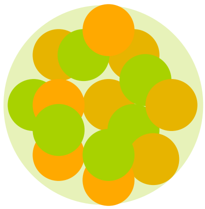
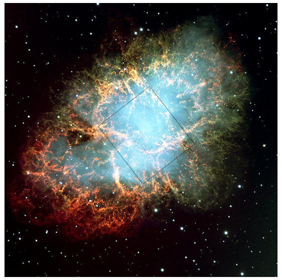
Numerical modeling of core-collapse supernovae with progress in nuclear physics and supercomputing



K. Sumiyoshi

(Numazu College of Technology)

Crab nebula



hubblesite.org

Talk mainly on:

- 3D calculations of neutrino-transfer

With H. Nagakura, S. Yamada,
H. Matsufuru, A. Imakura, T. Sakurai

Bridge @Nara, 2012. 12. 16.

Bridging nuclear, astrophysics by supercomputers

- Quark, Nuclear Physics
  - EOS, ν-reactions

A01, A02

- Massive Star Models
  - Mass, Metallicities

A03

- Simulations of supernovae
  - ν-radiation hydrodynamics

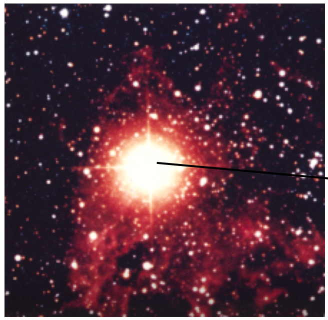
A03

- Supercomputing

A04

KEK YITP

Explosion mechanism



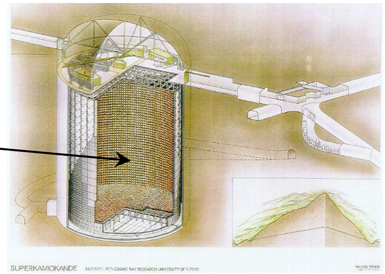
ν

SN1987A

Neutrino Astronomy

Super-Kamiokande

ν



Research products in 2008-2012 16 papers

- Equation of state (EOS) tables for supernovae
  - Shen EOS tables + Hyperons, Quarks
  - Mixture of nuclei, neutrino reactions

Phys. Rev x 3, ApJ x 2
JPG x 1
→ Togashi, Furusawa

- Neutrino signals as probe of EOS
  - Neutrino bursts from proto-NS and BH
  - Dependence on massive stars, EOS
    - 1D GR neutrino-radiation hydrodynamics

Phys. Rev x 2, ApJ x 4
PLB x 1
→ Nakazato

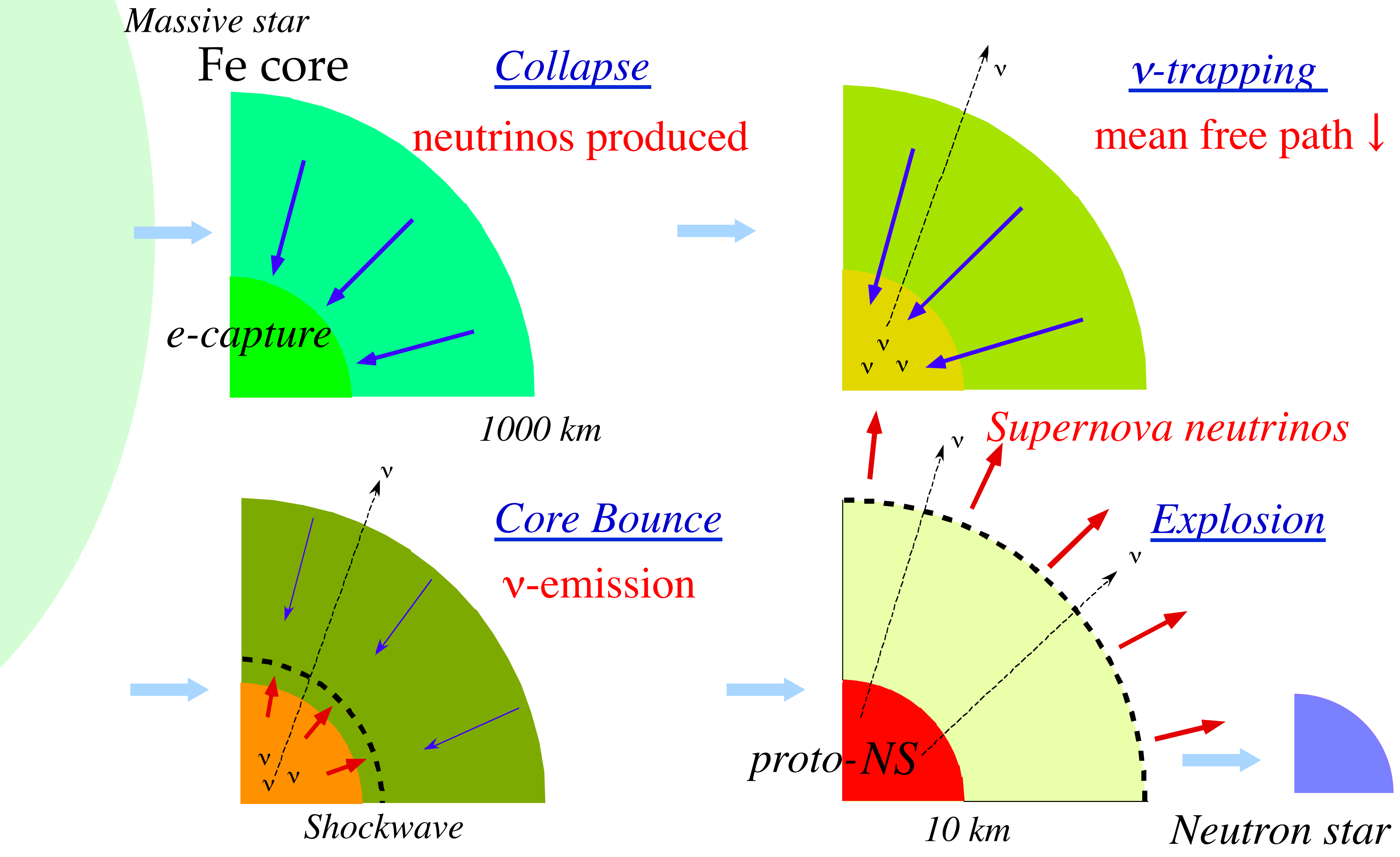
- 3D neutrino-transfer for supernovae
  - Solve Boltzmann eq. in 6D
  - a new method for matrix solver

ApJS x 1, PTEP x 1
JSIAM x 1
→ Imakura

Neutrino-transfer is important

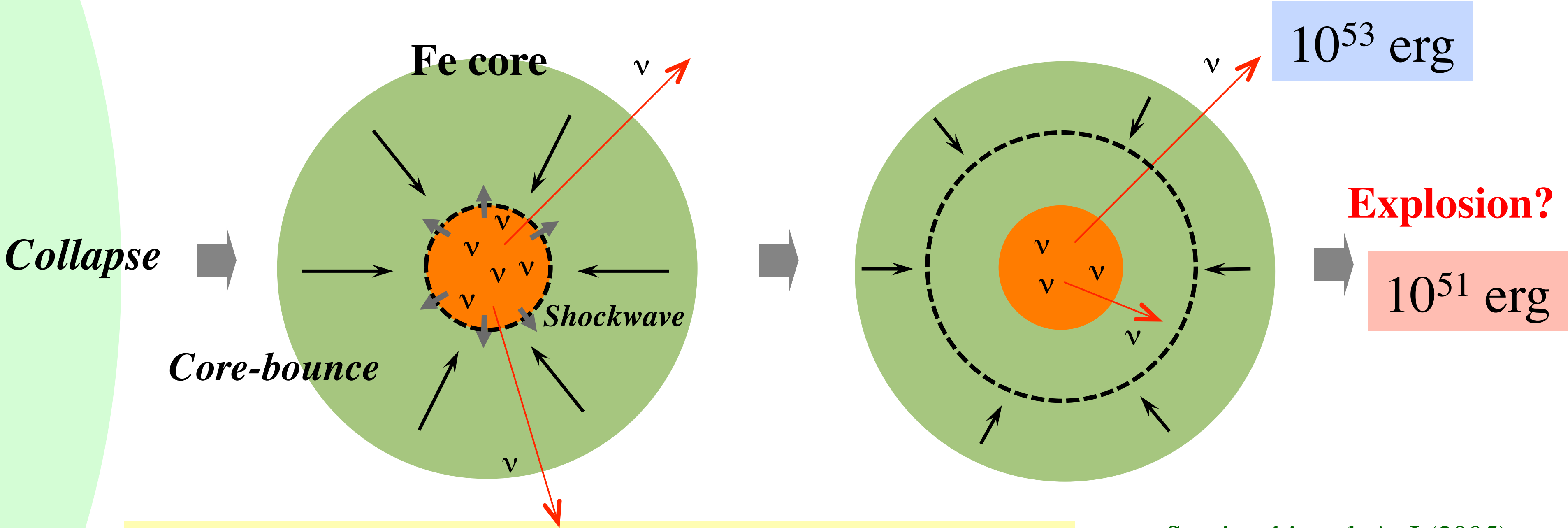
Neutrino heating for explosion

Role of neutrinos in supernova dynamics



Problem: shockwave stalls on the way

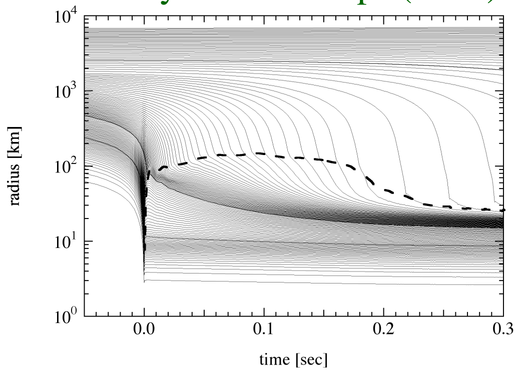
How to revive the shock propagation and trigger explosion?



- Multi-dimensional effects
- Microphysics (EOS, ν-reactions)
- Neutrino heating mechanism

~1% of neutrinos is used for explosion

Sumiyoshi et al. ApJ (2005)



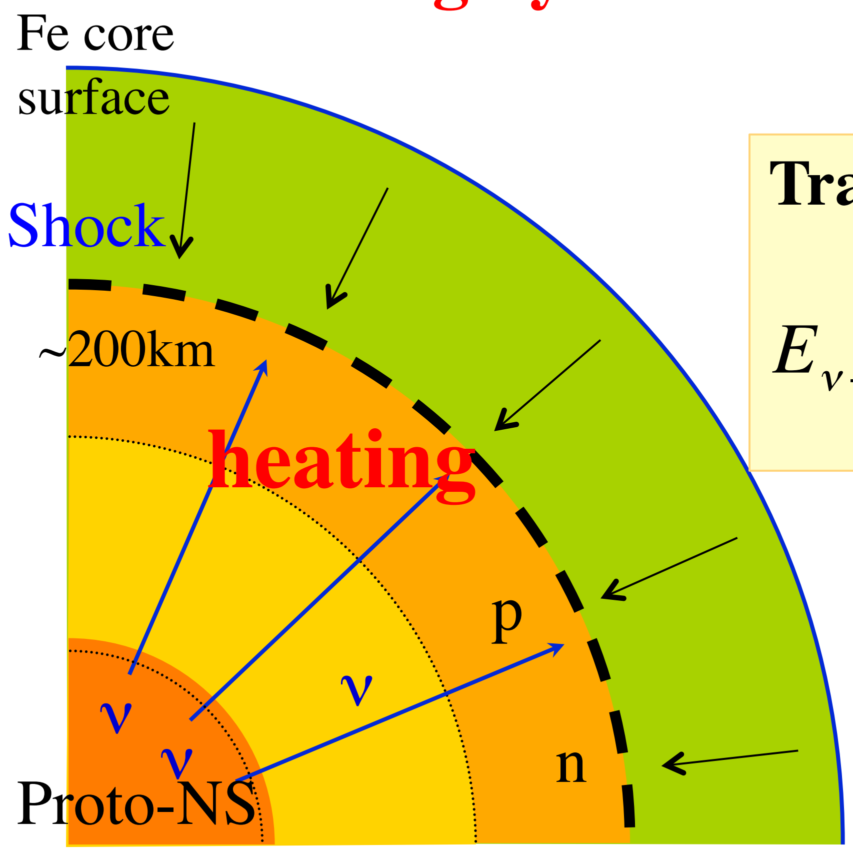
No explosion in 1D
(spherical calc.)

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

$\nu_e + n \rightarrow e^- + p,$

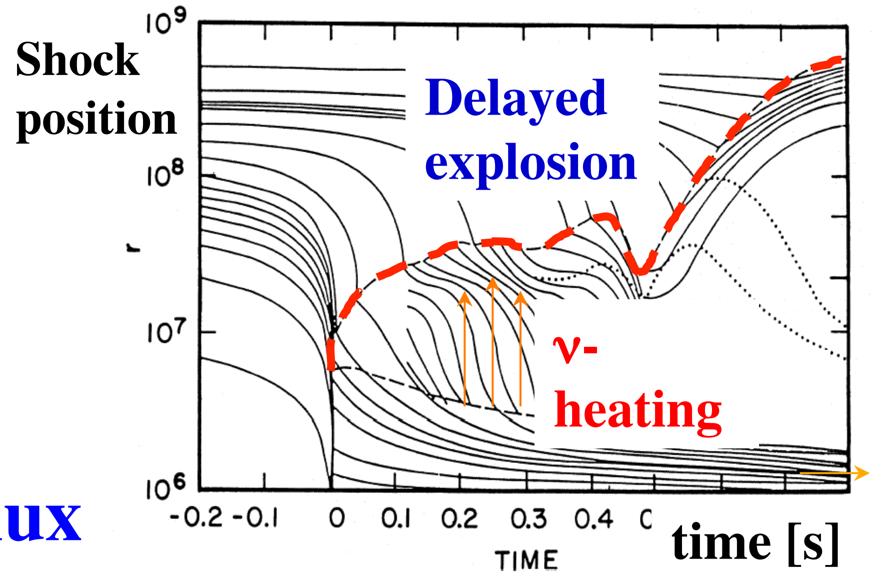
$\bar{\nu}_e + p \rightarrow e^+ + n$



100ms after bounce

Transfer of energy from ν Janka A&A (1996)

$$E_{\nu-heat} \sim 2.2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$



Bethe & Wilson ApJ (1985)

Depends on neutrino energy/flux targets

ν-heating occurs in the intermediate region

Need to solve neutrino-transfer

for angle distribution $f(E_\nu, \theta_\nu)$

ex. Diffusion approximation
is not enough

ν-heating rate Janka A&A (1996)

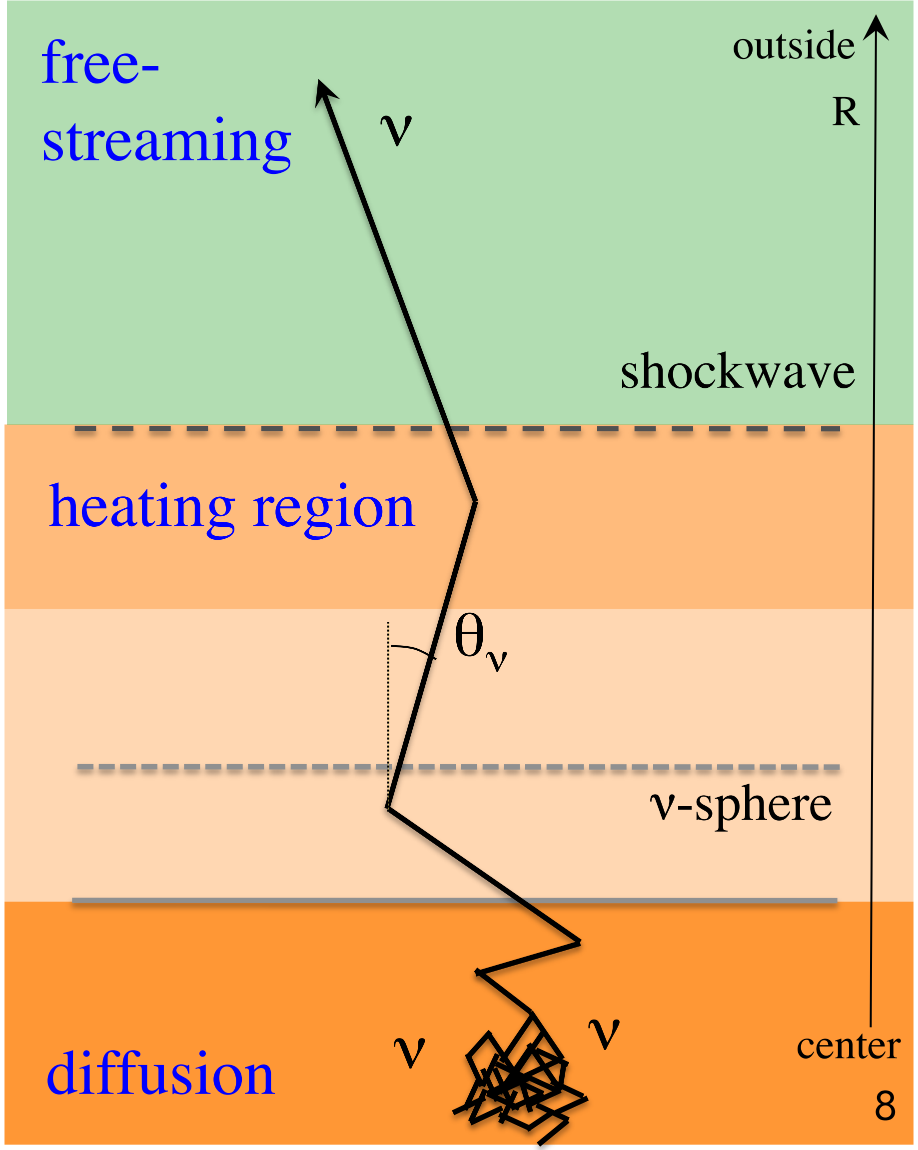
$$Q_\nu^i \approx 110 \frac{MeV}{s \cdot N} \left(\frac{L_\nu E_\nu^2}{R_7^2 < \mu >} X_i \right)$$

average energy, flux: E_ν, L_ν

flux factor: $< \mu > = < \cos\theta_\nu > = 0 \sim 1$

even 10~20 % change of ν-heating may affect the outcome: explosion

between diffusion & free-streaming



Numerical simulation of supernovae

Combination of hydrodynamics and neutrino transfer

Astrophysics

• Hydrodynamics

↑ ν-heating, cooling, pressure

↓ ρ, T, Y_e profiles

• ν-transfer(Boltzmann eq.)

distribution: $f(t, r, E_\nu, \theta_\nu)$

Nuclear Physics

• Equation of state (EOS)

(ρ, T, Y_e) — pressure →

↓ composition

• ν-reaction rates

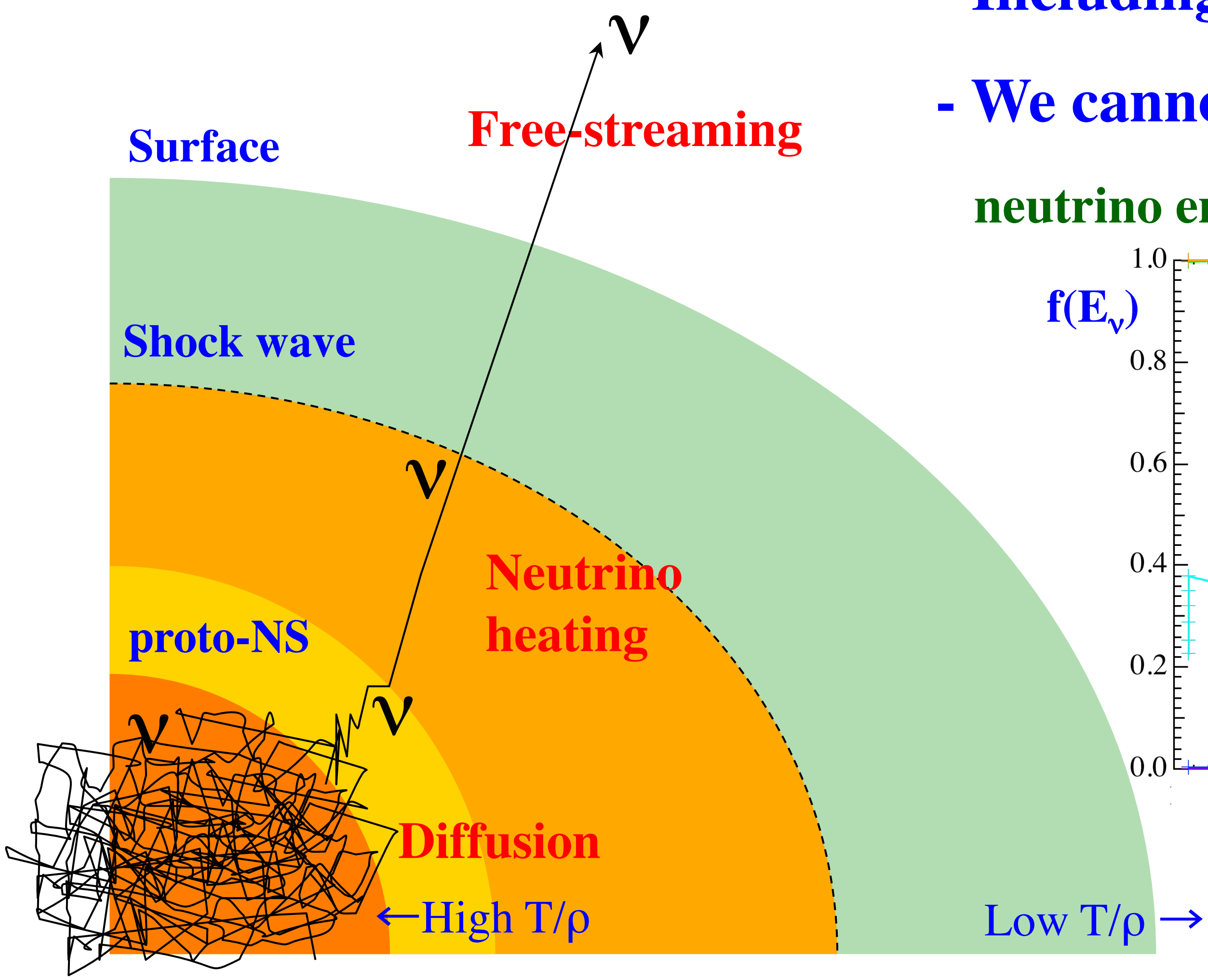
(ρ, T, μ_i, X_i) — absorb, emit, scatter →

3D Neutrino-transfer is a challenge

Boltzmann equation in 6D

Calculation of ν-radiation transfer

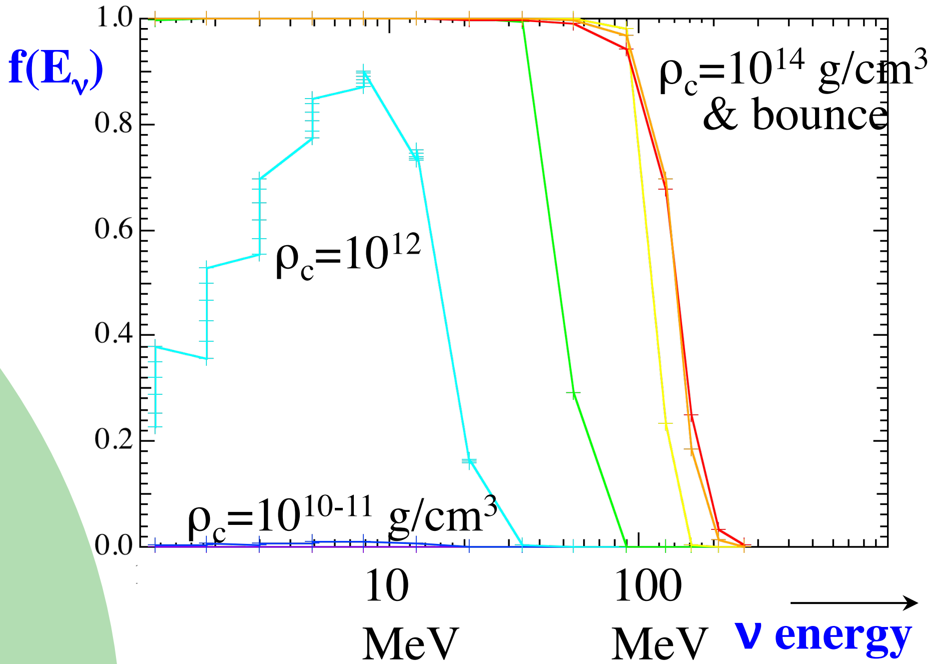
- **Neutrino propagation from supernova core to outside with neutrino reactions in dense matter**



- Including *non*-equilibrium situation

- We cannot use Fermi-distributions

neutrino energy distribution during collpase



To solve neutrino transfer in 3D

- Work in 6D: 3D space + 3D momentum

$$f_\nu(r,\theta,\phi;\ \varepsilon_\nu,\theta_\nu,\phi_\nu;\ t)$$

  - Neutrino energy (ε_ν), angle (θ_ν, ϕ_ν)

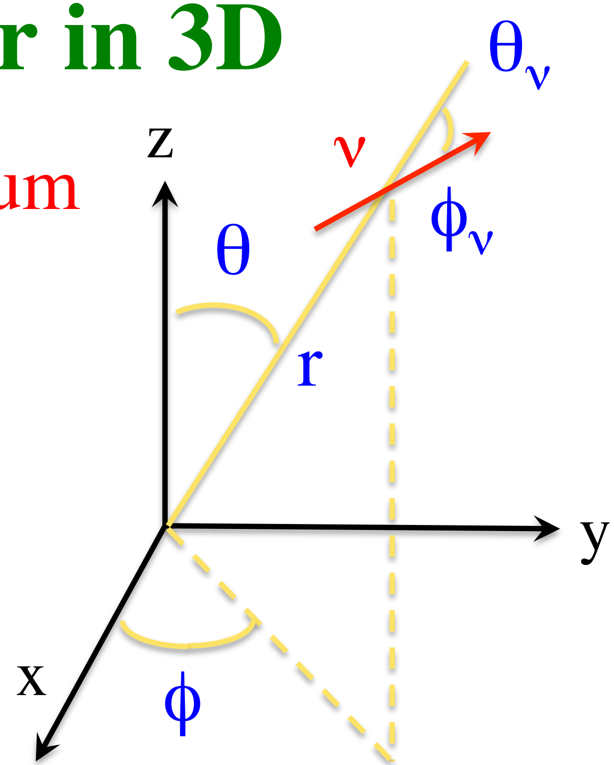
- Time evolution of 6D-distribution

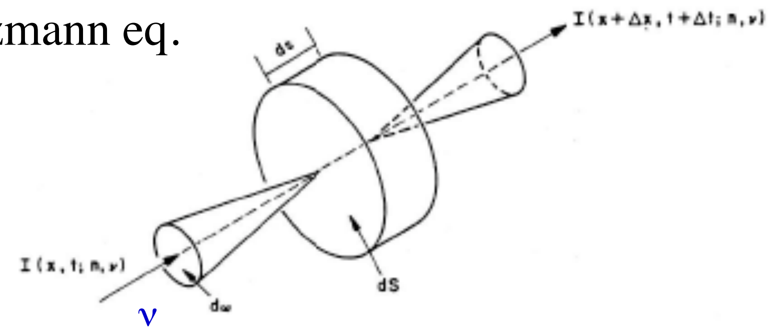
$$\frac{1}{c}\frac{\partial f_\nu}{\partial t} + \vec{n}\cdot\vec{\nabla} f_\nu = \frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

Boltzmann eq.

  - Left: Neutrino number change
  - Right: Change by neutrino reactions

- Energy, angle-dependent reactions
  - Compositions by EOS tables





Status of neutrino-transfer

- 1D: first principle calculations
- 2D, 3D: approximate treatment

– Diffusion (with flux limiter)

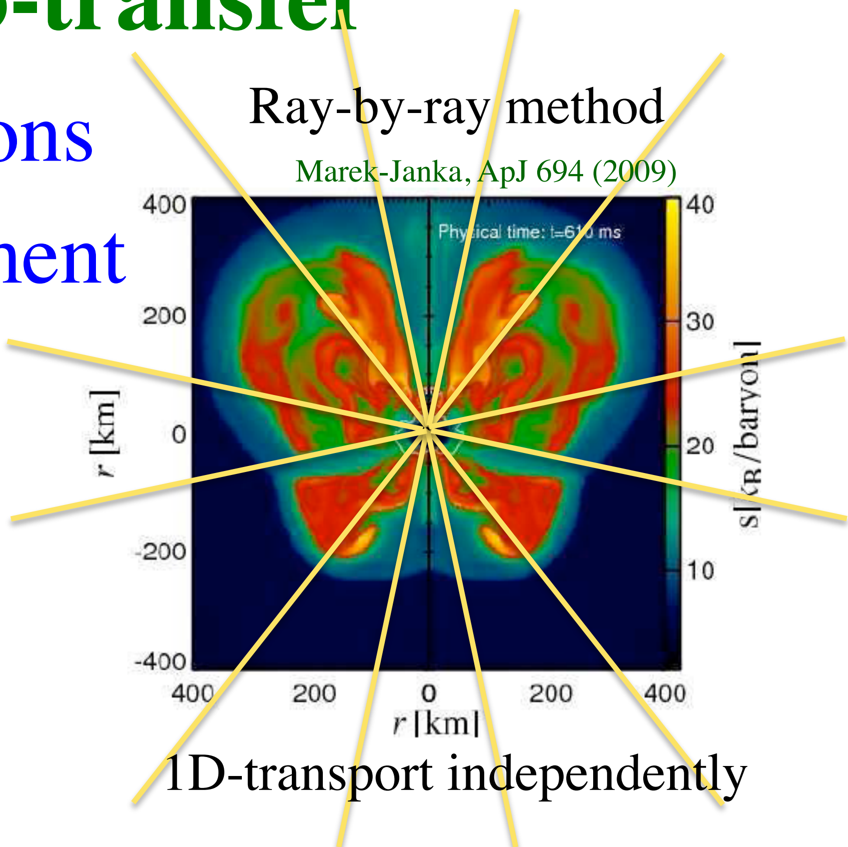
Only good in central part

– Ray-by-ray (radial transport)

Neglect lateral transport

Ray-by-ray method

Marek-Janka, ApJ 694 (2009)



1D-transport independently

- Need full 3D calculations

- examine the approximations, to the grand challenge

- New code to solve 3D neutrino-transfer
  - For the first time in the world

Sumiyoshi & Yamada, ApJS (2012)

See Ott et al. ApJ(2008) for 2D S_n-method

Boltzmann eq. in spherical coordinate

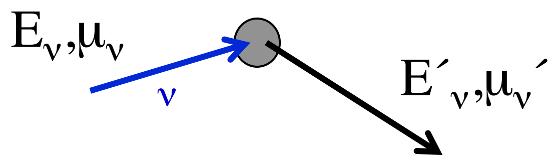
Sumiyoshi & Yamada, ApJS (2012)

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t}+\frac{\mu_\nu}{r^2}\frac{\partial}{\partial r}(r^2 f_\nu)+\frac{\sqrt{1-\mu_\nu^2}\cos\phi_\nu}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta f_\nu)+\frac{\sqrt{1-\mu_\nu^2}\sin\phi_\nu}{r\sin\theta}\frac{\partial f_\nu}{\partial\phi}$$

$$+\frac{1}{r}\frac{\partial}{\partial\mu_\nu}[(1-\mu_\nu^2)f_\nu]+\frac{\sqrt{1-\mu_\nu^2}\cos\theta}{r\sin\theta}\frac{\partial}{\partial\phi_\nu}(\sin\phi_\nu f_\nu)=\frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

- Discrete in conservative form (S_n method)
- Implicit method in time
  - stability, time step, equilibrium
- Collision term for ν-reactions
  - absorption, emission, scattering

Energy, angle dependent



$\mu_\nu = \cos\theta_\nu$

$$\frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}=j_{emission}(1-f_\nu)-\frac{1}{\lambda_{absoption}}f_\nu+C_{inelastic}[\int f_\nu(E'_\nu,\mu'_\nu)dE'_\nu]$$

Neutrino reactions in collision term

Basic sets for supernova simulations

Bruenn (1985) +Shen

- Emission & absorption:

  $e^- + p \leftrightarrow \nu_e + n$ $\quad$ $e^- + A \leftrightarrow \nu_e + A'$

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

- Scattering:

  $\nu_i + N \leftrightarrow \nu_i + N$ $\quad$ $\nu_i + A \leftrightarrow \nu_i + A$

- Pair-process:

  $e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$

  $N + N \leftrightarrow N + N + \nu_i + \bar{\nu}_i$

3 species:

$\nu_e, \bar{\nu}_e, \nu_\mu$

Notes: iso-energetic scattering, linearize pair process
Lorentz transformation being implemented

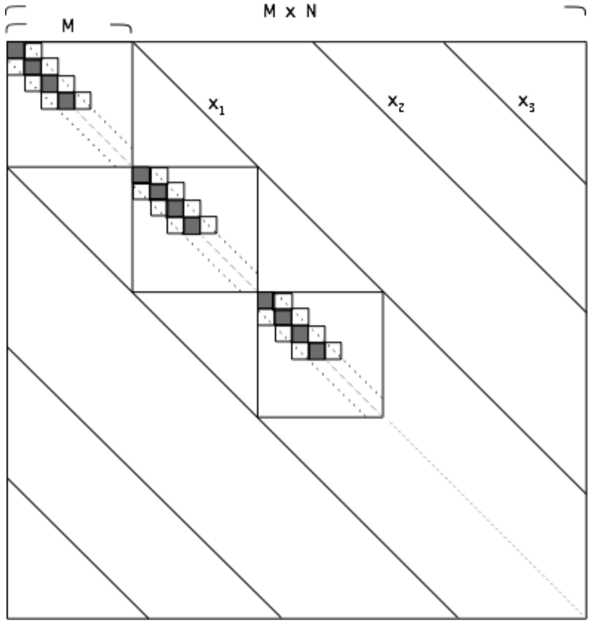
Supercomputing aspects: matrix solver

- Linear equation

$$A\vec{f}_\nu = \vec{d}$$

- Neutrino distribution
  - $N_{space}=n_r \times n_\theta \times n_\phi$
  - $N_\nu=n_\varepsilon \times n_{\theta\nu} \times n_{\phi\nu}$

  $N_{vector}\sim 10^6 \times 10^3$



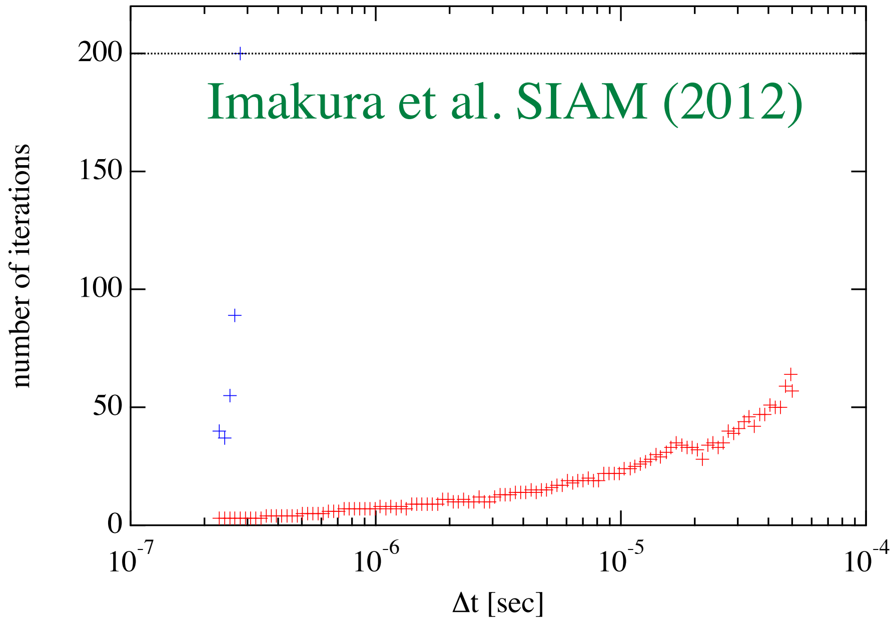
N_{vector} $\sim 10^9$

- Iterative method

  pre-conditioner by Imakura

  larger time step is possible

  ~factor 10 faster

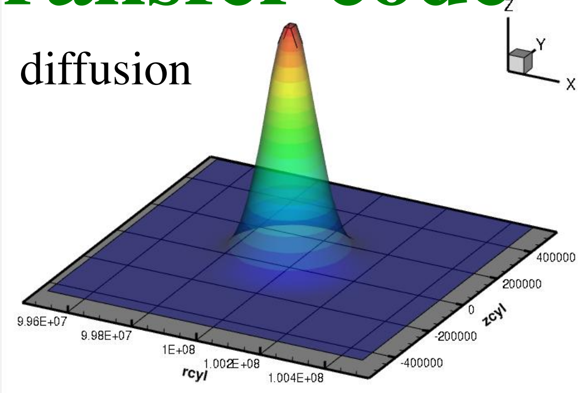


Validation of 3D-neutrino transfer code

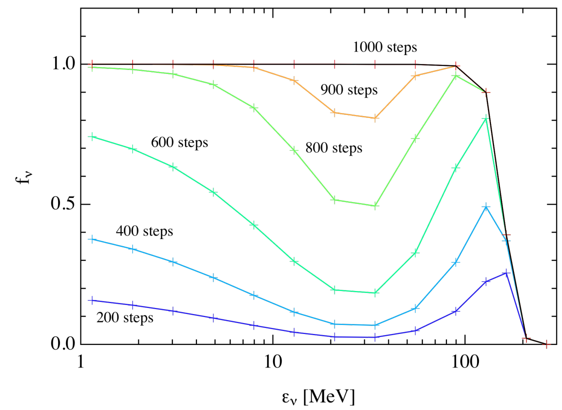
- by analytic solutions
  - Gauss packet, free space
  - Formal solution along path
  - Approach to equilibrium
- by spherical solutions
  - Fixed backgroud
    - collapse, bounce stages
  - density, flux, moments
  - ν-reactions, m. f. path

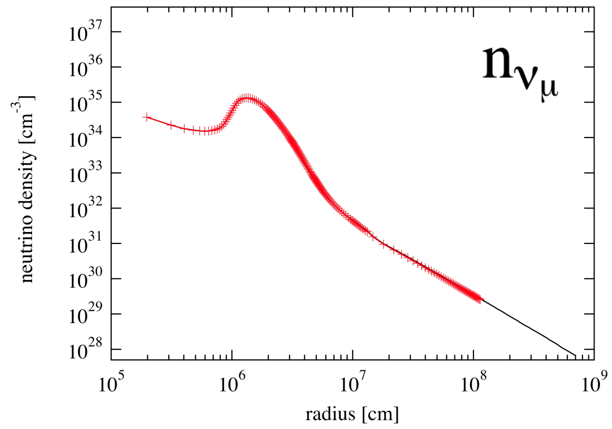
utilizing 1D ν-radiation hydrodynamics (GR)
by Sumiyoshi et al. ApJ (2005)

diffusion



equlibrium





Sumiyoshi & Yamada ApJ (2012)

Applications to 2D/3D supernovae

demonstration of 3D code

Axially symmetric supernova core

- **Fix the ρ, T, Y_e profile & Solve 3D ν-transfer**

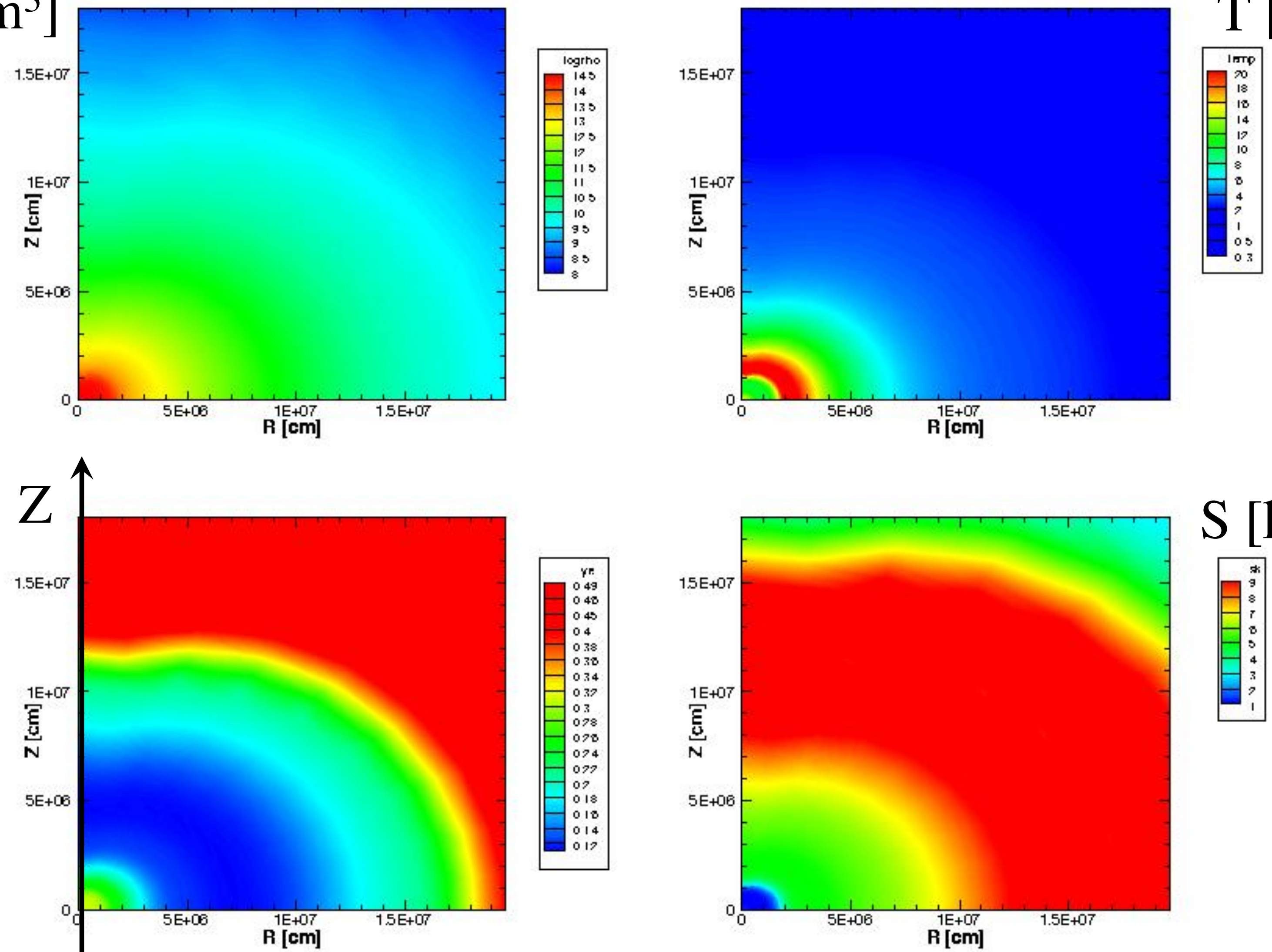
ρ[g/cm^3]

T [MeV]

Z

Y_e

S [k_B]



Sumiyoshi, Yamada ApJ (2012)

ref. 1D, 15M_{sun}, t_{pb}=100ms

Axially symmetric supernova core

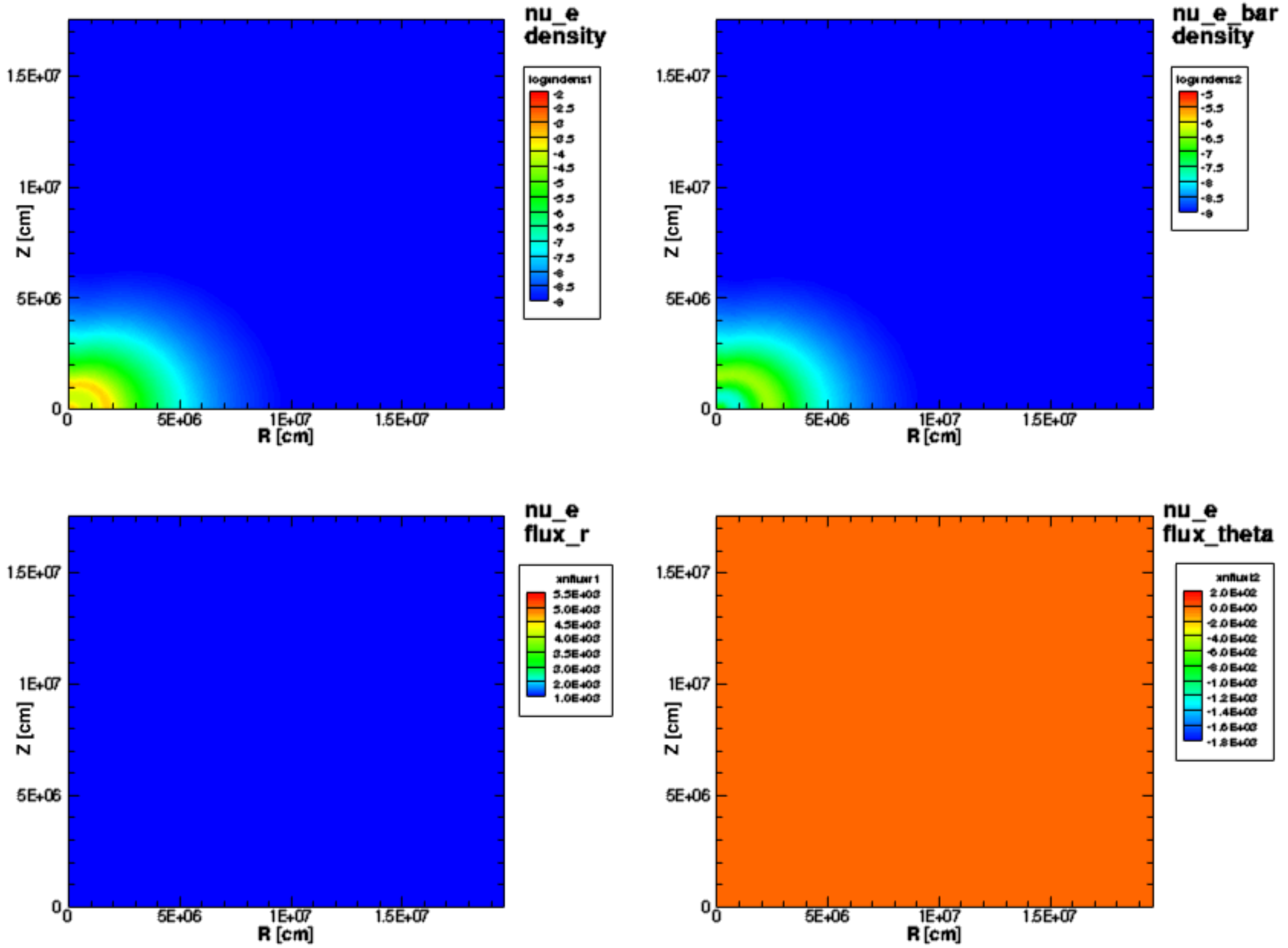
- **From small densities, the time evolution until the stationary state**

ν_e density

$\bar{\nu}_e$ density

ν_e Radial flux (r)

ν_e Polar flux (θ)

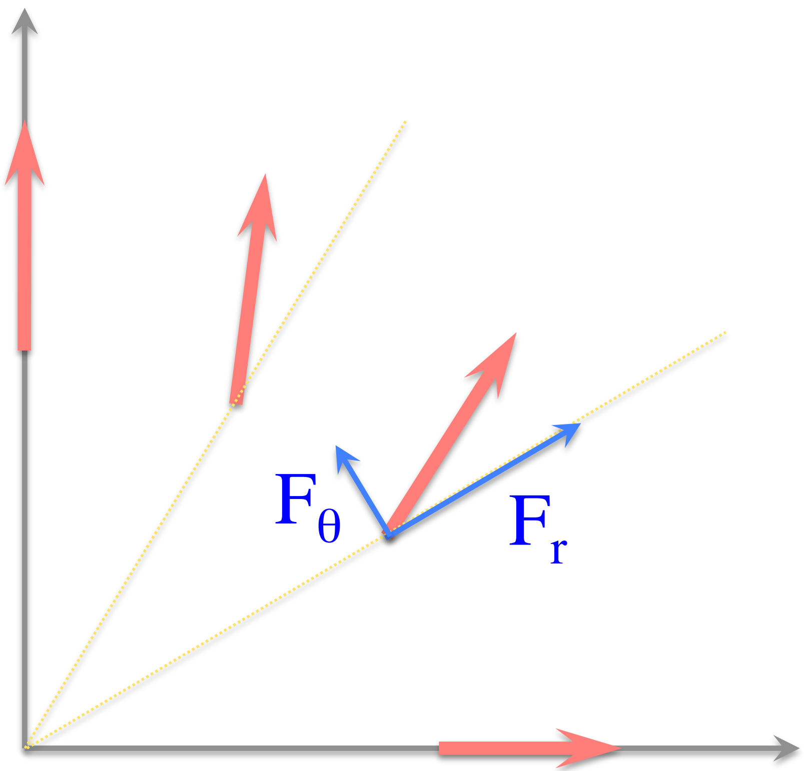


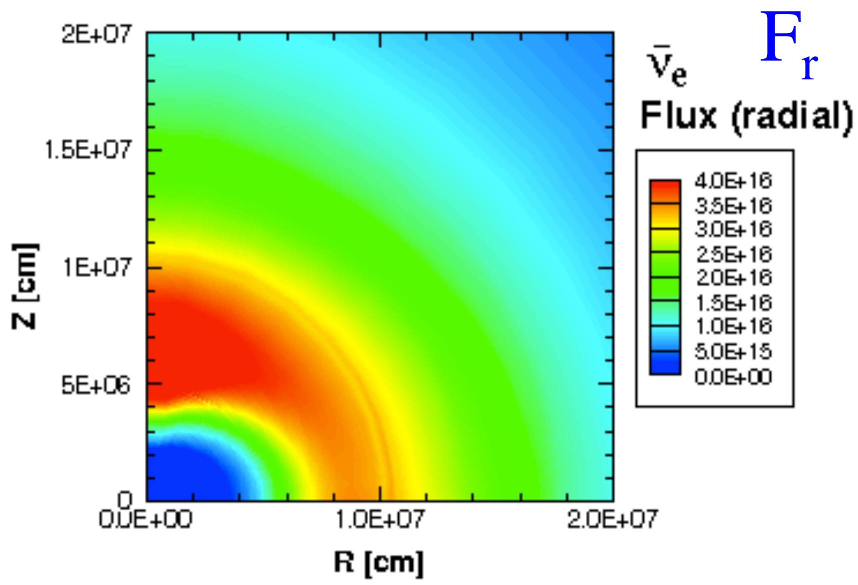
Sumiyoshi, Yamada ApJ (2012)

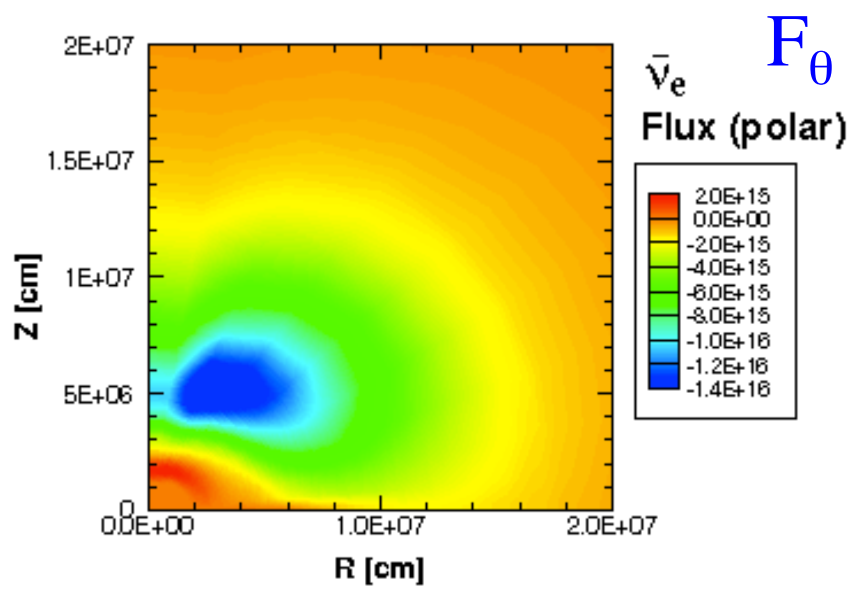
t=0~10ms

Advantage of 3D neutrino-transfer

- describes polar flux
  - beyond ray-by-ray
  - beyond diffusion







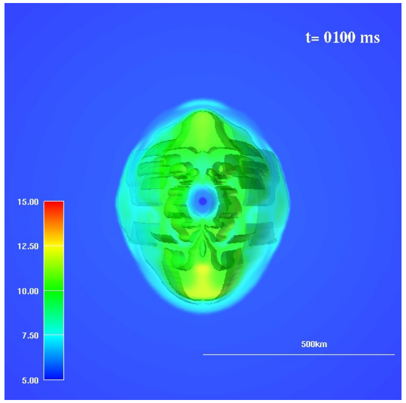
Sumiyoshi, Yamada ApJ (2012)

2D supernova core

$\bar{\nu}_e$ density distribution

- Check of ray-by-ray

  too strong angle dependence



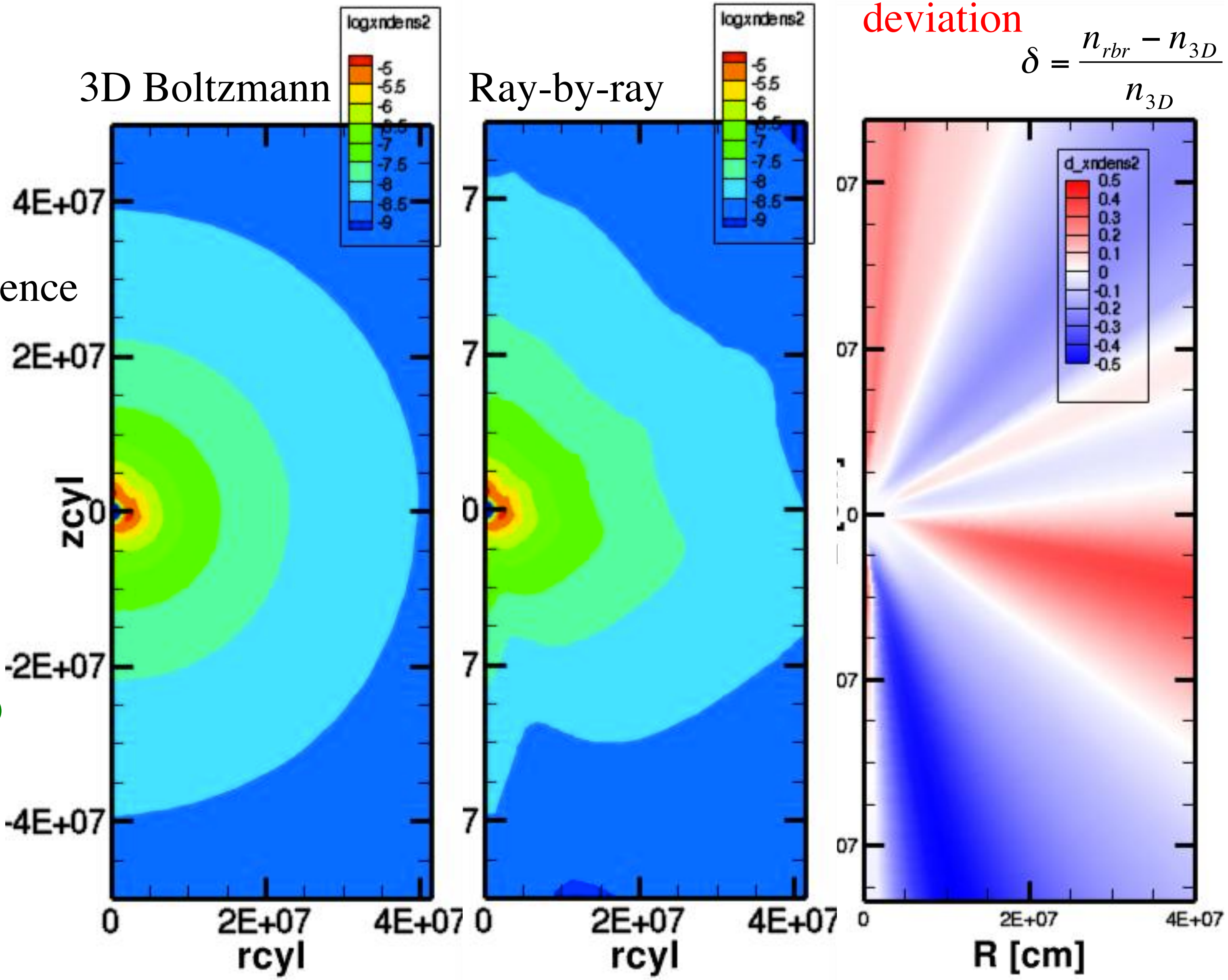
From Takiwaki (2011)

3D Boltzmann

Ray-by-ray

deviation

$$\delta = \frac{n_{rbr} - n_{3D}}{n_{3D}}$$



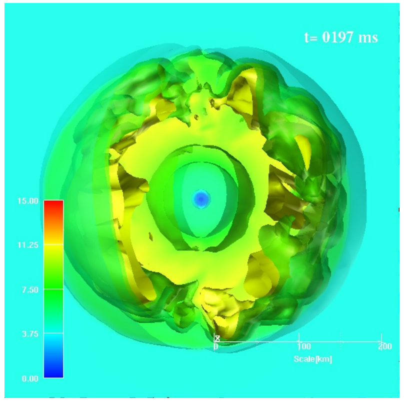
$11.2M_{sun}$, 2D

100ms

Preliminary

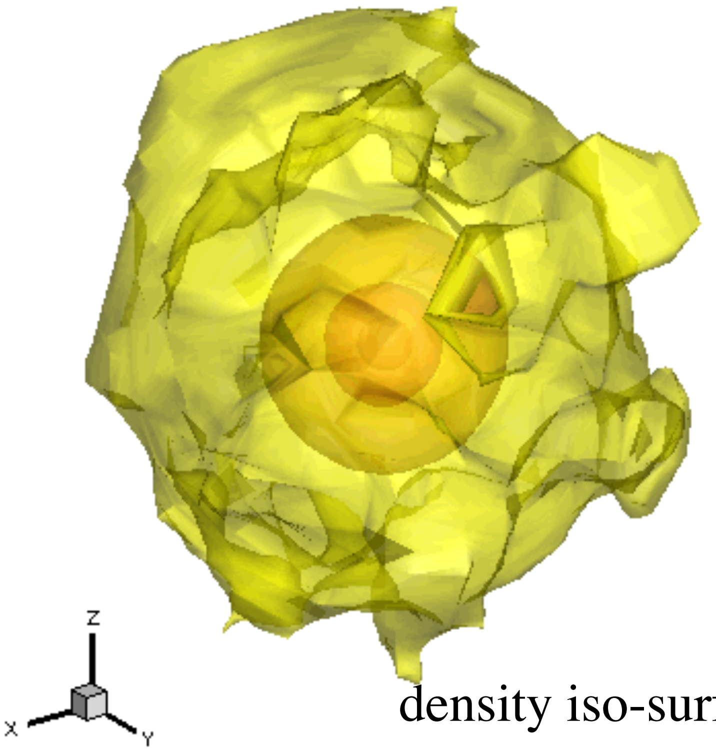
Study of 3D neutrino-transfer in supernova core

3D profile by Takiwaki (2011)

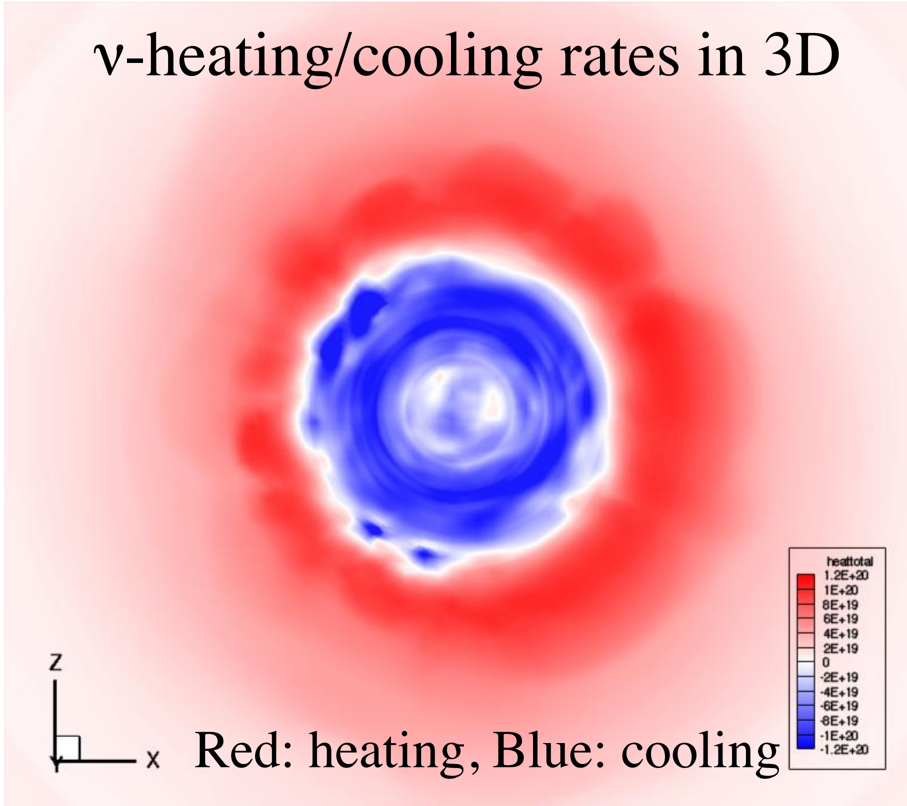


3D neutrino distributions, flux, spectrum

beyond approximations to explore new effects



$\bar{\nu}_e$
density iso-surface

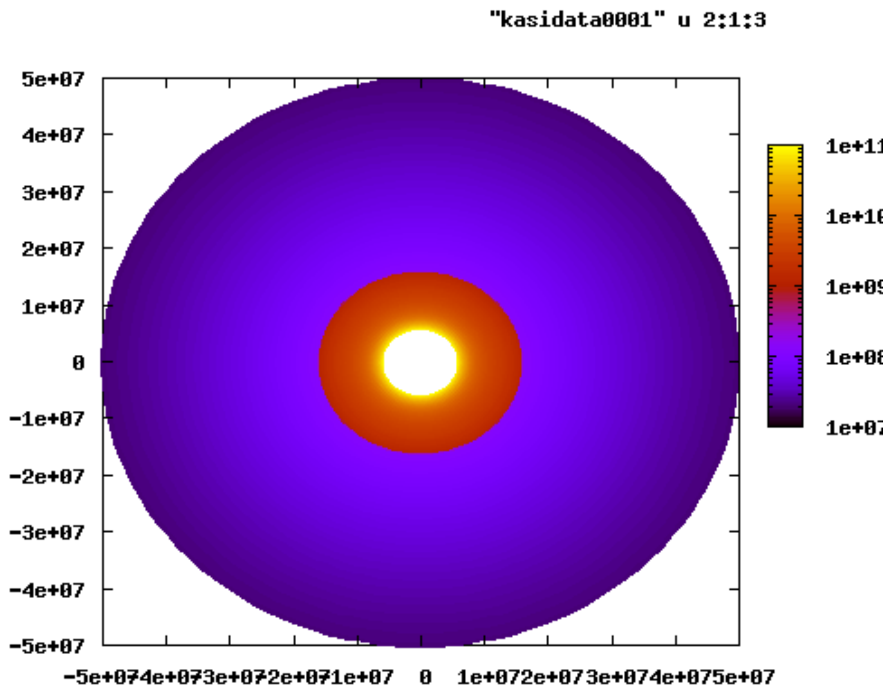


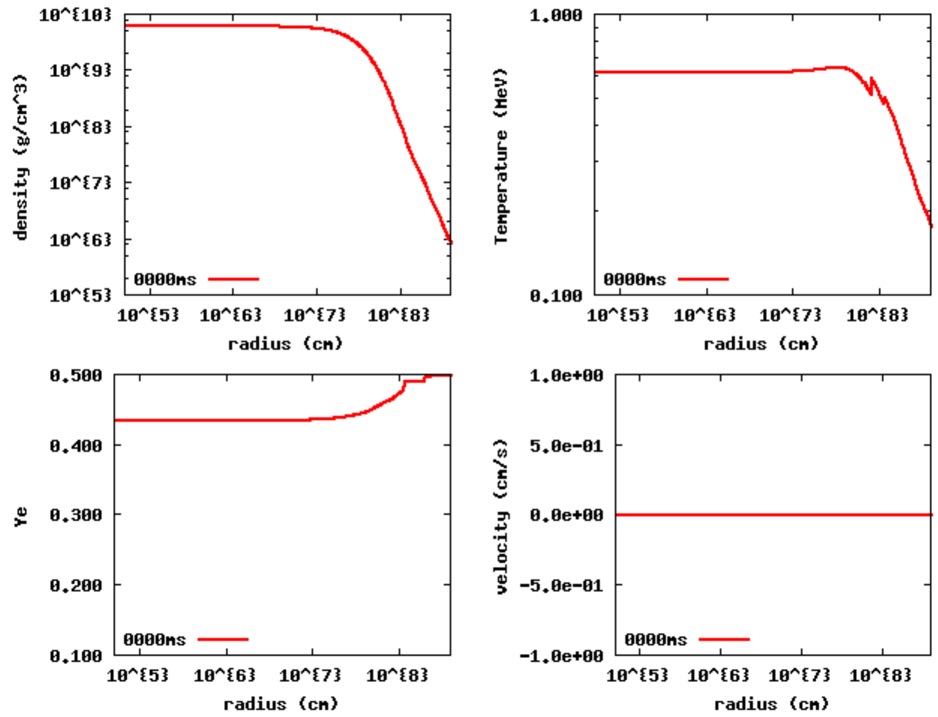
Preliminary

Coupling with hydrodynamics Nagakura

working on the code for 2D/3D neutrino-radiation hydrodynamics

- 2D hydro code is ready
- 1D collapse test





Computational load and future

- We have MPI parallel code + Hitachi tuning
- Matrix solver costs ~M^3N

Matsufuru, Hashimoto

machine	space	neutrino	memory	operations
Current	256 x 32 x 64	8 x 12 x 14	2TB	6 Tera-flop
K-computer	512 x 64 x 128	12 x 24 x 20	200TB	2 Peta-flop
Exascale	512 x 128 x 256	24 x 24 x 24	3PB	80 Peta-flop

Kotake et al. PTEP (2012)

- working on KEK, planned on K-computer
- needs Exa-scale for full 3D supernovae

Summary

- Neutrino-transfer in 3 dimensions is possible
  - Code to solve Boltzmann eq. in 6D
  - Collaboration with computational scientists (A04)
    - Matrix solver, Parallel coding, Tuning
- Applying to 2D/3D supernova cores
  - Unique feature: Non-radial fluxes
  - Examine the approximations used so far
- Ready to test ν-transfer + hydro. code
  - toward the grand challenge of 3D supernovae

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- HPCI Strategic Program Field 5
- Grant-in-Aid for Scientific Research (20105004, 20105005, 22540296, 24244036)
- Supercomputing resources at KEK, YITP, UT, RCNP, K-computer