

各反応熱フィードバックを考慮した 超新星爆発モデル

- SN explosion model incl. nuclear reaction energy

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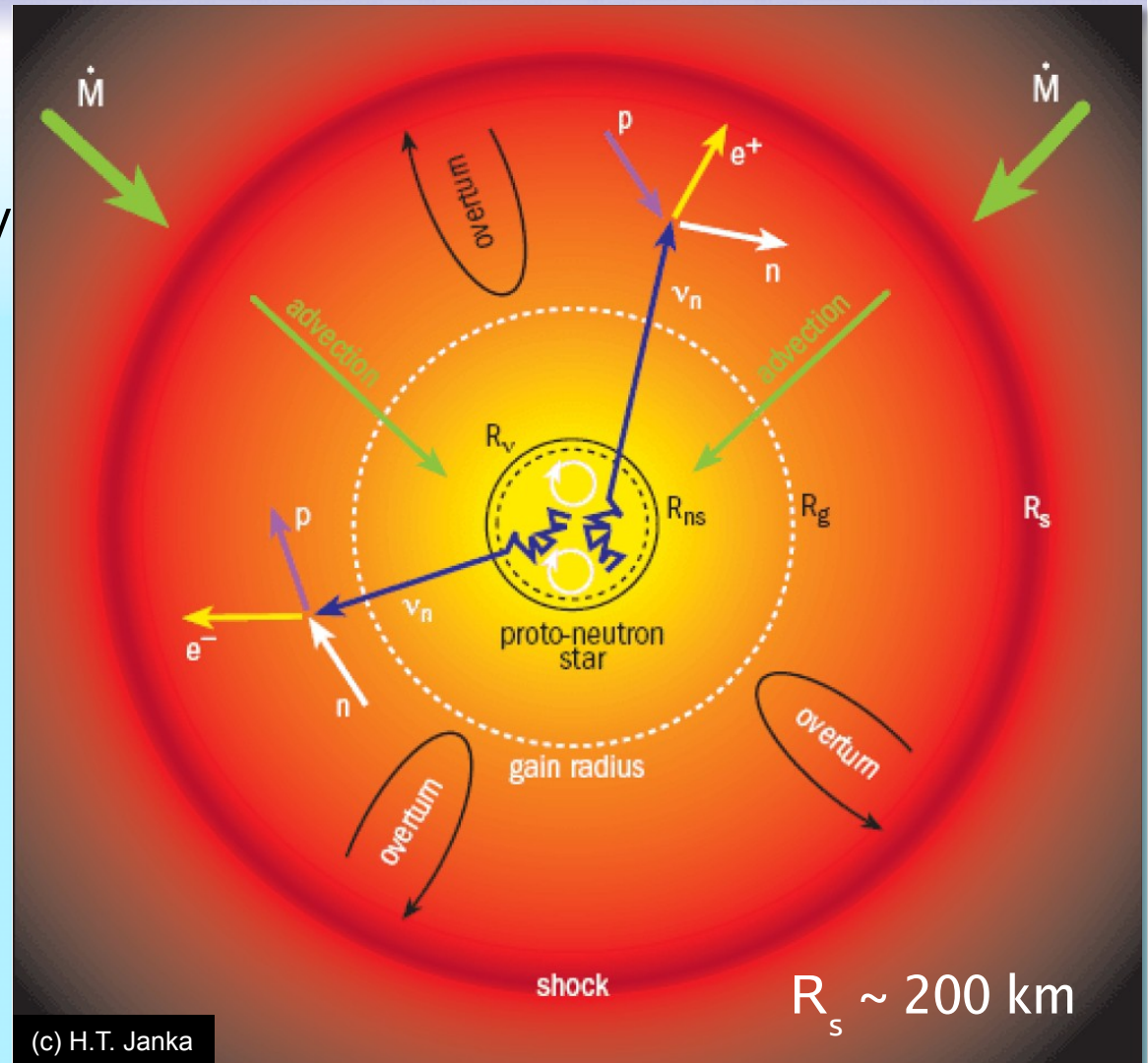
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Outline

- Core-collapse supernova explosion
 - collapse, bounce, and stalled
- Neutrino-driven explosion model
 - neutrino heating (and cooling)
 - Standing Accretion-Shock Instability (SASI)
- Shock revival and enhancement of expl. energy by nuclear reactions
 - 2-D simulations for 15.0 Msun model
 - using ZEUS-MP code incl. nuclear reaction network
- Summary

Neutrino-driven SN explosion mechanism

- Gravitational binding energy of the collapsing core ($> \sim 10^{53}$ erg) \gg Typical SN explosion energy ($\sim 10^{51}$ erg)
- Neutrinos carry away most of the energy, but ..
- A small fraction of emitted neutrinos can interact with the matter behind a shock, deposit energy, and revive the stalled shock wave.
- Hydrodynamic instabilities enhance the neutrino heating.



List of recent neutrino-radiation hydrodynamic simulations.
 (Table 1 of Kotake 2011 *arXiv:1110.5107*)

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	$E_{\text{exp}}(\text{B})$ @ t_{pb} (ms)	ν transport (Dim, $\mathcal{O}(v/c)$)
11.2 M_{\odot} (WHW02[72])	MPA[76] (2006)	ν -driven	2D (PN)	~ 100	~ 0.005 (~ 220)	"RBR" Boltzmann, 2, $\mathcal{O}(v/c)$
	Princeton+ [77] (2007)	Acoustic	2D (N)	$\gtrsim 1100$	$\sim 0.1^*$ (1000)	MGFLD 1, (N)
	NAOJ+ [78](2011)	ν -driven	3D (N)	~ 100	0.01 (300)	IDSA 1, (N)
12 M_{\odot} (WHW02[72])	Oak Ridge+ [79](2009)	ν -driven	2D (PN)	~ 300	0.3 (1000)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
13 M_{\odot} (WHW02[72])	Princeton+ [77](2007)	Acoustic	2D (N)	$\gtrsim 1100$	$\sim 0.3^*$ (1400)	MGFLD 1, (N)
(NH88[71])	NAOJ+ [80](2010)	ν -driven	2D (N)	~ 200	0.1 (500)	IDSA 1, (N)
15 M_{\odot} (WW95[73])	MPA[81] (2009)	ν -driven	2D (PN)	~ 600	0.025 (~ 700)	Boltzmann 2, $\mathcal{O}(v/c)$
(WHW02[72])	Princeton+ [77]	Acoustic	2D (N)			MGFLD 1, (N)
	OakRidge+ [79](2009)	ν -driven	2D (PN)	~ 300	~ 0.3 (600)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
20 M_{\odot} (WHW02[72])	Princeton+ [77](2007)	Acoustic	2D (N)	$\gtrsim 1200$	$\sim 0.7^*$ (1400)	MGFLD 1, (N)
25 M_{\odot} (WHW02[72])	Princeton+ [77](2007)	Acoustic	2D (N)	$\gtrsim 1200$	- (-)	MGFLD 1, (N)
	Oak Ridge+ [79](2009)	ν -driven	2D (PN)	~ 300	~ 0.7 (1200)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$

**ALL results DO NOT reach at the typical SN explosion energy !
 ($E_{\text{exp}} < 1$ Bethe = 10^{51} ergs)**

Various nuclear reactions in CCSNe

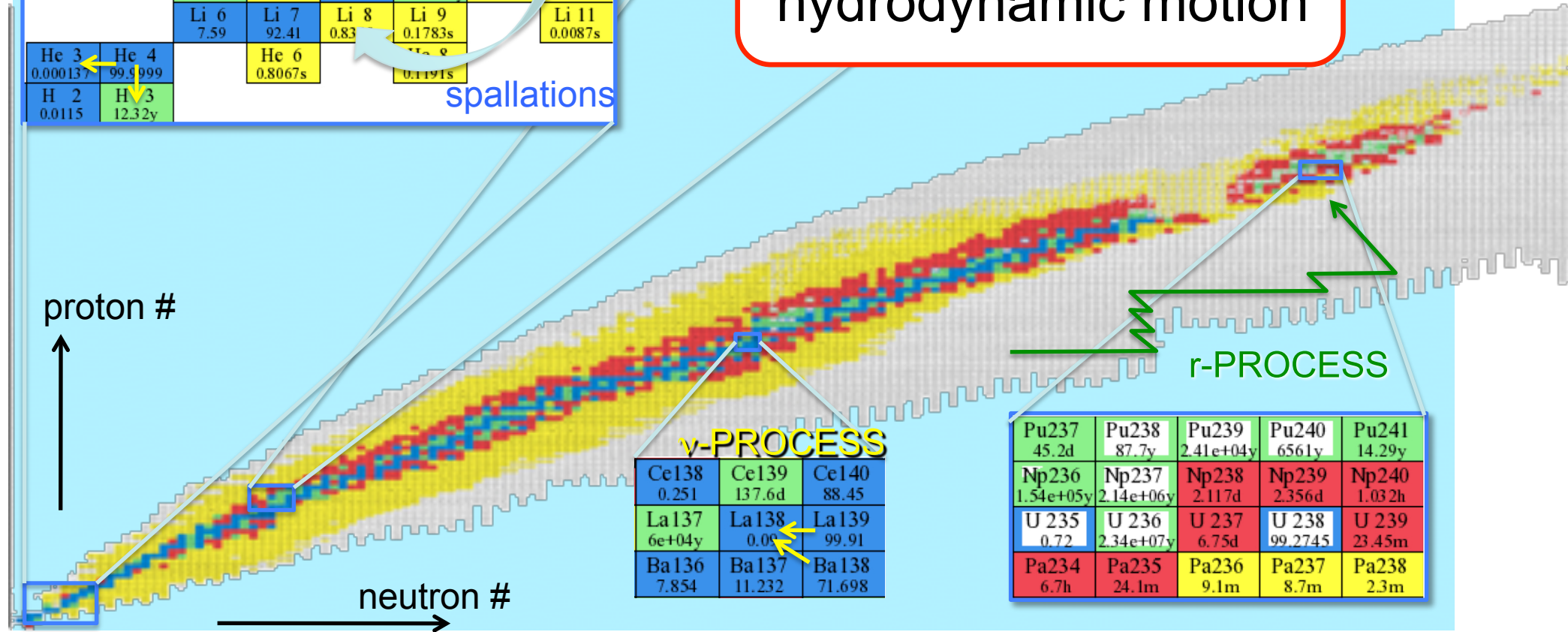
Ni 54 0.104s	Ni 55 0.2047s	Ni 56 6.075d	Ni 57 1.483d	Ni 58 68.0769
Co 53 1.247s	Co 54 4.48m	Co 55 17.53h	Co 56 77.23d	Co 57 271.7d
Fe 52 8.275h	Fe 53 8.51m	Fe 54 5.845	Fe 55 2.744y	Fe 56 91.754
Mn 51 46.2m	Mn 52 5.591d	Mn 53 3.7e+06y	Mn 54 312d	Mn 55 100
Cr 50 4.345	Cr 51 27.7d	Cr 52 83.789	Cr 53 9.501	Cr 54 2.365

α-PROCESS

Energy feedback to hydrodynamic motion

	O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.157
	N 11 0.09s	N 12 0.011s	N 13 9.965m	N 14 2.632	N 15 0.368
C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07
	B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s
	Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s
	Li 6 7.59	Li 7 92.41	Li 8 0.83	Li 9 0.1783s	Li 11 0.0087s
He 3 0.000137	He 4 99.9999	He 6 0.8067s	He 8 0.1191s	He 9 0.1191s	
H 2 0.0115	H 3 12.32y				

spallations



ν-PROCESS

Ce138 0.251	Ce139 137.6d	Ce140 88.45
La137 6e+04y	La138 0.09	La139 99.91
Ba136 7.854	Ba137 11.232	Ba138 71.698

Pu237 45.2d	Pu238 87.7y	Pu239 2.41e+04y	Pu240 6561y	Pu241 14.29y
Np236 1.54e+05y	Np237 2.14e+06y	Np238 2.117d	Np239 2.356d	Np240 1.032h
U 235 0.72	U 236 2.34e+07y	U 237 6.75d	U 238 99.2745	U 239 23.45m
Pa234 6.7h	Pa235 24.1m	Pa236 9.1m	Pa237 8.7m	Pa238 2.3m

Numerical scheme

Basic equations (Murphy & Burrows '08)

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p - \rho \nabla \Phi$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p)\mathbf{v}] = -p\mathbf{v} \cdot \nabla \Phi + \rho(H - C + Q)$$

$$\frac{dY_e}{dt} = Y_e \text{ prescription} / \Gamma_e$$

$$\Phi = -\frac{GM_{\text{in}}}{r},$$

Neutrino irradiation

$$L_{\nu_e} = L_{\bar{\nu}_e} = L_0 \exp(-t_{\text{pb}}/t_d)$$

neutrino heating/cooling (Janka '01)

$$H = 1.544e20 \times (L_{\nu_e} / 10^{52} \text{ erg s}^{-1}) \\ \times (r / 100\text{km})^{-2} (T_{\nu_e} / 4\text{MeV})^2 \\ \times (Y_n + Y_e) e^{-\tau}$$

$$C = 1.399e20 \times (T / 2\text{MeV})^6 \\ \times (Y_n + Y_e) e^{-\tau}$$

[erg/g/s]

Q: Nuclear reaction energy

← Network calculation incl. He-Ni

SASI

$$v_r(r, \theta) = v_r^0(r, \theta) + \delta v_r \\ \delta v_r = 0.01 \times \text{rand} \times v_r^0(r, \theta)$$

Progenitor model

derived from evolutionary calculation for a star with
M=15 Msun, Z=Zsun (Limongi & Chieffi '06)

Neutrino+SASI+nuclear-burning model

Snap shots of entropy distributions from our simulations with (*left*) and without (*right*) nuclear network calculation.

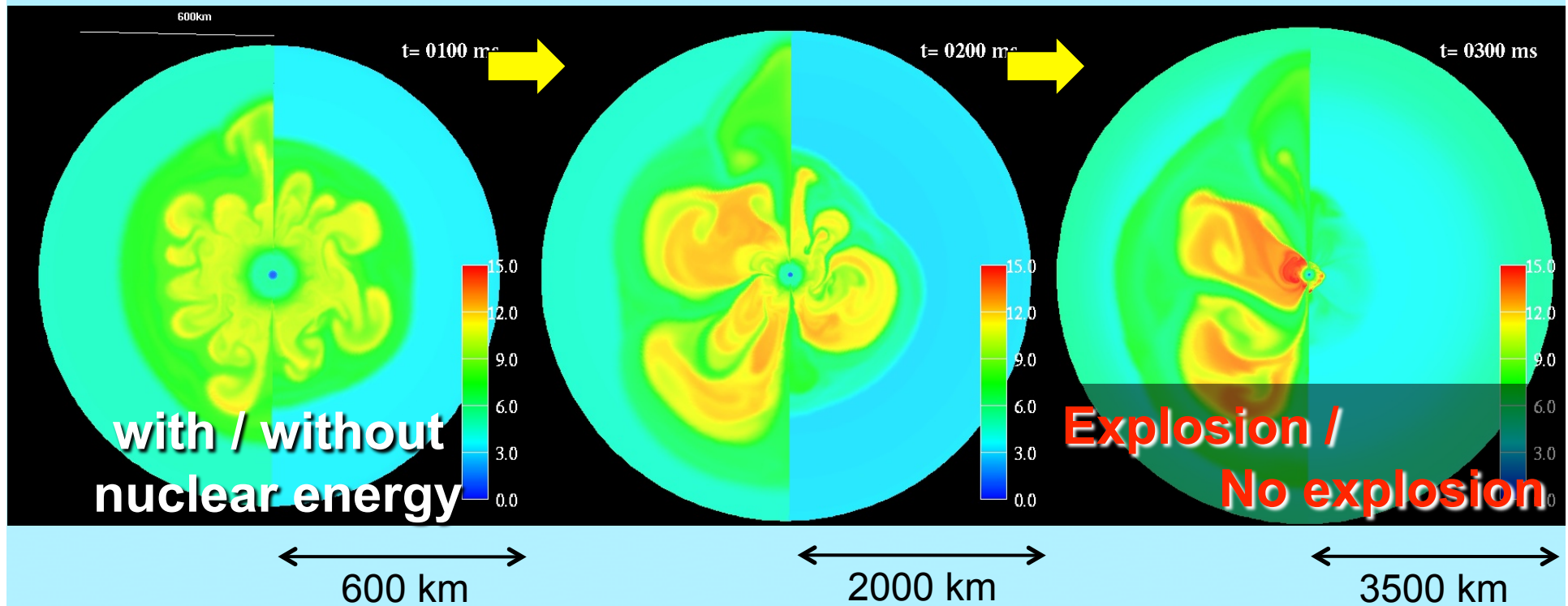
Example) $L_{\nu_e} = L_0 \exp(-t_{pb}/t_d) \leftarrow L_0 = 2.4 \times 10^{52} \text{ erg/s}, t_d = 1.1 \text{ s}$

Time after core bounce:

100 ms

200 ms

300 ms



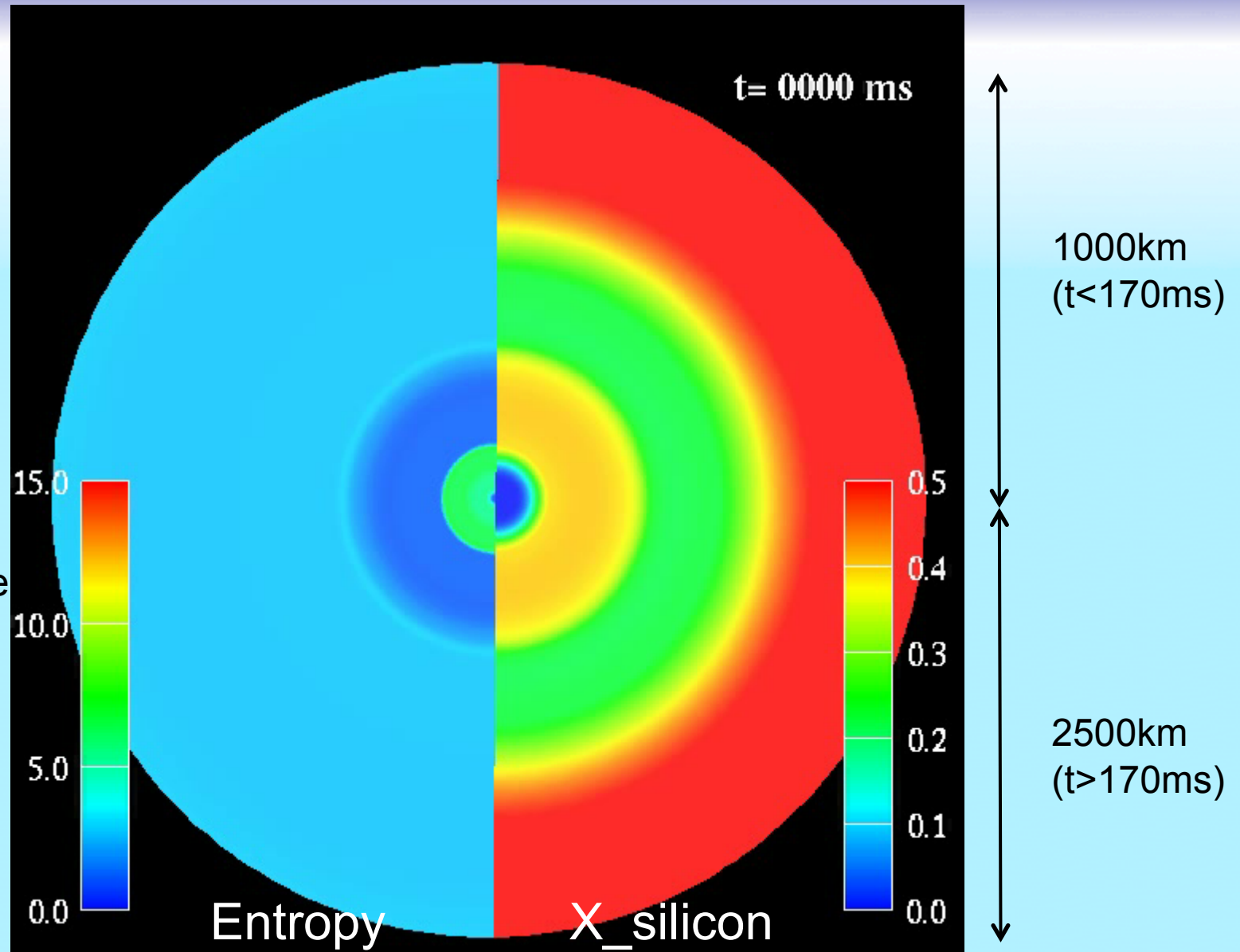
Neutrino+SASI+nuclear-burning model

-15Msun model

-2-dimensional
axi-symmetric
coordinates

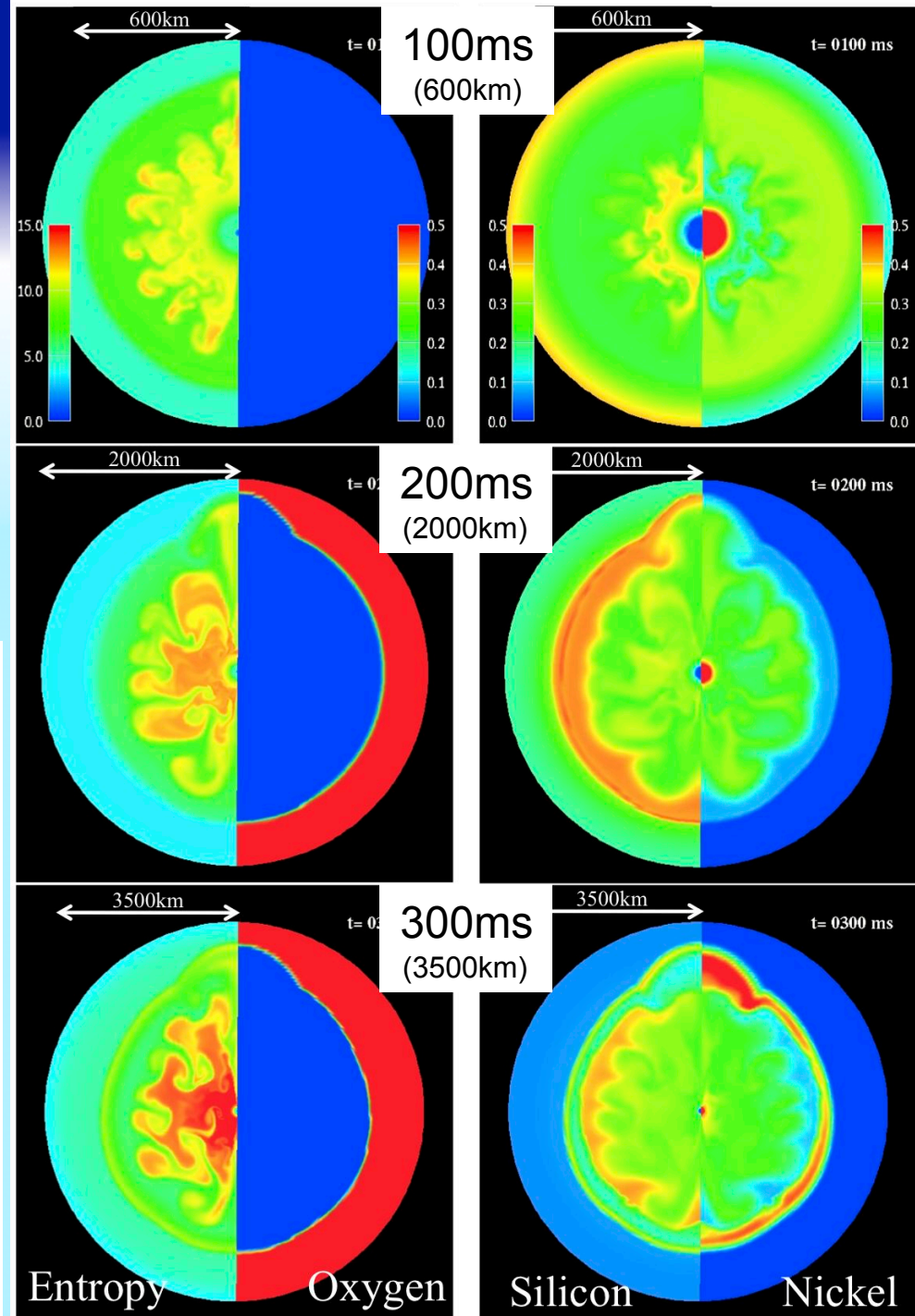
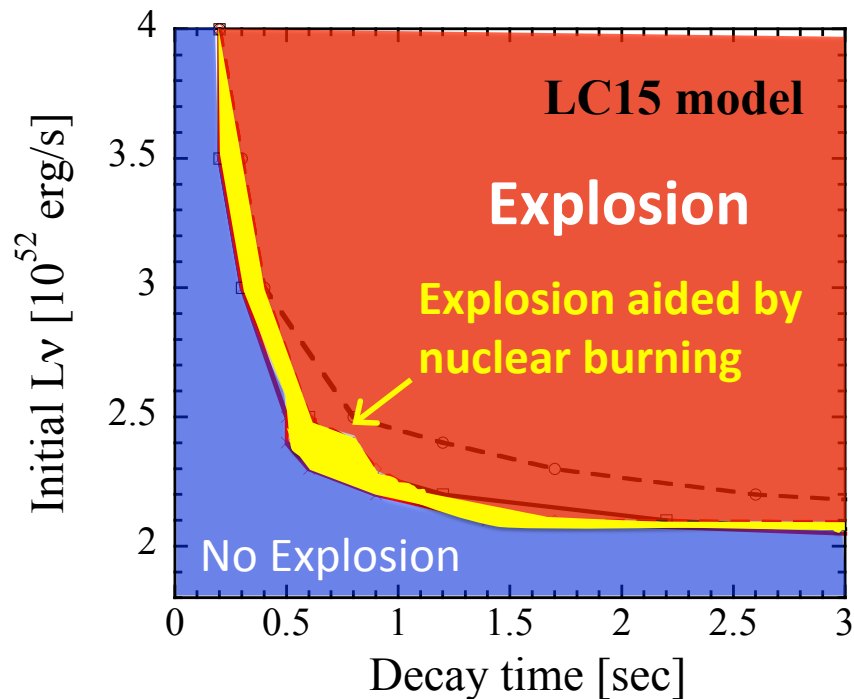
-300(r)*128(θ)
covering
r = 0-5000km
& $\theta = 0-\pi$

-ZEUS-MP code
equipped with
nucl. network



With/w.o. nucl. burning

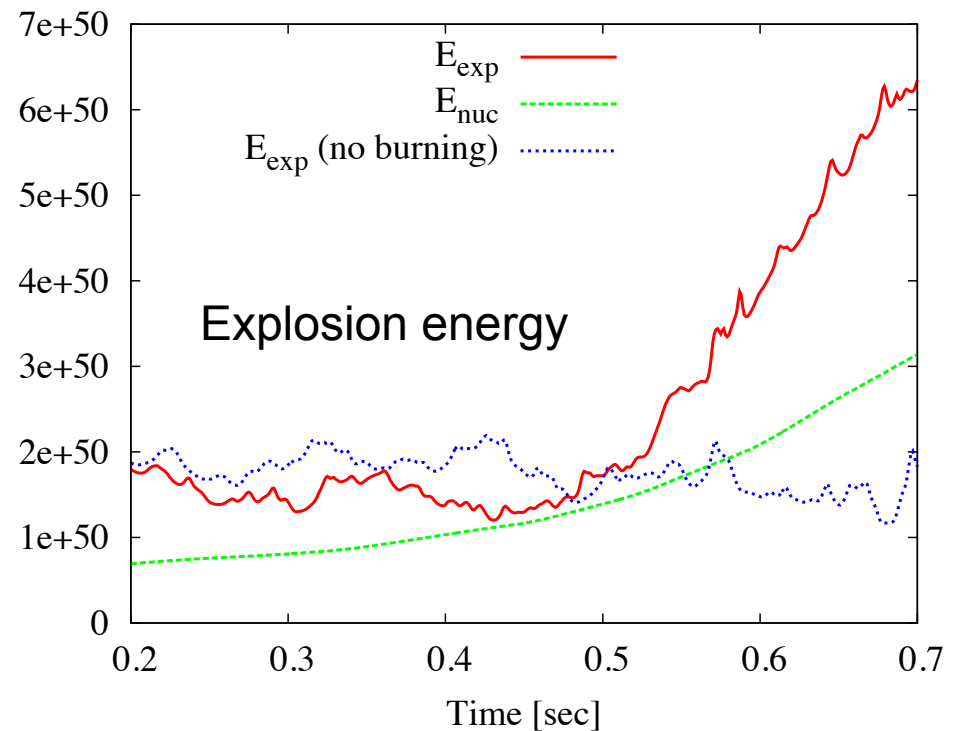
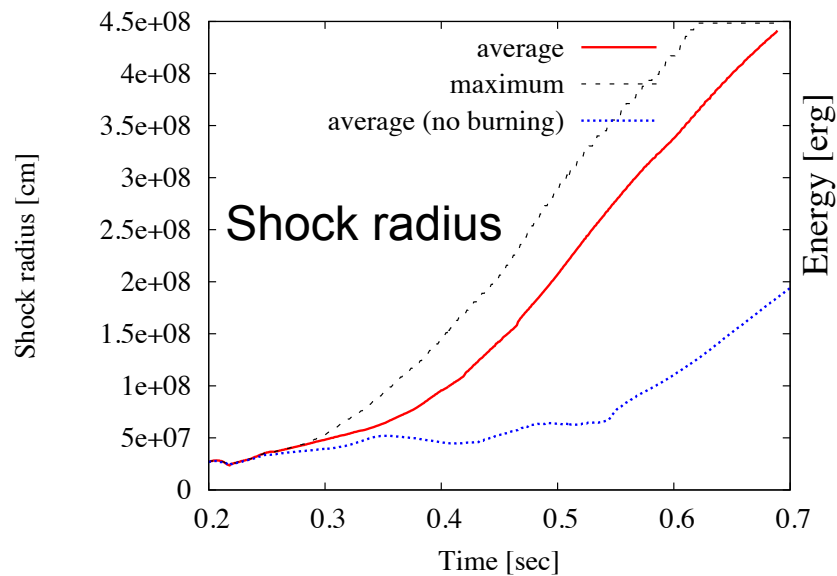
- Si & O burning
- “nuclear reaction-aided” supernova explosion
- corresponding parameter region is narrow, but ..



Contribution of nuclear reactions to explosion energy

- Explosion energy
 - **red**: explosion energy = $\Sigma(E_{kin} + E_{int} + E_{grv})_i$ for $v_{r_i} & E_{tot_i} > 0$
 - **green**: net burning energy
 - **blue-dotted**: explosion energy in the case without nuclear burning

$\ln_0 = 2.1e52$ [erg/s]
 $t_d = 2.0$ [s]



Summary

- Neutrino-driven model is one of the possible solution for Core-collapse SN explosion mechanism.
- **However**, it's less powerful to reproduce the typical SN explosion energy of 10^{51} erg (even with the aid of hydro. instabilities or acoustic oscillation).
- **We have demonstrated the 2-D simulations taking account of the effects of nuclear reactions on hydr.**
 - nuclear network including 13 alpha-nuclei from He to Ni.
- **We found that:**
 - explosion is available even if L_ν is low and/or t_d is short,
 - explosion energy is enhanced by the energy released via nuclear reactions,
 - and we could reproduce the typical SN explosion energy.