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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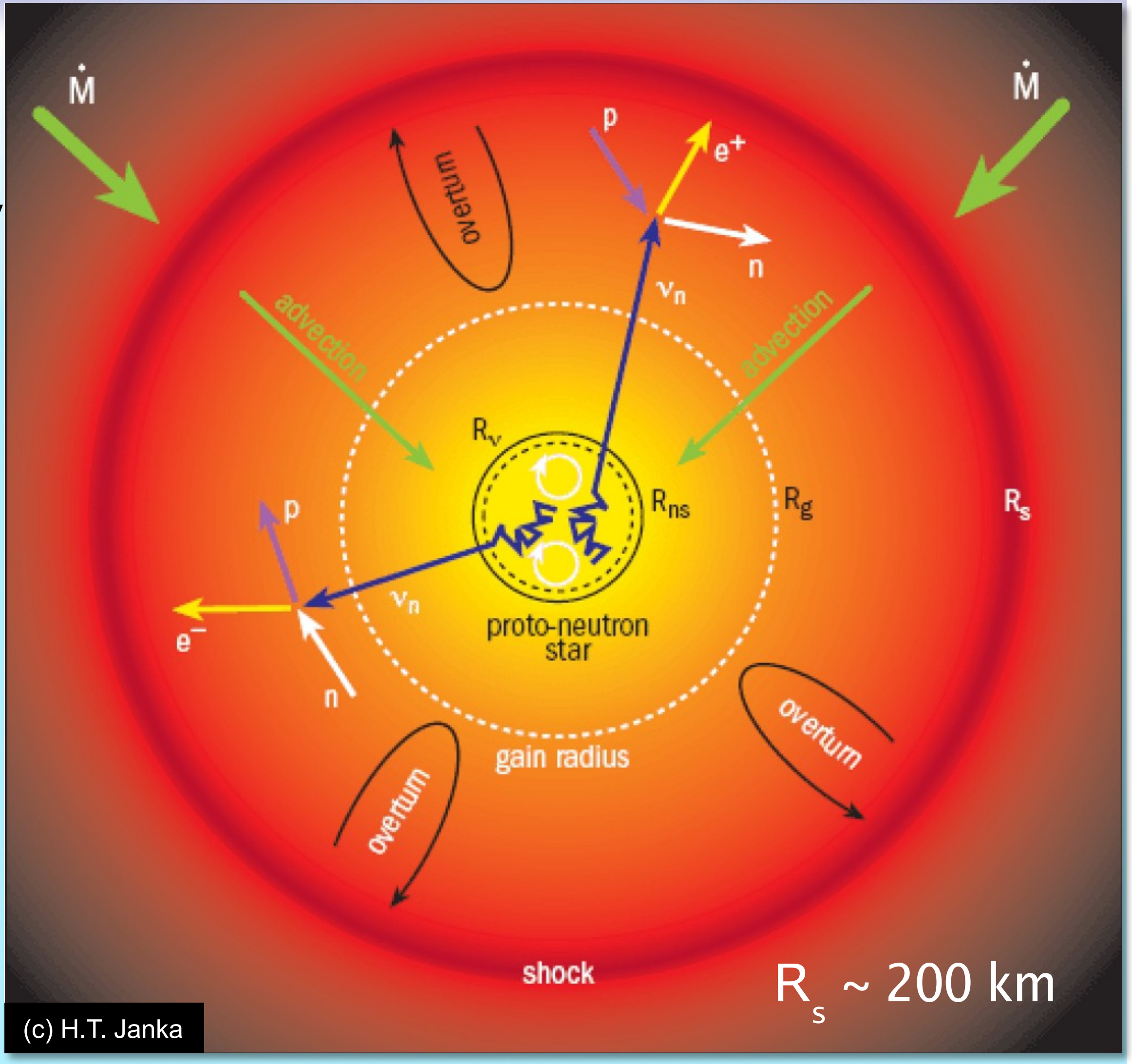
新領域-HPCI研究会 @ 合歓の郷　　**December 3-5, 2011**

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 (>∼10^{53} erg) >> Typical SN explosion energy (∼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.

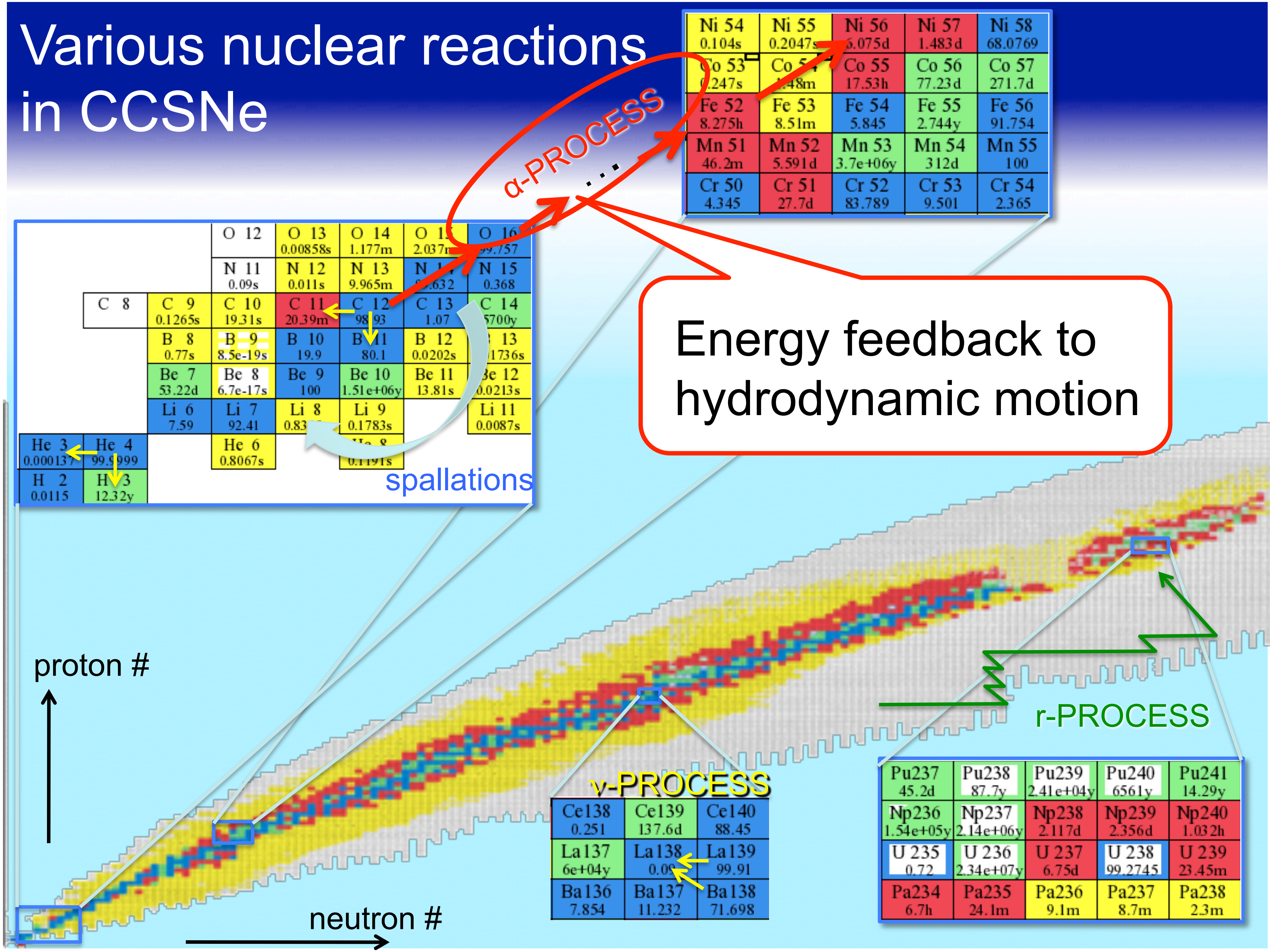


List of recent neutrino-radiation hydrodynamic simulations.
(Table 1 of Kotake 2011 *arXiv:1110.5107*)

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	E_{exp}(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	~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	~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)	[illegible]	[illegible] -)	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	~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 !
(Eexp < 1 Bethe = 10^{51} ergs)

Various nuclear reactions in CCSNe



Numerical scheme

Basic equations (Murphy & Burrows '08)

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

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

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

$$\frac{dY_{\mathrm{e}}}{dt} = Ye \text{ prescription} / \Gamma e$$

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

Neutrino irradiation

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

neutrino heating/cooling (Janka '01)

$H = 1.544\mathrm{e}20 \times (L_{\nu_e} / 10^{52} \text{ erg s}^{-1}) \times (r / 100\mathrm{km})^{-2} (T_{\nu_e} / 4\mathrm{MeV})^2 \times (Yn + Ye)\ e^{-\tau}$

$C = 1.399\mathrm{e}20 \times (T / 2\mathrm{MeV})^6 \times (Yn + Ye)\ e^{-\tau}$

[erg/g/s]

Q : Nuclear reaction energy

←Network calculation incl. He-Ni

SASI

$v_r(r,\theta) = v_r^0(r,\theta) + \delta v_r$

$\delta v_r = 0.01 \times rand \times v_r^0(r,\theta)$

Progenitor model

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

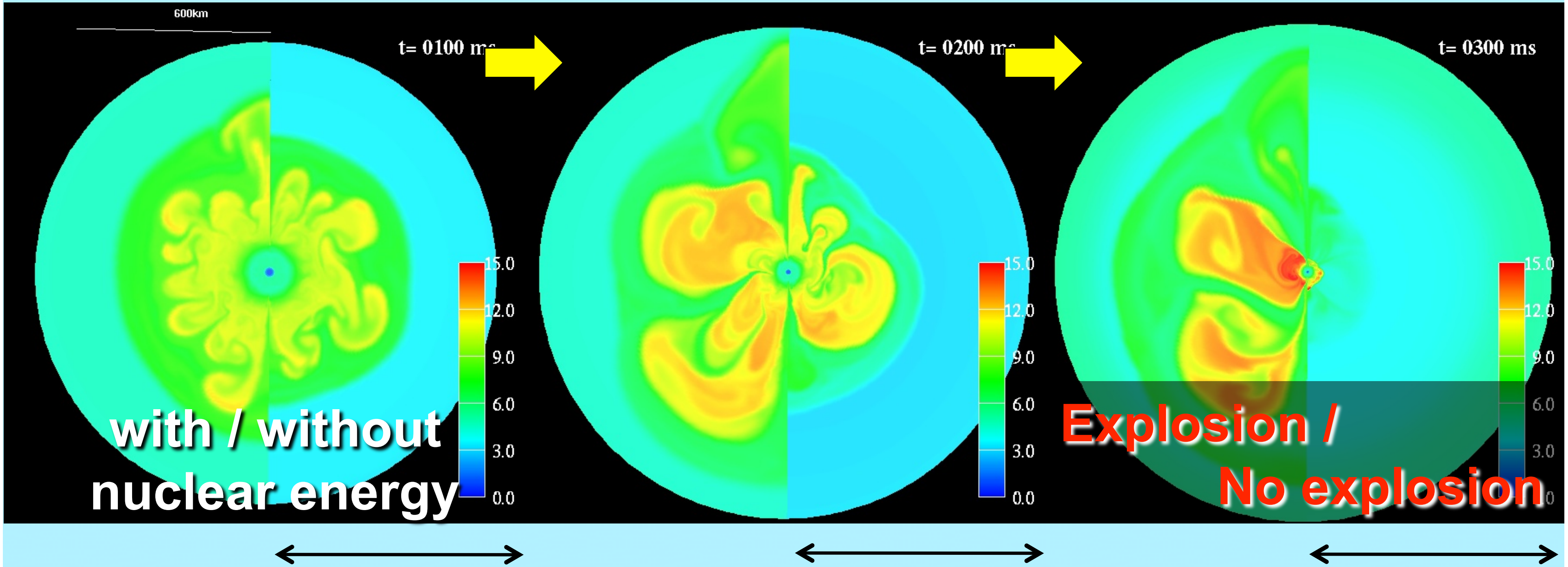
Neutrino+SASI+**nuclear-burning** model

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

Example) $L_{\nu_e} = L_0 \exp(-t_{pb}/t_d) \leftarrow L_0 = 2.4\times10^{52}$ erg/s, $t_d = 1.1$ s

Time after core bounce:

100 ms 200 ms 300 ms



600 km 2000 km 3500 km

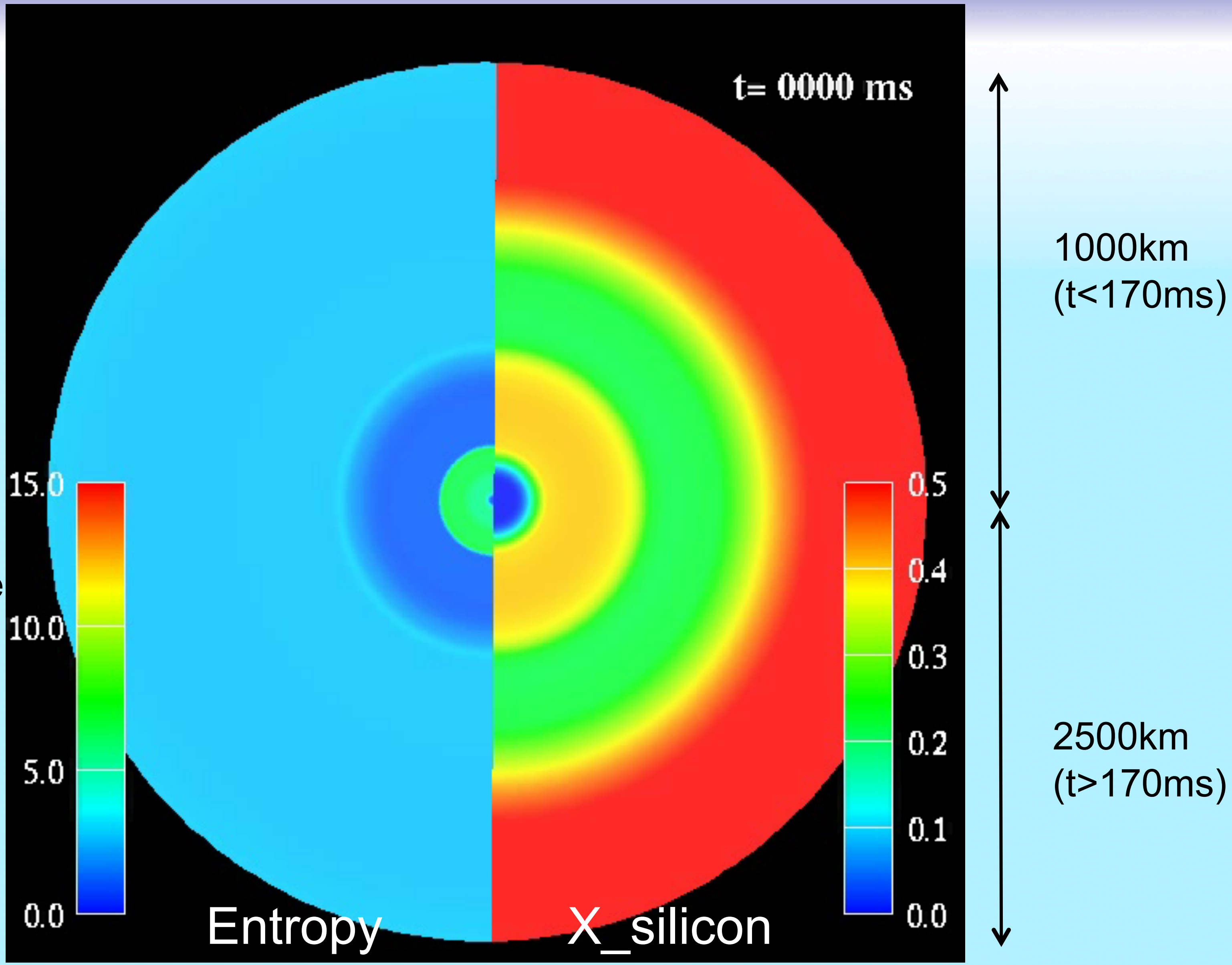
Neutrino+SASI+**nuclear-burning** model

-15Msun model

-2-dimensional axi-symmetric coordinates

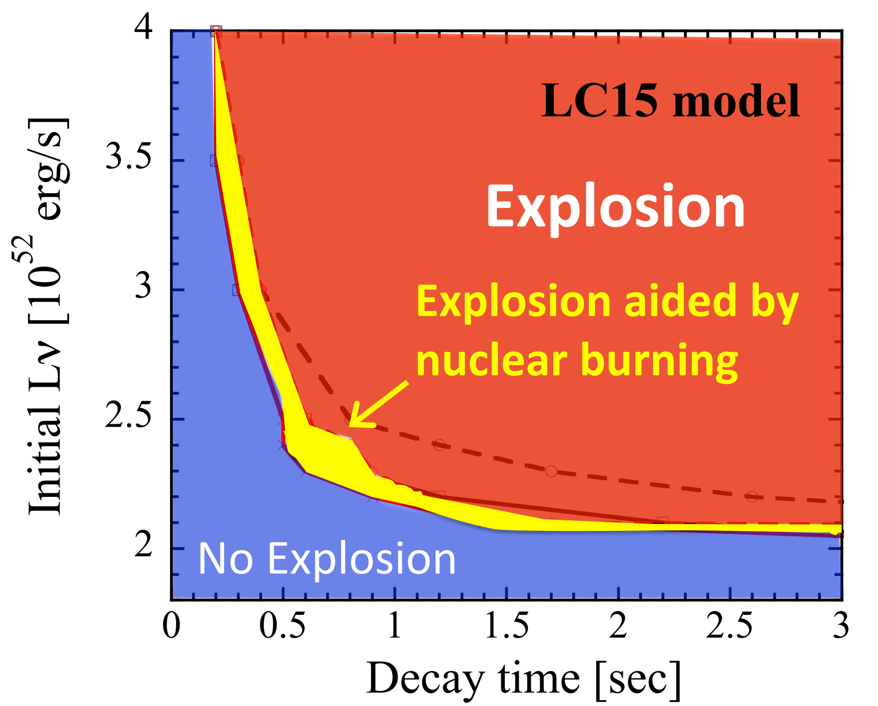
-300(r)*128(θ) covering r = 0-5000km & θ = 0-π

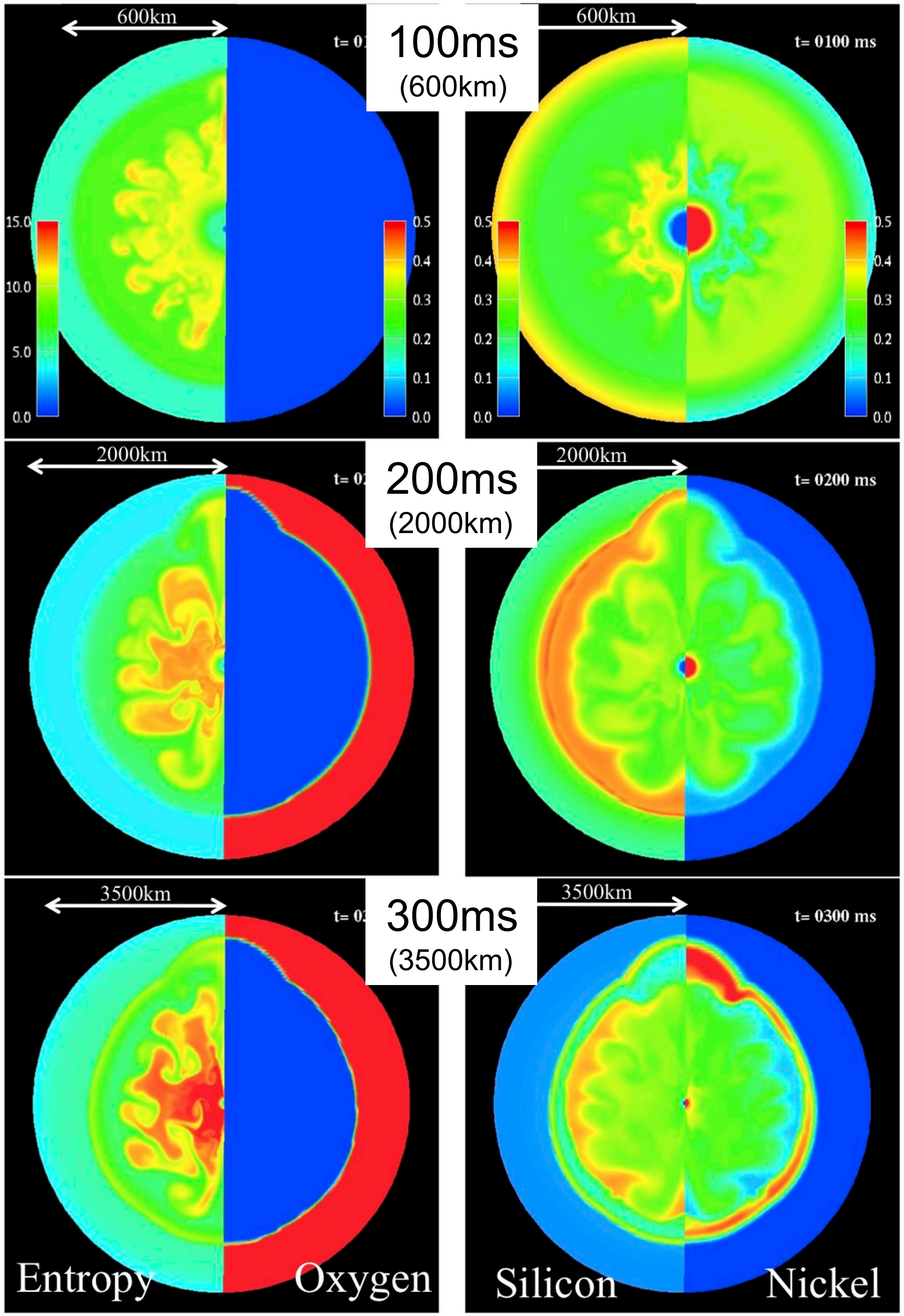
-ZEUS-MP code equipped with nucl. network



With/w.o. nucl. burning

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

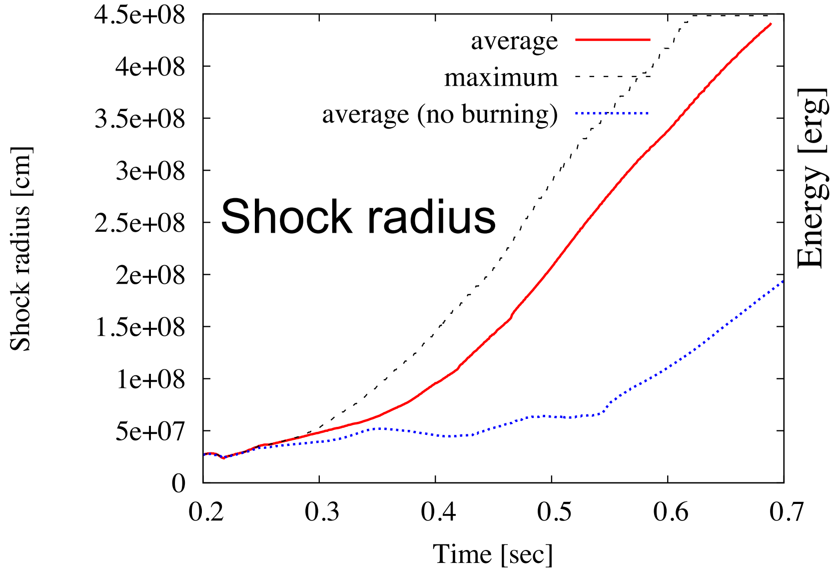


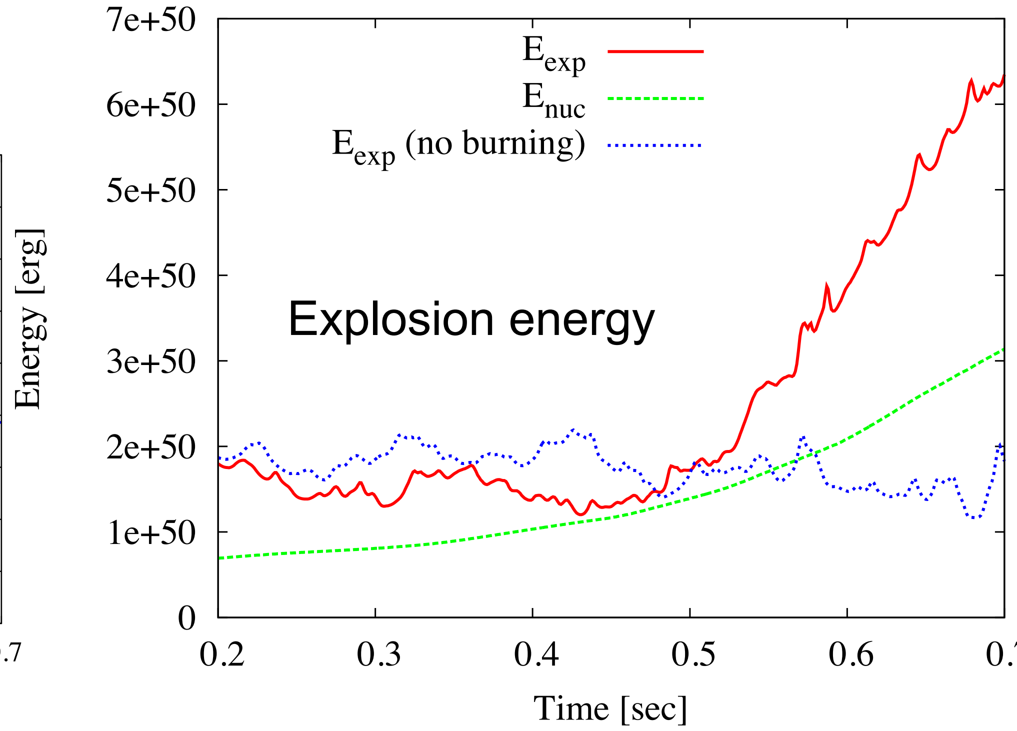


Contribution of nuclear reactions to explosion energy

- Explosion energy
  - red: explosion energy = Σ(Ekin + Eint + Egrv)$_i$ for vr$_i$ & Etot$_i$ > 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 $L\nu$ 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.