2D/3D Core-collapse supernovae explored by 6D Boltzmann neutrino transport

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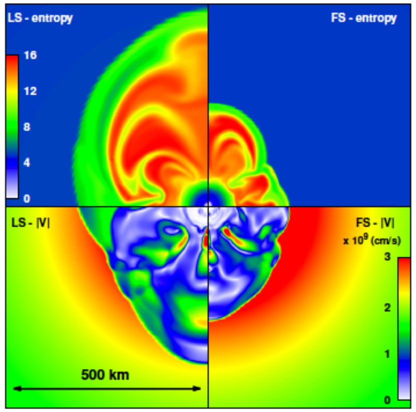


Nagakura arxiv:1702.01752

Solve Boltzmann equation in 6D
- Dynamics of 2D core-collapse supernovae
- Neutrino transport in 2D/3D astrophysical objects

K-Computer, Japan

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 principle calculations

- General relativistic neutrino-radiation hydrodynamics

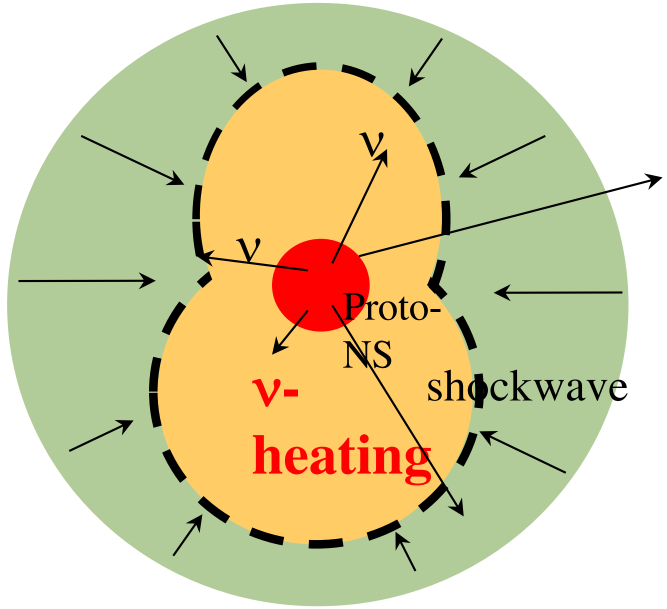
Variety of supernovae: explosive nucleosynthesis, neutrino bursts

Focus on neutrino transfer: full Boltzmann transport

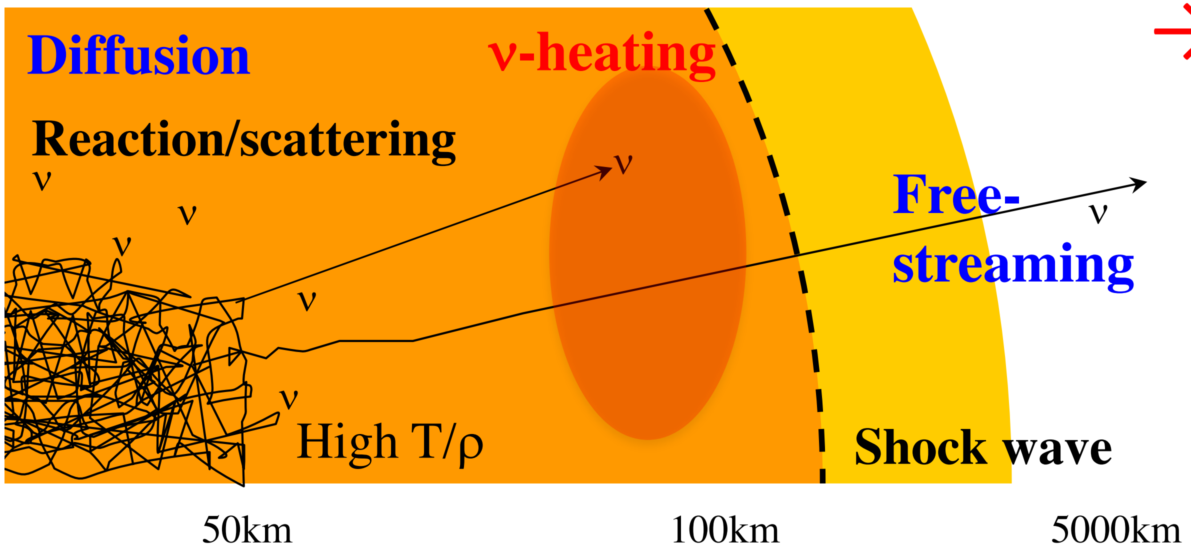
- First results of core-collapse simulations in 2D: 11M+2EOS
- Examine methods of neutrino transfer in 2D/3D

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

Lessons from ν-transfer in 1D (spherical)

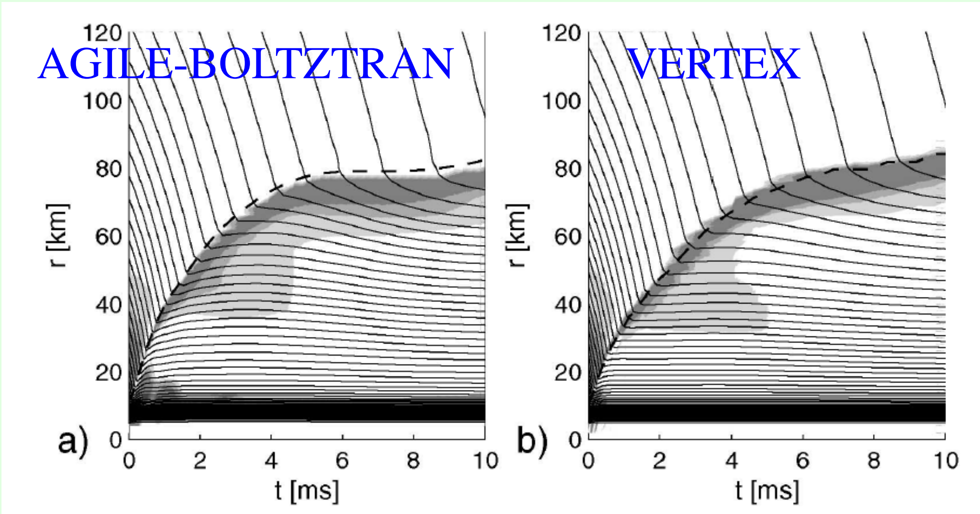
since 2000

First principle calculations in 1D provide:

- Established 1D neutrino transport
  - Examine approximations, comparison of methods
- No explosion in spherical symmetry
  - Examine influence of neutrino & nuclear physics

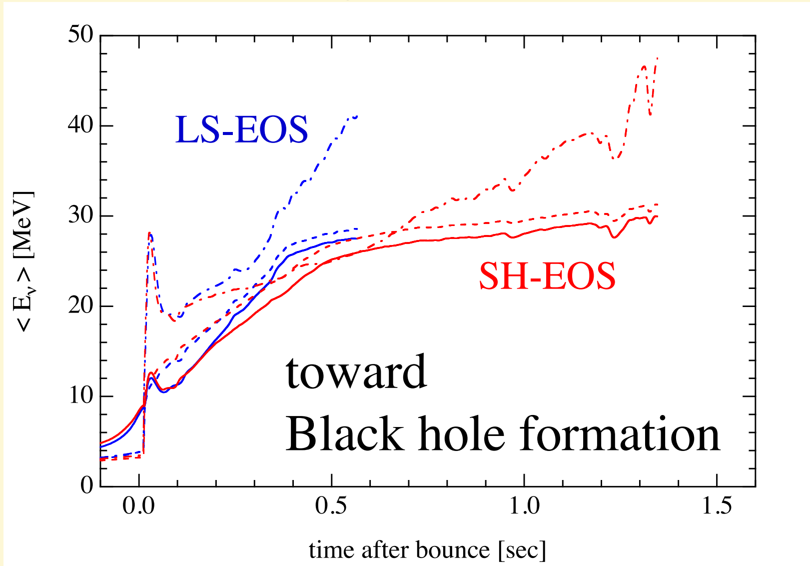
→ Necessary steps also in 2D/3D

Boltzmann solver vs Moment formalism



Liebendoerfer et al. (2005)

Influence of EOS on neutrino burst



Sumiyoshi et al. (2006) See also Fischer et al.

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 *Kuroda, Just, Shibata, Cardall*
  - 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

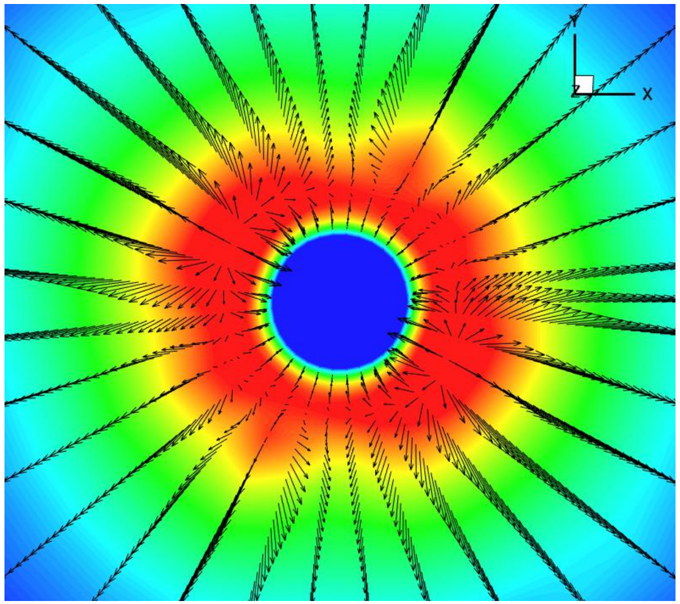
S_n method, implicit

- 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
- Comparison with Ray-by-ray
  - Local ν-heating ~20% difference

Sumiyoshi et al. ApJS (2015) *Background fix*

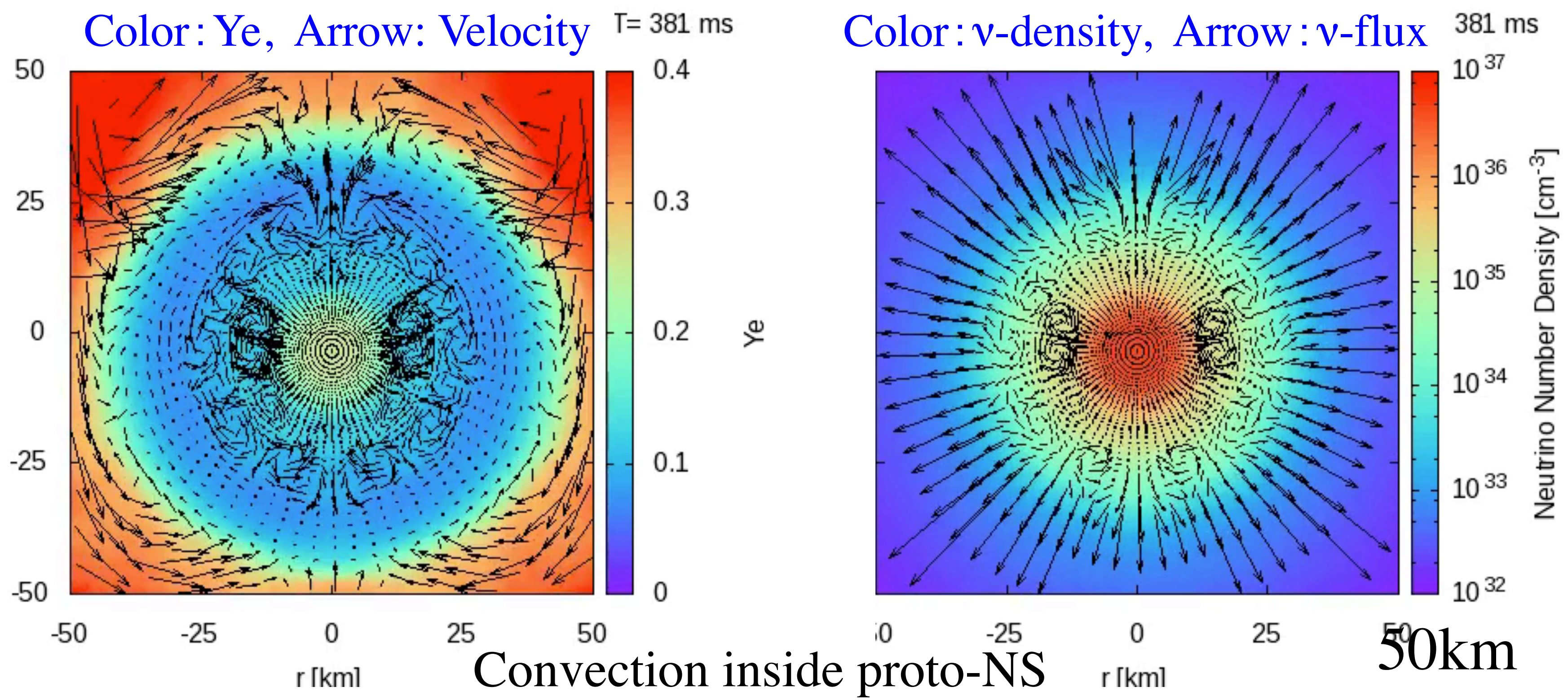
Flux: ϕ-direction



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)



Convection inside proto-NS

Seamless description of non-radial flux

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

Figure by Iwakami

2D axially symmetric simulations performed

Nagakura, Iwakami, Okawa, Harada et al. (2015-2017)

- Massive star: $11.2M_{sun}$ (WHW02)
  - 1D grav. collapse, bounce; 2D shock propagation
- Furusawa EOS table (cf. Lattimer-Swesty)
  - 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

Talk on Rotating model by Akira Harada

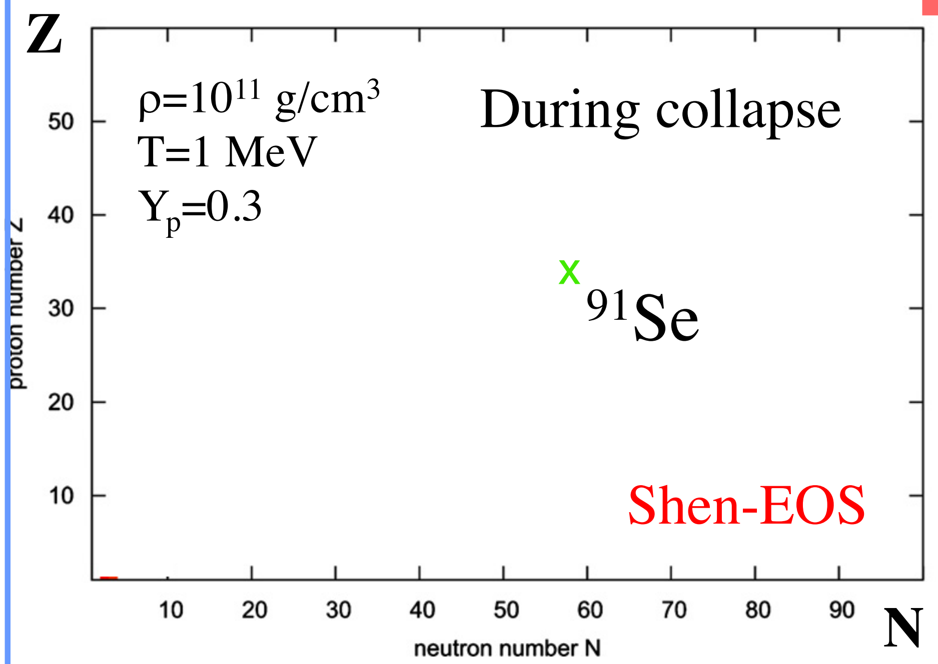
384 x 128, 10 x 6 x 20
4M node hours for 2M steps, Data ~100TB
on K-computer, Japan

K-Computer, Japan

Mixture of nuclei in supernova EOS tables

Shen-EOS

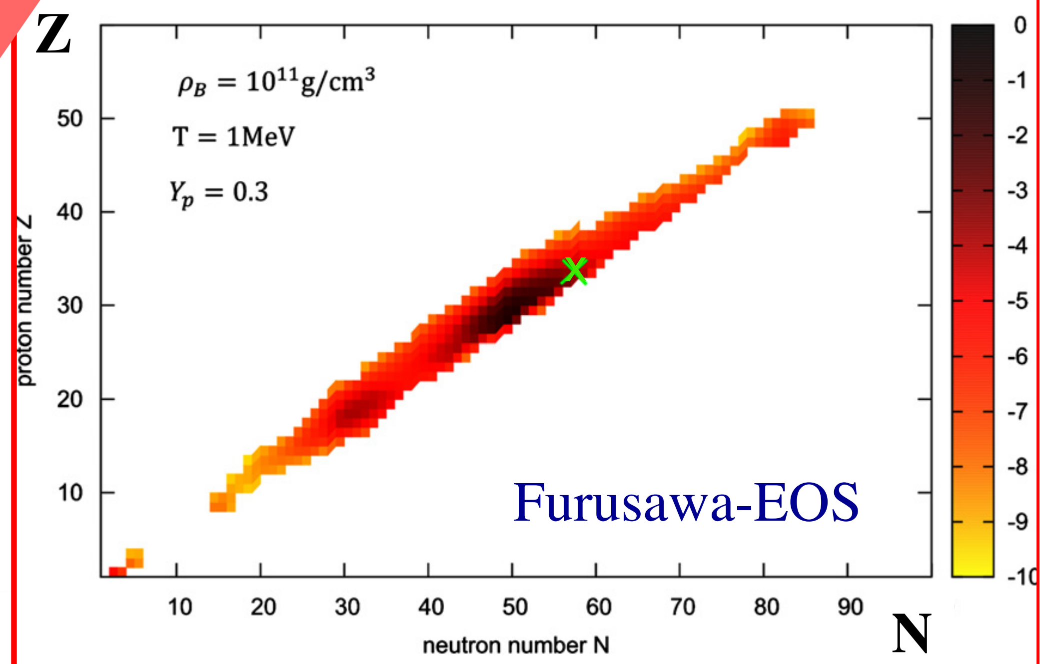
Neutron, proton, ^{4}He
One species of nuclei
approximation



A representative nuclei

Furusawa-EOS

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



Wide variety of nuclei

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

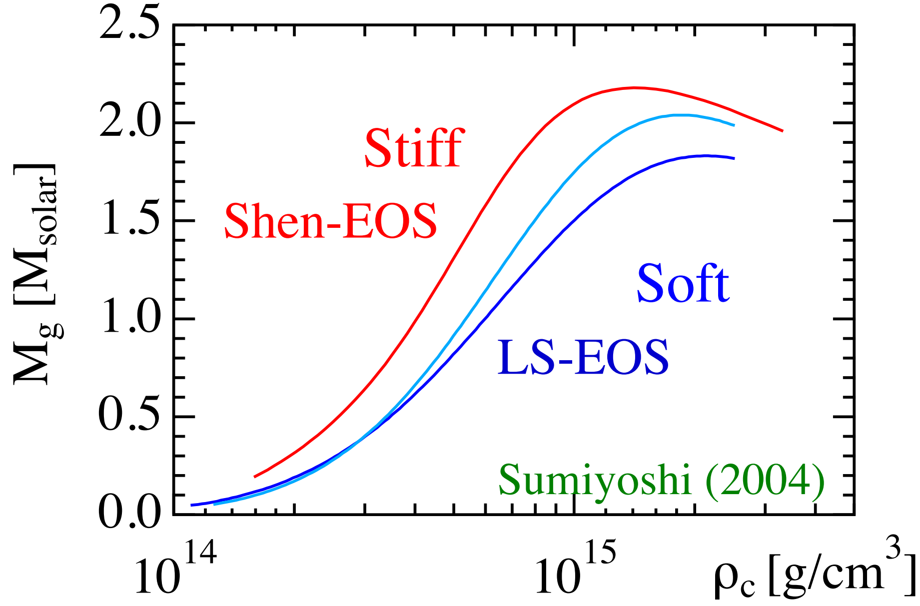
Influence of EOS tables

- 2 sets of EOS tables

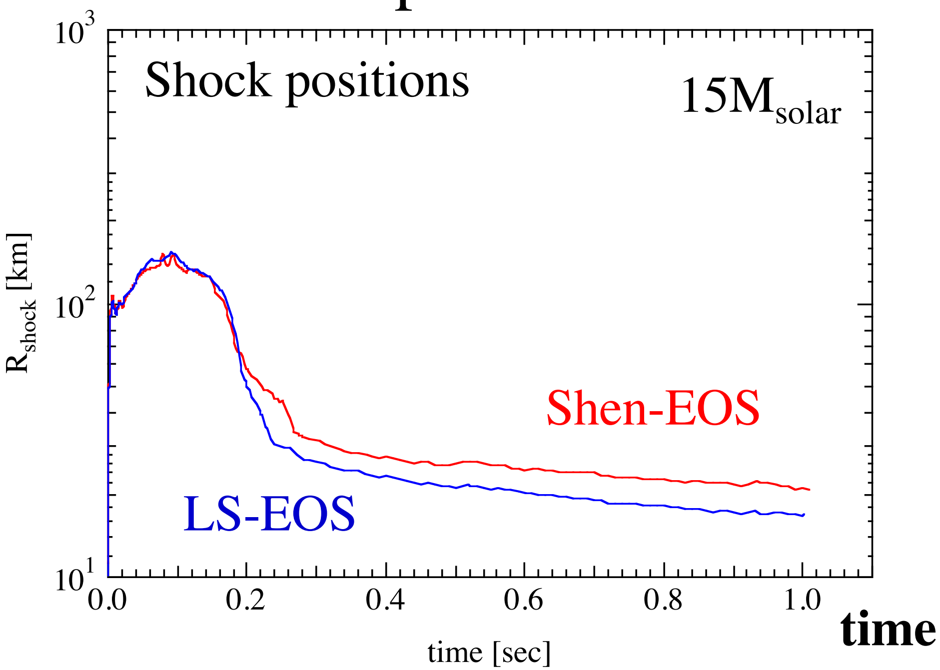
Stiff – Furusawa (Shen)

Soft – Lattimer-Swesty

Neutron star mass

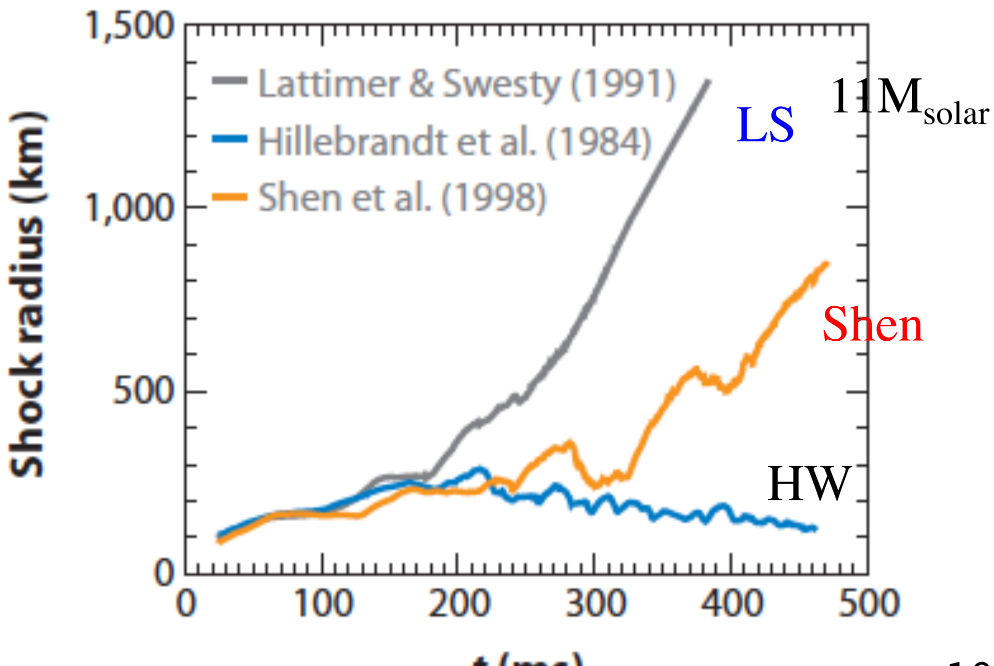


No explosion in 1D



Sumiyoshi et al. (2005)

Soft EOS is favorable in 2D?

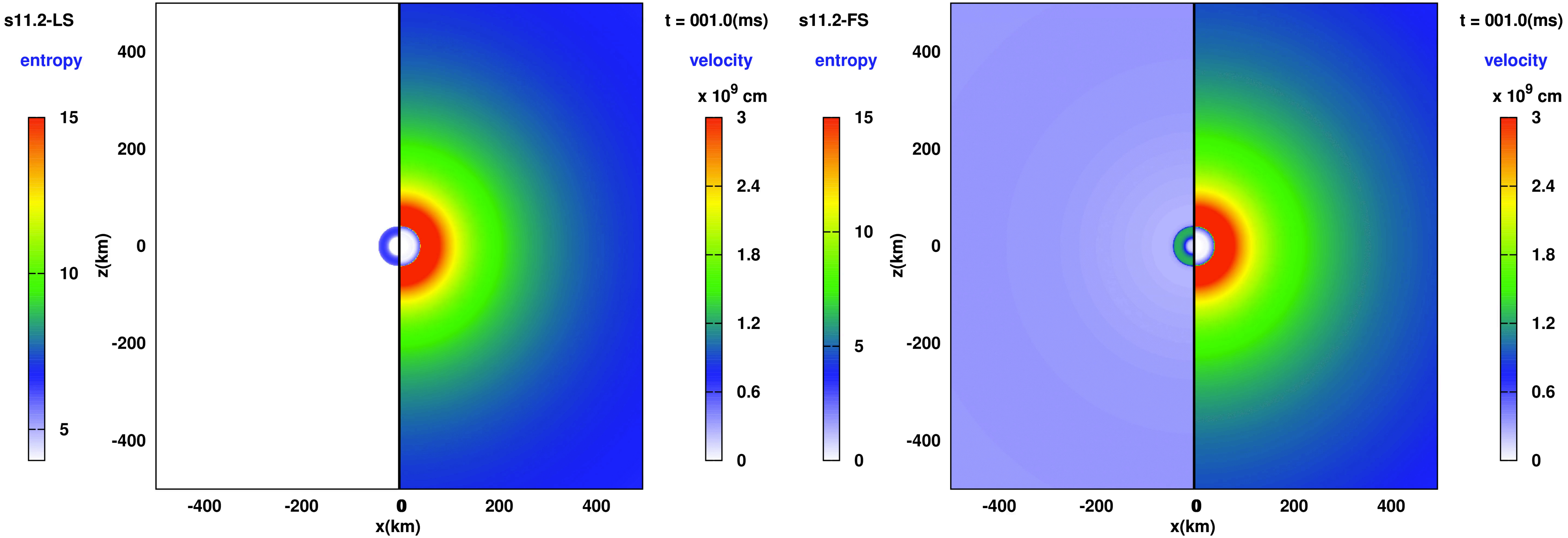


Janka ARNPS (2012)

Comparisons of 2D core-collapse simulations

Nagakura, Iwakami, Okawa, Harada et al. arxiv:1702.01752, submitted to ApJ

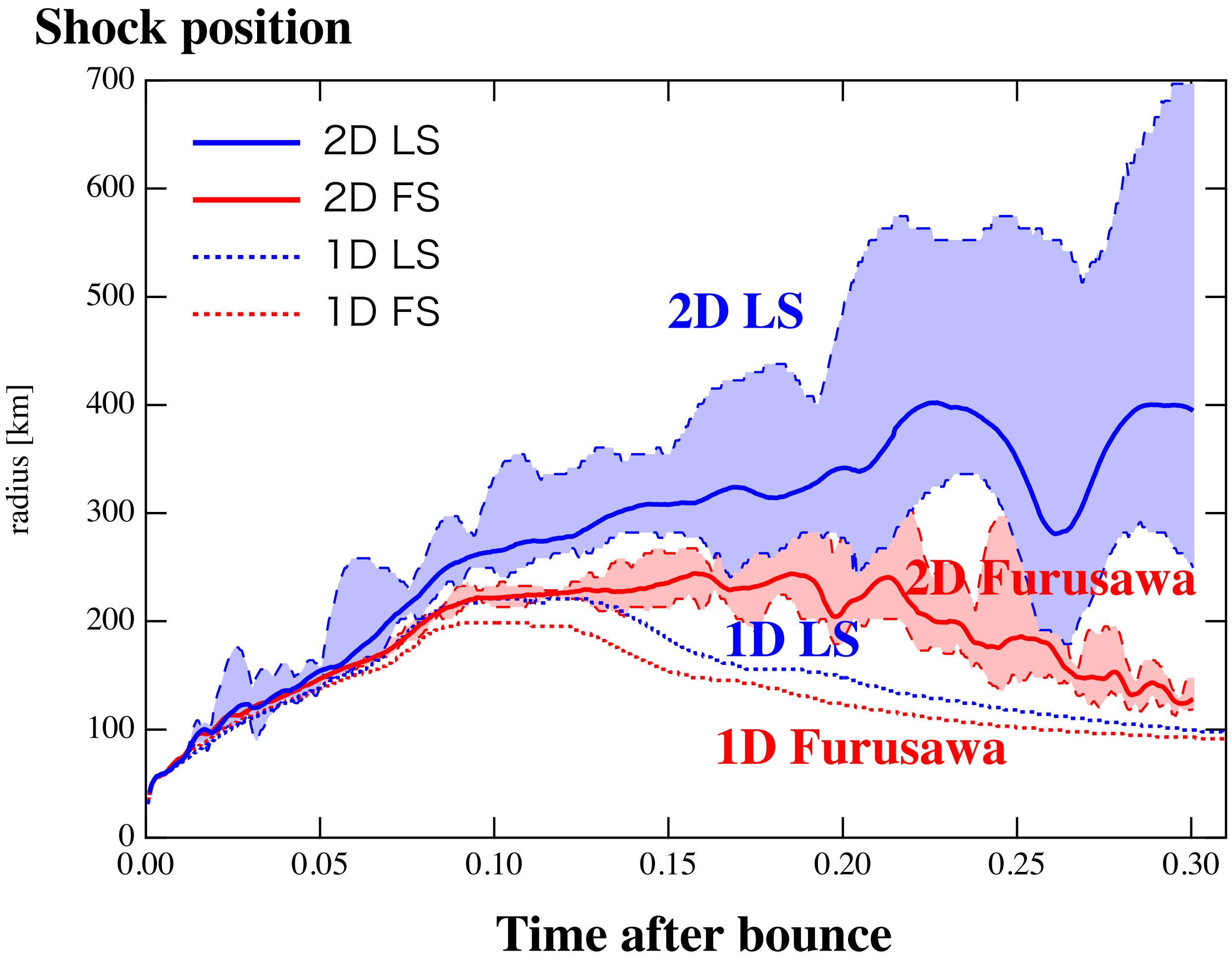
Lattimer-Swesty EOS VS Furusawa EOS

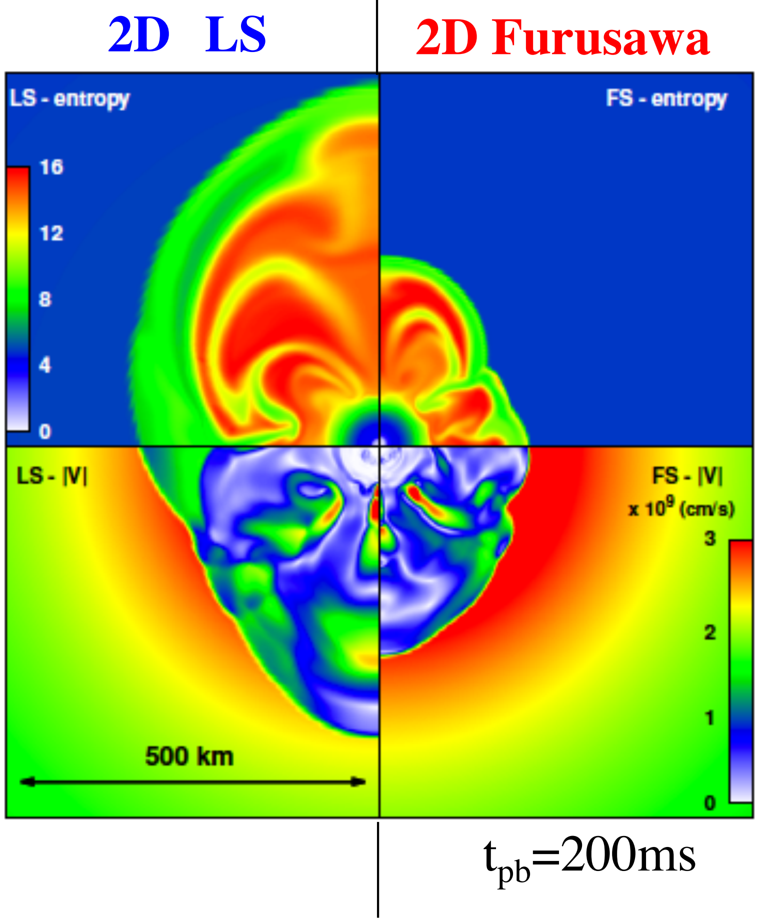


6D Boltzmann solver + 2D Hydrodynamics is working indeed

Influence of EOS: simulations with Boltzmann

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



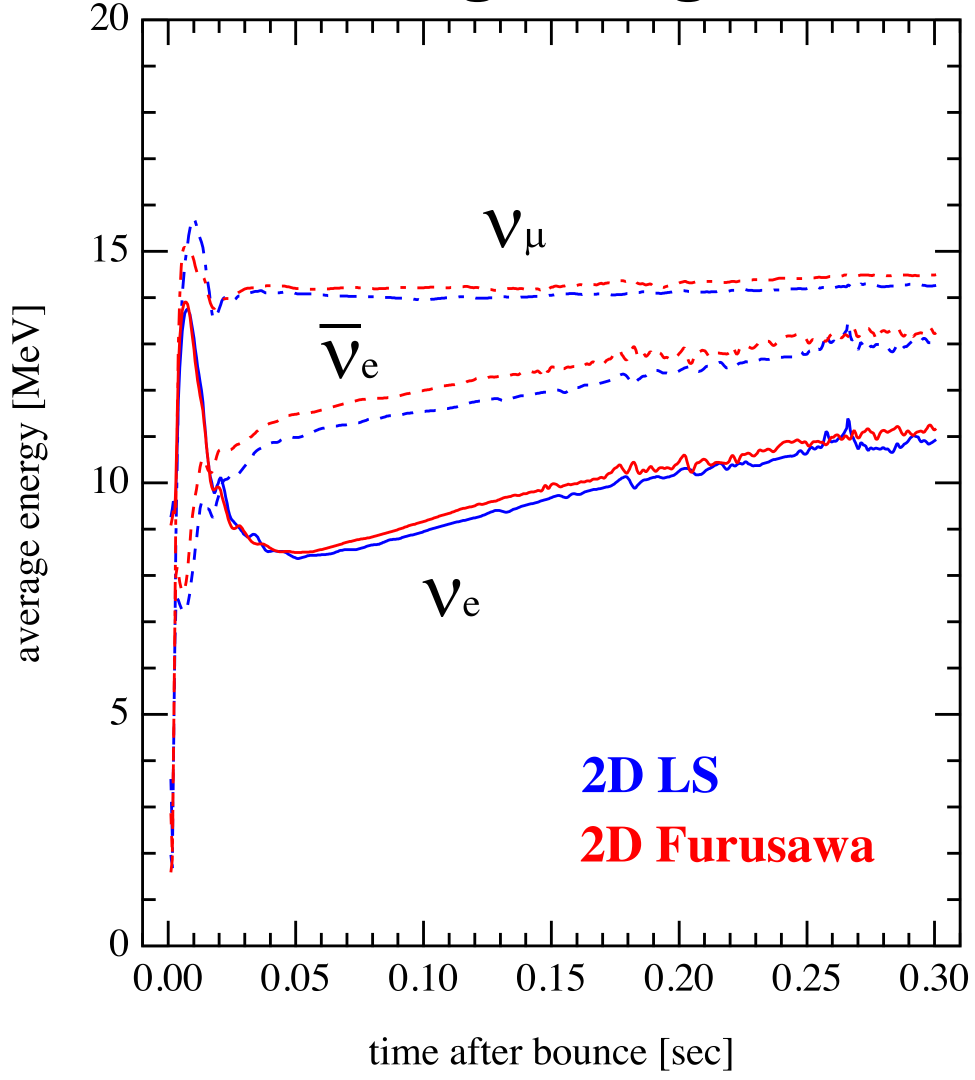


top : entropy
bottom : fluid velocity

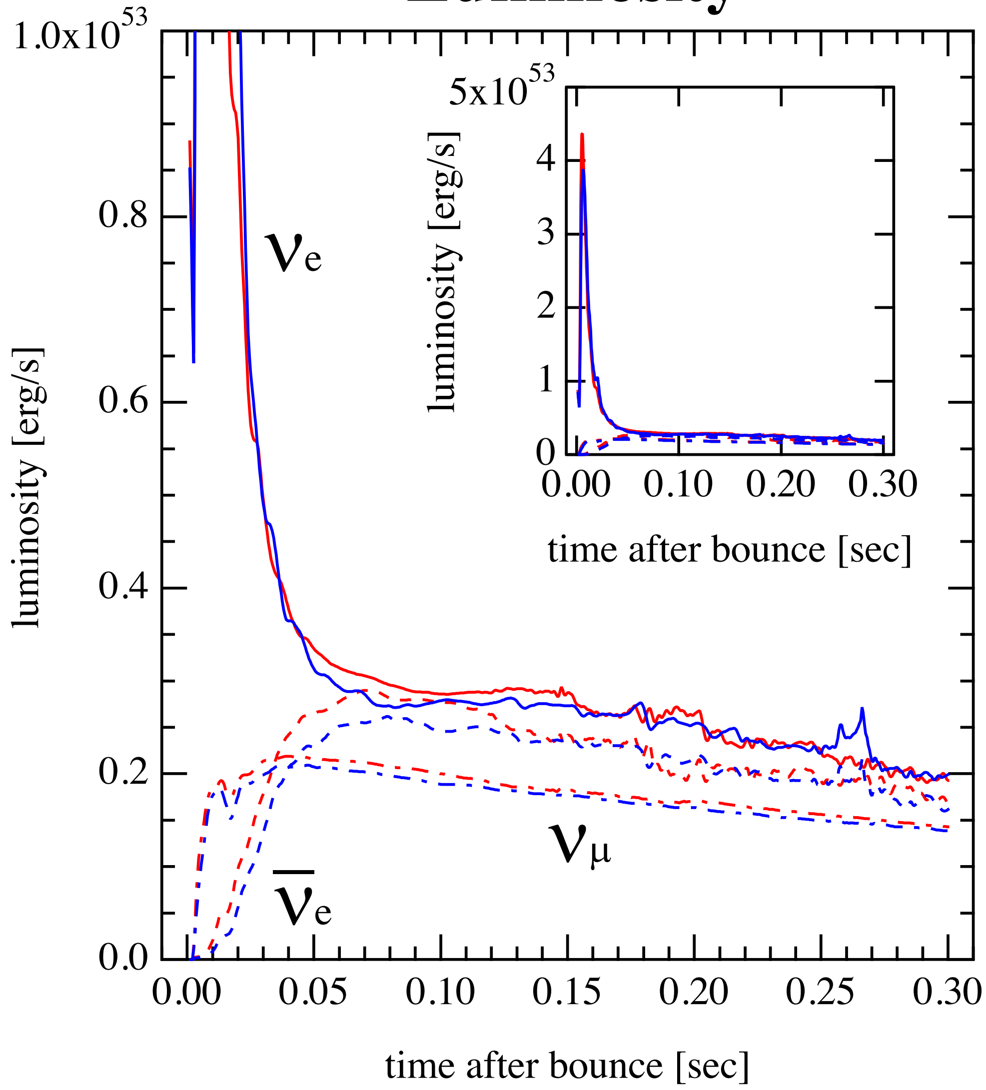
Nagakura, Iwakami, Okawa, Harada et al. arxiv:1702.01752, submitted to ApJ

Comparison of neutrino emissions

Average energies



Luminosity



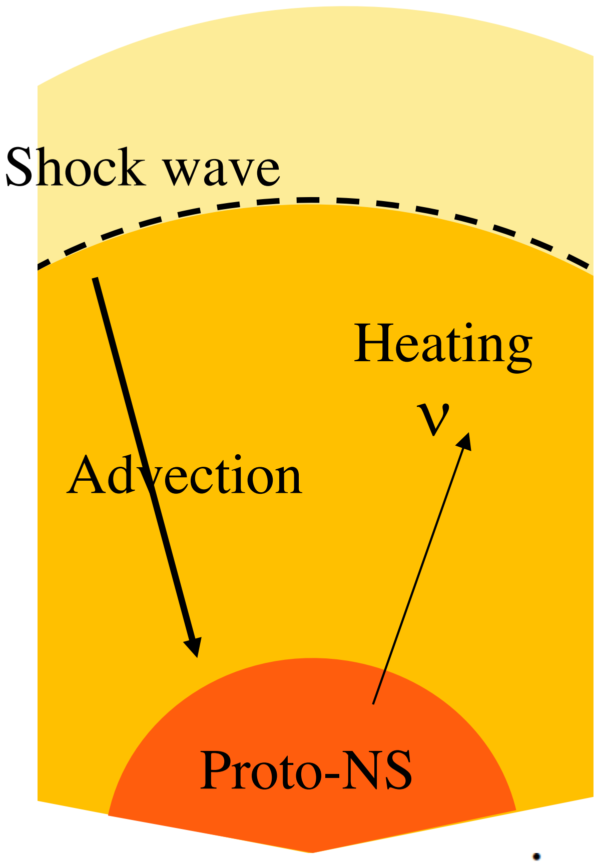
Rather close each other, but…

Nagakura, Iwakami, Okawa, Harada et al. arxiv:1702.01752, submitted to ApJ

Averaged over directions

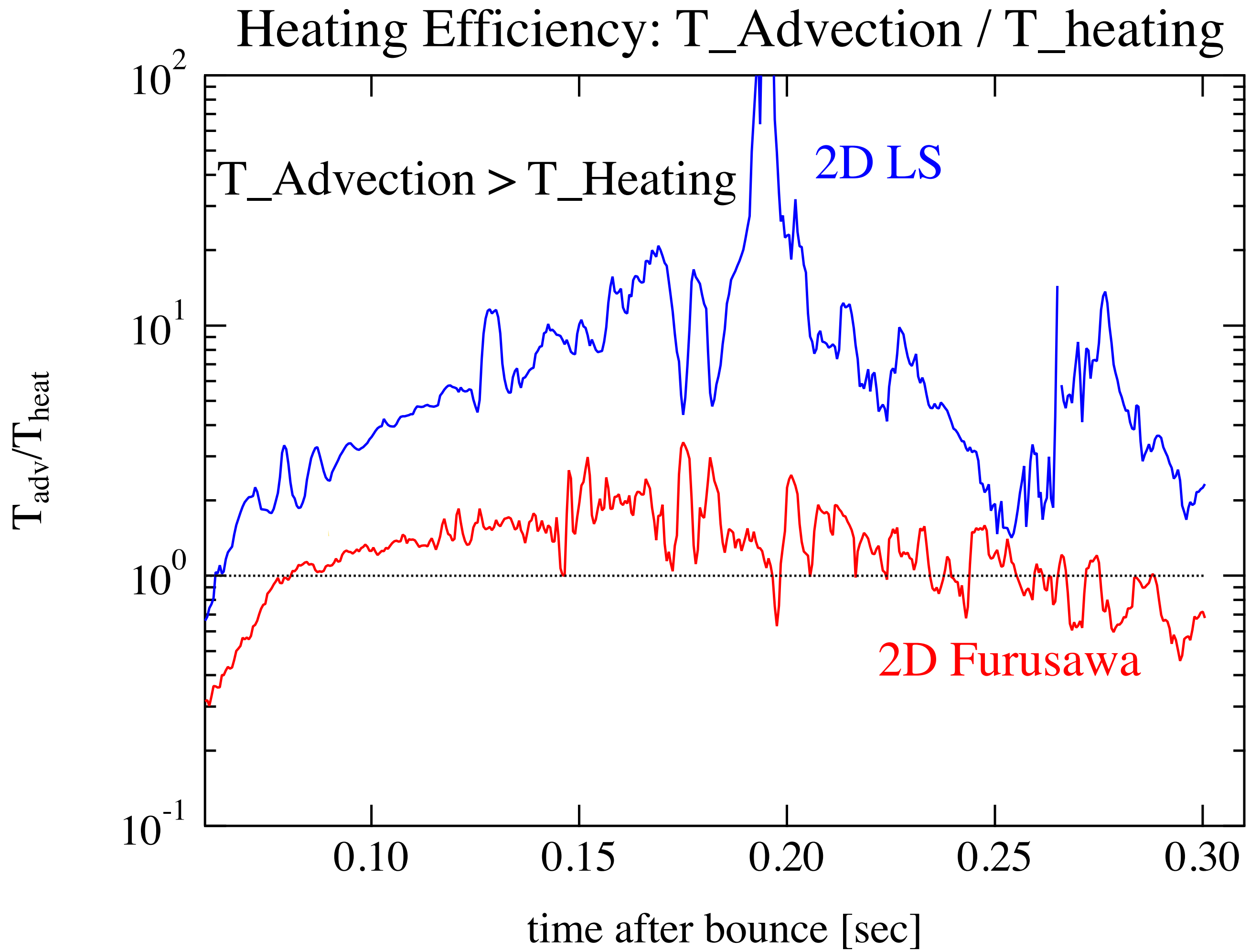
Difference in heating efficiency

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



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

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



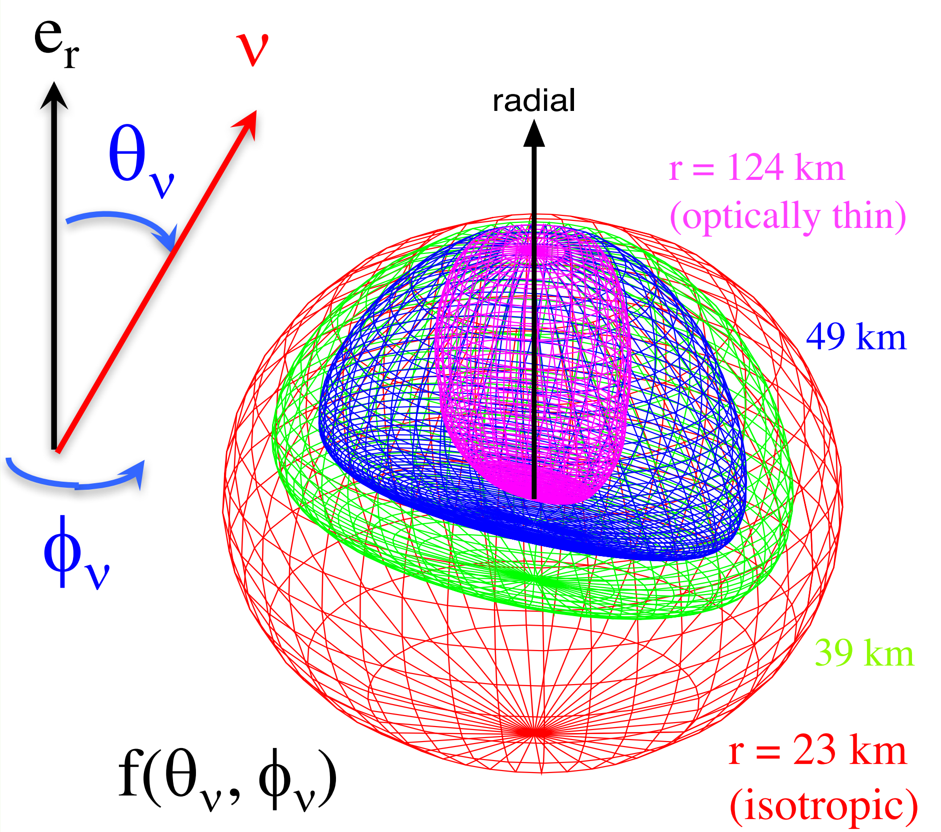
Nagakura, Iwakami, Okawa, Harada et al. arxiv:1702.01752, submitted to ApJ

Need further studies

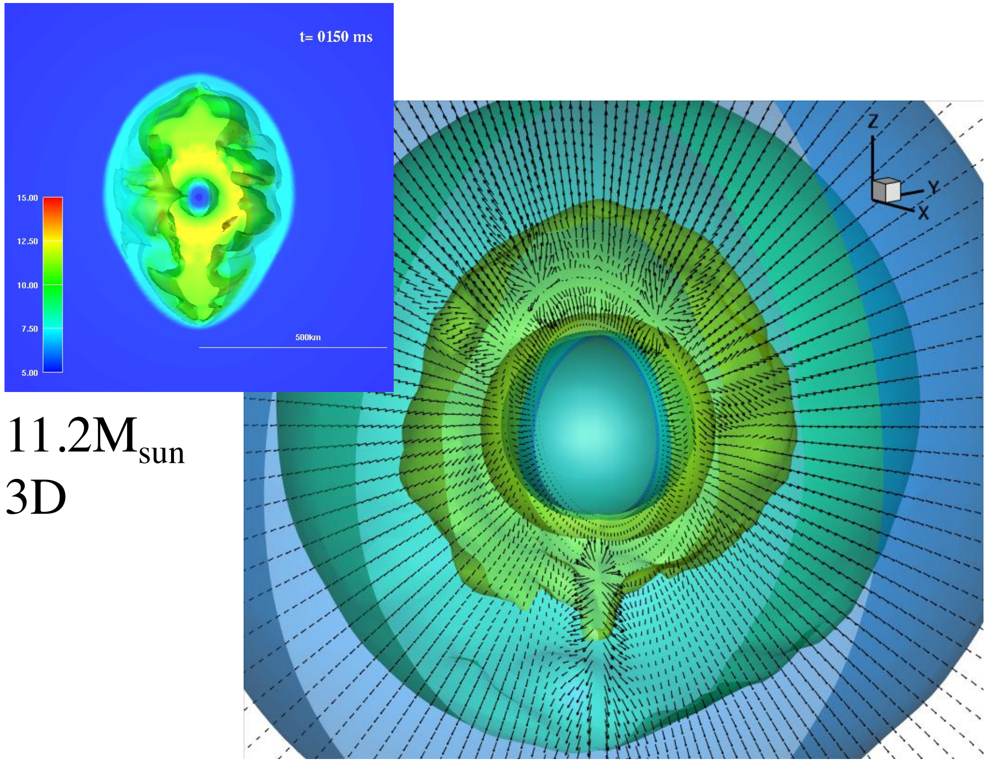
ν-transfer by 6D Boltzmann solver: fixed profile

- Evaluate stationary state of the neutrino distribution in 6D
  to get neutrino distributions for 2D/3D astrophysical objects
- We can examine Angle moments, Eddington factors, Heating rates

- Full angle information



- Non-radial fluxes in 3D core

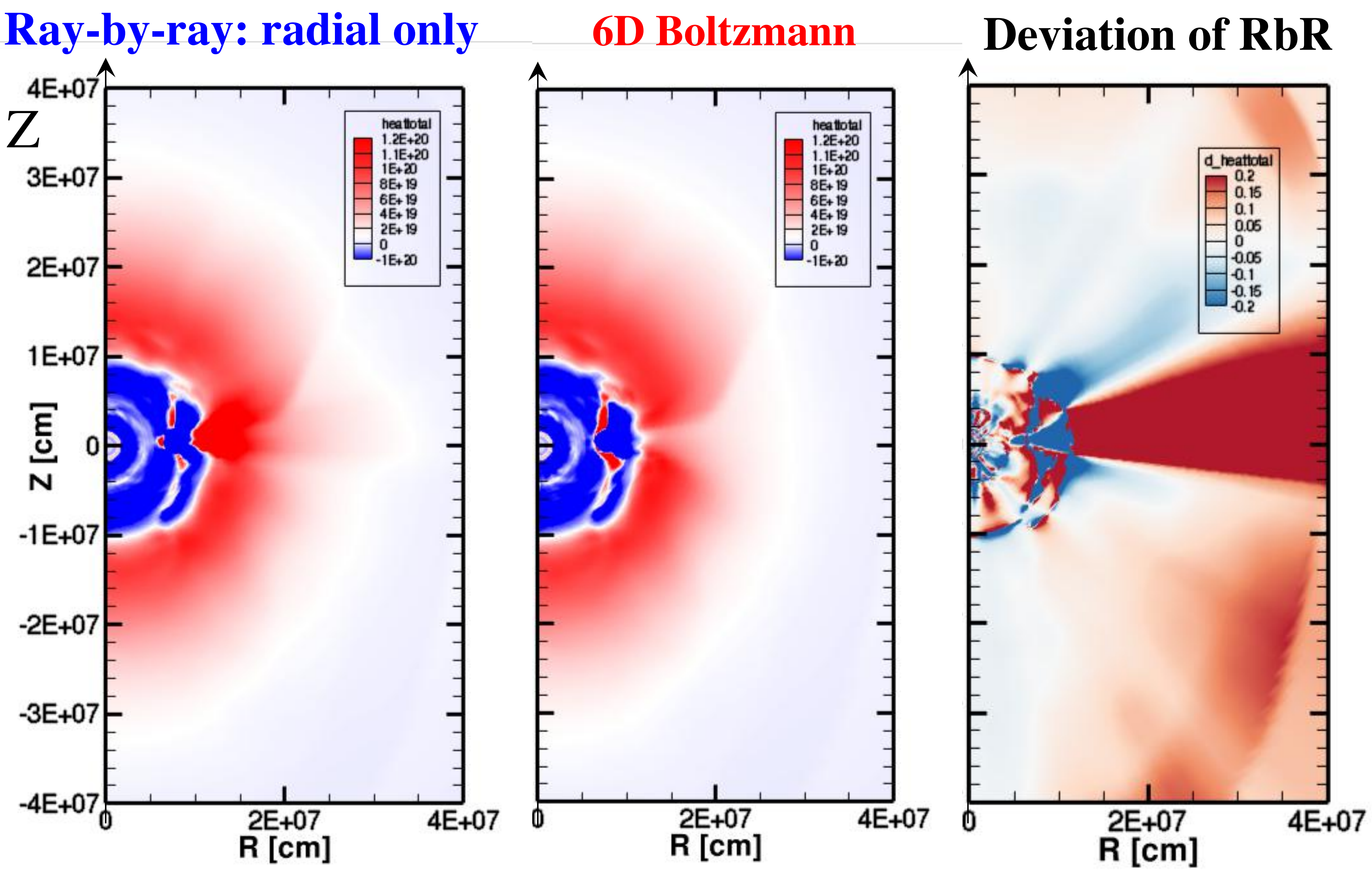


Nagakura et al. , arxiv:1702.01752

Sumiyoshi et al. ApJS (2015)

Comparison: ν-heating rate

$$\delta = \frac{Q_{RbR} - Q_{6D}}{Q_{6D}}$$



Sumiyoshi et al. ApJS (2015)

Red: heating, Blue: cooling

$11M_{sun}$, 150msec

Neutrino-transfer in 2D/3D space: fixed profile

Sumiyoshi et al. (2015, 2017)

- Examine neutrino quantities: angle moments etc.
- Validation of methods, Convergence of resolutions
- Check approximate methods and improve formulae

(1) Comparison with Ray-by-ray approximation

(2) Comparison with closure for moment formalism

- 6D Boltzmann directly gives pressure tensor

$$P^{ij}(\varepsilon_\nu) = \int d\Omega \varepsilon n_i n_j f(\varepsilon, \Omega) \qquad T^{ij}_{6D}(\varepsilon_\nu) = P^{ij}(\varepsilon_\nu) / E(\varepsilon_\nu)$$

- Closure relation by function form

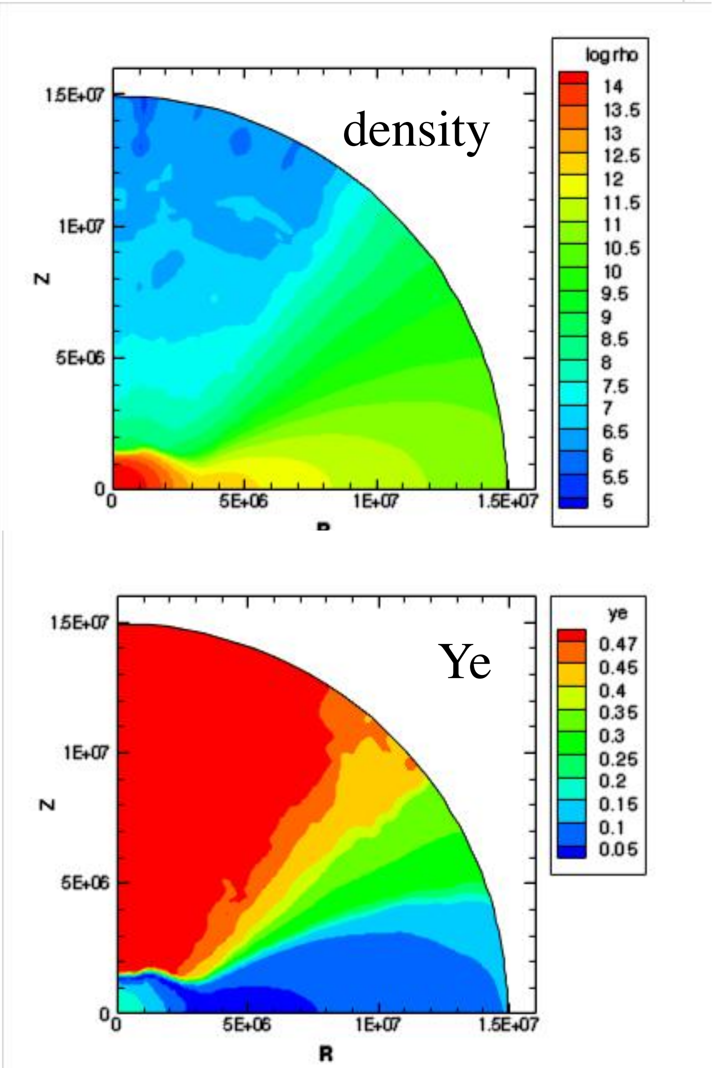
$$\vec{\mathbf{T}}_{CL} = \vec{\mathbf{I}}(1-\chi)/2 + \mathbf{nn}(3\chi - 1)/2 \quad \Rightarrow \quad \Delta T^{ij} = T^{ij}_{Cl} - T^{ij}_{6D}$$

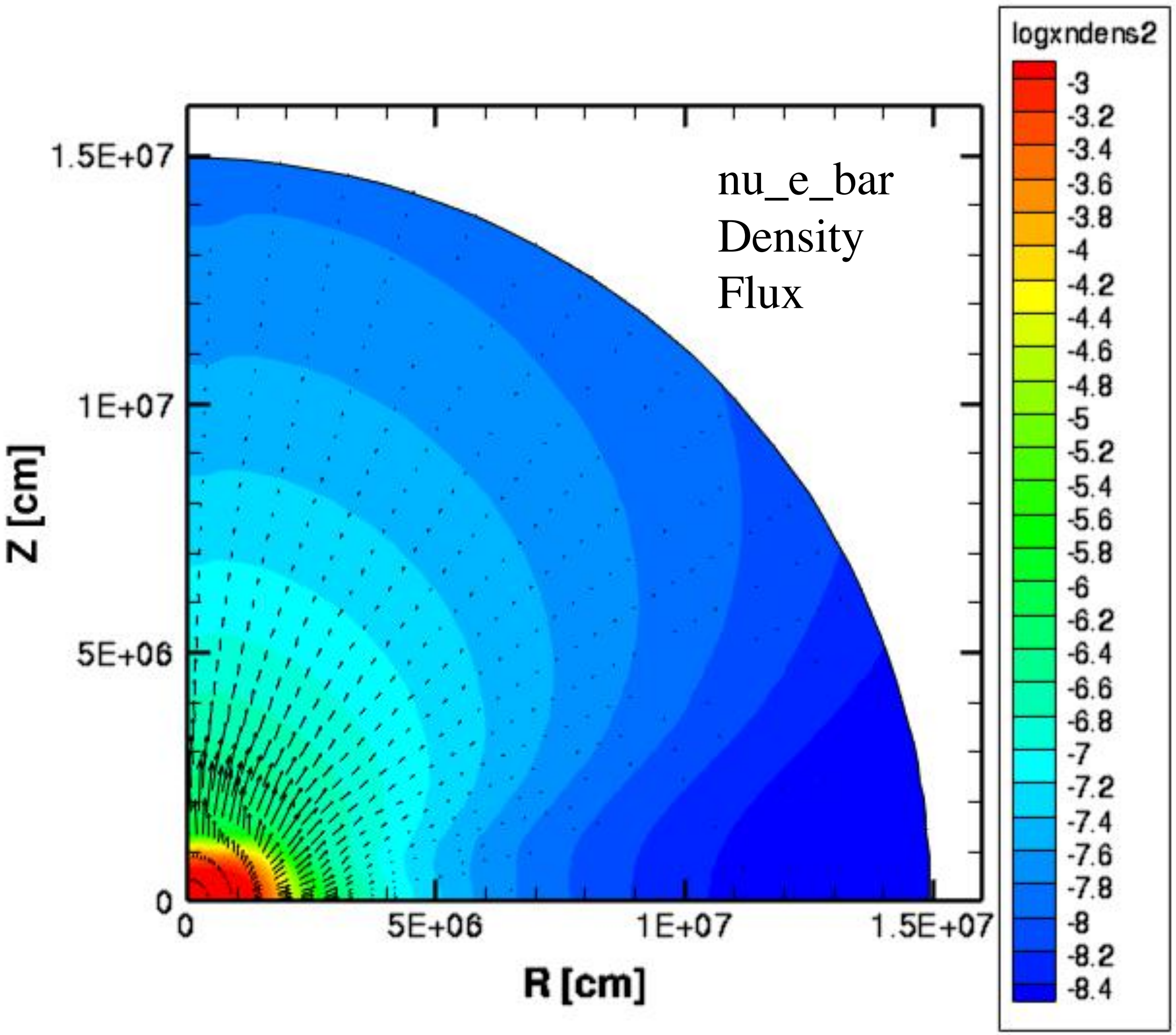
flux vectors $\mathbf{f} = f\mathbf{n}$ $\quad \chi = (1/3) + 2f^2/(2 + \sqrt{4 - 3f^2}) = (3 + 4f^2)/(5 + 2\sqrt{4 - 3f^2}).$

Levermore JQSRT (1984)

Eddington tensors in 2D compact objects

- 2D rotating collapse: deformed proto-NS with disk

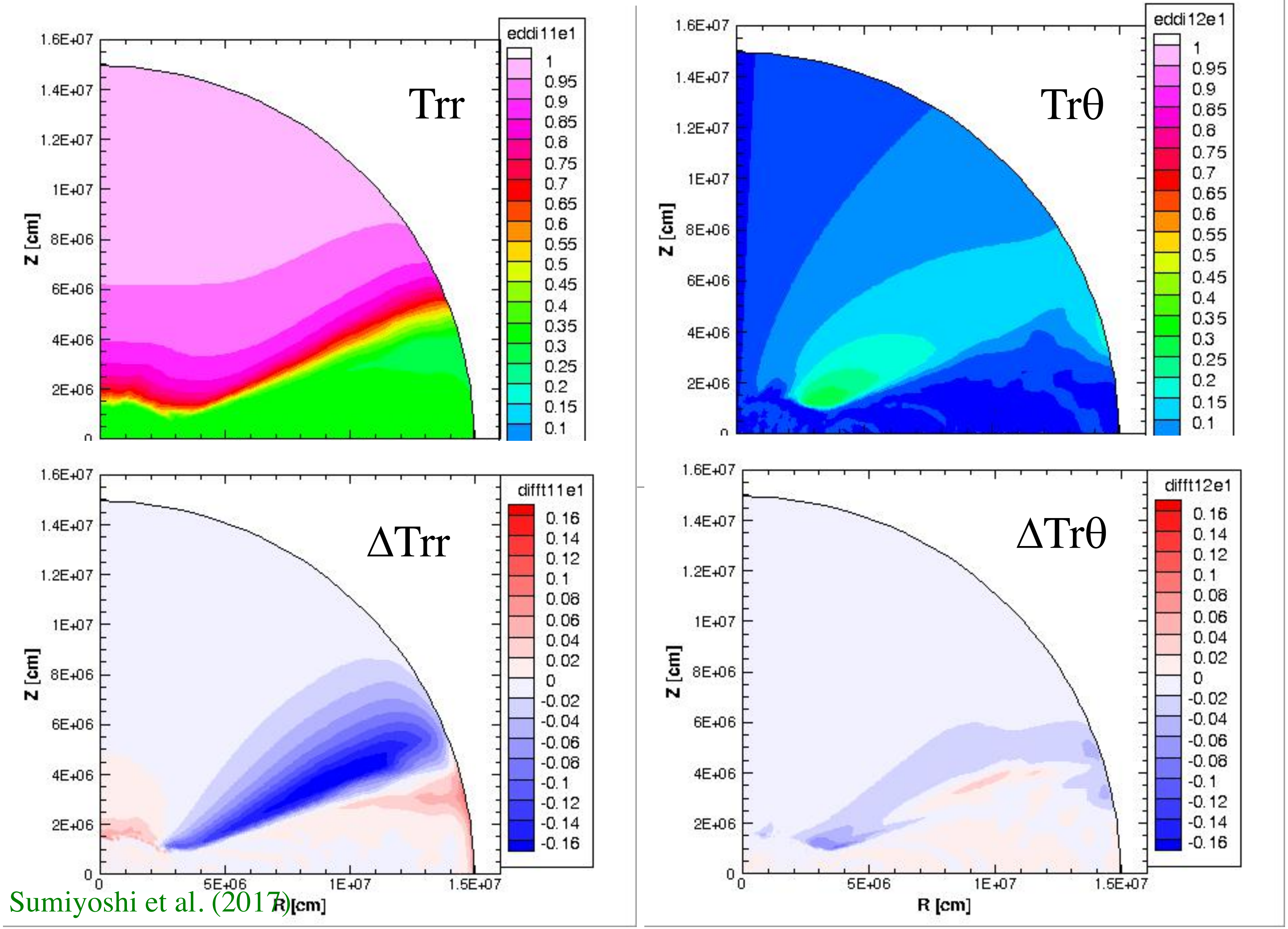




Core of UN08, $100M_{sun}$, Z_{solar} /200

Sekiguchi, KS (2015, 2017)

Examine Eddington tensors in 2D compact objects

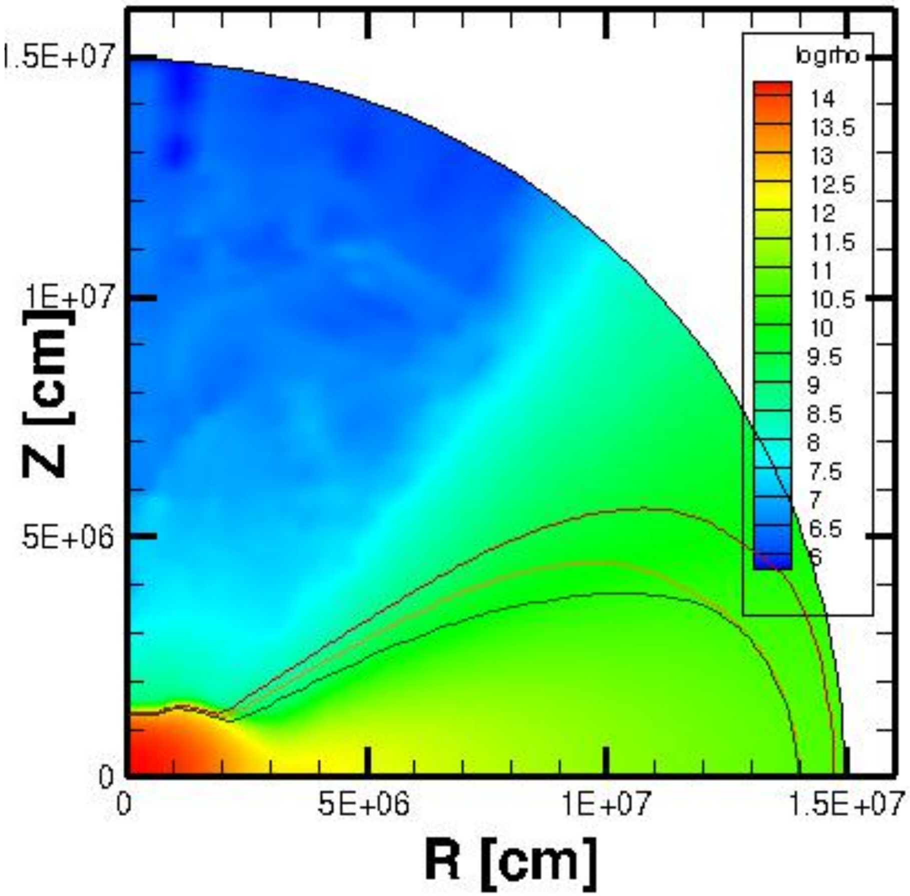


Sumiyoshi et al. (2017)

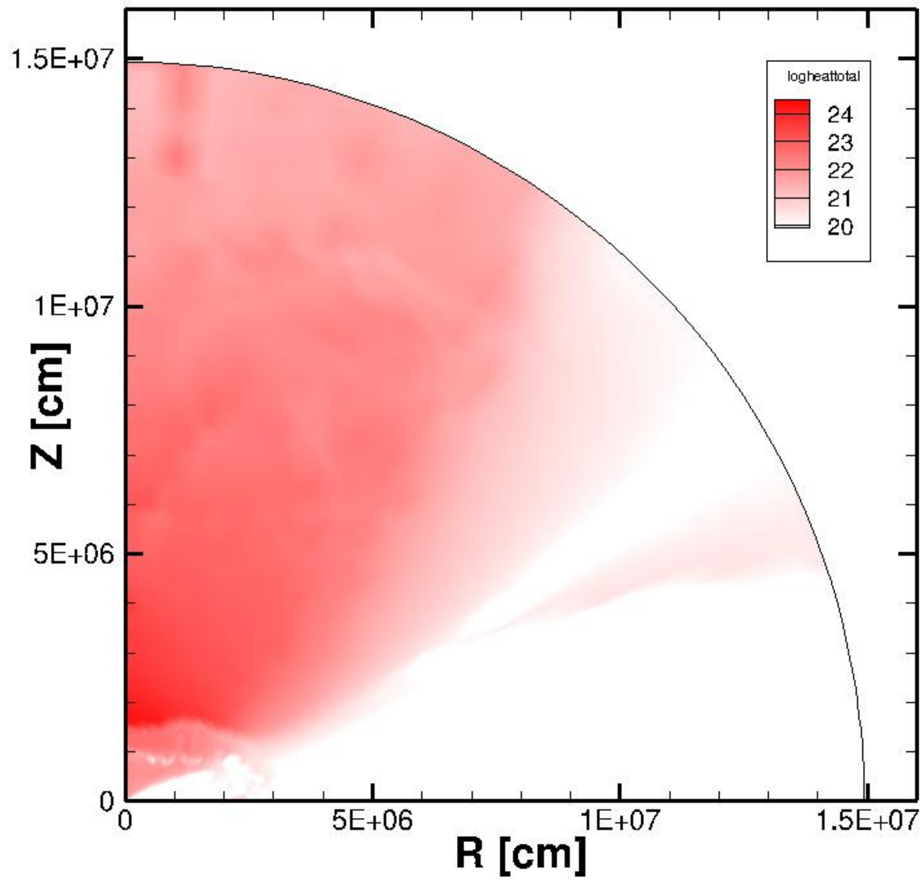
Analysis of neutrino-transfer in 2D compact objects

- Information on neutrino-emission, heating rates

Position of neutrino-sphere



Neutrino heating rate



- Modeling neutrino quantities in other simulations

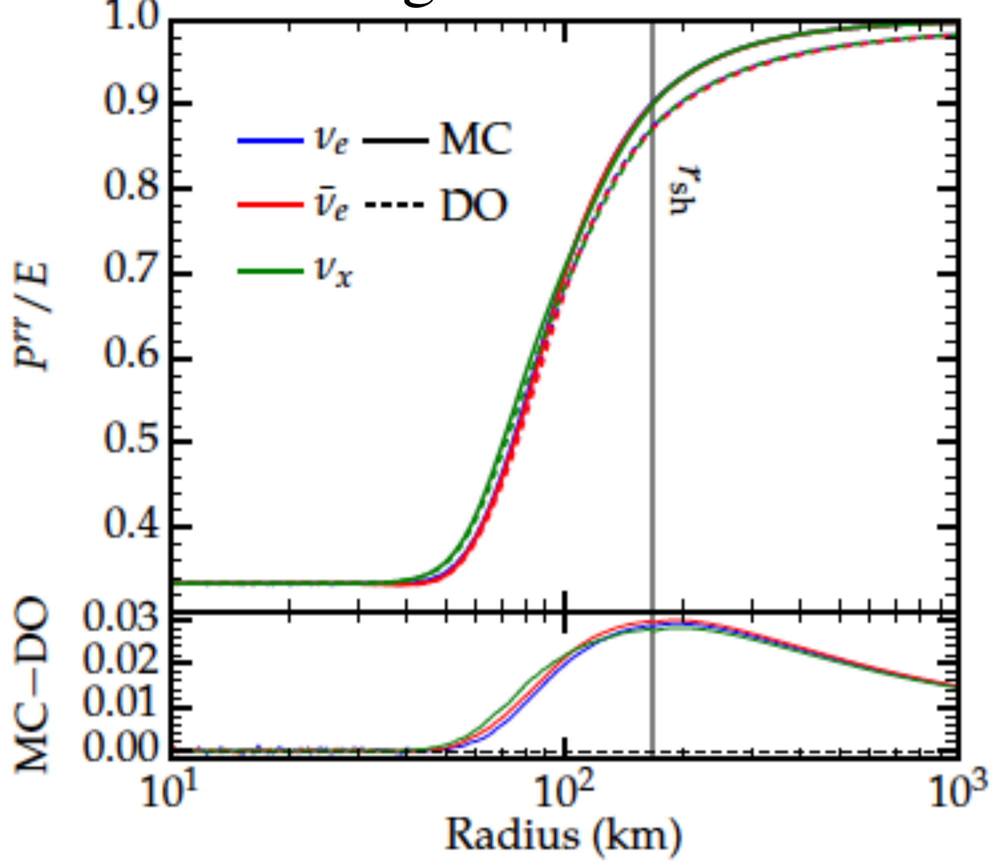
Sumiyoshi et al. (2017)

Comparison: 6D Boltzman vs Monte Carlo

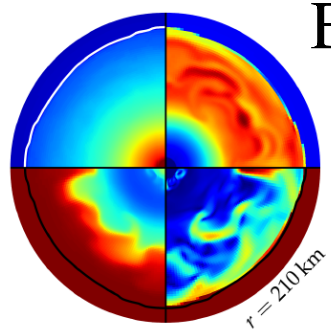
Richers, Nagakura et al. arxiv:1706.06187

- Neutrino quantities in two methods checked

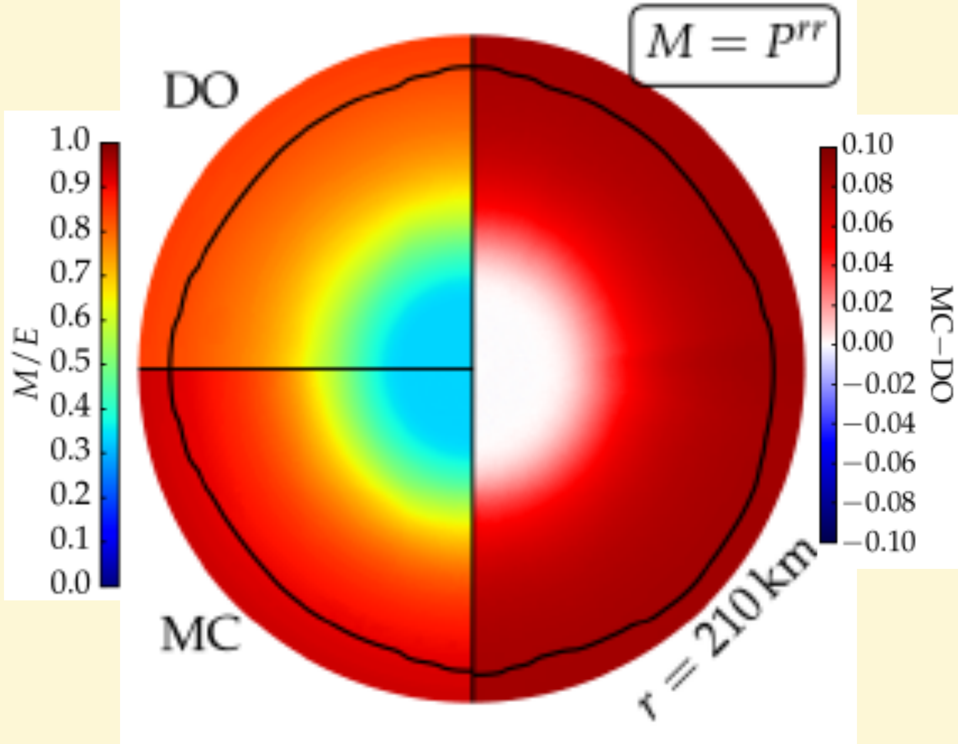
Eddington tensor in 1D



Eddington tensor in 2D



2D supernova core
Fixed profiel



Solving neutrino transfer by 6D Boltzmann eq.

for core-collapse supernovae and compact objects

- 2D core-collapse simulations
  - First series of post-bounce evolutions from $11M_{sun}$
    - No explosion with Furusawa EOS
    - Closer to explosion with Lattimer-Swesty EOS
  - Rotating collapse of massive star by Akira Harada's talk
- Study of neutrino transfer in 2D/3D
  - Validation of approximate methods: Eddington tensor
  - Characteristic of neutrino transfer in 2D compact objects
- Toward full understanding of supernovae
  - 2D core-collapse simulations with 15, 27M and other EOS
  - 3D core-collapse simulations ongoing project

    Exa-flops supercomputer, post-K project in Japan

Project in collaboration with

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

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