核反応熱を組み込んだ
多次元ニュートリノ爆発計算

中村 航 (Nakamura, Ko)

National Astronomical Observatory of Japan

Collaborators: T. Takiwaki, T. Kuroda, K. Kotake（NAOJ）
N. Nishimura（Univ. of Basel／GSI）

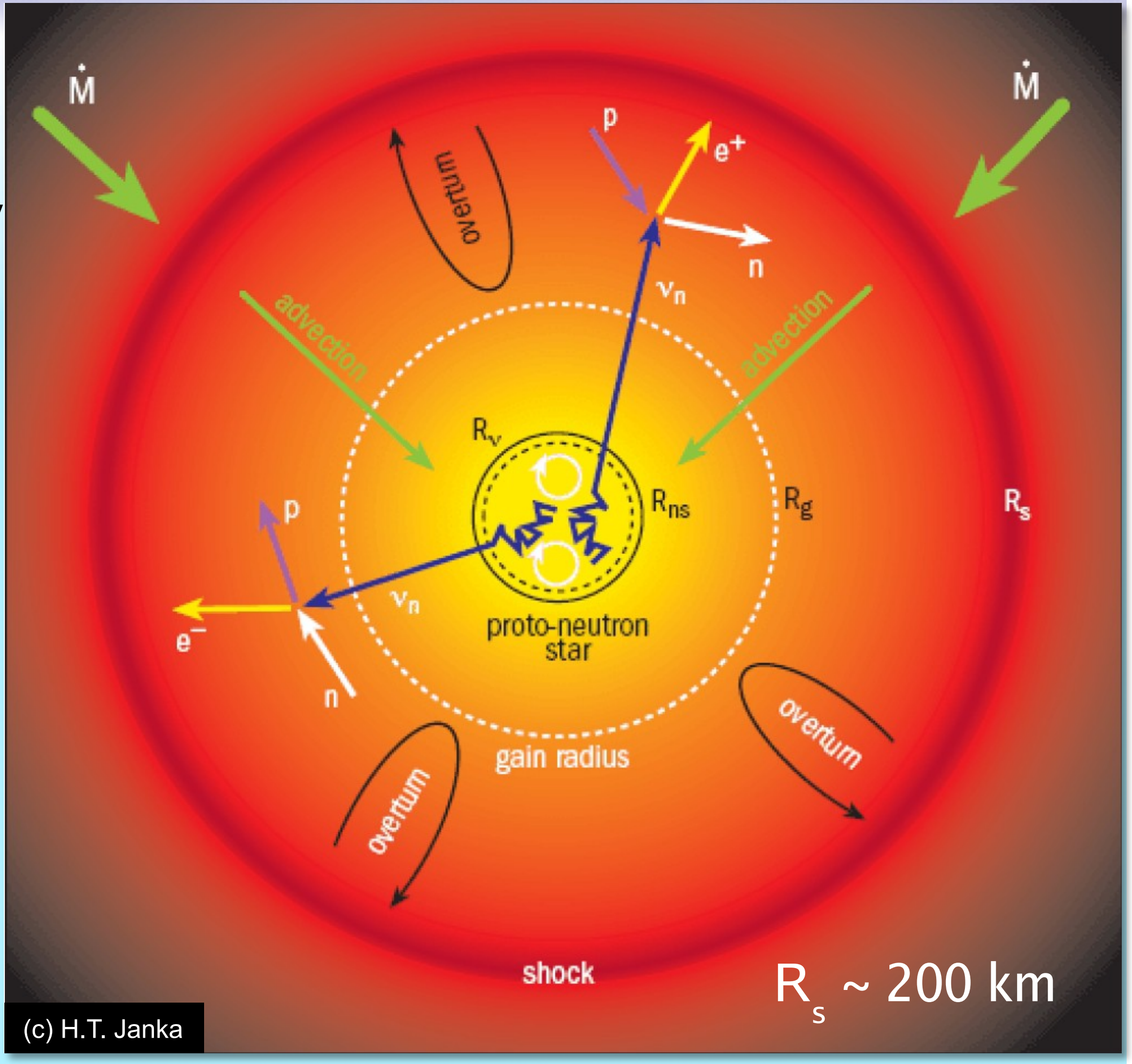
SN11 @ YITP **December 26-28, 2011**

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
  - 1-D and 2-D simulations for 11.2/15.0 Msun model
  - using ZEUS-MP code incl. nuclear reaction network
- 3-D simulations (primitive)
  - MPI-AMR code w.o. network
- Summary

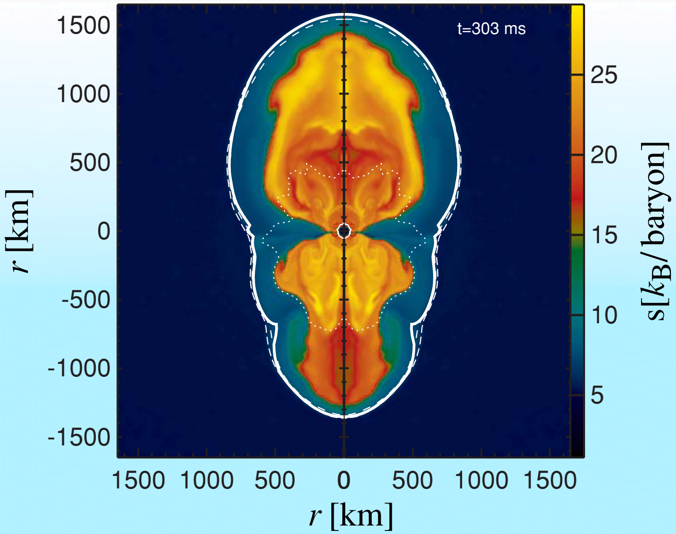
Neutrino-driven SN explosion mechanism

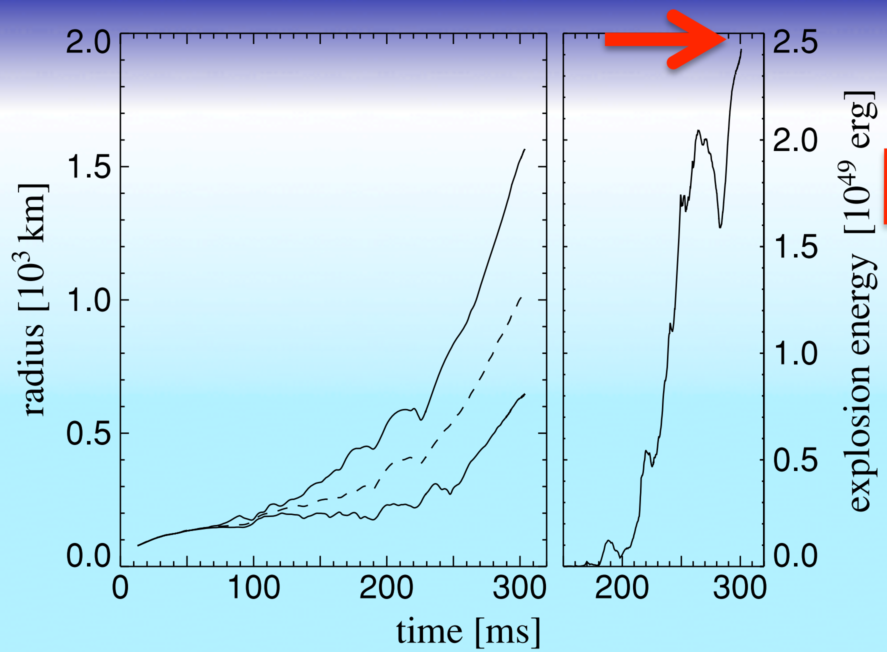
- Gravitational binding energy of the collapsing core (>∼10^{53} erg) >> Typical SN explosion energy (∼10^{51} erg)
- Neutrinos carry away most of the energy, but ..
- A small fraction of emitted neutrinos can interact with the matter behind a shock, deposit energy, and revive the stalled shock wave.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



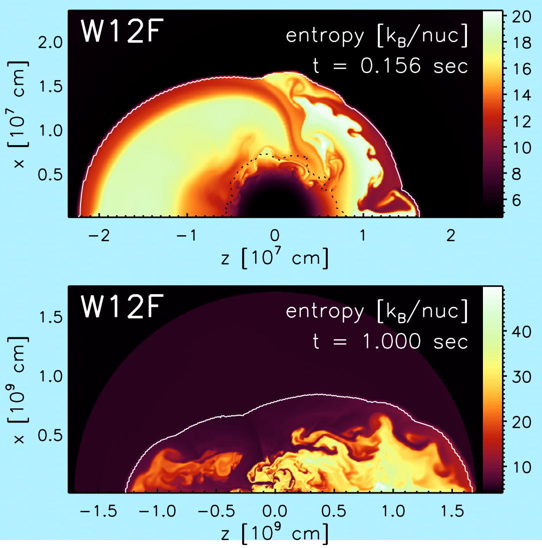
Previous studies of SASI+ν -induced explosion

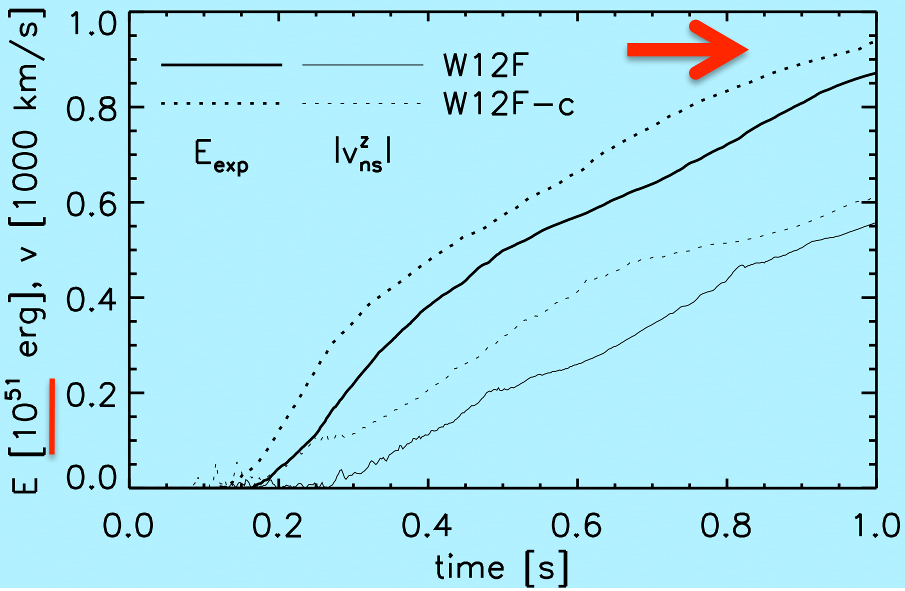
- Marek & Janka (2009)





- Scheck et al. (2008)





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

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	$t_{\rm exp}$ (ms)	$E_{\rm exp}$(B) @$t_{\rm pb}$ (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$1[illegible]	~0.3* (1400)	MGFLD 1, (N)
(NH88[71])	NAOJ+ [illegible]	ν-driven	2D (N)	~200	0.1 [illegible]	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	~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, $\mathcal{O}(v/c)$

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

Numerical scheme

Basic equations (Murphy & Burrows '08)

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

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

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

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

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

Neutrino irradiation

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

neutrino heating/cooling (Janka '01)

H = 1.544e20 × ($L\nu_e$ /10^{52} erg s^{-1})
× (r / 100km)$^{-2}$ ($T\nu_e$ / 4MeV)^2
× (Yn + Ye) $e^{-\tau}$

C = 1.399e20 × (T / 2MeV)^6
× (Yn + Ye) $e^{-\tau}$

[erg/g/s]

Q : Nuclear reaction energy
←Network calculation incl. He-Ni

SASI

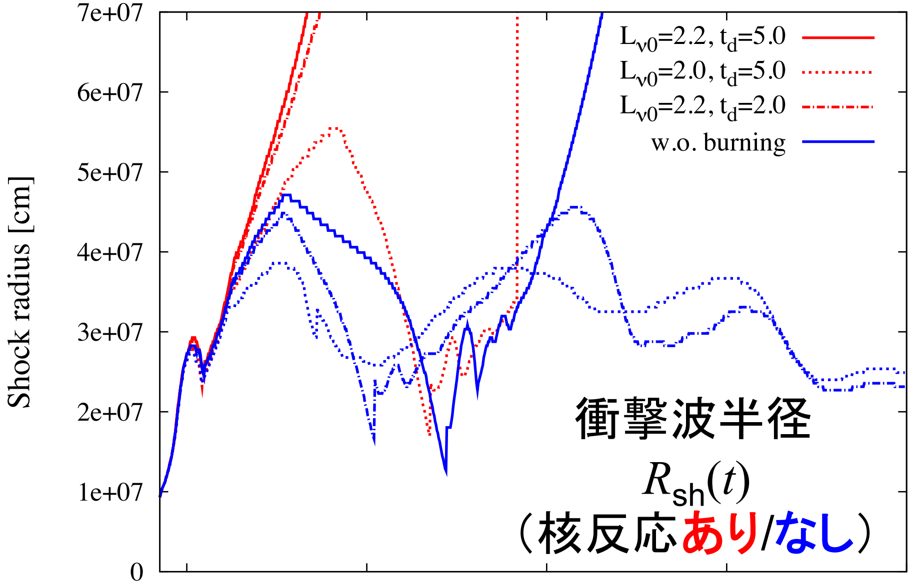
$v_r(r,\theta) = v_r^0(r,\theta) + \delta v_r$

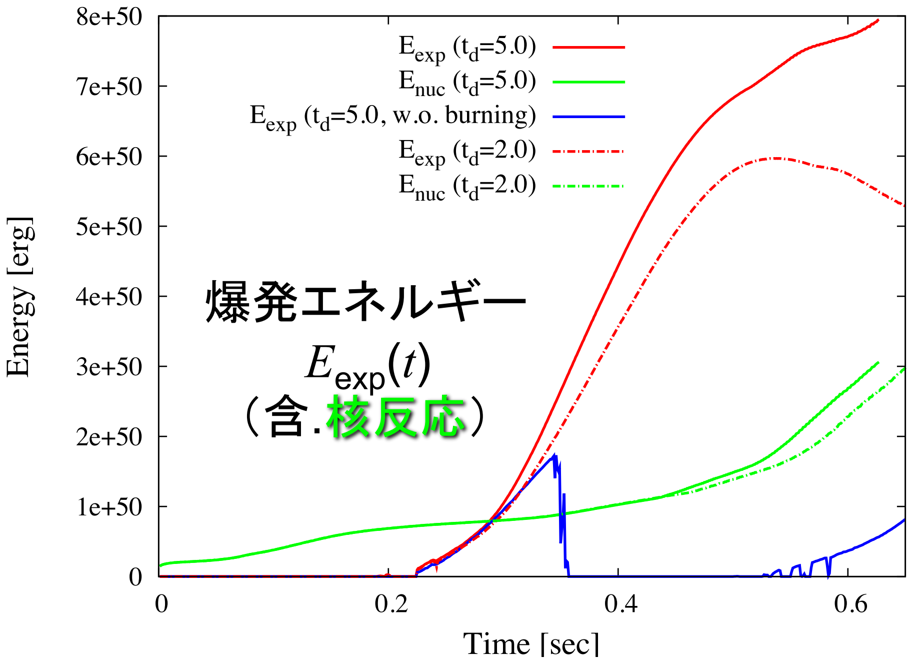
$\delta v_r = 0.01 \times rand \times v_r^0(r,\theta)$

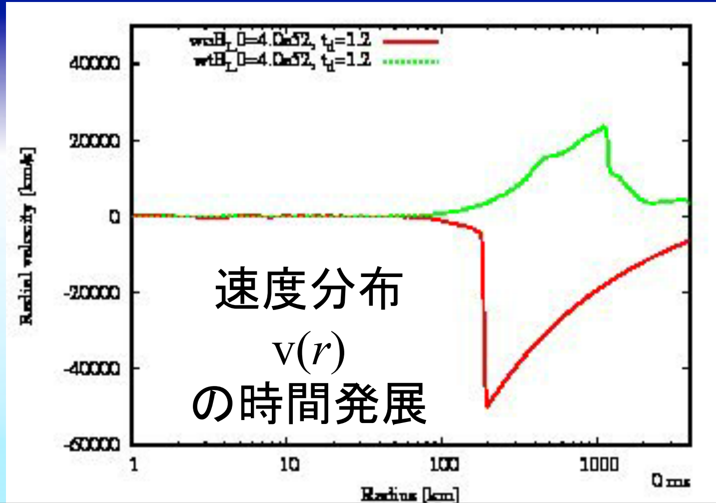
Progenitor model

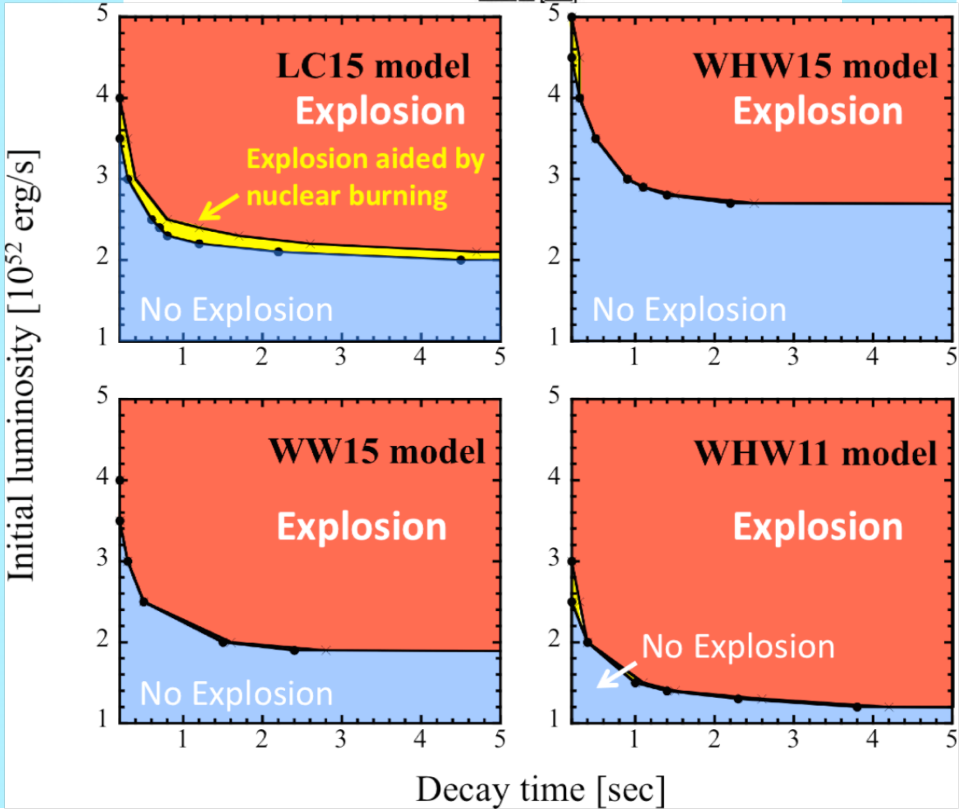
derived from evolutionary calculation for a star with M=11.2-15.0 Msun、Z=Zsun

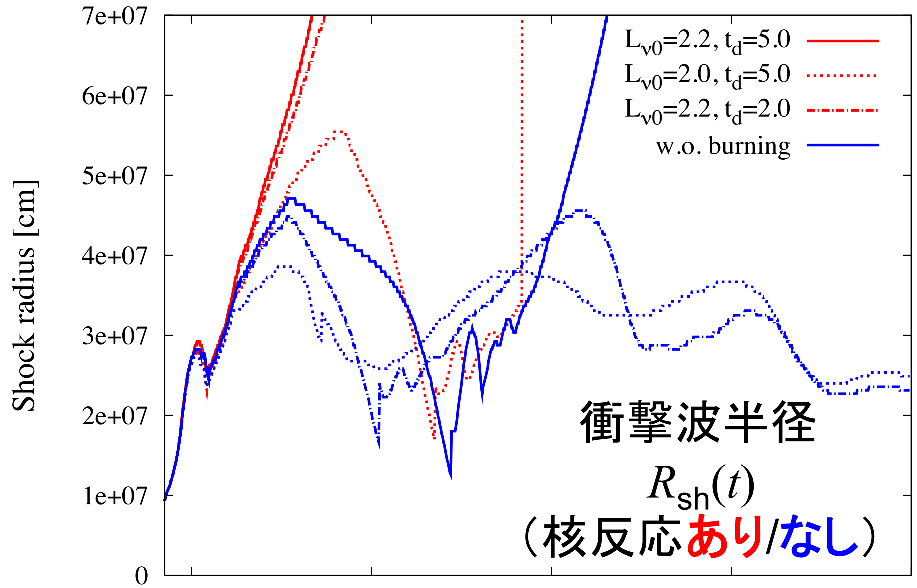
1-D simulation

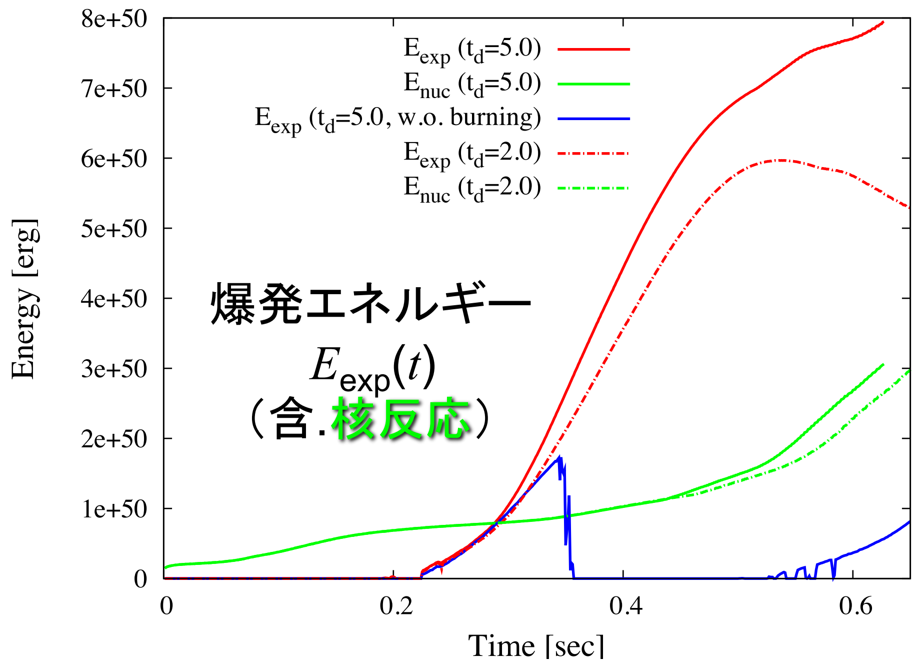


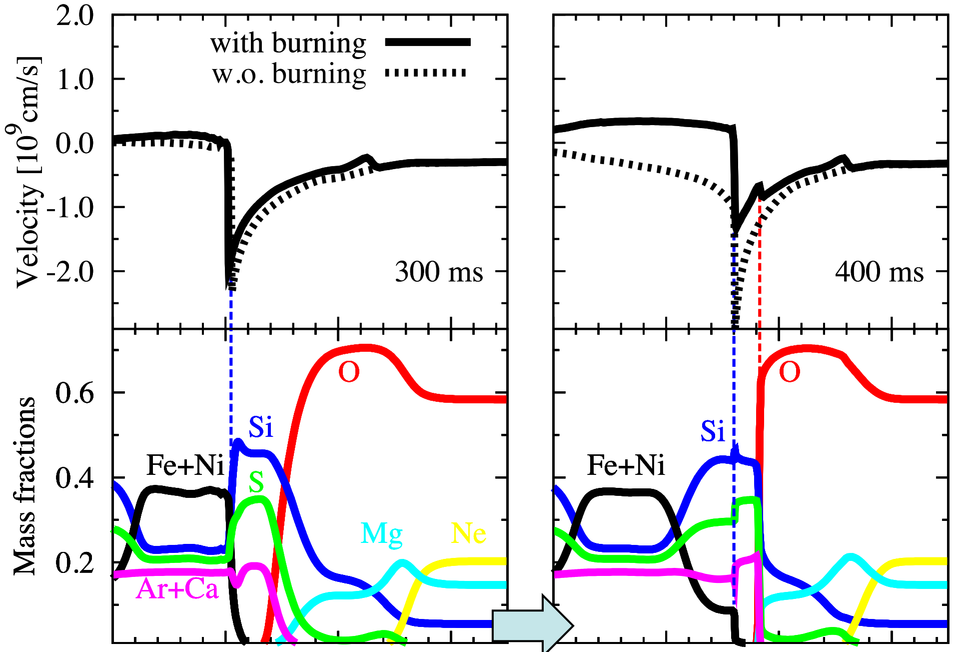


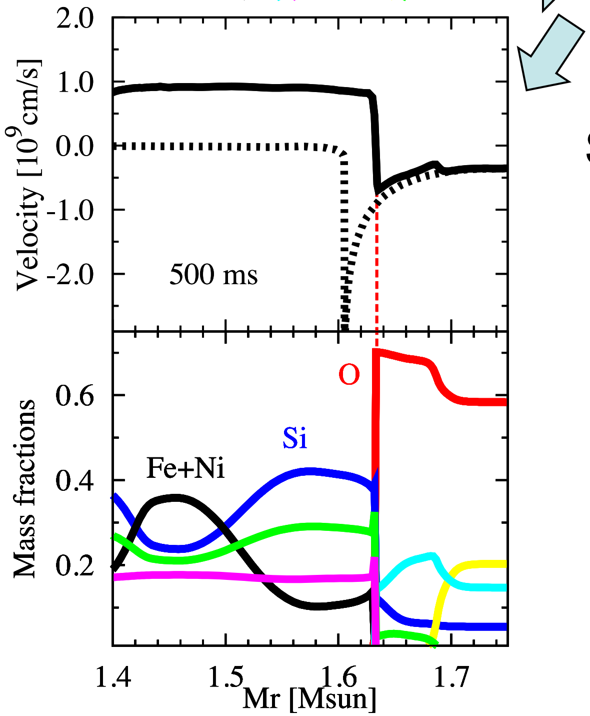












Snapshots:

LC15 model

Ln_0 = 2.2 [10^{52} erg/s]

t_d = 2.0 [s]

（左図の点破線）

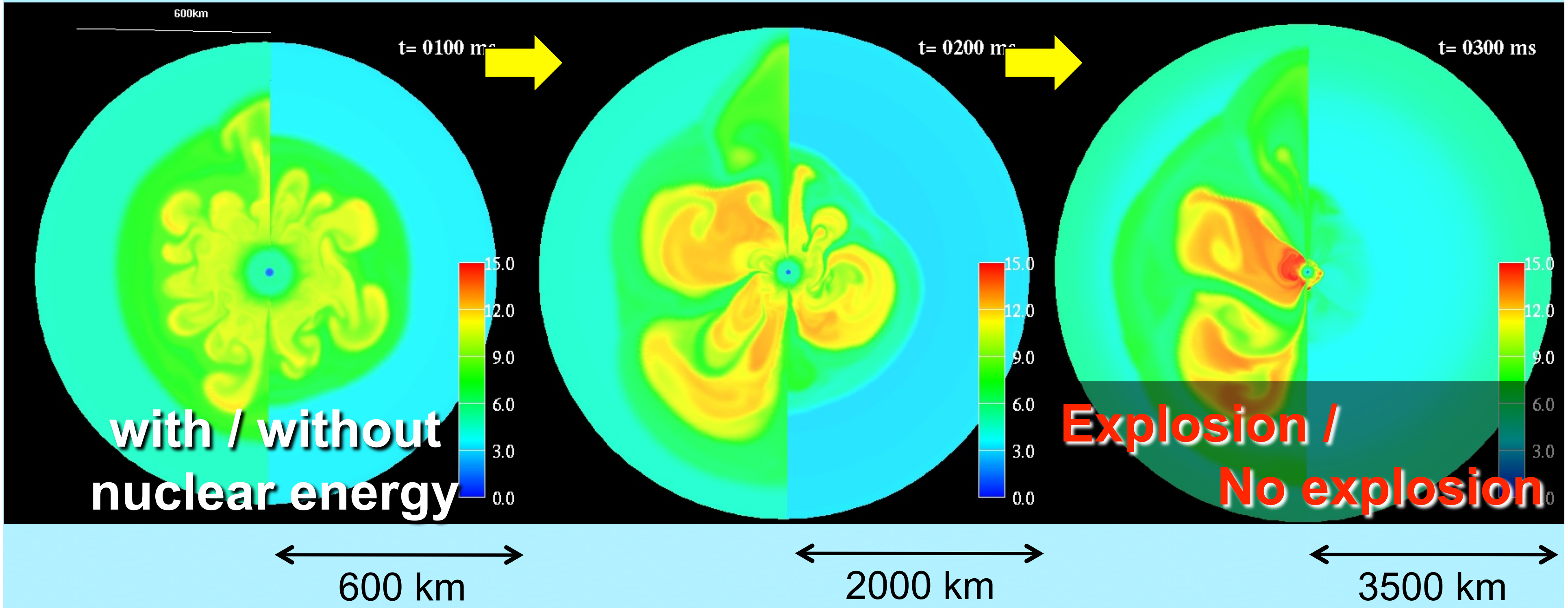
Neutrino(+SASI)+**nuclear-burning** model
2-D simulation

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



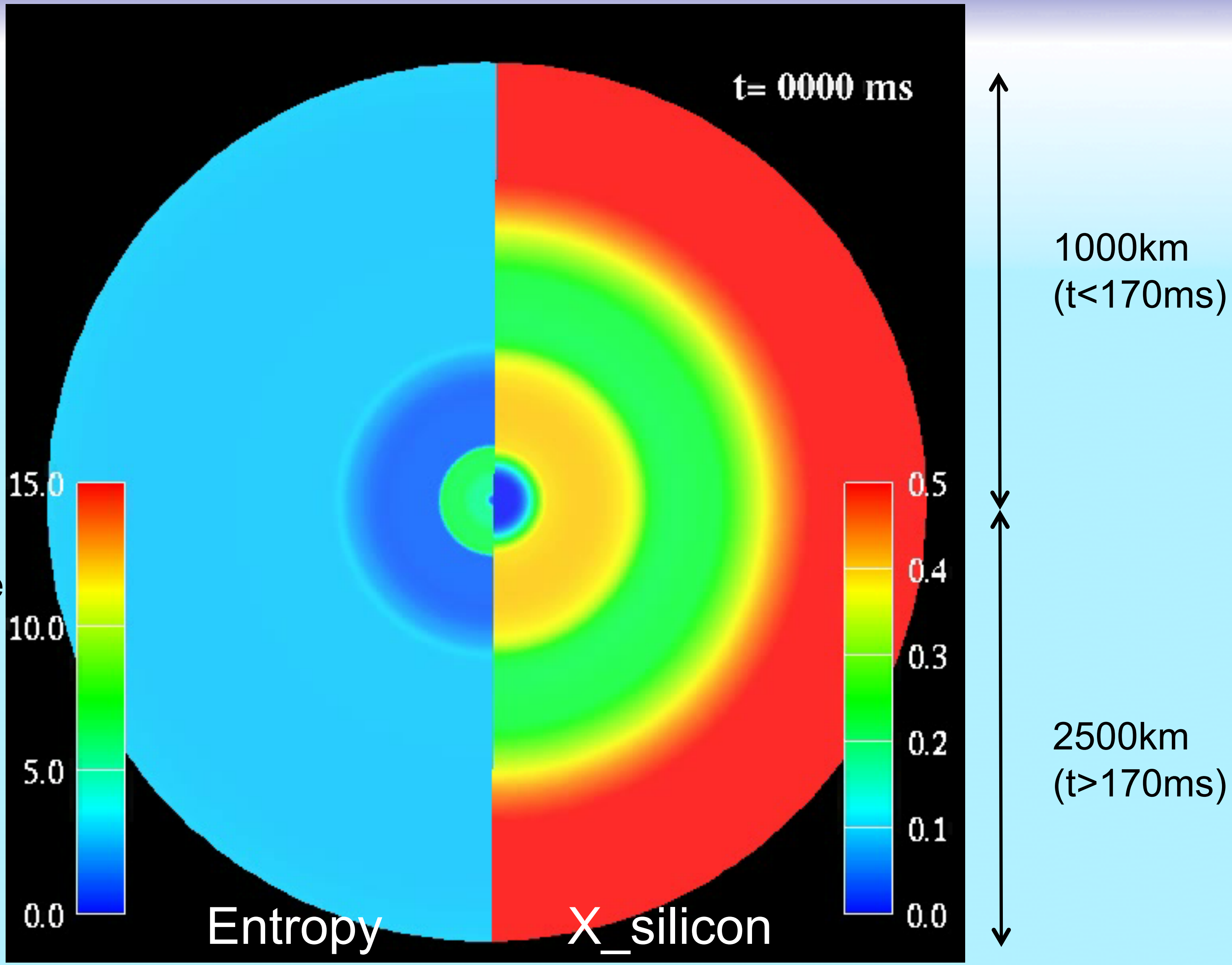
Neutrino(+SASI)+**nuclear-burning** model

-15Msun model

-2-dimensional
axi-symmetric
coordinates

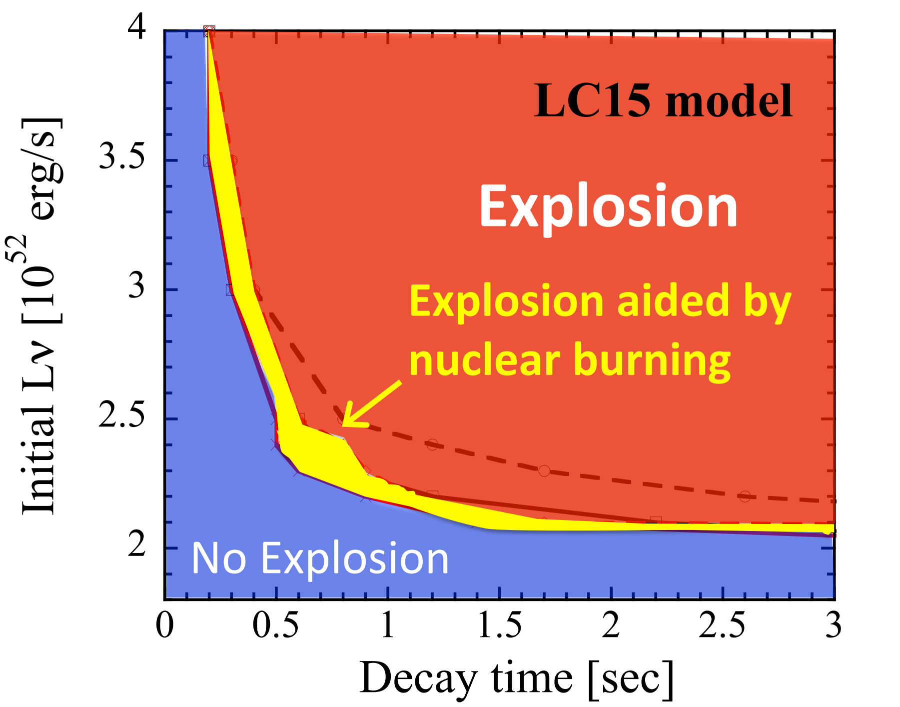
-300(r)*128(θ)
covering
r = 0-5000 km
θ = 0-π

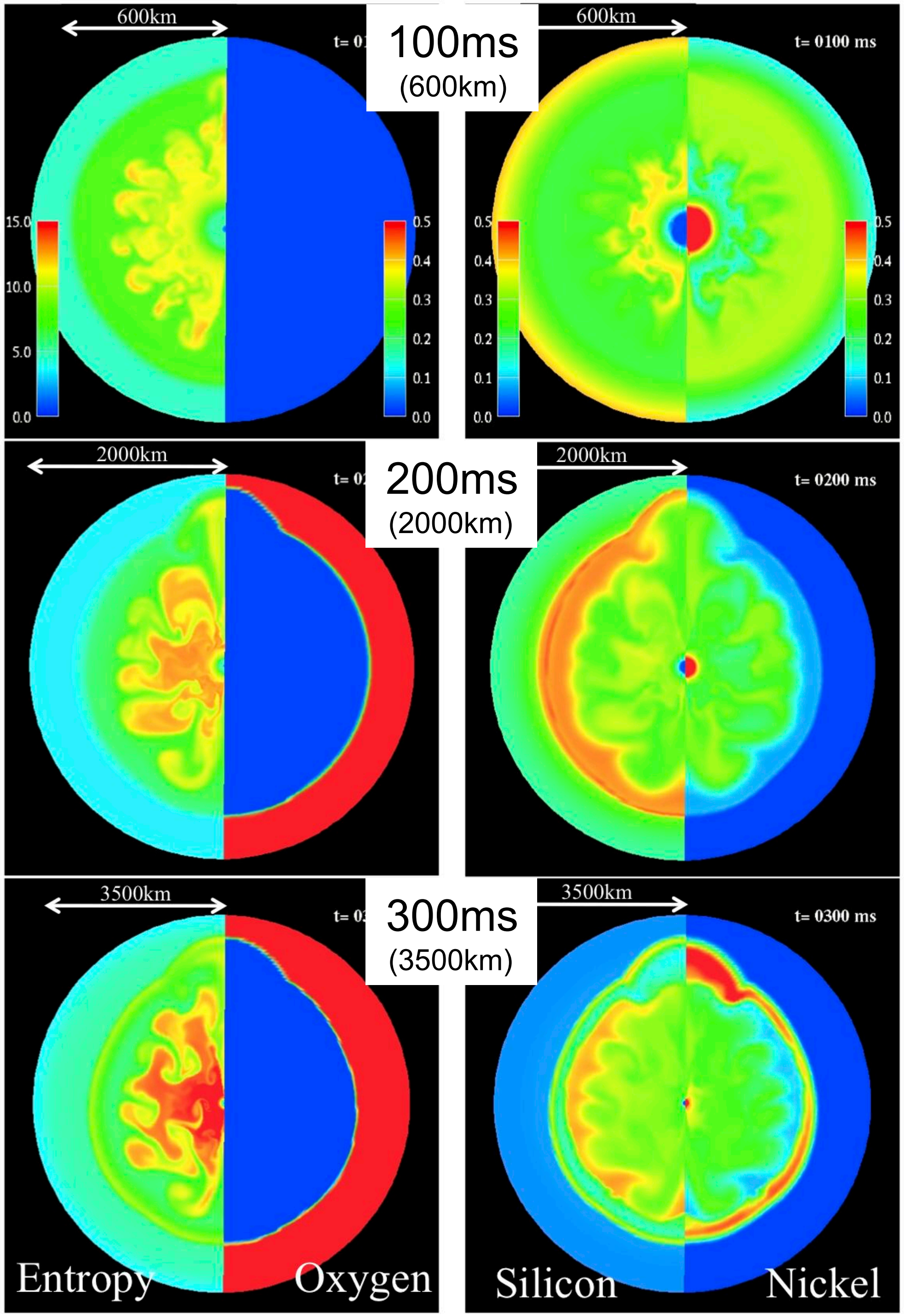
-ZEUS-MP code
equipped with
nucl. network



With/w.o. nucl. burning

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

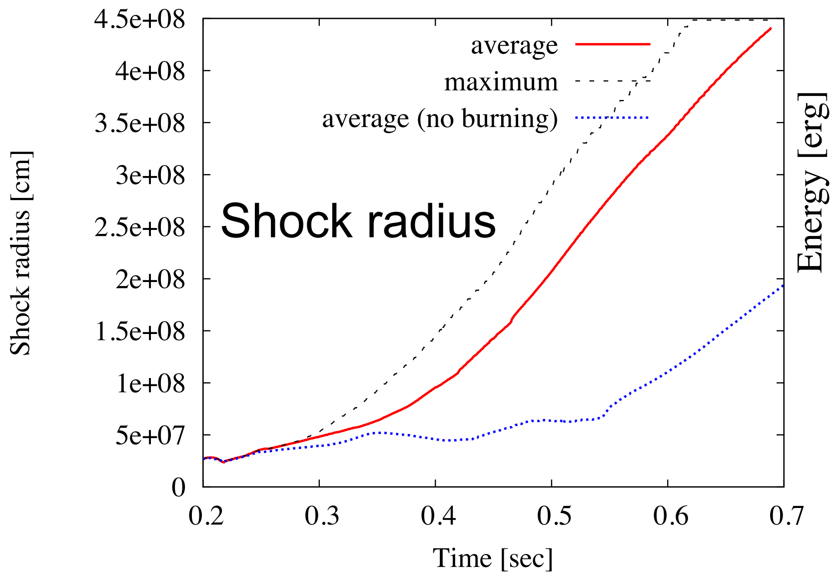


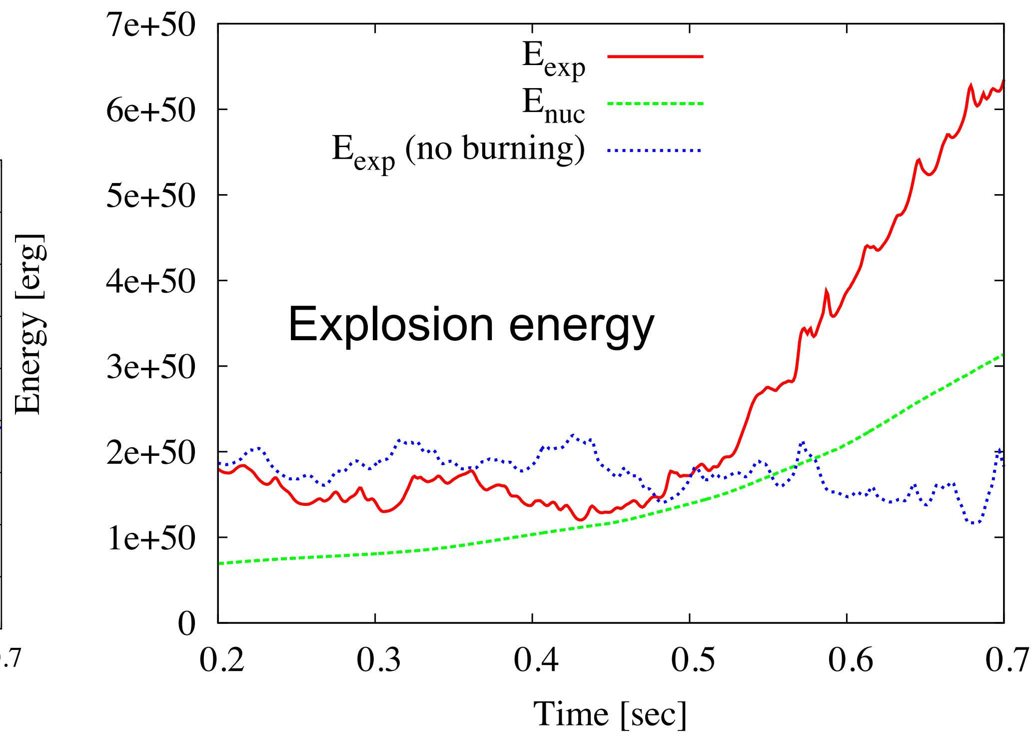


Contribution of nuclear reactions to explosion energy

- 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

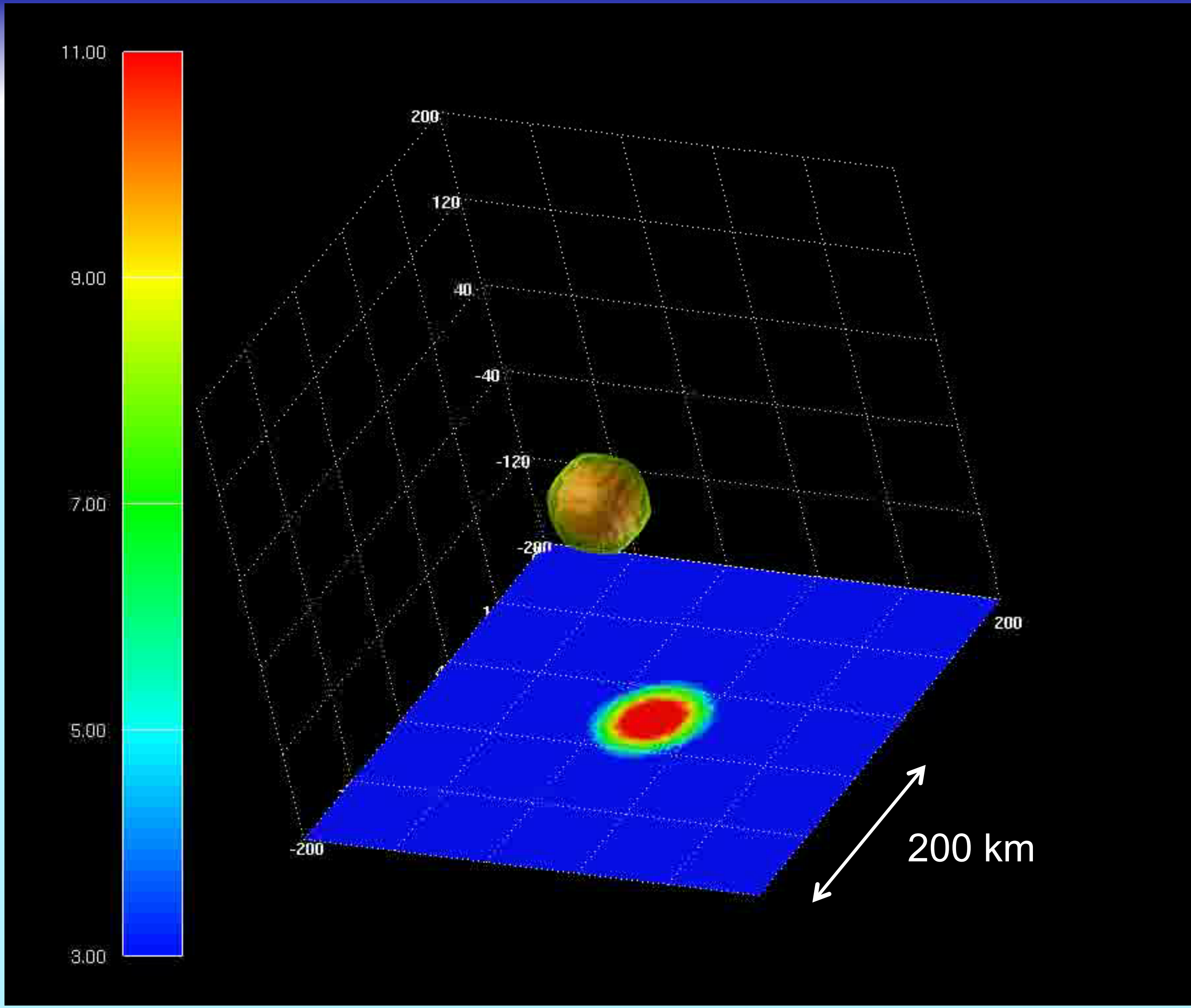
Ln_0 = 2.1e52 [erg/s]
t_d = 2.0 [s]





3-D simulation (primitive)

- WW95 モデル (15 Msun)
- 3-dimensional Cartesian coordinates
- Ln_0 = 1.5e52 [erg/s]
- t_d = ∞
- 核反応なし



Summary

- 重力崩壊型超新星においてニュートリノ爆発モデルは有力であるが、先行研究では典型的な爆発エネルギー(10^{51}erg)を再現できていない
- **ある種の流体不安定性や空間多次元効果がニュートリノ加熱の効率を上げるという報告はあるが、現時点では不十分**
- **核反応ネットワークを組み込んだ流体計算によって、反応エネルギーの流体運動への影響およびモデル/空間次元/ニュートリノ特性への依存性を調べた**
  - 11.2 Msun (WHW02), & 15.0 Msun (WW95, WHW02, LC06) models
  - nuclear network including 13 alpha-nuclei from He to Ni.
  - simple treatment of neutrino heating
- **1,2次元計算の結果**
  - 爆発しやすさ: WHW-11 > WW-15 > LC-15 > WHW-15、2次元>1次元
  - “核反応を入れることによって”爆発する ν パラメータ領域
  - すべてのモデルで核反応による爆発エネルギーの増加(1次元>2次元)
- **3次元計算に向けて**
  - AMR-MPI コード(12/27黒田さん)を用いて計算中
  - 核反応による加熱効率は上がる？