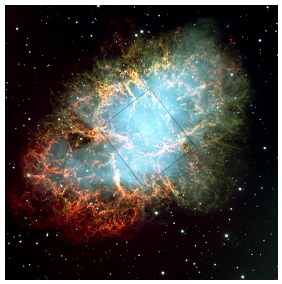
Neutrino radiation-hydrodynamics & equation of state

Crab nebula



hubblesite.org

K. Sumiyoshi

(Numazu College of Technology / KEK)

With K. Nakazato, S. Yamada, C. Ishizuka, H. Suzuki,
H. Matsufuru, A. Imakura, T. Sakurai,
H. Nagakura, S. Furusawa

KEK

YITP

Brief report on:

- Progress of EOS tables in astrophysics
- 3D neutrino-radiation hydrodynamics

Collaborations on supernova studies

- Quark, Nuclear Physics
  - EOS, ν-reactions

A01, A02

- Massive Star Models
  - Mass, Metallicities

A03

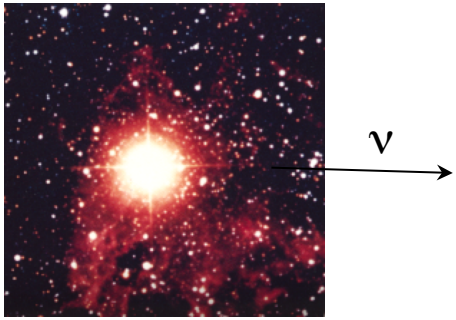
- Simulations of supernovae
  - ν-radiation hydrodynamics

A03

parallel computing

A04

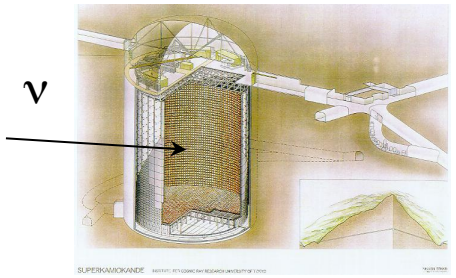
Explosion mechanism



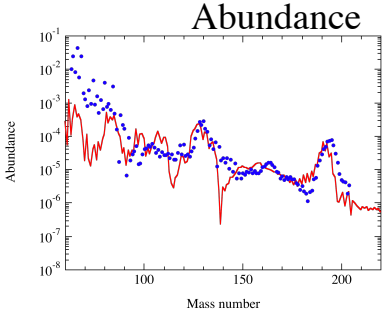
SN1987A

Neutrino Astronomy

Super-Kamiokande



Nucleosynthesis



Progress of EOS tables in astrophysics

- Web pages for EOS table **→石塚 12/3**
- Nuclear Compositions in supernovae

  Furusawa et al. ApJ (2011) **→古澤 12/4**
- Probe hyperon potential by neutrinos

  Nakazato et al. ApJ (2011) accepted

  (中里, 大西)
- QCD critical point sweep

  Ohnishi et al. Phys. Lett. B (2011)

Supernova EOS covering the wide range

- Tables of EOS frequently used
  - Lattimer-Swesty EOS (1991) LS-EOS
    - *Skyrme-interaction*
  - H. Shen, Toki, Oyamatsu & Sumiyoshi EOS (1998) Shen-EOS
    - *Relativistic Mean Field (RMF) approach*

1. Extension to high densities ($\rho > \rho_0 = 0.17 fm^{-3}$)
   - Hyperons, Quarks
     - *Ishizuka, Nakazato, H. Shen*

Softening of EOS

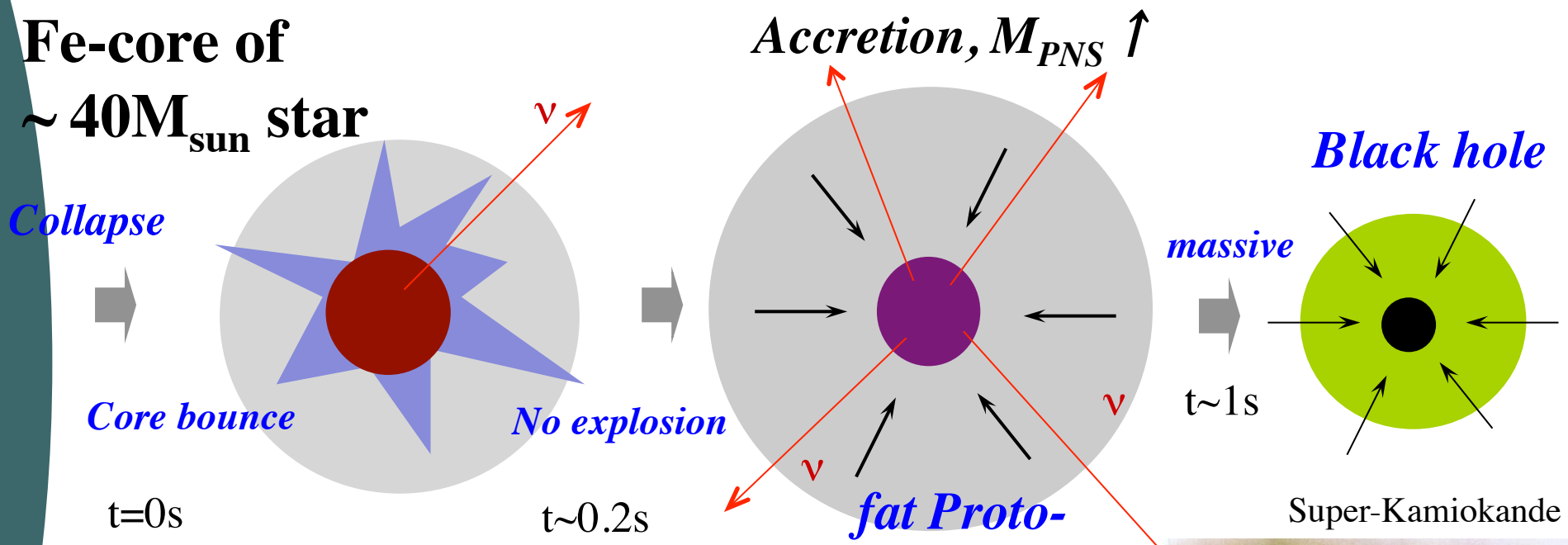
2. Extension to low densities ($\rho < \rho_0$)
   - Mixture of nuclei
     - *Furusawa*

Neutrino reactions

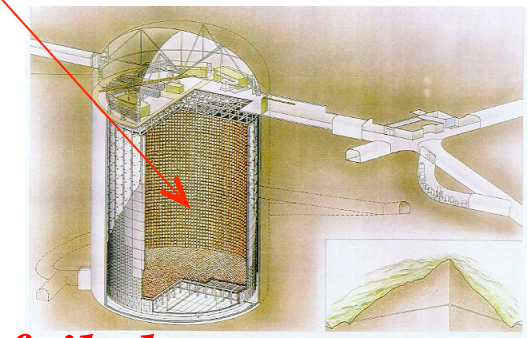
- Nuclear interactions, many body theories
  - G. Shen et al. (2011), Hempel et al. (2011)

→富樫 12/3

More massive stars lead to black holes



Super-Kamiokande



failed supernova ν

A Galactic case: 10^4 ν

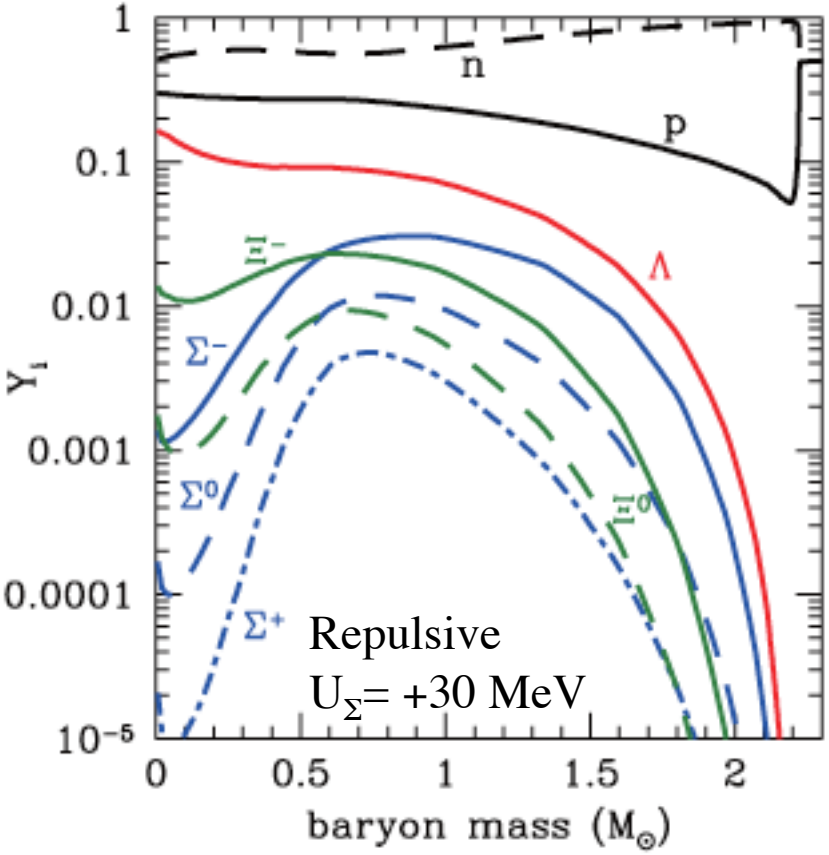
- Short duration of neutrino burst:
  - Shen EOS: 1.3s
  - Hyperon EOS: shorter
- Probe of exotic EOS at high ρ and T

Sumiyoshi et al. PRL (2006), ApJ (2009)

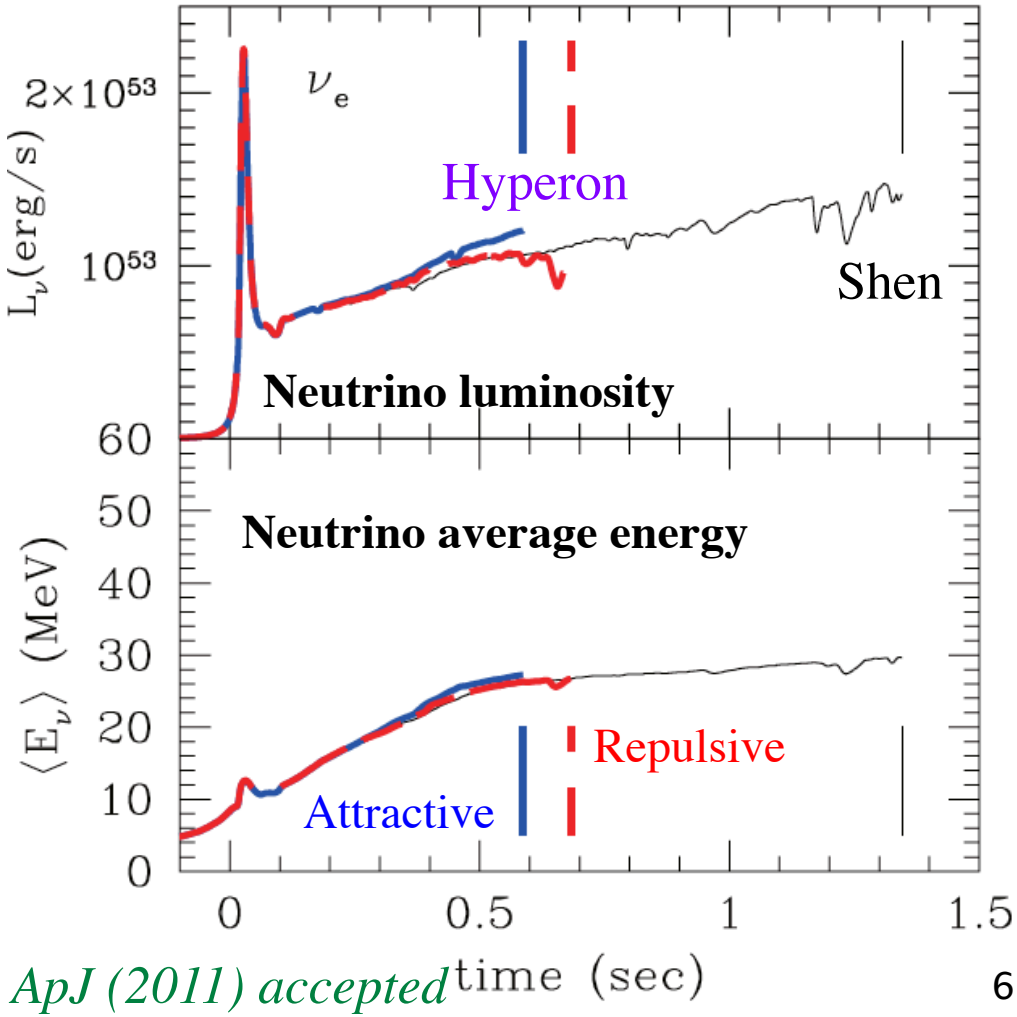
Nakazato et al. PRD (2010)

Neutrino burst from failed supernovae

- Probe EOS difference due to hyperon potential
  - Repulsive or attractive?: Σ-potential in matter



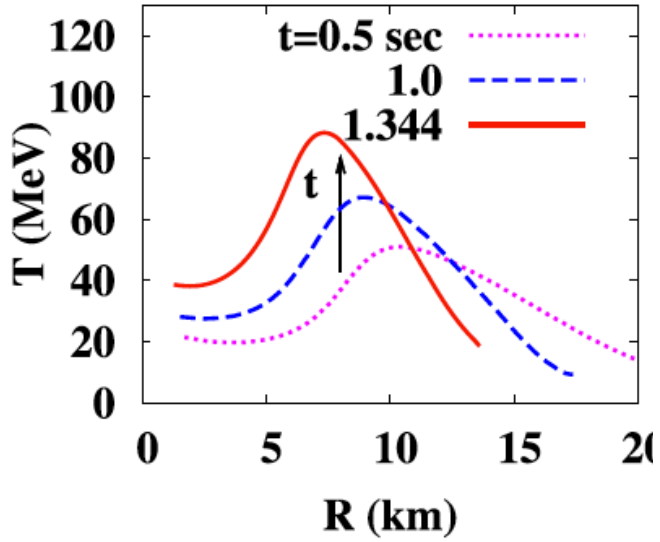
Hyperon mixture
in proto-neutron star

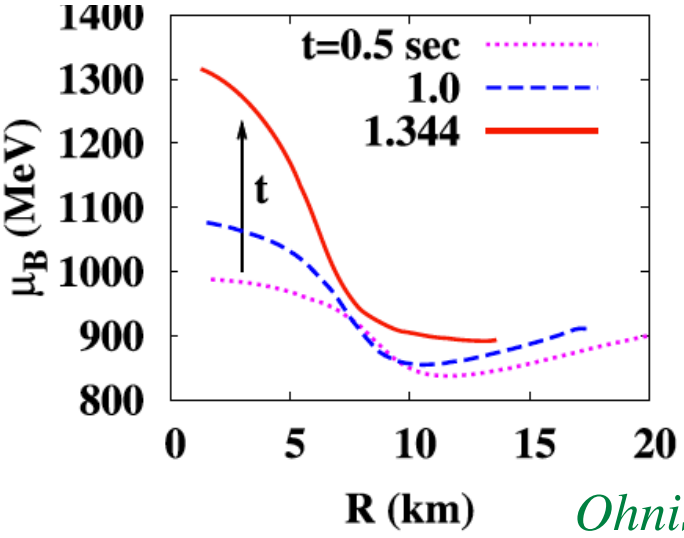


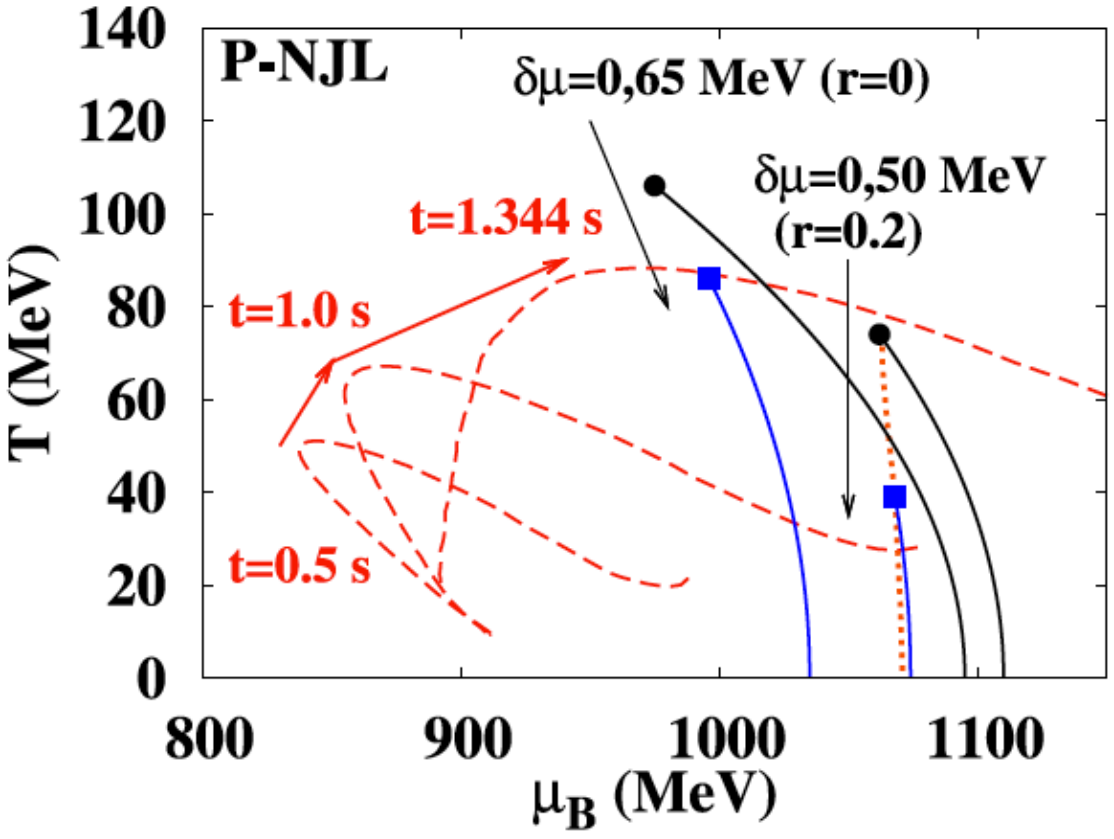
Nakazato et al. ApJ (2011) accepted

Probe of exotic phase during the collapse

- ρ & T sweep critical point / phase boundary







Ohnishi et al. Phys. Lett. B (2011)

3D neutrino-radiation hydrodynamics

- Code of 3D Neutrino transfer

  Sumiyoshi & Yamada, submitted to ApJ (2011)

- Code of Hydrodynamics **→長倉 12/5**
- Iterative method for matrix **→今倉 12/4**

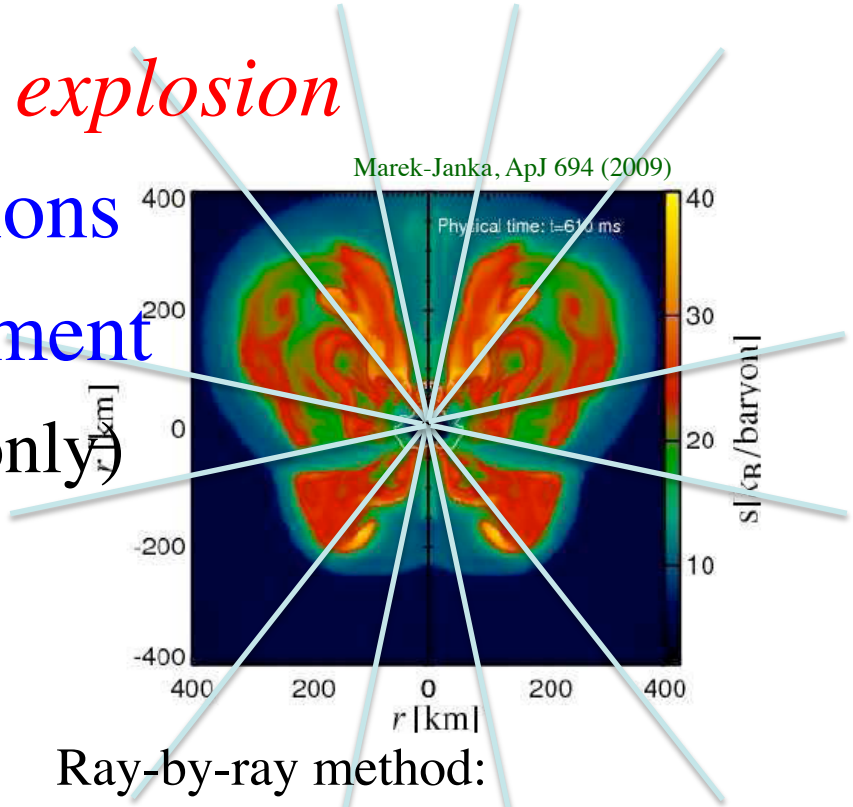
Status of neutrino radiation-transfer

- *Affect neutrino heating for explosion*
- 1D: first principle calculations
- 2D, 3D: approximate treatment

– Ray-by-ray (Radial transport only)

Neglect lateral transport

- Need full 3D calculations



Ray-by-ray method:
Solve 1D-transport Independently

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

– Applications to supernova cores

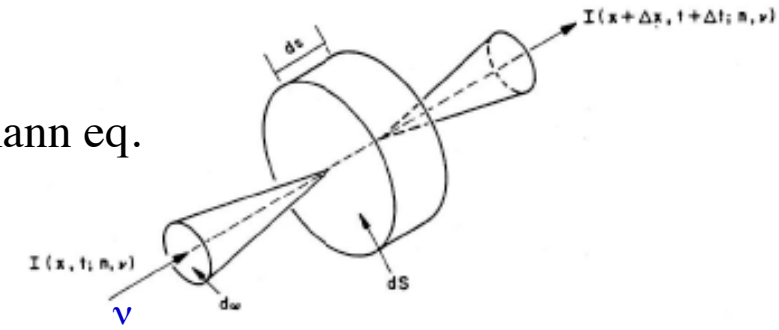
Sumiyoshi & Yamada, submitted to ApJ (2011)

To solve Neutrino transfer in 3D

- Time evolution of 6D-distribution

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

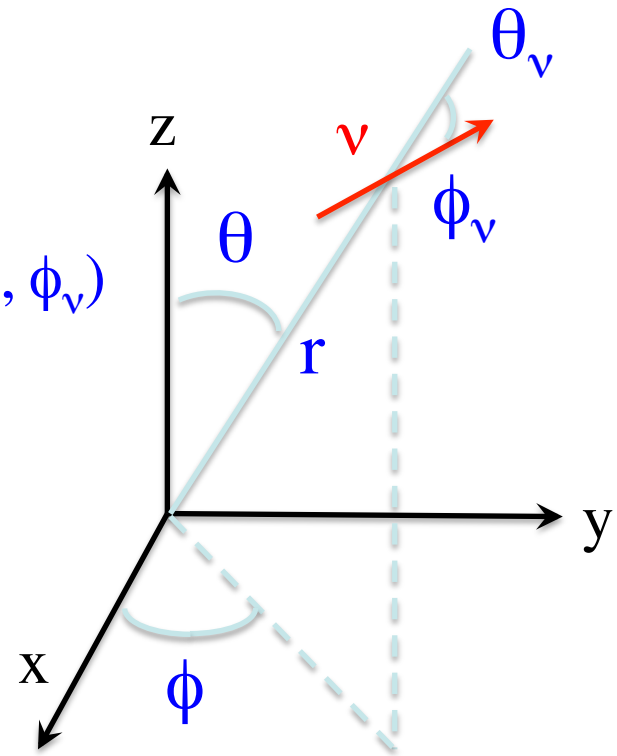
Boltzmann eq.



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

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

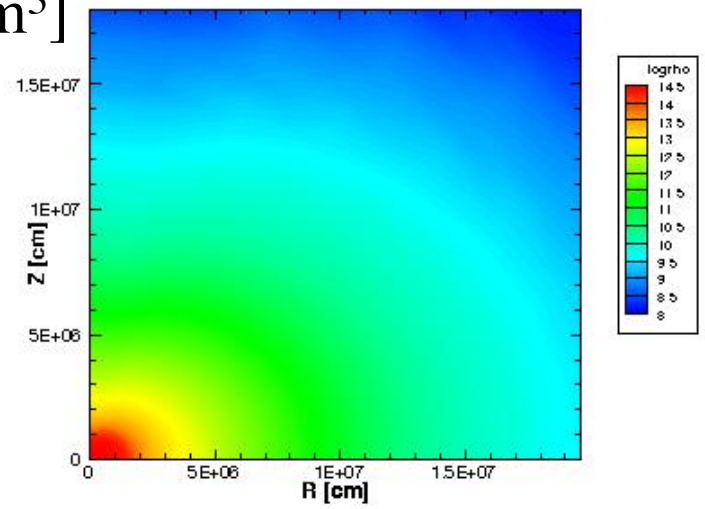
  - Neutrino energy (ε_ν), Neutrino angle (θ_ν, ϕ_ν)
    - 3D in spherical symmetry (r, ε_ν, θ_ν)
  - Neutrino reactions, EOS table
- Code: finite differencing, implicit
  - Linear eq. with large sparse matrix



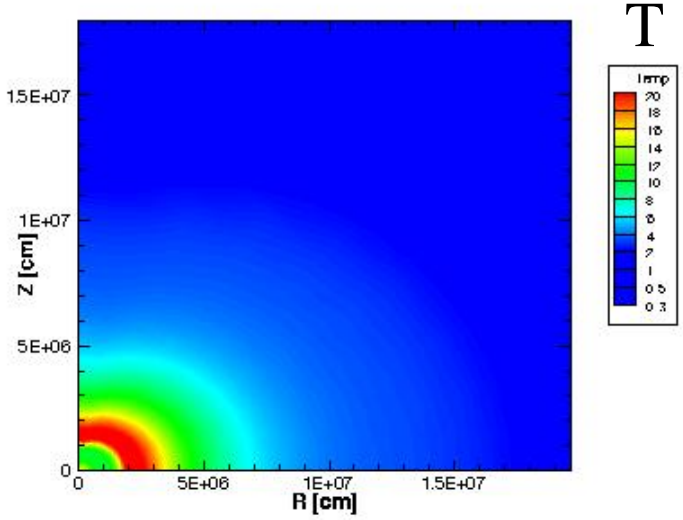
Axially symmetric supernova core

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

ρ[g/cm^3]

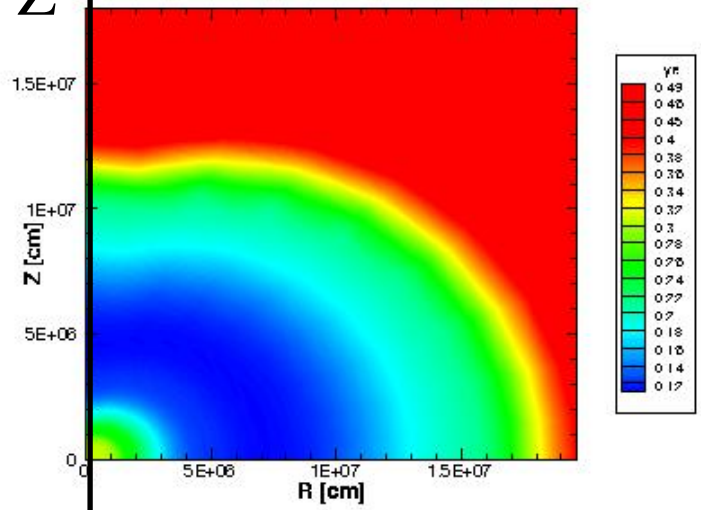


T [MeV]

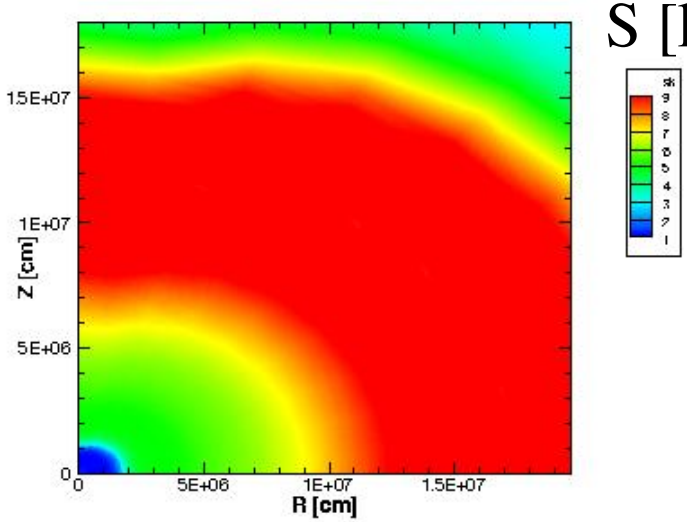


Z

Y_e



S [k_B]



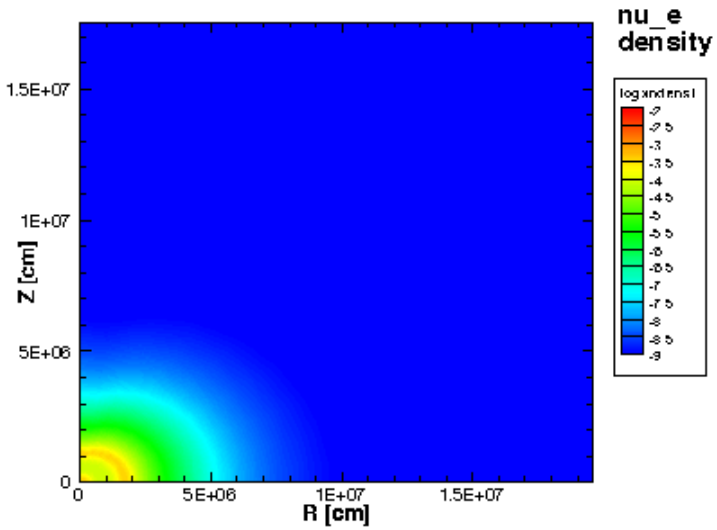
Sumiyoshi, Yamada ApJ (2011) submitted

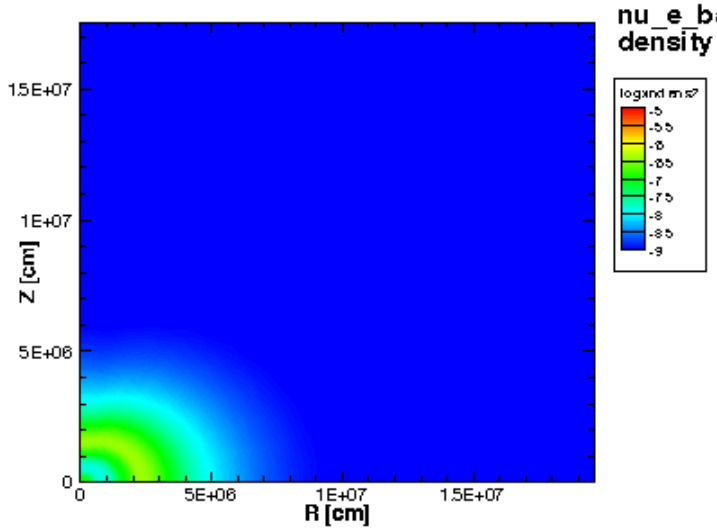
ref. 1D, 15M_{sun}, t_{pb}=100ms

Axially symmetric supernova core

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

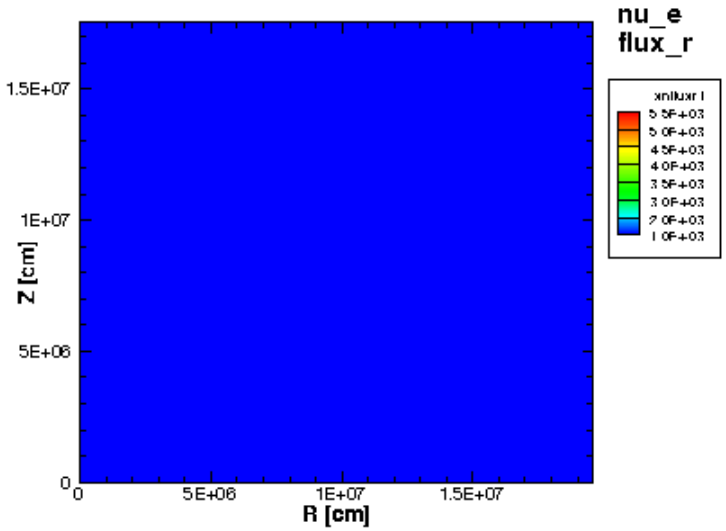
ν_e density

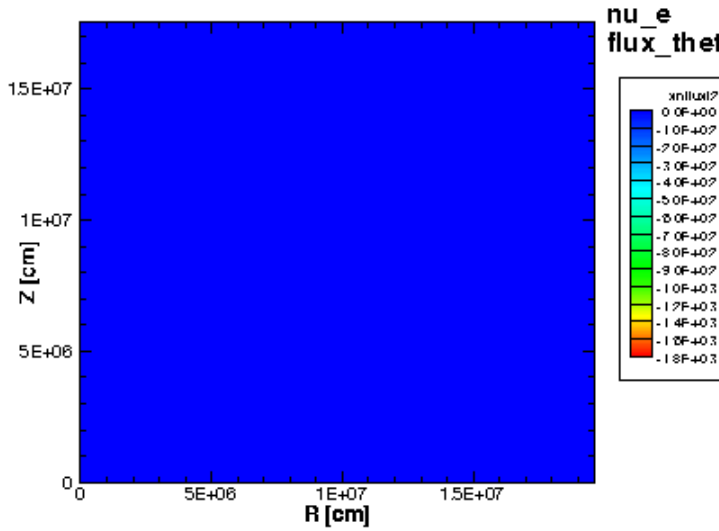




$\overline{\nu}_e$ density

ν_e Radial flux (r)





ν_e Polar flux (θ)

Sumiyoshi, Yamada ApJ (2011) submitted

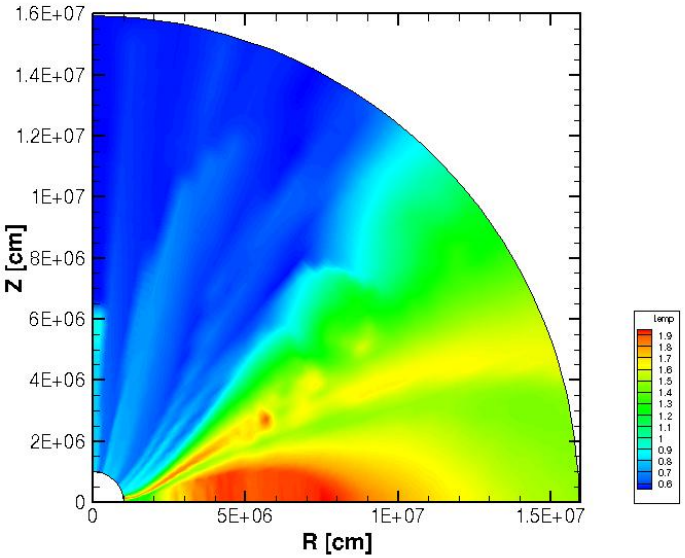
t=0~10ms

Accretion disk around BH in collapsar

From Sekiguchi (2011)

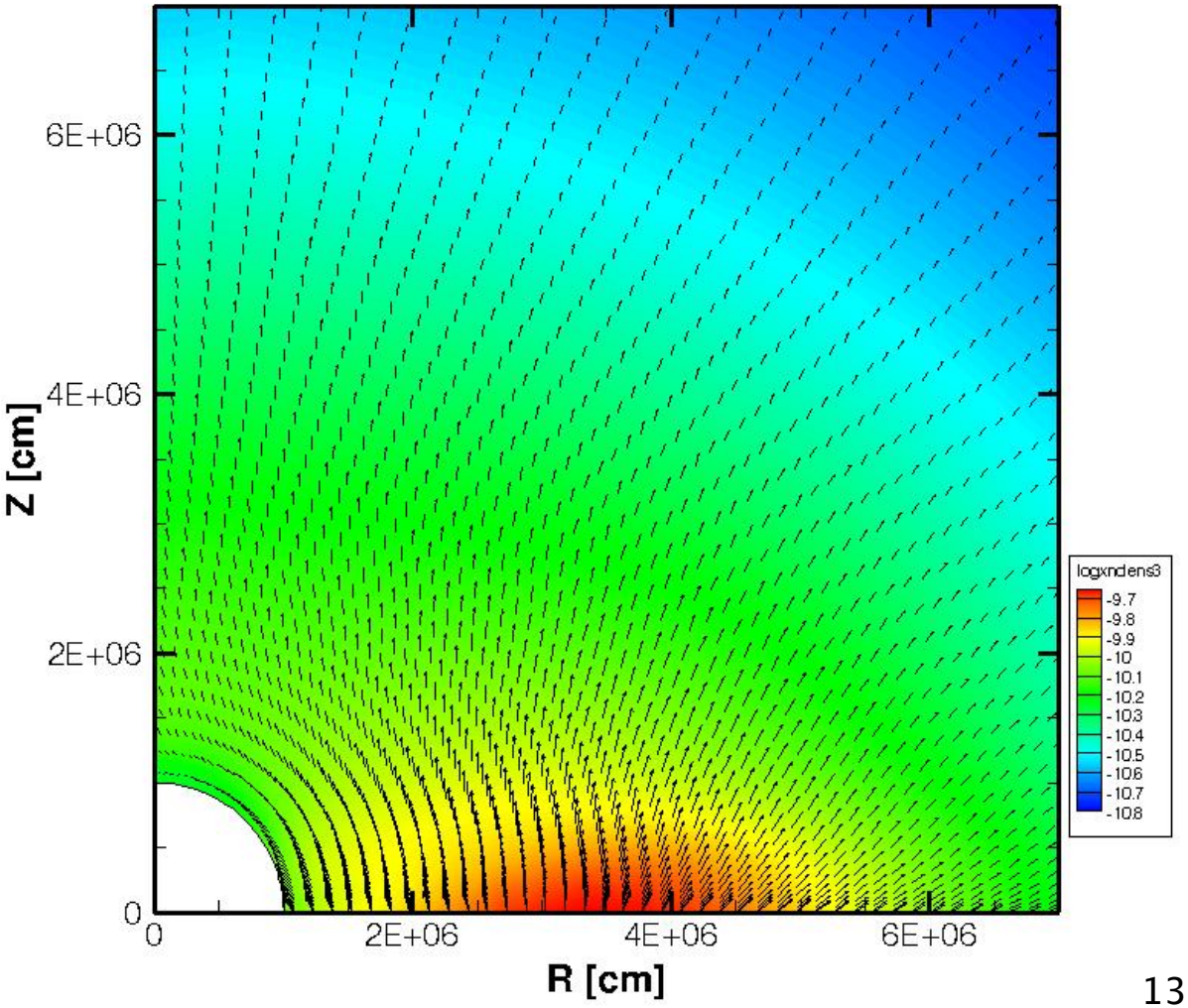
- **Polar flux of thermal neutrinos from disk**

Temperature [MeV]



ν_μ density & flux

Sumiyoshi (2011)



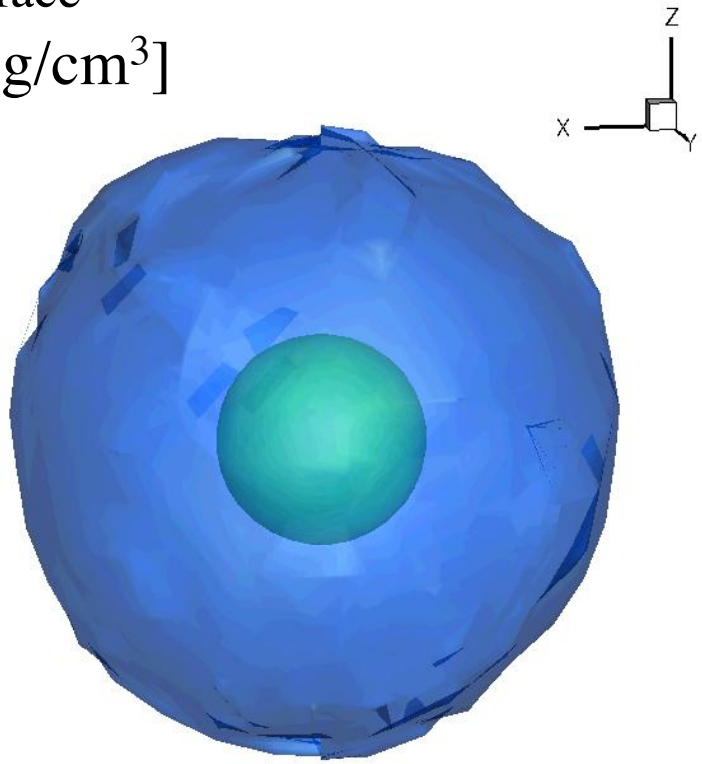
Preliminary

3D supernova core after bounce From Takiwaki (2011)

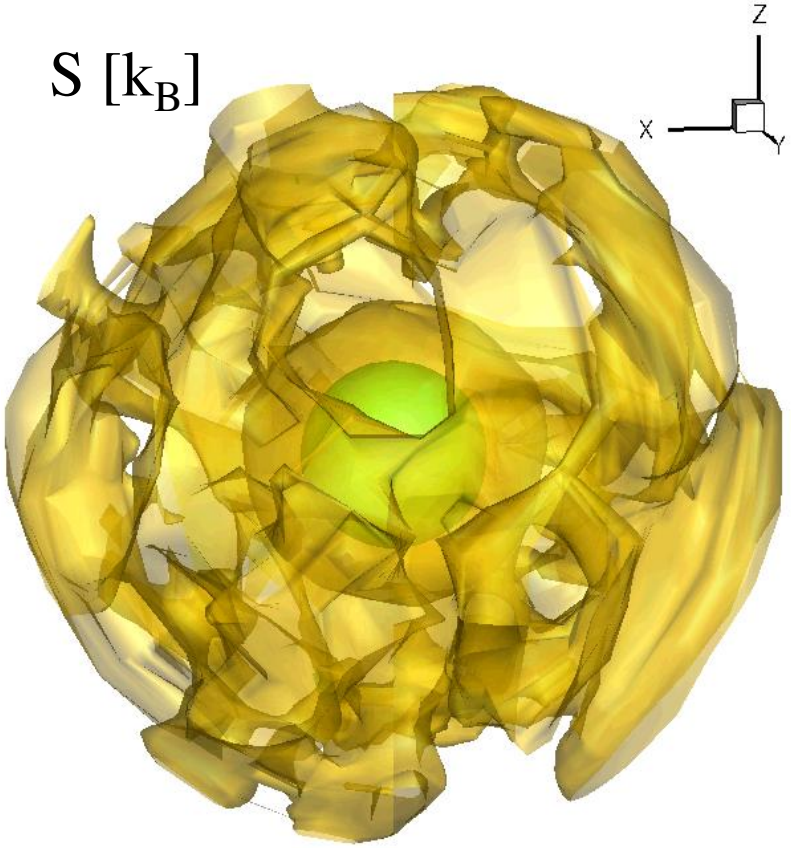
- **Fix the ρ, T, Y_e profile & Solve 3D ν-transfer**

Iso-Surface

ρ[g/cm^3]



S [k_B]



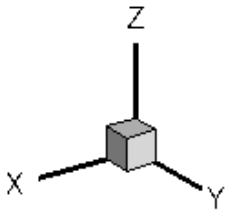
~ 200 km

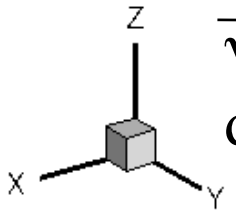
t=197ms

Time evolution of neutrino transfer in 3D

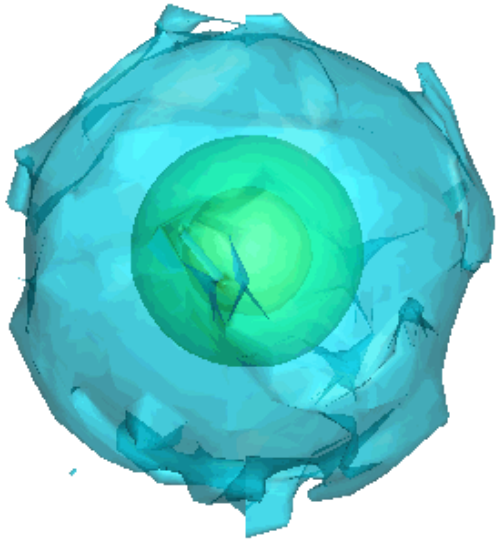
- **Emitted neutrinos diffuse out and propagate**

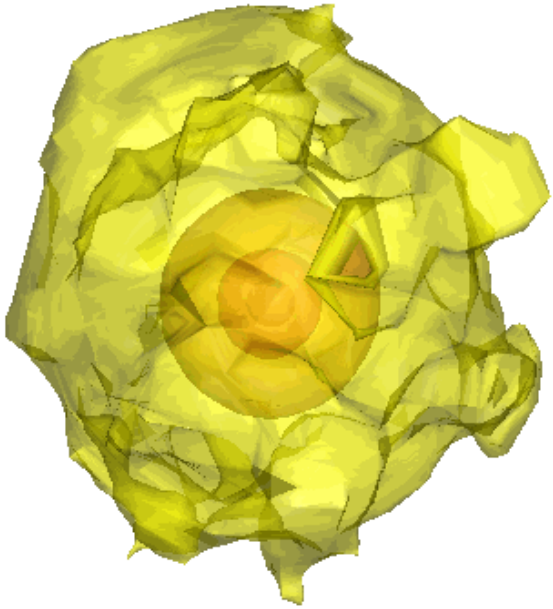
ν_e density Iso-Surface





$\bar{\nu}_e$ density





t=0~0.2ms

Preliminary

Development of 3D ν-transfer hydro. code

- 3D-neutrino transfer code: completed
  - Neutrino-reactions, EOS tables: implemented
    - Diffusion, free-streaming tests: checked
    - 1D profile, 2D, 3D formal solution: checked
- Study 3D neutrino-transfer for static profile
  - Applications to 2D, 3D profiles
    - Polar, azimuthal fluxes, beyond diffusion
- MPI parallel version: done by Matsufuru
- Matrix inversion improvement by Imakura
  - Need further optimizations to large systems
- Coupling with hydrodynamics by Nagakura

Thanks for collaboration with

- Supernova research
  - S. Yamada
  - K. Nakazato
  - H. Suzuki
  - H. Kikuchi
- RMF-EOS table
  - H. Shen
  - K. Oyamatsu
  - H. Toki
- Extension of EOS table
  - S. Furusawa
  - C. Ishizuka

- Supercomputing
  - H. Matsufuru
  - A. Imakura
  - T. Sakurai
- Numerical simulations
  - H. Nagakura
  - T. Takiwaki
  - K. Kotake
  - Y. Sekiguchi
- Many body theory
  - M. Takano
  - H. Togashi and others

Supercomputing resources at KEK, YITP, UT, RCNP, NAOJ, JAEA

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