R-process Nucleosynthesis in Magnetically dominated Core-Collapse Supernovae

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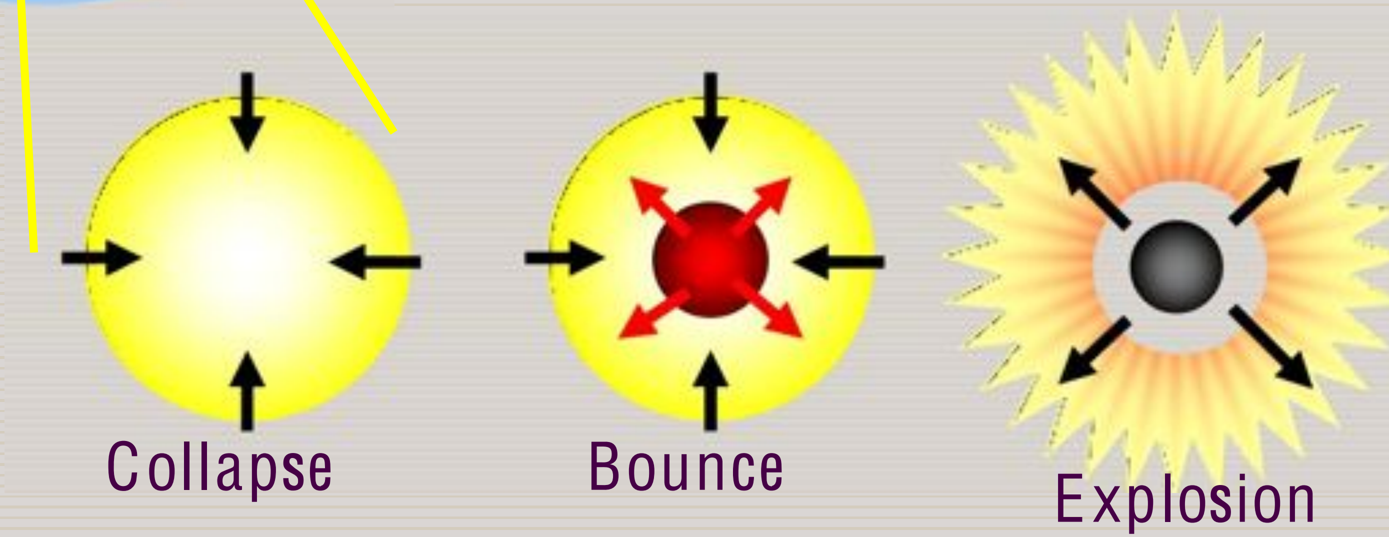
Outline

- Introduction
  - MHD SN as an astronomical r-process site
- Explosion models and nucleosynthesis
  - MHD Supernova model
  - Tracer particle motion and Ye evolution
  - *r*-process nucleosynthesis
- Summary

Massive star and supernova (SN) explosion

- Massive stars ($M/M_{\odot} \gtrsim 10$)
  incude Gravitational collapse
- Onion-like layers
  (H – He – O/C –Ne/O – Si –Fe)
- Explosive end & Compact object
  - Supernovae and Neutron stars
  - Black Holes, Jets
  - long GRBs, Hypernovae



r-process and core-collapse supernova

- Neutrino-Driven Explosion models
  - SASI (Iwakami et al. 2008, etc.)

  →canonical Supernova mechanism?

  →Proton-rich matter? (neutrino interaction)

  →Neutrino Driven Wind (from Proto-Neutron star)

  high-enthropy model
- Magneto-hydrocynamic Explosion models
  - MHD effect (Takiwaki et al. 2009, etc.)

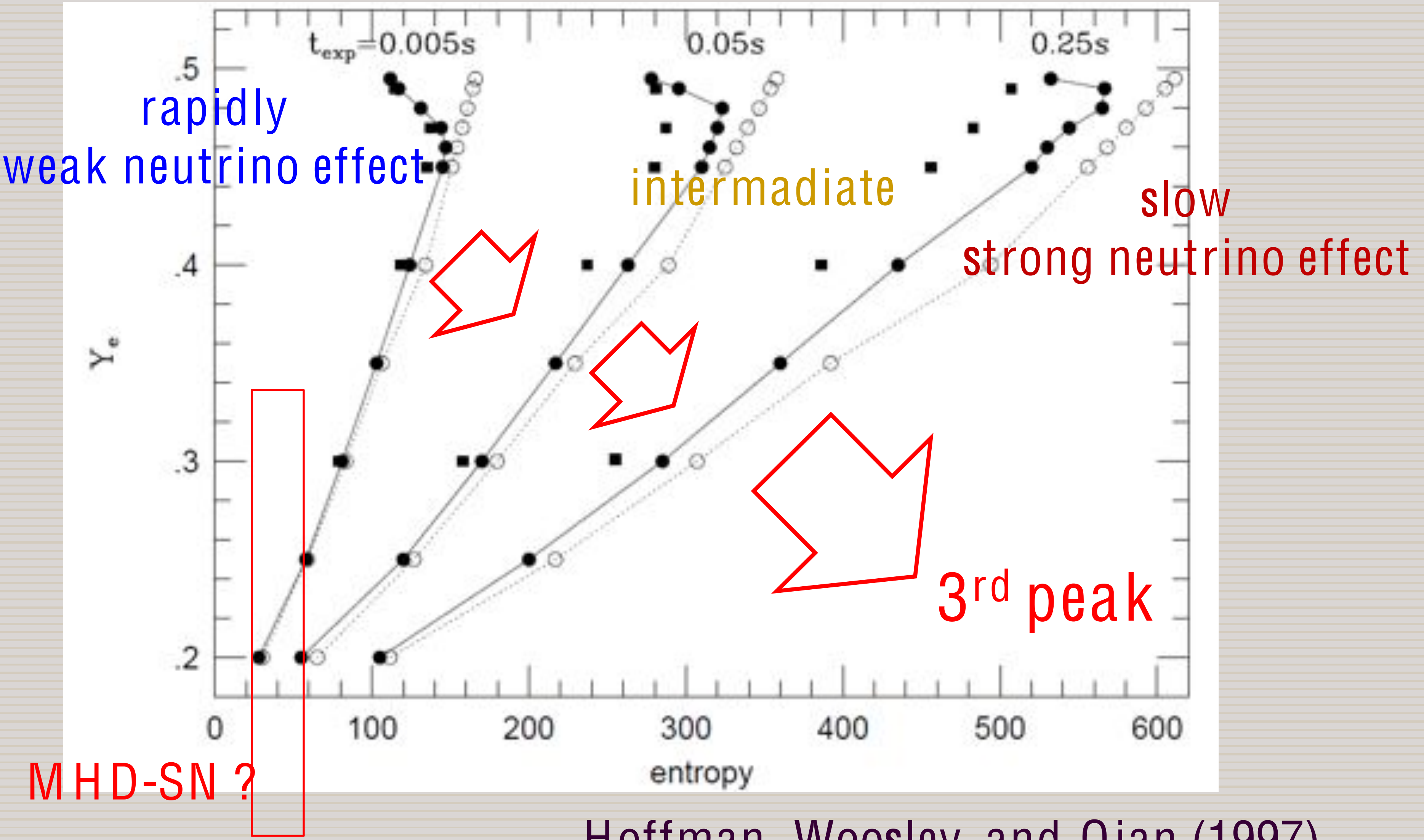
  →origin of Magnetars and GRBs ?

  →Neutron rich matter

  →a large amount of ejection mass

the condition of the 3rd peak elements

t_{exp}: time scale of expansion



Hoffman, Woosley, and Qian (1997)

Astrophysical Site

Solar system r-element(10^{-7} $M_\odot$) : log10(Mass)

Sites	r-element mass (log10 $M_\odot$)	Event rate (log10[/year/gal])	entropy	Ye
Neutrino Driven Wind (NDW)	? -5	-2	high (>100)	high (~0.3)
Neutron Star binary Merger	? -2	-5	Low	Low (~0.1)
MHD Supernova	?			
Collapsar Model (MHD)	-2	? -5	Very high	log

Woosley et al. 1996, Hoffman et al. 1997, Wanajo et al. 2001, Freiburghaus et al. 1999, Sumiyoshi et al. 2000, Fujimoto et al. 2007

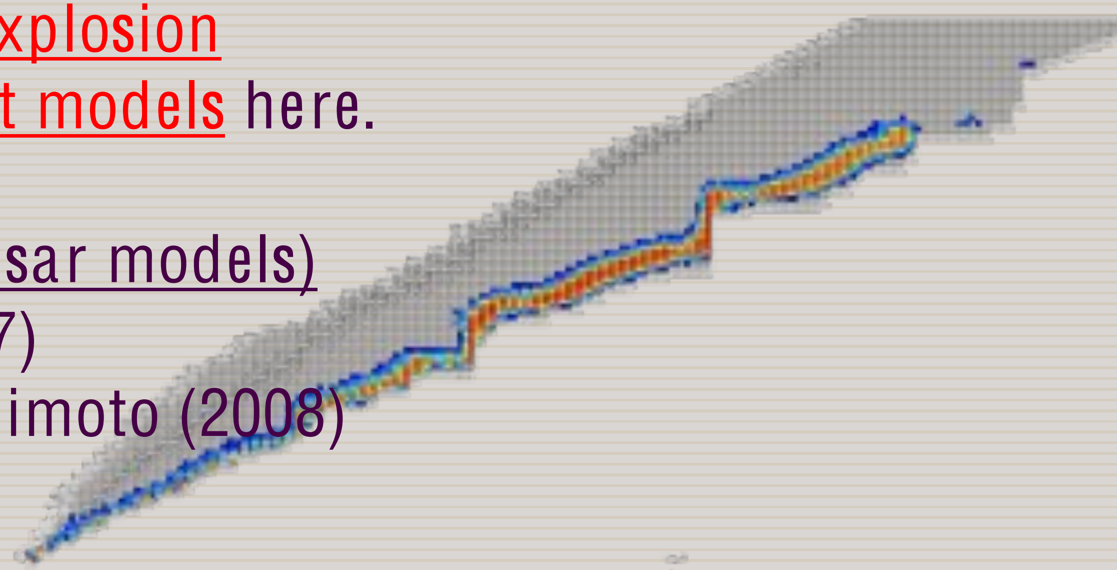
R-process nucleosynthesis in a MHD jet model

Astrophysical models for Nucleosynthesis studies
→ Hydrodynamic Calculations for SNe

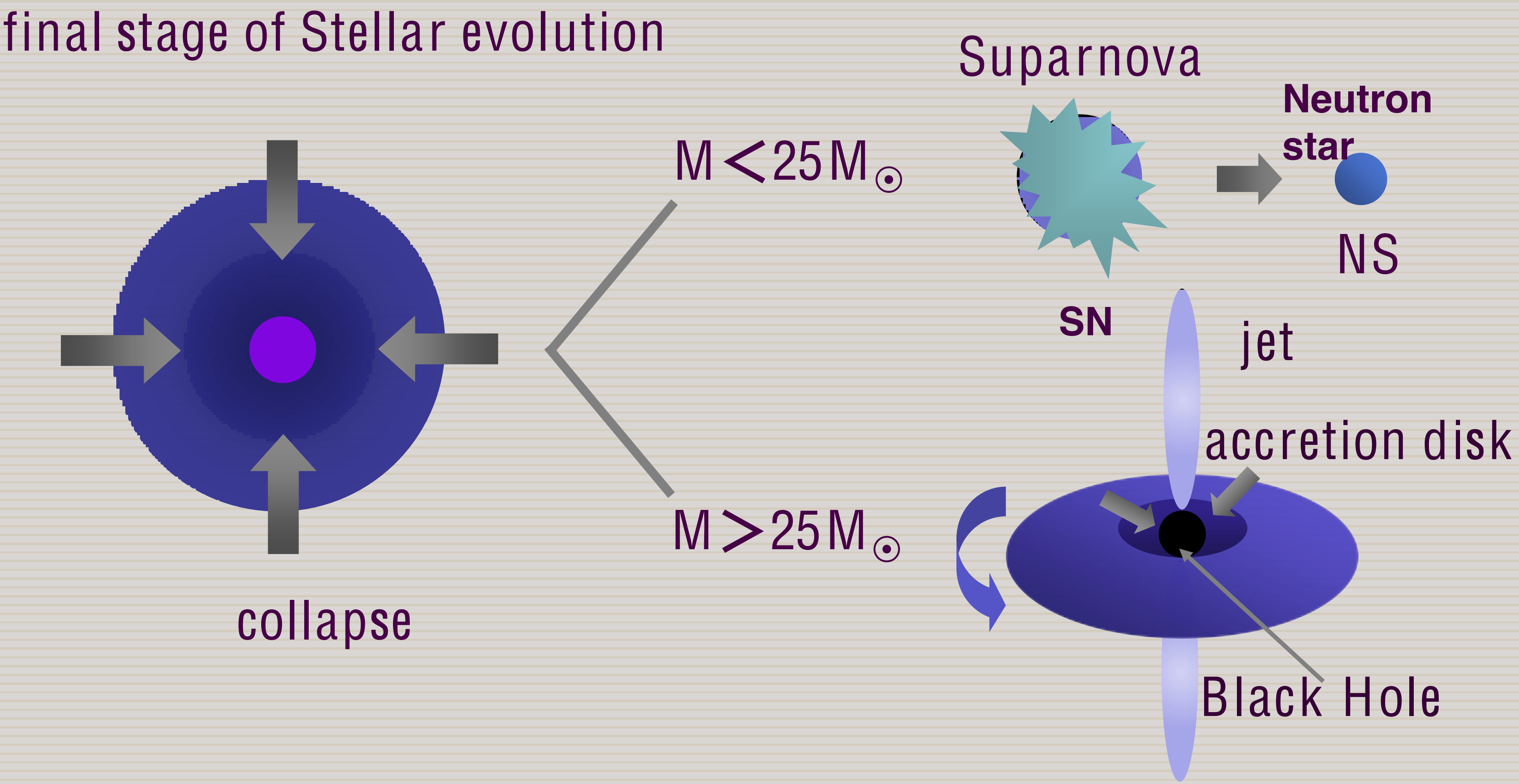
Magneto-hydrodynamic model

- Jet-like Supernova Explosion
  We use the MHD Jet models here.

- Black hole jets(Collapsar models)
  Fujimoto et al. (2007)
  Fujimoto, NN, Hashimoto (2008)



MHD Jet SN and MHD Collapsar Model

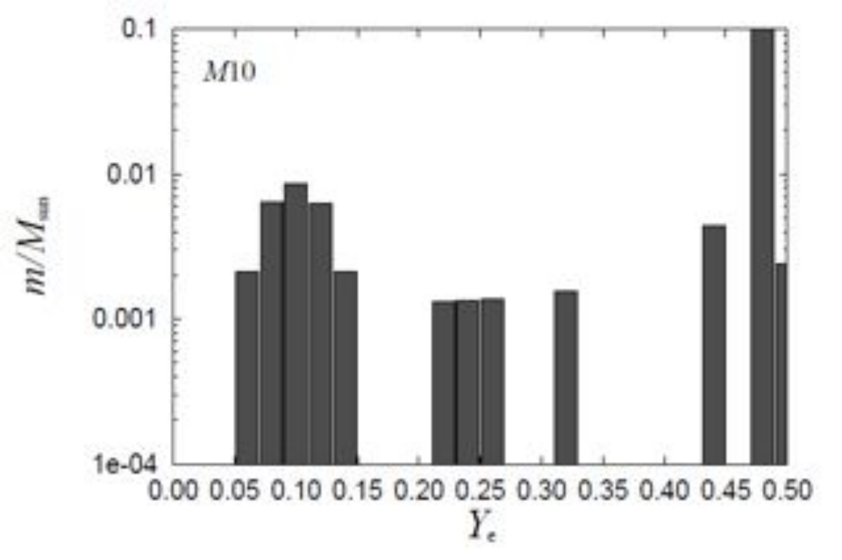


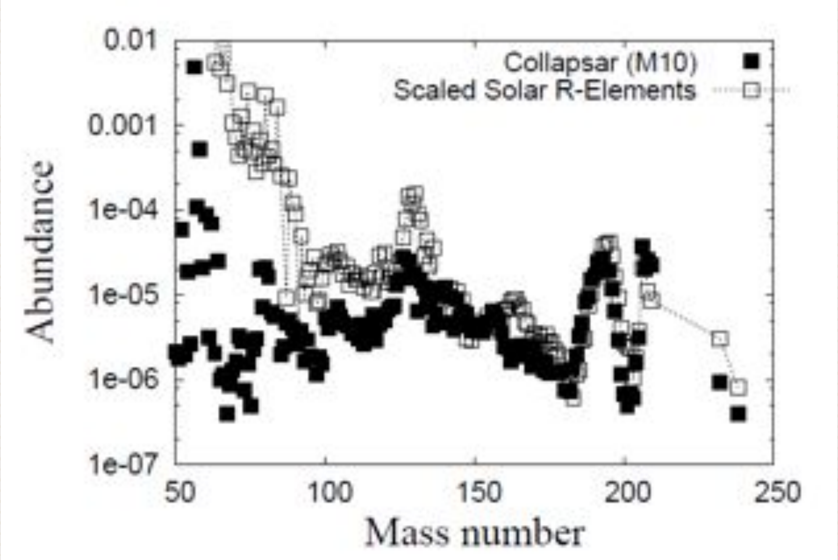
The central engine of GRBs

R-process for MHD Collapsar Model

MHD driven Jet from Collapsar model

Fujimoto, NN, Hashimoto (2008)



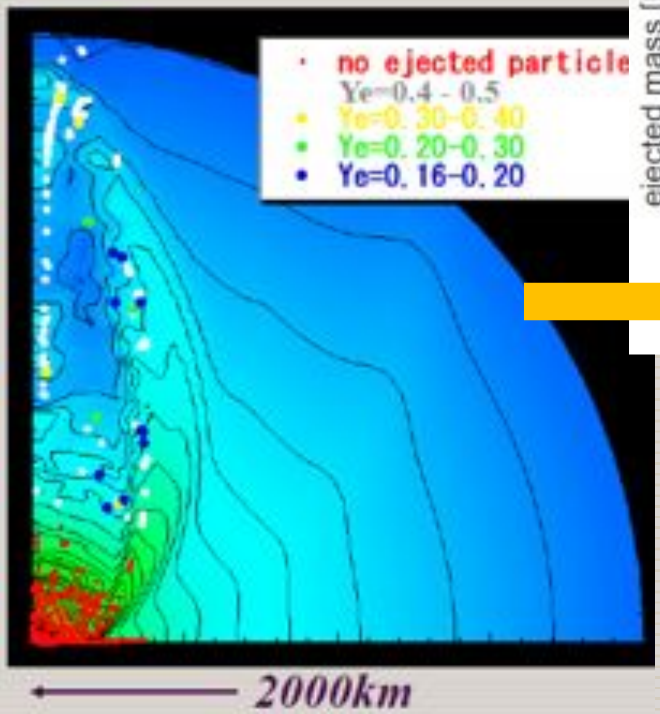


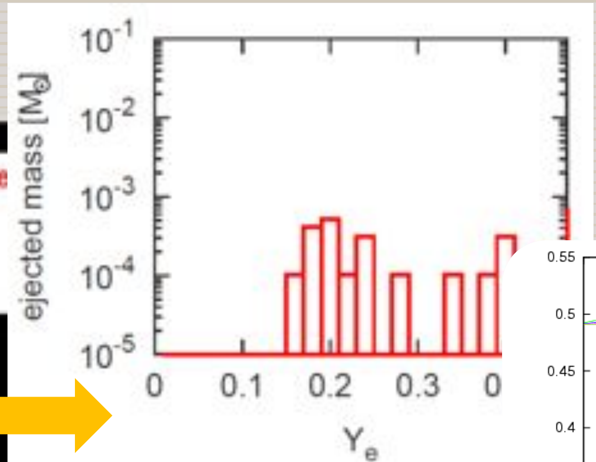
MHD Collapsar model

- Strong magnetic fields and rapidly rotation
- Newtonian MHD
- No neutrino effect (dynamics and r-process)

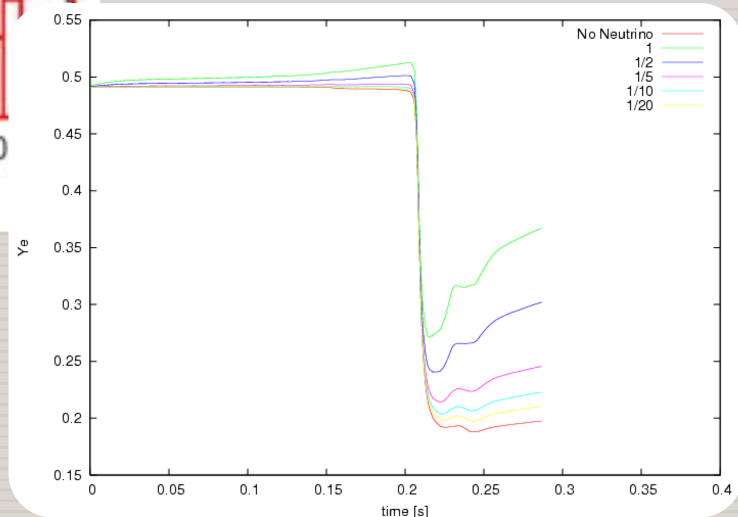
Previous work: r-process in MHD SN

- MHD Supernova Explosion model
- $13M_{\odot}$ (main sequence) pre-collapse model
- r-processes occur in two models
 (strong magnetic fields and rapidly rotation)





Neutrino effects



Nishimura et al. (2006)

Problems of previous work

MHD Explosion model

- Newtonian MHD simulation — SR-MHD Model
- No neutrino effect for dynamics (no cooling and heating) — Leakage Scheme

Nucleosynthesis

- Weak Interaction (electron and positron capture) — + inverse reaction by neutrino

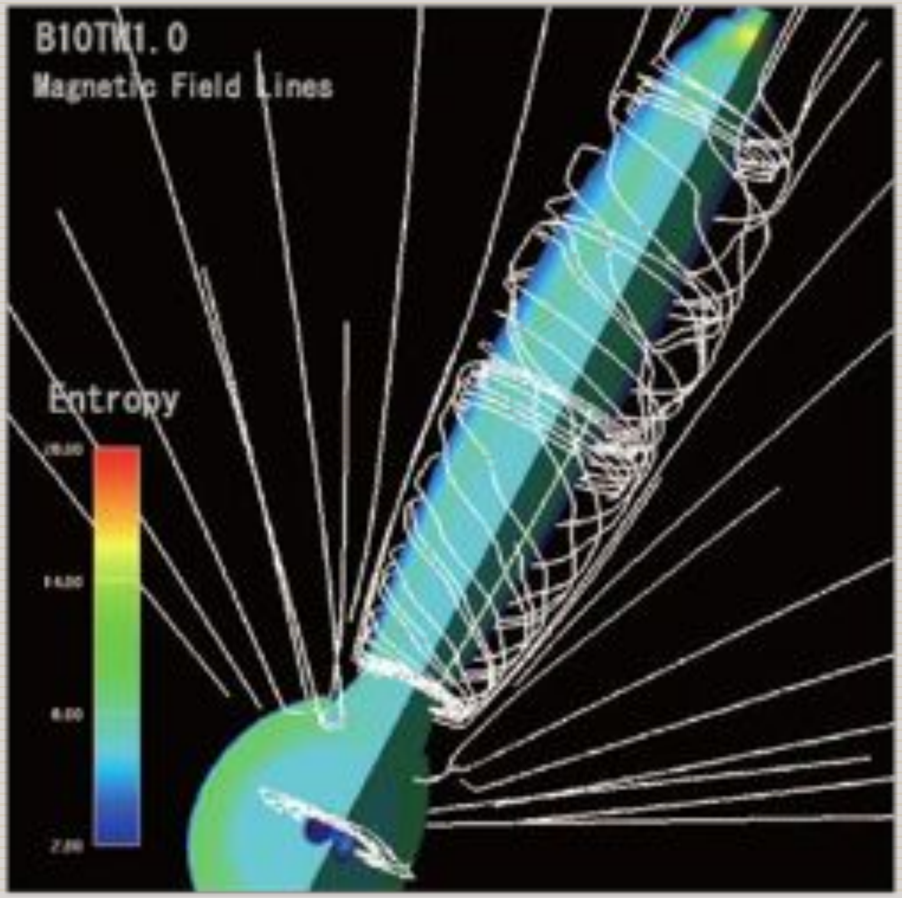
+ the number of Tracer Particles is NOT enough.

We improve some physical process.

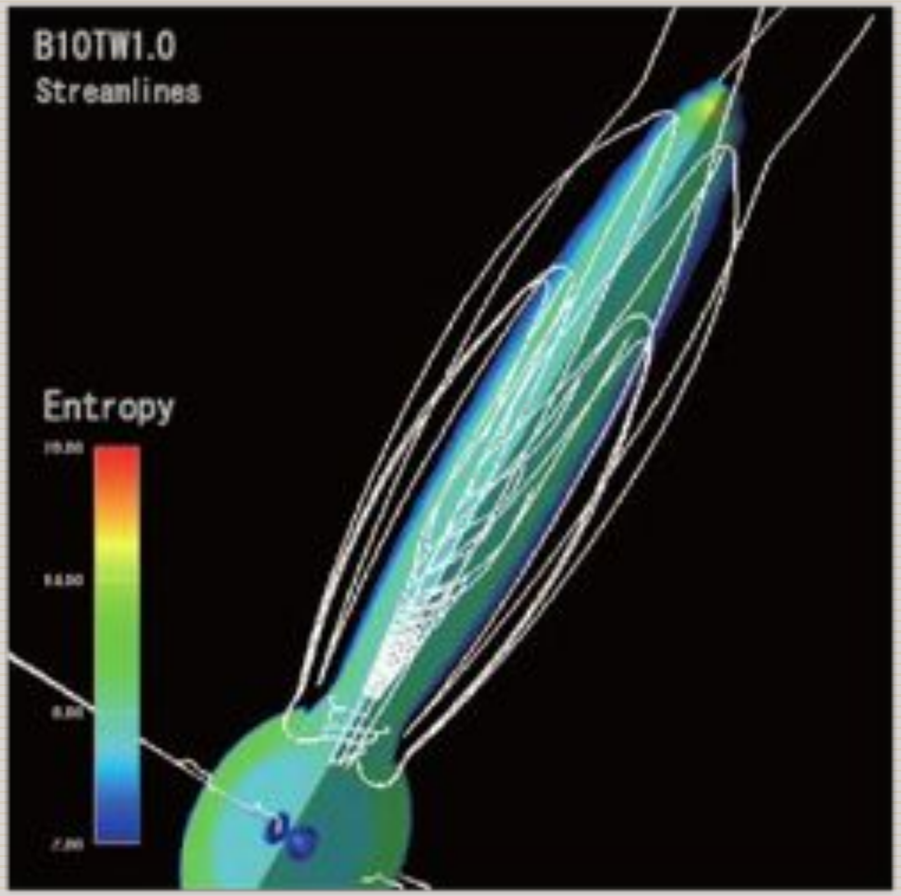
Special Relativistic MHD explosion models

SR MHD + Neutrino cooling (Takiwaki + 2009)

Magnetic Field Line



Streamlines



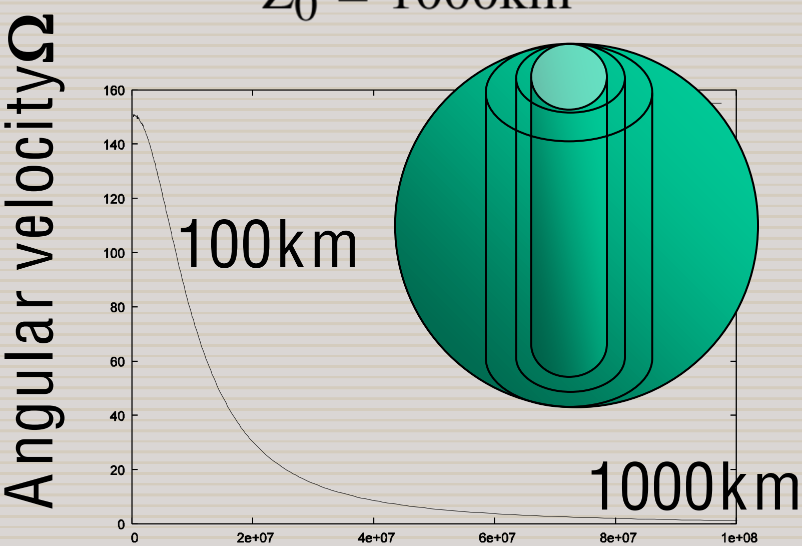
Initial models for MHD simulation

Stellar Density, Energy and Ye distributions are adopted from pre-collapse models ($25M_{\odot}$: Heger et al. 2000)

differential rotation

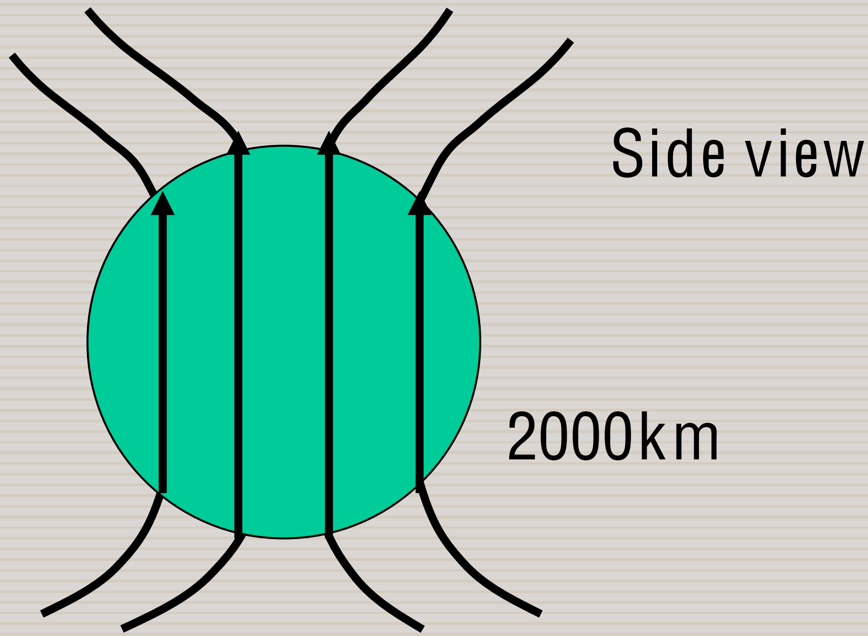
$$\Omega = \Omega_0 \frac{X_0^2}{X^2 + X_0^2} \frac{Z_0^4}{Z^4 + Z_0^4}$$

$$Z_0 = 1000\mathrm{km}$$



Poloidal magnetic field

$$B_z = B_p, B_\phi = 0$$



MHD Supernova Explosion models

We focus on the shortest time scale and most energetic models.

B12TW1.0 (Takiwaki et al. 2009)

		$T/\|W\|(\%)$		
		0.25%	1.0%	4.0%
B_0 (Gauss)	10^{10} G	B10TW0.25	B10TW1.0	B10TW4.0
	10^{11} G	B11TW0.25	B11TW1.0	B11TW4.0
	10^{12} G	B12TW0.25	B12TW1.0	B12TW4.0

This work

		$T/\|W\|(\%)$		
		0.25%	1.0%	4.0%
B_0(Gauss)	10^{10}G	122 ms	96 ms	104 ms
	10^{11}G	72 ms	27 ms	32 ms
	10^{12}G	32 ms	20 ms	25 ms

Figure 2. Classification of the computed models into the prompt (red blocks) or delayed (green blocks) MHD exploding model by the difference of $t_{1000\,\mathrm{km}}$ shown in this table, which is the shock-arrival time to the radius of 1000 km after bounce.

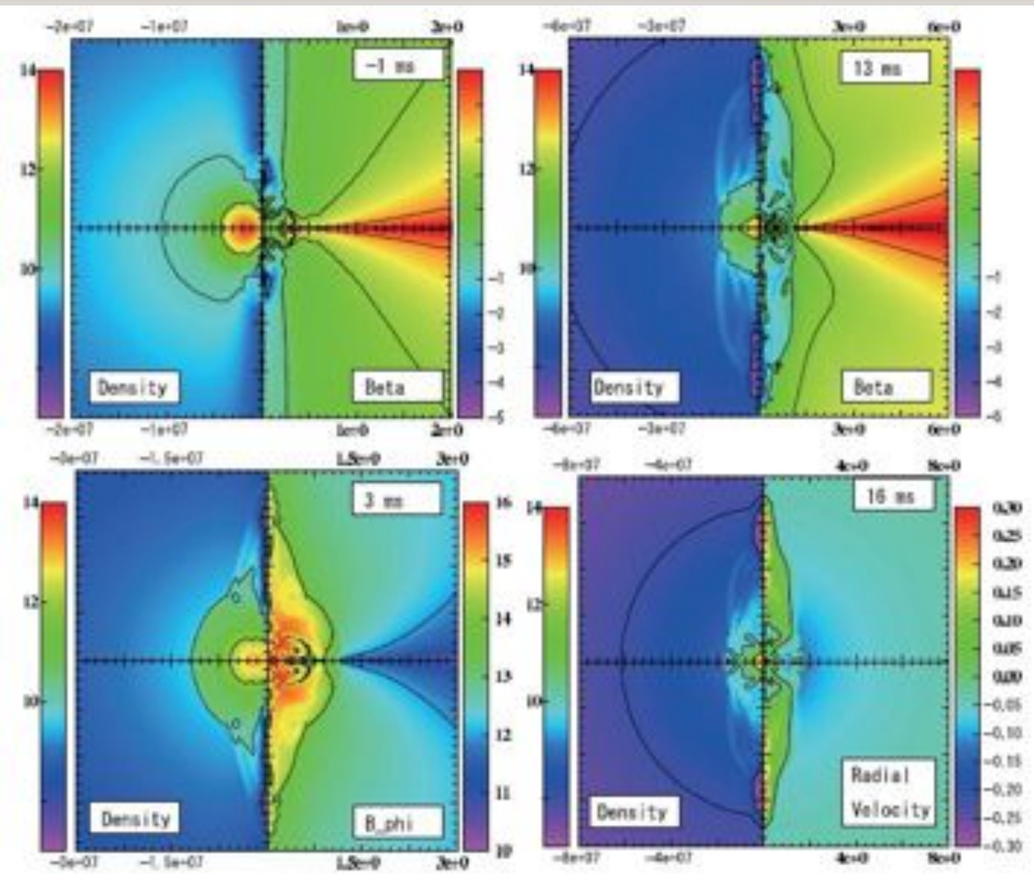
the shock-arrival time to the radius of 1000 km after bounce

T12TW1.0: hydrodynamic evolution

(Takiwaki et al. 2009)

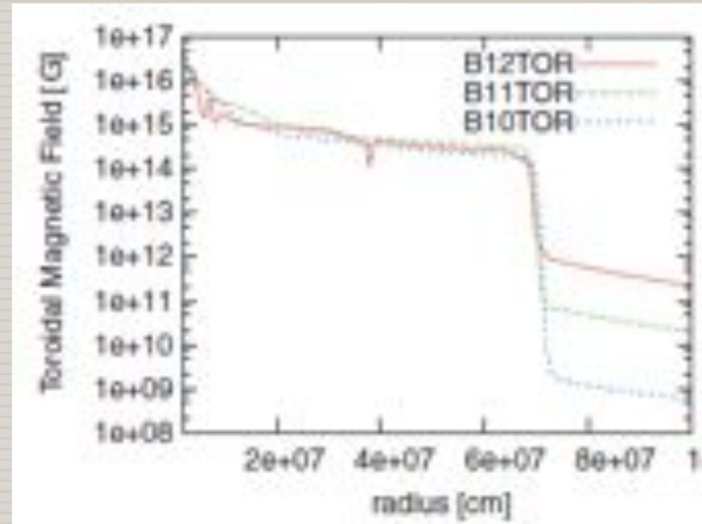
Left: **Density**

Right: **Plasma β**

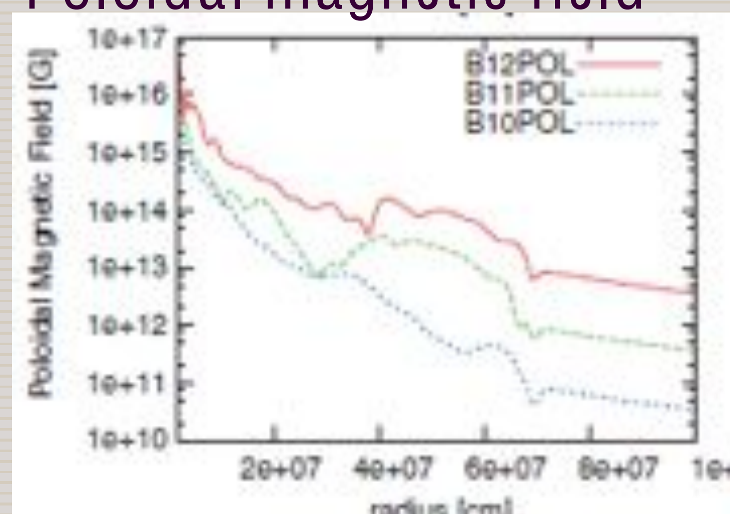


T12TW1.0: Red

Toroidal magnetic field



Poloidal magnetic field

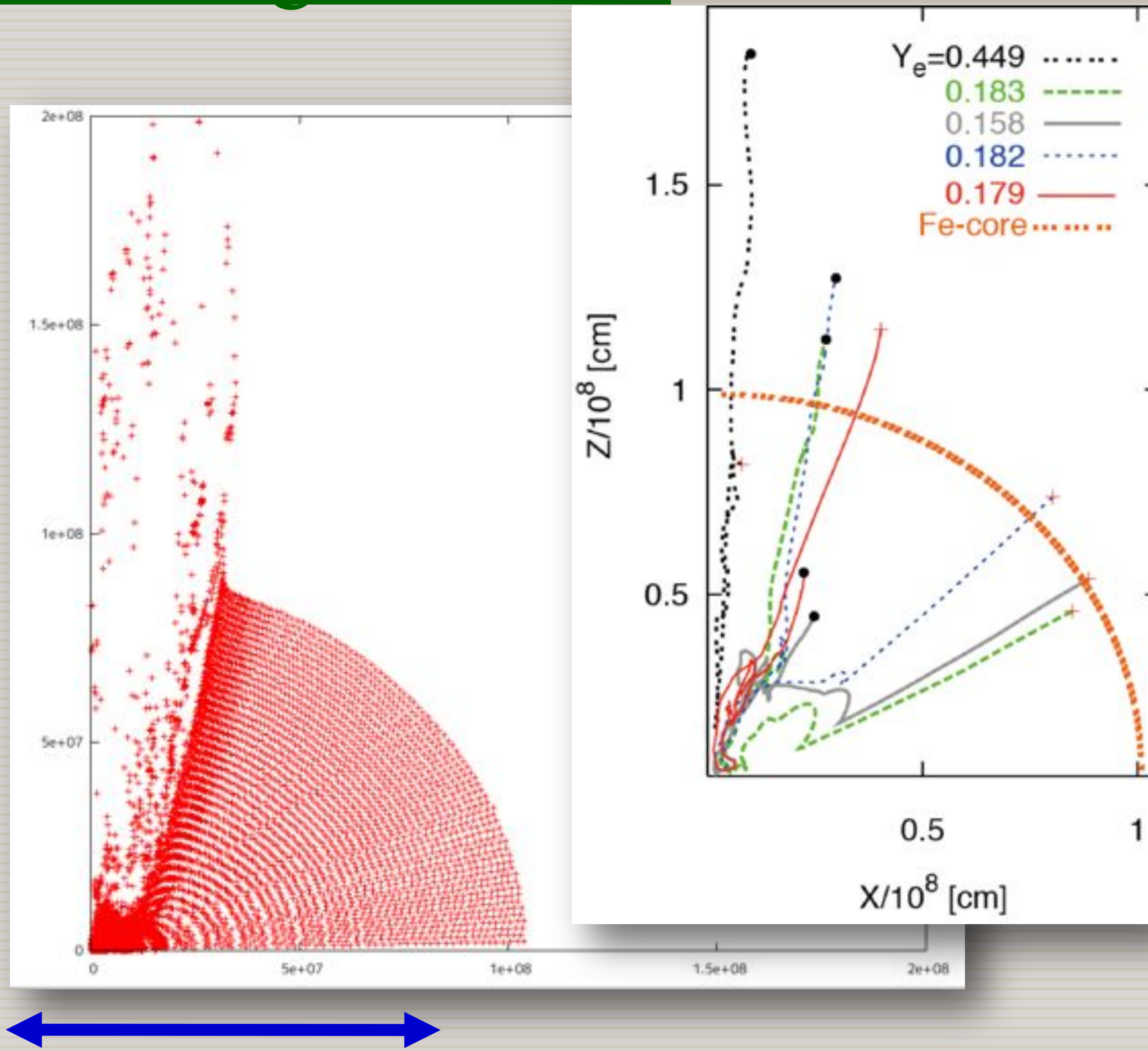


Tracer Particle: setting & motion

r-direction:
1000
θ-direction:
500

Total:
500,000

ejected:
～6,000



Fe core (1000km)

r-process: physical condition

① Neutronization (T > 0.5MeV) : Ye↓

- NSE(Nuclear Statistical Equilibrium) state
- electron capture ($p + e^- \rightarrow n + \nu_e$) : Core-Collapse

(reverse reaction ($n + \nu_e \rightarrow p + e^-$) : neutrino heating)

② Seed creation (T > 0.2MeV) : mass number ～ 100

- α-process (4He)

③ R-process

- (n,γ), β^- - decay
- (γ, n) (high temperature)

④ decay

- β^- - decay
- fission (heavy element)

Ye : electron fraction

$$Y_e \approx \frac{p}{n+p}$$

Low Ye＝Low p＝neutron-rich

Abundance Evolution (T ≳ 10 [GK])

- Abundance
  - Nuclear Statistical Equilibrium
  - Partition Function (REACLIB)
- Reaction
  - only weak process
  - reaction rate (FFN 1985)

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

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

Ye: time evolution

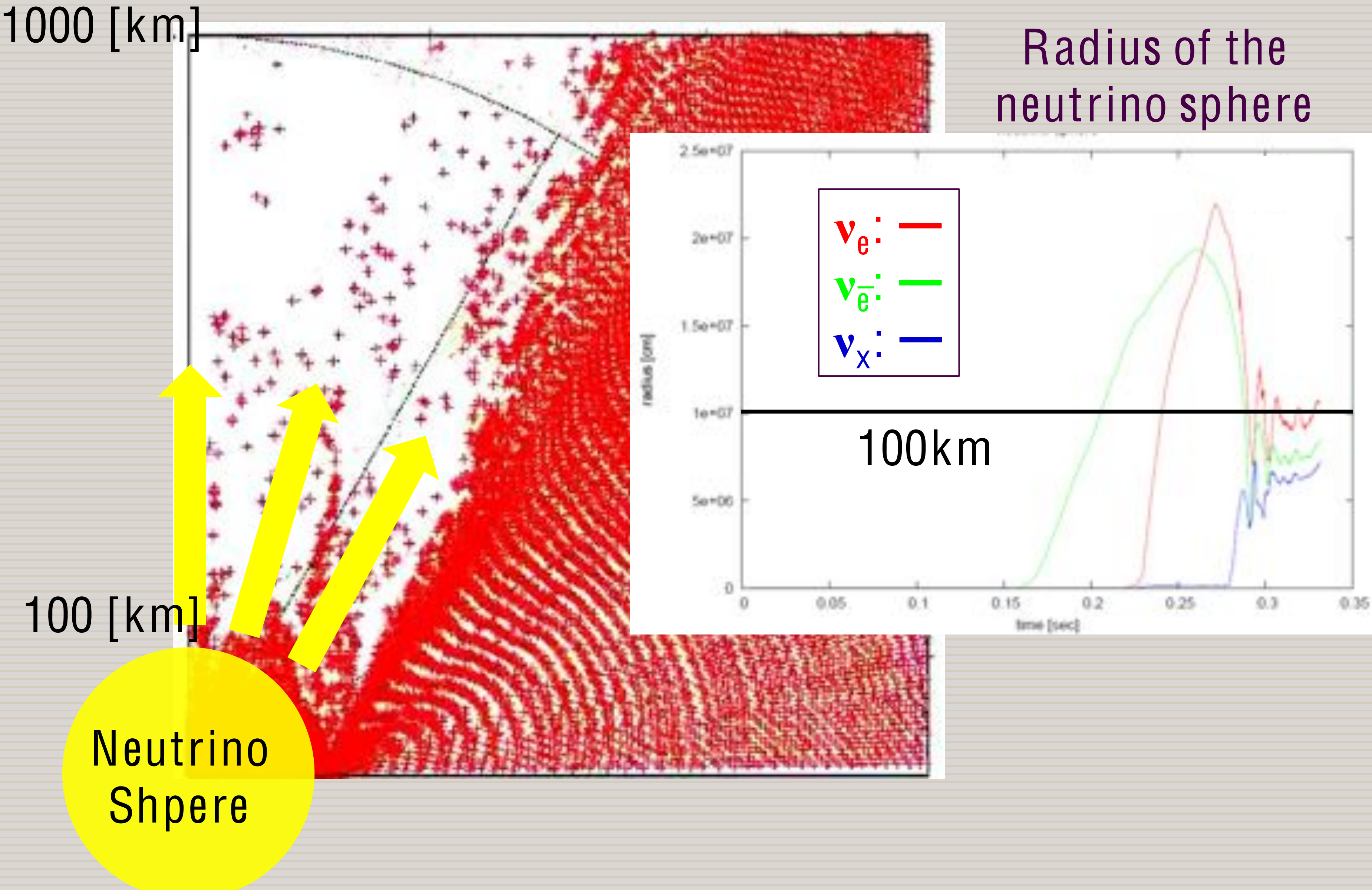
$$\frac{dY_e}{dt} = (\lambda_{\nu_e n} + \lambda_{e^+ n})(1 - Y_e) + (\lambda_{\bar{\nu}_e p} + \lambda_{e^- p})Y_e$$

Qian & Woosley (1996)

$$\lambda_{\nu_e n} \approx 4.83 L_{\nu_e,51} \left(\epsilon_{\nu_e,\mathrm{MeV}} + 2\Delta_{\mathrm{MeV}} + 1.2 \frac{\Delta^2_{\mathrm{MeV}}}{\epsilon_{\nu_e,\mathrm{MeV}}} \right) r_6^{-2}\ \mathrm{s}^{-1}$$

$$\lambda_{\bar{\nu}_e p} \approx 4.83 L_{\bar{\nu}_e,51} \left(\epsilon_{\bar{\nu}_e,\mathrm{MeV}} - 2\Delta_{\mathrm{MeV}} + 1.2 \frac{\Delta^2_{\mathrm{MeV}}}{\epsilon_{\bar{\nu}_e,\mathrm{MeV}}} \right) r_6^{-2}\ \mathrm{s}^{-1}$$

Effects Proto-Neutron Star (neutrino burst)



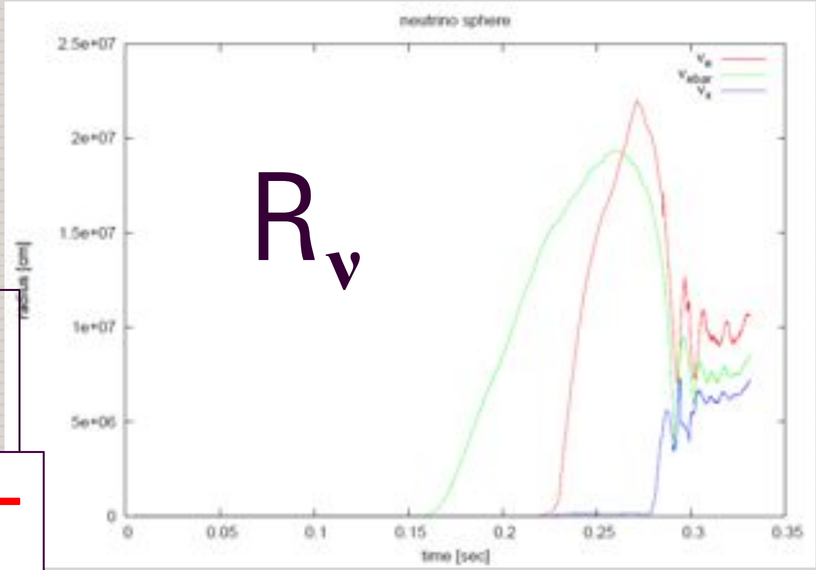
Physical quantities of neutrino sphere

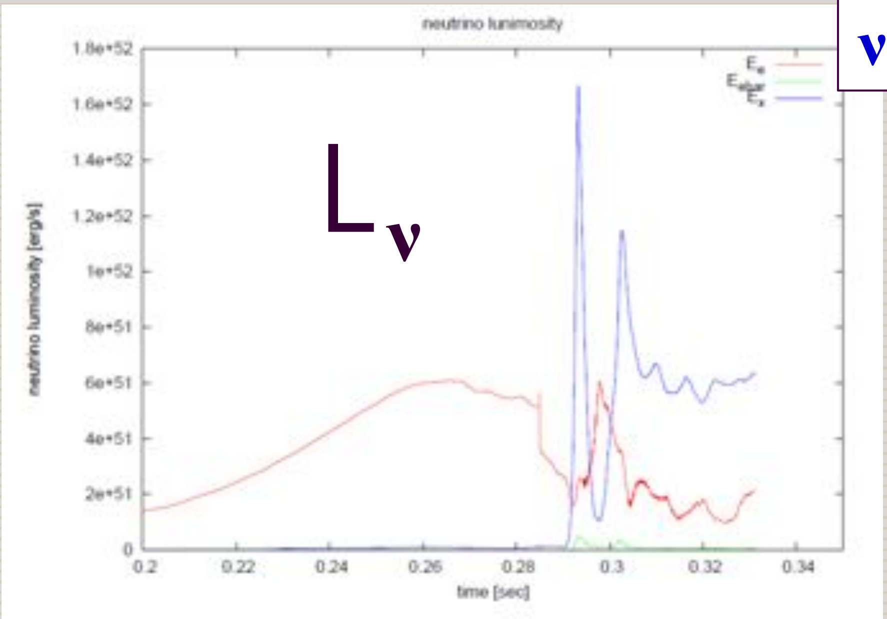
$$\lambda_{\nu_e n} = 4.83 L_{\nu_e,51}\left(\epsilon_{\nu_e,\mathrm{MeV}} + 2\Delta_{\mathrm{MeV}} + 1.2\frac{\Delta_{\mathrm{MeV}}{}^2}{\epsilon_{\nu_e,\mathrm{MeV}}}\right) r_6{}^{-2}\mathrm{s}^{-1}$$

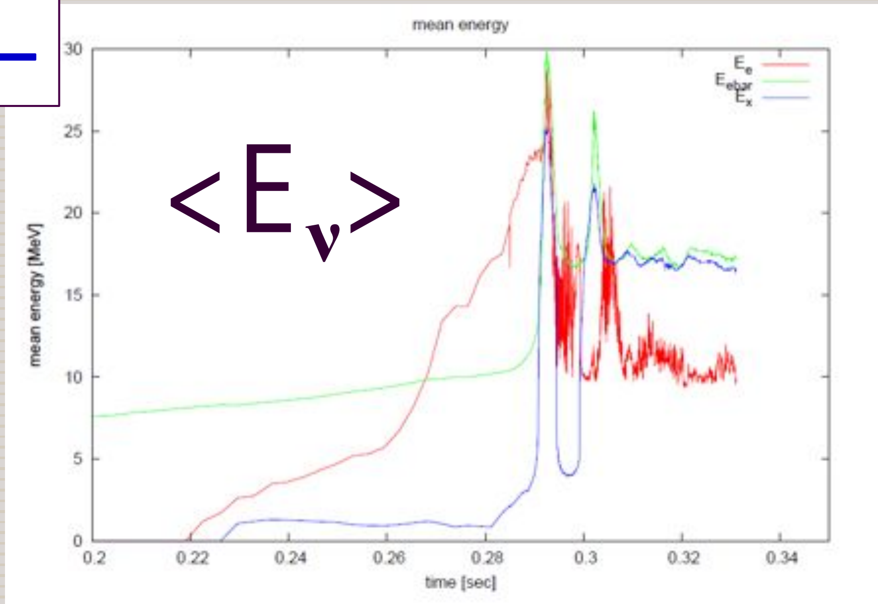
$$\lambda_{\nu_e n} = 4.83 L_{\nu_e,51}\left(\epsilon_{\nu_e,\mathrm{MeV}} + 2\Delta_{\mathrm{MeV}} + 1.2\frac{\Delta_{\mathrm{MeV}}{}^2}{\epsilon_{\nu_e,\mathrm{MeV}}}\right) r_6{}^{-2}\mathrm{s}^{-1}$$

- R_ν : radius of neutrino sphere
- $<E_\nu>$: mean energy
- L_ν : luminosity

ν_e : red line
$\nu_{\bar{e}}$: green line
ν_x : blue line



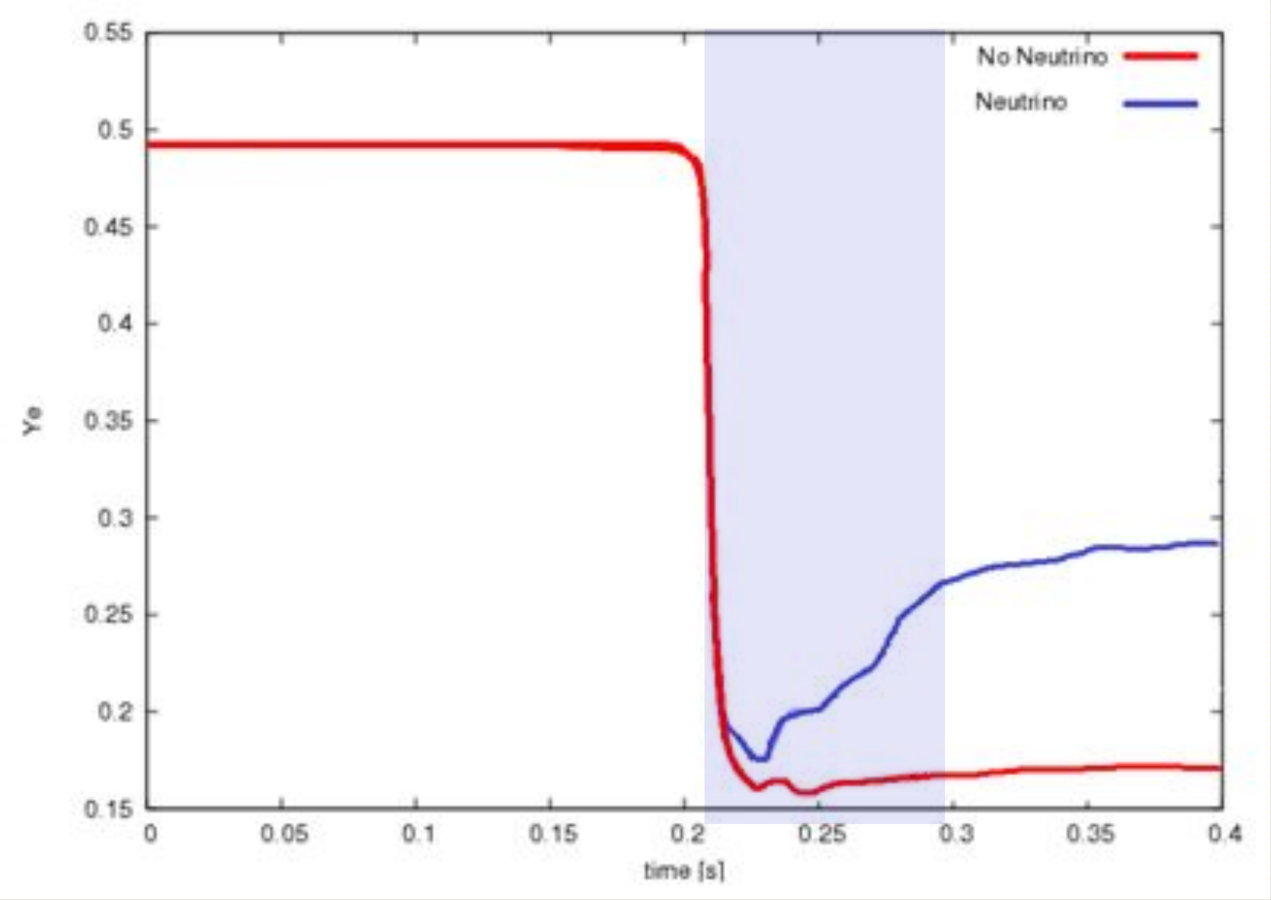




Ye evolution and neutrino effect

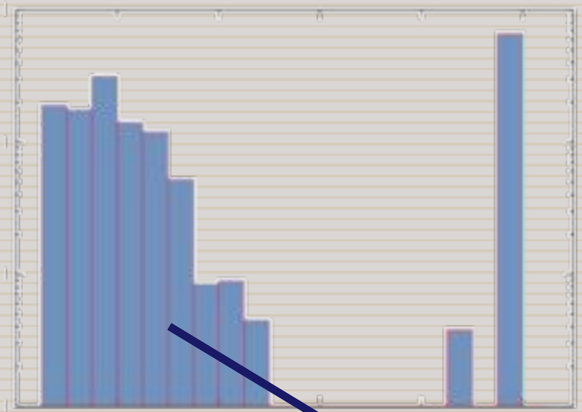
Ye evolution

Neutrino Burst

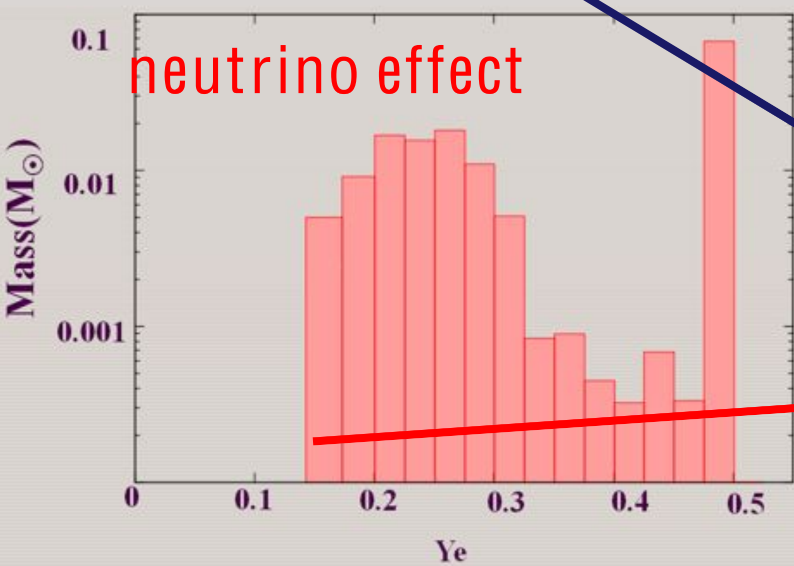


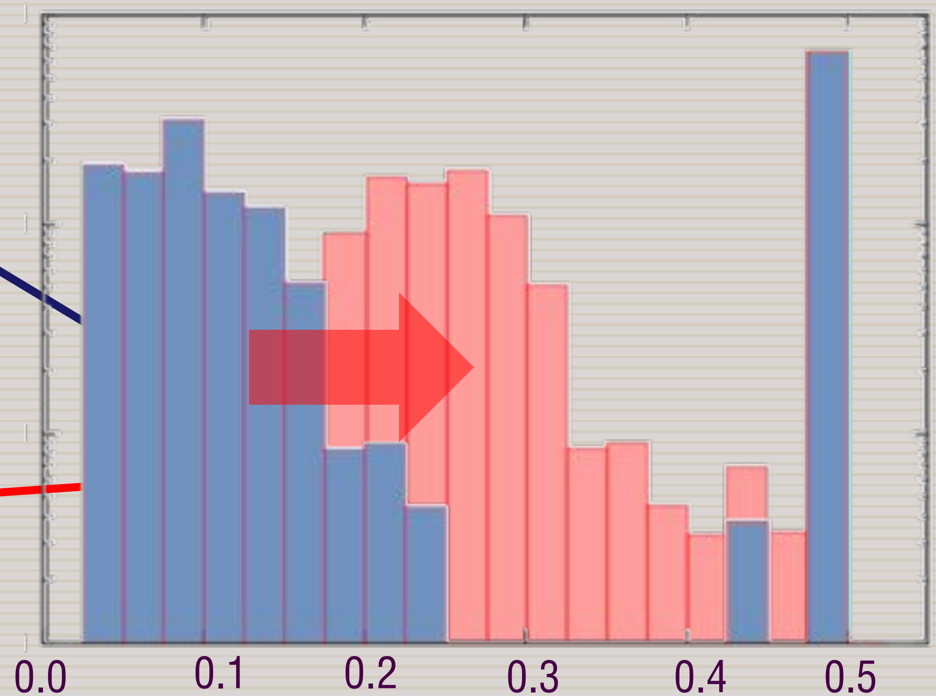
Ye distribution

no neutrino (only electron + positron capture)



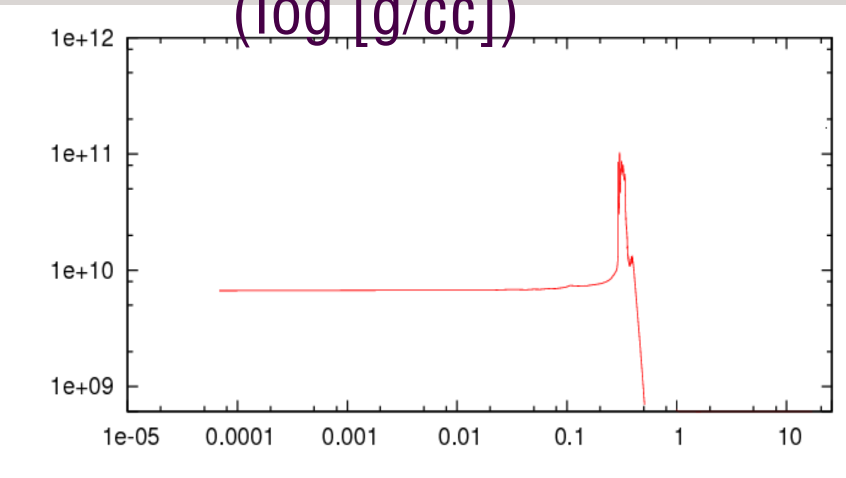
The distribution slant to the right.
Values of Ye are increased about 0.1.



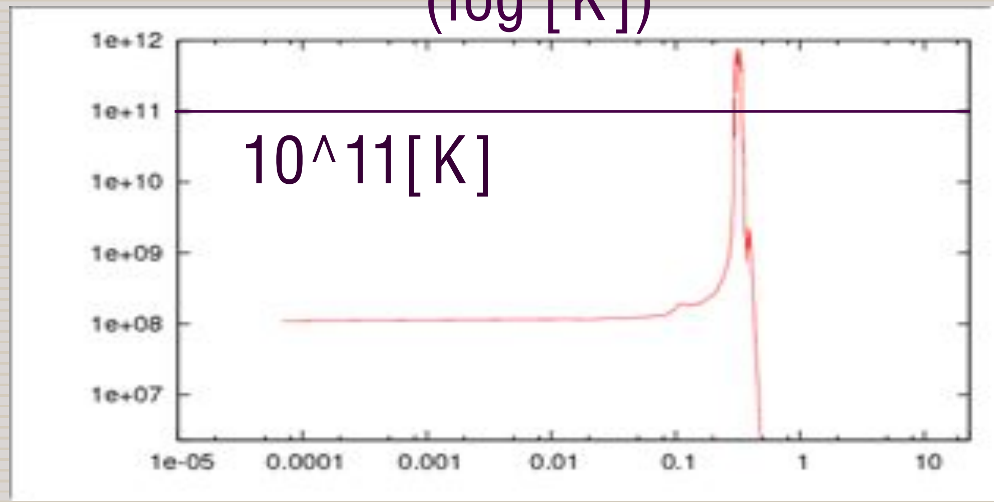


Density and Temperature: Ye～0.1

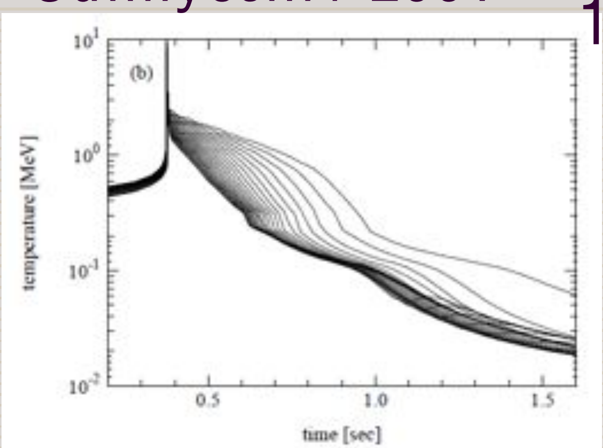
Density
(log [g/cc])



Temperature
(log [K])



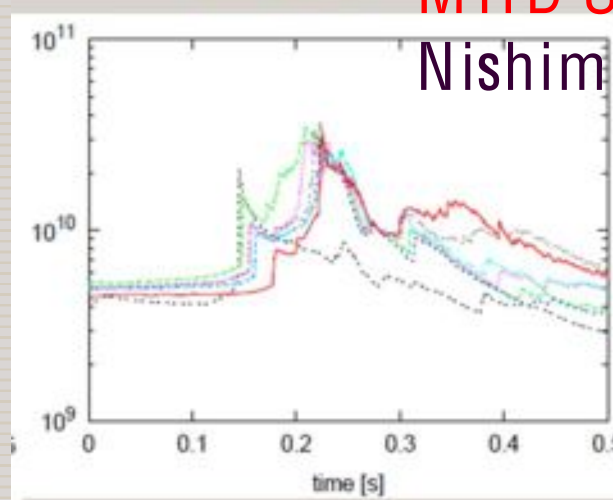
Prompt Explosion
Sumiyoshi+ 2001



10^11[K]

Temperature
(log [K])

MHD SN (13$M_{\odot}$)
Nishimura+ 2006



r-process: physical condition

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(reverse reaction ($n + \nu_e \rightarrow p + e^-$) : neutrino heating)

② Seed creation (T > 0.2MeV) : mass number ~ 100

- α-process (4He)

③ R-process

- (n,γ), β^- - decay
- (γ, n) (high temperature)

④ decay

- β^- - decay
- fission (heavy element)

Ye : electron fraction

$$Y_e \approx \frac{p}{n+p}$$

Low Ye = Low p = neutron-rich

Nuclear Reaction Network

Number fraction Y_i for i^{th} element

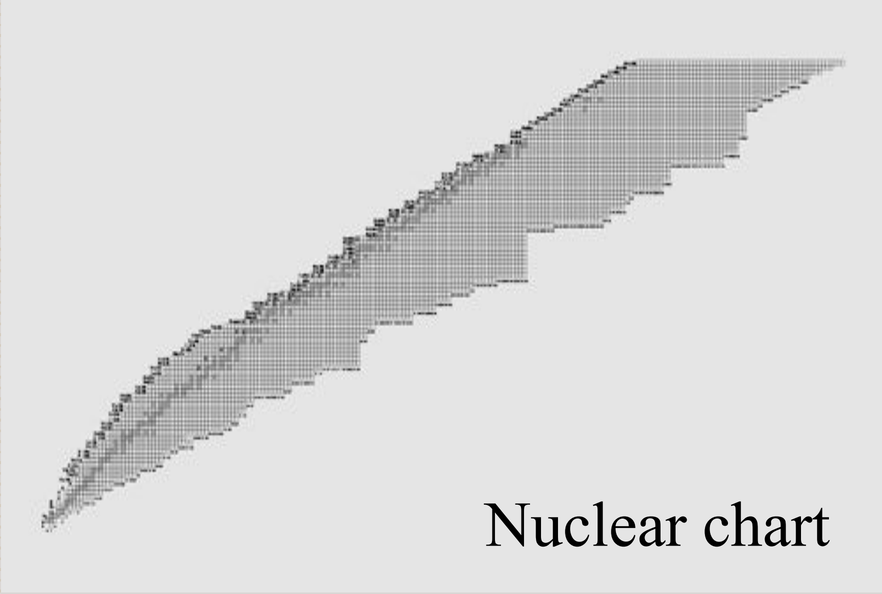
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_j N^i_{j,k} \rho N_A \langle \sigma v \rangle_{j,k} \lambda_j Y_j Y_k + \sum_j N^i_{j,k,l} \rho N_A \langle \sigma v \rangle_{j,k,l} \lambda_j Y_j Y_k Y_l$$

decay | two-body | three-body

$$N^i_j = N_i, \quad N^i_{j,k} = \frac{N_i}{N_j! N_k!}, \quad N^i_{j,k,l} = \frac{N_i}{N_j! N_k! N_l!}$$

Network r-process

- 4071 isotopes
- Reaction rates : REACLIB
- β-decay : theory
  FRDM mass formula

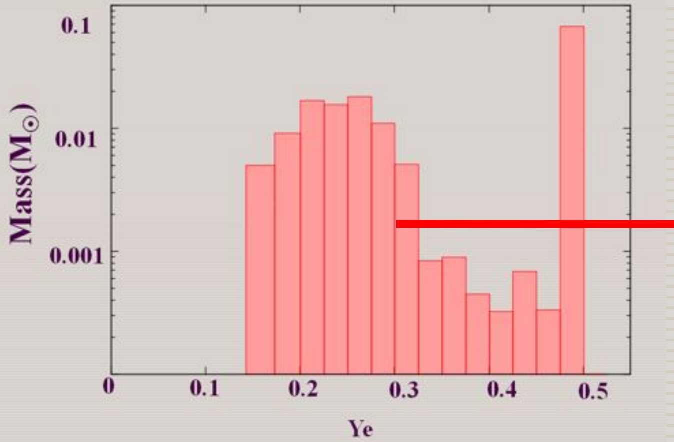


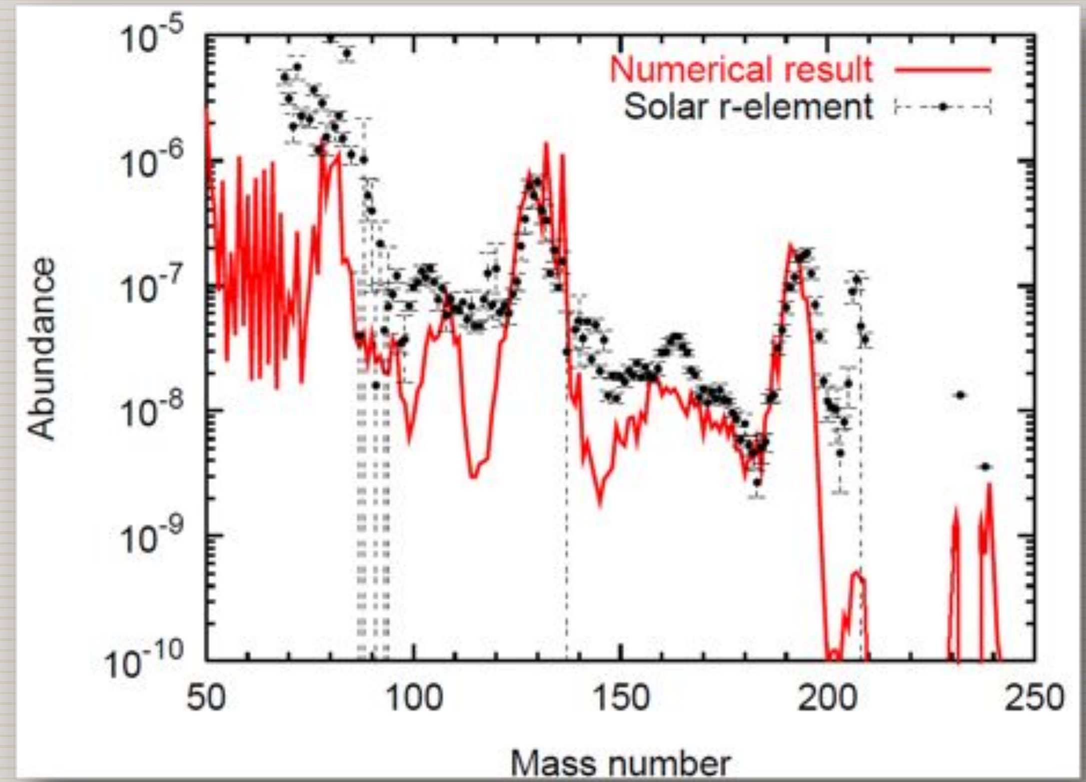
r-element abundances

The result of network simulation. Distribution r-process elements compared with solar r-element distribution.

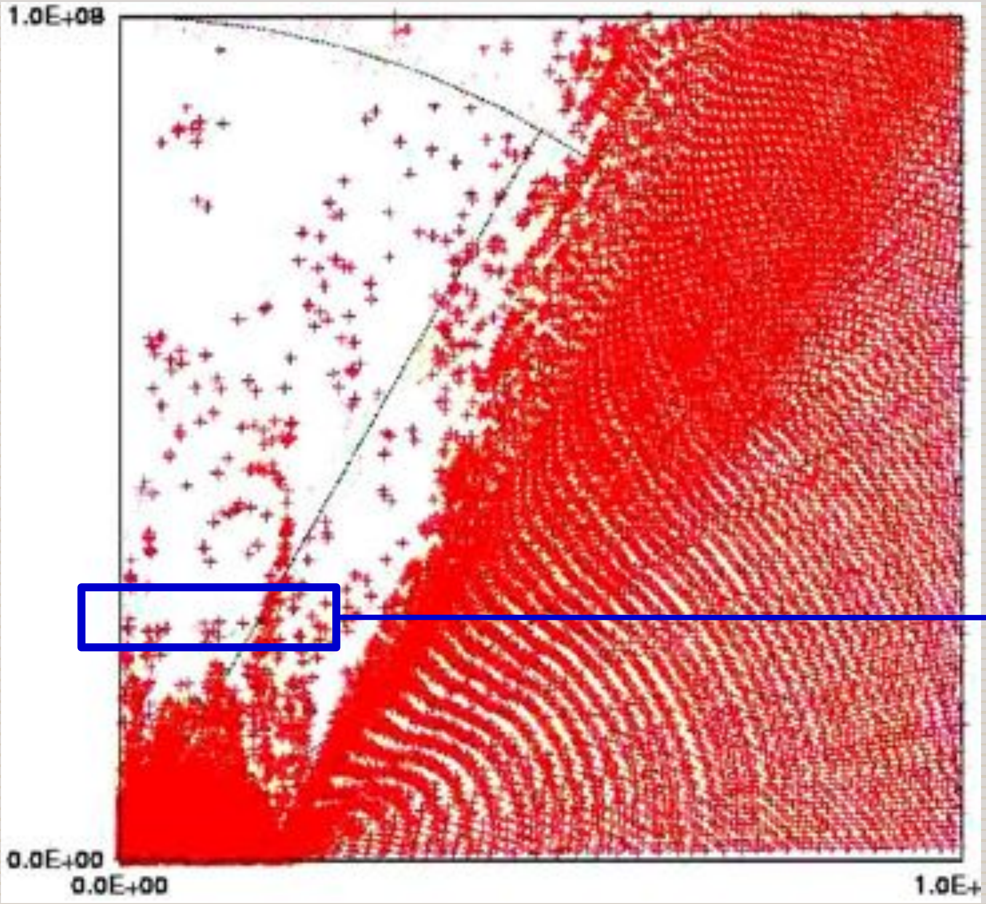
a vertical axis:
normalized mass fraction

neutrino effect





After the Jet: Wind like state



- R-element
  0.83E-2 (0.0083) $M_\odot$
- Other element
  4.32E-2 (0.0432) $M_\odot$

- Flow near the center
  2.3e-4 $M_\odot$ [/second]

Low resolution
(over estimate)

NOT Neutrino Driven Wind (MHD process)

Astrophysical Site

Solar system r-element(10^{-7} $M_\odot$) : log10(Mass)

Sites	r-element mass ($M_\odot$)	Event (1/year/gal)	entropy	Ye
Neutrino Driven Wind (NDW)	? -5	-2	Very high (~100)	high (~0.4)
Neutron Star binary Merger	? -2	-5	low	Low (~0.1)
MHD Supernova	-2	? -5	low	(~0.1)
Collapsar Model (MHD)	-2	? -5	Very high	Low
Collspar Model (ND Jet or outflow)	?	?	Very high?	High?

Magnetars

GRBs

Summary

MHD Supernova Explosion models

- Special Relativistic MHD
- Neutrino cooling

- NSE abundance evolution
  - more neutron rich matter
  - Ye is changed by neutrino effect(～+0.1)

- Heavy elements
  - r-element mass: 0.83E-2 (0.0083) $M_\odot$
  - Mass of 56Ni : 0.024 $M_\odot$ (Faint SN?)