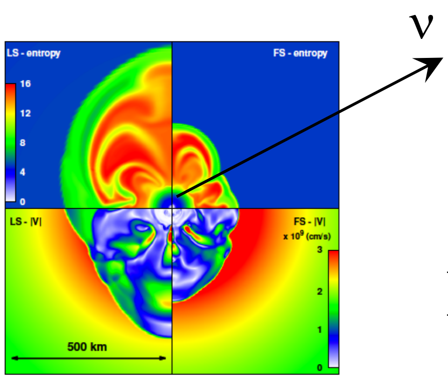
Progress of neutrino transfer and equation of state



K. 'Sumi'yoshi

National Institute of Technology
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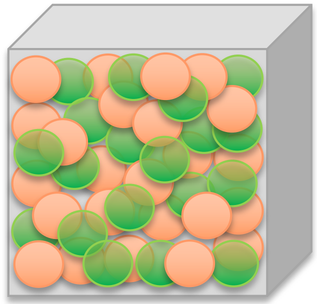
Wikipedia (trimmed)



Needs of EOS data with extensions for simulations

- Developments of Shen EOS and their influence
- Solver of Boltzmann equation for neutrino transfer

Early history of supernova EOS for simulations

1980's

- Systematic studies to explore EOS effects

  Analytic formulae *Takahara-Sato, Baron-Cooperstein-Kahana*

1990's

- A few sets for supernova EOS: classic

Skyrme-Hartree-Fock	*Hillebrandt-Wolff* (HW)	1984
Extended liquid drop	*Lattimer-Swesty* (LS)	1991
Relativistic Mean Field	*Shen-Toki-Oyamatsu-Sumi* (Shen)	1998

  – From my episodes:

Proto-type EOS table	*Sumi*	March 1993
Full table of EOS table	*Shen*	November 1998
First request e-mail	*Rosswog*	March 1999

2000's~

- Improvement of EOS tables & astrophysical applications

  See Oertel et al. RMP (2016)

Mixture of exotics	Mixture of nuclei
Interactions	Microscopic

CompOSE

  – Variety of EOS for neutron stars and supernovae

Developments of Shen EOS table

1990's ~

- Concept:
  - Numerical data table — cf. LS EOS subroutine
  - Cover wide range — Including T=0, Y_p=0
  - Smooth data for simulations

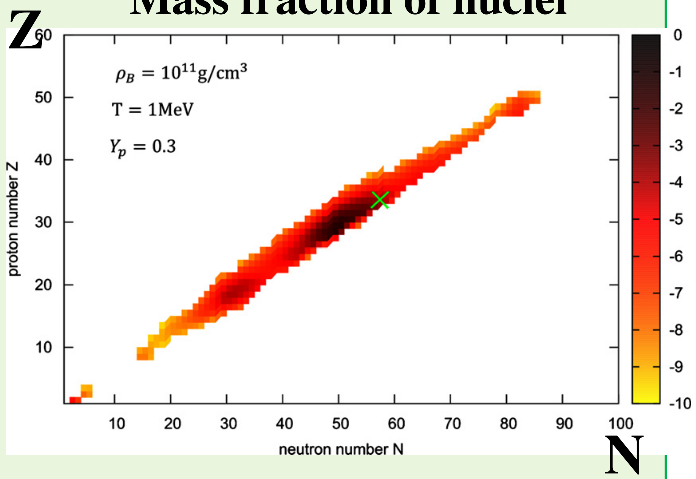
based on RMF from nuclear physics theory & inputs

- Extensions of RMF TM1 model:
  - Hyperon mixture — *Ishizuka 2008*
  - Quark phase transition — *Nakazato 2008*
  - Wider range, regular grids — *Shen 2011*
  - NSE: mixture of nuclei — *Furusawa 2011*

- Refine & explore exotic situations

by requests from astrophysical simulations (ex. BH formation)

Mass fraction of nuclei



NSE version

Furusawa 2017

Direction of supernova EOS tables

- Mean field frameworks — benchmark
  - Non-relativistic formula: Lattimer-Swesty — LS
  - Relativistic mean field: Shen-EOS — Shen

Classic

Realistic

Variations

I. Microscopic many body theories

Ab initio calculations, Variational method

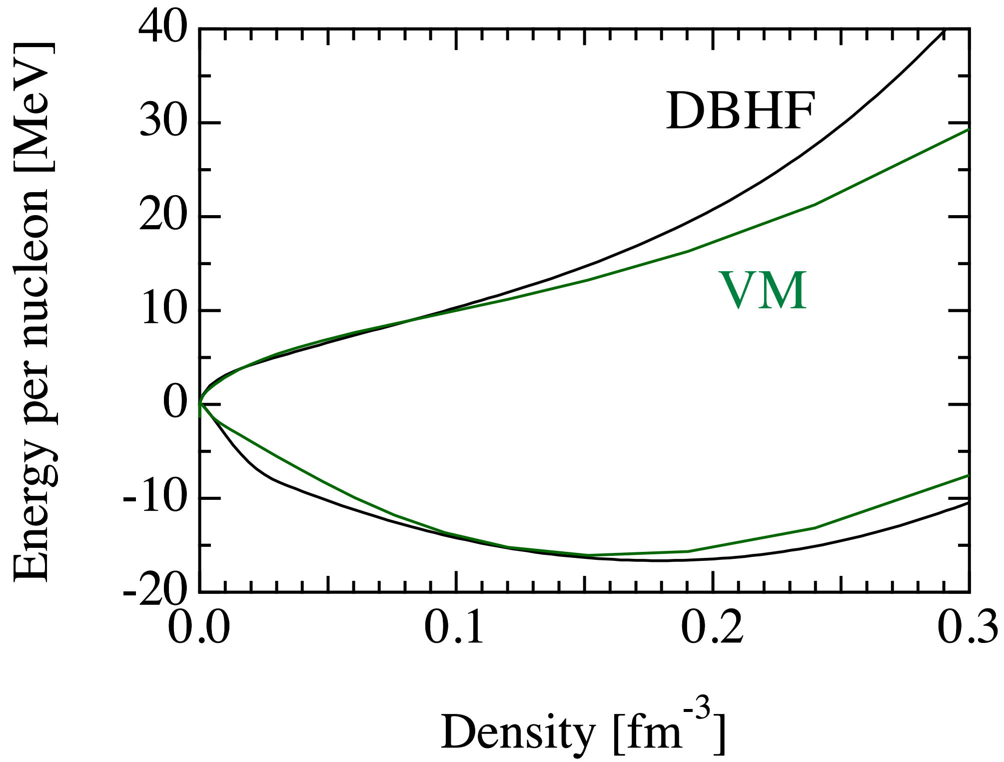
Brueckner Hartree-Fock (non-rela., Dirac)

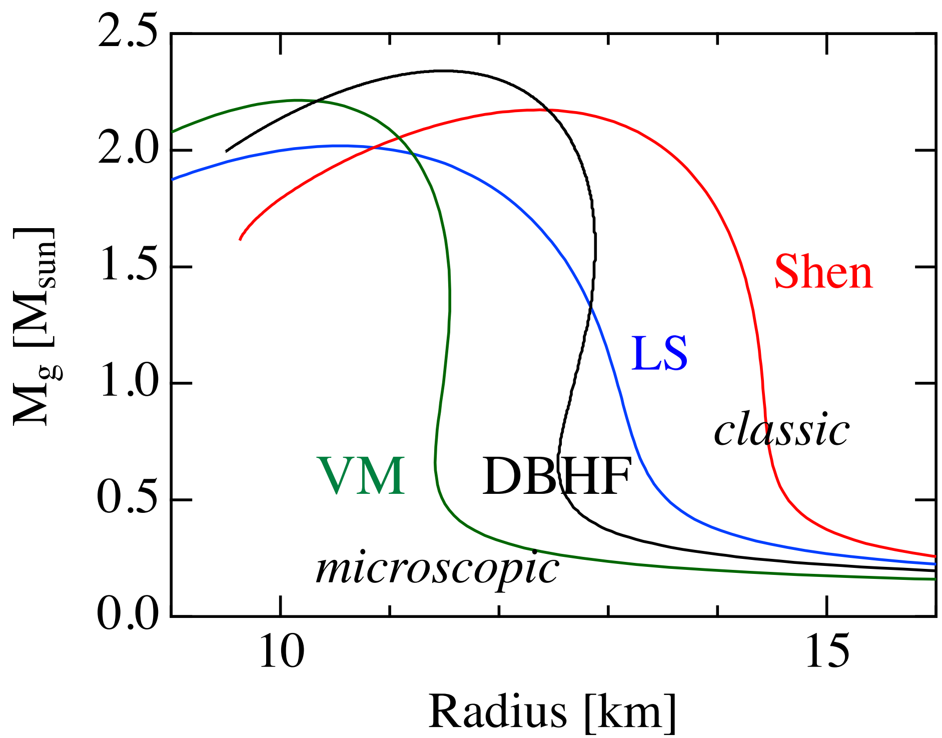
II. Systematic study of EOS effects

- Nuclear saturation parameters (K, L etc)
- Parameters in mean fields

Direction of EOS table I: microscopic approaches

- Variational method (VM) Togashi, NPA (2017), Furusawa JPG (2017)
  - Two-body AV18 + three-body UIX
- Dirac Brückner-Hartree Fock theory (DBHF) Katayama PRC (2013), Furusawa (2019)
  - Two-body Bonn-A, Saturation



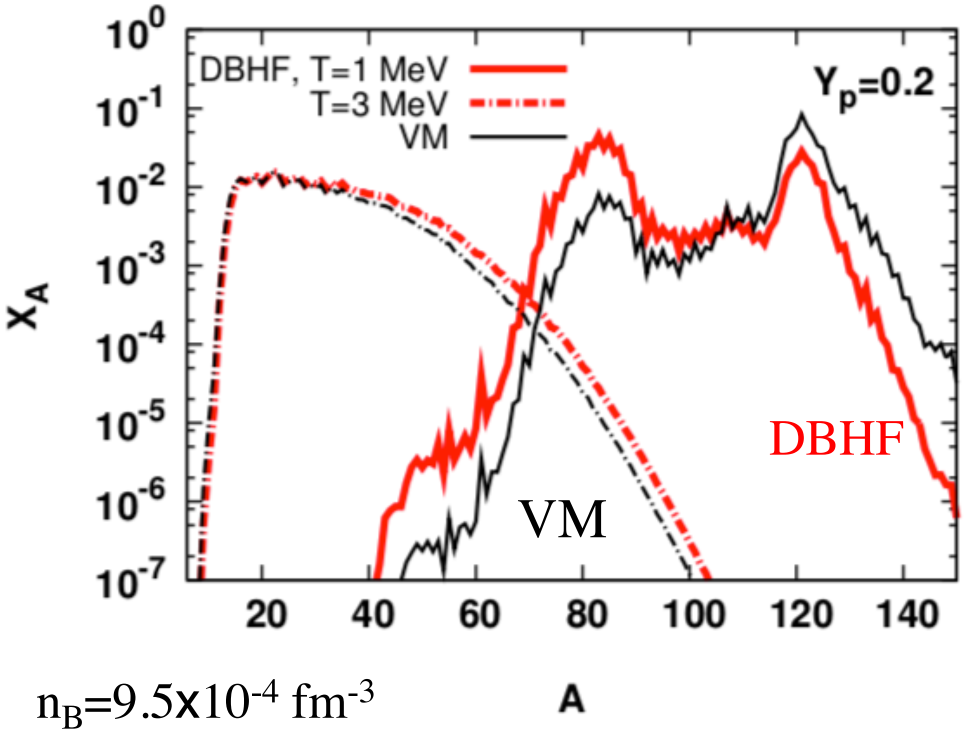


Non-relativistic vs Relativistic (ex. LS vs Shen)

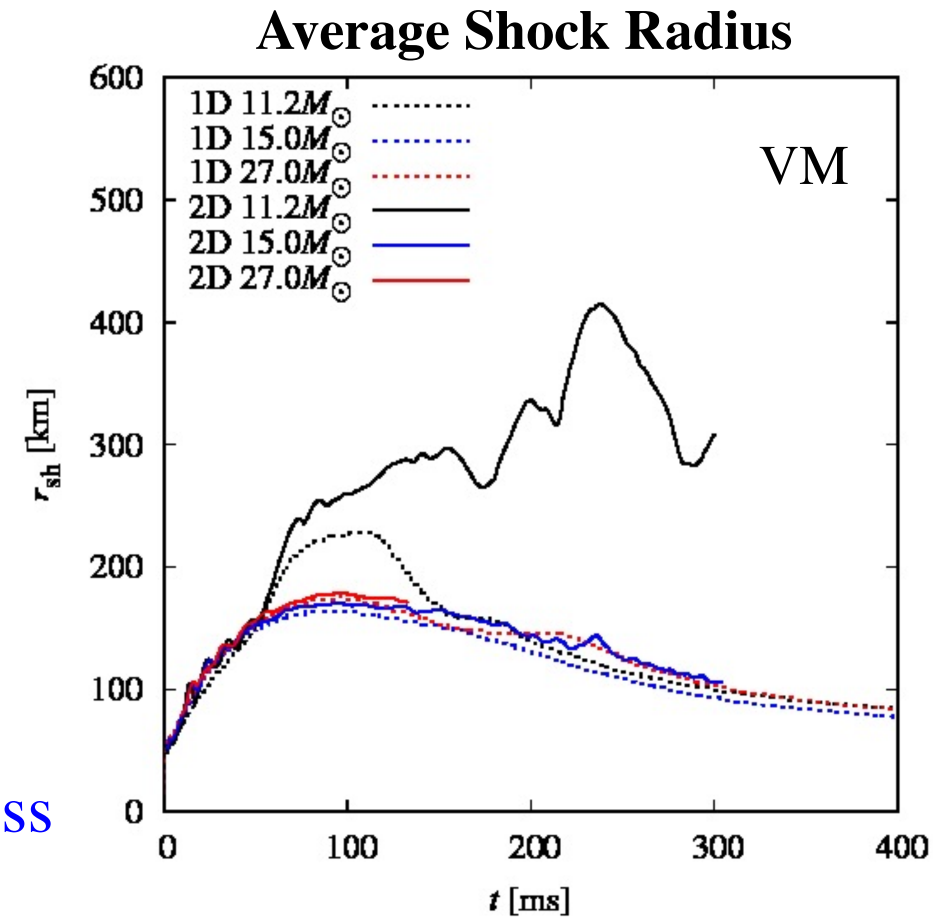
EOS table with microscopic approaches

Togashi et al. (2017), Furusawa et al. (2017, 2019, 2020)

- Energy of uniform matter from VM, DBHF
- NSE mixture of nuclei with liquid drop model



$n_B = 9.5 \times 10^{-4}$ fm^{-3}



Different compositions and stiffness

Furusawa et al. PTEP (2020)

1D/2D Boltzmann ν-radhyd

Direction of EOS table II : systematic study

- Shen EOS (1998, 2011) PTP, NPA, ApJS
  - Relativistic mean field (RMF) theory: TM1
  - Large symmetry energy (large NS radii)

    by limited knowledge of nuclei in 1990's Sugahara-Toki NPA (1994)

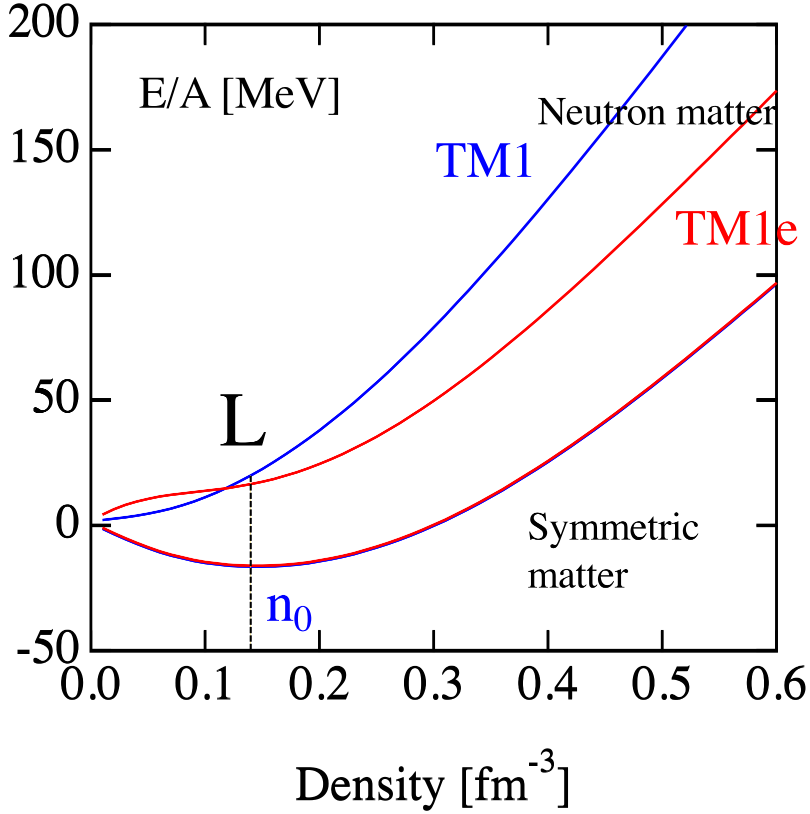
→ **Explore dependence on symmetry energy**

- Shen EOS (2020) ApJ
  - RMF: TM1e

    with $\omega^2\rho^2$ term

    Change only isovector
  - Modified L and E_{sym}

    Small symmetry energy

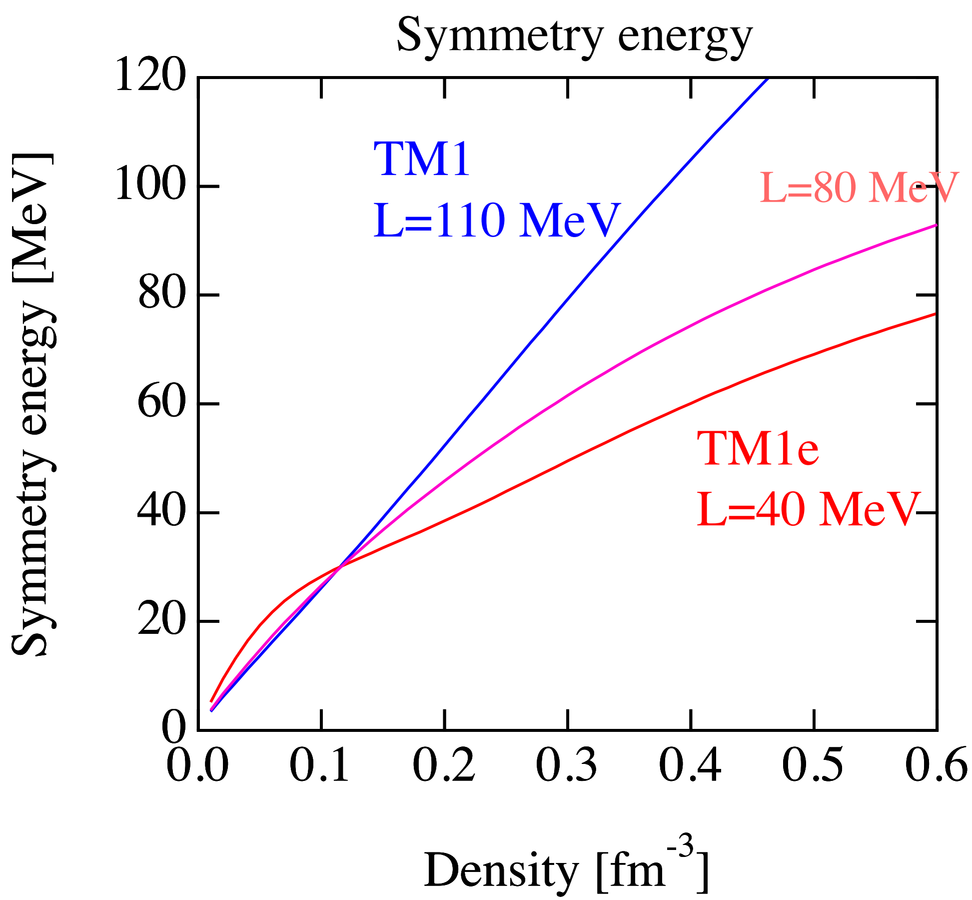


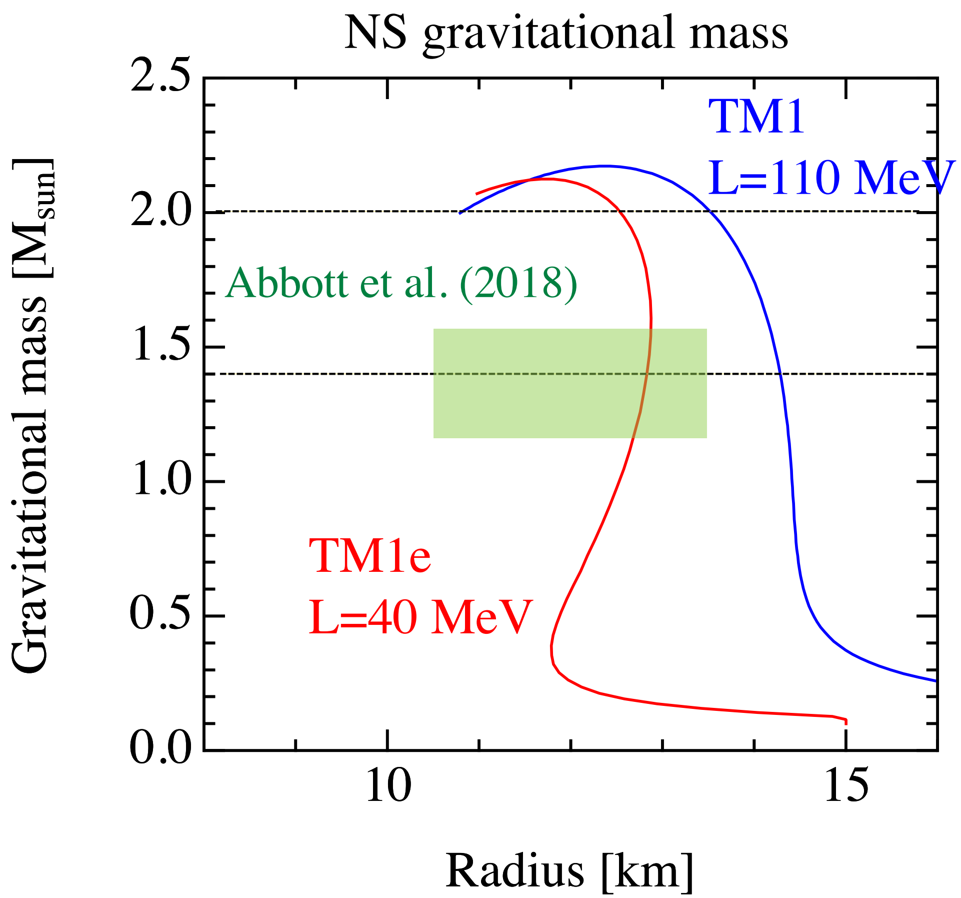
Sumiyoshi et al. ApJ (2019) Shen et al. (2020)

RMF calculations: change density-dependence, L

Bao & Shen (2014)

- Change of neutron matter, small neutron star radius





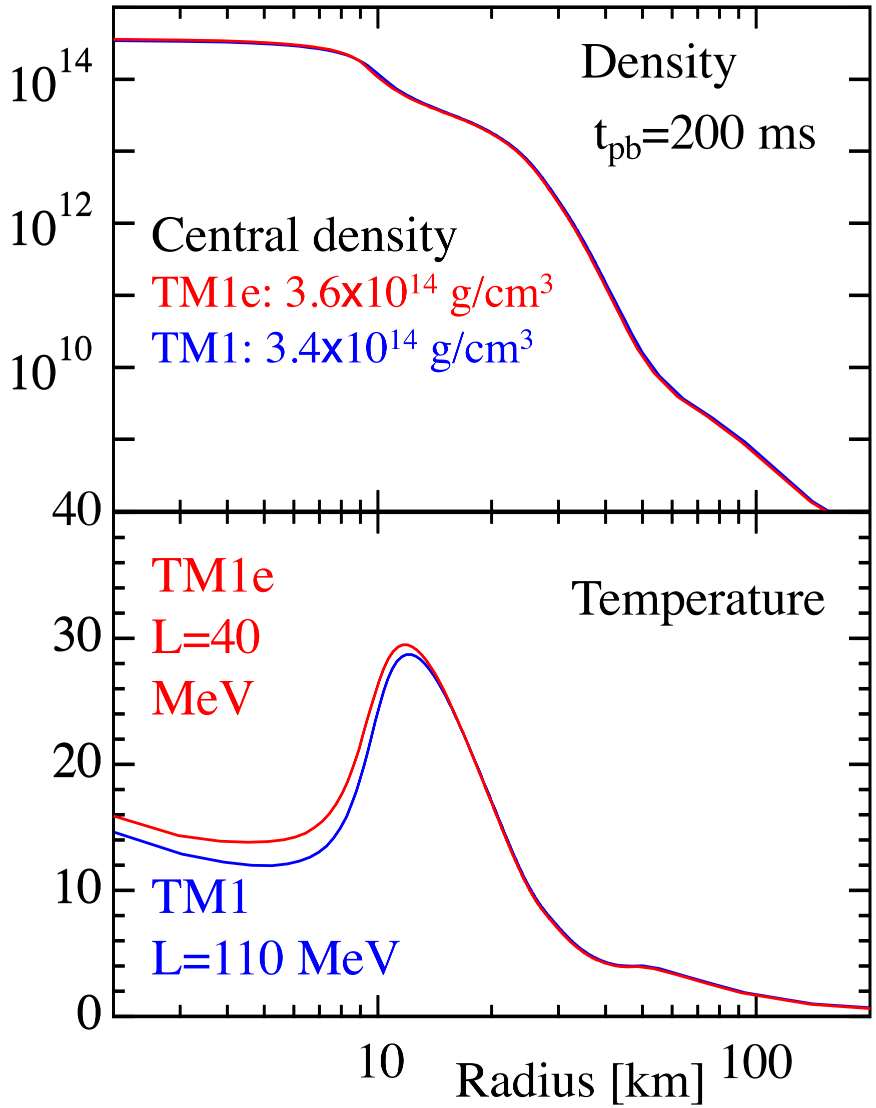
	L [MeV]	E_{sym} [MeV]
TM1	110.8	36.89
TM1e	40	31.38

Both reproduces nuclei well

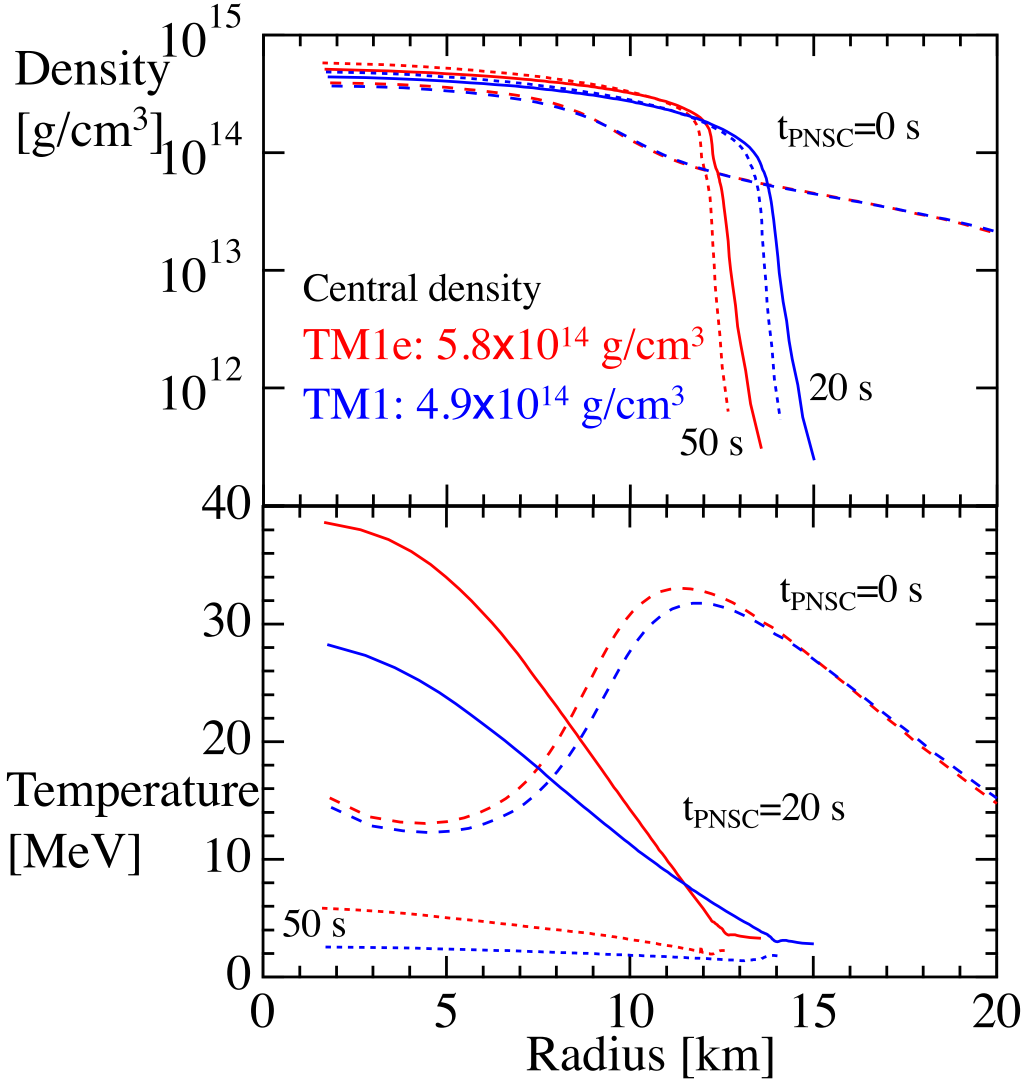
Sumiyoshi et al. (2019)

Applications to supernovae and proto-NS cooling

- **Very similar core bounce**



- **Different proto-NS**



Sumiyoshi et al. ApJ (2019) 1D GR ν-radhyd, $15M_{sun}$

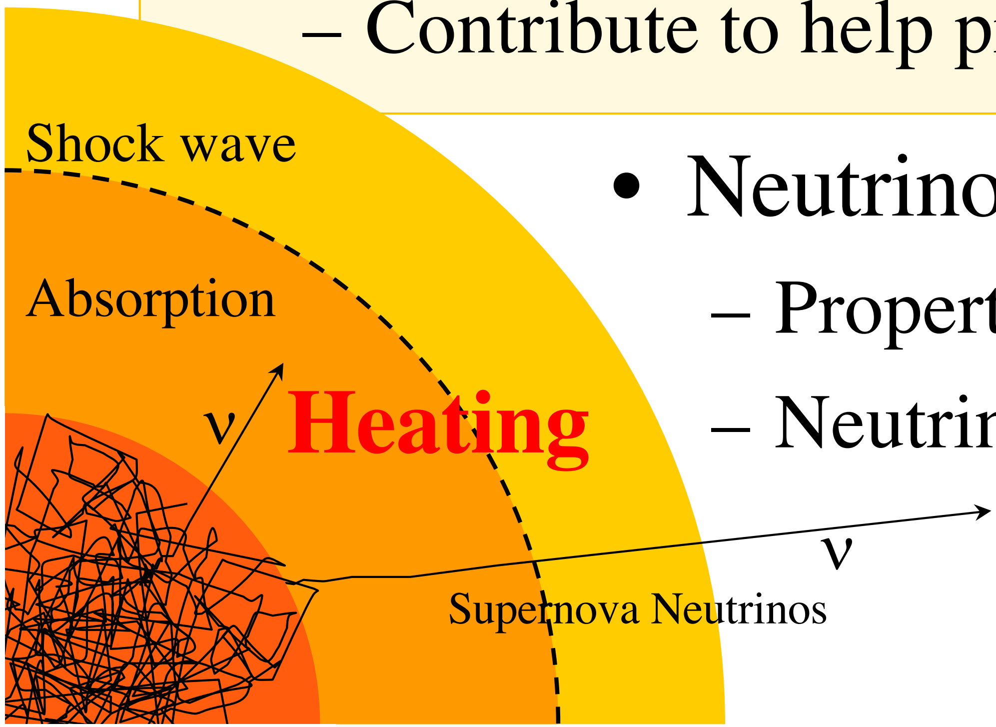
1D GR FLDν proto-NS cooling

Neutrinos are essential for supernova explosion

- Neutrinos are trapped during the collapse
  - Emitted as supernova neutrinos
- Neutrino heating mechanism (Bethe-Wilson 1985)
  - Absorption of neutrinos → Heating

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

  - Contribute to help propagation of shock wave



- Neutrino transfer & hydrodynamics
  - Properties of hot dense matter
  - Neutrino reactions with targets (nucleons, nuclei, leptons)

→ EOS with ν-reaction data

Explosion models in 2D & 3D simulations

Neutrino-heating with hydrodynamical instabilities

(No explosion in 1D)

- **Toward 1st principle calculation**

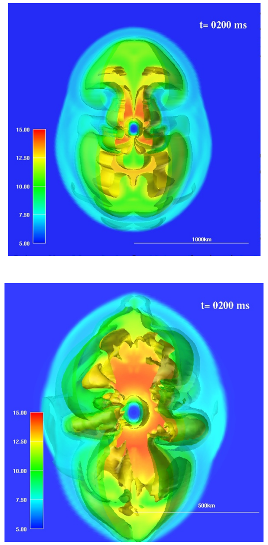
Neutrino-radiation hydrodynamics

neutrino-transport, general relativity

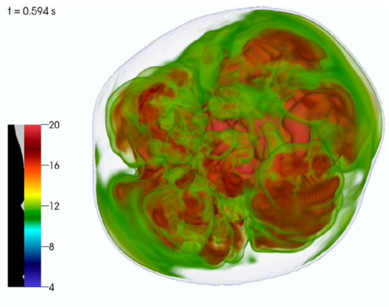
from approximate to strict method

2D

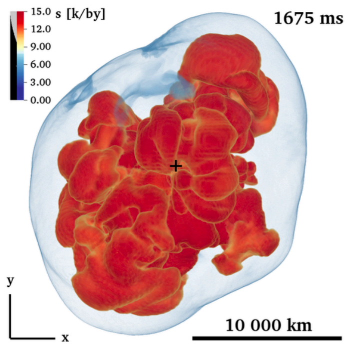
3D



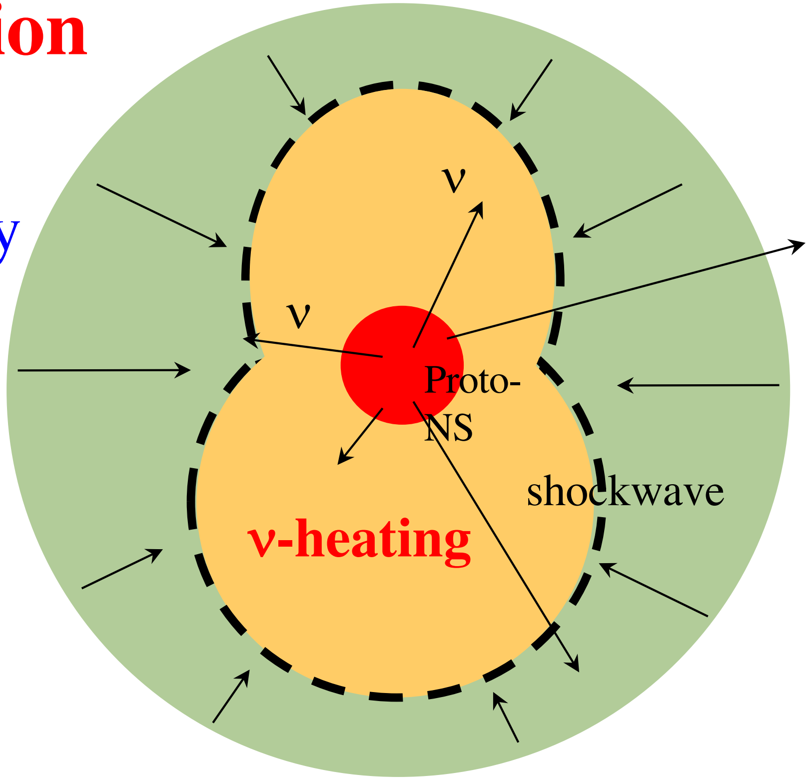
Takiwaki et al. (2015)



Burrows et al. (2020)



Bollig et al. (2020)



Deformation of shock, convection

→ Longer time for ν-heating

- **Remaining issue**

Nuclear physics: Equation of state and weak reaction rates

Numerical code to solve 6D Boltzmann eq.

Neutrino radiation hydrodynamics without approximation

Sumiyoshi & Yamada, ApJS (2012)
Nagakura et al. ApJS (2014, 2015)

- 6D Boltzmann equation

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

Time evolution + Advection = Collision

- Neutrino distribution in 6D

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

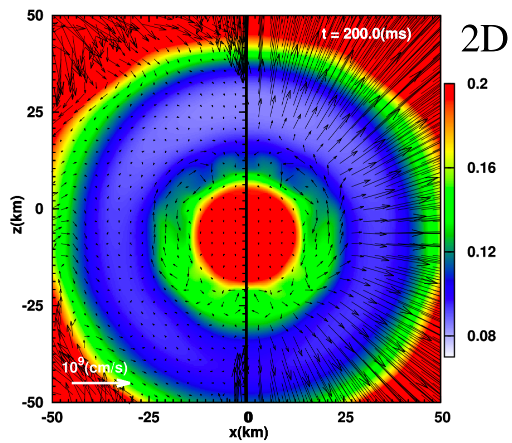
→ Huge memory & computation

- Check approximate methods: diffusion, ray-by-ray, moment closure

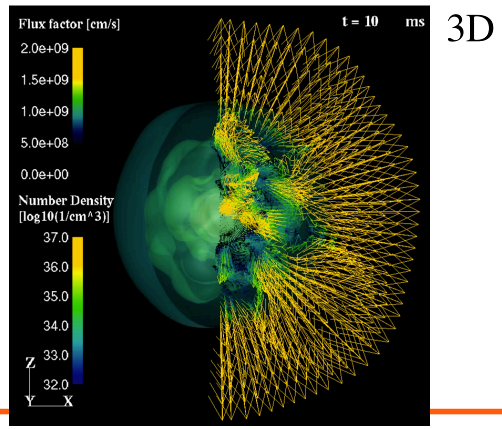
- Coupled with 2D/3D Hydrodynamics + Newtonian Gravity
  - Neutrino-transfer in dynamics
  - from diffusion to transparent
- Core-collapse simulations

  $11.2M_{sun}$, $15M_{sun}$ stars

  LS, Furusawa-Shen, Togashi



Nagakura et al. ApJL (2019)



Iwakami et al. ApJ (2020)

Influence of EOS on explosion in 2D simulations

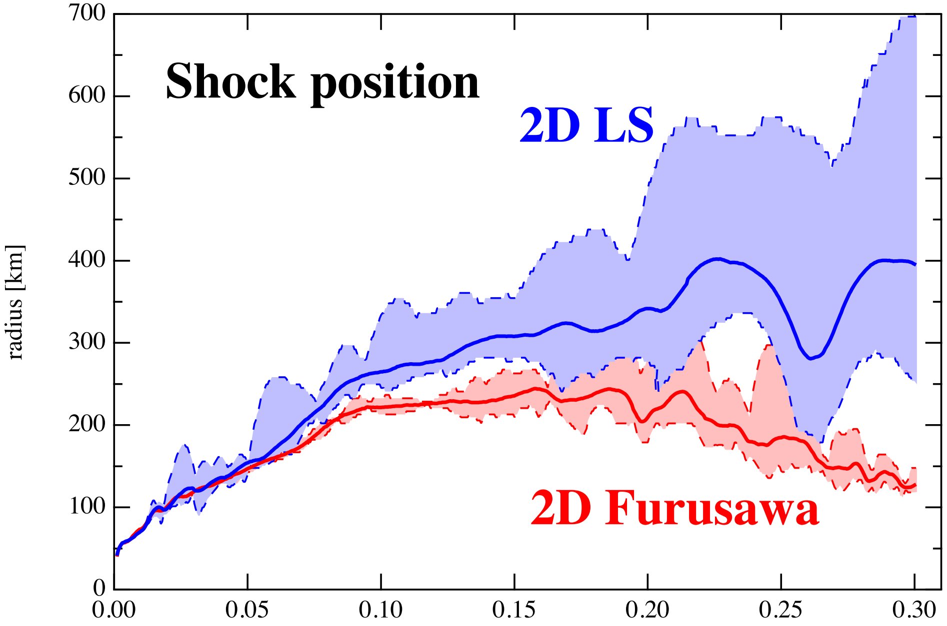
- Simulation with 6D Boltzmann
  - Explosion with LS (soft)
  - No explosion with Furusawa (stiff)

    Extended Shen

What we found is:

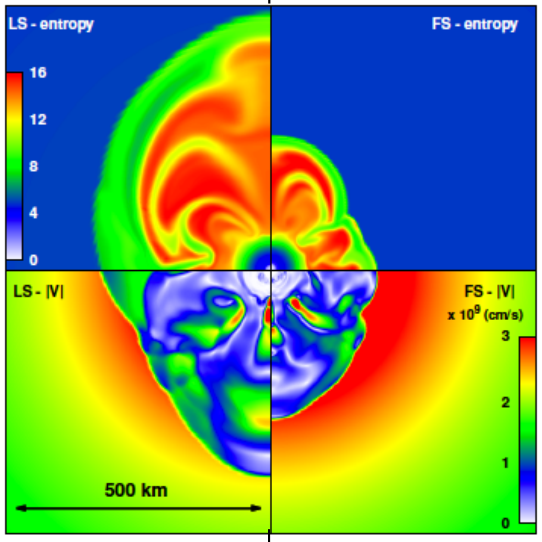
- Different composition
- Early trigger of convection

- Minor soft/stiff difference



Time after bounce

2D LS 2D Furusawa



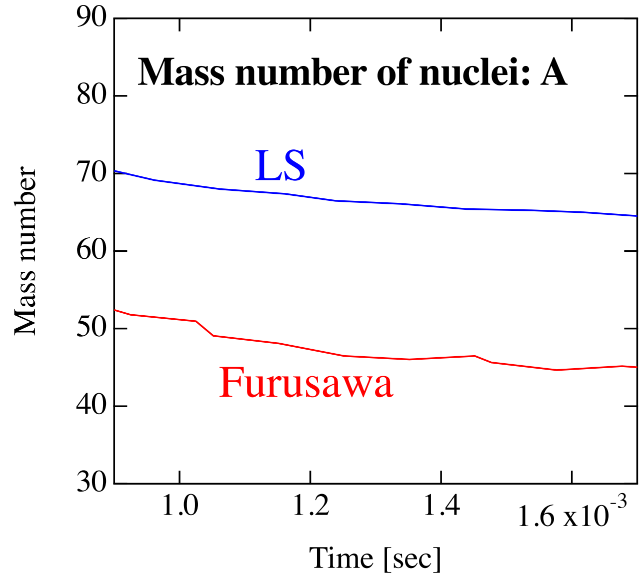
t_{pb}=200ms

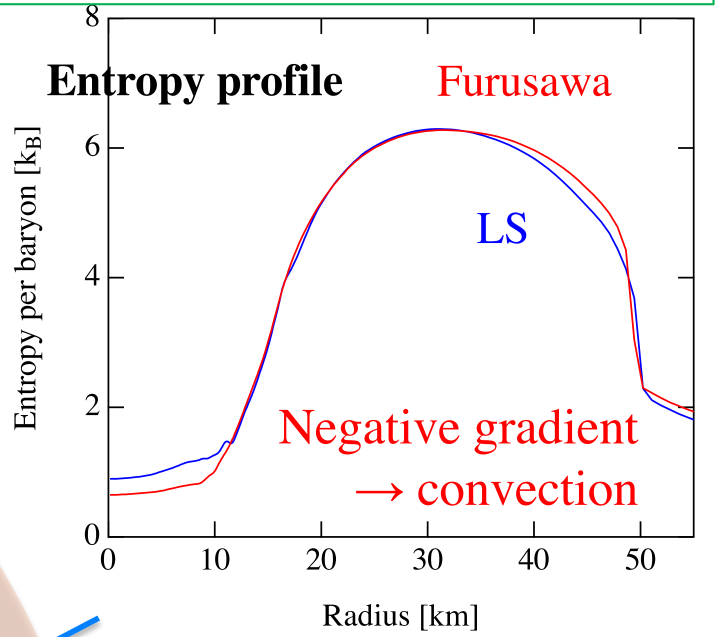
top : entropy, bottom : fluid velocity

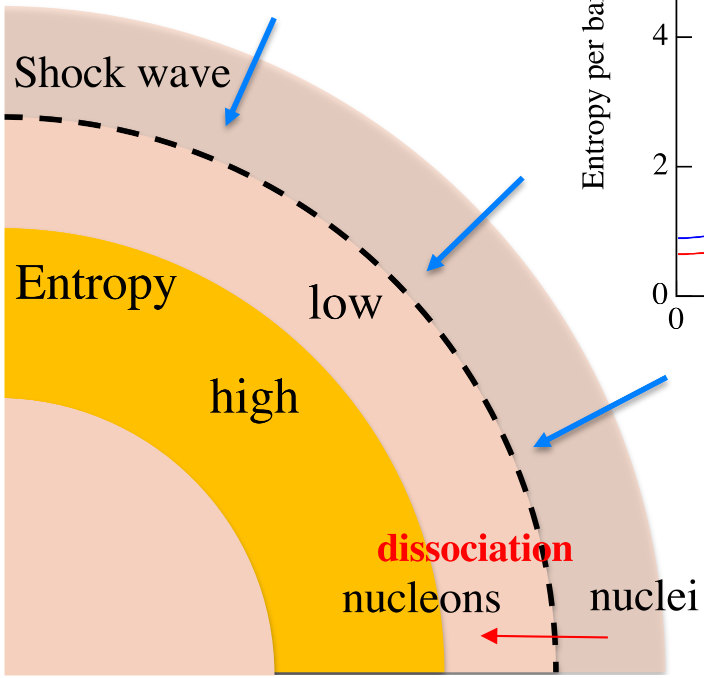
Nagakura et al. ApJ (2018) 11.2M_{sun}

EOS influence on convection: example in 2D

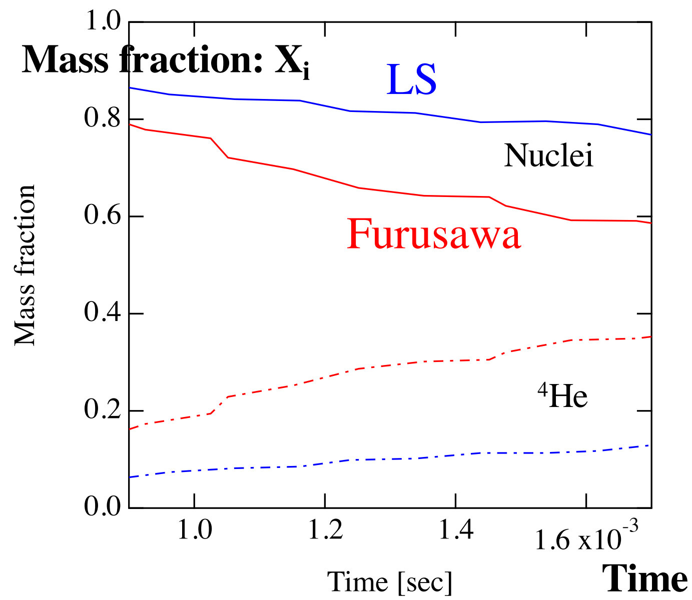
- Different composition:
  - Species of nuclei in LS vs Furusawa
- Dissociation of nuclei at shock:
  - Different Loss of shock energy
  - Change entropy profile → Convection







Earlier convection in LS
(More massive nuclei
→ Larger loss at shock)

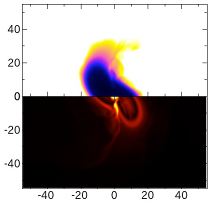


Harada et al. ApJ (2020)

Neutrino transfer in neutron star merger

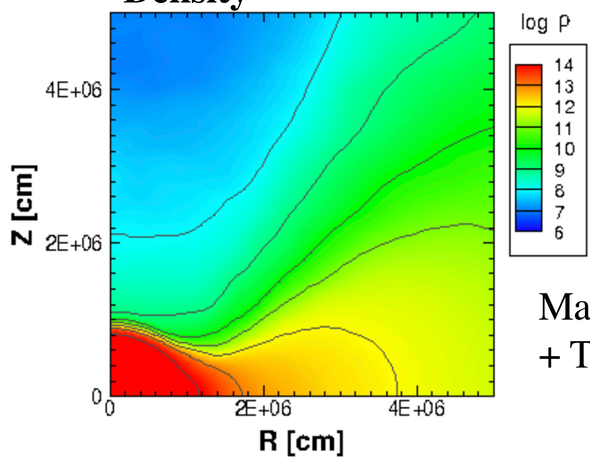
Sumiyoshi et al. ApJ (2021)

- Simulation with 6D Boltzmann



  - Fixed background of profile
  - Remnant of NS-NS merger
  - Check of approximations

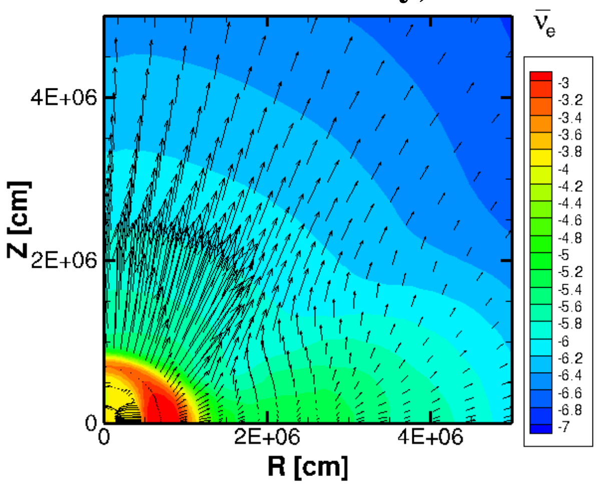
Density



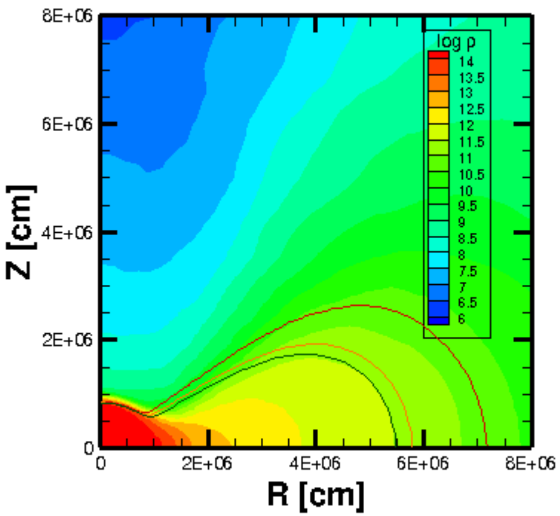
Massive NS
+ Torus

- Examine neutrino distributions
  - Neutrino flux, spectra, neutrino sphere, heating rate

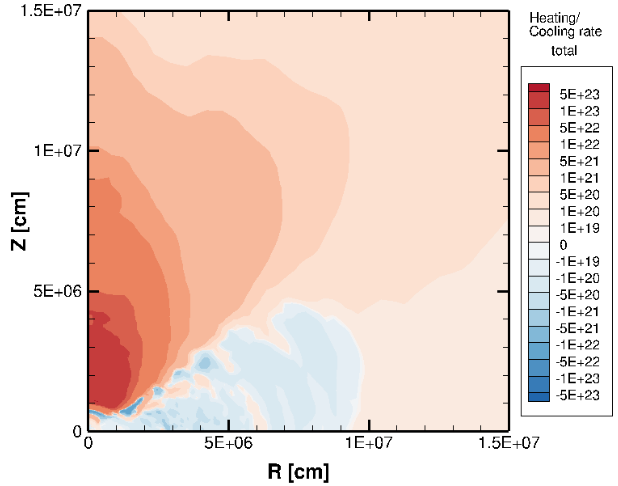
neutrino density, flux



neutrino-sphere



neutrino heating rate



Need more neutrino reaction rates with EOS for the first principle calculation

Progress of EOS table & neutrino transfer

- Directions of research on EOS tables
  - Microscopic approach and systematic trend
- Needs of neutrino reactions in dense matter
  - Extended data entry for weak rates with EOS

- Developments of EOS tables
  - Variational method and Dirac-Bruckner HF
  - Shen EOS table updated with L=40 MeV
- 6D Boltzmann solver for neutrino transfer
  - Toward first principle calculation
  - Neutrinos in supernova and neutron star merger

Projects in collaboration with

- Numerical simulations
  - A. Harada
  - W. Iwakami
  - H. Okawa
  - H. Nagakura
  - S. Yamada
- Supernova research
  - Y. Suwa
  - K. Nakazato
  - T. Takiwaki
  - K. Kotake
  - K. Takahashi
- Supercomputing
  - H. Matsufuru, A. Imakura
- EOS tables
  - S. Furusawa, H. Togashi
  - H. Shen, J. Hu,
  - K. Oyamatsu, H. Toki
- Super-Kamiokande
  - Y. Koshio, R. A. Wendell
  - M. Mori, M. Harada

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K-Computer *Post-K (Fugaku) , Japan*

Innovative areas on Gravitational Wave: Genesis