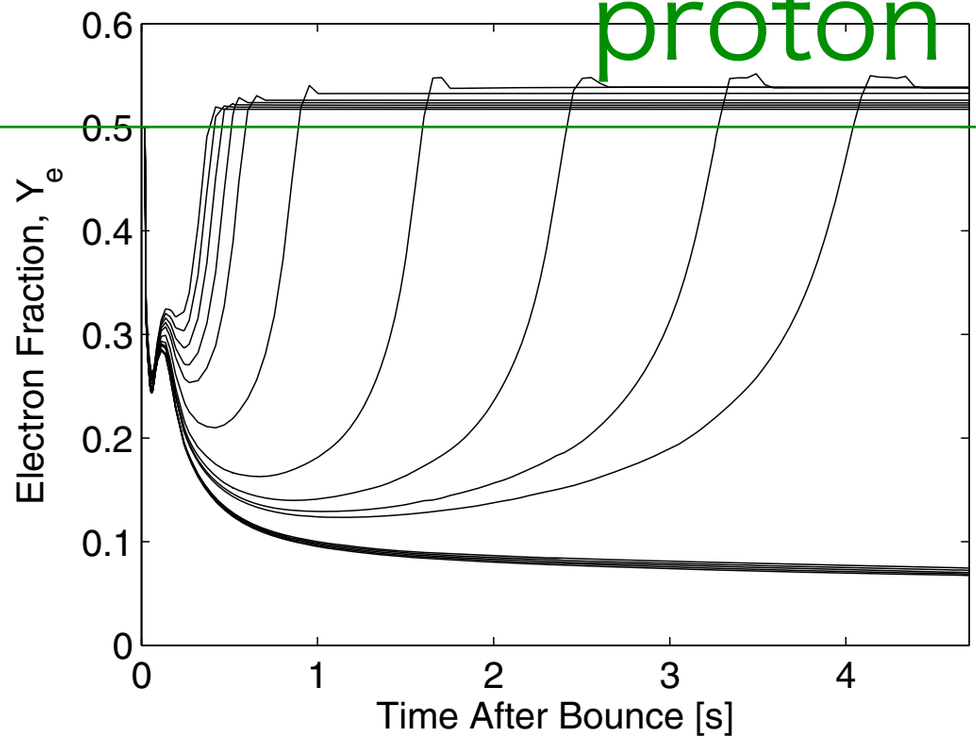
self-consistent simulation of NDW based on
state of the art hydrodynamic simulation
(in 1D: spherical symmetry) (Fischer et al. 2010)

progenitor: 10.8 $M_\odot$



progenitor: 8.8 $M_\odot$

proton rich



$$e^- + p \rightleftharpoons n + \nu_e,$$

$$e^+ + n \rightleftharpoons p + \bar{\nu}_e,$$

$$e^- + \langle A, Z \rangle \rightleftharpoons \langle A, Z-1 \rangle + \nu_e,$$

NDW's are proton-rich
rather than neutron-rich

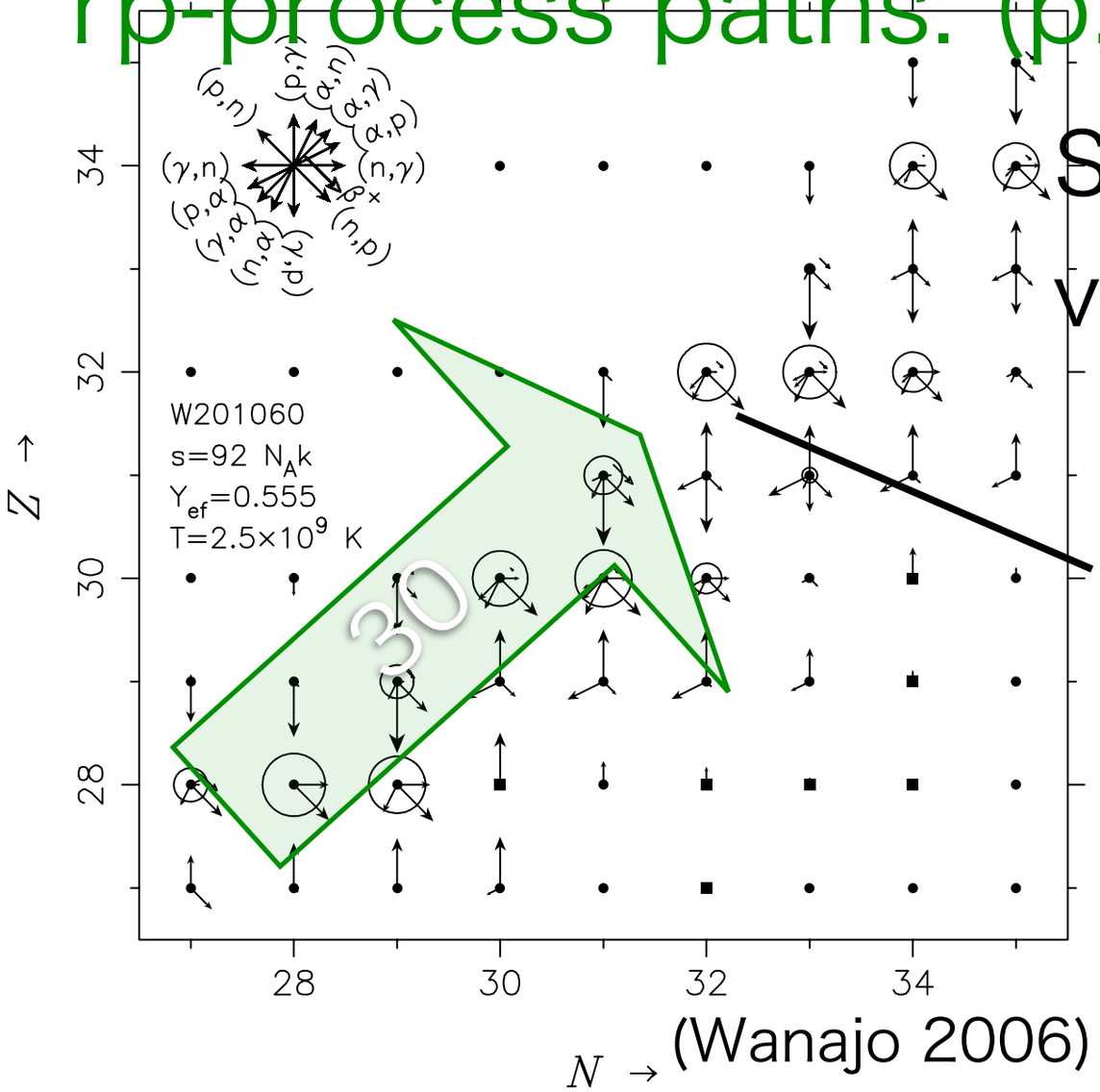
"ν p-process" (neutrino induced rp-process)

explosive proton-rich environment:

similar to "classical" rp-process condition

(X-ray Burster: H fall on to binary NS surface)

rp-process paths: (p, γ) and β^+-decay



(Wanajo 2006)

SNe environment:

very short time scale ~ 1 s

^{64}Ge (Z=N=32)

τ_{β} ~ 1 min.

⇒ the flow is suspended

“ν p-process” (neutrino induced rp-process)

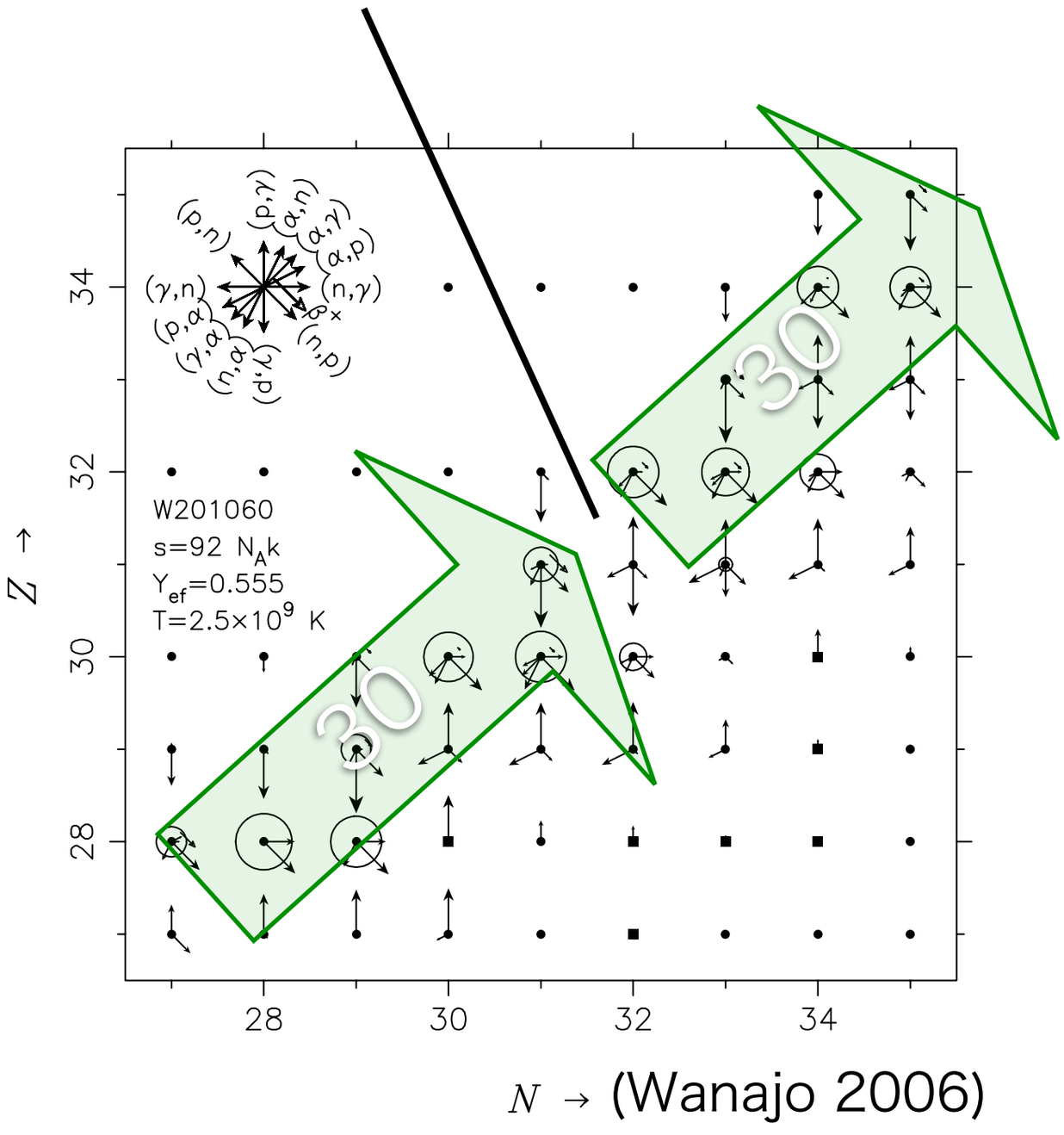
neutrino reactions

open new bypasses

$$\nu_e + n \rightarrow p + e^-$$

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

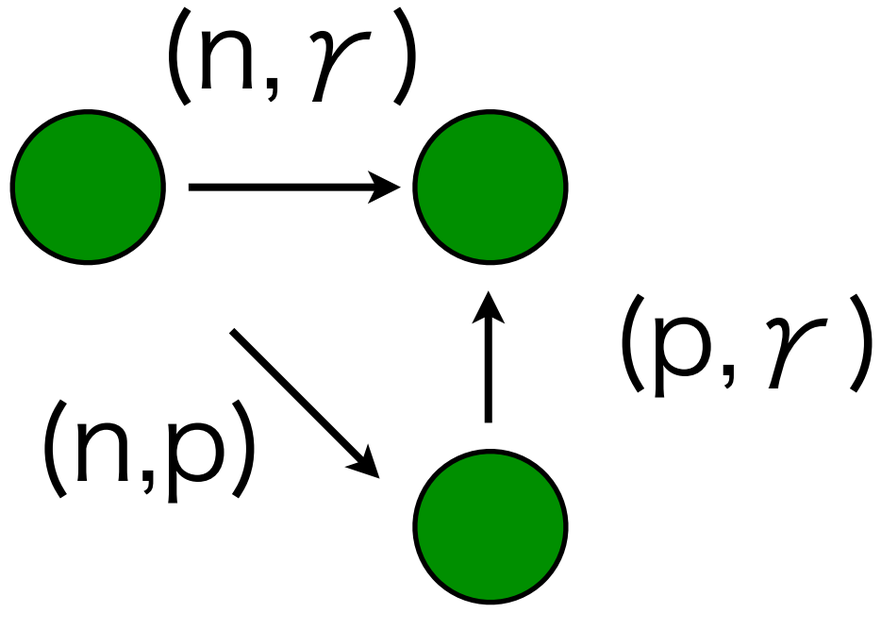
neutron source



(Wanajo 2006)

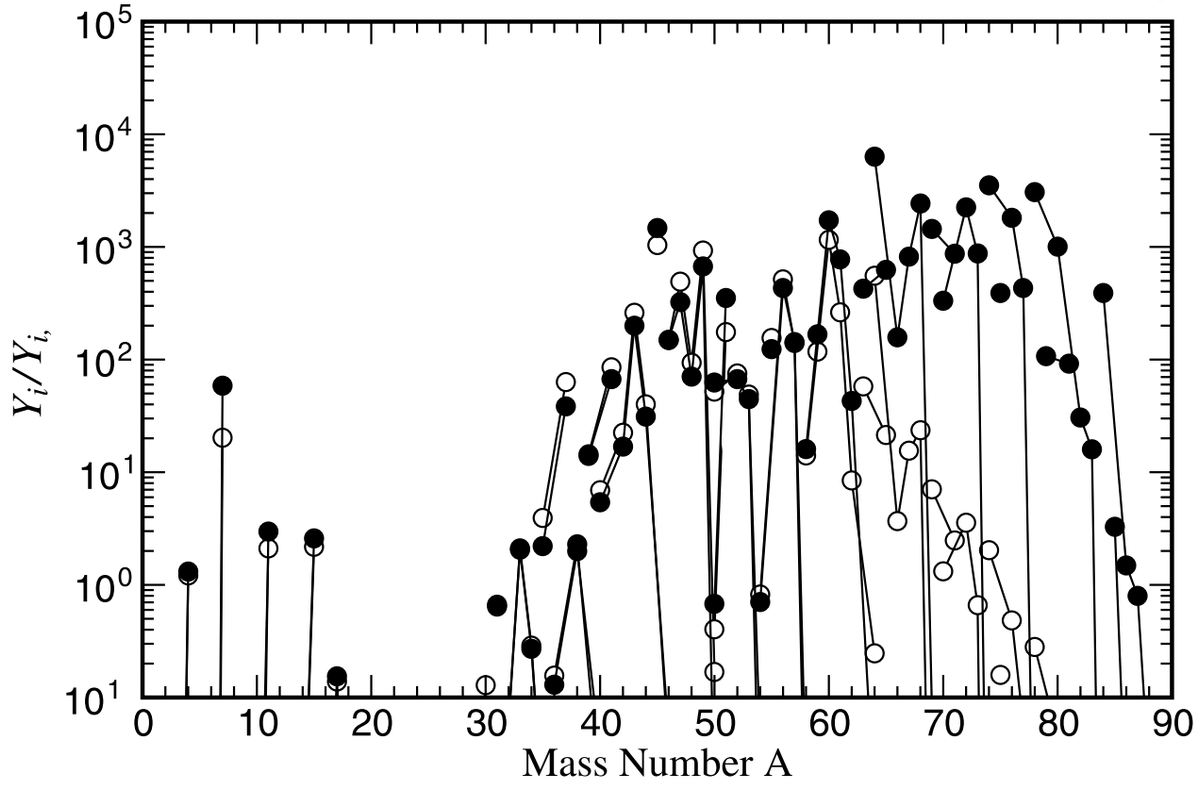
$$(Z, N) + n \rightarrow (Z-1, N+1) + p$$

$$(Z, N) + n \rightarrow (Z, N+1) + \gamma$$



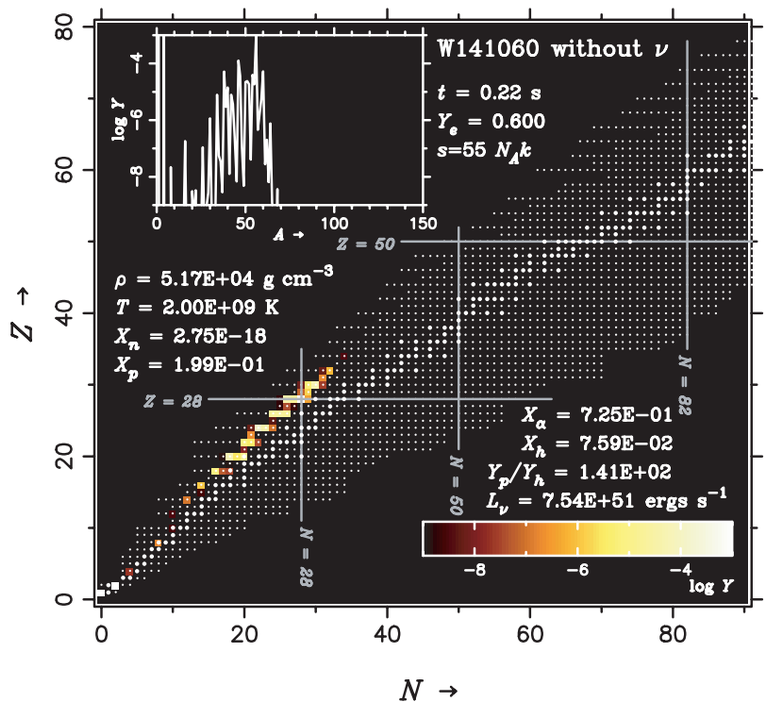
“ν p-process” (neutrino induced rp-process)

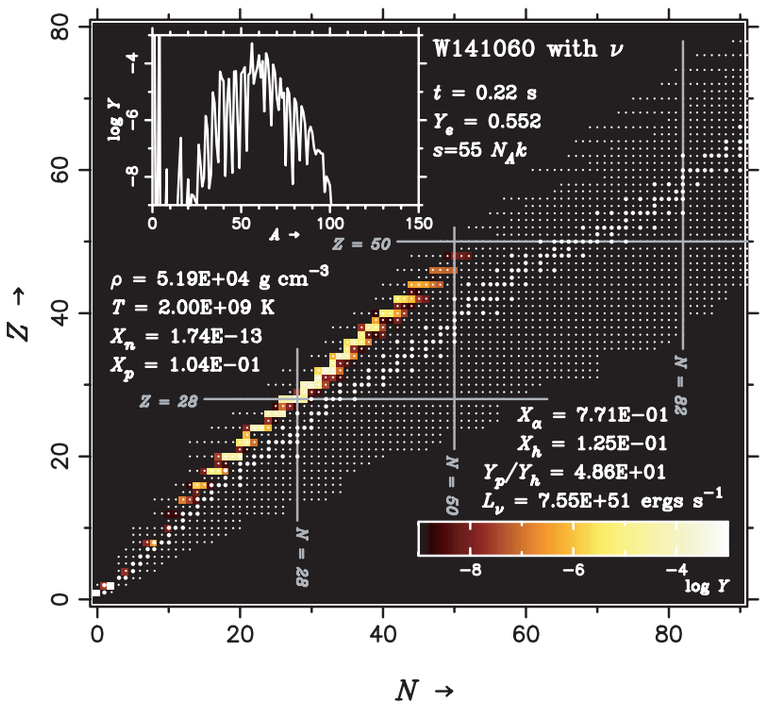
Fröhlich et al. PRL 2006 (proton-rich ejecta)



neutrino captures enhance the production of heavier elements

Wanajo 2006 (NDW)

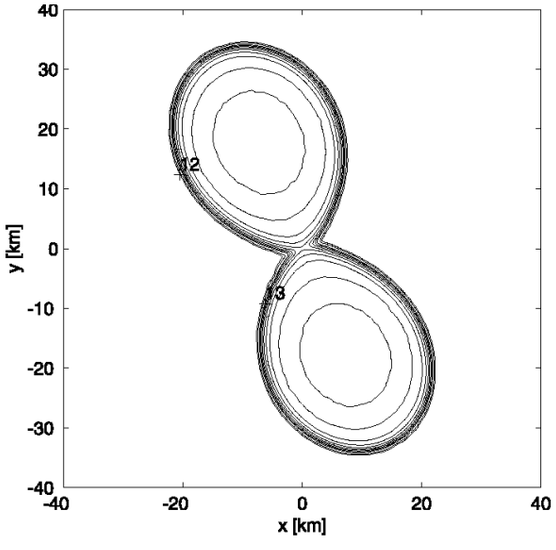


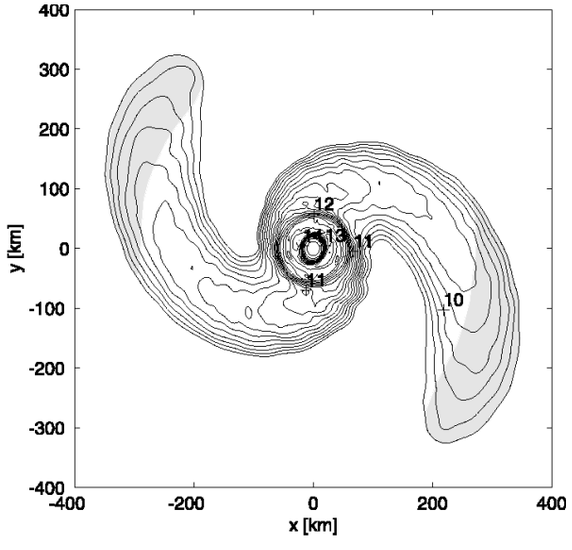


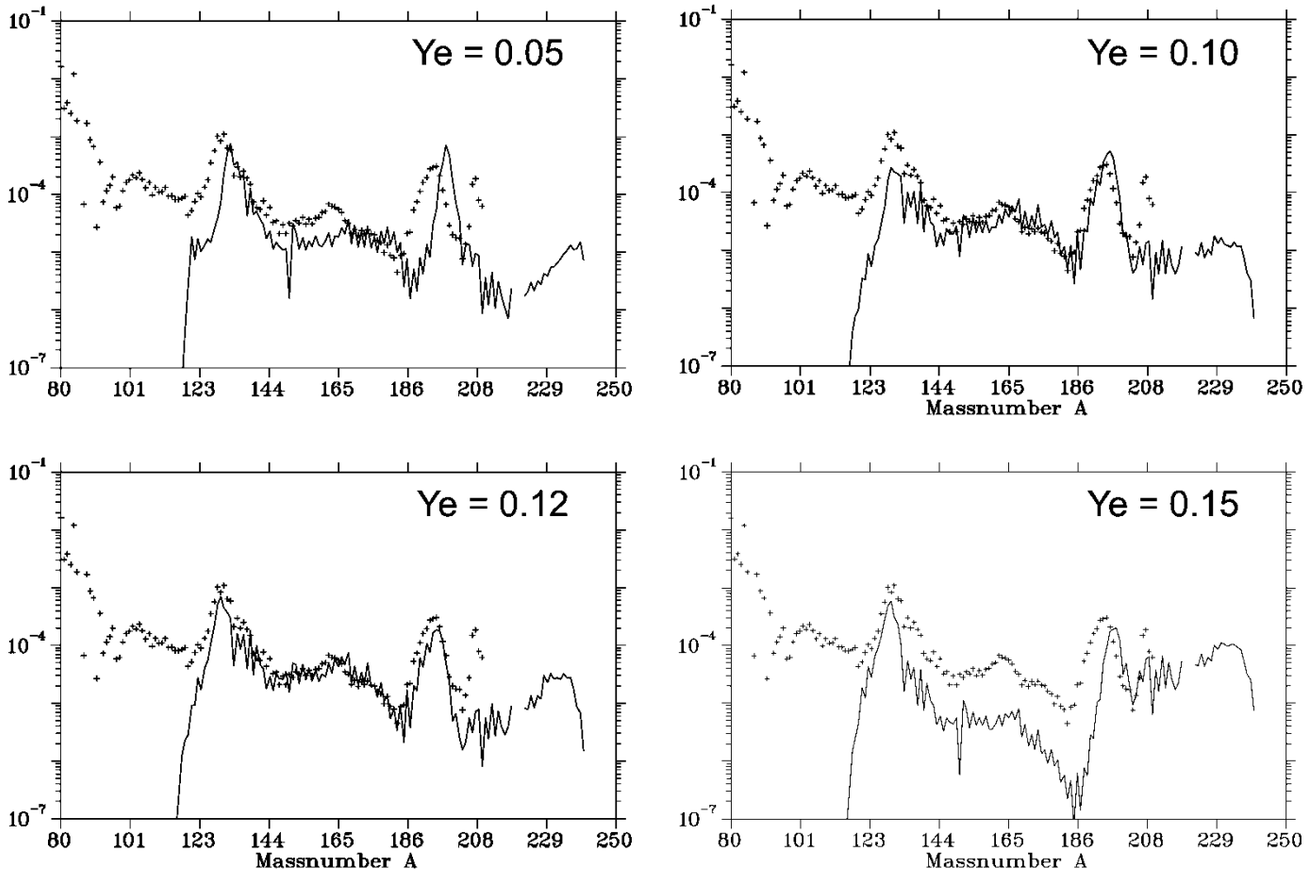
Compact star binary mergers

- quantitative understandings are very uncertain
  (more challenging than CC-SNe?)
- some hydrodynamic simulations
  - pioneer work (by Basel Group)
  - problem: too strong r-process?

Freiburghaus et al. 1999

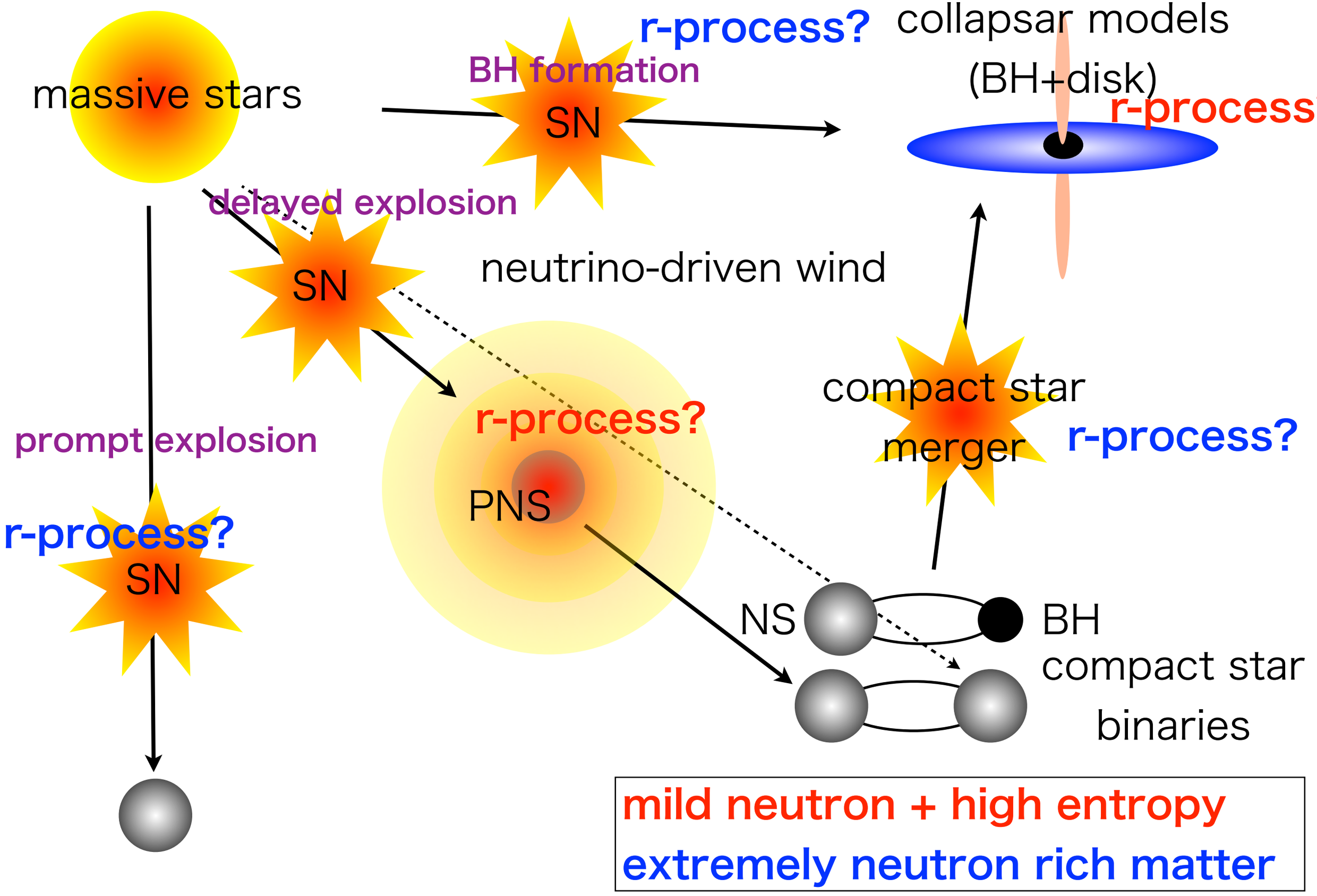






and recent works by Goriely (2012) and Rosswog (2012)

Where are the astronomical sites?



mild neutron + high entropy

extremely neutron rich matter

Where are the astronomical sites?

- Core-Collapse Supernovae
  - prompt : impossible to explode stars
  - normal SNe: mainly $Y_e \sim 0.5$
  - lighter SNe (ONeMg core): very “weak”
- Neutrino Driven Wind
  - proton-rich
    - different process (ν p-process)

- Compact Star Mergers
  - too strong?

Core-Collapse Supernovae themselves are no more the r-process site?

extra-scenarios are still possible

- MHD Jet supernova (Strong Mag. fields)
  → Magnetars
- quark-hadron phase transition
  → Quark/Hybrid Stars

both are explosion mechanisms
avoiding neutrino heating (= destroy neutrons)

Observational aspects

- single/multiple astrophysical site(s)?
- single/multiple process(es)?

→ open question!

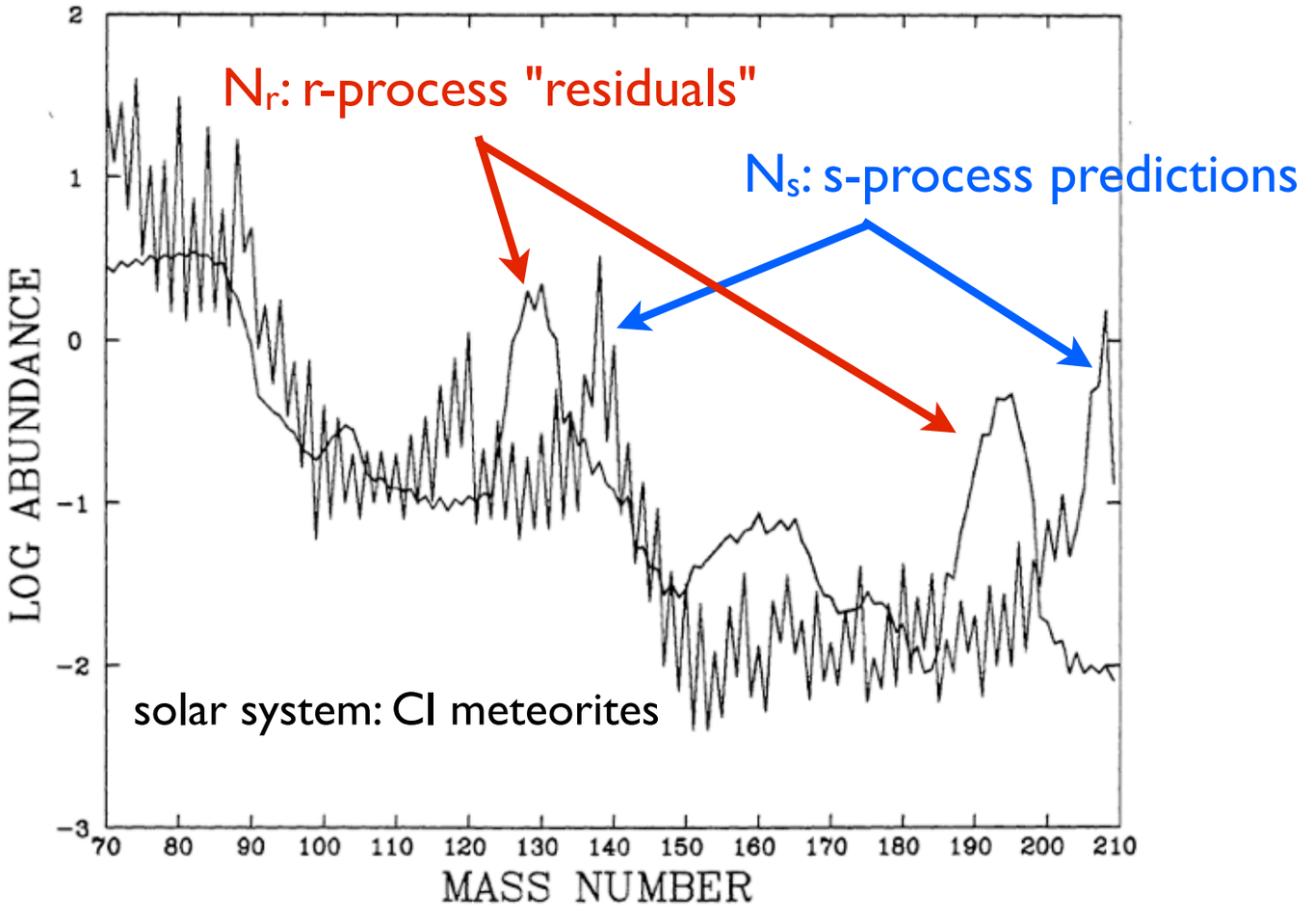
Solar “r-elements”

$$N_r = N_{total} - N_s$$

note: p-elements

- rare (1% of neutron-rich)
- exist proton rich side

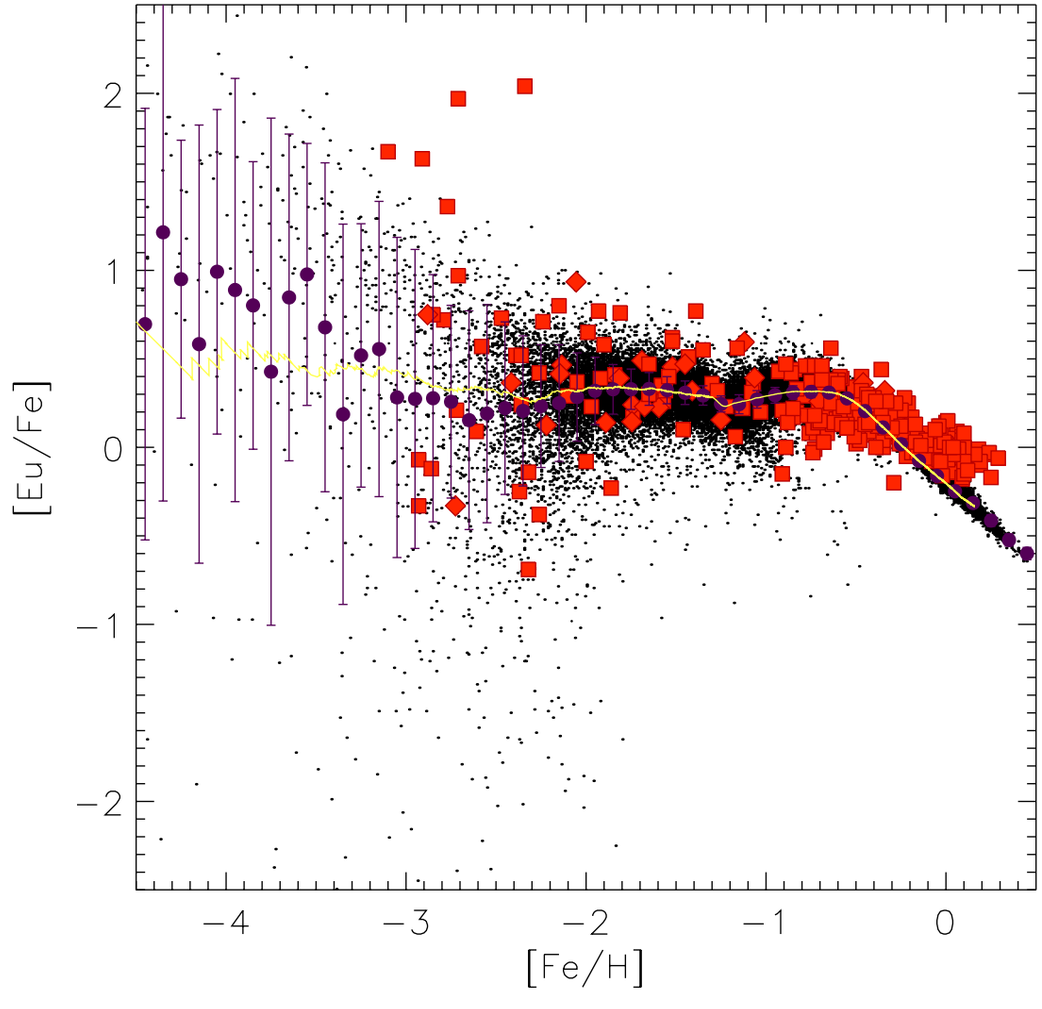
→ easily distinguish

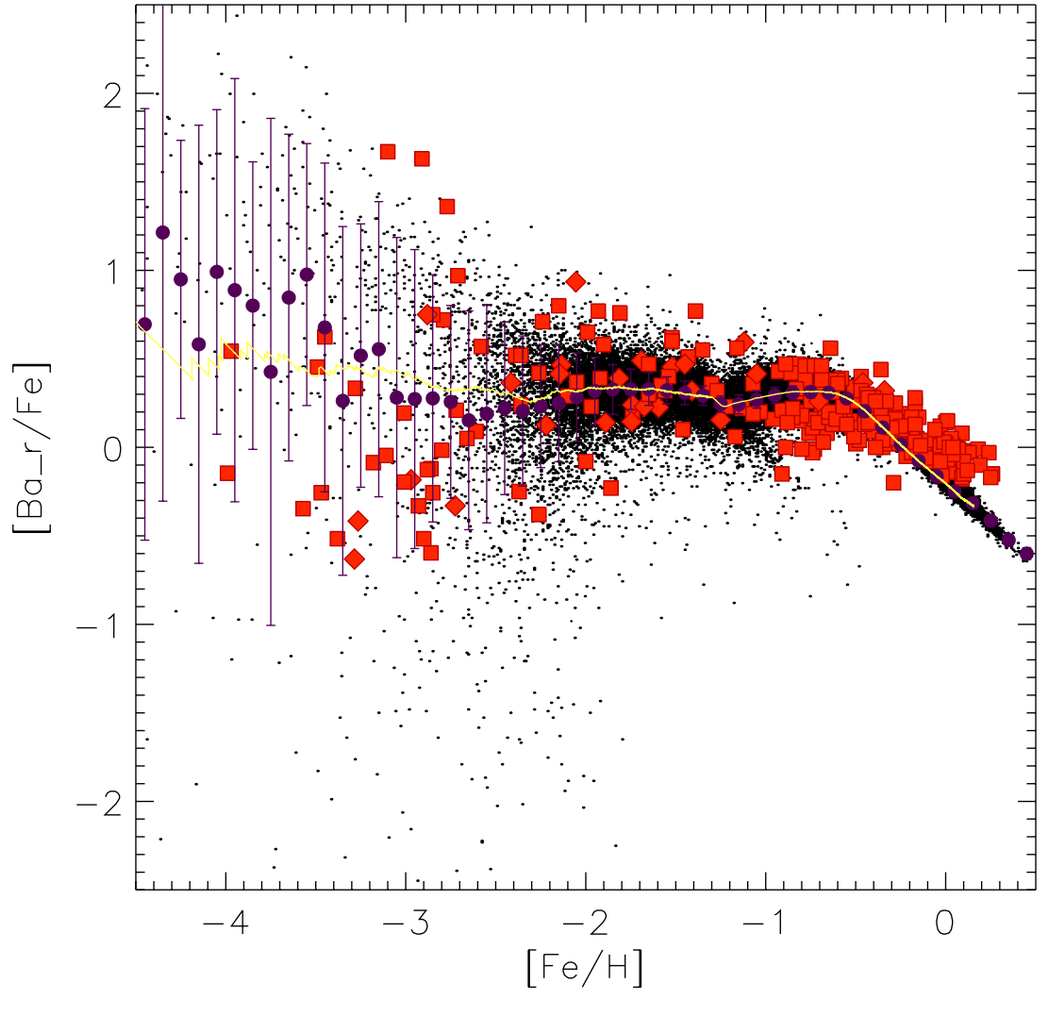


Observational aspects

- Magnetars : 1 % of all neutron stars
- Quark/Hybrid stars : very unknown

dispersion of Eu in metal poor stars
suggests multiple r-process sites?　Argast et al. (2004)

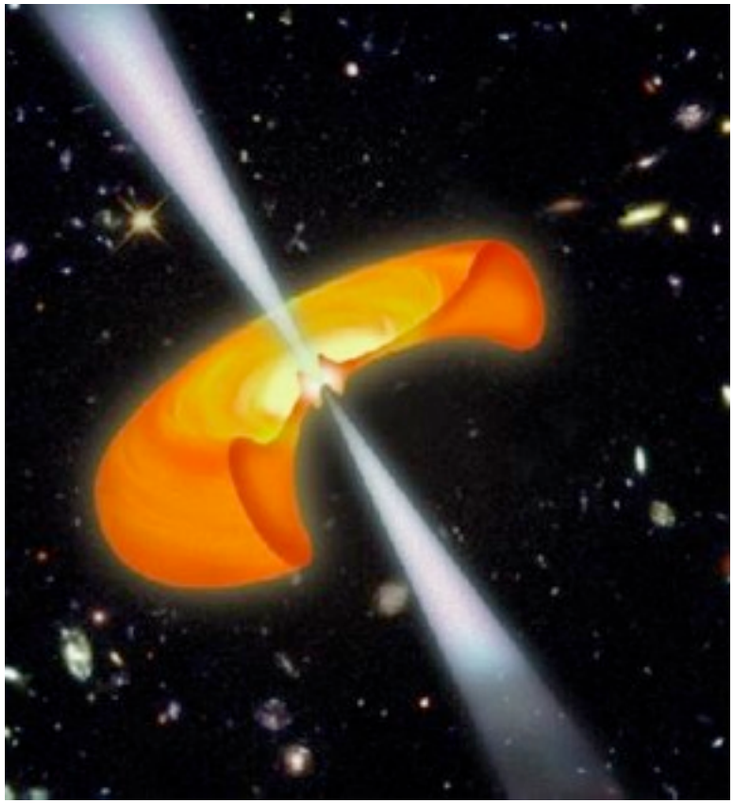




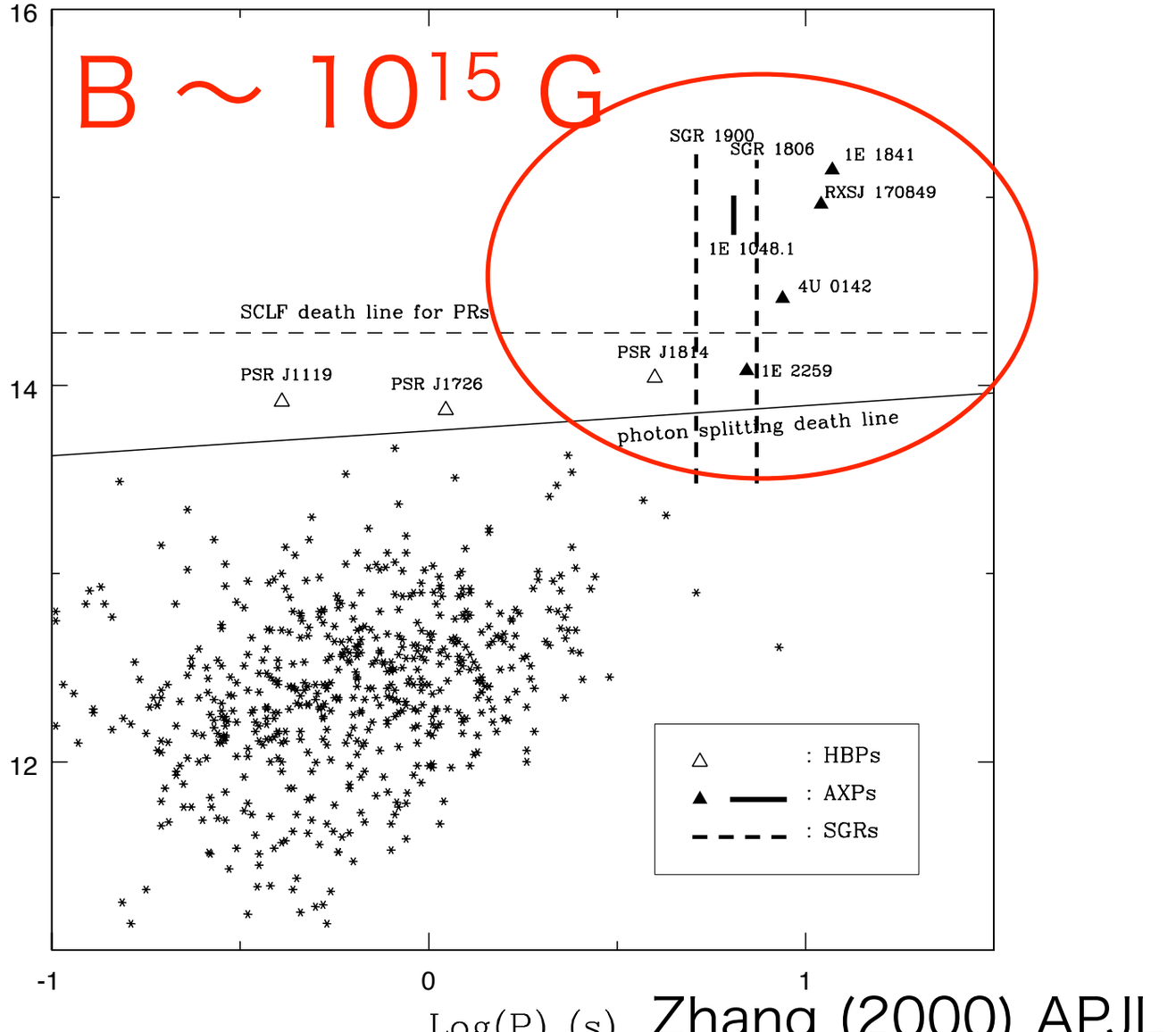
MHD Supernovae

Jet-like Supernova explosions

- neutron stars have strong magnetic fields
  - neutron stars (pulsars) : ～ 10^{12} G
  - magnetar : ～ 10^{15} G (～ 1 % of the neutron stars)
- Jet-like Explosions
  - GRB central engine
  - Hypernovae



jet/hypernova image (NASA)

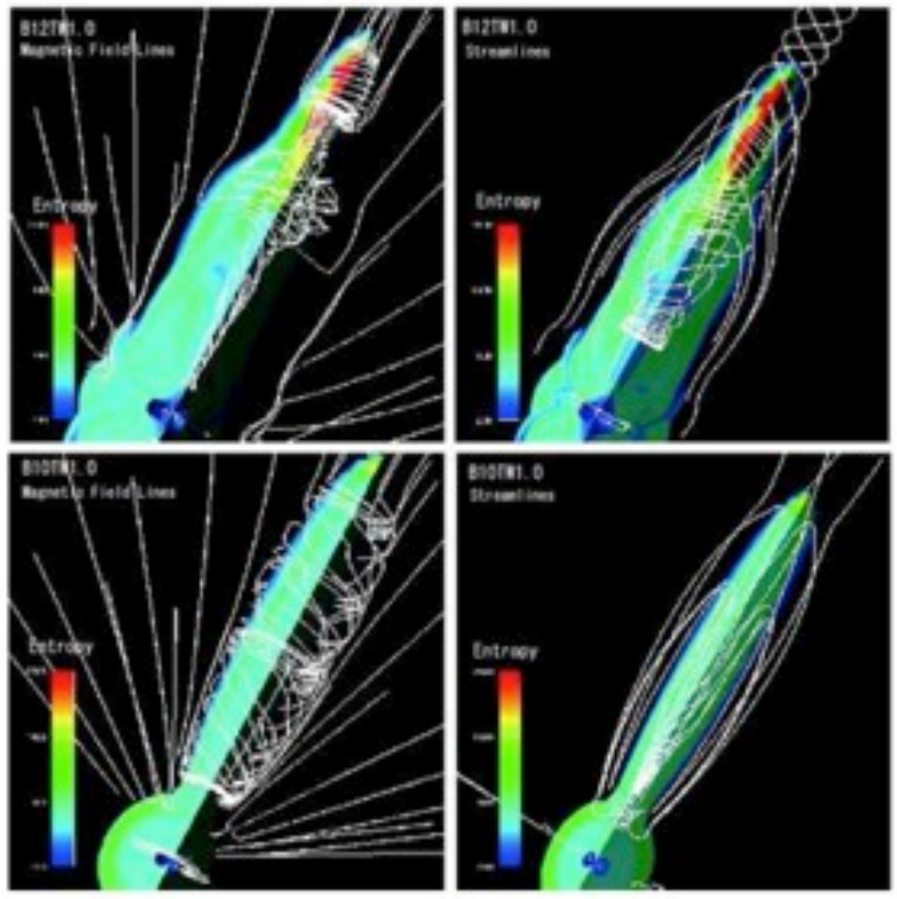


Zhang (2000) APJL

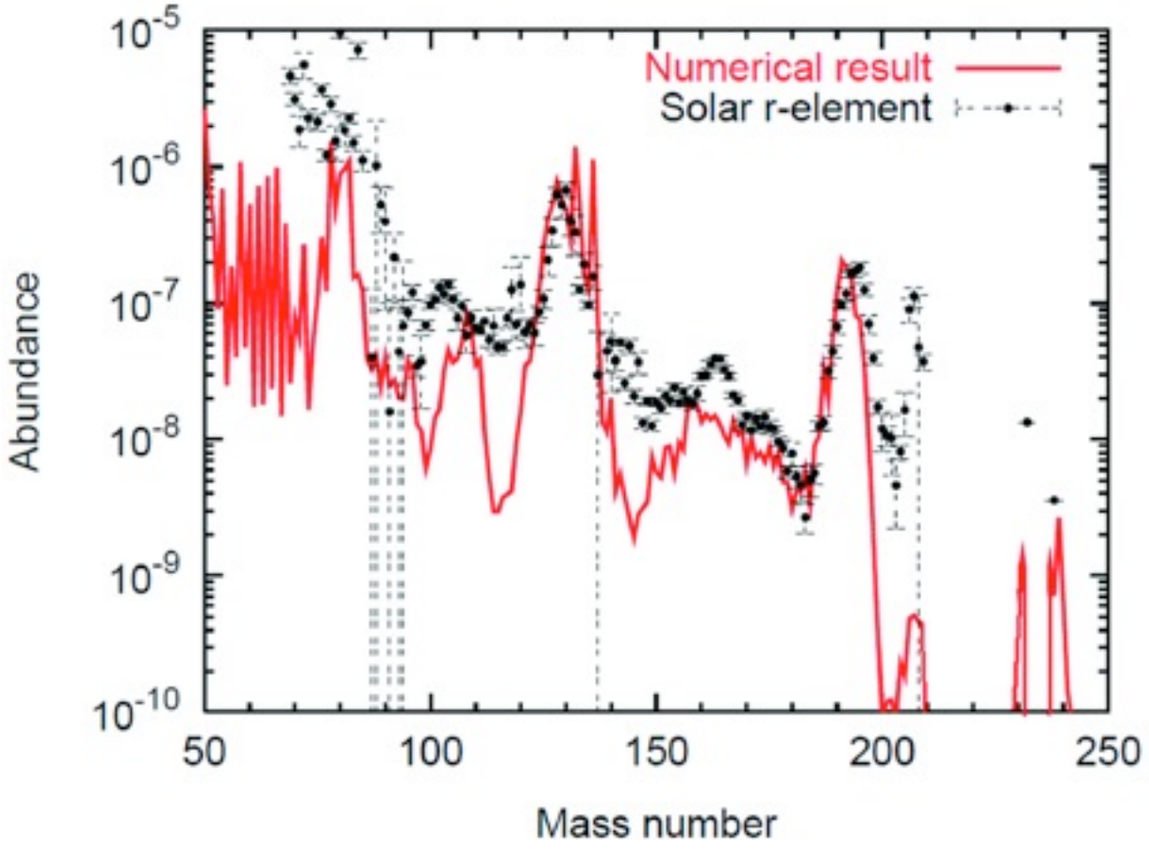
MHD “Jet” supernova explosion :

- 2D Newtonian without neutrino
  - MHD-SN: Nishimura et al. 2006
  - “Collapsar model” (BH + disk): Fujimoto et al. (2007, 2008)
- 2D Relativity and neutrino cooling:
  - explosion model: Takiwaki et al. 2009
  - nucleosynthesis: Nishimura et al. (2010, 2012 prep)

Takiwaki 2009



Nishimura 2010



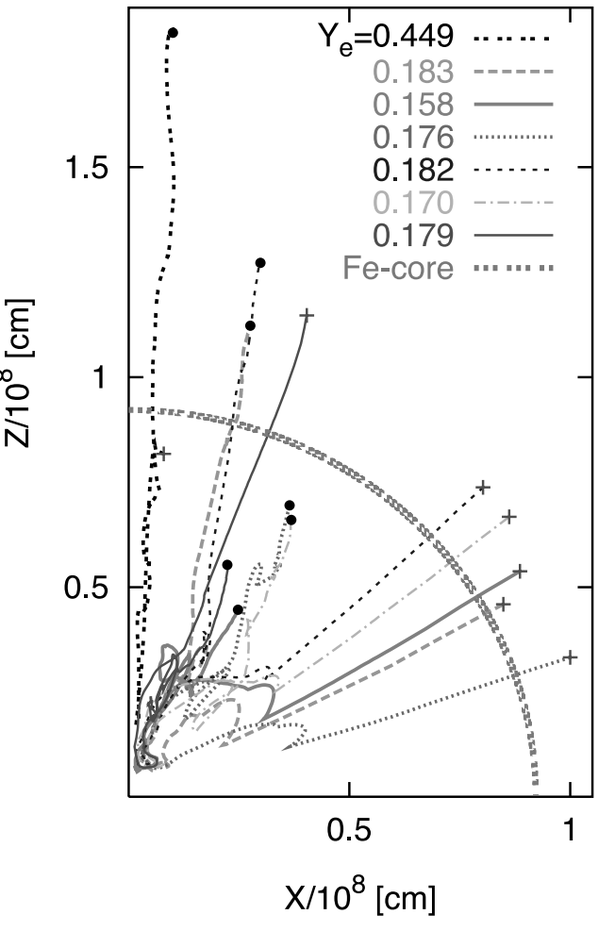
Nucleosynthesis simulation

- (general) nuclear reaction network
  - Post processing based on T, ρ and neutrino by SN model
  - full Nuclear Reaction Network
    (details in Nishimura et al. 2011, 2012)
  - more than 4000 isotopes
    - related reactions (REACLIB)
    - experimental data (REACLIB, NACRE, ...)
    - theoretical rates
      - basically FRDM (P. Möller)
  - + weak interaction (FFN + LMP reaction rates)

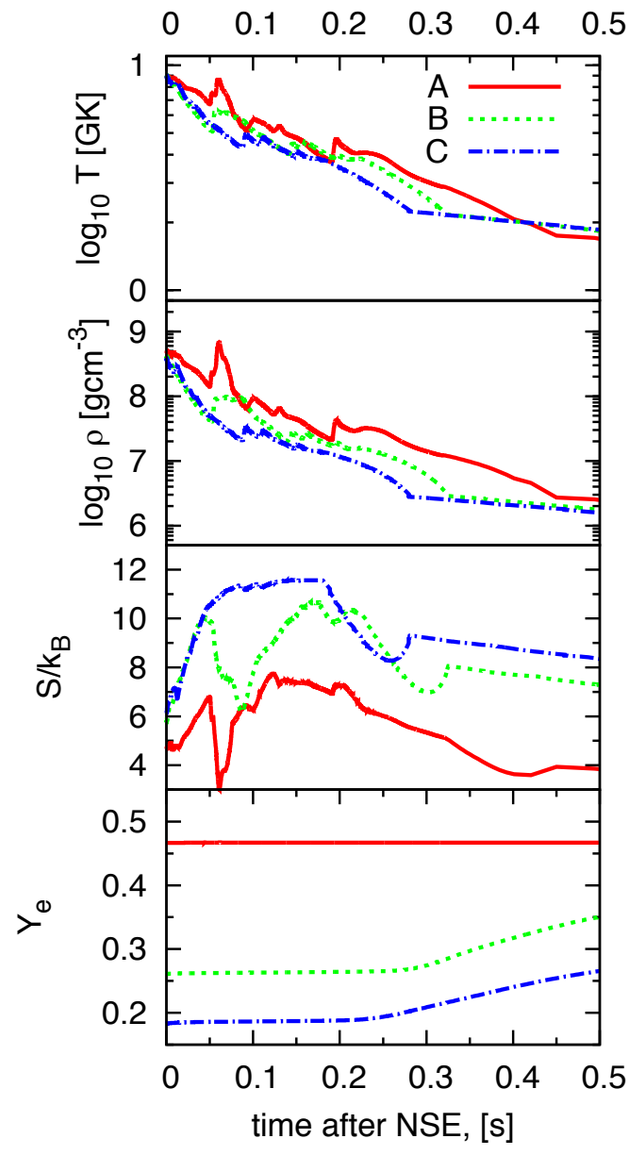
Nucleosynthesis simulation

MHD-SN (Nishimura 2006)

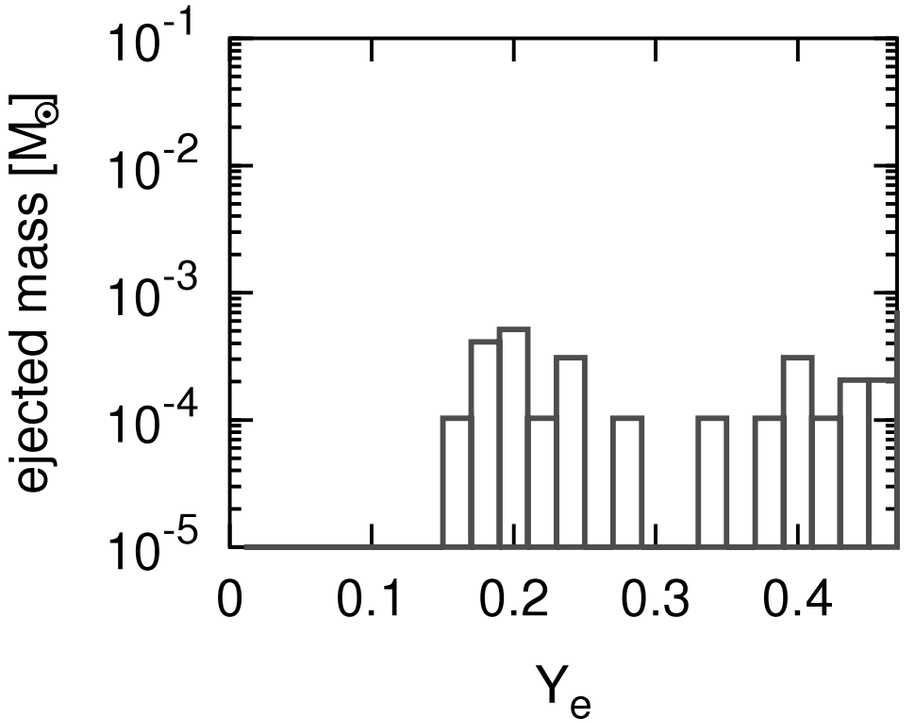
hydrodynamic models



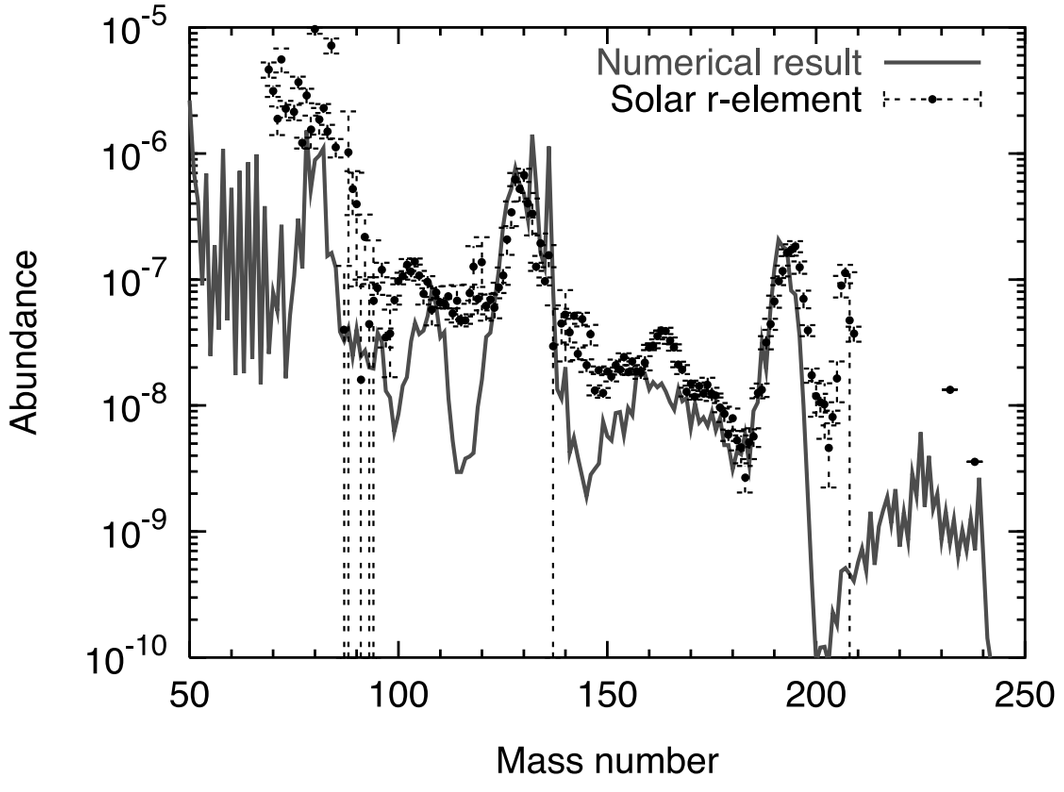
the evolution of thermodynamic quantities



electron fractions



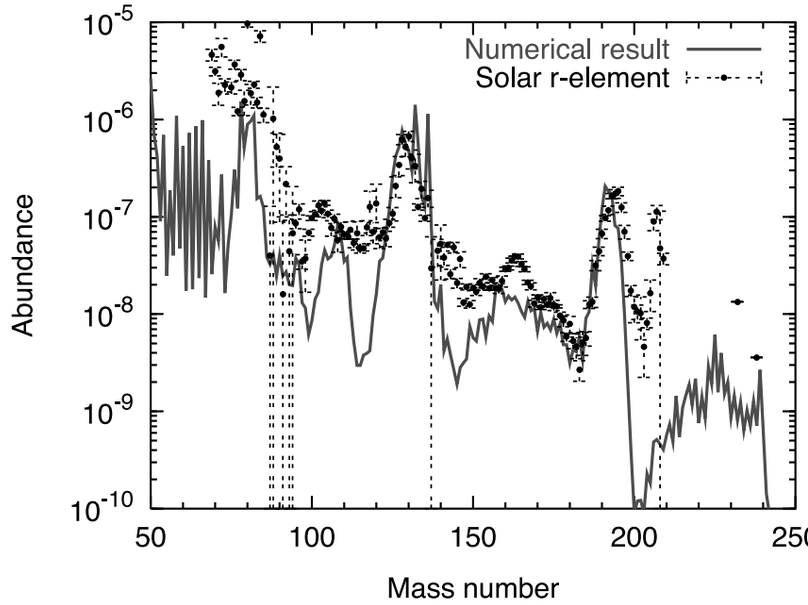
final product of ejecta



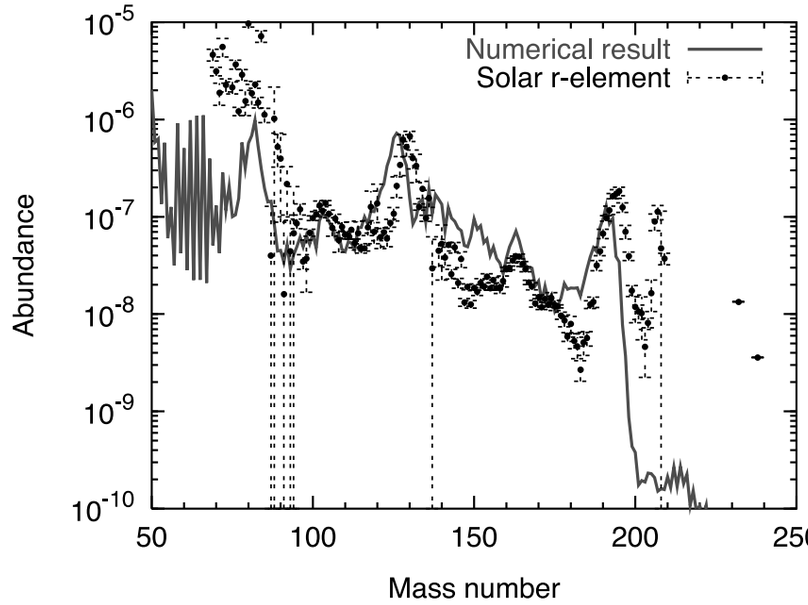
Nucleosynthesis: uncertainties of nuclear physics

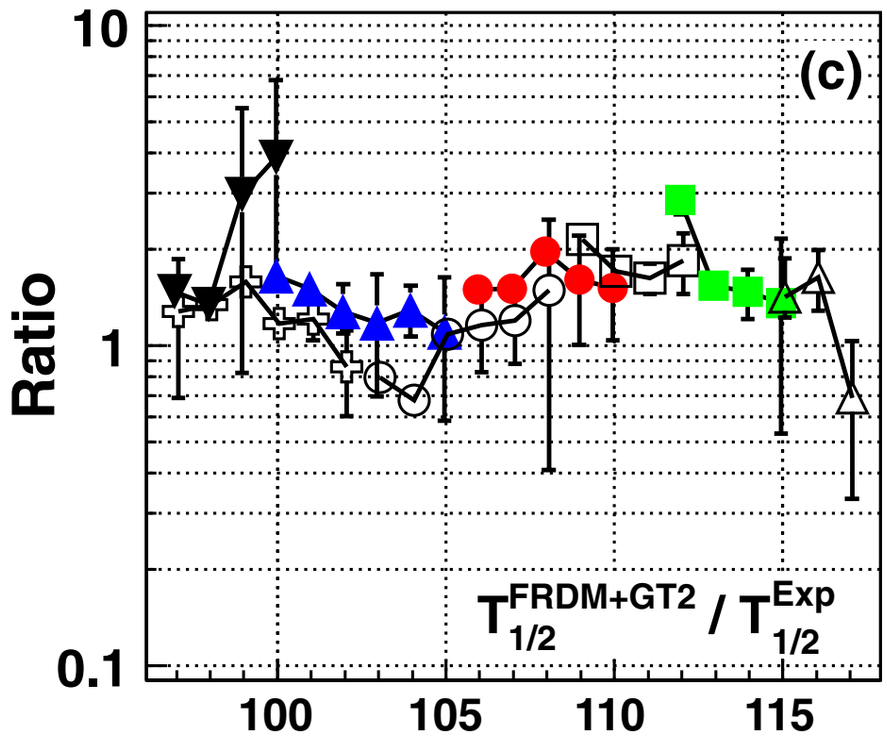
same astronomical model (MHD-SN)

FRDM



ETFSI





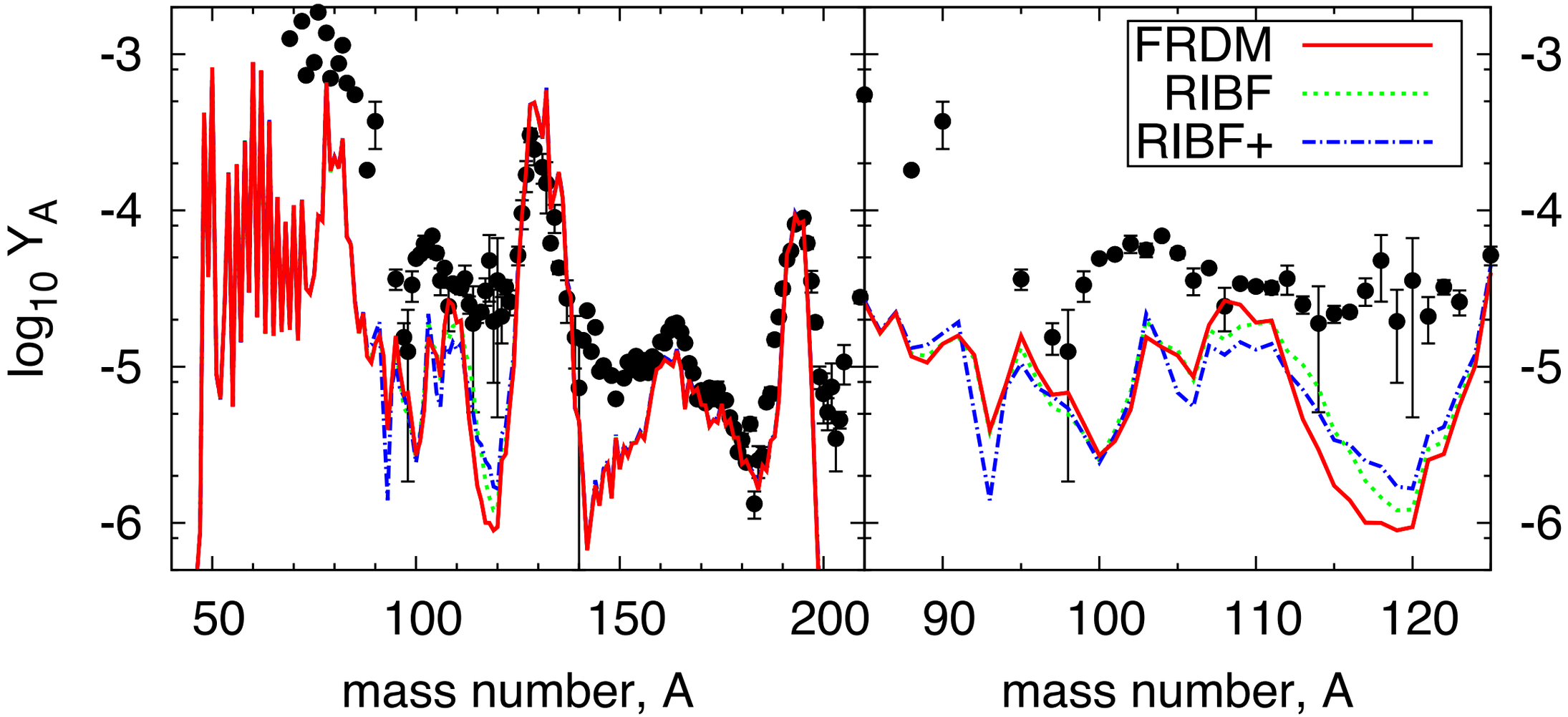
FRDM vs RIBF new data:
half lives A∼110
on the r-process path
(S. Nishimura PRL 2011)
RIKEN group

Nucleosynthesis simulation

- FRDM
- RIBF
- RIBF+

(γ,n) and (γ,n)

$$Q_+ = \begin{cases} Q - 0.3\ [\mathrm{MeV}] & (\ 97 \leq A \leq 103) \\ Q + 0.5\ [\mathrm{MeV}] & (104 \leq A \leq 107) \\ Q + 1.0\ [\mathrm{MeV}] & (108 \leq A \leq 115) \end{cases}$$

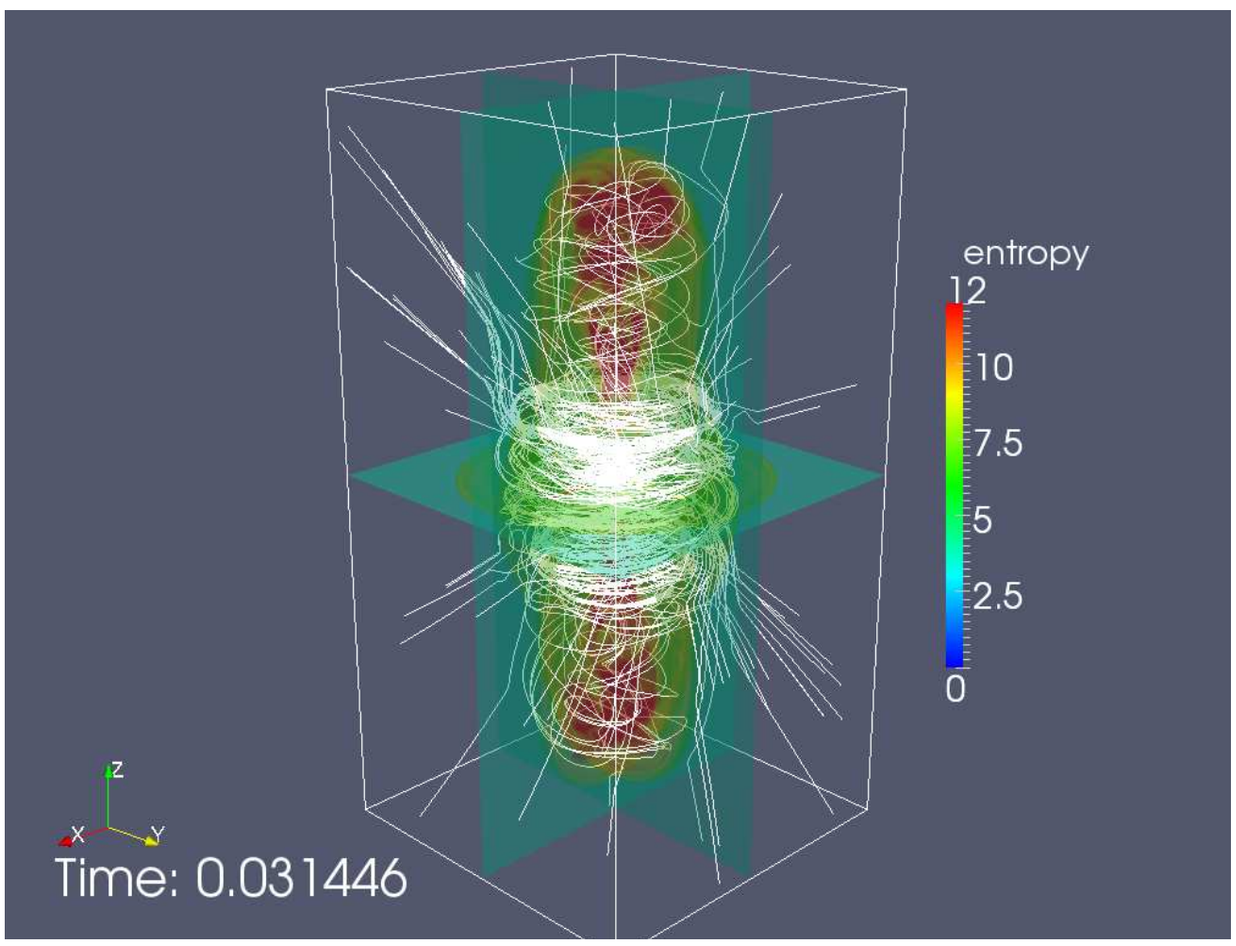


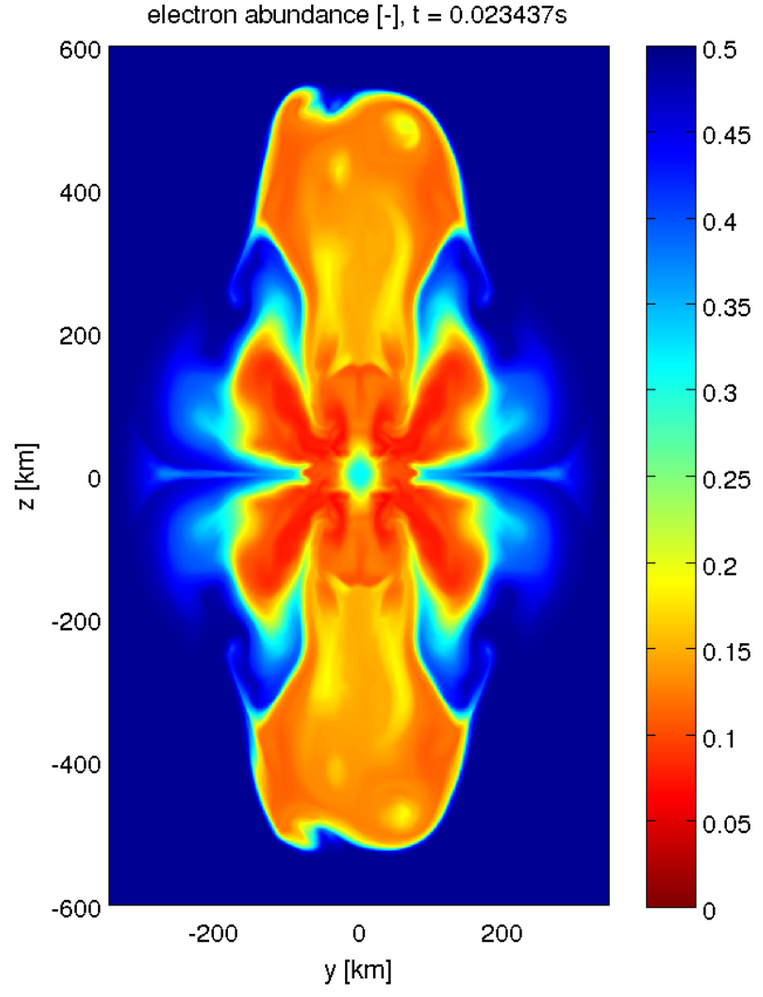
The first study of r-process based on 3D MHD-SN models

Magneto-rotationally driven Supernovae as the origin of early galaxy r-process elements?

C. Winteler [1], R. Käppeli [2], A. Perego [1], A. Arcones [1,3], N. Vasset [1], N. Nishimura [1], M. Liebendörfer [1], F.-K. Thielemann [1]

ApJL 2012; (Basel collaboration)





MHD “Jet” supernova explosion :

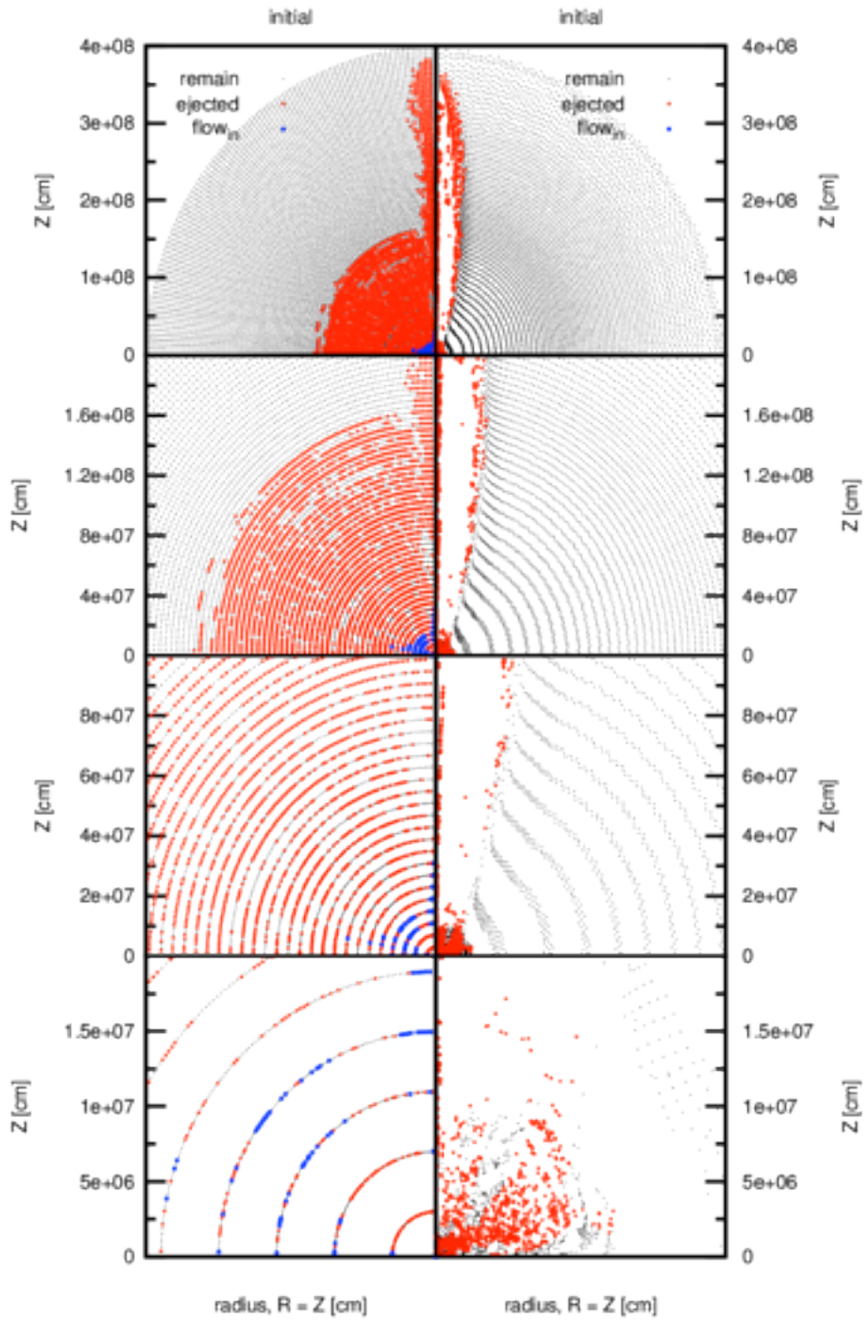
ejected r-elem. mass

$M_{\text{r-elem.}} \sim 10^{-3}$ to $10^{-2}\, M_{\odot}$

(typically)

movie

Nishimura at al. (2012 prep.)
based on MHD-SN model
by Takiwaki 2009

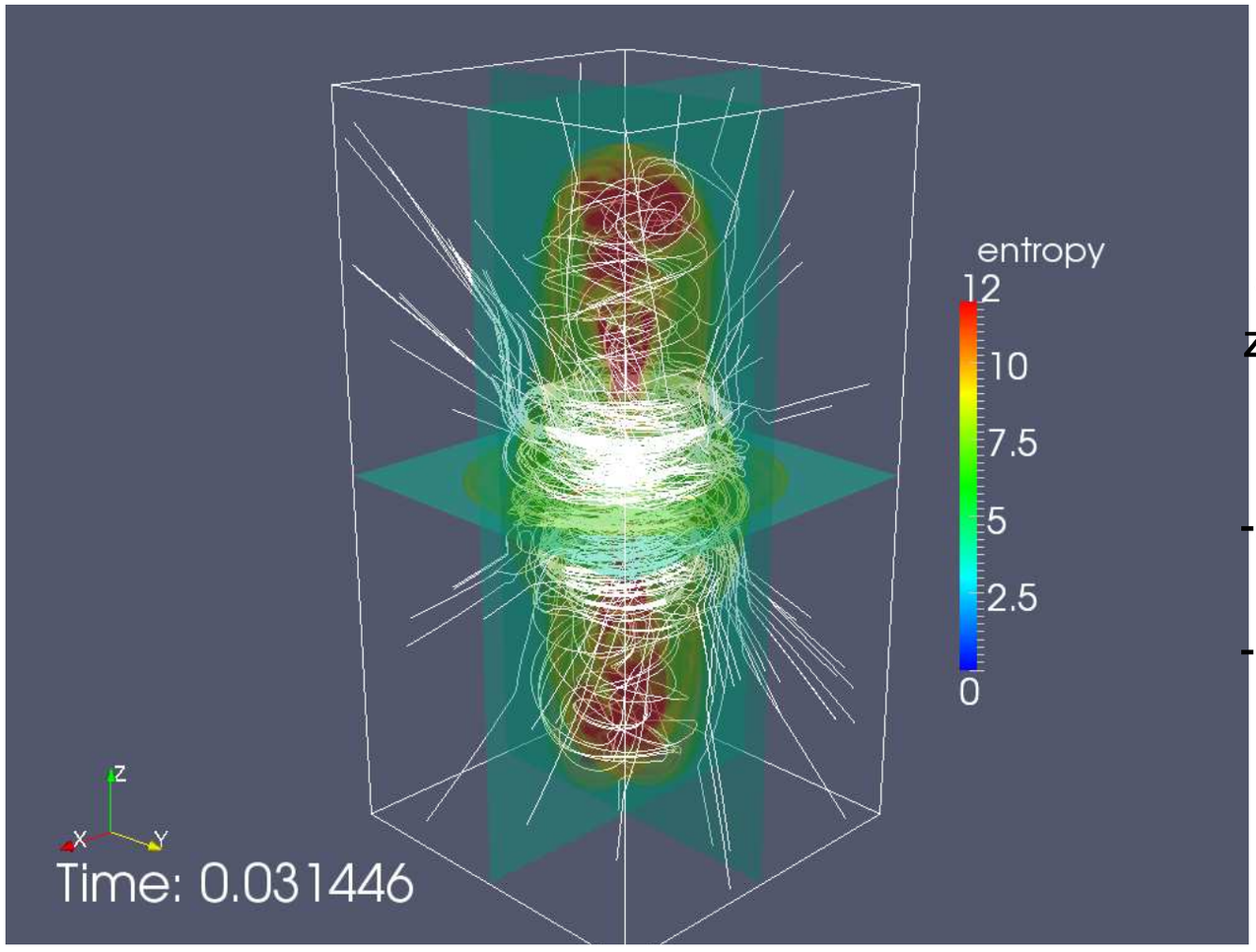


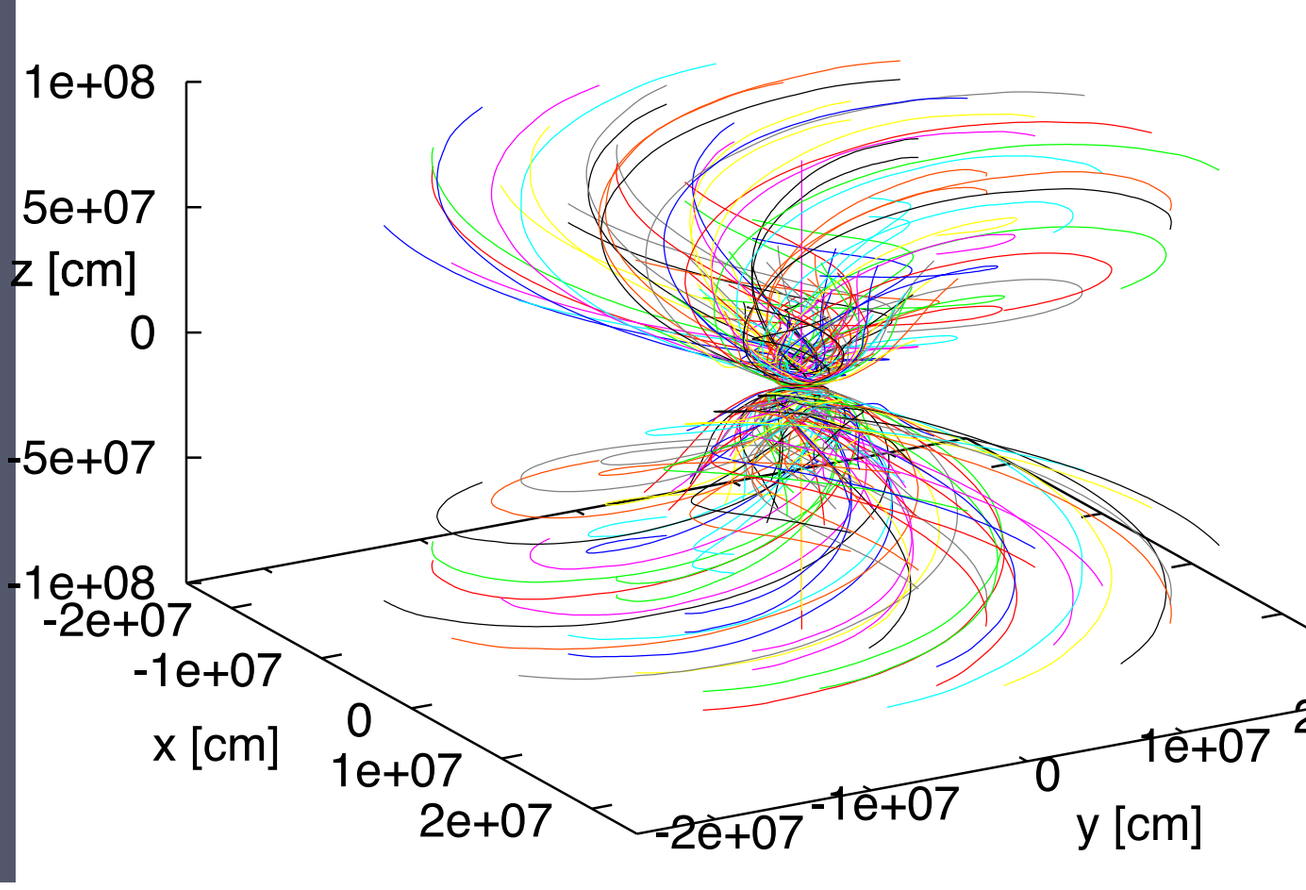
3D-MHD Supernova models

MHD code : FISH (Käppeli et al. 2011)

progenitor : $15M_{\odot}$ (Heger&Woosely 2002)

magnetic fields : poloidal 5×10^{12} [G] (initial)

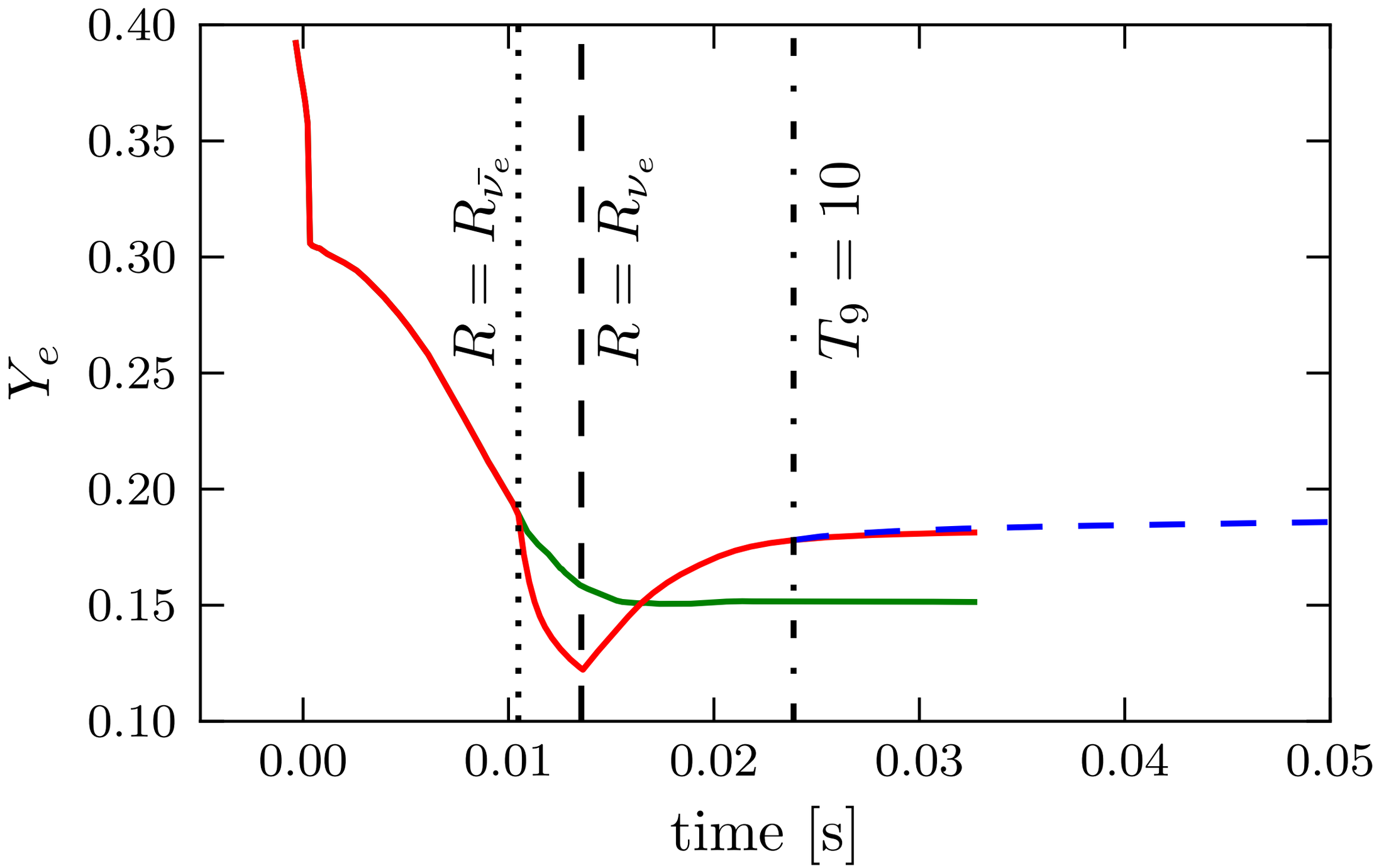




NEW 3D MHD models: the result

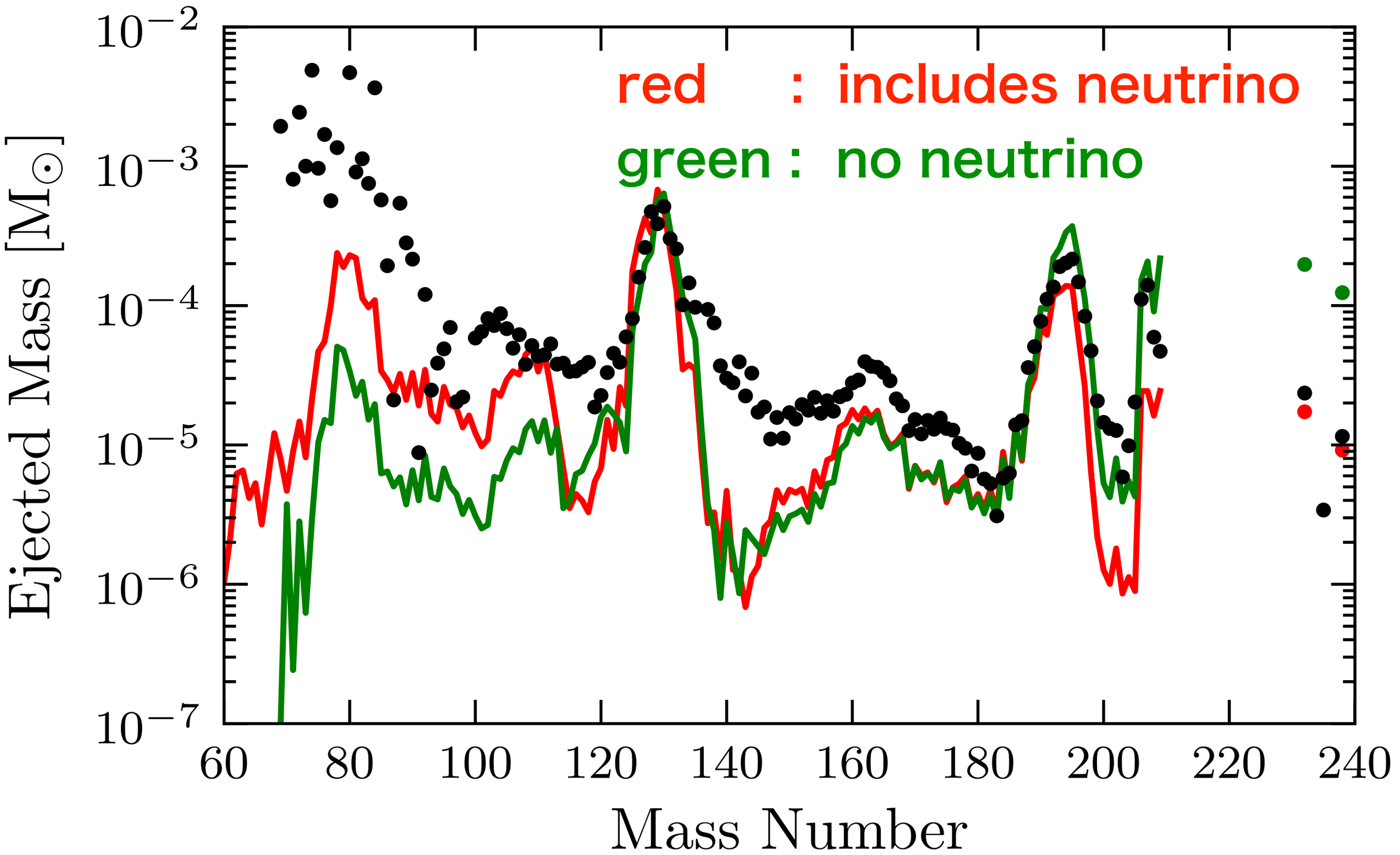
red : includes neutrino absorption

green : no neutrino



NEW 3D MHD models: the result

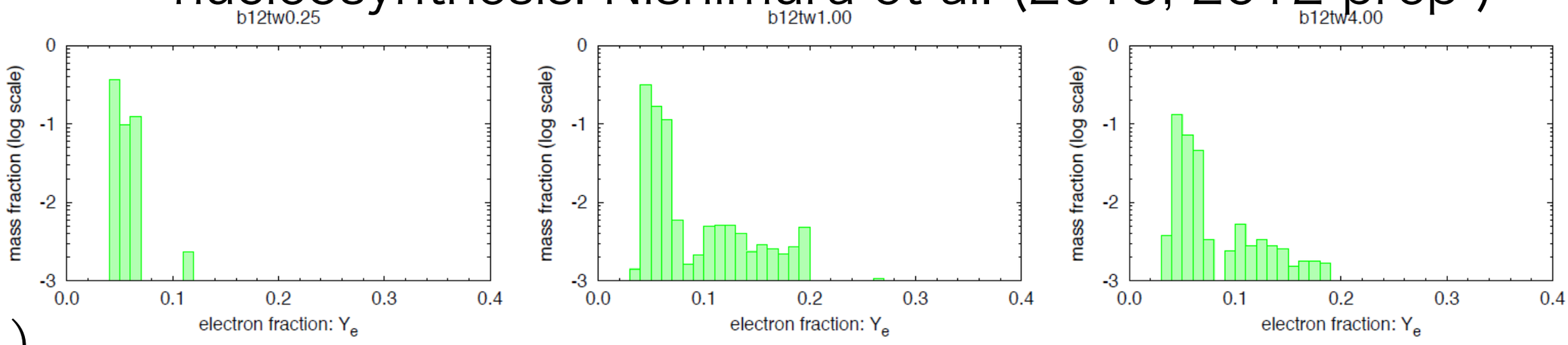
$M_{ej} = 0.672\ 10^{-2}\ M_\odot$



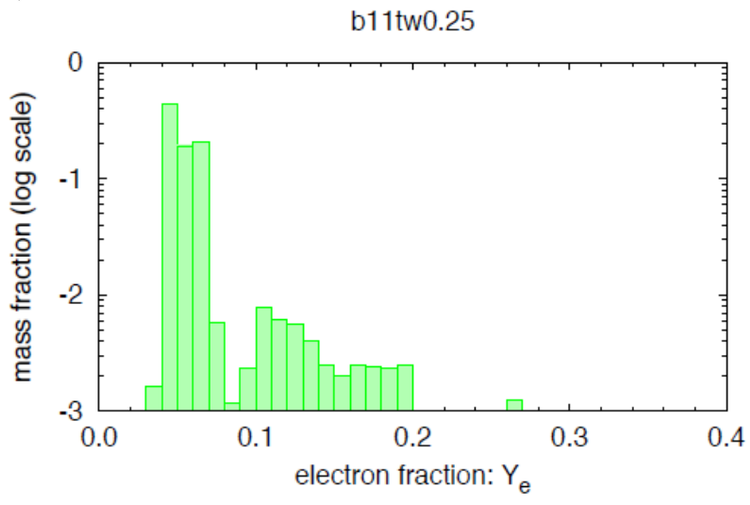
2D MHD models: prep.

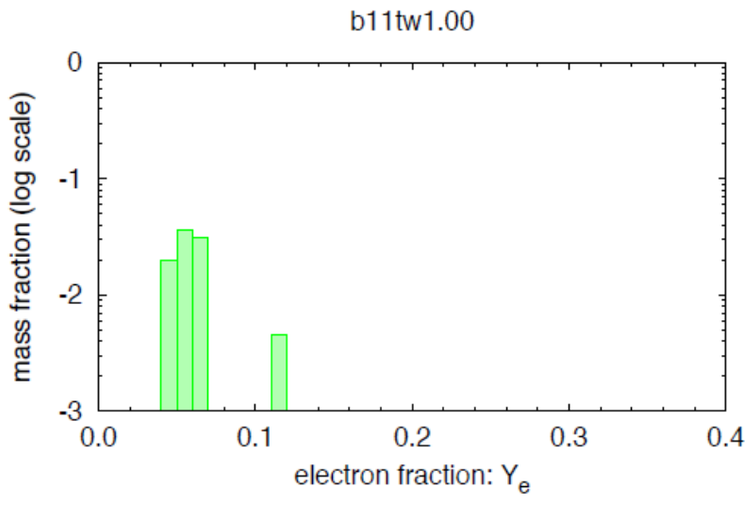
2D but detailed physics and parametric servey

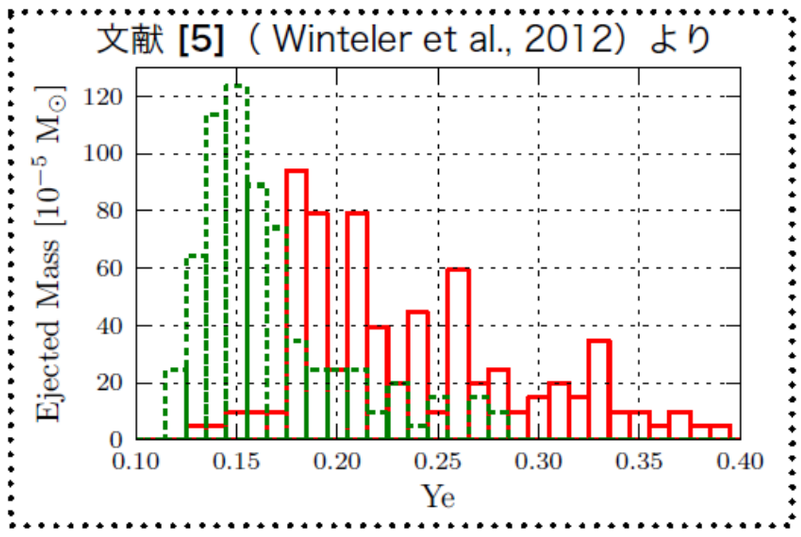
- 2D Relativity and neutrino cooling:
  - explosion model: Takiwaki et al. 2009
  - nucleosynthesis: Nishimura et al. (2010, 2012 prep)



1)







optimistic results (prep.)

MHD Supernovae: summary

- strong magnetic field and rotation
  - both of axisymmetric and 3D
  - successful r-process (up to 3rd peak)
  - ν_e absorptions are not destroy r-process
- initial B-fields and rotation dependency
  - still unknown (We should do this!)
- survey to multiple explosion models
  - wide range of initial conditions
  - long-term simulation in axisymmetry

Core-Collapse Supernovae induced by the Quark-Hadron phase transition

“Nucleosynthesis in core-collapse supernova explosions triggered by Quark-Hadron phase transition”

Nishimura et al. (arXiv: 1112.5684)

collaborators

<u>Basel</u>

F.-K. Thielemann

M. Hempel

R. Käppeli

T. Rauscher

C. Winteler

<u>GSI Darmstadt</u>

T. Fischer

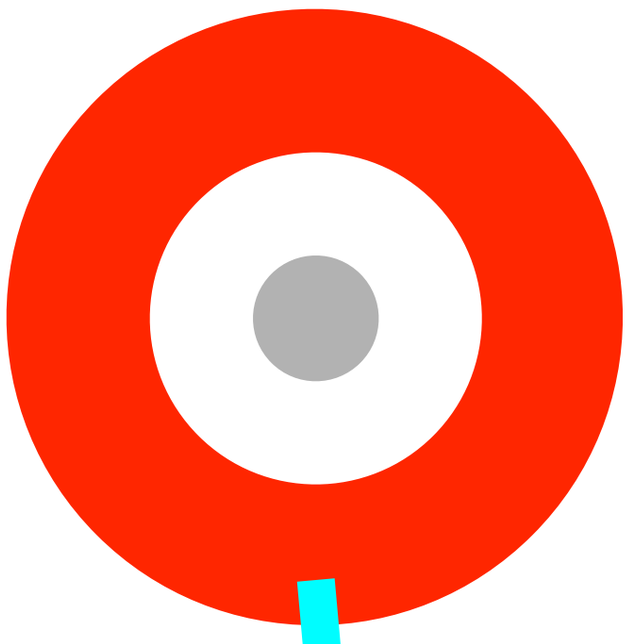
G. Martínez-Pinedo

C. Frölich (North Carolina)

I. Sagert (Michigan)

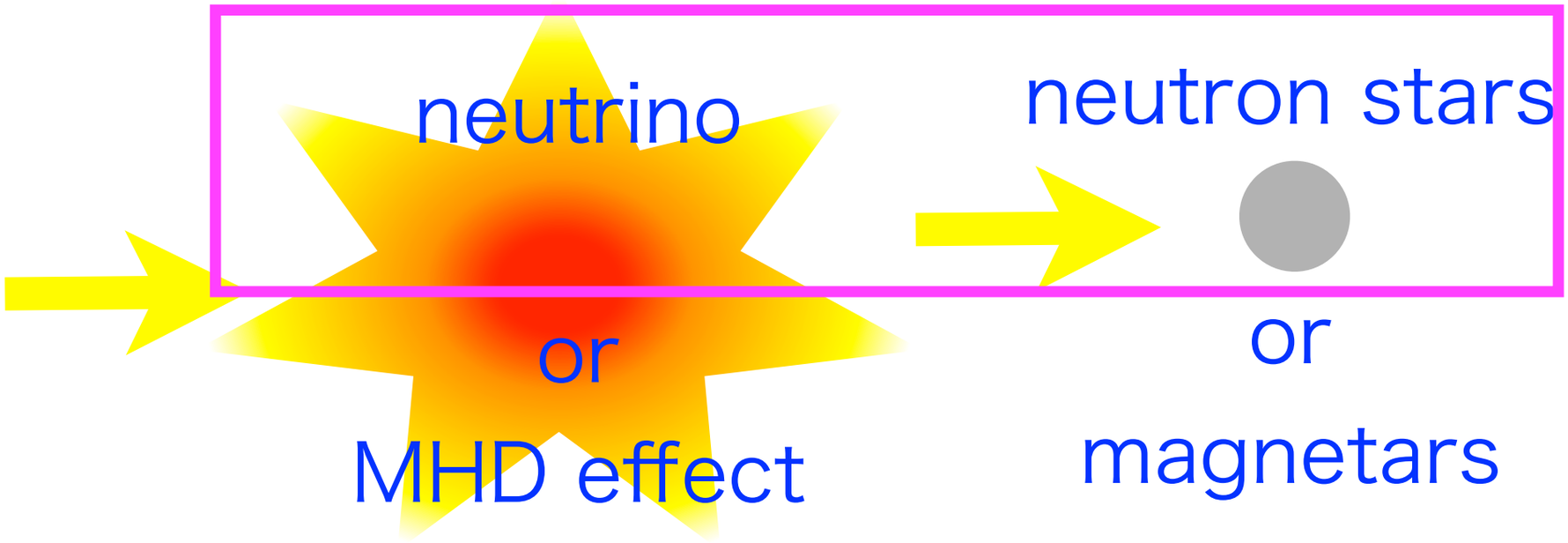
CC-SN via quark-hadron phase transition

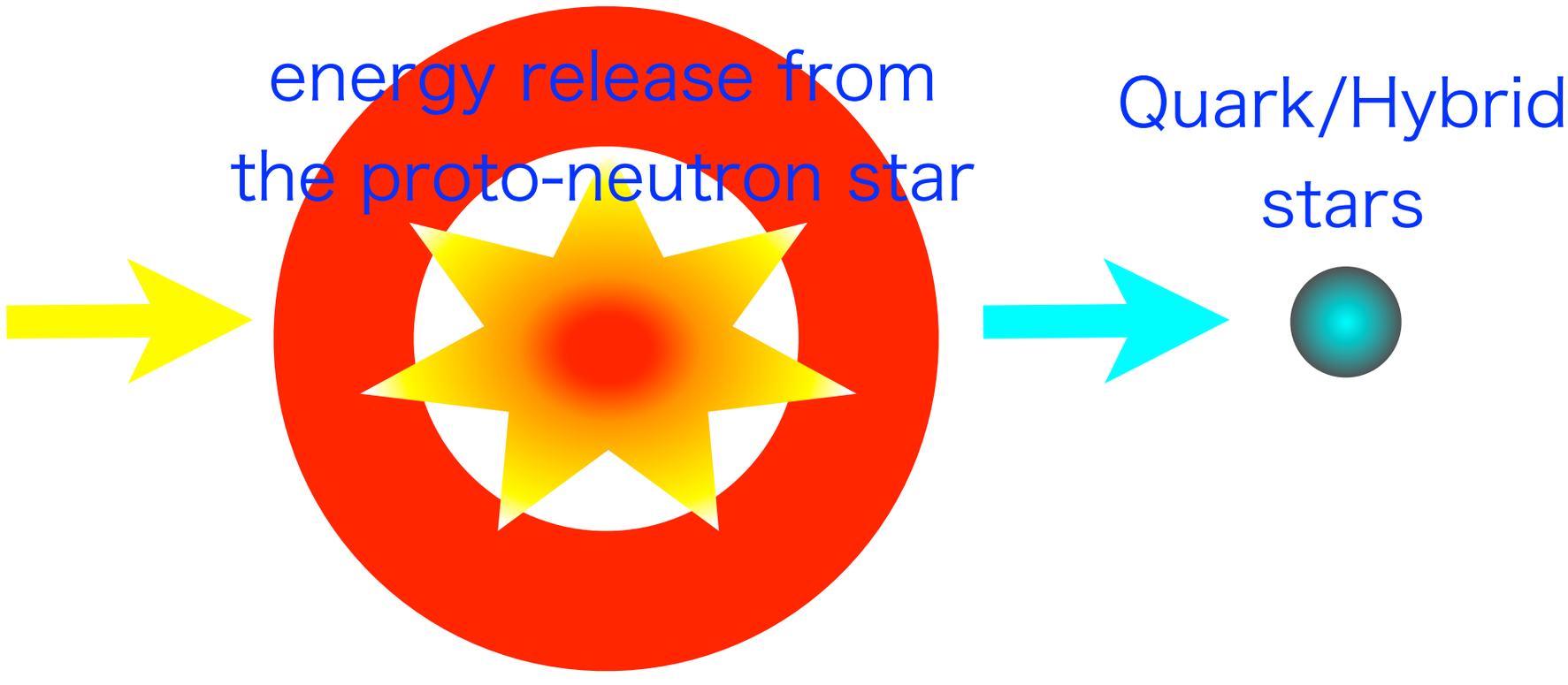
collapse



QCD phase transition

standard (disadvantage to r-proc.)



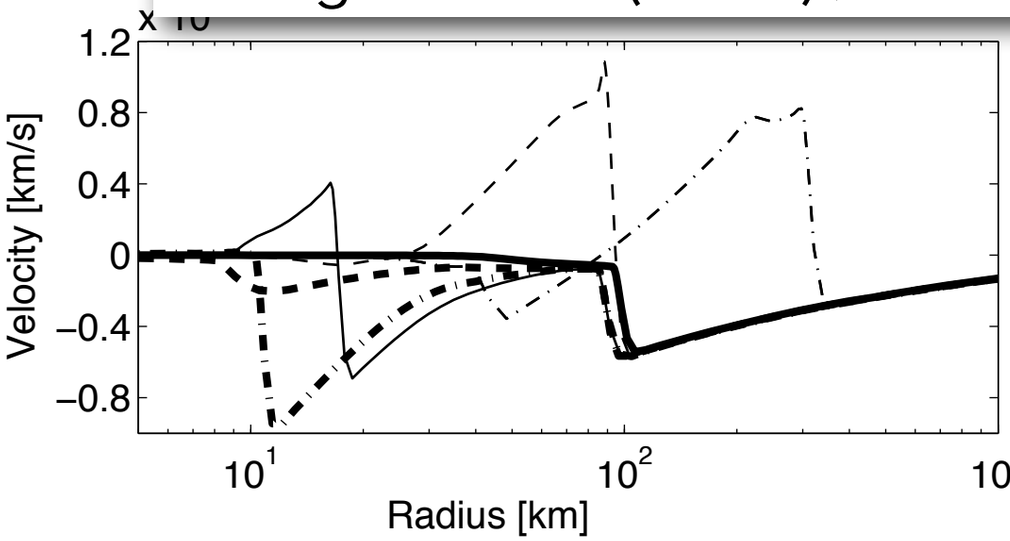


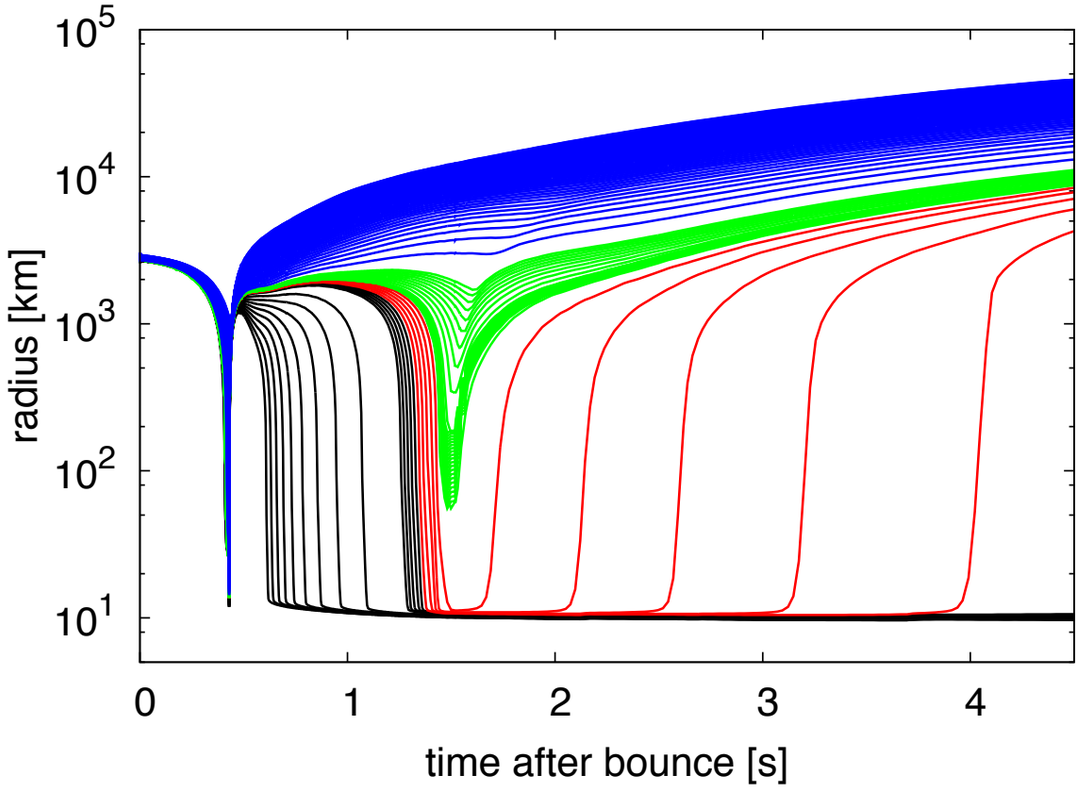
SNe via the quark-hadron phase transition

quark-hadron phase transition occurs

after the normal core-bounce :

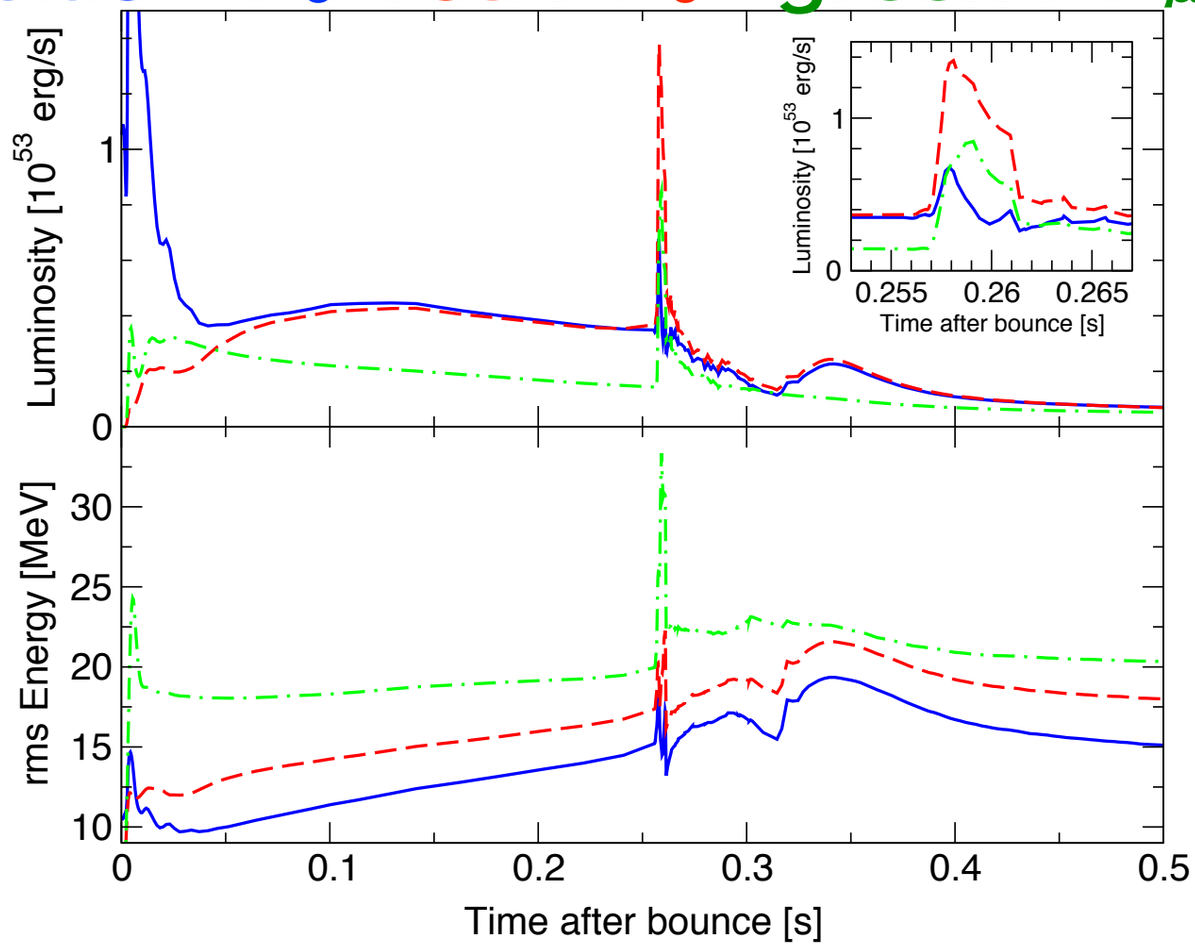
Sagert et al. (2009)、Fischer et al. (2011)





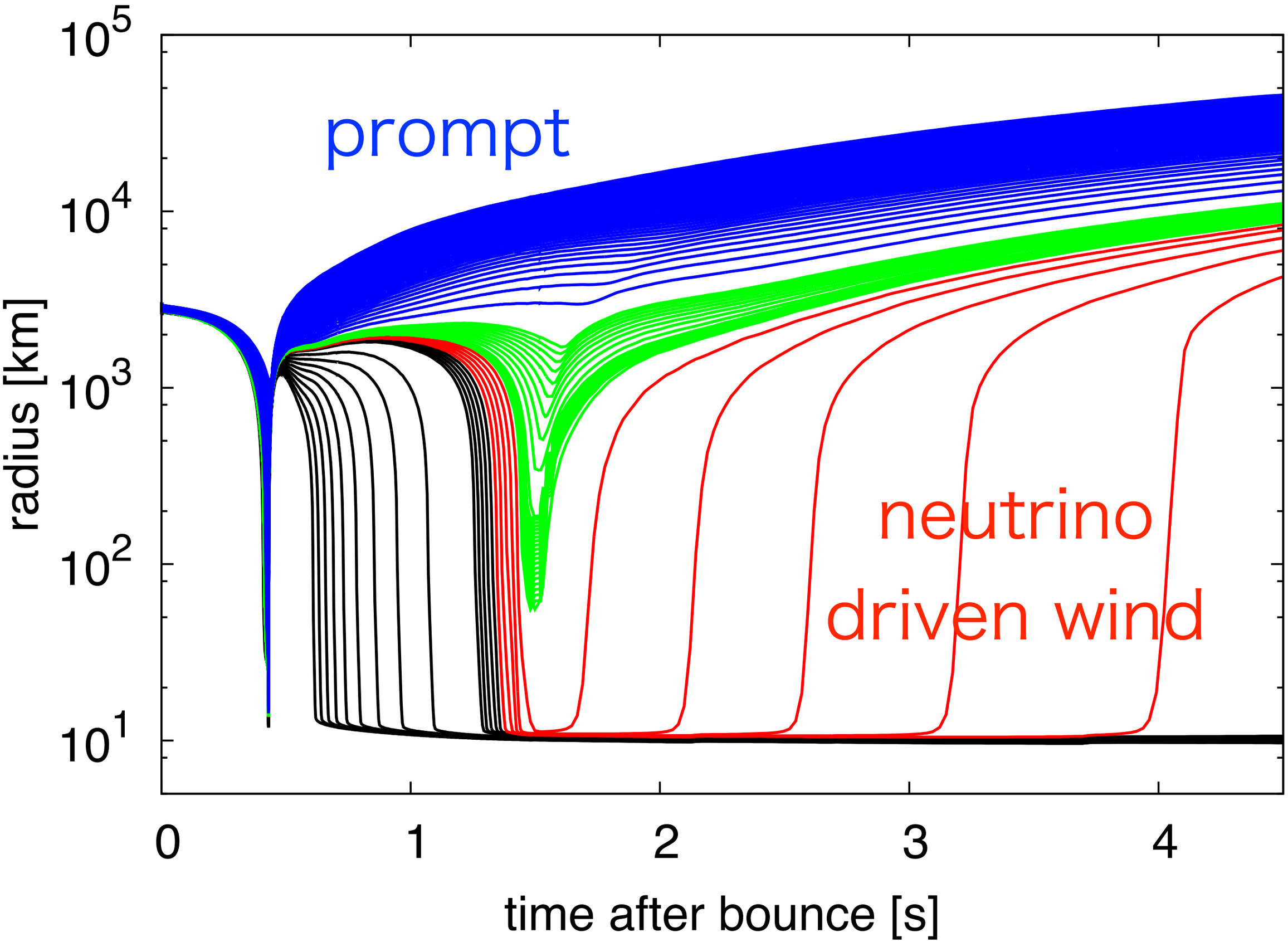
- GR-hydro. + neutrino transport
- EOS : Shen EOS + MIT bag model

blue : ν_e red : $\bar{\nu}_e$ green : $\nu_{\mu/\tau}$

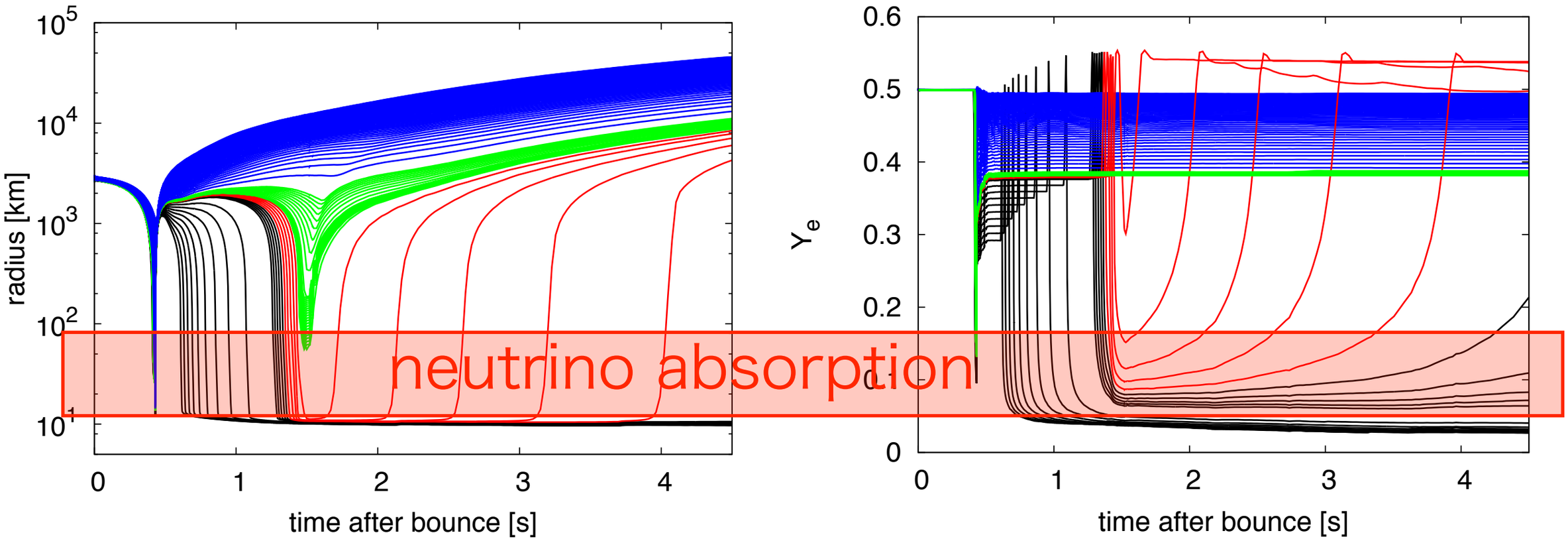


Dasgupta et al. PRD 81 (2010)

the explosion model



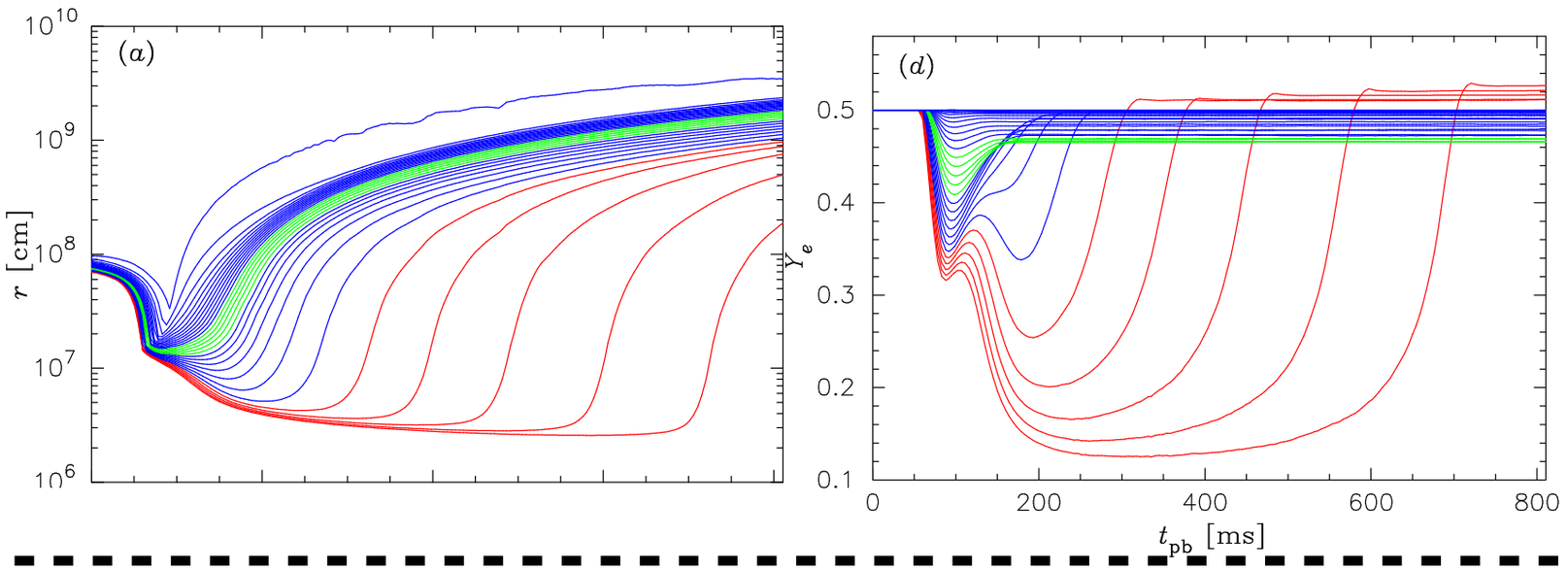
ejection process & neutron richness



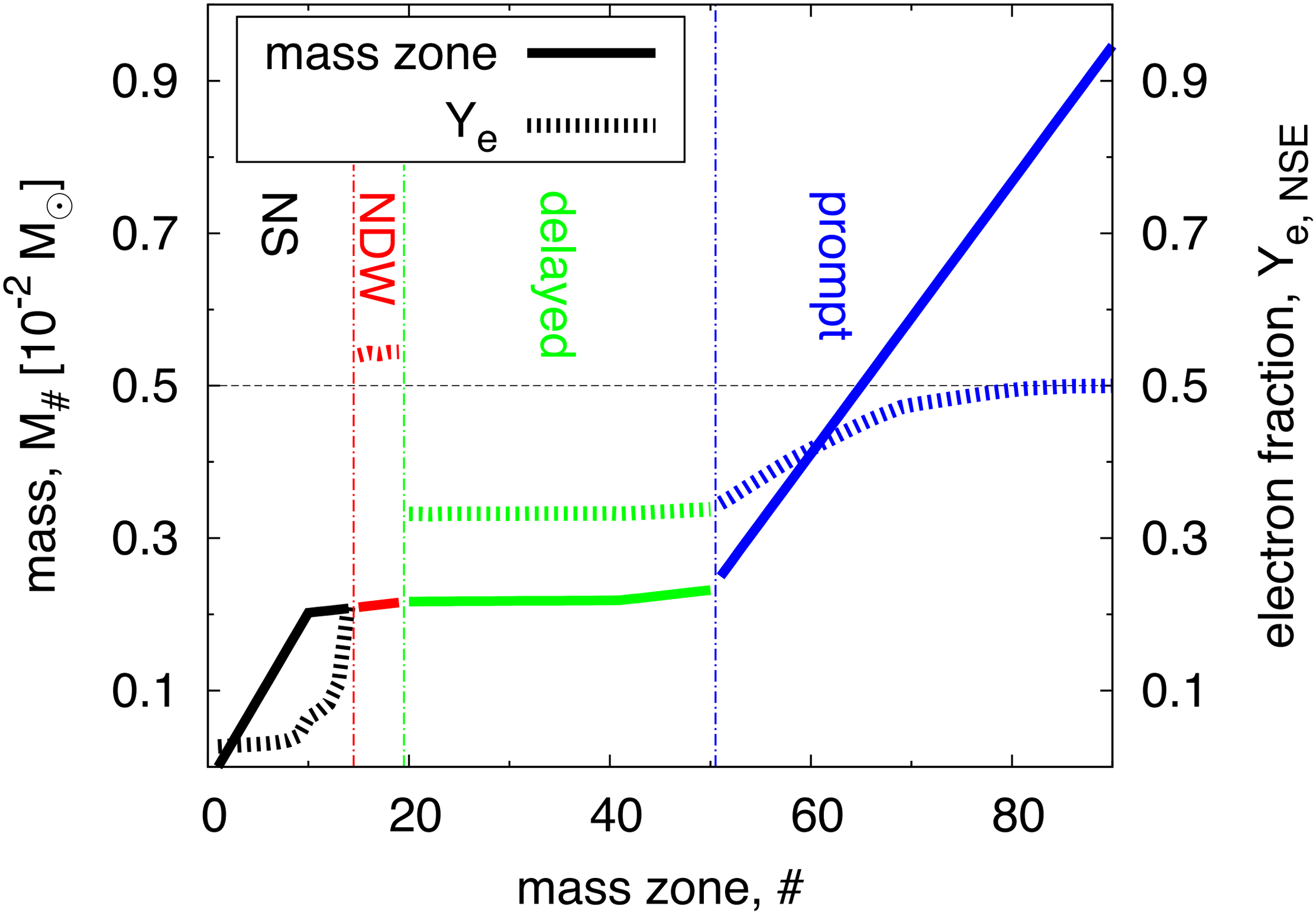
neutrino absorption

ONeMg(8 $M_\odot$)

Kitaura et al. 2006

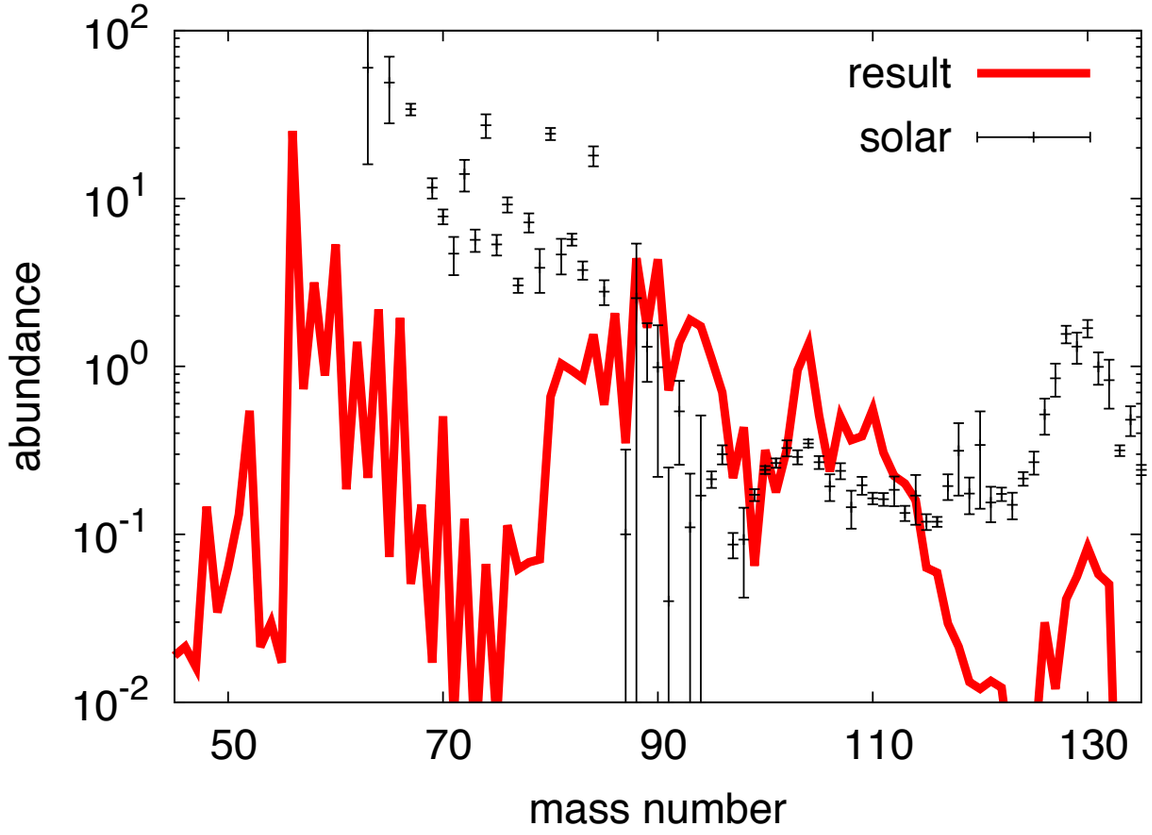


entropy & Y_e : the end of NSE (T = 9 GK)

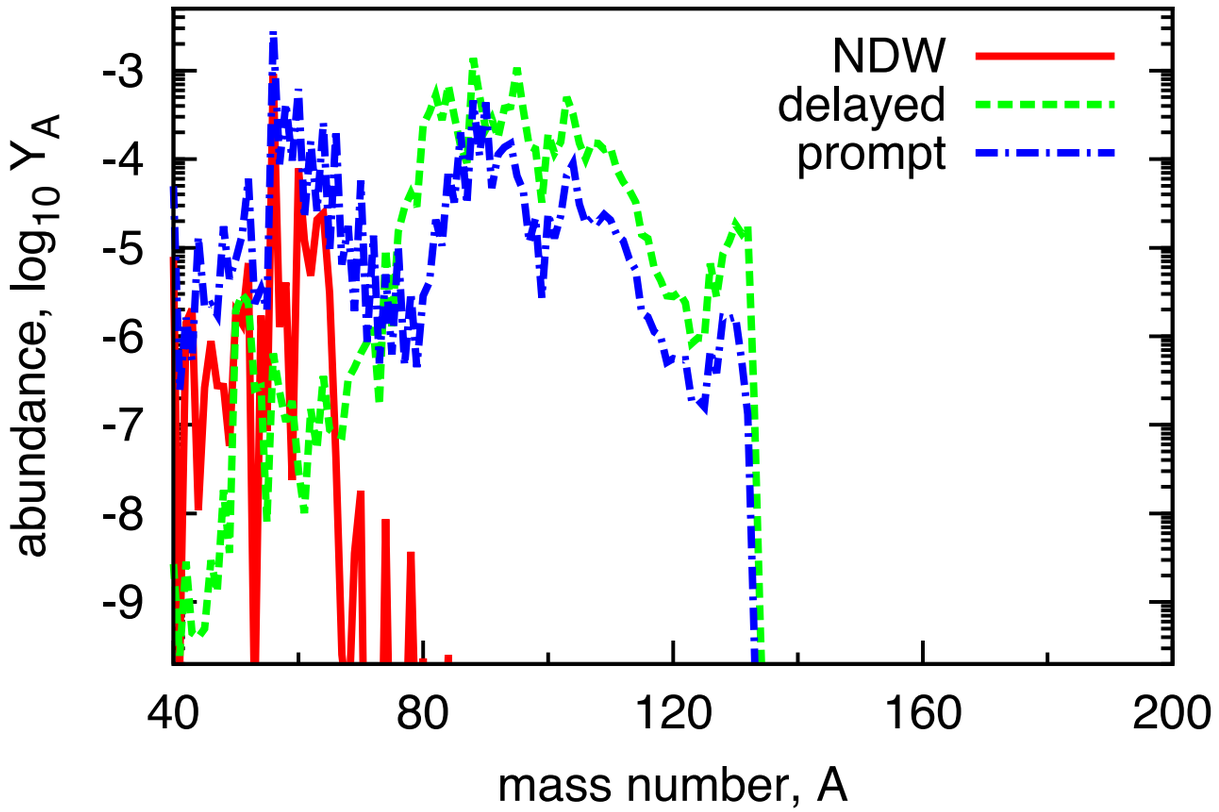


the final abundances:

total ejecta



each zone

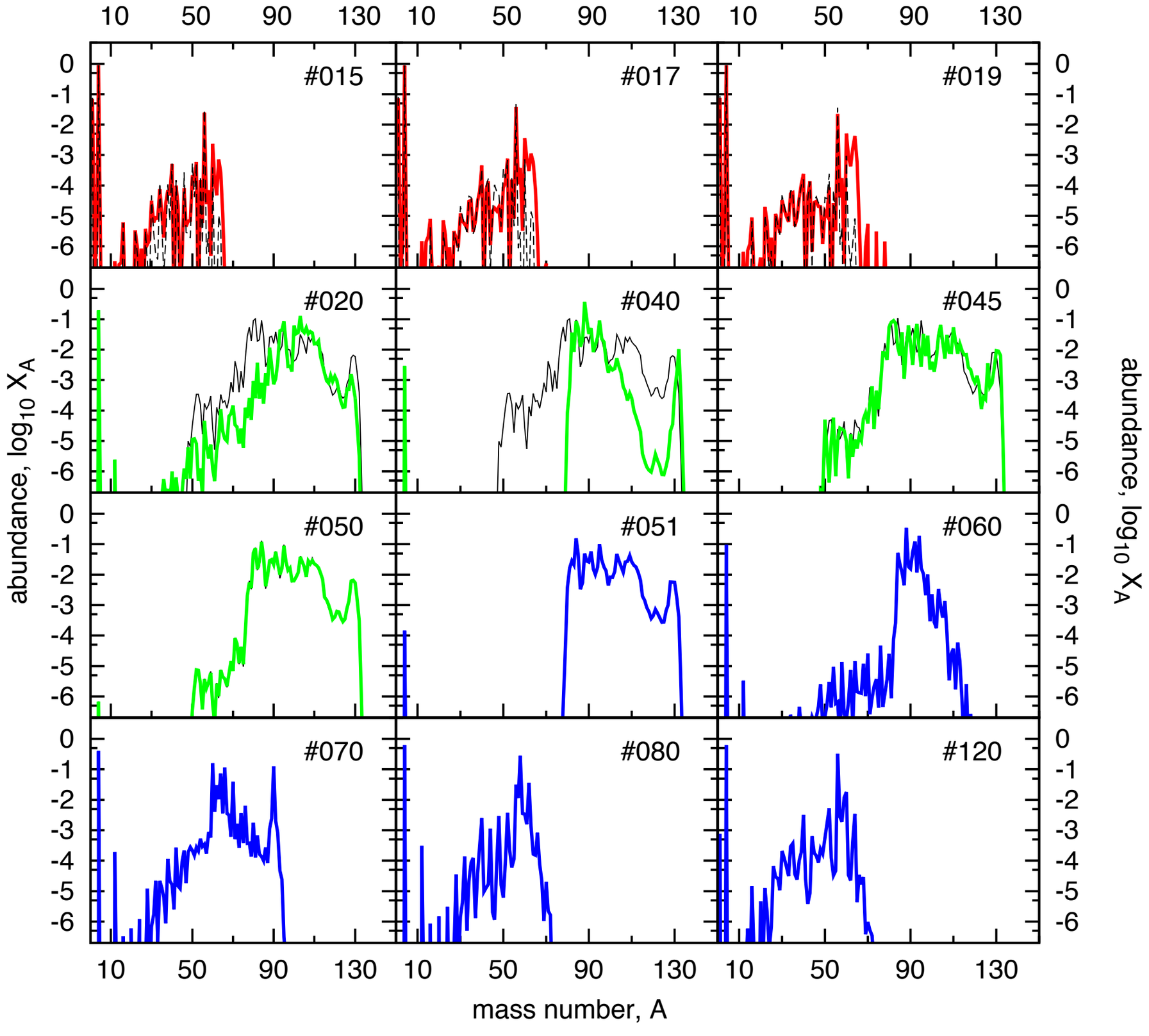


final abundances (represented) : each zone

neutrino driven wind

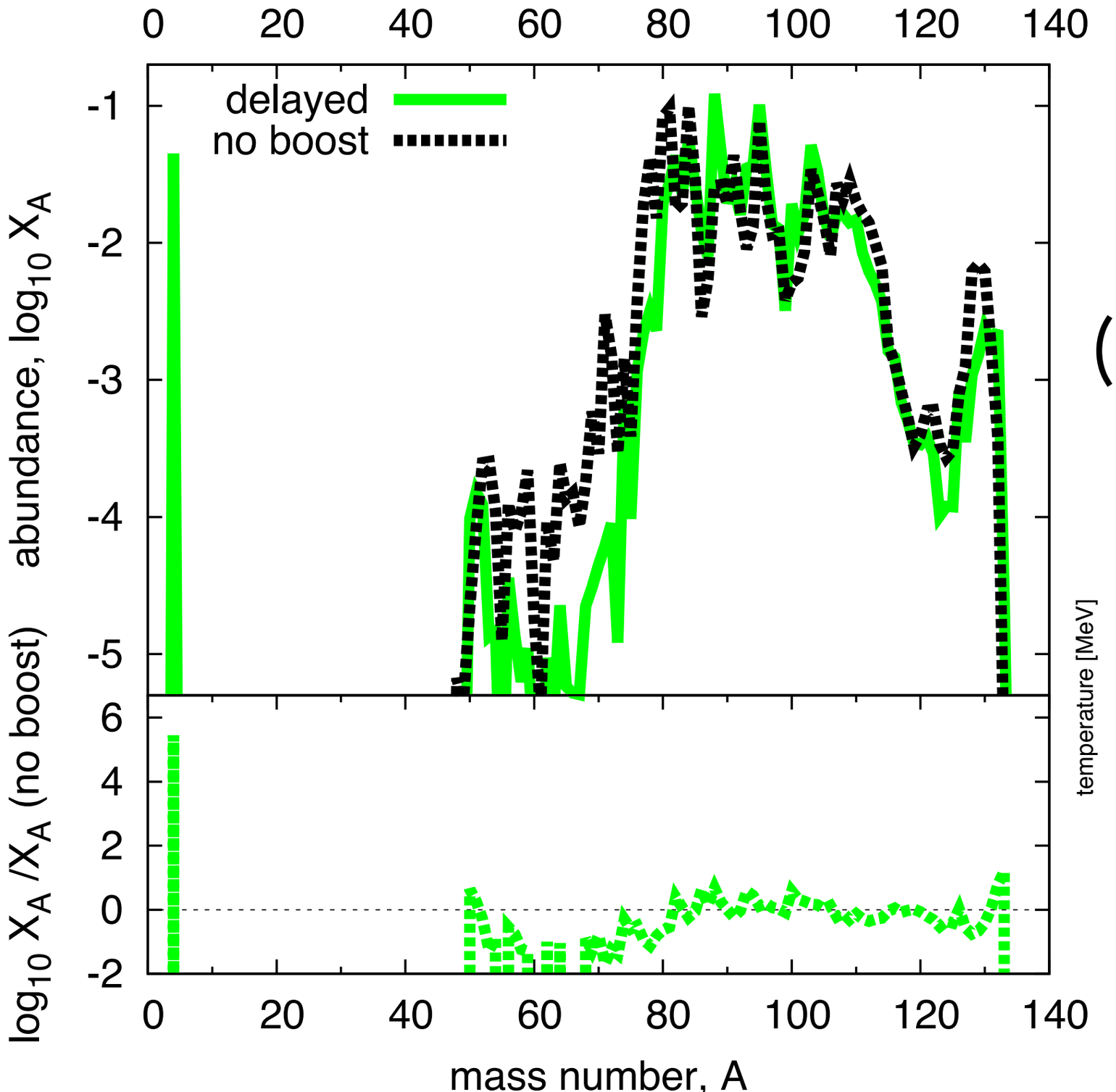
inner "delayed"

outer "prompt"

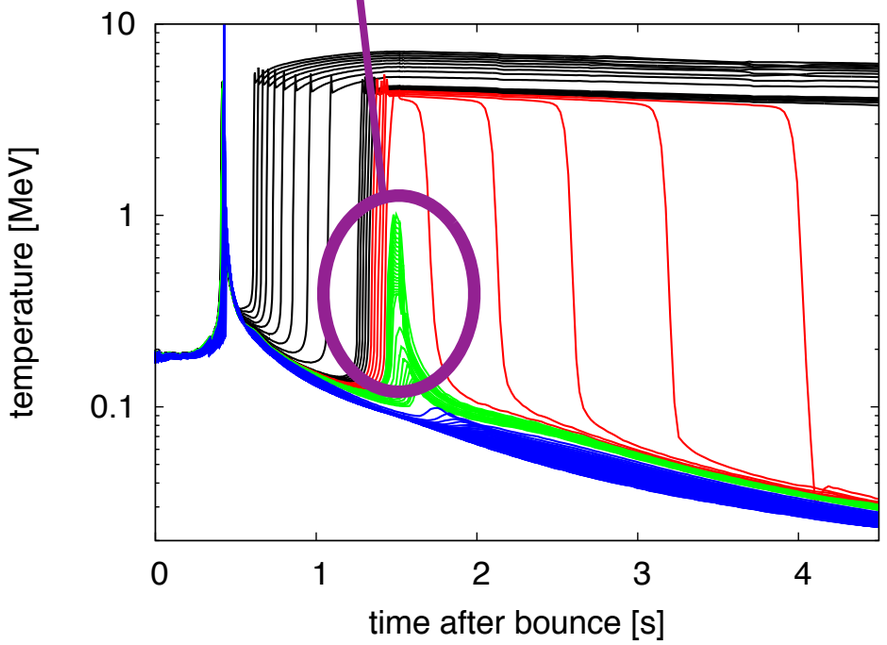


the properties of "boosted" matter

acceleration (re-heating) destroy heavy isotopes

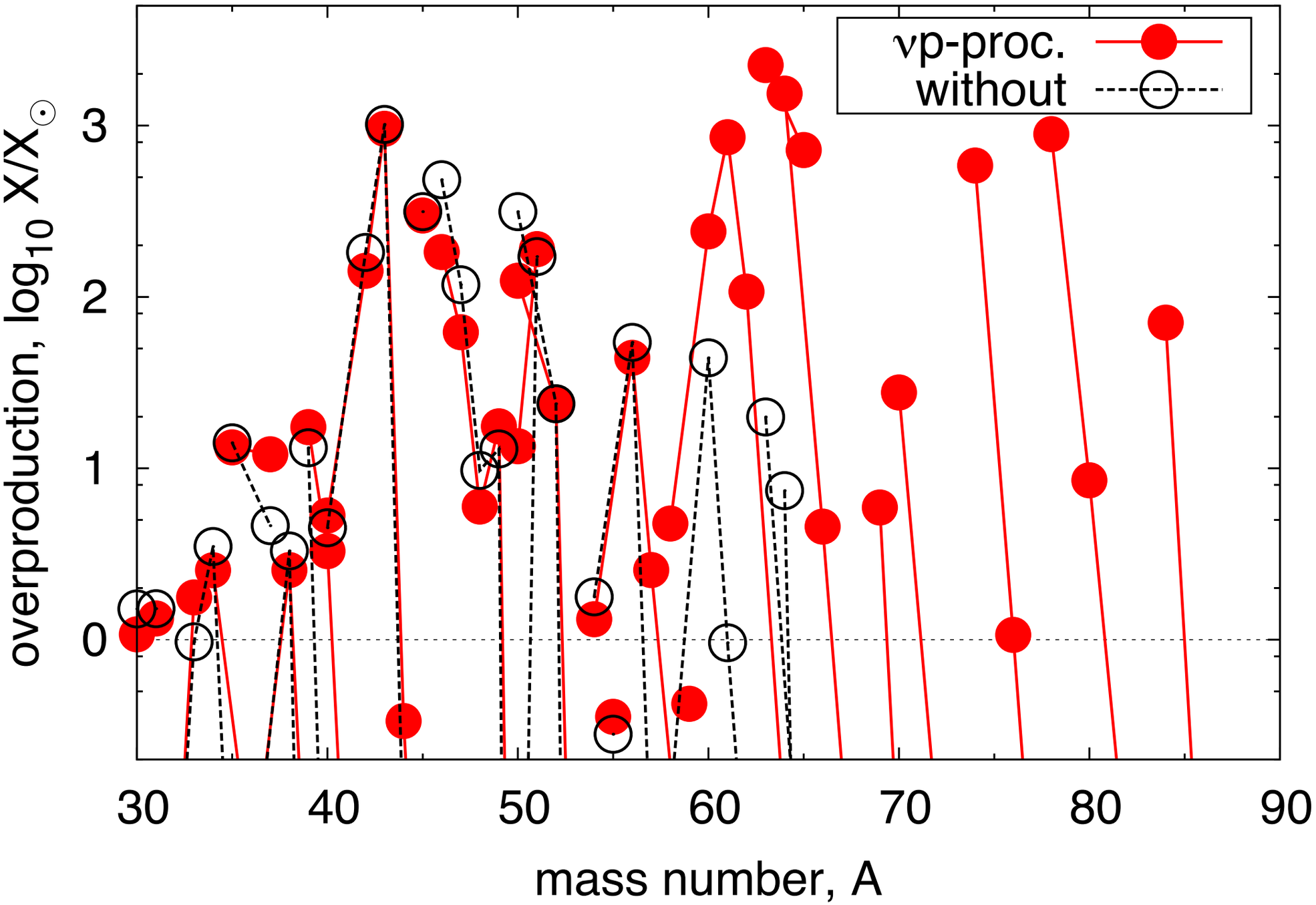


no boost
(ignore the pinch)



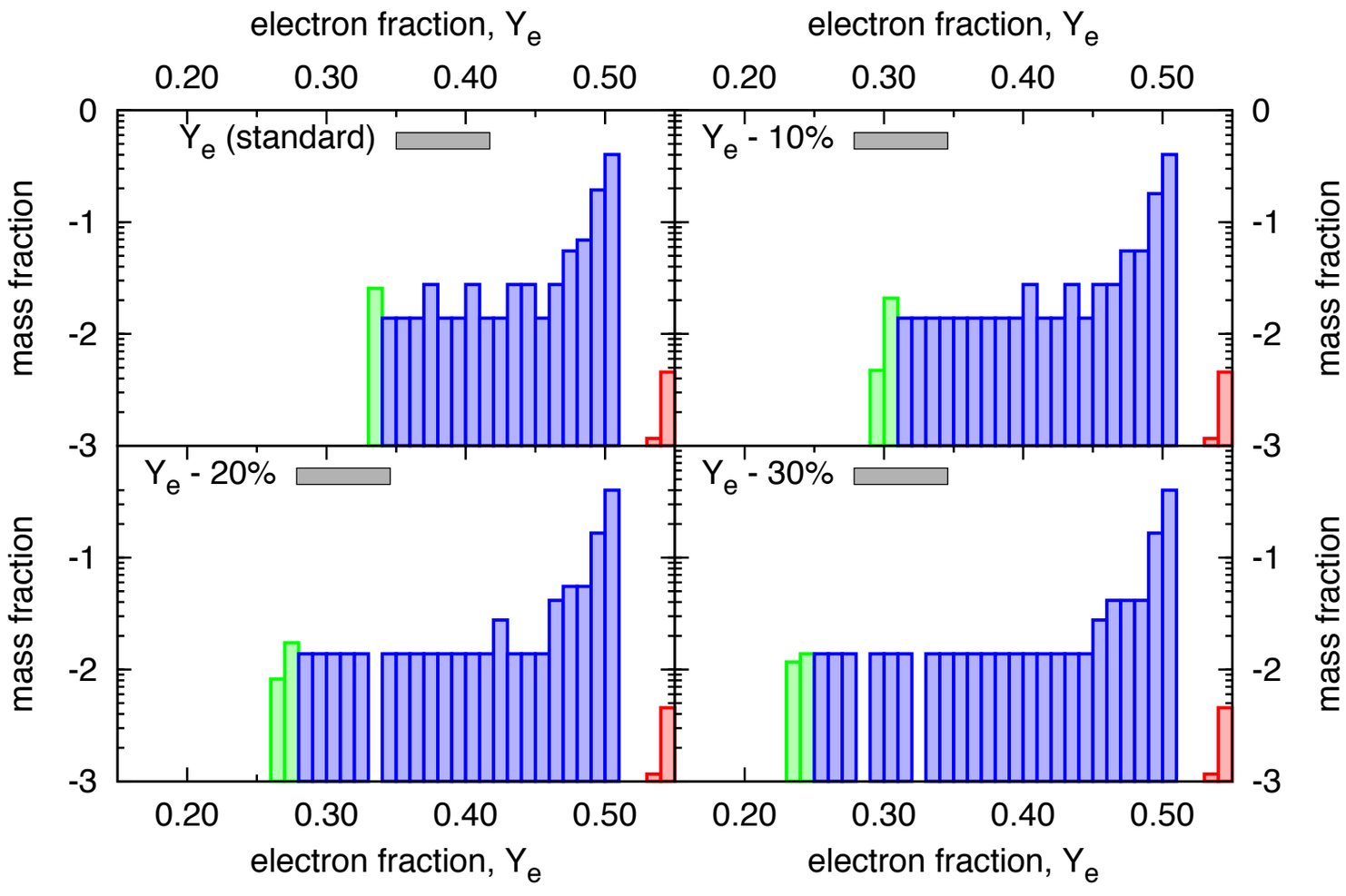
final abundances: neutrino driven winds

A < 85 elements are produced via ν p-process



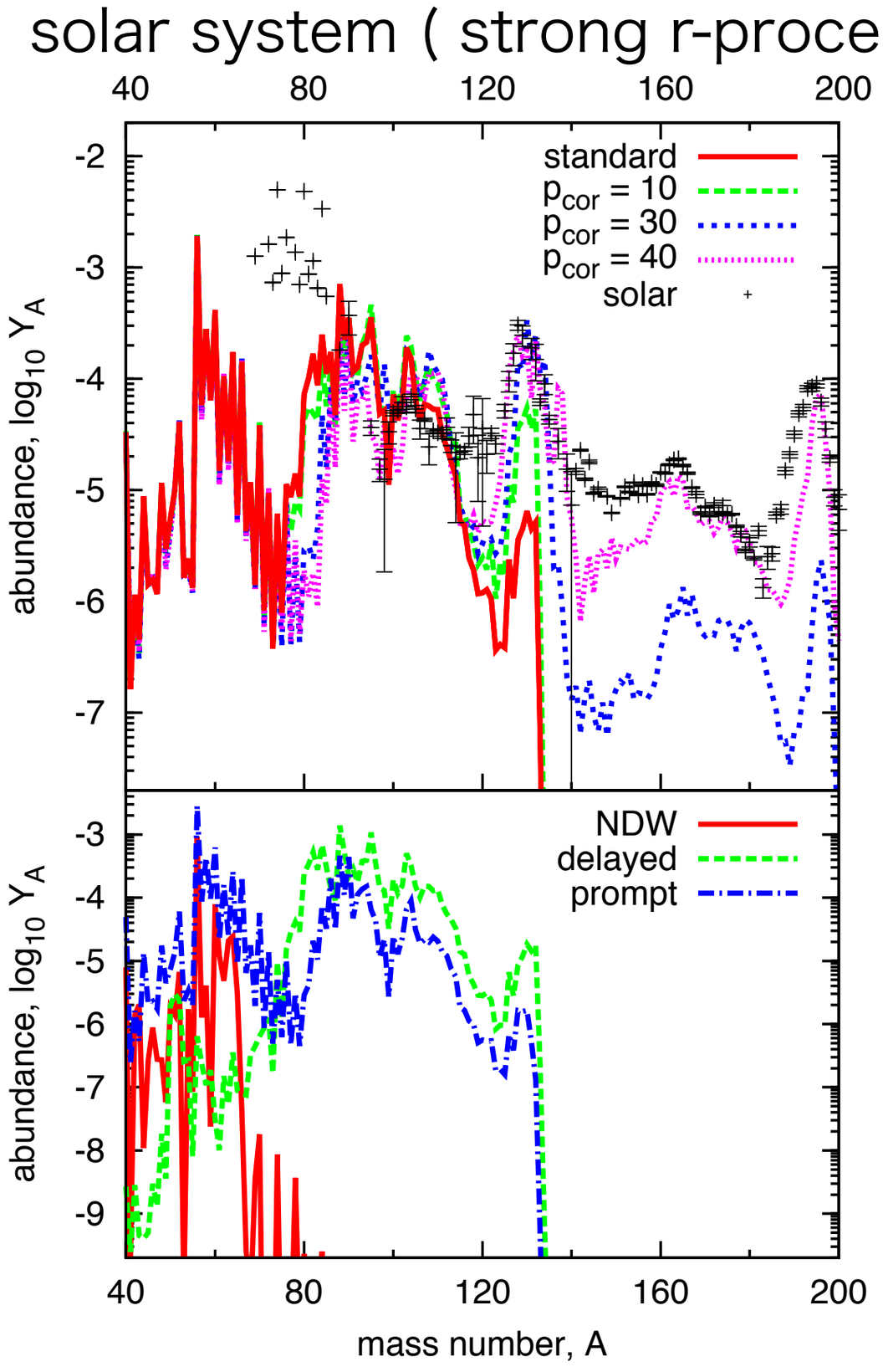
physical uncertainties: Y_e

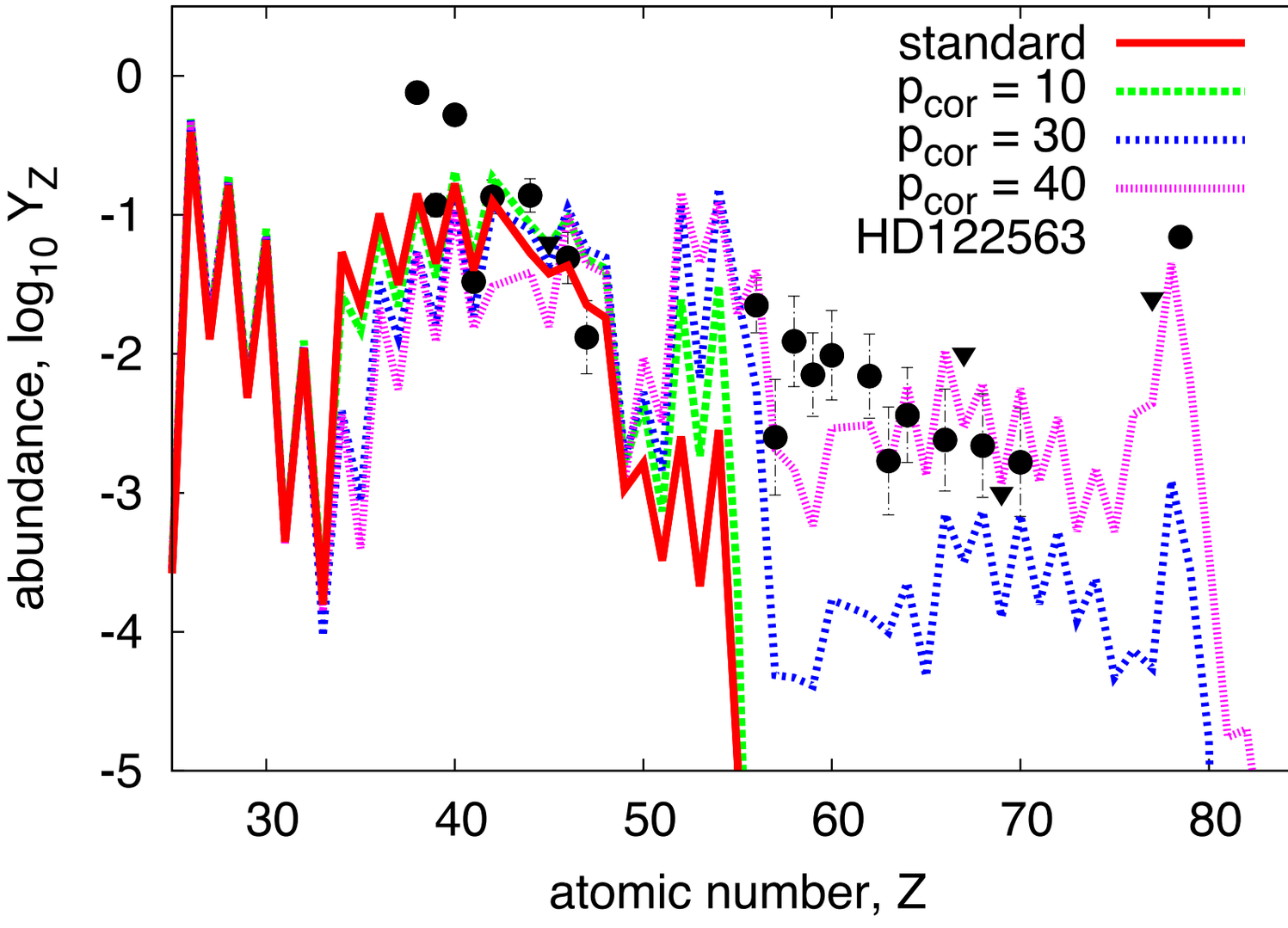
$$Y_{\mathrm{e,\,cor}} = 0.5 + (Y_{\mathrm{e}} - 0.5) \times \left(1 + \frac{p_{\mathrm{cor}}}{100}\right)$$



over 10% reductions are becoming unphysical for current model

Physical uncertatinties





conclusion

- r-process nucleosynthesis
  - reproduce A～110 r-element (“weak” r-process)
  - 2nd peak is the limit within the physical uncertainty

    “strong” r-process require 30% decrease of Y_e‘s
    → need different model (multi-D, progenitor, EoS etc.)
- neutrino driven wind
  - similar environment to normal CC-SNe
  - A ～ 90 proton-rich isotopes (ν p-process)

The Core-Collapse Supernova itself is no longer the r-process site?

- MHD Jet supernova (Strong Mag. fields)
  - still optimistic (but need more detailed studies)
  - have large uncertainties in initial condition (magnetic fields and rotation)

- quark-hadron phase transition
  - 1D explosion model:
    “weak” r-process (up to 2nd peak)
  - still have large uncertainties in dynamics
    - multi-D models must eject more neutron rich matter