# Stellar core-collapse simulations with the Boltzmann-radiation-hydrodynamics code under axisymmetry

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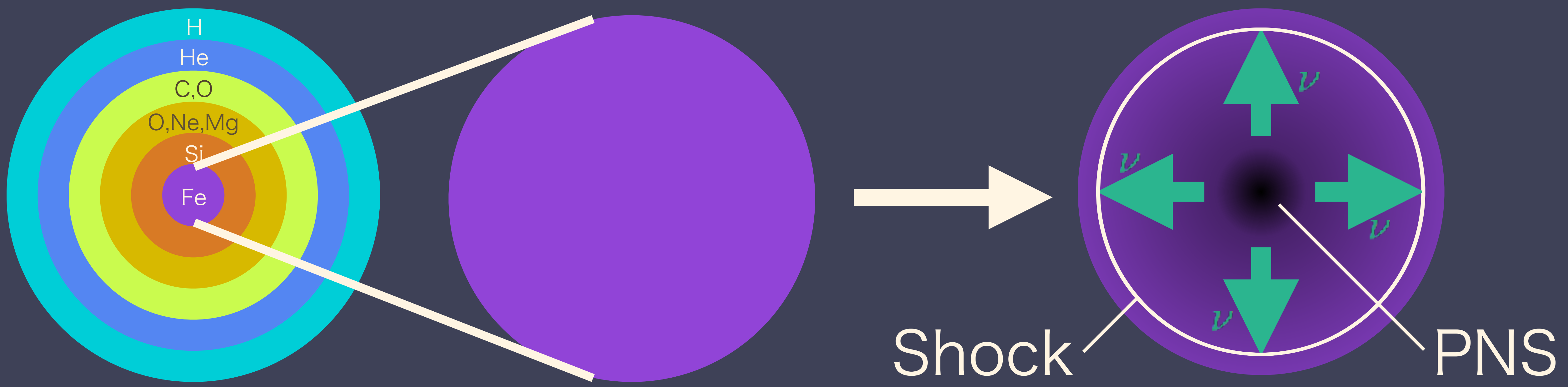
# Core-collapse supernovae

- Core-collapse Supernovae:
  explosive death of massive star
- Stellar core-collapse
  → explosion by released gravitational energy

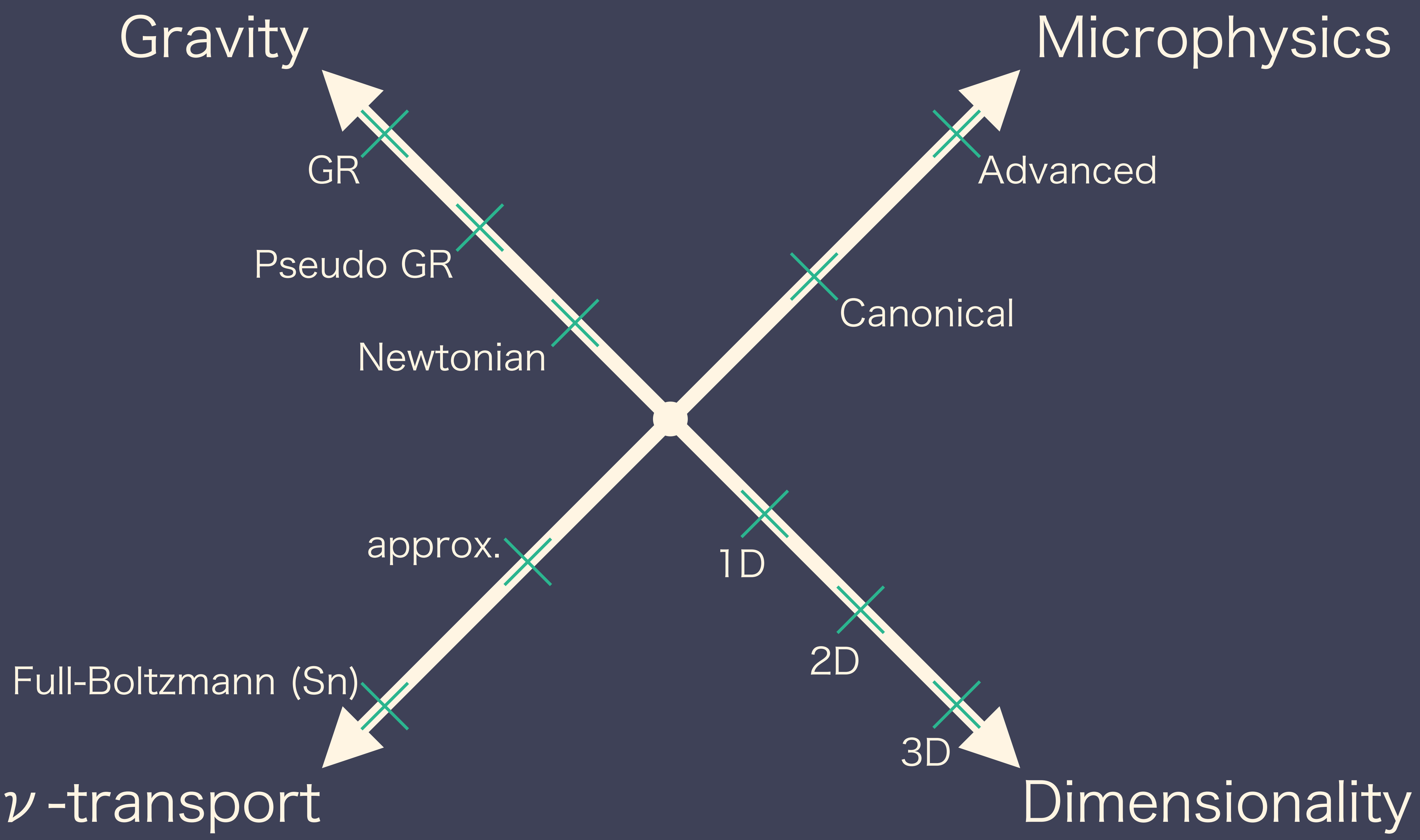
SN1987A

# CCSN explosion mechanism

- Collapse→Bounce→Stalled Shock
- The central proto-neutron star emits neutrinos.
- The shock is re-energized by the neutrino heating.



# The progress in CCSNe sim.



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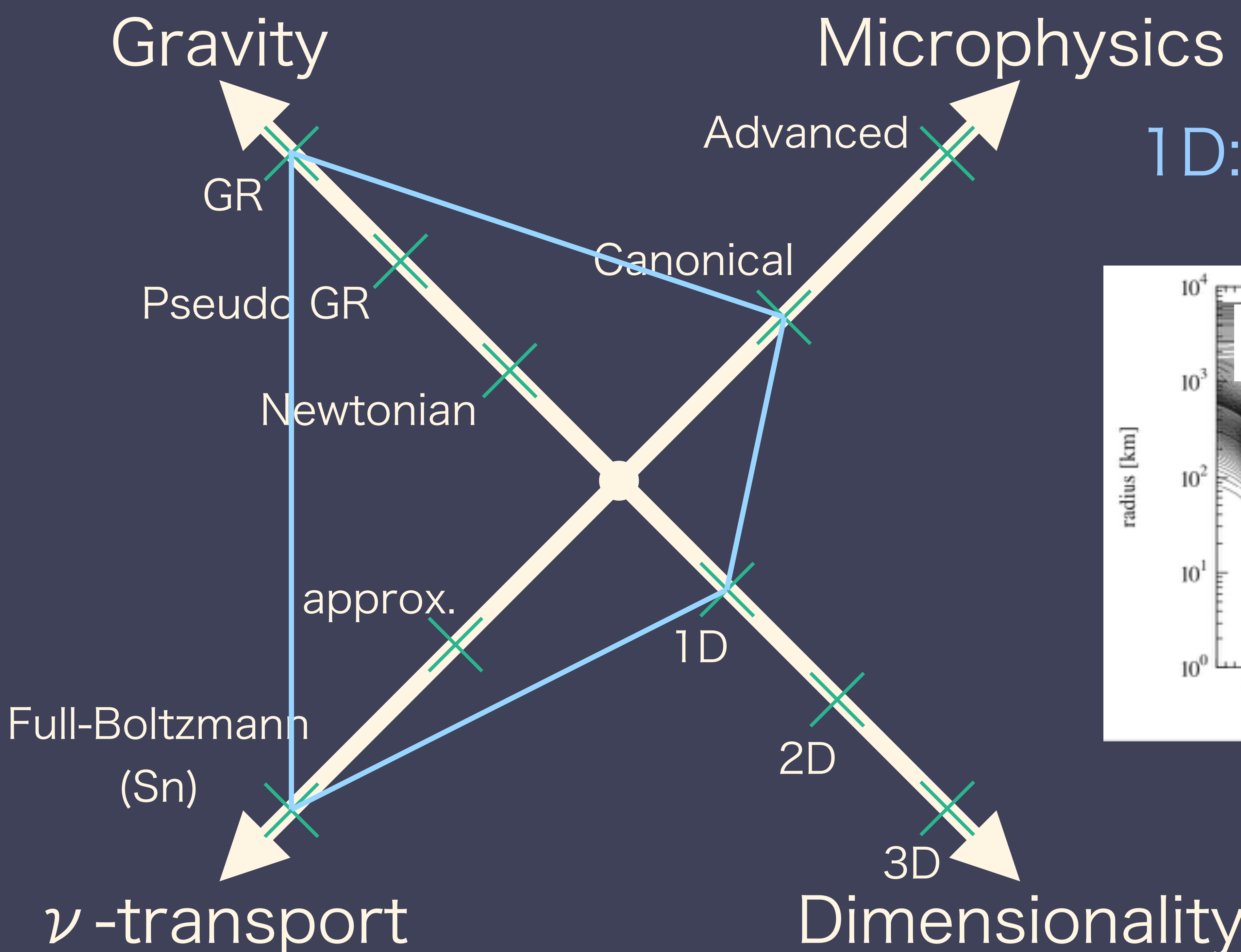
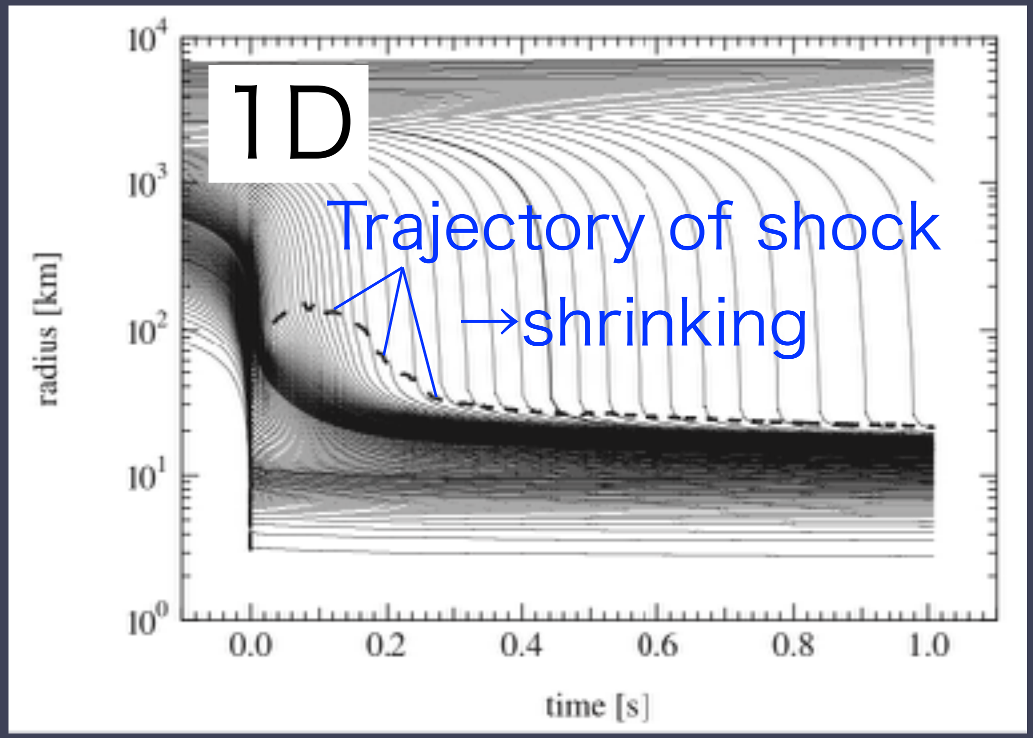
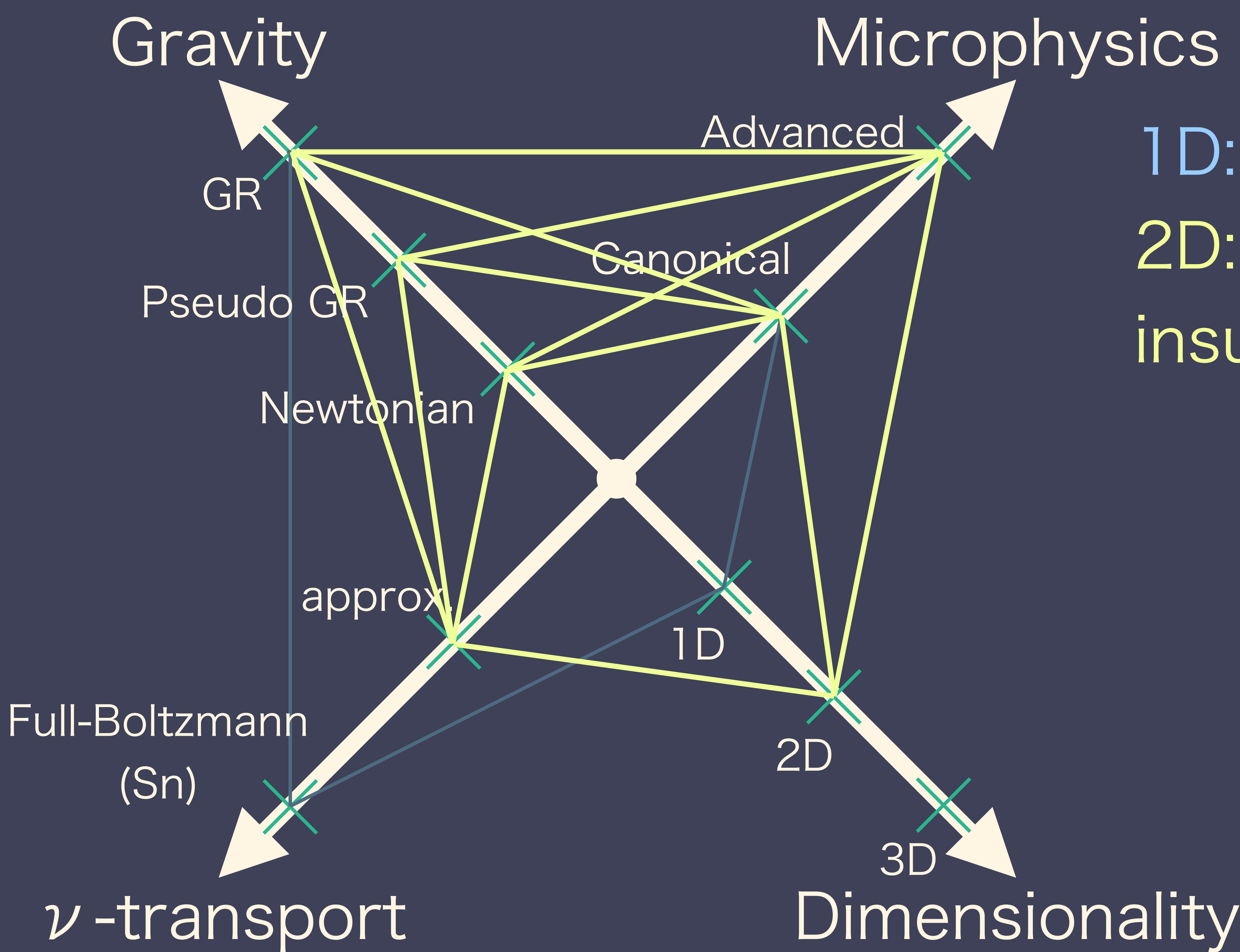



1D: fail to explode




Sumiyoshi+(2005)

# The progress in CCSNe sim.

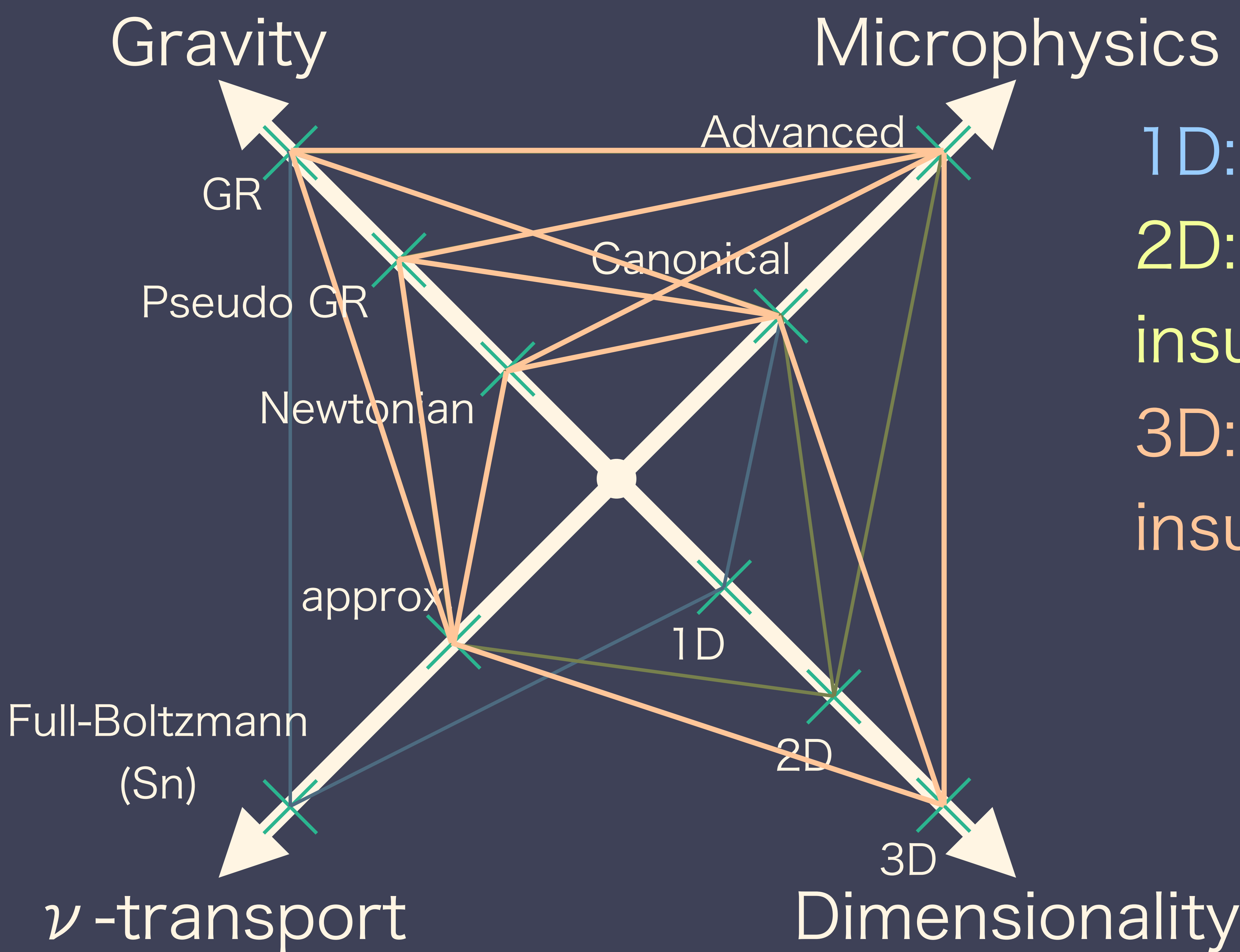



1D: fail to explode

2D: shock revives

insufficient energy

# The progress in CCSNe sim.

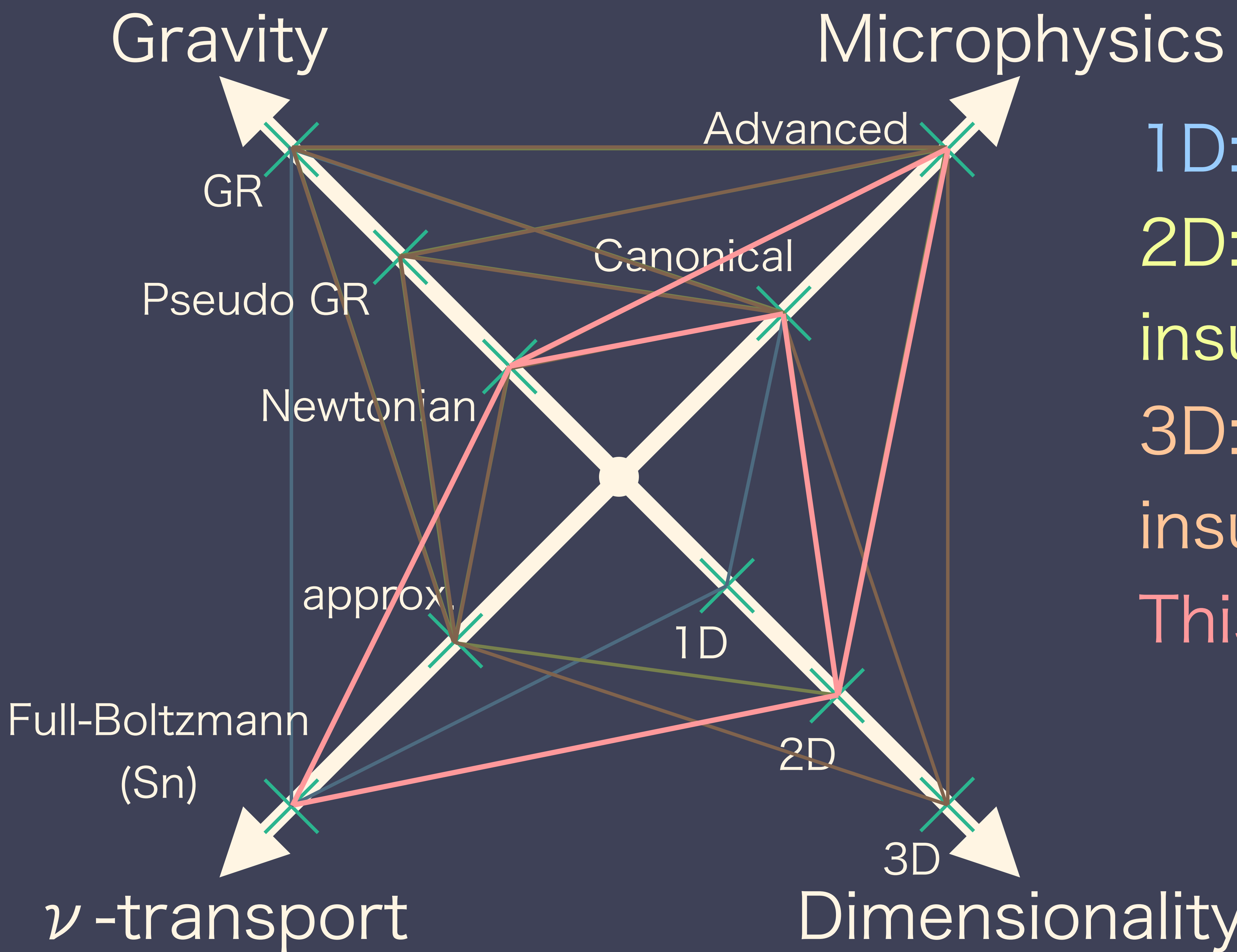



1D: fail to explode

2D: shock revives insufficient energy

3D: shock revives insufficient energy

# The progress in CCSNe sim.



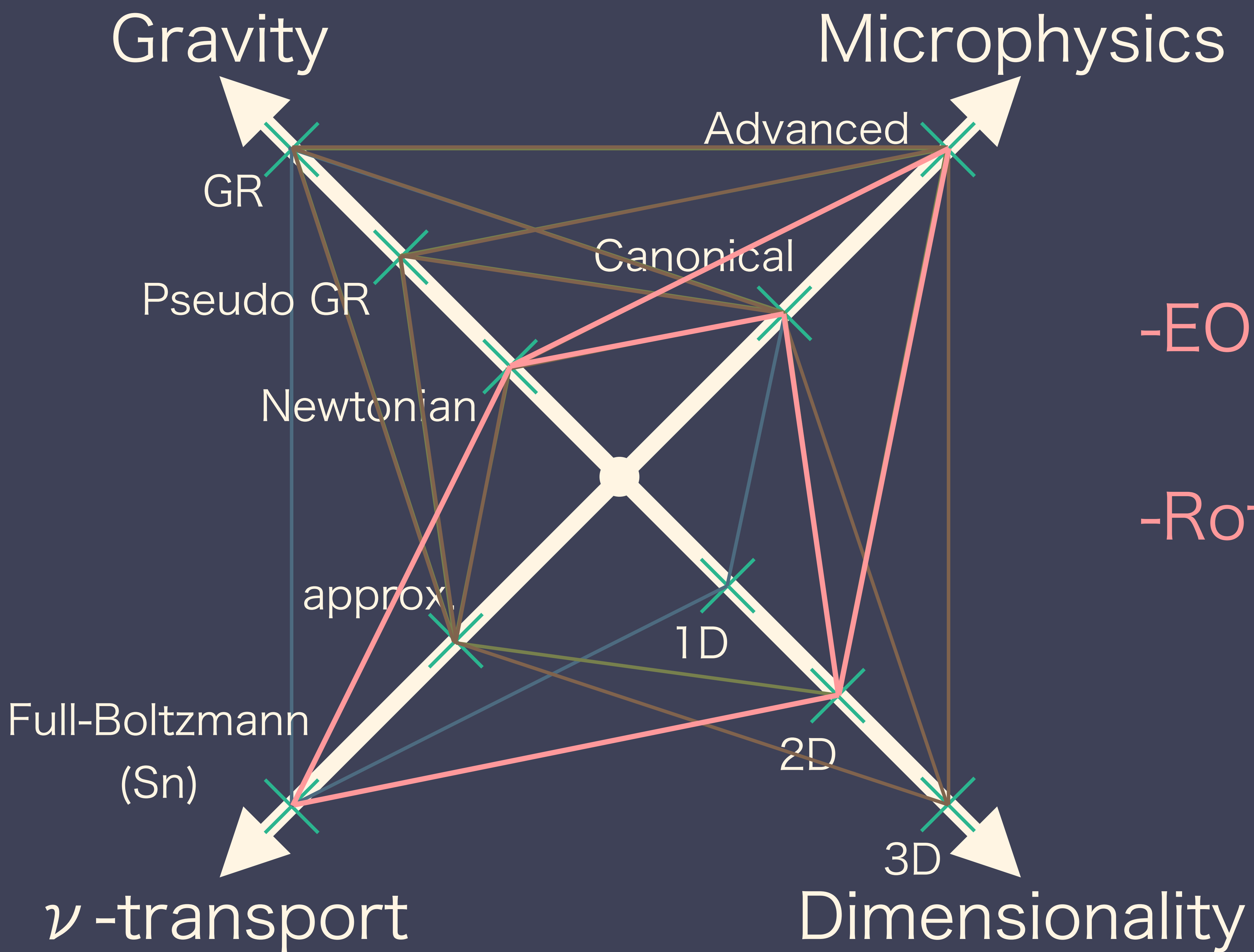

1D: fail to explode

2D: shock revives insufficient energy

3D: shock revives insufficient energy

This work

# The progress in CCSNe sim.




-EOS comparison

-Rotation

# Setup

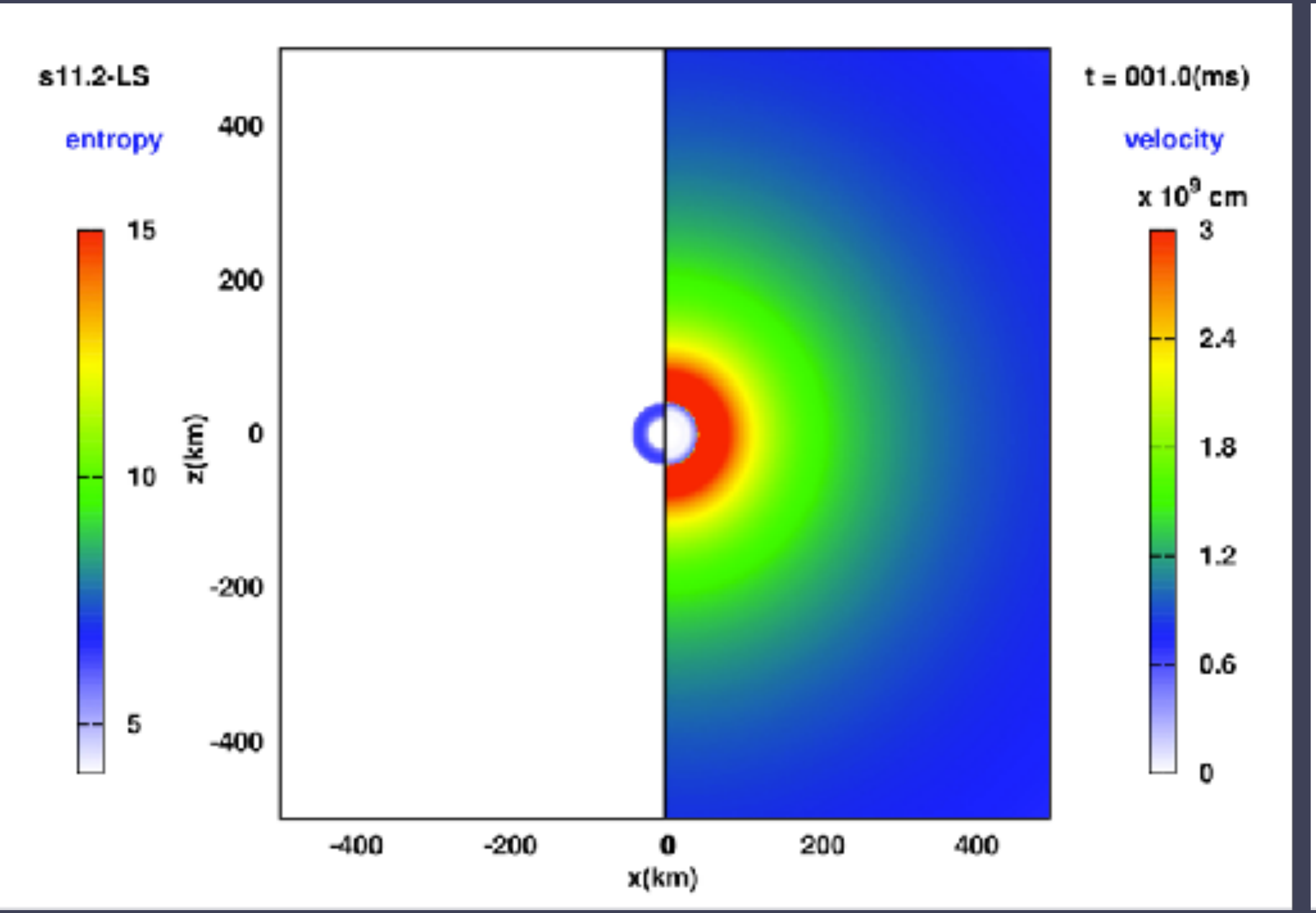
- 11.2 $M_\odot$ progenitor of Woosley+ (2002)
- Neutrino reactions

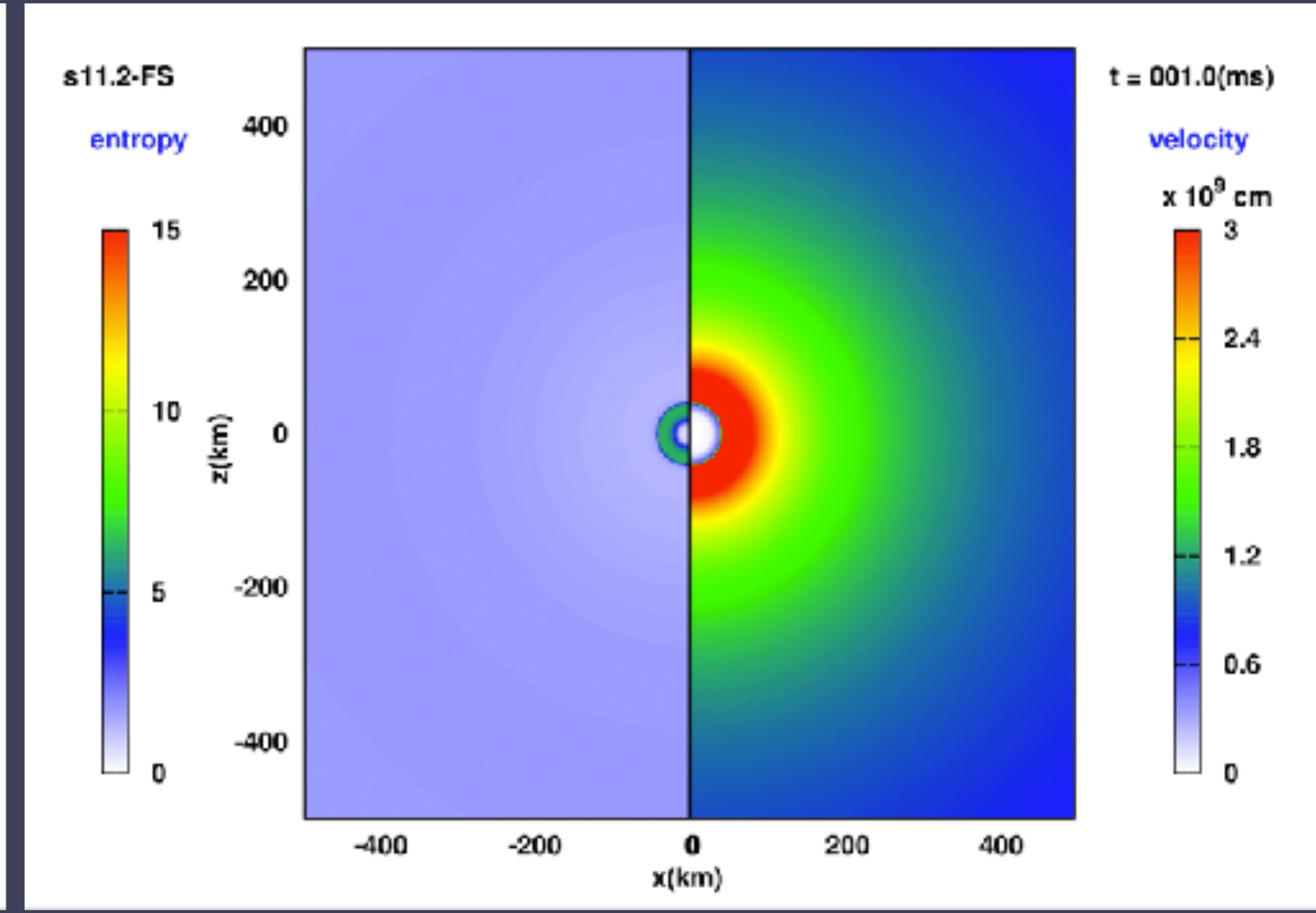
$$
\begin{aligned}
\nu_e + \mathrm{n} &\leftrightarrow \mathrm{e}^- + \mathrm{p} & \nu + A &\leftrightarrow \nu + A \\
\bar{\nu}_e + \mathrm{p} &\leftrightarrow \mathrm{e}^+ + \mathrm{n} & \nu + \mathrm{e}^- &\leftrightarrow \nu + \mathrm{e}^- \\
\nu_e + A &\leftrightarrow \mathrm{e}^- + A' & \nu + \bar{\nu} &\leftrightarrow \mathrm{e}^- + \mathrm{e}^+ \\
\nu + N &\leftrightarrow \nu + N & N + N &\leftrightarrow N + N + \nu + \bar{\nu}
\end{aligned}
$$

- Lattimer-Swesty EOS and Furusawa-Shen EOS

# Shock evolution

- Entropy and absolute value of velocity

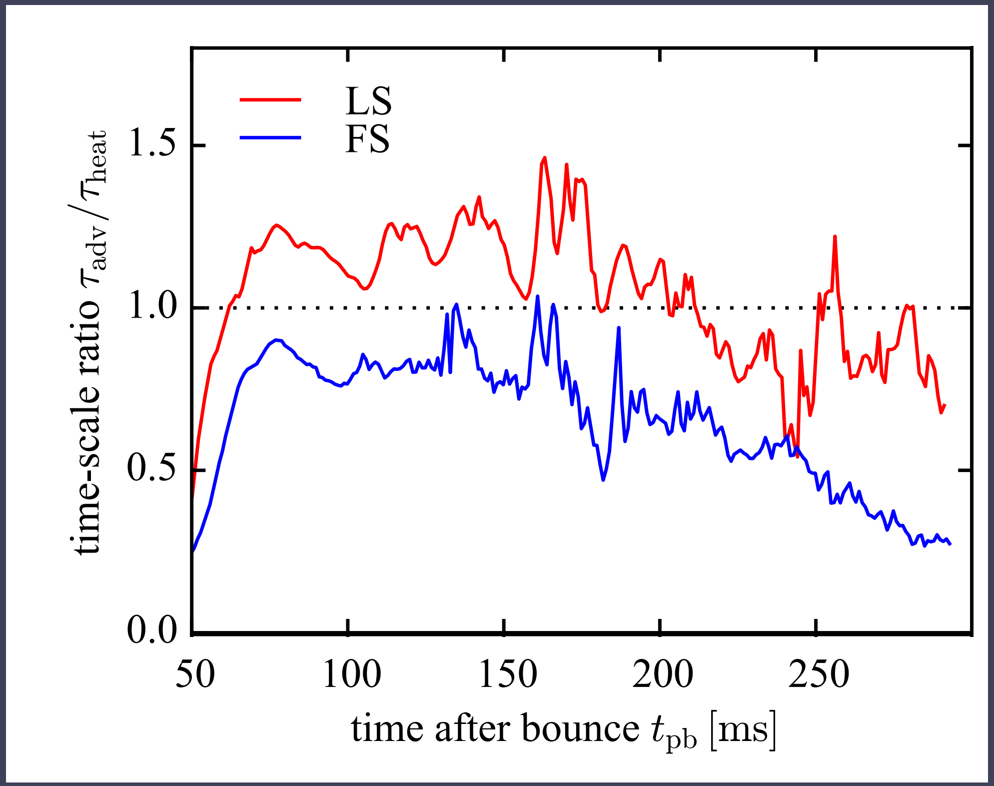


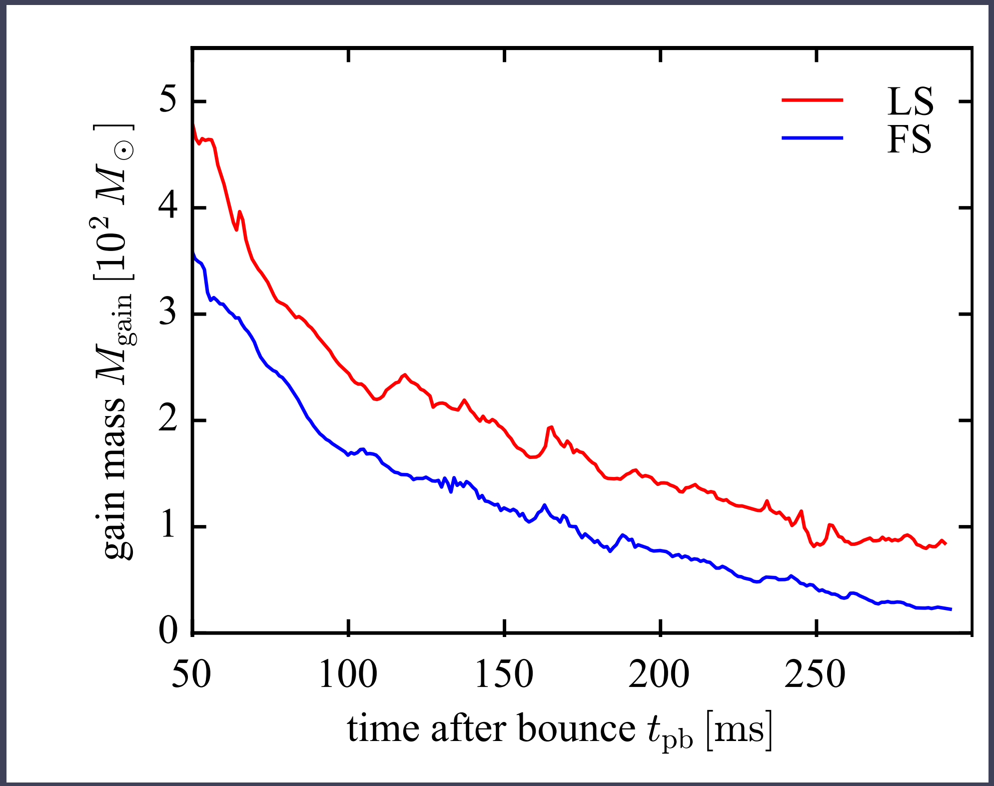



# Timescale ratio

- Shock revives when the timescale ration exceeds 1:

$$\tau_{\rm adv}/\tau_{\rm heat} \text{ with } \tau_{\rm adv} = M_{\rm gain}/\dot{M},\ \tau_{\rm heat} = E_{\rm gain}/Q_{\rm gain}$$



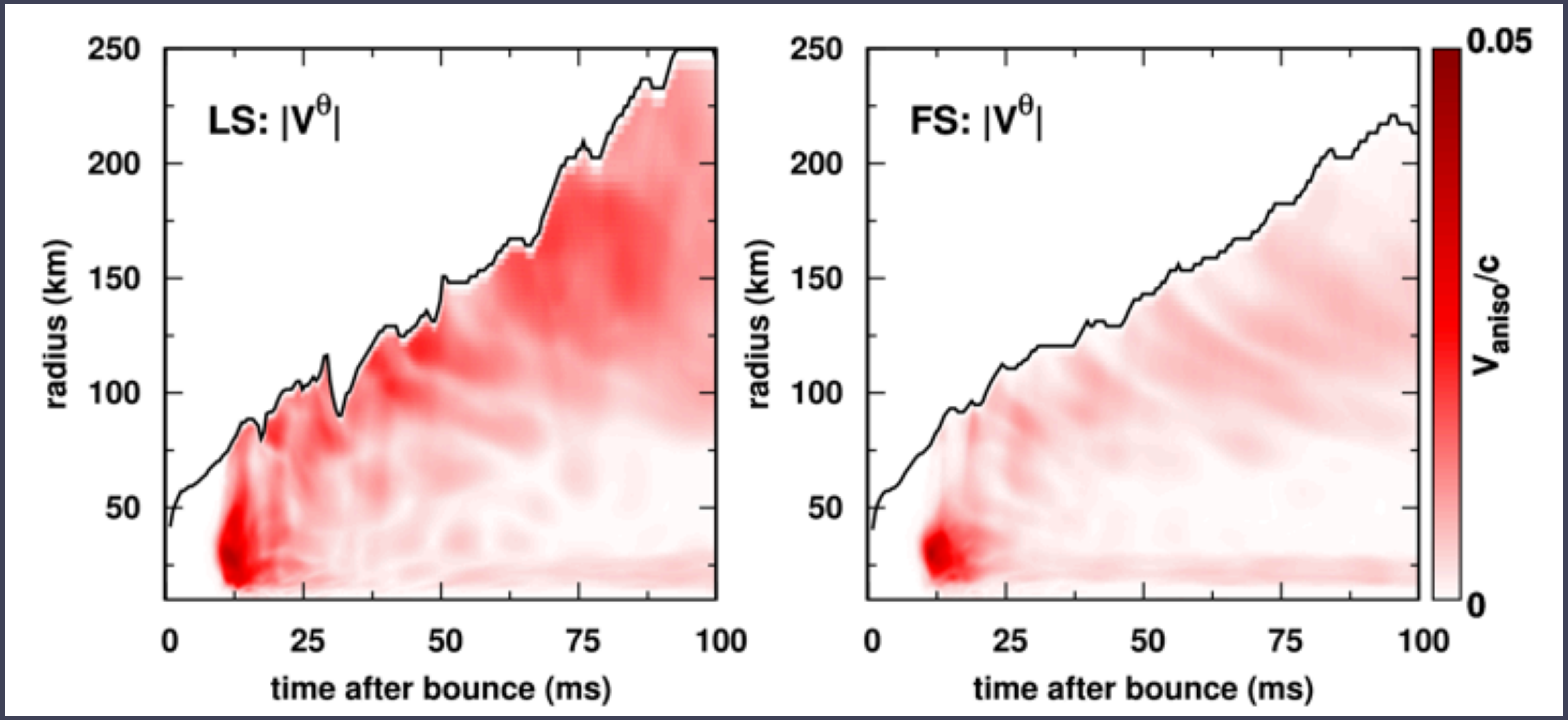




Harada+ in prep.

- All quantities are similar except for $M_{\rm gain}$

# Difference in turbulence

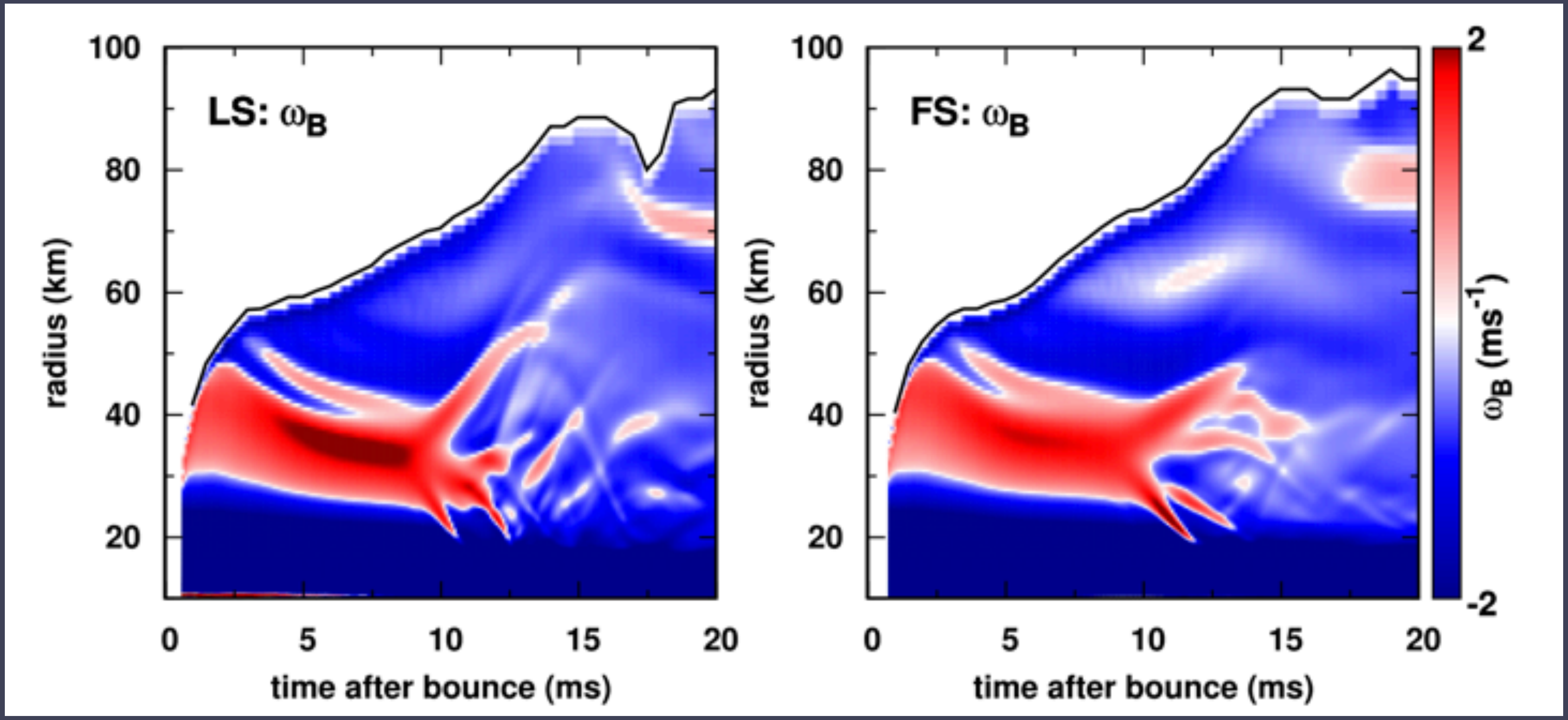
- All quantities are similar except for $M_{\mathrm{gain}}$
- Stronger turbulence in LS model




Nagakura+(2018)

# Difference in turbulence

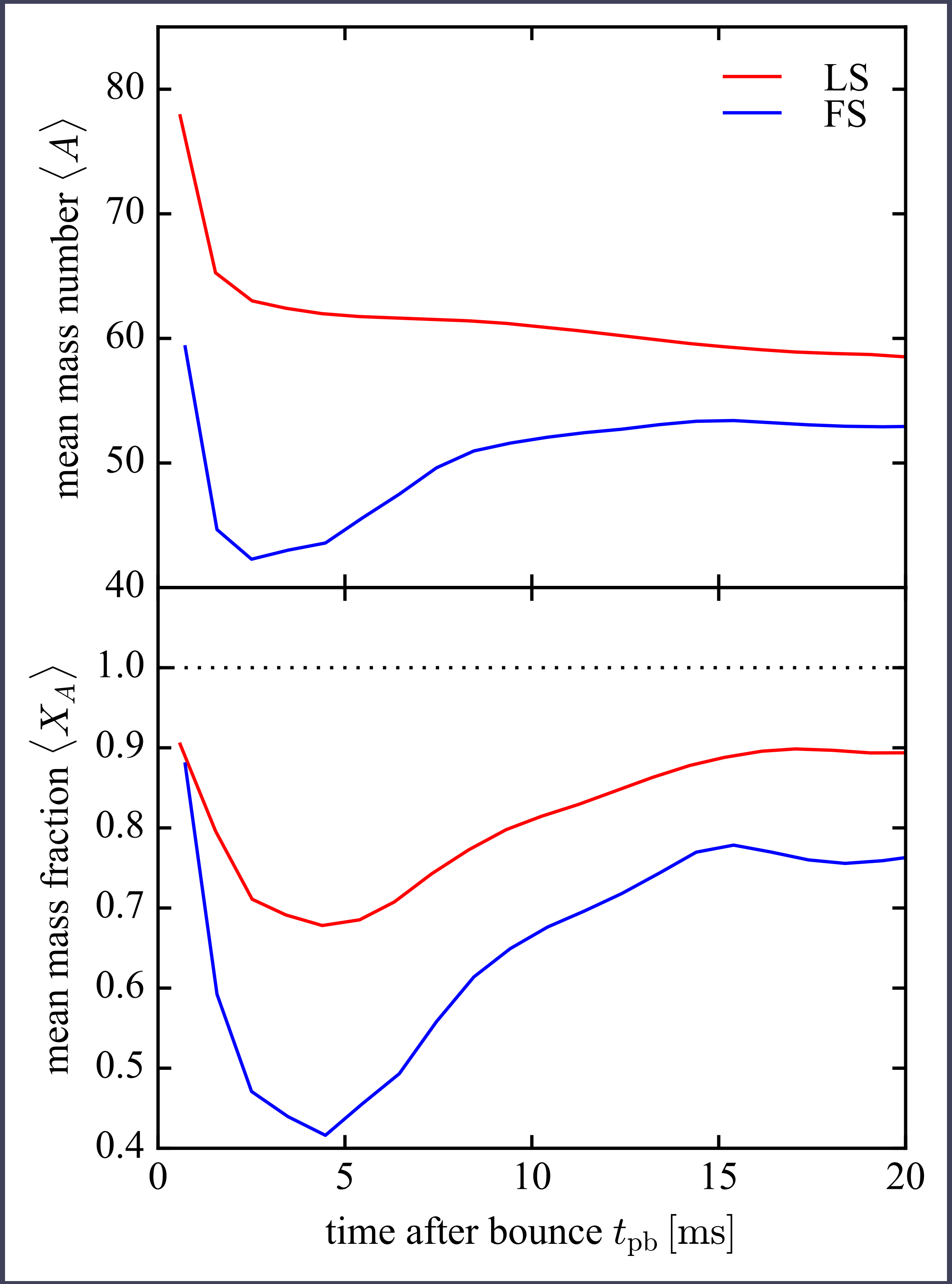
- All quantities are similar except for $M_{\rm gain}$
- Stronger turbulence in LS model
- Larger convection growth rate (Brunt-Vaisala freq.)




Nagakura+(2018)

# Difference in composition

- Nuclear composition of accretion flow is different: larger and more heavy nuclei in LS.
- More energy loss by nuclear photodissociation
- Shock is weakened rapidly and steep entropy gradient is formed
- Stronger prompt convection

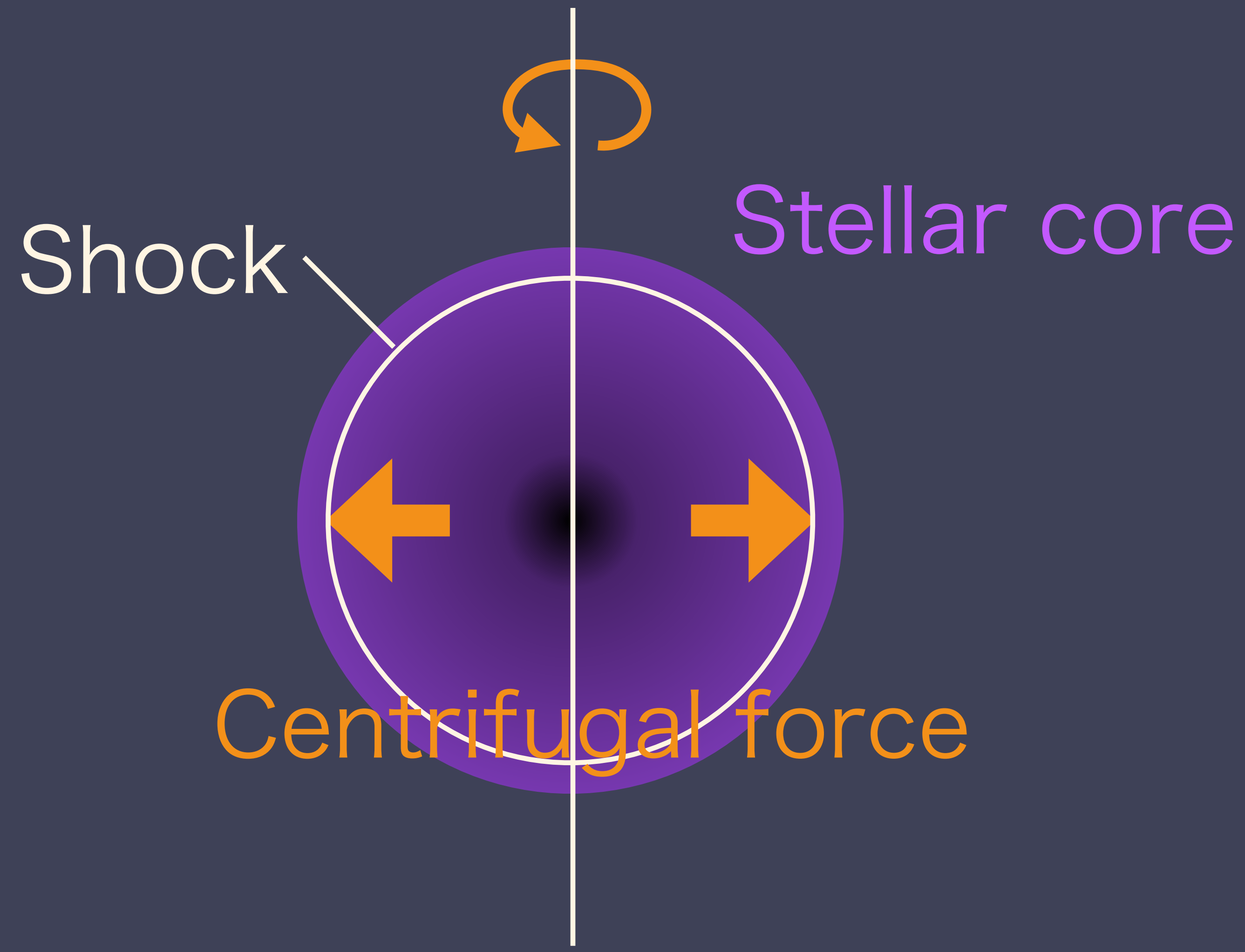



Harada+ in prep.

# Rotation

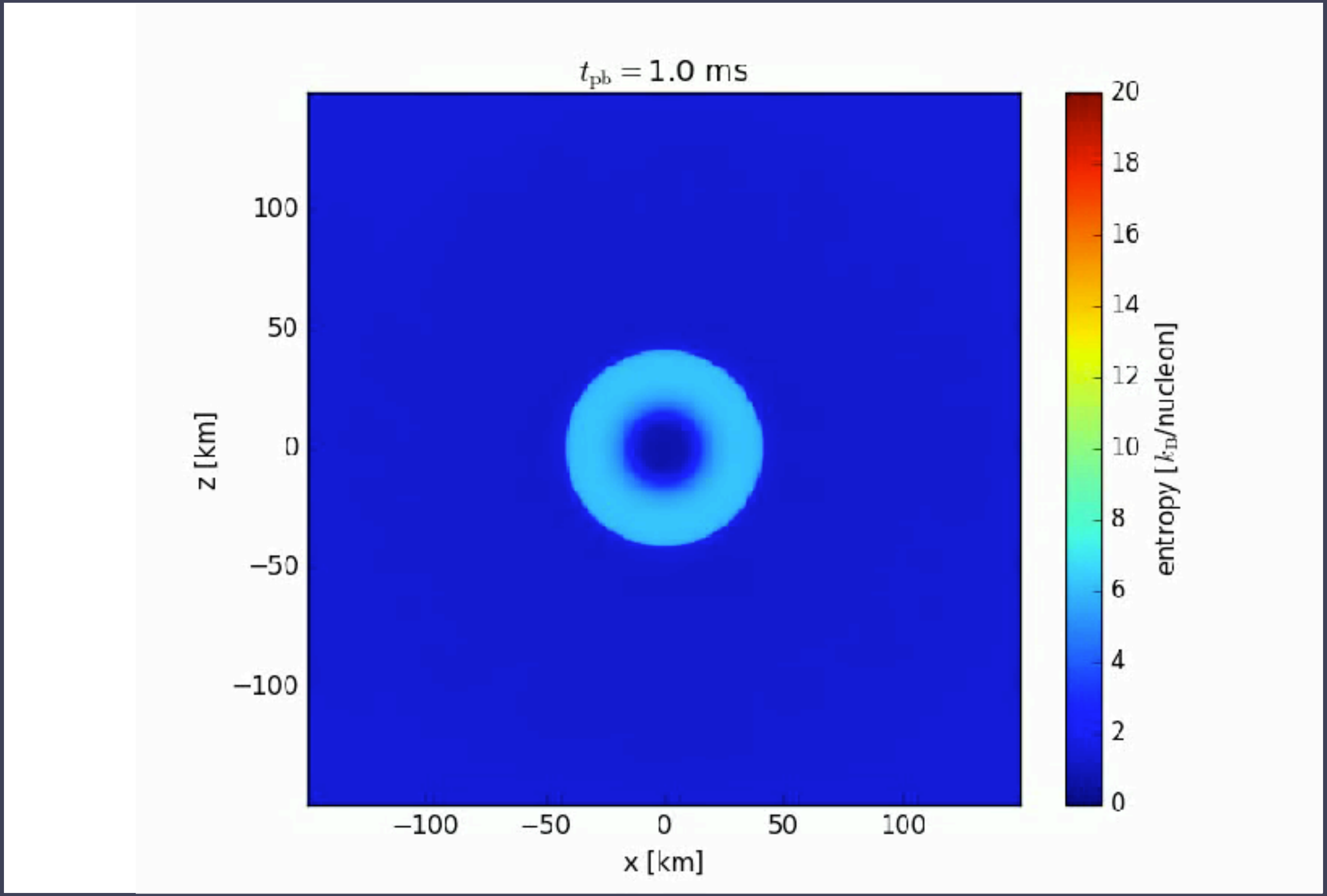
- Both positive and negative effects on shock revival
- Neutrino distributions are distorted
- (Thanks to the Boltzmann solver,) The accuracy of approximation is checked.
- Imposed rotation:

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



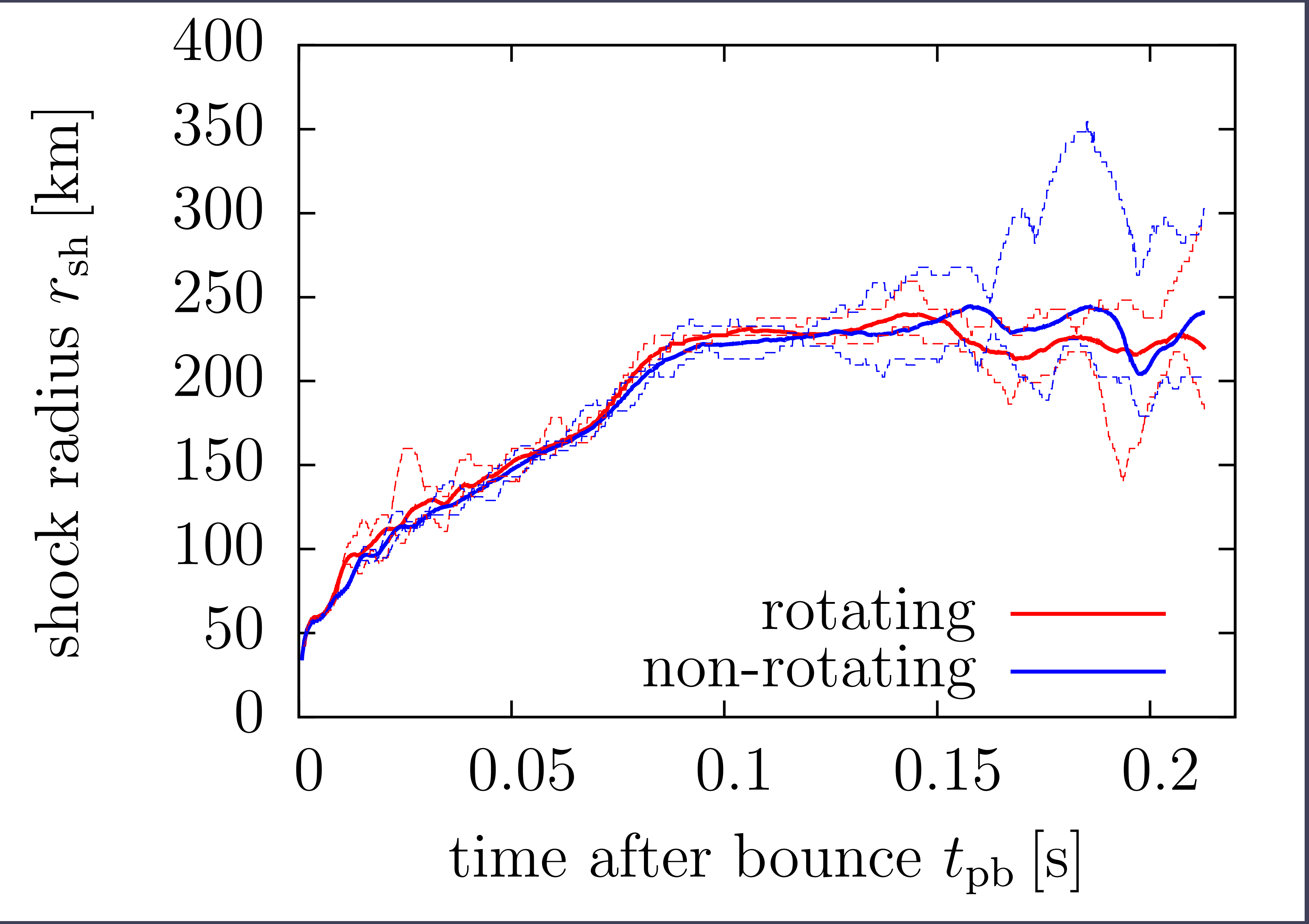
# Entropy distribution

- Time evolution until ~200 ms after bounce.



# Shock evolution

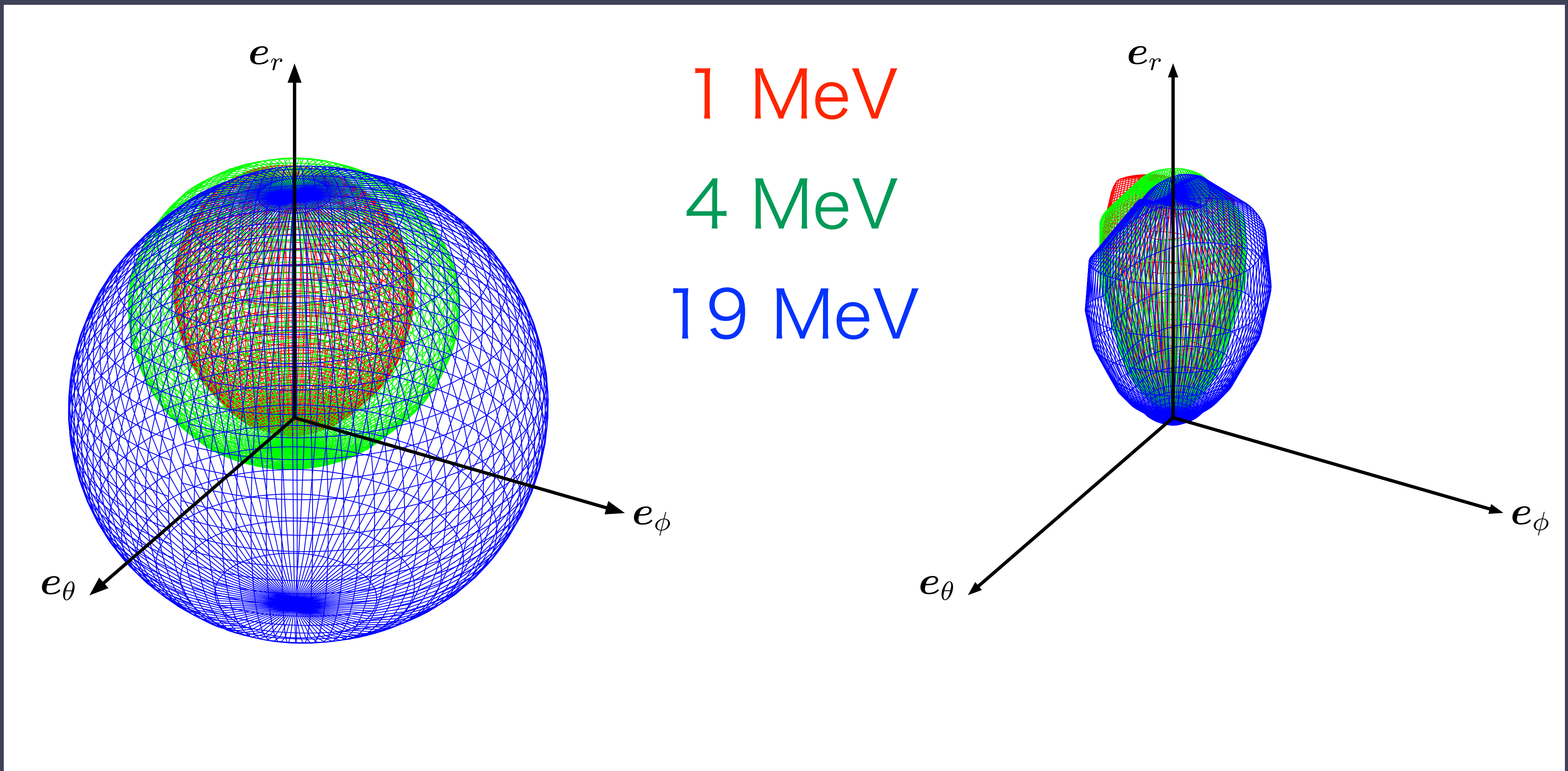
- Postbounce evolution until ~200 ms
- The difference between rotating & non-rotating model




Harada+(2018)

# Neutrino ang. distribution

- Distribution functions at ~10 ms after bounce.




~60 km

~170 km

Harada+(2018)

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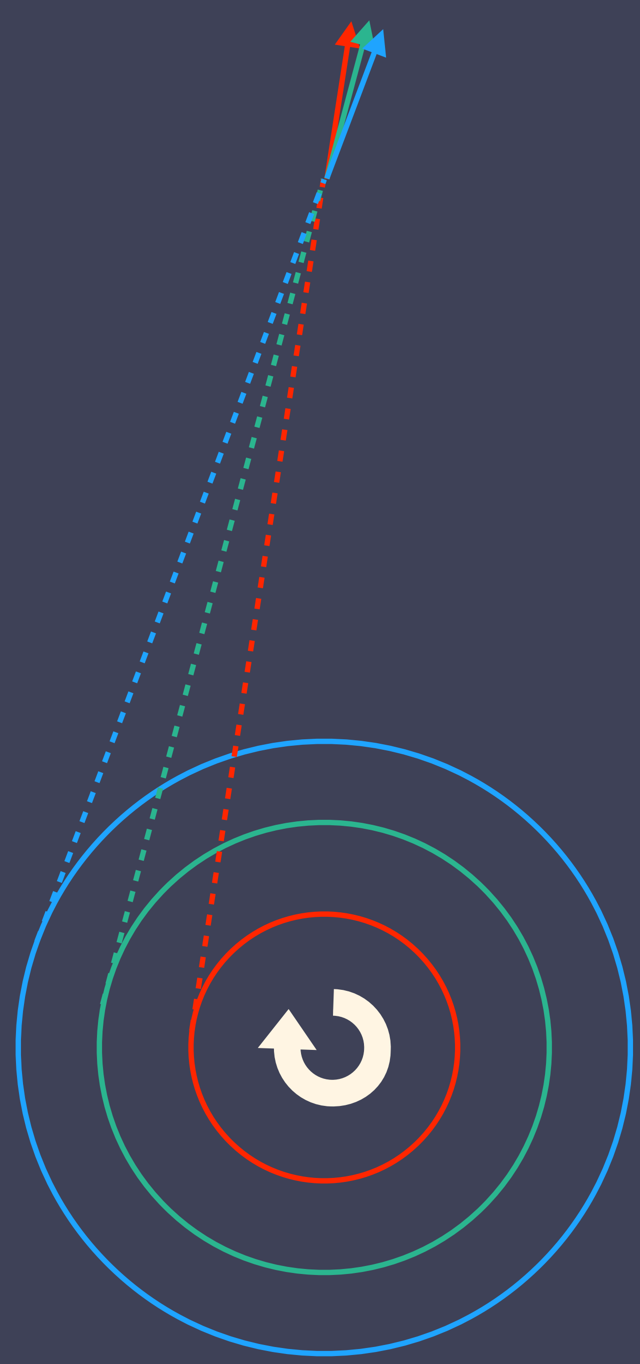
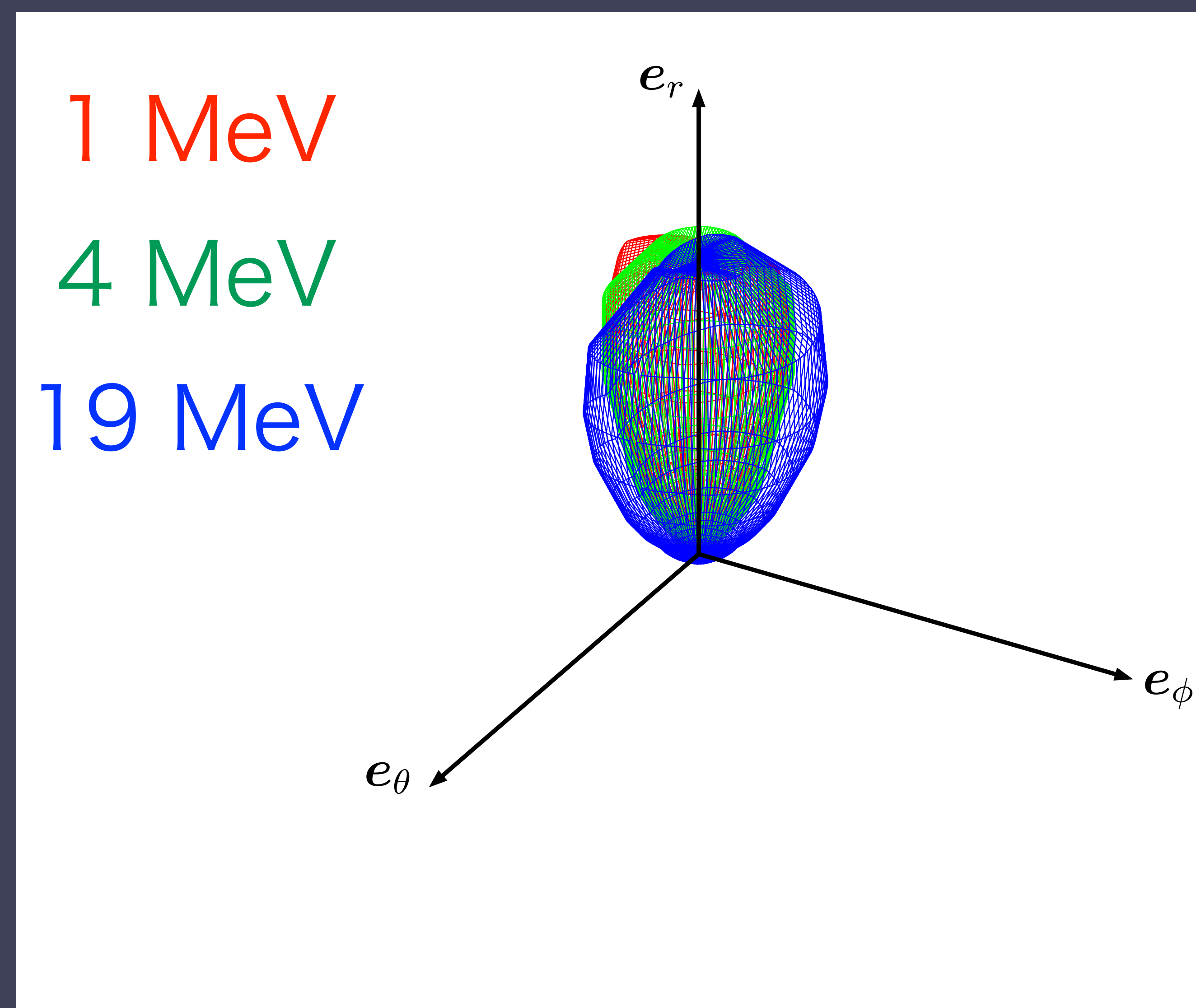


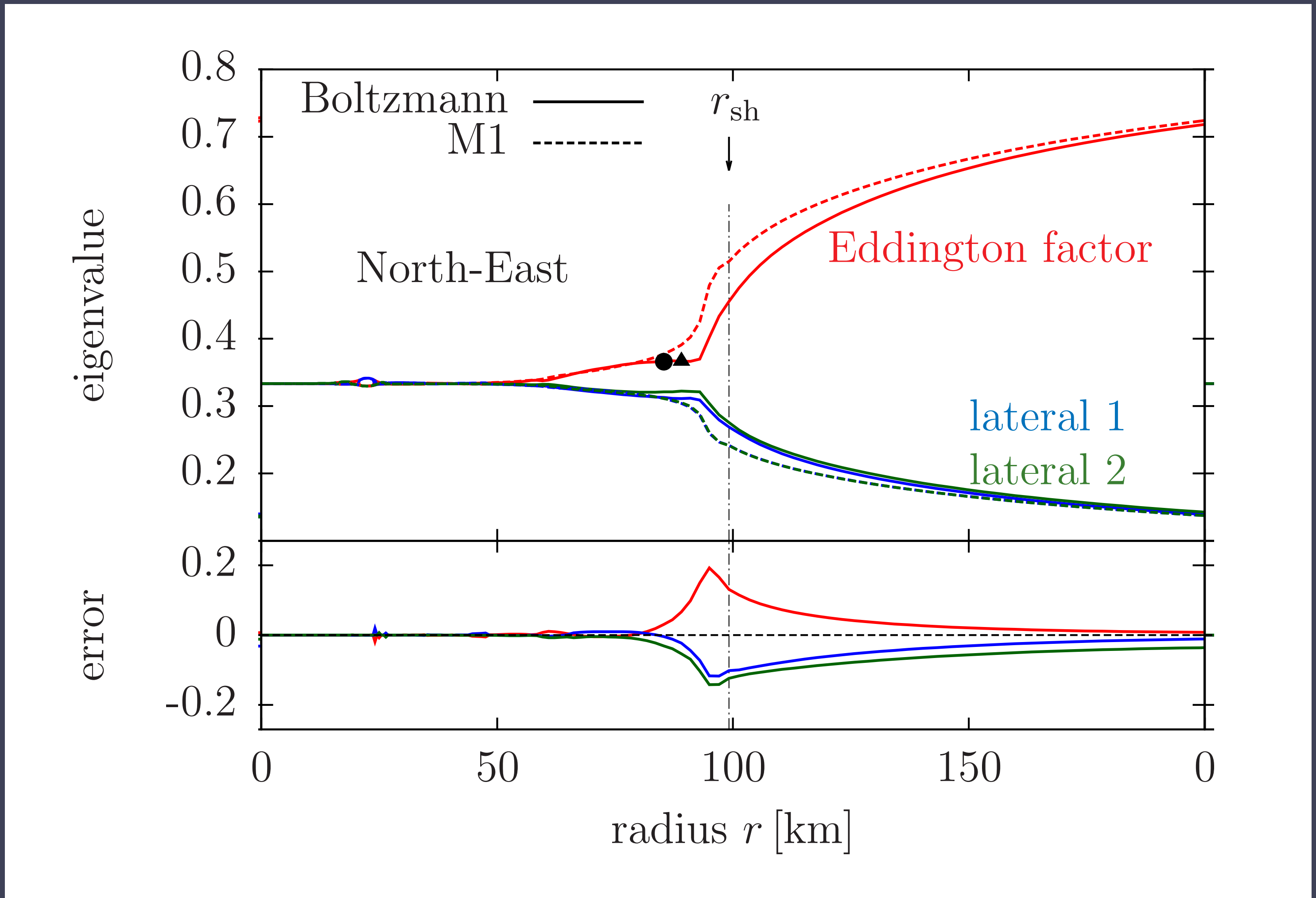



~170 km

Harada+(2018)

# Eddington factor

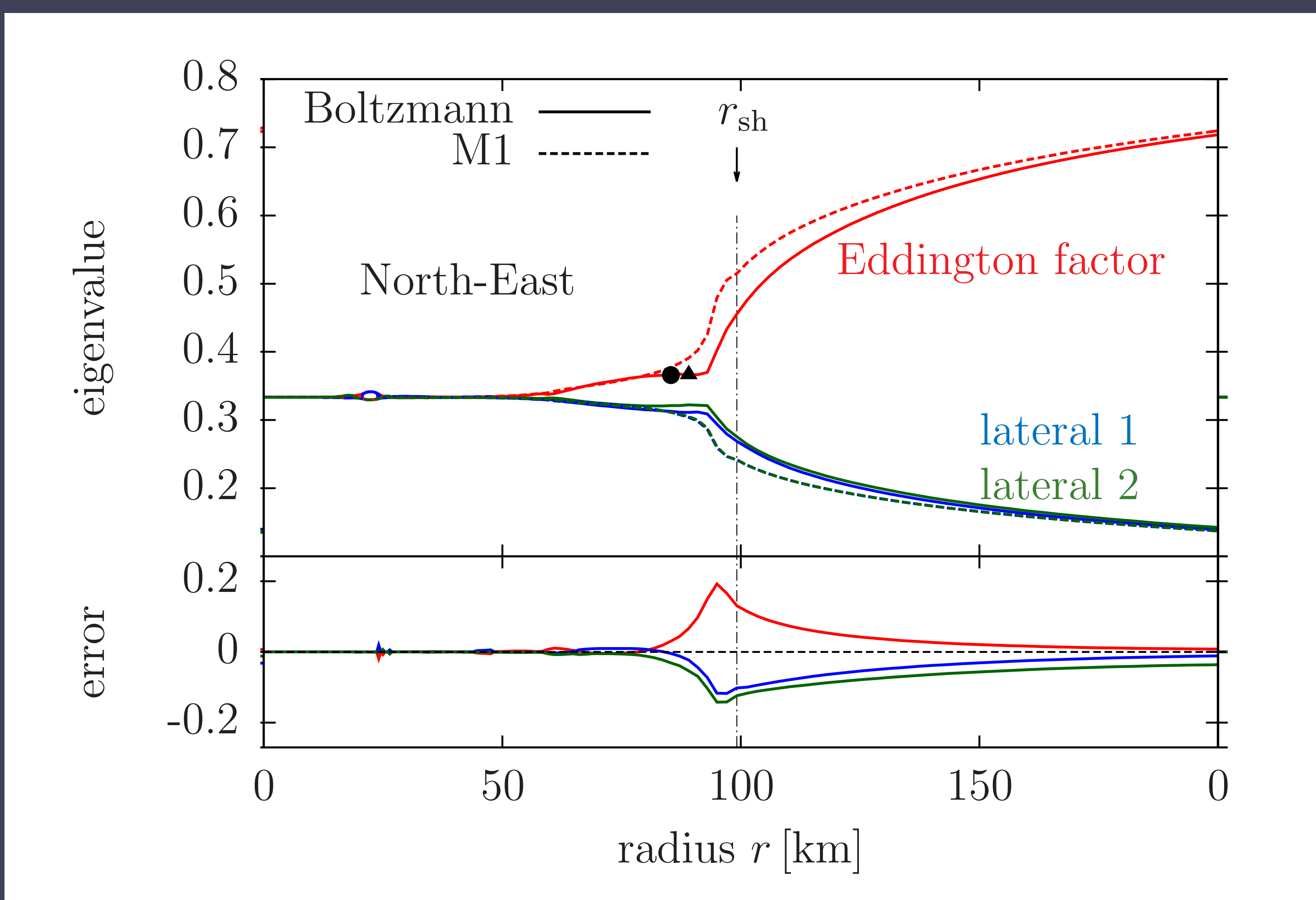
- Eddington tensor at ~10 ms after bounce
- spatial distribution of eigenvalues
- ~20% difference in M1-closure scheme




Harada+(2018)

# Eddington factor

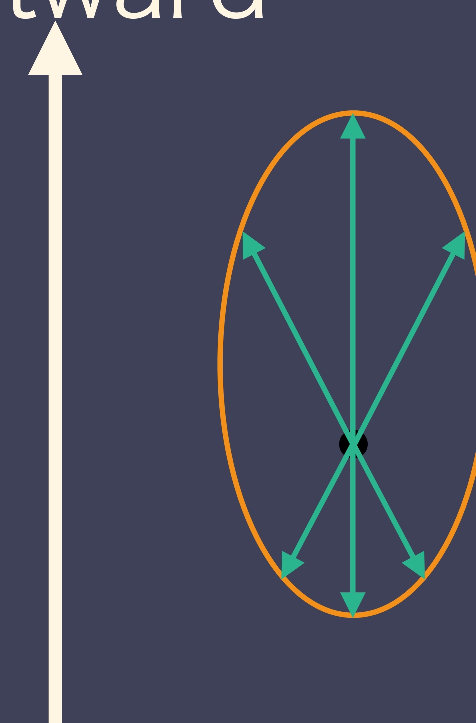
- Eddington tensor at ~10 ms after bounce
- Comparison between Boltzmann- and M1-Edd. factors




Harada+(2018)

- Prolateness of distribution
- M1: estimated from deviation

outward



inward

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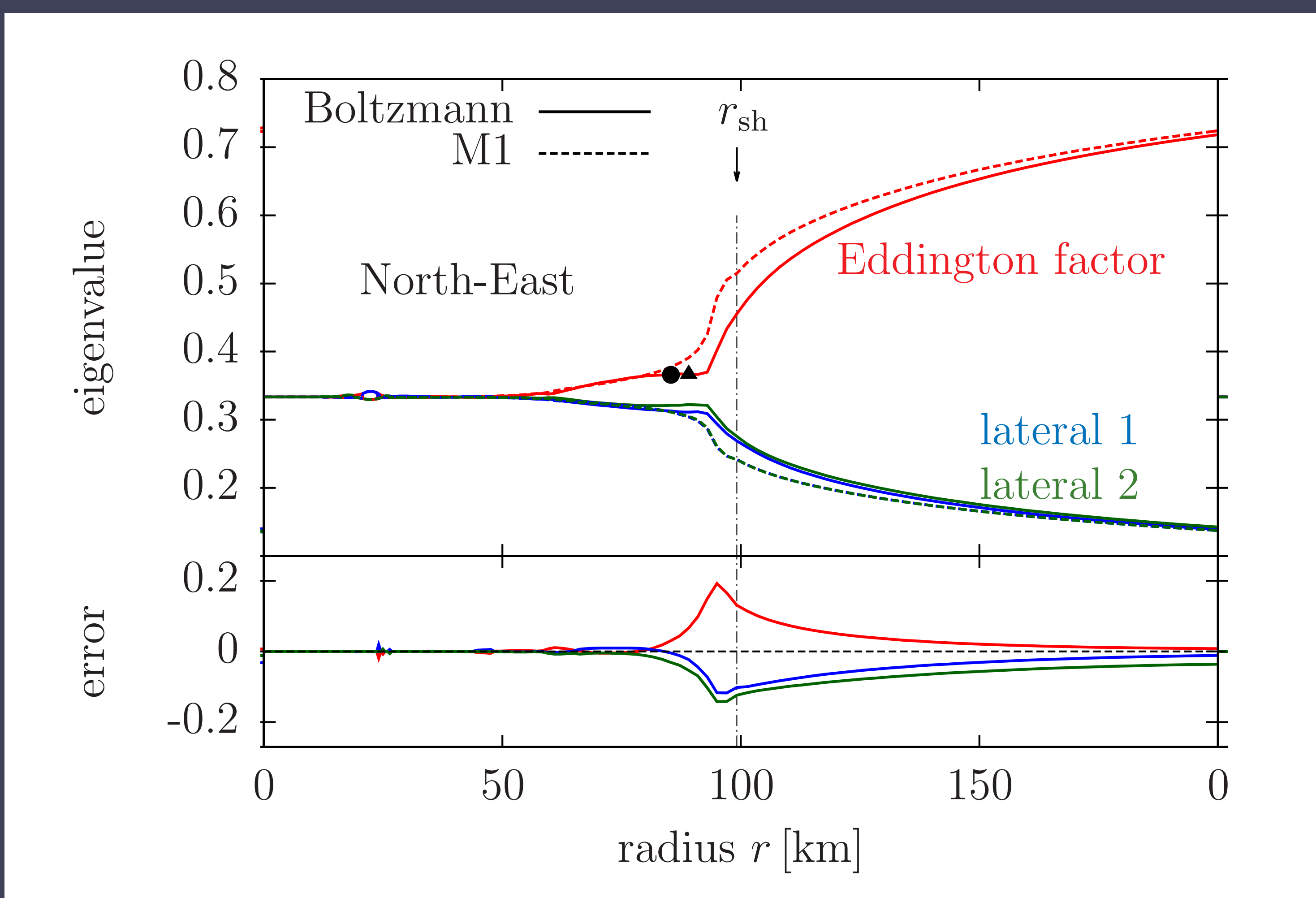
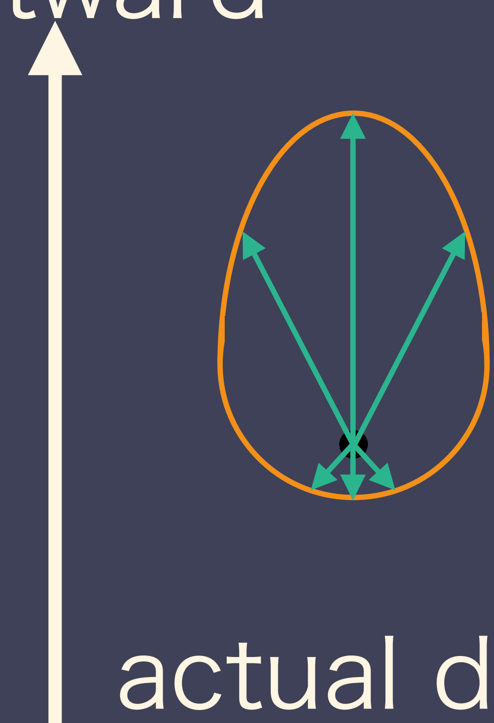



Harada+(2018)



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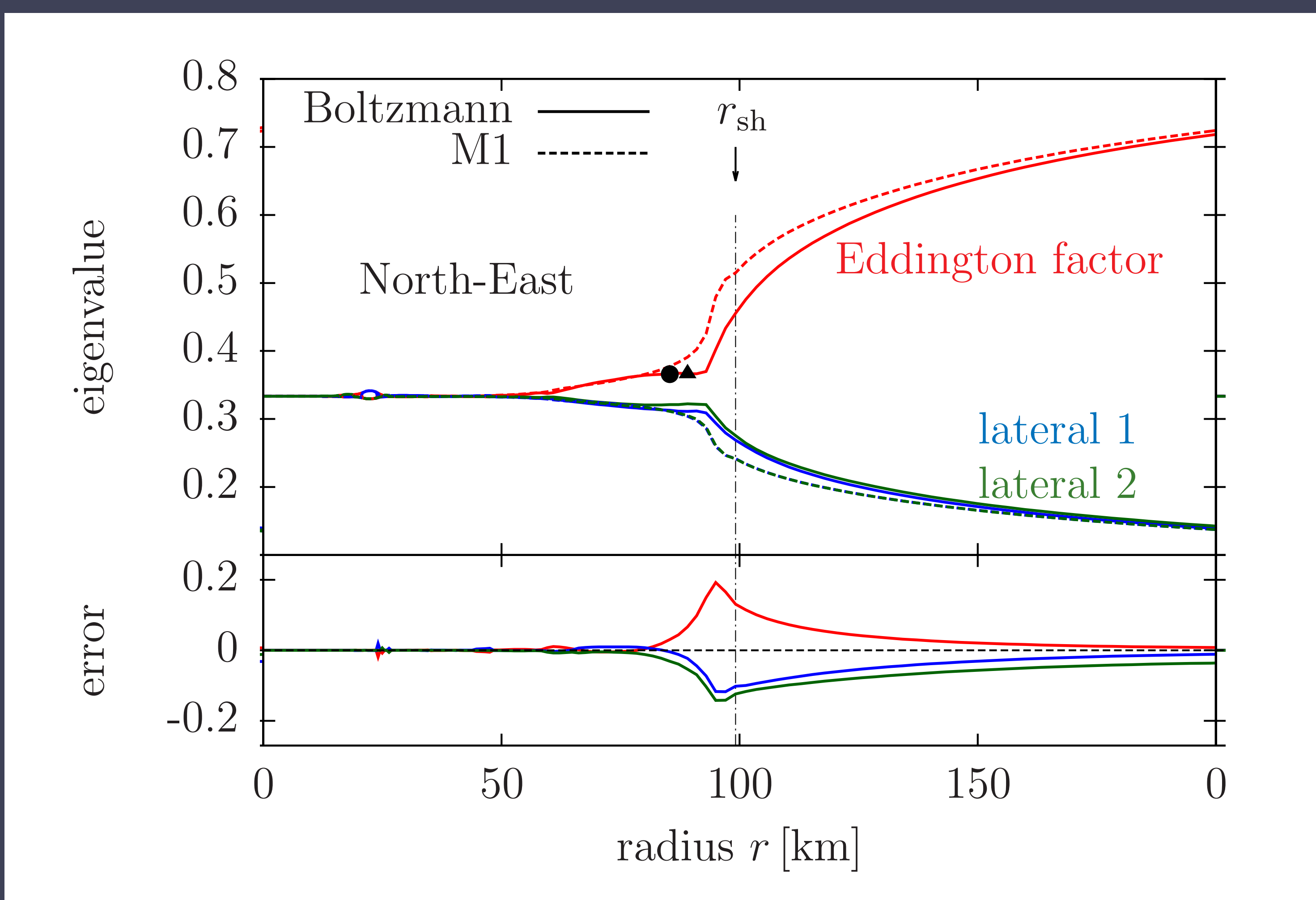


Harada+(2018)

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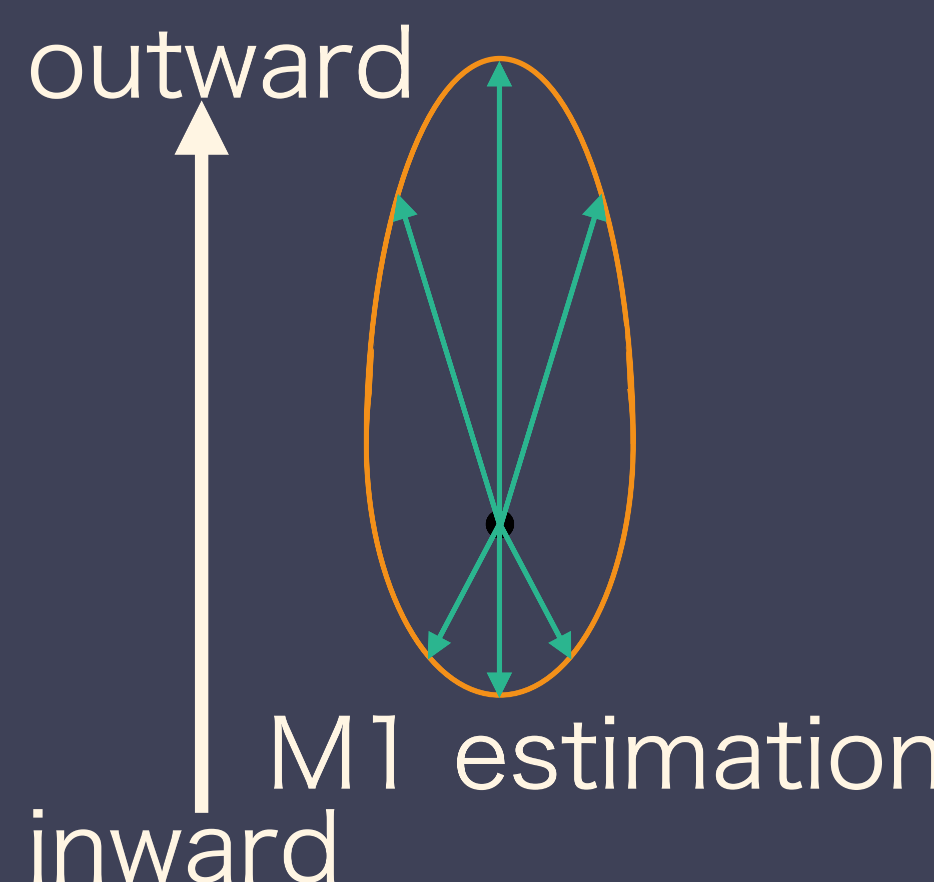
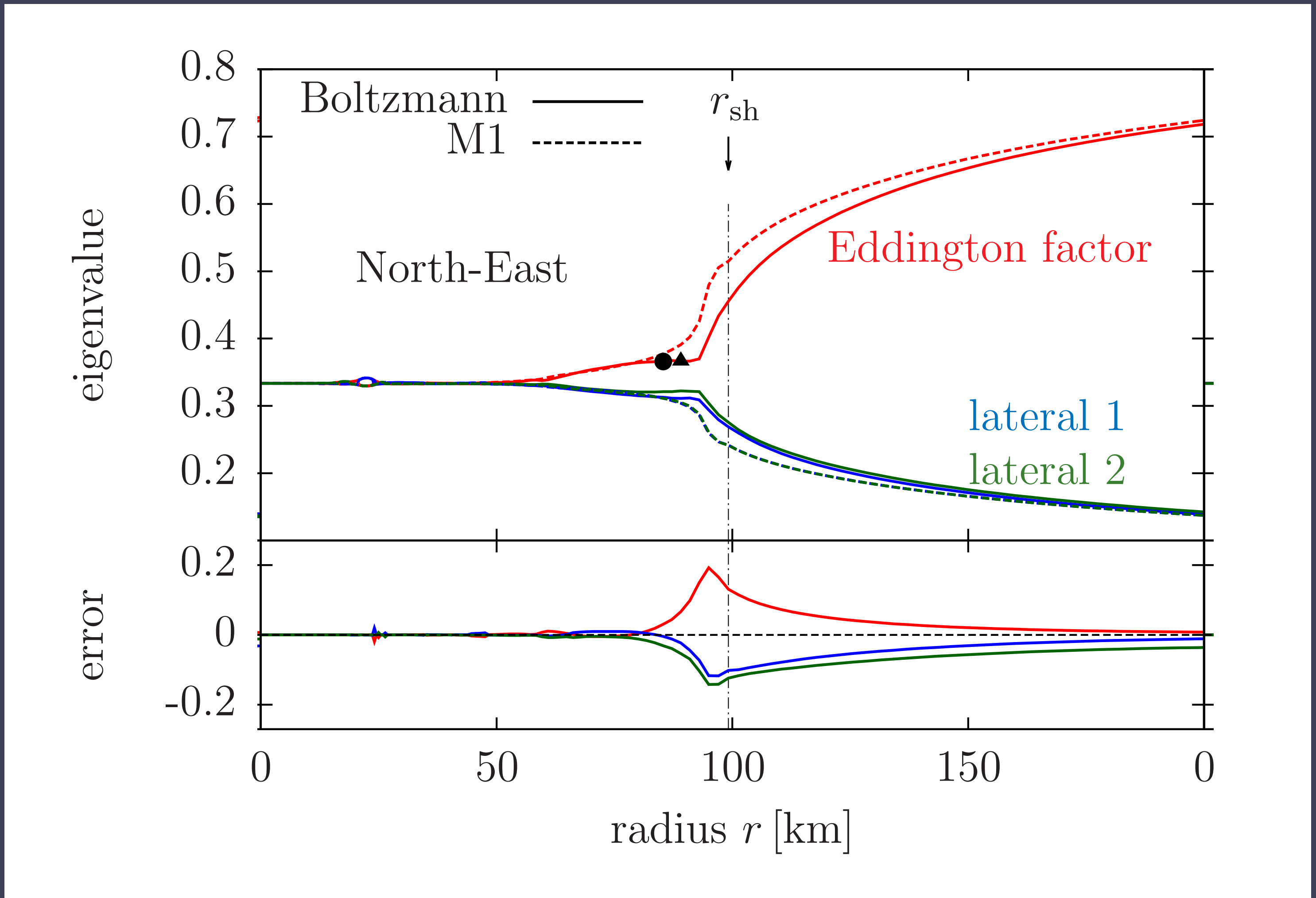


# Eddington factor

- Eddington tensor at ~10 ms after bounce
- Comparison between Boltzmann- and M1-Edd. factors
- Information which distinguish these situations may improve the approximation

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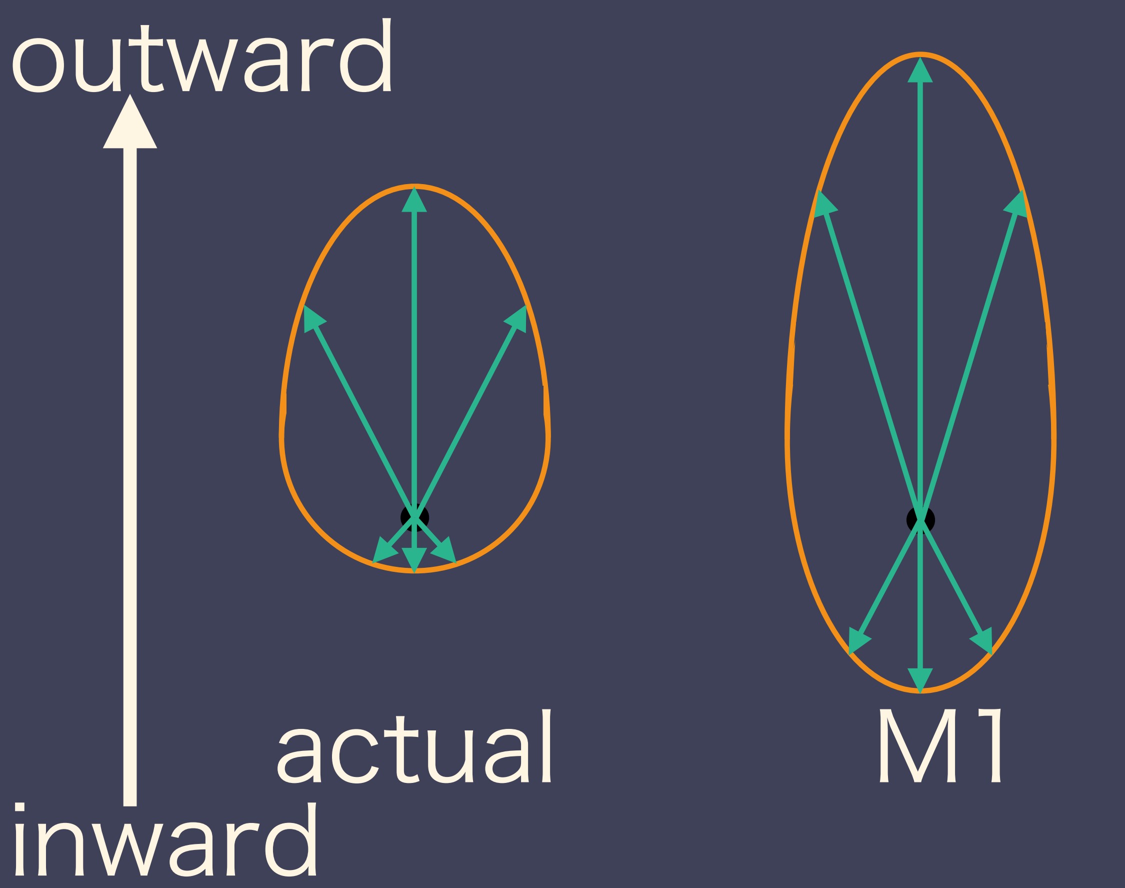
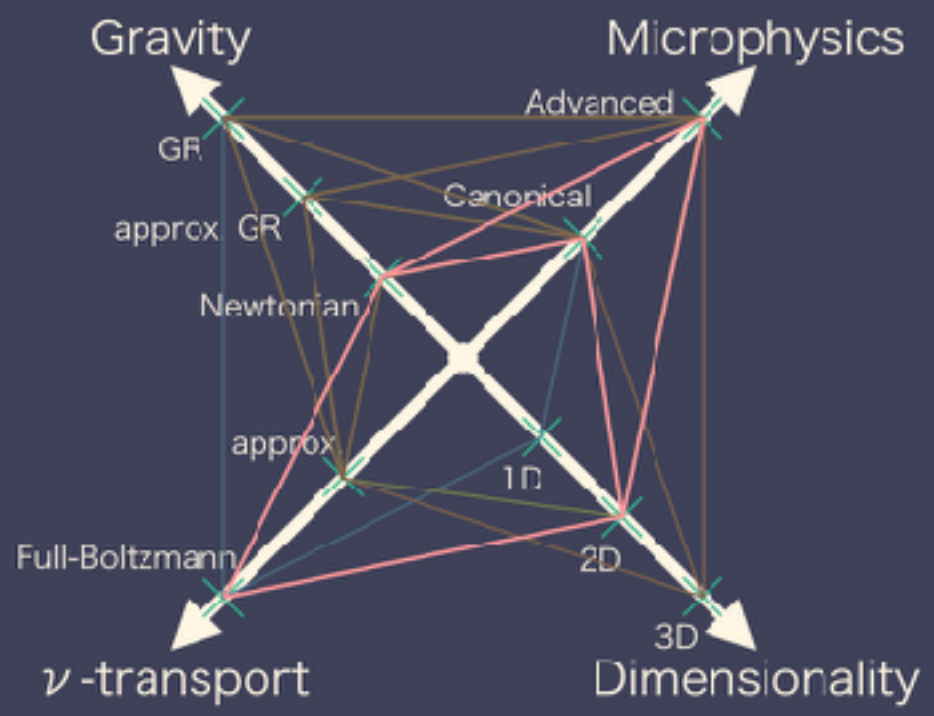
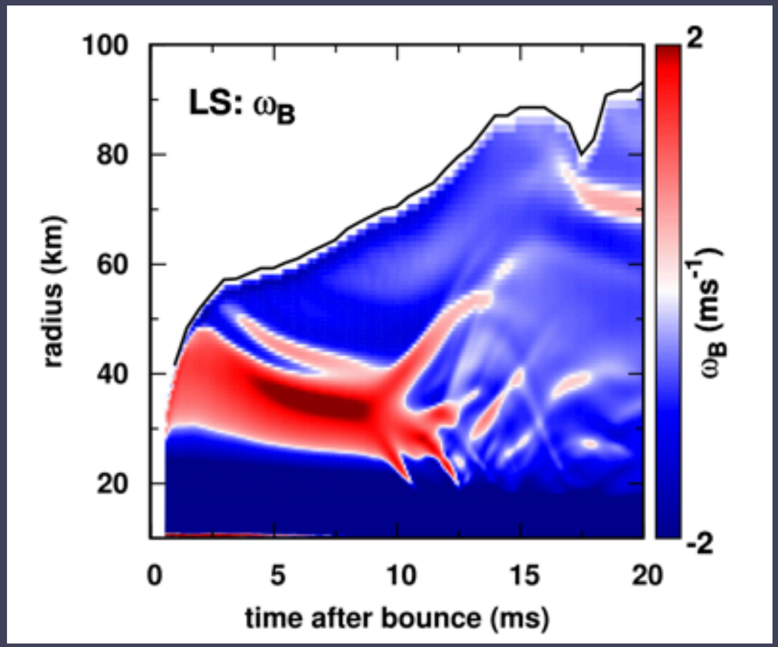
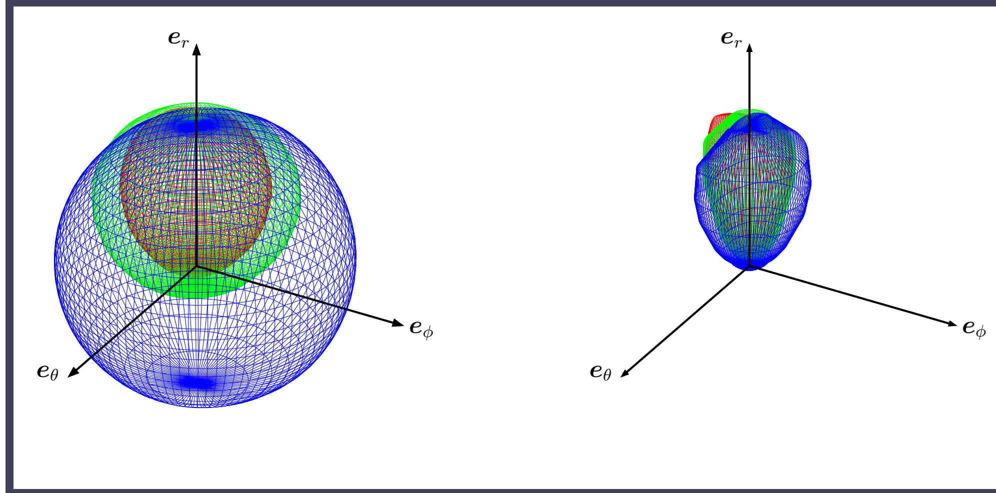


# Summary

- Core-collapse supernova simulations with the Boltzmann-radiation-hydrodynamics have been performed.
- Nuclear composition in EOS seems to play an important role.
- Unique feature is obtained by using the Boltzmann code.



Thank you for listening!