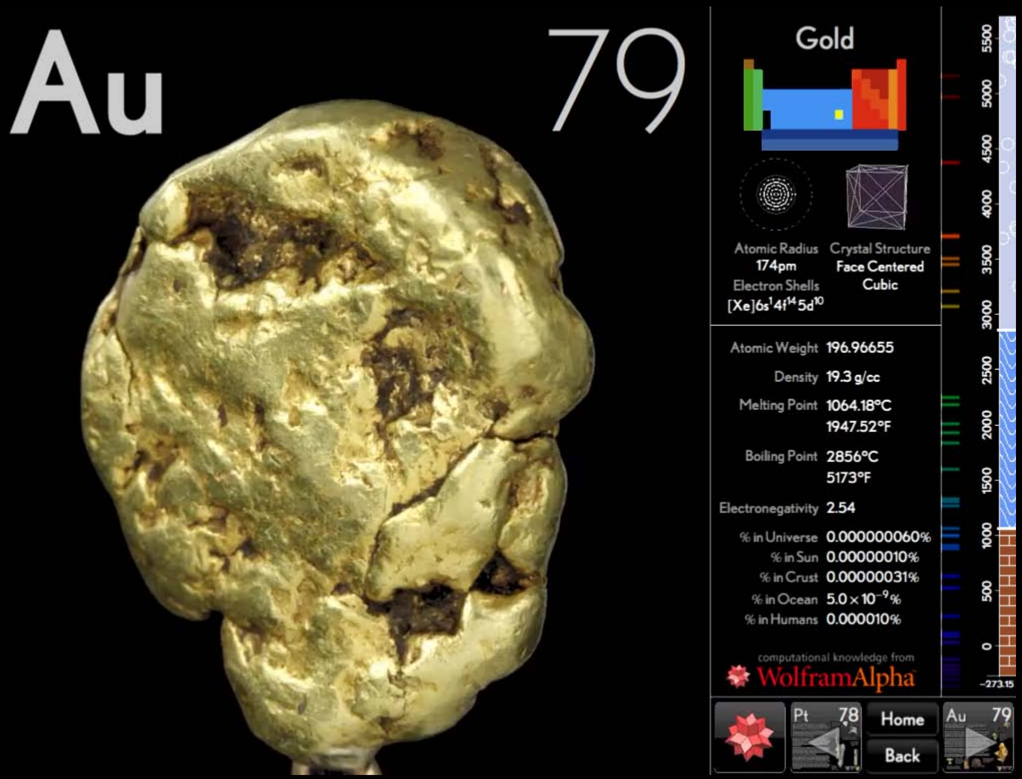
The r-process

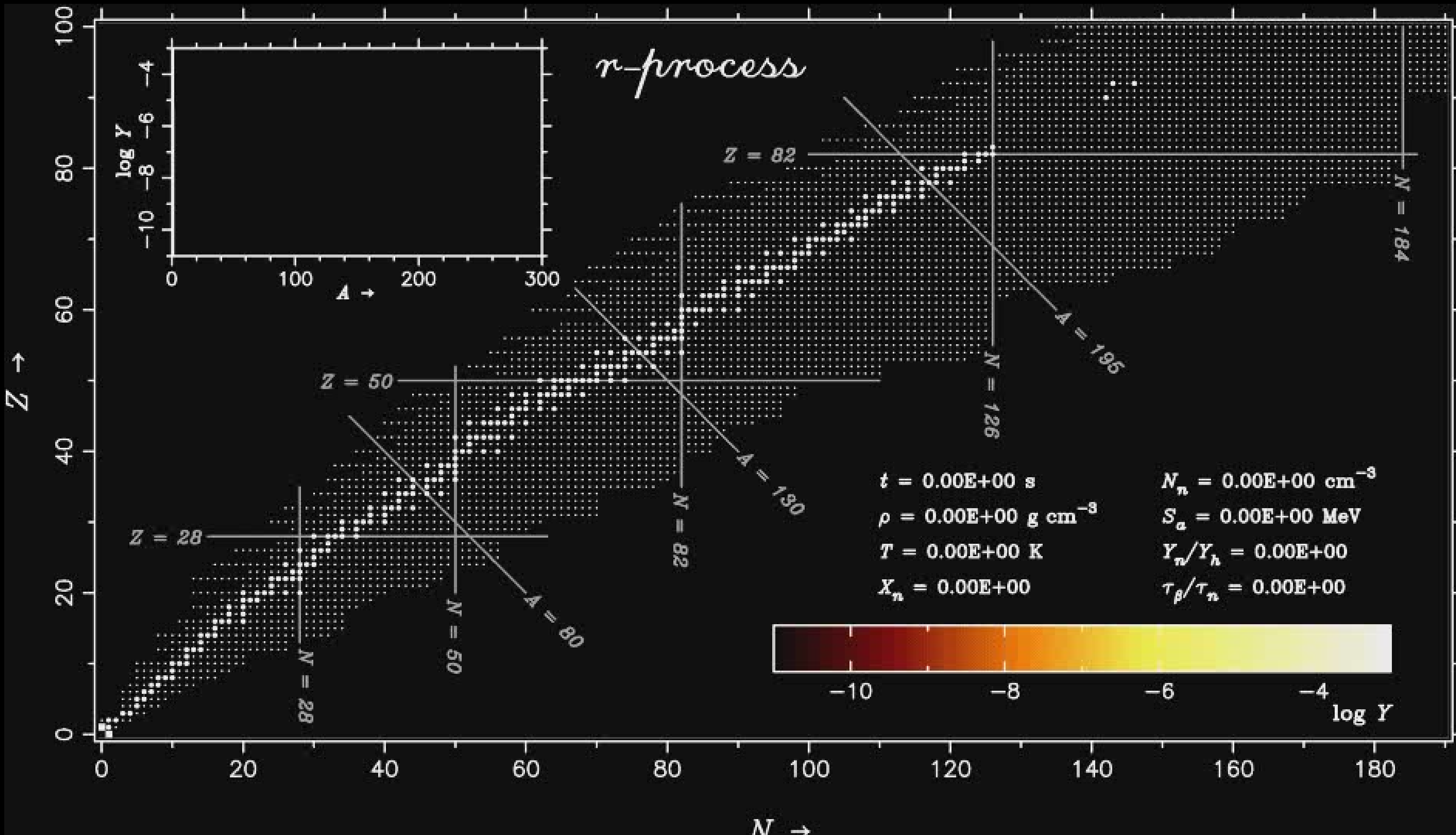
theoretical / astrophysical side

Wanajo (TUM/MPA), Janka, Müller (MPA)



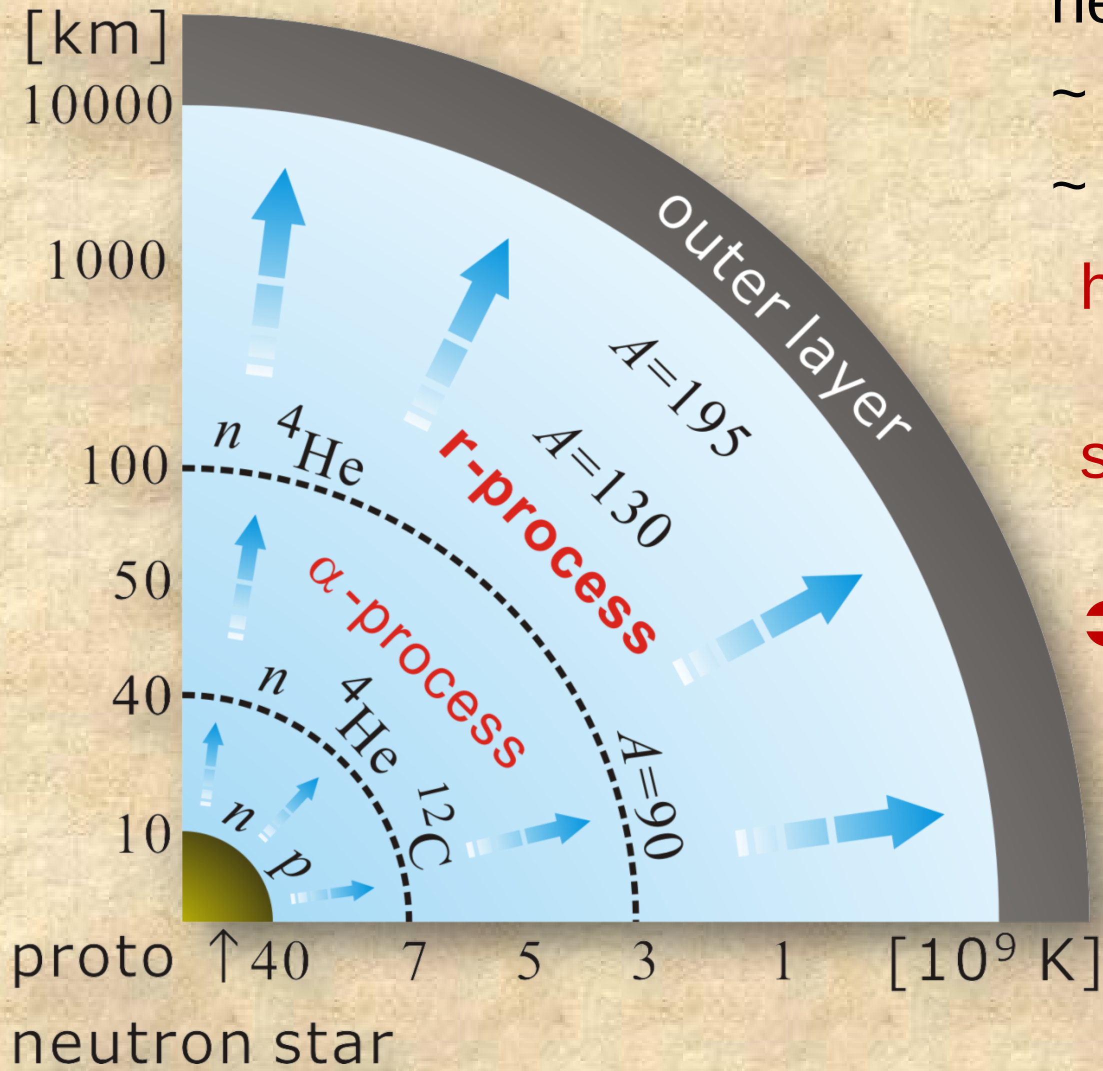
contents

1. the weak r-process in the 2D electron capture supernova (ONeMg SN)
2. the main r-process in the black hole winds of neutron star mergers



r-process
Z →
N →
log Y
A →
Z = 28
Z = 50
Z = 82
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.00E+00 s
ρ = 0.00E+00 g cm^−3
T = 0.00E+00 K
X_n = 0.00E+00
N_n = 0.00E+00 cm^−3
S_a = 0.00E+00 MeV
Y_n/Y_h = 0.00E+00
τ_β/τ_n = 0.00E+00
−10
−8
−6
−4
log Y

key parameters for the r-process



neutron/seed

~ A(3rd peak) - A(seed)

~ 100

high entropy:

S_{rad} ($\propto T^3/\rho$) > 200 k/nuc

short expansion timescale:

τ_{exp} < 10 ms

➲ prevent seed production

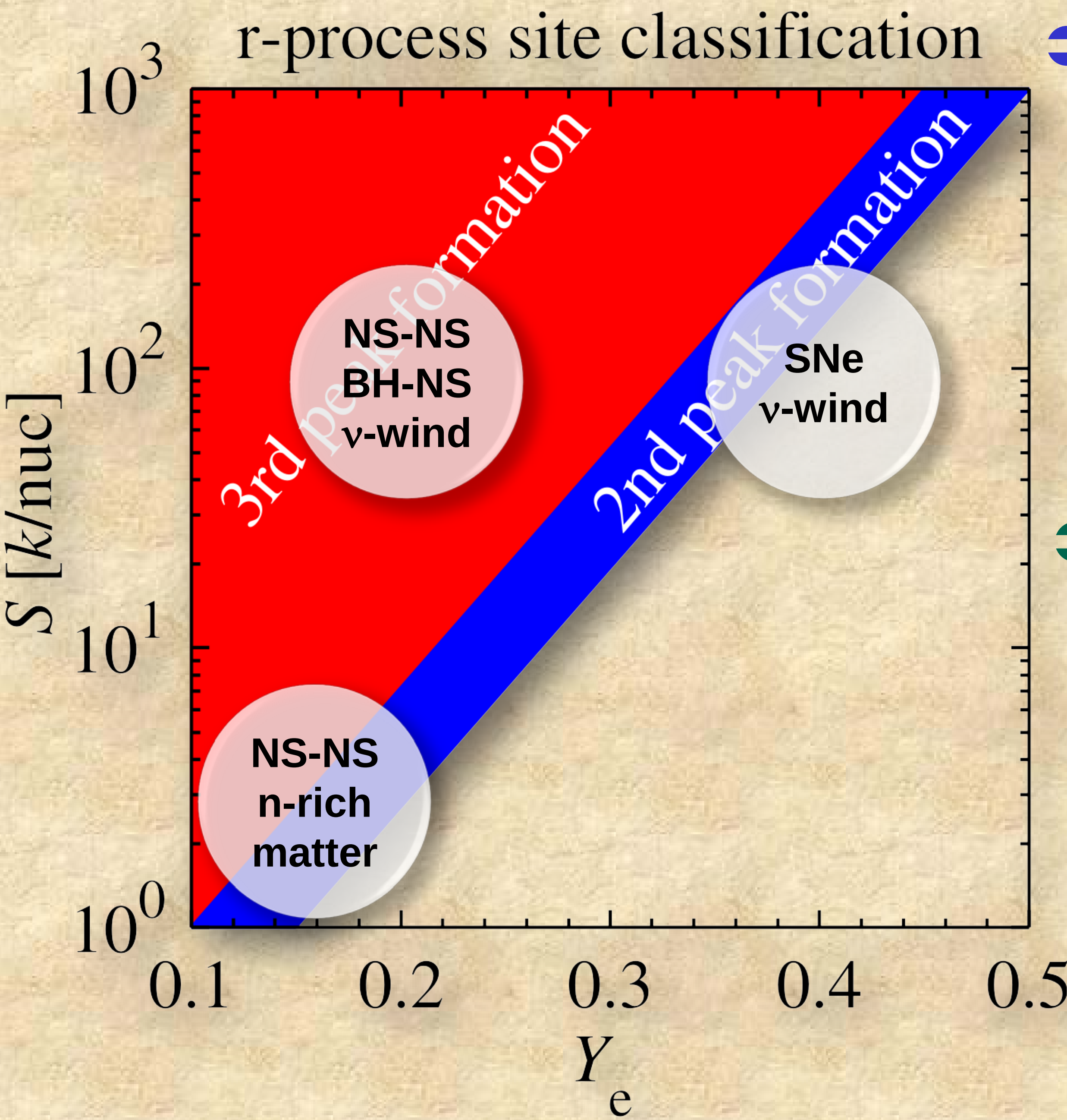
low electron fraction (proton per nucleon):

$Y_e < 0.2$

➲ leave free neutrons

cf. Hoffman et al. 1997

surviving scenarios for the r-process



➲ neutrino-driven winds of SNe
Woosley et al. 1994
Takahashi et al. 1994
Qian & Woosley 1996
Hoffman et al. 1997
Otsuki et al. 2000
Wanajo et al. 2001
Thompson et al. 2001, etc.

➲ neutron-rich decompressed matter of NS-NS
Freiburghaus et al. 1999
Goriely et al. 2005
Metzger et al. 2010, etc.

➲ black hole winds of NS-NS, BH-NS
Surman et al. 2008

1. weak r-process in supernovae

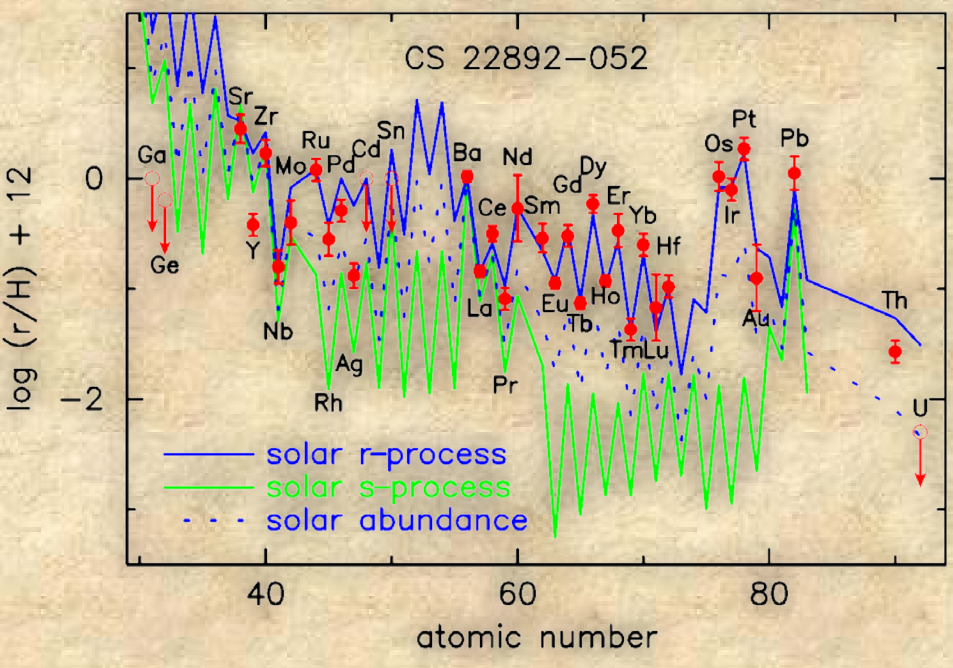
based on the 2D self-consistently exploding model of an electron capture supernovae

Wanajo, Müller, & Janka, in prep.

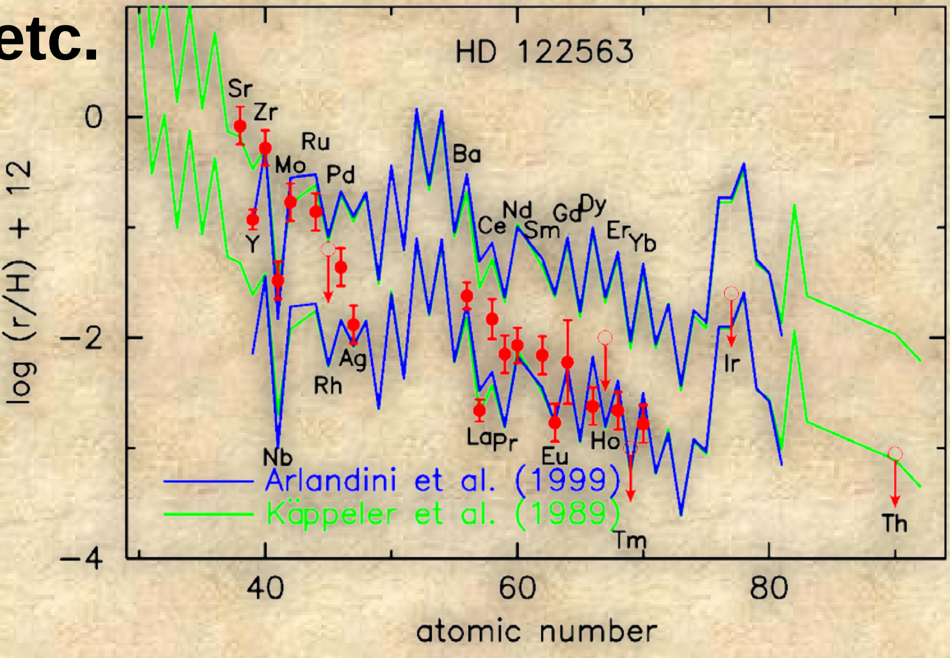
“main” and “weak” r-processes

Honda, Aoki, Ishimaru, Wanajo, Ryan 2006

- **main r-process stars: CS22892-052, CS31082-001, etc.**
  good agreement with solar r-process composition,
  BUT slight underabundance of Z < 56 elements?

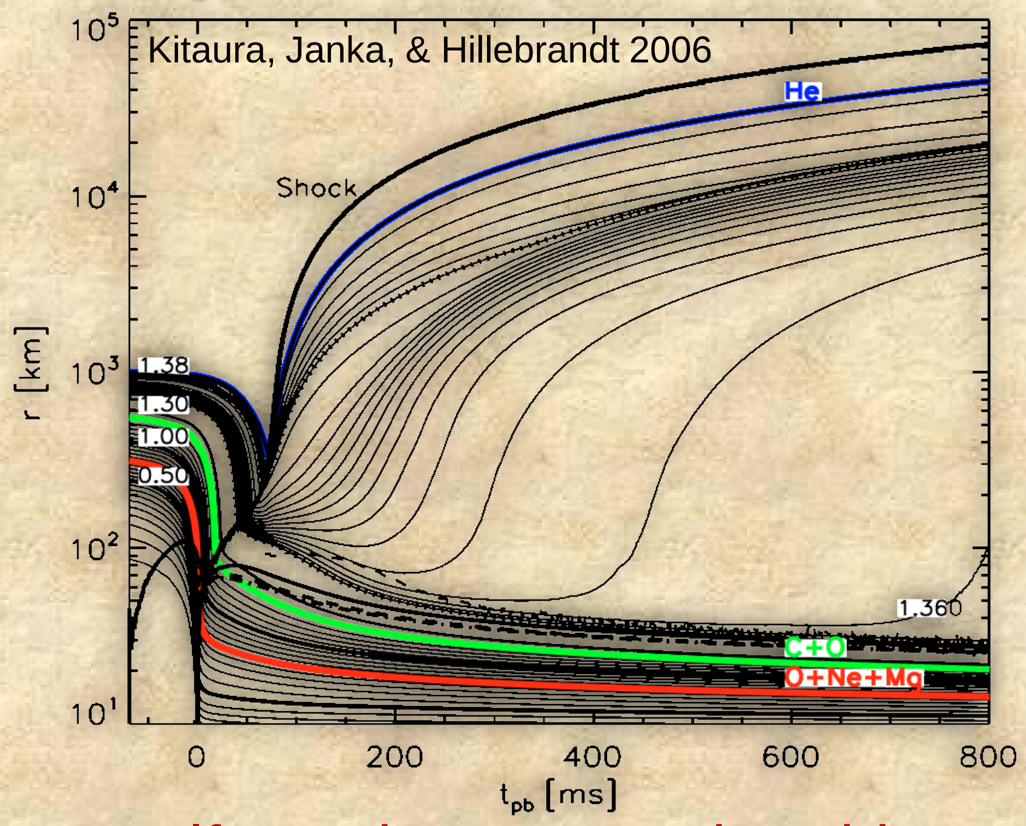


Sneden et al. 2003



- **weak r-process stars: HD122563, HD88609**
  enhancements of only Z < 56 elements
  additional r-process site
  LEPP; Travaglio et al. 2004
  CPR; Qian & Wasserburg 2008

no r-process in the 1D self-consistent SN



r-process in 8-10 $M_\odot$ stars (with ONeMg core)?

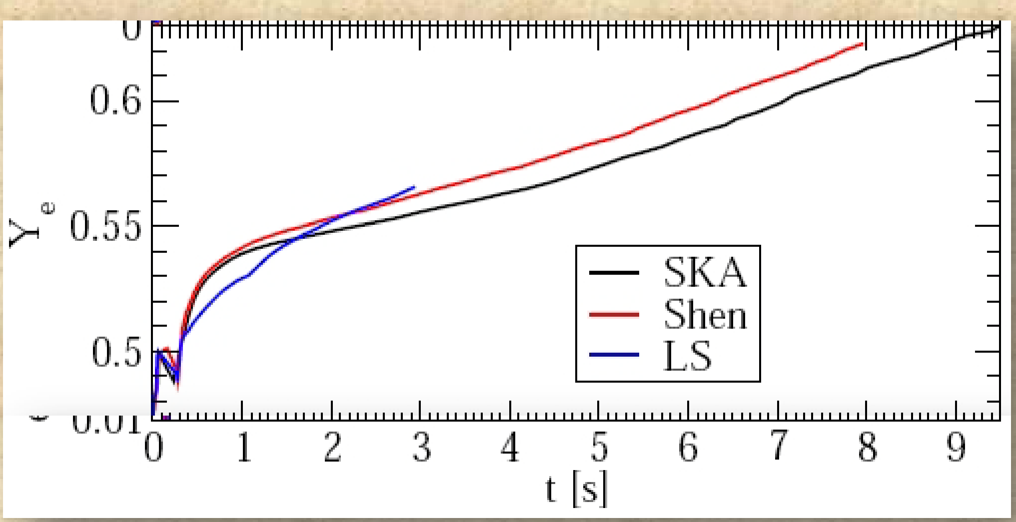
- ➲ prompt explosion?
  Hillebrandt et al. 1984
  Wanajo et al. 2003
  cf. Sumiyoshi et al. 2000 for and iron core SN
- ➲ shock-heated core-surface layers?
  Ning et al. 2008

1D, self-consistent, neutrino-driven explosion of a 9 $M_\odot$ star

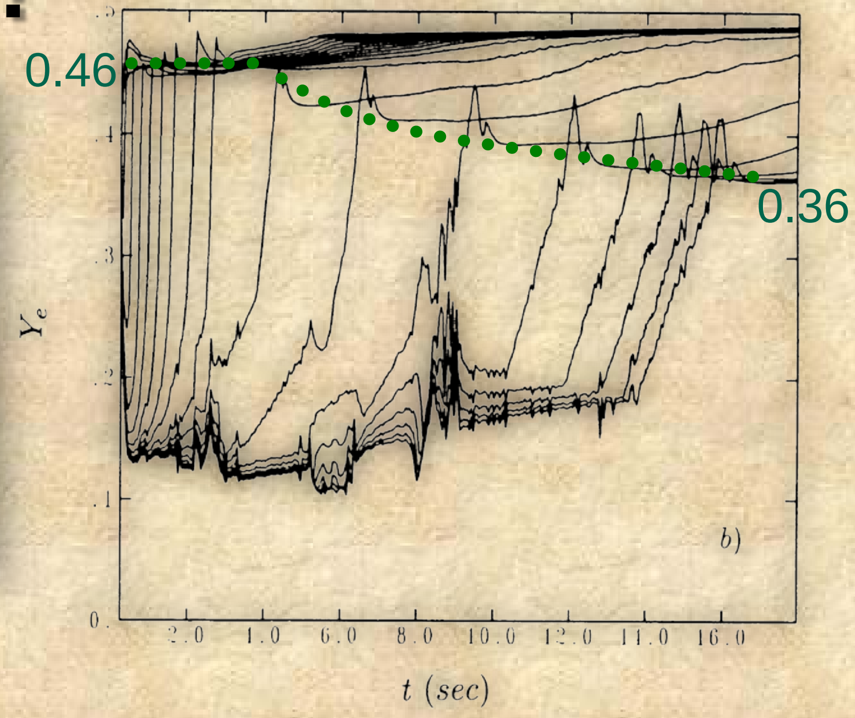
Kitaura, Janka, & Hillebrandt 2006; with the initial model of Nomoto 1984, 1987

- ➲ no r-process Hoffman et al. 2008; Janka et al. 2008, Wanajo et al. 2009
- ➲ no νp-process, but, production of Zn and light p-nuclei in the first 1 s after core bounce Wanajo et al. 2009; Roberts et al. 2010

no r-process in proto n~~eutron~~ star winds at all?



self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl et al. 2009 .

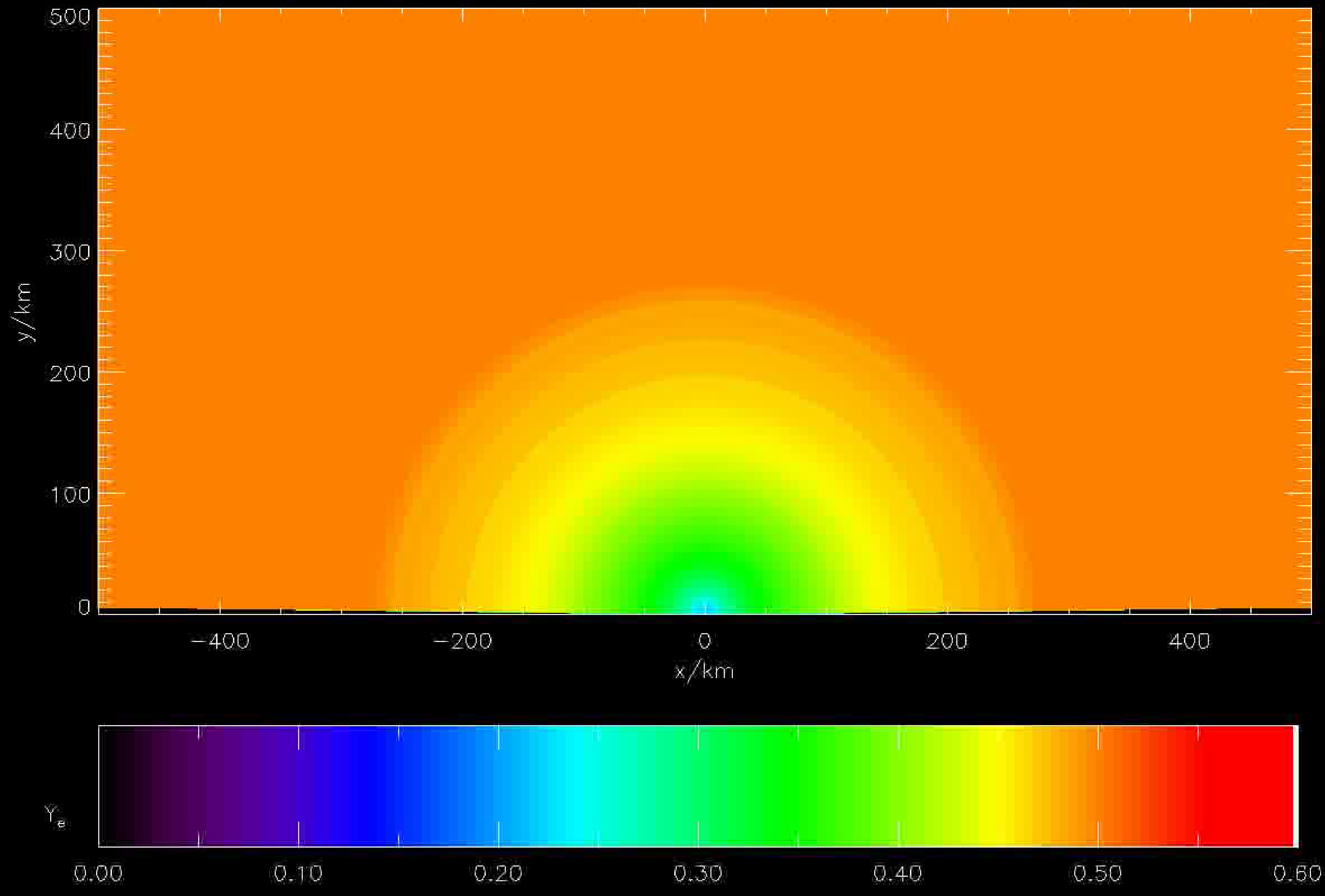


Woosley et al. (1994)

- ➲ Y_e > 0.5 all the way in the neutrino-driven phase due to the similar neutrino energies for all flavors
  Hüdepohl et al. 2009, Roberts et al. 2010; cf. Fischer et al. 2009 for iron core SNe
- ➲ no (weak nor main) r-process in the neutrino-driven winds!!
  BUT we should wait the self-consistent simulations of iron-core SNe

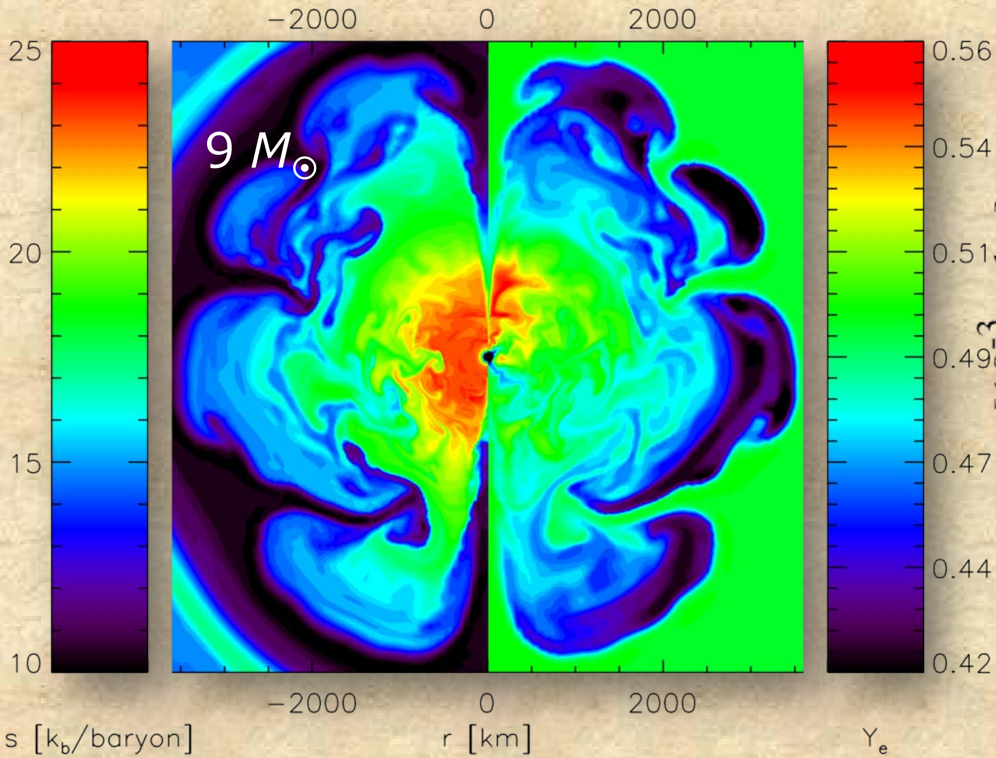
2D self-consistently exploding model of an electron capture supernova (ONeMg SN)

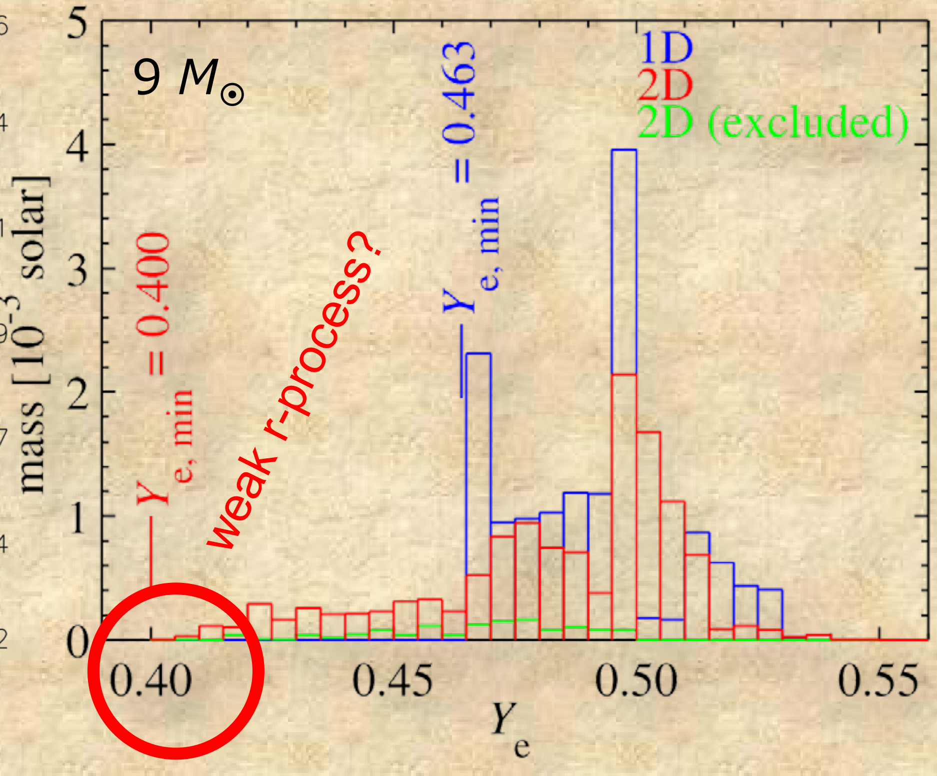
by B. Müller & Janka, in prep.



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

2D self-consistent explosion of a 9M star



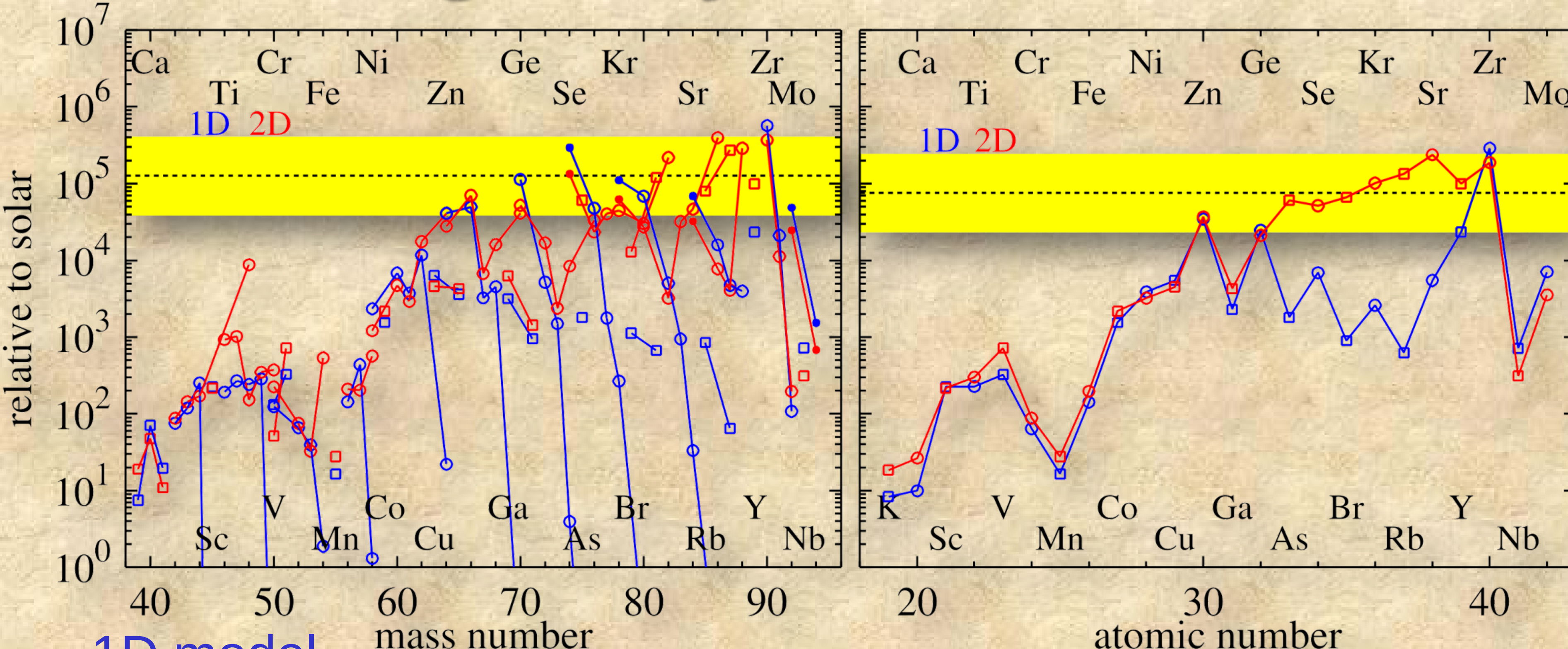


(by B. Müller & H.-T. Janka)

➲ low-Y_e bubbles appear (down to $Y_{e,\,min} = 0.40$)

➲ weak r-process? (Sr, Y, Zr, ..., Pd, Ag, ...)

mass-integrated yields relative to solar



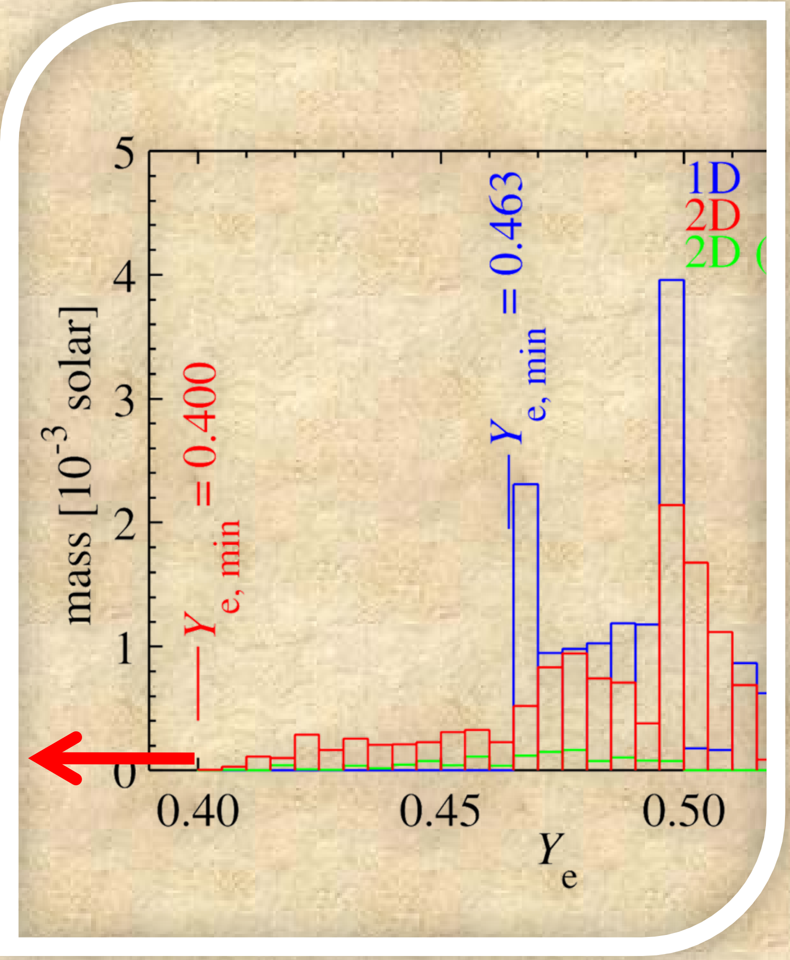
1D model

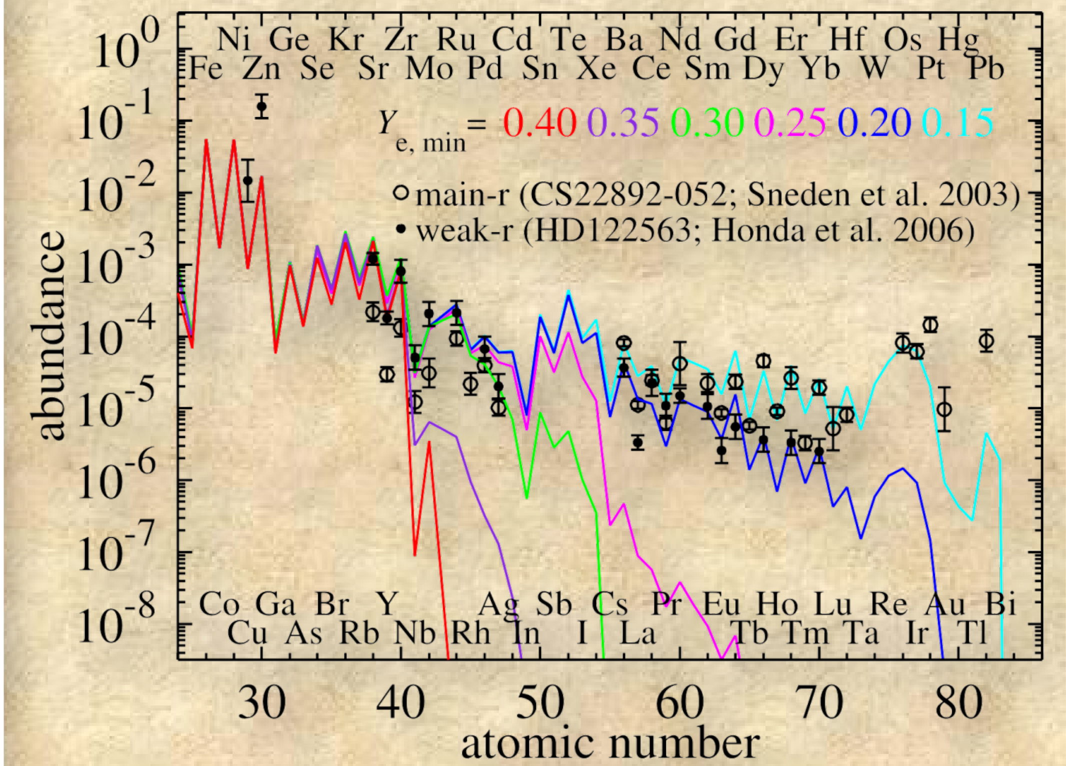
- ➲ only up to N = 50 (A = 90)
- ➲ only p-rich isotopes (^{64}Zn, ^{90}Zr, and light p-nuclei)

2D model

- ➲ still up to N = 50 (A = 90)
- ➲ but the source of many elements (Zn, Ge, ..., Sr, Y, Zr)

how low $Y_{e,\,min}$ is needed for the weak-r?





comparison with a weak r-star

Honda, Aoki, Ishimaru, Wanajo, Ryan 2006

- $Y_{e,\,min}$ = 0.40: up to Sr, Y, Zr
- $Y_{e,\,min}$ = 0.30: up to Pd, Ag
- $Y_{e,\,min}$ = 0.20: all (but extreme!)

test calculations

- $Y_{e,\,min}$ = 0.40, 0.35, 0.30, ...
  (1-2×10^{-5} $M_\odot$ for ΔY_e = 0.005)

summary 1

nucleosynthesis in the self-consistent 2D SN of a $9M_{\odot}$ star

- ➲ maximum contribution: a few % of all core-collapse events
- ➲ production of many light “n-capture” elements between the iron-group and Sr-Y-Zr
- ➲ significant reduction of $Y_{e,\,\mathrm{min}}$ (~ 0.3) is still needed even for weak r-processing (Pd, Ag); a 3D study is needed!

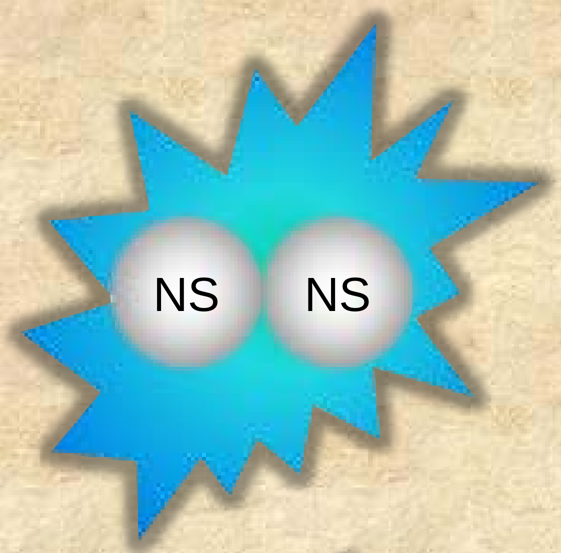
2. main r-process in black hole winds

based on the semi-analytic model of spherically symmetric neutrino-driven winds

Wanajo & Janka, in prep.

black hole winds

= neutrino-driven winds from the torus around an accreting black hole



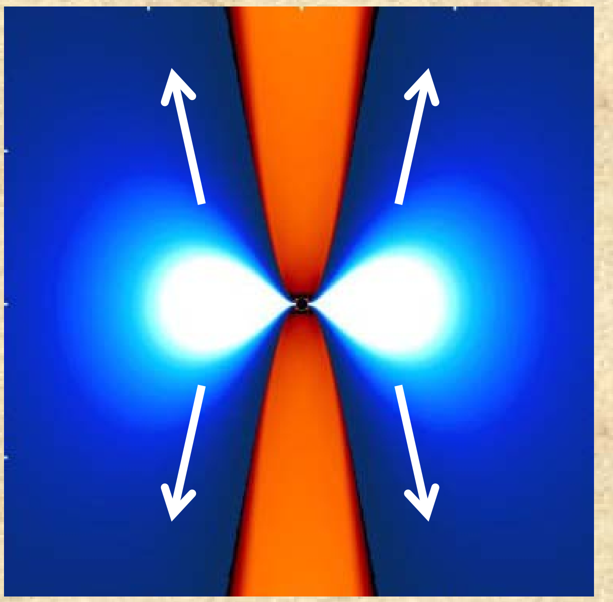
NS-NS or BH-NS mergers

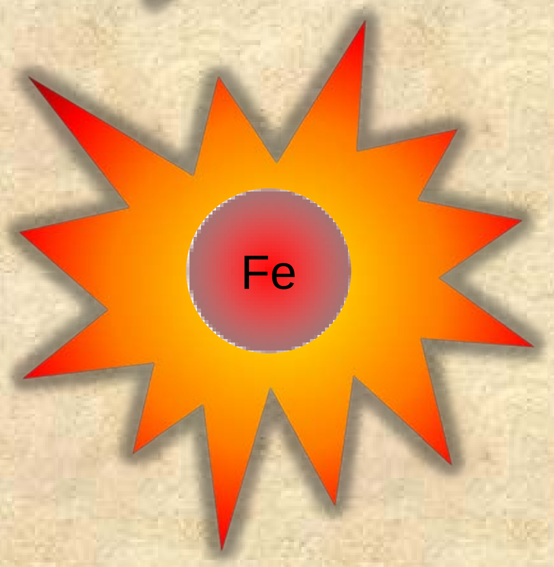
➲ low Y_e (~0.1-0.3)

$M_{core} \geq 2.5\ M_{\odot}$

black hole formation

black hole winds



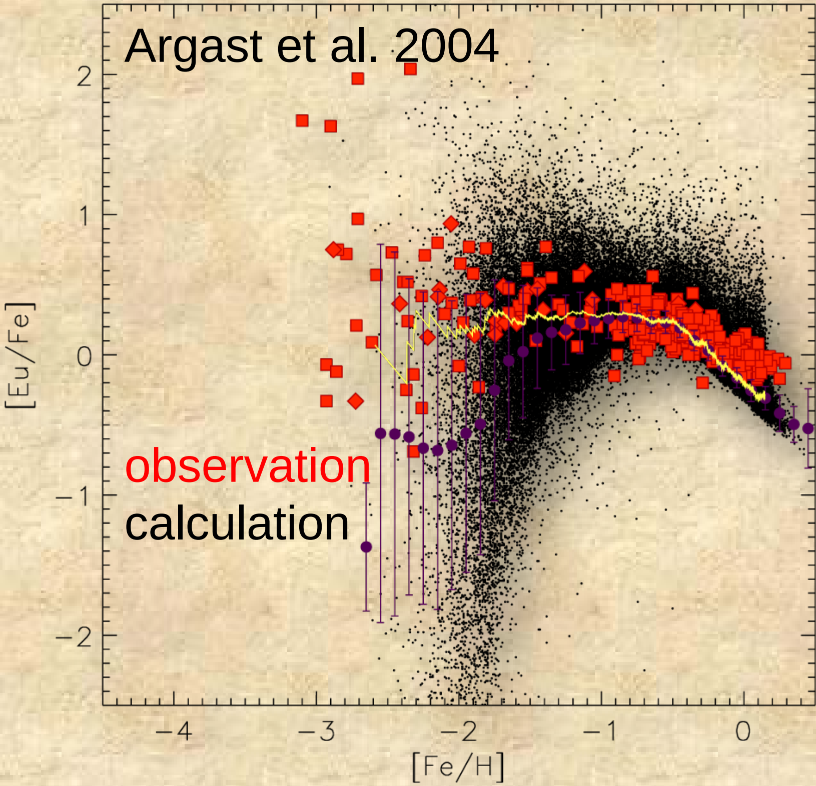


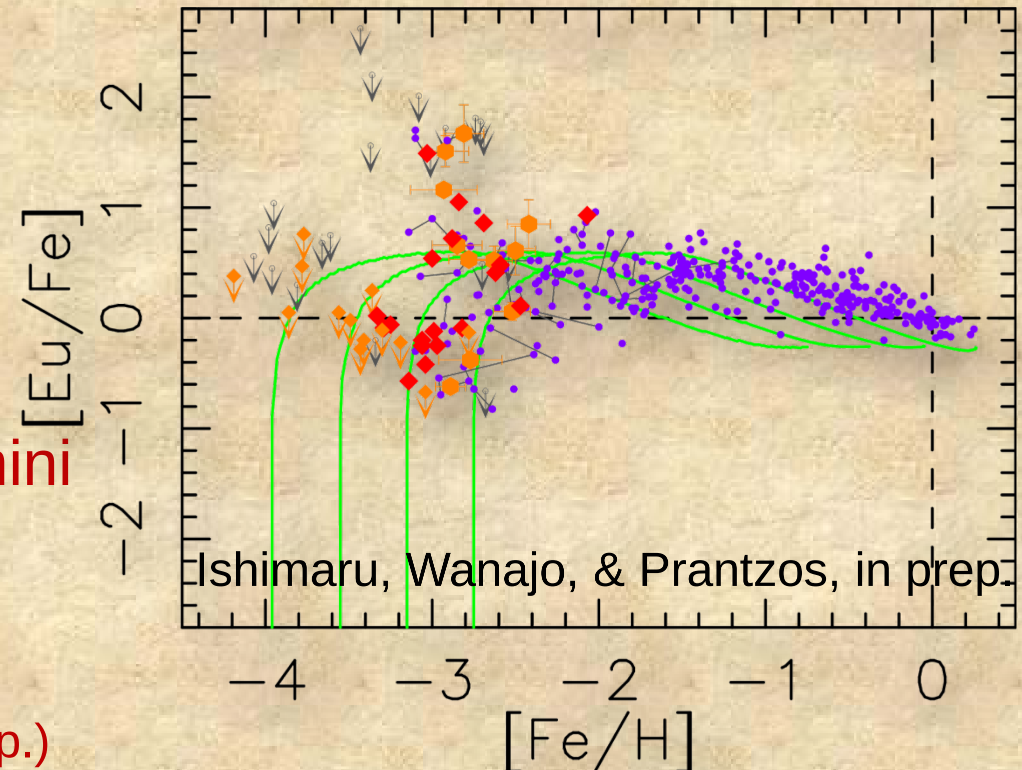
hypernovae (collapsars)

➲ high Y_e (~0.5 or larger)

neutron star mergers?

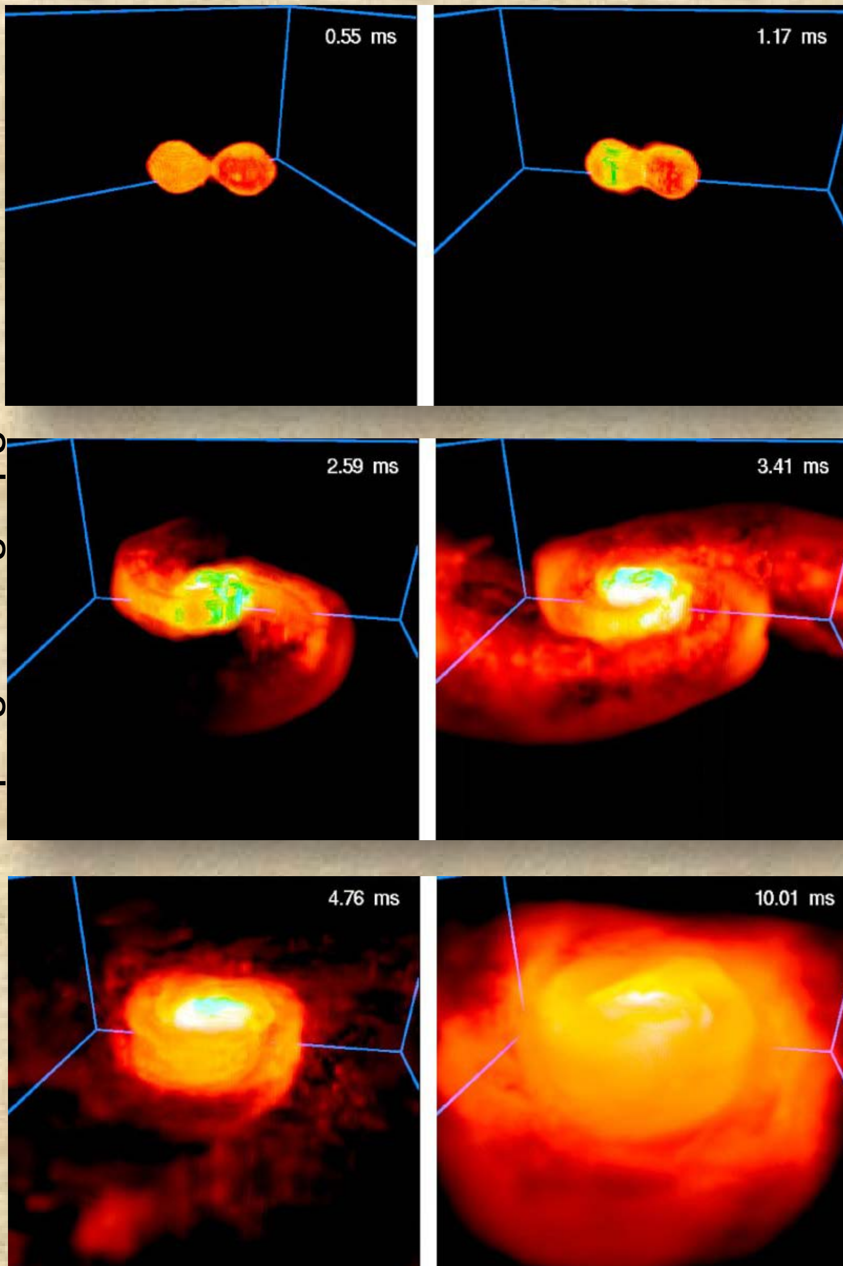
- ➲ long lifetime (> 100 Myr) and low frequency (10^{-5} yr^{-1}) would lead to the delayed appearance of r-elements and too large scatter in the Galaxy (Qian 2000; Argast et al. 2004)





- ➲ BUT a clustering model of mini halos does not exclude this possibility!!
(Prantzos 2006, 2008;
Ishimaru, Wanajo, & Prantzos, in prep.)

formation of a black-hole accretion torus



www.mpa-garching.mpg.de

coalescence

tidal disruption of n-rich matter
(only for NS-NS)

➲ r-process?

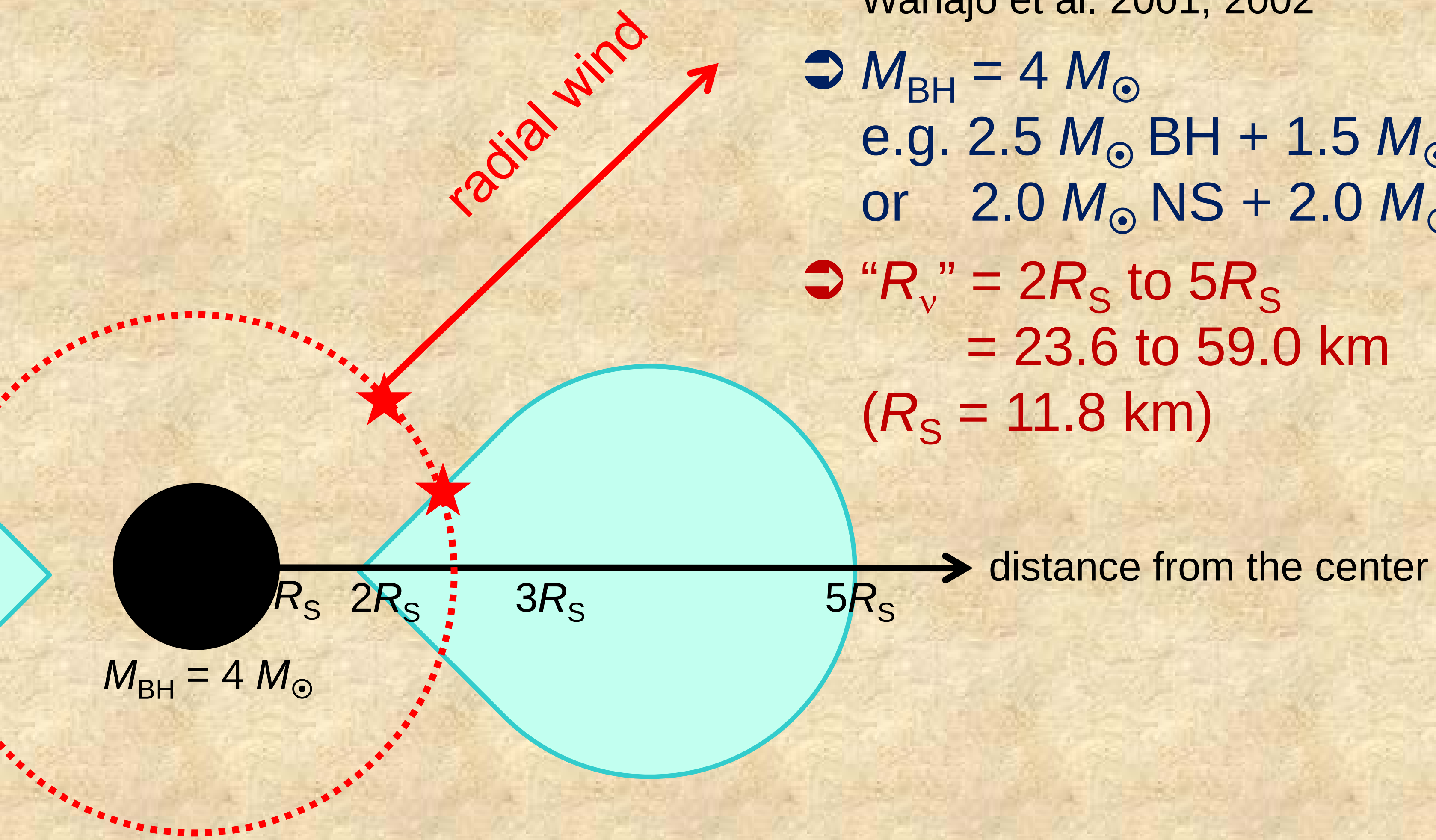
neutrino-driven winds from the
black hole accretion torus

➲ r-process? short GRB?

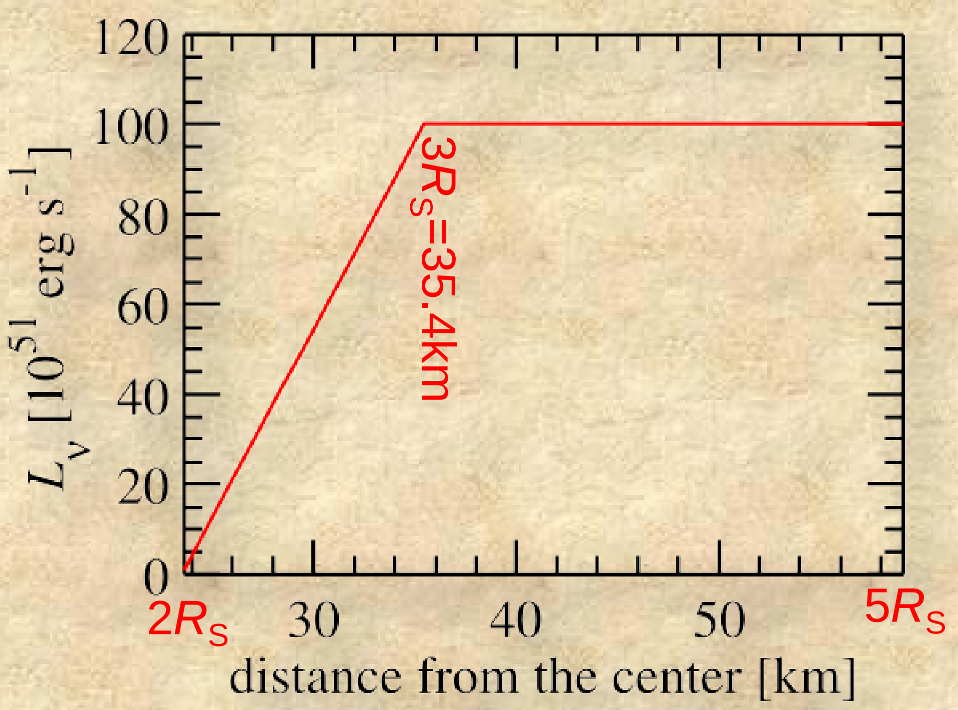
modeling the black hole winds

spherically symmetric wind model
Wanajo et al. 2001; 2002

- $M_{BH} = 4\ M_\odot$
  e.g. 2.5 $M_\odot$ BH + 1.5 $M_\odot$ NS
  or 2.0 $M_\odot$ NS + 2.0 $M_\odot$ NS
- "R_ν" = $2R_S$ to $5R_S$
  = 23.6 to 59.0 km
  (R_S = 11.8 km)



“ad hoc” neutrino luminosity



inner wind from 2-3 R_S

➲ linearly increasing

L_ν = 10^{51} to 10^{53} erg s^{-1}

outer wind from 3-5 R_S

➲ constant

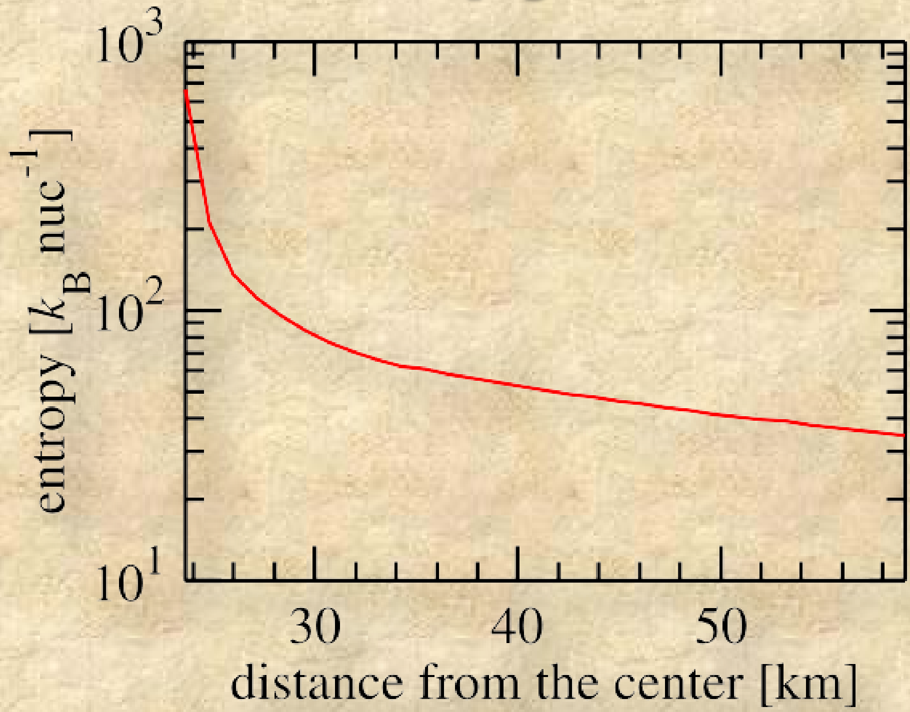
L_ν = 10^{53} erg s^{-1}

ε_ν = 15, 20, 30 MeV

for *e*, anti-*e*, others

e.g. Janka et al. 1999

entropy and mass ejection rate

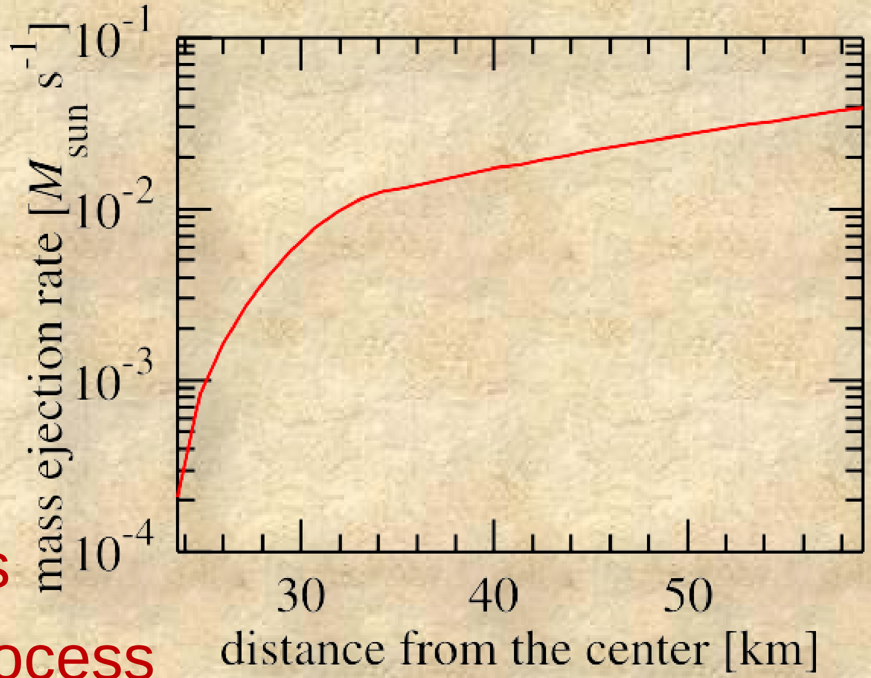


inner wind

➲ s ~100-1000 k_B, τ_{exp}~1-10 ms

outer wind

➲ s ~30-50 k_B , τ_{exp}~10-100 ms

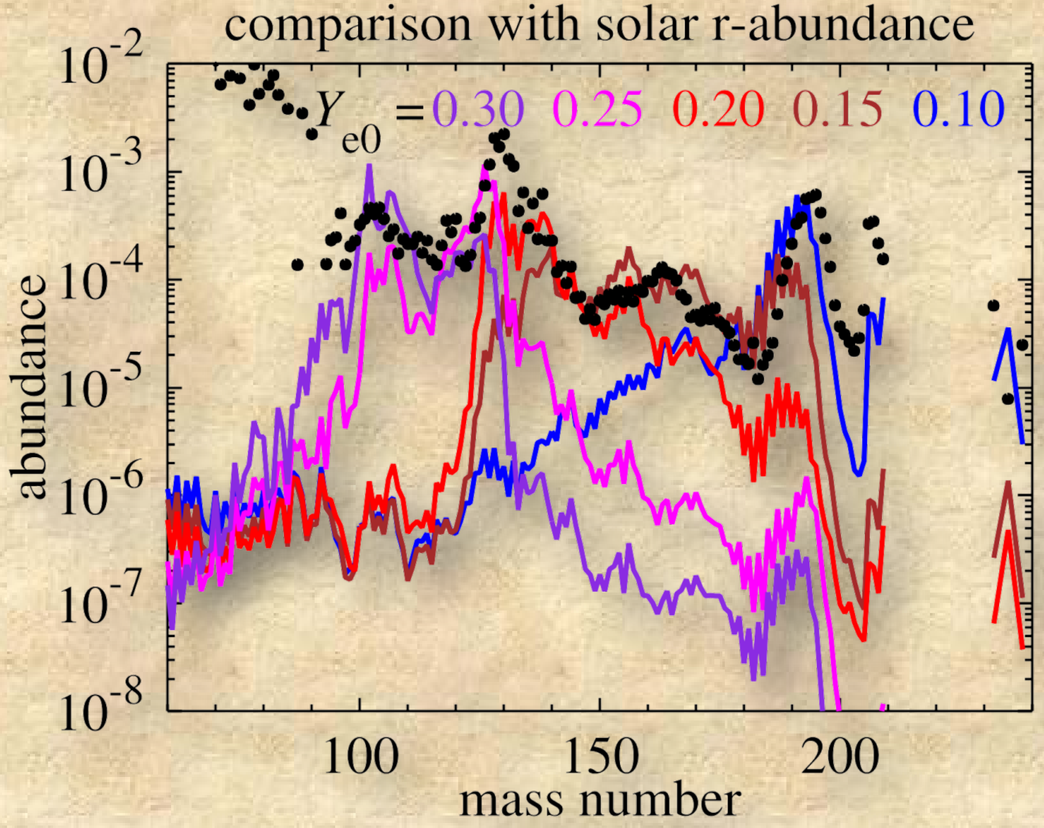


small mass ejection from the inner wind

➲ contribution from the outer winds dominates

➲ low Y_e is essential for r-process

nucleosynthesis



total r-nuclei mass (A>100)

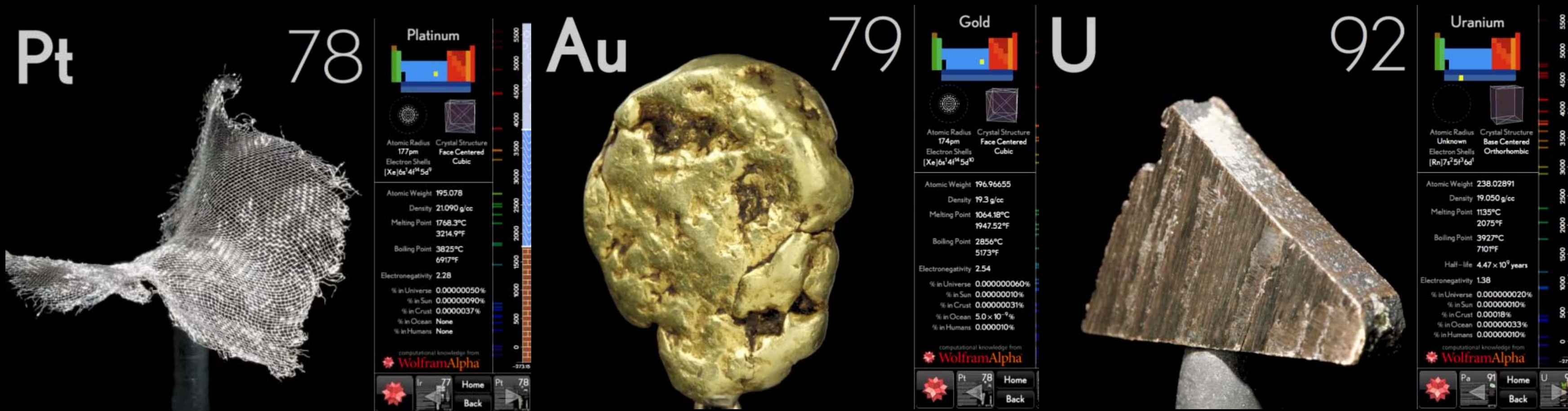
➲ $M_r \sim 0.05\ M_\odot$ assuming τ_{acc} = 100 ms

➲ event rate should be $\sim 10^{-5}$ yr $^{-1}$

r-abundance distribution

➲ reasonable combination with Y_{e0} = 0.1 - 0.3 can fit the solar r-pattern

summary 2



black hole winds resulting from NS-NS (or BH-NS) mergers
➲ expected low Y_e (=0.1-0.3) leads to production of the heavy r-process elements
➲ more studies are needed ! (hydro., nucleosynthesis, Galactic chemical evolution, relevance to GRB, etc.)