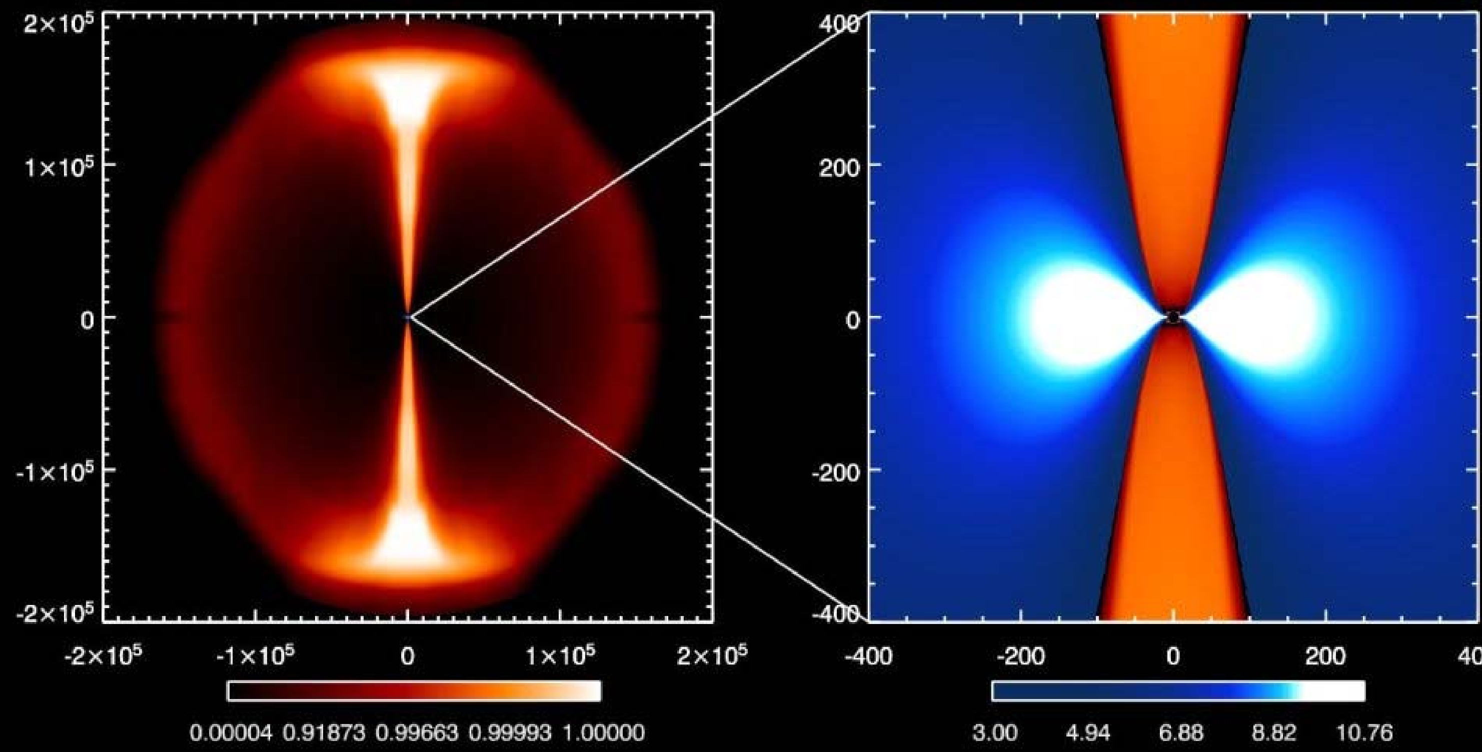
The weak vs. main r-process in neutrino-driven winds



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Shinya Wanajo & Thomas Janka

(Excellence Cluster Universe, TUM / MPA)

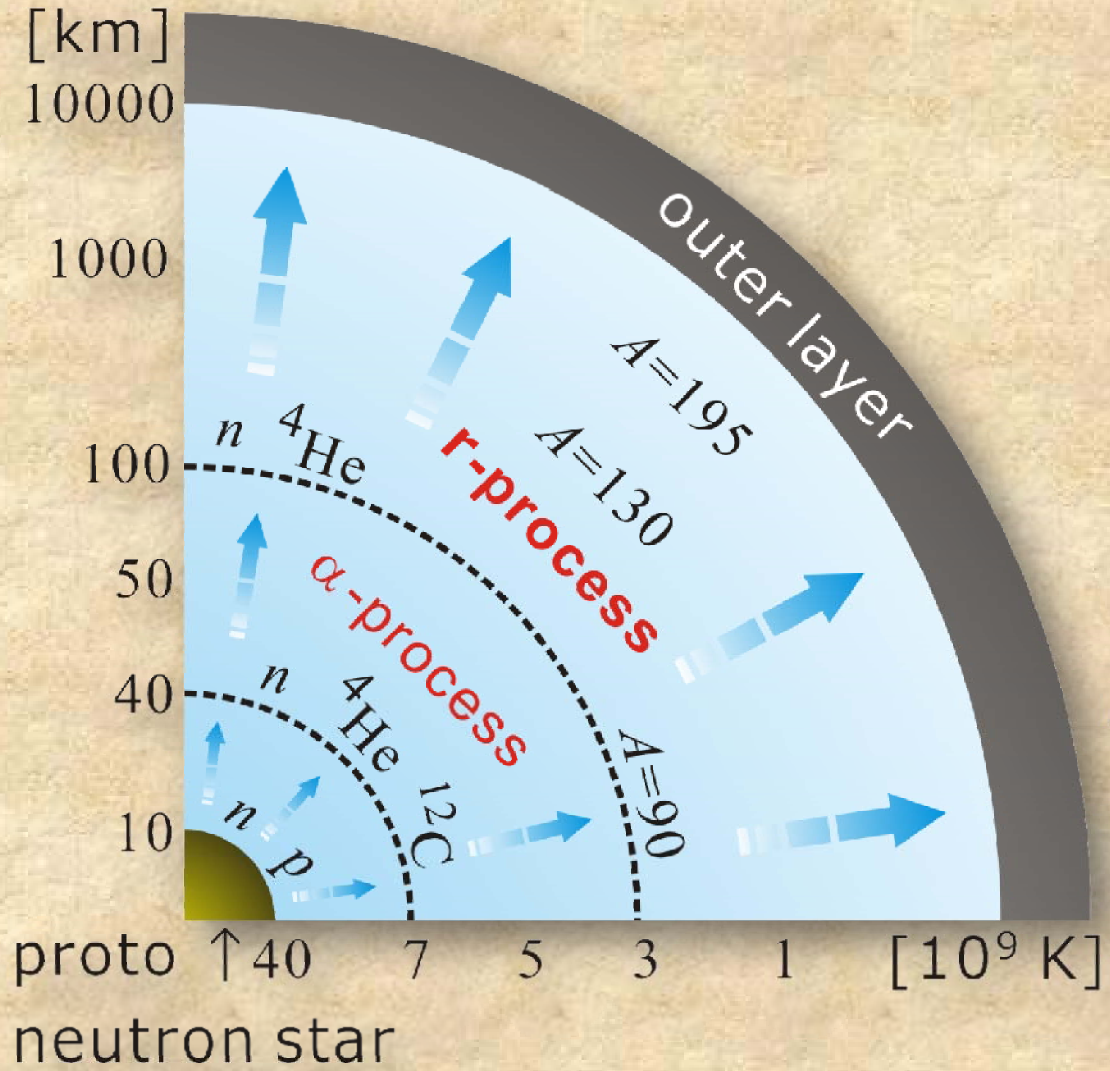
0. astrophysical r-process scenarios

1. weak r-process in supernovae

2. main r-process in black hole winds

0. astrophysical r-process scenarios

key parameters for 3rd peak formation



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

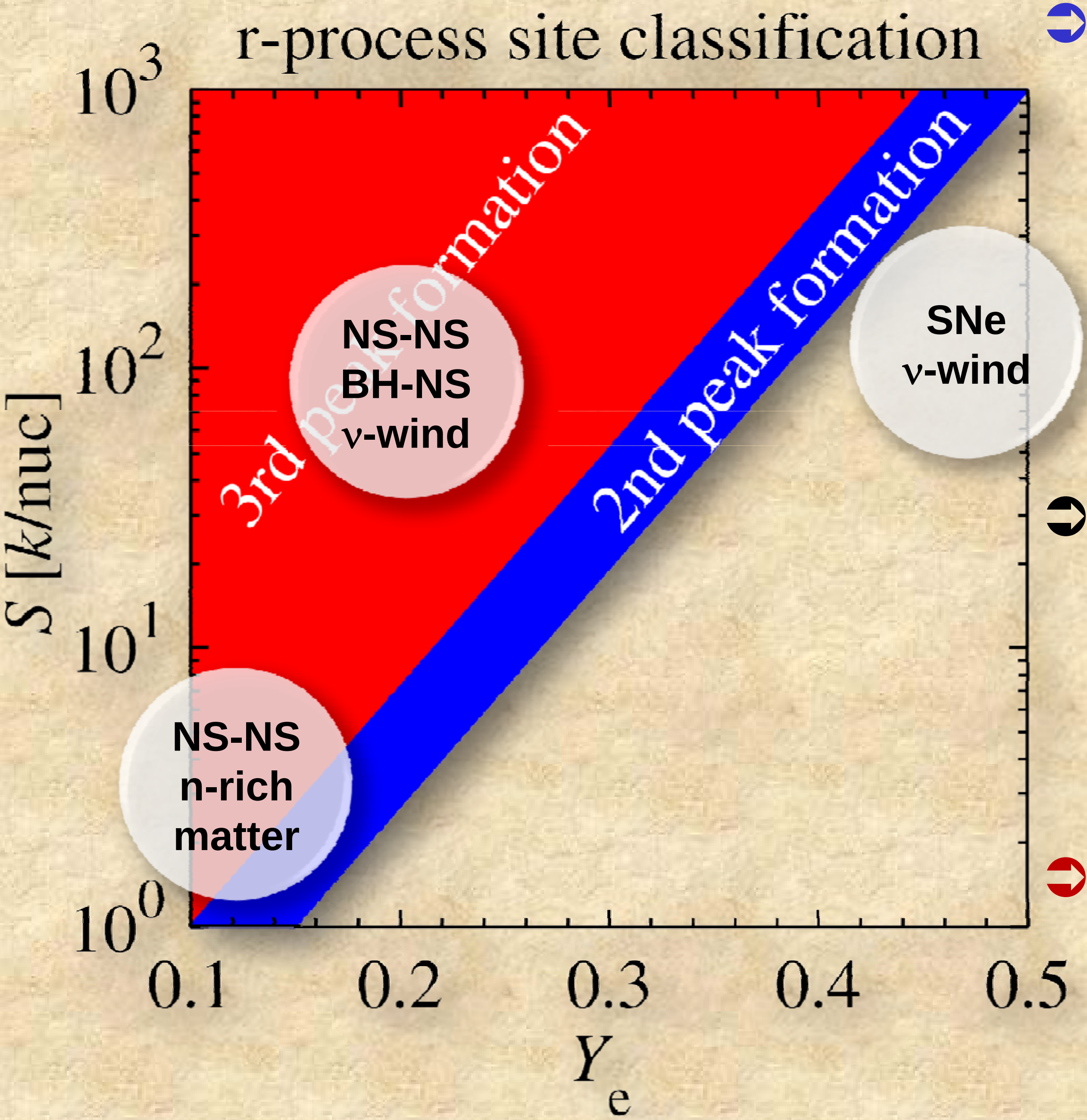
low electron fraction (proton per nucleon):

$Y_e < 0.2$

➲ 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., etc.

➲ black hole winds of NS-NS, BH-NS
Surman et al. 2008
least studied one !!

1. weak r-process in supernovae

Neutrino-driven wind model

➲ spherical steady flows in Schwarzschild geometry

Newtonian: Qian & Woosley 1996

General Relativety: Cardal & Fuller 1997; Otsuki et al. 2000

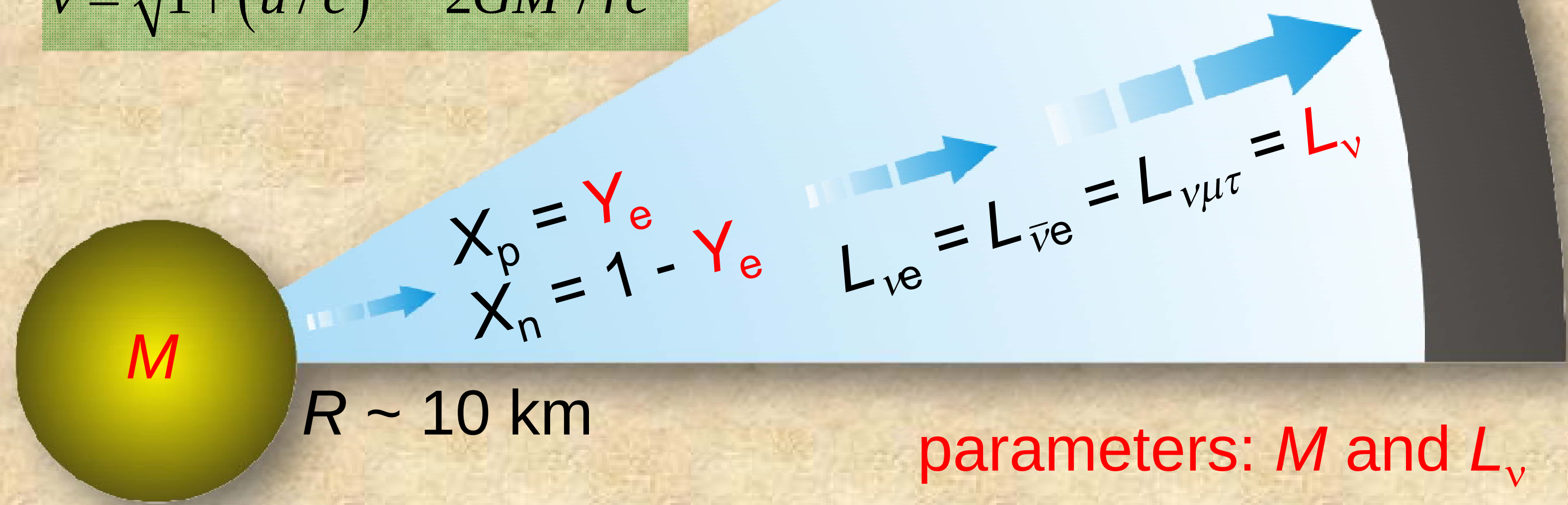
Wanajo et al. 2001, 2002; Thompson et al. 2001

$$\dot{M} = 4\pi r^2 \rho u$$: mass ejection rate

$$u\frac{du}{dr} = -\frac{1+(u/c)^2 - 2GM/rc^2}{\rho(1+\varepsilon/c^2)+P/c^2}\frac{dP}{dr} - \frac{GM}{r^2}$$: equation of motion

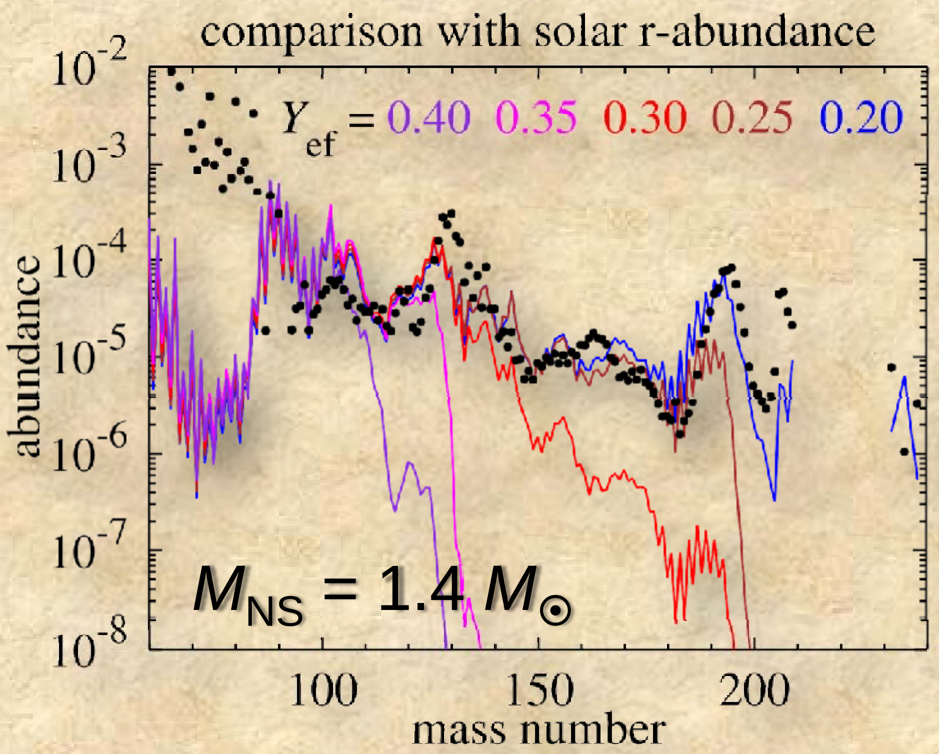
$$\dot{q} = u\left(\frac{d\varepsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right)$$: heating (cooling) rate

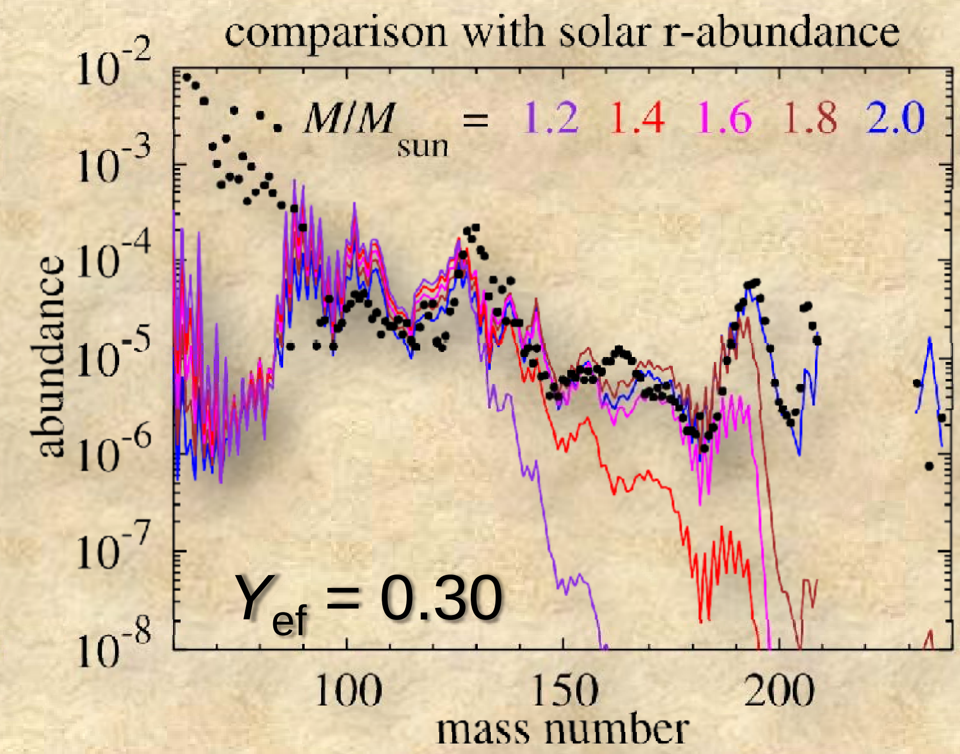
$$v = \sqrt{1+(u/c)^2 - 2GM/rc^2}$$



parameters: M and L_ν

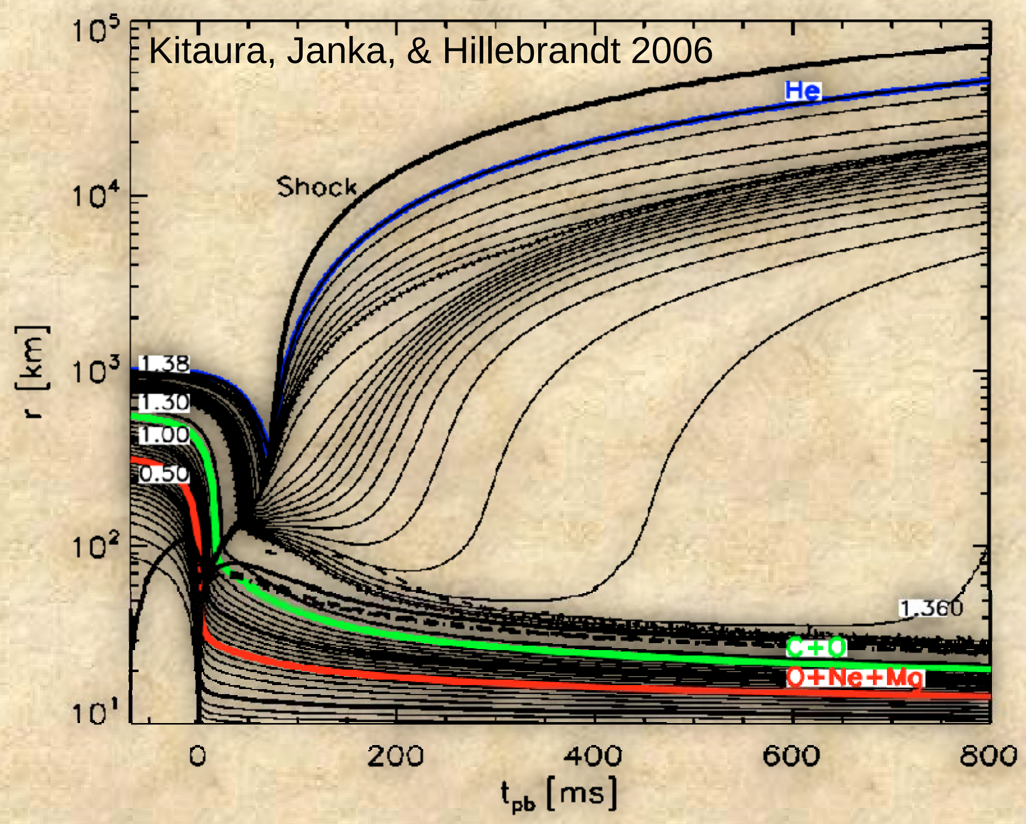
only weak r-process in neutrino winds?





- ➲ *A* ~ 130 with reasonable parameter choices of $M_{NS} = 1.4\ M_\odot$, $Y_{ef} = 0.30$ (weak r-process; Wanajo & Ishimaru 2006)
- ➲ "extreme" parameters of $Y_{ef} \sim 0.2$ or $M_{NS} = 2.0\ M_\odot$ for the main r-process

BUT, no r-process in an “exploding” SN



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

➲ prompt explosion?
Hillebrandt et al. 1984
Wanajo et al. 2003

➲ shocked-heated matter?
Ning et al. 2008

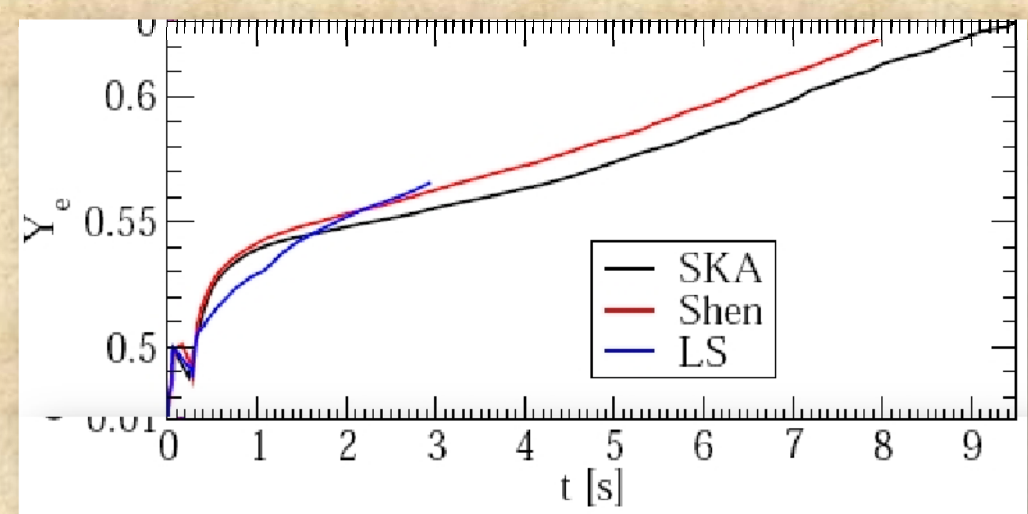
weak neutrino-driven (not prompt) explosion of a 9 $M_\odot$ star
Kitaura, Janka, & Hillebrandt 2006

➲ no r-process Hoffman et al. 2008; Janka et al. 2008

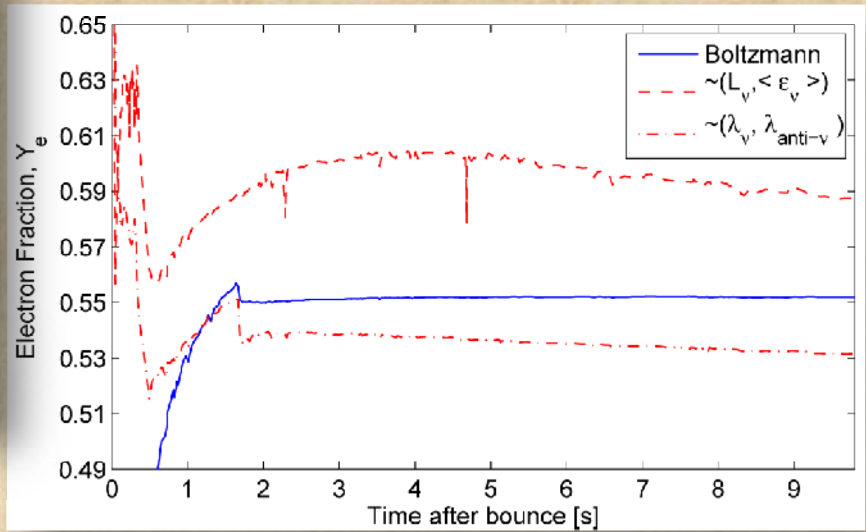
➲ but, production of Zn and light p-nuclei Wanajo et al. 2009

➲ later neutrino winds? (no, perhaps....)

no r-process in protoneutron star winds?



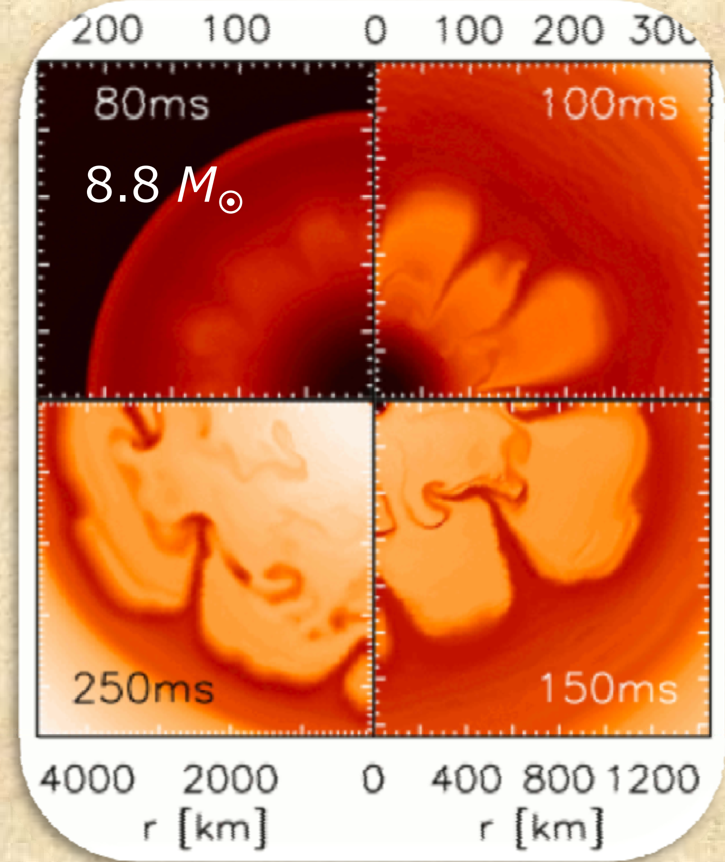
self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl et al. 2009 .



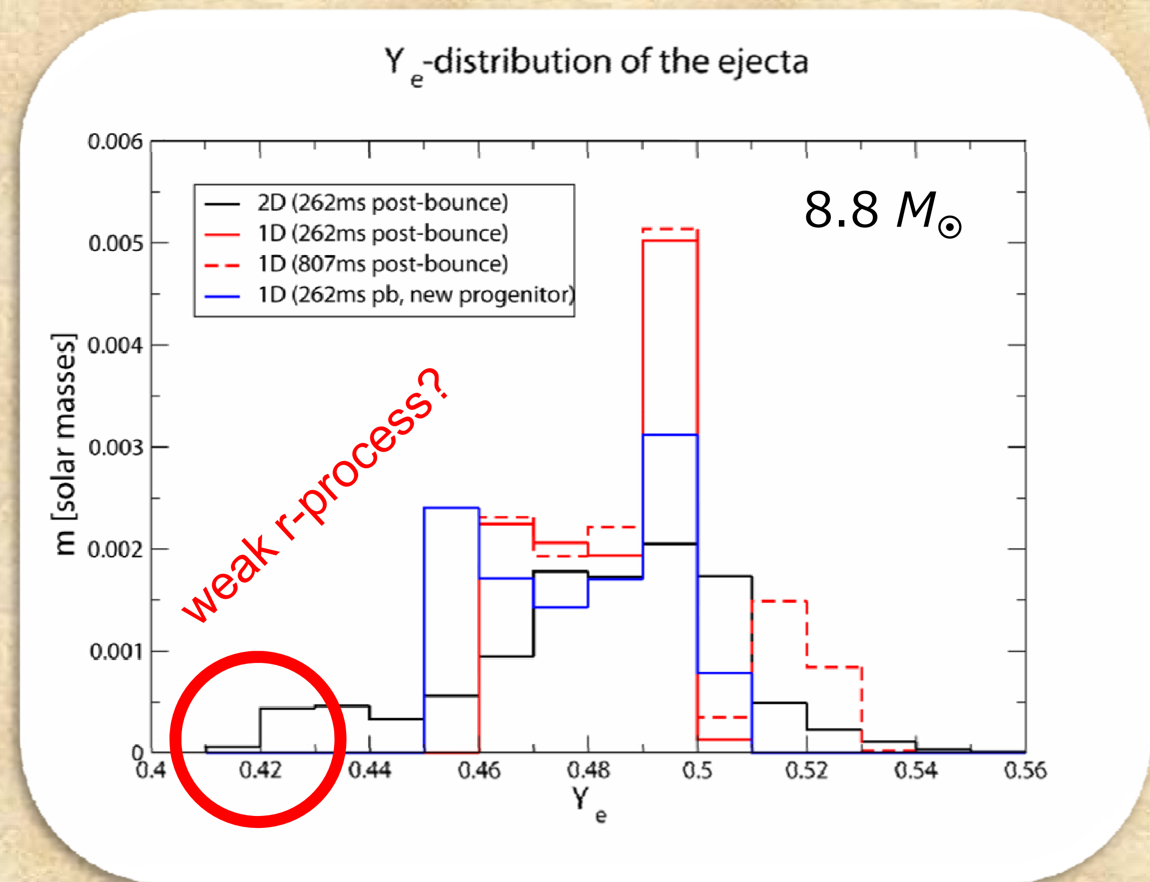
artificial explosion of a 10 $M_\odot$ star
Fischer et al. 2009

- ➲ $Y_e > 0.5$ all the way in the latest long-term simulations
- ➲ no r-process is expected .... (but νp-process?)

2D effect ?



(Kitaura et al. 2006)

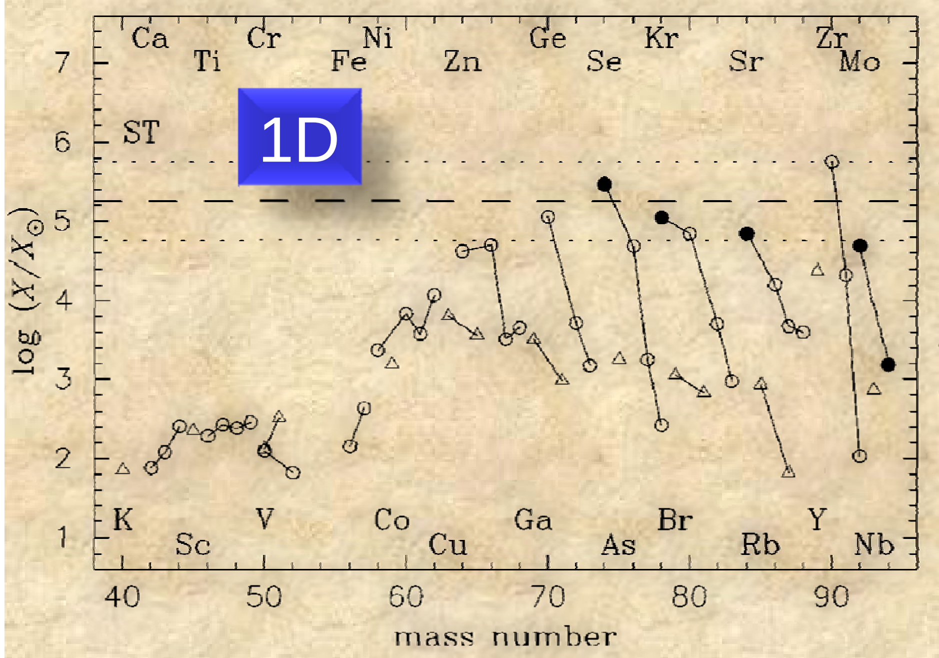


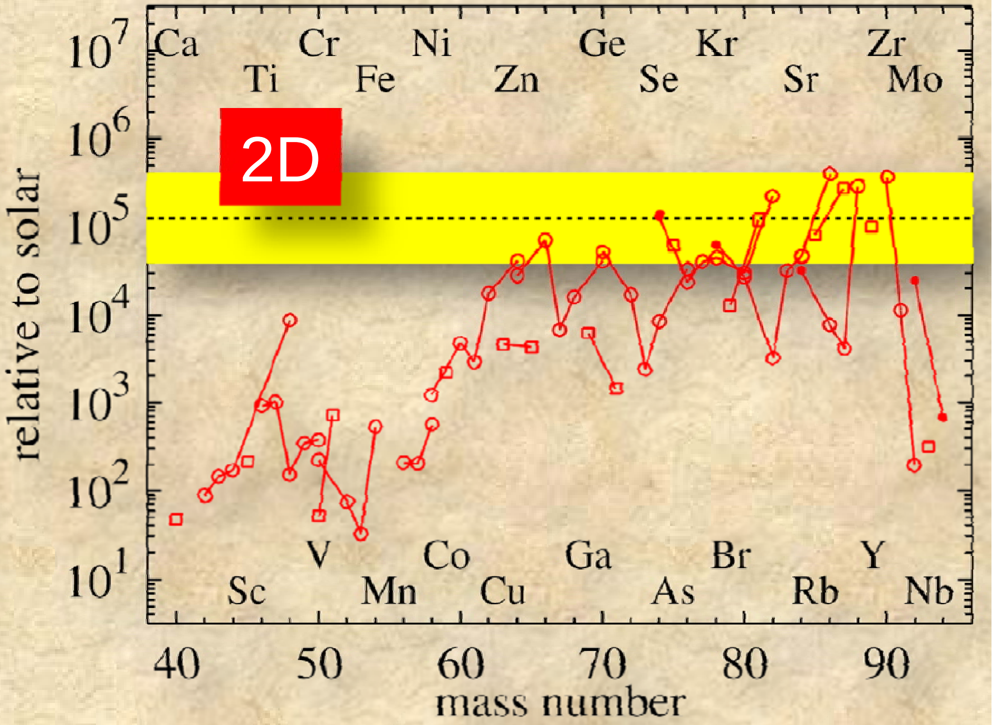
(Müller & Janka in prep.)

➲ low-Y_e bubbles appear (down to ~0.4)

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

mass-averaged yields





1D model

Wanajo et al. 2009

also Hoffman et al. 2008

➲ only up to N = 50 (A = 90)

➲ and only the source of p-rich isotopes

2D model

Wanajo, Janka, Müller, in prep.

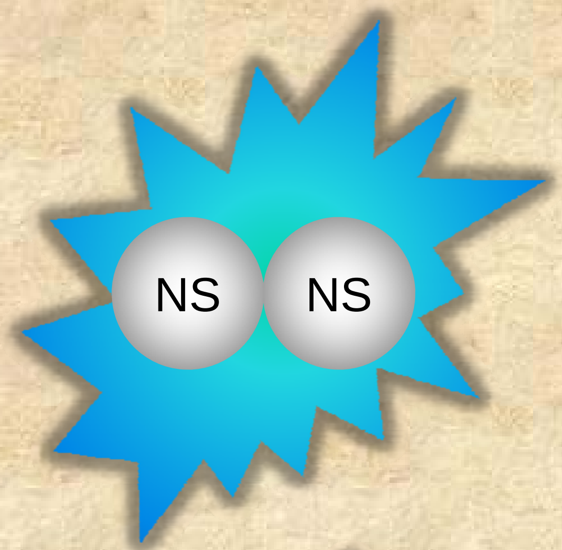
➲ still up to N = 50 (A = 90)

➲ but the source of "n-capture" elements of Zn, Ge, Se, Br, Kr, Rb, Sr, Y, Zr

3. main r-process in black hole winds

black hole winds

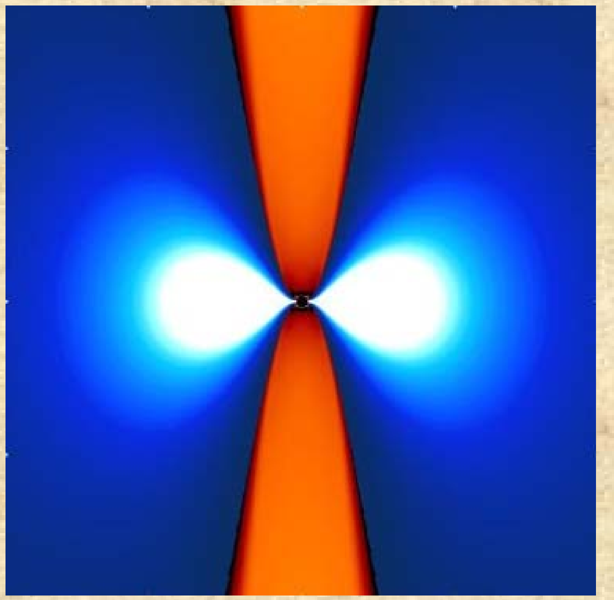
= neutrino-driven winds from the torus around an accreting black hole



NS-NS or BH-NS mergers

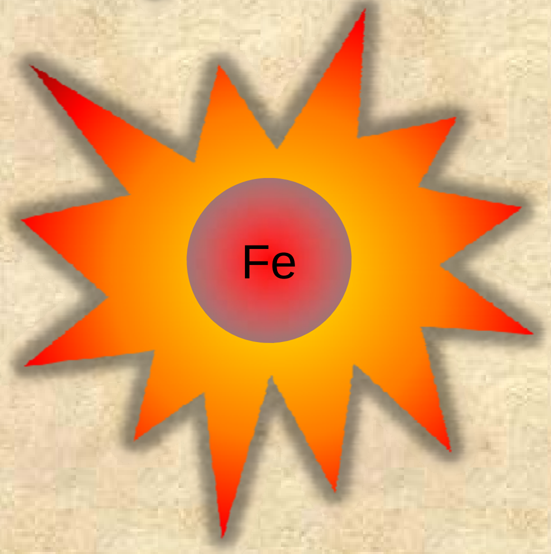
➲ low Y_e (~0.1-0.3)

black hole winds



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

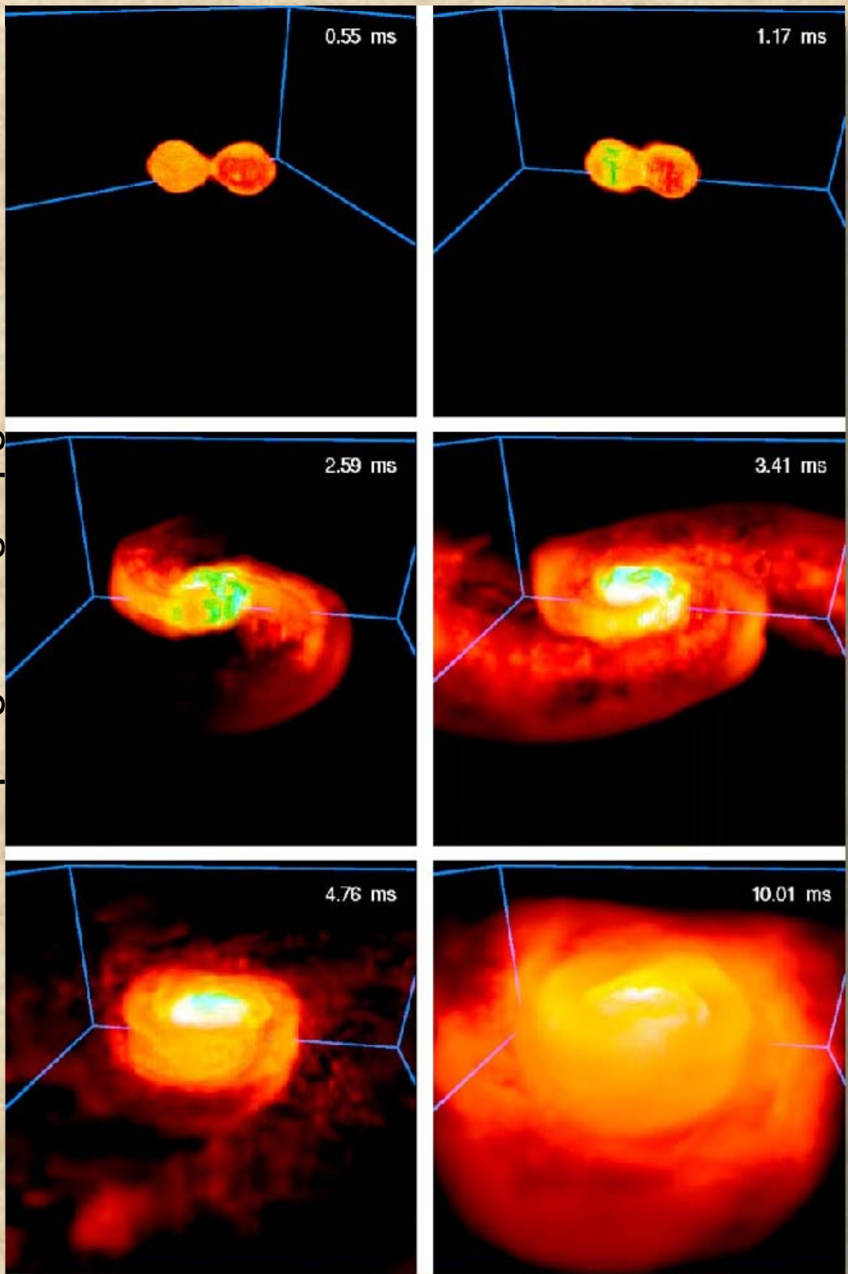
black hole formation



massive supernovae (hypernovae)

➲ high Y_e (~0.5)

formation of a black-hole accretion torus



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coalescense

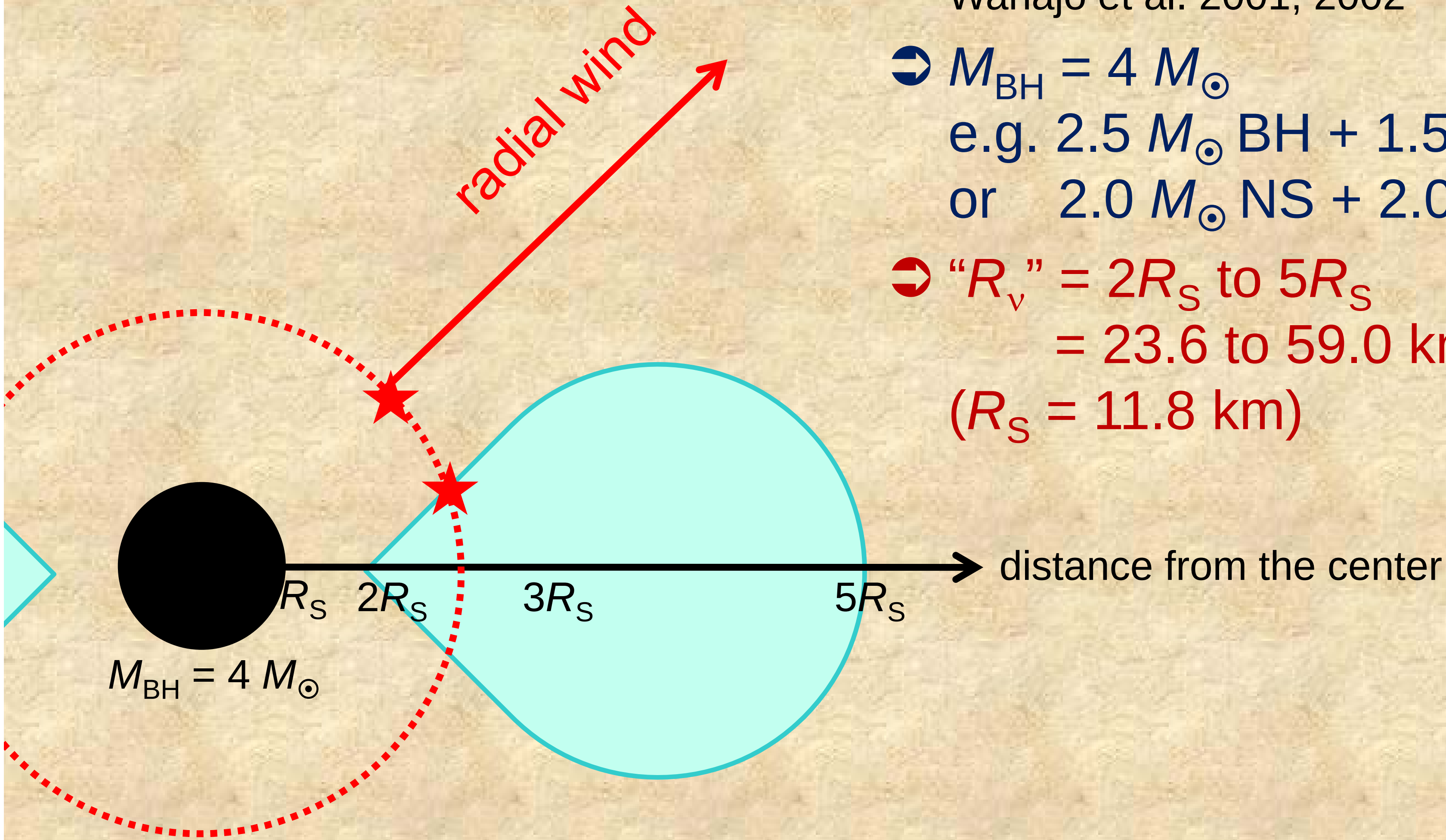
tidal disruption of n-rich matter (only for NS-NS)

➲ r-process?

neutrino-driven winds from the black hole accretion torus

➲ r-process? short GRB?

modeling the black hole winds

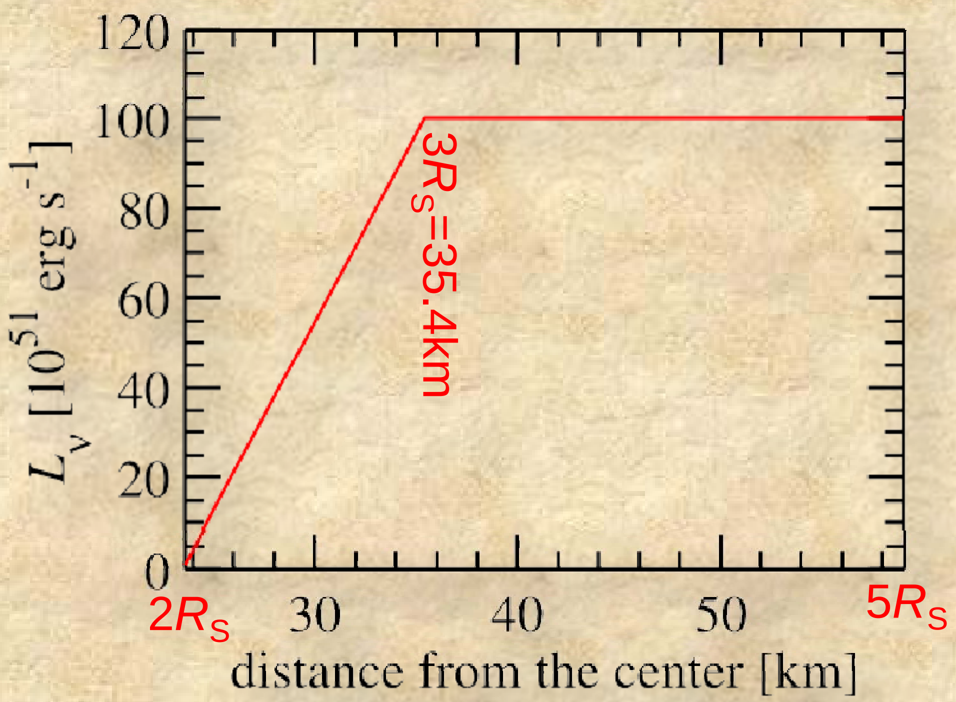


spherically symmetric model

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

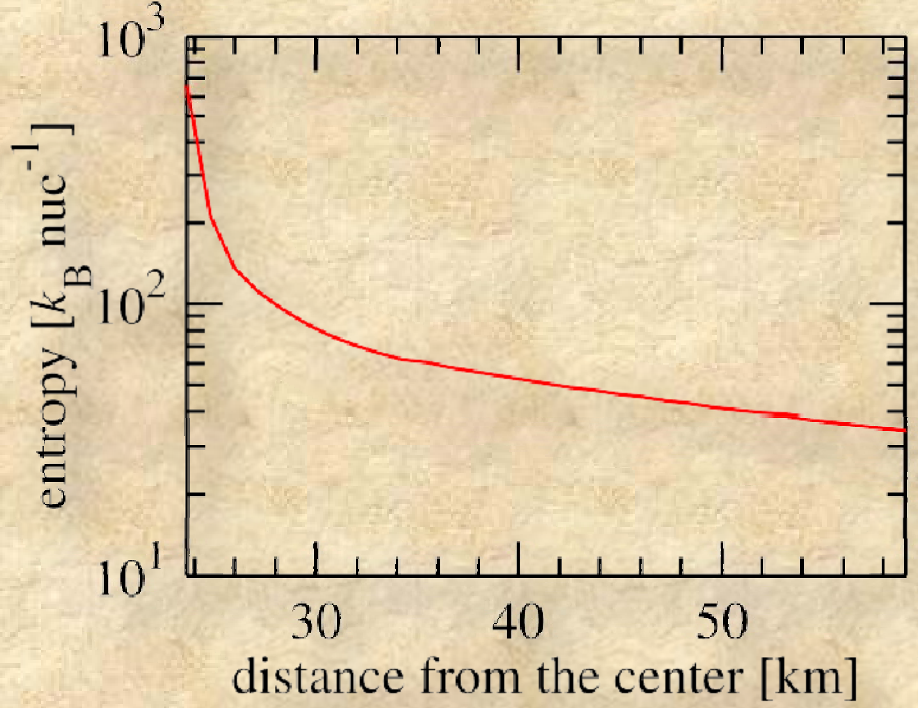
L_ν = 10^{53} erg s^{-1}

ε_ν = 15, 20, 30 MeV

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

e.g. Janka et al. 1999

entropy and timescale

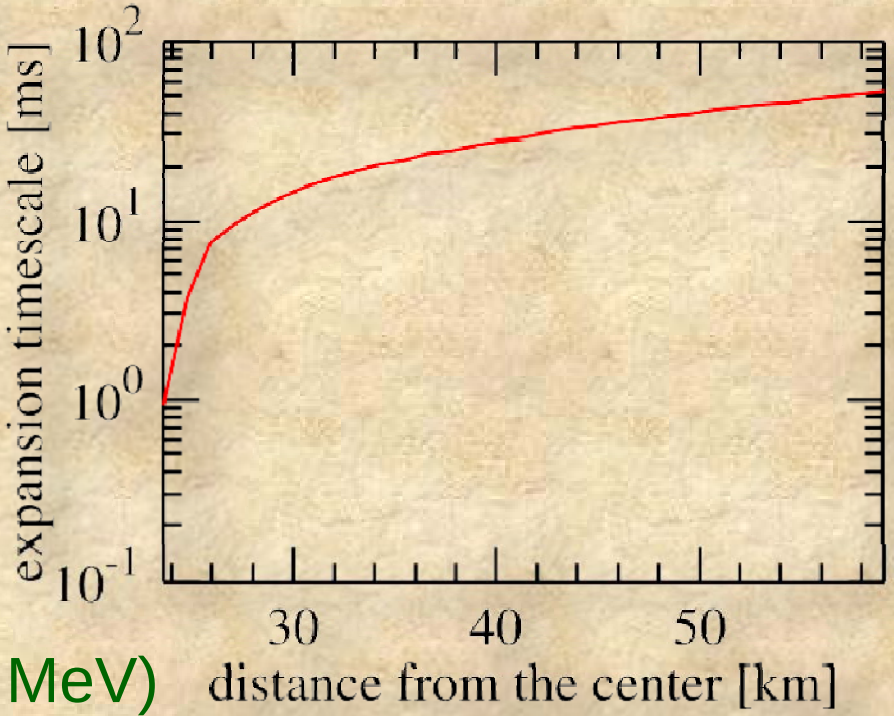


inner wind

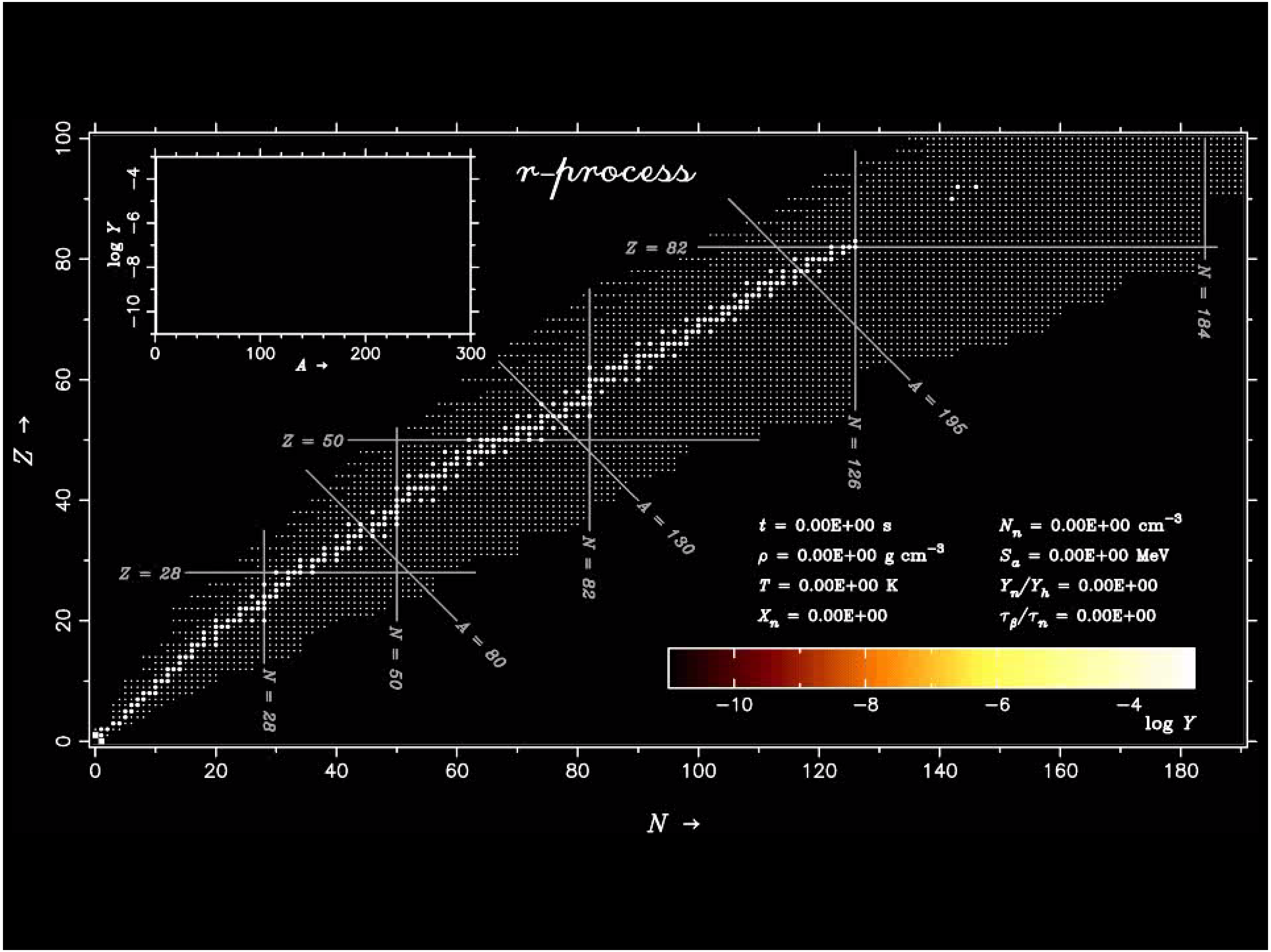
➲ s ~100-1000 k_B, τ_{exp}~1-10 ms

outer wind

➲ s ~30-50 k_B , τ_{exp}~10-100 ms

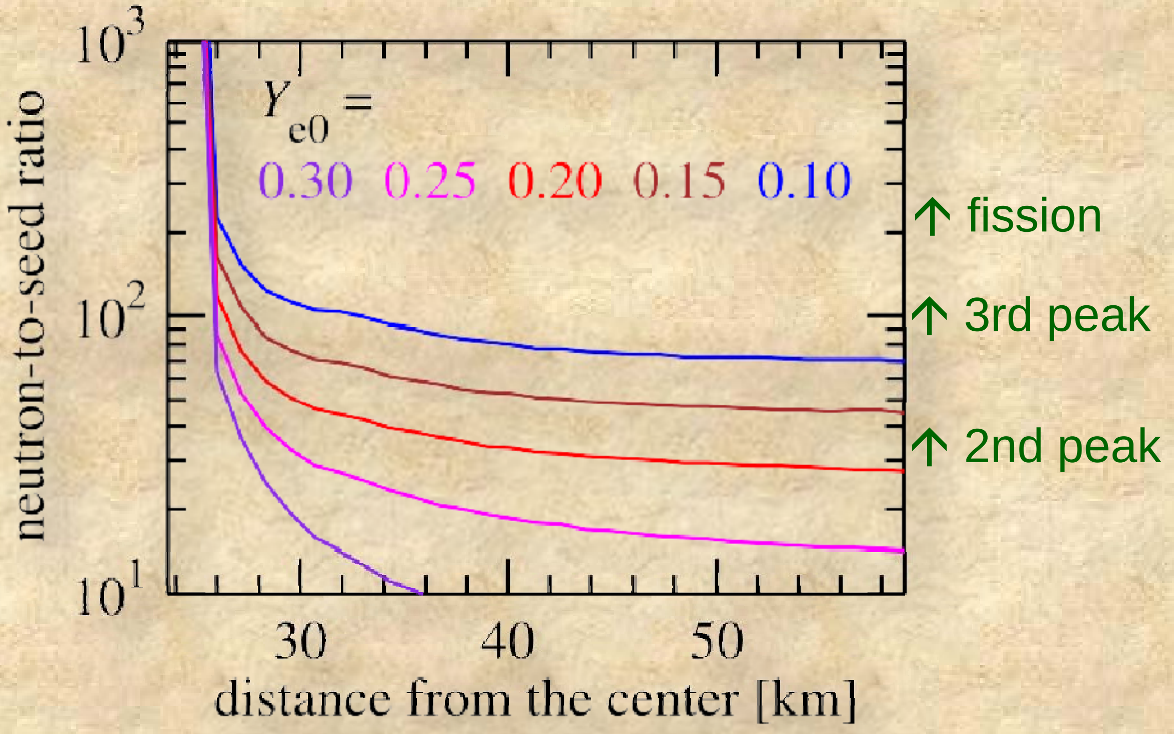


$\tau_{exp} = t(0.5 \text{ MeV}) - t(0.5/e \text{ MeV})$



r-process
Z = 82
Z = 50
Z = 28
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
log Y
A →
N →
Z →

neutron-to-seed ratio (at T_9 = 2.5)



initial Y_e (at T_9 = 9)

➲ Y_{e0} = 0.1, ..., 0.30
e.g., Setiawan et al. 2006

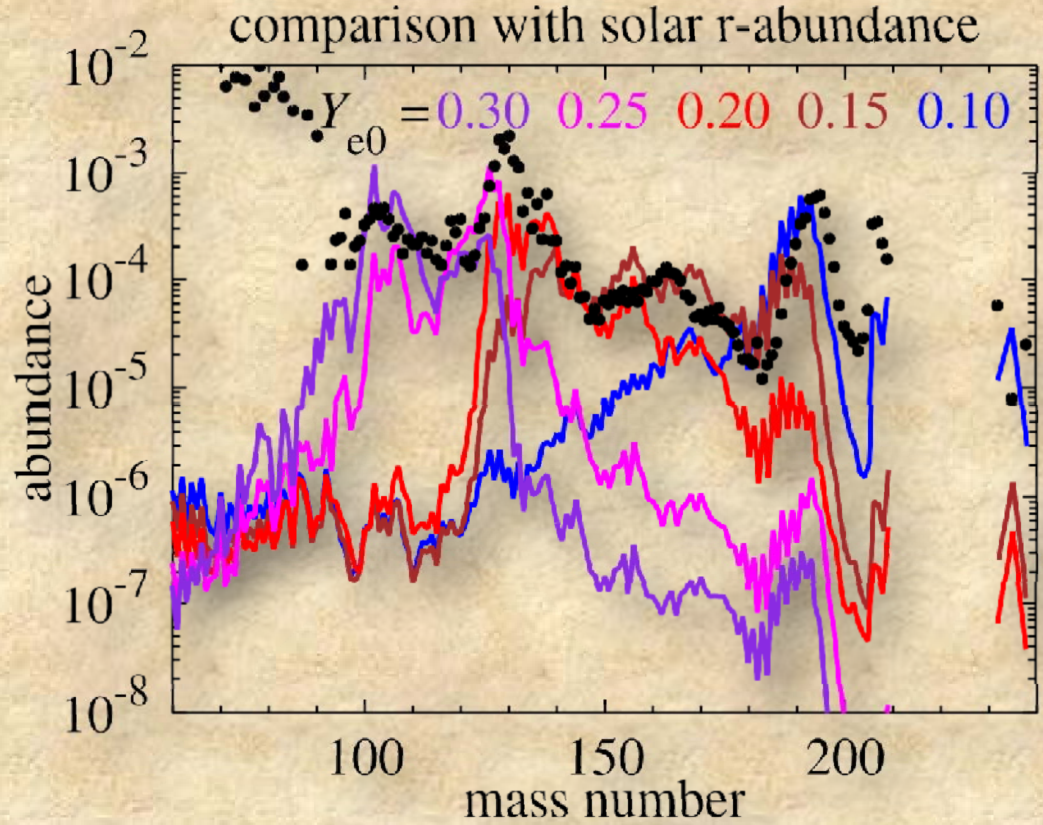
outer wind

➲ n/seed ~ 30-50
2nd peak formation

innermost wind

➲ n/seed ~ 100-1000
3rd peak formation
fission cycling

nucleosynthesis



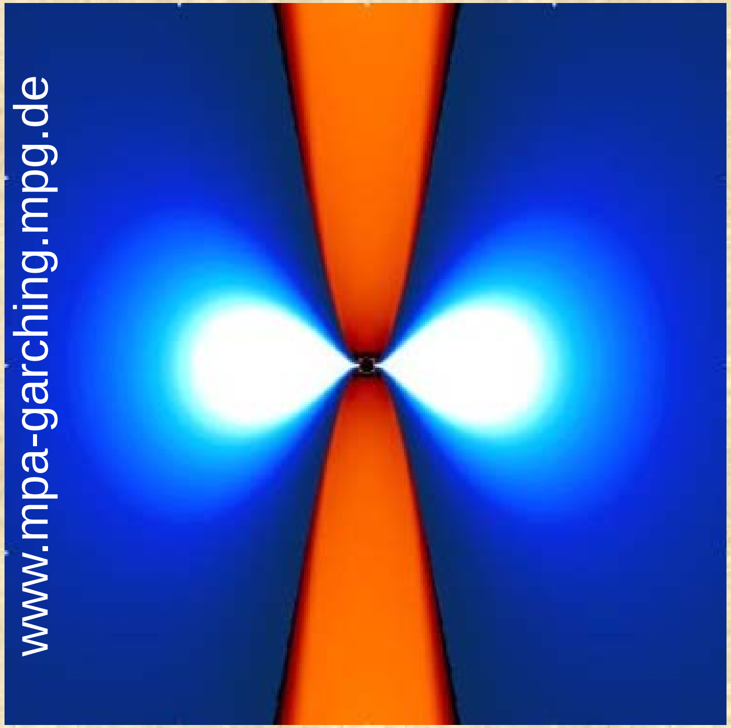
total r-nuclei mass (*A*>100)

- ➲ $M_r \sim 0.1\ M_\odot$ assuming τ_{acc} = 200 ms
- ➲ event rate should be ~ 10^{-5} - 10^{-6} yr $^{-1}$

r-abundance distribution

- ➲ reasonable combination with Y_{e0} = 0.1 - 0.3 can fit the solar r-pattern
  e.g., variation in time and space; Setiawan et al. 2006

summary



neutrino-driven winds of core-collapse supernovae

➲no r-process, or at best, weak r-process

➲source of up to *N* = 50 nuclei (Sr, Y, Zr)

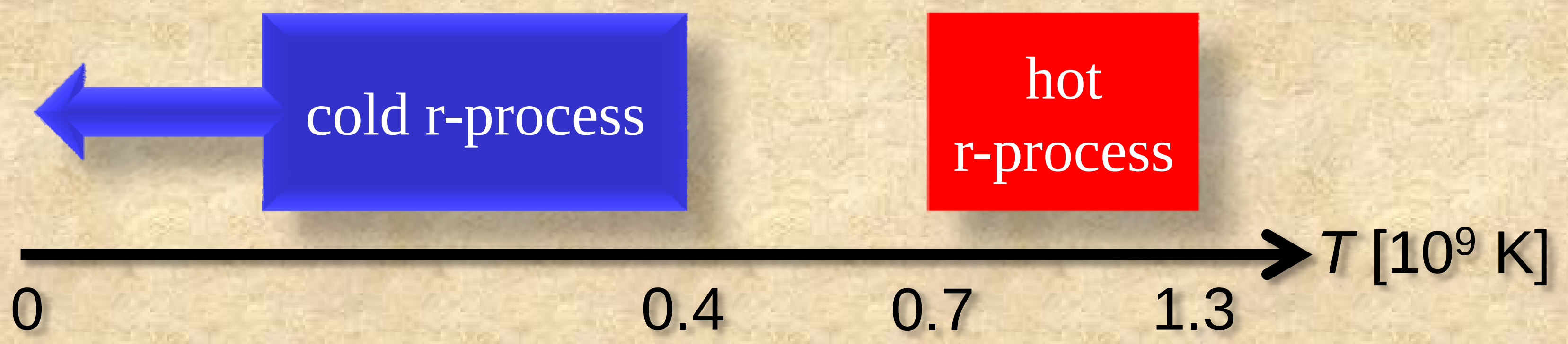
black hole winds of NS-NS or BH-NS mergers (or hypernovae)

➲main r-process? (at least with a simple model with low Y_e)

➲source of all r-process nuclei? (fission in the inner winds)

cold vs. hot r-processes

Wanajo 2007; also Blake & Schramm 1976



- n-capture and β-decay determine the r-path (no nγ-γn equilibrium)
- insensitive to temperature
- relevant to many sites (e.g., low-mass SNe, NS-NS, BH-NS, collapsars)

- nuclear masses determine the r-path (nγ-γn equilibrium holds)
- sensitive to temperature
- relevant to limited site (e.g., massive SNe)