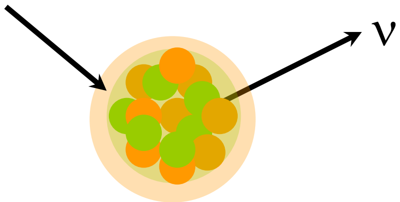
Nuclear physics and neutrino transfer in supernovae and compact objects

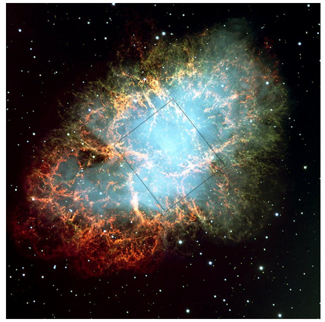
Nuclei and neutrinos



K. ‘Sumi’yoshi

Numazu College of Technology
Japan

Crab nebula



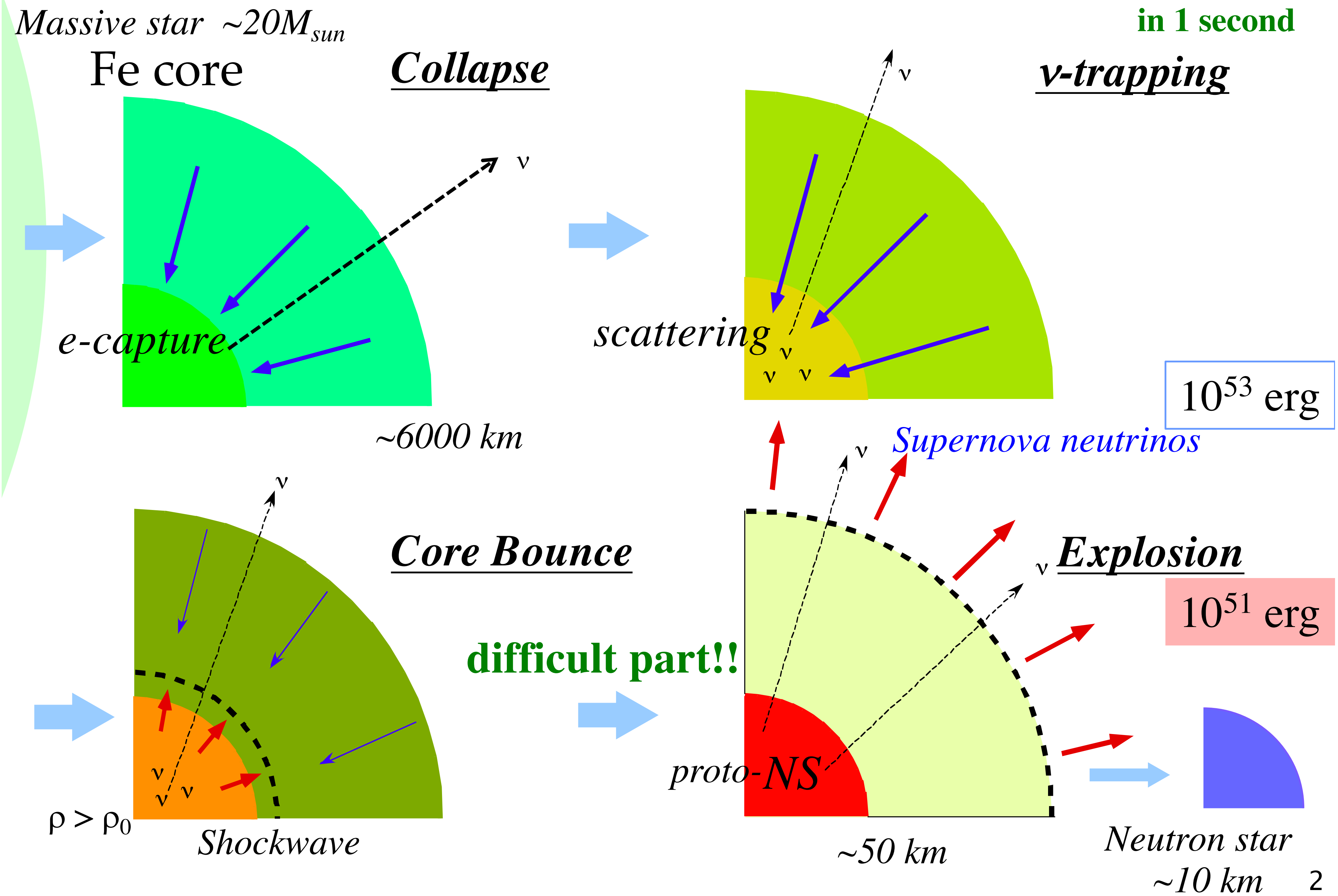
hubblesite.org

- Neutrino transfer: Solver of 6D Boltzmann equation
- Equation of state: Composition of dense matter

Numazu near Mt. Fuji

Wikipedia (trimmed)

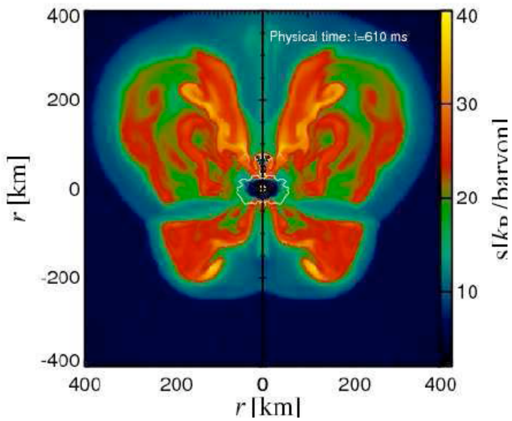
Core-collapse SNe: collapse, bounce and explosion



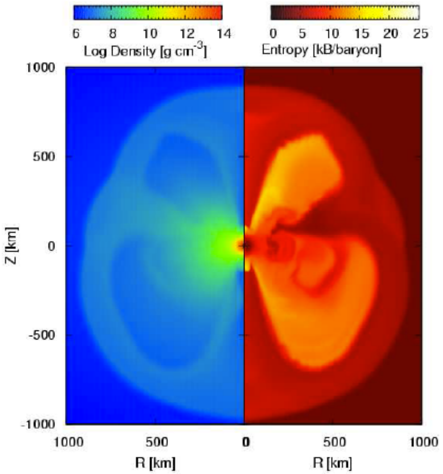
Explosions mechanism in 2D & 3D

neutrino-heating with hydro instabilities

- Convection, SASI, rotation, magnetic etc

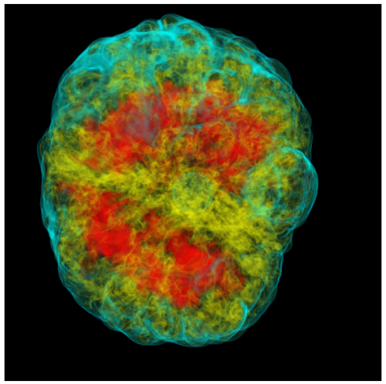


Marek et al, ApJ (2009)

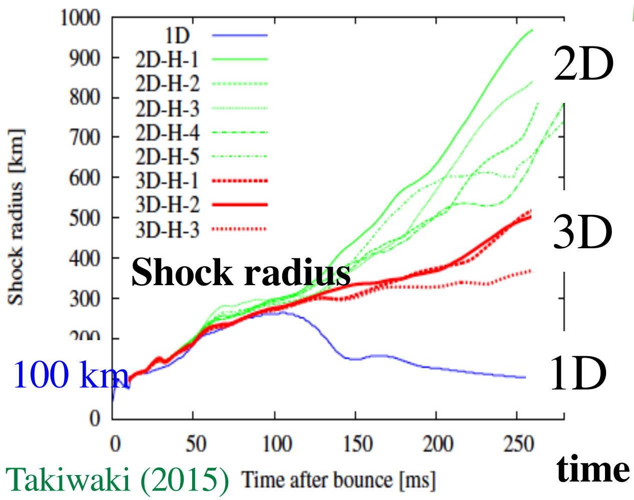


Suwa et al. (2010) PASJ

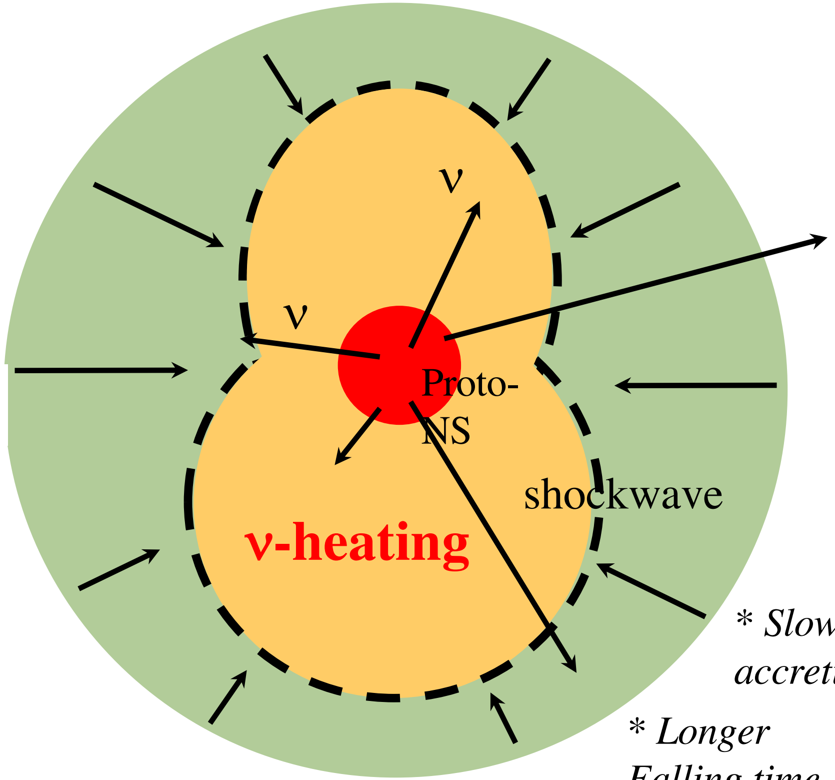
Deformation of shock Convection → Enough time for ν-heating



Roberts ApJ (2016)



Takiwaki (2015)



* *Slower accretion*

* *Longer Falling time*

Remaining issues of explosion mechanism

- Main trigger, 2D vs 3D, low explosion energy?
- **Evaluation of neutrino-heating**
- **Dependence on nuclear physics**

- To clarify the problem we need full simulations

Nuclear Physics

- Equation of state
- Neutrino reactions

  at 10^5-10^{15} g/cm^3, ~10^{11} K

Astrophysics

- Hydrodynamics
- Neutrino transfer
- General Relativity

Supercomputing technology

- Numerical simulations of core-collapse supernovae

  Huge supercomputing power is necessary

K-Computer, Japan

Neutrino transfer in 2D/3D supernovae

From approximate to exact
neutrino-radiation hydrodynamics

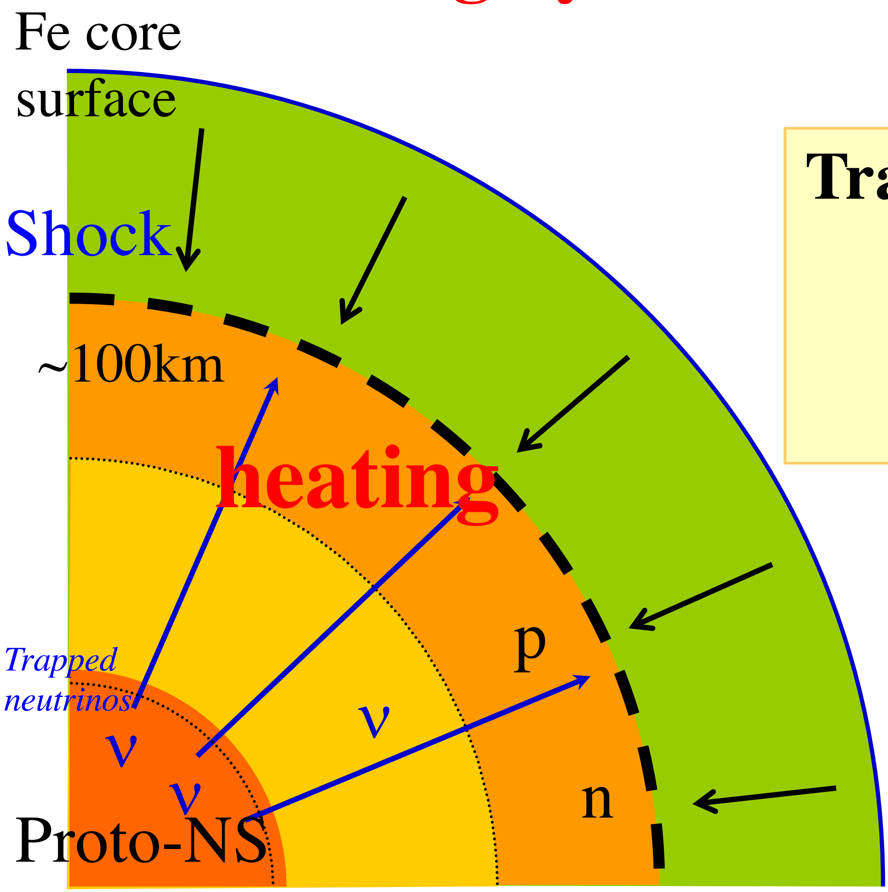
Nagakura et al., ApJS (2014, 2016)
Sumiyoshi et al., ApJS (2012, 2015)

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

$\nu_e + n \rightarrow e^- + p,$

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



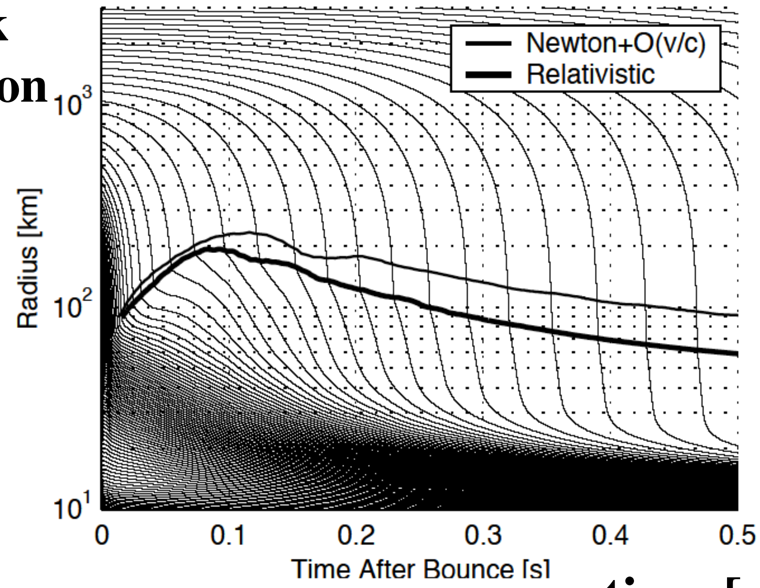
100ms after bounce

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

$$E_{\nu-heat} \sim 2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$

No explosion by modern 1D simulations

Shock position



time [s]

Liebendörfer et al. (2000)

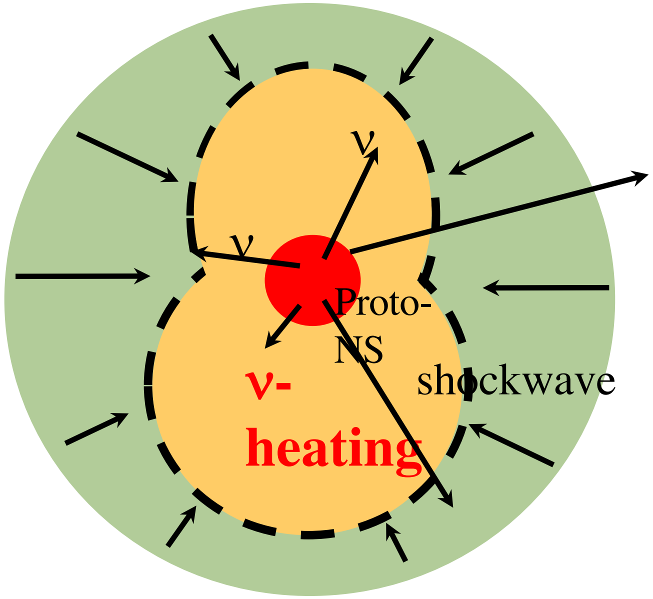
Neutrino energy/flux from trapped neutrinos

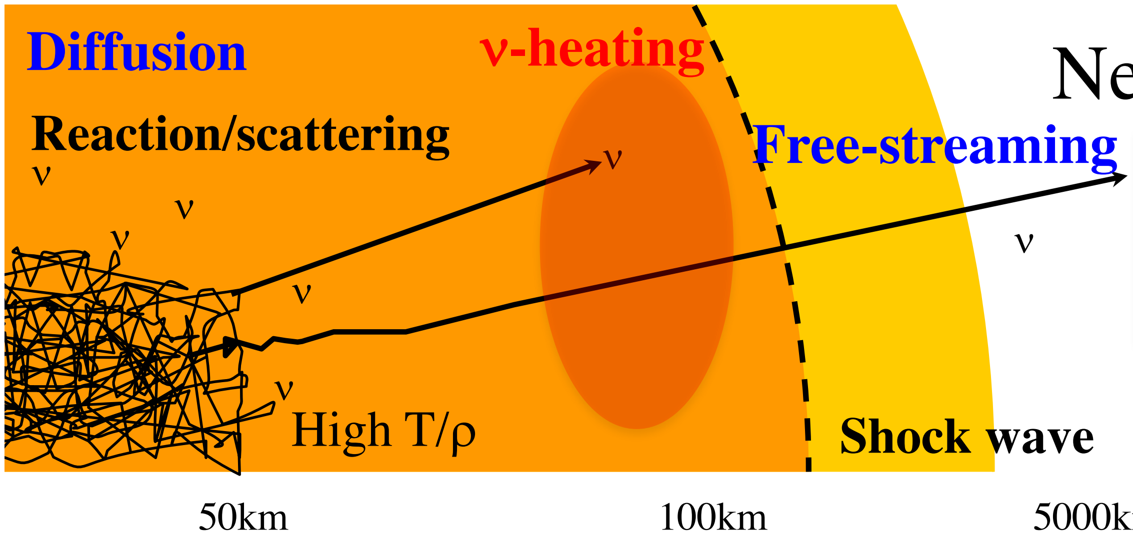
ν-transfer to determine ν-heating

2D/3D hydrodynamics + neutrino heating

- Neutrino flux & heating
  - ν-trapping, emission, absorption
- From diffusion to free-streaming
  - Intermediate regime is important

→ From approximate to exact





Need to solve Boltzmann eq.

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

formidable so far

New code solves 6D Boltzmann eq.

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

Sumiyoshi & Yamada, ApJS (2012)

Boltzmann eq.

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

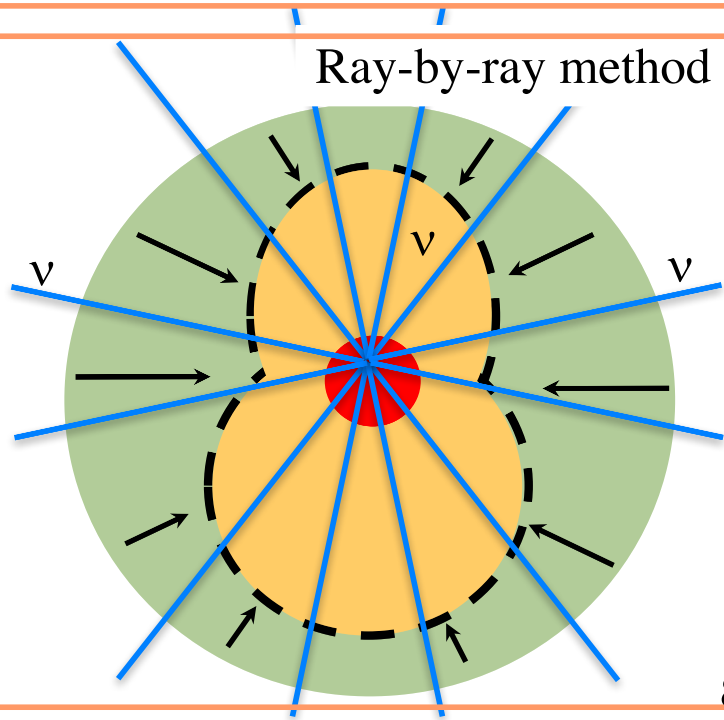
Time evolution + Advection = Collision

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

→ Huge computation

- Approximations used so far
  - 2D/3D: Diffusion, Ray-by-Ray method
  - (1D spherical: 1st principle calculations)
- Comparison with Ray-by-ray
  - Local ν-heating ~20% difference

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



Neutrino-transfer in 3D space: fixed profile

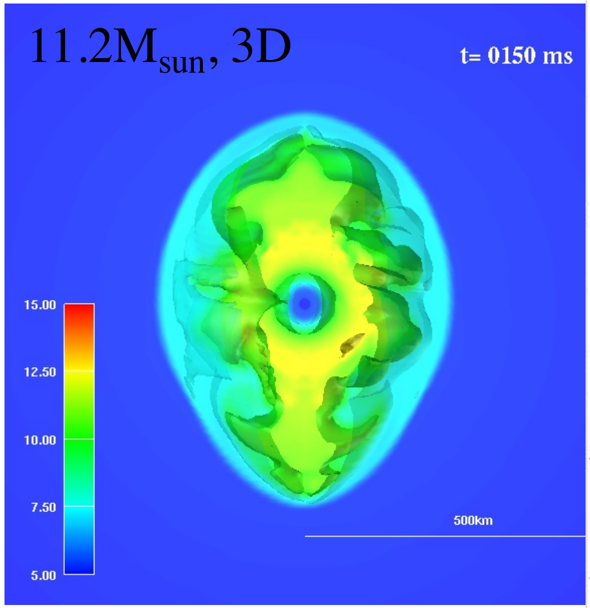
Sumiyoshi et al. ApJS (2015)

Fix hydro. variables, solve time evolution by 6D Boltzmann eq.

- Evaluate stationary state of the neutrino distributions in 6D
- Study neutrino transfer in 3D, heating rates, angle moments

3D supernova core at 150ms

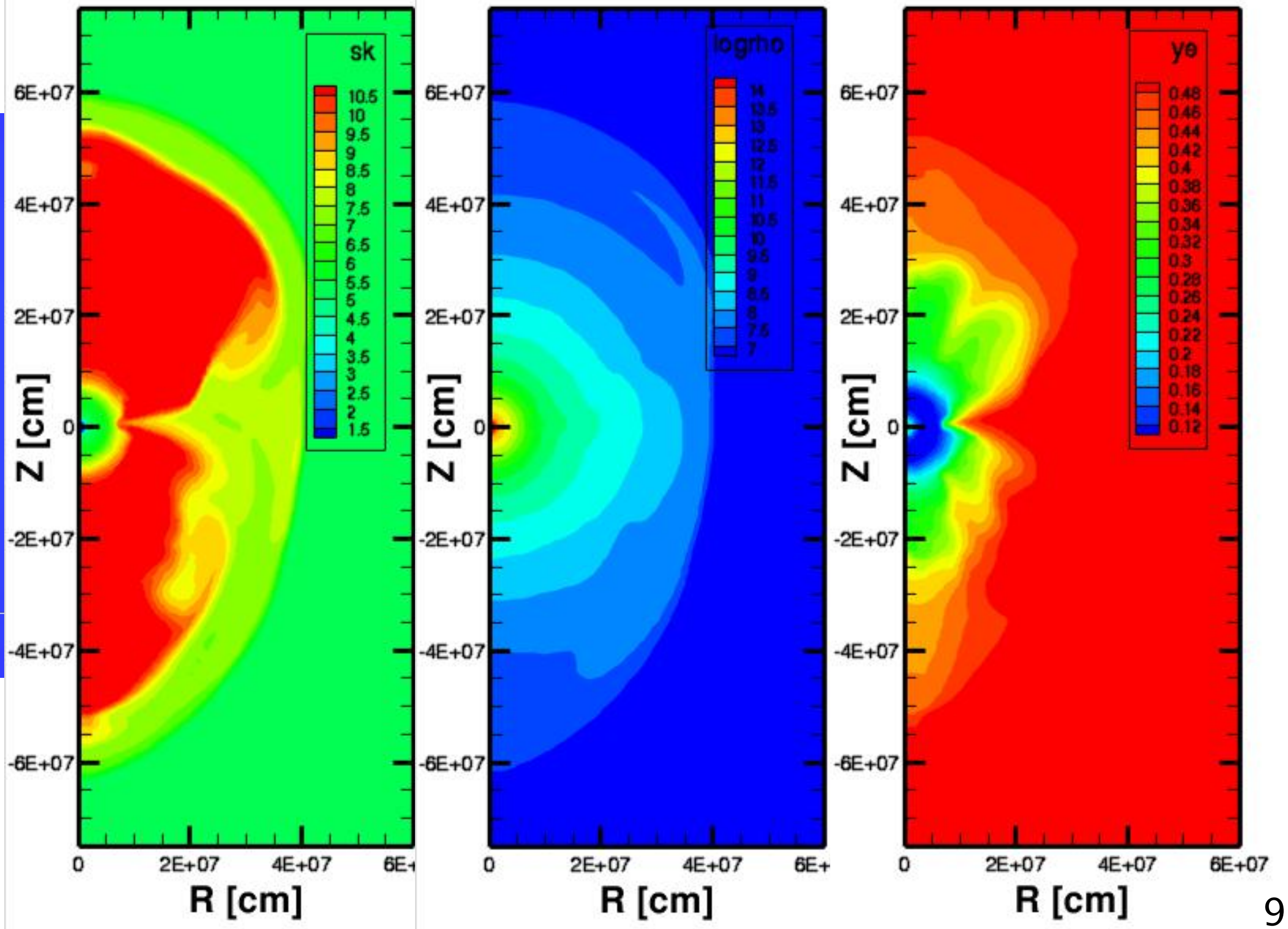
entropy



150 msec after bounce

R_{shock}~250-400km

From Takiwaki et al. ApJ (2012)



Comparison with approximation

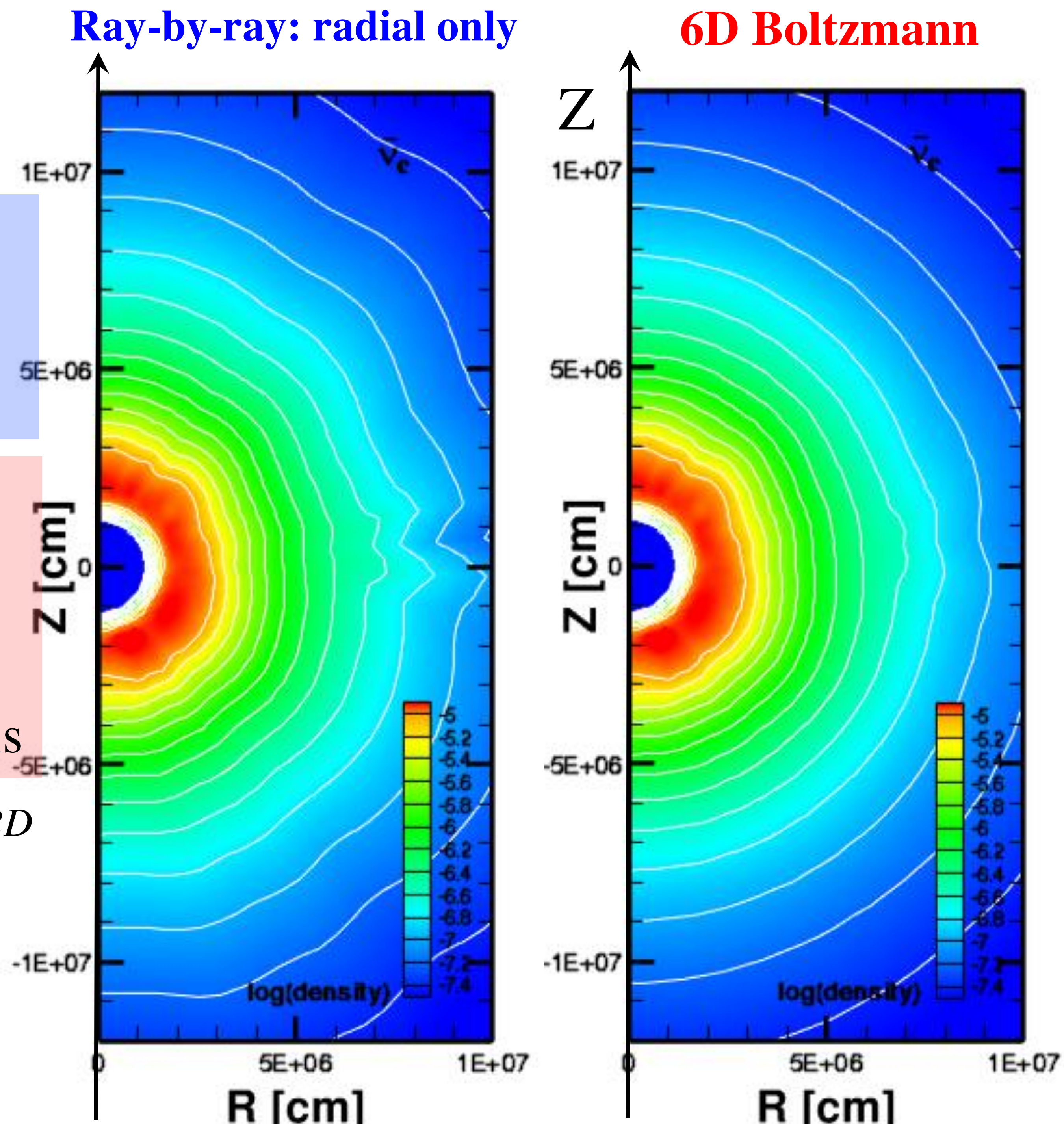
- **Ray-by-ray**
- Only radial transfer
- Anisotropy enhanced

- **6D Boltzmann**
- Non-radial transfer
- Integrated values from various directions

Consistent with Ott-Brandt in 2D

$\bar{\nu}_e$ density: color

View from side: ϕ-slice

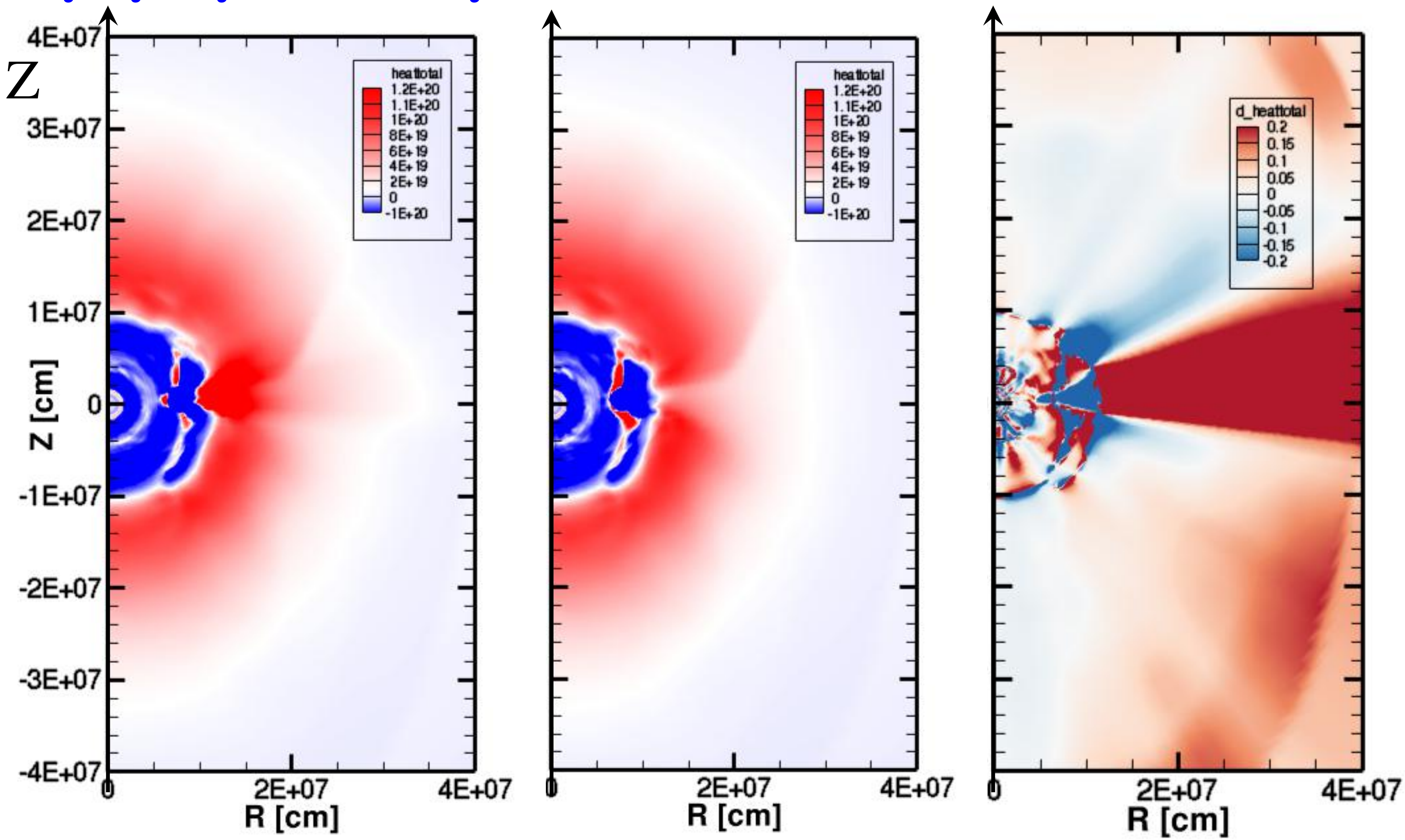


150msec

Comparison: ν-heating rate

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

Ray-by-ray: radial only | 6D Boltzmann | Deviation of RbR



Sumiyoshi et al. (2013,2014)

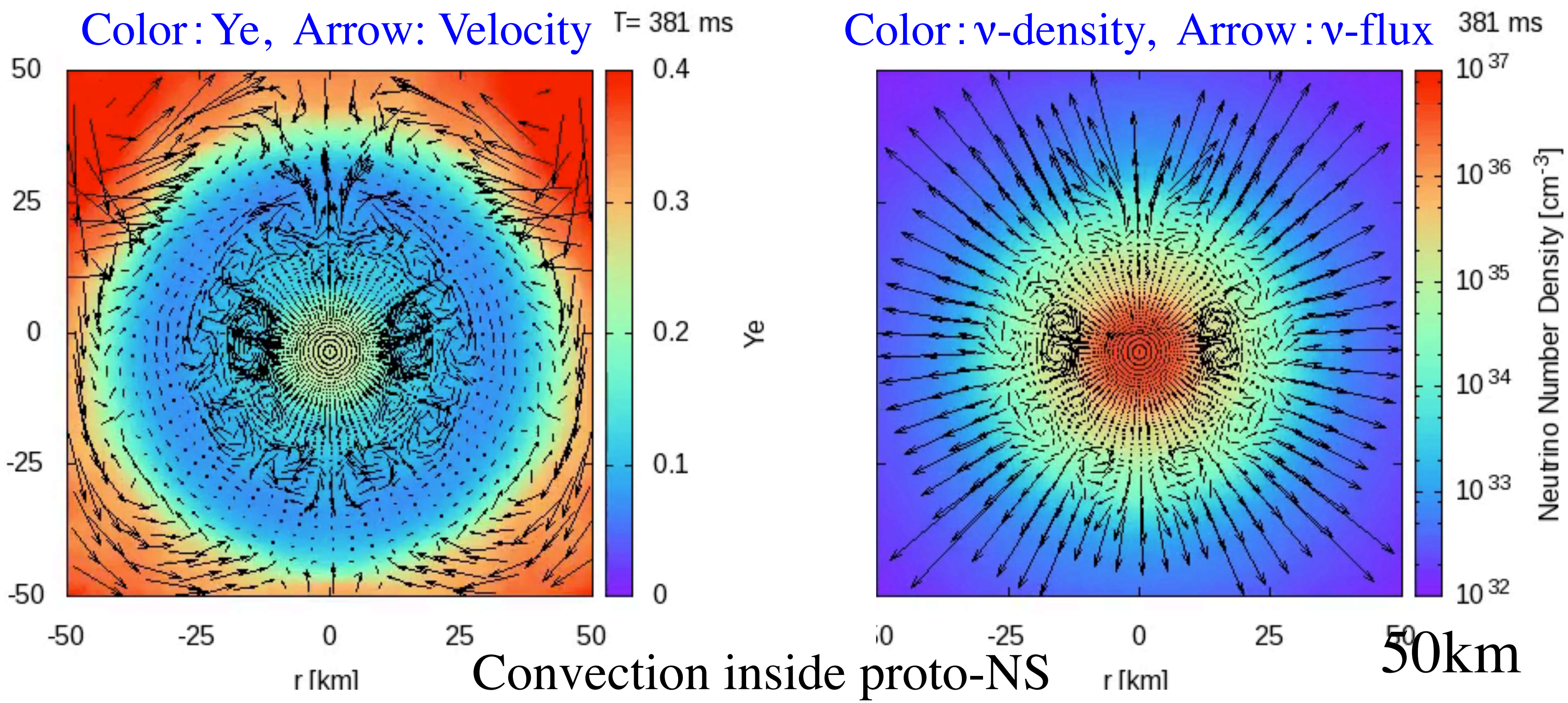
Red: heating, Blue: cooling

$11M_{sun}$, 150msec

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)



Non-radial neutrino flux in the whole region cf. Ray-by-ray approx.

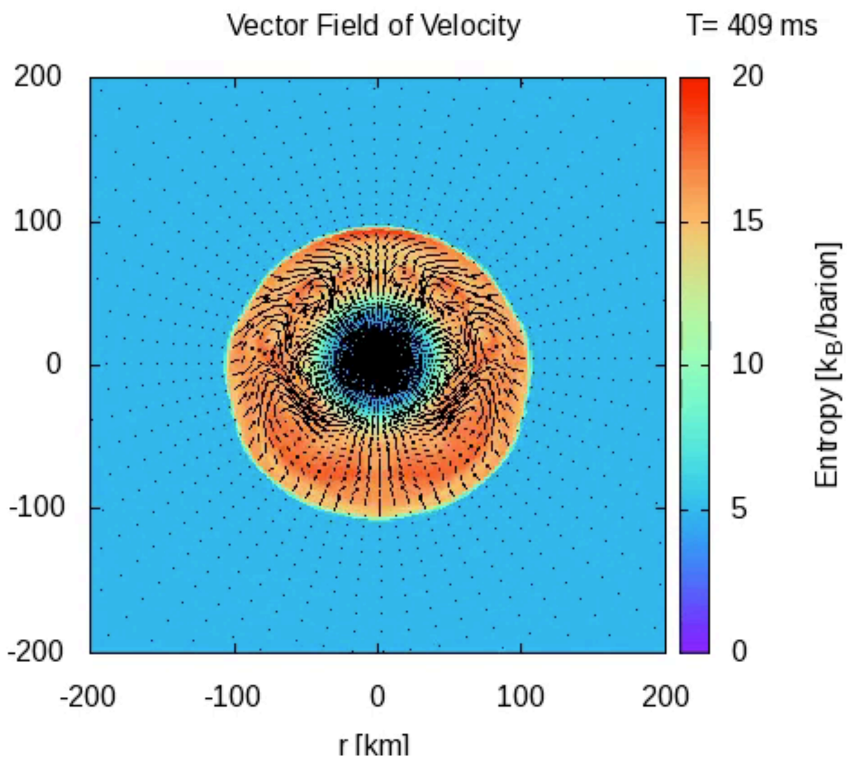
Figure by Iwakami

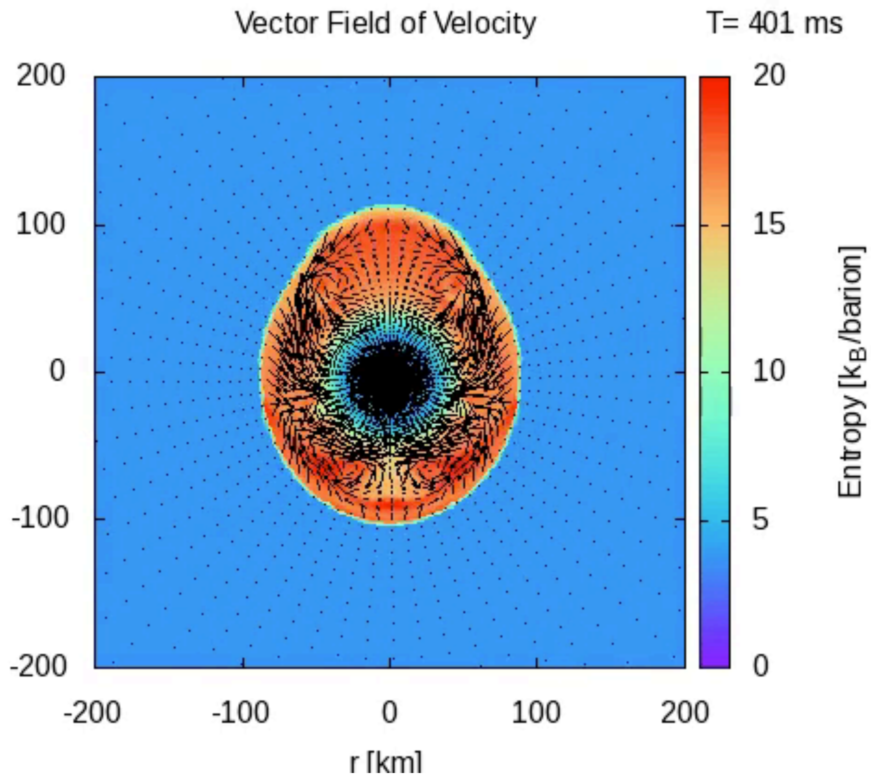
First results of core-collapse simulations

Nagakura, Iwakami et al. (2016)

- Collapse, bounce and shock propagation of 2 models

$11.2M_{sun}$ **Color: entropy, Arrow: Velocity** $15M_{sun}$





with Furusawa EOS table with NSE & GSI e-capture rates

(RMF-TM1, "extended Shen EOS")

2D dynamics depends ρ-profiles

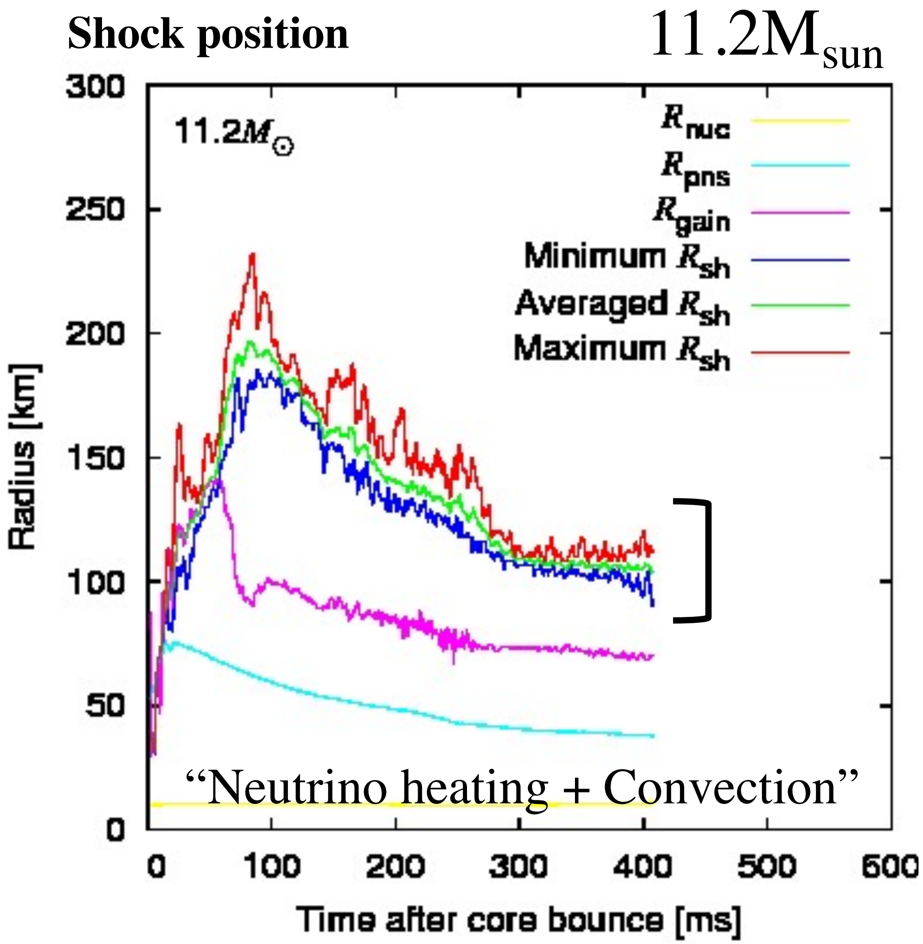
K computer

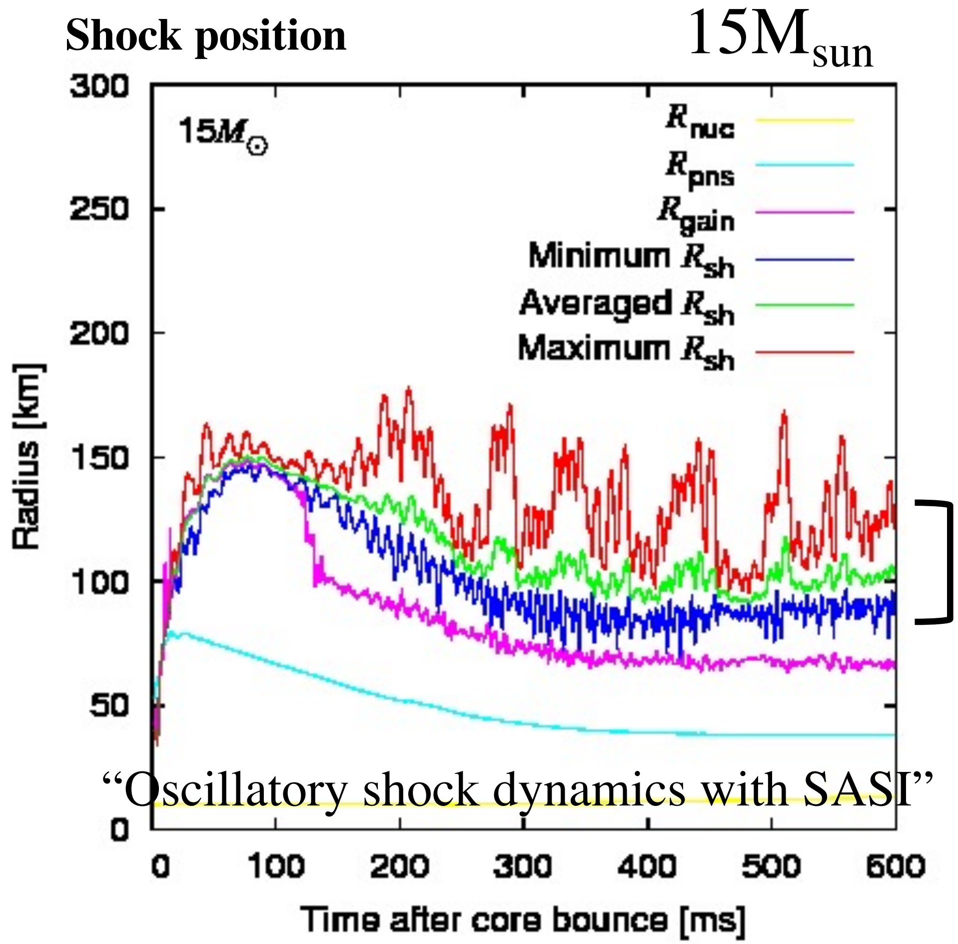
K-Computer, Japan

No explosion found in 2D Hydro+Boltzmann

Nagakura, Iwakami et al. (2016)

- No revival of shock in 2 models but depends ρ-profiles





Need further study: Nuclear physics, General Relativity?

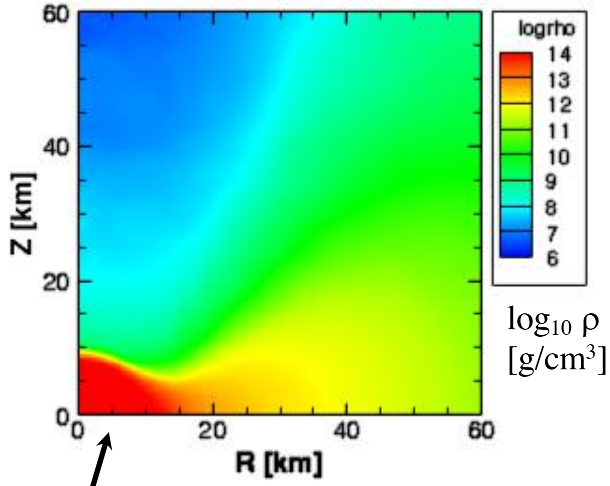
Neutrino transfer in neutron star merger

Provide information
for neutrino-radiation hydrodynamics

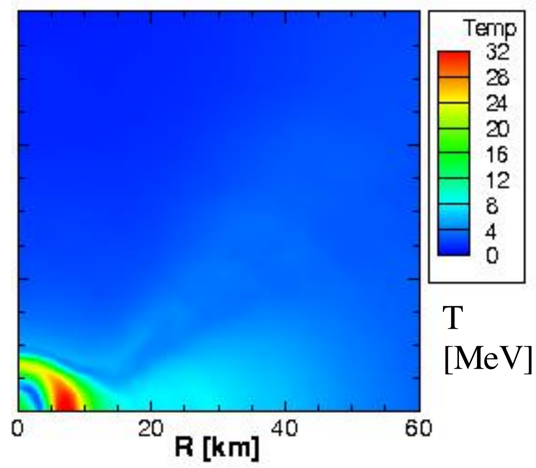
In collaboration with Fujibayashi, Sekiguchi

Neutrino emission from hyper massive neutron star

- Study of 2D Neutrino transfer in deformed objects

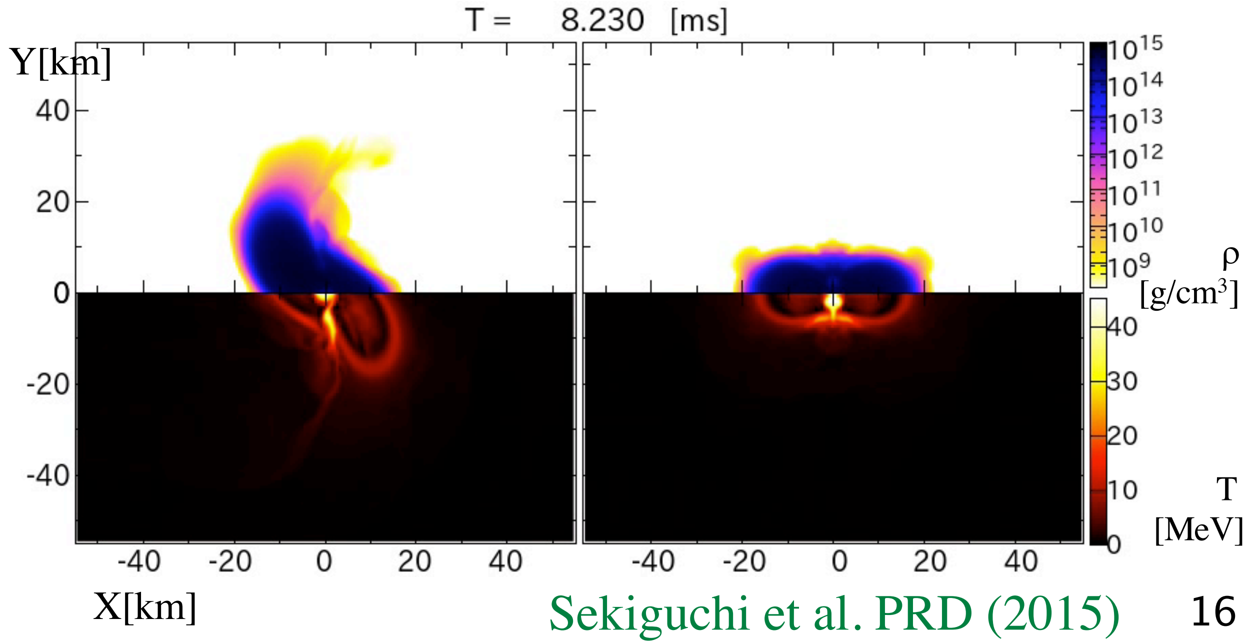


Hyper-massive NS



- Neutrino emission
- Neutrino heating via pair process
- Electron fraction of ejecta

- Merger of binary NSs
  - 1.35M + 1.35M
- Rotating hot NS
  - $M \sim 2.6 M_{sun}$
  - Hempel DD2 EOS
  - $M_{max} \sim 2.4 M_{sun}$



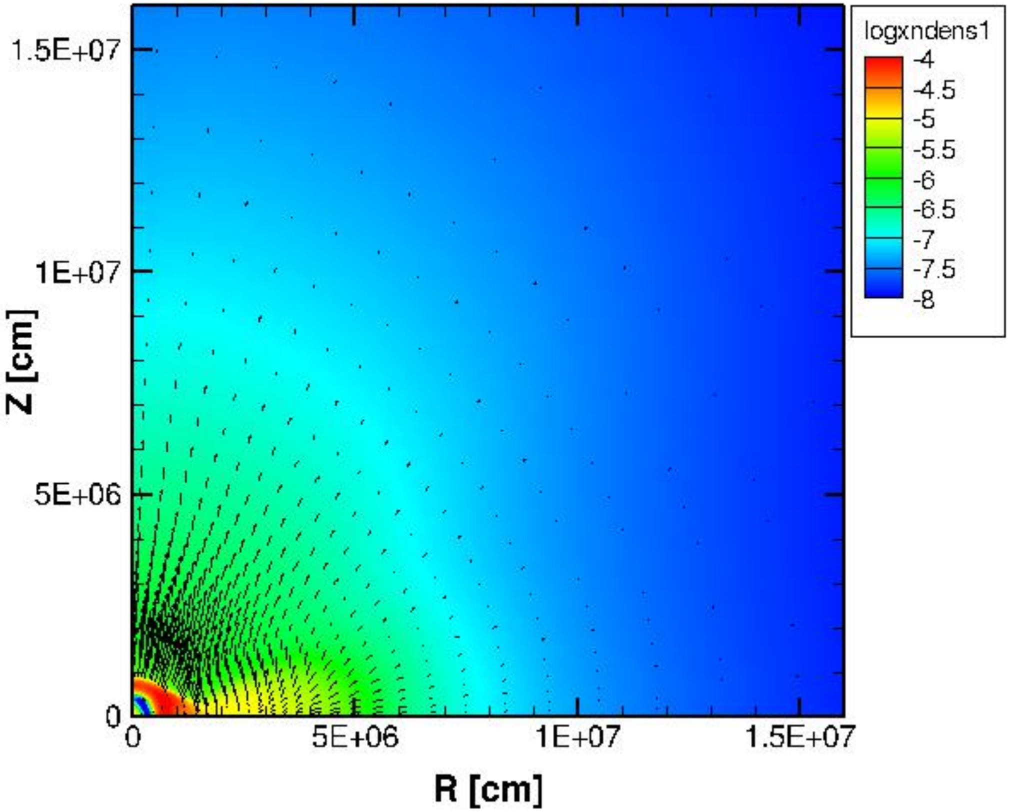
Fujibayashi (2016)

Sekiguchi et al. PRD (2015)

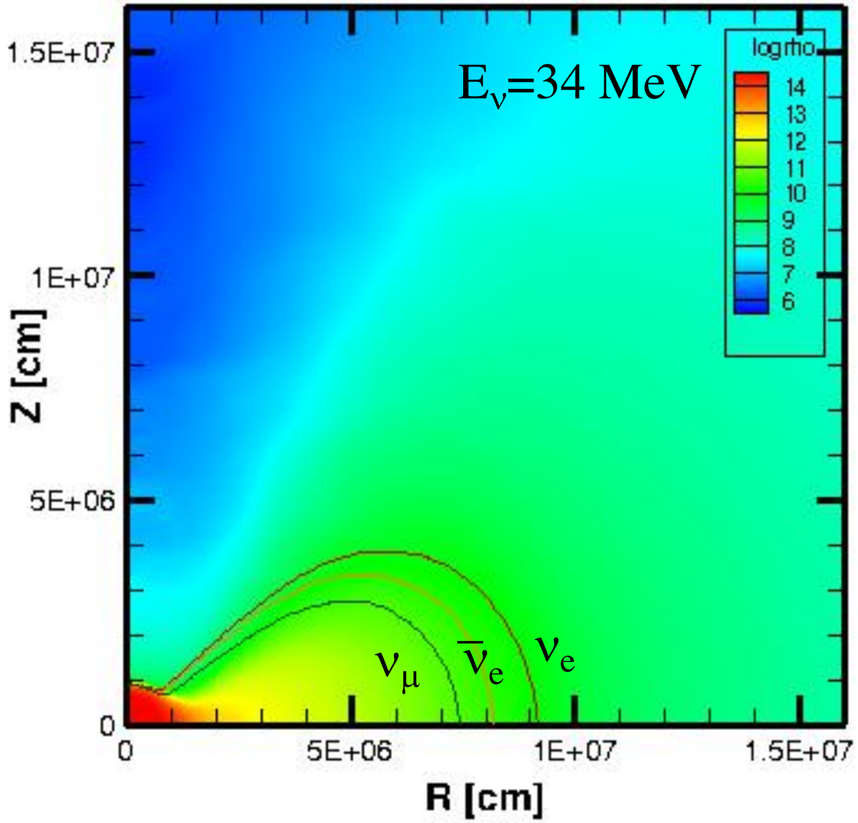
Evaluation by 6D Boltzmann eq. solver

- Describes full angle energy distributions

Neutrino density, flux



Neutrino sphere



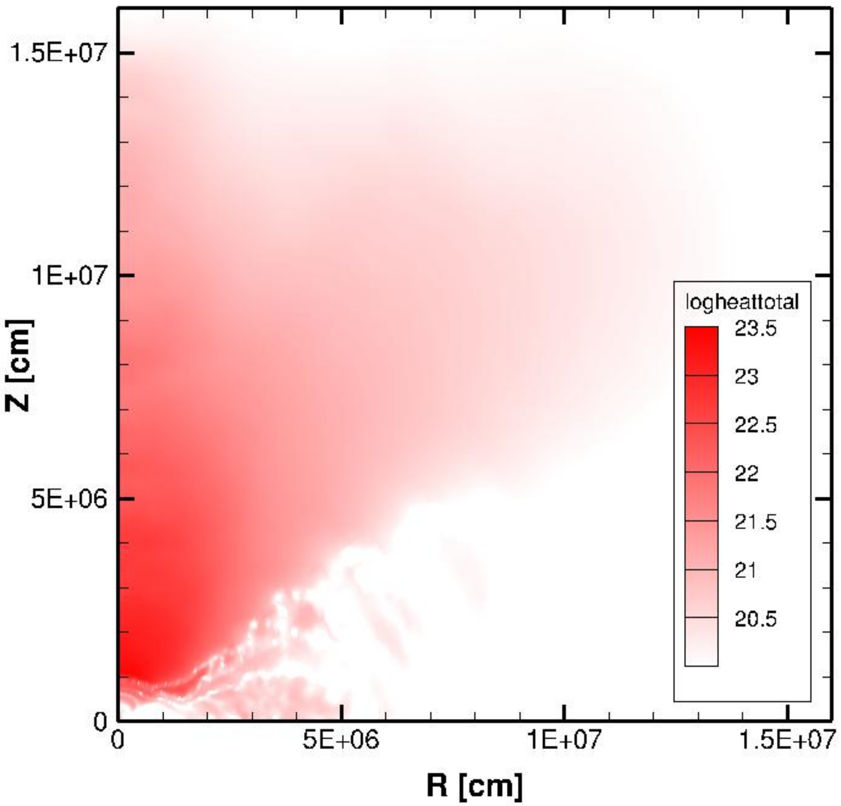
for emission mechanism of neutrinos from NS mergers

cf. Monte Carlo by Richers, M1 by Just, Adv. Leakage by Perego

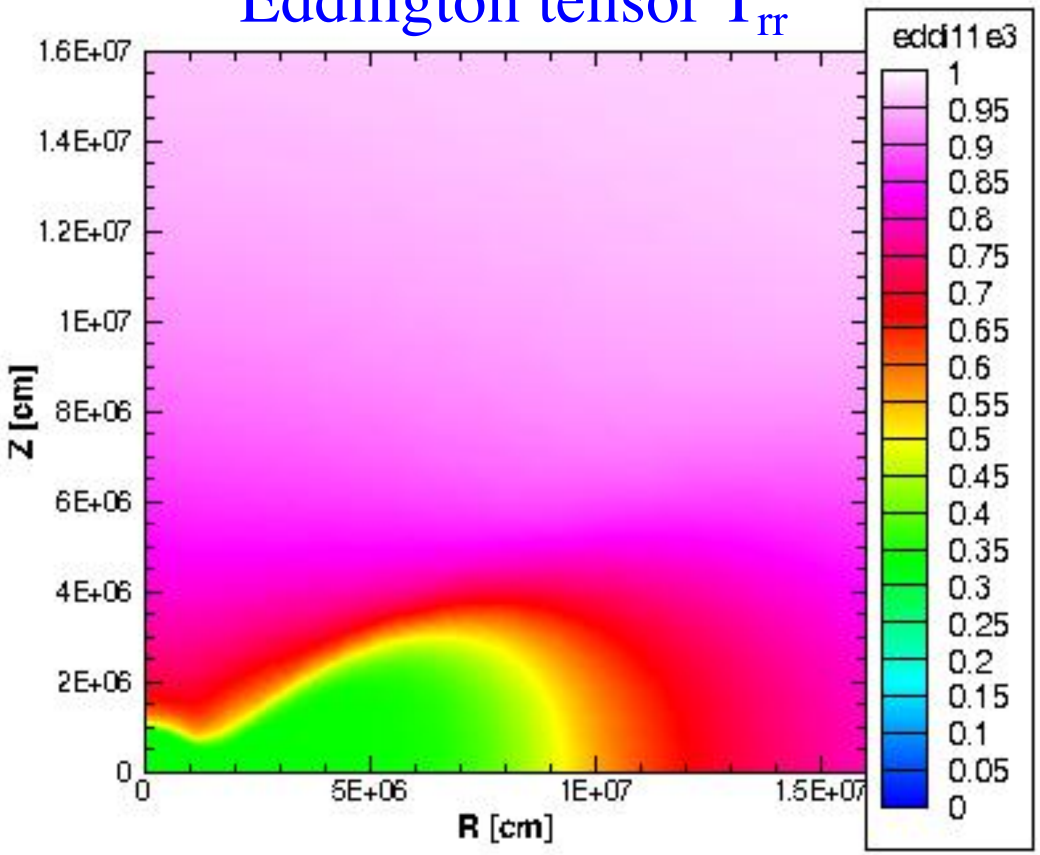
Evaluation by 6D Boltzmann eq. solver

- Can be used to validate approximate methods

Neutrino heating rate



Eddington tensor T_{rr}



for dynamical calculations in moment formalism with M1

by Fujibayashi

Equation of state in supernovae

effects on explosion?

EOS table for supernova simulations

- Data covers wide range
  - ρ : $10^{5.1} \sim 10^{16}$ g/cm^3
  - Y_p : $0 \sim 0.65$
  - T : $0 \sim 400$ MeV
- Consistent framework
- Experiments of nuclei
- Observations of neutron stars

Models	Framework	Reference	
Nucleon benchmark 1990's~	Skyrme Hatree-Fock Extended Liquid-Drop Relativistic Mean Field	Wolff-Hillebrandt Lattimer-Swesty Shen	LS-EOS Shen-EOS
Nucleon updates 2000's~	Relativistic Mean Field Nuclear many body	G. Shen, Oertel, Peres Togashi, Constantinou	
Nucleon updates+NSE	Relativistic Mean Field Mixture of nuclei	Hempel, Steiner, Fischer Furusawa	Furusawa
Nucleon +Hyperon	Relativistic Mean Field Hyperon interactions	Ishizuka Gulminelli, Oertel, Banik	
Nucleon +Quark	Relativistic Mean Field Bag model	Nakazato Sagert, Fischer	

Based on Oertel, Hempel, Klaehn & Typel (2016)

Comparison of EOS sets: benchmark

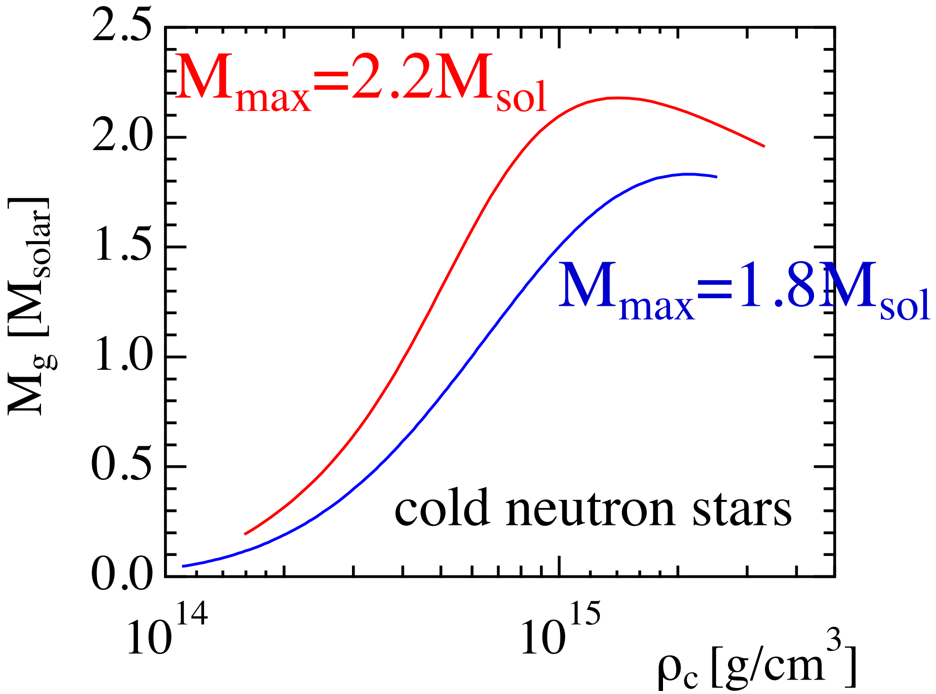
- Difference in stiffness & symmetry energy

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

180, 220: Frequently used for many simulations

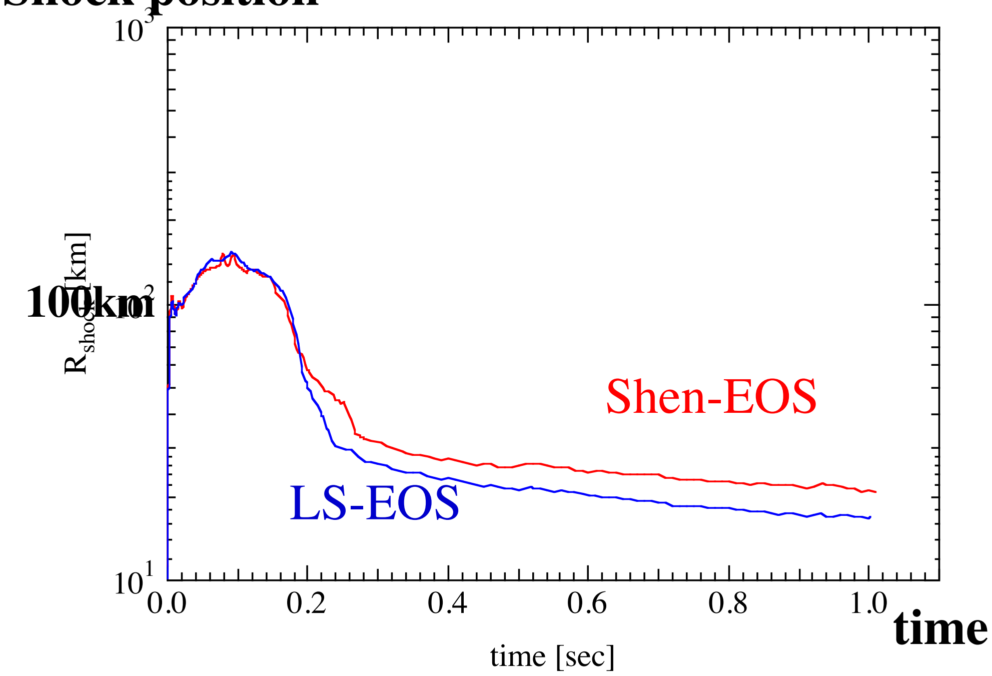
- Two representatives

- Extremes in modern sense



Sumiyoshi (2004)

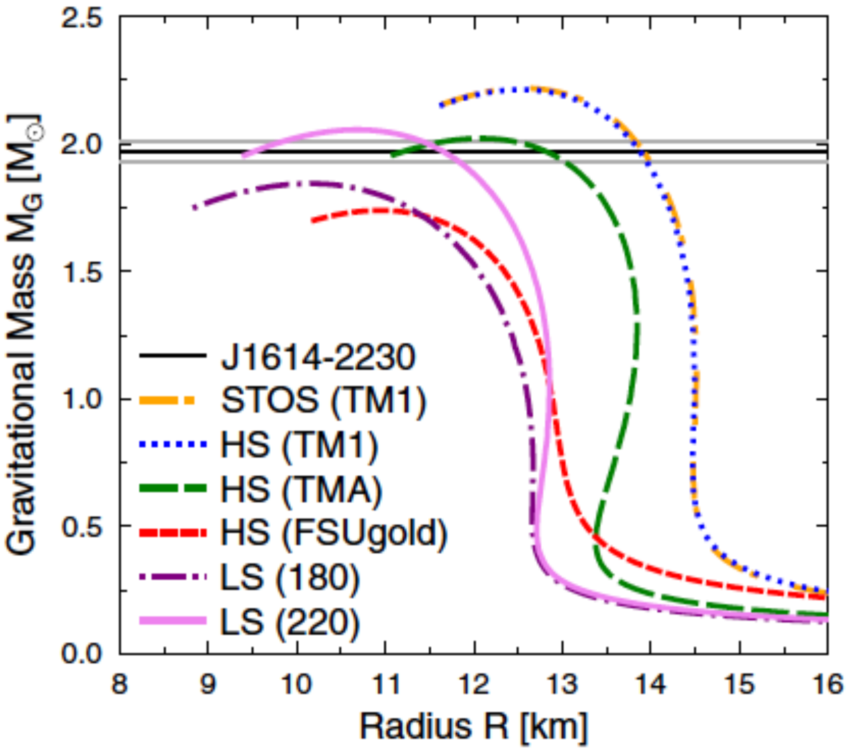
Shock position



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

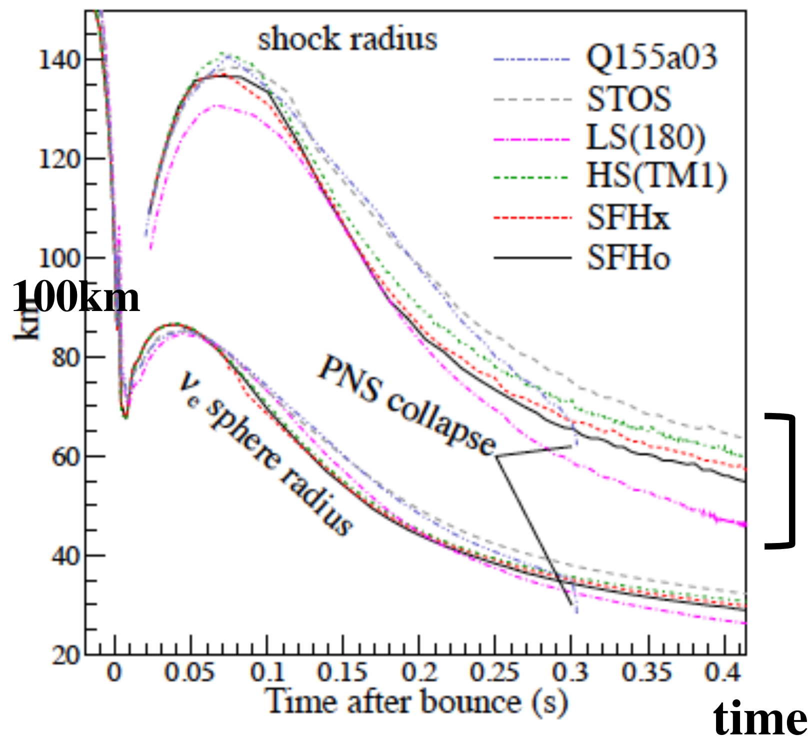
Comparison of EOS sets: more recent

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



Hempel (2012)

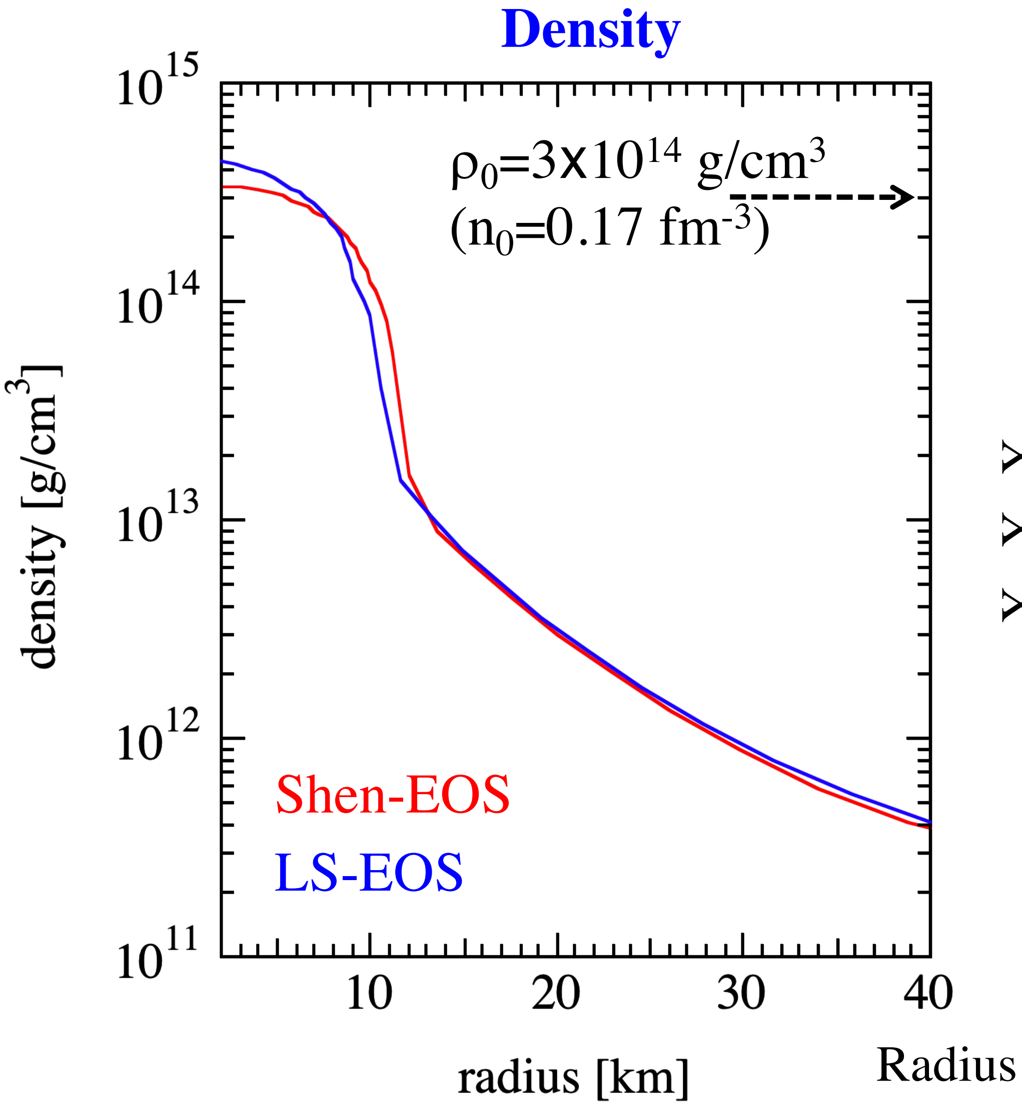
Shock position

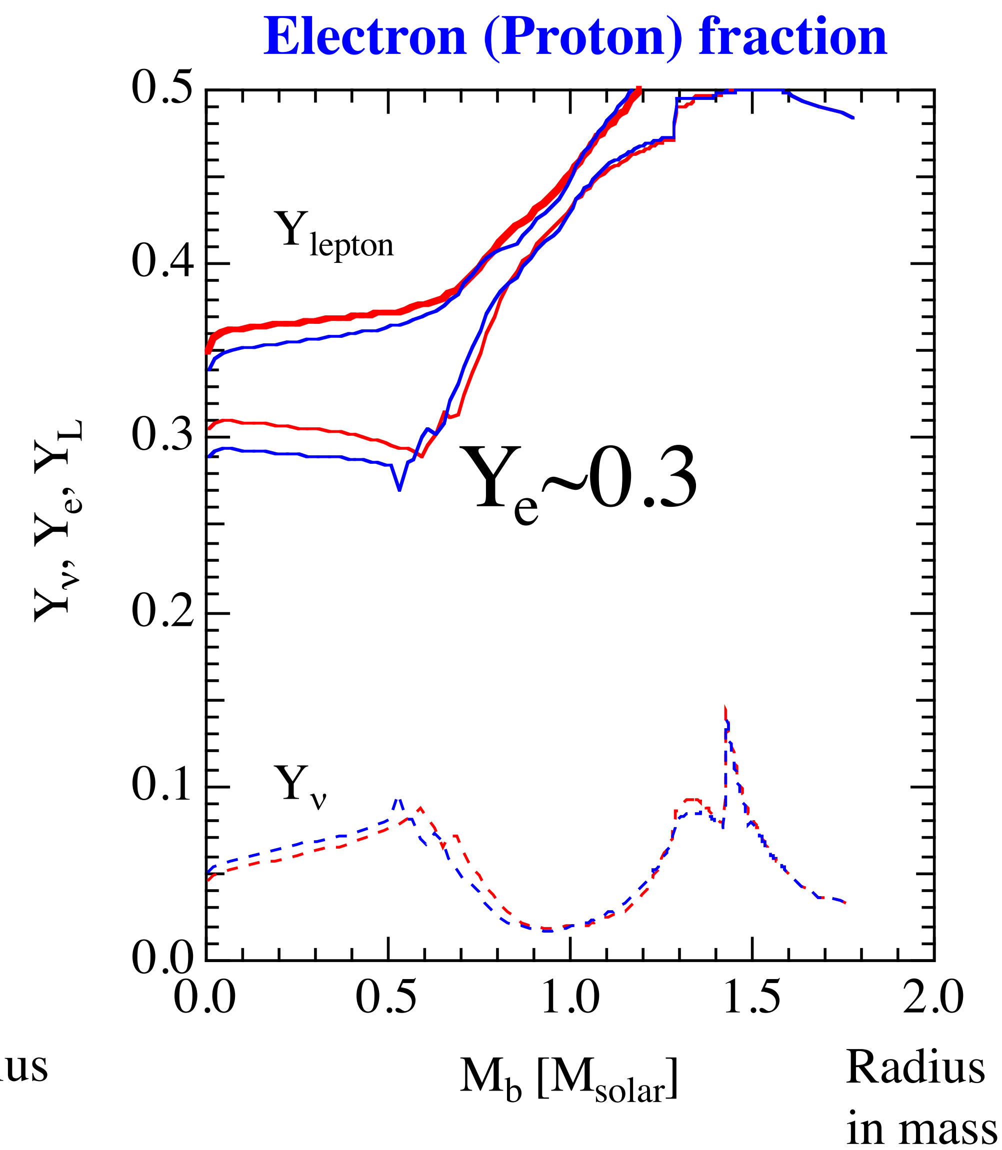


$11.2M_{solar}$ Steiner et al. (2013)

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

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

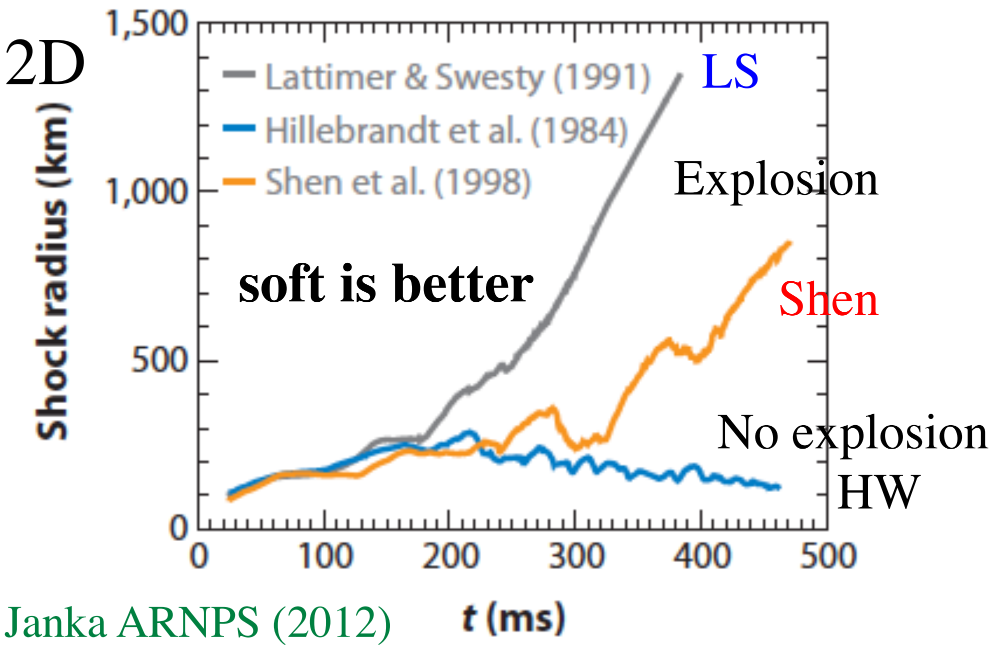




Sumiyoshi et al. ApJ 629 (2005) 922.

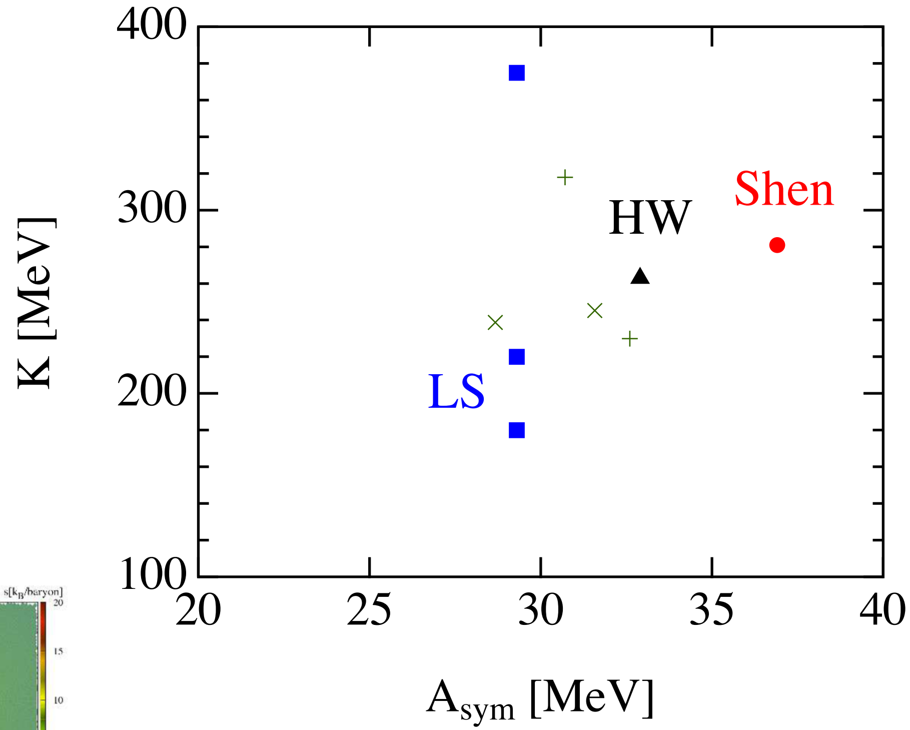
EOS effects in multi-D: larger than 1D?

2D

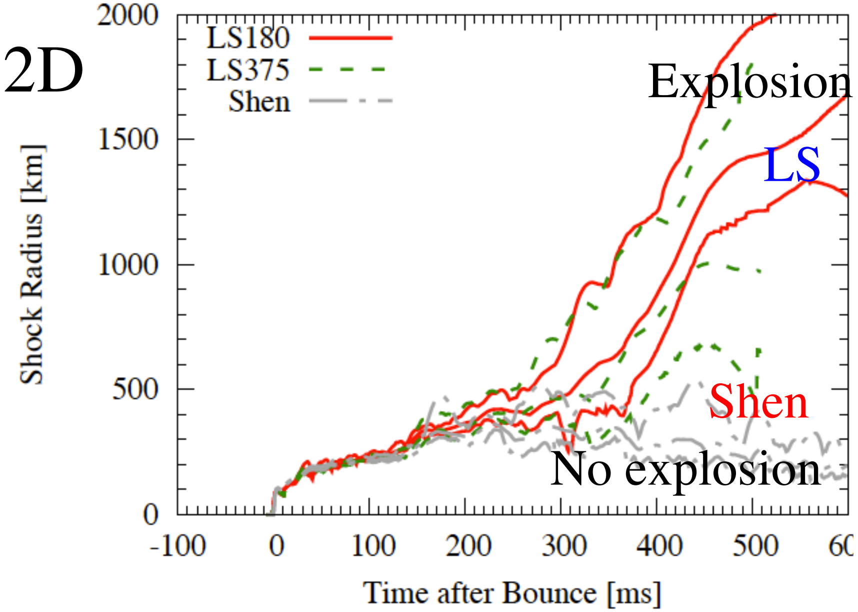


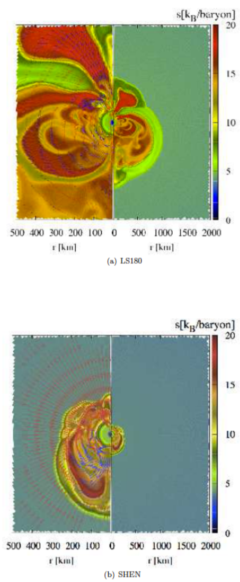
Janka ARNPS (2012)

Need more systematic studies



2D





Suwa et al. ApJ (2013)

In 3D, LS 220MeV so far

Takiwaki (2012), Hanke (2013), Bruenn (2014), Lentz, Melson (2015) Robert (2016)

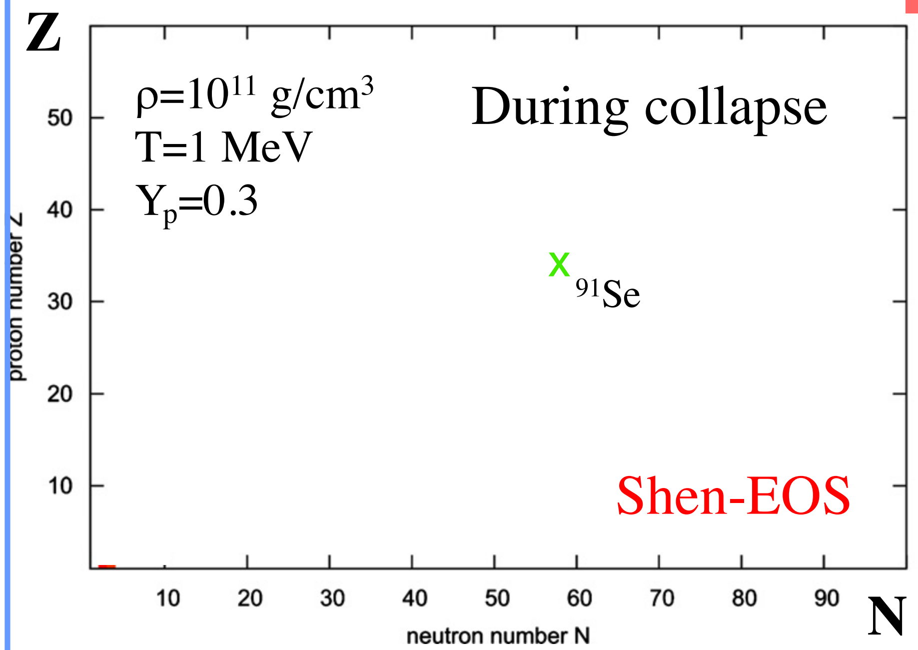
Equation of state in supernovae

Effect of composition

Mixture of nuclei in supernova EOS tables

Shen-EOS

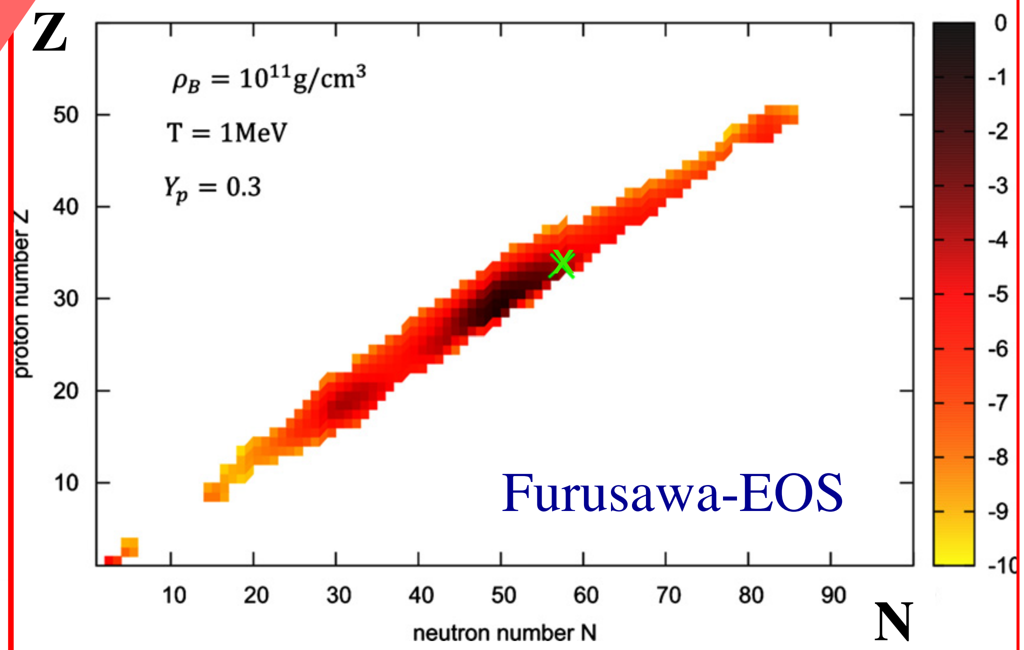
Neutron, proton, ^{4}He
One species of nuclei
approximation



A representative nuclei

Furusawa-EOS

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



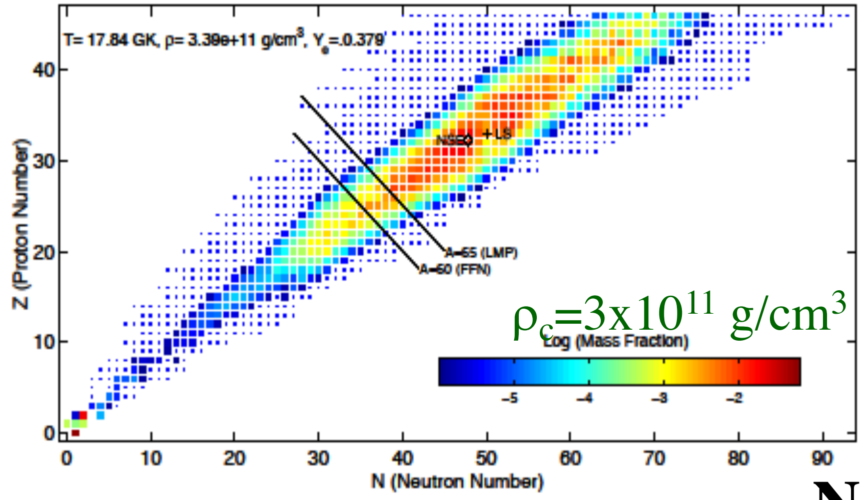
Wide variety of nuclei

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

e-capture on mixed nuclei during collapse

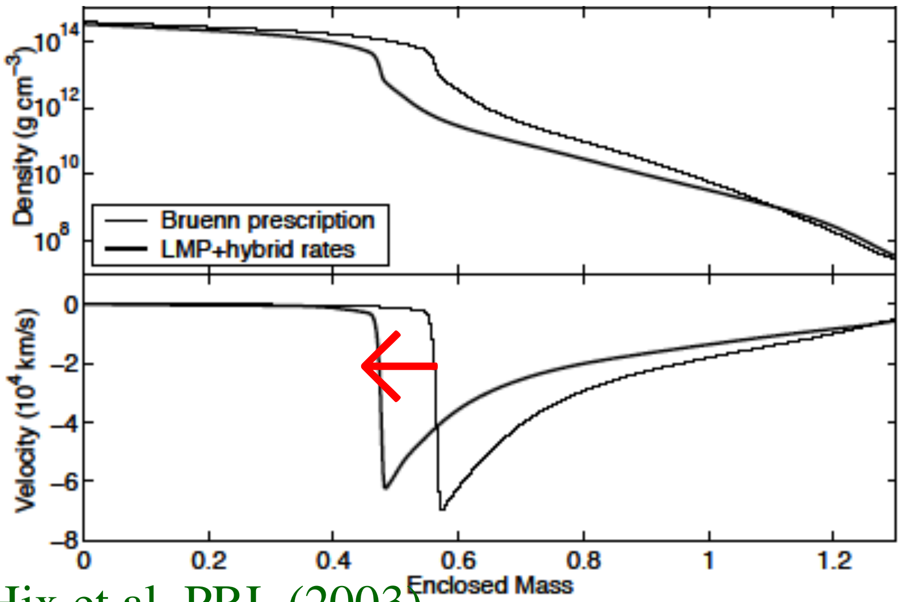
Nuclear statistical equilibrium

Z



N

profile of core bounce



Hix et al. PRL (2003)

- Composition of nuclei

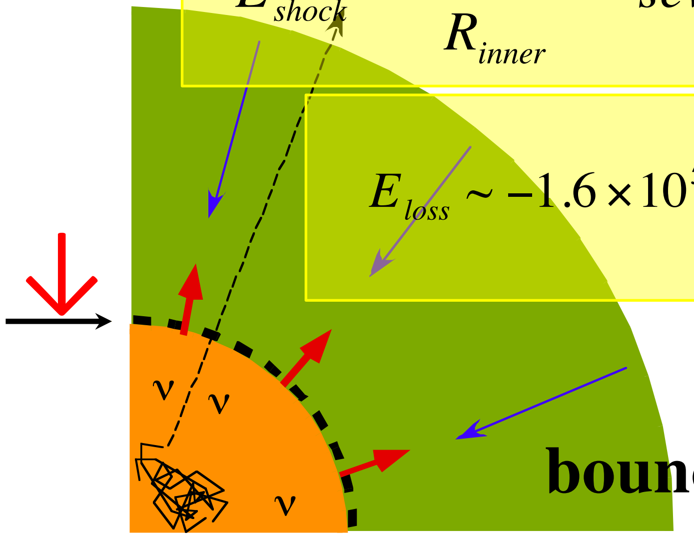
  1-species & ^{4}He → Mixture

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

Initial energy & loss

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

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



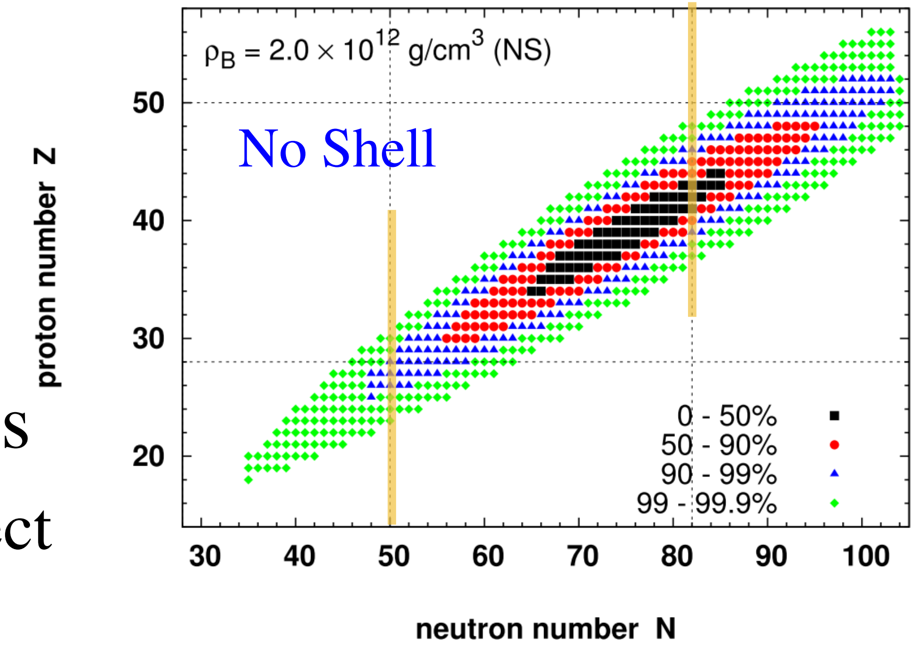
bounce & after

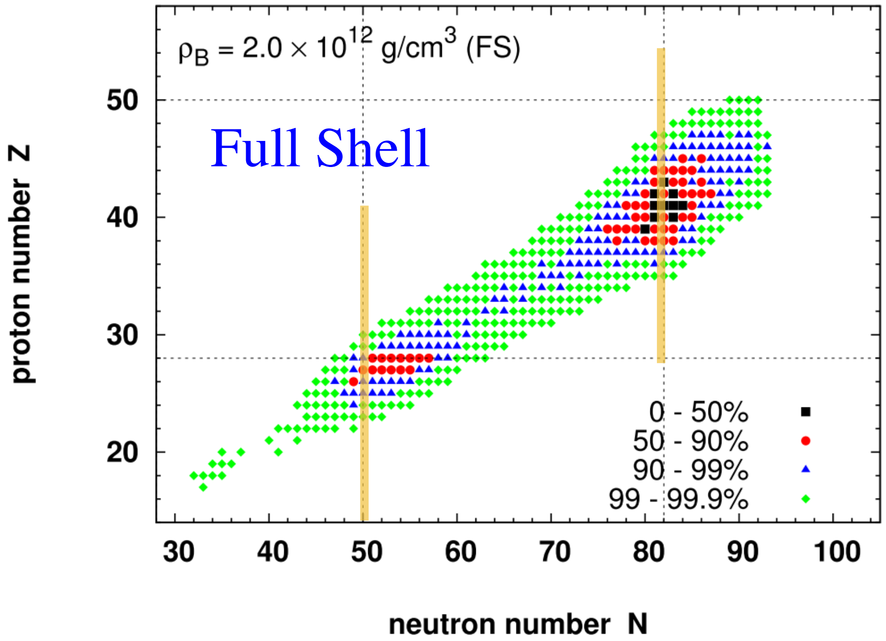
Bounce core

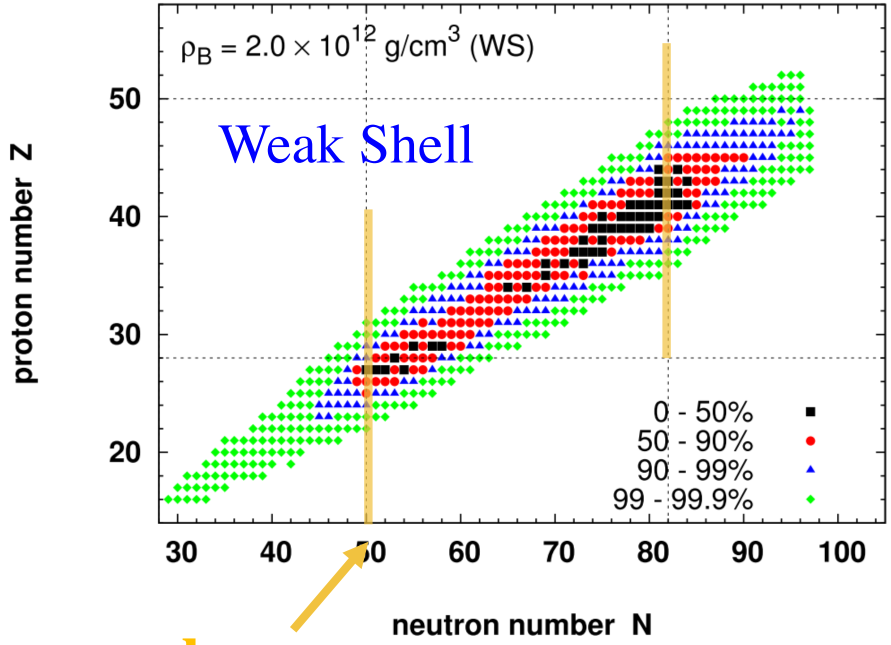
Fe core

Shell effect on mixture of nuclei in supernova core

- Shell smearing
  - at finite temperature
- Shift of abundance peak affects electron capture rates
  - ~30% with/without shell effect







Magic numbers

Furusawa et al. PRC (2016) submitted

Slide From Furusawa

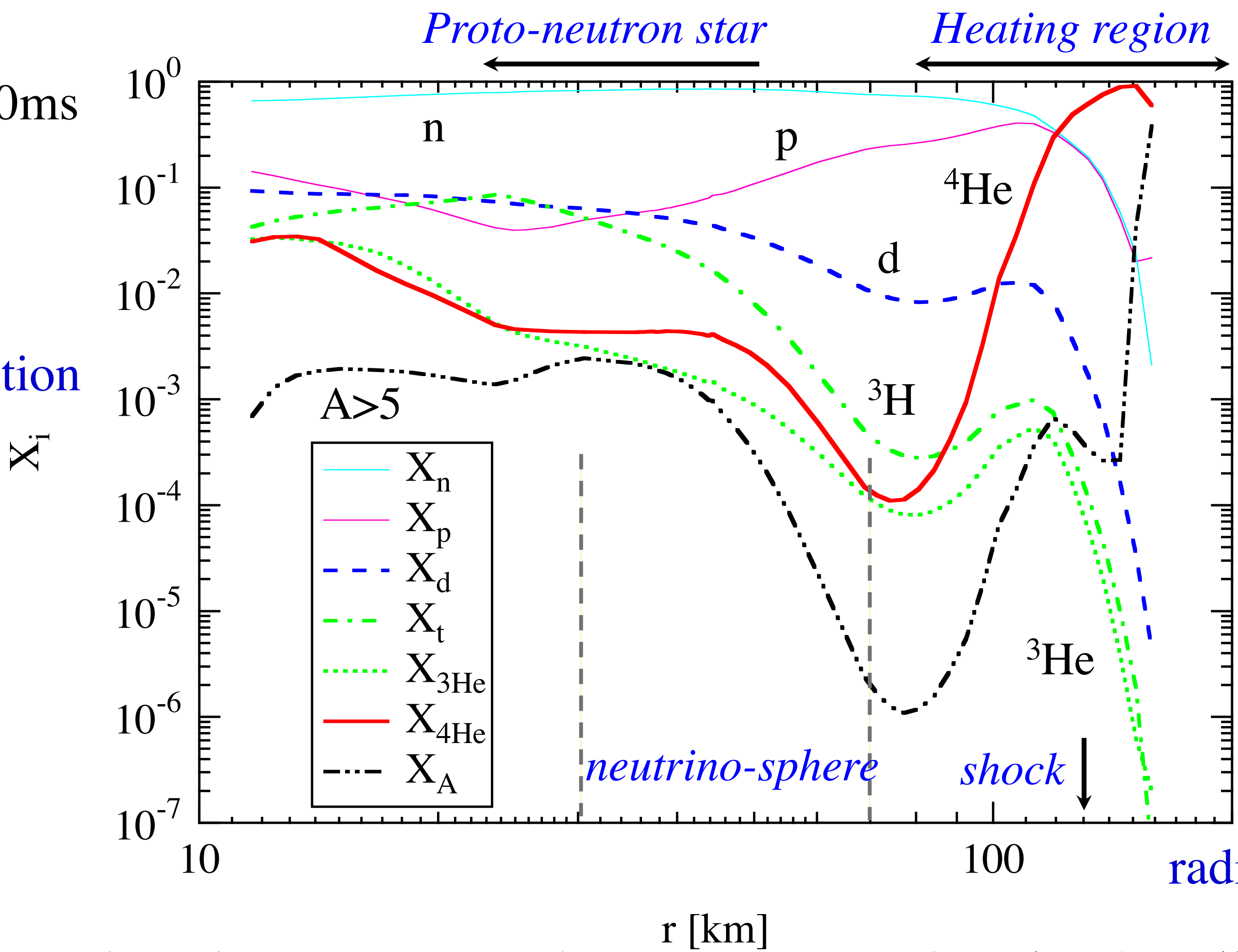
Light clusters + ^{4}He can appear after bounce

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

Sumiyoshi & Röpke PRC (2008)

At t_{pb}=150ms

Mass fraction



radius [km]

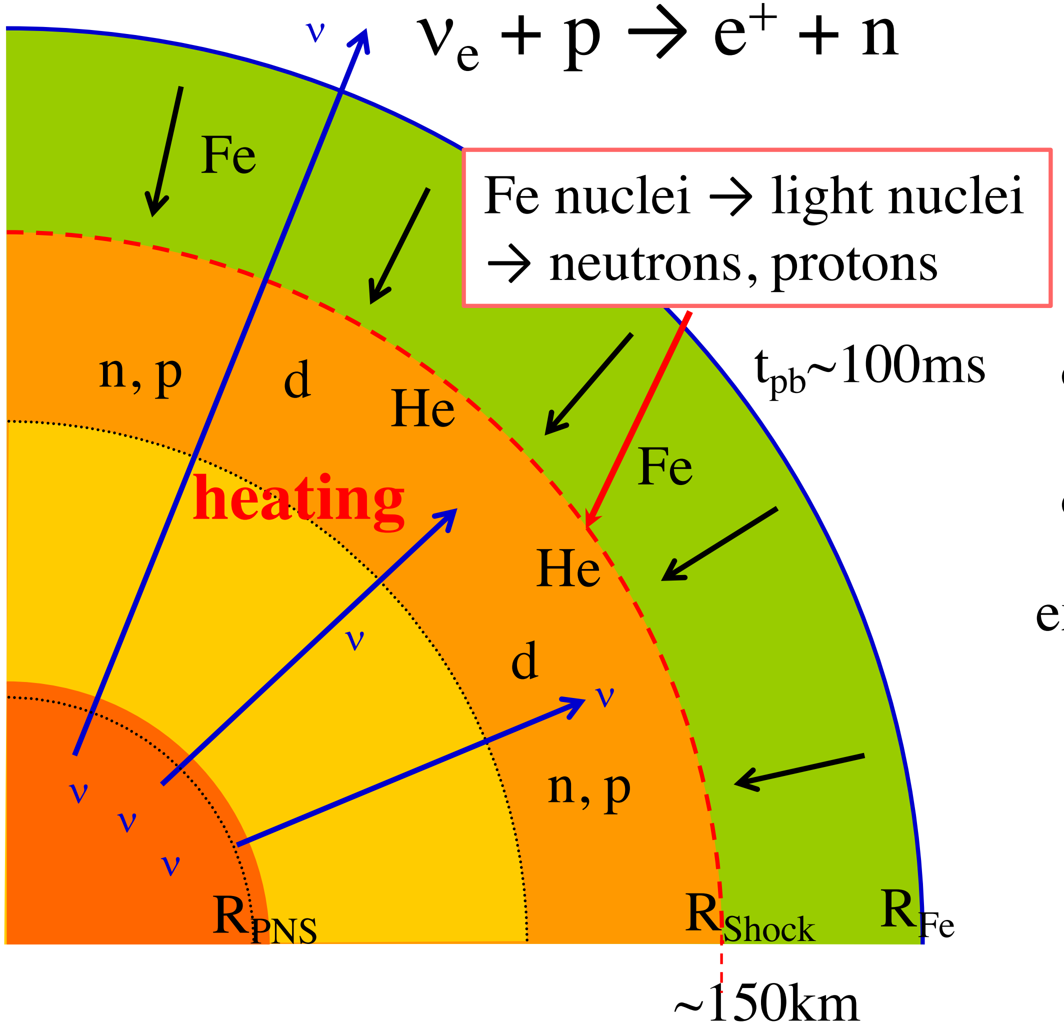
- ^{4}He abundant at r > 100km → heating/cooling rates
- d, t, ^{3}He abundant at r < 50km → ν-emission, absorption

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

Absorption of neutrinos: neutrino heating

- Nucleons: ~200MeV/s

$$\nu_e + n \rightarrow e^- + p,$$
$$\nu_e + p \rightarrow e^+ + n$$



- Nuclei: 0~30MeV/s

$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$

depends on species!!

- Fe, ^{4}He — Haxton PRL (1988)
- Light nuclei (d, t, ^{3}He)

ex.

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

Nakamura et al. PRC (2009)
O'Connor et al. PRC (2007)

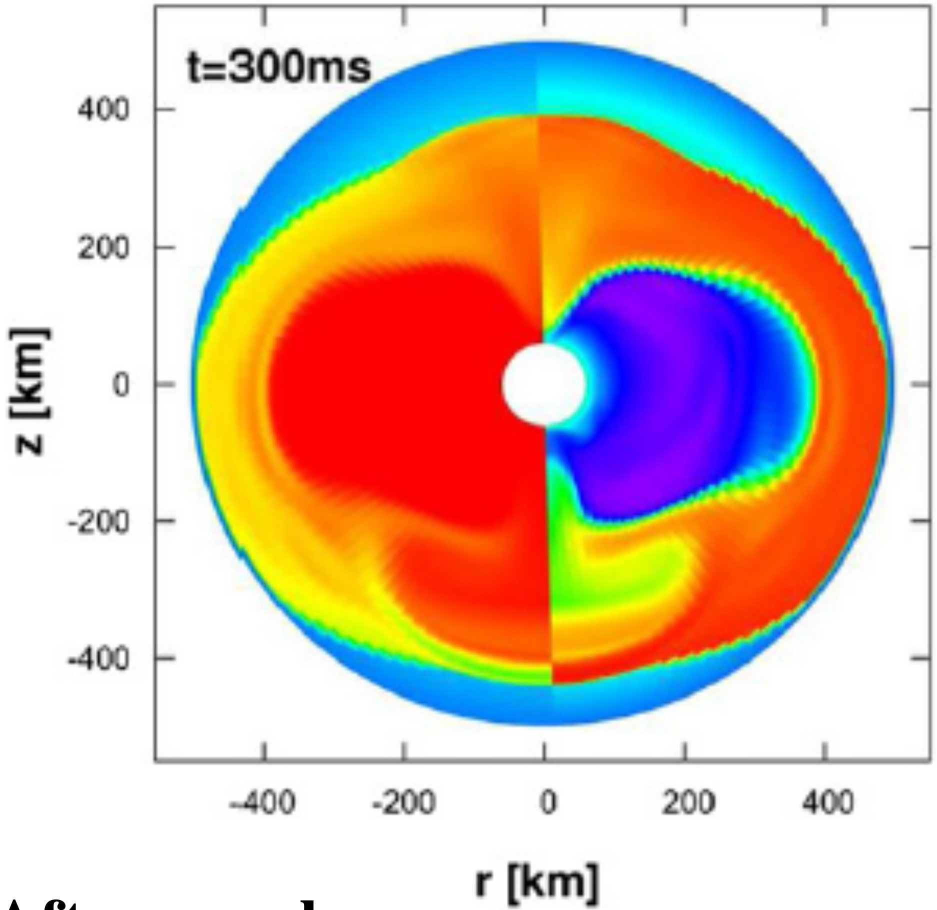
2D supernova simulations with light clusters

Furusawa et al. ApJ (2013)

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

Abundance

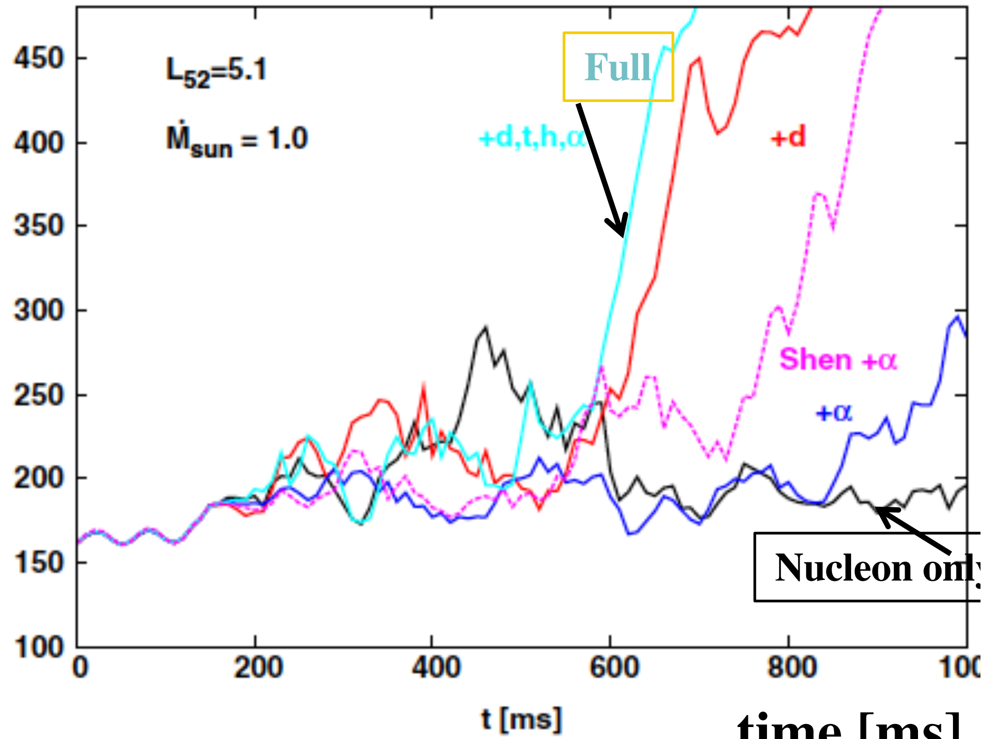
n, p **d, ^{3}He, t, ^{4}He**



After core bounce

Shock radius

[km]



time [ms]

- Possible effects on shock revival when it is marginal

Emission of neutrinos via light clusters

- Deuterons

ex. $d + e^- \to n + n + \nu_e,$

$d + e^+ \to p + p + \bar{\nu}_e,$

Nasu et al. PRC (2015)

- Proton, neutrons

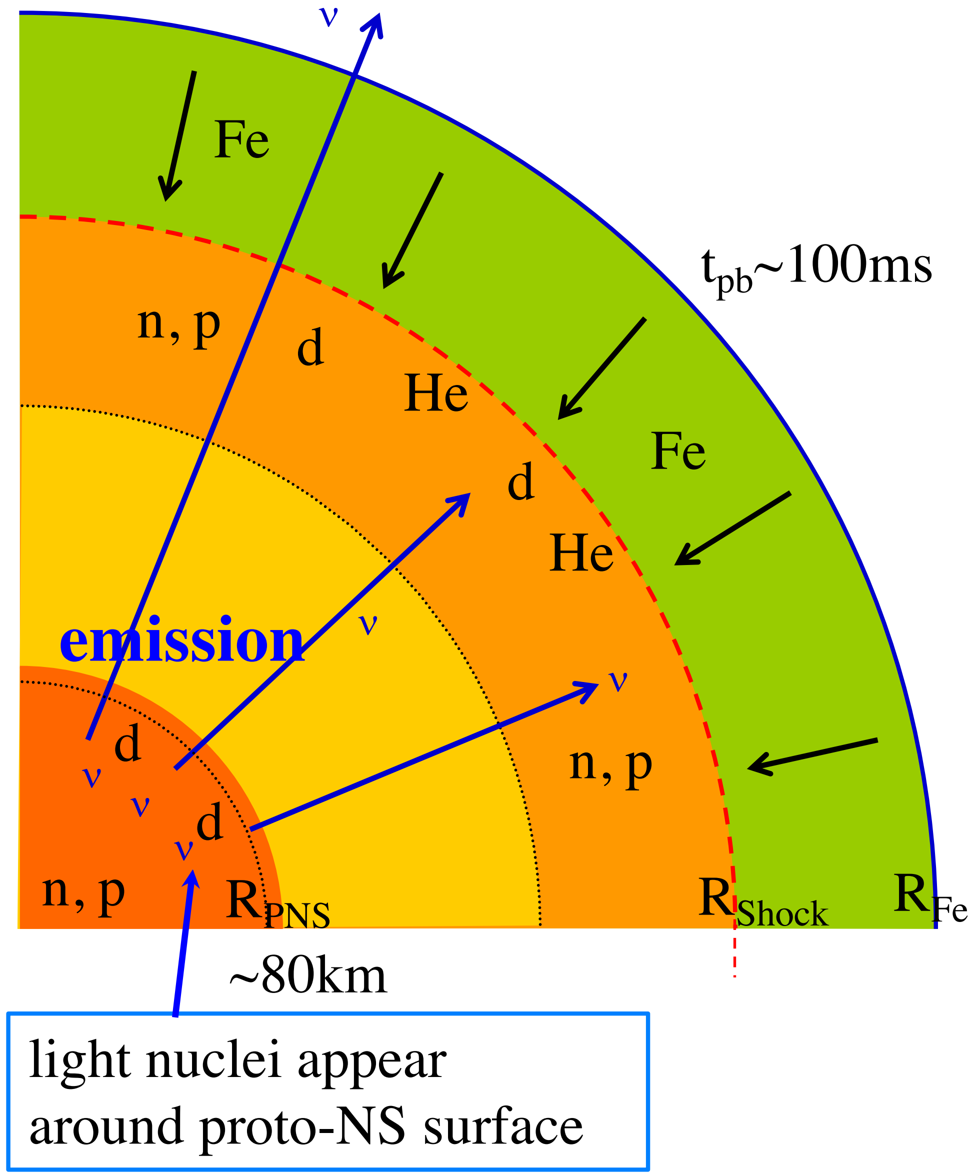
cf. $p + e^- \to n + \nu_e$

$n + e^+ \to p + \bar{\nu}_e$

- Triton, ^{3}He

O'Connor, Arcones PRC (2007, 2008)

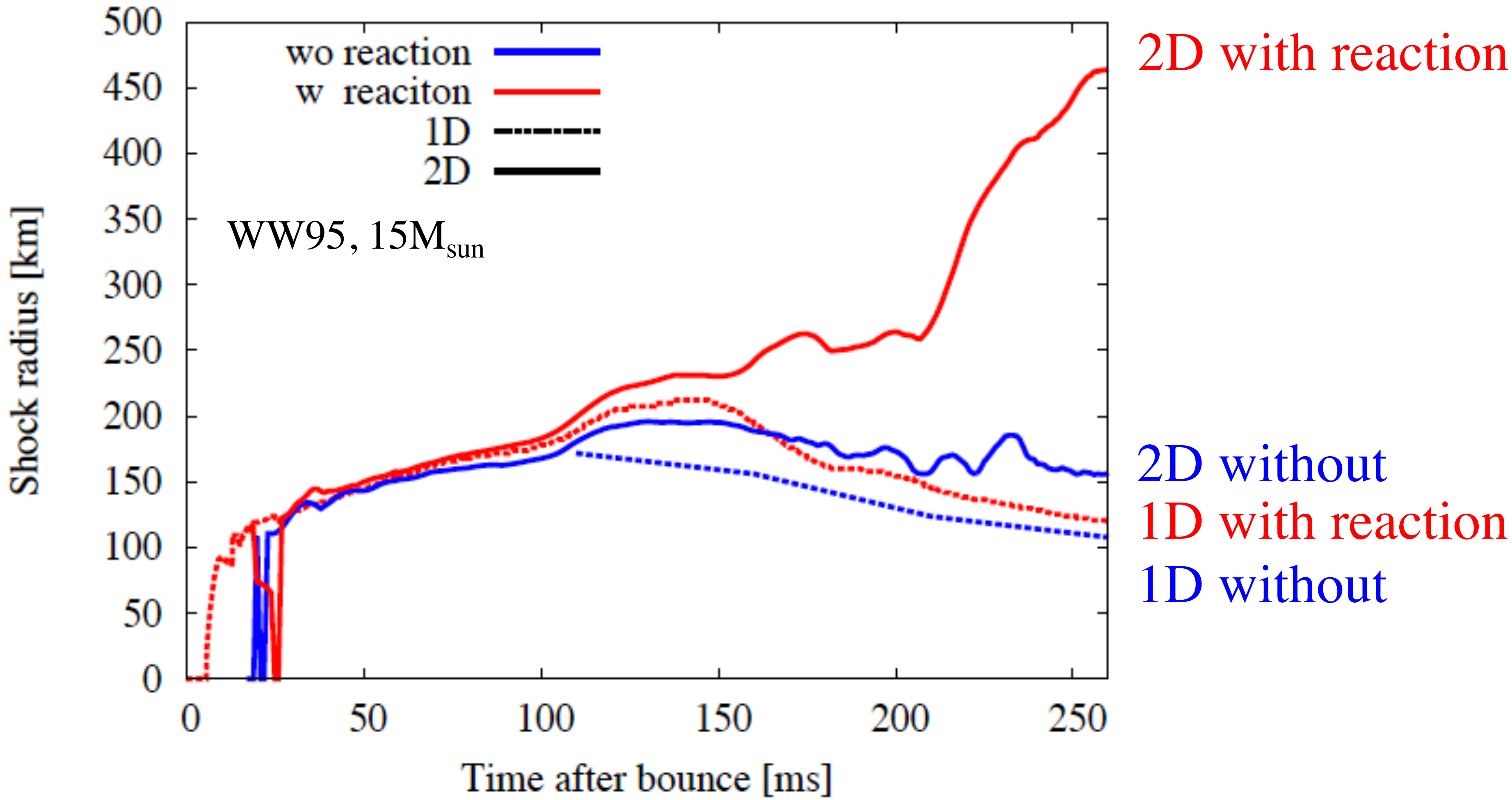
- Modifications of
  - ν-sphere, emissivity



2D supernova simulations with light clusters

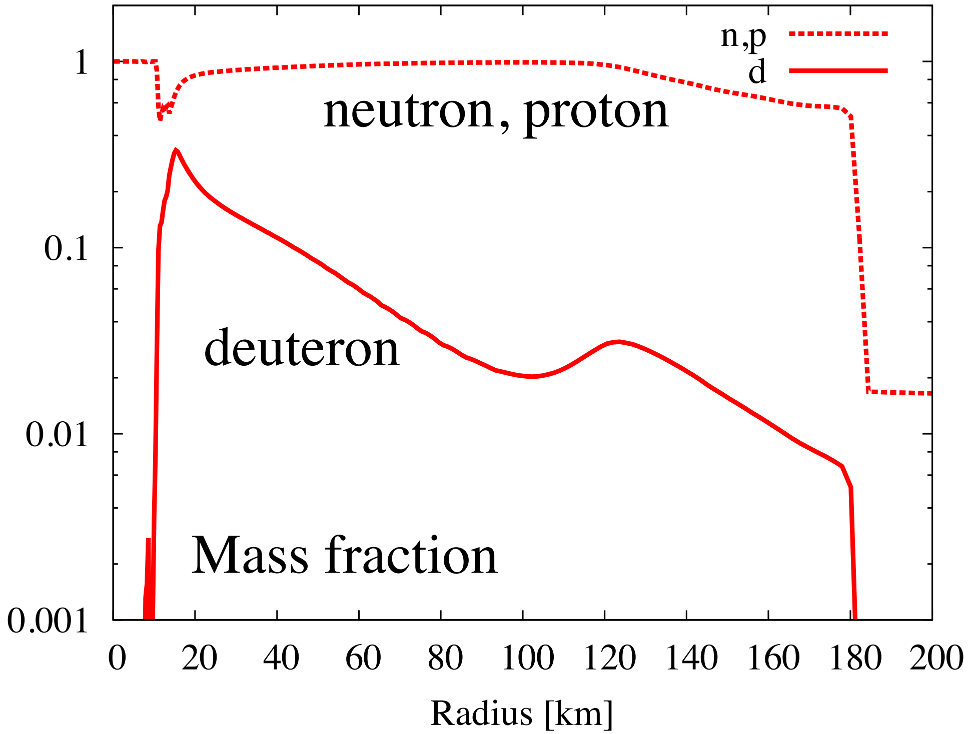
Takiwaki et al. (2016) in preparation

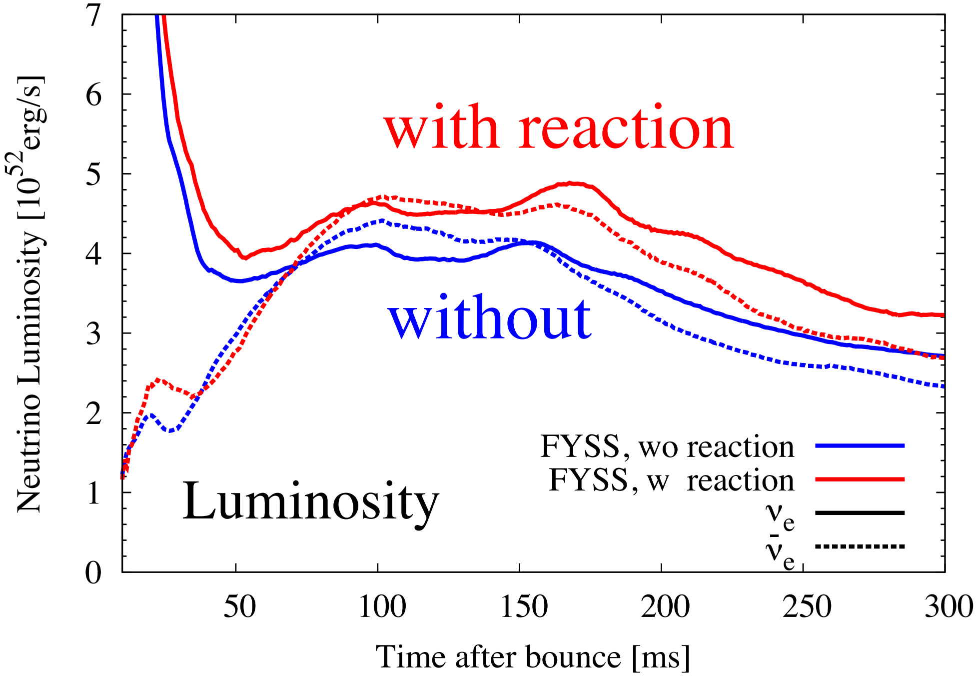
- With/without reactions via deuterons
  - Using abundance of nuclei from Furusawa EOS

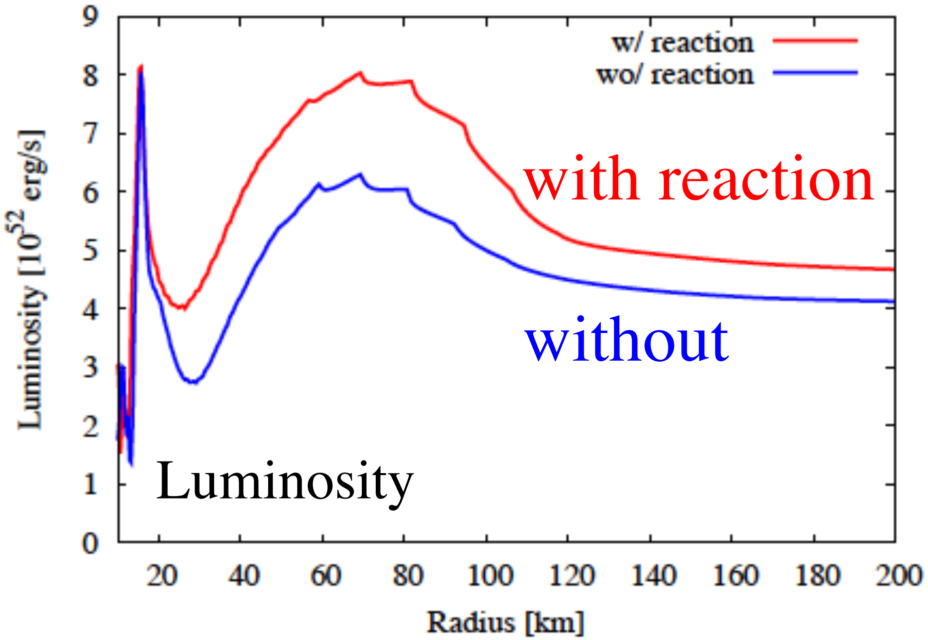


Slide From Takiwaki

1D case: t_{pb}=100ms





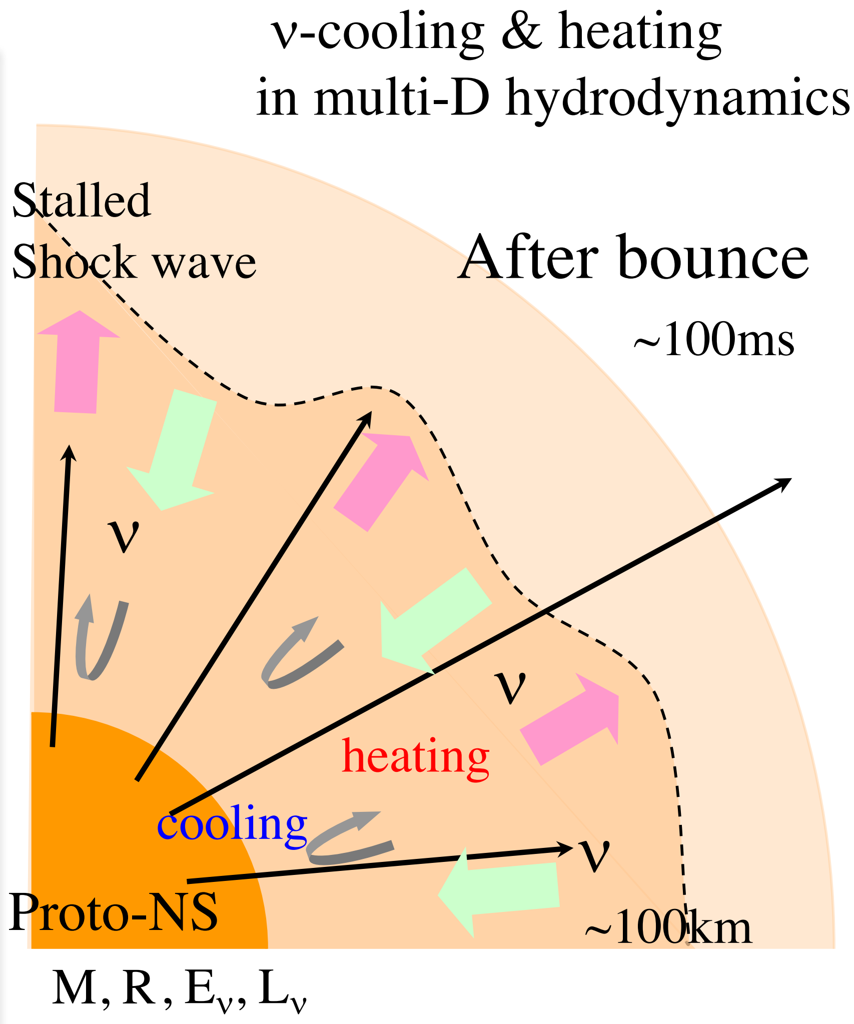


- Emission via deuteron affects
  - Increase of luminosity,
  - Modify cooling/heating
  - Shock radius in 1D/2D
- Reaction channels
- Neutrino-transfer

Stiffness & Composition of EOS in multi-D

Favorable for explosion

- **More ν-absorption**
  at heating region ~$10^{-5}\,\rho_0$
- **More ν-emission**
  at proto-NS surface ~$10^{-2}\,\rho_0$
  composition & ν-reactions
- **EOS soft** $> \rho_0$
  Compact, Inner ρ, T ↑
  ν-luminosity, energy ↑



IF opposite, maybe weaken explosions

Examine nuclear physics in multi-D simulations

Summary: Nuclear physics and neutrino transfer

for core-collapse supernovae and compact objects

- Applications of 6D Boltzmann eq. solver
  - Explosion mechanism of core-collapse supernovae
    - Neutrino-radiation hydrodynamics in 2D
  - Neutrino transfer in compact objects
    - Validation of approximate methods
- Tables of equation of state with mixture of nuclei
  - Modification of electron capture rates
  - Neutrino absorption & emission for explosions
- Toward 1st principle calculations of 3D supernovae
    - General relativistic neutrino-radiation hydrodynamics
  - Exa-flops supercomputer by post-K project in Japan
  - Need reliable equation of state, neutrino reactions

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
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- EOS tables & neutrino rates
  - H. Shen, K. Oyamatsu, H. Toki
  - C. Ishizuka, A. Ohnishi
  - S. Furusawa
  - S. X. Nakamura, T. Sato

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