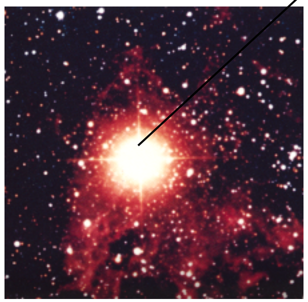
Roles of dense matter & neutrino transfer in core-collapse supernovae

ν

SN1987A



Mann "Shadow of a Star"

K. Sumiyoshi

Numazu College of Technology
Japan

Supercomputers

KEK SR16000

1. Effects of dense matter (EOS) on explosions
2. 3D neutrino transfer by 6D Boltzmann equation

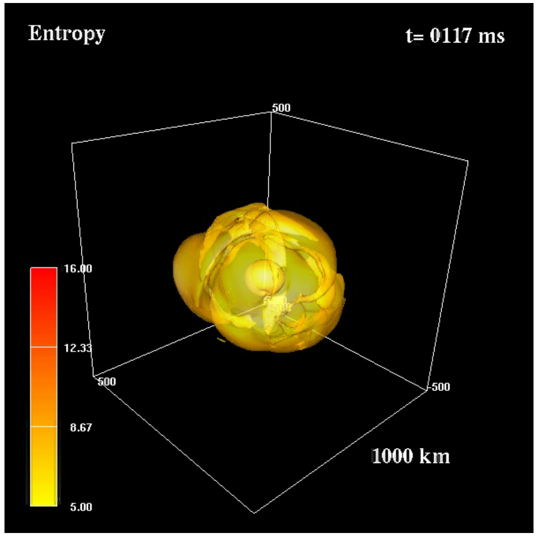
Originally Tomoya Takiwaki's Talk
Please invite him again
to talk Travel Problems

From nuclear physics to astrophysics

- Equation of state
- Neutrino reactions
- Nuclear data

- Hydrodynamics
- Neutrino transfer
- Stellar models

- Numerical simulations of core-collapse supernovae
  - Supercomputing technology toward exa-scale



- What is the main trigger of explosion?

- What is the role of nuclear physics?

Takiwaki's 3D simulation (11M_{sun})by K-computer

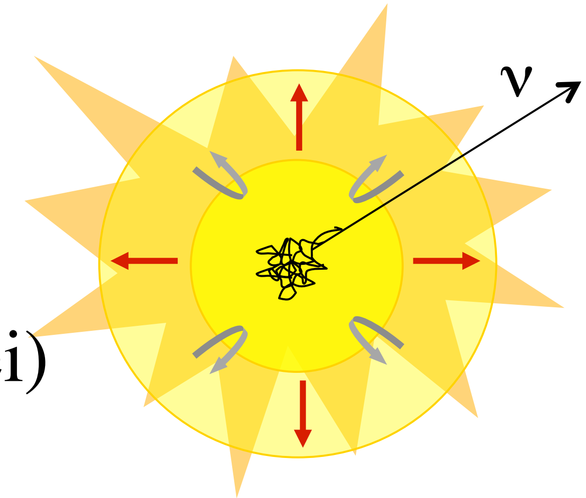
Effects of dense matter

Stiffness & Composition are important also in 2D/3D simulations

EOS is necessary inputs for numerical simulations

- Properties of dense matter determines:

1. Pressure-Density
   - Stellar structure, Dynamics
   - Neutron star mass, radius
2. Composition (proton, neutron, nuclei)
   - ν-reaction, ν-energy spectra



- Supernova EOS tables to cover wide range of (ρ, T, Y_e)

Benchmark 1990~

- *Extension of liquid-drop models (Skyrme-like):* **LS EOS**
- *Relativistic Mean Field approach:* **Shen EOS**

Recent 2000~

- *Mixture of nuclei: GShen, Hempel, Furusawa,…* **HS, SF**
- *RMF extensions: Sagert, Ishizuka, Nakazato, Steiner,…*
- *Nuclear many body: Togashi, Constantinou,…*

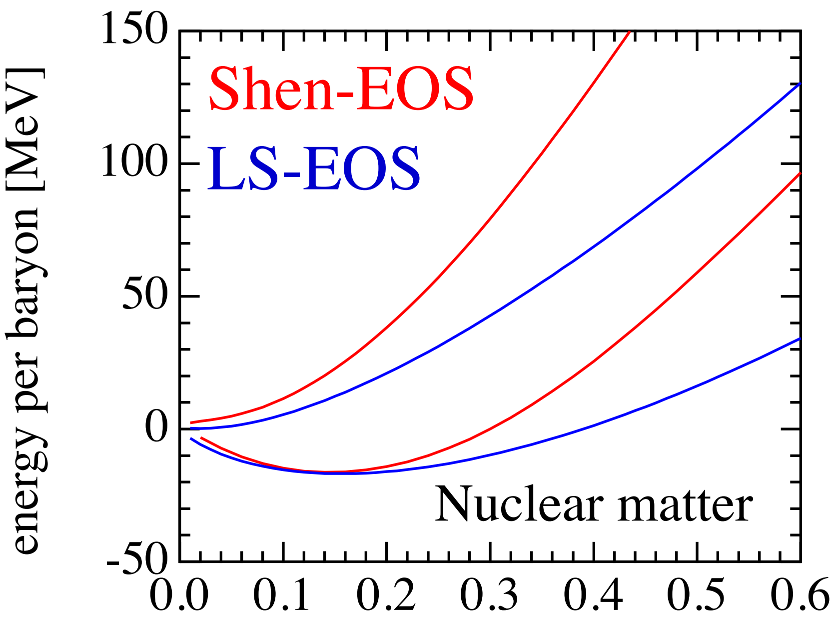
Comparison of EOS sets: benchmark

- Difference in stiffness & symmetry energy

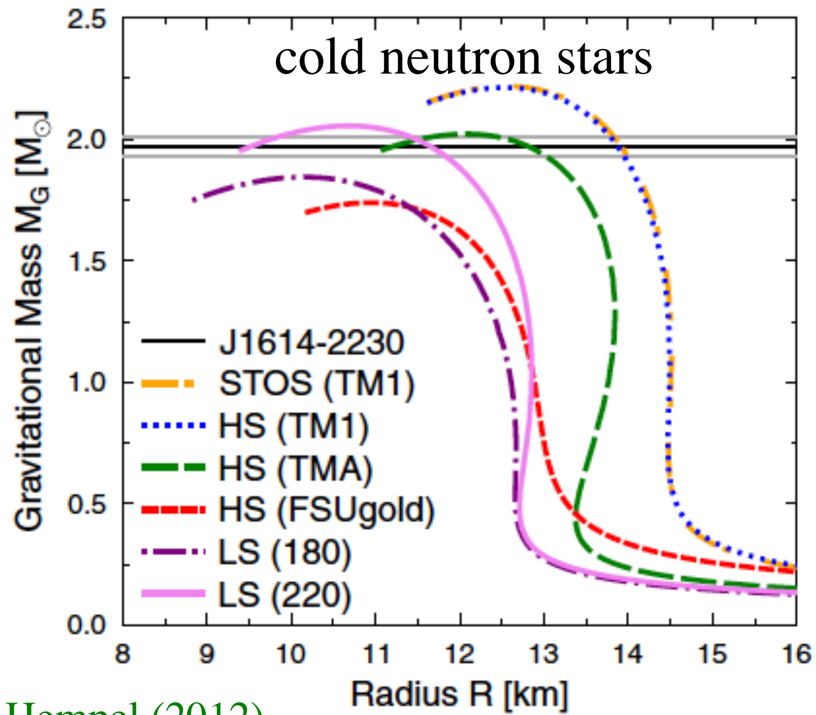
	LS-EOS	Shen-EOS
K [MeV]	180, 220, 375	281
A_{sym} [MeV]	29.3	36.9

- Two representatives
- Extremes in modern sense

180, 220: Frequently used for many simulations



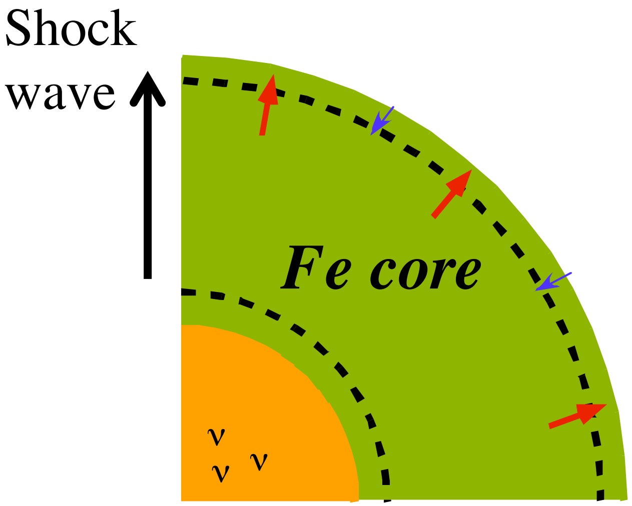
Sumiyoshi (2004) baryon density [fm^{-3}]



Hempel (2012)

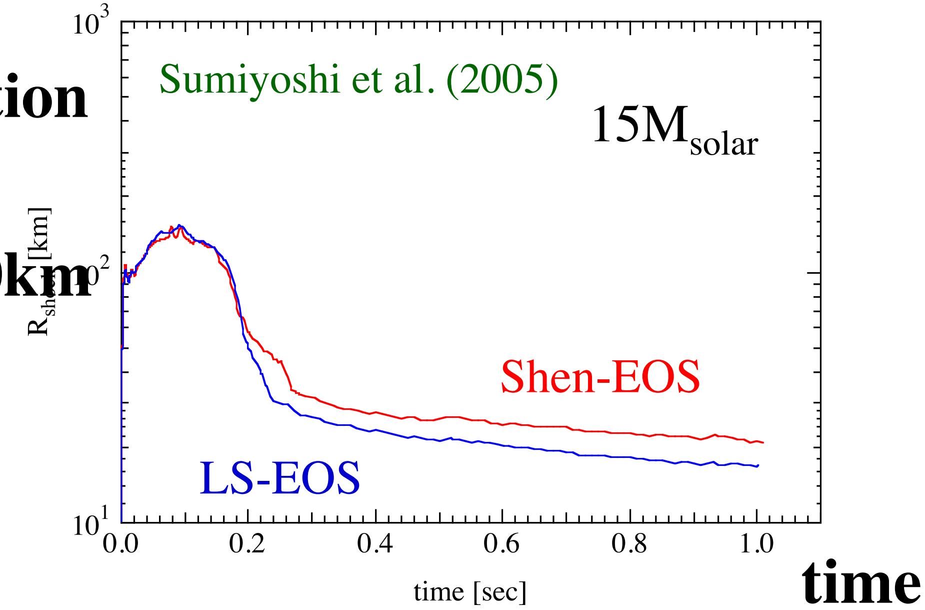
No explosion for all EOS in 1D spherical

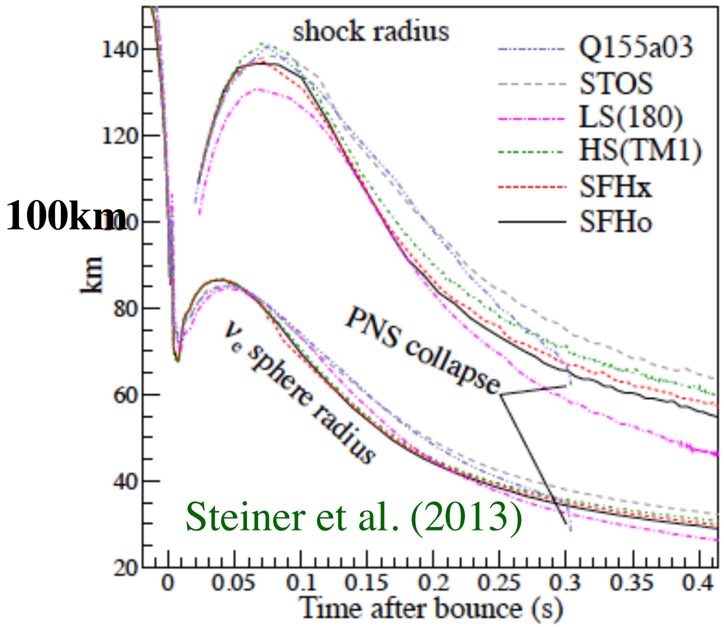
See also $8M_{sun}$ / quark cases



Bounce Core

Shock position





Shock wave stalls on the way

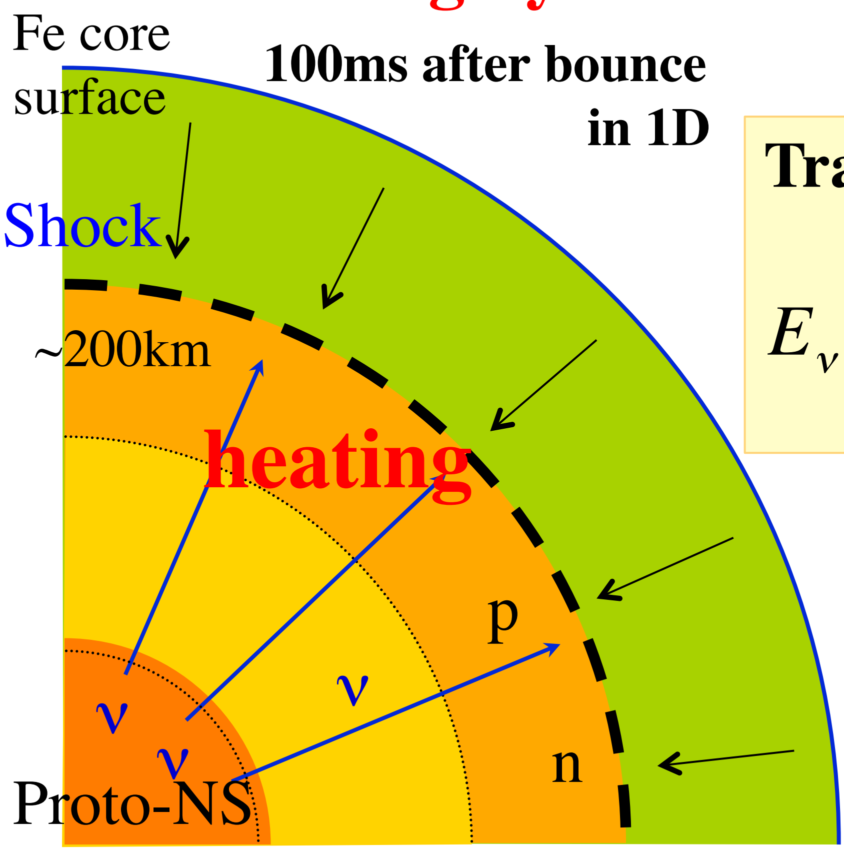
Energy loss due to Fe dissociation

$$E_{loss} \sim -1.6\times10^{51}\left(\frac{M_{outer}}{0.1M_{solar}}\right)erg$$

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

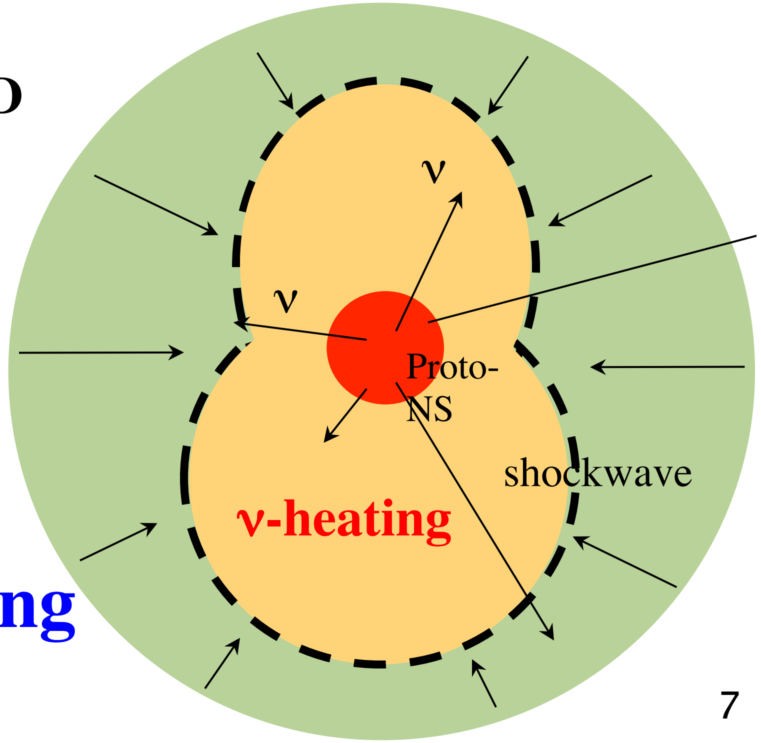
$$\nu_e + n \rightarrow e^- + p,$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



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

$$E_{\nu-heat} \sim 2.2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$

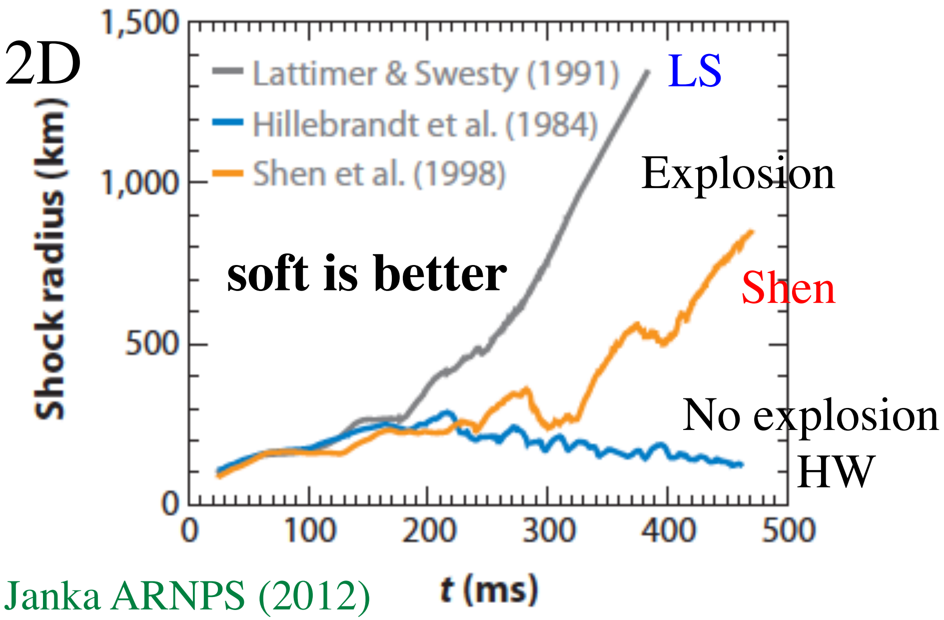
In 2D/3D



- **Depends on ν-energy/flux, targets**
- **Hydro instability to get more heating**

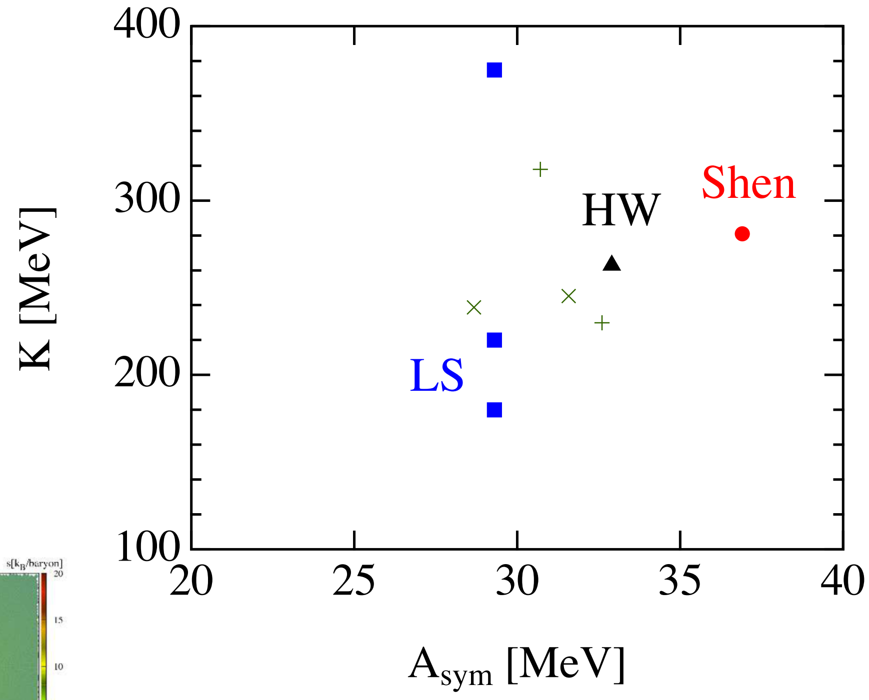
EOS effects in multi-D: larger than 1D?

2D

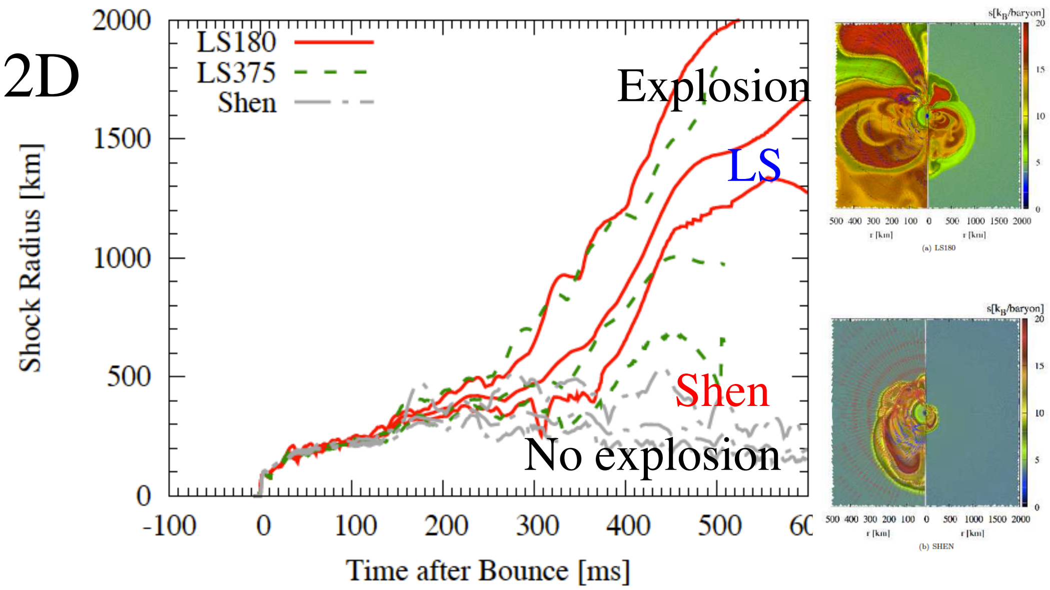


Janka ARNPS (2012)

Need more systematic studies



2D

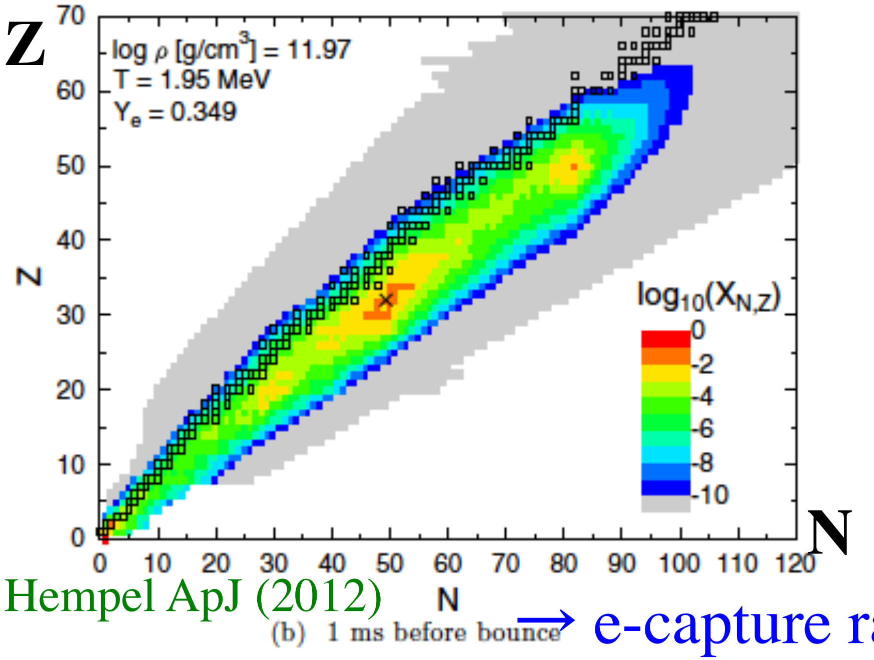


Suwa et al. ApJ (2013)

In 3D, LS 220MeV so far

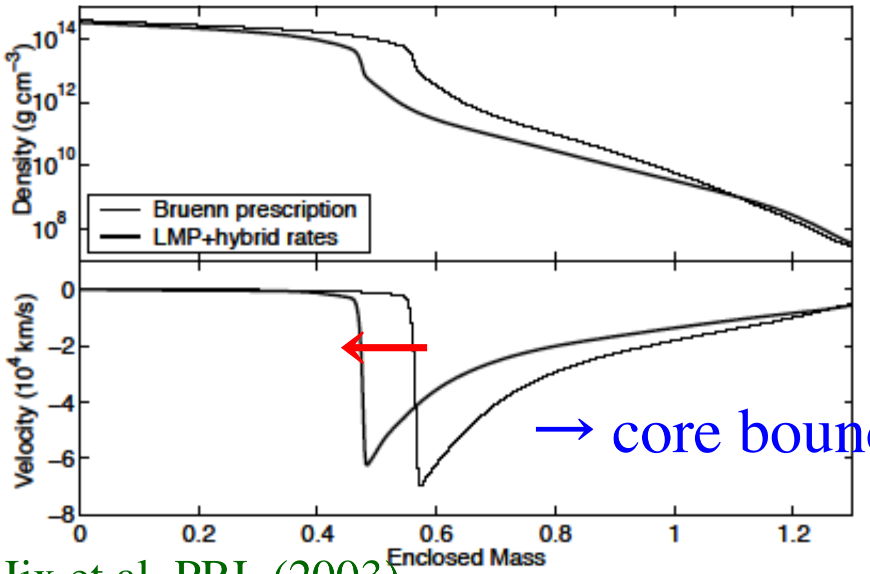
Takiwaki (2012), Hanke (2013), Bruenn (2014)

Composition of supernova matter: e-capture



Hempel ApJ (2012)

→ e-capture rates



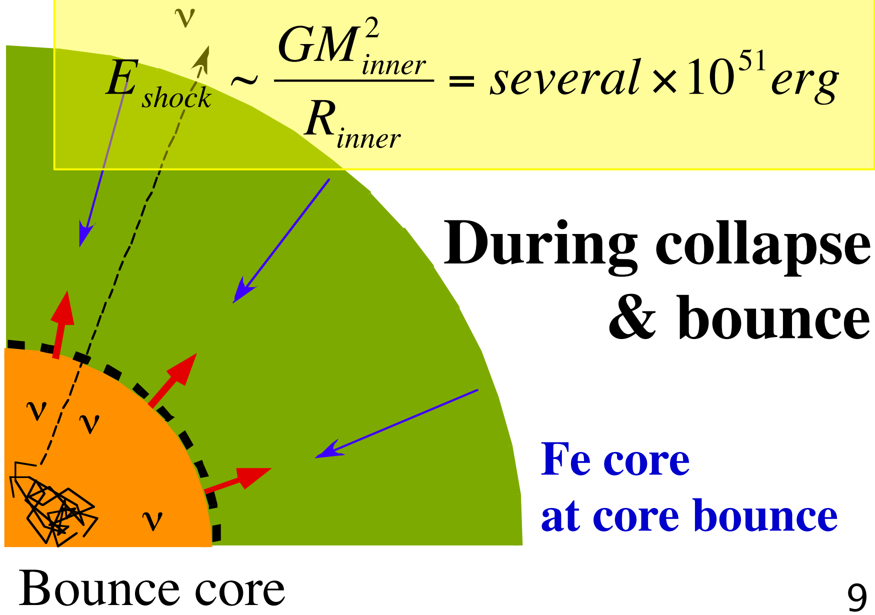
→ core bounce

Hix et al. PRL (2003)

- Composition of nuclei
  - 1-species & ^{4}He (Shen, LS)
  - → Mixture (Hempel, Furusawa)
- Electron capture on nuclei
  - – FFN, GSI rates

Initial shock energy

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



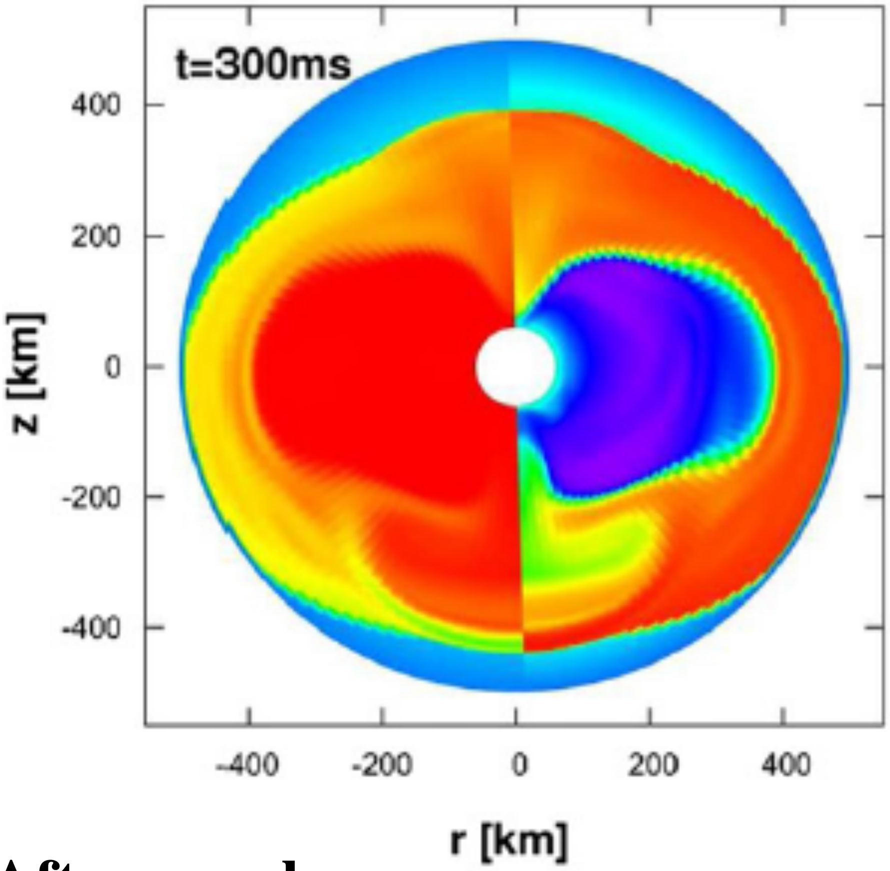
Composition of supernova matter: light nuclei

Schwenk, Sumiyoshi & Röpke, Arcones. Typel

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

Abundance

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

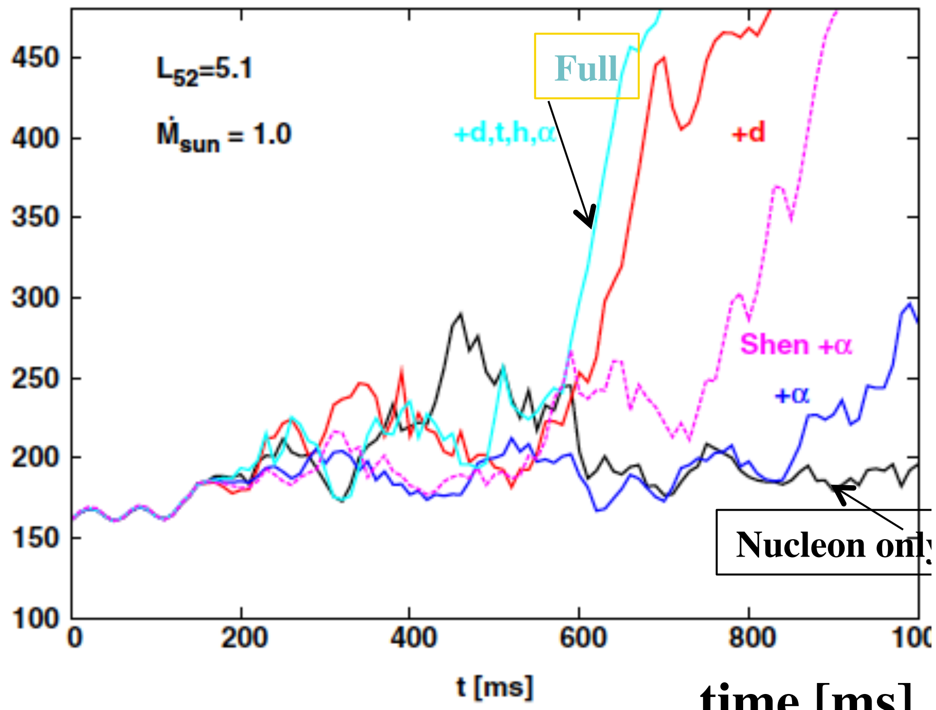


After core bounce

Furusawa et al. ApJ (2013)

- Neutrino - (d, ^{3}He, t)
  - absorption & emission

[km] **Shock radius**



time [ms]

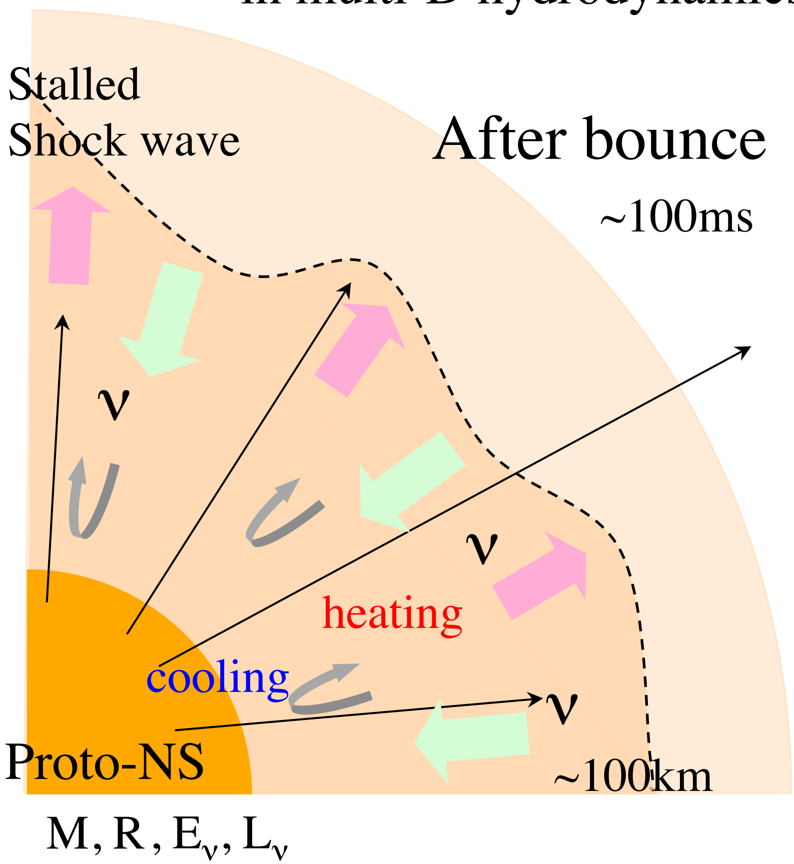
- Possible effects on shock revival when it is marginal

Stiffness & Composition of EOS in multi-D

Favorable for explosion

- **More ν-absorption, emis.**
  - at heating region ~10^{-5} ρ_0
  - at proto-NS surface ~10^{-2} ρ_0
  - Composition & ν-reactions
- **EOS soft** $> \rho_0$
  - Compact, Inner ρ, T ↑
  - ν-luminosity, energy ↑

ν-cooling & heating
in multi-D hydrodynamics



IF opposite, may weaken explosions

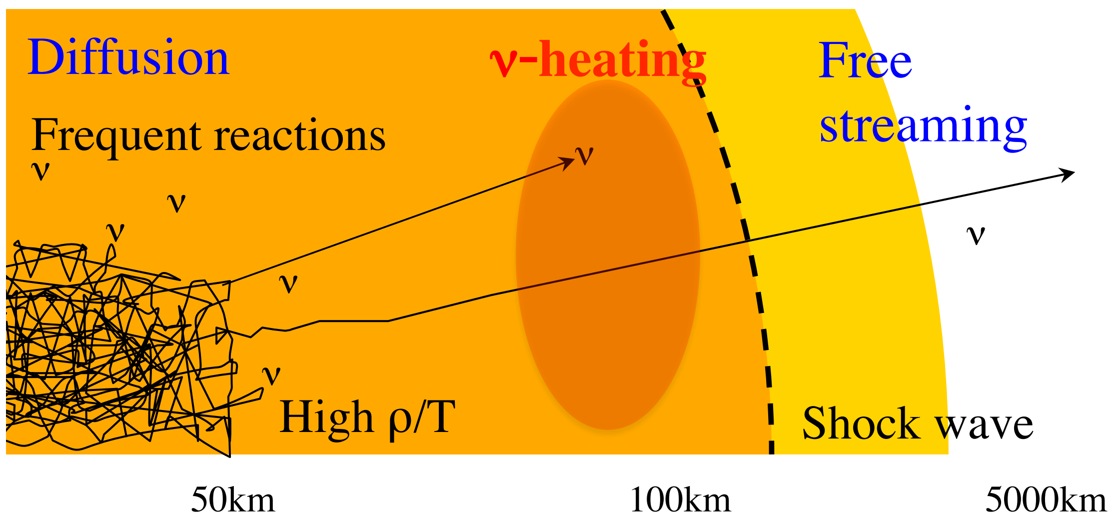
Examine nuclear physics in multi-D simulations

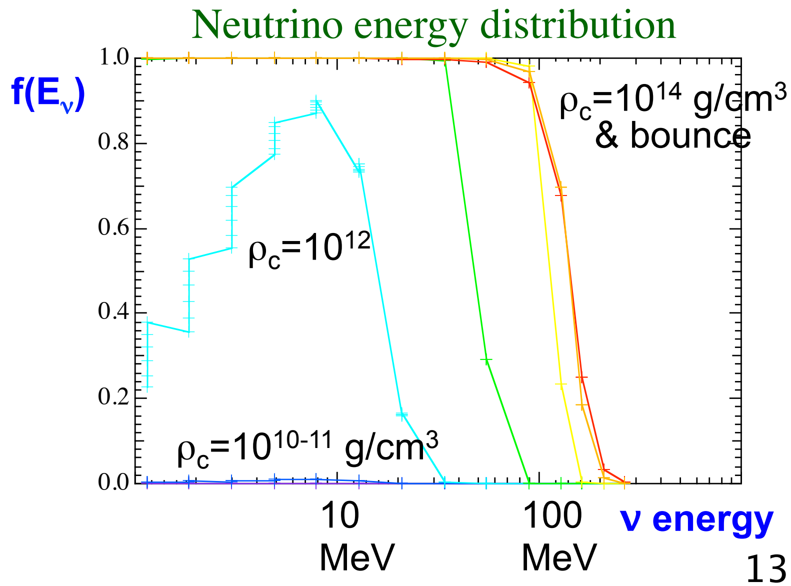
Challenge of neutrino transfer in 3D

6D Boltzmann equation works
to determine the neutrino heating

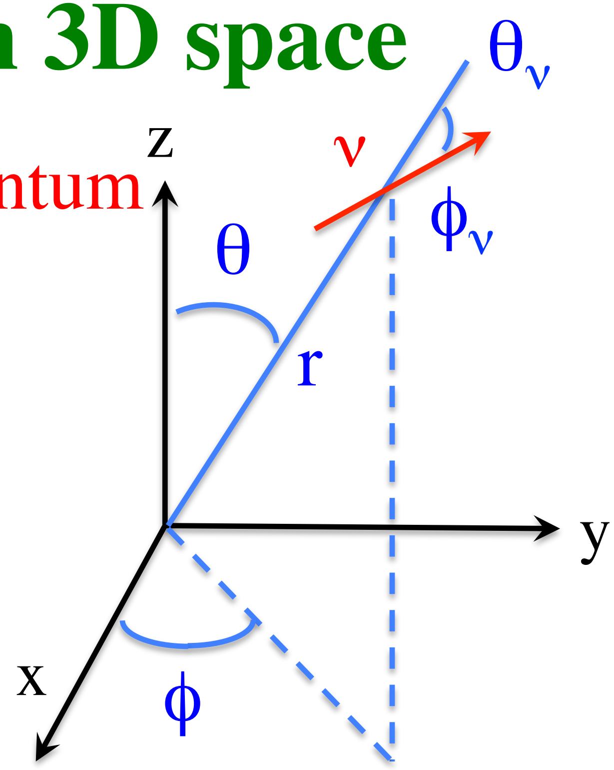
To describe neutrino reactions & transport

- **Neutrino transfer** +Hydrodynamics + Nuclear Physics
  - Amount of neutrino trapping
  - Neutrino flux/energy from proto-NS
  - Absorption by material: neutrino heating
- **From diffusion to free-streaming**
  - Intermediate region is important: **Boltzmann eq.**





To solve neutrino transfer in 3D space



- Work in 6D: 3D space + 3D ν-momentum

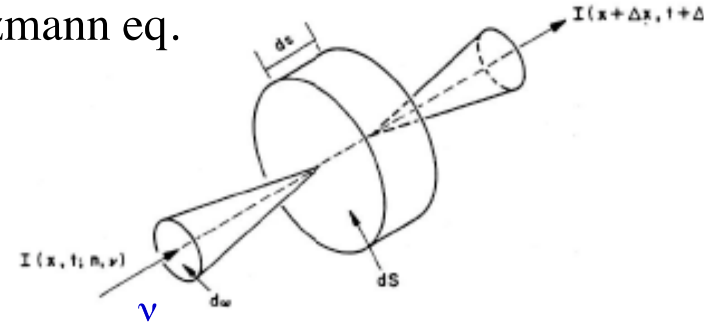
$$f_\nu(r,\theta,\phi;\ \varepsilon_\nu,\theta_\nu,\phi_\nu;\ t)$$

  - Neutrino energy (ε_ν), angle (θ_ν, ϕ_ν)

- 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

- Energy, angle-dependent reactions
  - Compositions in dense matter (EOS table)

Progress of neutrino transfer

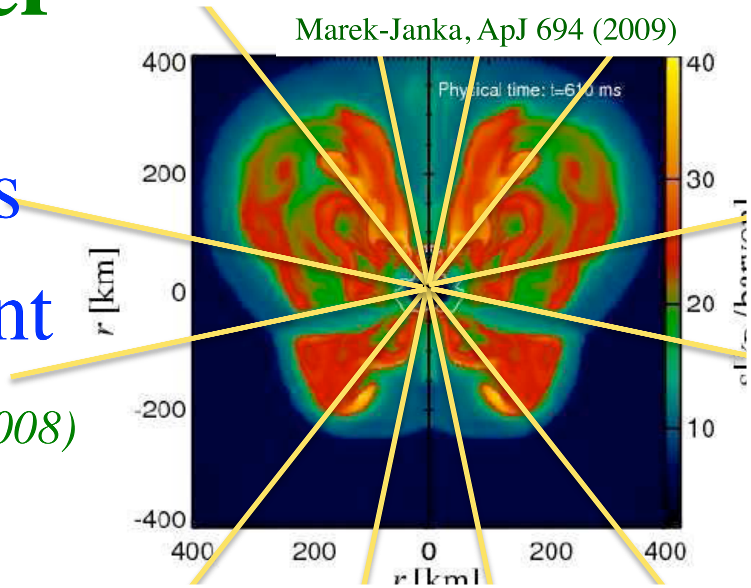
Mezzakappa-Bruenn, Liebendoerfer, Thompson-Burrows,…
Yamada-Sumiyoshi, Kotake-Takiwaki, Rampp-Marek-Janka,…

- 1D: first principle calculations
- 2D, 3D: approximate treatment
  - Diffusion, IDSA *S_n-method in 2D: Ott (2008)*
  - Ray-by-ray: radial-transport

    Dropping lateral transport

Ray-by-ray method

Marek-Janka, ApJ 694 (2009)



1D-transport independently

- New code to solve 3D neutrino-transfer

6D Boltzmann equation *Sumiyoshi & Yamada, ApJS (2012)*

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t}+\frac{\mu_\nu}{r^2}\frac{\partial}{\partial r}(r^2 f_\nu)+\frac{\sqrt{1-\mu_\nu^2}\cos\phi_\nu}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta f_\nu)+\frac{\sqrt{1-\mu_\nu^2}\sin\phi_\nu}{r\sin\theta}\frac{\partial f_\nu}{\partial\phi}$$

$$+\frac{1}{r}\frac{\partial}{\partial\mu_\nu}[(1-\mu_\nu^2)f_\nu]+\frac{\sqrt{1-\mu_\nu^2}\cos\theta}{r\sin\theta}\frac{\partial}{\partial\phi_\nu}(\sin\phi_\nu f_\nu)=\frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

Neutrino reactions in collision term

Basic sets for supernova simulations

Bruenn (1985) +Shen

- Emission & absorption:
  - $e^- + p \leftrightarrow \nu_e + n$
  - $e^- + A \leftrightarrow \nu_e + A'$
  - $e^+ + n \leftrightarrow \bar{\nu}_e + p$
- Scattering:
  - $\nu_i + N \leftrightarrow \nu_i + N$
  - $\nu_i + A \leftrightarrow \nu_i + A$
- Pair-process:
  - $e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$
  - $N + N \leftrightarrow N + N + \nu_i + \bar{\nu}_i$

3 species: $\nu_e, \bar{\nu}_e, \nu_\mu$

+ EOS table

```
cccccccccccccccccccccccccccccccccccccccccc
 Temperature=  1.000000E-01

5.100000E+00  7.581421E-11 -2.000000E+00  1.000000E-02 -1.524779E+00
5.200000E+00  9.544443E-11 -2.000000E+00  1.000000E-02 -1.502472E+00
5.300000E+00  1.201574E-10 -2.000000E+00  1.000000E-02 -1.480166E+00
5.400000E+00  1.512692E-10 -2.000000E+00  1.000000E-02 -1.457861E+00
5.500000E+00  1.904367E-10 -2.000000E+00  1.000000E-02 -1.435557E+00
5.600000E+00  2.397456E-10 -2.000000E+00  1.000000E-02 -1.413255E+00
5.700000E+00  3.018218E-10 -2.000000E+00  1.000000E-02 -1.390953E+00
5.800000E+00  3.799711E-10 -2.000000E+00  1.000000E-02 -1.368653E+00
5.900000E+00  4.783553E-10 -2.000000E+00  1.000000E-02 -1.346354E+00
6.000000E+00  6.022137E-10 -2.000000E+00  1.000000E-02 -1.324056E+00
6.100000E+00  7.581421E-10 -2.000000E+00  1.000000E-02 -1.301759E+00
6.200000E+00  9.544443E-10 -2.000000E+00  1.000000E-02 -1.279464E+00
6.300000E+00  1.201574E-09 -2.000000E+00  1.000000E-02 -1.257169E+00
6.400000E+00  1.512692E-09 -2.000000E+00  1.000000E-02 -1.234876E+00
6.500000E+00  1.904367E-09 -2.000000E+00  1.000000E-02 -1.212584E+00
6.600000E+00  2.397456E-09 -2.000000E+00  1.000000E-02 -1.190294E+00
```

composition
chemical
potential…

$$\frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision} = j_{emission}(1 - f_\nu) - \frac{1}{\lambda_{absoption}} f_\nu + C_{inelastic}\left[\int f_\nu(E'_\nu, \mu'_\nu) dE'_\nu\right] + \ldots$$

Multi-energy, angle

Main computational load: matrix solver

- Linear equation

$$A\vec{f}_\nu = \vec{d}$$

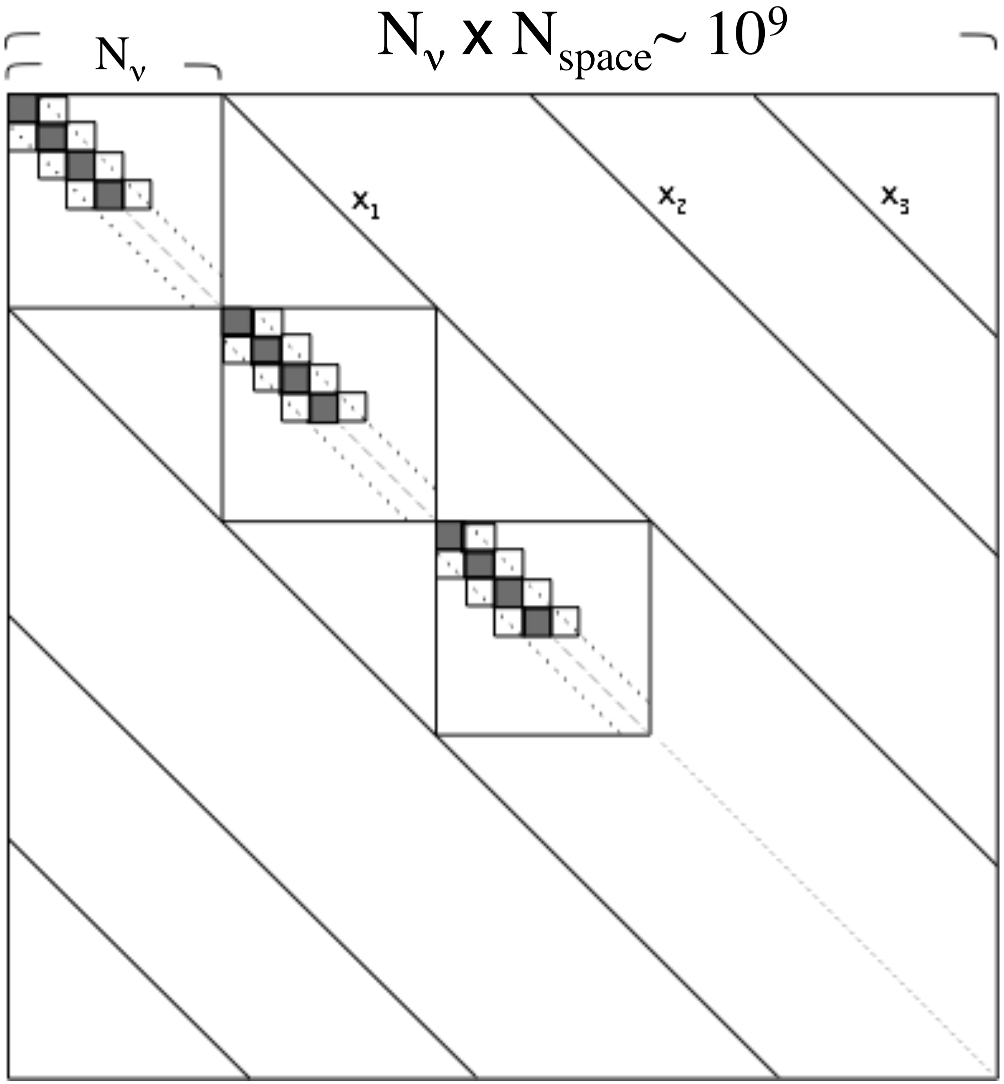
- Neutrino distribution
  - $N_{space}=n_r \times n_\theta \times n_\phi$
  - $N_\nu=n_\varepsilon \times n_{\theta\nu} \times n_{\phi\nu}$

  $N_{vector}\sim 10^6 \times 10^3$
- Memory size

  ν-distribution：>10GB

  matrix: >1TB
- Iterative method
  - Pre-conditioner

Imakura et al. JSIAM (2012)



Kotake et al. PTEP (2012)

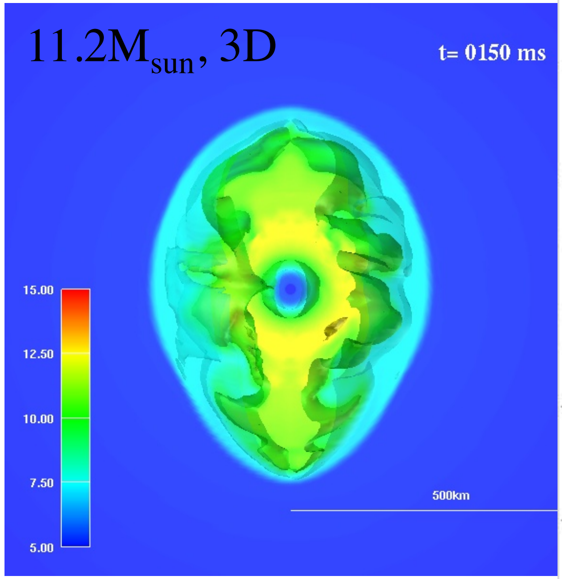
Example: 3D supernova core (11M_{sun}) at 150ms

Fix the background profile, evolution by 6D Boltzmann eq.

→ obtain stationary state of the neutrino distributions in 6D

Sumiyoshi et al. arXiv:1403.4476

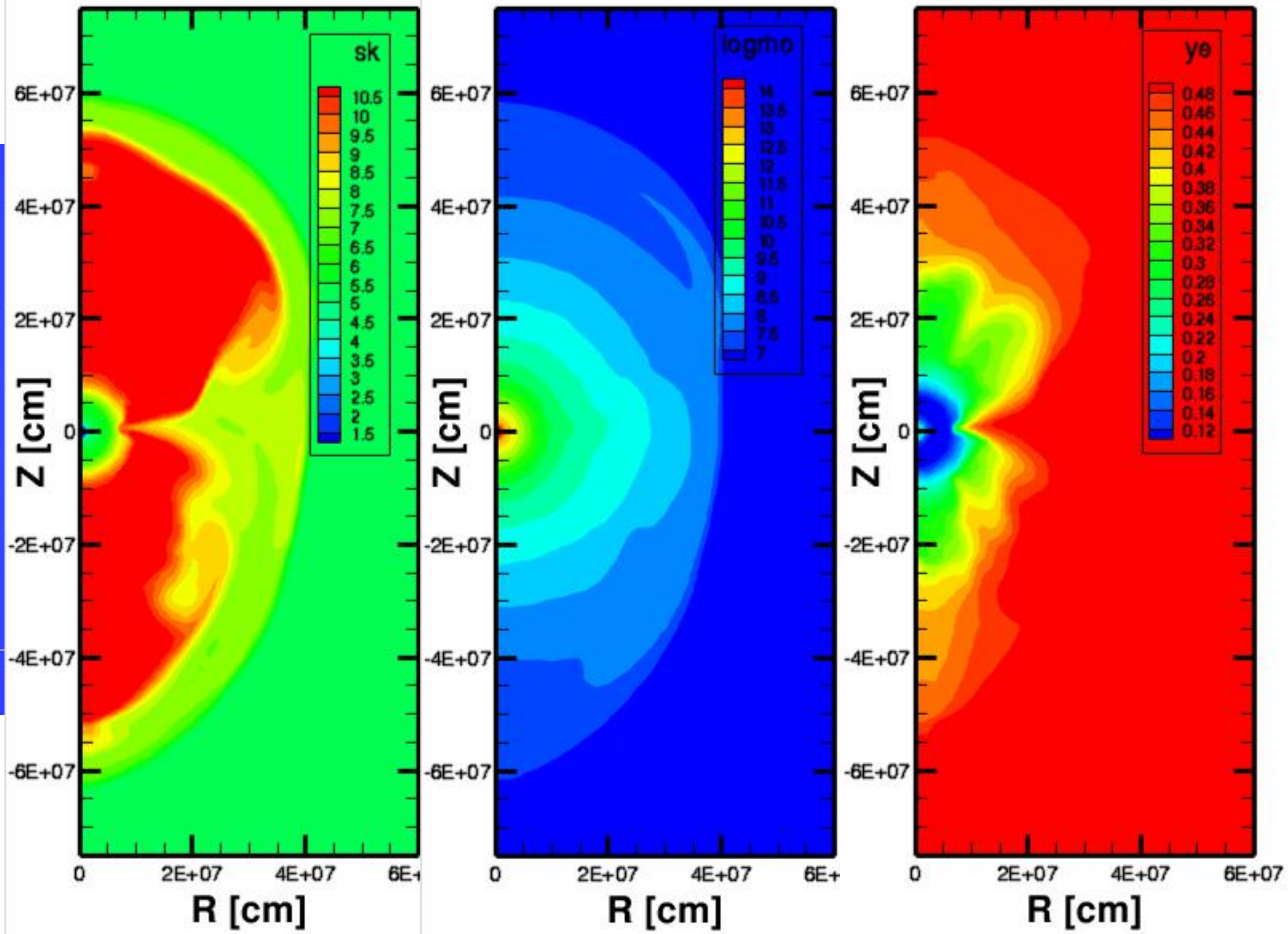
entropy



150 msec after bounce

R_{shock}~250-400km

entropy density Y_e

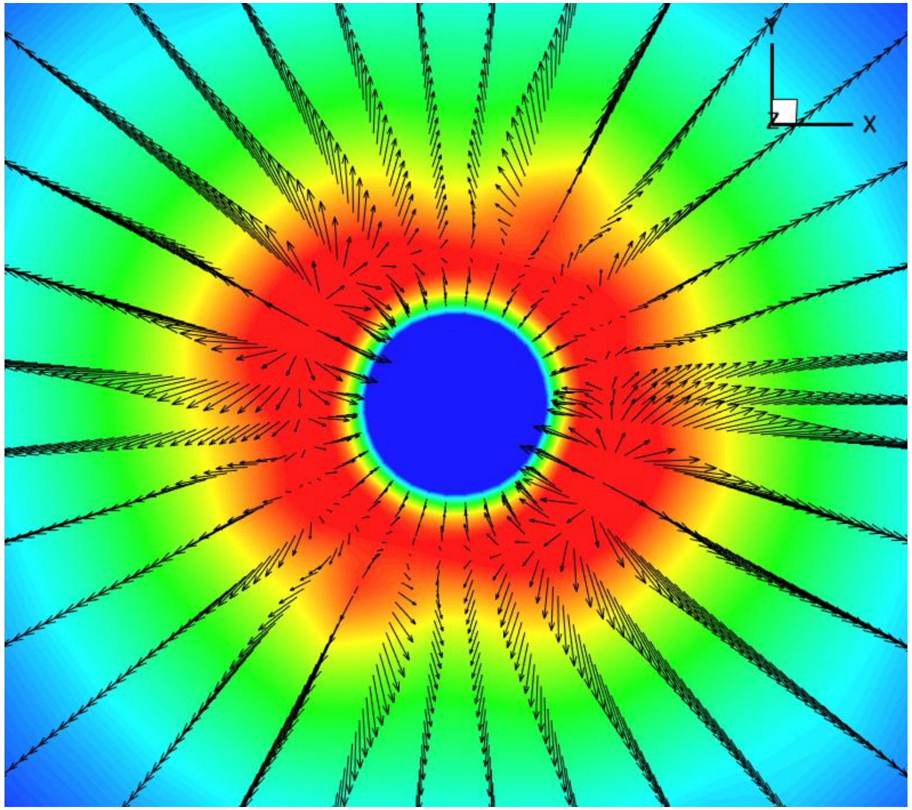


From Takiwaki et al. ApJ (2012)

6D Bolzmann in 3D SN core

Describes non-radial transport

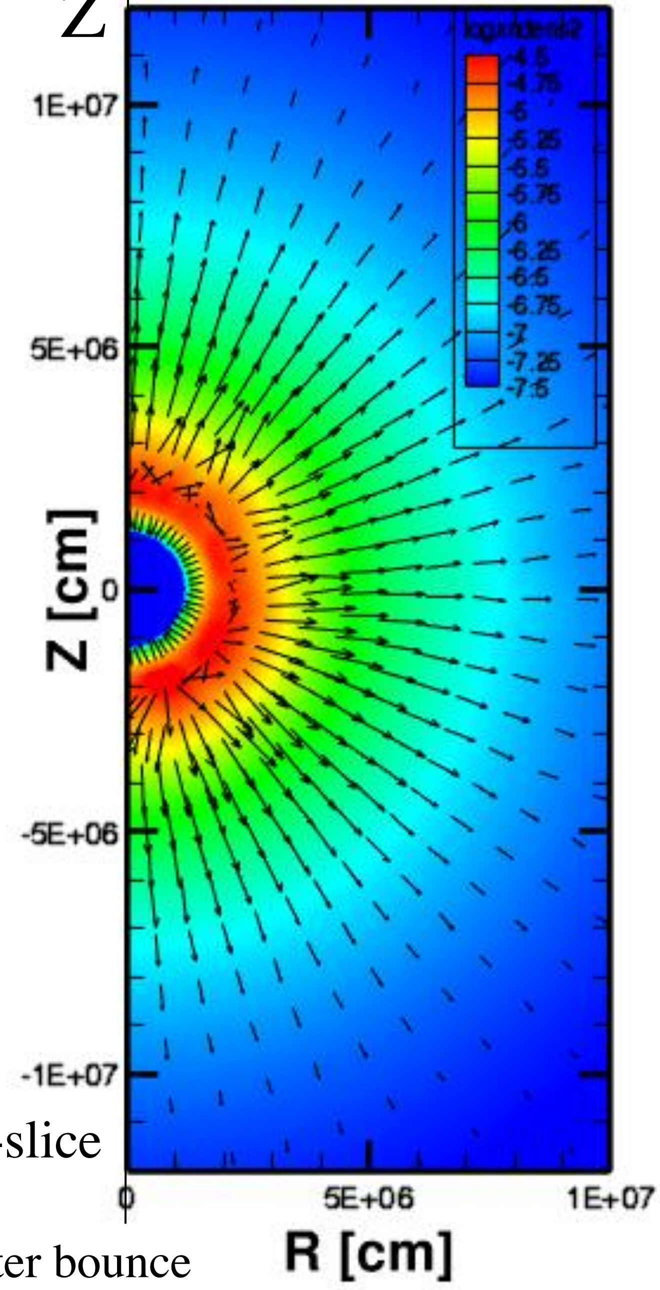
Flux: ϕ-direction



$\bar{\nu}_e$ density: color (flux: arrow)

View from north-pole

Flux: θ-direction



View from side: ϕ-slice

Sumiyoshi et al. (2013,2014) 3D Supernova core 150msec after bounce

Comparison with approximation

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

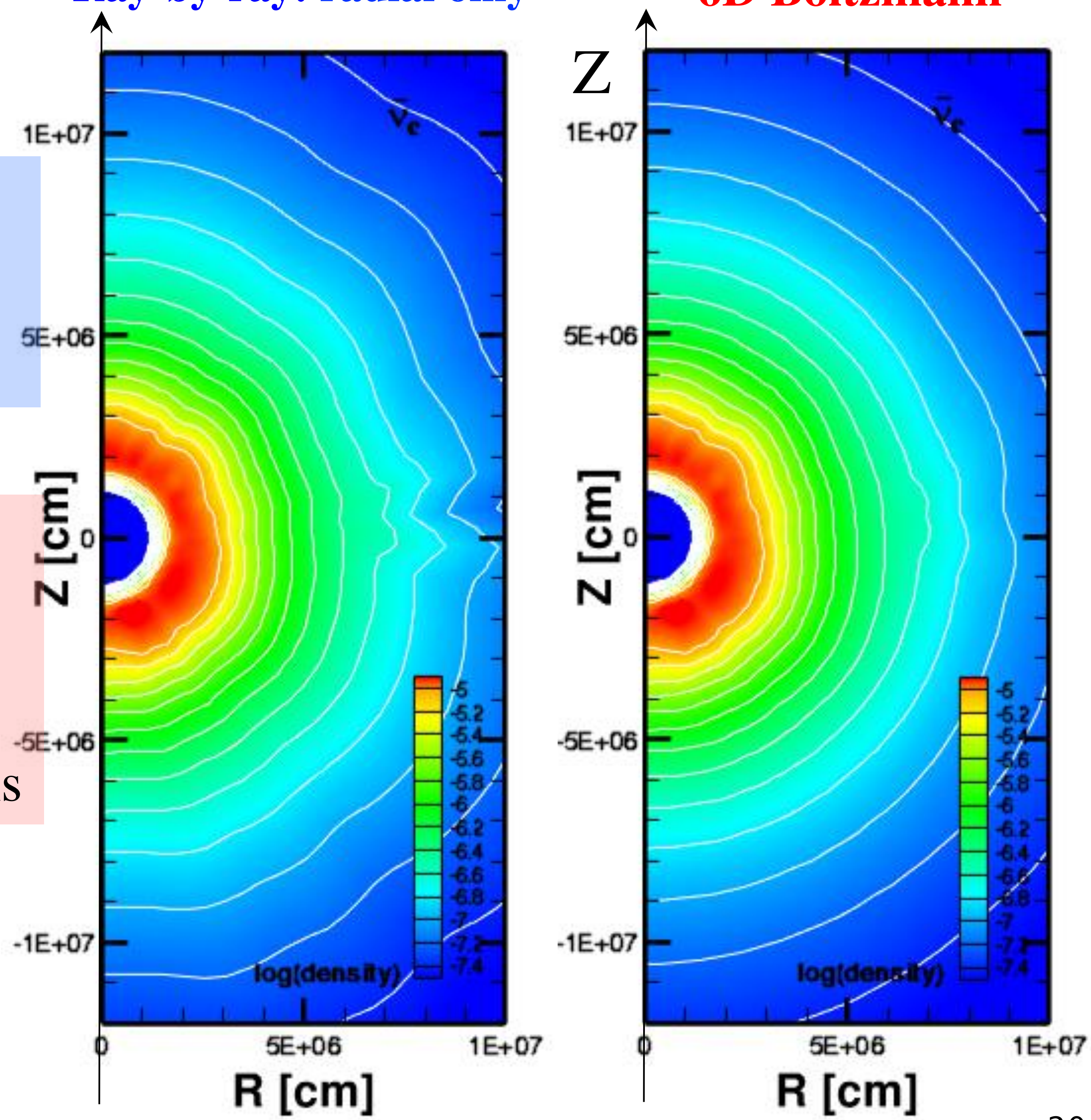
- **6D Boltzmann**
- Non-radial transfer
- Integrated values from various directions

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

View from side: ϕ-slice

Ray-by-ray: radial only

6D Boltzmann



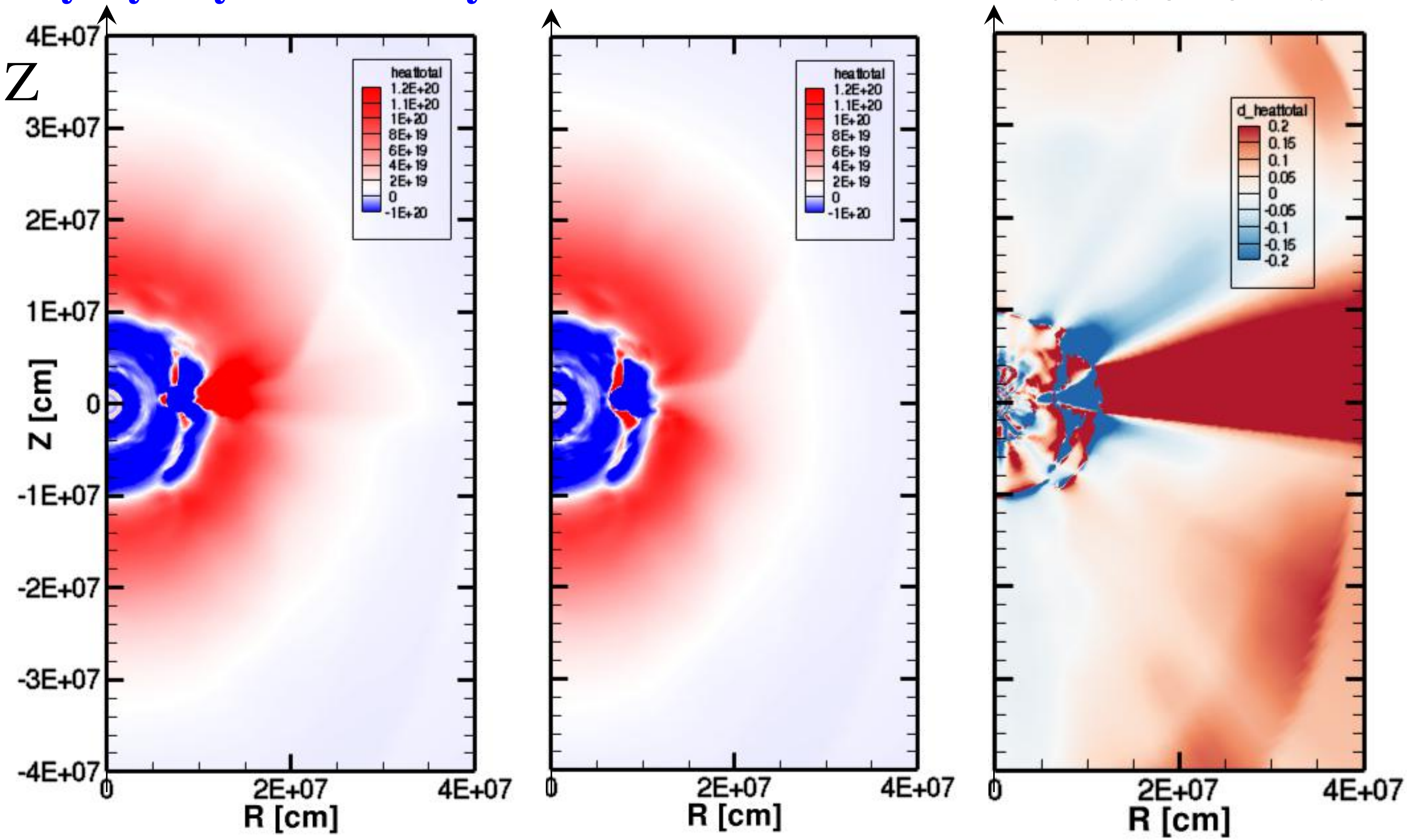
Sumiyoshi et al. (2013,2014)

150msec

Comparison: ν-heating rate

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

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

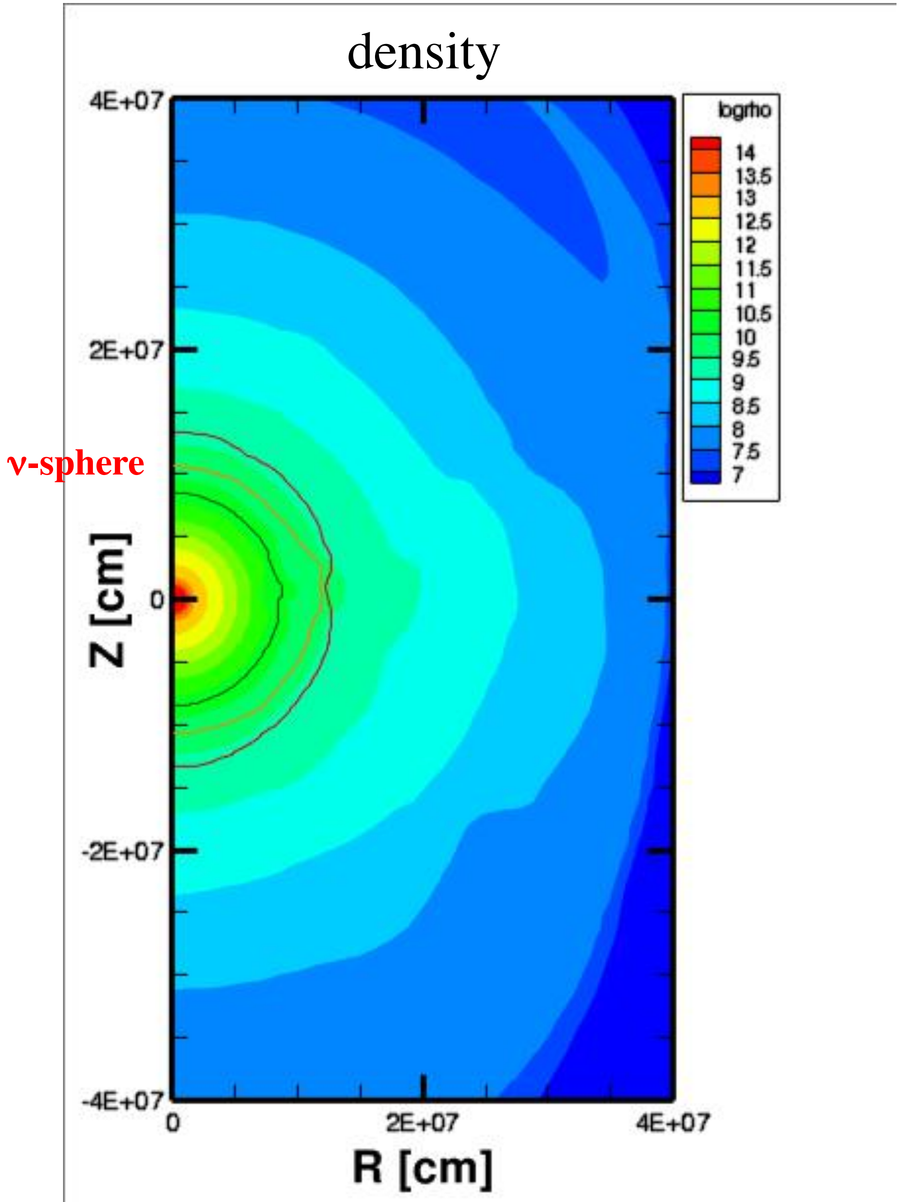


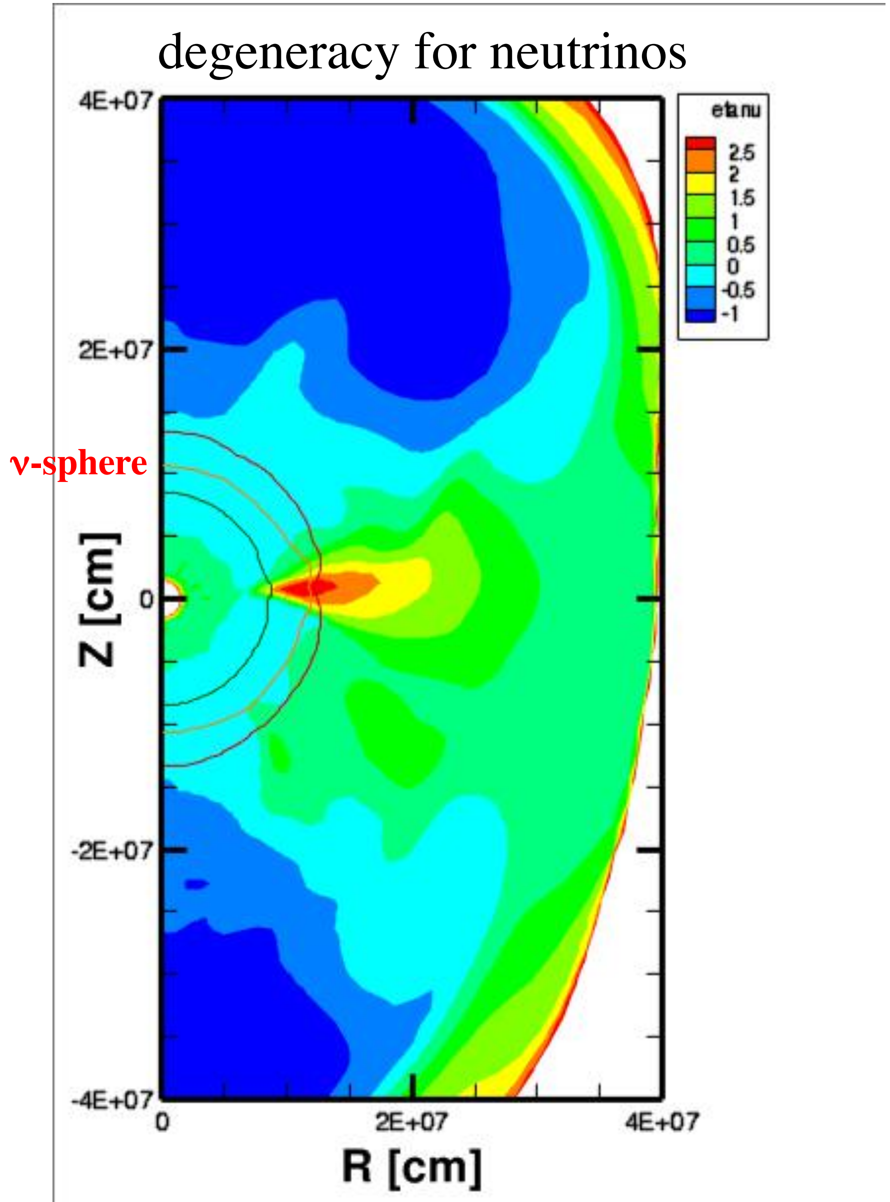
Sumiyoshi et al. (2013,2014)

Red: heating, Blue: cooling

$11M_{sun}$, 150msec

Local fluctuations of neutrino degeneracy: hotspot



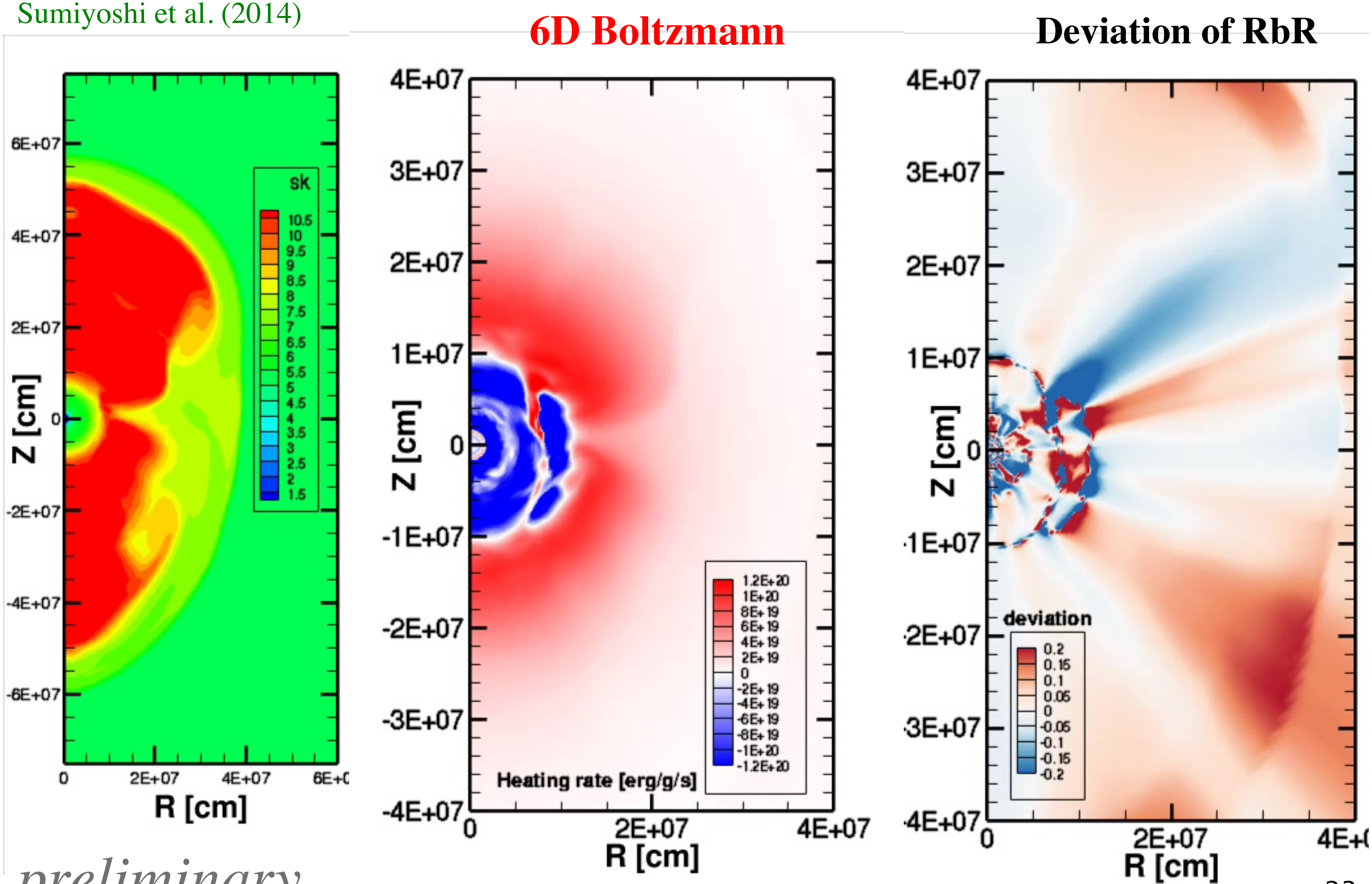


Sumiyoshi et al. (2013,2014)

$11M_{sun}$, 150msec

Time evolution: deviation lasts for 10ms: 145ms - 155ms

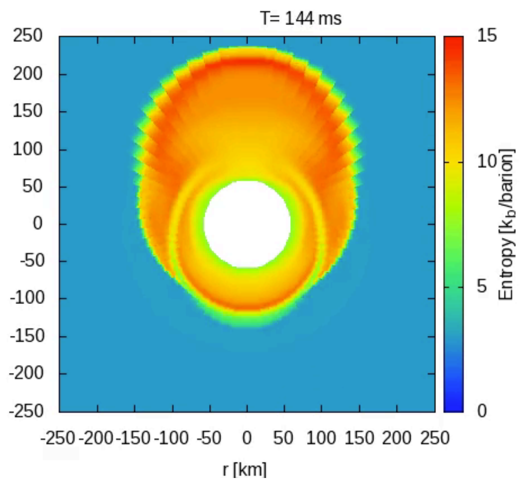
Sumiyoshi et al. (2014)



preliminary

Approximate to Exact: 3D neutrino transfer

- Solving 6D Boltzmann solver is possible
  - Non-radial transport in 3D Supernova core
- Characters of Ray-by-ray approximation
  - May enhance angle variations, ex. hot-spot
- Provide information for approximate methods

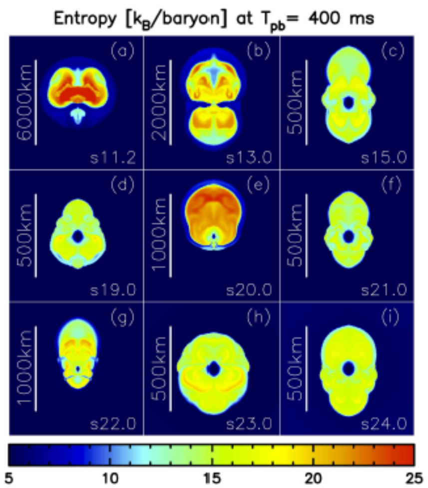


- Coupling with hydrodynamics
  - Special Relativistic code
    Nagakura ApJS (2014)
- Full 2D/3D simulations
  - From Peta To Exa-scales

Toward ascertaining explosion in 3D

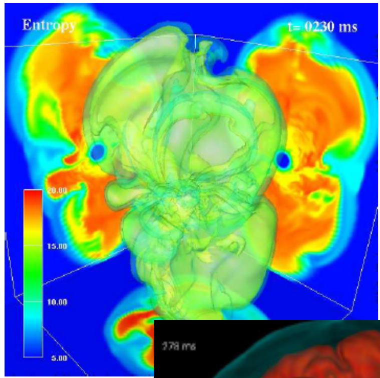
- Examine uncertainties in nuclear physics
- Removing approximations in ν-transfer

2D



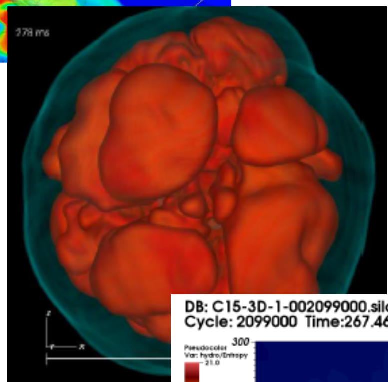
Nakamura (1406.2415)

3D



11M exp.

Takiwaki (2012)



27M No exp.

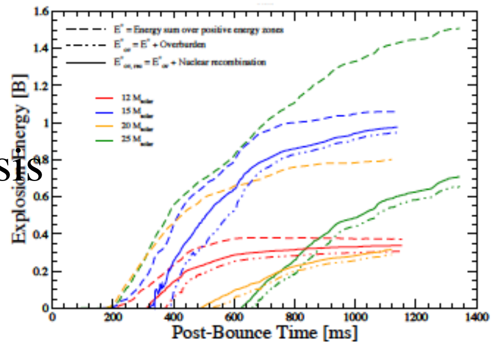
Hanke (2013)

- 6D Boltzmann
- Full GR

beyond Exa-scale

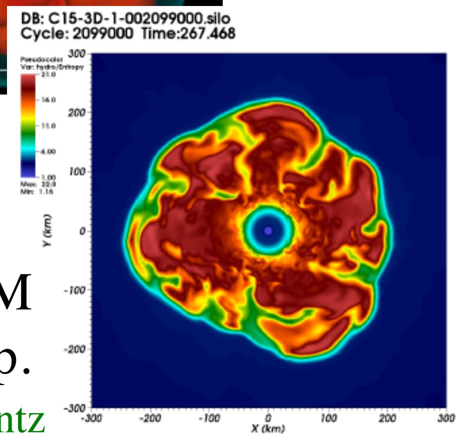
Need Nucl. Physics!

Explore in 2D
Progenitors
E_{exp}, M_{ns}
Nucleosynthesis



Mezzacappa (1405.7075)

15M Exp.



Lentz

Thanks for collaboration with

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  - Y. Sekiguchi
- Supercomputing
  - H. Matsufuru
  - A. Imakura
  - T. Sakurai
- EOS tables & neutrino rates
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