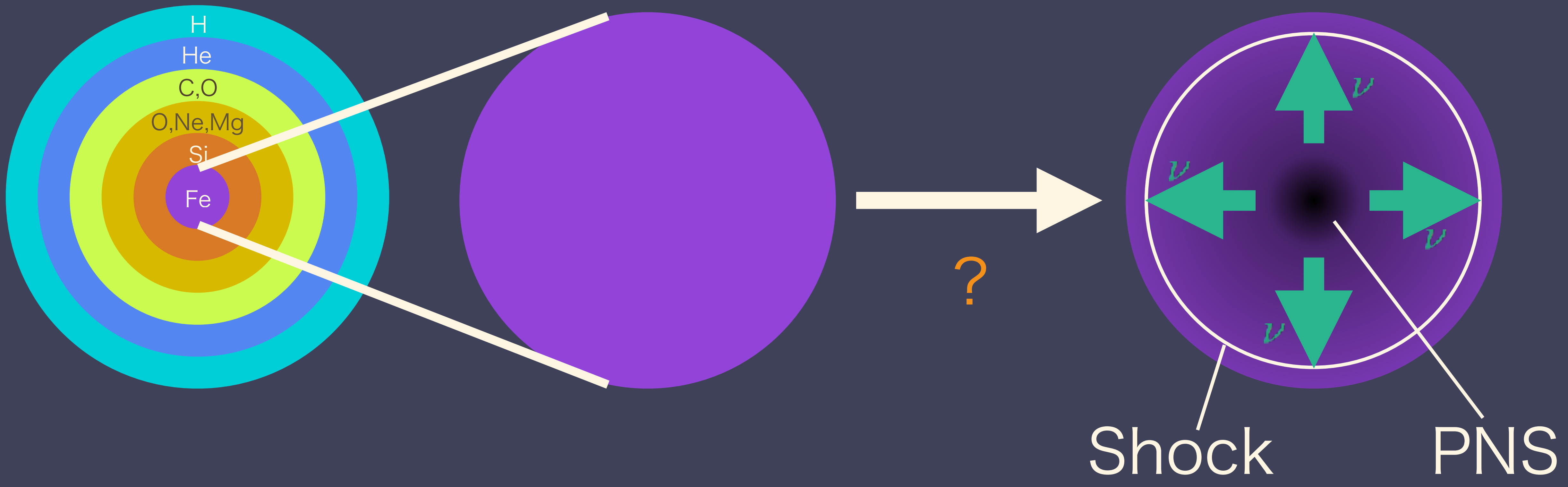
The Rotating Core-Collapse Supernova Dynamics and Neutrino Distributions by Full Boltzmann Neutrino Transport

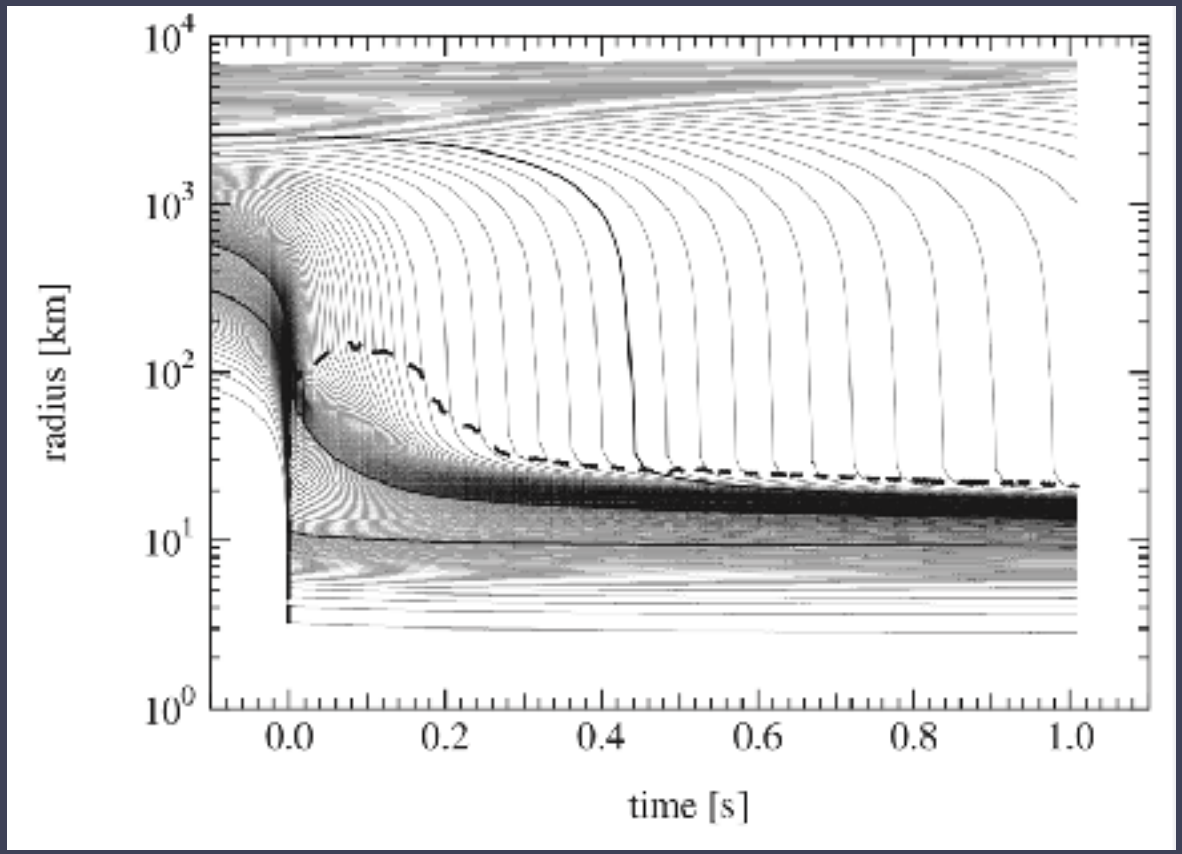
Akira Harada (University of Tokyo)
Collaborators: W. Iwakami, H. Okawa、S. Yamada (Waseda)
H. Nagakura (Princeton), K. Sumiyoshi (Numazu),
H. Matsuhuru (KEK)

Core-Collapse Supernovae

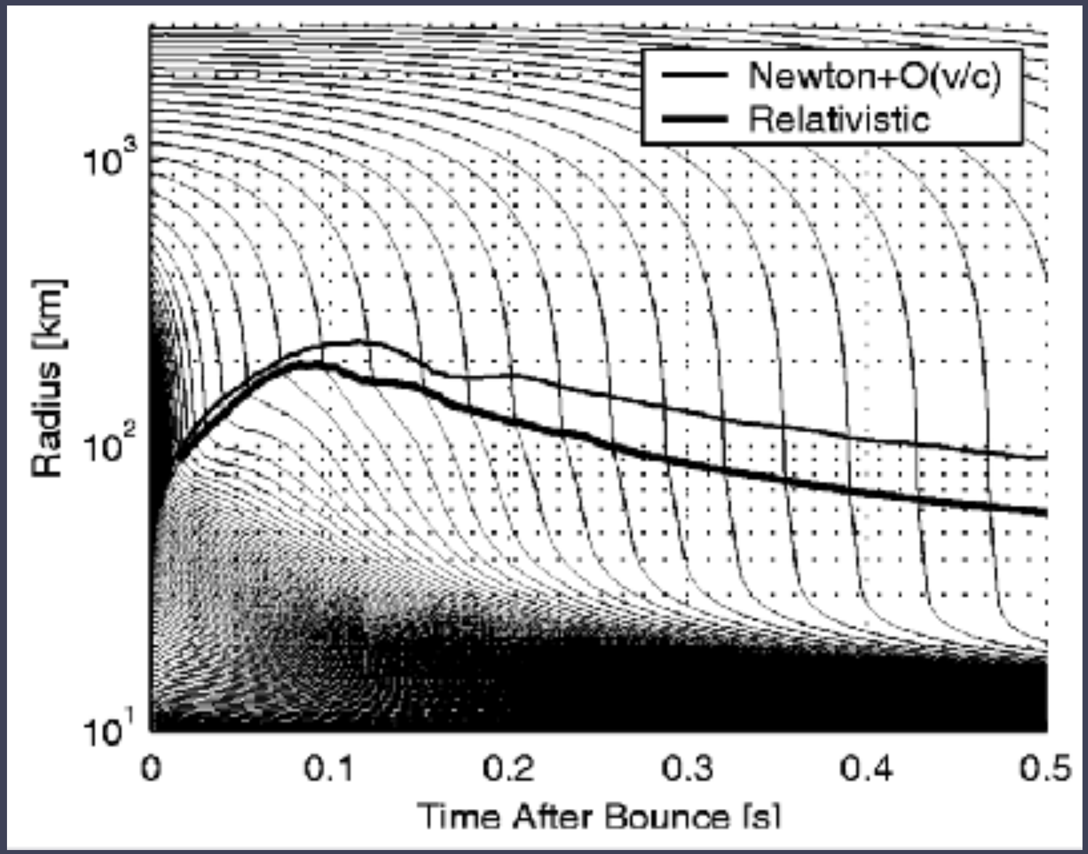


- Gravitational Collapse→Core Bounce
  →Stalled shock
- Neutrino Heating Mechanism？

Boltzmann Neutrino Transport



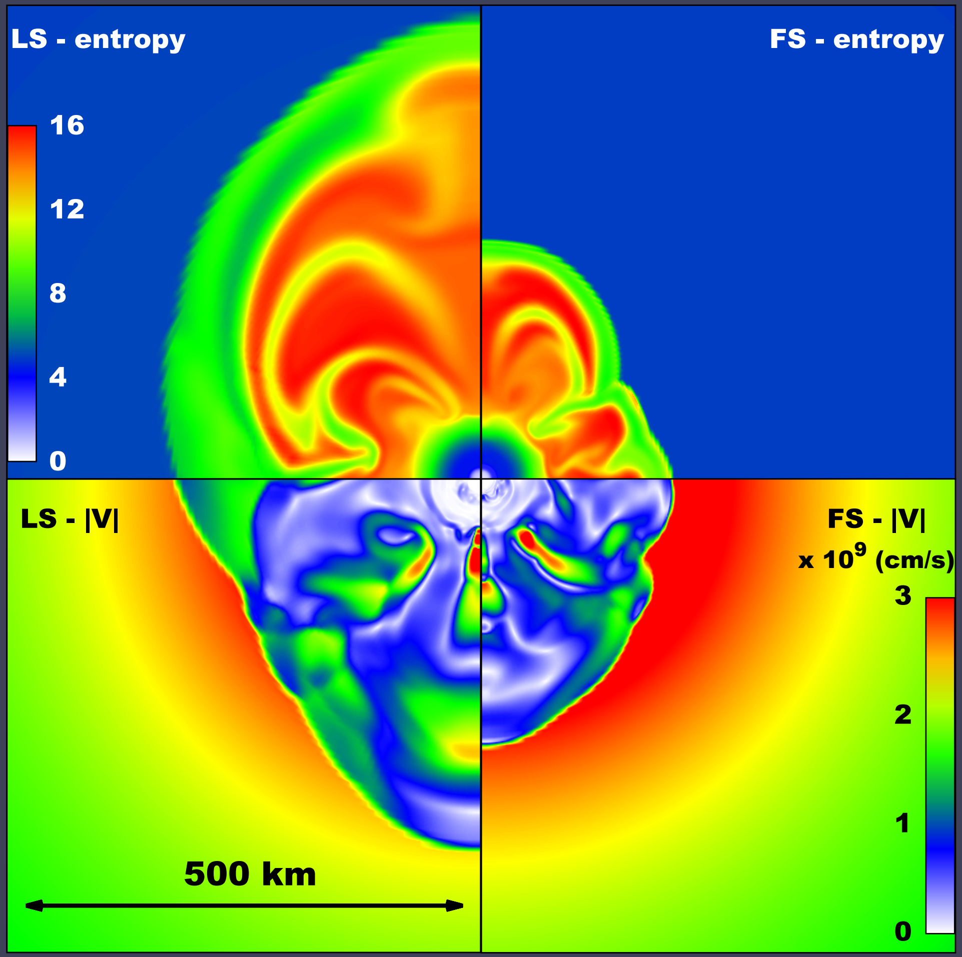
Sumiyoshi+ (2005)



Liebendoerfer+ (2001)

- Explosion failed in 1D ← confirmed by the Boltzmann transport
- The Boltzmann transport is also required for multi-D simulations.

Multi-D Boltzmann Simulation



Nagakura+ (2018)

- Results of multi-D Boltzmann simulations
- Collapse of the 11.2 M⊙ (Woosley+ 2002) progenitor
- Comparison of the equations of state is shown

Setup

- Progenitor: 11.2 $M_\odot$ (Woosley+ 2002)
- EOS: Furusawa EOS (multi-nuclear species、Relativistic Mean Field theory)
- ν-reactions: Standard set of Bruenn (1985)
  +GSI electron capture、Bremsstrahlung
- Rotational velocity: Sheller rotation

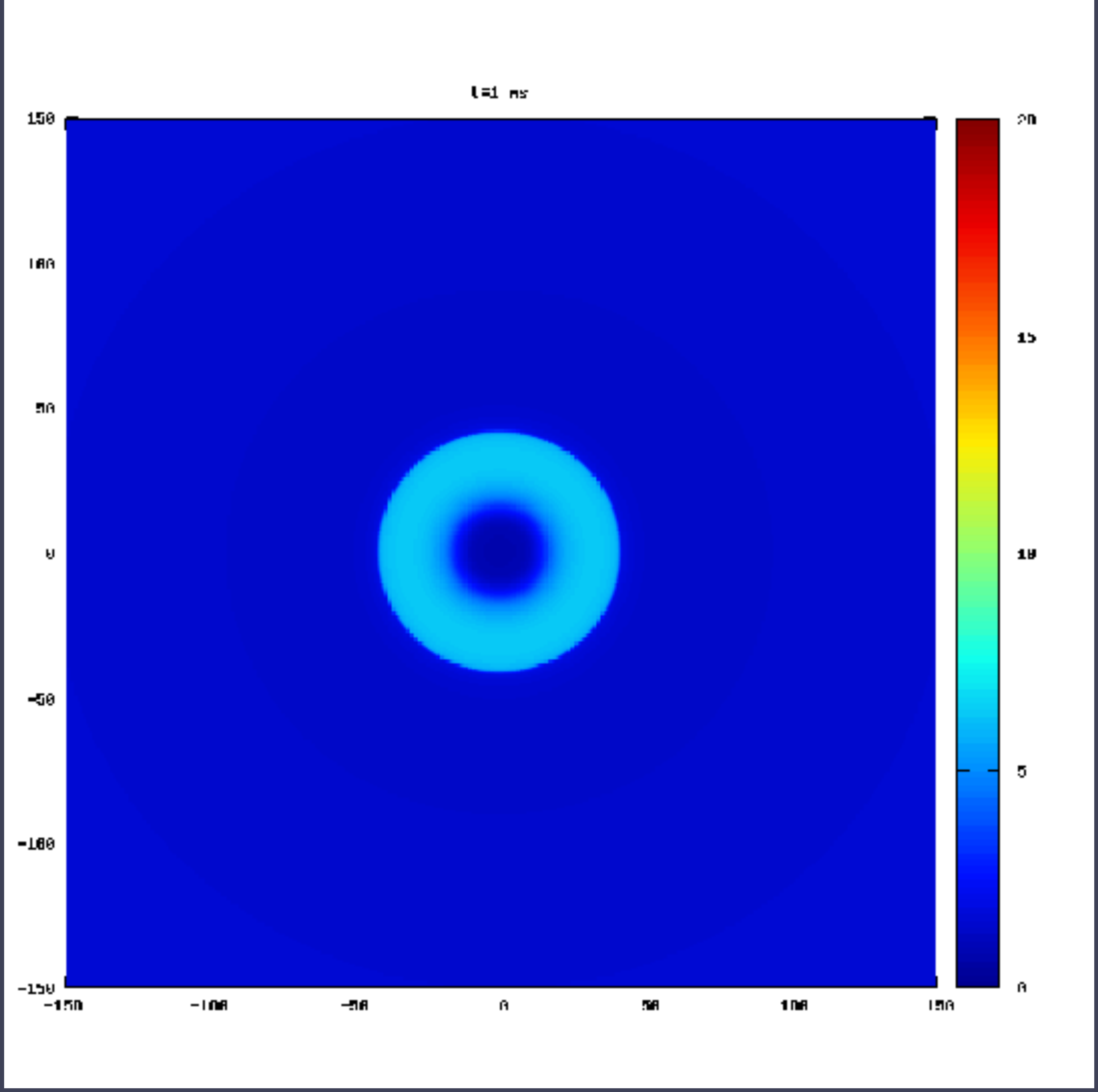
$$\Omega(r) = \frac{1\,\mathrm{rad/s}}{1 + (r/10^8\,\mathrm{cm})^2}$$

- Grid number:

$$(N_r, N_\theta, N_\phi, N_\nu, N_{\bar{\theta}}, N_{\bar{\phi}}) = (384, 64[128], 1, 20, 10, 6)$$

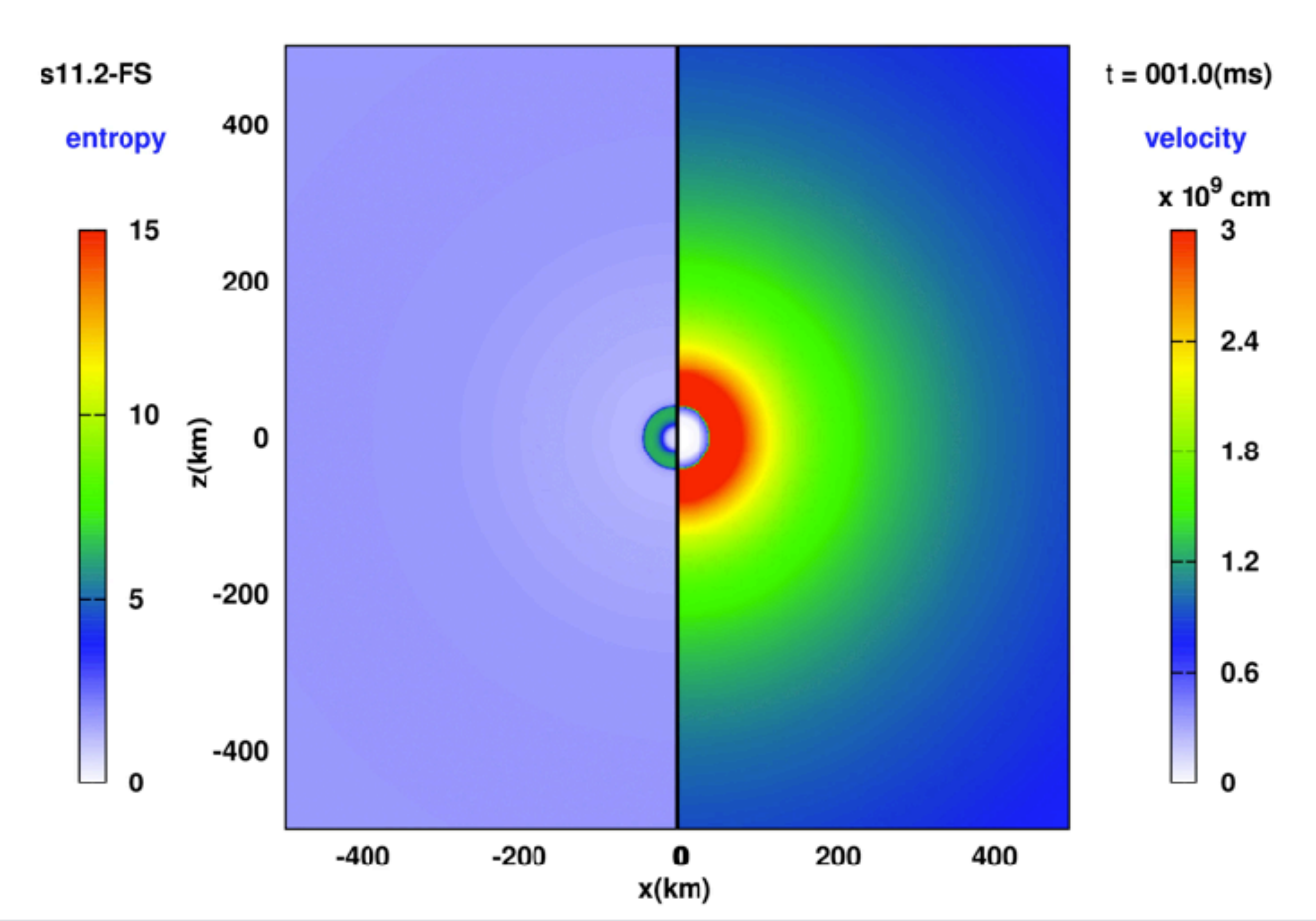
Entropy (rotating)

- Evolution until ~ 200 ms after bounce



Entropy (non-rotating)

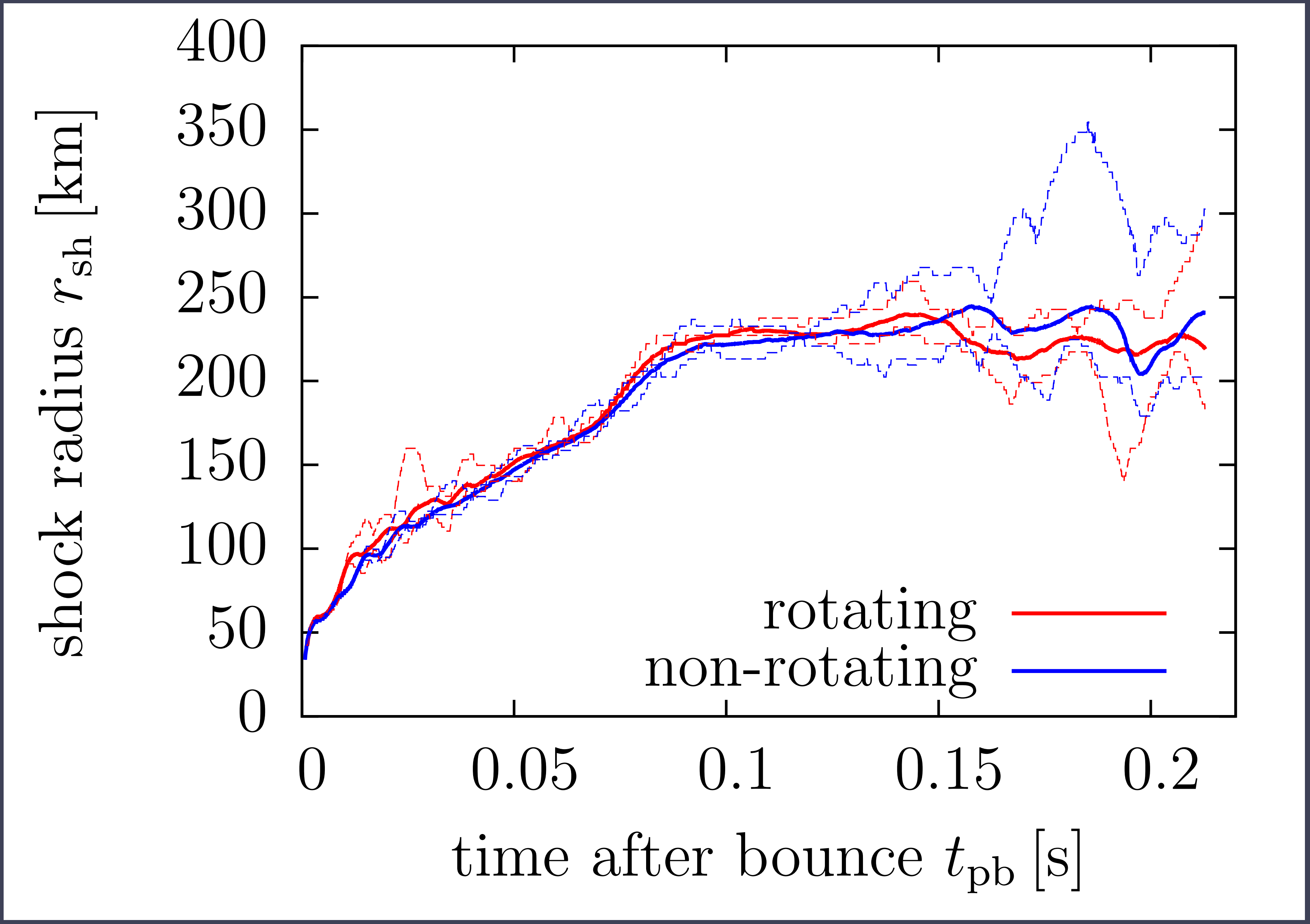
- Evolution until ~ 200 ms after bounce



Nagakura+ (2018)

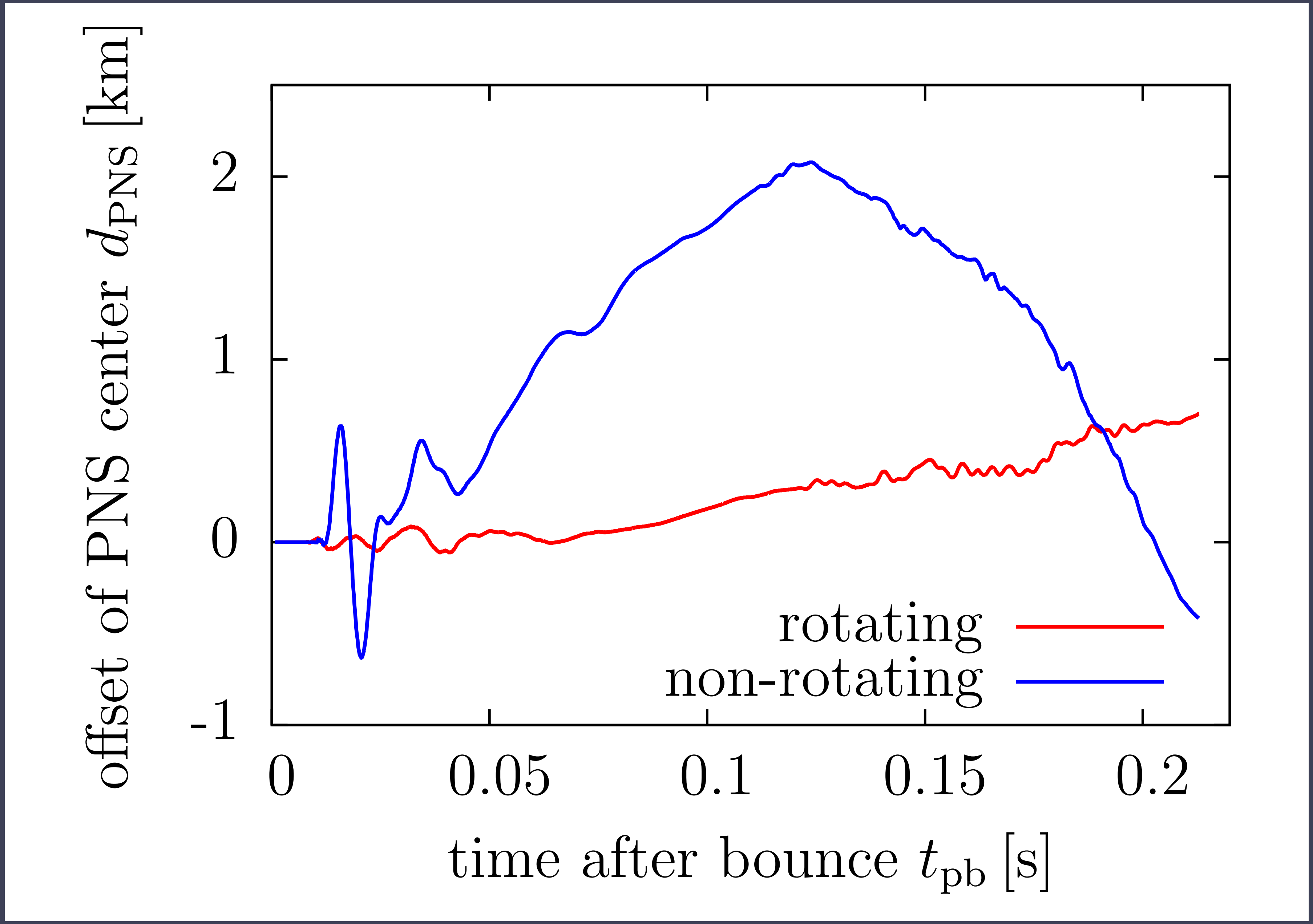
Time evolutions of shock radii

- Evolution until ~ 200 ms after bounce
- Comparison between rotating and non-rotating models.



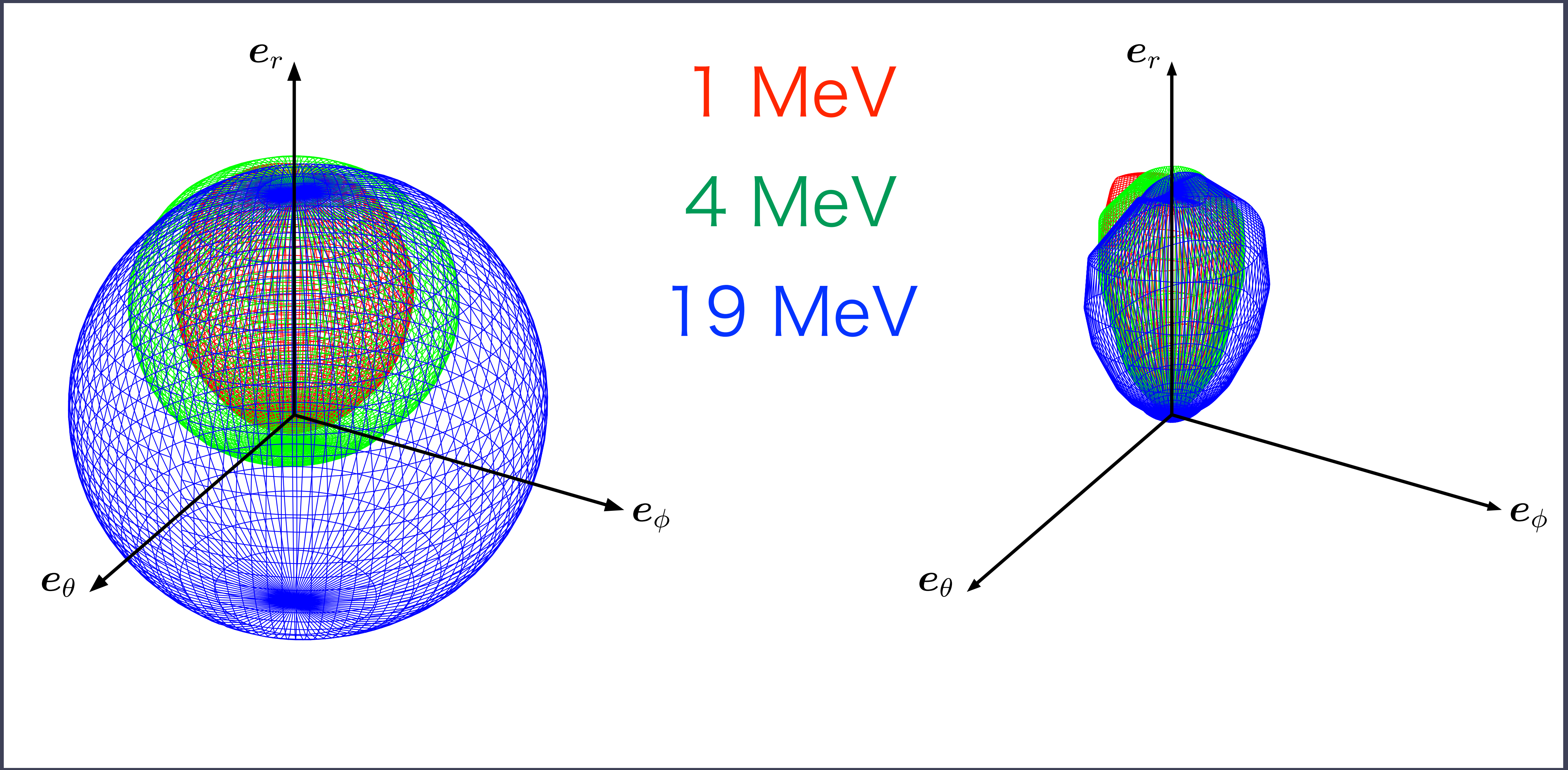
Trajectory of the PNS center

- Evolution until ~ 200 ms after bounce
- Comparison between rotating and non-rotating models.



Neutrino Distributions

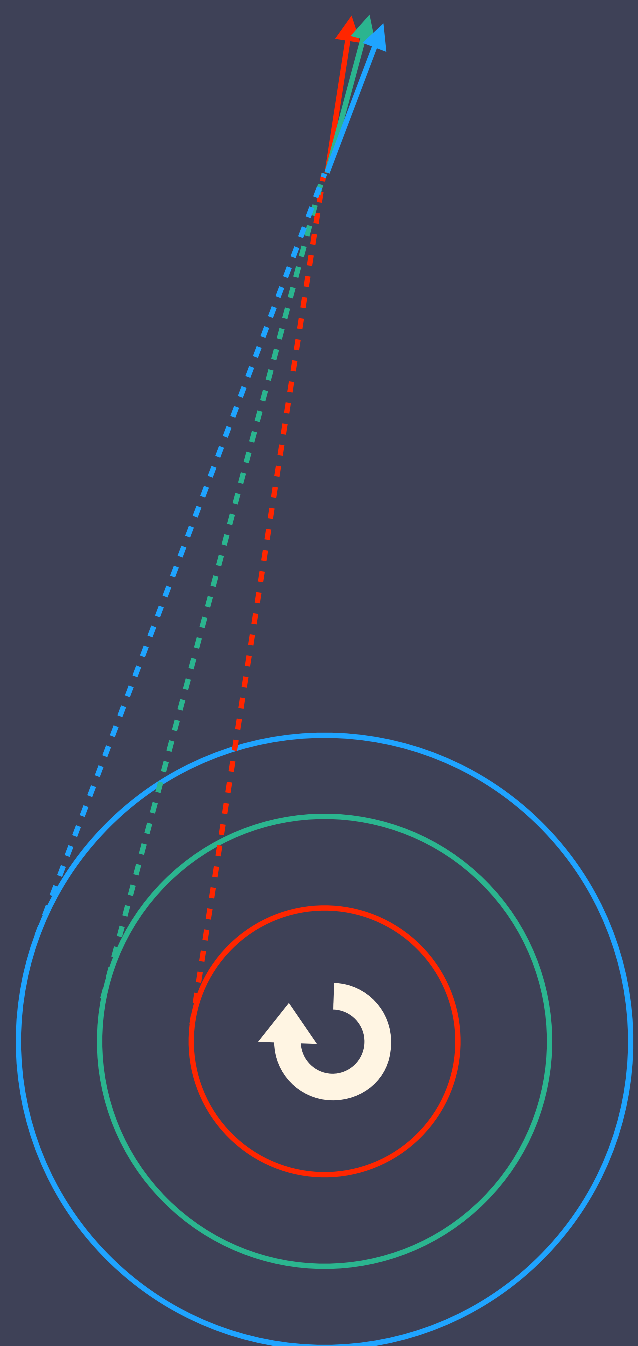
- Neutrino Distribution functions at ~ 10 ms after bounce.

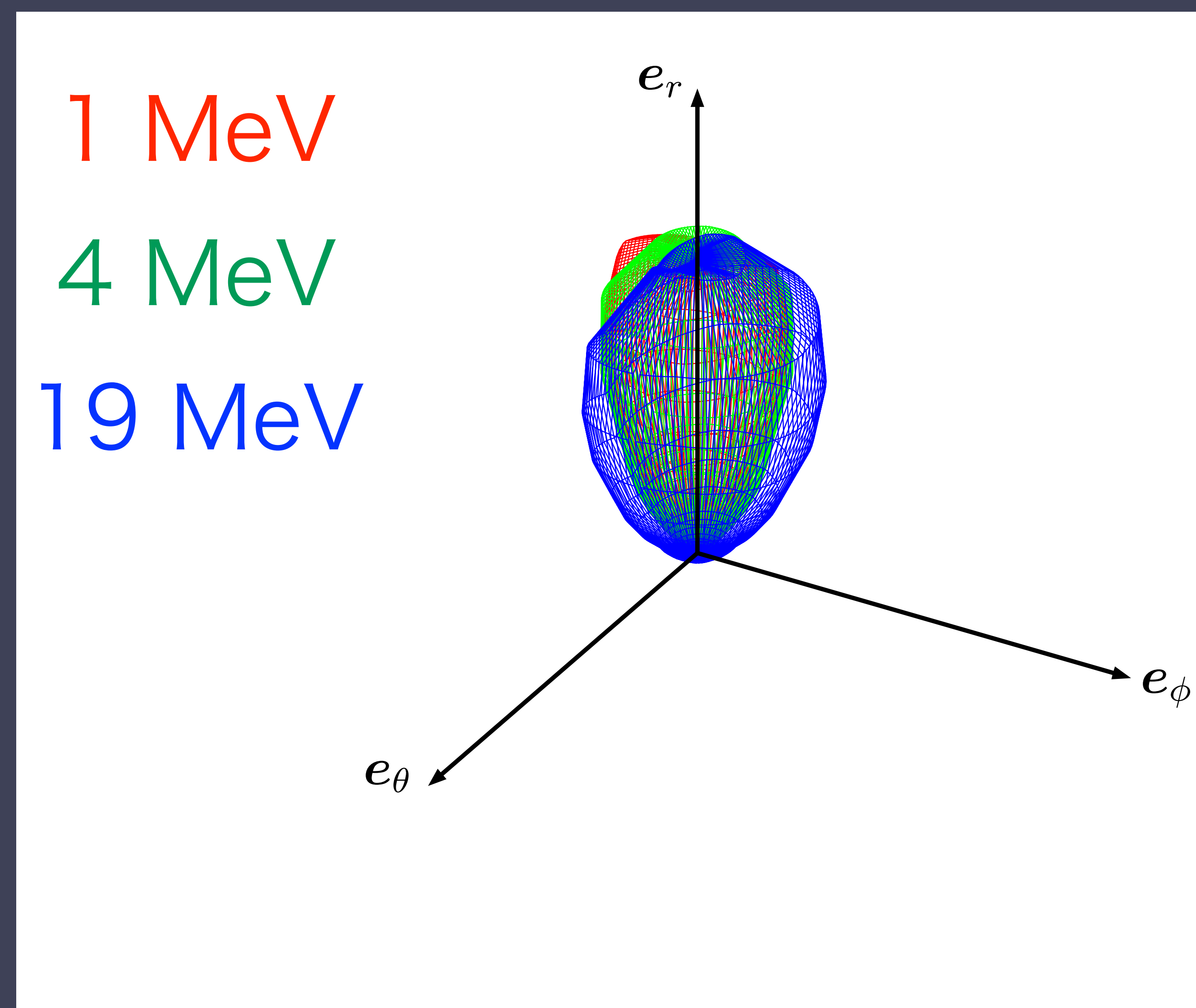


~60 km ~170 km

Neutrino Distributions

- Neutrino Distribution functions at ~ 10 ms after bounce.

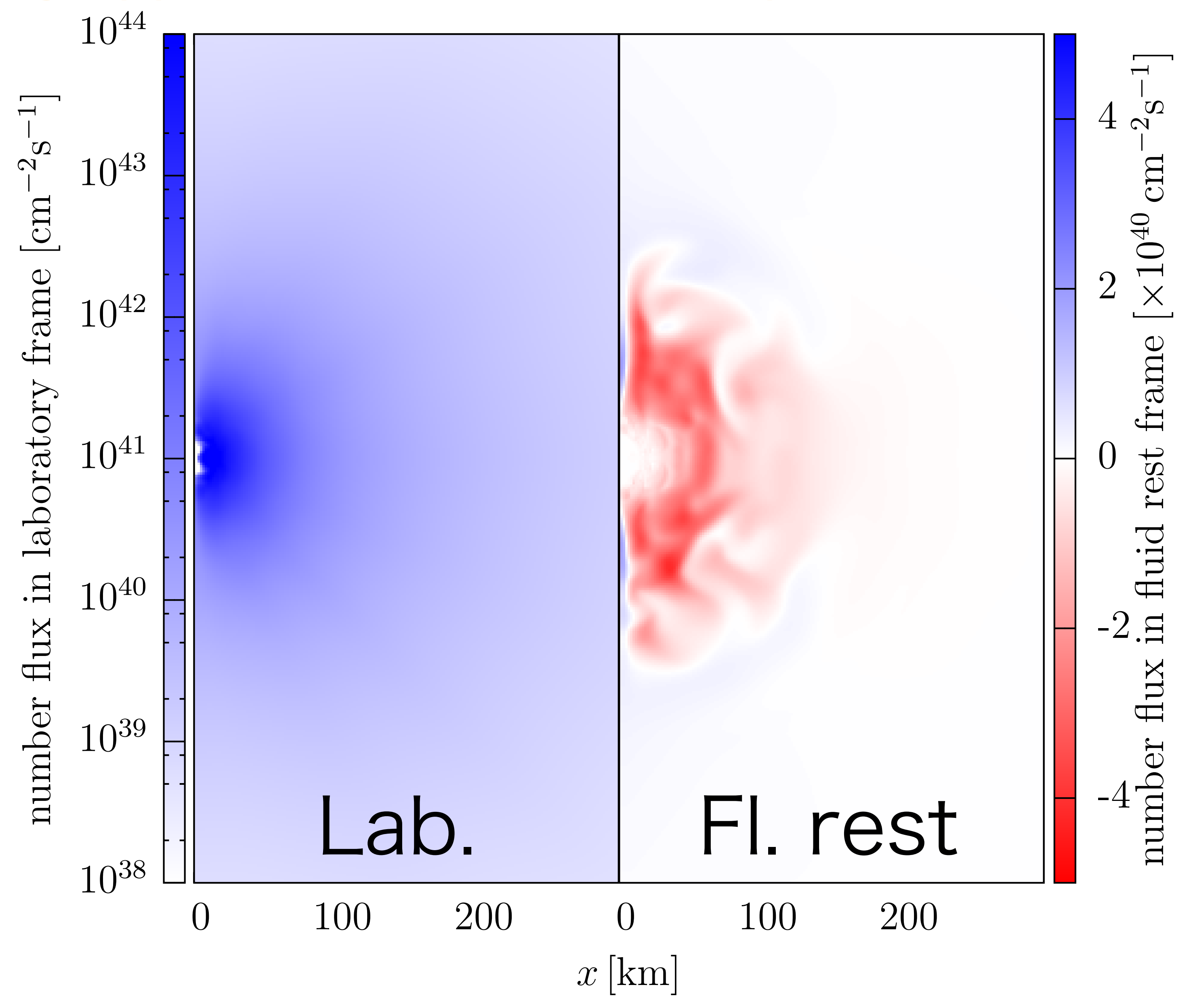


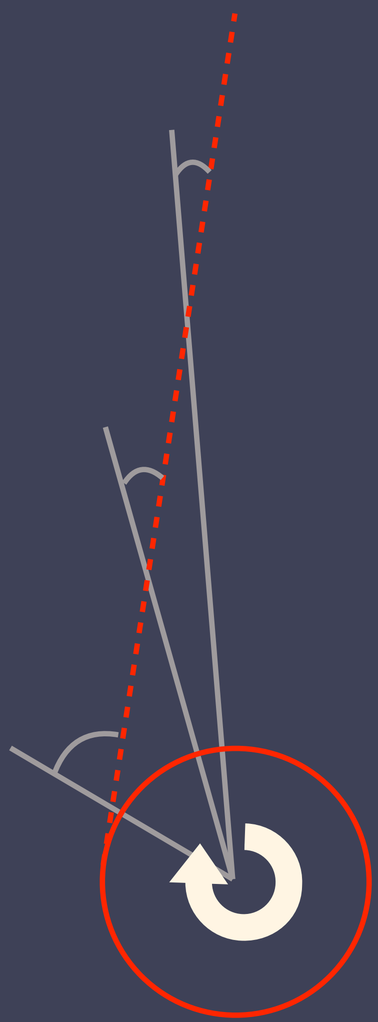


~170 km

Neutrino fluxes

- ϕ-component of the neutrino flux at ~ 10 ms after bounce
- The sign of the flux is different between in the fluid-rest-frame and in the laboratory frame.
- The Ray-by-Ray approximation can not capture this feature.





Eddington Tensor

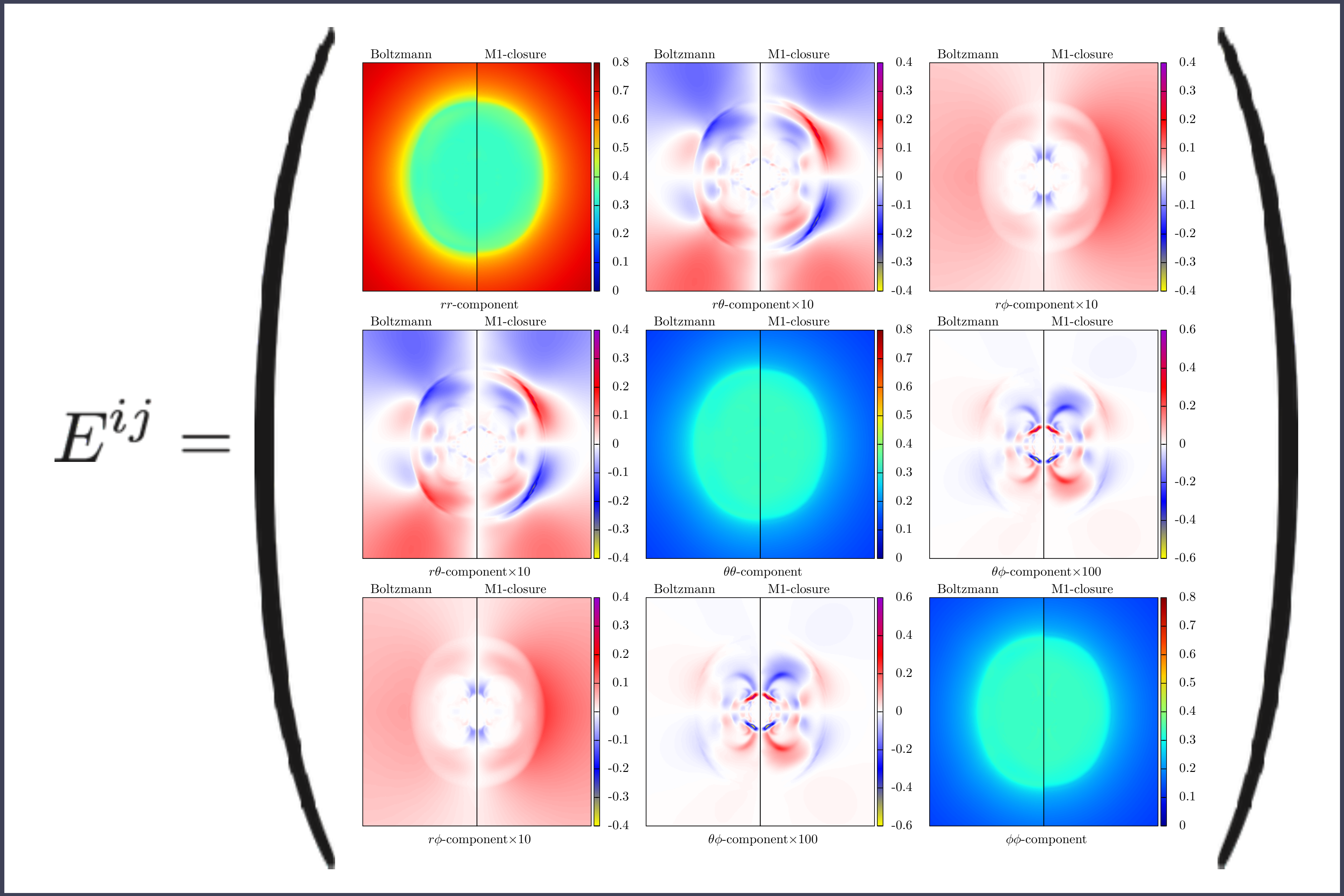
- Evaluating M1-closure method-Eddington tensor

$$E^{ij} = \begin{cases} \dfrac{\int f n^i n^j \mathrm{d}\Omega}{\int f \mathrm{d}\Omega} \\ \dfrac{3\chi - 1}{2}\delta^{ij} + \dfrac{1-\chi}{2}\dfrac{F^i F^j}{F^2} \end{cases}$$

$$\mathrm{w}/\ \chi = \frac{3 + 4\tilde{F}^2}{5 + 2\sqrt{4 - 3\tilde{F}^2}},\ \tilde{F} = \frac{|\boldsymbol{F}|}{E}$$

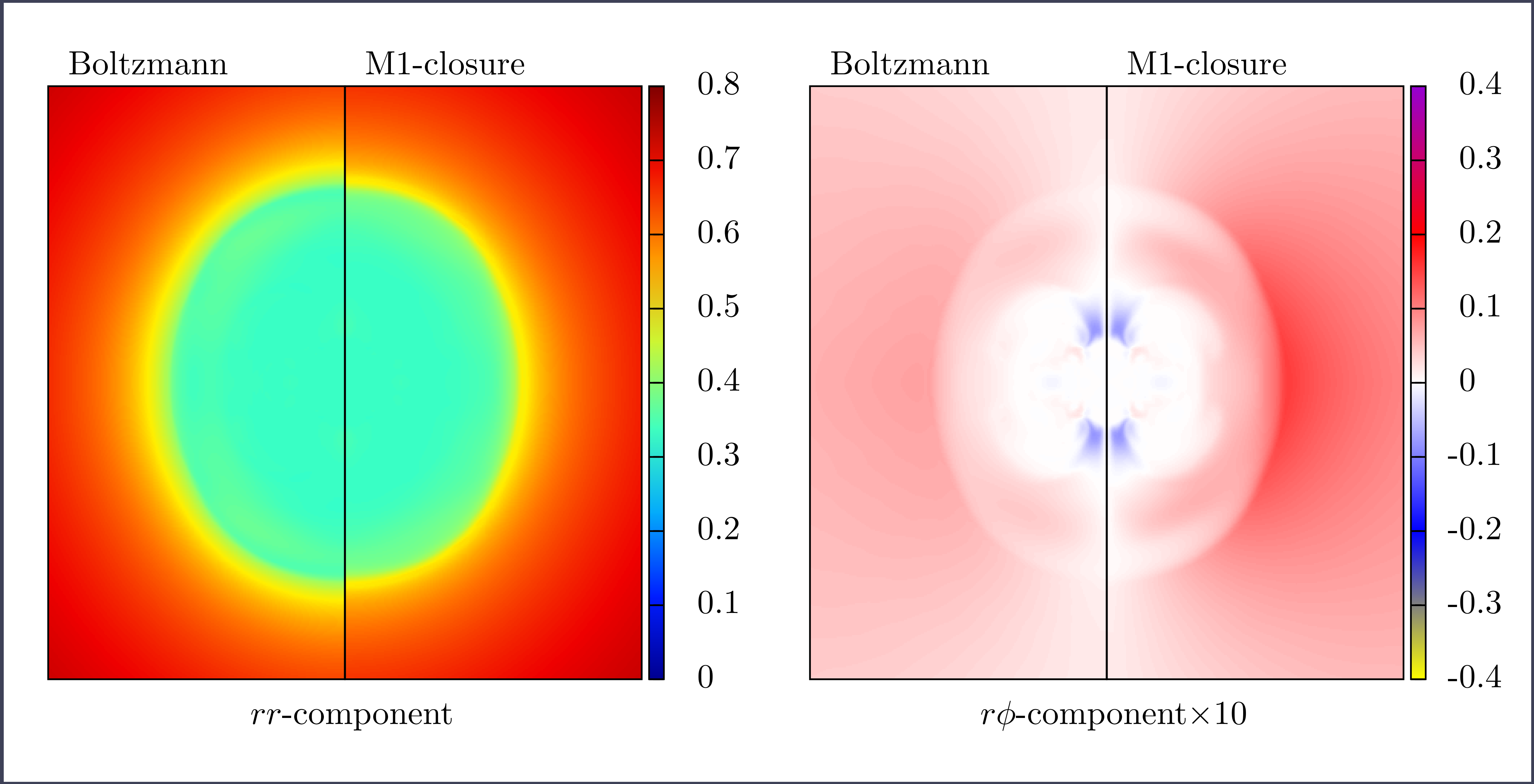
Eddington tensor

- Eddington tensor at ~ 10 ms after bounce



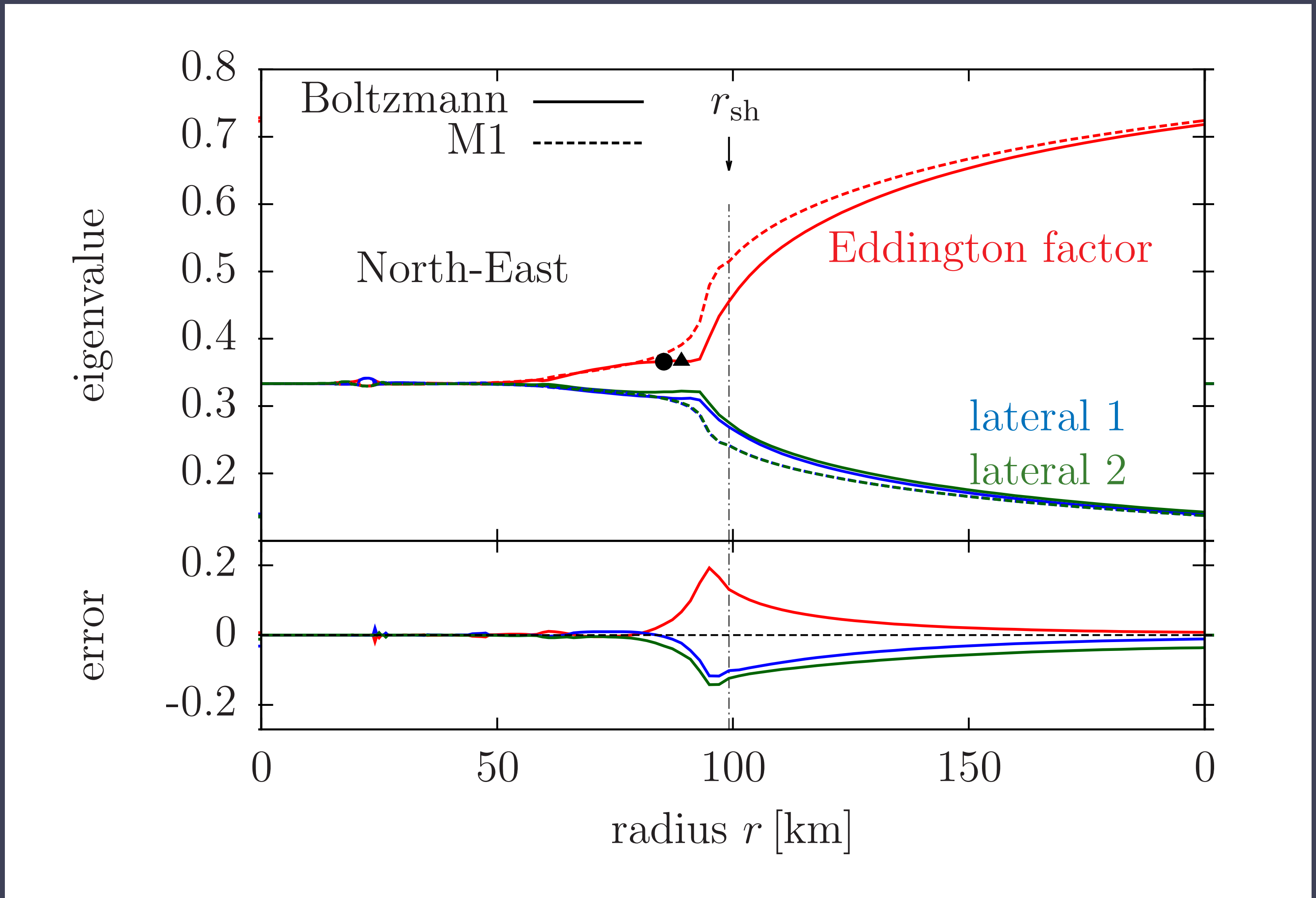
Eddington tensor

- Eddington tensor at ~ 10 ms after bounce
- Tensors calculated by the distribution functions and the M1-closure



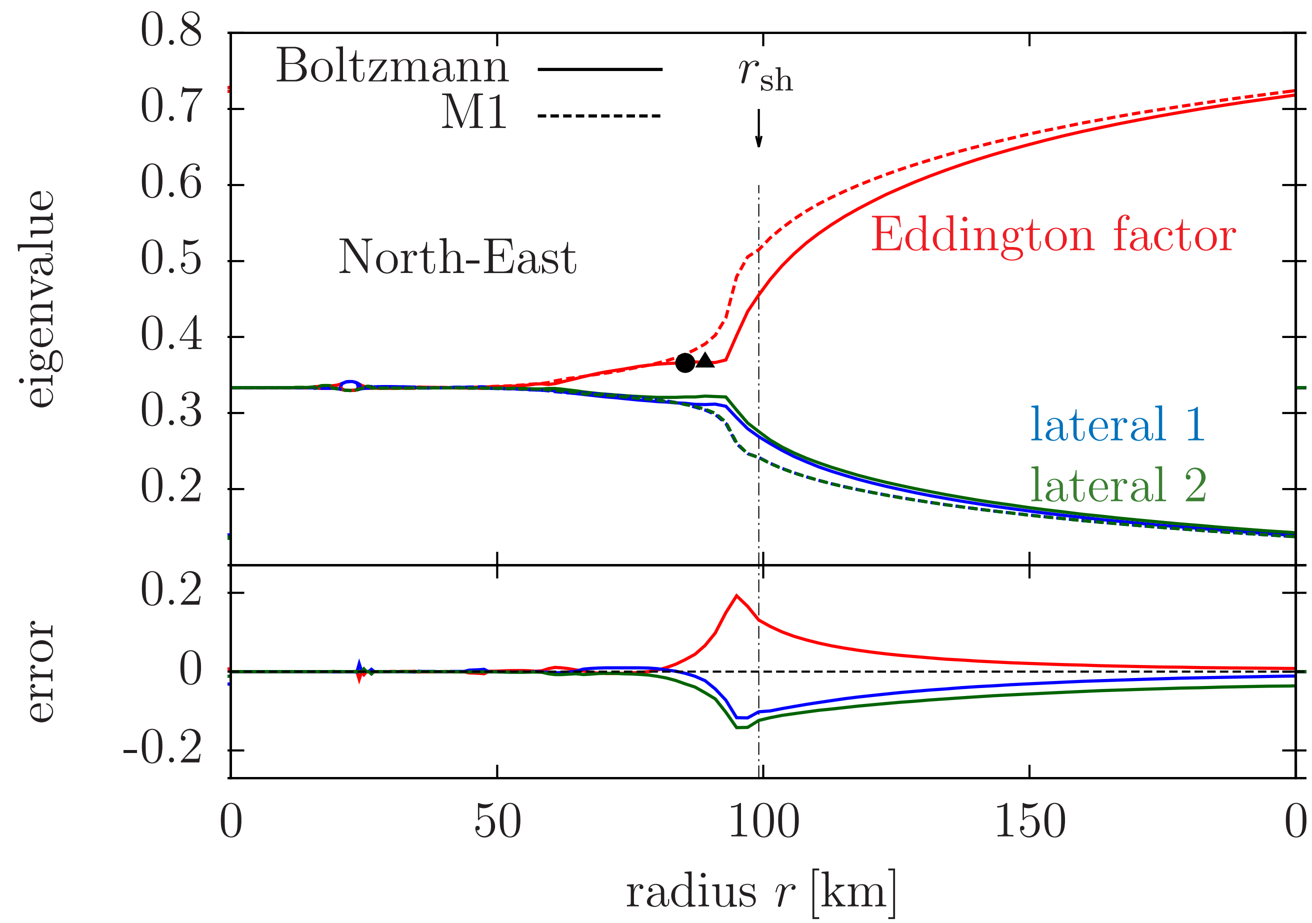
Eddington tensor

- Eddington tensor at ~ 10 ms after bounce
- Radial profiles of eigenvalues
- ~20% errors in M1-closure method



Eddington tensor

- The Eddington factor does not necessarily increase with the flux factor increasing.

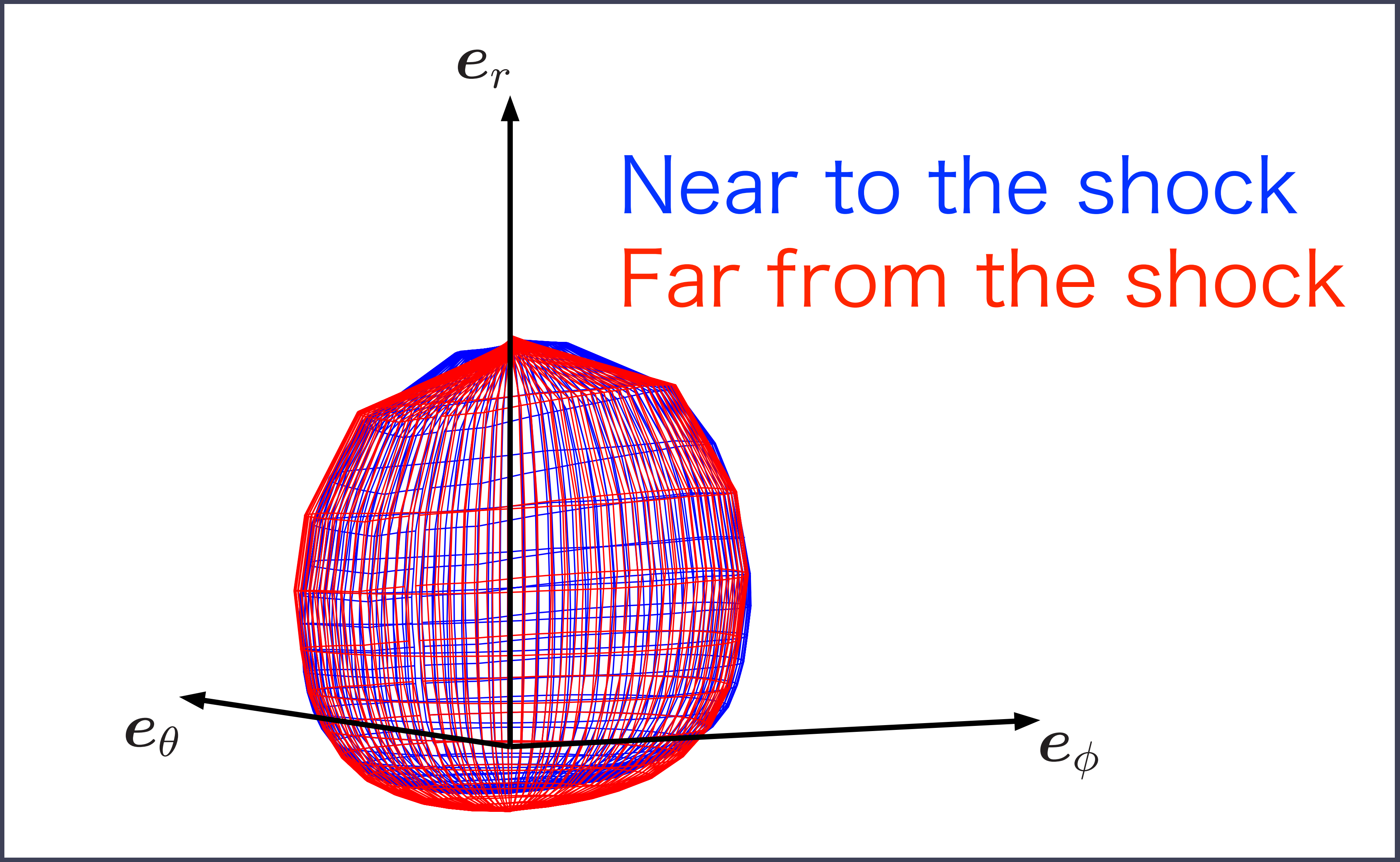


$$\chi = \frac{3+4\tilde{F}^2}{5+2\sqrt{4-3\tilde{F}^2}}, \quad \tilde{F} = \frac{|\boldsymbol{F}|}{E}$$

$\tilde{F} \nearrow \Leftrightarrow \chi \nearrow$ for M1

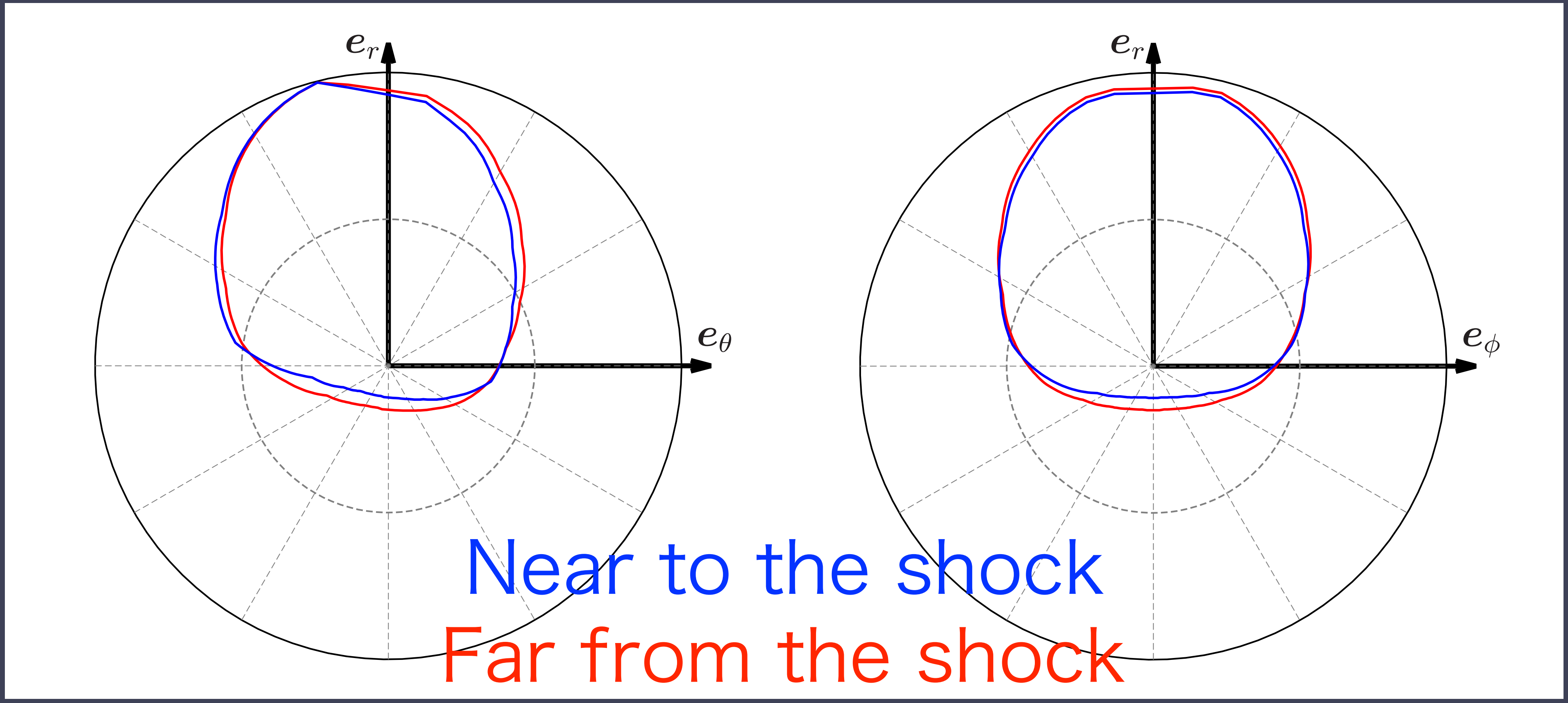
Eddington tensor

- The Eddington factor does not necessarily increase with the flux factor increasing.
- Comparison of distribution functions



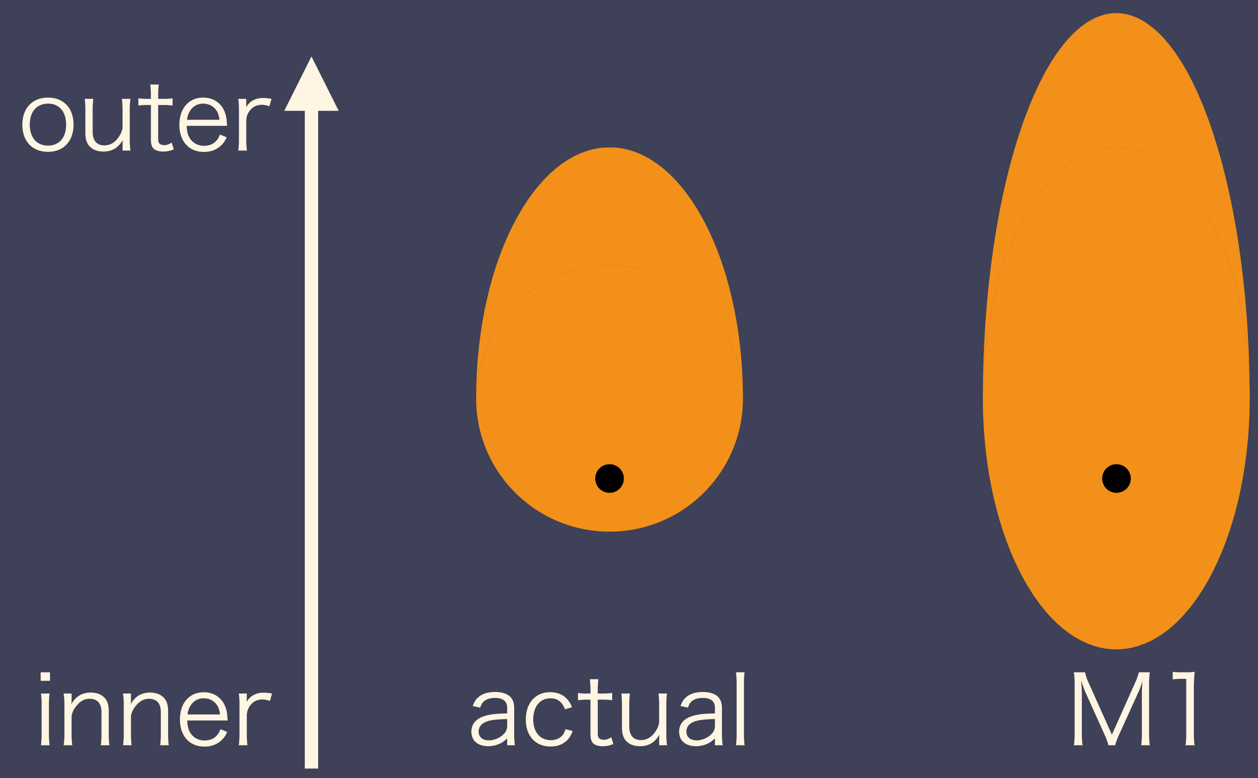
Eddington tensor

- The flux factor $\propto \langle \cos\theta_\nu \rangle$
- The Eddington factor $\propto \langle \cos^2\theta_\nu \rangle$
- The distribution function at $\cos\theta_\nu \sim -1$ decreases with getting closer to the shock→The flux factor increases and the Eddington factor decreases.



Eddington factor

- Prolateness of distribution
- M1: prolateness is estimated from deviation of distribution



Summary

- Collapse of rotating progenitor is simulated by Boltzmann-Radiation-Hydro code.
- Features which can not be reproduced by approximate methods are discovered.
- The accuracy of the M1-closure method is evaluated.