Nucleosynthesis of trans-iron elements in core-collapse supernovae and neutron-star mergers

Shinya Wanajo (TUM/MPA)

EMMI-JINA workshop:
Nucleosynthesis beyond iron and the lighter element primary process
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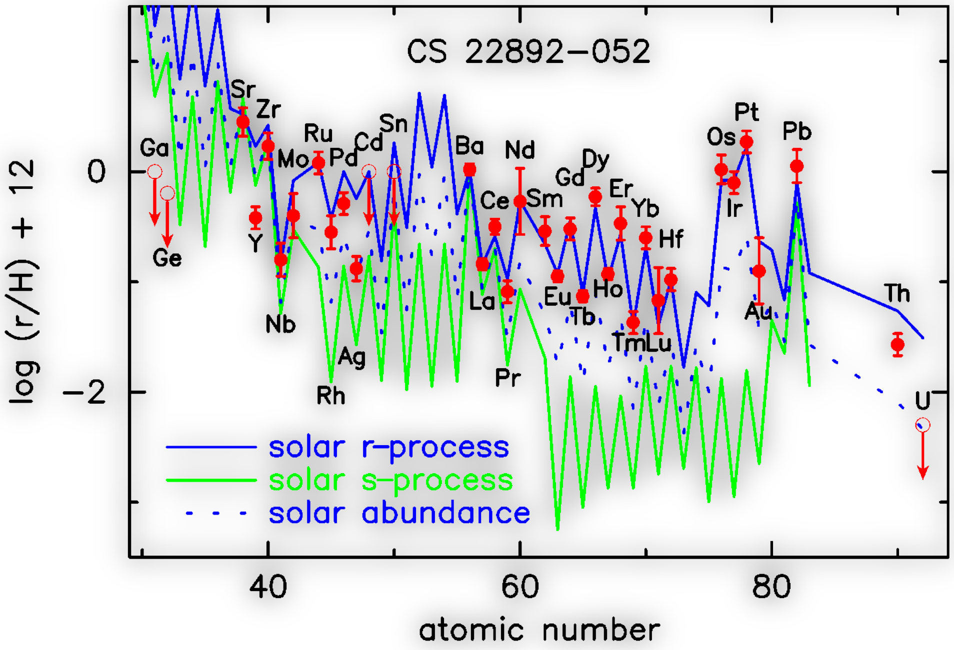
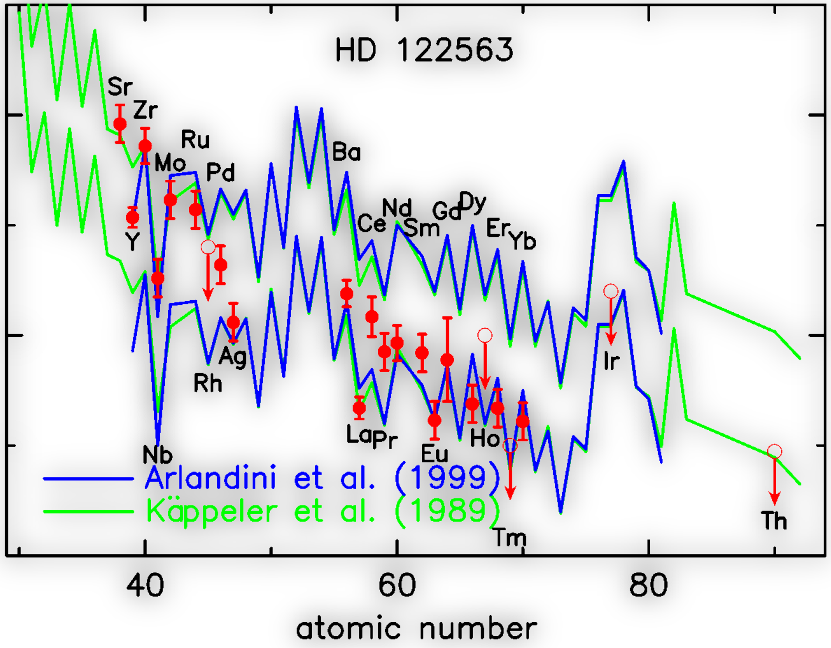
Max Planck Institute
for Astrophysics

r-process “rich” and “poor” stars

Sneden, Cowan+2003



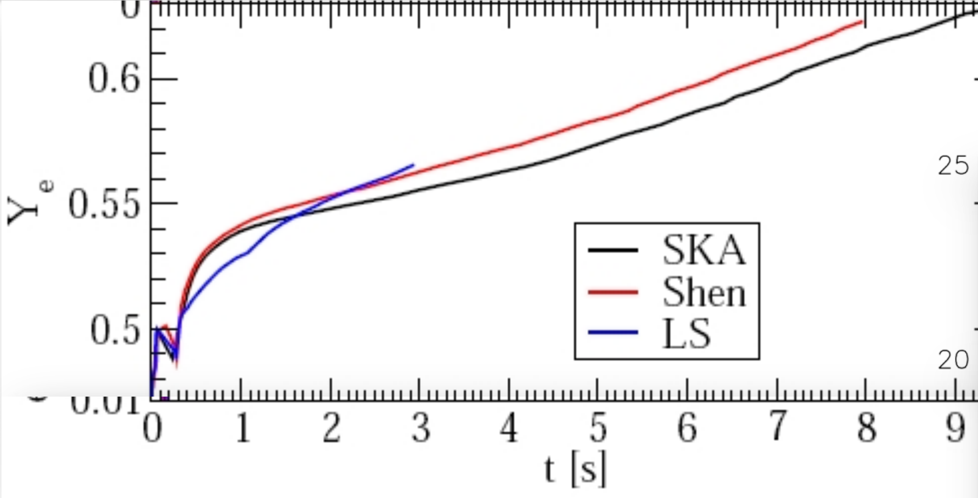
Honda, Aoki, Ishimaru, Wanajo, Ryan 2006



- ❖ r-rich: a few % of EMP stars
- ❖ good agreement with the solar r-pattern for $Z > 50$
- ❖ not good for $Z < 50$, slightly underproduced?

- ❖ r-poor: bulk of EMP stars
- ❖ poor agreement with solar r-process or s-process patterns
- ❖ high Sr-Y-Zr/Ba-Eu, downward trend with Z

neutrino-driven wind is "proton-rich"

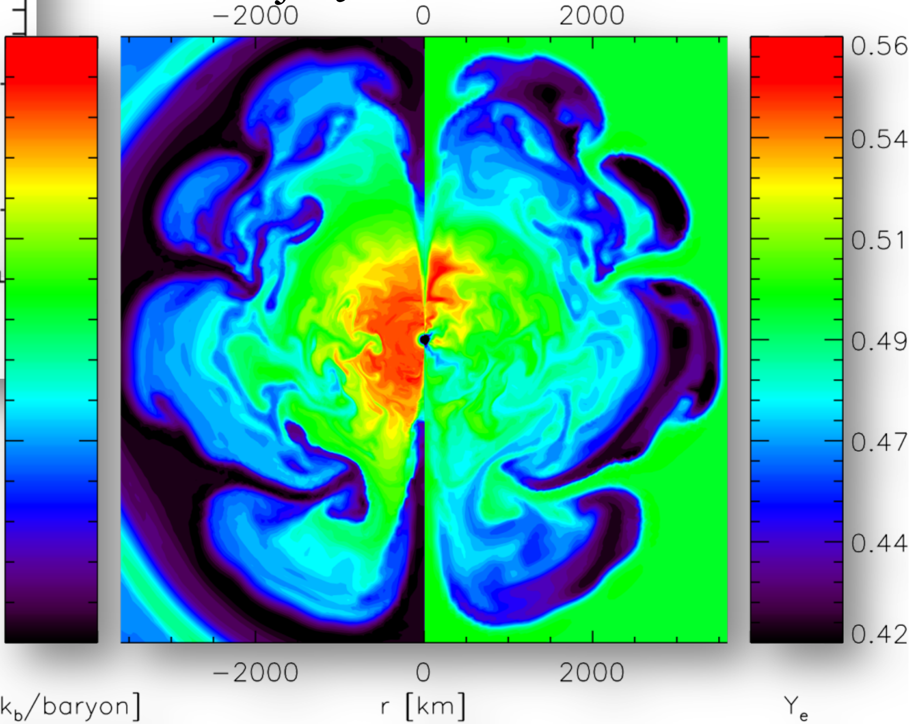


self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl+2009

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

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

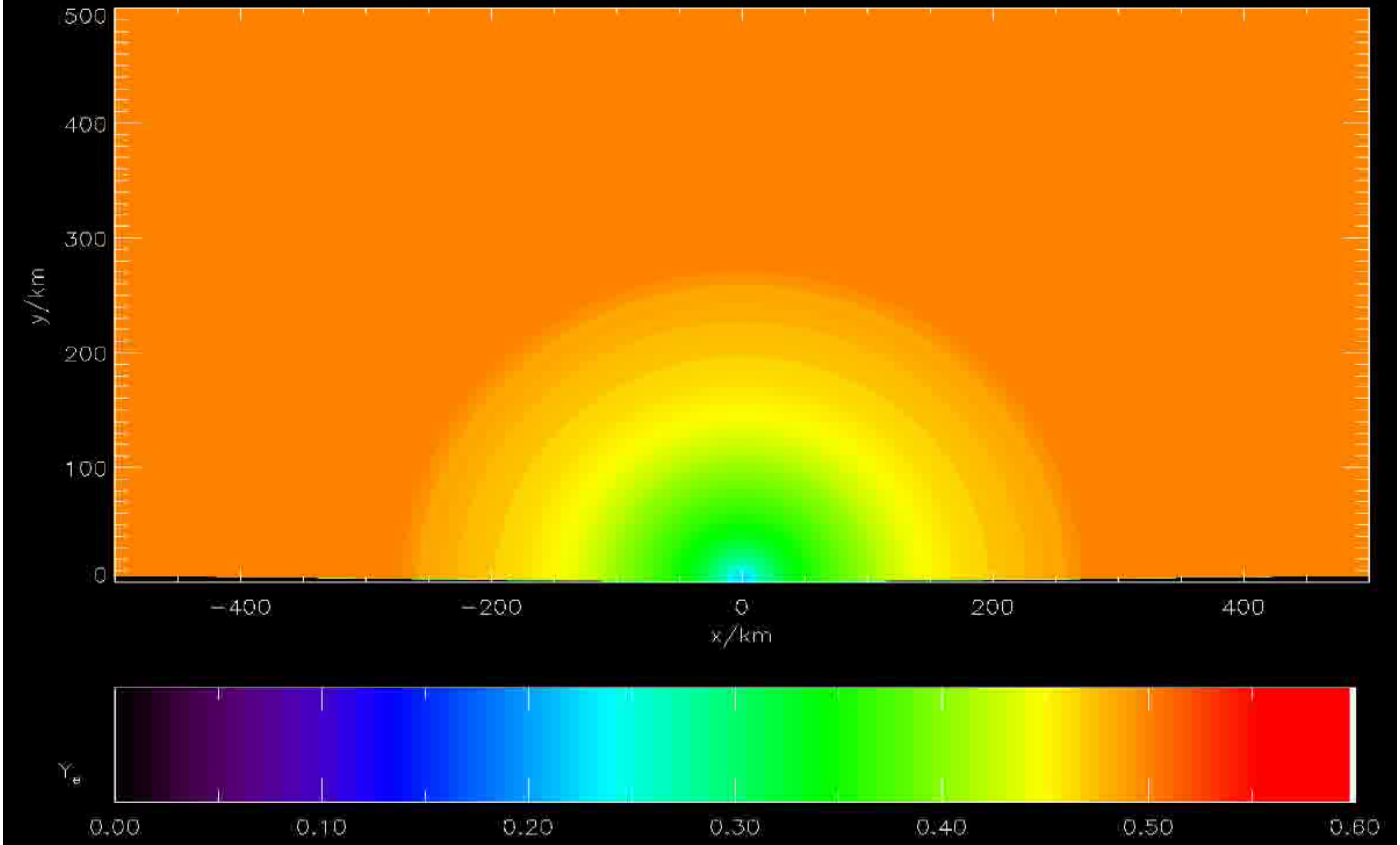
2D supernova simulation
Wanajo, Janka, Müller 2011



- $Y_e > 0.5$ in all recent neutrino-transport simulations because of similar neutrino energies and luminosities for all flavors (i.e., protons are favored due to the p-n-mass difference)
- but, early convective blobs have some n-rich pockets (< 10 $M_\odot$ only)

2D self-consistently exploding model of a 9 $M_\odot$ supernova

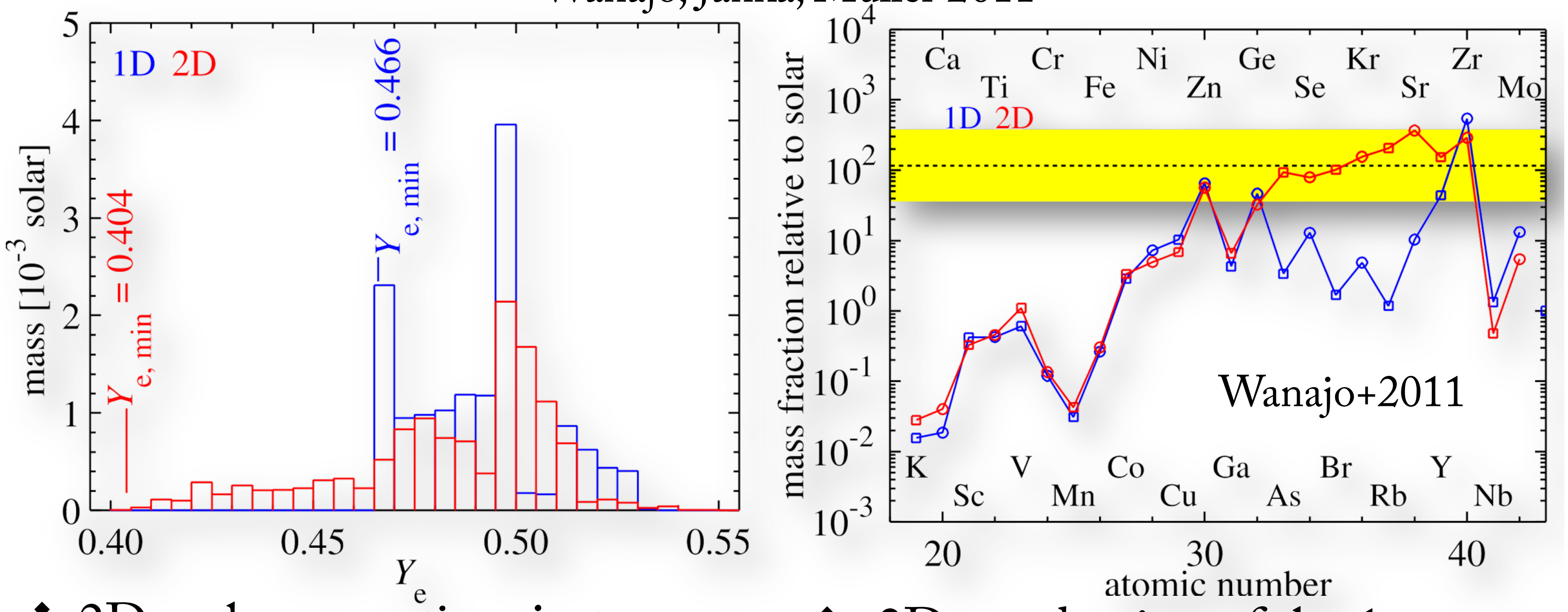
simulation by Bernhard Müller



500
400
300
200
100
0
y/km
−400
−200
0
200
400
x/km
Y_e
0.00
0.10
0.20
0.30
0.40
0.50
0.60

supernovae at the low-mass end

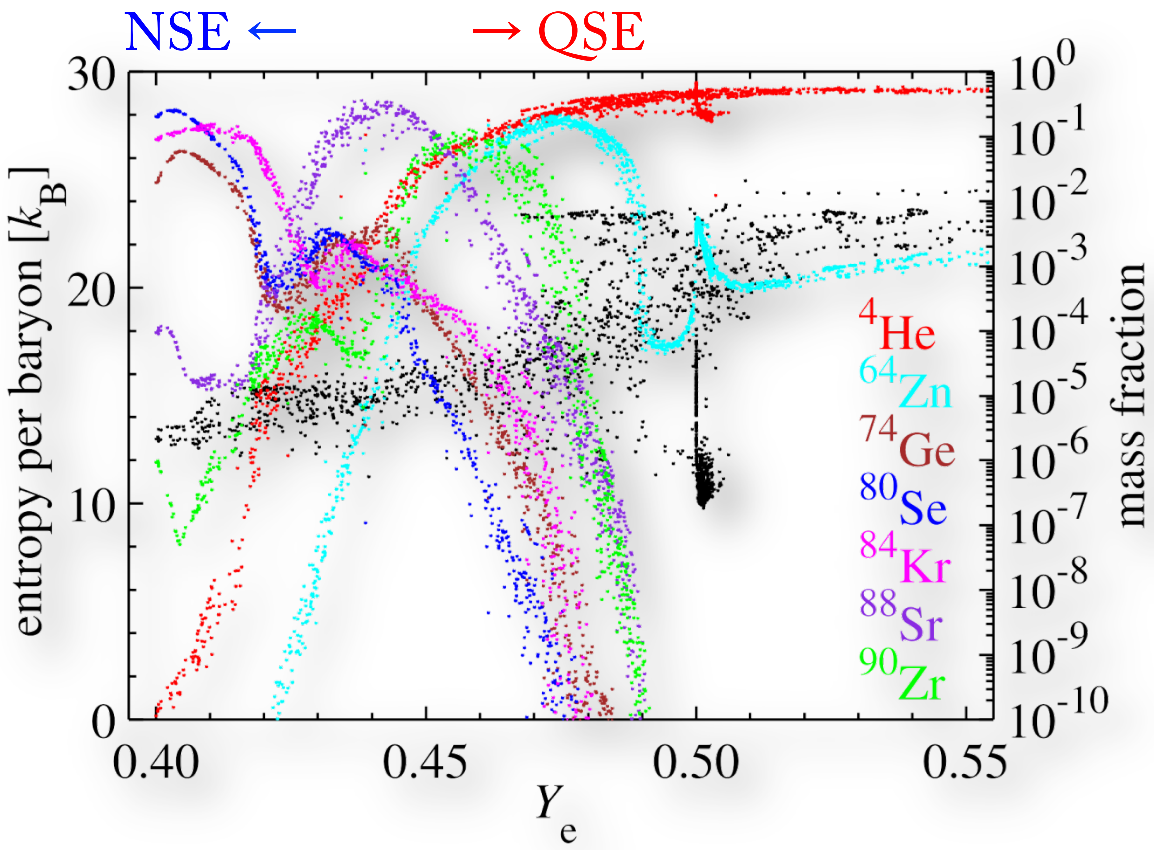
Wanajo, Janka, Müller 2011



- ❖ 2D early convective ejecta: $Y_{e,\,min} \approx 0.40$ with $S_{rad} \approx 13\ k_B/\mathrm{nuc}$
- ❖ 1D ejecta: $Y_{e,\,min} \approx 0.47$ with $S_{rad} \approx 20\ k_B/\mathrm{nuc}$

- ❖ 2D: production of the 1st peak ^{80}Se and up to ^{90}Zr
- ❖ but of nuclei beyond $N = 50$
- ❖ production factor of ~100 → ~ 4% of all SNe

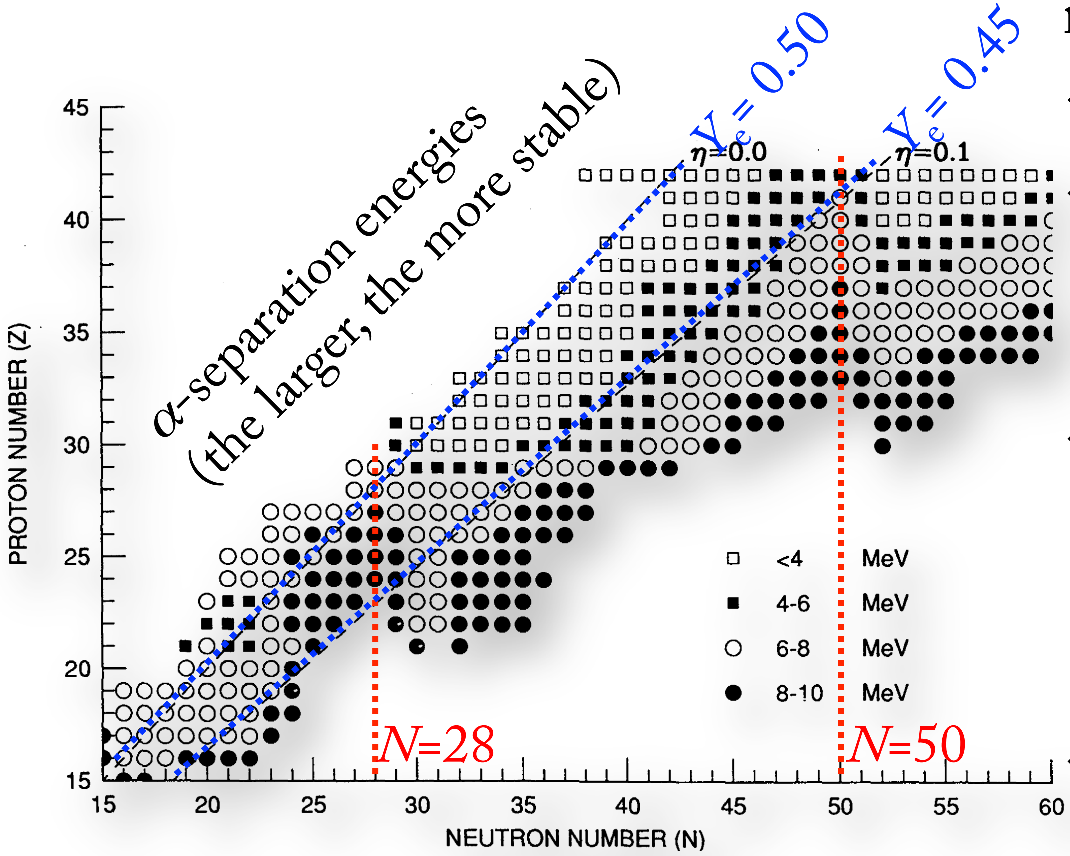
NSE+QSE make nuclei A = 64 – 90



for all tracer particle;
Wanajo, Janka, Müller 2011

- QSE (quasi nuclear equilibrium)
  $Y_e \geq 0.45$, $S \geq 15$ k_B/nuc
  α-rich freezeout
  Zn, Sr, Y, Zr
- NSE (nuclear statistical equilibrium)
  $Y_e \leq 0.45$, $S \leq 15$ k_B/nuc
  α-deficient freezeout
  Ge, Se, Kr

n-rich QSE makes Zn and Sr-Y-Zr



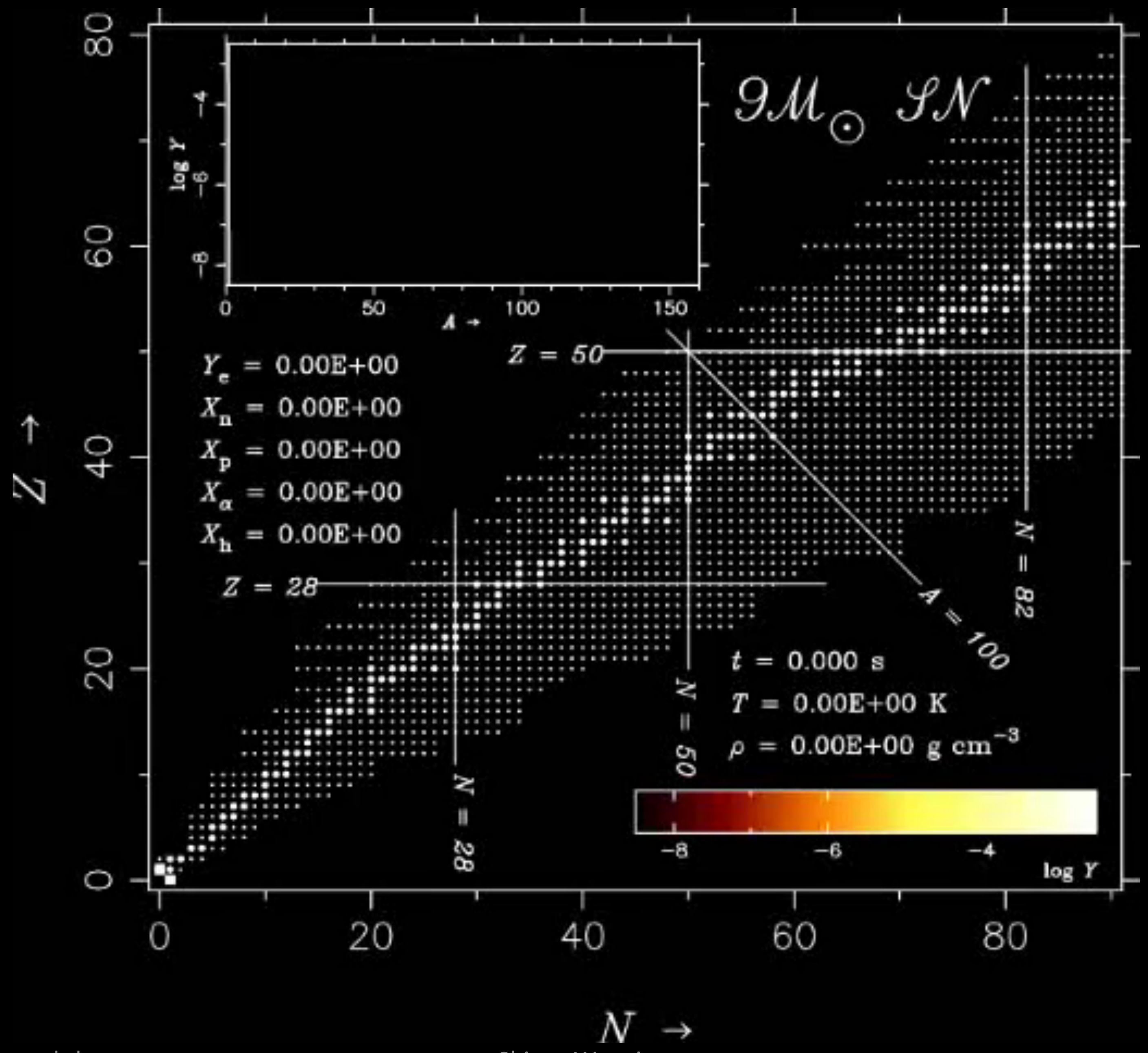
Woosley & Hoffman 1992

n-rich QSE (Y_e ~ 0.45)

- α-rich freezeout from NSE
- formation of N ~ 28 and 50 isotopes (e.g., ^{64}Zn, ^{88}Sr, ^{89}Y, ^{90}Zr)
- few N = 35 – 49 isotopes (Z ~ 31 – 37) because of the strong binding at N = 28 and 50
- cf. not the "α-process" nor "charged particle process"!! (Meyer+1998)

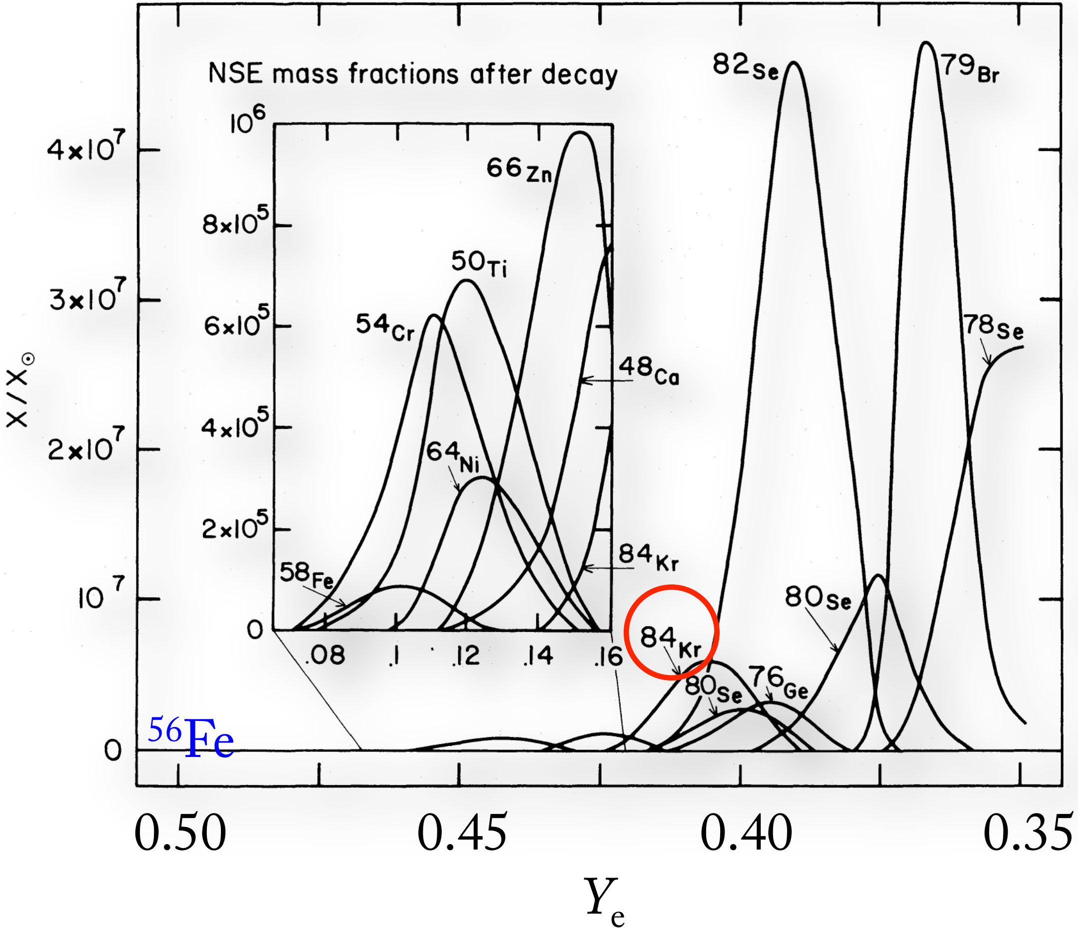
$Y_e = 0.47$

QSE


9M⊙ SN
log Y
−4
−6
−8
0
50
100
150
A →
Y_e = 0.00E+00
X_n = 0.00E+00
X_p = 0.00E+00
X_α = 0.00E+00
X_h = 0.00E+00
Z = 50
Z = 28
N = 28
N = 50
N = 82
A = 100
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm^{-3}
−8
−6
−4
log Y
Z →
0
20
40
60
80
N →
0
20
40
60
80

n-rich NSE fills the gap at A = 74 – 84

$T = 3.5\times10^9$ K, $\rho = 10^7$ g cm^{-3}

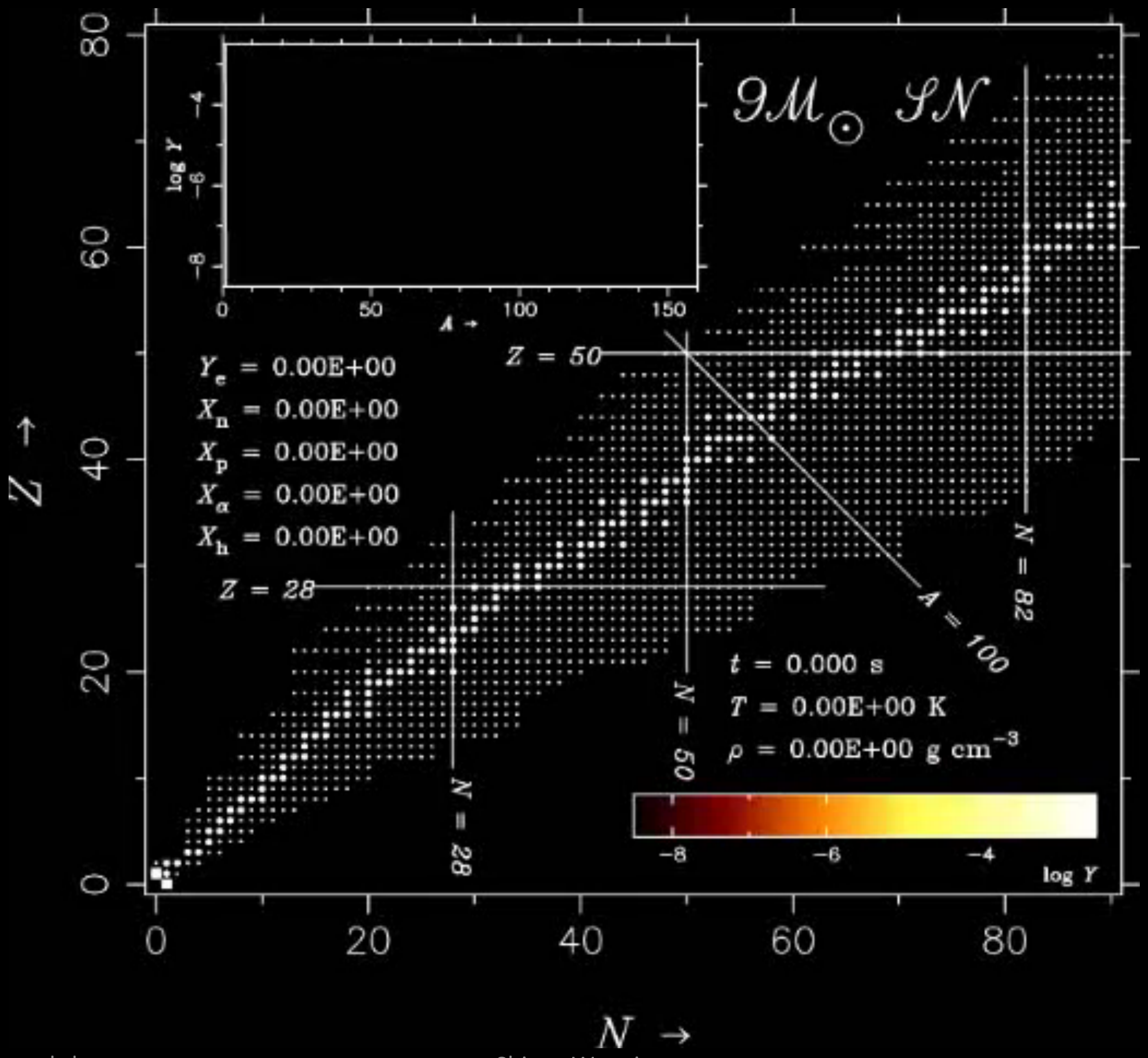


Hartmann+1985

n-rich NSE (Y_e ~ 0.4)

- ❖ formation of A ~ 74 – 84 isotopes (N = 44 – 50) up to ^{84}Se (→ ^{84}Kr)
- ❖ cf. NSE with Y_e = 0.5 ^{56}Ni at N = 28 (→ ^{56}Fe)

$Y_e = 0.40$
NSE


9M☉ SN
Y_e = 0.00E+00
X_n = 0.00E+00
X_p = 0.00E+00
X_α = 0.00E+00
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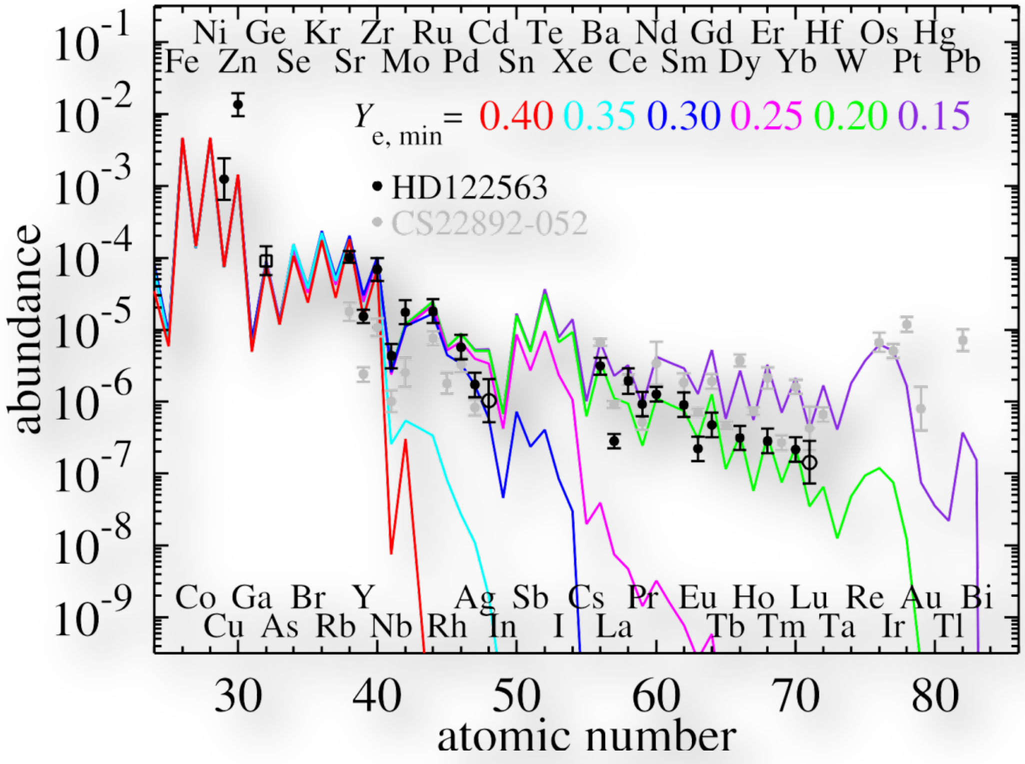
ρ = 0.00E+00 g cm^{-3}
Z = 28
Z = 50
N = 28
N = 50
N = 82
A = 100
log Y
−8
−6
−4
0
50
100
150
A →
Z →
N →
0
20
40
60
80

weak r-process; missing n-rich ejecta?



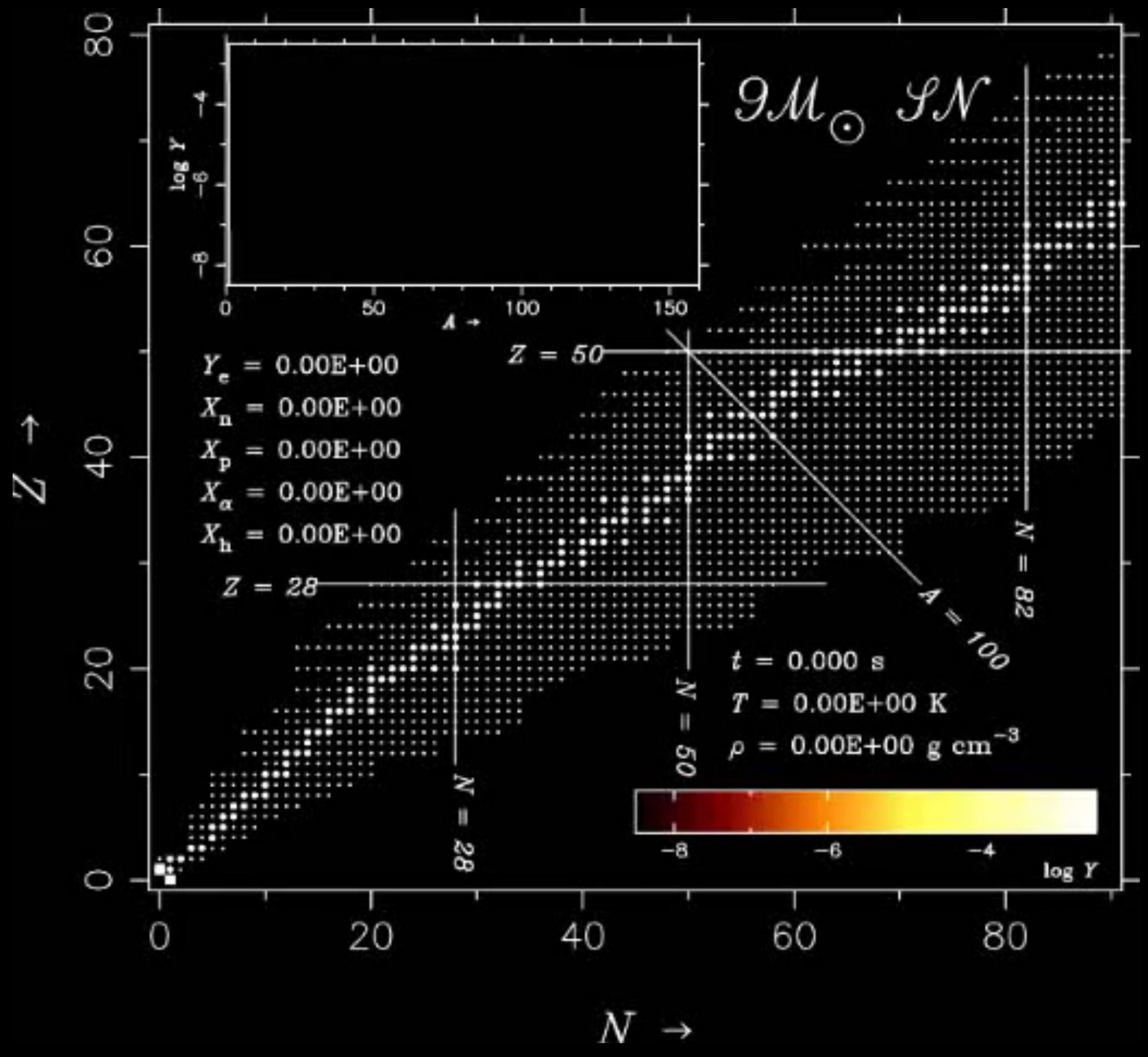
Wanajo, Janka, Müller 2011

comparison with an r-poor star HD 122563 (Honda +2006; Cowan+2005; Roederer+2010)

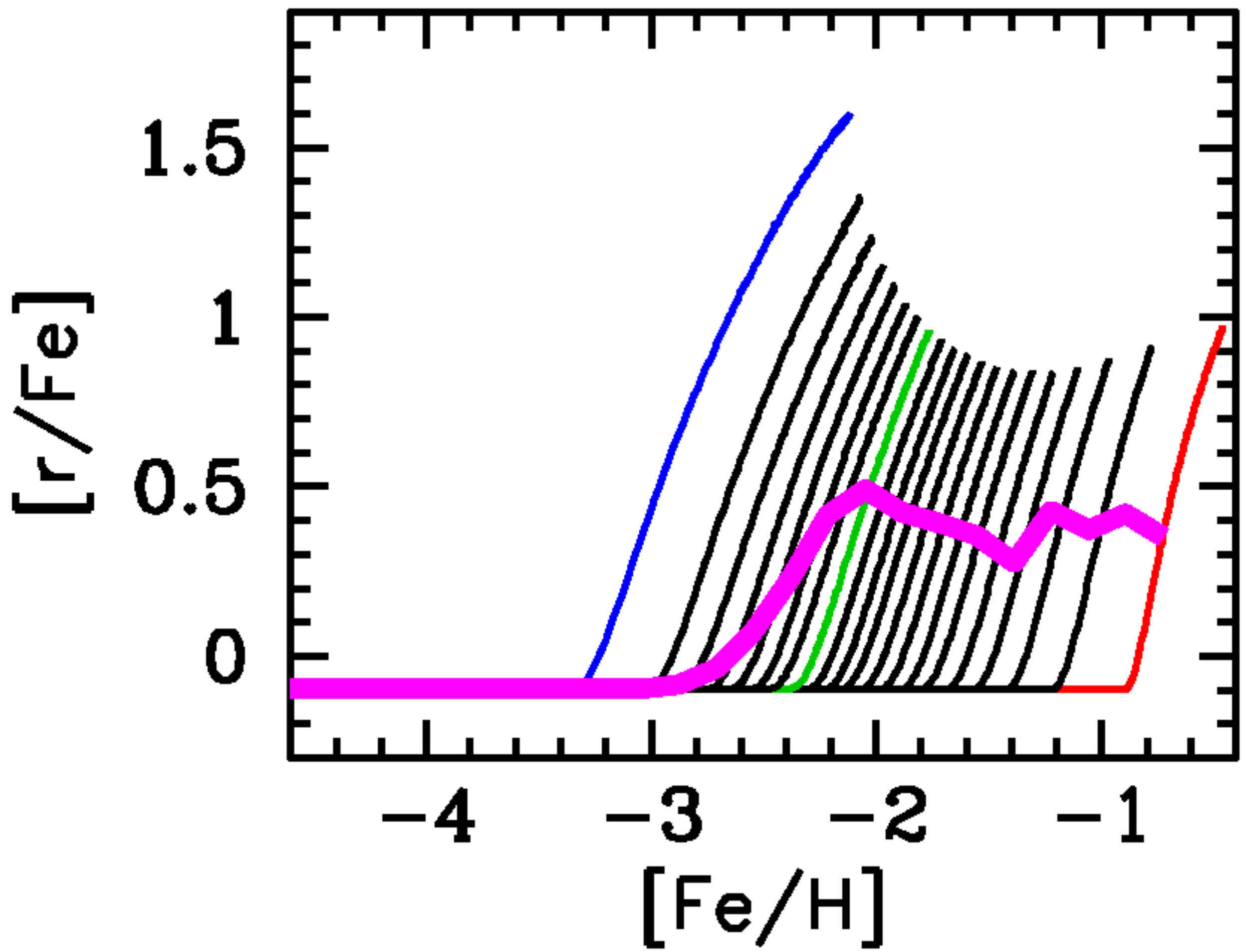
- ❖ original ($Y_{e,\,min}$ = 0.40): agreement from Ge to Sr-Y-Zr
- ❖ $Y_{e,\,min}$ ➘ 0.30 (mild) up to Pd, Ag, Cd
- ❖ $Y_{e,\,min}$ ➘ 0.20 (extreme) up to Pd, Ag, Cd
- ❖ missing tiny amount (~ 10^{-4} $M_\odot$) of n-rich pockets?

$Y_e = 0.30$

weak r-process

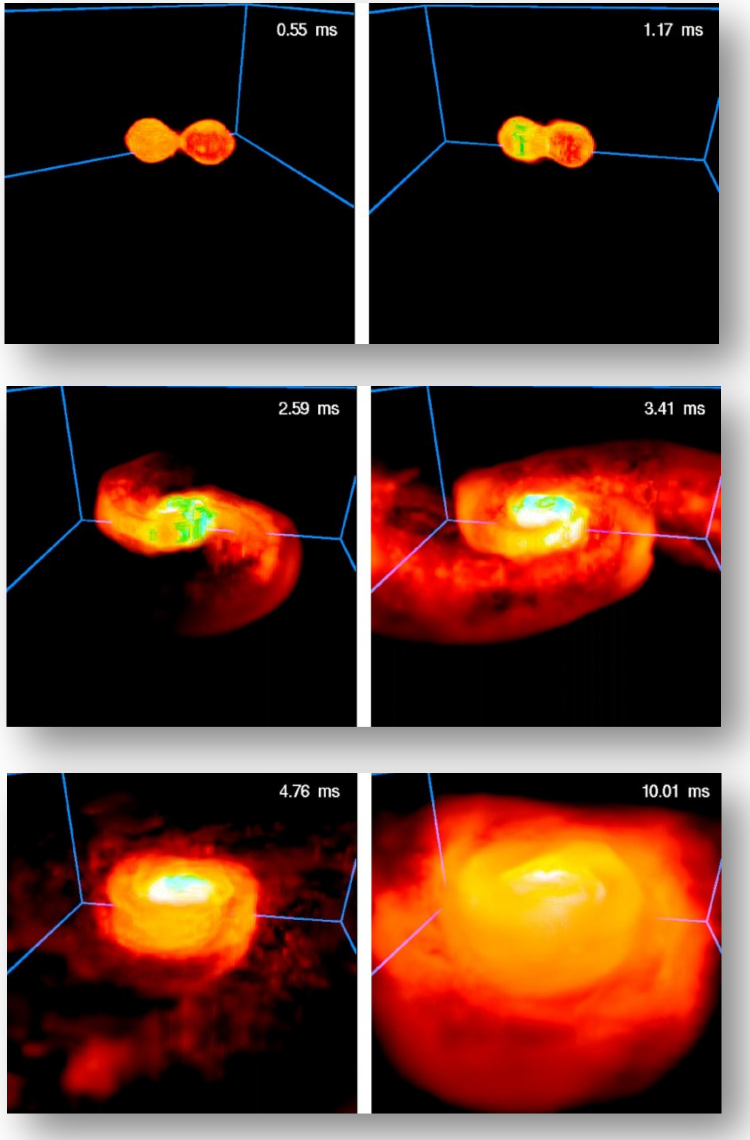

9M⊙ SN
log Y
−4
−6
−8
0
50
100
150
A →
Ye = 0.00E+00
Xn = 0.00E+00
Xp = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Z = 50
Z = 28
N = 28
N = 50
N = 82
A = 100
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm−3
−8
−6
−4
log Y
Z →
0
20
40
60
80
N →
0
20
40
60
80

NS mergers as another posibility



from the talk by N. Prantzos

NS mergers as another posibility



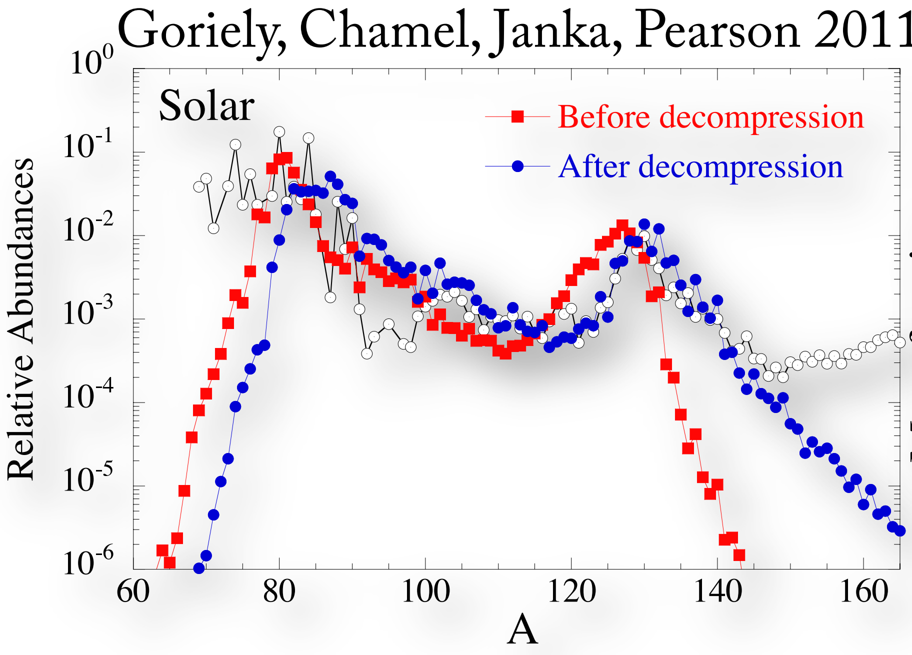
www.mpa-garching.mpg.de

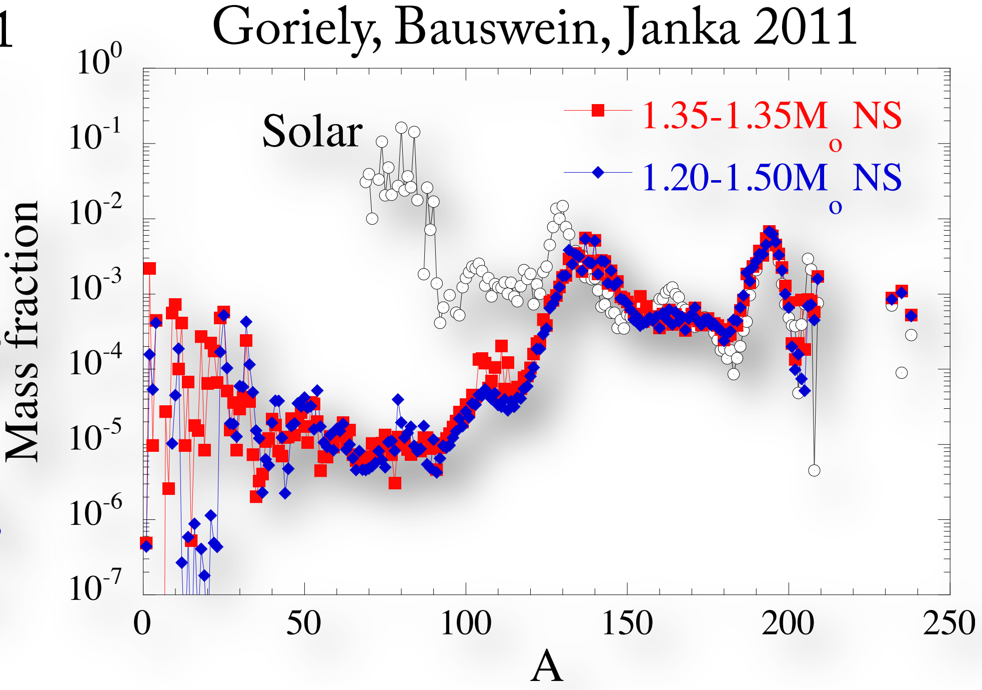
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources for short GRB)

- tidal ejection of n-rich matter with $Y_e < 0.1$ (Goriely, Bauswein, Janka 2011)

- neutrino- (or viscous, MHD) winds from the BH accretion torus with $Y_e \sim 0.2 - 0.4$ (Wanajo & Janka 2011)

NS mergers: dynamical components


Goriely, Chamel, Janka, Pearson 2011


Goriely, Bauswein, Janka 2011

outer crust

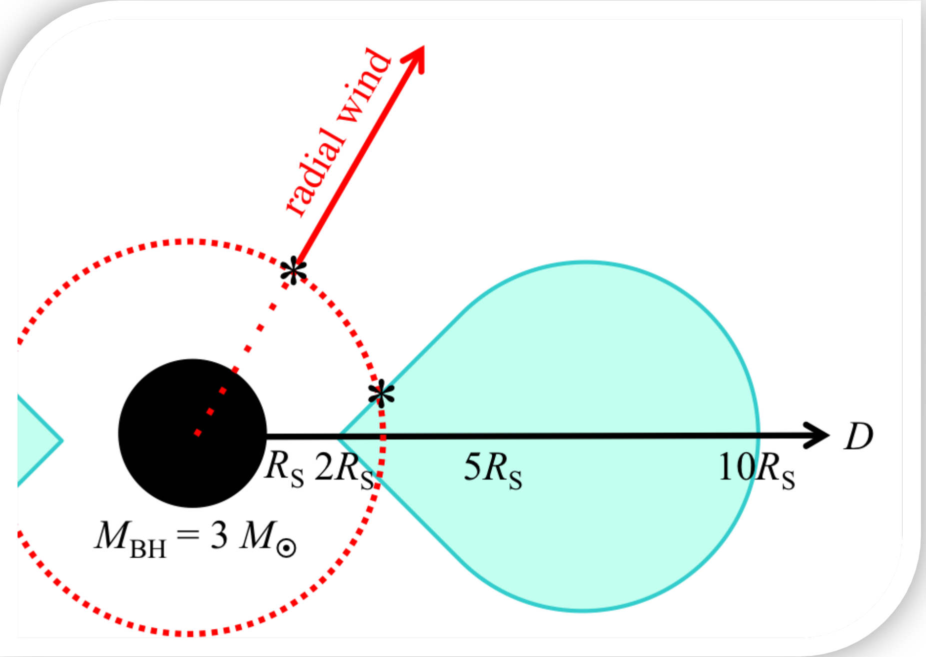
- formation of trans-Fe nuclei up to $A \sim 130$ (mostly in NSE)
- but ejecta mass is too small? $(\sim 10^{-5}\ M_\odot)$

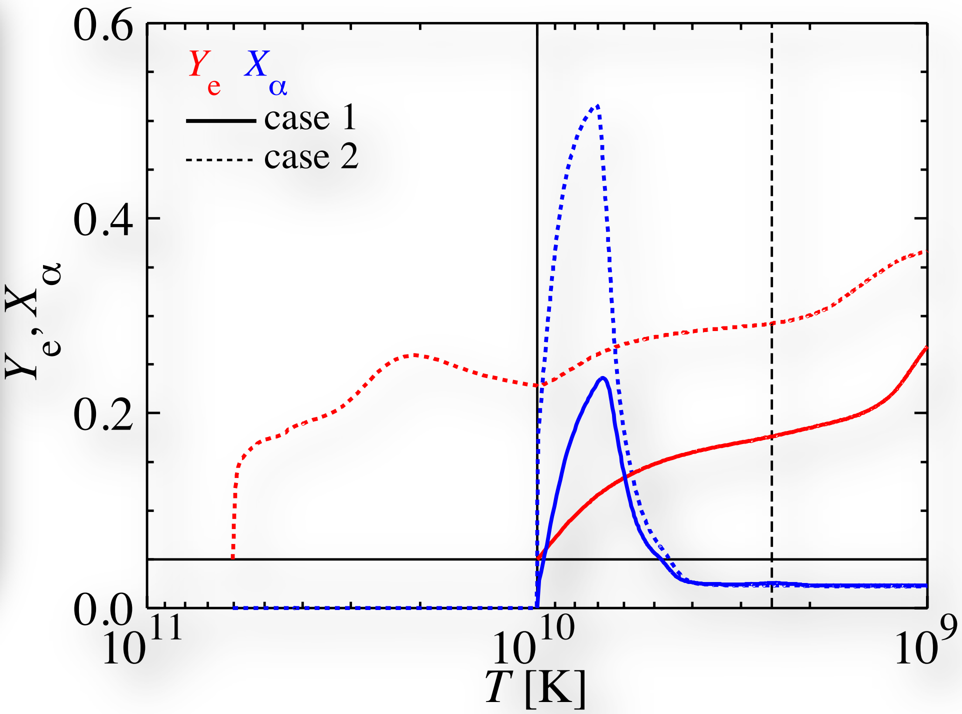
inner crust

- r-process with fission cyclyng
- but only $A > 130$, another source is needed for $A < 130$

NS mergers: wind components

Wanajo & Janka 2011





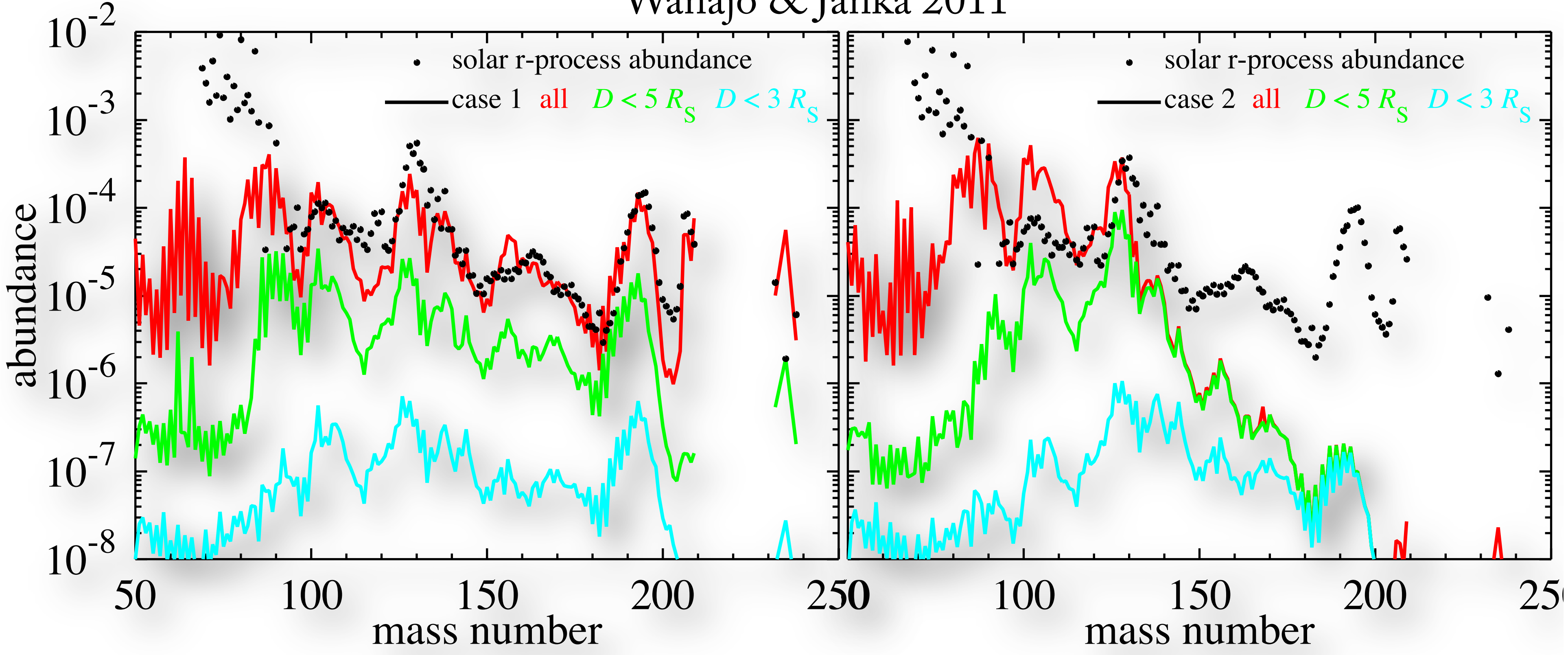
semi-analytic wind model

- ❖ neutrino-driven wind from the BH-accretion torus
- ❖ spherical PNS wind model is applied with modifications

for weak interactions on n and p

- ❖ case 1: from $T = 1 \times 10^{10}$ K
- ❖ case 2: from $T \approx 6 \times 10^{10}$ K (at the inner boundary)

NS mergers: wind components



Wanajo & Janka 2011

case 1

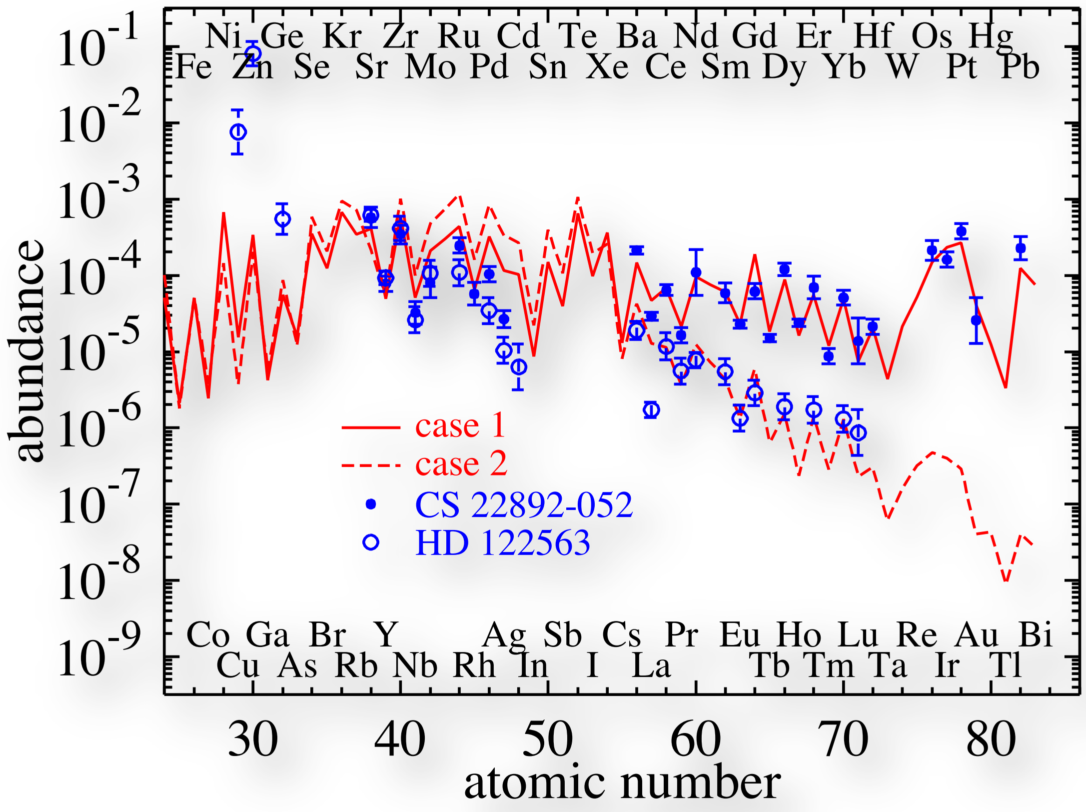
- $Y_{e,\,\mathrm{min}} \sim 0.2$
- full (main) r-process

case 2

- $Y_{e,\,\mathrm{min}} \sim 0.3$
- weak r-process

NS mergers: the source of trans-Fe?

Wanajo & Janka 2011



BH-torus winds can be the origins of

- ❖ r-rich star abundances if $Y_{\mathrm{e,\,min}} \sim 0.2$ (case 1)
- ❖ r-poor star abundances if $Y_{\mathrm{e,\,min}} \sim 0.3$ (case 2)
- ❖ but, not very good agreement (e.g., Ge, Ag) because of high entropy $S \sim 30\ k_{\mathrm{B}}/\mathrm{nuc}$ (not NSE, but QSE)

summary

- ❖ SNe at the low mass end (ECSNe, ONeMg SNe, AGB SNe)
  trans-Fe up to Sr-Y-Zr in 2D ($Y_{\mathrm{e,\,min}} \approx 0.4$)
  up to the Pd-Ag-Cd (if $Y_{\mathrm{e,\,min}}$ ➘ 0.3)
- ❖ NS mergers
  weak r-process (wind) and/or main r-process (dynamical ejecta)
  but we should wait refined hydro models…
- ❖ nucleosynthesis relevant to trans-Fe elements (in n-rich matter)
  up to Sr-Y-Zr: NSE + QSE (nuclear equilibrium)
  up to Pd-Ag-Cd: weak r-process (incomplete r-process)
- ❖ physical conditions
  low entropy ($S \sim 10 - 20\ k_{\mathrm{B}}$/nuc) and
  moderately low electron fraction ($Y_{\mathrm{e,\,min}} \sim 0.3 - 0.4$)