Multi-dimensional core-collapse supernova simulations with the Boltzmann-radiation-hydrodynamics code

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Core-collapse supernovae

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

SN1987A
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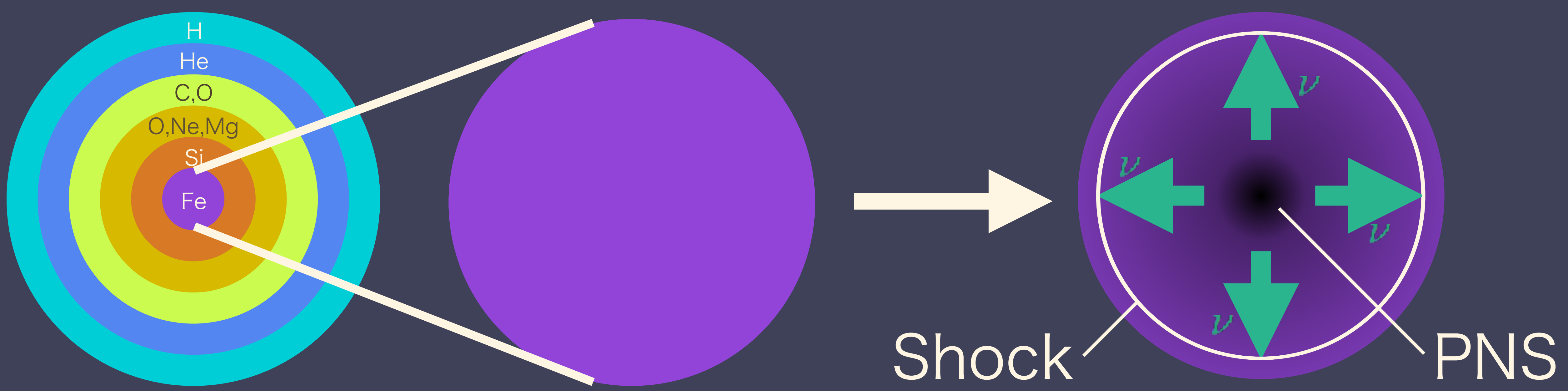
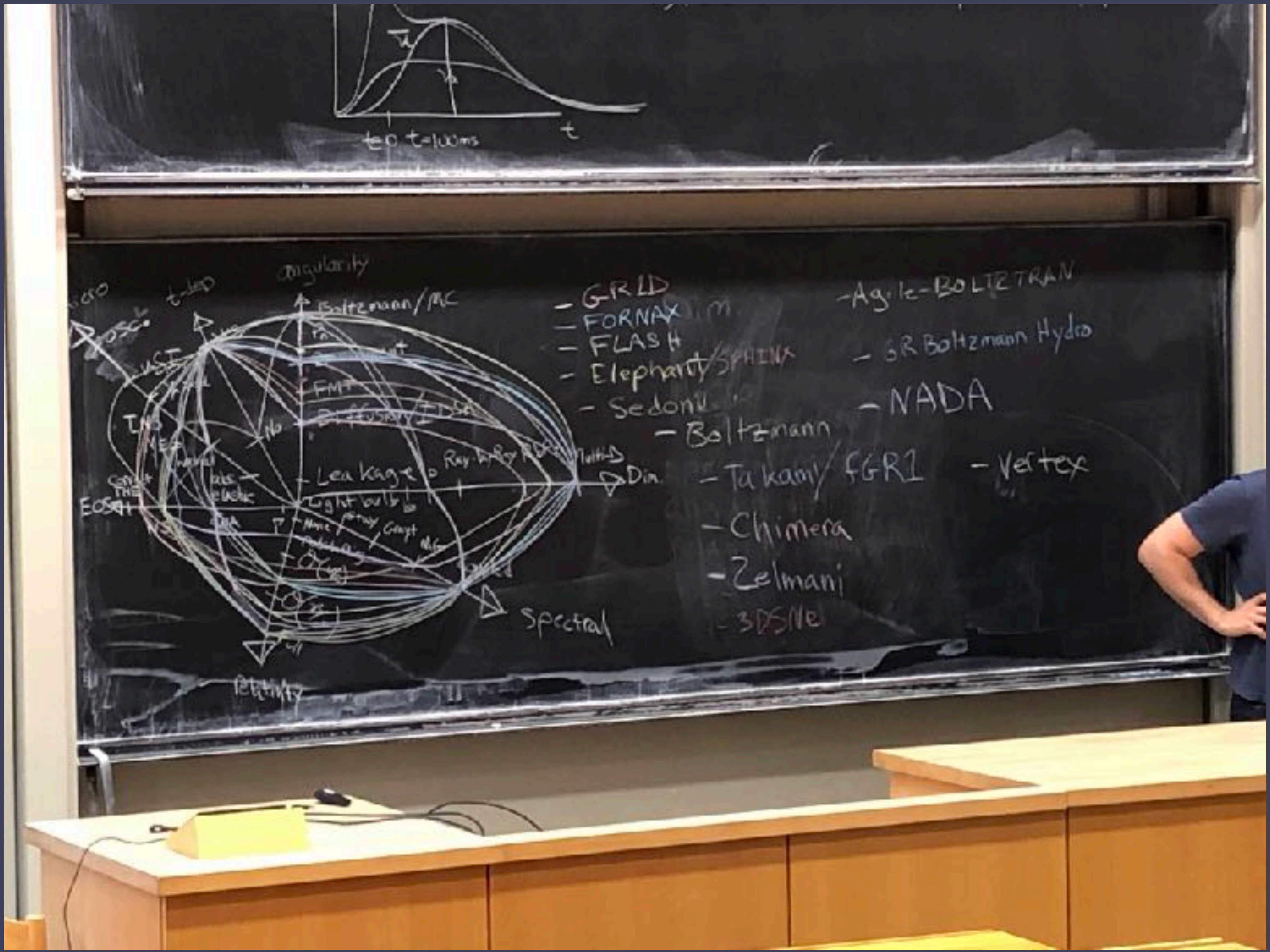
CCSN explosion mechanism

- 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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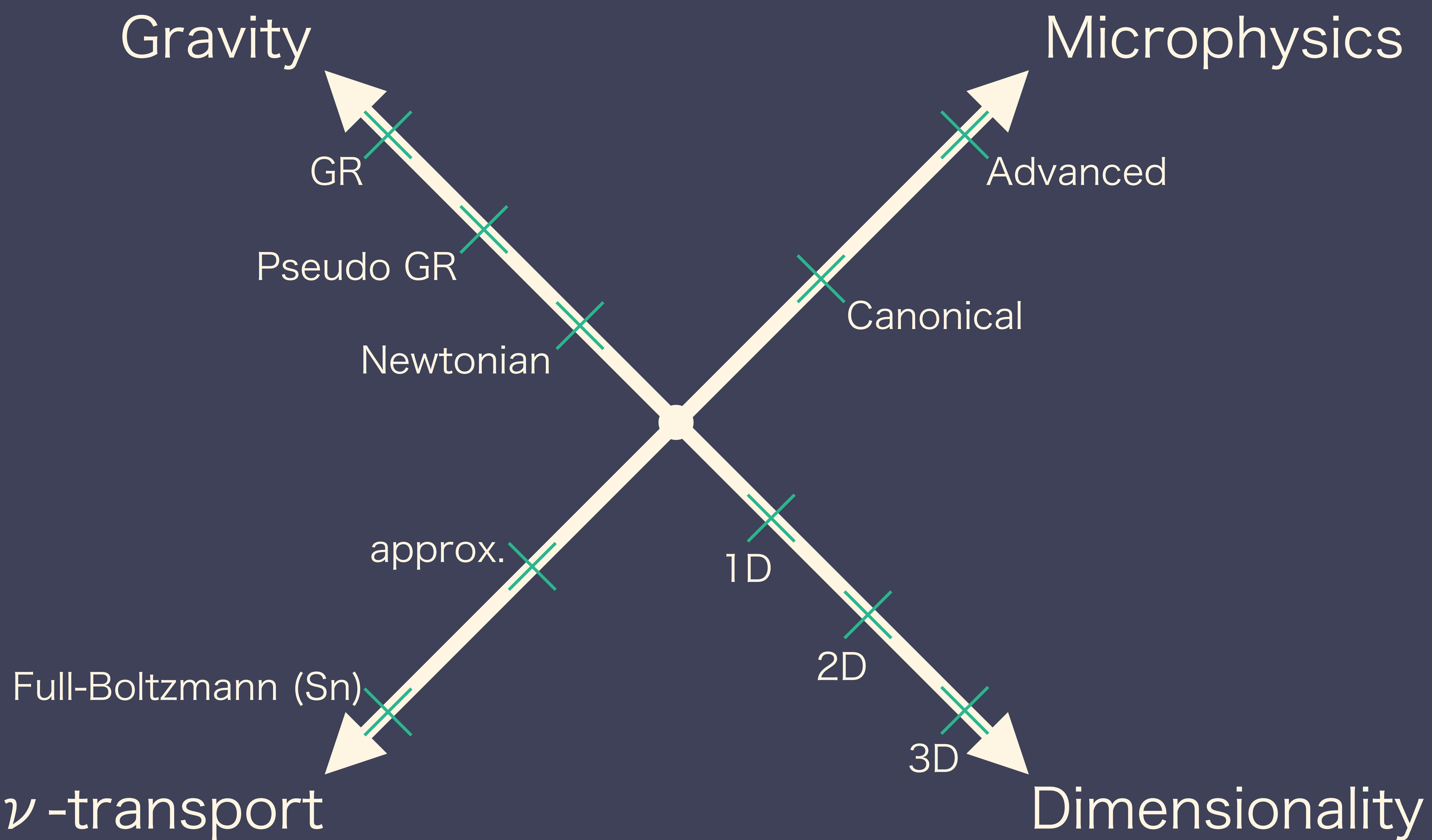

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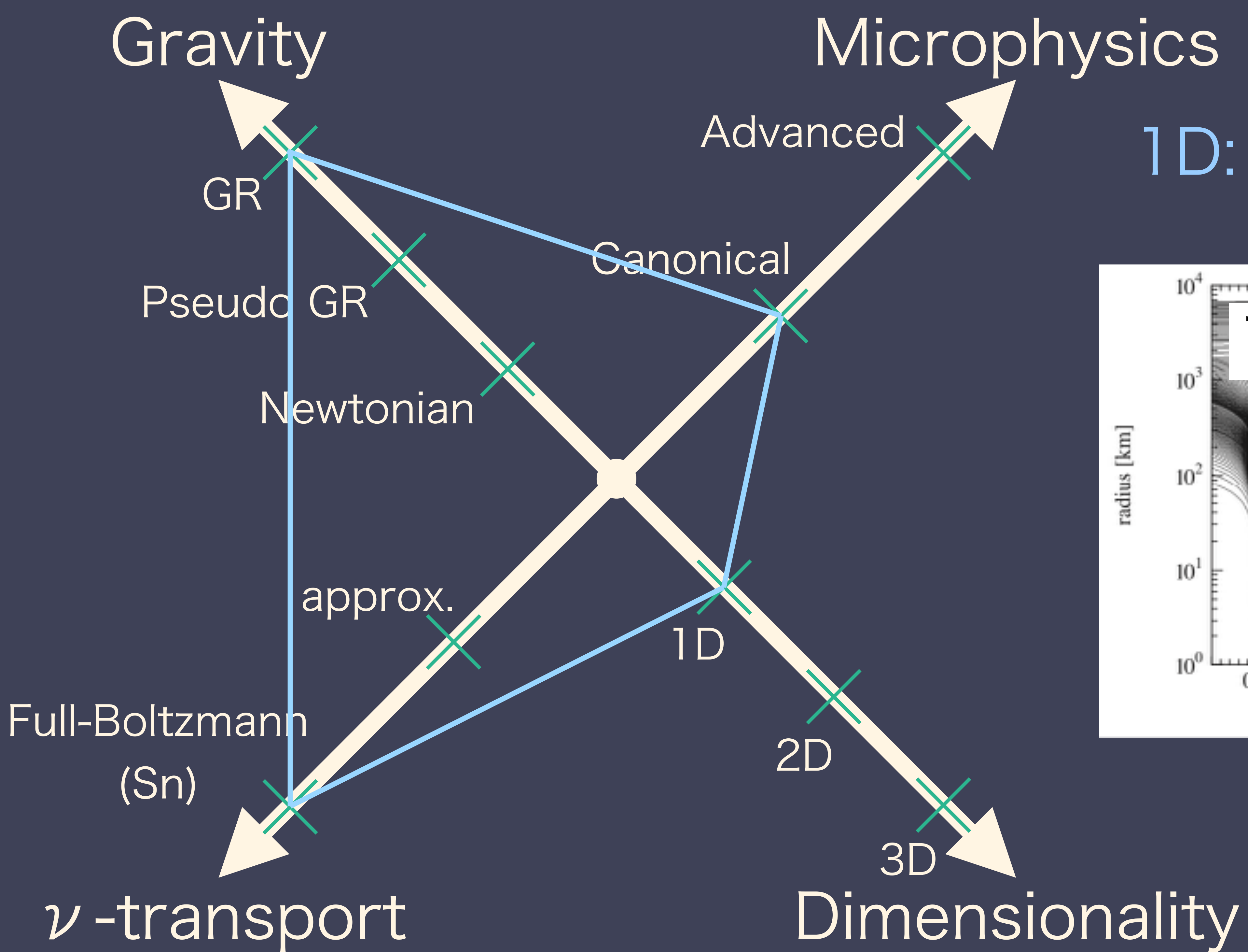
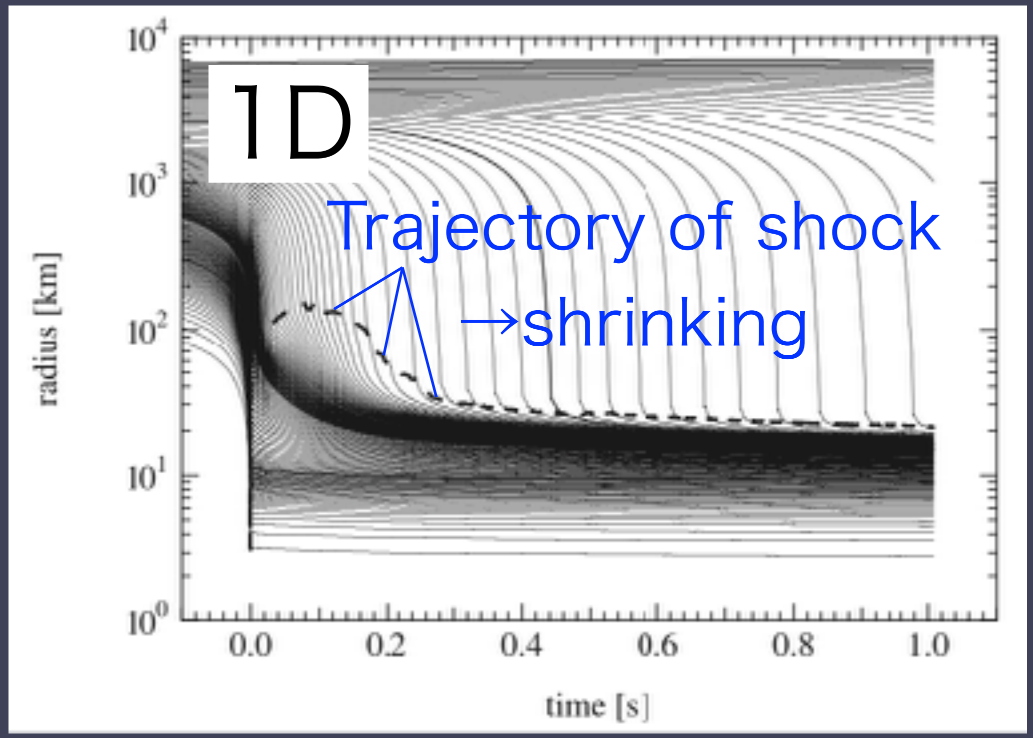
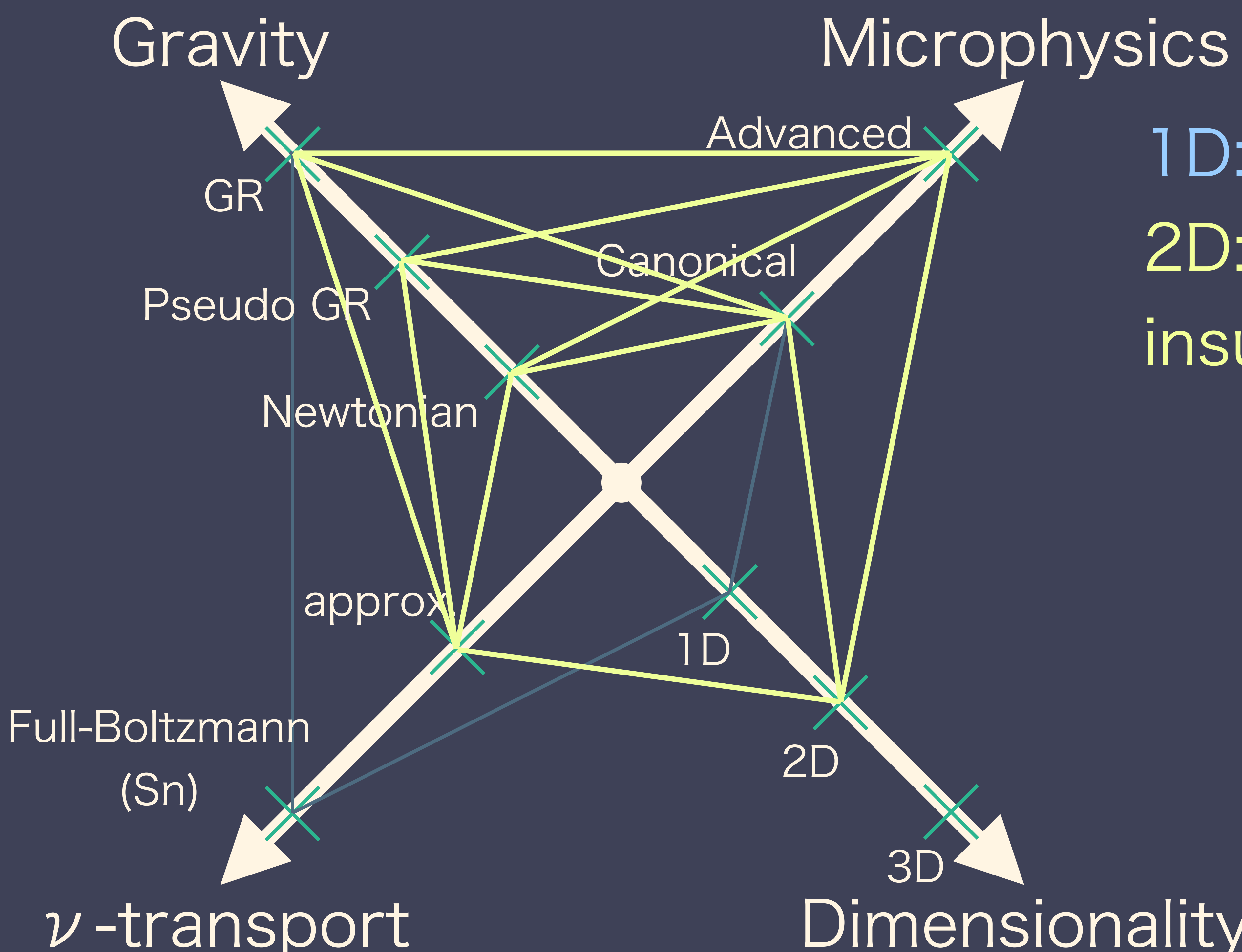


1D: fail to explode



Sumiyoshi+(2005)

The progress in CCSNe sim.

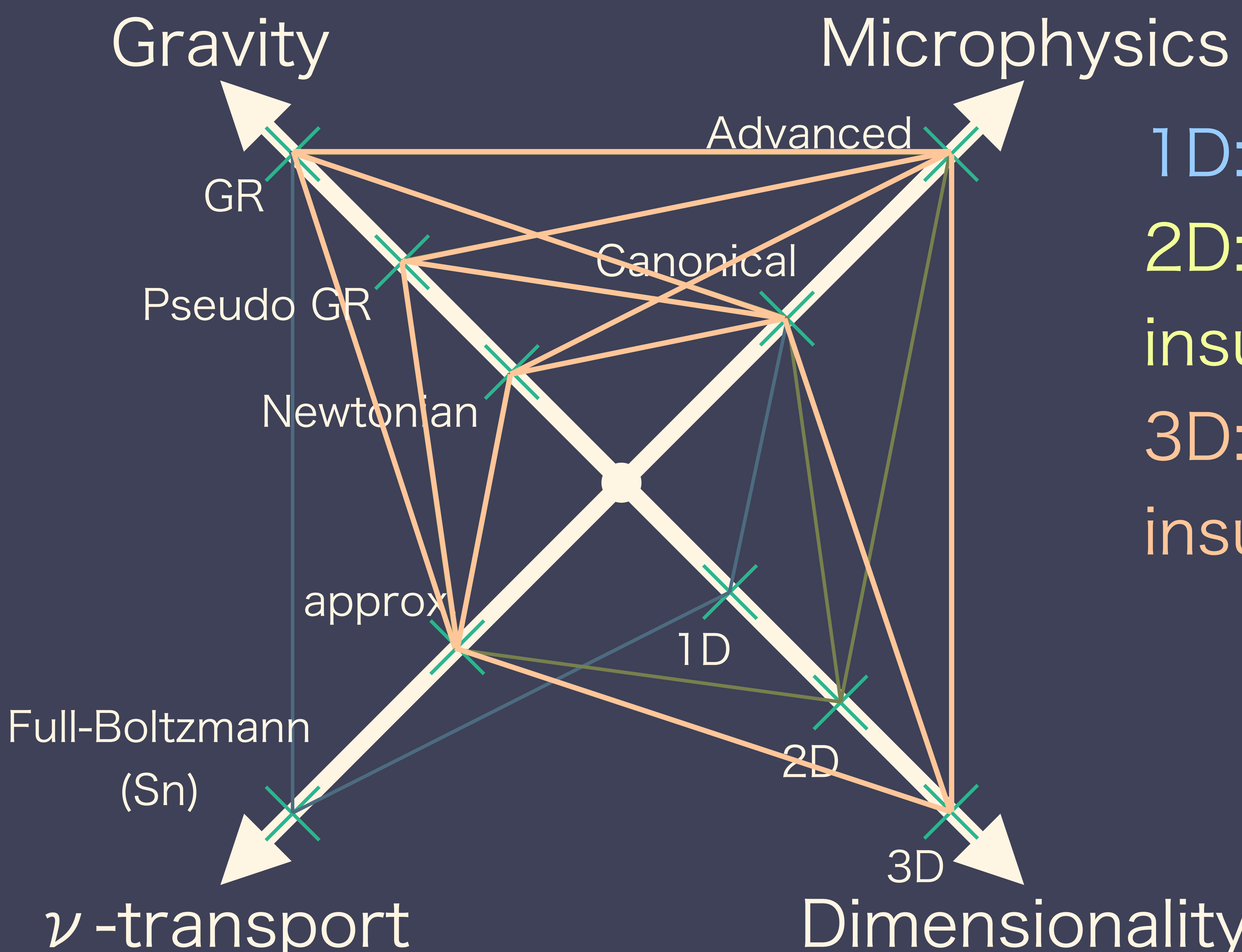


1D: fail to explode

2D: shock revives

insufficient energy

The progress in CCSNe sim.

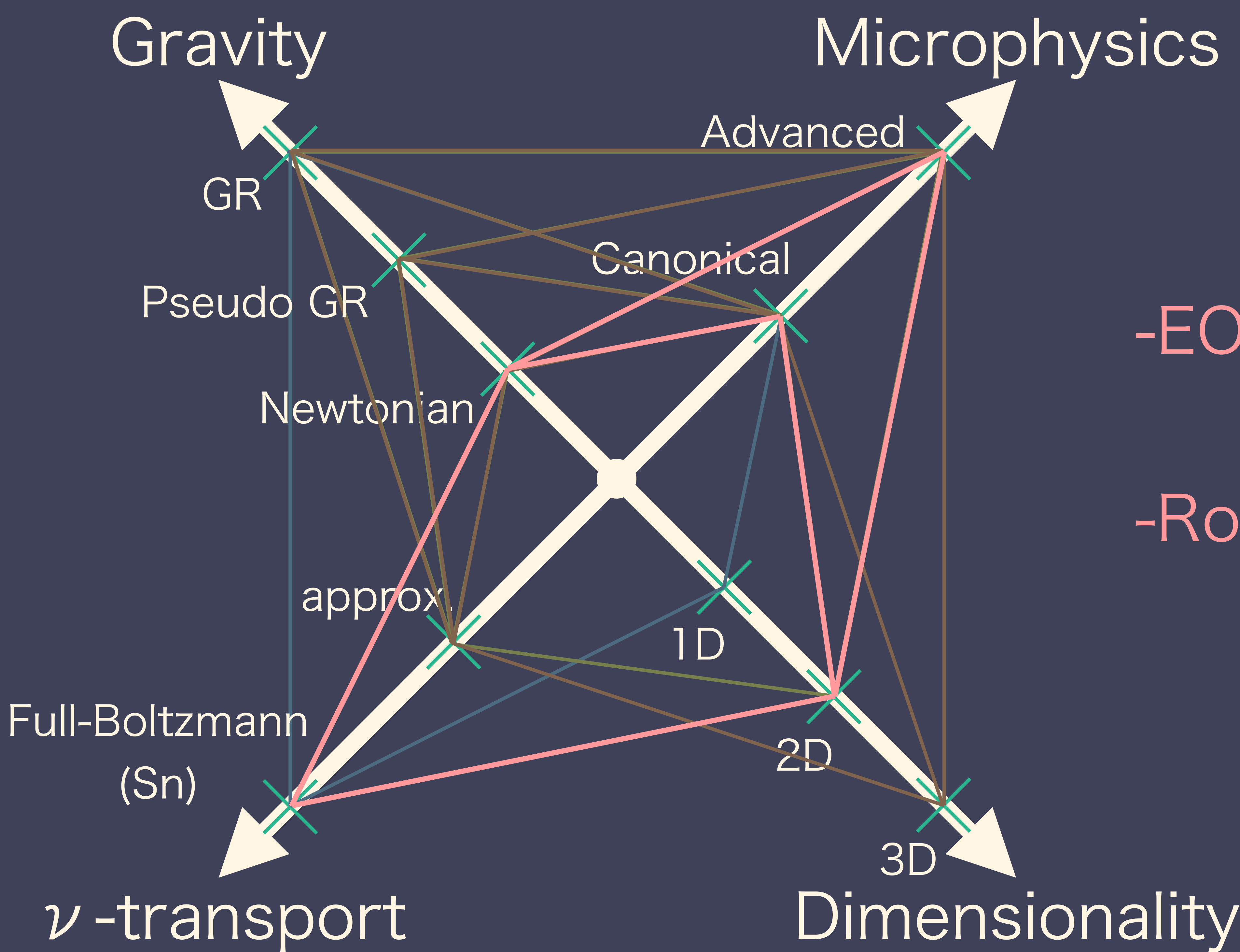


1D: fail to explode

2D: shock revives insufficient energy

3D: shock revives insufficient energy

The progress in CCSNe sim.



-EOS comparison

-Rotation

Setup

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

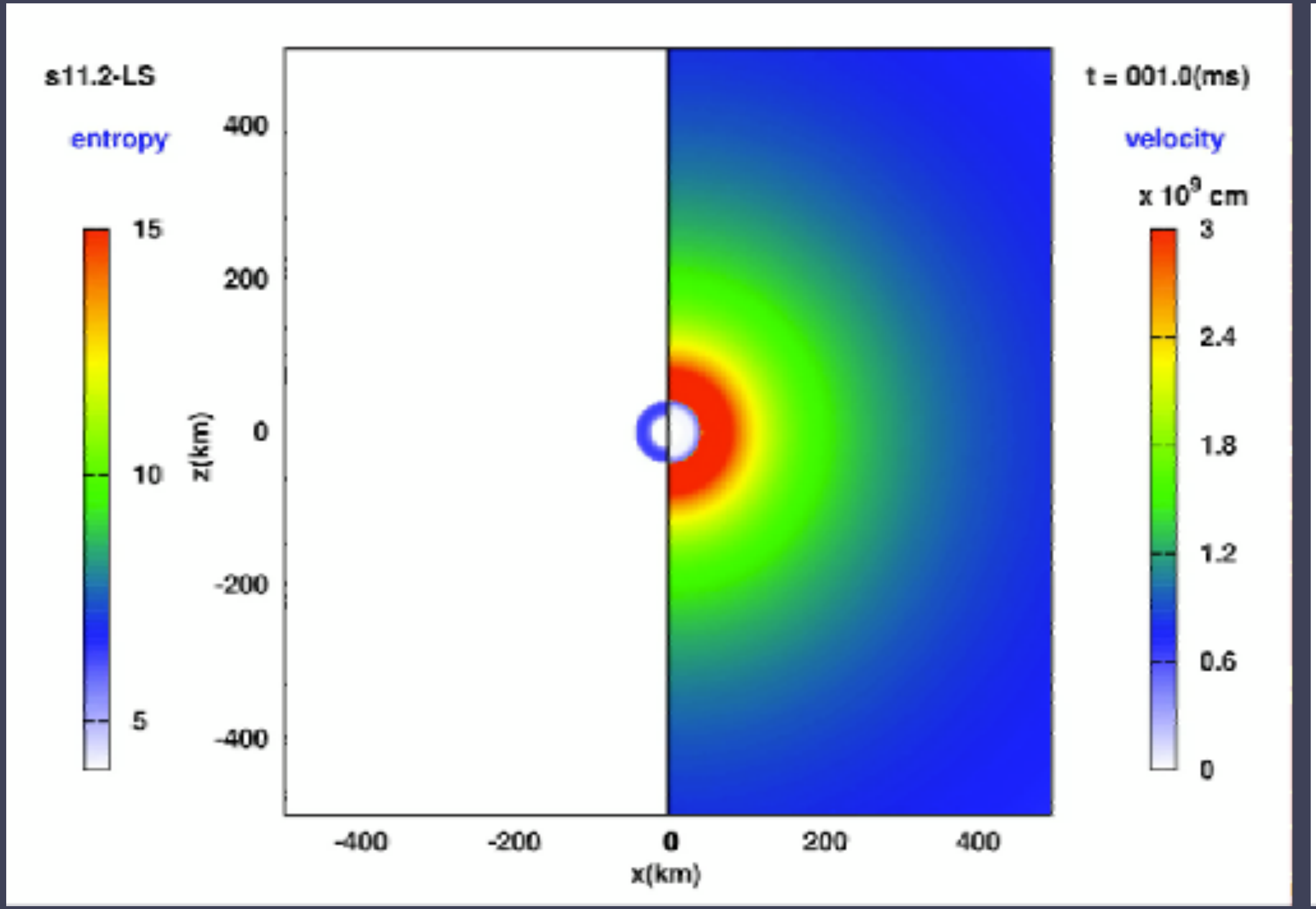
$$\begin{aligned} \nu_e + n &\leftrightarrow e^- + p & \nu + A &\leftrightarrow \nu + A \\ \bar{\nu}_e + p &\leftrightarrow e^+ + n & \nu + e^- &\leftrightarrow \nu + e^- \\ \nu_e + A &\leftrightarrow e^- + A' & \nu + \bar{\nu} &\leftrightarrow e^- + e^+ \\ \nu + N &\leftrightarrow \nu + N & N + N &\leftrightarrow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

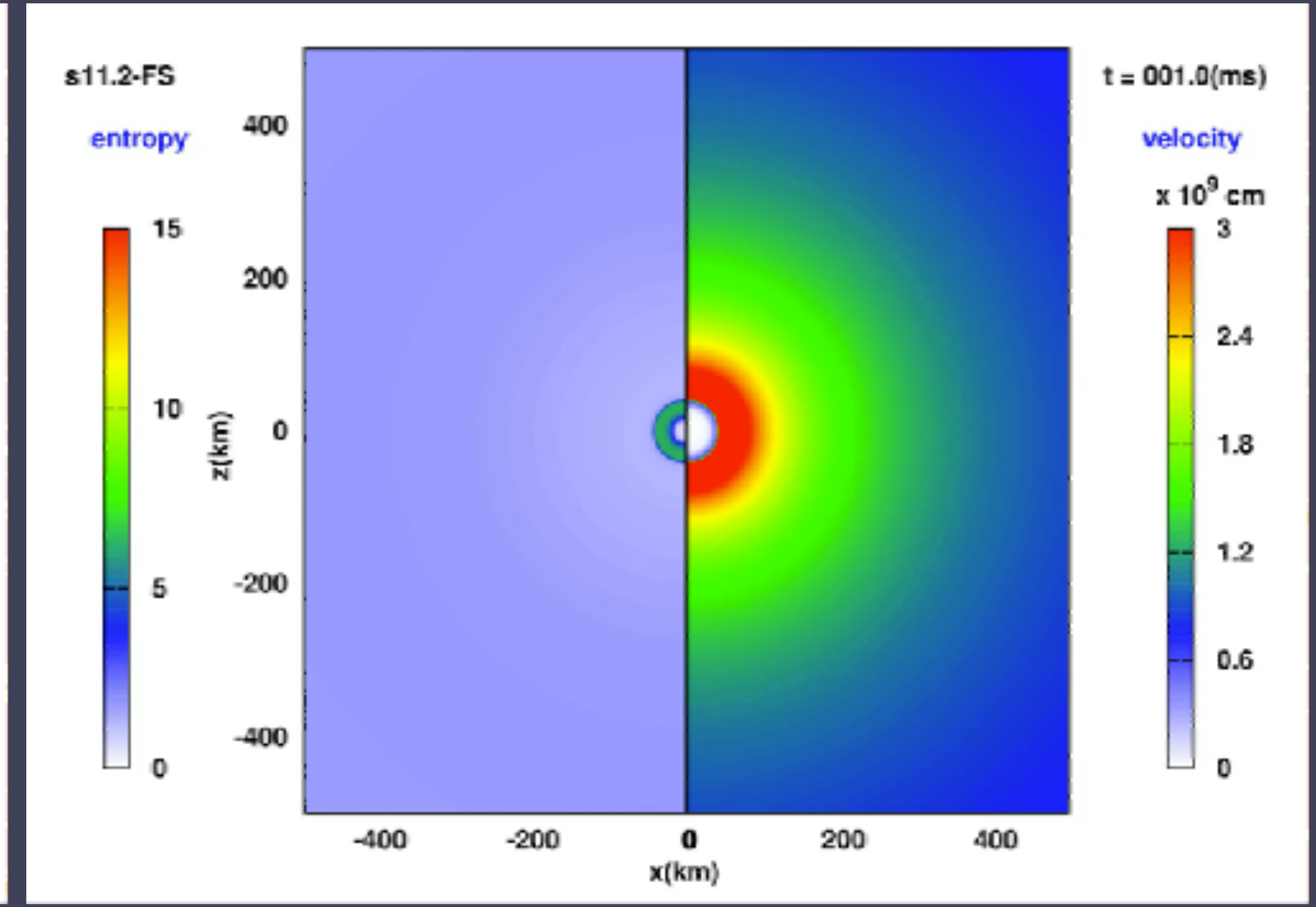
- Lattimer-Swesty EOS and Furusawa-Shen EOS

Lattimer-Swesty EOS	Furusawa-Shen EOS
Skyrm-type	RMF
SNA	NSE

Shock evolution

- Entropy and absolute value of velocity

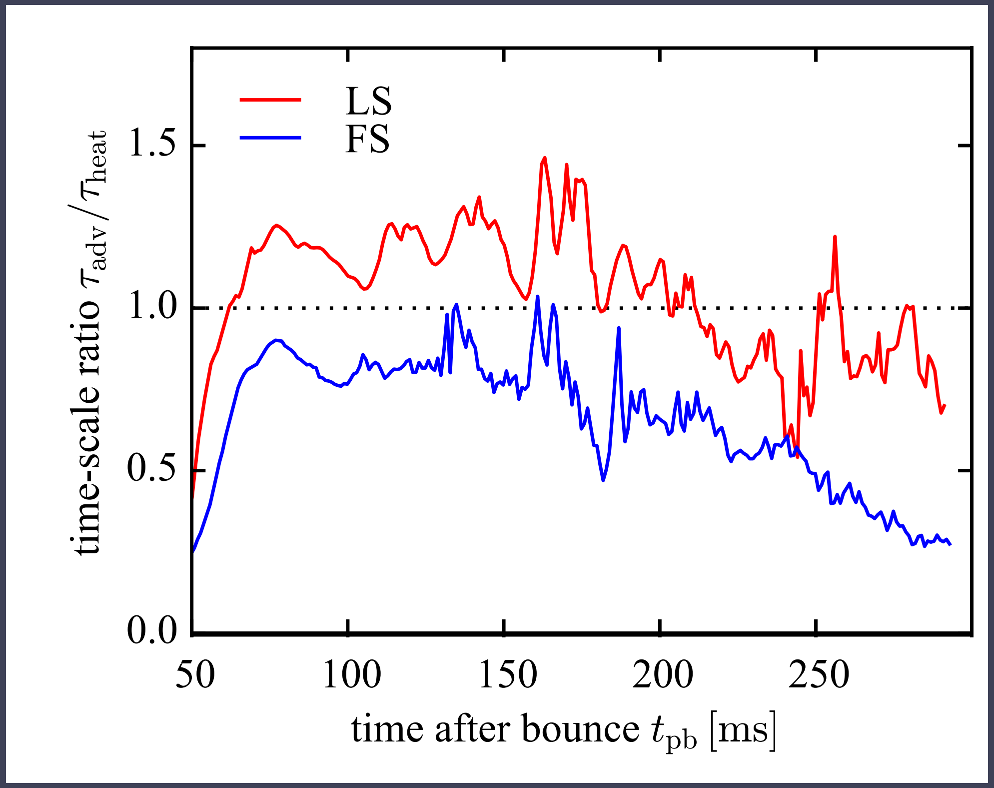


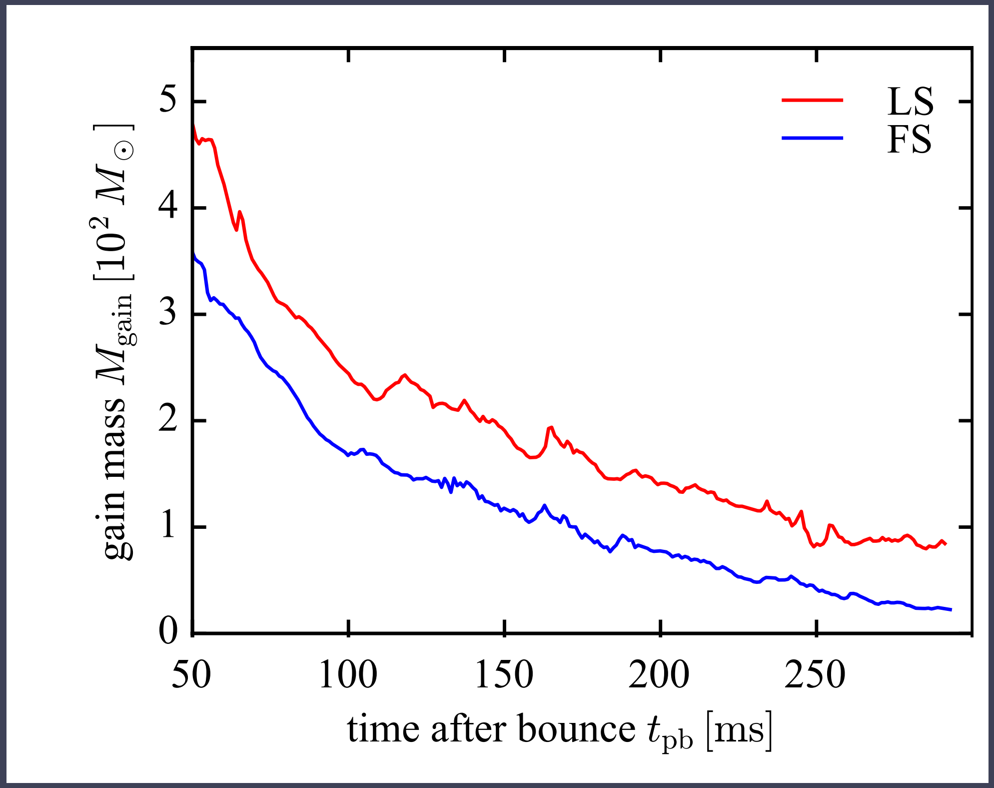


Timescale ratio

- Shock revives when the timescale ration exceeds 1:

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



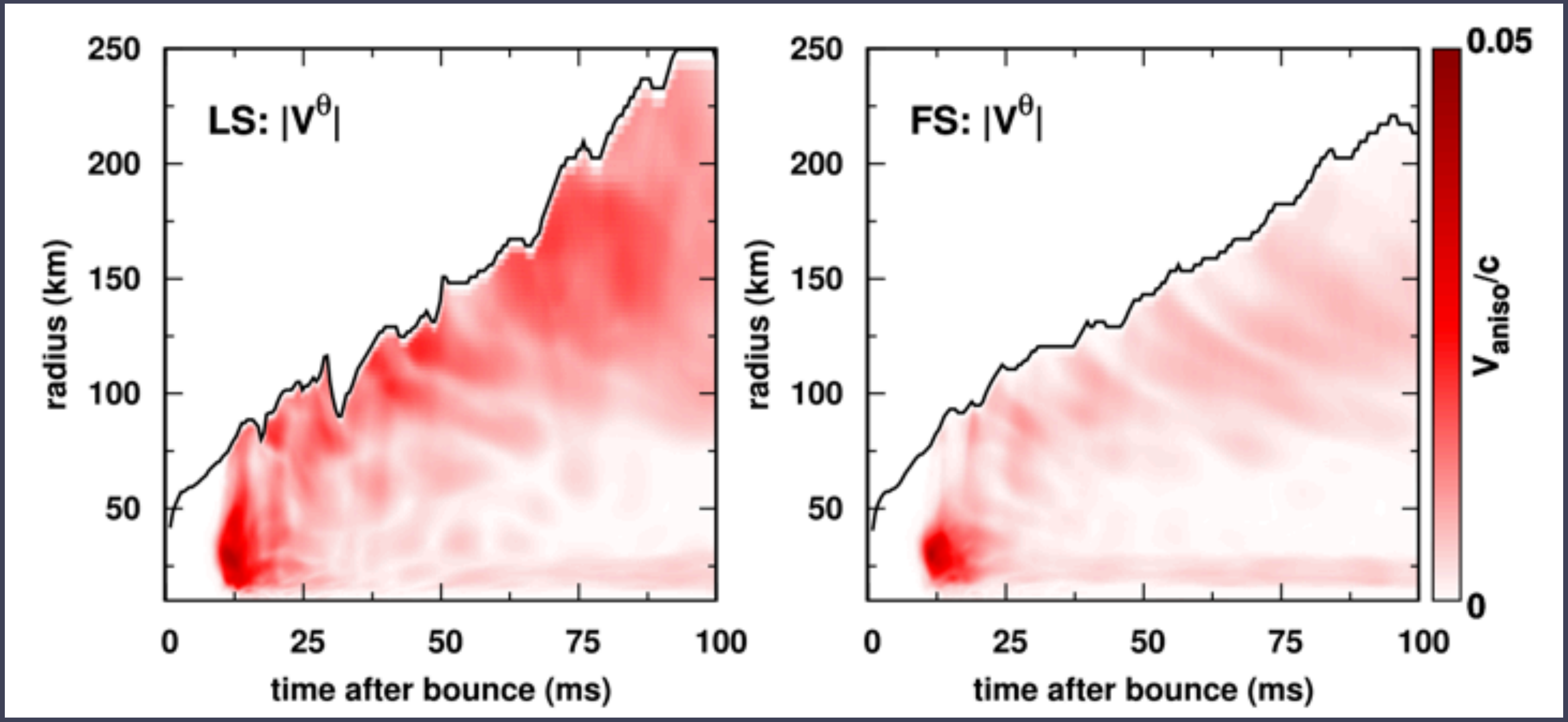


AH+ in prep.

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

Difference in turbulence

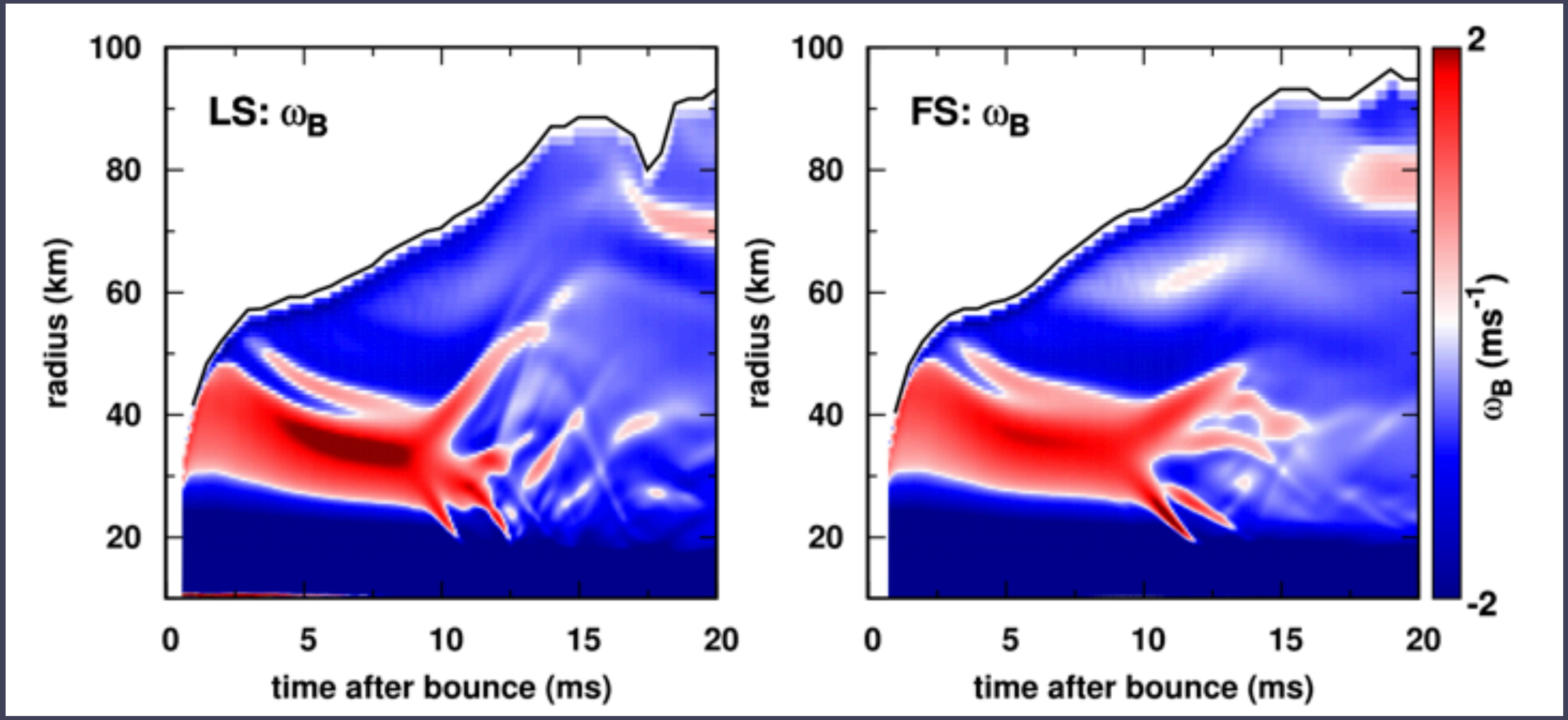
- All quantities are similar except for $M_{\rm gain}$
- Stronger turbulence in LS model



Nagakura+(2018)

Difference in turbulence

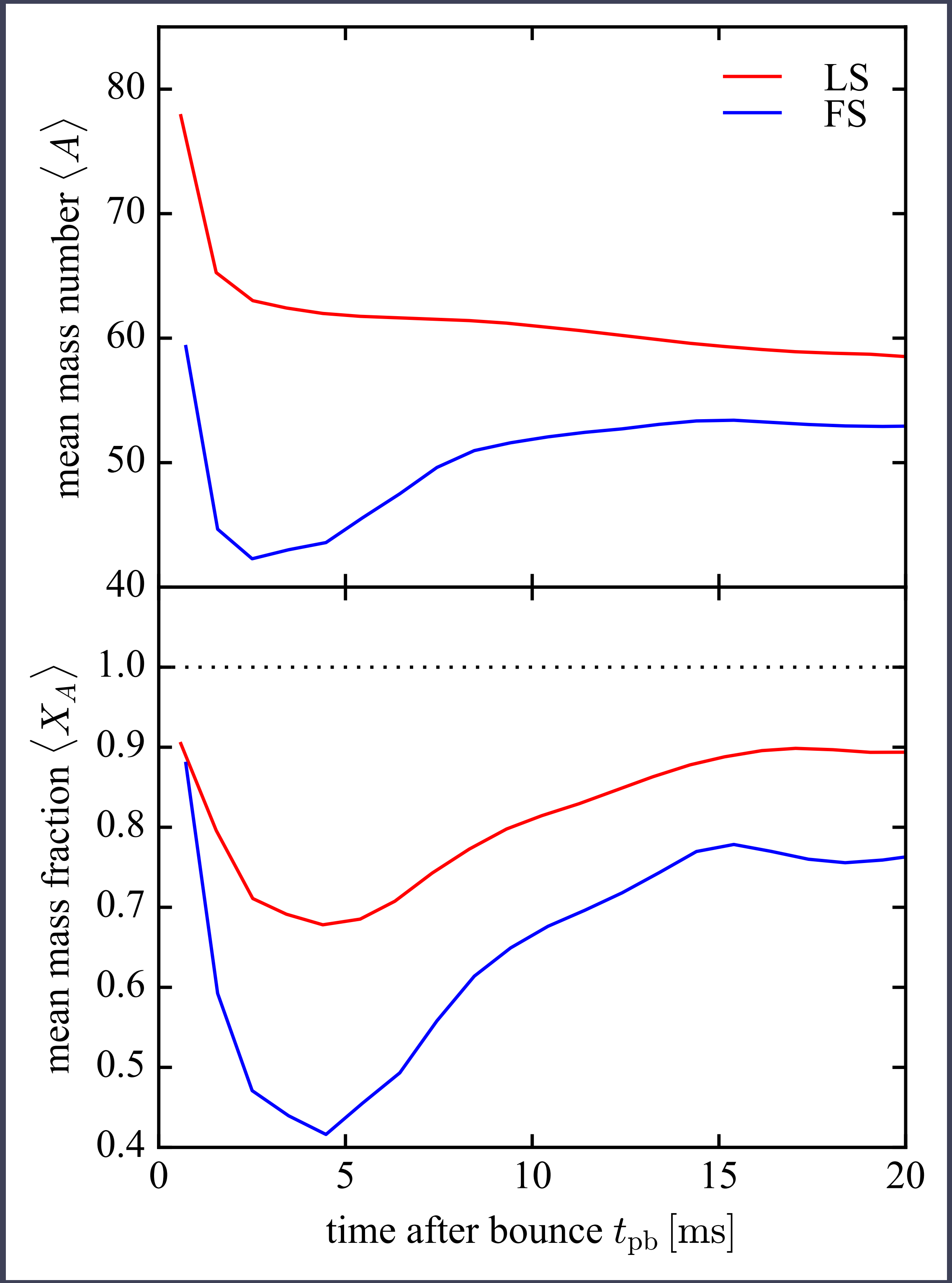
- All quantities are similar except for $M_{\rm gain}$
- Stronger turbulence in LS model
- Larger convection growth rate (Brunt-Vaisala freq.)



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

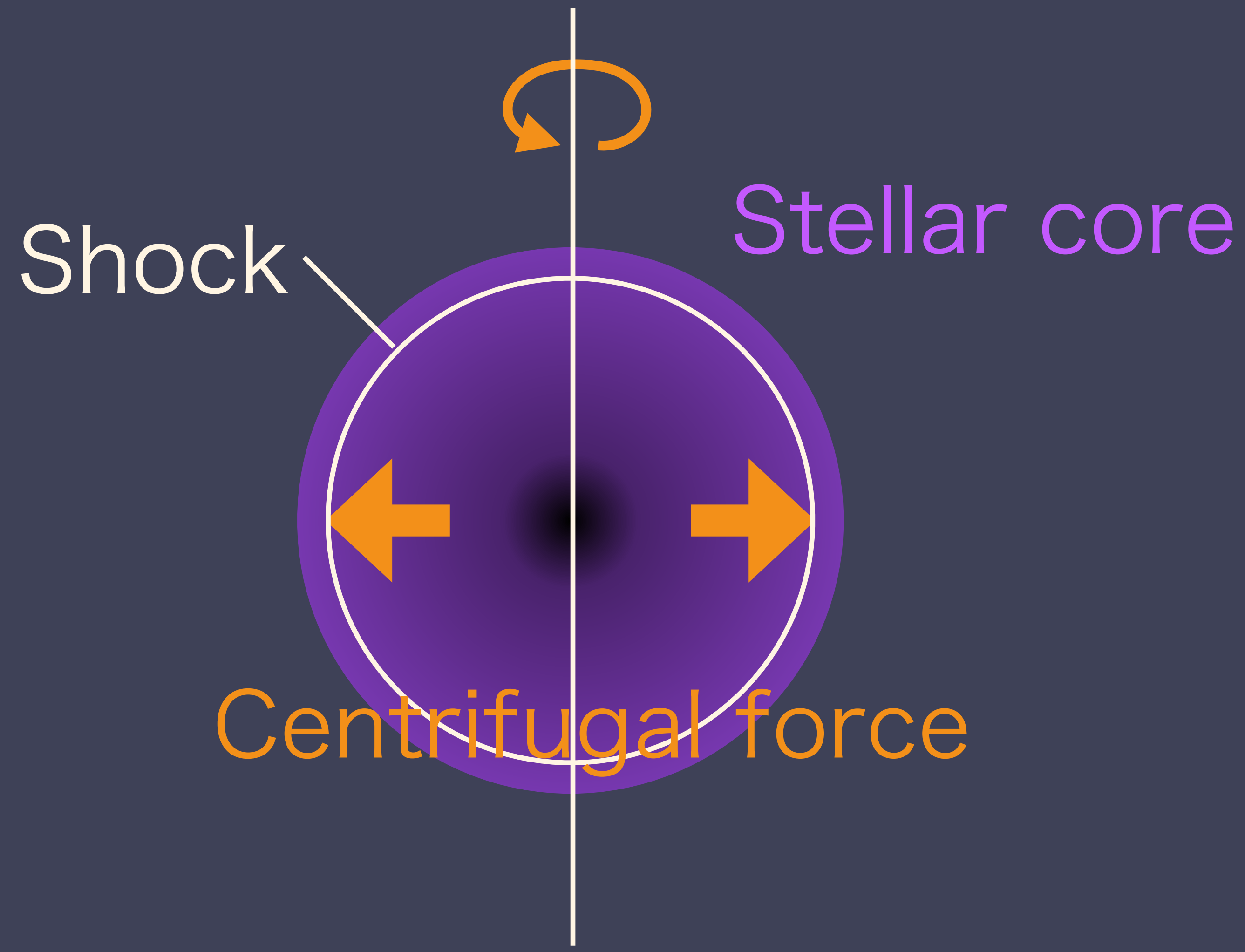


AH+ in prep.

Rotation

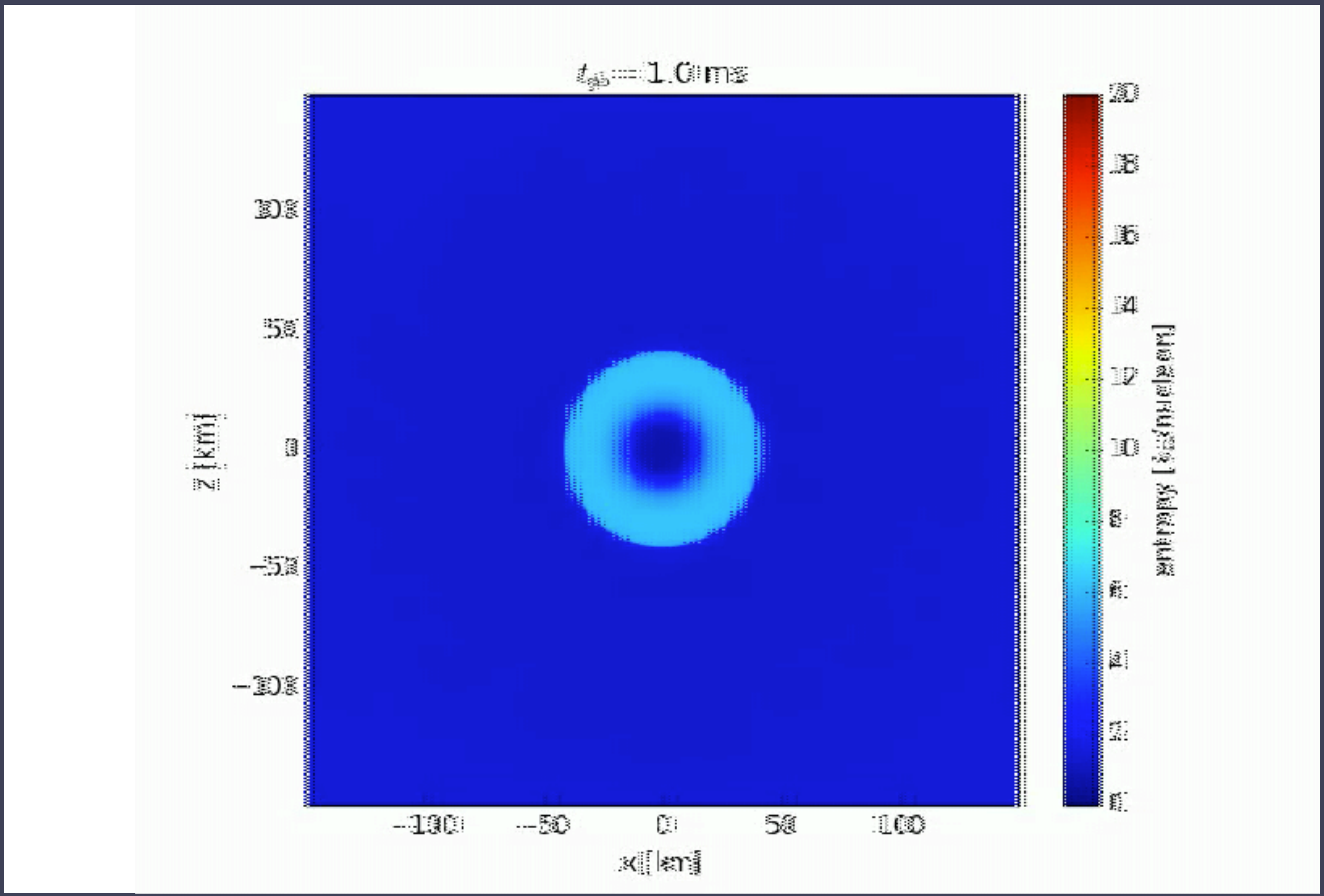
- Both positive and negative effects on shock revival
- Neutrino distributions are distorted
- (Thanks to the Boltzmann solver,) The accuracy of approximation is checked.
- Imposed rotation:

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



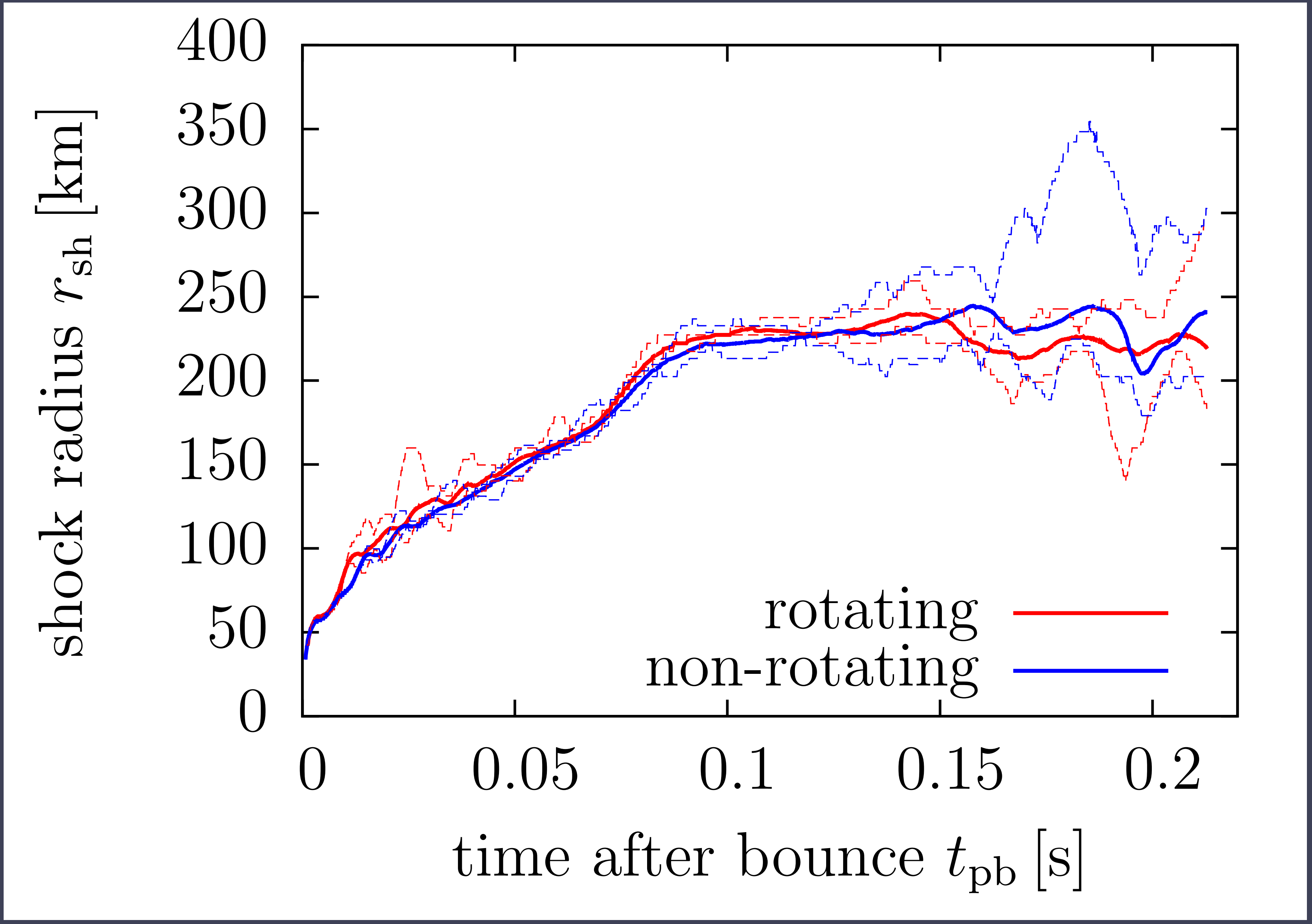
Entropy distribution

- Time evolution until ~200 ms after bounce.



Shock evolution

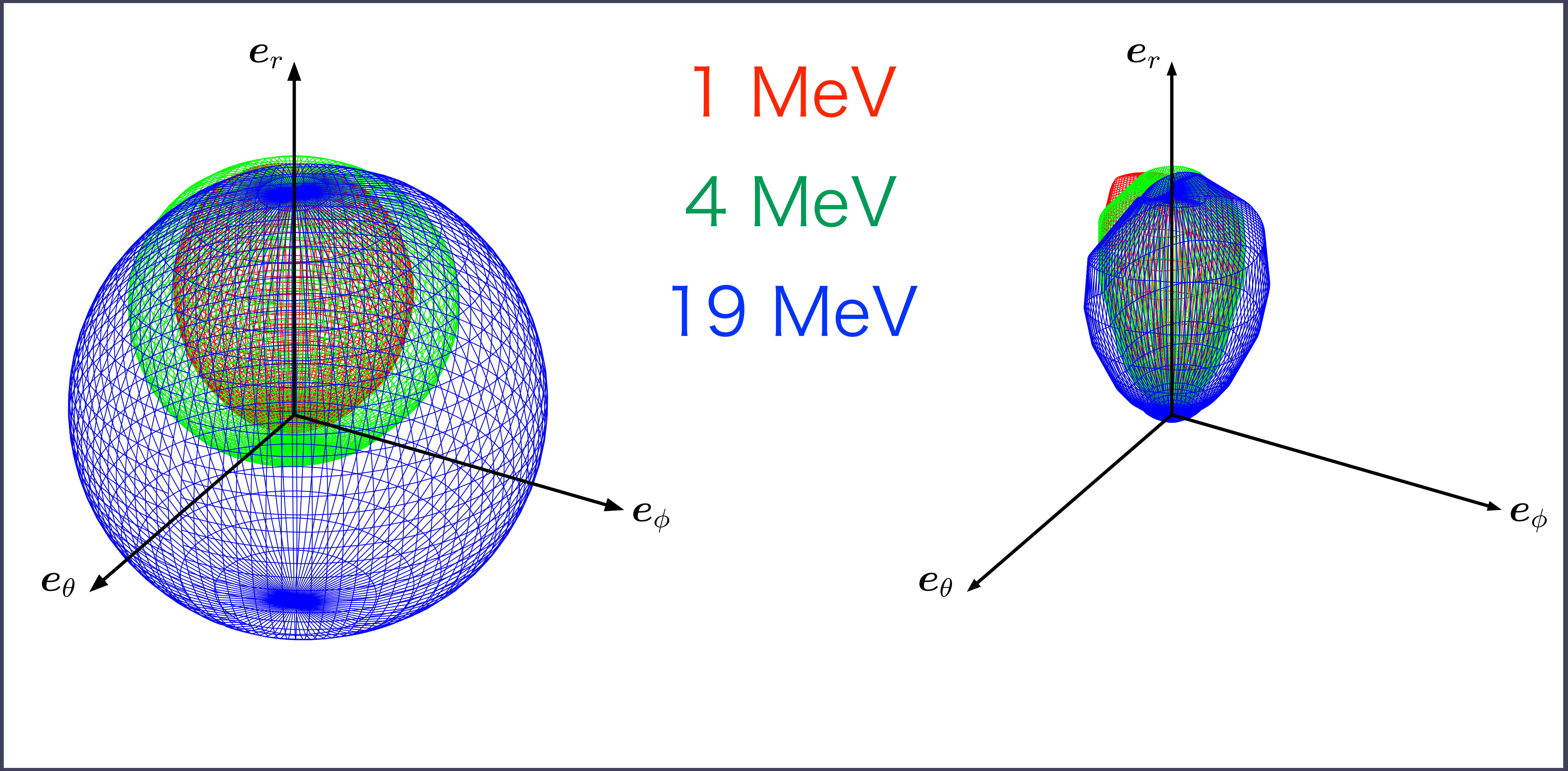
- Postbounce evolution until ~200 ms
- The difference between rotating & non-rotating model



AH+(2018)

Neutrino ang. distribution

- Distribution functions at ~10 ms after bounce.



~60 km

~170 km

AH+(2018)

Neutrino ang. distribution

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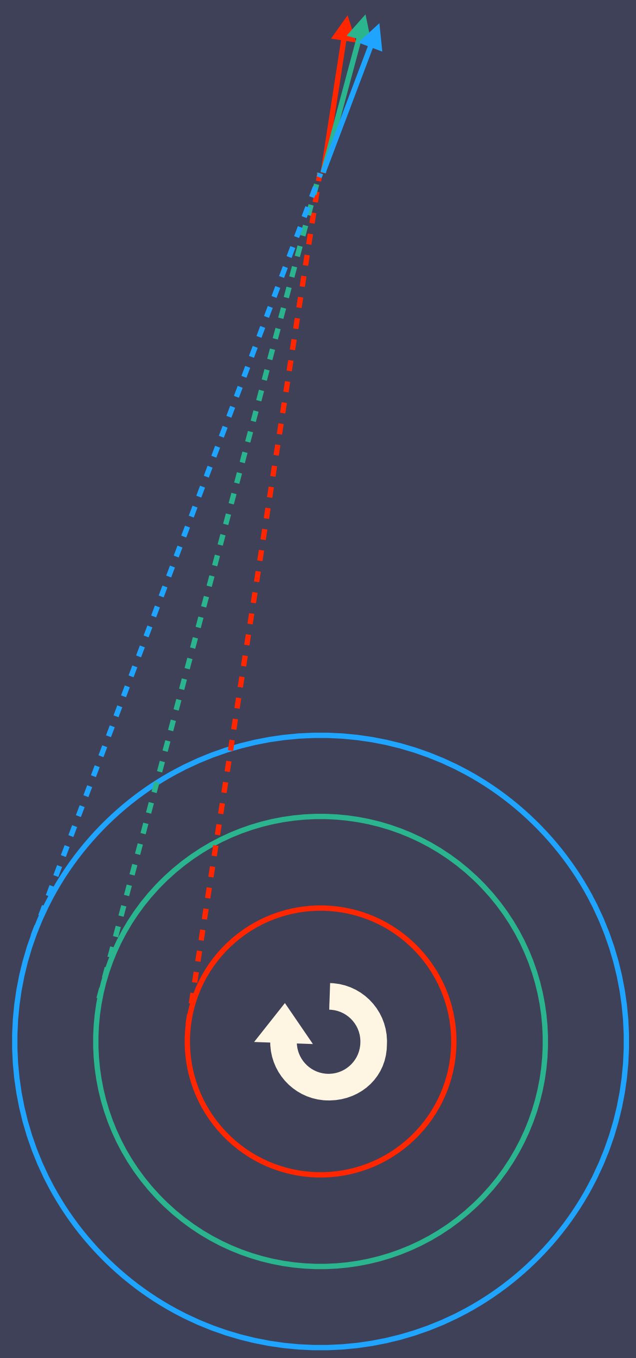
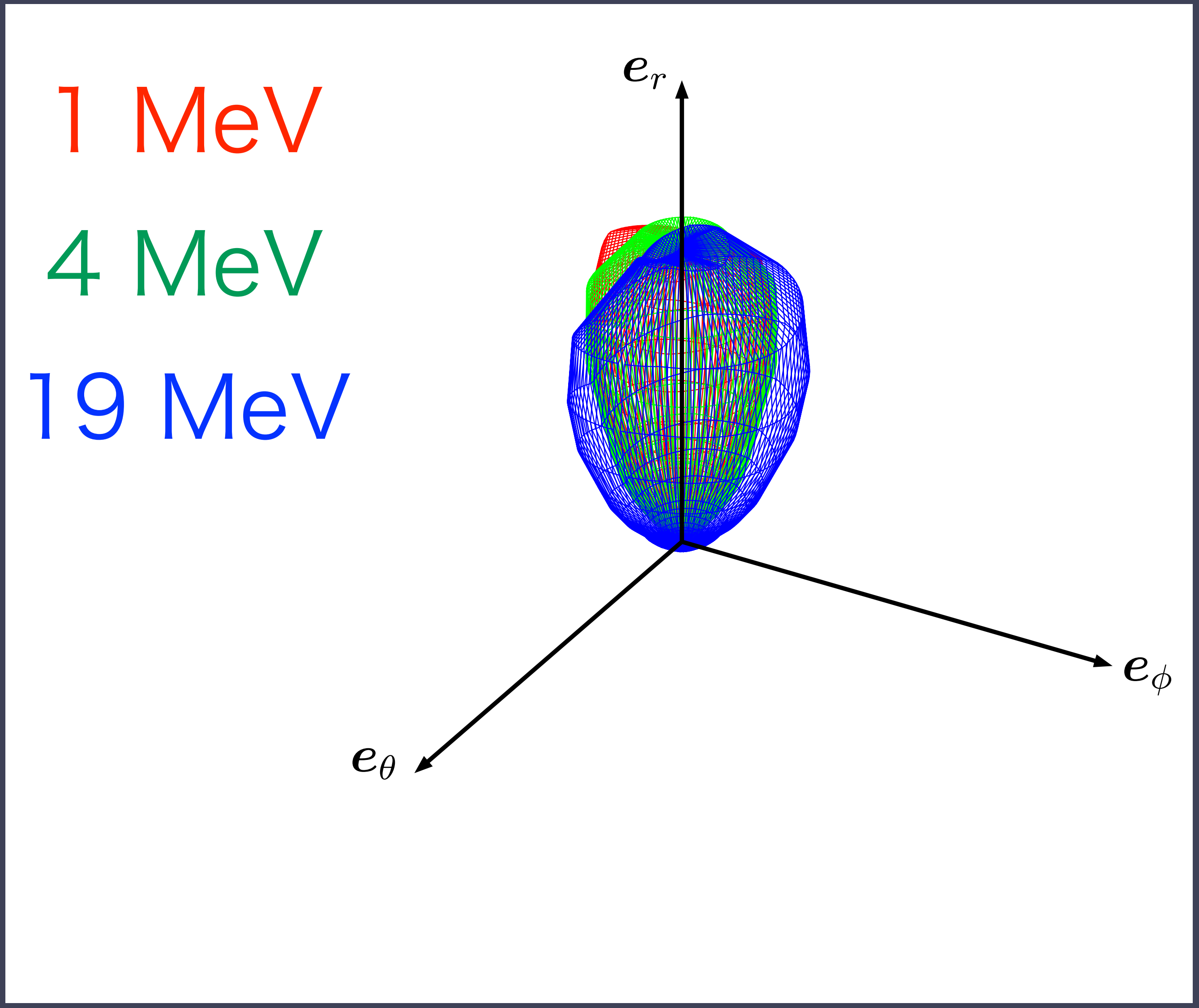


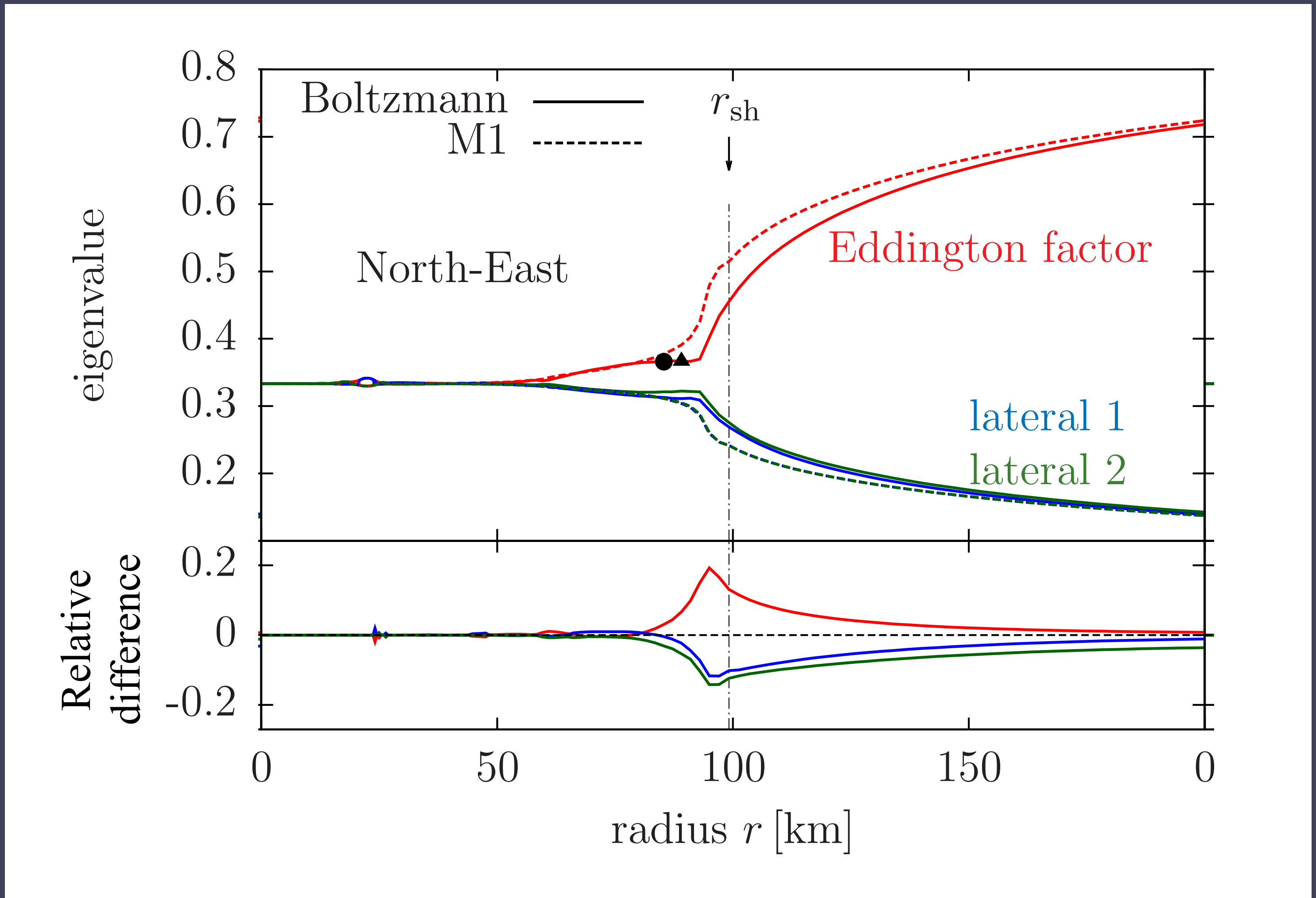


~170 km

AH+(2018)

Eddington factor

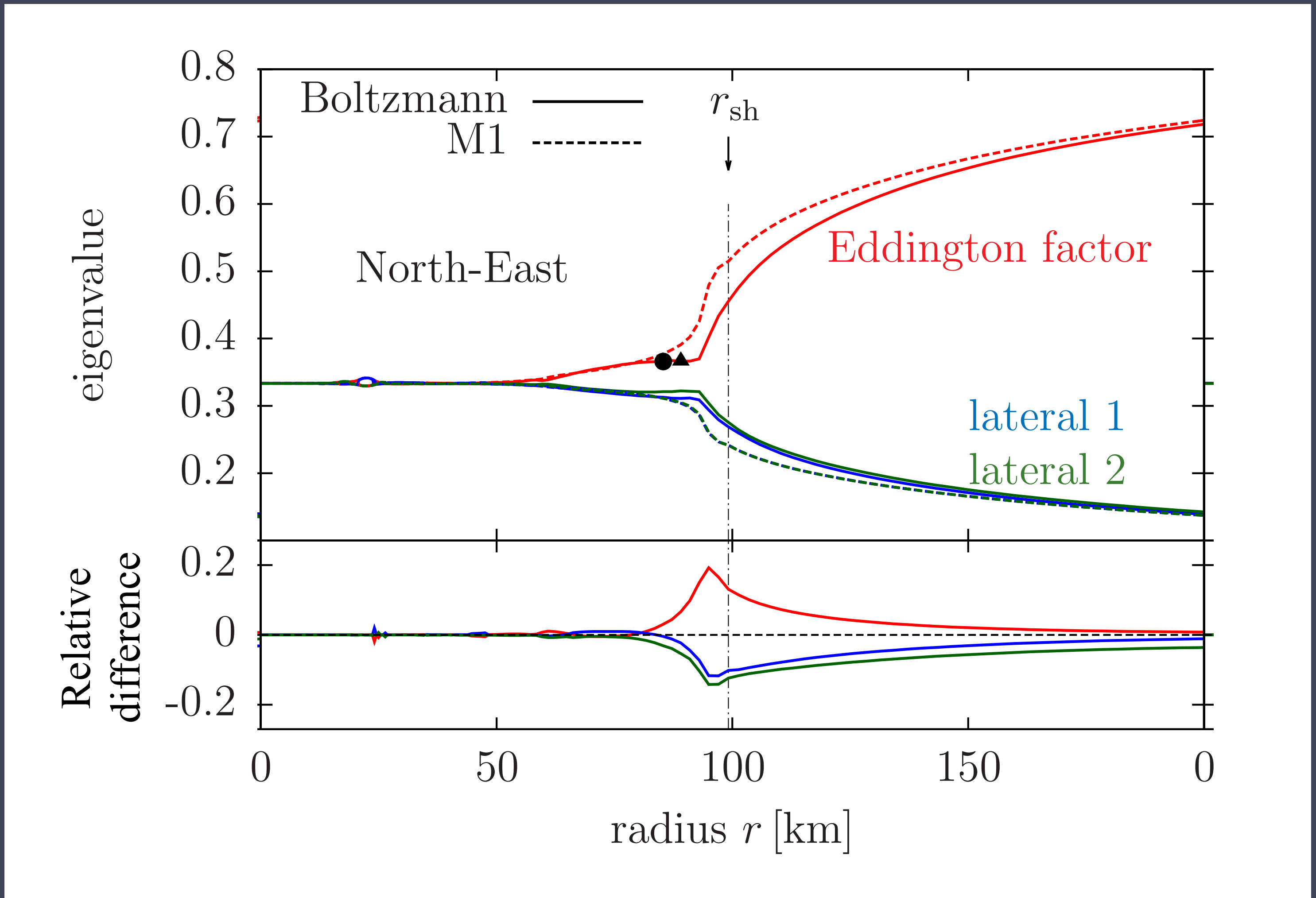
- Eddington tensor at ~10 ms after bounce
- spatial distribution of eigenvalues
- ~20% difference in M1-closure scheme



AH+(2018)

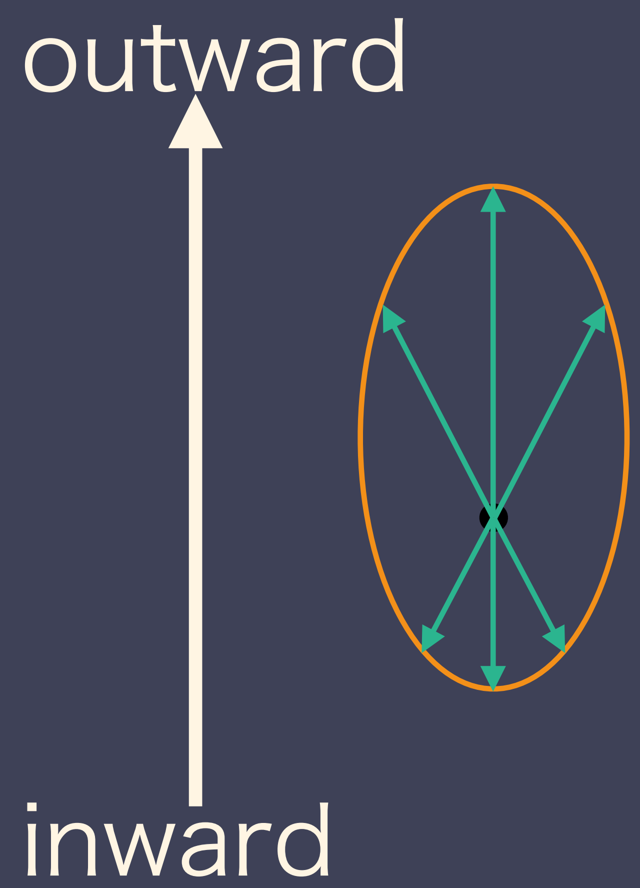
Eddington factor

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



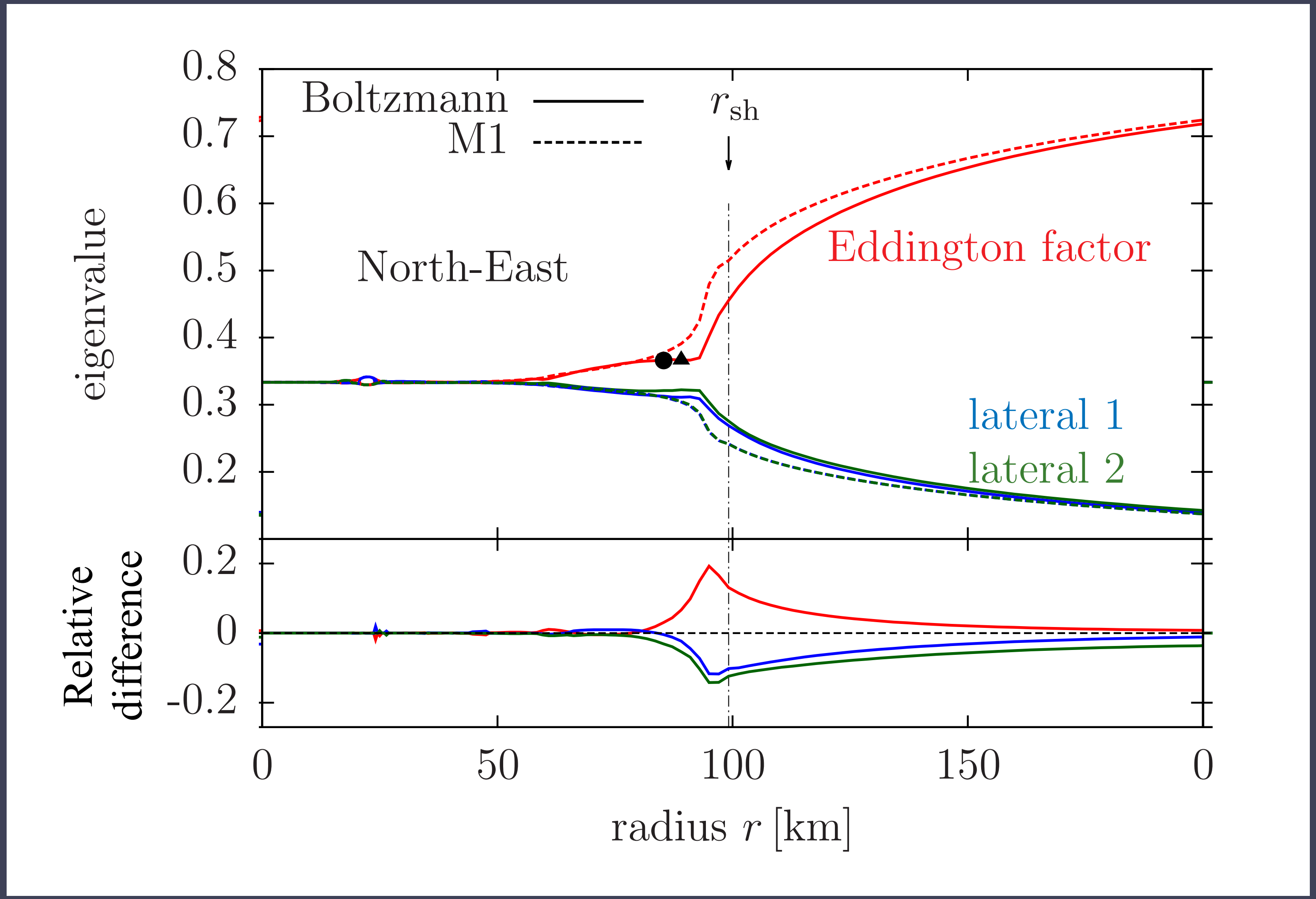
AH+(2018)

- Prolateness of distribution
- M1: estimated from deviation

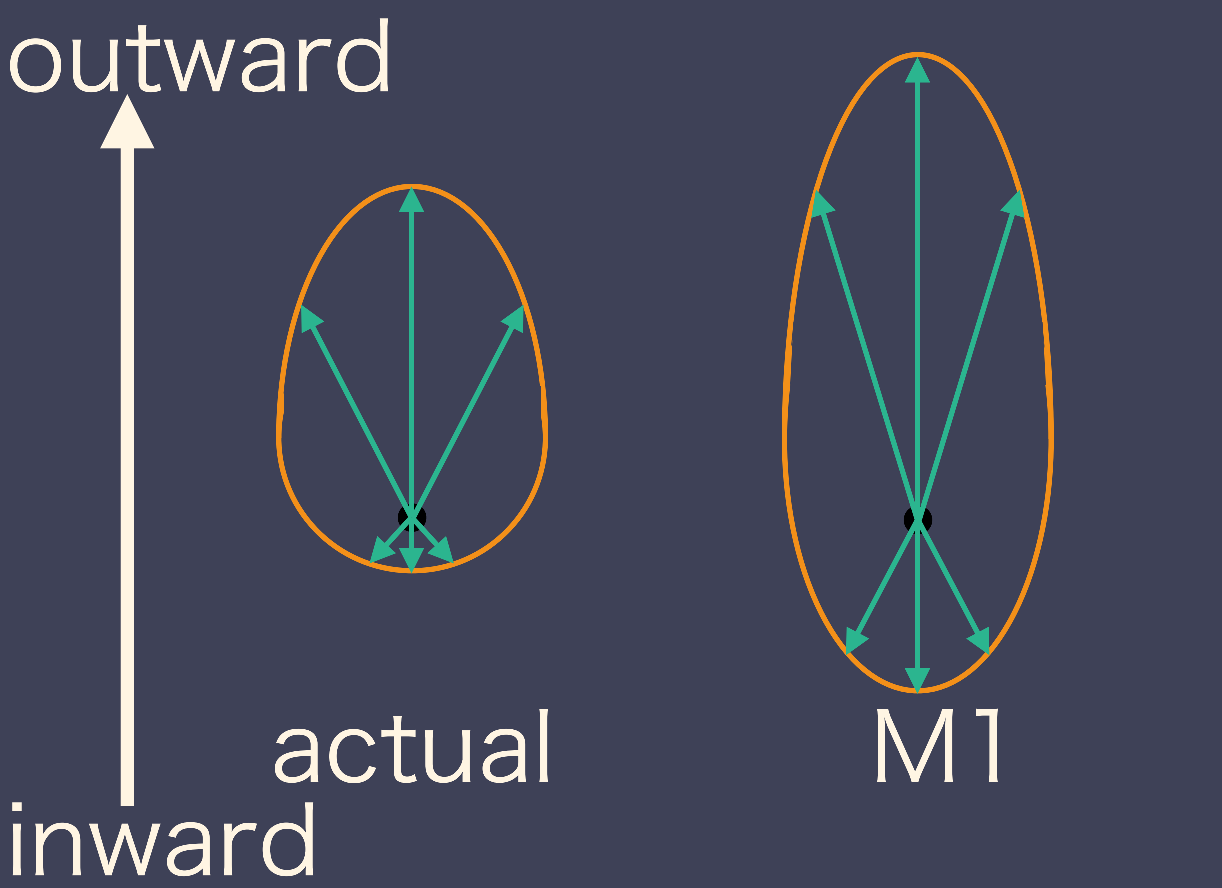


Eddington factor

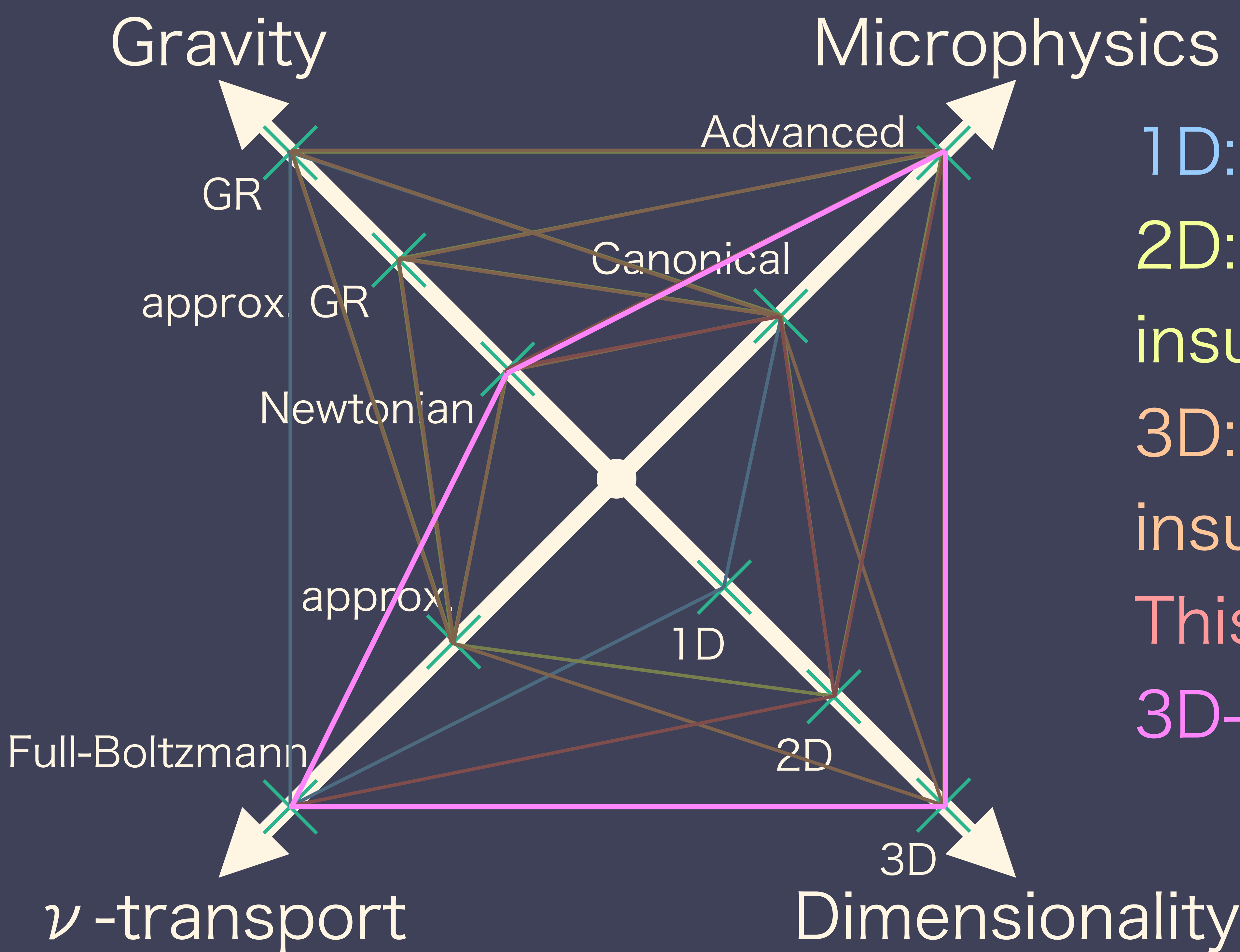
- Eddington tensor at ~10 ms after bounce
- Comparison between Boltzmann- and M1-Edd. factors
- Information which distinguish these situations may improve the approximation



AH+(2018)



The progress in CCSNe sim.



1D: fail to explode

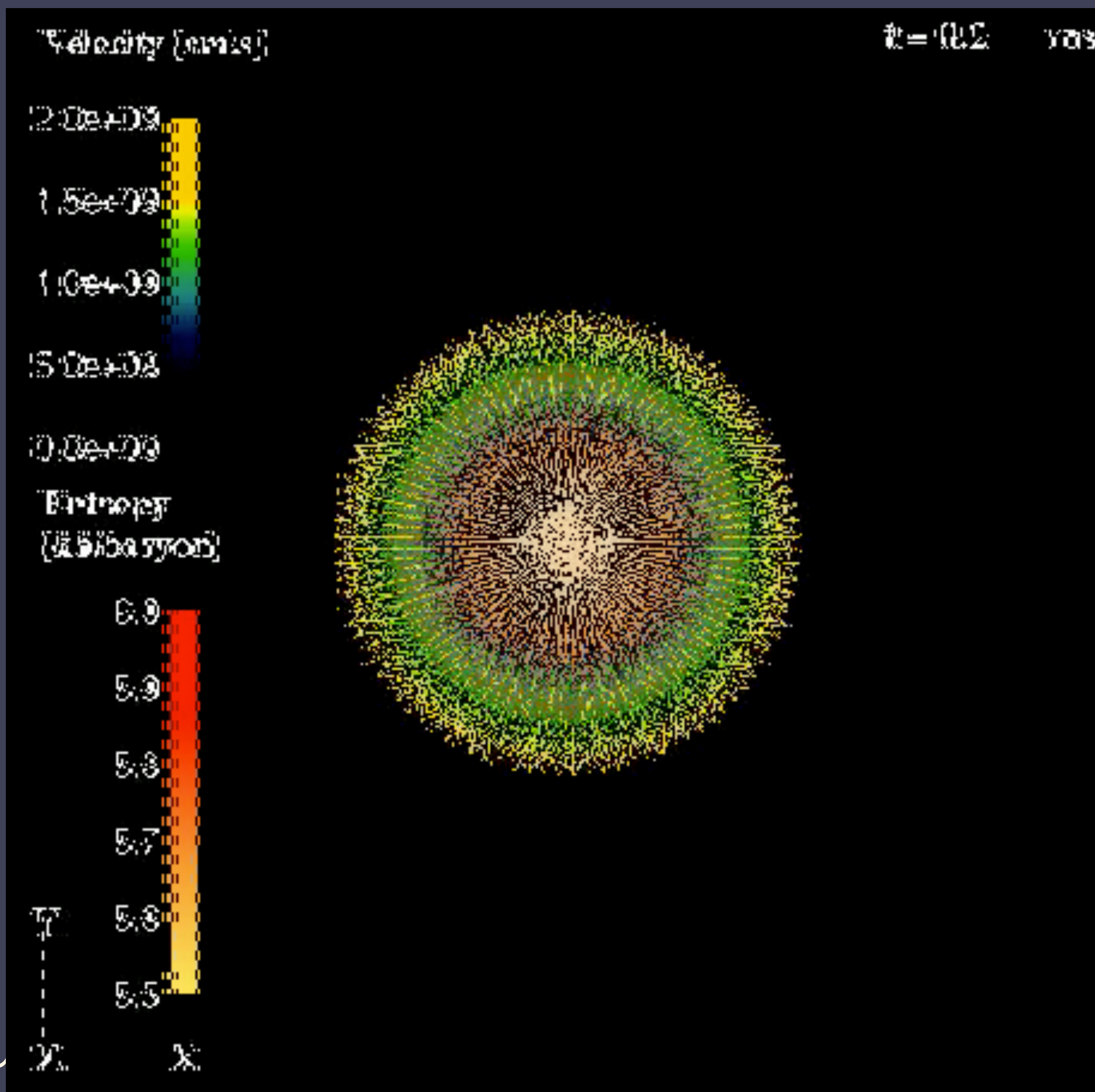
2D: shock revives insufficient energy

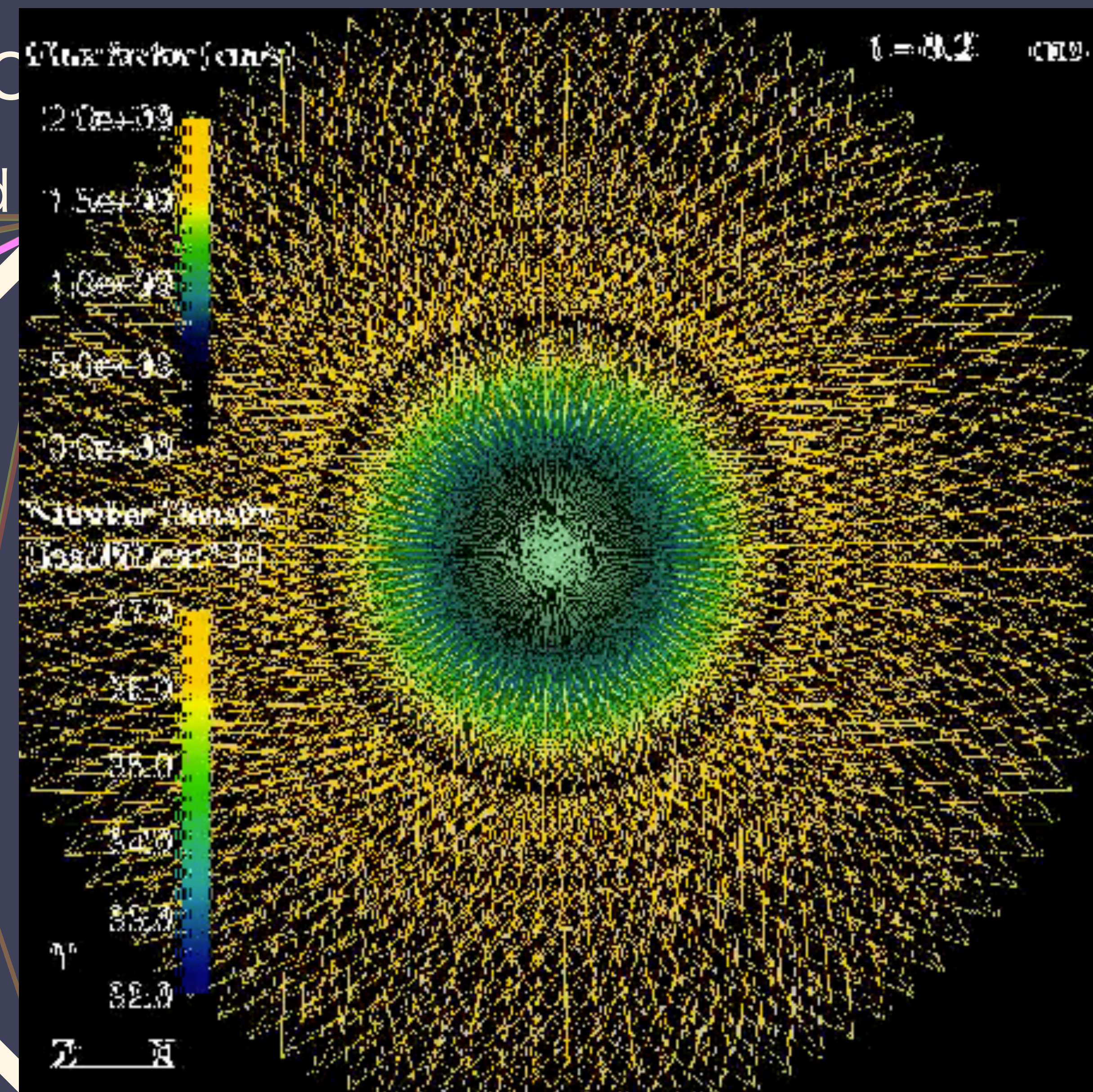
3D: shock revives insufficient energy

This work

3D-Boltzmann

The progress in CCSNe sim.





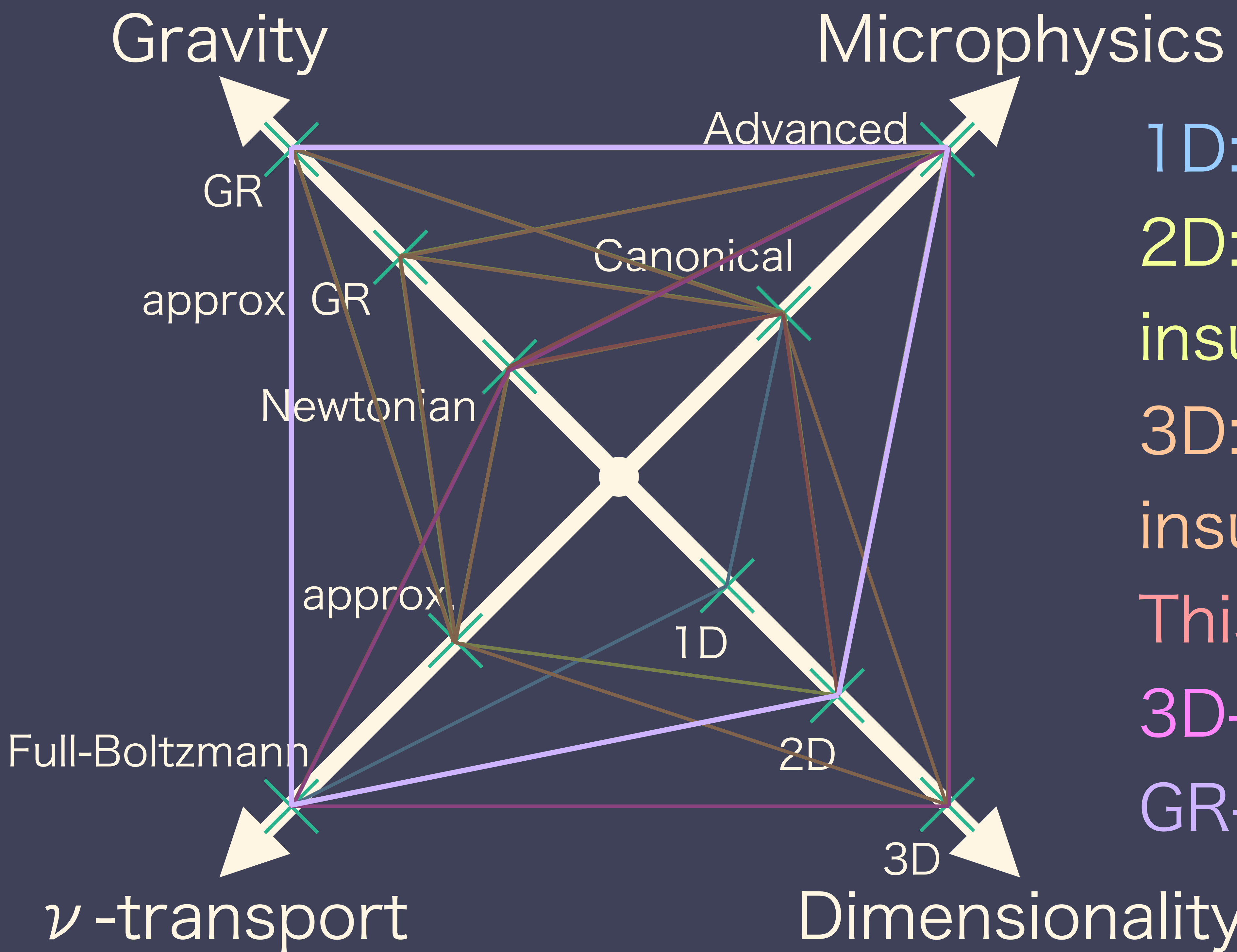
Iwakami+ in prep.

3D

ν-transport

Dimensionality

The progress in CCSNe sim.



1D: fail to explode
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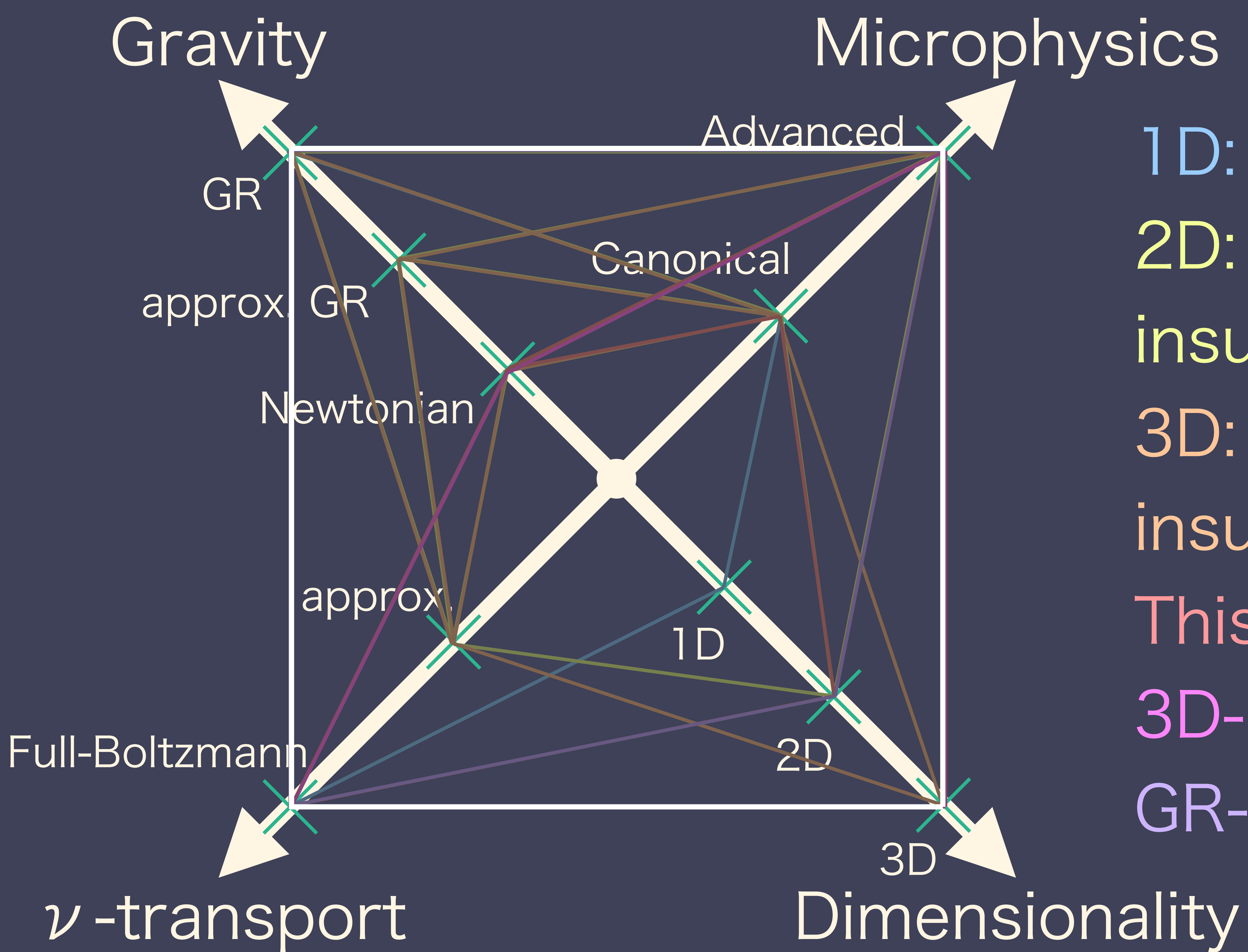
This work
3D-Boltzmann
GR-Boltzmann

The progress in CCSNe sim.



1D: fail to explode
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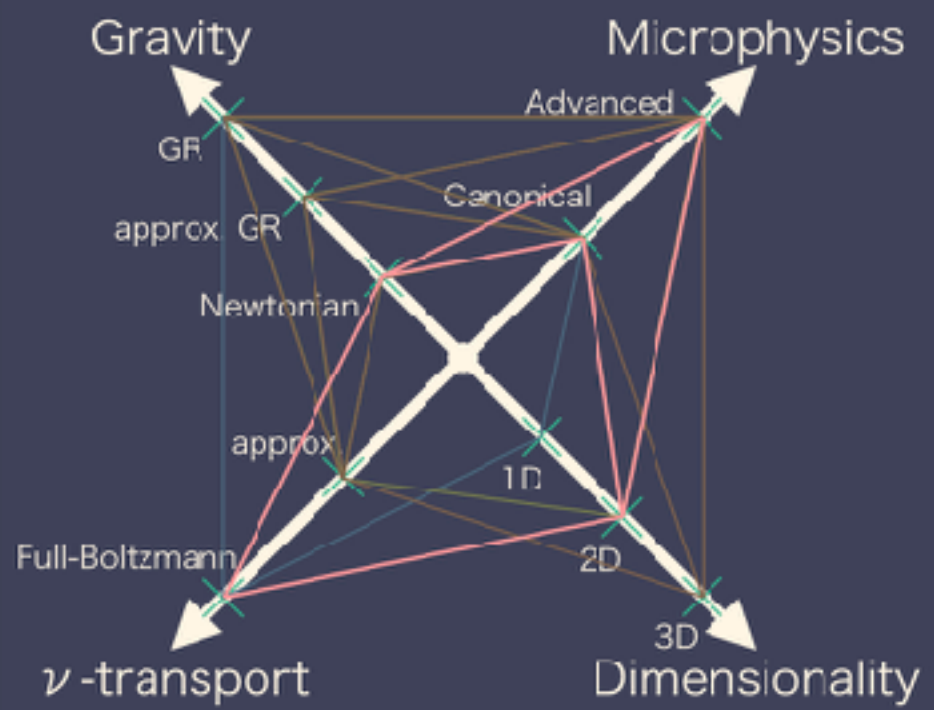
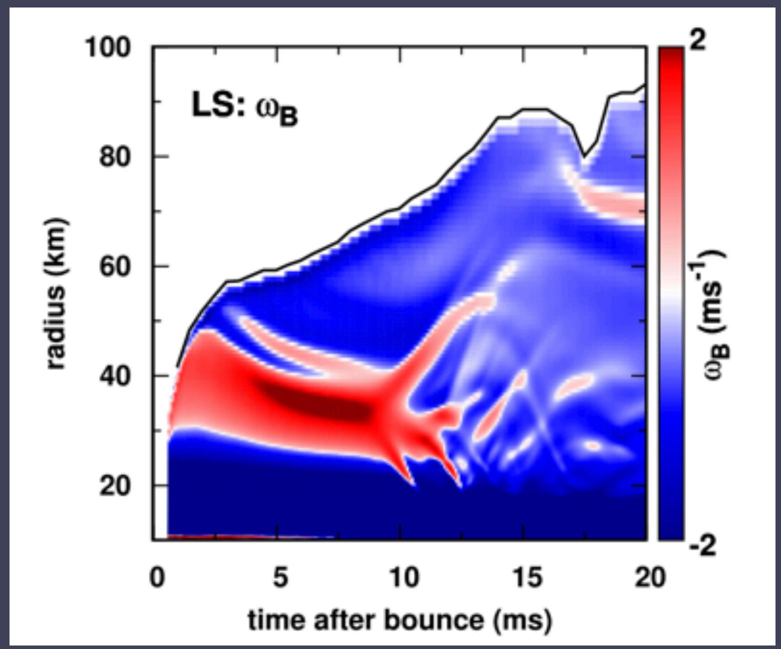
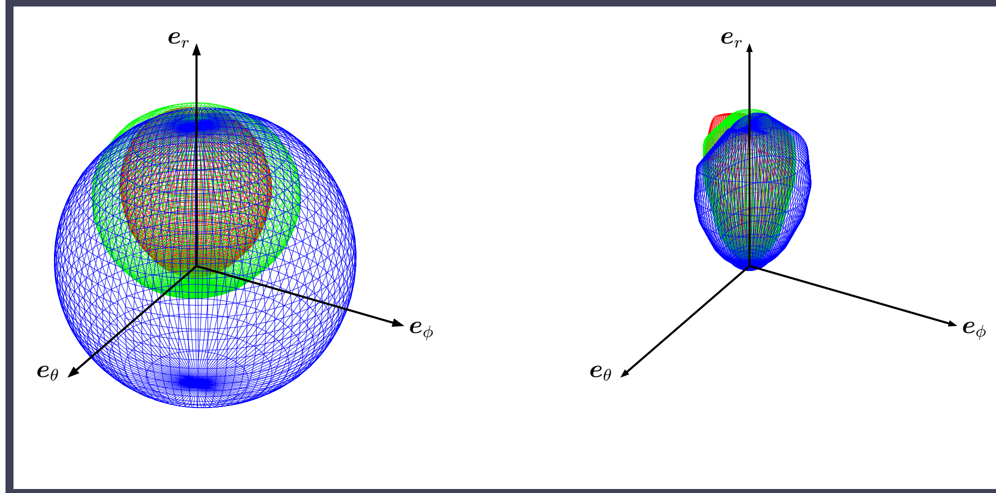
This work
3D-Boltzmann
GR-Boltzmann

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.
- Further development is going on.







Thank you for listening!