NIC12 r-process workshop
04 - 05 August 2012

UNI BASEL

# "Are Core-Collapse Supernovae still possible sites for the r-process?"

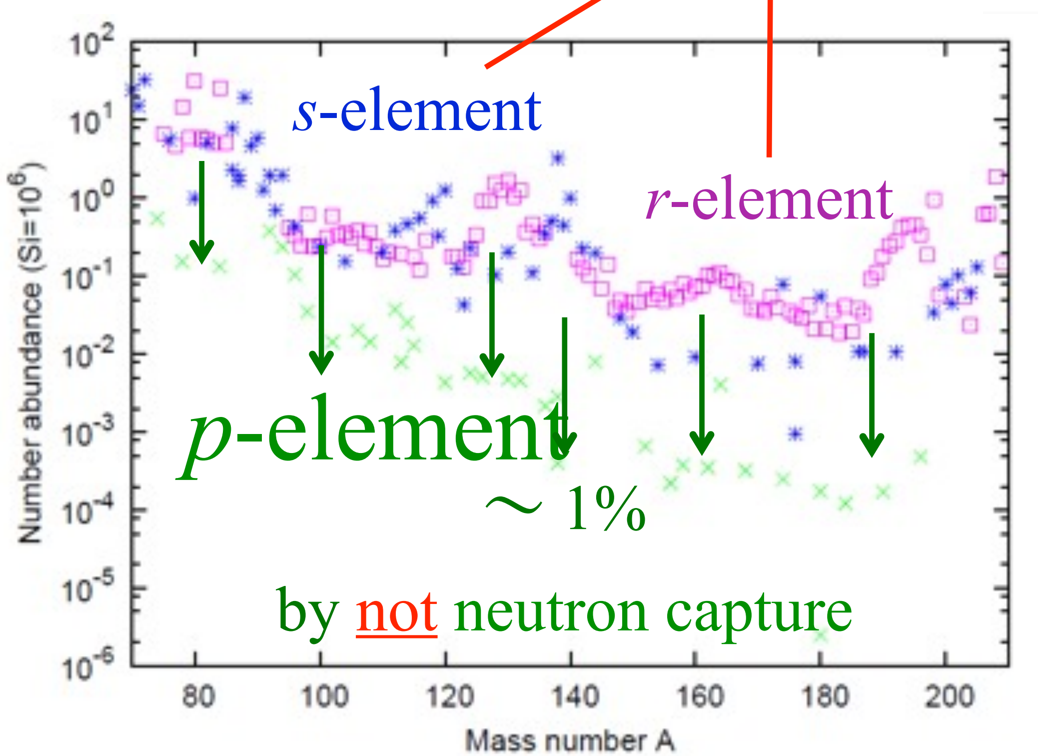
「重力崩壊型超新星は、（まだ）
R過程サイトの天体サイト候補なのか？」

Nobuya Nishimura

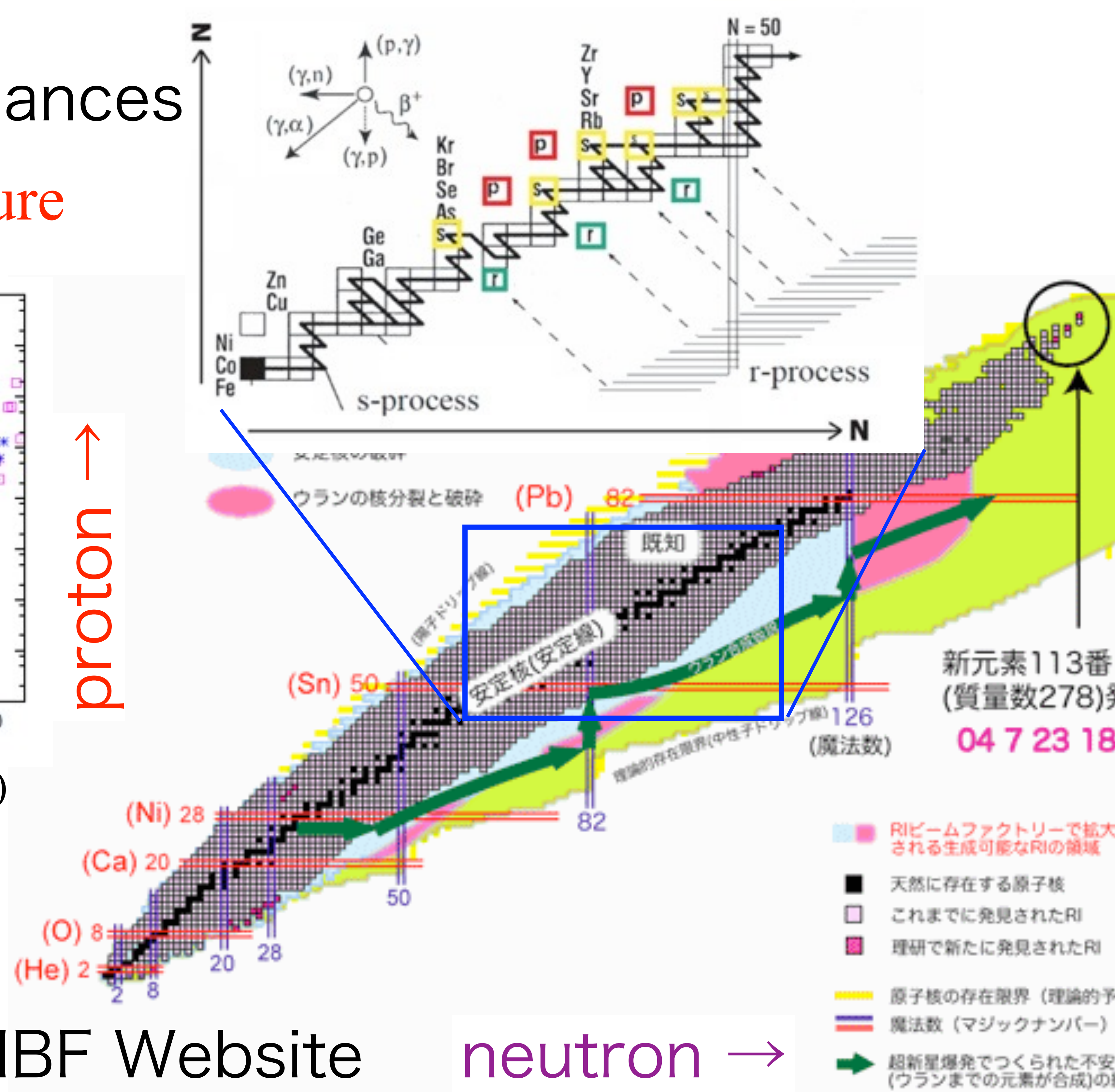
（西村 信哉）

# heavy element nucleosynthesis beyond iron

Solar system abundances

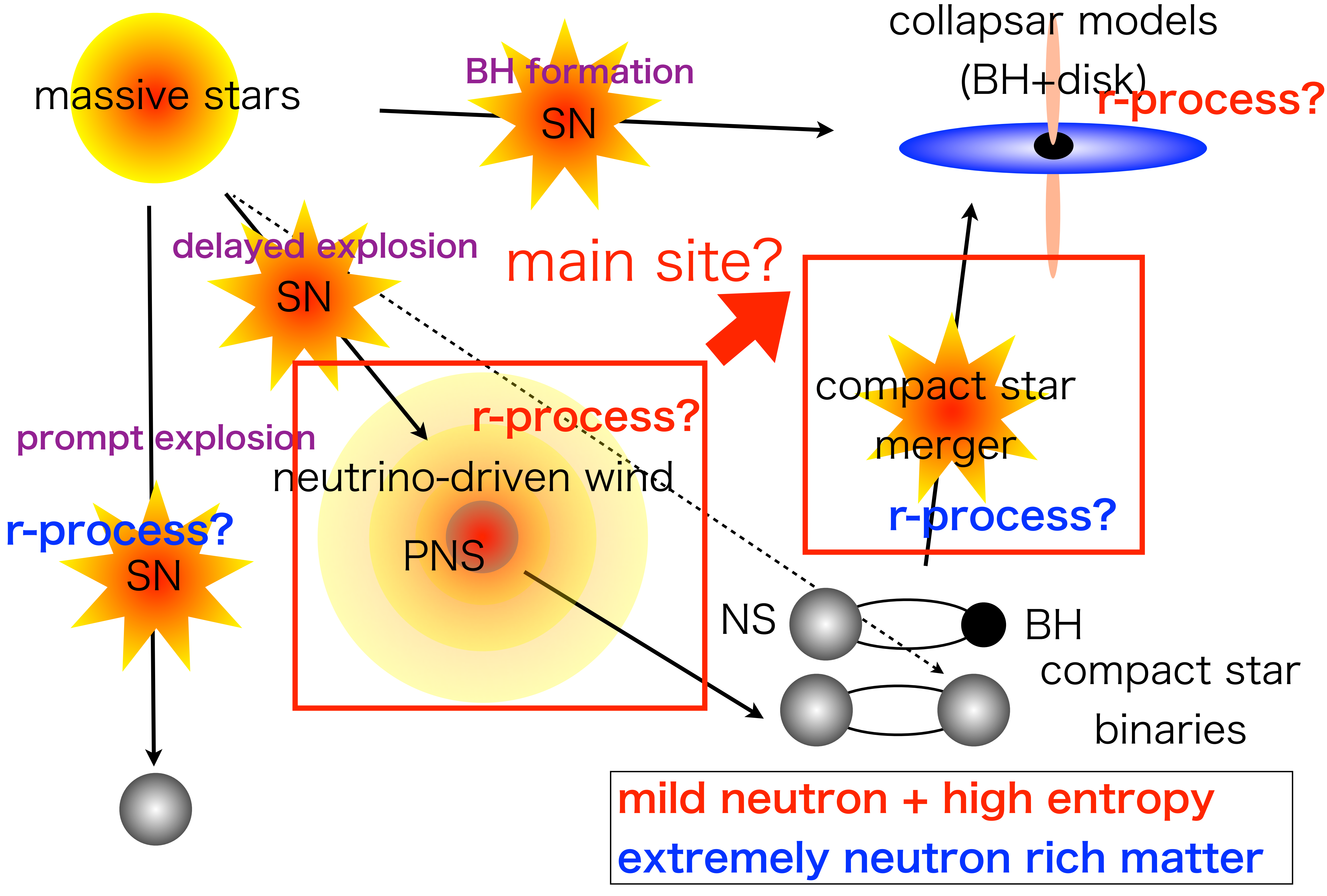



Anders & Grevesse (1989)




RIKEN RIBF Website

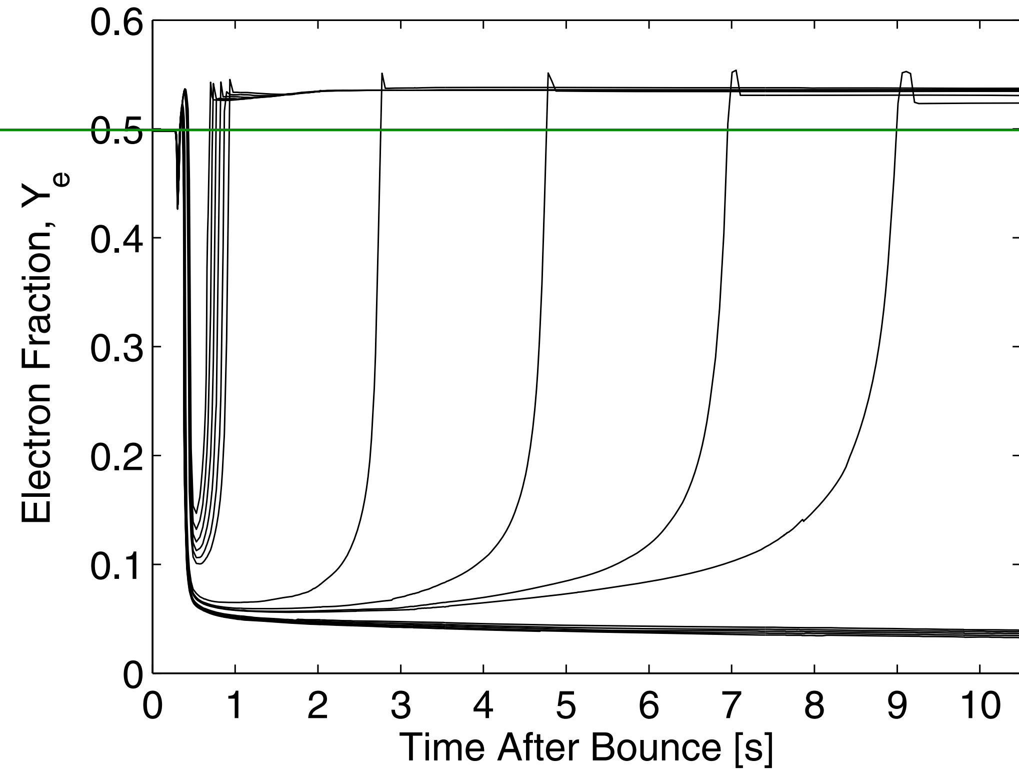
# Where are the astronomical sites?



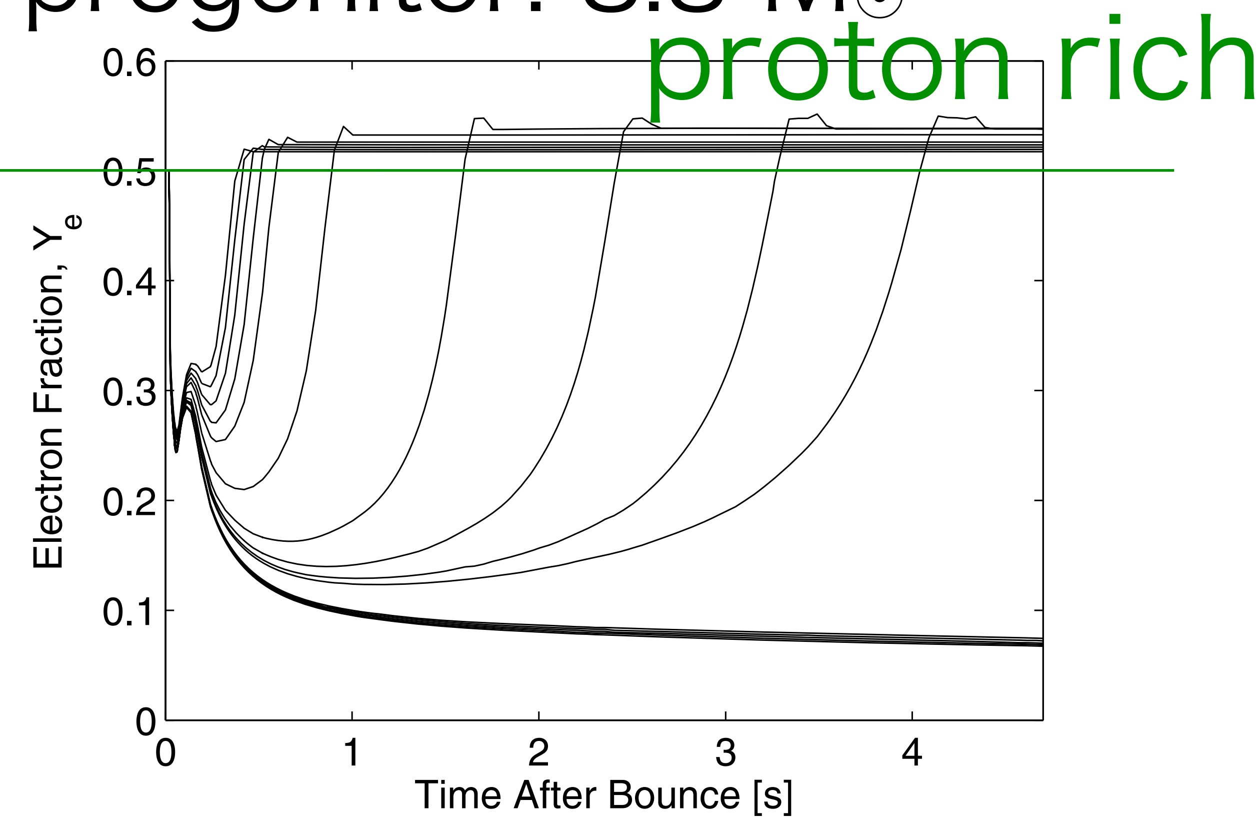
# Newtrino Driven Wind

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 $M_{\odot}$




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

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

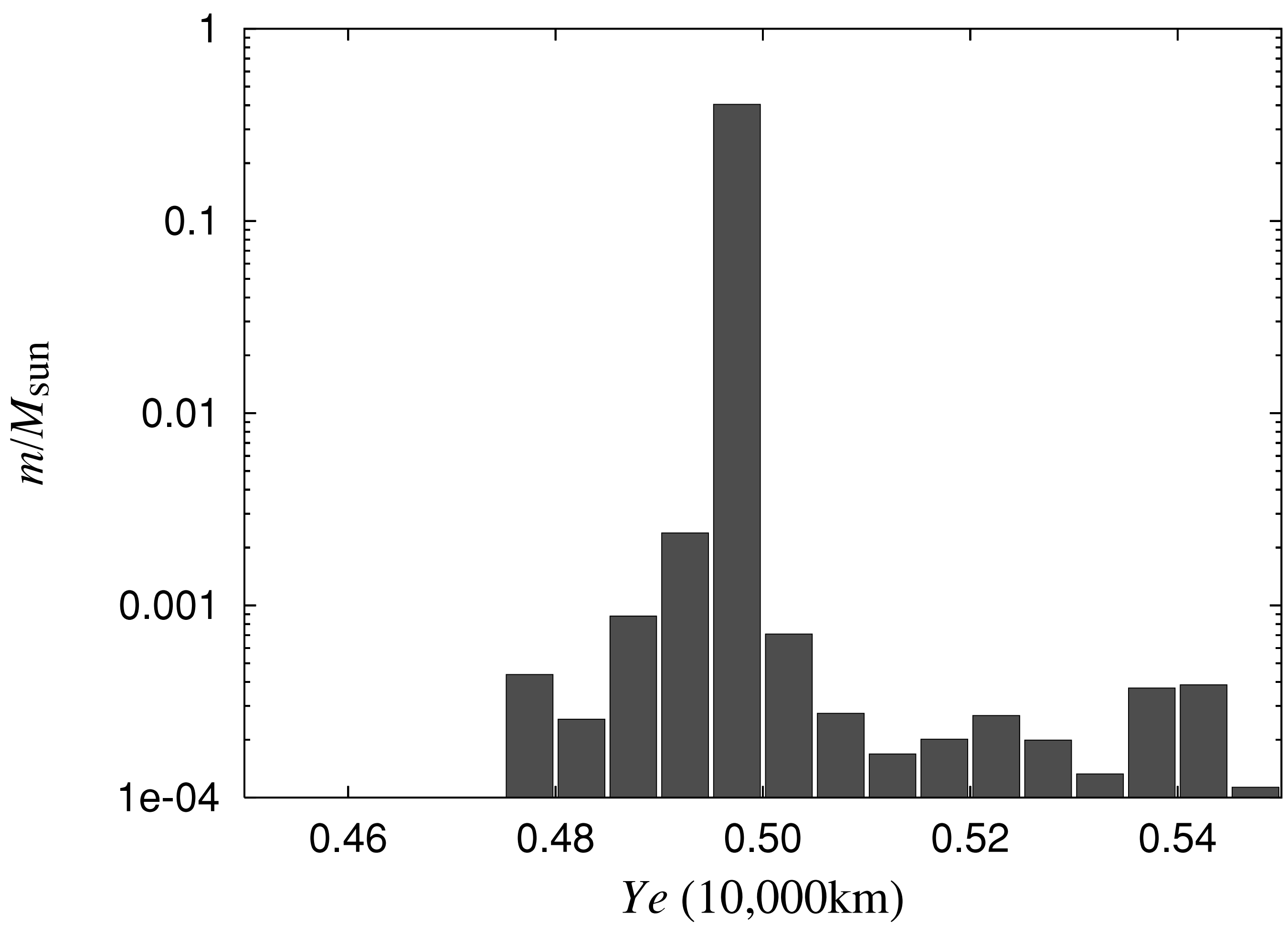
$$e^- + \langle A, Z \rangle \rightleftharpoons \langle A, Z-1 \rangle + \nu_e,$$

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

# SN simulation & nucleosynthesis

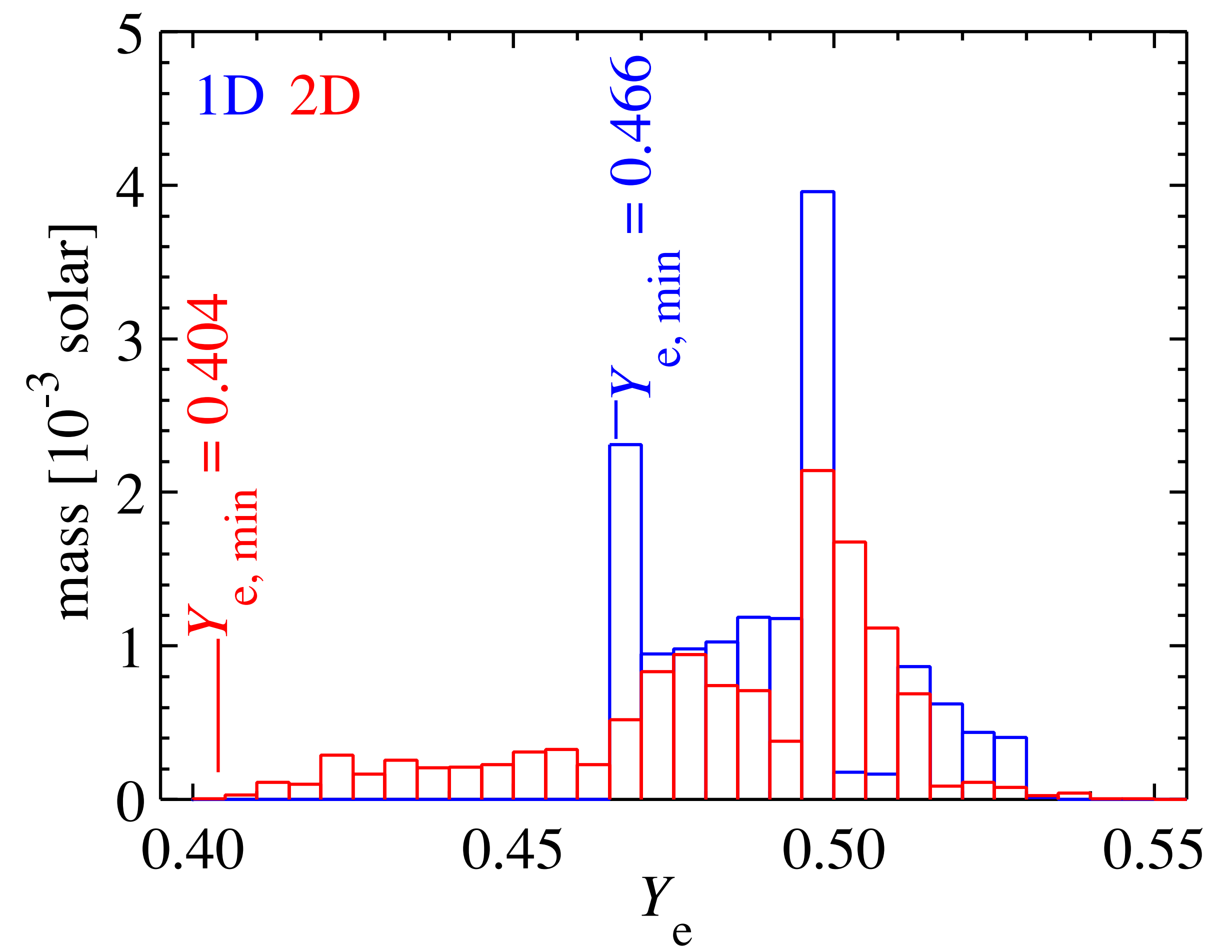
- normal SNe via neutrino heating ( > $10M_\odot$ )
  - $Y_e > 0.48$ ( Fujimoto et al. 2011 )
- ( ONeMg stars ) SNe
  - successful explosion models ( both 1D and 2D )
  - $Y_e > 0.4$ ( 2D model ); weak r-process ( Wanajo 2009, 2011 )

> 10 $M_\odot$ (2D)( Fujimoto 2011 )




~8 $M_\odot$ (1D&2D)

( Wanajo 2011 )



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

extra-scenarios are still certain candidate

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

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

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

Nishimura et al., ApJ in press ( arXiv: 1112.5684 )

# collaborators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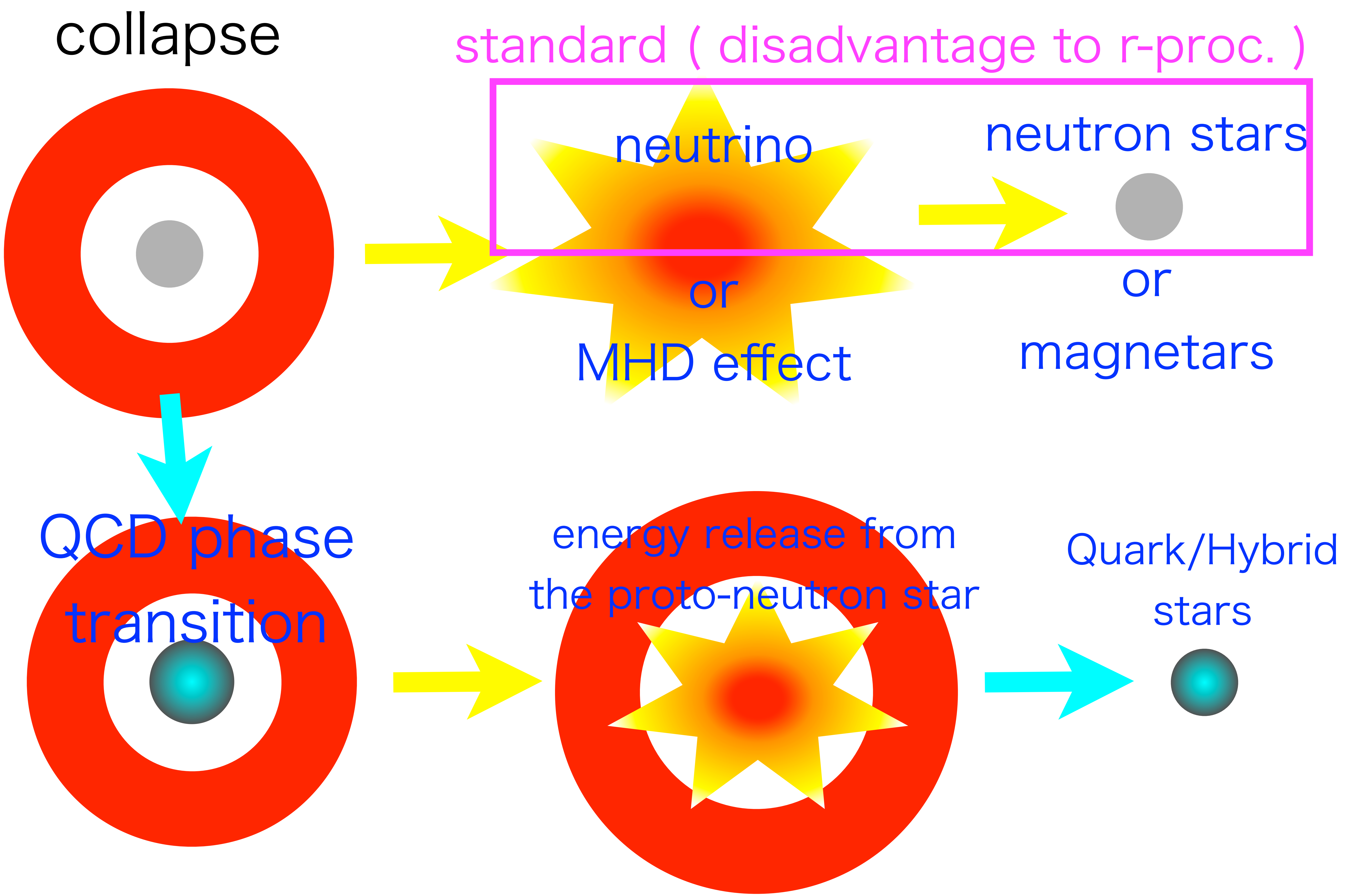
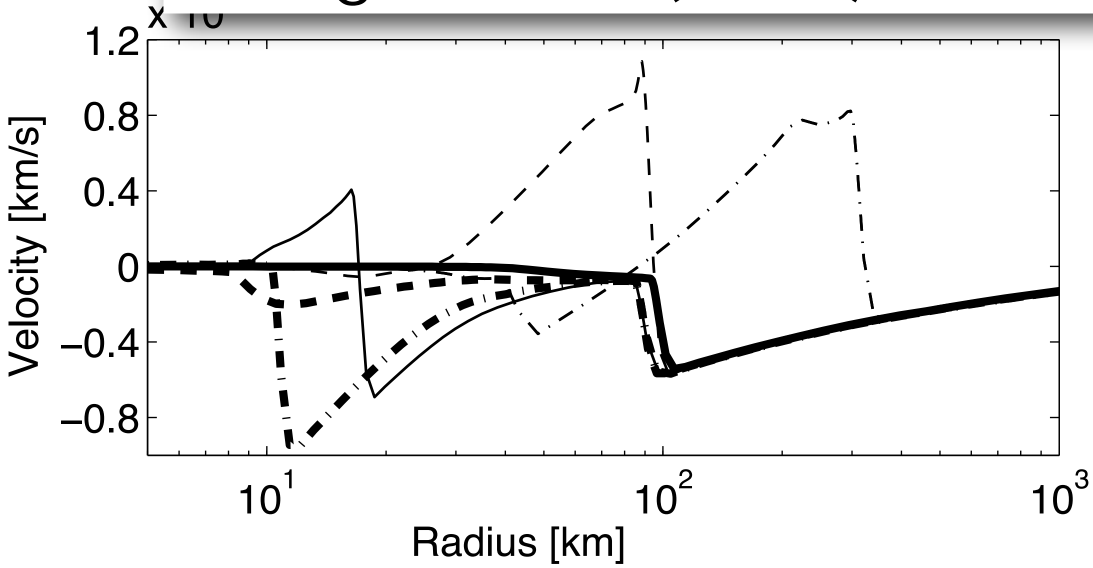
# CC-SN via quark-hadron phase transition



# SNe via the quark-hadron phase transition

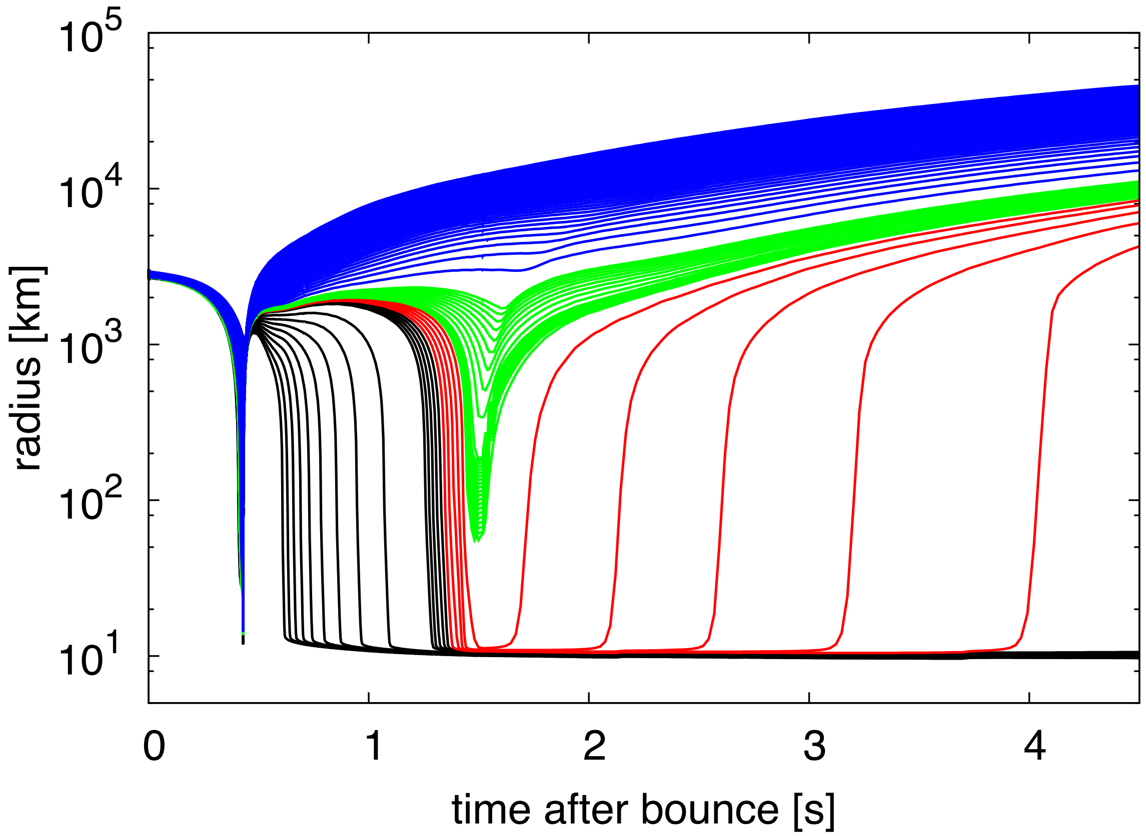
quark-hadron phase transition occurs
after the normal core-bounce :

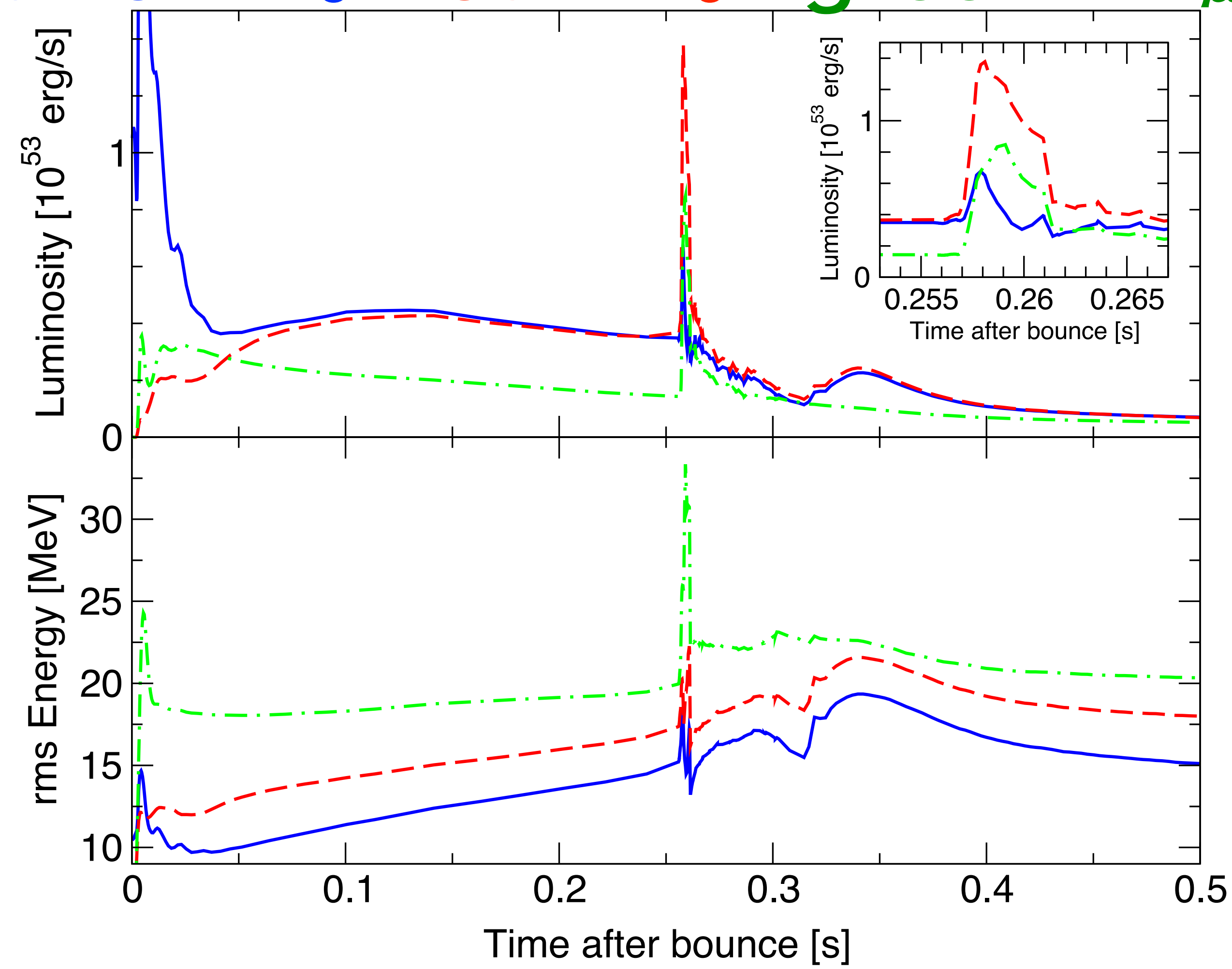
Sagert et al. (2009)、Fischer et al. (2011)




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

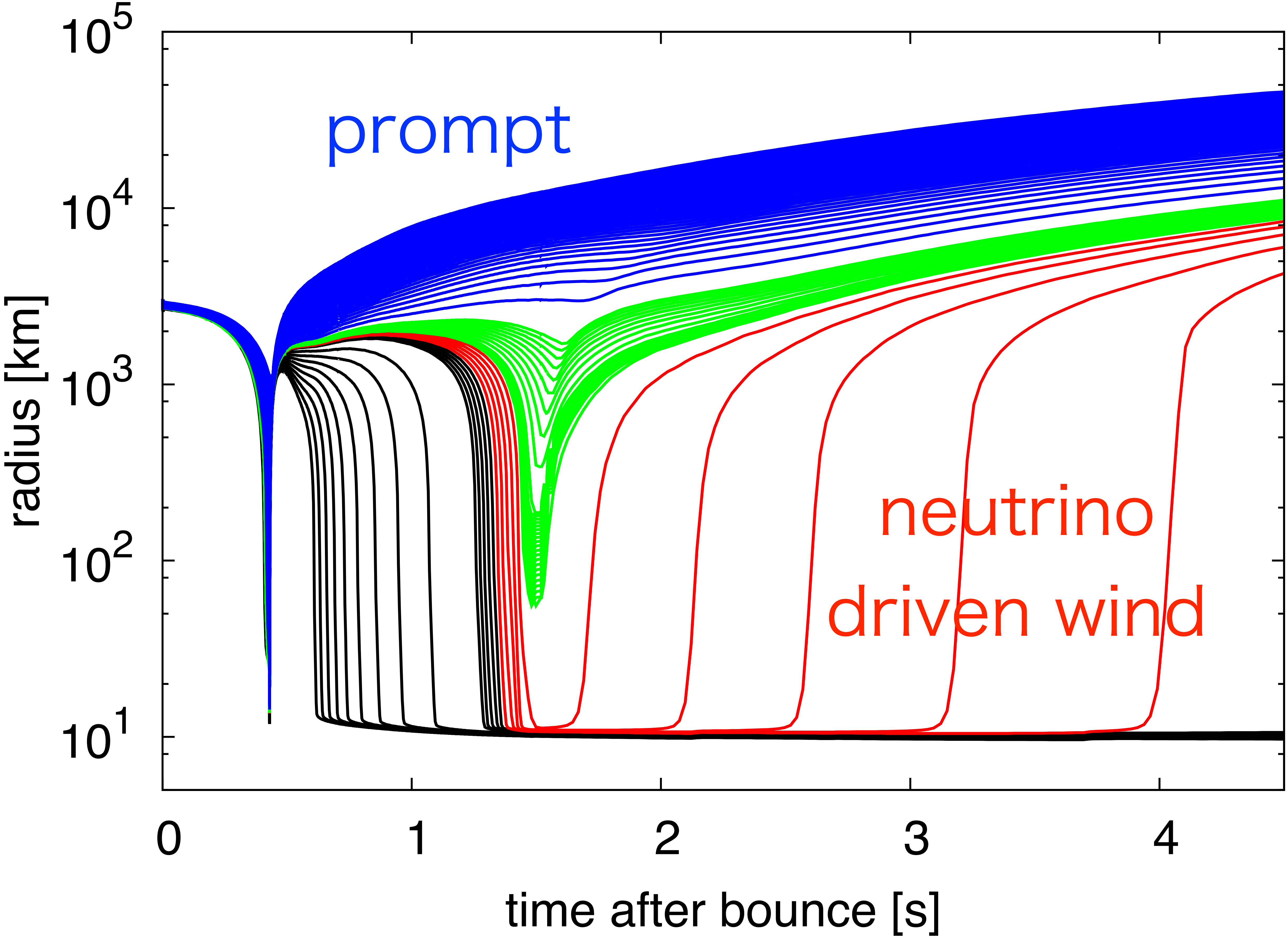
**blue : $\nu_e$ red : $\bar{\nu}_e$ green : $\nu_{\mu/\tau}$**



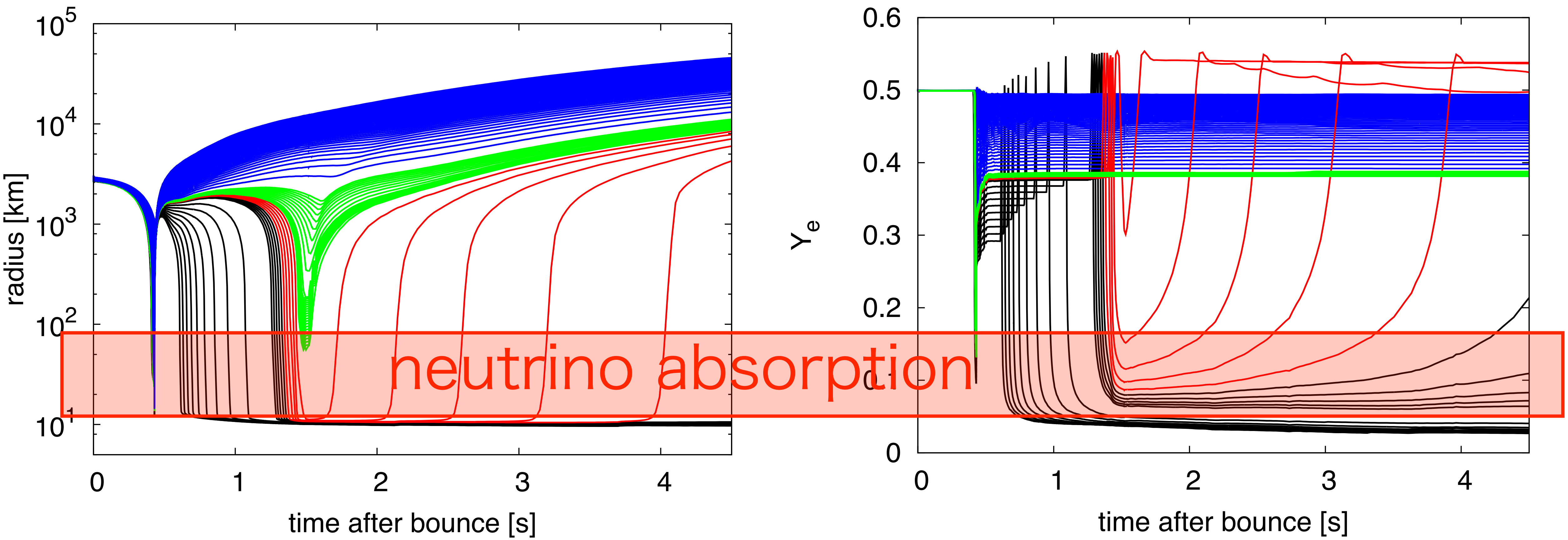




Dasgupta et al. PRD 81 (2010)

# the explosion model



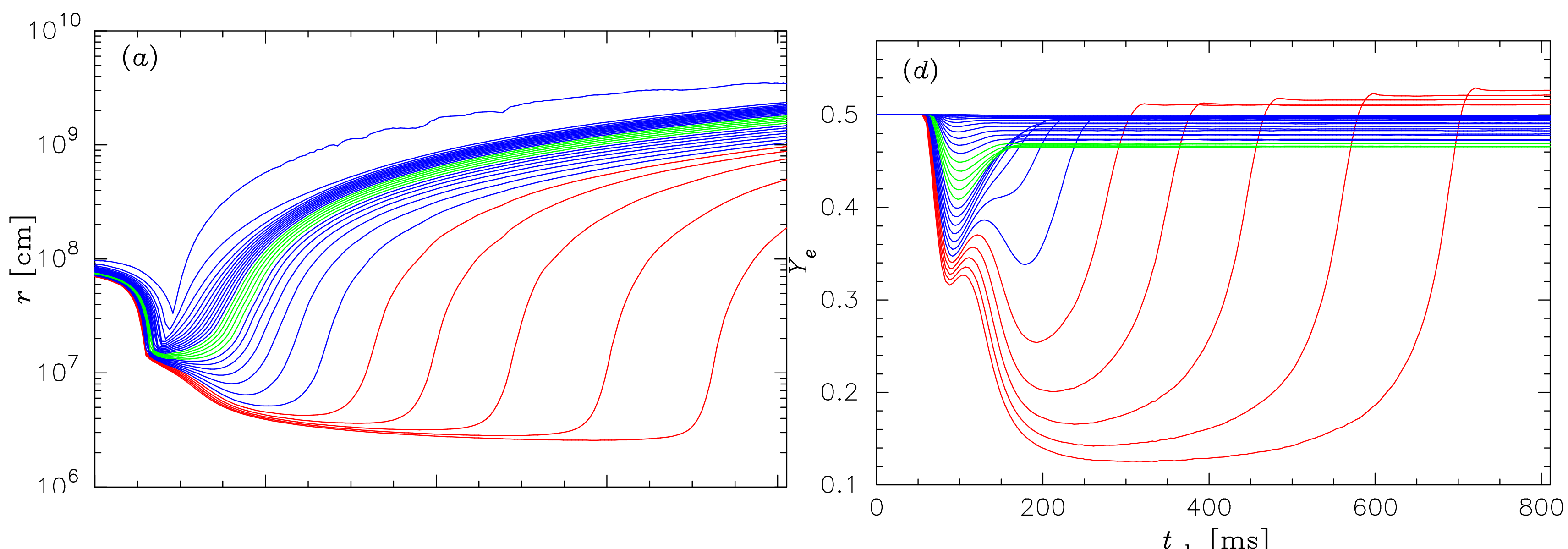
# ejection process & neutron richness



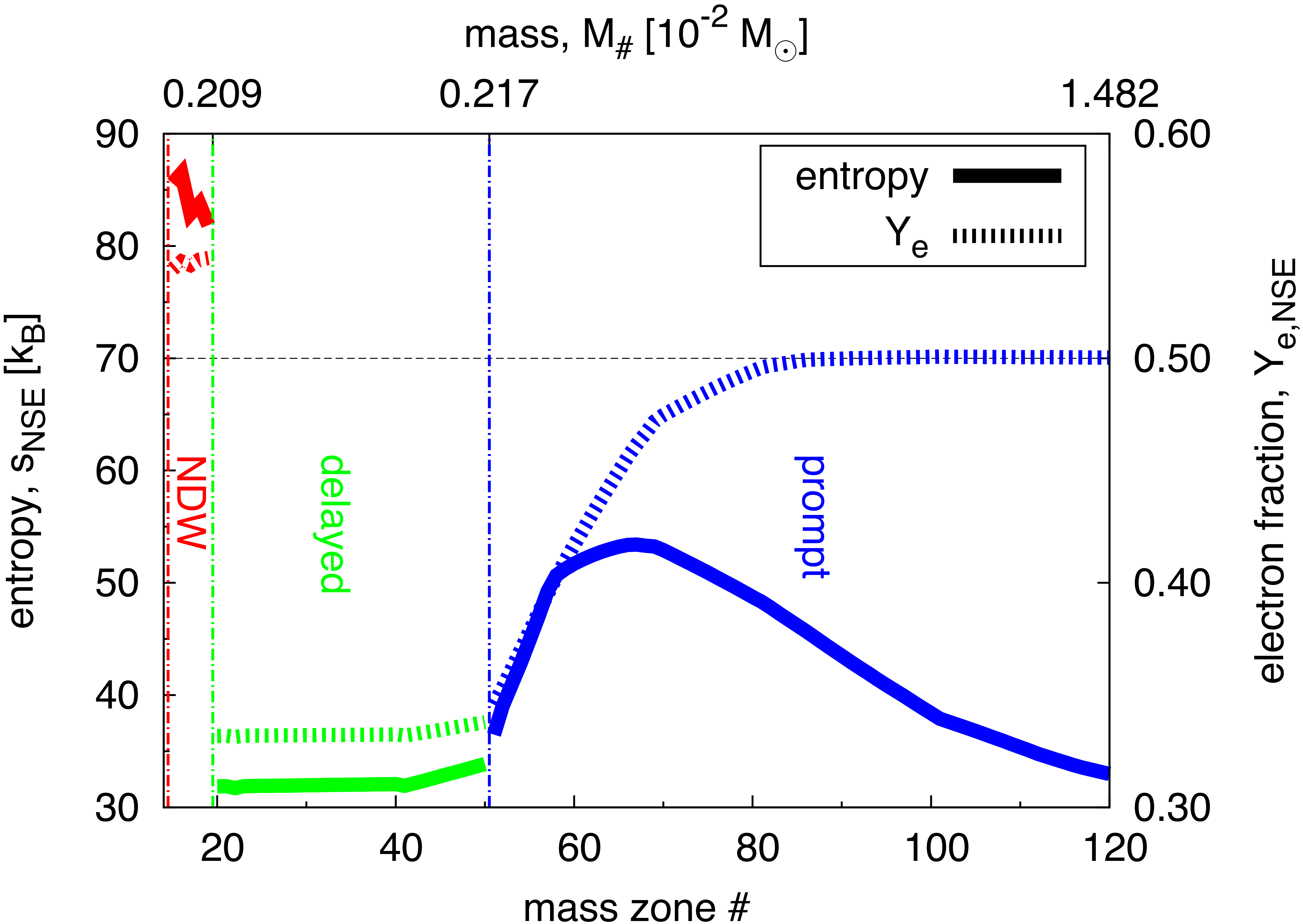

ONeMg( 8 M$_\odot$)

Kitaura et al. 2006

(MPA group)

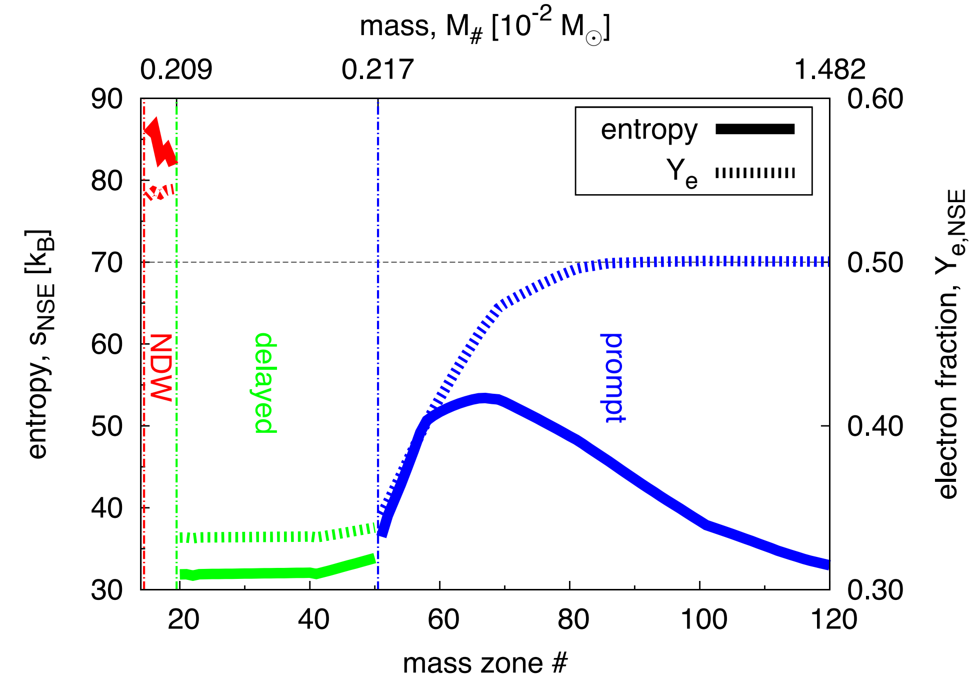


# entropy & $Y_e$ : the end of NSE ( T = 9 GK )

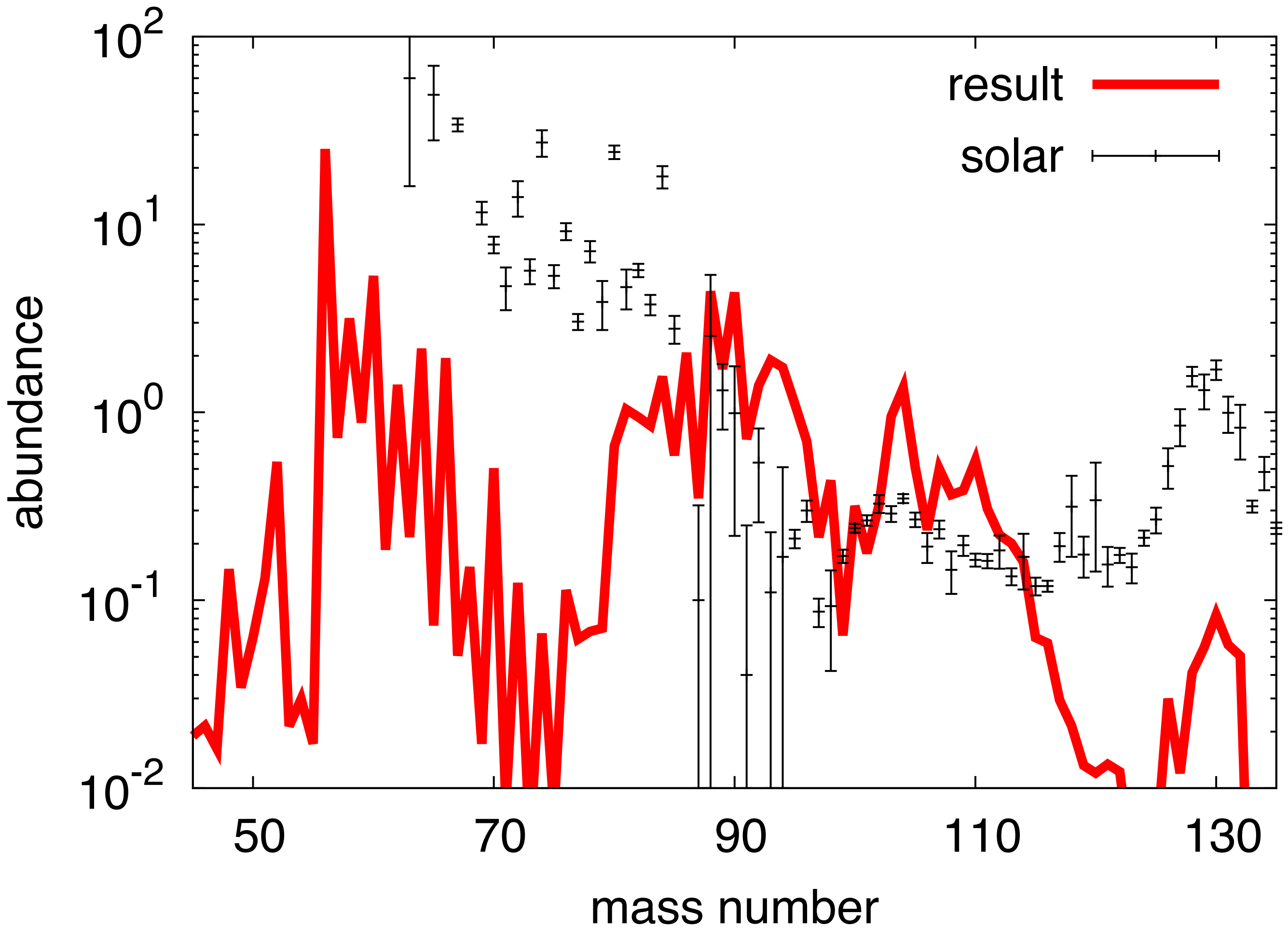


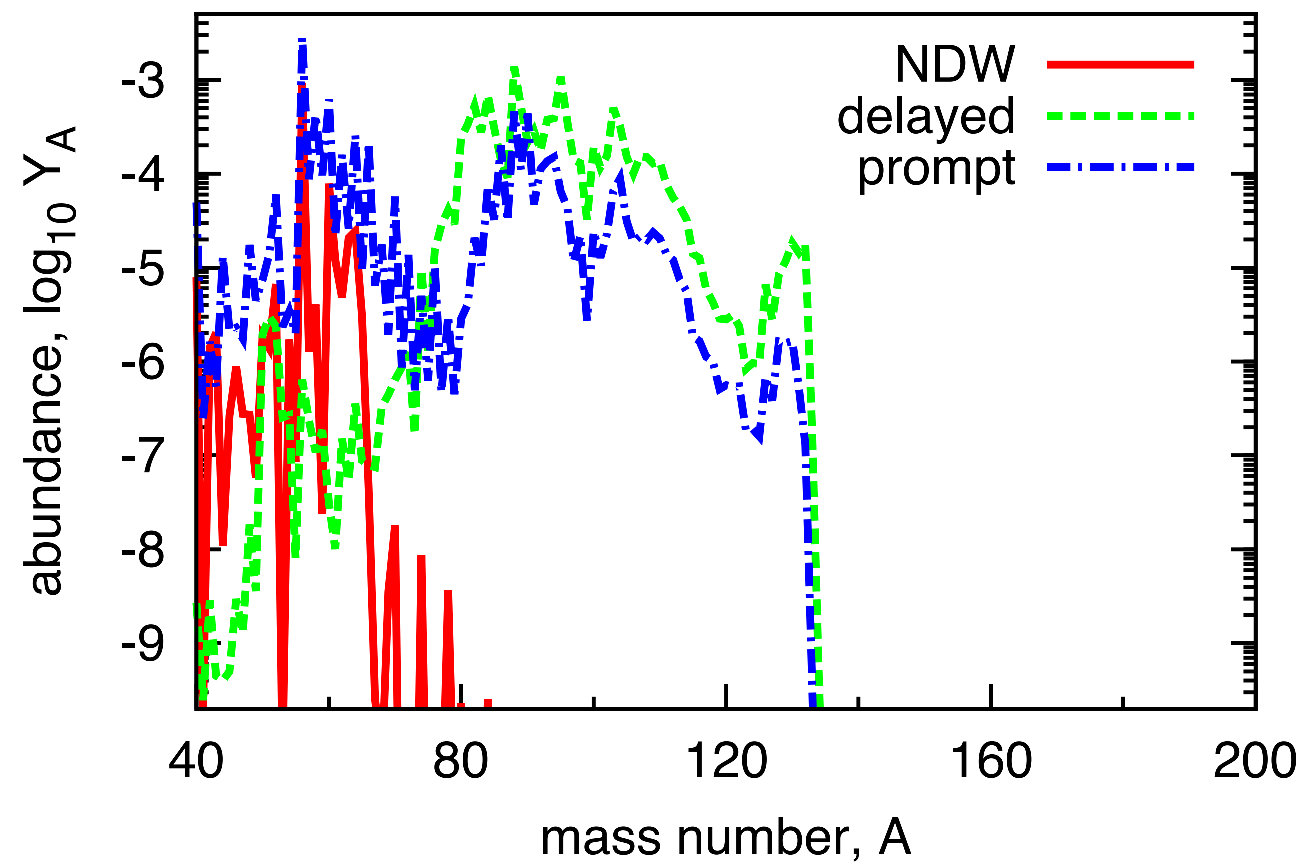
# the final abundances:

## each zone




## total ejecta



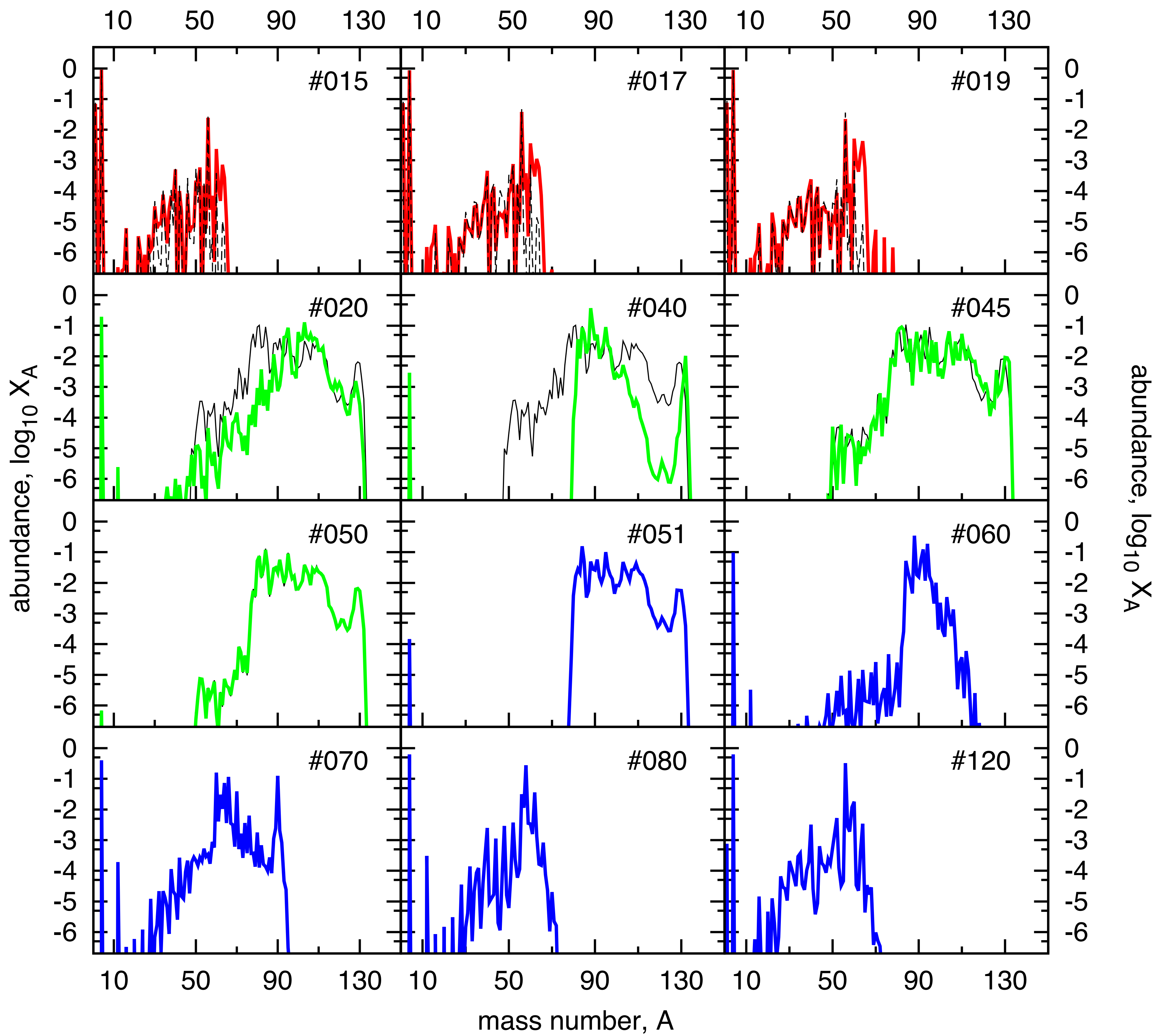



# final abundances (represented) : each zone

neutrino driven wind

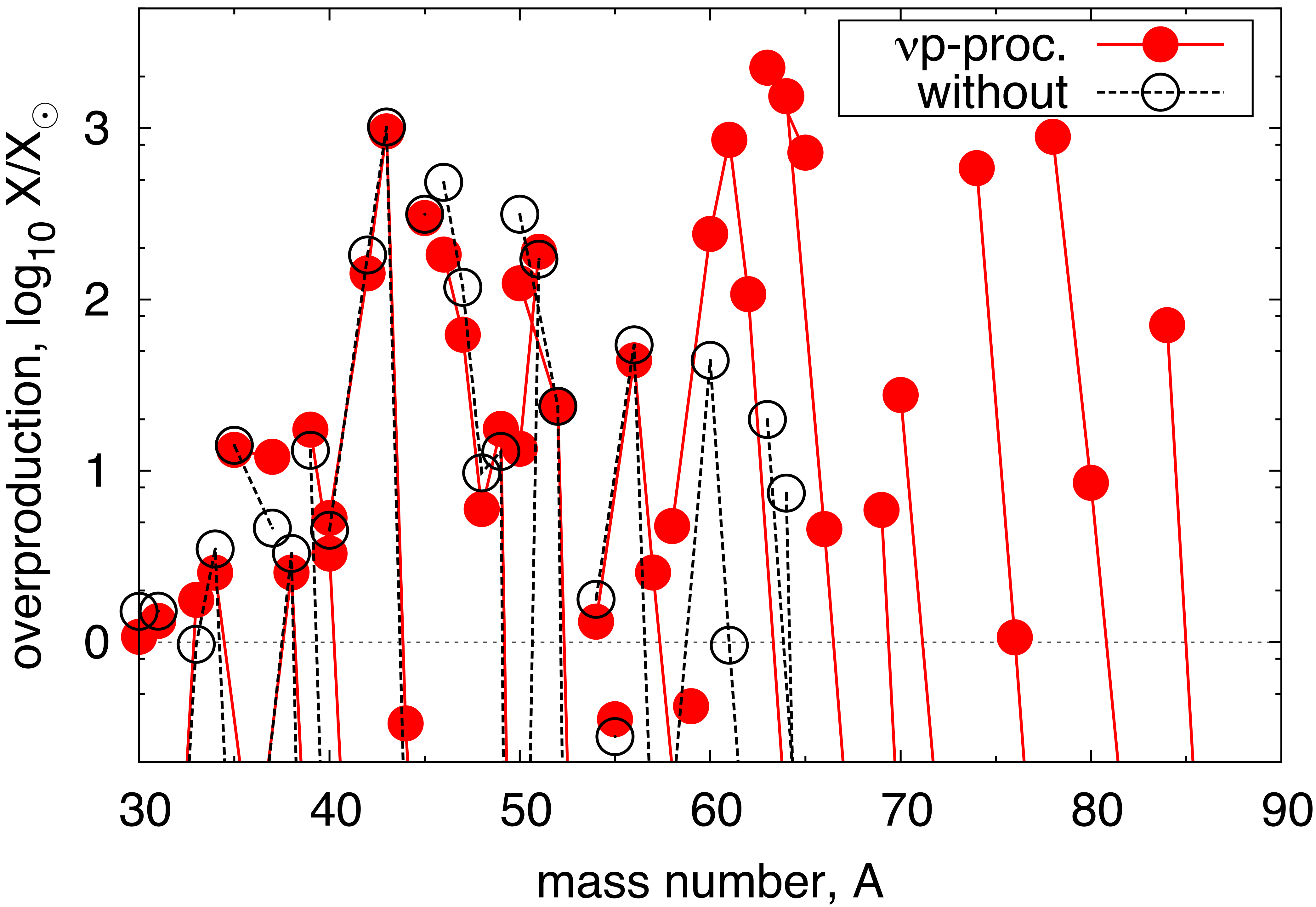
inner "delayed"

outer "prompt"



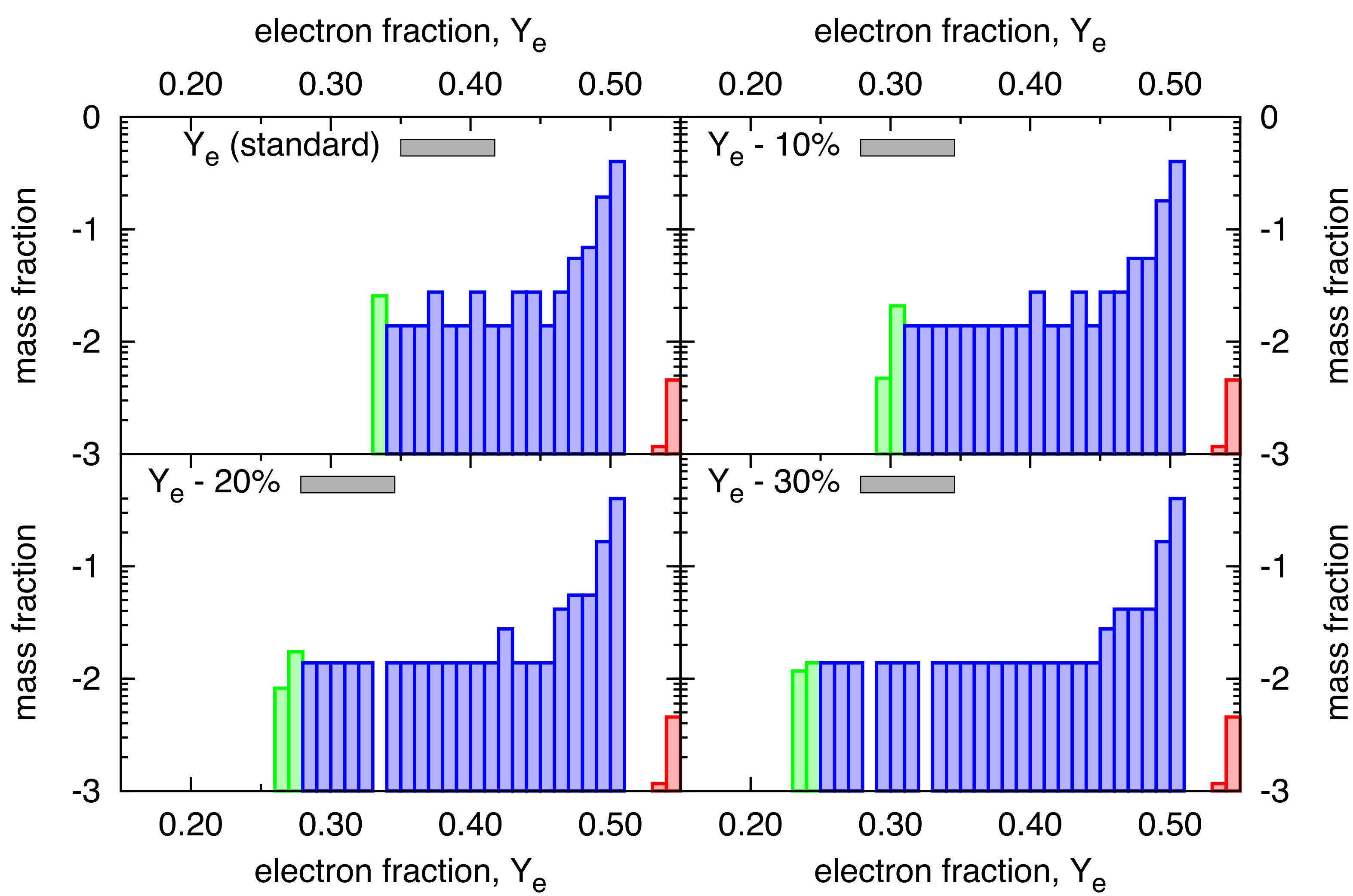
# final abundances: neutrino driven winds

A < 85 elements are produced via $\nu$ p-process



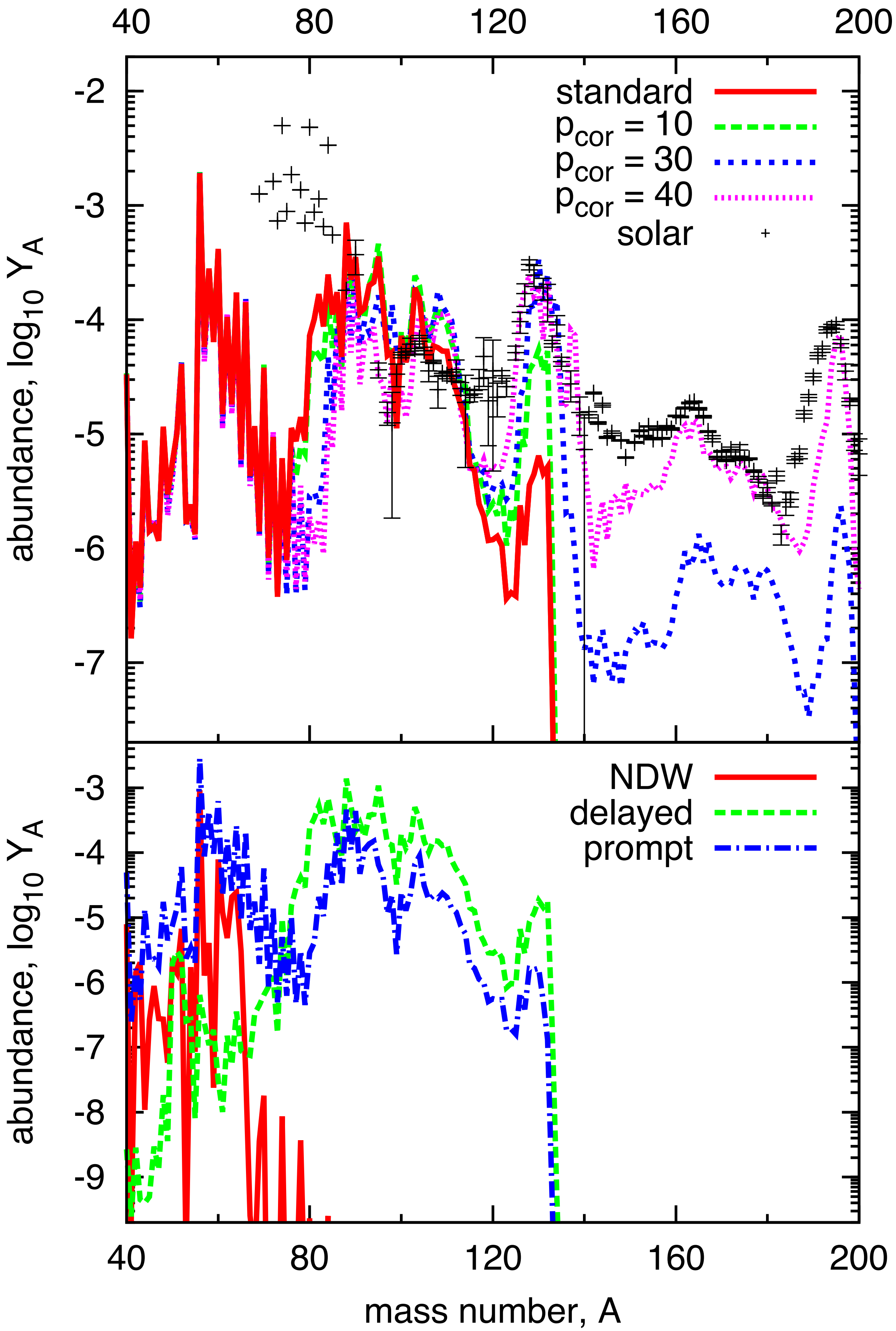
# physical uncertainties: $Y_e$

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



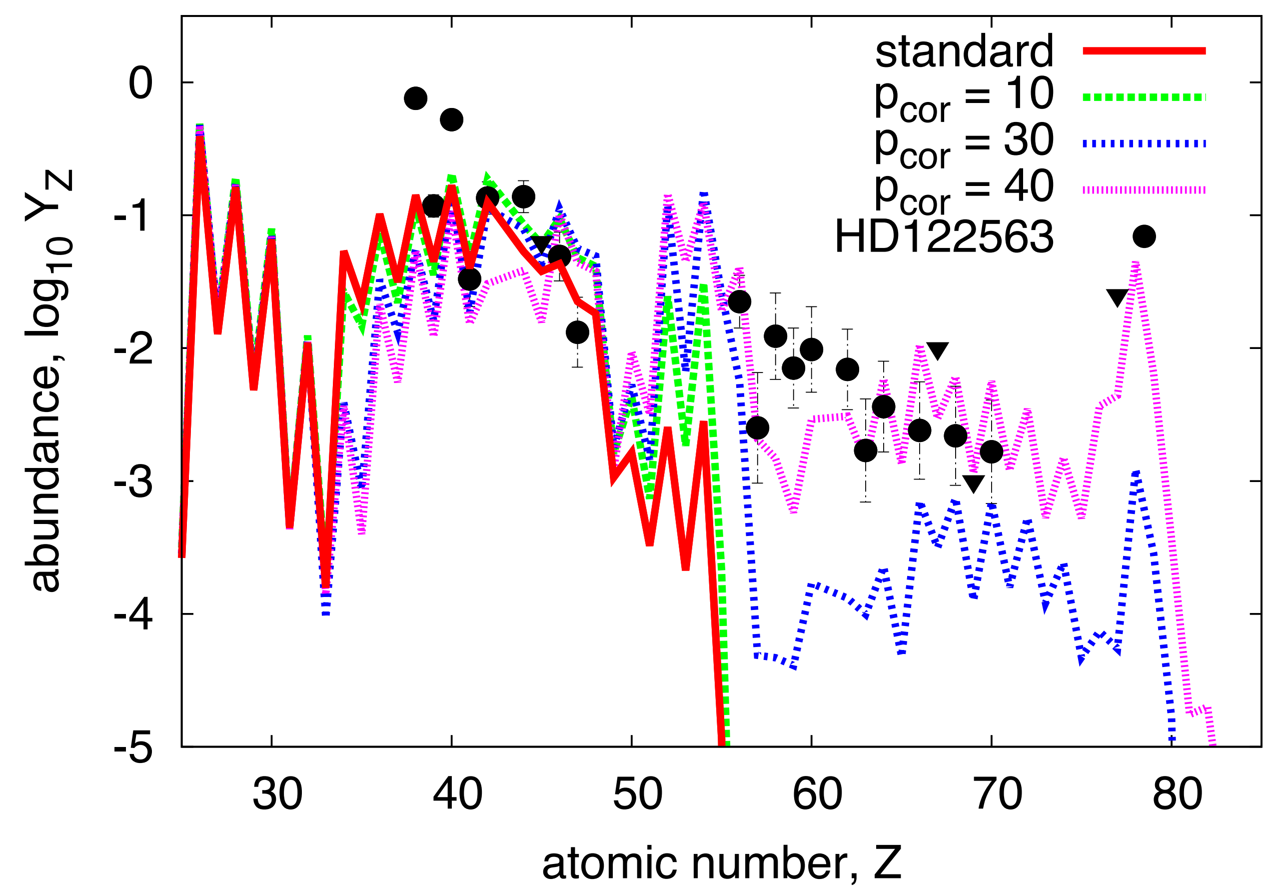

over 10% reductions are becoming unphysical for current model

# $Y_e$ uncertainties with observation




solar system ( strong r-process )

Metal poor stars ( weak r-process )

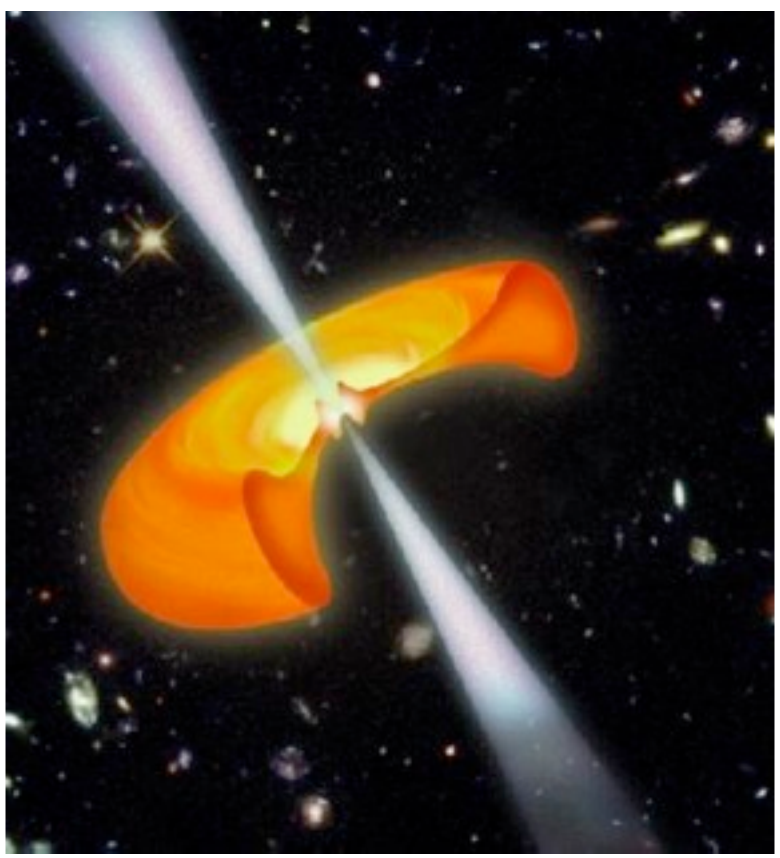


# conclusion

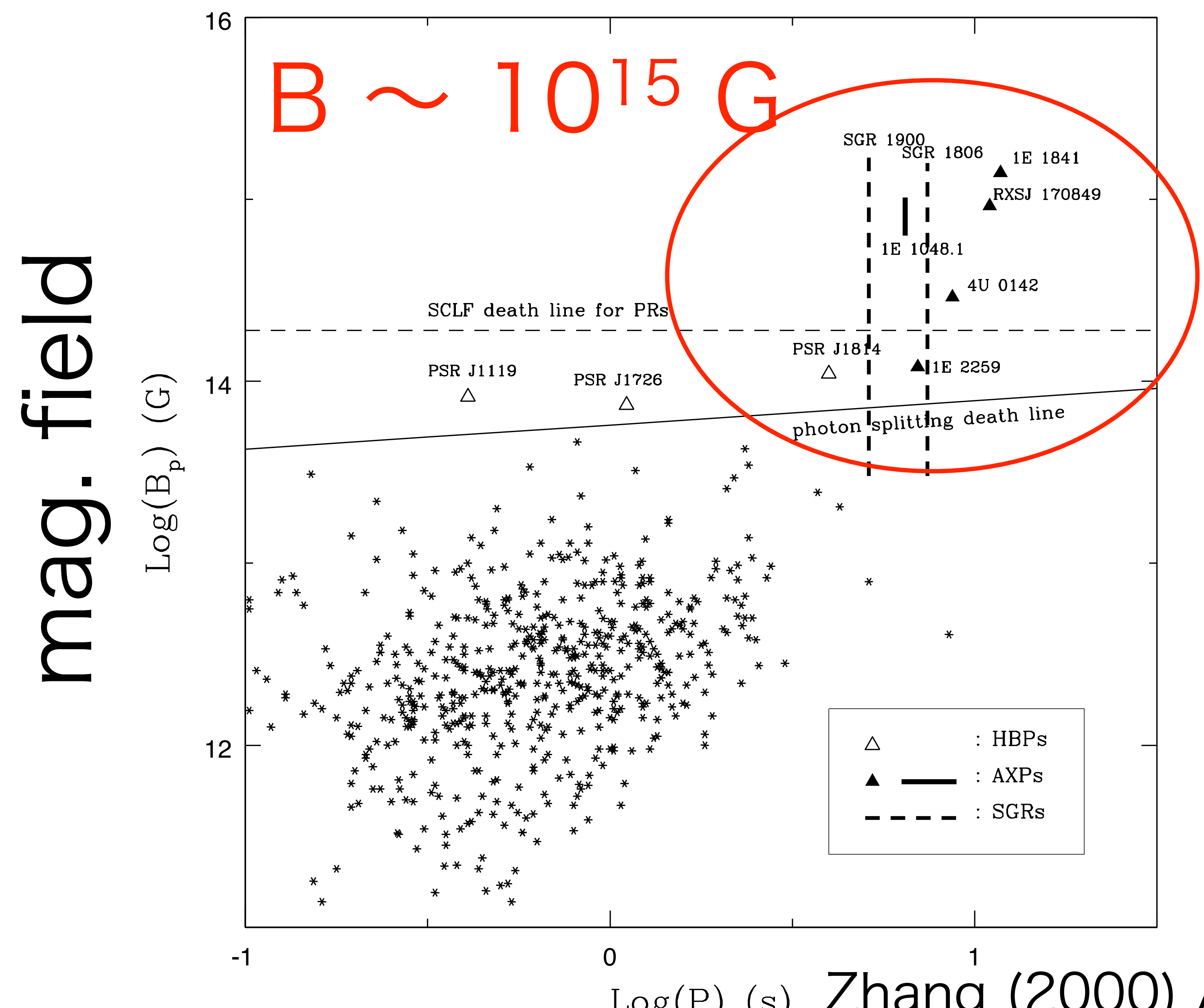
- r-process nucleosynthesis
  - reproduce A～110 r-element ( “weak” r-process )
  - $2^{nd}$ peak is the limit within the physical uncertainty
  - “strong” r-process require 30% decrease of $Y_e$‘s
    → need different model ( multi-D, progenitor, EoS etc. )
- neutrino driven wind
  - similar environment to normal CC-SNe
  - A ～ 90 proton-rich isotopes ( $\nu$ p-process )

# Jet-like SN induced by Magnetic fields

- 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

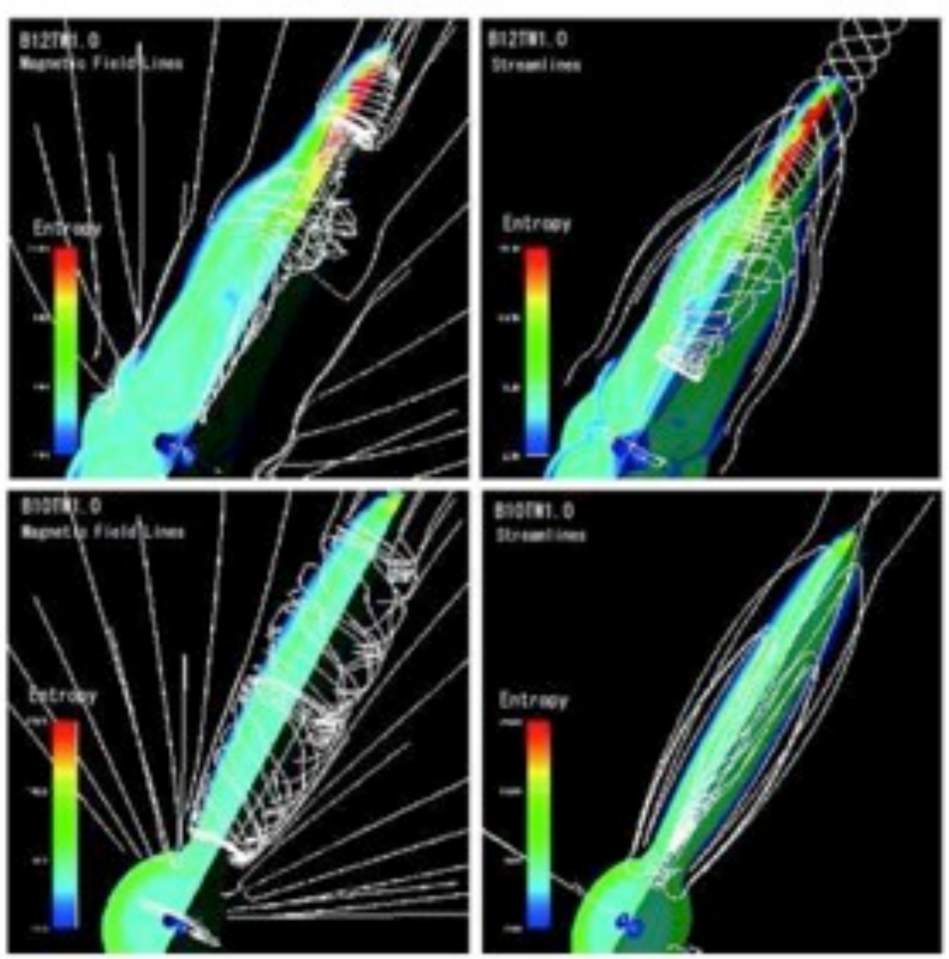



Zhang (2000) APJL

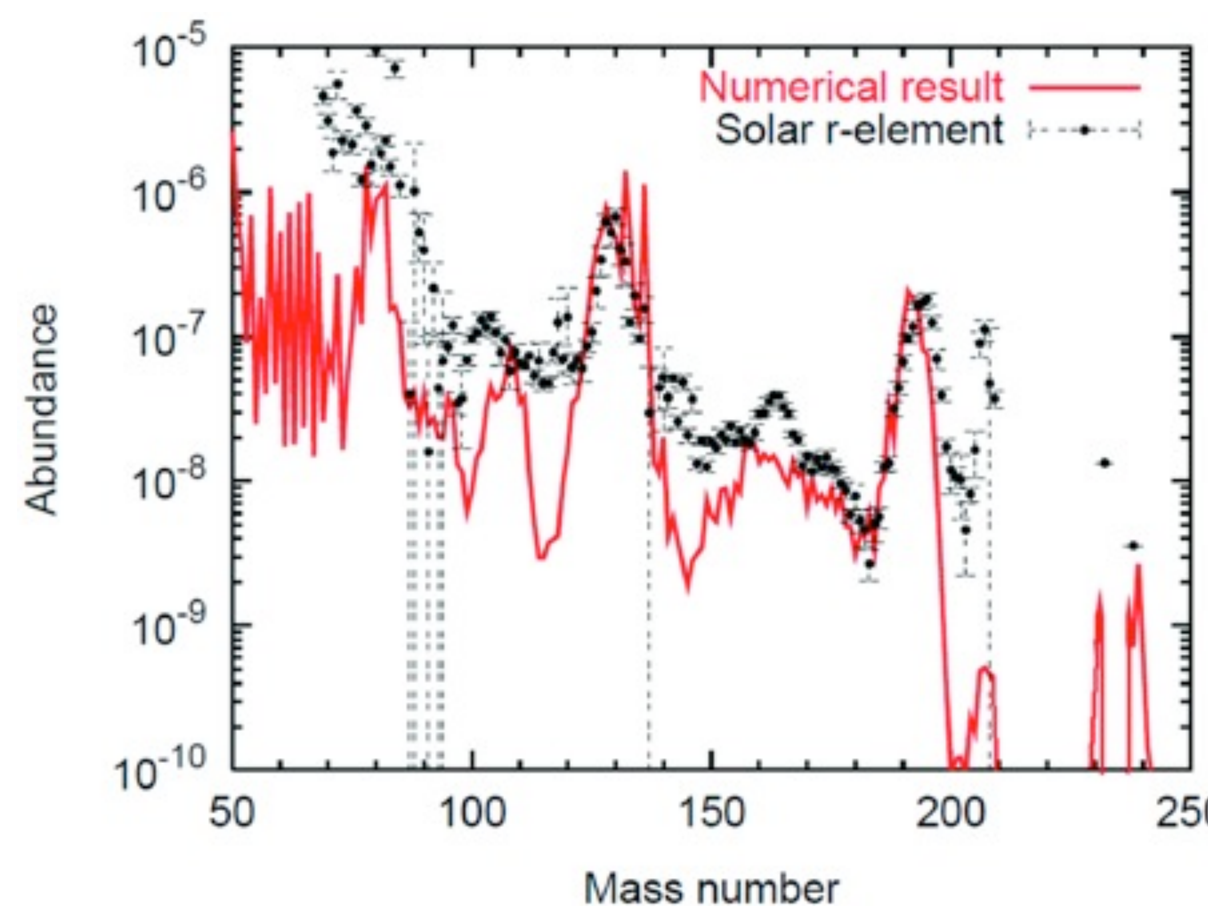
# MHD "Jet" supernova explosion :

- 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

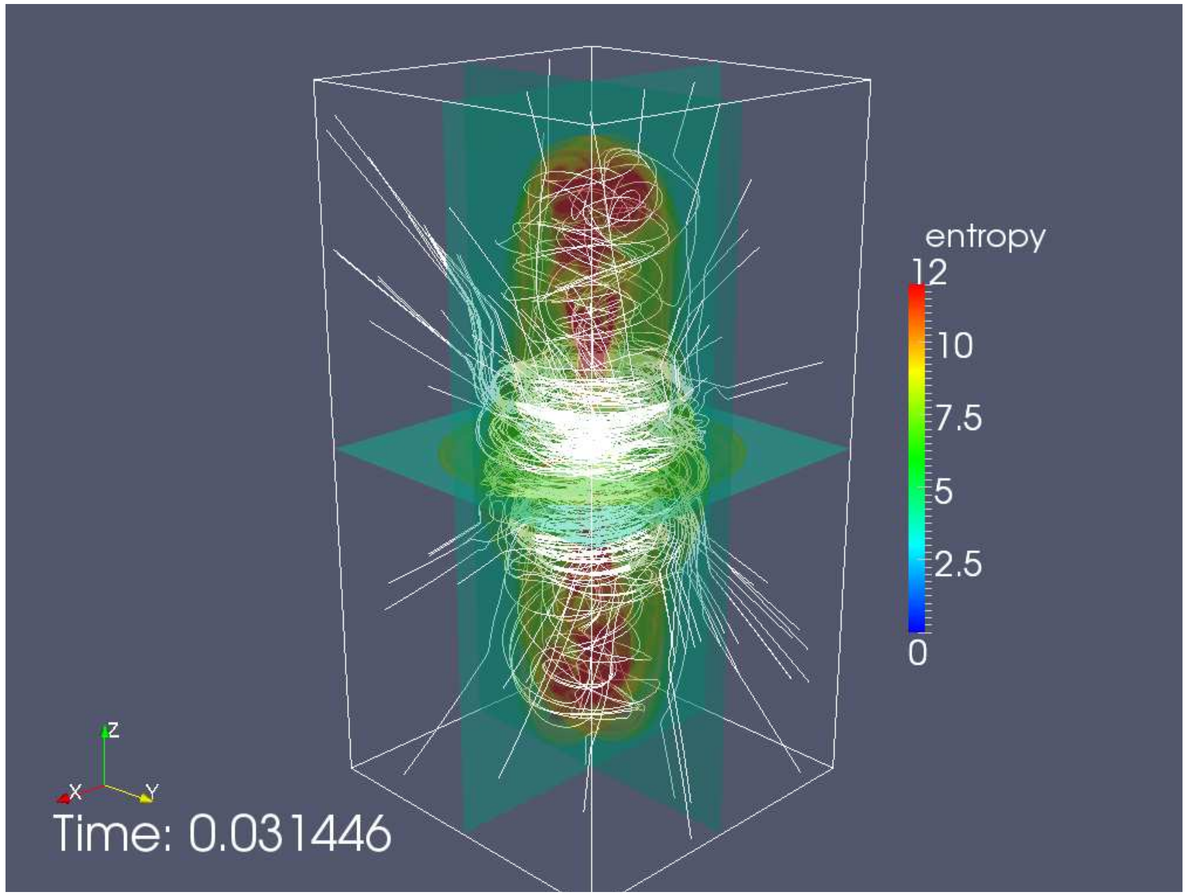


Nishimura 2010



# The first r-proc. study based on 3D MHD models

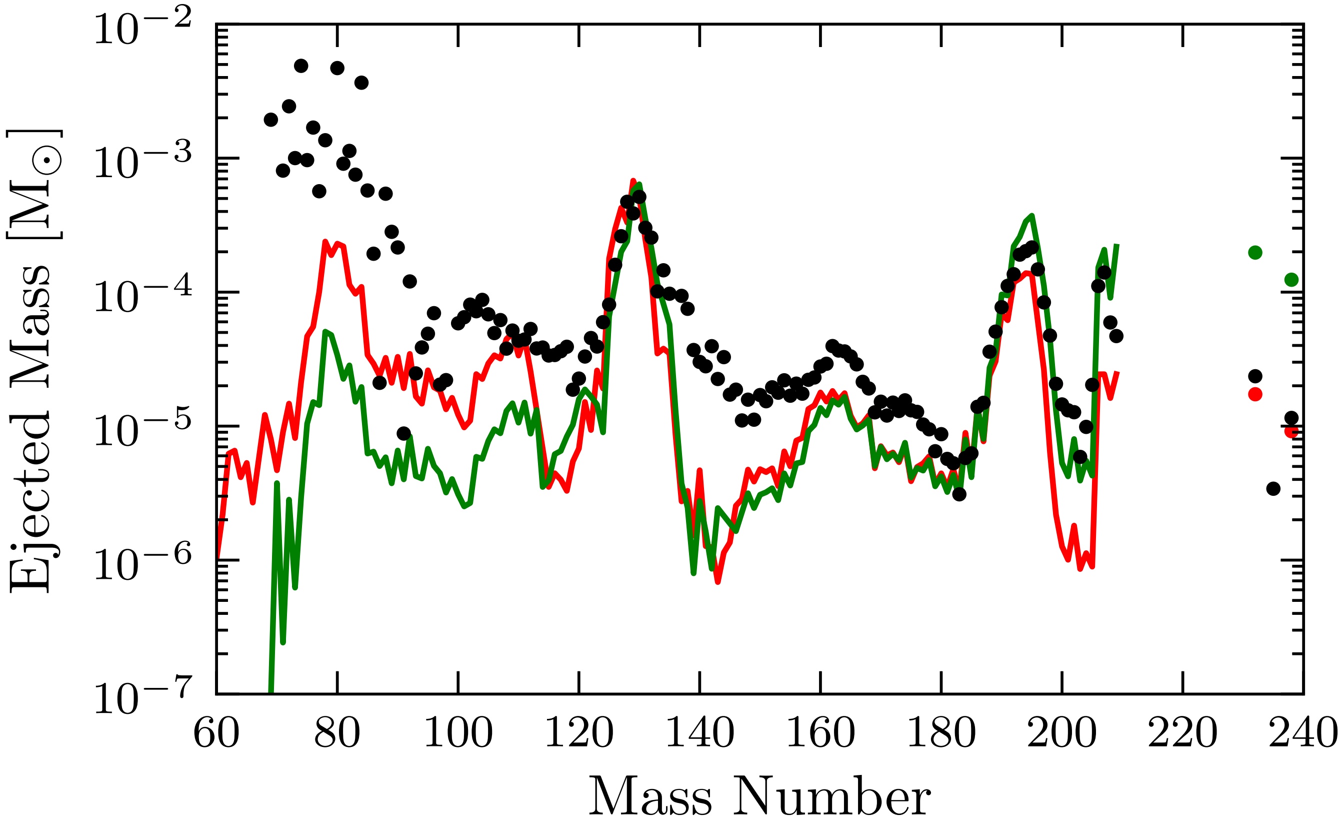
Winteler et al. ApJL 2012; ( Basel collaboration )




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

**red : includes neutrino**

**green : no neutrino**



# The first r-proc. study based on 3D MHD models

In the context of r-proc. study (and also explosion mechanism), there are still a lot of open questions.

- long-term simulations
- systematic survey of wide range of mag. and rot.
- weak initial mag. field rot.
- detailed micro-physics (neutrino, EOS and mag. fields, etc.)
- detailed macro-physics (magneto-rotational instabilities)
- relation to (optical) observation
- large breaking of axis-symmetry
  - different rotational and mag. axis ...
- ...

long-term simulations based on wider range of initial conditions under axis-symmetry. (2D hydro. with rot. and mag. fields)

# 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