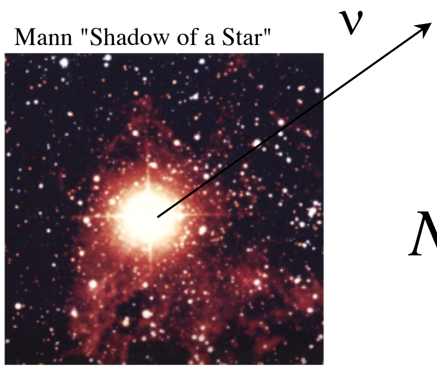
Numerical studies of core-collapse supernovae: progress toward the first-principles calculations

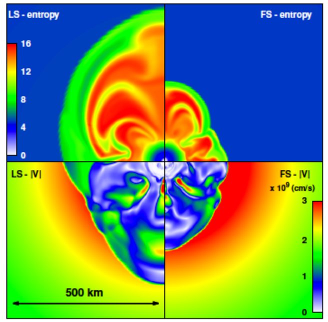
Mann "Shadow of a Star"



SN1987A

K. 'Sumi'yoshi

National Institute of Technology
Numazu College, Japan



Nagakura et al. ApJ (2018)

with H. Nagakura, W. Iwakami, H. Okawa, A. Harada,
S. Furusawa, H. Togashi, H. Matsufuru and S. Yamada

K-Computer, Japan

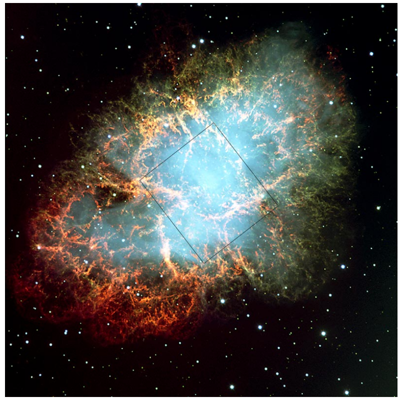
Supernova Explosions in the Universe

- Core-collapse supernovae

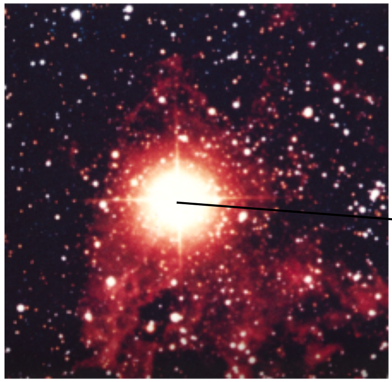
10^{51} erg

  - Death of massive stars
  - Birth place of neutron stars (or BH)
  - Production of heavy elements
  - Neutrinos, gravitational waves

Hubble



Crab nebula
SN1054



Mann "Shadow of a Star"

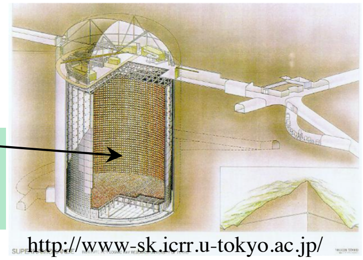
SN1987A

Neutrino bursts from SN1987A

ν

10^{53} erg

Kamioka, Japan



http://www-sk.icrr.u-tokyo.ac.jp/

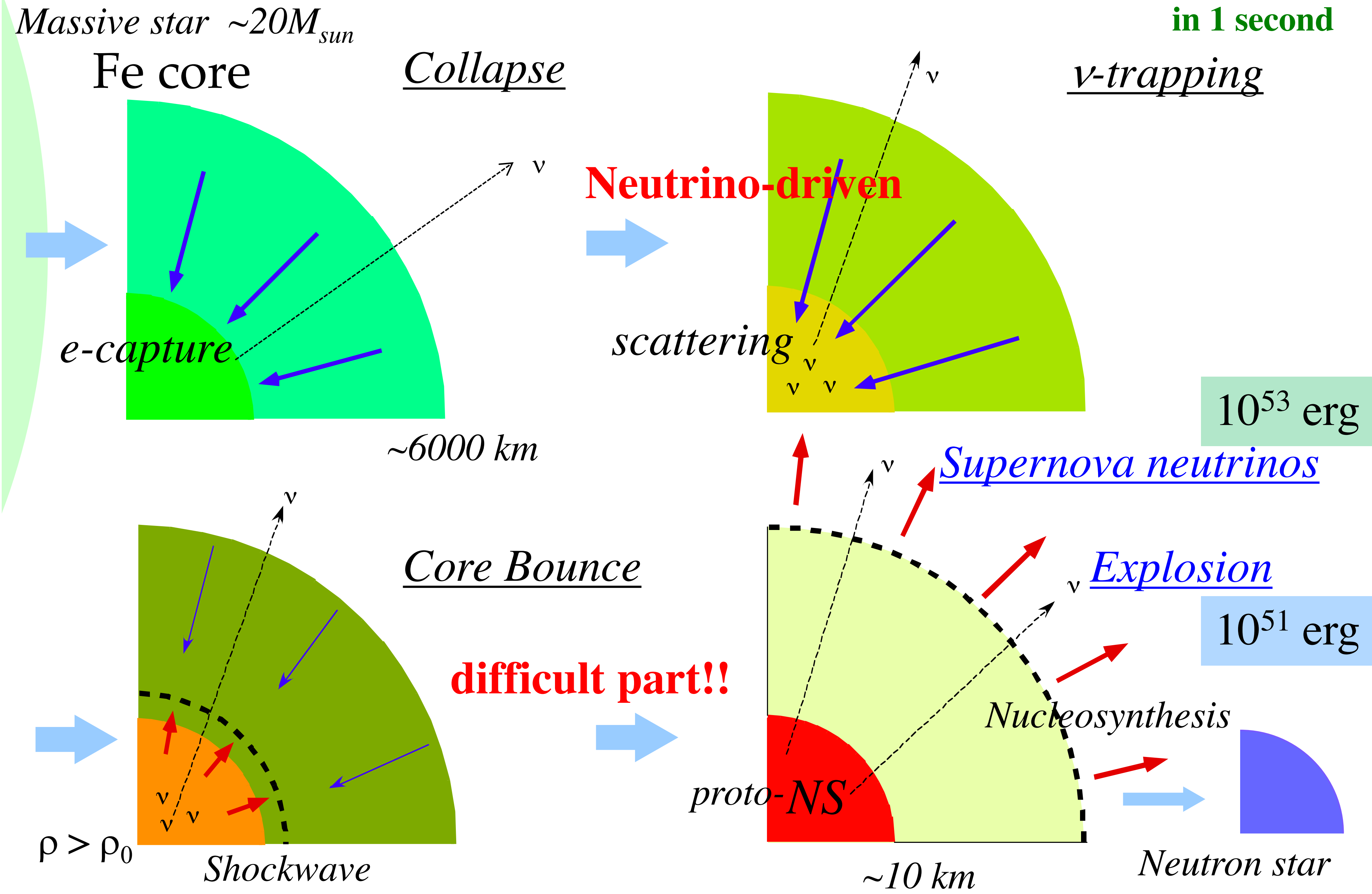
Nobel Prize, Prof. Koshiba

http://nobelprize.org/

- People ask us whether it explodes or not?
  - *Not so simple*. Solving a challenging problem for decades

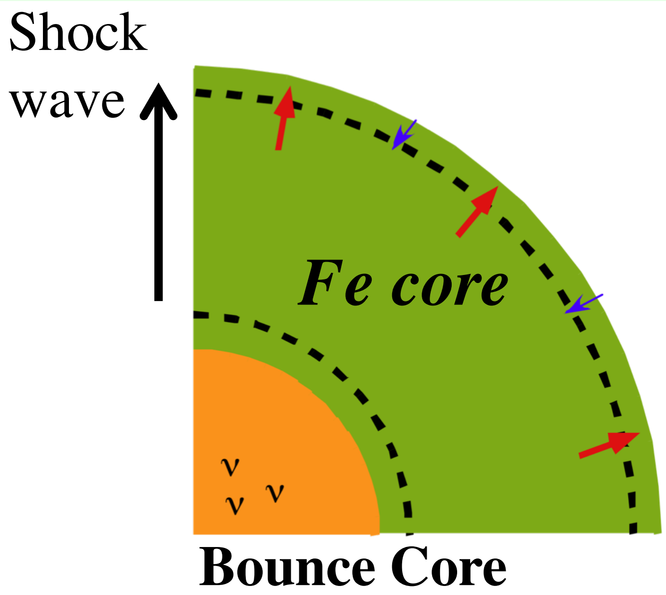
Core-collapse SNe: collapse, bounce and explosion

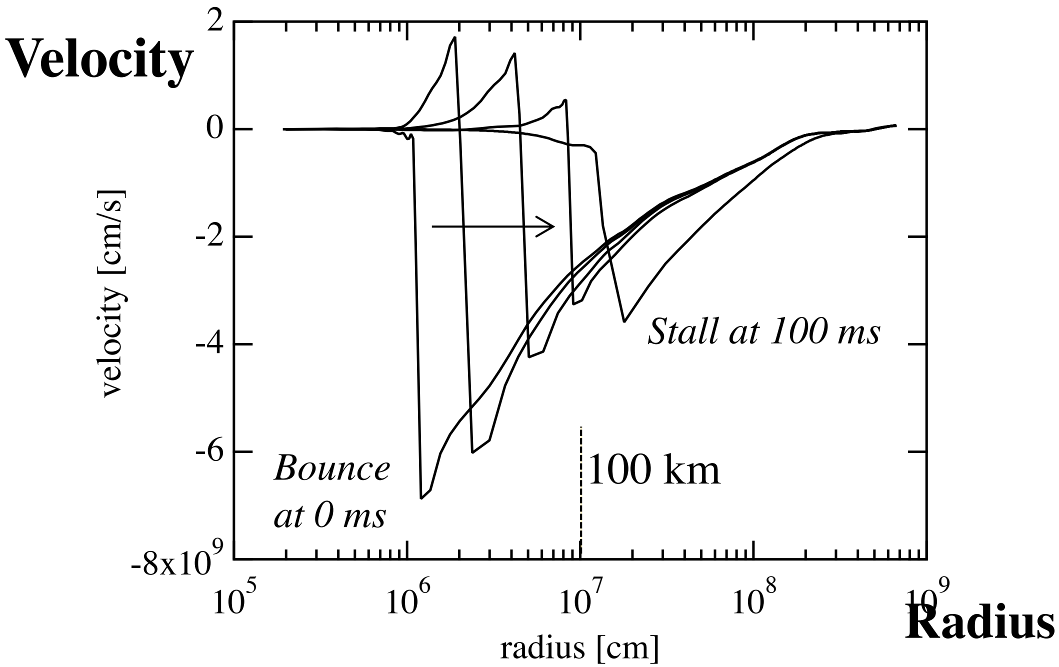
in 1 second



Difficulties: shock wave stalls on the way

1. Initial shock energy is used up by Fe dissociation
2. No explosion occurs in spherical (1D) simulations





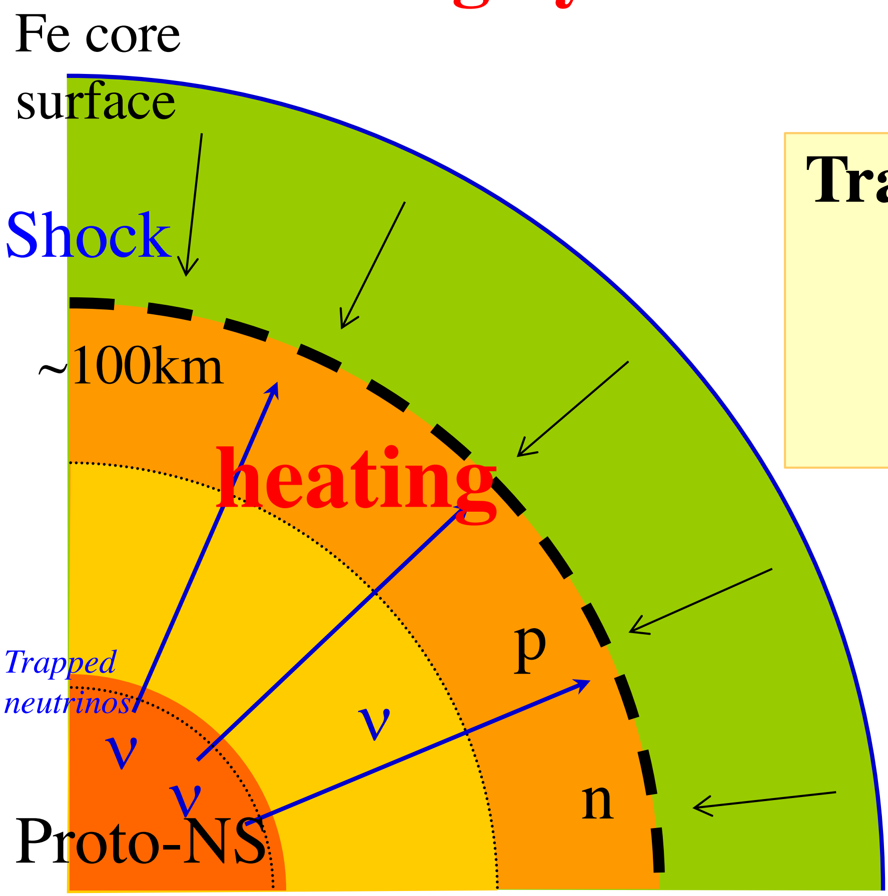
How to revive the stalled shock wave?

- Neutrino heating mechanism
- Multi-dimensional effects

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

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

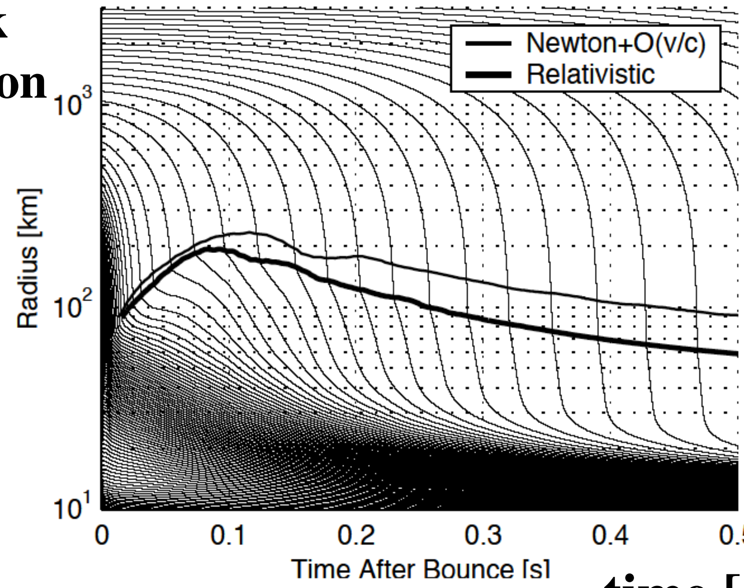


Transfer of energy from ν — Janka A&A (1996)

$$E_{\nu-heat} \sim 2\times 10^{51}\left(\frac{\Delta M}{0.1 M_{solar}}\right)\left(\frac{\Delta t}{0.1 s}\right) erg$$

No explosion by modern 1D simulations

Shock position



time [s]

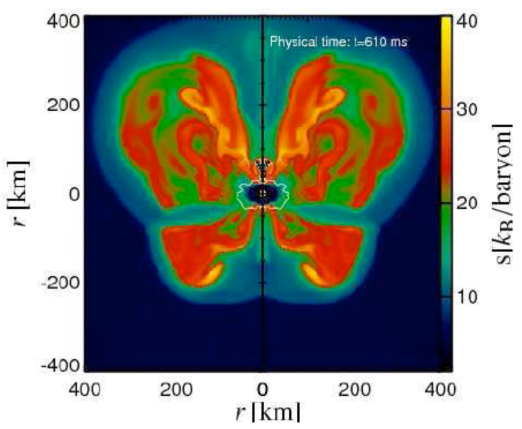
Liebendörfer et al. (2000)

Neutrino energy/flux from trapped neutrinos

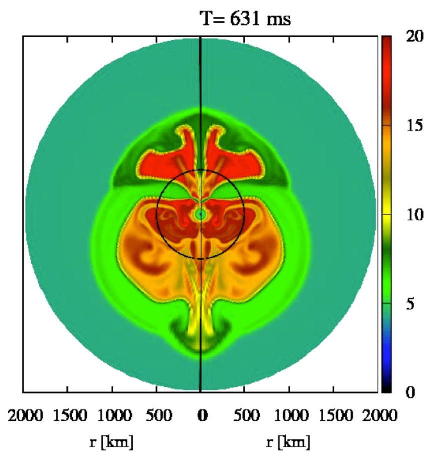
Explosions mechanism in 2D & 3D

neutrino-heating with hydro instabilities

- Remaining issues: main trigger, low explosion energy, 2D or 3D

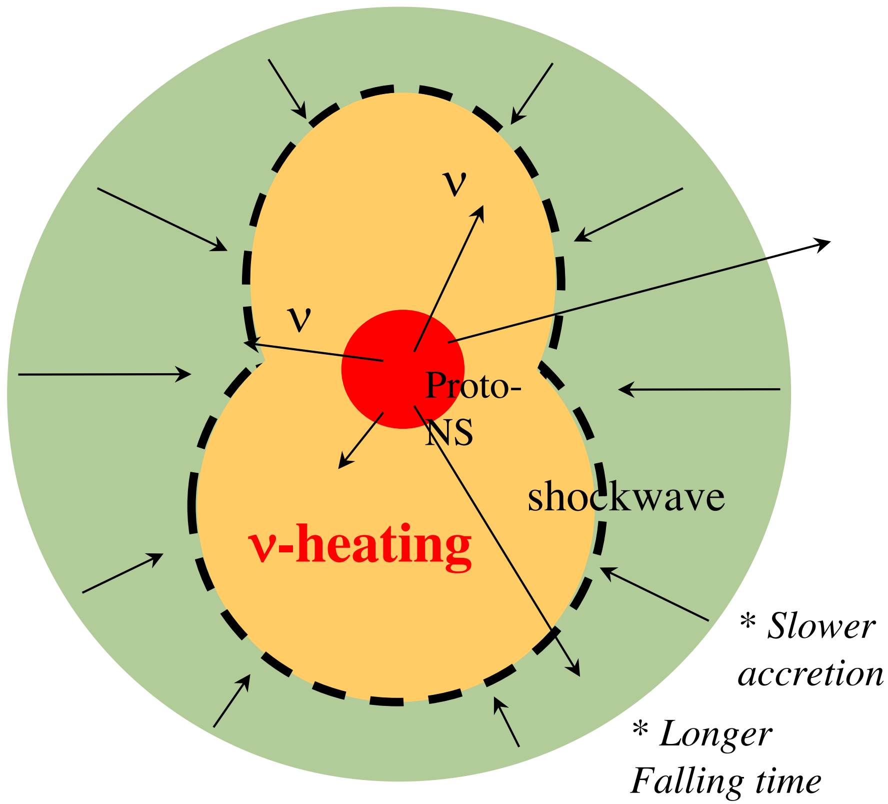


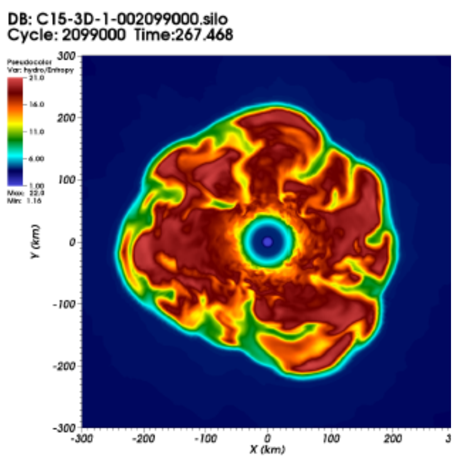
Marek et al, ApJ (2009)



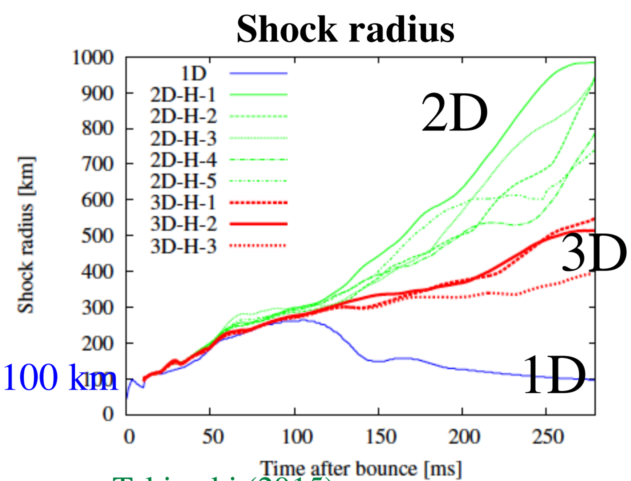
Suwa et al. (2010) PASJ

Deformation of shock Convection, SASI → Enough time for ν-heating





Lentz ApJ (2015)



Takiwaki (2015)

Understanding core-collapse supernovae

Nuclear physics

- Equation of state
- Neutrino reactions
- Nuclear data

  at ~10^{15} g/cm^3, ~10^{11} K

Astrophysics

- Stellar models
- Hydrodynamics
- Neutrino transfer
- General relativity

First principles calculations

- General relativistic neutrino-radiation hydrodynamics

  Variety of supernovae: explosive nucleosynthesis, neutrino bursts

- Needs extensive studies step by step

  - Detailed examination & Systematic survey

K computer

Equation of state in supernovae

effects on explosion?

Comparison of EOS sets: benchmark

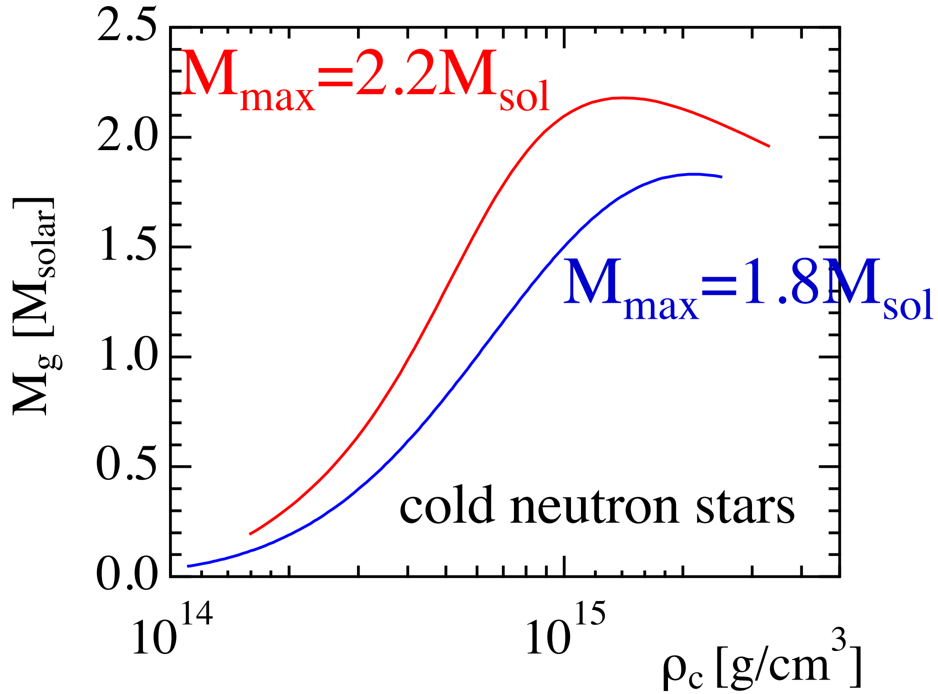
- Difference in stiffness & symmetry energy

	LS-EOS	Shen-EOS
K [MeV]	180, 220, 375	281
A_{sym} [MeV]	29.3	36.9

- Two representatives

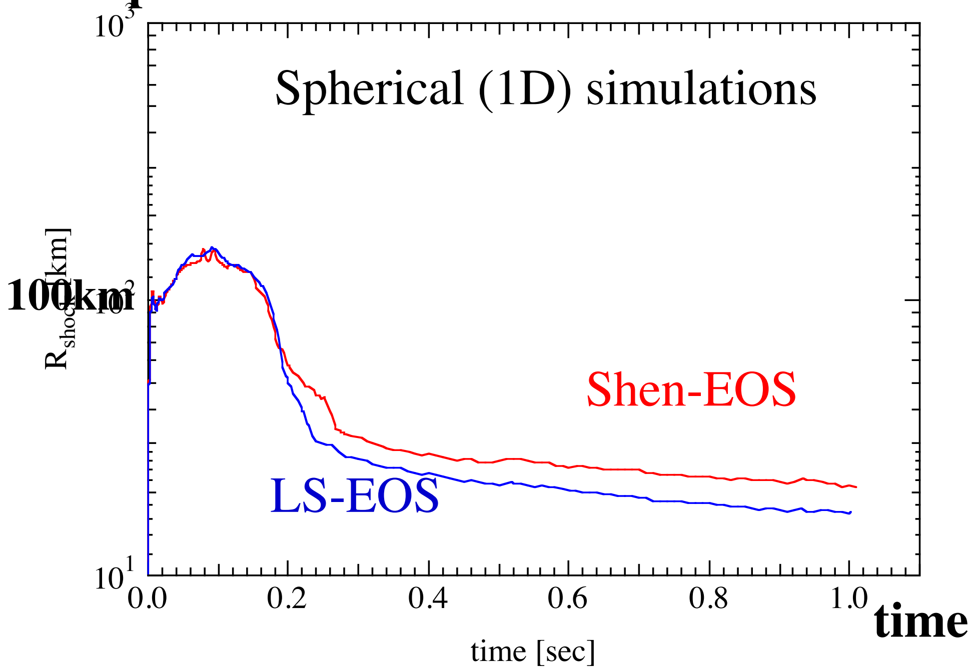
- Extremes in modern sense

180, 220: Frequently used for many simulations



Sumiyoshi (2004)

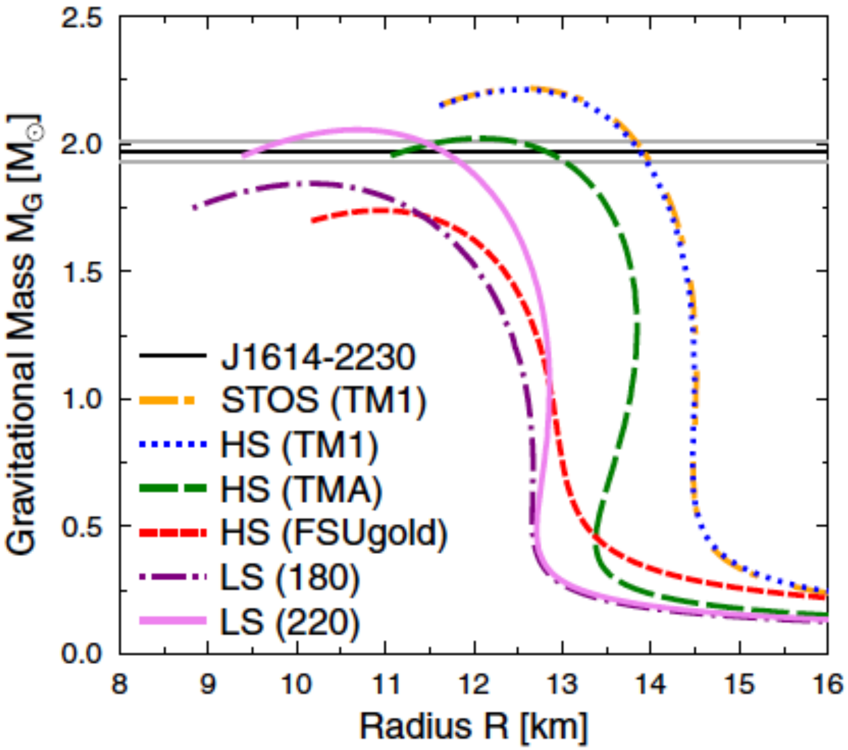
Shock position



$15M_{solar}$ Sumiyoshi et al. (2005)

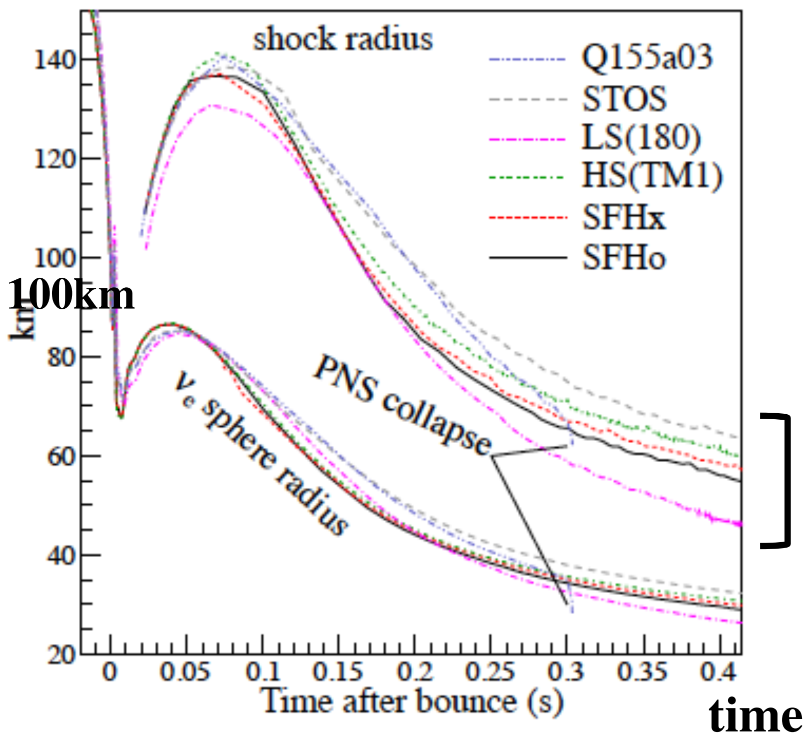
Comparison of EOS sets: more recent

- Choice of nuclear interaction (stiffness, radius, …)
- No explosion in 1D with various EOS tables



Hempel (2012)

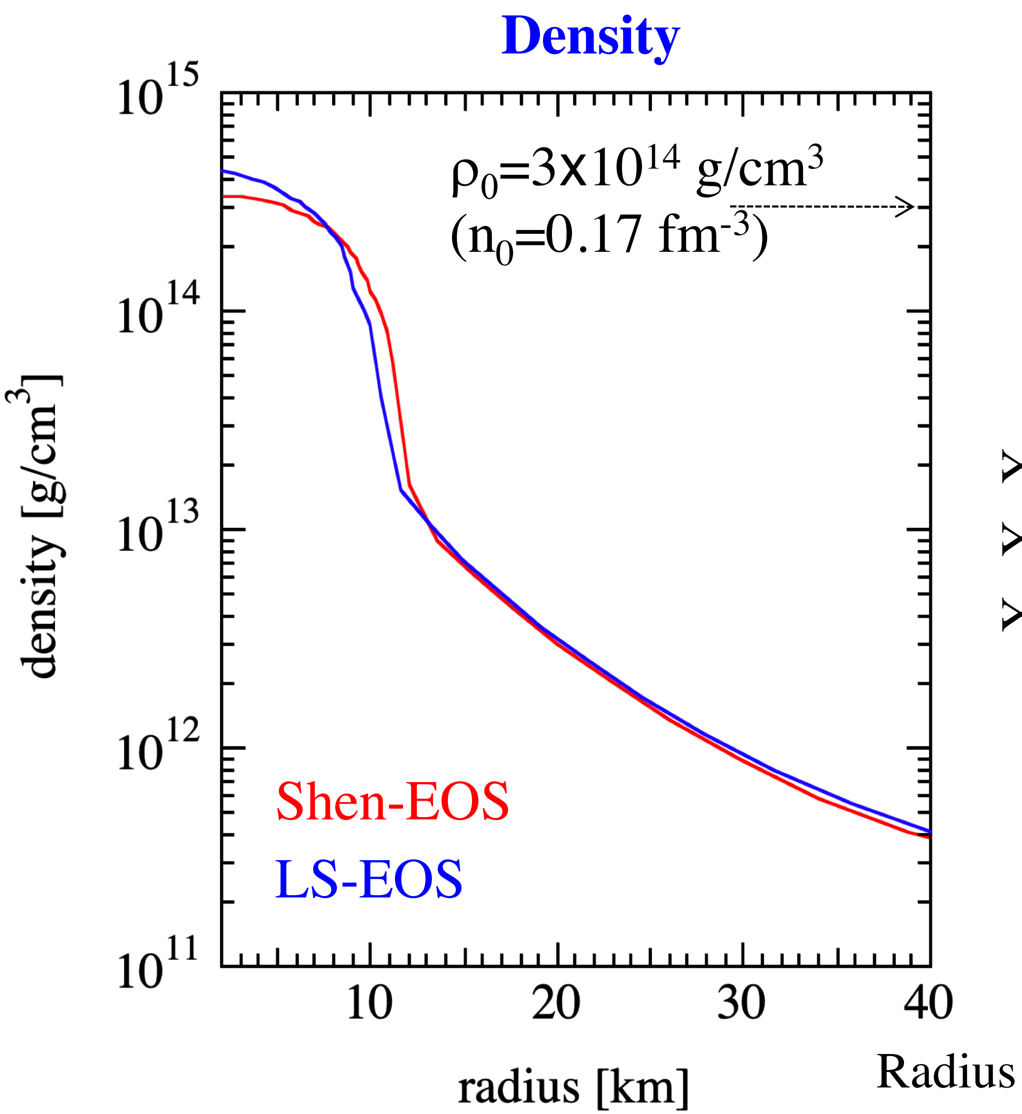
Shock position

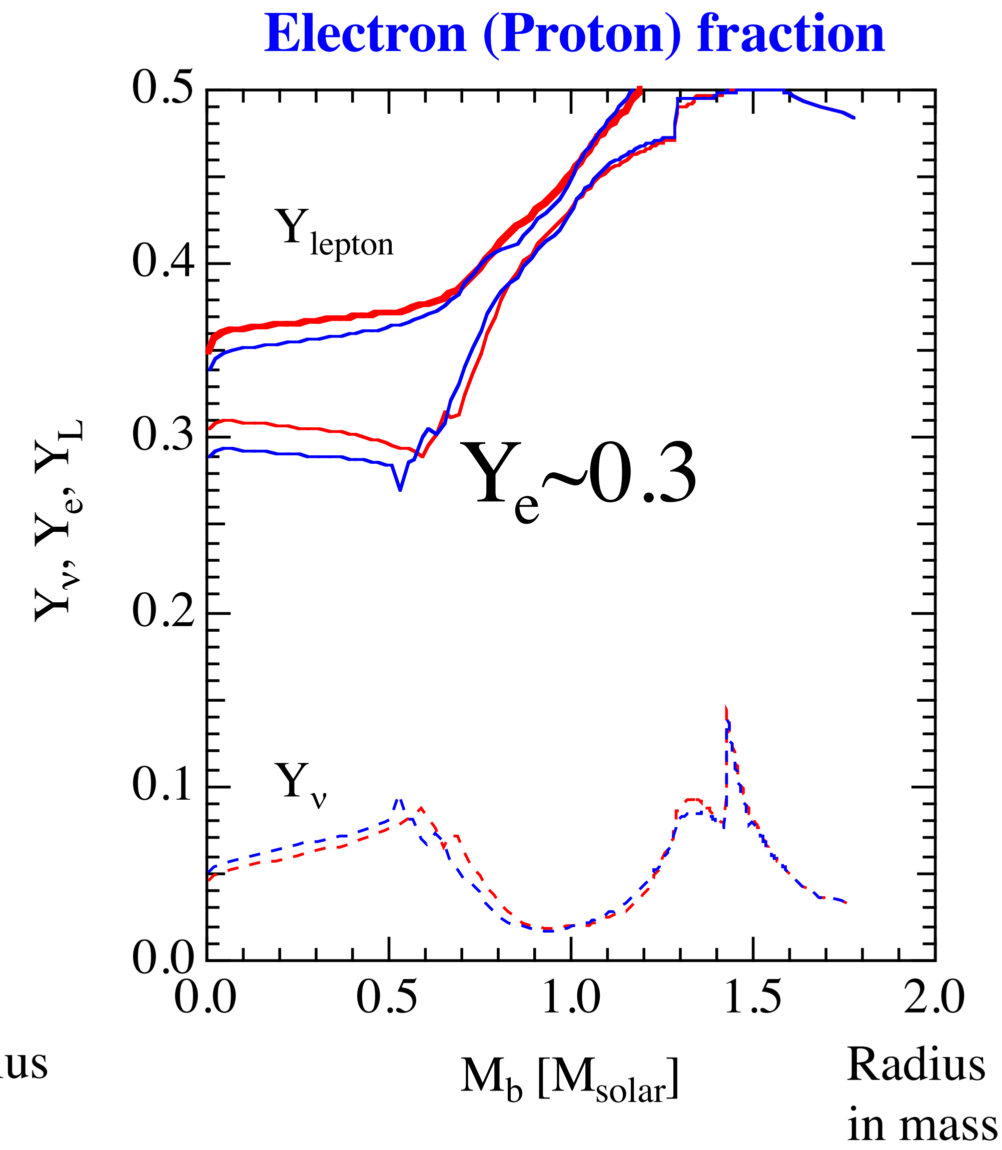


$11.2M_{solar}$ Steiner et al. (2013)

Supernova profiles at core bounce: t_{pb}=0 ms

ρ: just above ρ_0, T~10 MeV, Y_p: not so neuron-rich yet





Sumiyoshi et al. ApJ 629 (2005) 922.

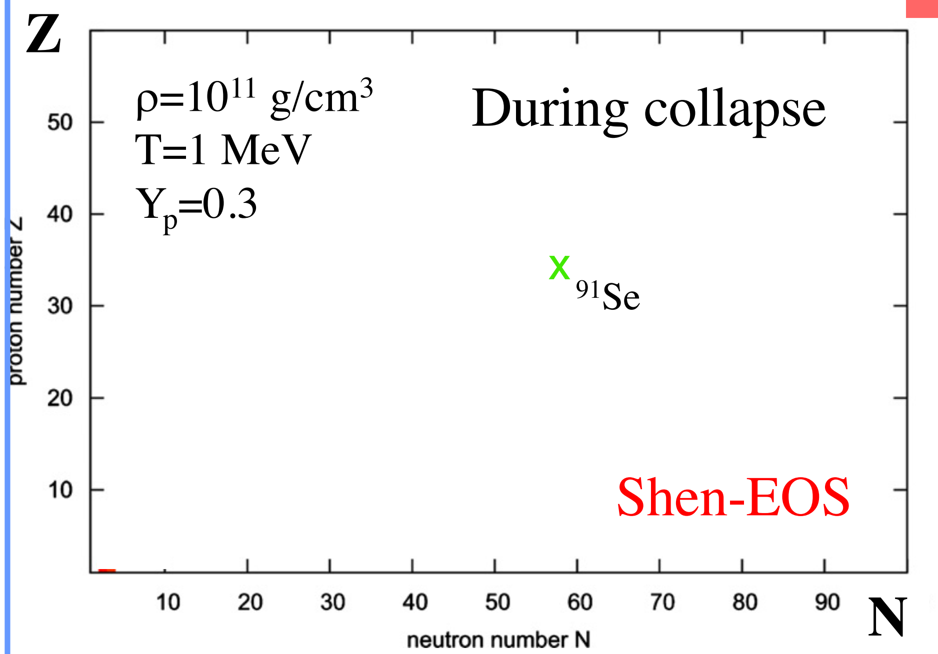
Equation of state in supernovae

Effect of composition

Mixture of nuclei in supernova EOS tables

Shen-EOS

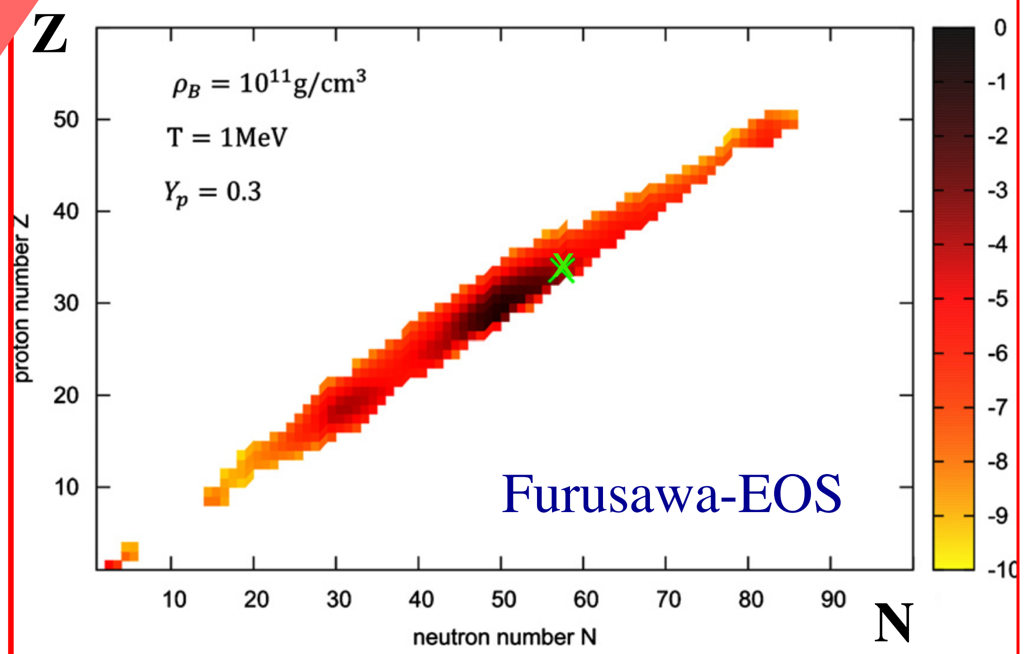
Neutron, proton, ^4He
One species of nuclei
approximation



A representative nuclei

Furusawa-EOS

Neutron, proton, d, t, ^3He, ^4He,…
All of nuclei up to A~1000
In nuclear statistical equilibrium



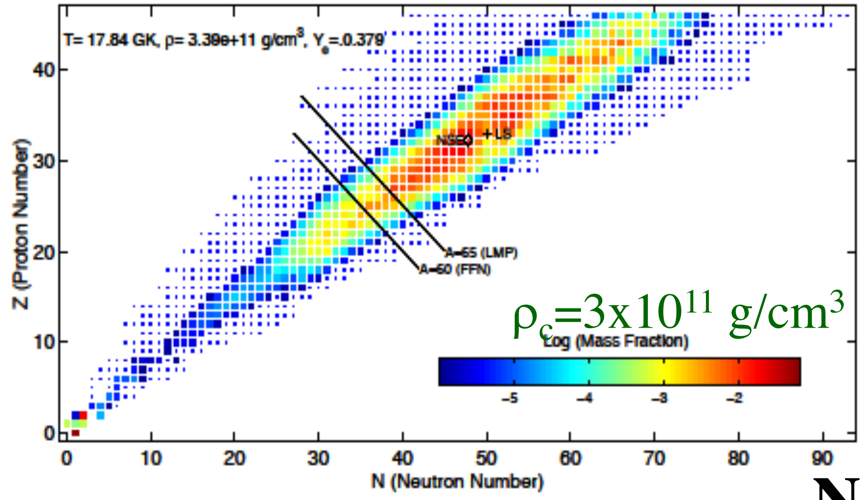
Wide variety of nuclei

Furusawa, Yamada, Sumiyoshi & Suzuki ApJ (2011, 2013, 2016)

e-capture on mixed nuclei during collapse

Z

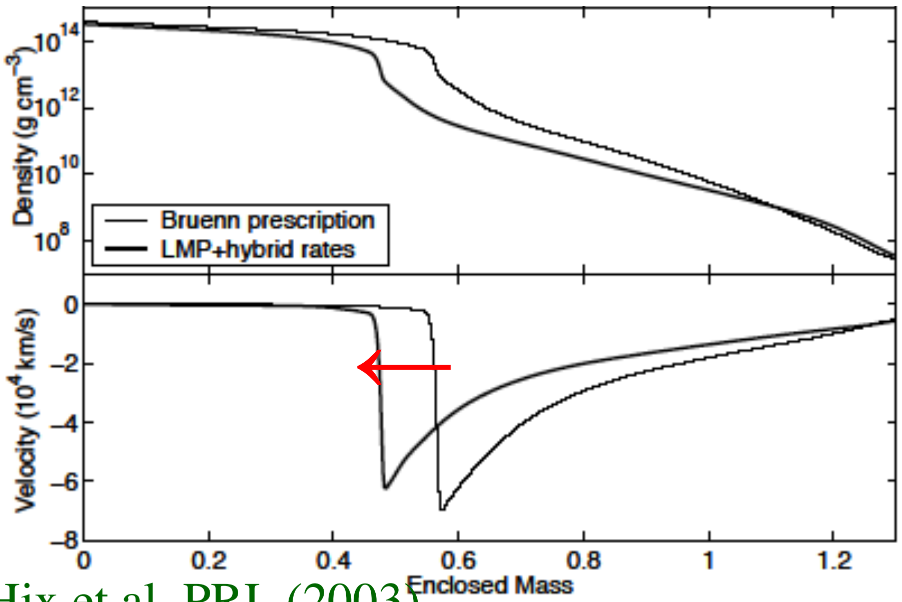
Nuclear statistical equilibrium



ρ_c=3x10^{11} g/cm^3

N

profile of core bounce



Hix et al. PRL (2003)

- Composition of nuclei

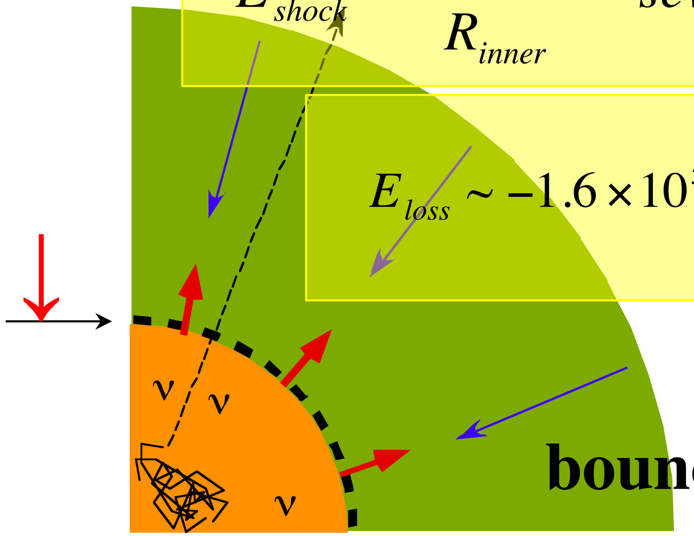
  1-species & ^{4}He → Mixture

- Electron capture on nuclei
  - Bruenn -> GSI rates
  - Single -> NSE average

Initial energy & loss

$$E^{\nu}_{shock} \sim \frac{GM^2_{inner}}{R_{inner}} = several \times 10^{51} erg$$

$$E_{loss} \sim -1.6 \times 10^{51} \left(\frac{M_{outer}}{0.1 M_{solar}} \right) erg$$



bounce & after

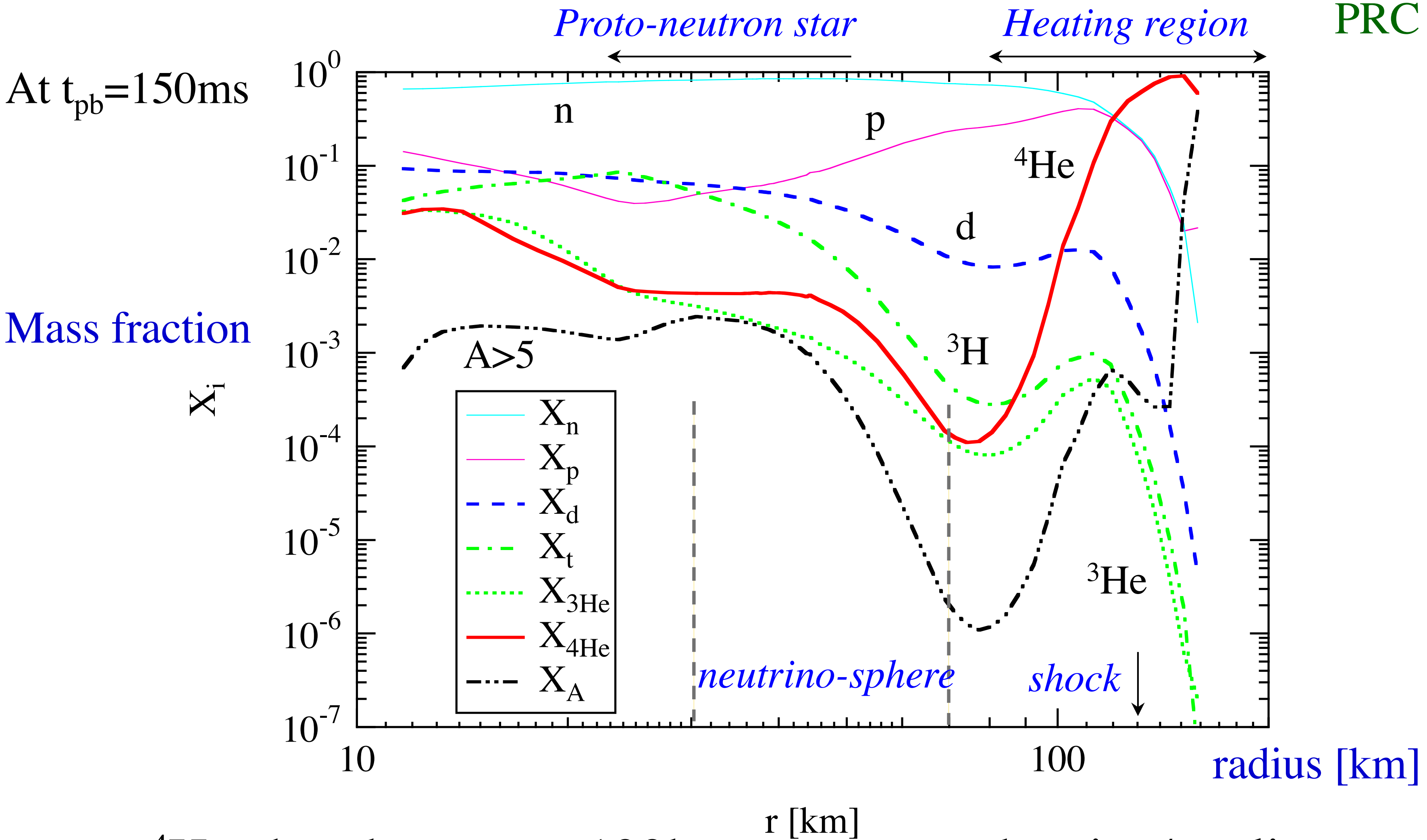
Bounce core

Fe core

Light clusters + ^{4}He can appear after bounce

Multi-compositions with p, n, d, ^{3}H, ^{3}He, ^{4}He, nuclei

Sumiyoshi & Röpke
PRC (2008)



- ^{4}He abundant at r > 100km → heating/cooling rates
- d, t, ^{3}He abundant at r < 50km → ν-emission, absorption

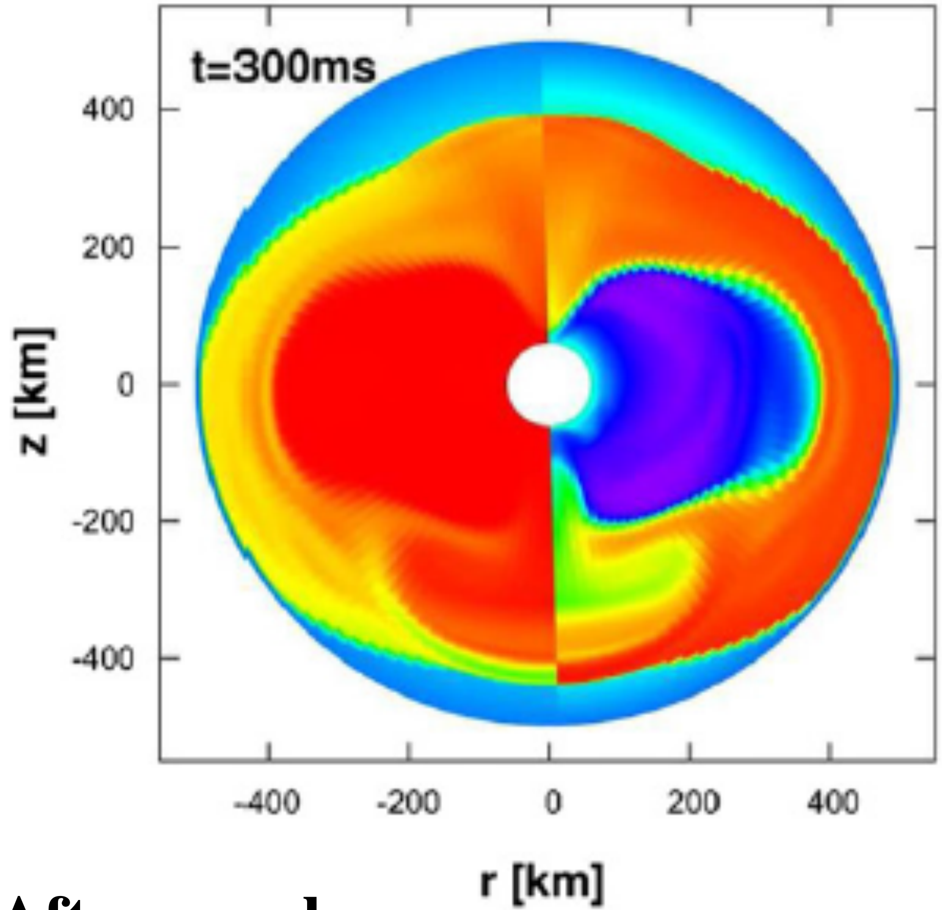
See also Arcones et al. PRC (2008) for proto-NS

2D supernova simulations with light clusters

Furusawa et al. ApJ (2013)

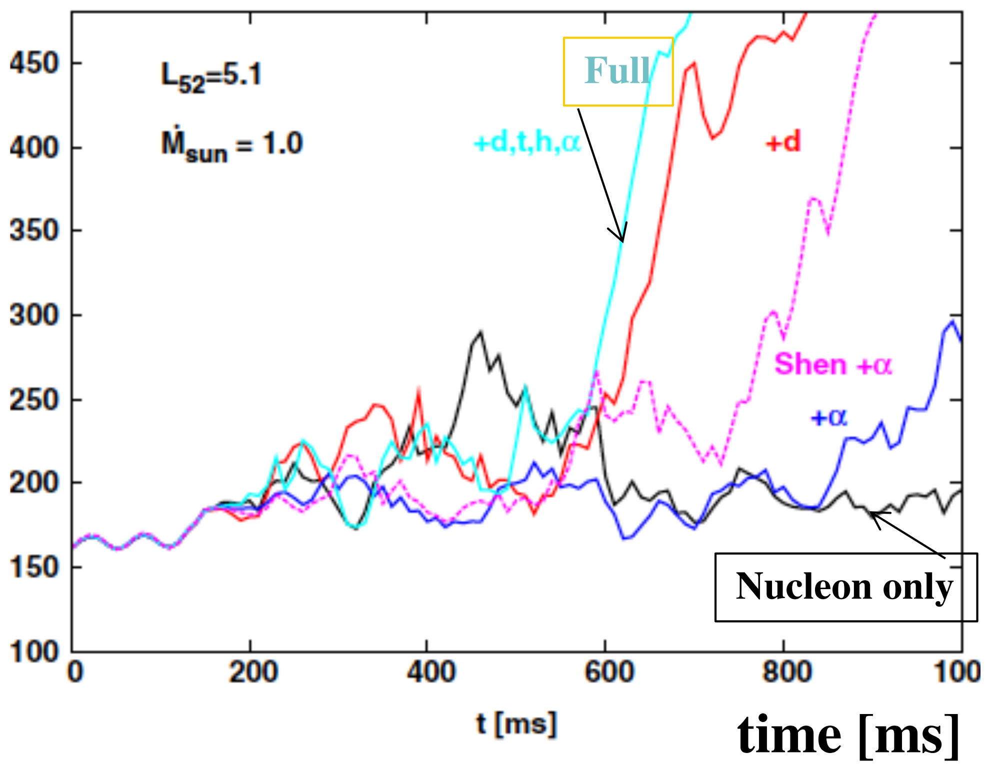
- (d, ^{3}He, t, ^{4}He) appear
- ν-absorption (d, ^{3}He, t)

Abundance



After core bounce

Shock radius



- Possible effects on shock revival when it is marginal

Stiffness & Composition of EOS in multi-D

Favorable for explosion

- **More ν-absorption**

  at heating region $\sim 10^{-5}\,\rho_0$

- **More ν-emission**

  at proto-NS surface $\sim 10^{-2}\,\rho_0$

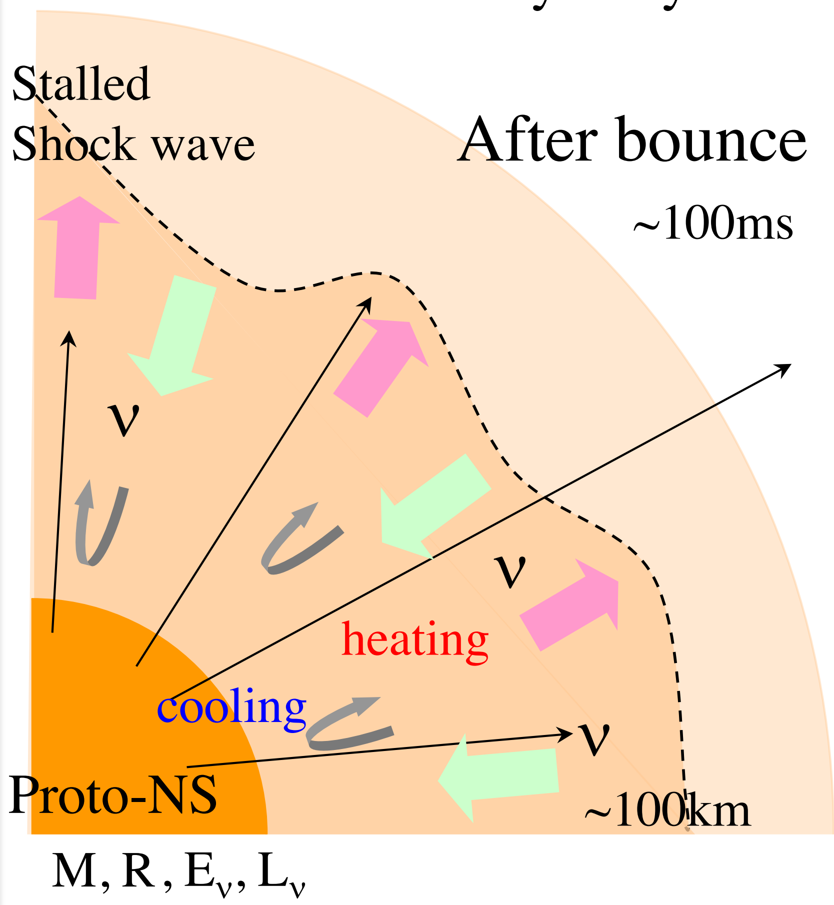
  composition & ν-reactions

- **EOS soft** $> \rho_0$

  Compact, Inner ρ, T ↑

  ν-luminosity, energy ↑

ν-cooling & heating
in multi-D hydrodynamics



IF opposite, maybe weaken explosions

Examine nuclear physics in multi-D simulations

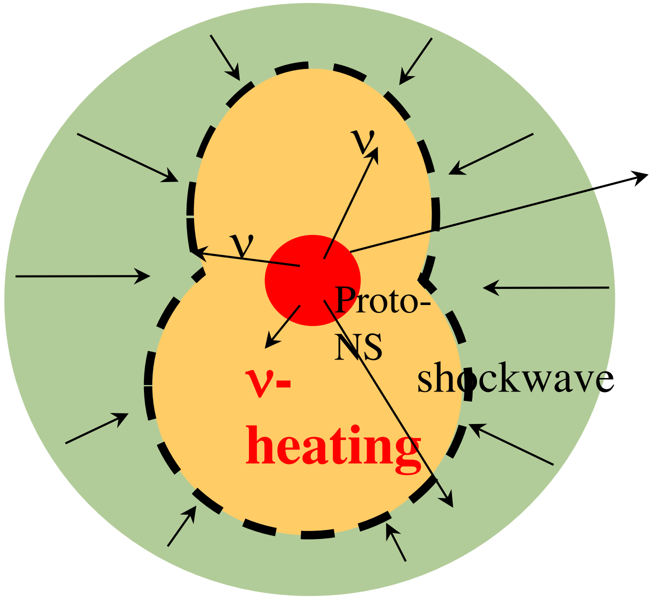
Neutrino transfer in 2D/3D supernovae

From approximate to exact
neutrino-radiation hydrodynamics

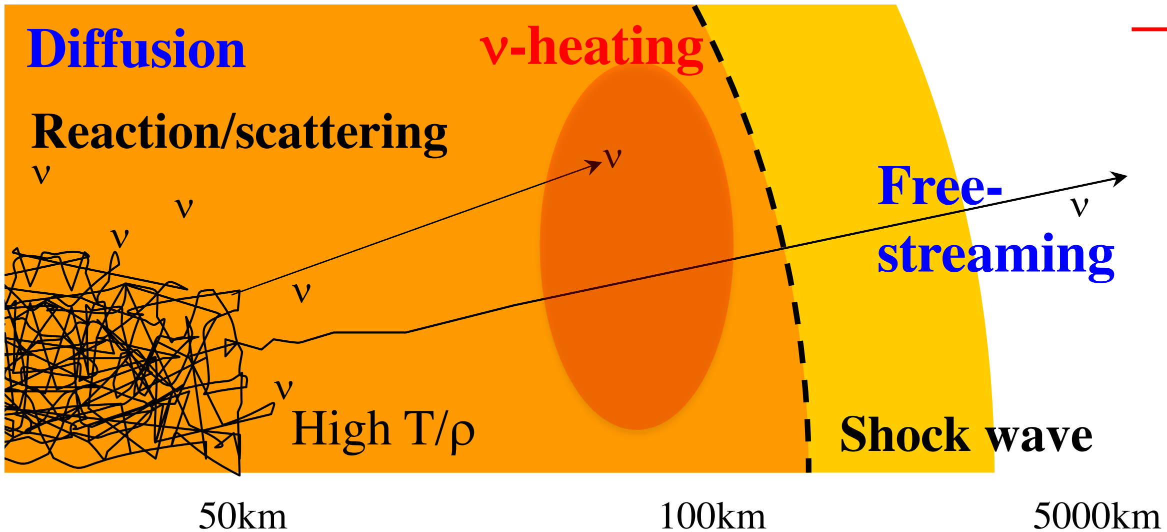
Nagakura et al., ApJS (2014, 2016)
Sumiyoshi et al., ApJS (2012, 2015)

Difficult problems of ν-transfer in SNe

- Neutrino flux & heating
  - ν-trapping, emission, absorption
- From diffusion to free-streaming
  - Intermediate regime is important
- Interplay with nuclear physics
  - Neutrino reactions and EOS



2D/3D hydrodynamics
+ neutrino heating



→ Solve ν-transfer to clarify influence

shift from approximate to exact calculations

Progress of ν-transfer in 2D/3D

- Approximate methods
  - Diffusion/IDSA methods, closure relations for moments
  - Ray-by-ray (along radial transport, moment/diffusion)
- Toward full evaluations of ν-transfer
  - Moment methods with variable closure *Just, Radice. Robert, Kuroda*
  - Boltzmann equation in 5D/6D *Ott, Sumiyoshi*
  - Monte Carlo methods *Abdikamalov, Richers*
- Need to validate approximations/methods
  - Independent investigations by different approaches

Our approach: Solving Boltzmann equation in 6D

2D core-collapse supernovae & examine approximate methods

Our code solves 6D Boltzmann eq.

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

Sumiyoshi & Yamada, ApJS (2012, 2015)

Boltzmann eq.

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

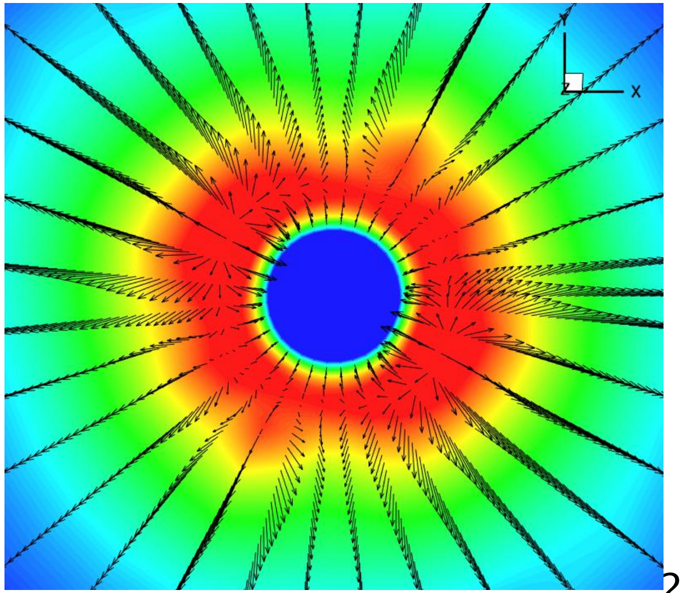
Time evolution + Advection = Collision

S_n method, implicit

- Collision Term is tough
  - Energy, angle dependent
  - Stiff, non-linear
  - Frame dependent
  - → Huge computation

- Describe non-radial fluxes in 3D
  - Provide angle factors, Eddington tensors
- Checked by MC method
  Richers et al. ApJS (2017)
- Comparison with Ray-by-ray
  - Local ν-heating ~20% difference
  Sumiyoshi et al. ApJS (2015)

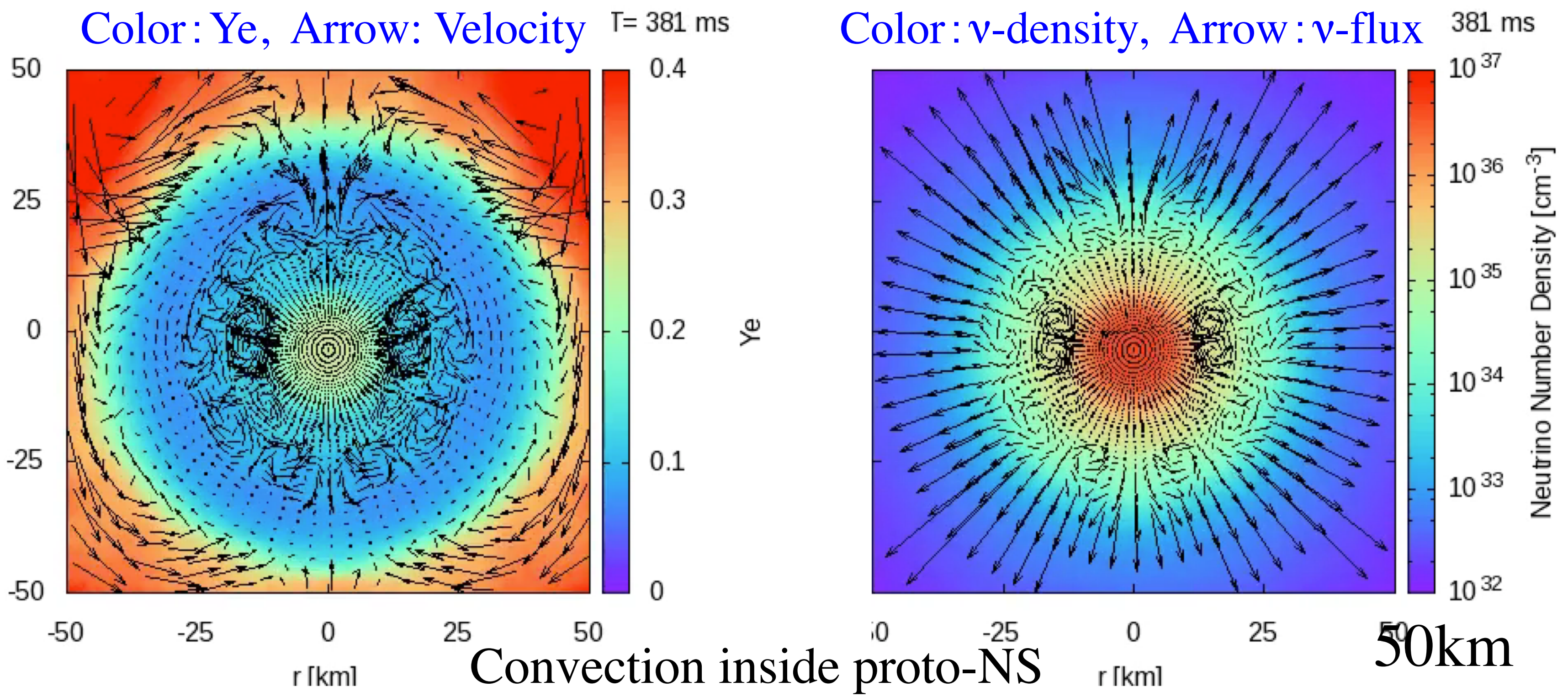
Flux: ϕ-direction



Neutrino-radiation hydrodynamics: 2D dynamics

Nagakura et al. ApJS (2014, 2016)

- 6D Boltzmann solver ＋ 2D Hydrodynamics + 2D gravity
  - Relativistic effects: Doppler, angle aberration, moving mesh
  - Neutrino transfer in fluid flow (from diffusion to free-streaming)



Seamless description of non-radial flux

cf. Ott (2008) without v/c-terms

Figure by Iwakami

2D core-collapse simulation

neutrino-radiation hydrodynamics in 2D
by solving Boltzmann equation

Nagakura, Iwakami, Furusawa, Okawa, Harada,
Sumiyoshi, Yamada, Matsufuru and Imakura, ApJ 854 (2018) 136

2D axially symmetric simulations performed

Nagakura, Iwakami, Okawa, Harada et al. (2015-2018)

- Massive star: 11.2M_{sun} (WHW02)
  - 1D grav. collapse, bounce; 2D shock propagation
- Furusawa EOS table vs Lattimer-Swesty EOS
  - Extended Shen EOS RMF-TM1 with NSE
- Basic reaction rates by Bruenn + updates
  - GSI e-capture rates on nuclei, NN bremsstrahlung

→ time evolution over 300 ms after bounce

Poster on Rotating model by Harada, 27M star by Iwakami

384 x 128, 10 x 6 x 20
4M node hours for 2M steps, Data ~100TB
on K-computer, Japan

K-Computer, Japan

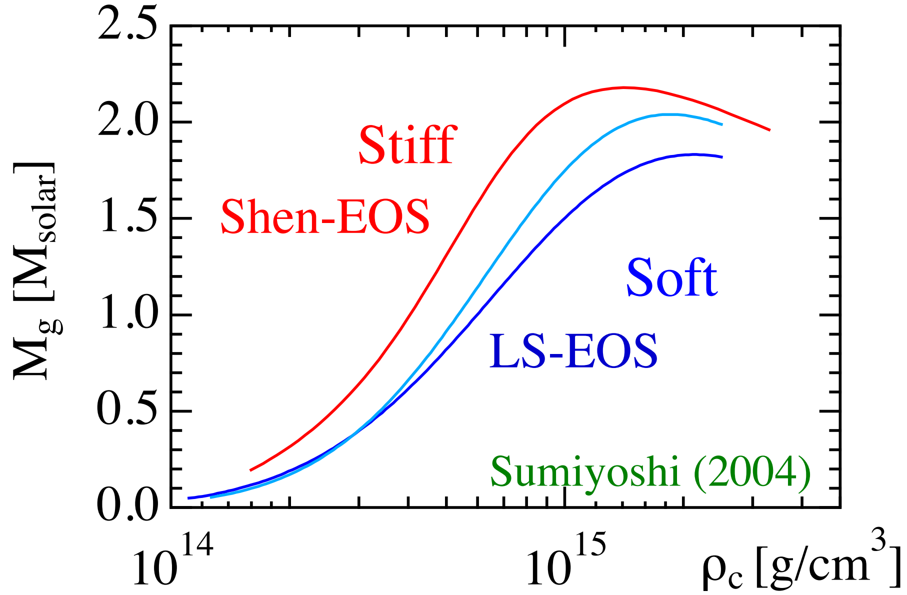
Influence of EOS tables

- 2 sets of EOS tables

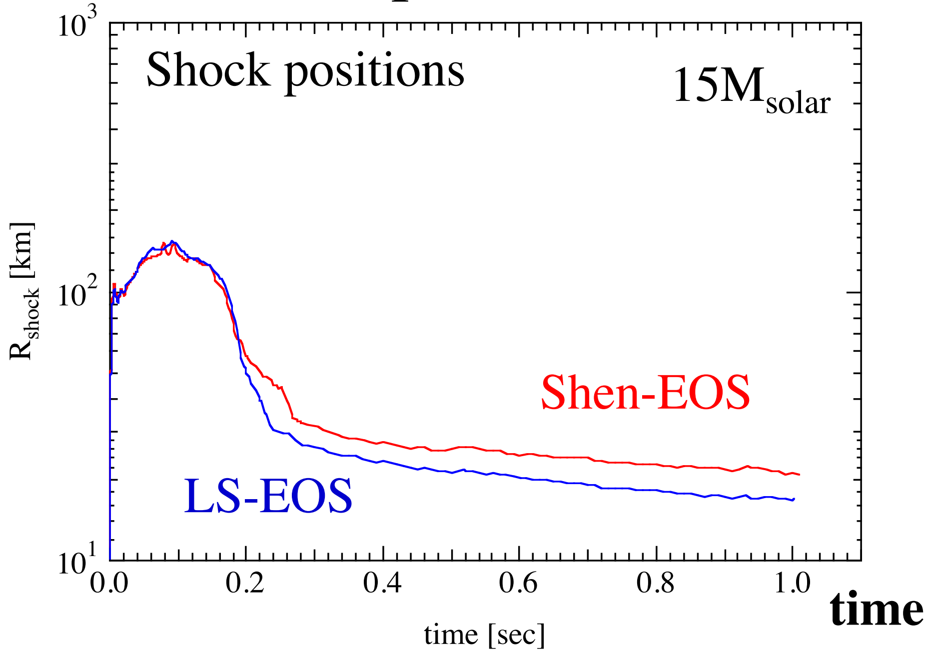
Stiff – Furusawa (Shen)

Soft – Lattimer-Swesty

Neutron star mass

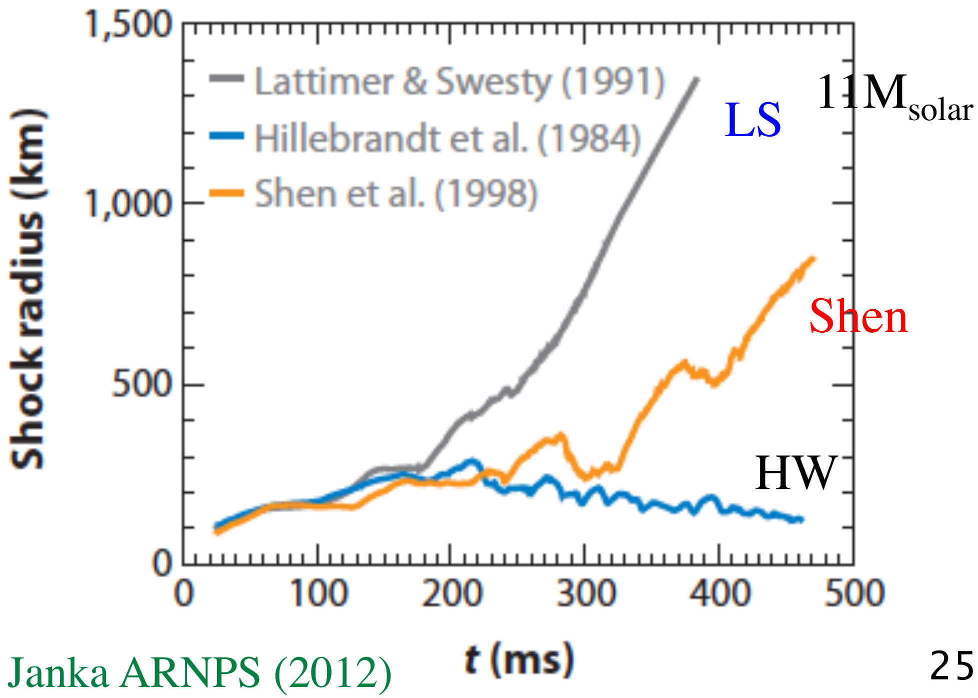


No explosion in 1D



Sumiyoshi et al. (2005)

Soft EOS is favorable in 2D?

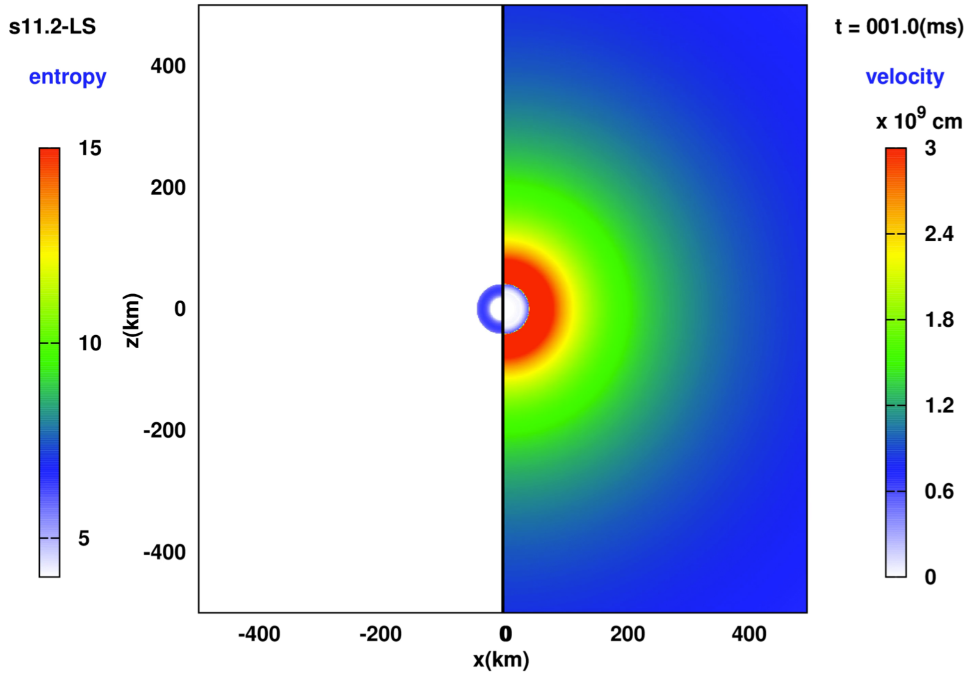


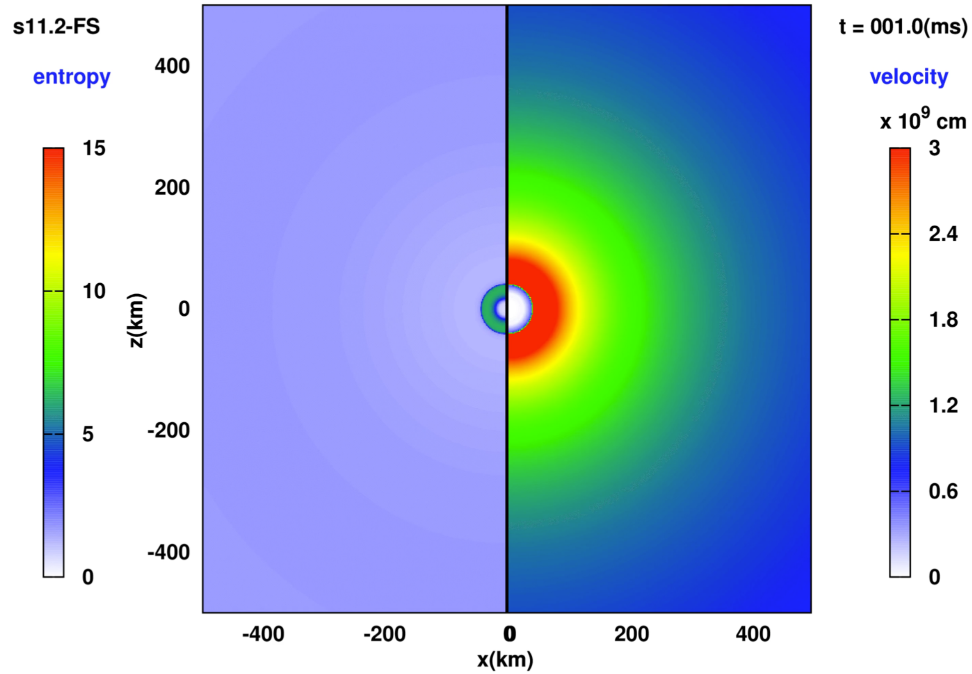
Janka ARNPS (2012)

Comparisons of 2D core-collapse simulations

Nagakura et al. ApJ (2018)

Lattimer-Swesty EOS　VS　Furusawa EOS

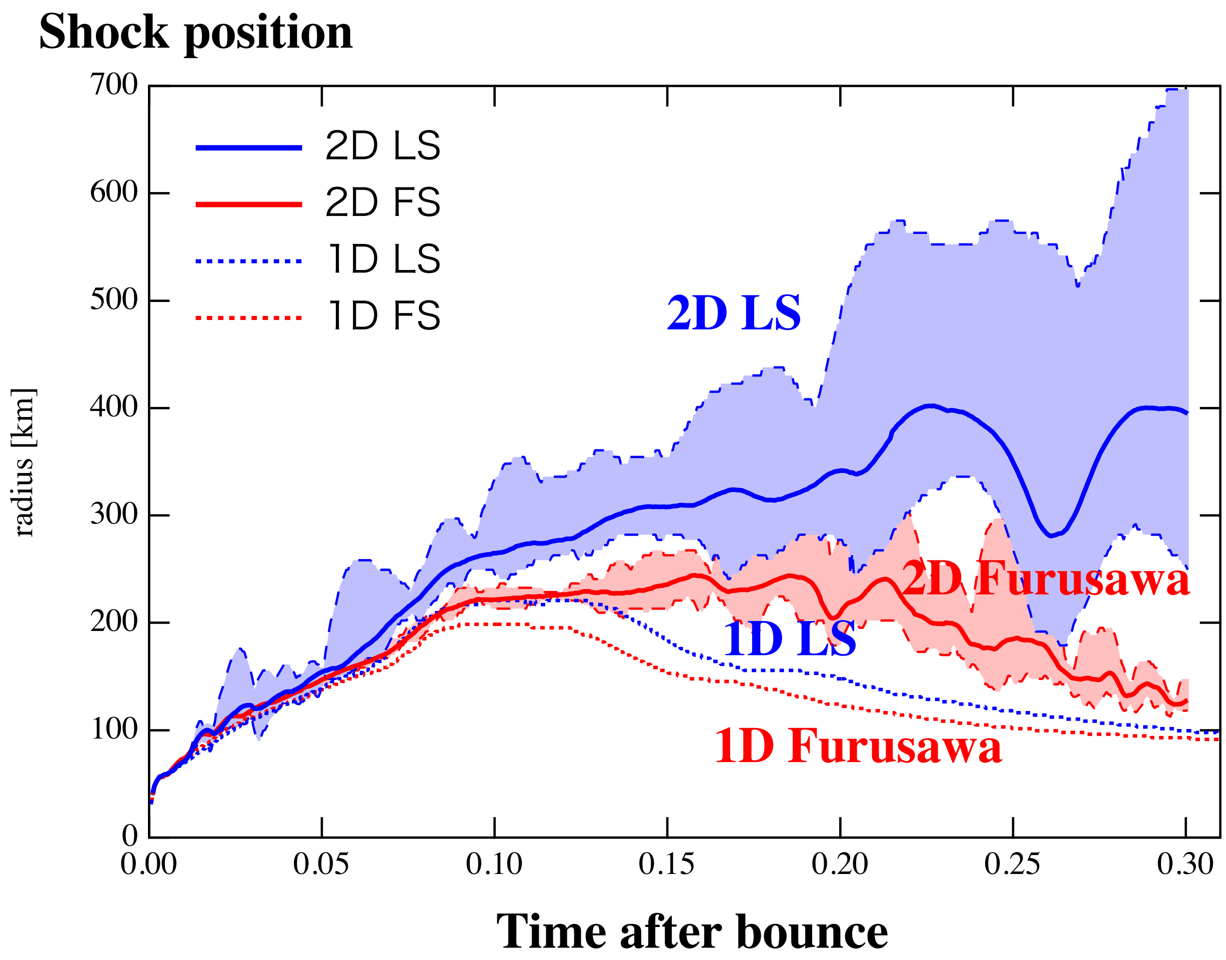


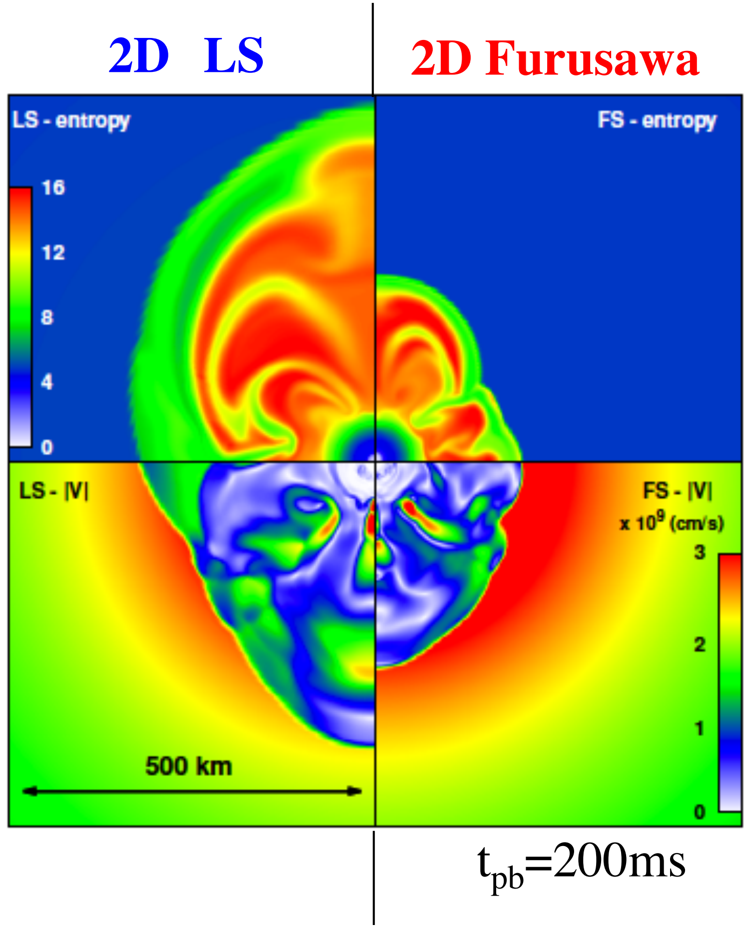


6D Boltzmann solver + 2D Hydrodynamics + 2D Gravity on K computer

Influence of EOS: simulations with Boltzmann

- 2D: Soft EOS (LS) close to explosion
  - 1D: No explosions and small difference



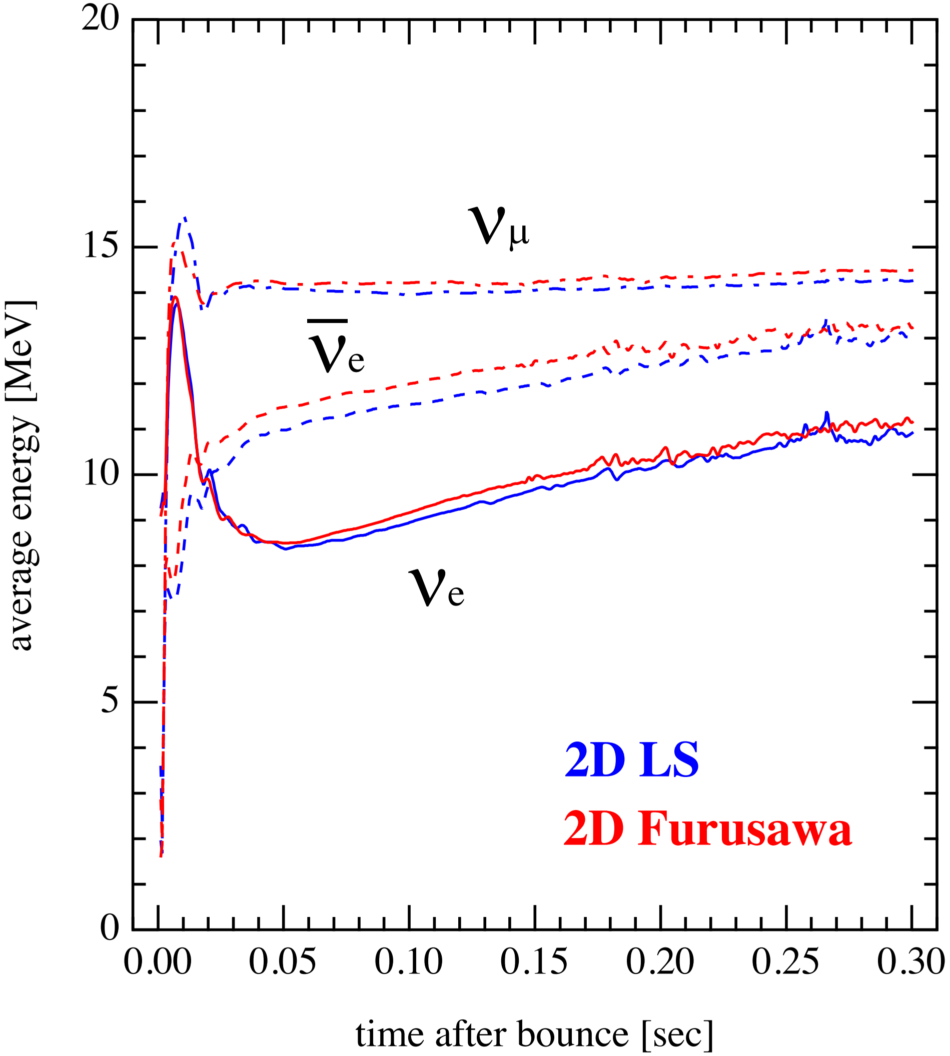


top : entropy
bottom : fluid velocity

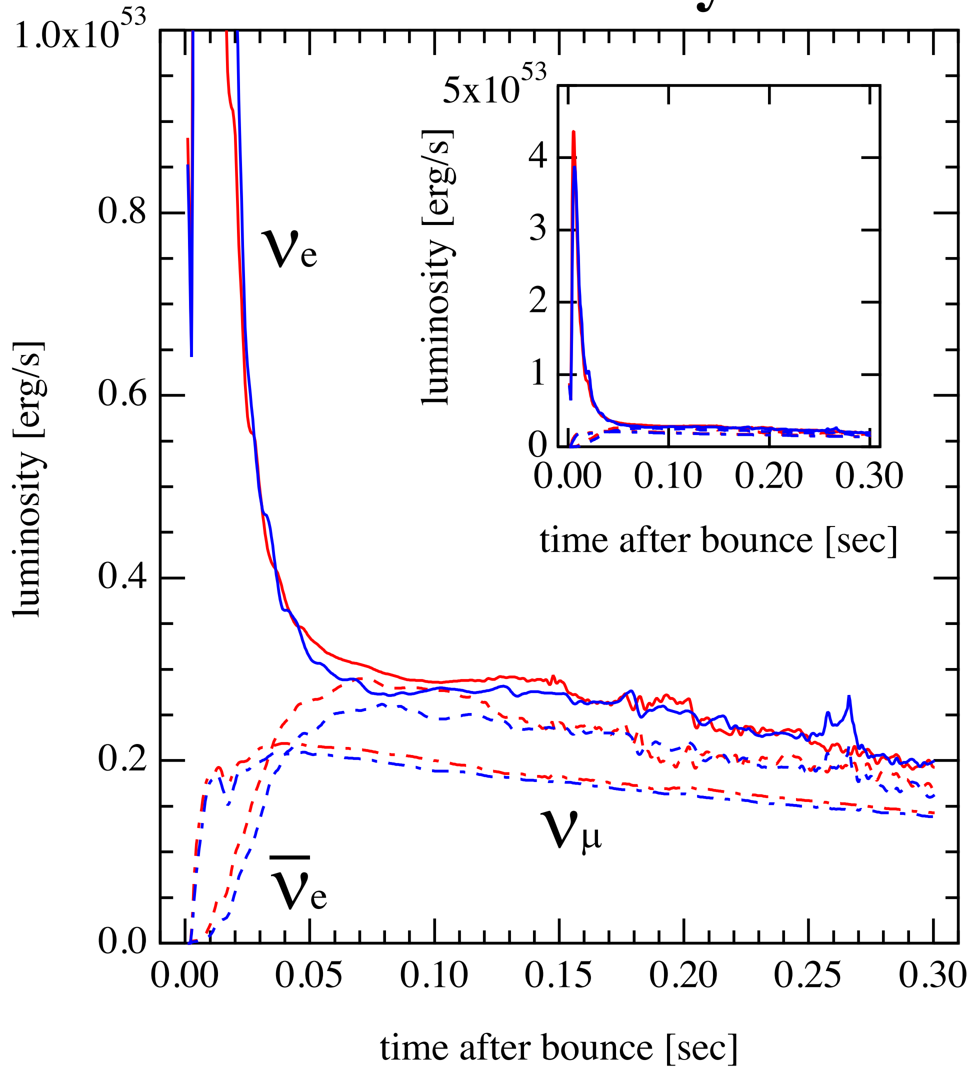
Nagakura, Iwakami, Okawa, Harada et al. ApJ (2018)

Comparison of neutrino emissions

Average energies



Luminosity



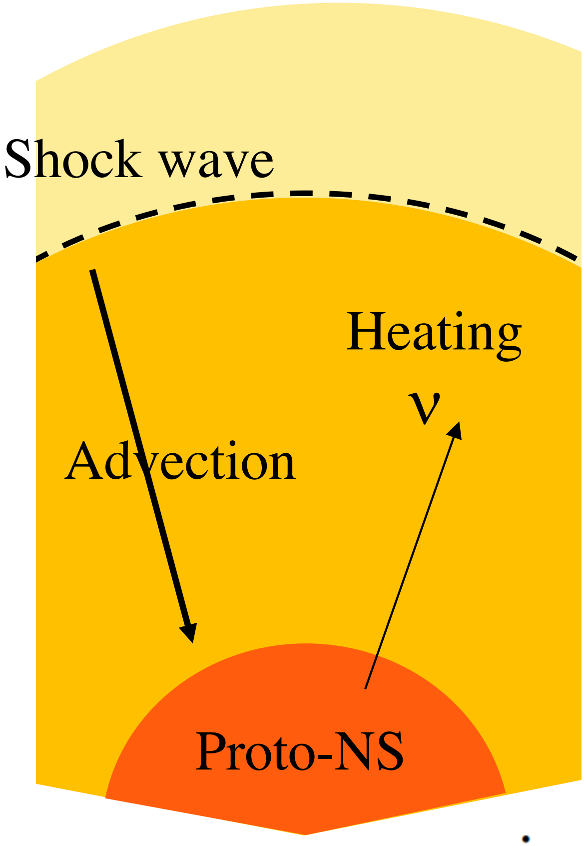
Rather close each other, but…

Nagakura, Iwakami, Okawa, Harada et al. ApJ (2018)

Averaged over directions

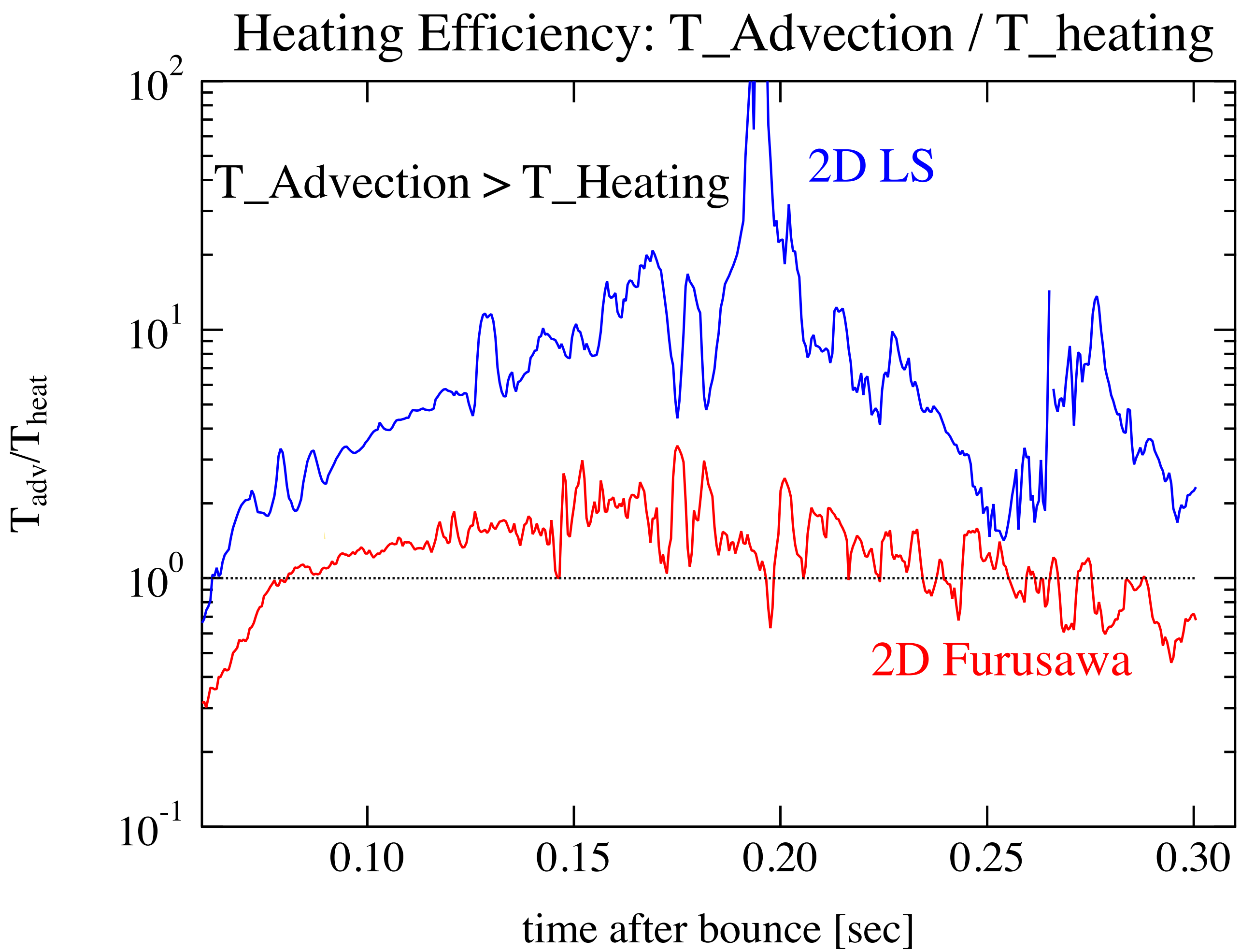
Difference in heating efficiency

- Efficient heating if Advection time > Heating time
  - More favorable in LS than Furusawa



$$T_{\rm adv} = M_{\rm g}/\dot{M}$$

$$T_{\rm heat} = |E_{\rm tot}|/\dot{Q}_\nu$$



Nagakura, Iwakami, Okawa, Harada et al. ApJ (2018)

Need further studies

Convective motion is different in two models

- Convection is more active in LS EOS

LS Furusawa

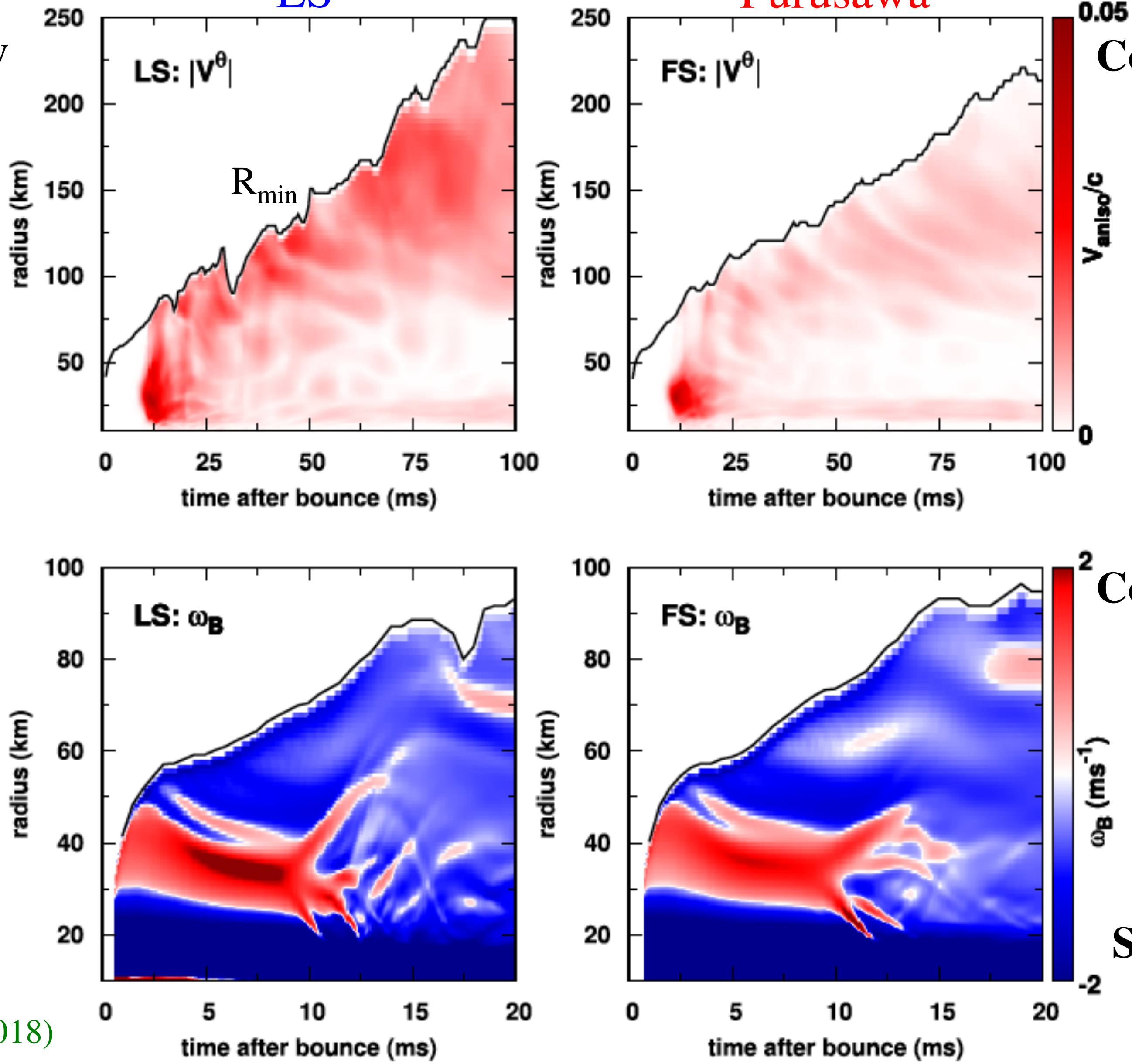
Lateral velocity

Convective

Brunt–Väisälä frequency

Convective

Stable



Nagakura et al. ApJ (2018)

Extensive studies by 2D simulations

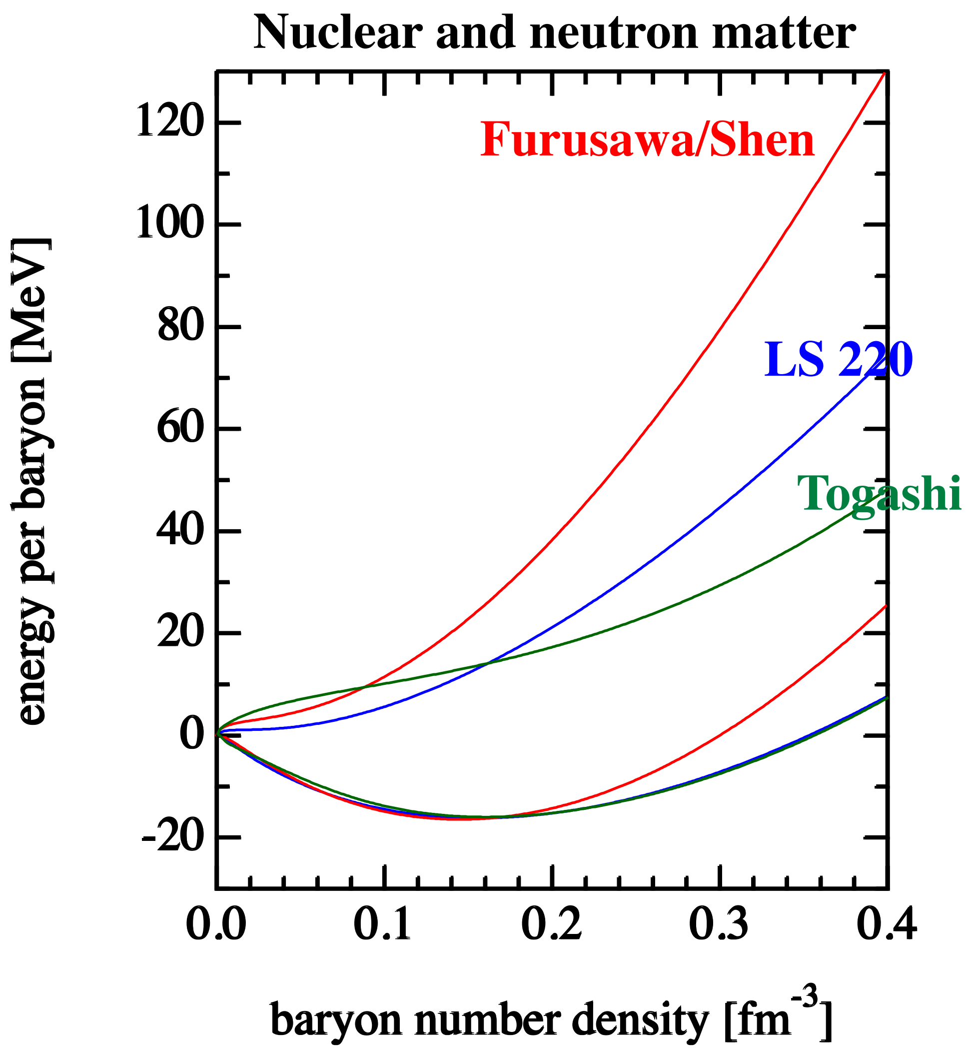
neutrino-radiation hydrodynamics in 2D
by Boltzmann solver are running

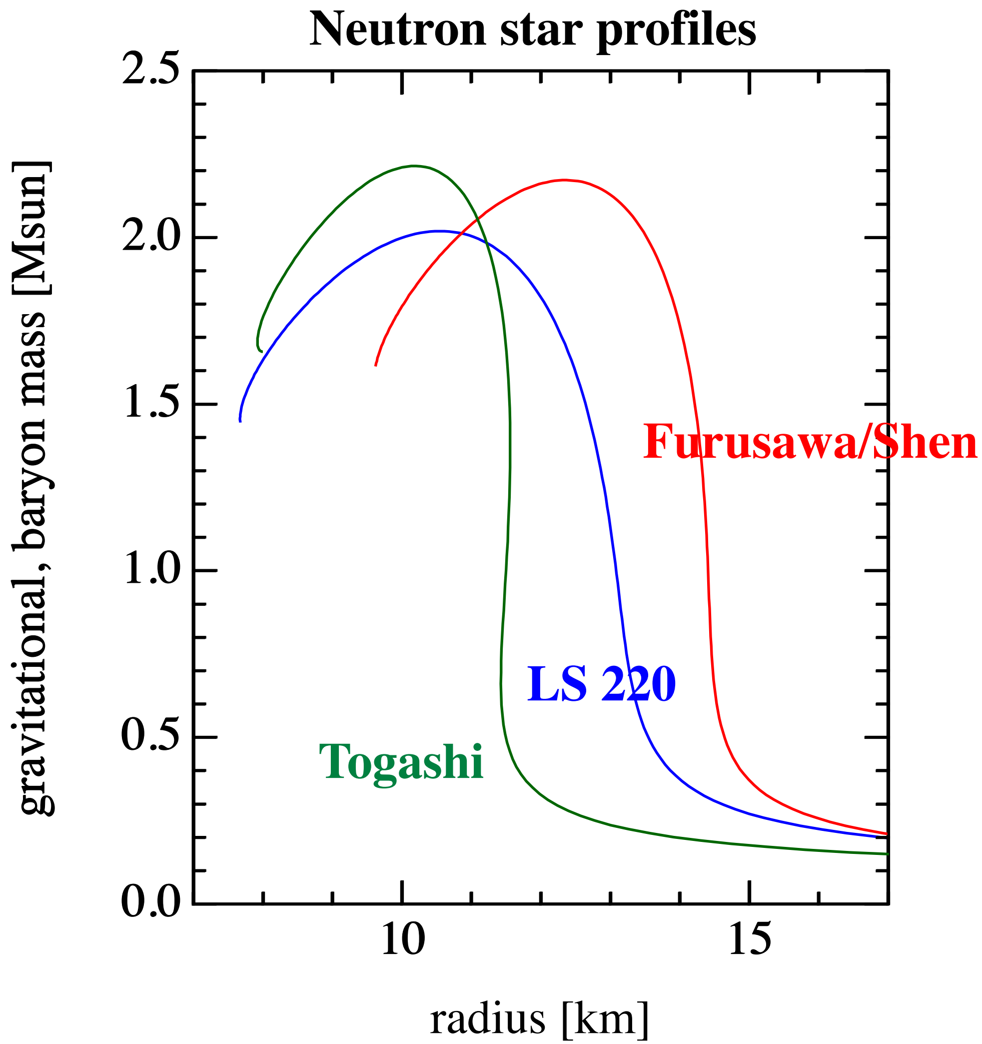
Togashi EOS by Nagakura
27M star by Iwakami
Rotations by Harada
3D models by Iwakami/Okawa

Influence of EOS: Togashi EOS

Furusawa, Togashi JPG (2017)

- Variational method, Multi-composition



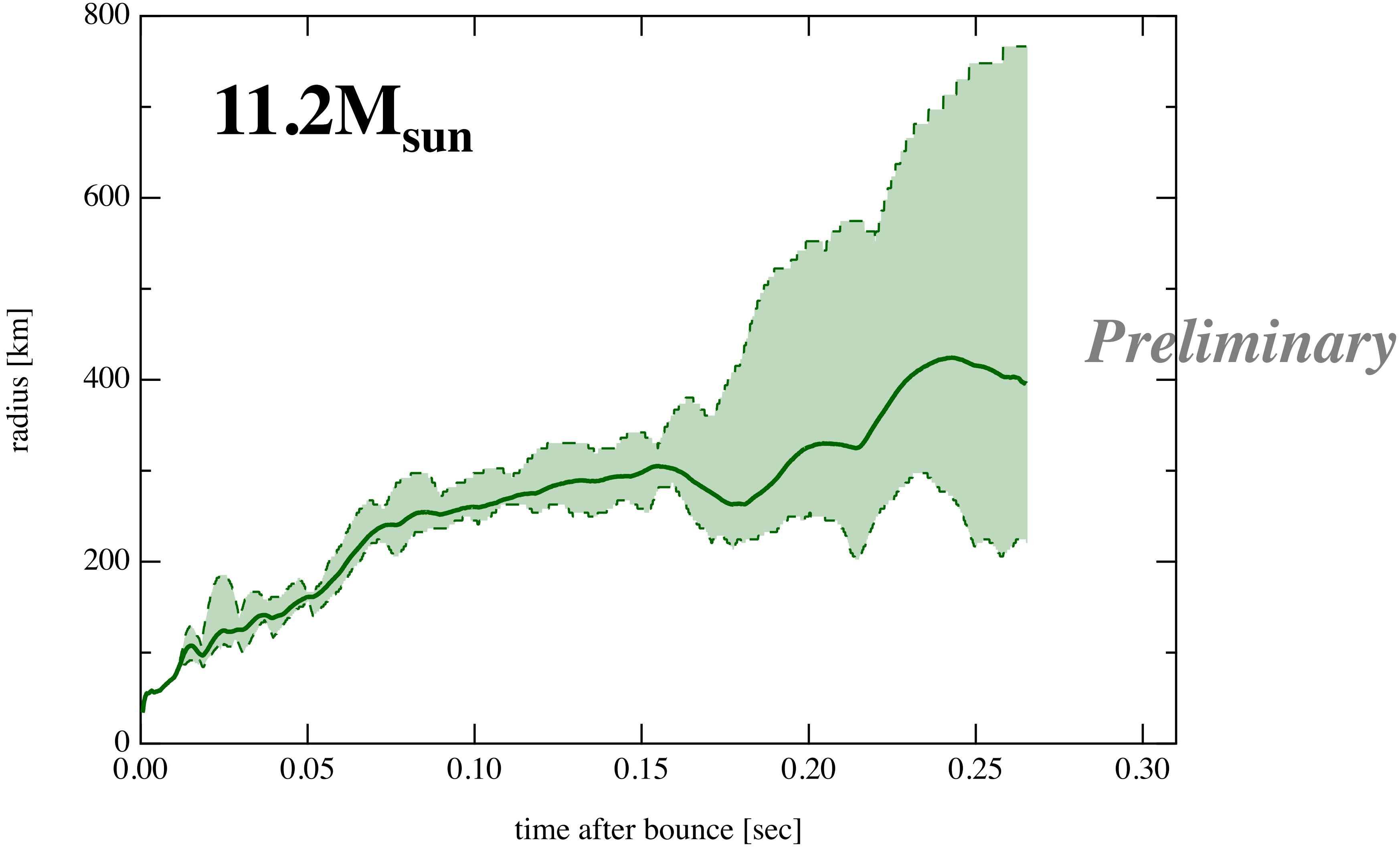


Data from H. Togashi (2018)

2D simulations with Togashi EOS

- Close to explosion, similar to LS?

Nagakura et al. (2018)

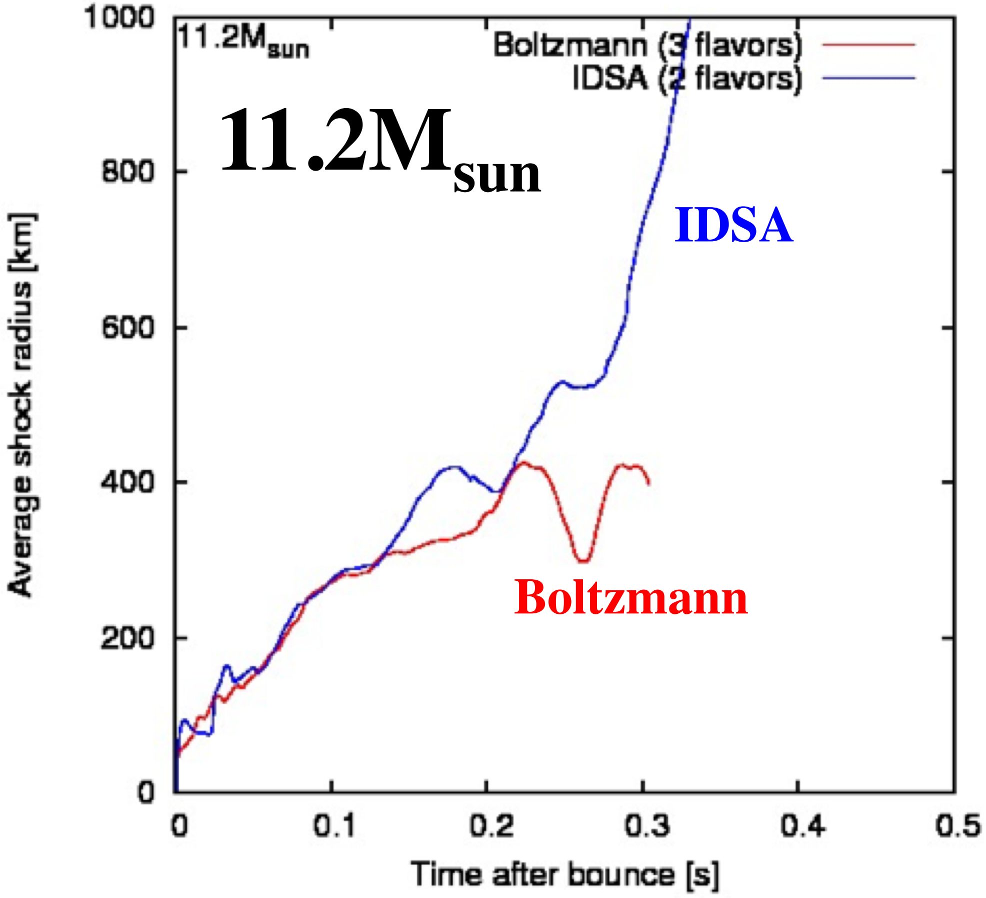


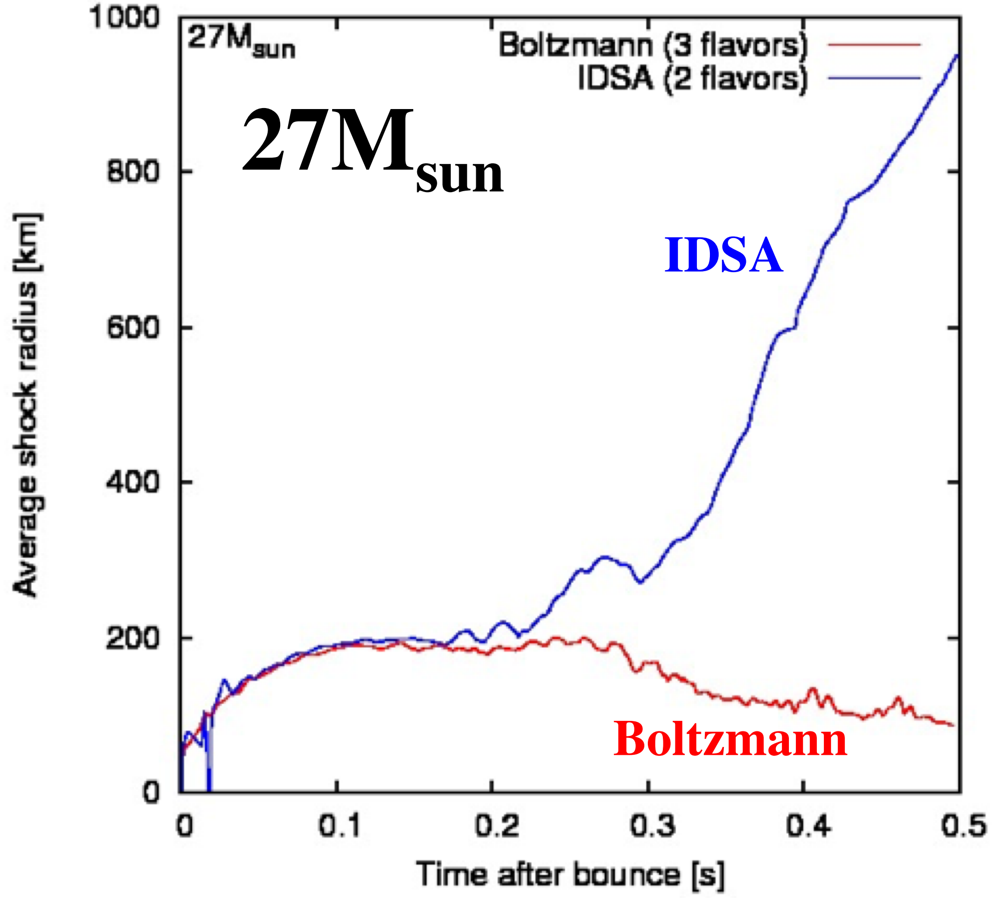
6D Boltzmann solver + 2D Hydrodynamics + 2D Gravity on K computer

2D simulation of 27M star with LS EOS

Iwakami poster

- Comparison with IDSA simulations





Iwakami, Nakamura et al. (2018)

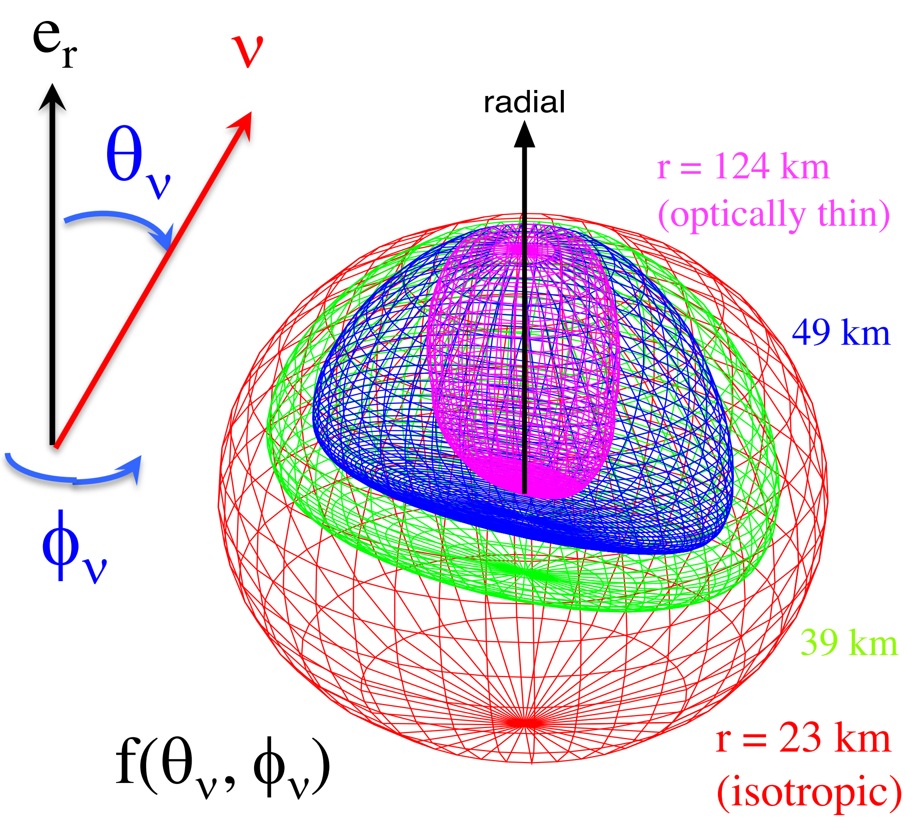
Applications of 6D Boltzmann solver

Provide valuable information for approximate methods

Applications of ν-transfer by 6D Boltzmann solver

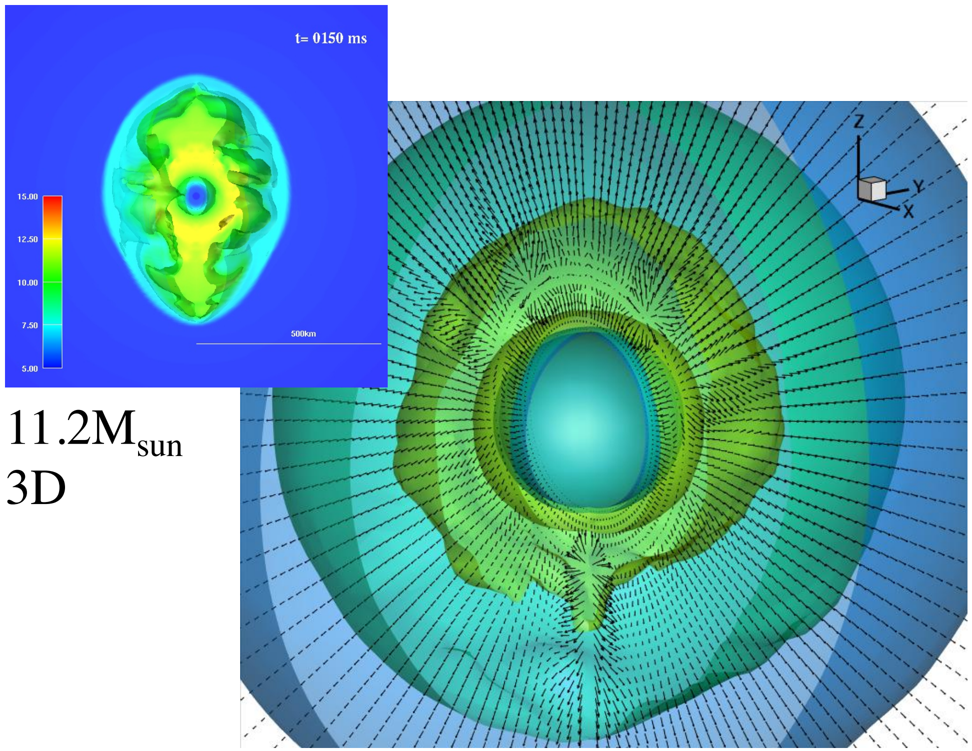
- Evaluate neutrino distributions for 2D/3D astrophysical objects
- Provide angle moments, Eddington factors, heating rates
- We can examine approximations and improve formulae

- Full angle information



Nagakura et al. ApJ (2018)

- Non-radial fluxes in 3D core

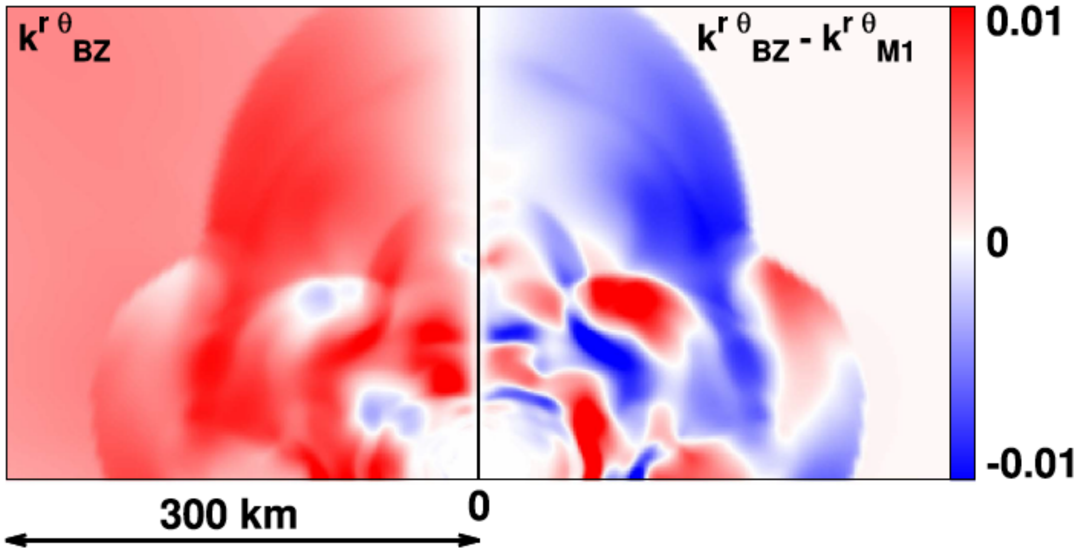


$\bar{\nu}_e$ density iso-surface and flux

Sumiyoshi et al. ApJS (2015)

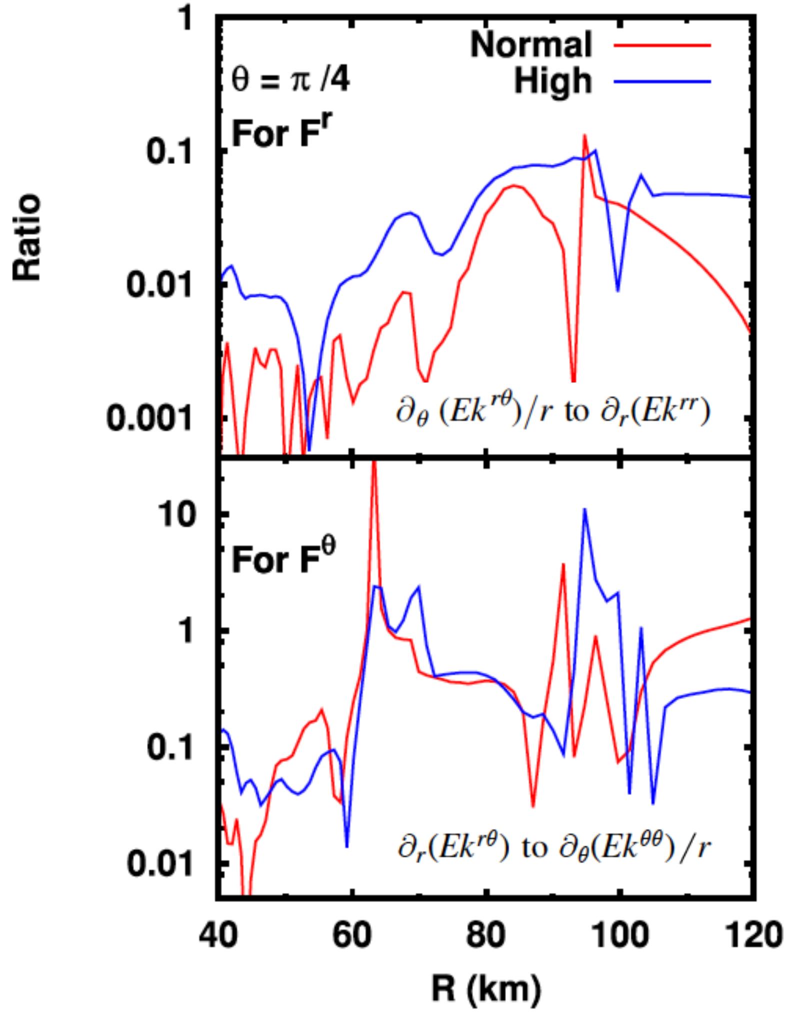
6D Boltzmann eq. to provide information

- Non-radial flux and pressure tensor



Eddington tensor $k^{ij} = \frac{P^{ij}_\nu}{E_\nu}$

$$P^{ij}_\nu = \int \frac{d\varepsilon\, \varepsilon^2}{(2\pi)^3} \int d\Omega \varepsilon n_i n_j f(\varepsilon, \Omega)$$



$$\partial_t(F^r) \sim -\partial_r(Ek^{rr}) - \frac{1}{r}\partial_\theta(Ek^{r\theta}),$$

$$\partial_t(F^\theta) \sim -\partial_r(Ek^{r\theta}) - \frac{1}{r}\partial_\theta(Ek^{\theta\theta}),$$

M1 prescription

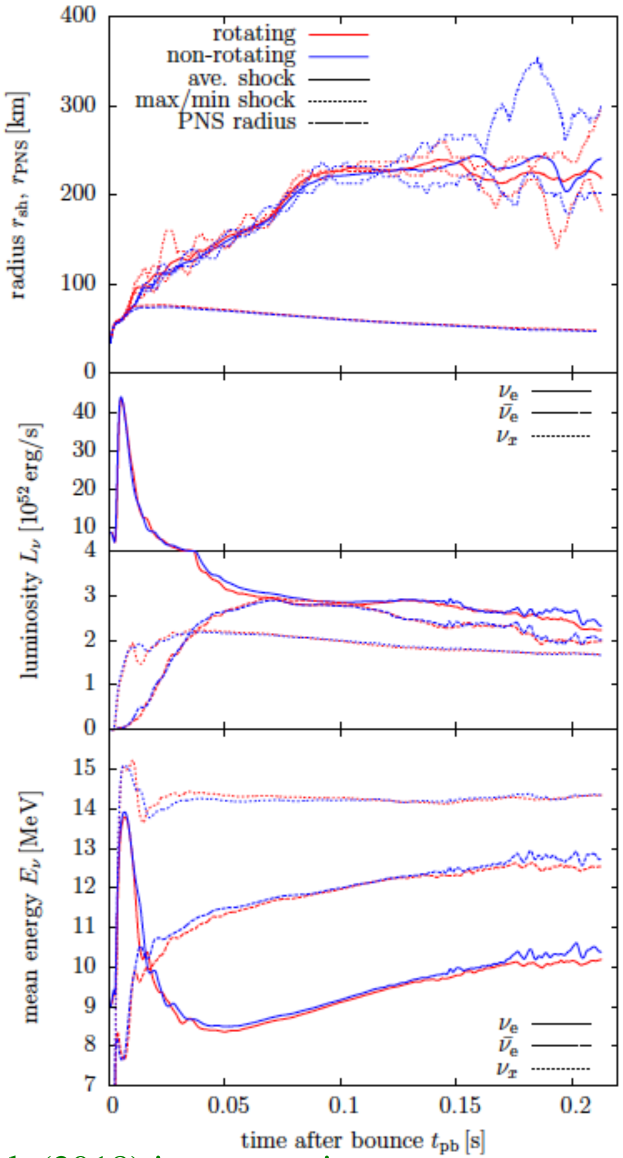
$$P^{ij}_{\rm M1}(\varepsilon) = \frac{3\zeta(\varepsilon) - 1}{2} P^{ij}_{\rm thin}(\varepsilon) + \frac{3(1 - \zeta(\varepsilon))}{2} P^{ij}_{\rm thick}(\varepsilon),$$

Nagakura et al. ApJ (2018)

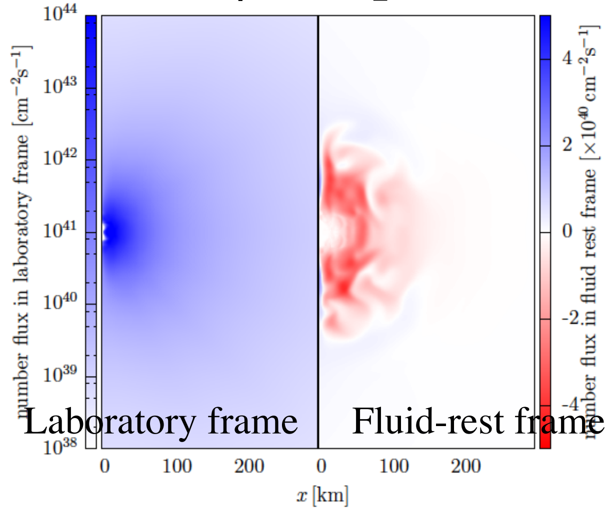
Neutrino transfer in rotating situation

Harada poster

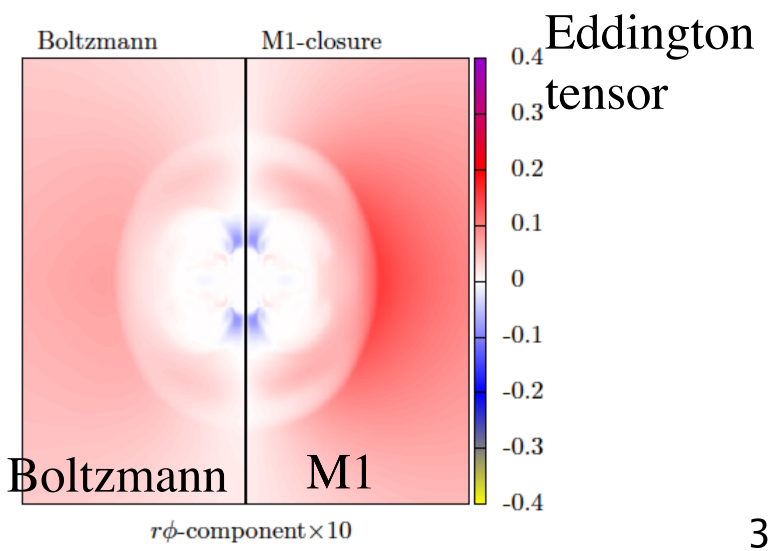
- 2D simulations of collapse, bounce and shock wave



Azimuthal (ϕ) component of flux



Non-diagonal (rϕ) component of k_{ij}



Harada et al. (2018) in preparation

Toward the first principles calculation

- General relativistic treatment — Harada, Nagakura
  - Moving mesh to track proto-NS move — Nagakura ApJ (2017)
- Extension to 3D, expensive by ~100 — Okawa, Iwakami
- Needs Exa-scale supercomputer — Also GPU-accel. See Matsufuru
  - Post-K Supercomputer project 2020-

Together with

- Systematic studies on various massive stars
  - Approximate methods are necessary
  - Boltzmann calculations help to validate

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Solving the explosion mechanism of supernovae

Neutrino-radiation hydrodynamics by Boltzmann eq.

- 2D core-collapse simulations are running
  - First series of post-bounce evolutions from $11M_{sun}$
    - No explosion with Furusawa EOS
    - Closer to explosion with Lattimer-Swesty EOS
  - Additional models: Togashi EOS, 27M star
  - Rotating collapse of massive stars
  - Characteristic of neutrino transfer in 2D and 3D
- Toward the first principles calculation
  - ongoing project for 3D core-collapse simulations in GR

    Exa-flops supercomputer, post-K project in Japan
- Importance of microphysics
  - Nuclear and neutrino physics remains crucial

Project in collaboration with

- Numerical simulations
  - H. Nagakura
  - W. Iwakami
  - H. Okawa
  - A. Harada
  - S. Yamada
- Supernova research
  - T. Takiwaki
  - K. Nakazato
  - K. Kotake
  - K. Takahashi
- Supercomputing
  - H. Matsufuru, A. Imakura
- EOS tables & neutrino rates
  - S. Furusawa,
  - H. Shen, K. Oyamatsu, H. Toki
  - S. X. Nakamura, T. Sato
- Neutron star merger
  - Y. Sekiguchi, S. Fujibayashi

Supported by
- *MEXT and JICFuS*
- *for K-computer and Post-K machine*

- *K-computer: hp170230, hp170031*
- *HPC resources at KEK, YITP, UT, RCNP*

Grant-in-Aid for Scientific Research
(15K05093, 17H06365)

K-Computer, Japan