星の重力崩壊に伴う爆発的天体現象

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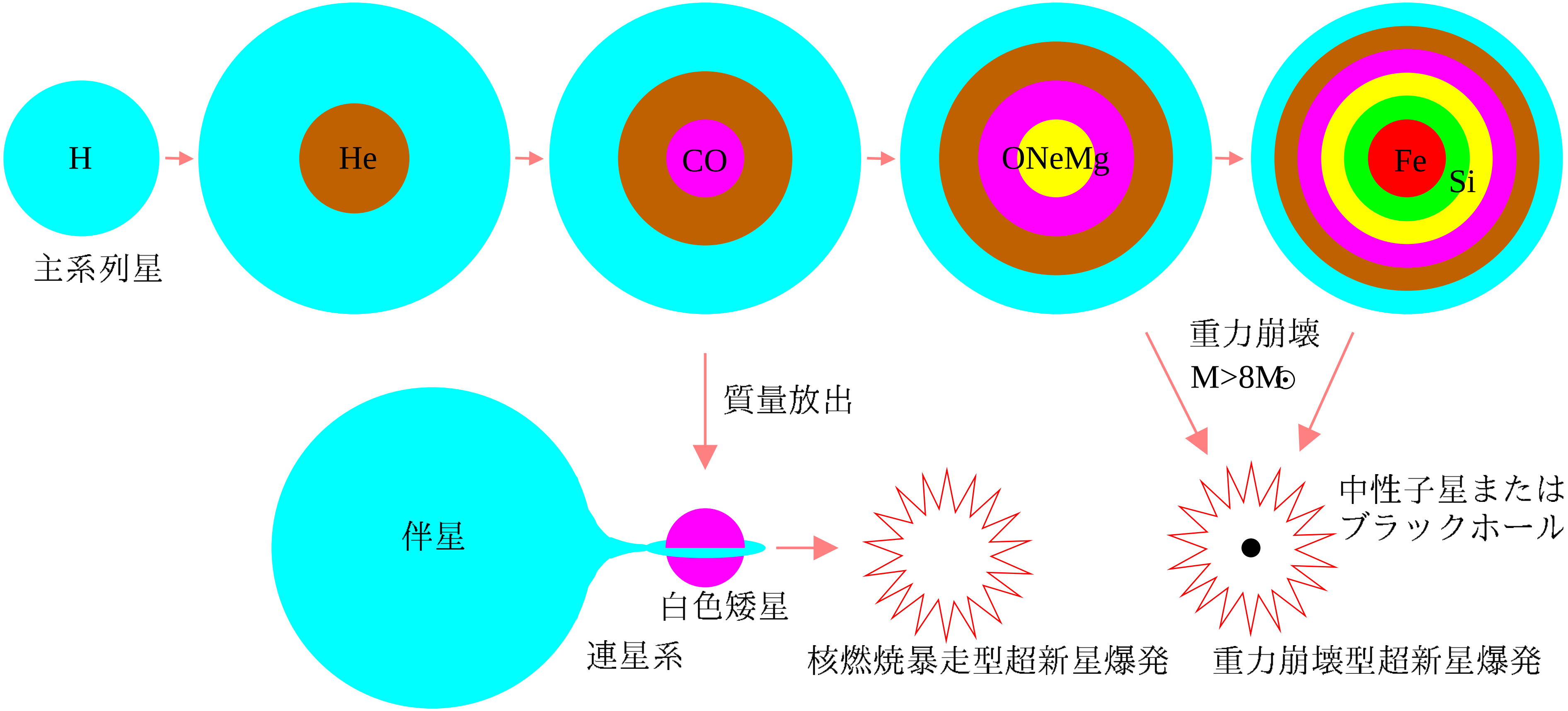


H

主系列星

He

CO

ONeMg

Fe

Si

重力崩壊

$M>8M_{\odot}$

質量放出

伴星

白色矮星

連星系

中性子星または
ブラックホール

核燃焼暴走型超新星爆発

重力崩壊型超新星爆発

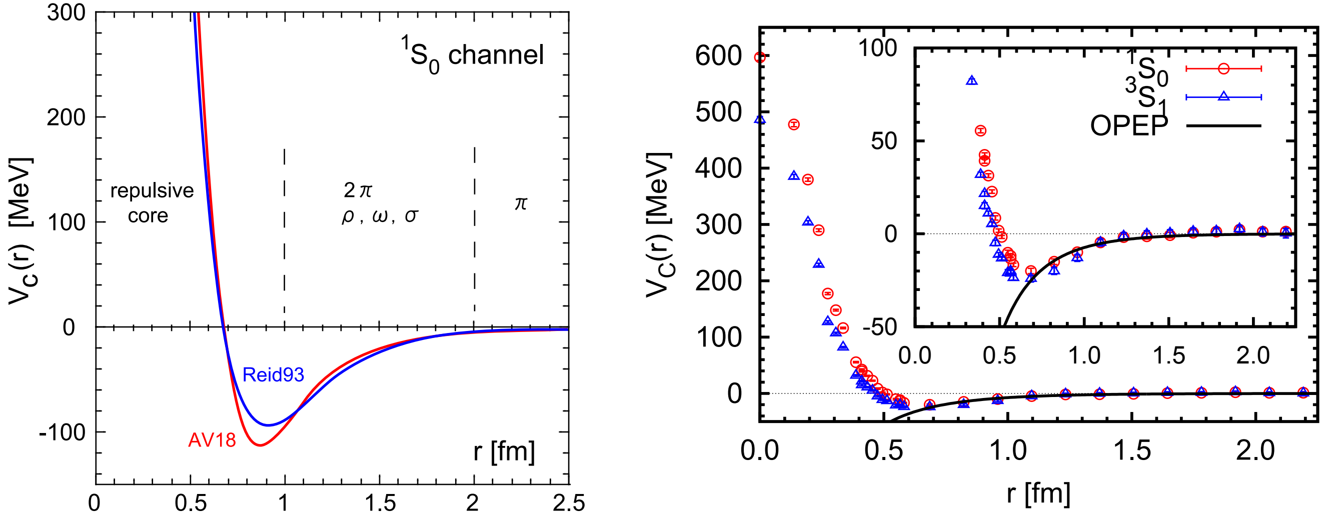
重力崩壊型超新星爆発

超新星コア中心部 $(T \sim 10\mathrm{MeV}, \rho \gtrsim 10^{14}\mathrm{g/cm^3})$

- コア中心部 $\tau_{\mathrm{weak}} \ll \tau_{\mathrm{dyn}}$　ニュートリノトラッピング
  νも熱平衡、化学平衡、$n_\nu \sim n_\gamma \sim n_{\mathrm{e}}$
  平均自由行程 $\lambda_\nu \gg \lambda_\gamma, \lambda_{\mathrm{e}}, \lambda_N \Rightarrow$ ニュートリノ輸送が重要

- 一般相対論

- 有限温度高密度物質の状態方程式とニュートリノ反応



核力ポテンシャル：現象論的モデルと格子 QCD の計算結果

N. Ishii, S. Aoki and T. Hatsuda, Phys. Rev. Lett. 90 (2007) 022001

平成 20-24 年度新学術領域科研費

「素核宇宙融合による計算科学に基づいた重層的物質構造の解明」

A01 量子色力学に基づく真空構造とクォーク力学

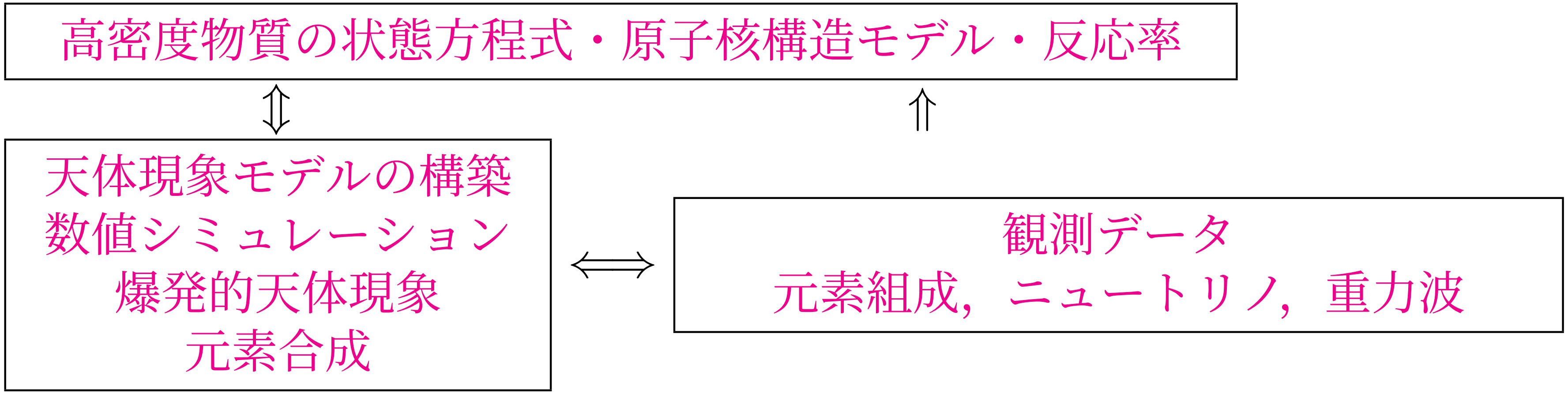
A02 クォーク力学に基づく原子核構造

A03 クォーク力学・原子核構造に基づく爆発的天体現象と元素合成
鈴木英之、研究分担者： 柴田大、梶野敏貴、住吉光介、梅田秀之
連携研究者： 大西明、山田章一、瓜生康史、千葉敏、岩本信之、吉田敬、親松和浩、鷹野正利

A04 分野横断アルゴリズムと計算機シミュレーション

宇宙の観測

- 電磁波: すばる望遠鏡など
  金属欠乏星の元素組成 → 個々の超新星の元素合成
- ニュートリノ: Super-KAMIOKANDE など
  → 天体現象モデル、核物質の性質
- 重力波: LIGO など
  → 天体現象モデル、核物質の性質
- 宇宙線: TA, Cangaroo など



高密度物質の状態方程式・原子核構造モデル・反応率

⇕ ⇑

天体現象モデルの構築
数値シミュレーション
爆発的天体現象
元素合成

⟺

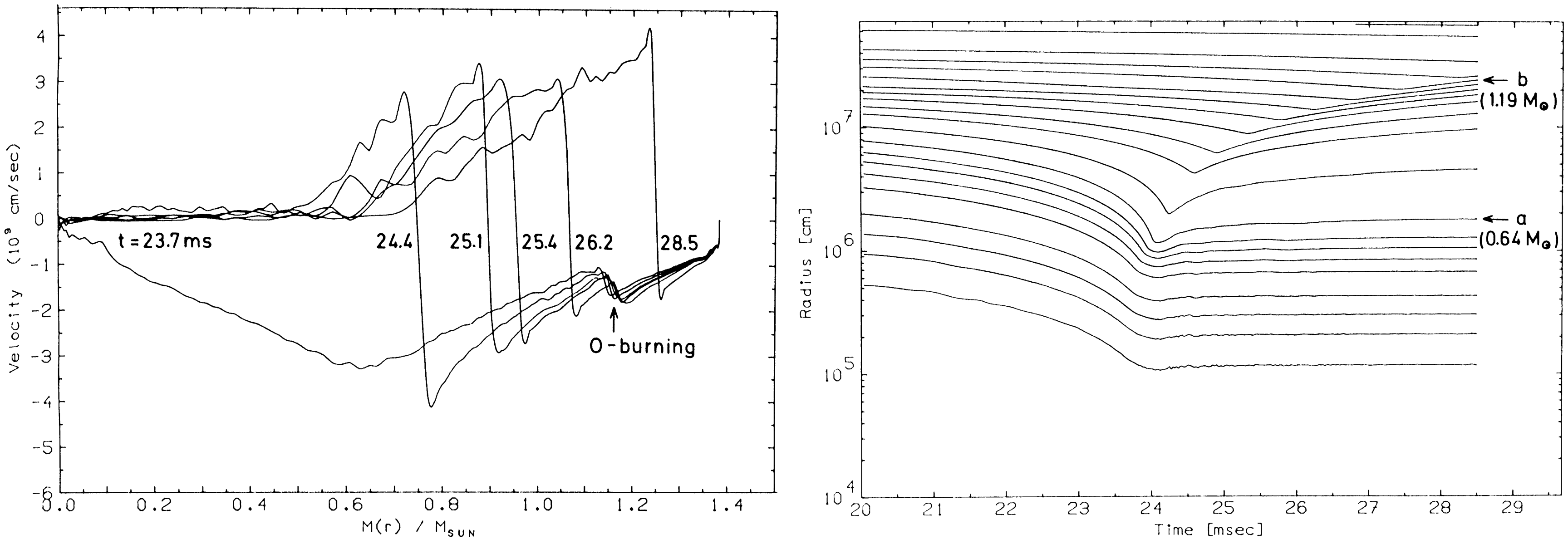
観測データ
元素組成，ニュートリノ，重力波

1　SN1987A 以前

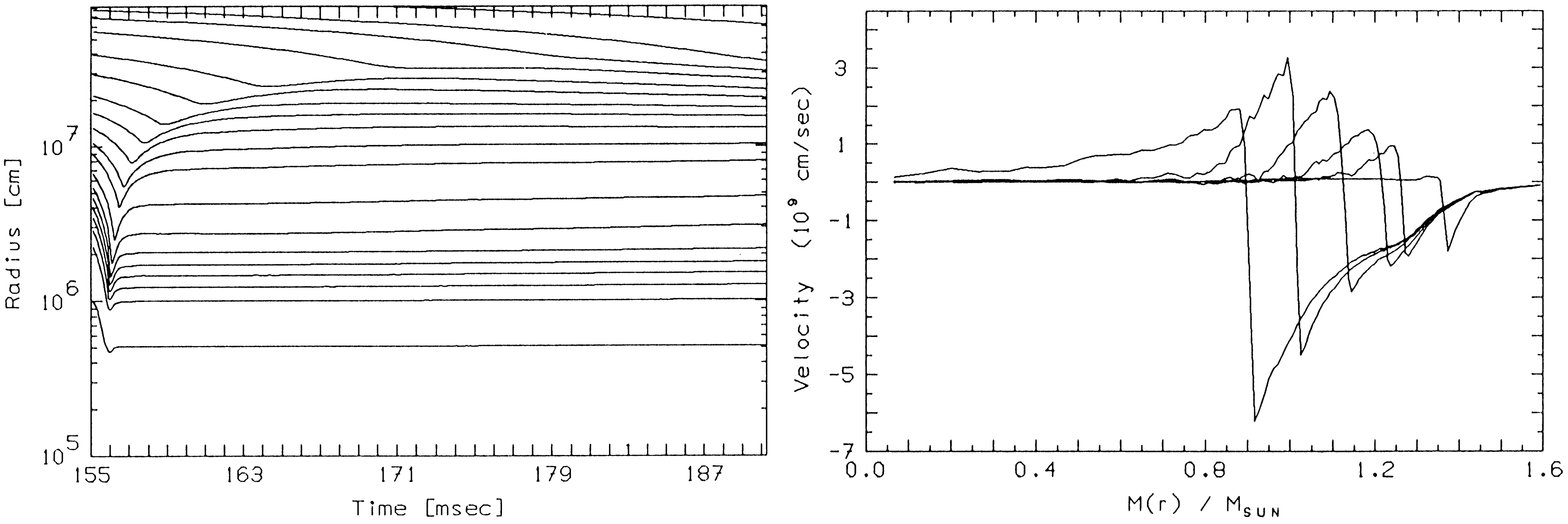
- ～1930 年代
  中性子の発見、中性子星のアイデア、
  重力崩壊による超新星爆発と中性子星形成のシナリオ (Baade and Zwicky)

- 1960～70 年代
  数値シミュレーションによる重力崩壊型超新星爆発の研究
  (Colgate、Arnett、Wilson ら)
  バウンスによる衝撃波形成とニュートリノによるエネルギーデポジット

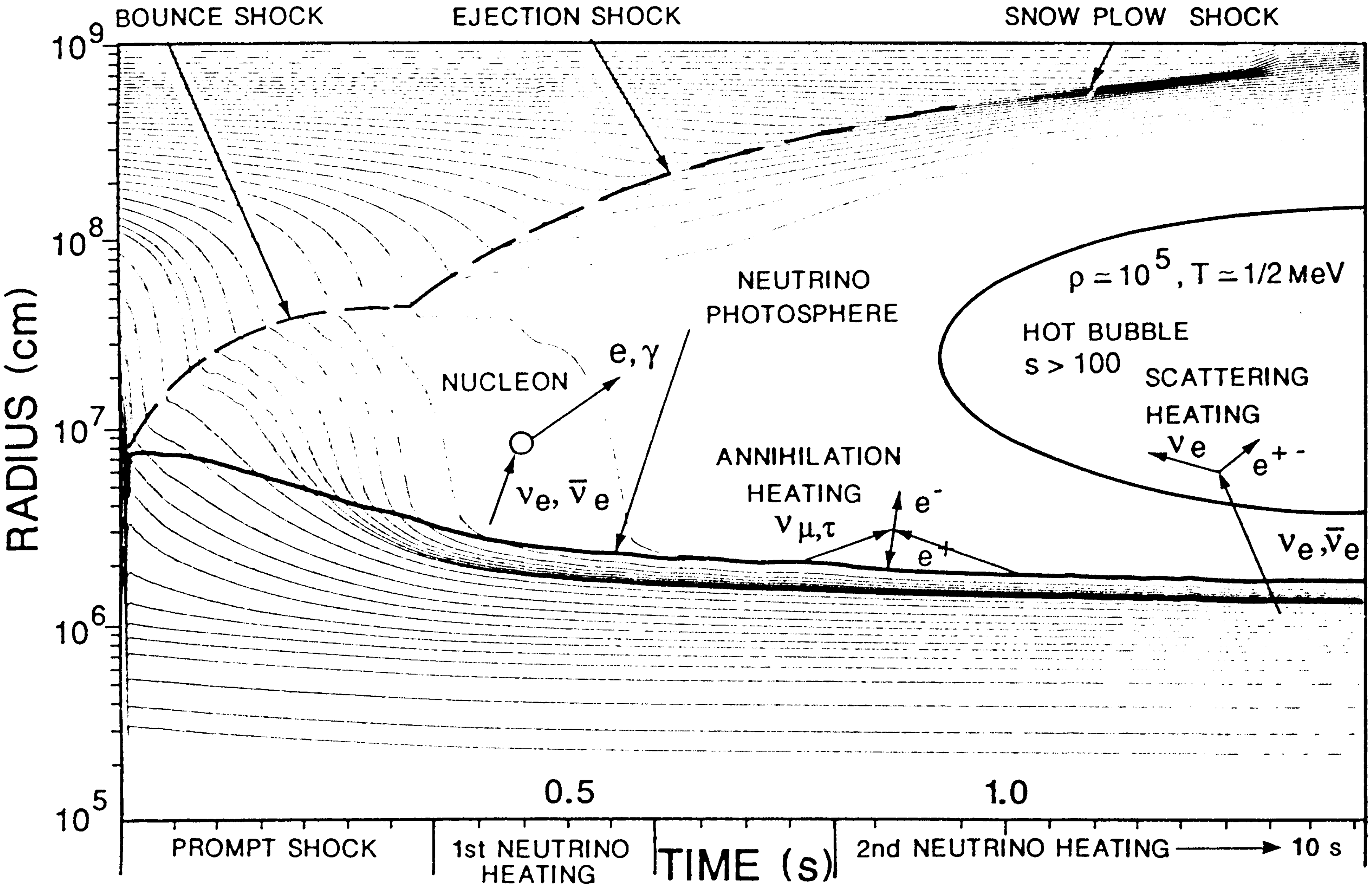
- 1970～80 年代
  弱い相互作用における中性カレントの発見、
  超新星コアにおけるニュートリノ閉じ込め (佐藤、Mazurek)、
  ニュートリノ輸送 (MGFLD まで) を考慮した 1D(球対称) 数値シミュレーション
  Prompt Explosion or Delayed Explosion(Wilson)?
  原始中性子星の冷却 (Burrows and Lattimer)
  状態方程式 (EOS)、ニュートリノ反応、一般相対論、対流、磁場 (2D) の影響



Prompt explosion (Hillebrandt, Nomoto and Wolff 1984). $M_{\rm MS} = 9M_\odot$



Failed Prompt explosion (Hillebrandt 1987). $M_{\rm MS} = 20M_\odot$



Wilson's Delayed explosion model (Colgate 1989).

SN1987A

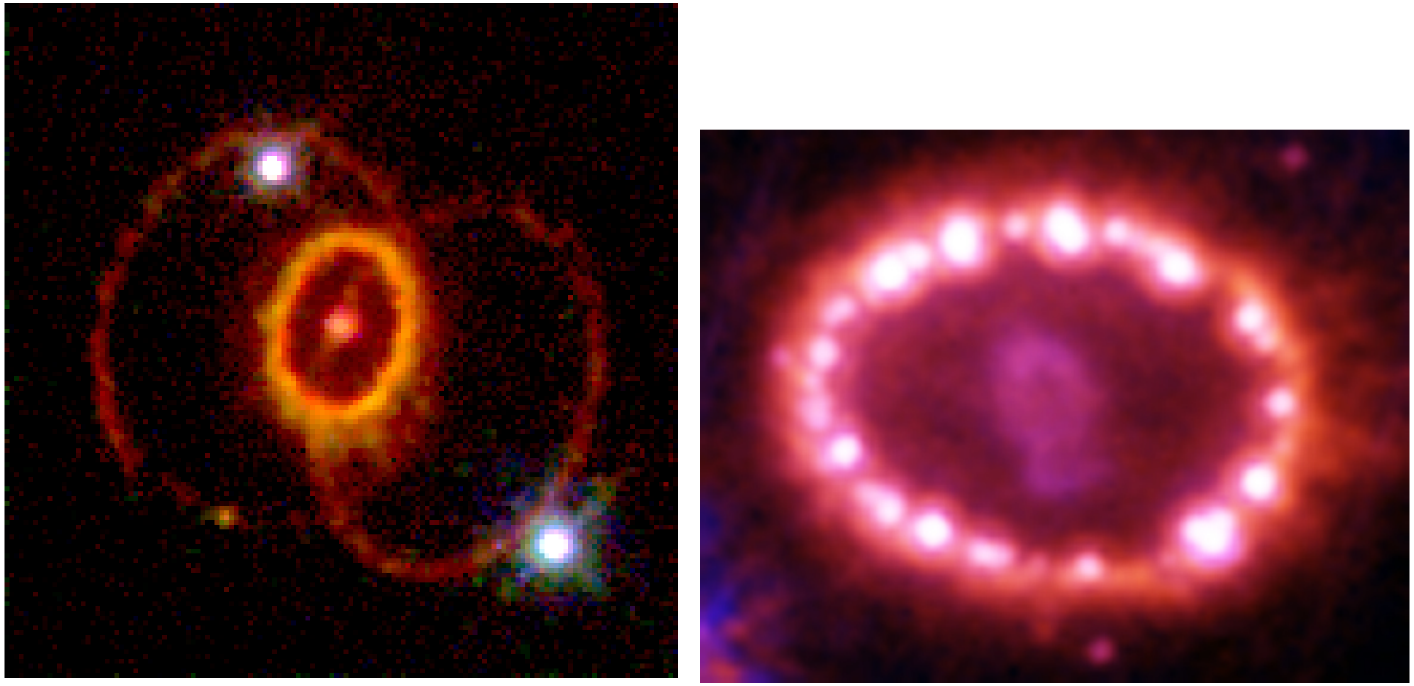
星の進化，重力崩壊型超新星爆発、超新星ニュートリノに関するモデルの大枠が正しいことが確認された

2 SN1987A 以降

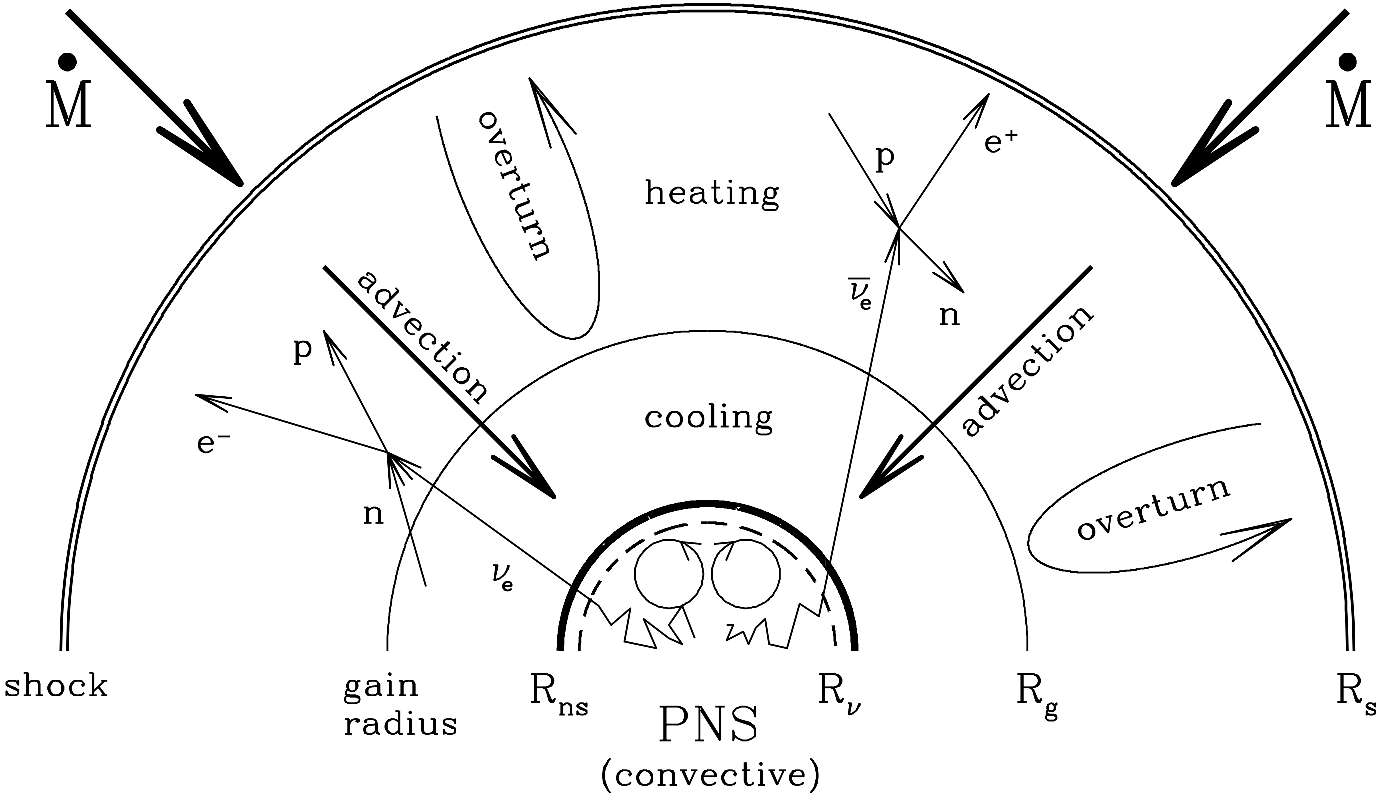
非球対称性の観測

- 偏光観測 polarization
- 物質混合 mixing (large $v_{\rm Fe} > 3000$km/sec(Fe II IR line), early detection of X-ray, 847keV/1238keV ^{60}Co line), slow H velocity (~ 800km/sec)
- asymmetric image

⇒ 流体不安定性、回転、磁場



HST image of SN1987A on 1994.2 and 2003.11.28



(Janka 1997)

gain radius: 正味のニュートリノ加熱率 (加熱 − 冷却)=0

- 原始中性子星内部 (∼ neutrinosphere 内部) での不安定性
- 衝撃波と neutrinosphere 間における不安定性

PNS Convection: convection inside the proto neutron star:

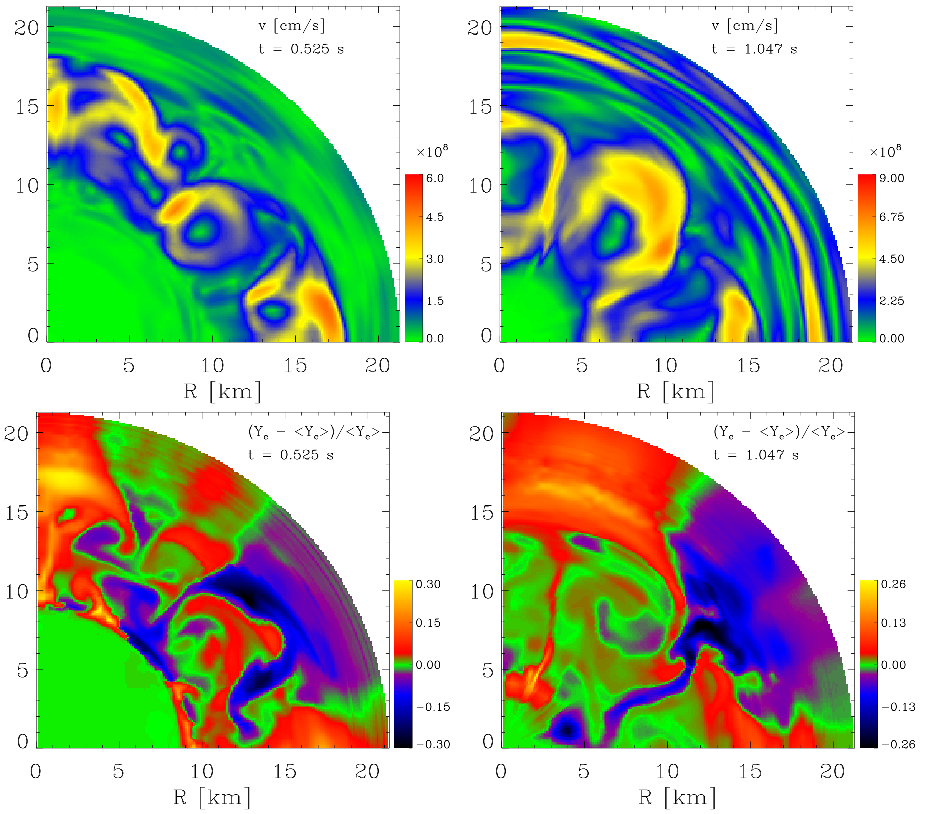
hot lepton-rich material deep inside $\longrightarrow$ surface/neutrinosphere
$\longrightarrow$ $L_\nu \nearrow$, neutrino heating in the hot bubble $\nearrow$

- Wilson's Delayed explosion model
  neutrinosphere 内部での neutron finger($\frac{dS}{dr} > 0$, $\frac{dY_L}{dr} < 0$, Ledoux stable but $\tau_S < \tau_{Y_L}$) による対流を考慮しないと、ちゃんと爆発しない。

- Bruenn *et al.*, 95,04: $\tau_S > \tau_{Y_L}$ no neutron finger
  inward flow of $\bar{\nu}_{\mathrm{e}}$ transports Y_L outward

- Buras *et al.*, 03: Ledoux convection is too deep to increase L_ν

machanism/effects of PNS convection is still controversial



Keil, Janka and Müller, ApJ 473 (1996) L111, Fig.3

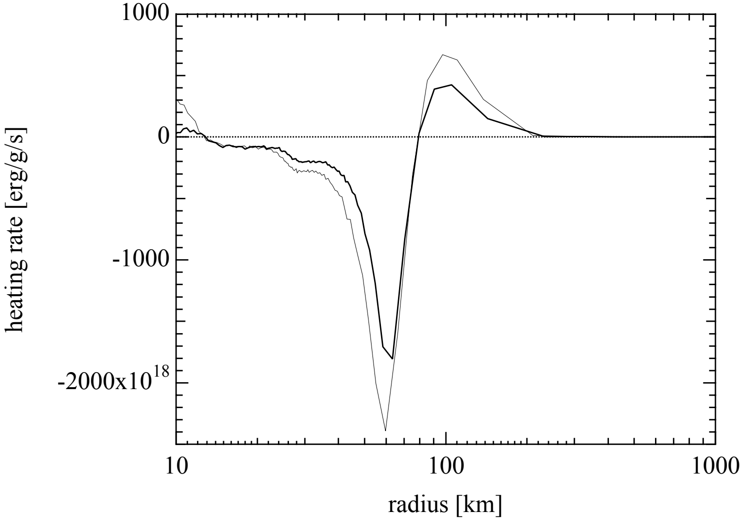
2D hydro with radial-ray (1D) ν transfer(SGFLD)
$\Phi = \Phi^{GR}_{1D} + (\Phi^{NR}_{2D} - \Phi^{NR}_{1D})$
Y_L-driven convection evolves (whole PNS)

$L_\nu \nearrow$ factor 2,
$\langle \omega_\nu \rangle \nearrow$ factor 1.1-1.2

F_ν angular variation 5~10%
$\Rightarrow v_{\rm kick} \sim 10{\rm km/s} \ll v_{\rm PSR}$

Postshock Convection: 衝撃波と neutrinosphere 間における不安定性

1. 超音速で落下する物質 (原子核)
2. 衝撃波面を通過 ($\mathrm{A} \rightarrow \mathrm{np}$)
3. ゆっくりと落下: $R_{\mathrm{shock}} > r > R_{\mathrm{gain}}$
   ($\nu_{\mathrm{e}}\mathrm{n} \rightarrow \mathrm{e}^{-}\mathrm{p}$, $\bar{\nu}_{\mathrm{e}}\mathrm{p} \rightarrow \mathrm{e}^{+}\mathrm{n}$ による加熱)
4. gain radius を通過: $r < R_{\mathrm{gain}}$
   (ニュートリノ放出により冷却)
5. 原始中性子星の上に降着
   重力エネルギー $\Rightarrow$ ニュートリノ放出

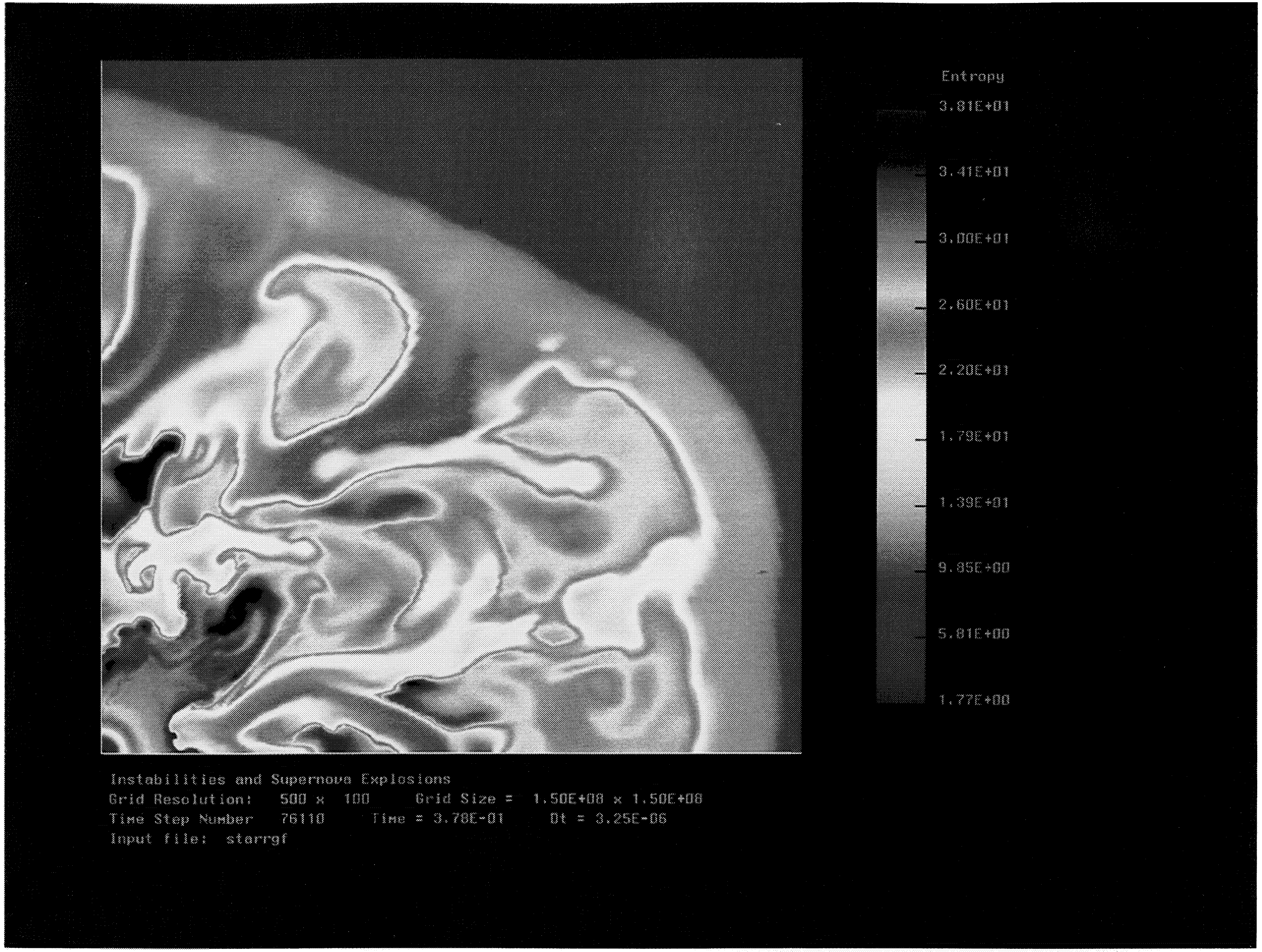


Sumiyoshi *et al.*, ApJ629(2005)922 Fig.7

$dS/dr(R_{\mathrm{gain}} < r < R_{\mathrm{shock}}) < 0$: S-driven = ν-driven convection

対流が、R_{gain} で暖められた物質を、ニュートリノ放出 ($\propto T^6, T^9$) によって冷えてしまう前に衝撃波面へ運ぶ。

accretion による L_ν の維持と、外向きの運動の両立



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Instabilities and Supernova Explosions
Grid Resolution:   500 x  100      Grid Size =  1.50E+08 x 1.50E+08
Time Step Number   76110      Time = 3.78E-01      Dt = 3.25E-06
Input file:  starrgf
```

FIG. 26.—Same as Fig. 24, but at $t = 378$ ms. The highest entropies (at ~ 38 units) are found in clumps.

Burrows, Hayes and Fryxell 1995 (2D + radial-ray ν tr.)

本質的な爆発機構かどうかは不明

Sensitivity to Neutrino Heating Rate

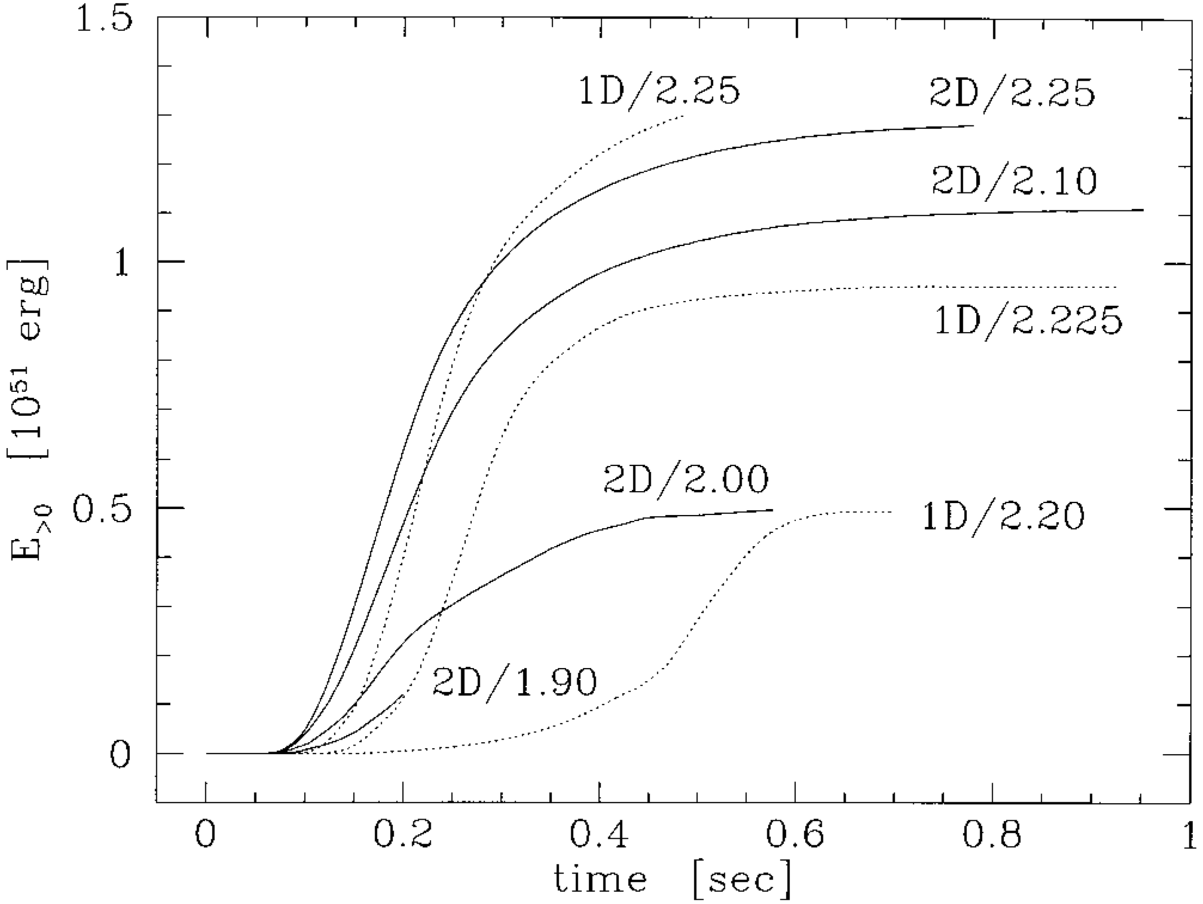


FIG. 1.—Explosion energies vs. time after the start of the simulations (~25 ms after bounce) for exploding one-dimensional (*dotted lines*) and two-dimensional models (*solid lines*). The numbers denote the initial ν_e and $\bar{\nu}_e$ luminosities in 10^{52} ergs s^{-1}.

1D/2.10: no exp. ⇔ 1D/2.20: exp.

(Janka and Müller, ApJ 448 (1995) L109, Fig.1)

球対称ニュートリノ輸送計算の進歩

- FLD (Flux Limited Diffusion) Max-Planck, Burrows ’80s

  $n_\nu(t,r), u_\nu(t,r)$

$$F_\nu = -\frac{c\Lambda_\nu}{3}\frac{\partial u_\nu}{\partial r} = \begin{cases} -\frac{c\lambda_\nu}{3}\frac{\partial u_\nu}{\partial r} & \text{diffusion}(\lambda \to 0) \\ c u_\nu & \text{free streaming}(\lambda \to \infty) \end{cases}$$

- MGFLD (Multigroup FLD) Scheme Wilson, Bruenn, Suzuki ’80-’90s

  $\frac{dn_\nu}{d\omega}(t,r,\omega)$

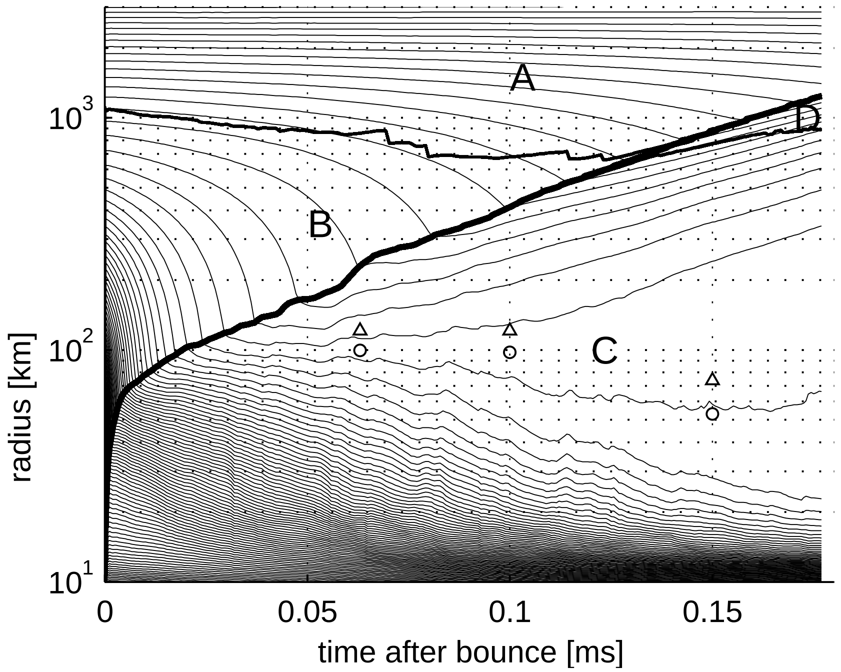
  ニュートリノ加熱率を過小評価 (Yamada *et al*.97)

$\Downarrow$

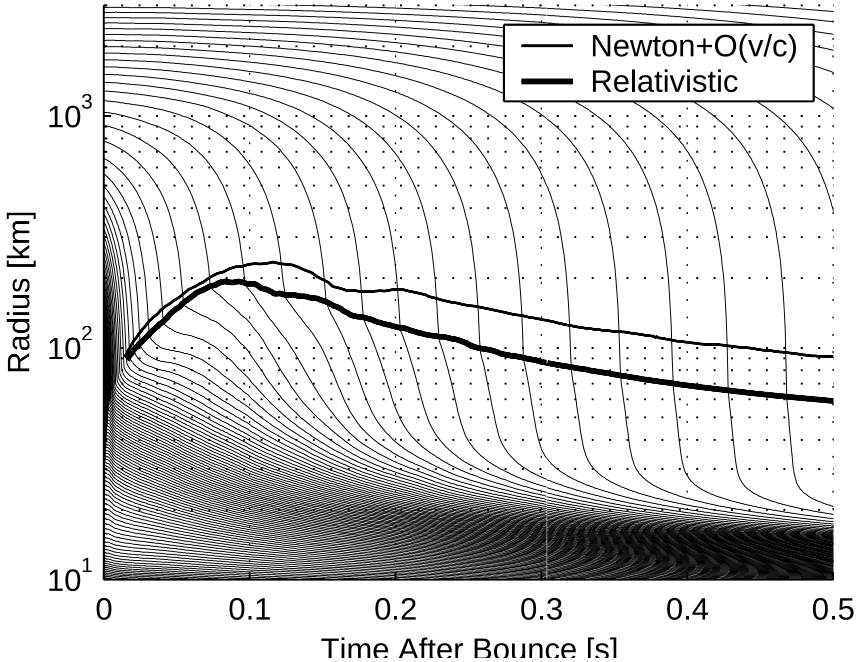
- Boltzmann solver (Mezzacappa, Burrows, Janka, 住吉・山田 $\gtrsim$ 2000)

  $f_\nu(t,r,\omega,\mu)$ 球対称の輸送方程式を直接解く

Opacity: ニュートリノ反応率



mistake: $\sigma(\nu \mathrm{N} \to \nu \mathrm{N})$ too small ⇒ Explosion!.
Liebendörfer *et al.*, astro-ph/0006418 v1 Fig.4



No Explosion!. NH $13M_\odot$, GR Boltzman, LS EOS+Si burning, $S = 103, E = 12, A = 6, 3\nu$
GR→ compact PNS → $T \nearrow L_\nu \nearrow$,
Boltzmann → heating rate ↗
Liebendörfer *et al.*, Phys.Rev. D63 (2001) 103004 (astro-ph/0006418 v2) Fig.6

Neutrino Interactions (standard: Bruenn'85)

$\mathrm{e^- p} \longleftrightarrow \nu_\mathrm{e} \mathrm{n}$　$\mathrm{e^+ n} \longleftrightarrow \bar{\nu}_\mathrm{e} \mathrm{p}$　$\mathrm{e^- A} \longrightarrow \nu_\mathrm{e} \mathrm{A'}$　$\mathrm{e^+ A} \longrightarrow \bar{\nu}_\mathrm{e} \mathrm{A'}$

$\mathrm{e^- e^+} \longleftrightarrow \nu\bar{\nu}$　$\text{plasmon} \longleftrightarrow \nu\bar{\nu}$　$\mathrm{NN} \longrightarrow \mathrm{NN}\nu\bar{\nu}$　$\nu_\mathrm{e}\bar{\nu}_\mathrm{e} \longleftrightarrow \nu_x\bar{\nu}_x$

$\nu \mathrm{N} \longrightarrow \nu \mathrm{N}$　$\nu \mathrm{A} \longrightarrow \nu \mathrm{A}$　$\nu \mathrm{e}^\pm \longrightarrow \nu \mathrm{e}^\pm$　$\nu\nu' \longrightarrow \nu\nu'$

反応率の精密化

- 核子制動輻射 $\mathrm{NN'} \longleftrightarrow \mathrm{NN'}\nu\bar{\nu}$

  Suzuki and Ishizuka: One Pion Exchange model

  $\nu_x\bar{\nu}_x$生成: $\rho > 10^{13}\mathrm{g/cm}^3, T \sim 10\mathrm{MeV}$ で低エネルギーνに対して $\mathrm{e^-e^+} \to \nu_x\bar{\nu}_x$ を上回る。

  低エネルギーニュートリノを enhance $L_{\nu_x} \nearrow$、$\langle\omega_{\nu_x}\rangle \searrow$

  一方 multiple scattering suppression (Raffelt and Seckel 1991) は低エネルギーニュートリノの核子制動輻射を抑制

  (Hannestad and Raffelt, Raffelt and Seckel 1998, Shen and Suzuki, Burrows *et al*. 2000)

- down scattering ($\nu\mathrm{e}^- \to \nu\mathrm{e}^-$, $\nu\mathrm{A} \to \nu\mathrm{A}^*$) により、$\omega_\nu \searrow, S \nearrow \to \lambda_\nu \nearrow$ $Y_{L,\mathrm{trap}} \searrow, E_{\mathrm{shock}} \searrow$

- ion screening (Horowitz 1997, Bruenn and Mezzacappa 1997)

  Coulomb effect → ions in correlated states
  $\sigma(\nu\mathrm{A} \to \nu\mathrm{A})$ decreases when the wave length of neutrinos > ion seperation

- νN 散乱によるエネルギー交換: $\rho > 10^{11}\mathrm{g/cm}^3, \omega_\nu > 10\mathrm{MeV}$ で ES を上回り $\langle\omega_{\nu_x}\rangle \searrow$

- νNN 散乱によるエネルギー交換: νN 散乱の影響に埋もれる

- $\nu\mathrm{N} \leftrightarrow \mathrm{eN}'$ に対する weak magnetism ($\leftarrow$ 核子の異常磁気モーメント):
  $\sigma_{\bar{\nu}_\mathrm{e}\mathrm{p}}(20\mathrm{MeV}) : -15\%$

- $\nu_\mathrm{e}\bar{\nu}_\mathrm{e} \leftrightarrow \nu_x\bar{\nu}_x,\ \nu\nu' \longrightarrow \nu\nu' \Rightarrow \langle\omega_{\nu_x}\rangle \sim \langle\omega_{\bar{\nu}_\mathrm{e}}\rangle$

- 多体効果 effective mass, nucleon density/spin fluctuations
  $\Rightarrow$ reduction of opacity $\rightarrow L_\nu \nearrow$
  (Sawyer 1995, München group 1995-1998, Burrows and Sawyer 1998-1999, Reddy *et al.* 1998-1999, Yamada and Toki 1999-2000)

  多体効果は状態方程式と密接に関連

- shell model に基づく新しい電子捕獲率/β 崩壊率の計算 (LMP: Langanke and Martinez-Pinedo)

  LMSH: $N > 40$ の原子核による電子捕獲率を評価

  Bruenn'85: $\mathrm{p}(f_{7/2}) \rightarrow \mathrm{n}(f_{5/2})$ の Gamow-Teller transition
  $N < 40$: possible, $N \geq 40$: impossible

  X_p だけが重要ではない、電子捕獲率 $\nearrow$ $\quad Y_{L\mathrm{trap}} \searrow$

有限温度高密度物質状態方程式 (EOS)

e.g. $P(\rho, S, Y_\mathrm{e})$ for 流体の運動、$T(\rho, S, Y_\mathrm{e}), \mu_i(\rho, S, Y_\mathrm{e})$ for ν 反応率

1. Wolff 数値テーブル (非相対論的 Hartree-Fock): 現在入手不可
   $10^{9-11} \lesssim T \lesssim 10^{10-12.6}$K, $10^6 \lesssim \rho_B \lesssim 10^{15}$g/cm^3, $0.025 \lesssim Y_\mathrm{e} \lesssim 0.525$: 不十分

2. Shen *et al.* 1998: 数値テーブル
   相対論的平均場理論 (n,p,σ, ρ, ω)
   TM1 パラメーターセット ($g_\rho, \cdots$) $\Leftarrow$ 不安定核を含む実験データ
   一様物質相 ($\rho \gtrsim \rho_0$) と原子核相 (Thomas-Fermi 近似)

   entries: ρ_B, n_B, Y_e, T, F, U, P, S, A, Z, M^*, X_n, X_p, X_α, X_A, μ_n, μ_p

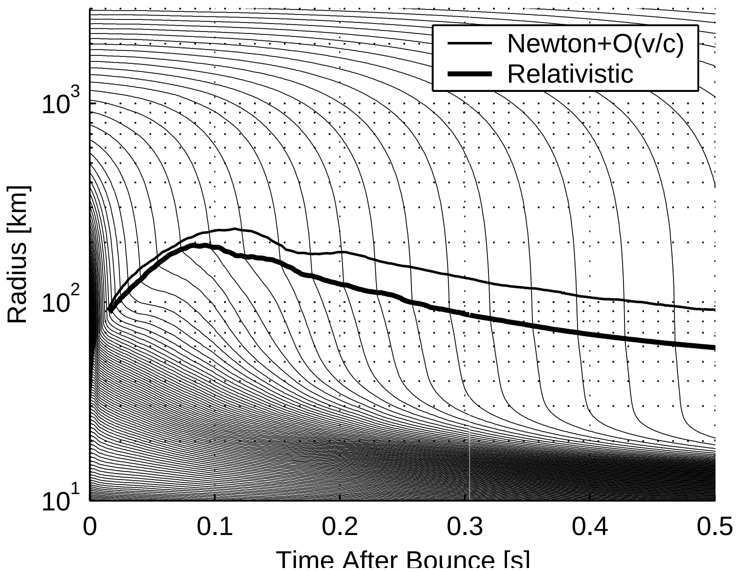
   grids: 広い対応範囲 $T = 0, 0.1 \sim 100$MeV　$\Delta \log T = 0.1$
   $Y_e = 0, 0.01 \sim 0.56$　$\Delta \log Y_e = 0.025$
   $\rho_B = 10^{5.1} \sim 10^{15.4}$g/cm^3　$\Delta \log \rho_B = 0.1$

   非圧縮率 $K_s = 281$MeV, 対称エネルギー $S_v = 36.9$MeV

3. Lattimer-Swesty 1991: FORTRAN サブルーチン (一般的に使用されてきた)
   非相対論的液滴モデル: $K_s = 180, 220, 375$MeV, $S_v = 29.3$MeV
   $E/n \sim -B + K_s(1 - n/n_s)^2/18 + S_v(1 - 2Y_\mathrm{e})^2 + \cdots$
   対応範囲: $T \gtrsim 0.5$MeV, $\rho_B \gtrsim 10^7$g/cm^3, $0.03 < Y_\mathrm{e} < 0.55$:
   原始中性子星冷却計算には拡張が必要 $\Rightarrow$ $Y_\mathrm{e} = 0$ を含むテーブルを作成

Wilson: パイ中間子によるソフト化?、大西グループ: ハイペロン、鷹野グループ: 変分法

Recent simulations with GR 1D Boltzmann ν-transfer(普通のコアは爆発しない)



NH 13$M_\odot$, GR Boltzman, LS EOS+Si burning Liebendörfer *et al.*, Phys.Rev. D63 (2001) 103004 (astro-ph/0006418 v2) Fig.6

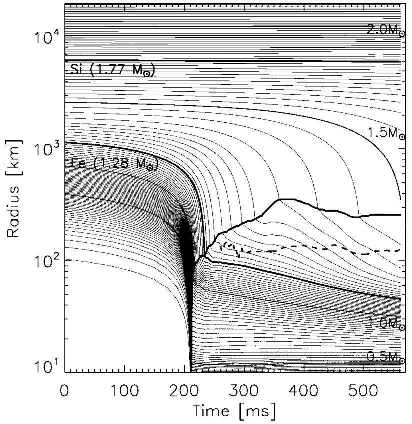
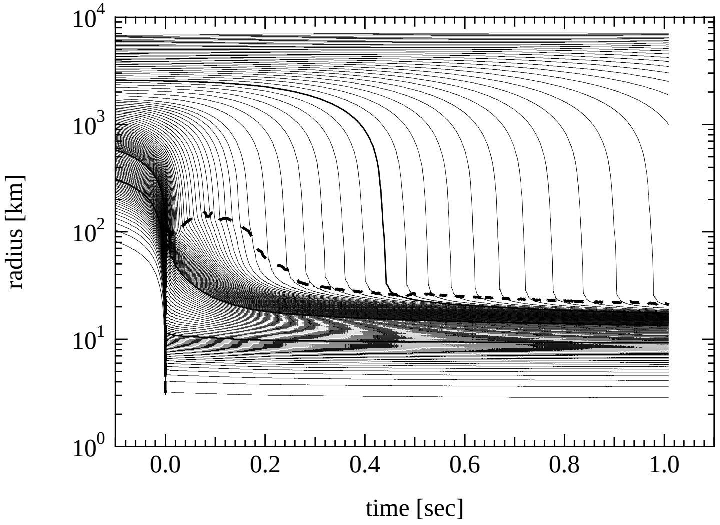


FIG. 1.—Trajectories of selected mass shells vs. time from the start of the simulation. The shells are equidistantly spaced in steps of 0.02 $M_\odot$, and the trajectories of the outer boundaries of the iron core (at 1.28 $M_\odot$) and of the silicon shell (at 1.77 $M_\odot$) are indicated by thick lines. The shock is formed at 211 ms. Its position is also marked by a thick line. The dashed curve shows the position of the gain radius.

WW 15$M_\odot$, $M_{\rm Fe} = 1.28 M_\odot$, NR Boltzmann (tangent-ray method), only $\nu_{\rm e}$,$\bar{\nu}_{\rm e}$, without $\rm e^- e^+ \leftrightarrow \nu\bar{\nu}$, LS EOS, Rampp *et al.*, ApJ 539 (2000) L33 Fig.1



15$M_\odot$, Shen EOS, Sumiyoshi *et al.*, 2005.

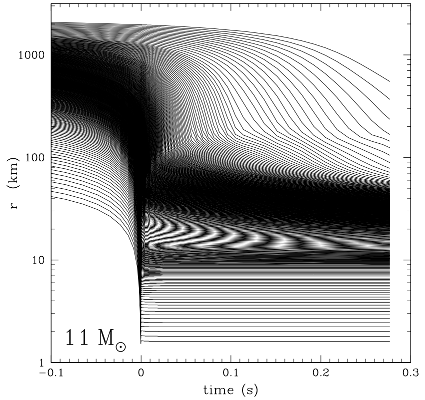


FIG. 5.—Radial position (in km) of selected mass shells as a function of time in our fiducial 11 $M_\odot$ model.

NR 1D Boltzmann ν-transfer, Thompson *et al.*, ApJ 592 (2003) 434 Fig.5

Boltzmann solver の比較

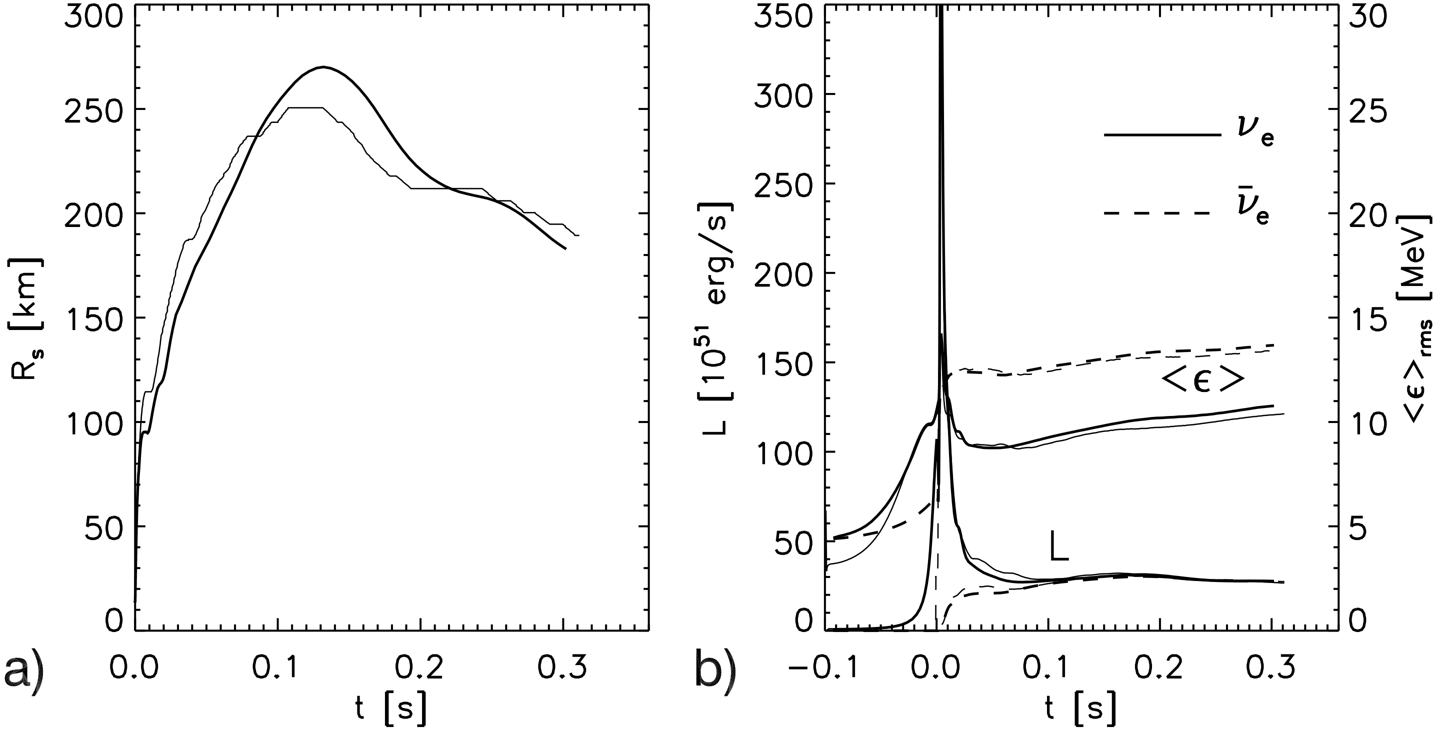


FIG. 5.—(*a*) Shock position as a function of time for model N13. The shock in VERTEX (*thin line*) propagates initially faster and nicely converges after its maximum expansion to the position of the shock in AGILE-BOLTZTRAN (*thick line*). (*b*) Neutrino luminosities and rms energies for model N13 are presented as functions of time. The values are sampled at a radius of 500 km in the comoving frame. The solid lines belong to electron neutrinos and the dashed lines to electron antineutrinos. The line width distinguishes between the results from AGILE-BOLTZTRAN and VERTEX in the same way as in (*a*). The luminosity peaks are nearly identical; the rms energies have the tendency to be larger in AGILE-BOLTZTRAN.

Liebendörfer *et al.*, ApJ620(2005)840 Fig.5

状態方程式 (Lattimer-Swesty, Shen *et al.* など)、ニュートリノ反応率も、かつてより標準化されてきた。

軽い ONeMg core + CO shell($1.38M_\odot$) の弱い ($O(10^{50})$erg) 球対称爆発

(Progenitor: Nomoto 8-10$M_\odot$)

衝撃波面を通過する物質の密度の減少と CO-He 層境界の急激な密度勾配により、衝撃波が進む。ν-wind と核燃焼による弱い爆発

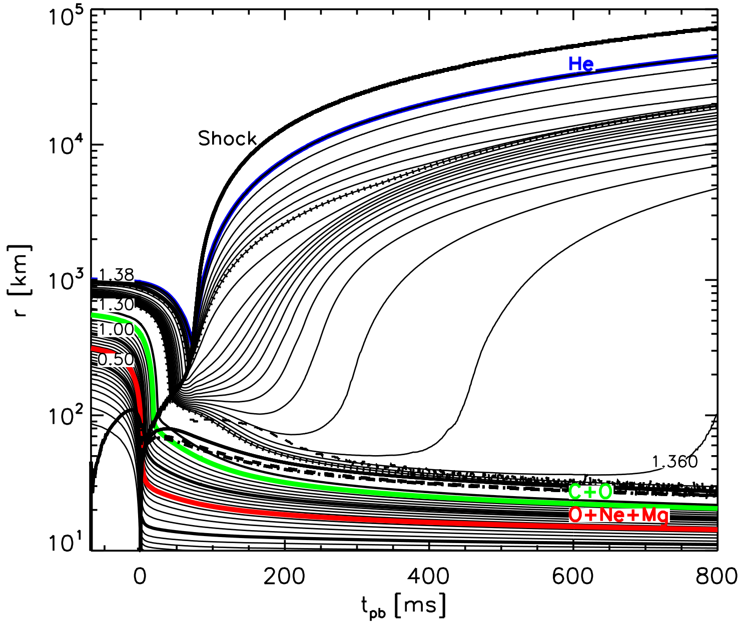


Fig. 1. Mass trajectories for the simulation with the W&H EoS as a function of post-bounce time (t_{pb}). Also plotted: shock position (thick solid line starting at time zero and rising to the upper right corner), gain radius (thin dashed line), and neutrinospheres (ν_e: thick solid; $\bar{\nu}_e$: thick dashed; ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$: thick dash-dotted). In addition, the composition interfaces are plotted with different bold, labelled lines: the inner boundaries of the O-Ne-Mg layer at ~0.77 $M_\odot$, of the C-O layer at ~1.26 $M_\odot$, and of the He layer at 1.3769 $M_\odot$. The two dotted lines represent the mass shells where the mass spacing between the plotted trajectories changes. An equidistant spacing of $5 \times 10^{-2} M_\odot$ was chosen up to 1.3579$M_\odot$, between that value and 1.3765$M_\odot$ it was $1.3 \times 10^{-3} M_\odot$, and $8 \times 10^{-5} M_\odot$ outside.

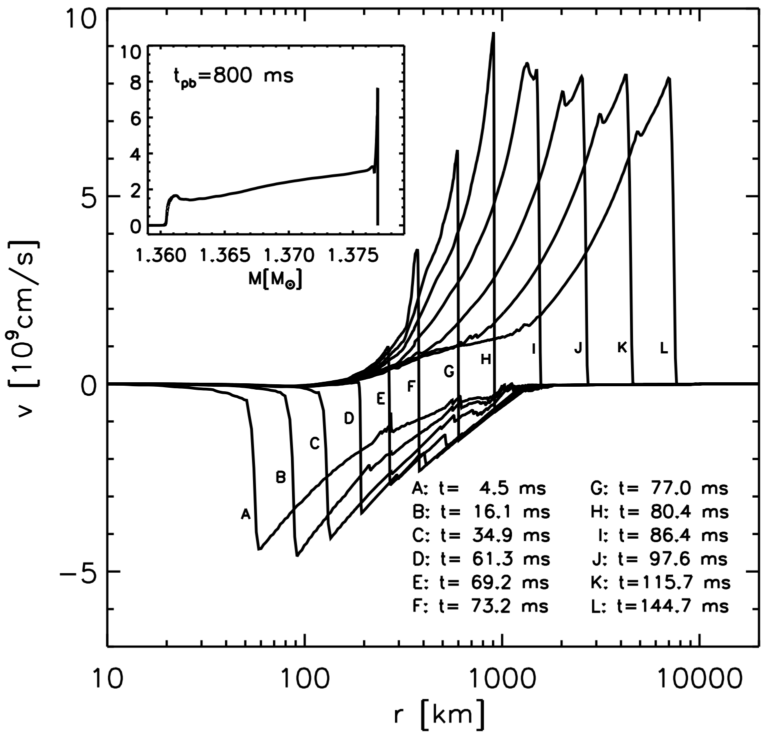
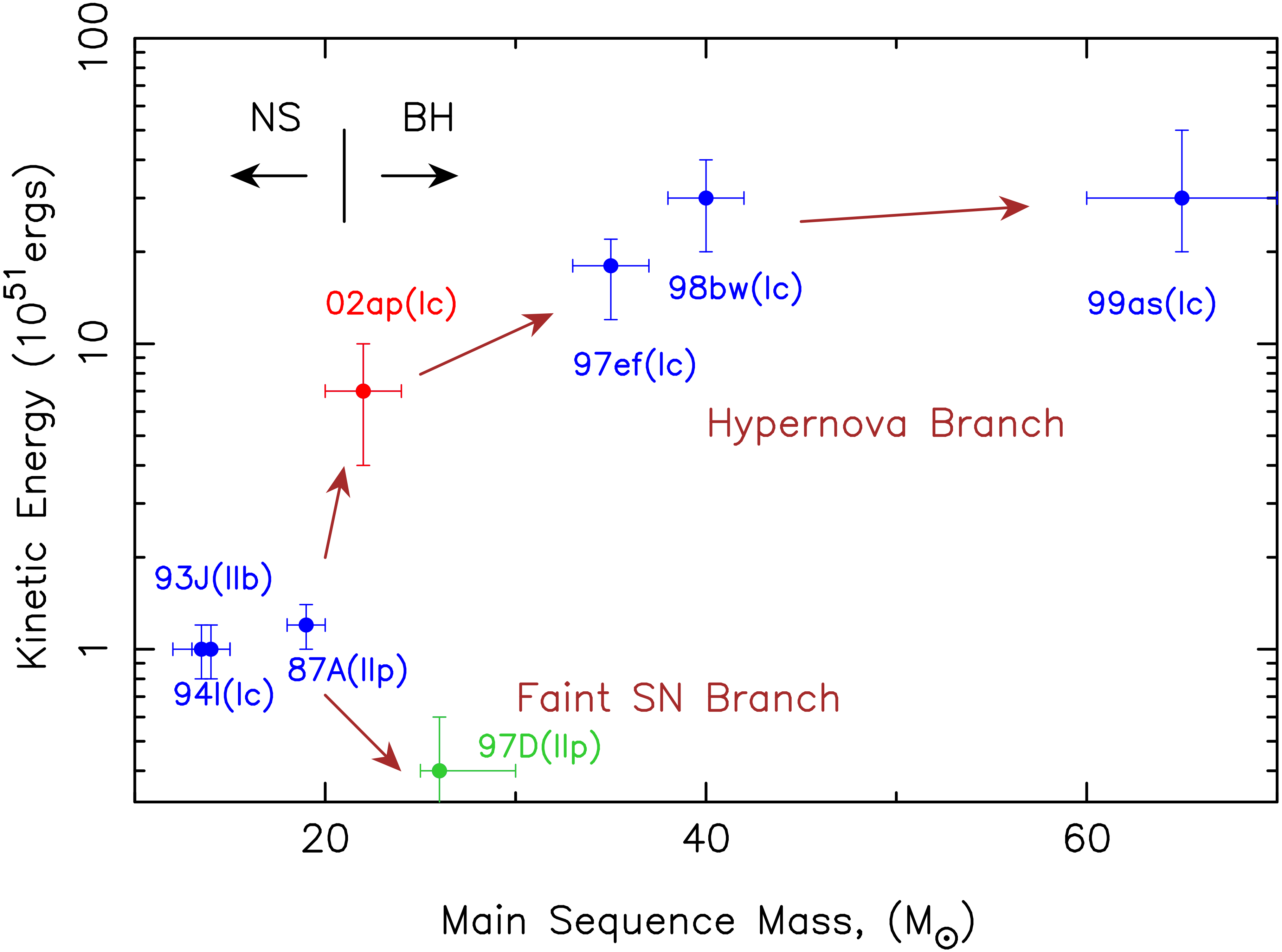


Fig. 3. Velocity profiles as functions of radius for different post-bounce times for the simulation with the W&H EoS. The insert shows the velocity profile vs. enclosed mass at the end of our simulation.

Kitaura *et al.*, AAp 450(2006)345

(Mezzacappa'07: 11.2$M_\odot$モデルも核燃焼入れて 1sec くらいで爆発)



Nomoto *et al.*, astro-ph/0308136

重いコアの球対称重力崩壊によるブラックホール形成とニュートリノシグナル

住吉，山田、鈴木、千葉

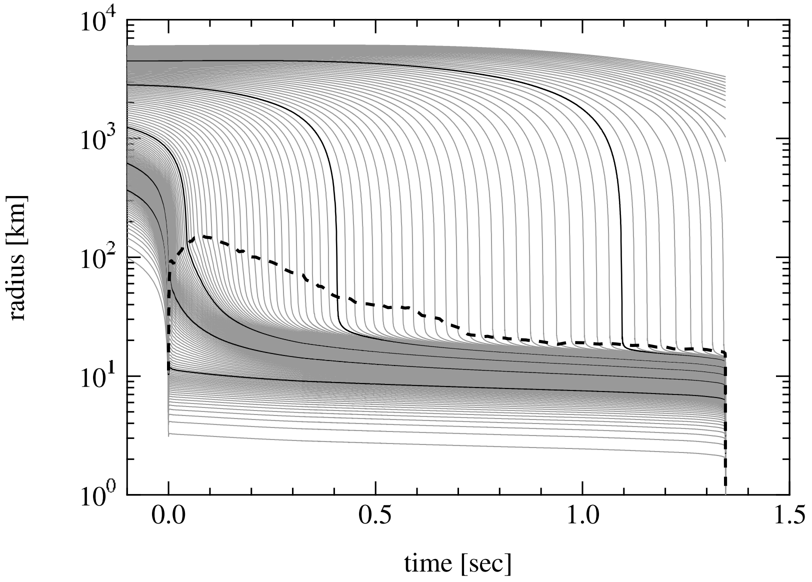


FIG. 1.—Radial trajectories of mass elements of the core of a 40 $M_\odot$ star as a function of time after bounce in the SH model. The location of the shock wave is shown by a thick dashed line.

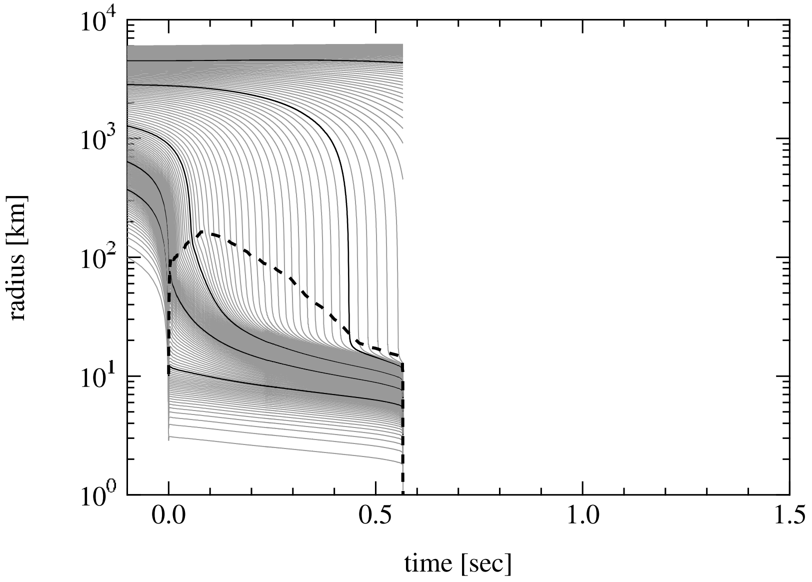
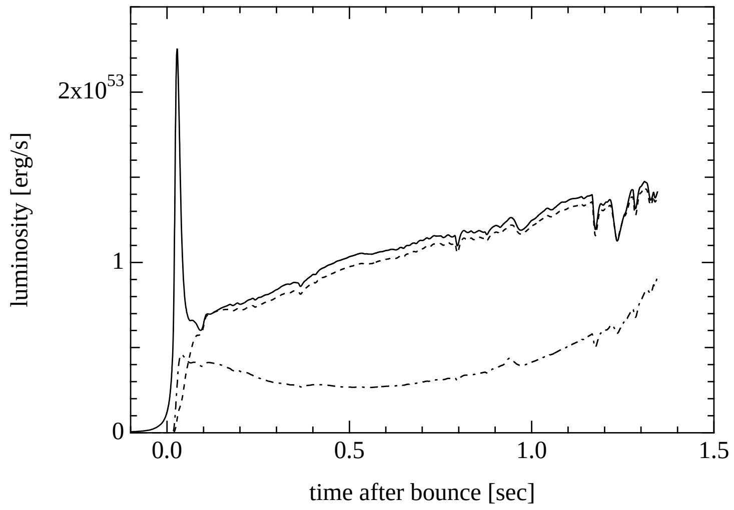
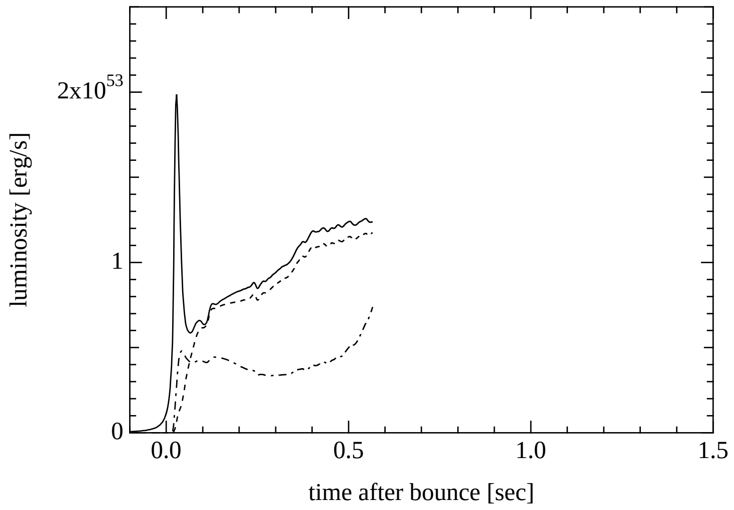


FIG. 2.—Radial trajectories of mass elements of the core of a 40 $M_\odot$ star as a function of time after bounce in the LS model. The location of the shock wave is shown by a thick dashed line.





Progenitor 40$M_\odot$, left: Shen EOS, right: Lattimer-Swesty EOS 180

ニュートリノ振動パラメターと SK での観測イベント予想。

Nakazato *et al.*, Phys.Rev.D78:083014,2008

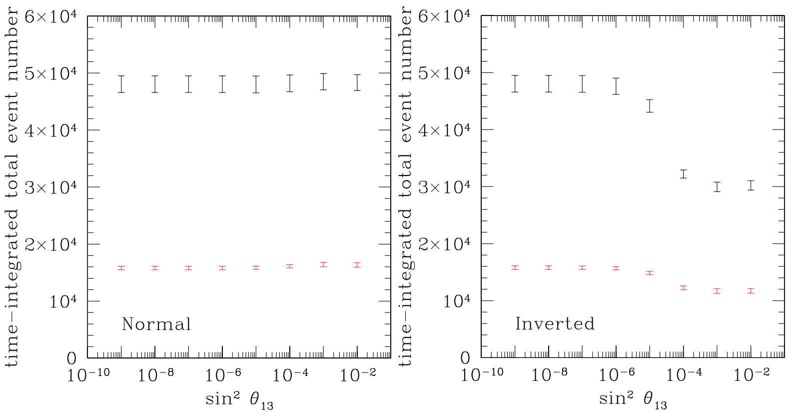


FIG. 8: Time-integrated total event number of failed supernova neutrinos for the normal mass hierarchy (left) and the inverted mass hierarchy (right). Error bars represents the upper and lower limits owing to the different nadir angles. The upper and lower sets represent models W40S and W40L, respectively.

ハイペロン状態方程式 (石塚，大西による Shen EOS の拡張)

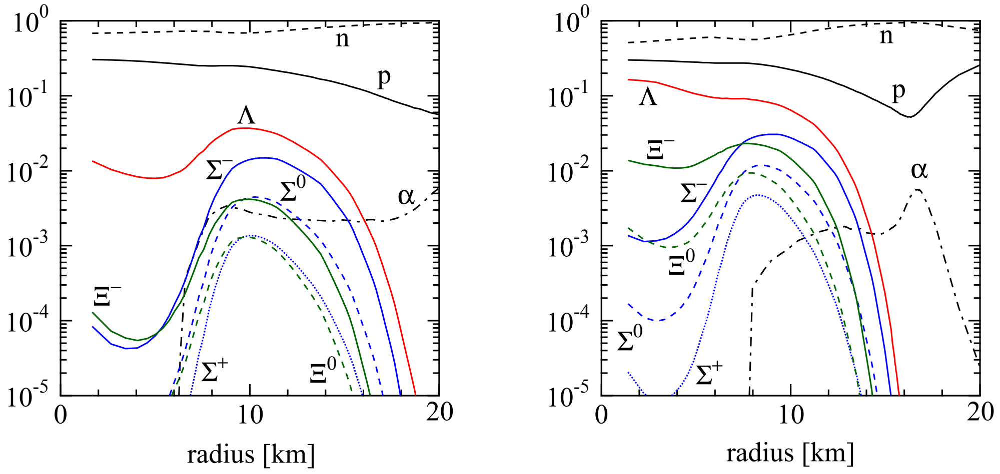


Fig. 2.— Mass fractions of hyperons in model IS are shown as a function of radius at t_{pb}=500 (left) and 680 ms (right).

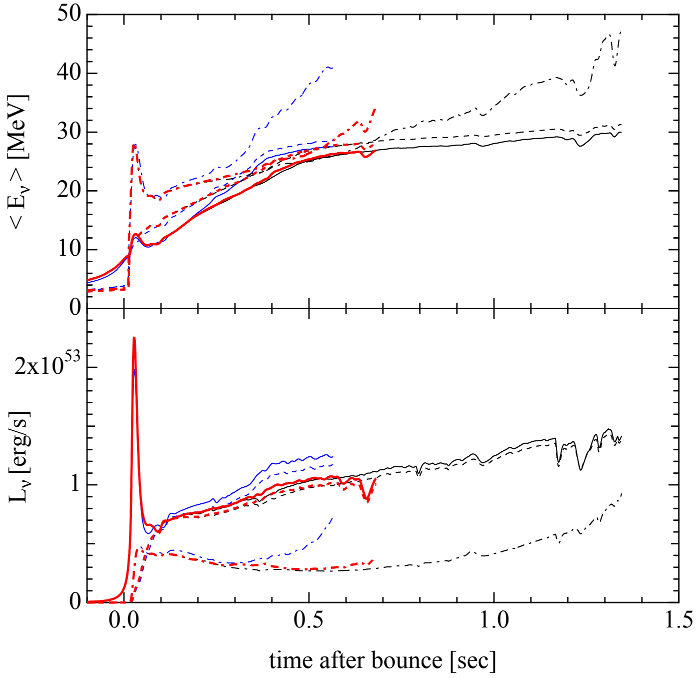


Fig. 3.— Average energies and luminosities of ν_e (solid), $\bar{\nu}_e$ (dashed) and $\nu_{\mu/\tau}$ (dash-dotted) for model IS are shown as a function of time after bounce. The results for model SH and LS are shown by thin lines with the same notation.

Sumiyoshi *et al.*, Astrophys. J. 690 (2009) L43-L46

有限温度高密度物質の状態方程式と球対称爆発的天体現象

- 格子 QCD 計算で得られたバリオン間ポテンシャルを用いた高密度物質の状態方程式、特にクォークやハイペロンを含む有限温度の状態方程式や核構造の情報 (電子捕獲反応率やニュートリノ原子核反応率) を用いた超新星爆発・中性子星冷却・ブラックホール形成の数値シミュレーション

  $$\Downarrow$$

  これらのハドロン物理が天体現象に及ぼす影響
  観測プローブとなるニュートリノの振舞 (特に BH 形成時は $\rho \gg \rho_0$)
  親星モデル (質量、金属量、物質混合モデルなど) などからくる不定性の範囲
  放出される元素組成への影響

- 核統計平衡状態の状態方程式やニュートリノ反応率と高密度物質の状態方程式の整合

再び、2/3 次元

2D/3D Hydrodynamics + さまざまなレベルのν-transfer　　GR 効果は近似的

ニュートリノ輸送 $f_\nu(t, \vec{r}, \vec{p}_\nu)$ ($\Leftrightarrow$ 球対称 $f(t, r, p_\nu, \cos\theta_\nu)$)

$\tau_\nu(\mathrm{core}) \ll \tau_{\mathrm{dyn}} \Rightarrow$ 陰解法が必要

SASI: Standing Accretion Shock Instability

Blondin *et al.*, 2003

停滞衝撃波と原始中性子星の間の領域で $\ell = 1, 2$ などの不安定性が成長
(amplifying advective-accoustic cycle)

ニュートリノ加熱を助け軽いコアは弱い爆発?普通のコアは?

Accoustic Explosion?

Burrows *et al.*, 2006

accretion → excitation of g-mode in PNS → sound wave
→ dissipation behind the shock front → robust explosion

↔ g-mode の振幅は小さいのでは?

自転/磁場? コアの角運動量は小さい? (Heger *et al.*, 2005)

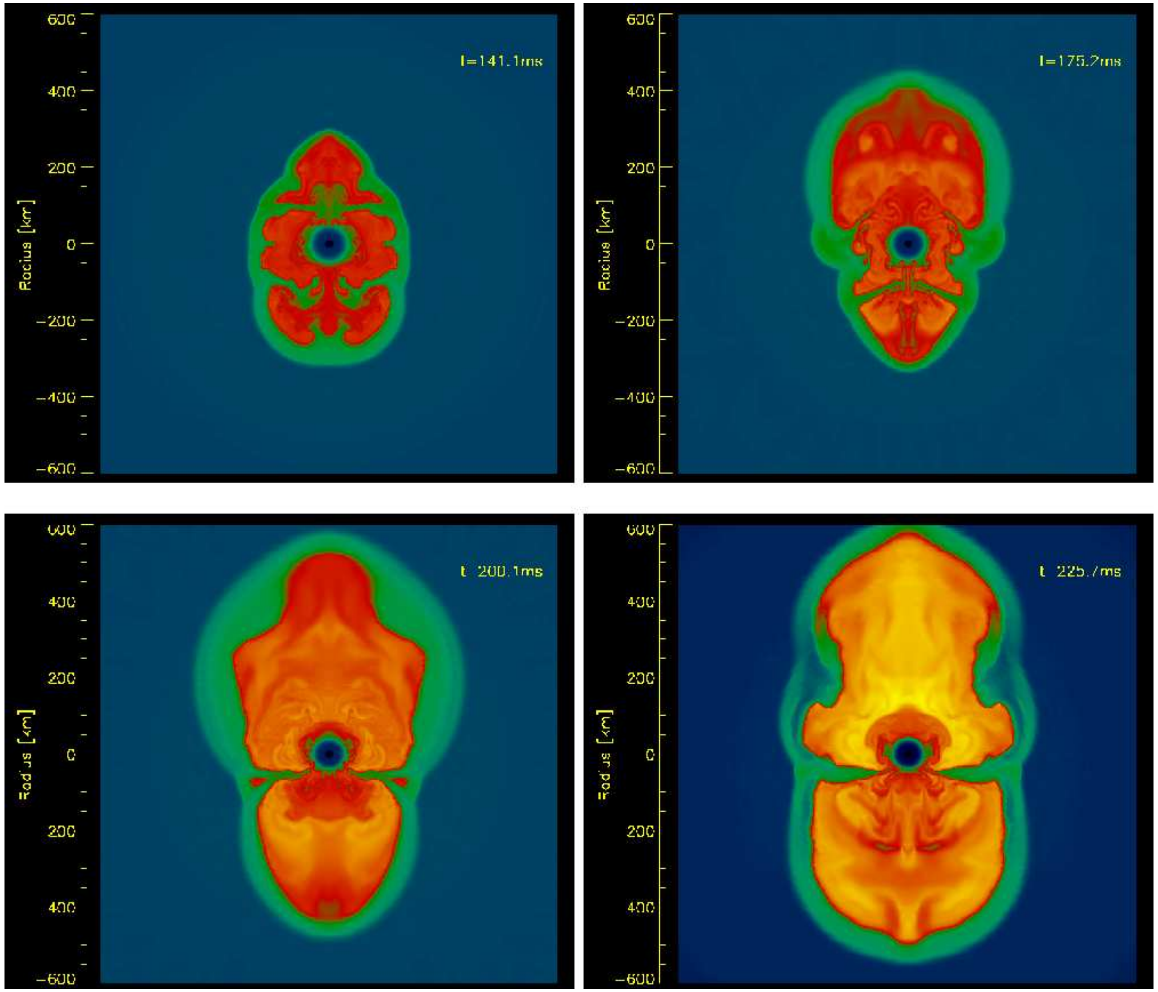
非等方ニュートリノ放出によるジェット状爆発

自転による対流不安定性の抑制

マグネター ($B = 10^{15}$G) 形成時は、磁場が効く

Janka *et al*.., 2006, 非回転 $11.2M_\odot$ 星の 2D 計算
⇒ weak explosion due to SASI+ν-heating

$\frac{\pi}{4} \le \theta \le \frac{3\pi}{4}$ の計算は爆発せず、$0 \le \theta \le \pi$ の計算は爆発
$l = 1, 2$ の非対称性 (SASI) が発達 → kick velocity?



エントロピー分布の時間発展。Janka *et al*., astro-ph/0612072

$\tau_{\rm adv} \nearrow > \tau_{\rm heat}$: SASI は$\nu$-heating を補助

Marek and Janka, 2007: $15M_\odot$ SASI+ν 加熱で爆発しそう

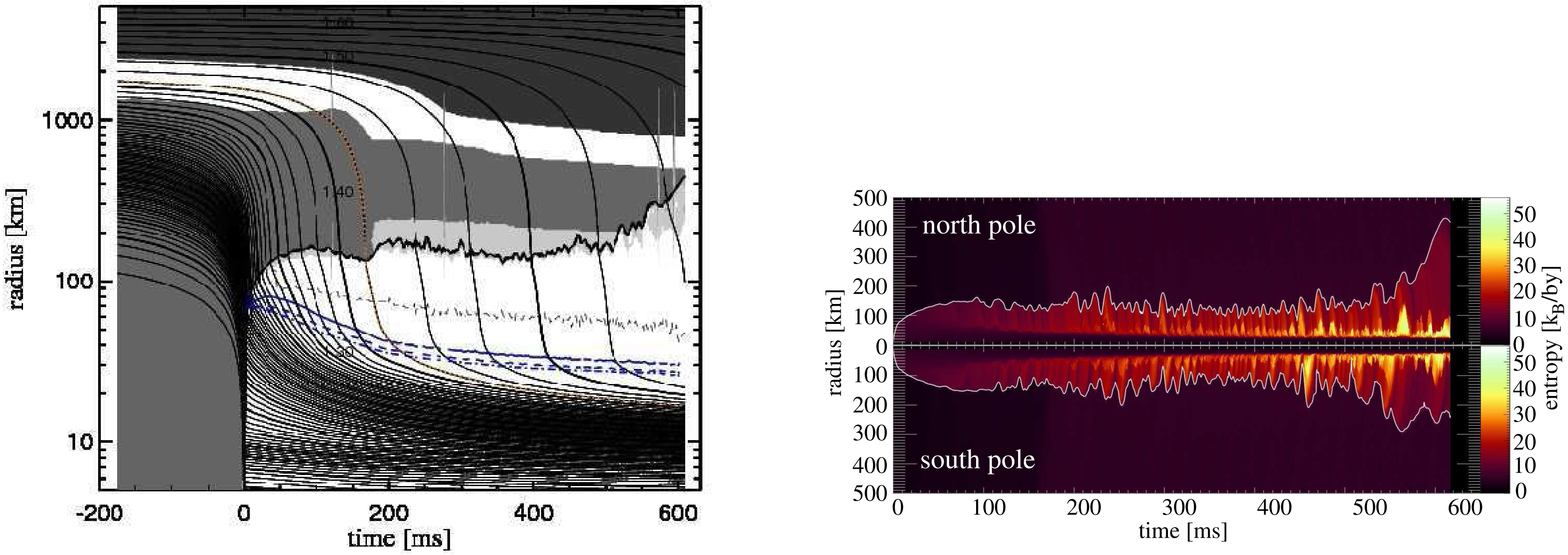


FIG. 2.— Evolution of Model M15LS-rot. *Left:* Mass shells versus time. In this 2D simulation with rotation, the mass-shell lines mark the radii that enclose certain values of the rest mass. The bold solid line indicates the (arithmetically) averaged shock position, the blue lines represent the mean neutrinospheres of ν_e (solid), $\bar{\nu}_e$ (dashed), and heavy-lepton neutrinos (dash-dotted), the black dashed curve indicates the mean gain radius, and the composition boundary between silicon shell and oxygen-enriched Si-layer at $1.42\,M_\odot$ is highlighted by a red dashed line. Dark grey denotes regions where the mass fraction of oxygen is larger than 10%, medium grey where the mass fraction of heavy nuclei with mass numbers $A \geq 56$ exceeds 10%, and light grey those regions where more than 30% of the mass is in α-particles. *Right:* Radial positions of the shock near the north and south poles as functions of post-bounce time (white lines). The color coding represents the entropy per nucleon of the stellar gas. The quasi-periodic, bi-polar shock expansion and contraction due to the SASI can be clearly seen.

Marek and Janka, astro-ph/0708.3372 Fig.2

Blondin and Mezzacappa, astro-ph/0611680: 3D SASI (without ν-transfer) → NS spin?

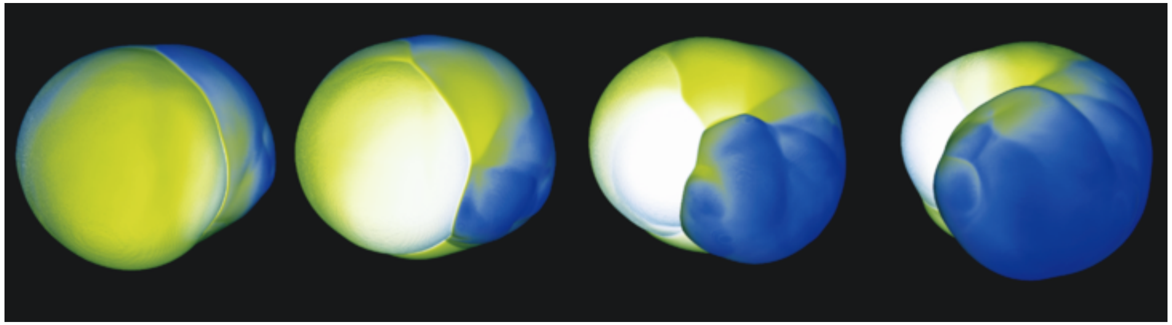


Figure 1 | The evolution of the supernova accretion shock illustrates the rotation of the spiral mode of the SASI. The blue portion of the shock surface represents the leading portion of the spiral SASI wave, seen here propagating from right to left across the front face of the shock. The discontinuity between the blue and white surfaces is the shock triple point marking the leading edge of the SASI wave. An animation of this evolution is available in Supplementary Information.

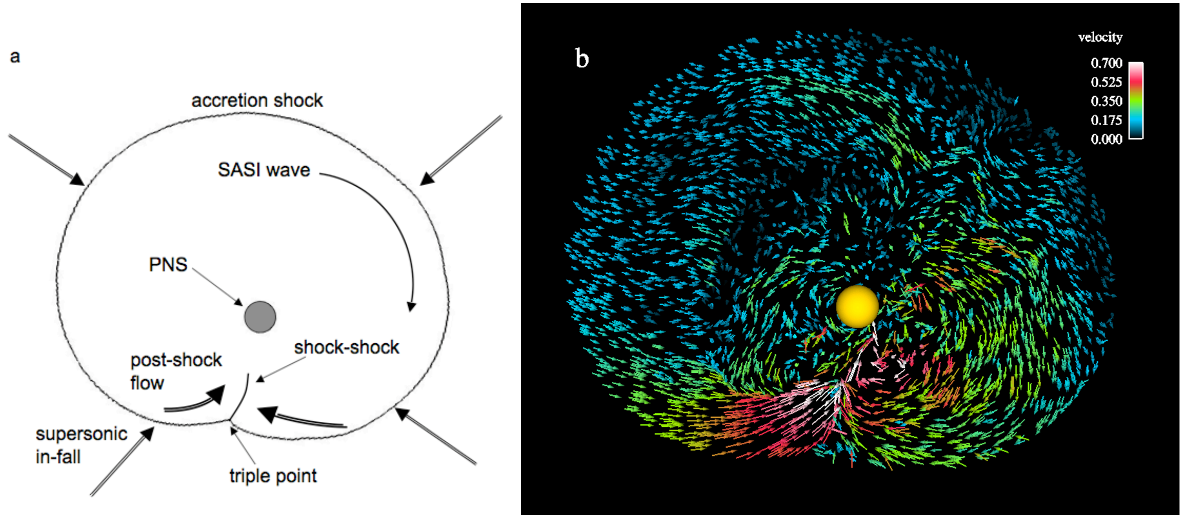
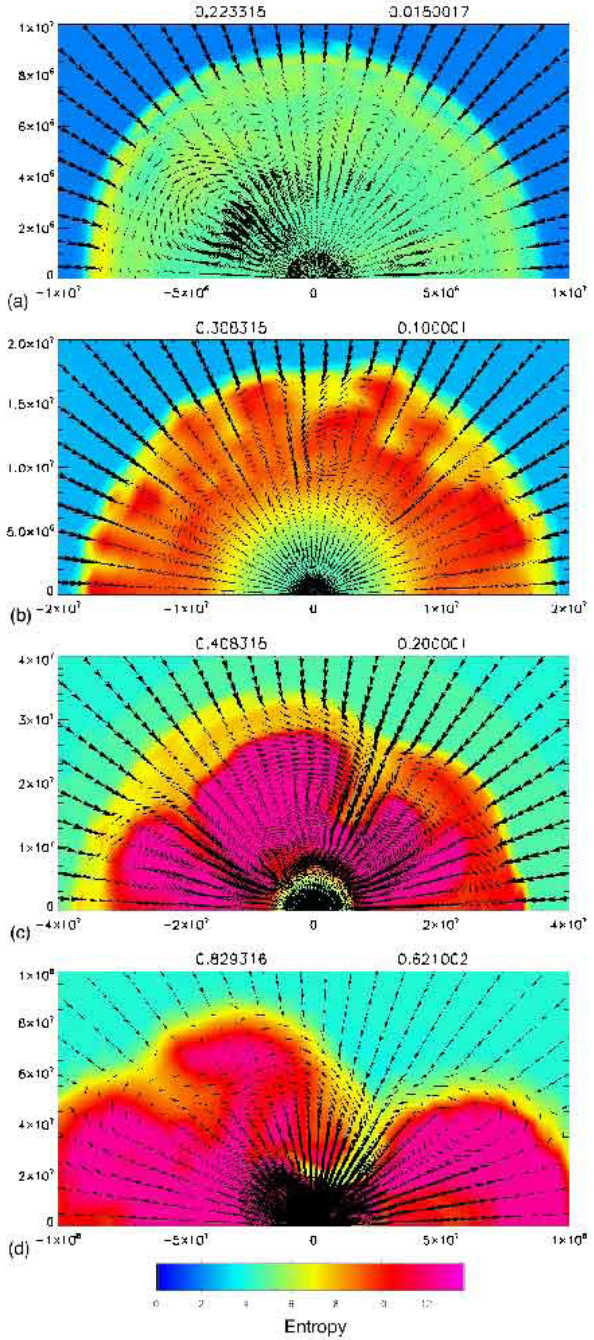


Figure 2 | The flow in the equatorial plane of the spiral SASI mode drives accretion of angular momentum onto the PNS. a, This diagram illustrates the shock structure and corresponding post-shock accretion flow created by the spiral SASI wave. The location of the accretion shock is taken from the equatorial plane of a three-dimensional simulation with the shock pattern (the SASI wave) propagating in a clockwise direction. The leading edge of the internal SASI wave is marked by a shock-shock[13]: a shock wave formed by the steepening of a pressure wave propagating along the inside surface of the accretion shock. This shock-shock connects to the accretion shock at a triple point, seen as a discontinuity in the surface of the accretion shock. In three dimensions this triple point is a line segment on the surface of the accretion shock that spans roughly half the circumference, as seen in Fig. 1. **b**, The flow vectors highlight two strong rotational flows. On the right the flow is moving clockwise along with the shock pattern, whereas at the bottom left the post-shock flow is being diverted into a narrow stream moving anticlockwise, fuelling the accretion of angular momentum onto the PNS.



Bruenn *et al.*, astro-ph/0709.0537 Fig.2: $15M_\odot$NR 2D MGFLD(ray-by-ray plus)

ν-driven convection + SASI + O burning

Burrows: Accoustic Explosion ?

accretion → excitation of g-mode in PNS → sound wave → dissipation behind the shock front → robust explosion

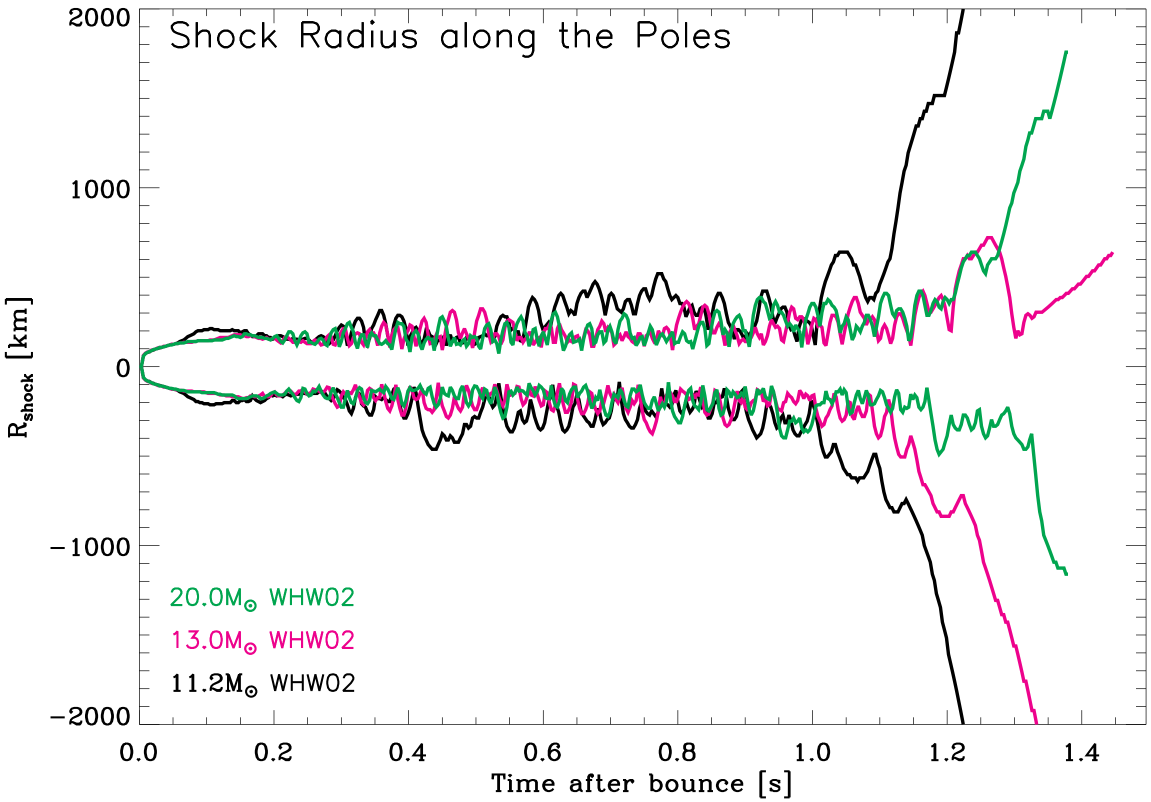


FIG. 4.— Time evolution of the outer shock radius (in km) along the poles for the 11.2-M$_\odot$(black), 13-M$_\odot$(magenta), and 20-M$_\odot$(green) models of WHW02. The radii extend from 2000 km to -2000 km.

ApJ 655(2007) 416 Fig.4

↔ g-mode の振幅は小さいのでは?

回転?

- Yamada and Sato 1994. 回転周期 ↘ 遠心力 ↗ $\rho_{\rm bounce}$ ↘ $E_{\rm shock}$ ↘
- Shimizu *et al*. 1994,2001: asymmetric neutrino emission from the rotating protoneutron star (deformed)
  → jet-like explosion $E_{\rm shock}$ ↗

  球対称モデルと比べて、加熱率はあまり変わらないが、冷却率が下がっている。

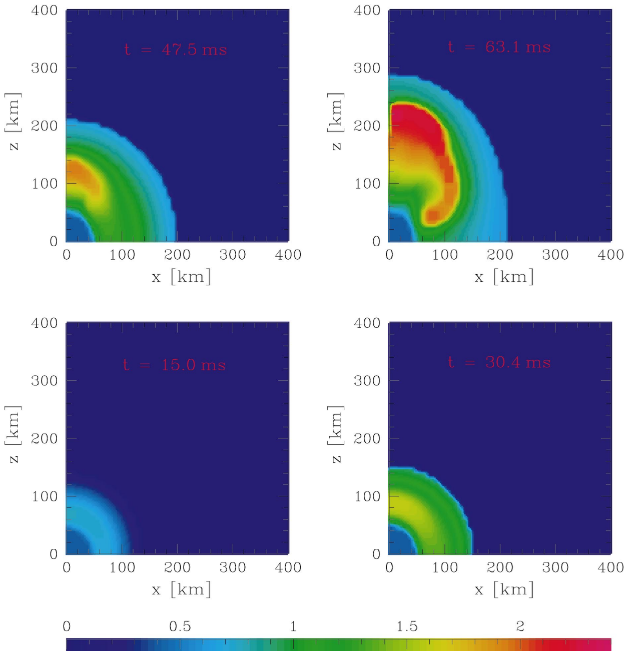


FIG. 8.—Plots of the entropy distribution in time sequence for the model of $l_z/l_x = 1.05$ and $T_\nu = 4.7$ MeV (*facg10547*) during the relatively early stages. The growth of the hot bubble is essentially the same as that of *facg1247* (Fig. 6), except for slow evolution in this less anisotropic case.

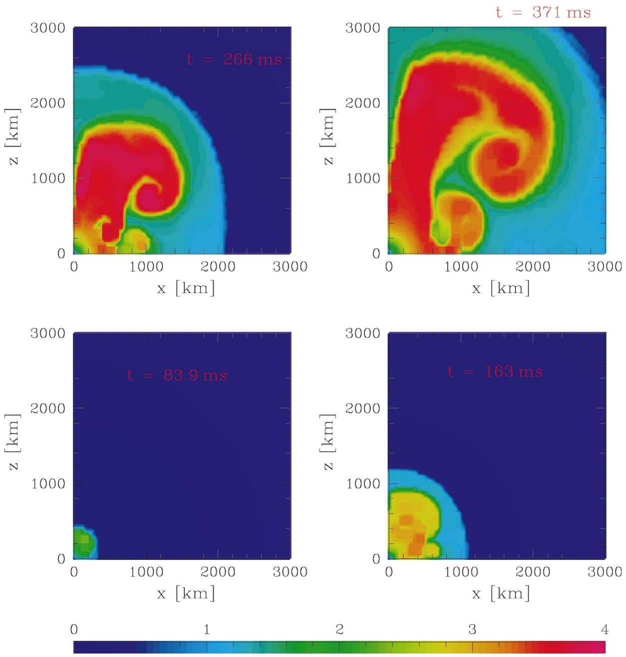


FIG. 9.—Same as Fig. 8 (*facg10547*), except at the late stages. Note the jetlike motion in the high-entropy hot bubble.

Shimizu *et al*., ApJ 552 (2001) 756, Fig.8,9

- Janka *et al.*, 2001

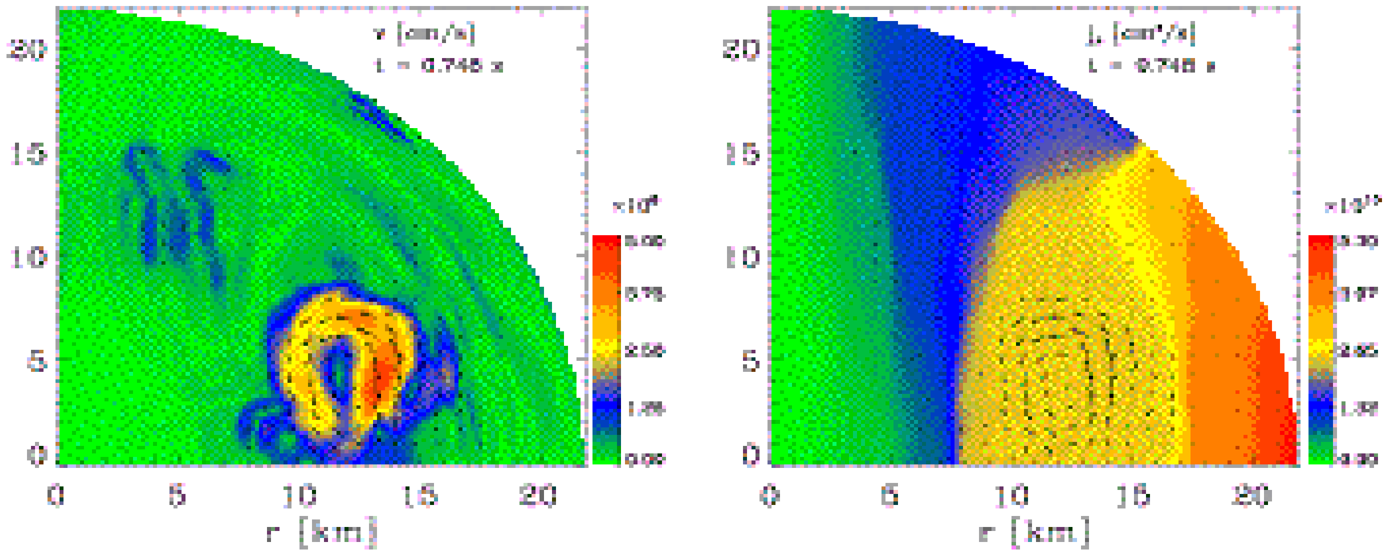


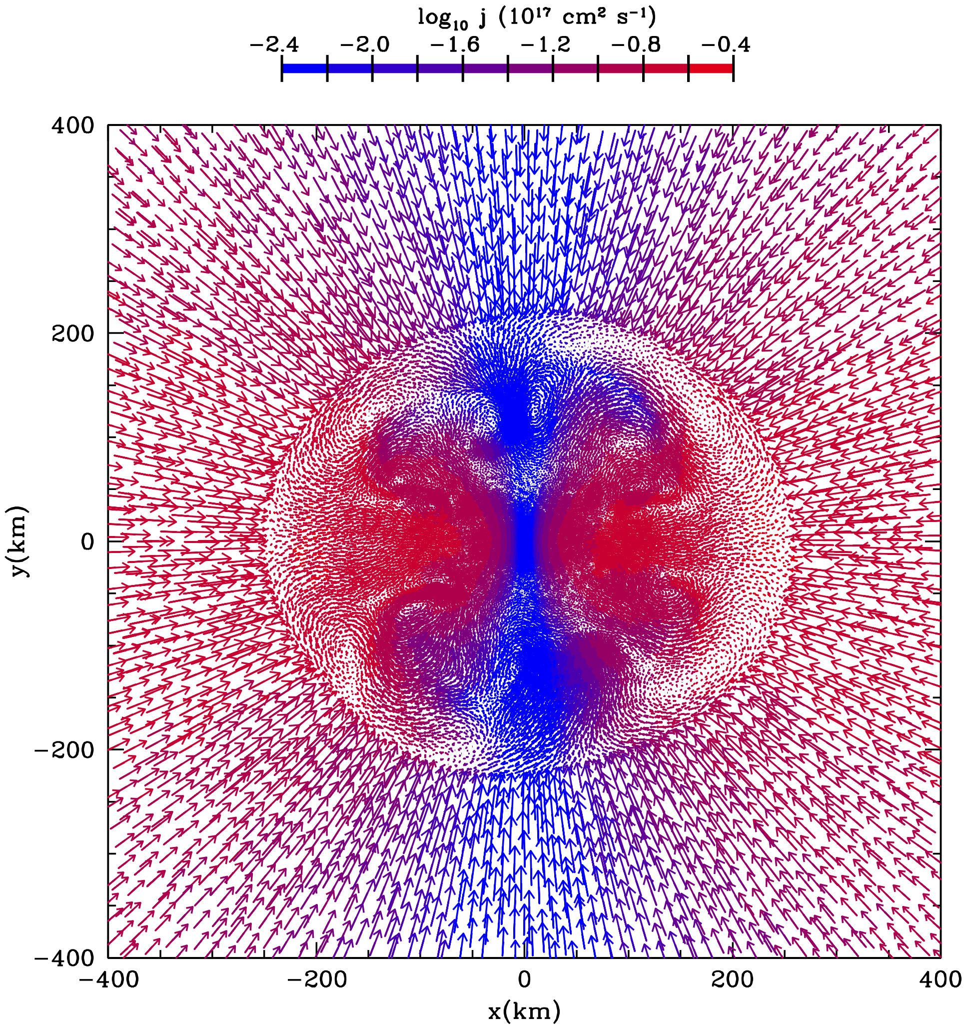
Fig. 14. Absolute value of the gas velocity in a convecting, rotating proto-neutron star about 750 ms after bounce (left). Convection is suppressed near the rotation axis (vertical) and develops strongly only near the equatorial plane where a flat distribution of the specific angular momentum j_z (right) has formed.

2D Rotating PNS. (Janka *et al.*, Lect.Notes Phys. 578 (2001) 333, Fig.14)

suppression of convective motion near the rotation axis. (Solberg-Høiland criterion : $\frac{dj_z^2}{dx}$ が安定化)

- Fryer and Warren, astro-ph/0309539 Fig.8

3D SPH, EIFLD, tree-based gravity algorithm → quick explosions



PNS 回りの shocked region では、回転により赤道面の対流が抑制される。

Takiwaki *et al.*, 2004: 磁場と自転

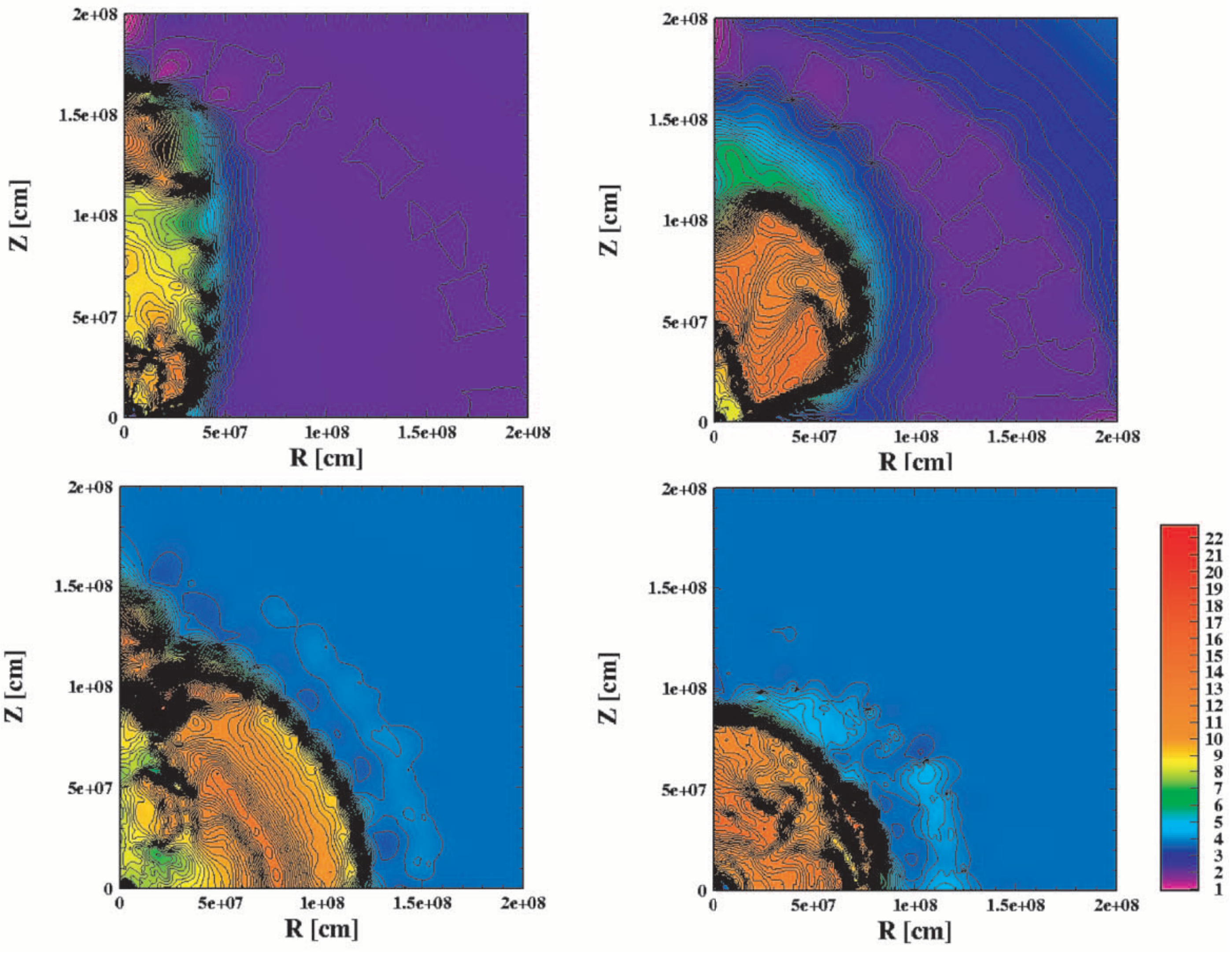
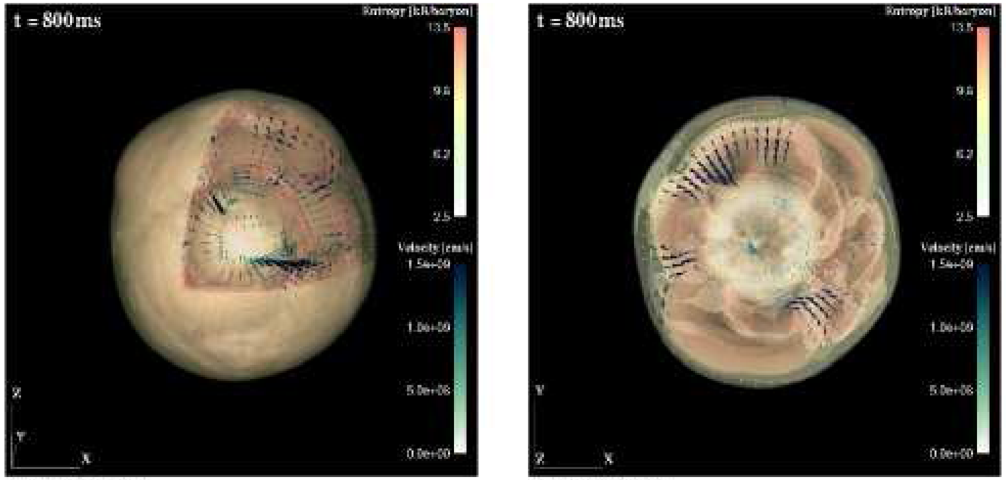
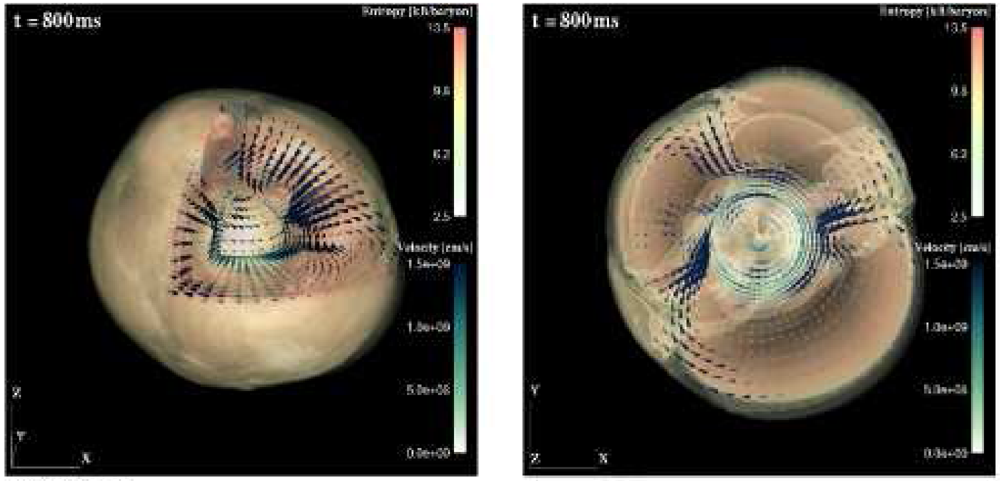


Fig. 2.—Profiles of the shock propagation in the various models: B12TW2 at 60 ms from core bounce (*top left*), B10.5TW1 at 127 ms (*top right*), B10.5TW2 at 219 ms (*bottom left*), and B9TW4 at 404 ms (*bottom right*). Profiles show color-coded contour plots of entropy (k_B) per nucleon. Various profiles are found by changing the strength of the initial magnetic field and rotation.

Takiwaki *et al.*, ApJ 616 (2004) 1086 Fig.2



(a) Model C0 (b) Model C0



(c) Model C1 (d) Model C1

Fig. 9.— Partial cutaway view of the iso-entropy surfaces and the velocity vectors on the cutting plane at t = 800ms (a), (b) without rotation for Models C0 and (c), (d) with rotation for Model C1. One can see (a), (c) the object having three cutting planes from the $-y$ direction and (b), (d) its equatorial section from z direction.

Iwakami *et al.*, 2008: SASI と回転

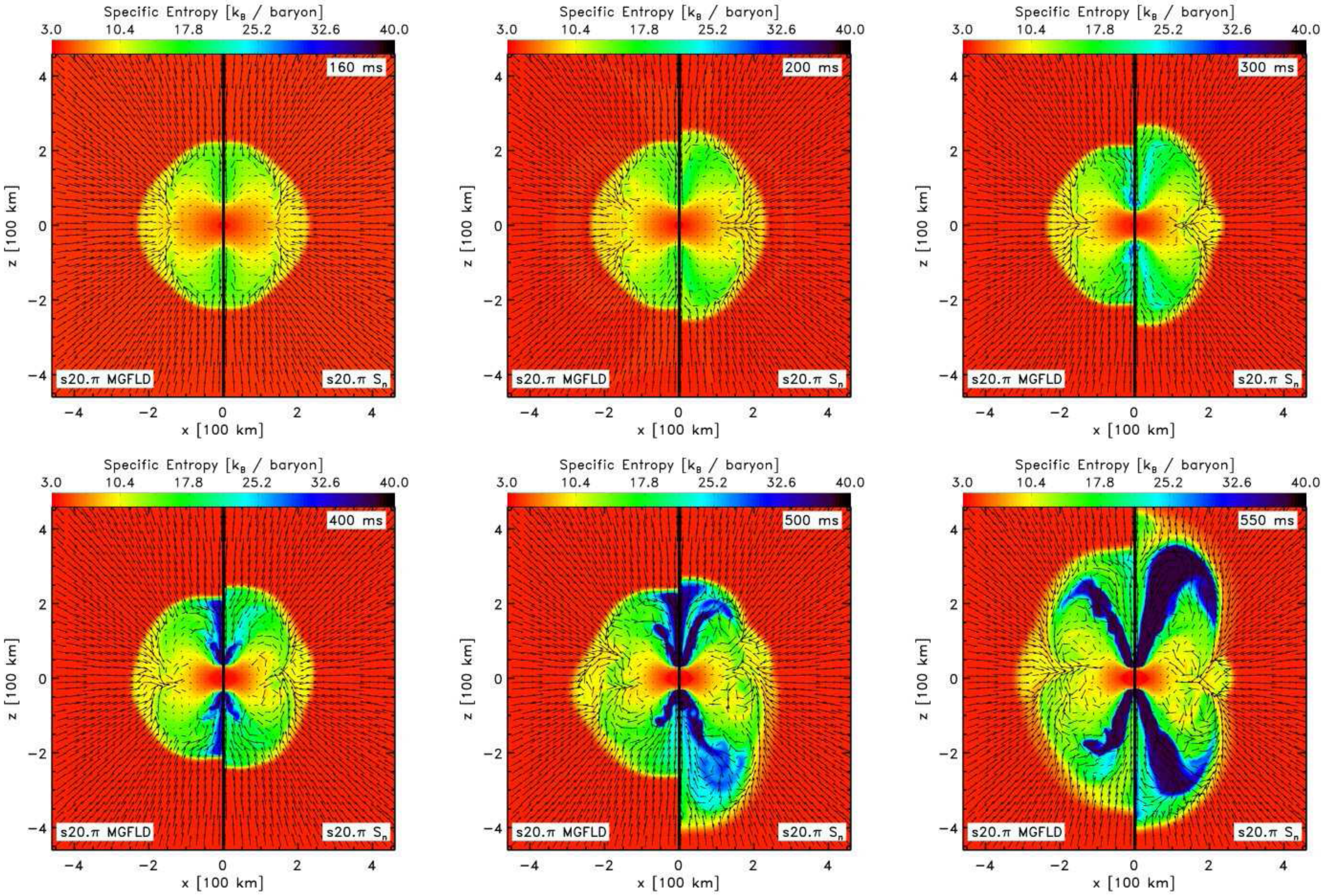


FIG. 21.— 2D entropy colormaps portraying the postbounce evolution of the rapidly-rotating model s20.π between 160 ms (top-left panel) and 550 ms (bottom-right panel) after core bounce. Fluid-velocity vectors are superposed to relay an impression of the flow and convey the partial suppression of convective overturn in regions of positive specific angular momentum gradient. As in Fig. 20, we plot the MGFLD result on the left-hand side and the S_n result on the right-hand side of each panel. Easily discernible is the immediate increase in the polar shock radius in the S_n calculation. This is a direct consequence of the increased polar neutrino heating in this variant (Figs. 15 and 16). At intermediate times, S_n and MGFLD shock positions grow closer, but later on in the postbounce evolution, the S_n variant begins to develop larger top-bottom SASI-like asymmetry and polar shock excursions at earlier time than its MGFLD counterpart.

Ott *et al.*, 2008: 2D rotation + $S_N \nu$-tr.

Burrows *et al.*, 2007: 磁場と自転とニュートリノ

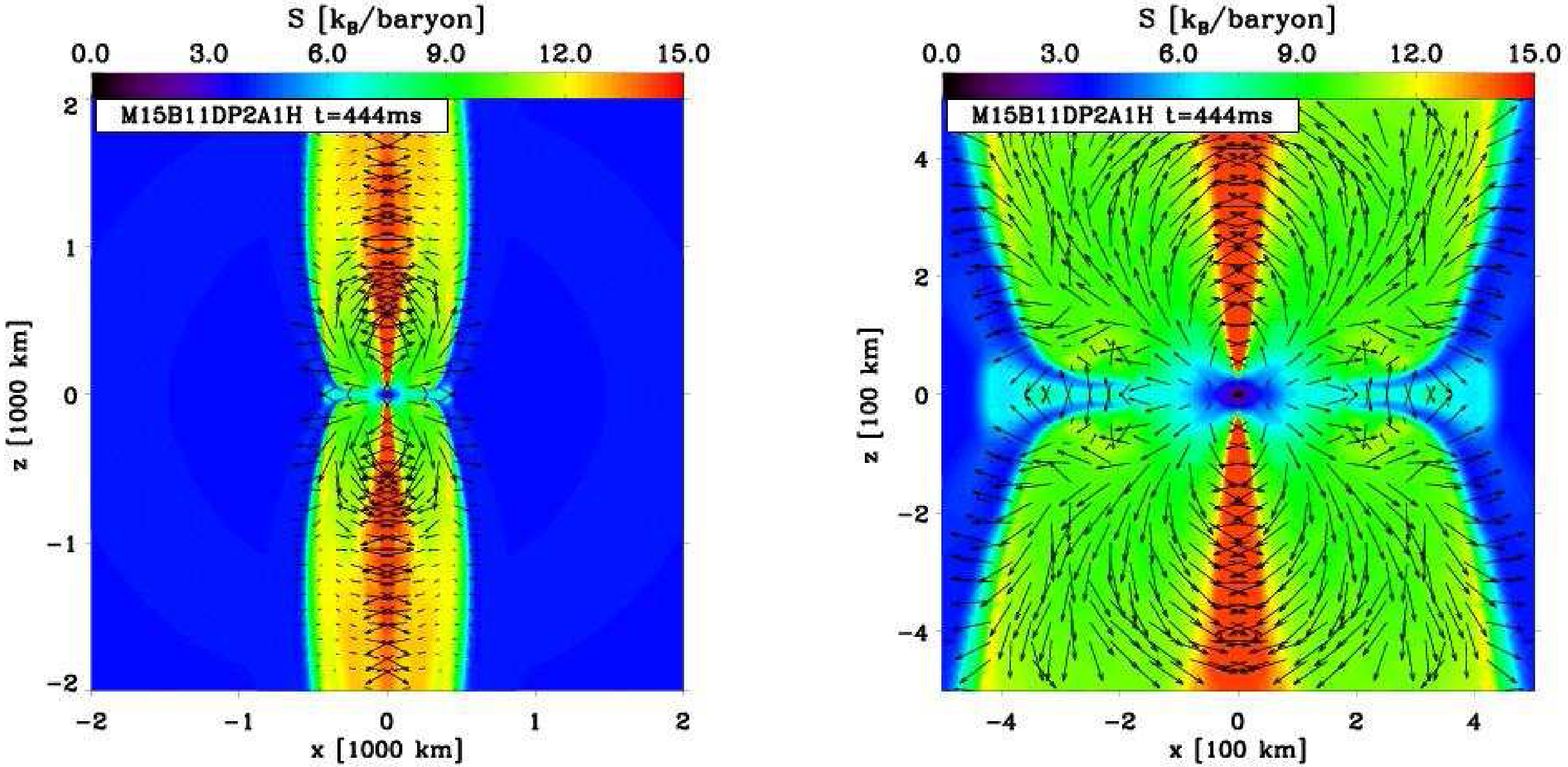


Fig. 12.— On the left-hand-side is a colormap of the entropy at 444 ms after bounce for model M15B11DP2A1H on a 4000 km×4000 km scale. We overplot the $(\nabla \times \vec{B}) \times \vec{B}$ vector field, with a length of 15% of the width of the display corresponding to a saturation value of $10^{18}\,\mathrm{g\,cm^{-2}\,s^{-2}}$. This term enters the momentum equation and thus represents the acceleration due to the magnetic field, revealing here, in particular, the role of hoop stresses in confining the jet as it moves to large distances. The right panel is the same as the left panel, but for the inner 1000 km×1000 km region.

ApJ 664(2007) 416 Fig.12

Summary

- state-of-the-art inputs(EOS, ν int.) とボルツマンコードによるニュートリノ輸送を使った球対称シミュレーション

  $\Rightarrow$ no prompt explosion
  軽いコアの弱い爆発
  $\sim 20M_\odot$ の星の 10^{51}erg の爆発は、未再現

  further sophistication of inputs?
  (weak int. rates of nuclei and many body effects consistent with EOS)

  非球対称性 convetion? SASI? rotation? magnetic field?

- きちんとした入力物理を使った長時間の多次元数値シミュレーション
  SASI $+\nu$ heating explosion? accoustic explosion? EOS モデルの影響?

  NS kick velocity, ejecta mixing, GW, pulsar spin?

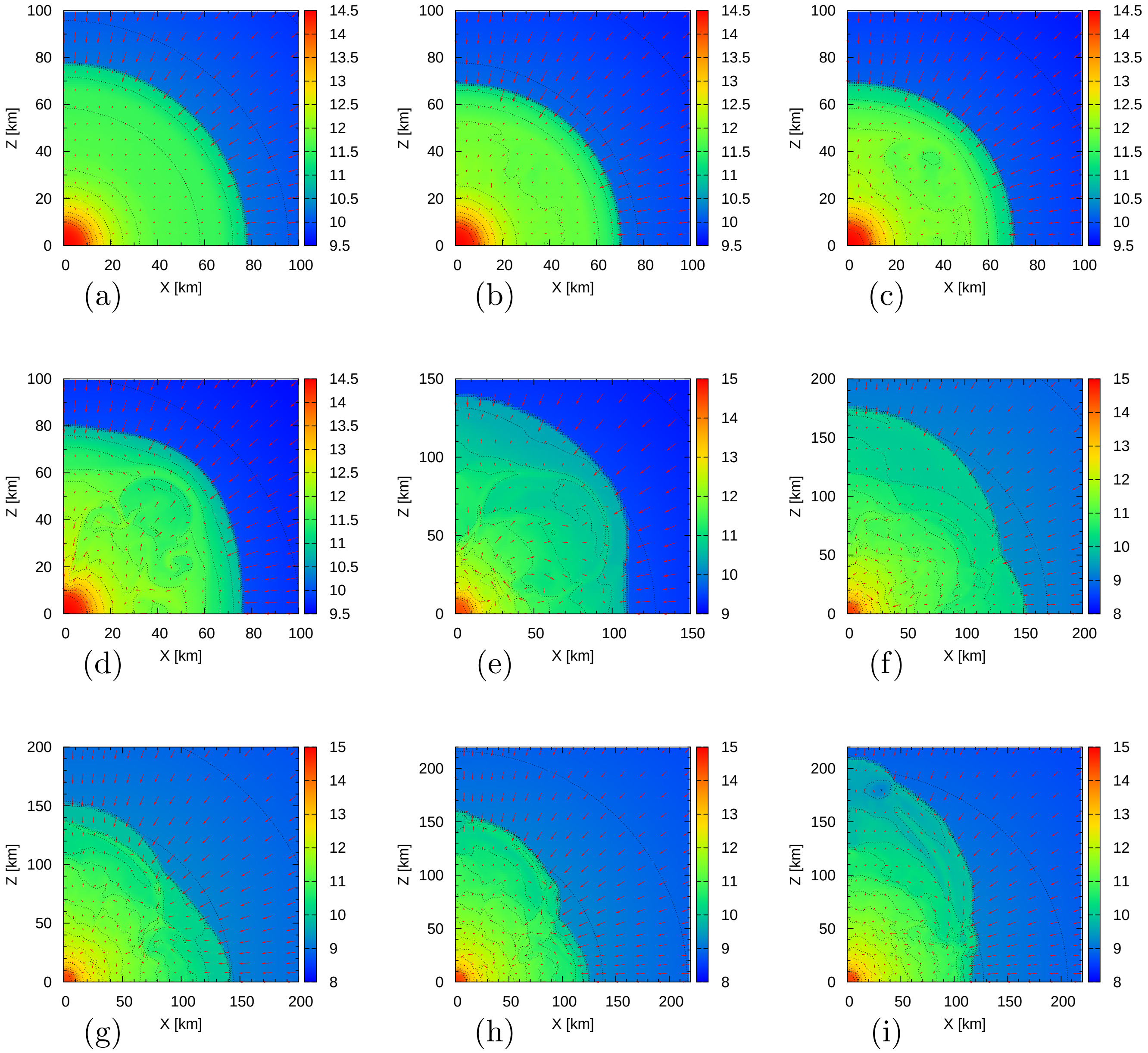
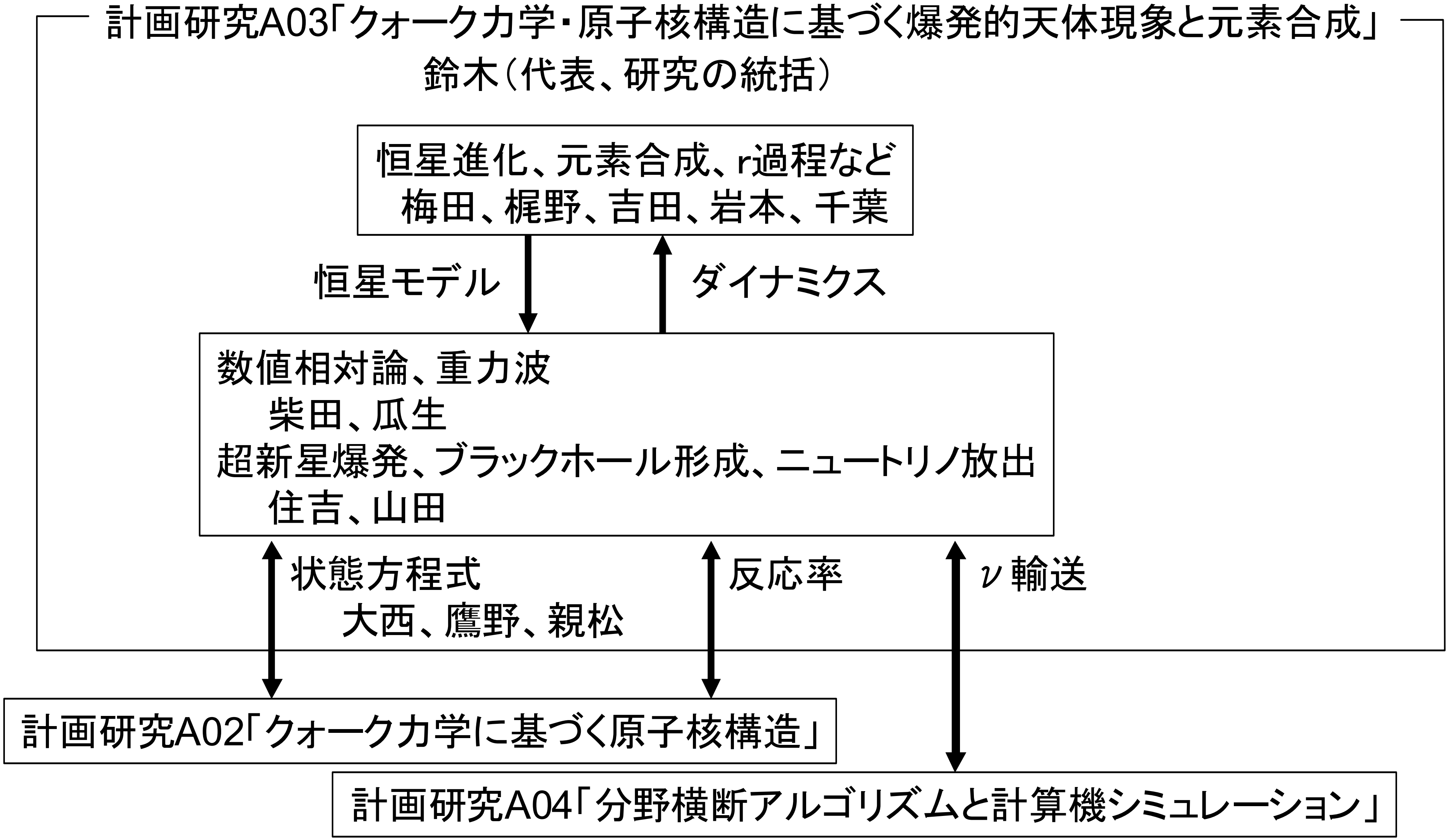


Fig. 10. Snapshots of the density contours and the velocity fields in the x-z plane for model S24 at (a) $t = 283.7$, (b) 285.7, (c) 286.7, (d) 288.2, (e) 291.1, (f) 294.2, (g) 300.2 , (h) 301.8, (i) 304.7 ms.

Sekiguchi 2008, $24M_\odot$, GR+Shen EOS+e-capture+leakage ν-tr.

- 恒星の進化 (元素合成と崩壊前のコア)
  第一世代星、自転、対流モデル、核反応率、質量放出、磁場
- 高密度物質の状態方程式
  核統計平衡状態、パスタ状態，一様核物質、ハイペロン，クォーク？
- ニュートリノ反応率
  様々な原子核による電子捕獲率、ニュートリノ加熱率、状態方程式とコンシステントな多体効果を考慮したニュートリノ反応率
- 非球対称性？
  対流，SASI、自転，磁場
- 一般相対論
  ブラックホール形成，重力波
- 動的段階の元素合成ネットワーク計算
  超新星、極超新星、高密度天体合体、ニュートリノ駆動風、下限質量中性子星の爆発などにおける密度，温度、電子フラクションの変化、Mass Cut の決定、不安定核の崩壊率と反応率、核分裂の影響
- 流体計算
- ニュートリノ輸送計算アルゴリズム
- 観測からのフィードバック、観測データテンプレート
  ニュートリノ検出反応、重力波検出器、$\nu\nu$ 相互作用を含むニュートリノ振動



計画研究A03「クォーク力学・原子核構造に基づく爆発的天体現象と元素合成」
鈴木（代表、研究の統括）

恒星進化、元素合成、r過程など
梅田、梶野、吉田、岩本、千葉

恒星モデル

ダイナミクス

数値相対論、重力波
柴田、瓜生
超新星爆発、ブラックホール形成、ニュートリノ放出
住吉、山田

状態方程式
大西、鷹野、親松

反応率

ν 輸送

計画研究A02「クォーク力学に基づく原子核構造」

計画研究A04「分野横断アルゴリズムと計算機シミュレーション」

さらなる連携を

MHD, GRB, $\cdots$