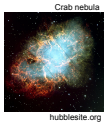
Numerical code of neutrino-transfer in 3D for core-collapse supernovae



K. Sumiyoshi[1], H. Nagakura[2], S. Furusawa[2] and S. Yamada[2]
Numazu College of Technology[1] and Waseda University[2]

Sumiyoshi and Yamada, ApJS 199 (2012) 17

e-mail: sumi@numazu-ct.ac.jp

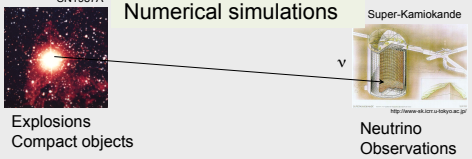
Neutrino transfer:

Key role in dynamics of SNe

- Hydrodynamics
- Neutrino-transfer
- Magnetic fields

⇔

- Equation of state
- Neutrino reactions
- Electron captures



- Neutrinos as agents of energy transfer
- Carry information of compact objects

• We developed the numerical code to solve neutrino transfer in 3D

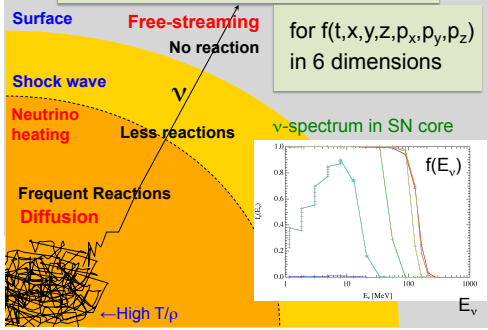
Neutrinos inside & outside

- From diffusion to free-streaming
- Intermediate regime is important

Boltzmann equation

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

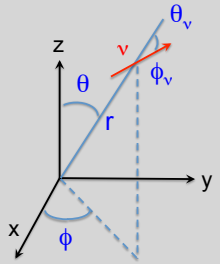
for f(t,x,y,z,p_x,p_y,p_z) in 6 dimensions



Numerical calculations of neutrino transfer in 3D

Solve Boltzmann equation in spherical coordinate

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



- Time evolution of neutrino distributions in 6D

$f_\nu(r,\theta,\phi;\ \varepsilon_\nu,\theta_\nu,\phi_\nu;\ t)$ • 3D space + ν-energy, 2 angles

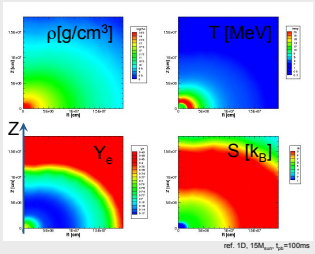
- Multi-energy, Multi-angle (S_n-method) finite differencing (upwind+central), time-implicit method
- Collision term: set of neutrino reactions with supernova EOS table

• 3D neutrino-transfer became possible by our code on supercomputers

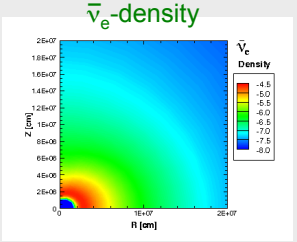
New code reveals the 3D features of neutrino transfer

ν-transfer in 2D supernova core

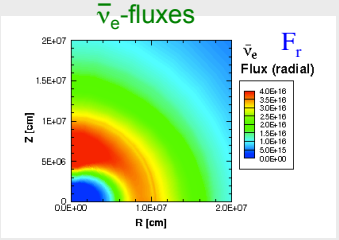
for the ρ, T, Y_e profile

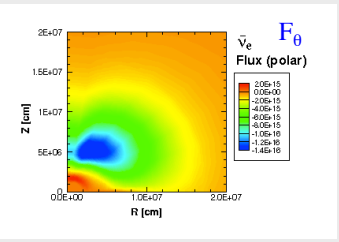


$\bar{\nu}_e$-density



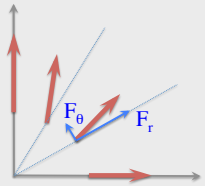
$\bar{\nu}_e$-fluxes





- Radial flux is enhanced near pole
- Polar flux is significant

cf. ray-by-ray method
diffusion approximations



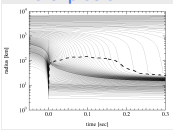
• Describes even non-radial fluxes beyond the previous approximations

Frontier in 3D simulations

Progress of neutrino transfer

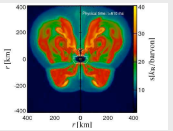
- 1D: first principle calculations
  - Examine Microphysics, Systematics
- 2D: approximate treatment
  - Recent state-of-the-art calculations
- 3D: numerical challenges
  - Explore hydrodynamical instabilities

• No explosion in 1D



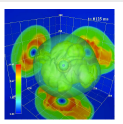
Sumiyoshi et al. ApJ (2005)

• Explosion dynamics in 2D



Marek-Janka, ApJ 694 (2009)

in 3D



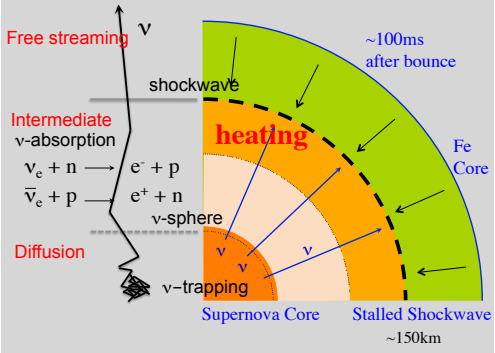
Takiwaki ApJ (2012) arXiv:1108.3989

• Need full 3D calculations

- To establish the supernova mechanism
- Hydrodynamical instabilities with ν-heating

ν-heating mechanism

Revival of shockwave by energy transfer via ν-absorptions depends on ν-energy, flux, reactions → neutrino transfer



Inside the numerical code:

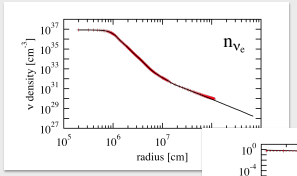
Collision terms:

Essential set of neutrino reaction rates

Bruenn ApJS (1985) + Extensions

- Emission/Absorption:
  $e^- + p \leftrightarrow \nu_e + n$
  $e^+ + n \leftrightarrow \nu_e + p$
  $e^- + A \leftrightarrow \nu_e + A'$
- Scattering:
  $\nu_i + N \leftrightarrow \nu_i + N$
  $\nu_i + A \leftrightarrow \nu_i + A$
- Pair-processes:
  $e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$
  $N + N \leftrightarrow N + N + \nu_i + \bar{\nu}_i$

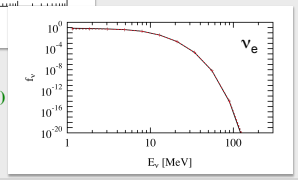
- energy, angle dependence
- EOS tables
  Shen, LS etc
- Three species
  ν_e, $\bar{\nu}_e$, ν_μ
- Code check:
  - Free-streaming
  - Diffusion tests



tested by 1D calc.

Sumiyoshi et al. ApJ (2005)

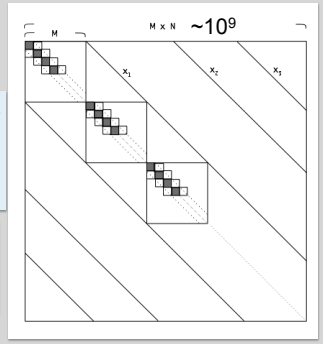
Formal solutions



Solve large sparse matrix:

Linear equation for ν-distributions $A\vec{f}_\nu = \vec{d}$

Parallel code by MPI



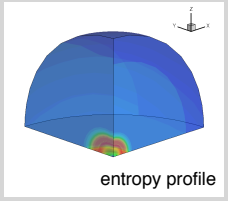
$N_{vector} \sim 10^6 \times 10^3$

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

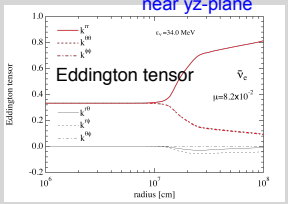
memory:
vector >20GB
matrix >1TB

ν-transfer in 3D supernova core

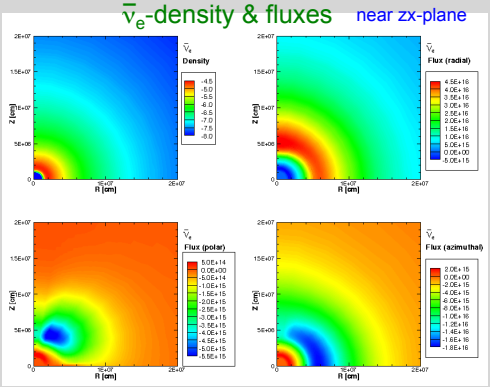
Deformation with ϕ-dependence



near yz-plane



$\bar{\nu}_e$-density & fluxes near zx-plane



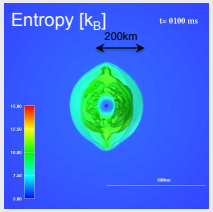
- Azimuthal flux as well as polar flux
- Applicable even outside the diffusion regime

- Provide necessary information of ν-transfer in 3D for hydrodynamics

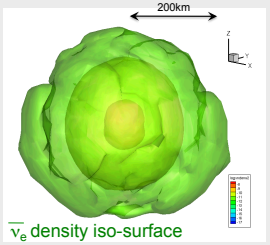
Applications to 2D & 3D simulations:

3D supernova core after bounce

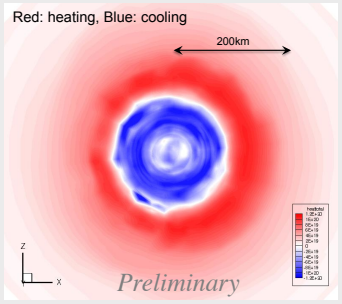
- Neutrino densities, flux, reaction, heating rate in 3D



Takiwaki et al. (2011)

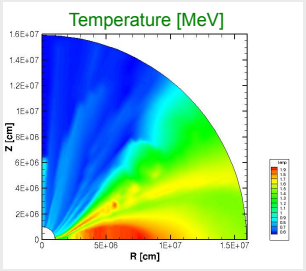


ν-heating/cooling rates



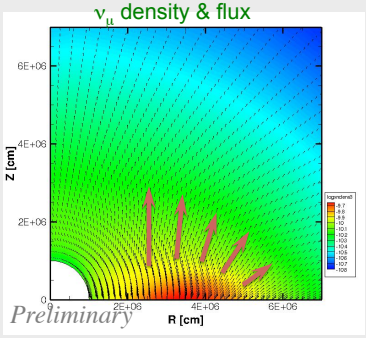
Accretion disk around BH in collapsar

- Non-radial fluxes of thermal neutrinos from disk



Sekiguchi et al. (2011)

ν_μ density & flux



- 3D ν-transfer code as a tool to explore the neutrino influence in dynamics

Summary:

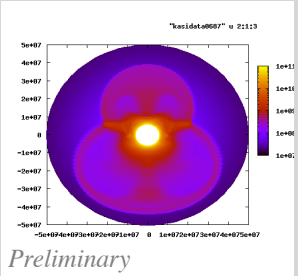
- A new code to solve 3D ν-transfer
  - Applied to 2D, 3D supernova cores
  - Reveal the role of neutrinos in 3D
- Toward the full 3D simulations
  - Working on coupling with hydro-code
  - 3D ν-radiation hydrodynamics
- Grand challenge calculations
  - To clarify the 3D explosion mechanism

Core-collapse supernovae is one of the target simulations on K-computer

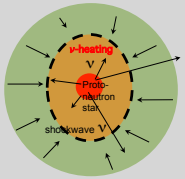
Coupling with hydro-code

Nagakura et al. (2012)

To study effects of ν-transfer in SASI conditions

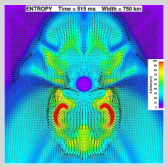


Light bulb
→ Boltzmann eq.



Beyond the approximations:

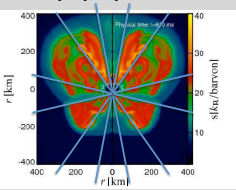
Flux-limited diffusion



Usage of Flux limiter
- intermediate regime?

Acoustic Powered
Burrows et al. ApJ 640 (2006) 878

Ray-by-ray method



Solve Indep. 1D-transport
- lateral transport?

SASI + Neutrino-heating
Marek-Janka, ApJ 694 (2009) 664

Numerical simulations are performed at the supercomputing resources at UT, KEK, RCNP, NAOJ, JAEA, YITP

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