Boltzmann-radiation-hydrodynamics simulations of the stellar core-collapse under axisymmetry
status report of group C02 of GW-genesis II

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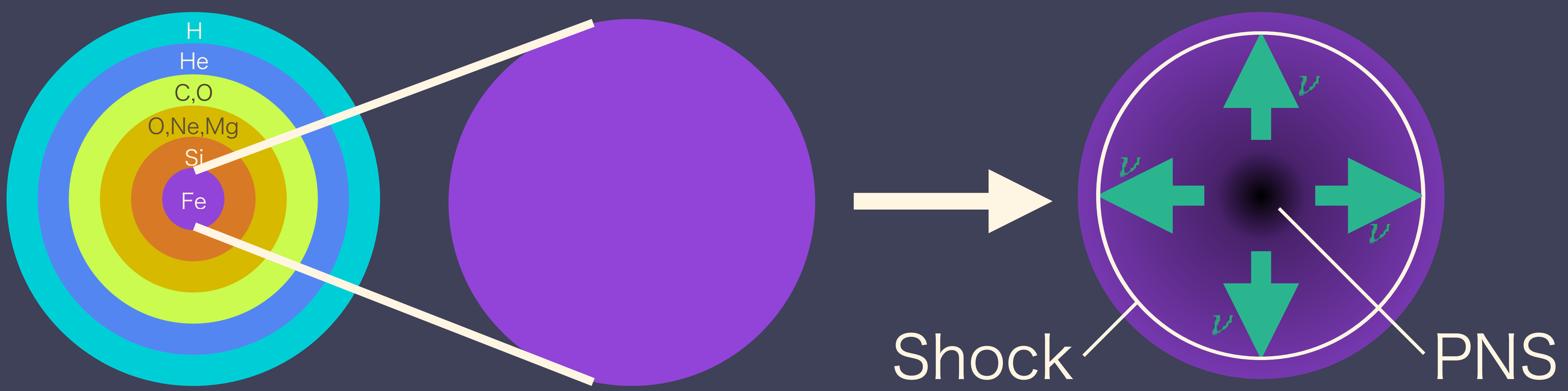
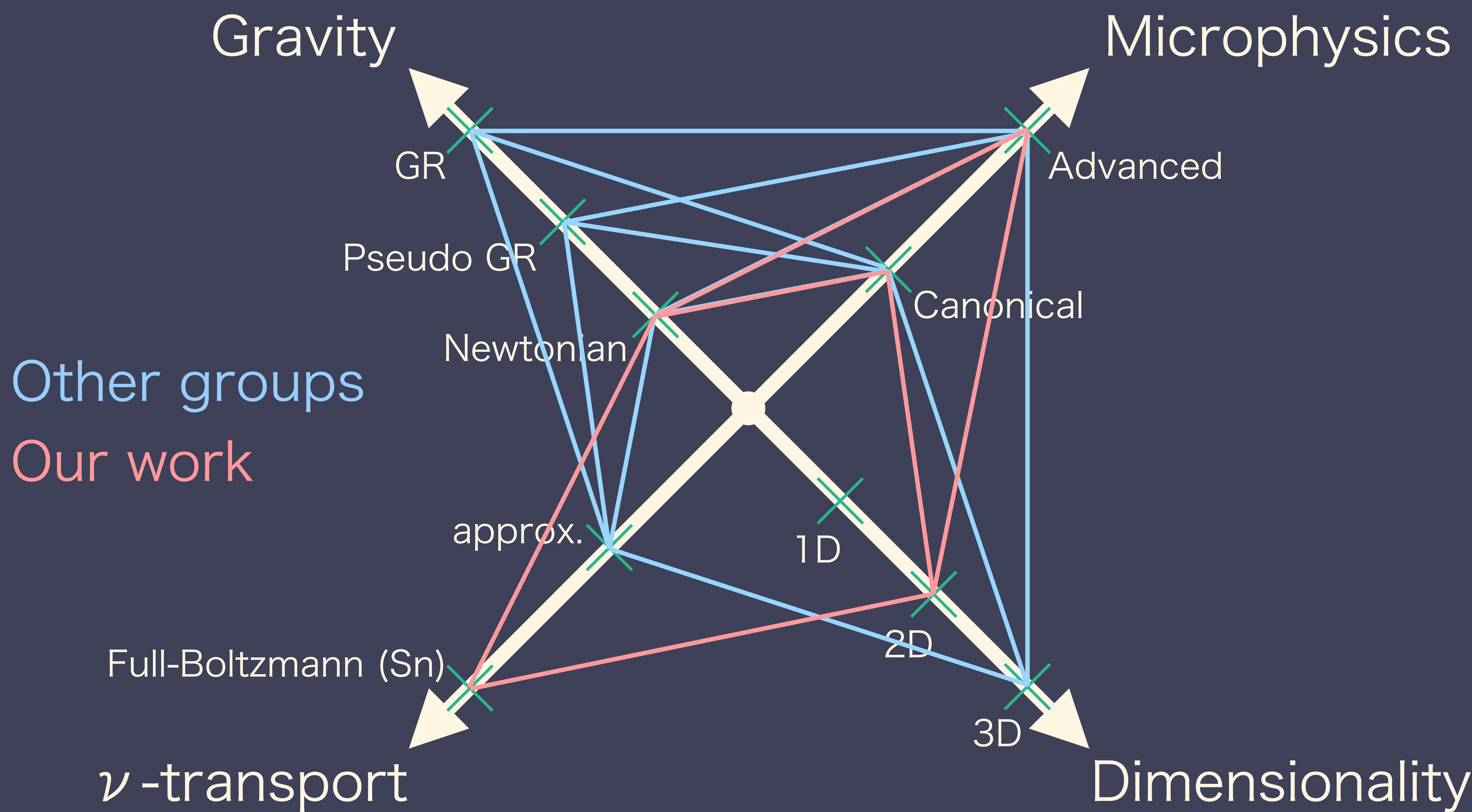
CCSN explosion mechanism: the neutrino heating mechanism

- Explosive death of massive star
- The central proto-neutron star emits neutrinos.
- The shock is re-energized by the neutrino heating.



The Boltzmann-radiation-hydrodynamics code



Basic equations

Acceleration terms to track the PNS

PNS kick may be found (Nagakura in prep.)

- Boltzmann equation

$$\frac{\mathrm{d}x^\alpha}{\mathrm{d}\tau}\frac{\partial f}{\partial x^\alpha}\bigg|_{p^i} + \frac{\mathrm{d}p^i}{\mathrm{d}\tau}\frac{\partial f}{\partial p^i}\bigg|_{x^\alpha} = (-p^\alpha \hat{u}_\alpha) S_{\mathrm{rad}}$$

- Newtonian Hydrodynamics

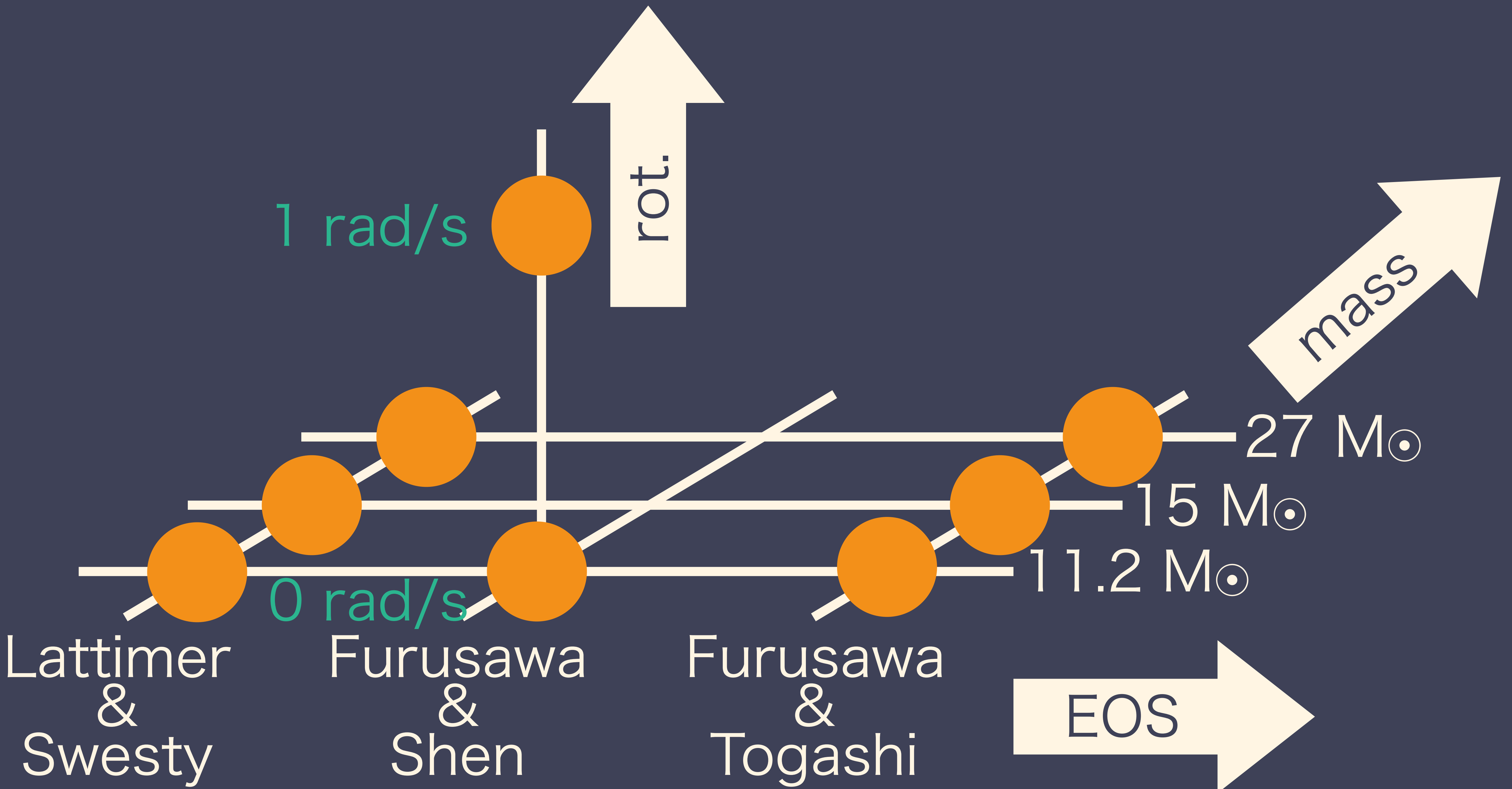
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \qquad \frac{\partial \rho Y_{\mathrm{e}}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} Y_{\mathrm{e}}) = \rho \Gamma$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + P\boldsymbol{I}) = -\rho \nabla \Phi + \boldsymbol{M}^i + \rho \dot{\boldsymbol{\beta}}$$

$$\frac{\partial \rho (e + \frac{1}{2}\boldsymbol{v}^2)}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v} (e + \frac{1}{2}\boldsymbol{v}^2 + \frac{P}{\rho}) \right) = -\rho \boldsymbol{v} \cdot \nabla \Phi + Q + \rho \boldsymbol{v} \cdot \dot{\boldsymbol{\beta}}$$

- Newtonian Gravity $\Delta \Phi = 4\pi G \rho$

Our models



rot.
mass
1 rad/s
0 rad/s
27 M☉
15 M☉
11.2 M☉
Lattimer & Swesty
Furusawa & Shen
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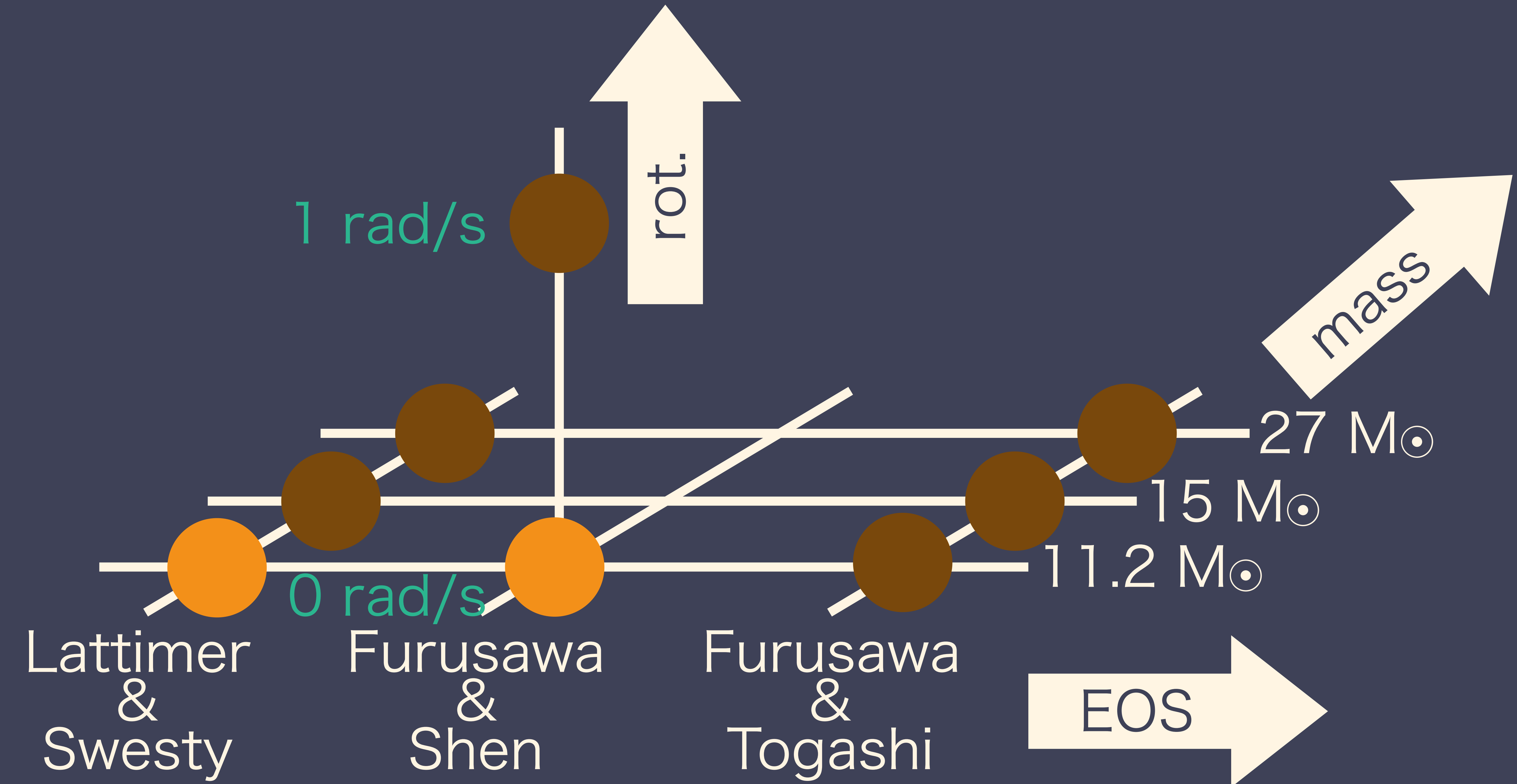
EOS

Nuclear EOS

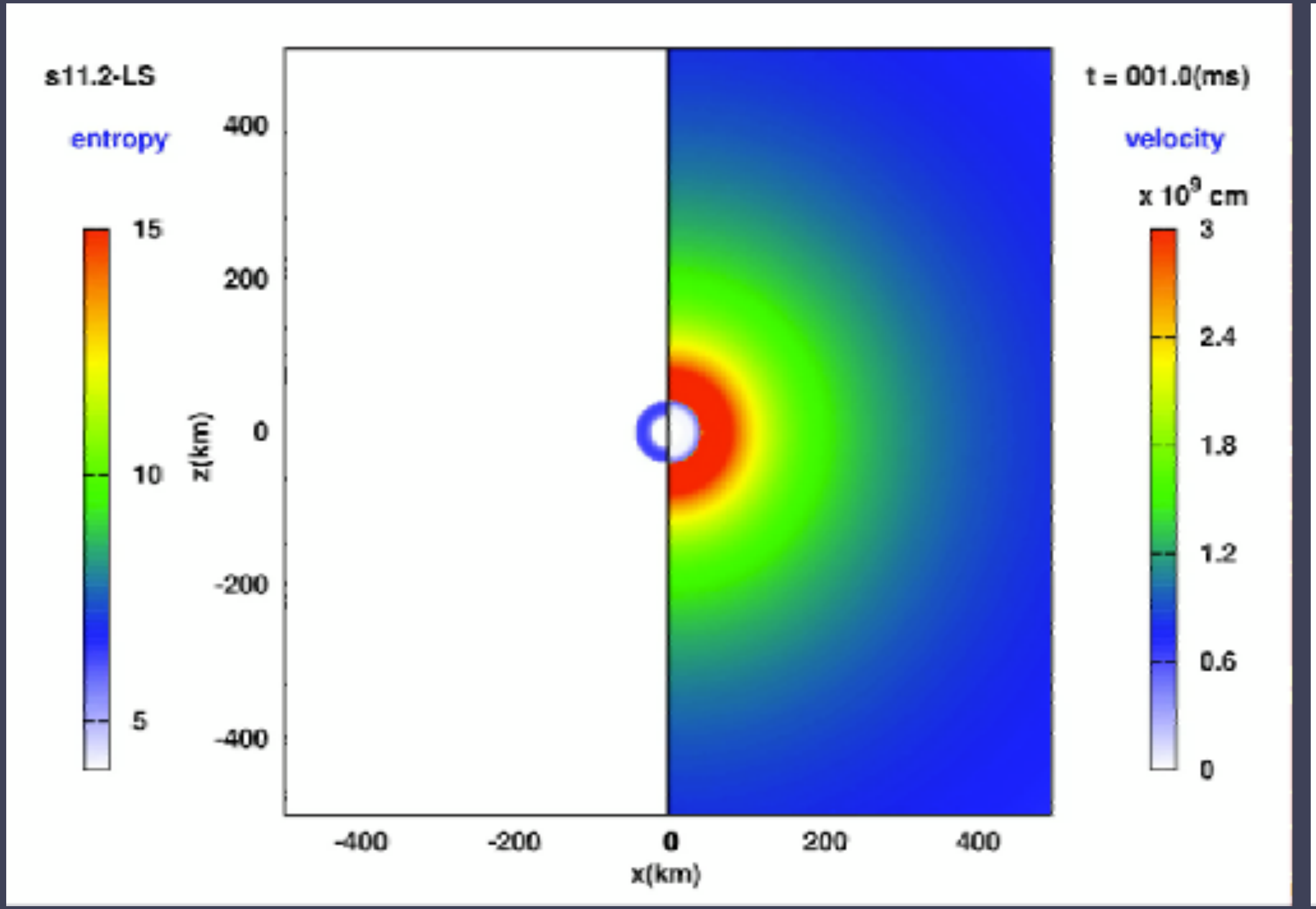


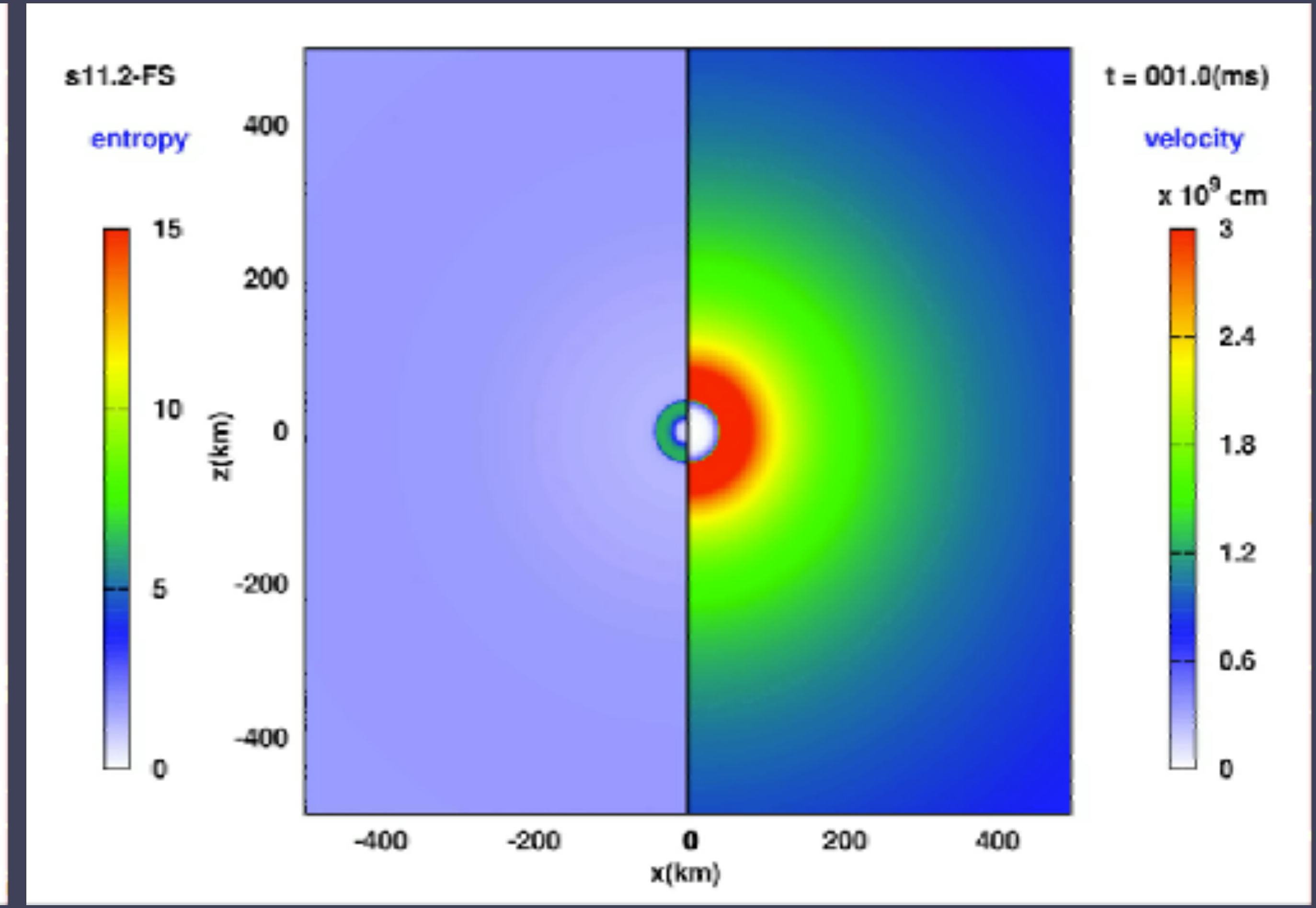
Skyrm-type RMF

SNA NSE

Shock evolution

- Entropy and absolute value of velocity

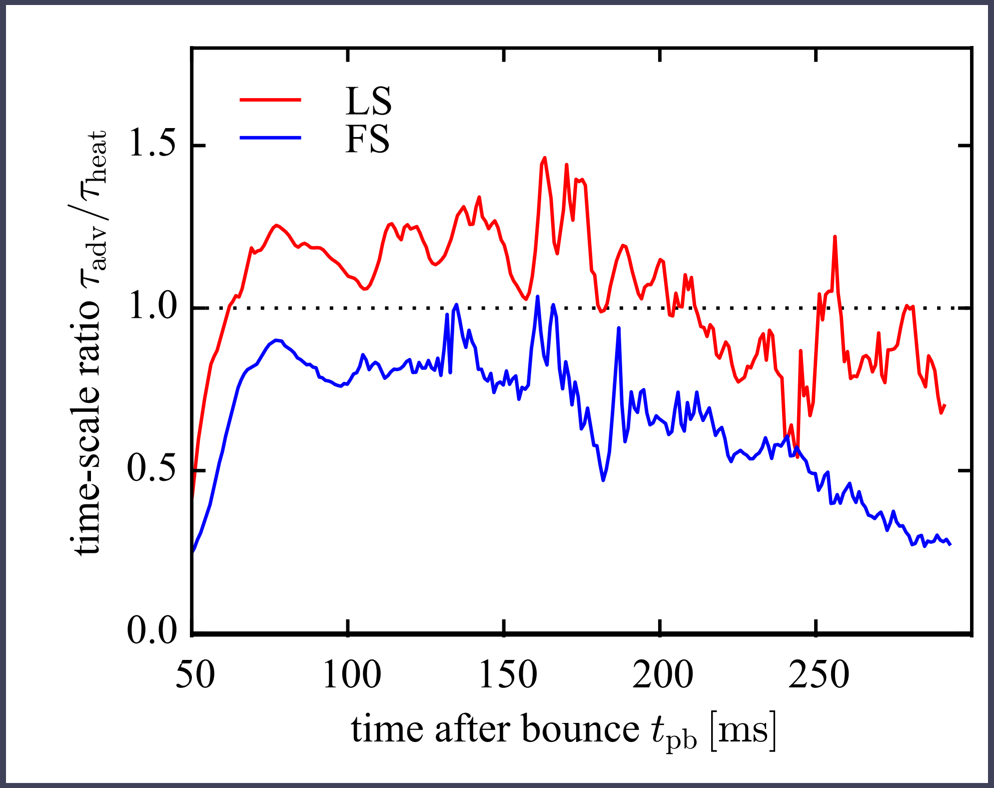


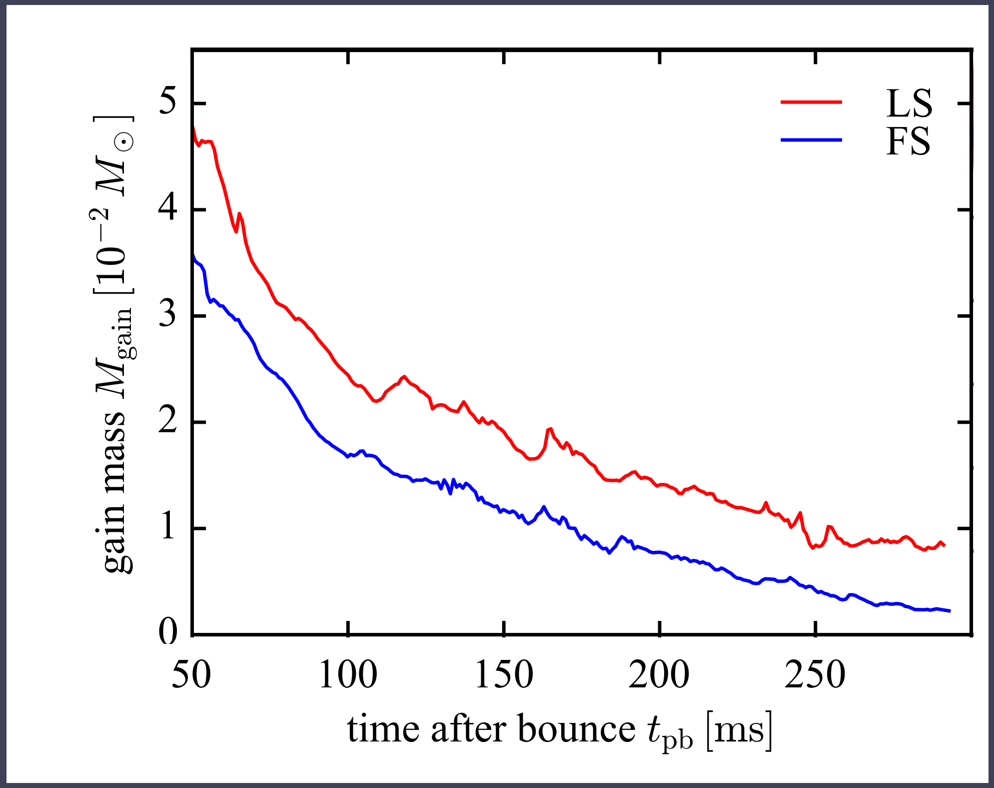


Timescale ratio

- Shock revives when the timescale ration exceeds 1:

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



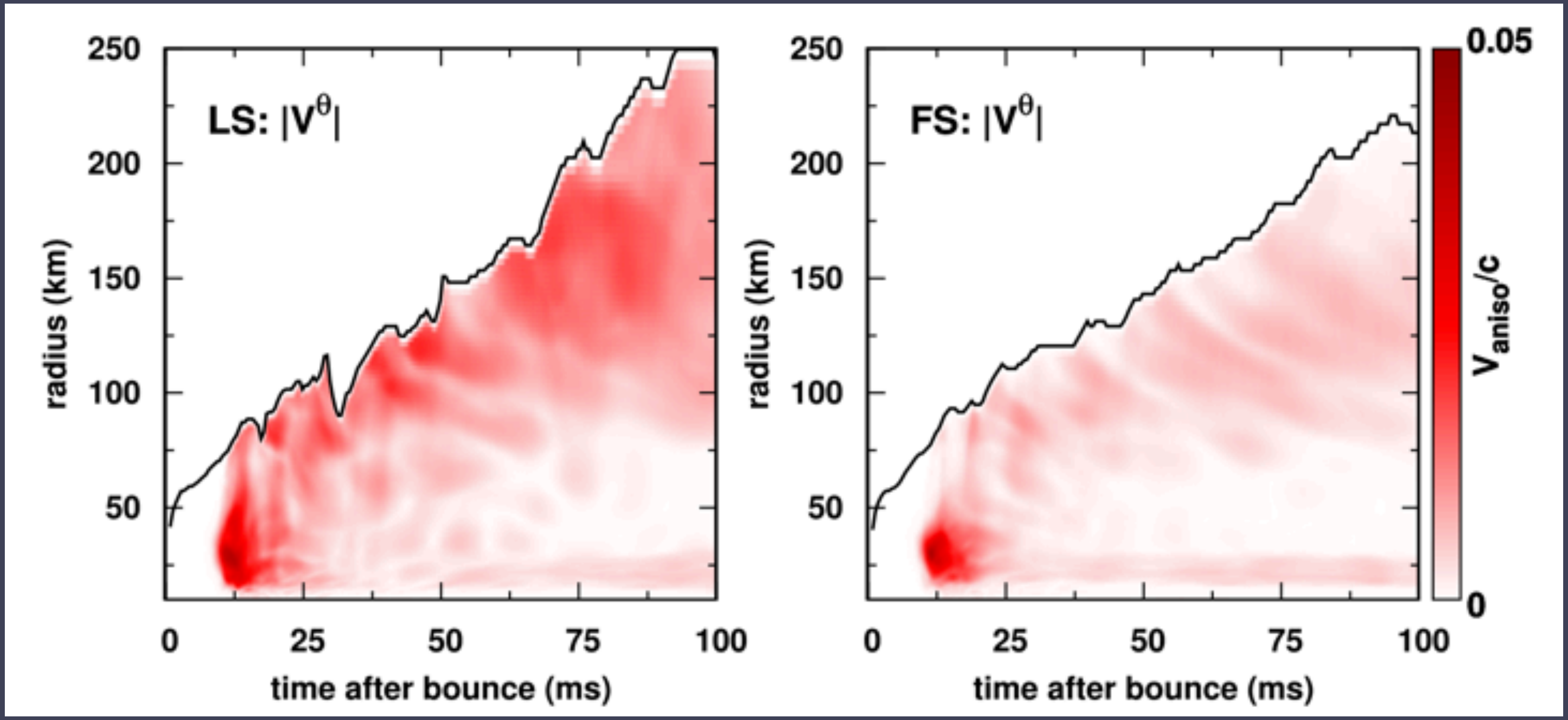


AH+ in prep.

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

Difference in turbulence

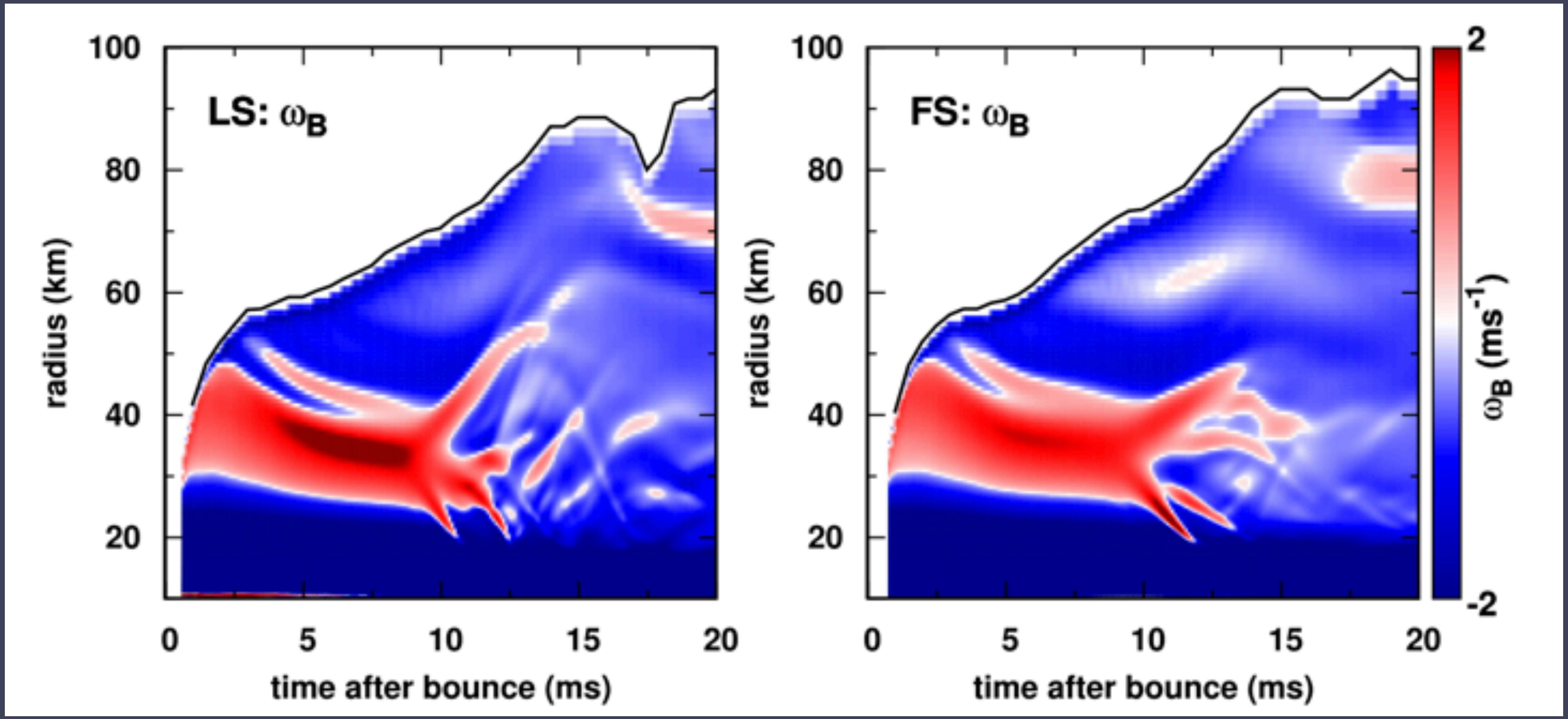
- All quantities are similar except for M_{gain}
- Stronger turbulence in LS model



Nagakura+(2018)

Difference in turbulence

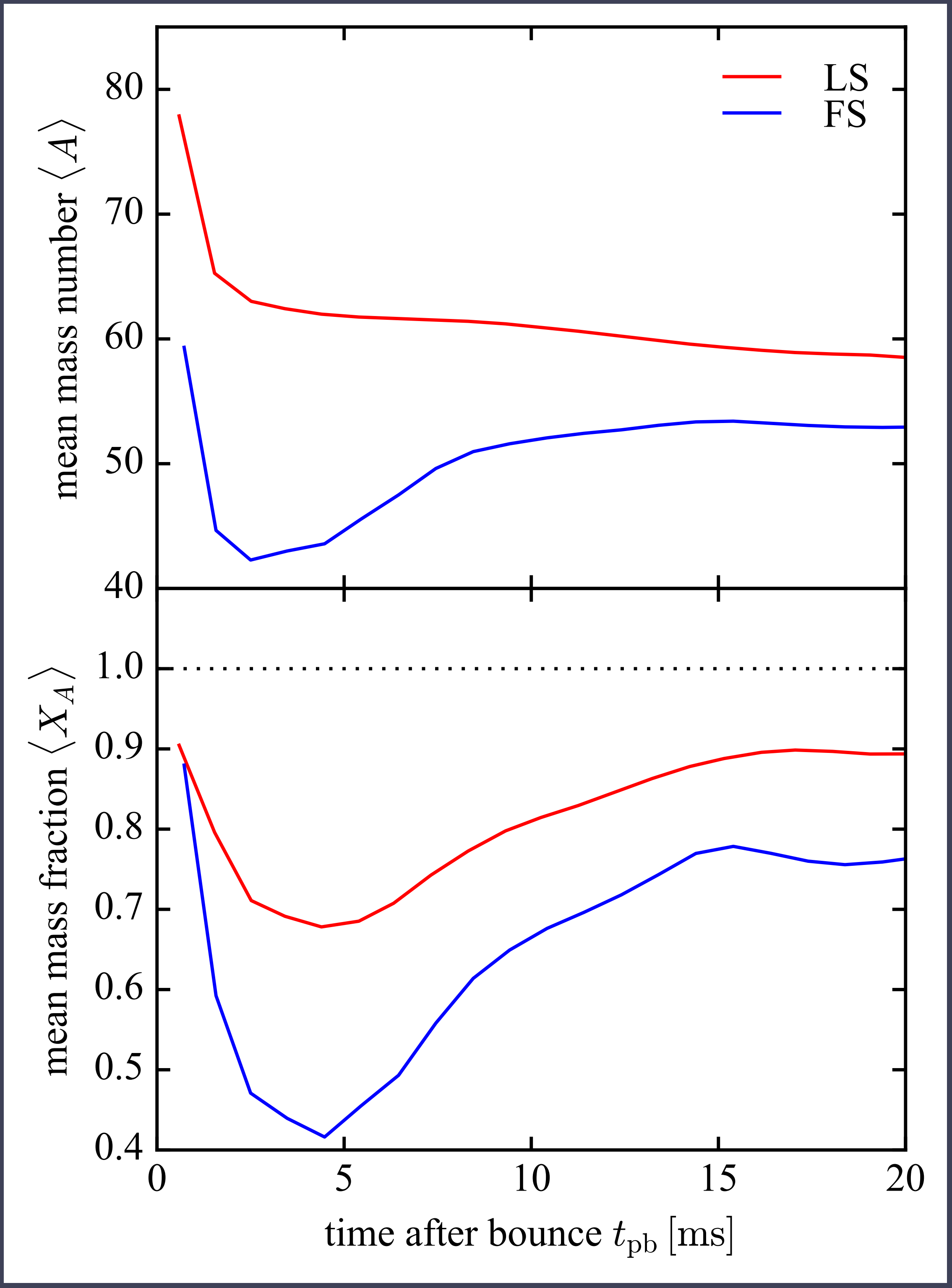
- All quantities are similar except for $M_{\rm gain}$
- Stronger turbulence in LS model
- Larger convection growth rate (Brunt-Vaisala freq.)



Nagakura+(2018)

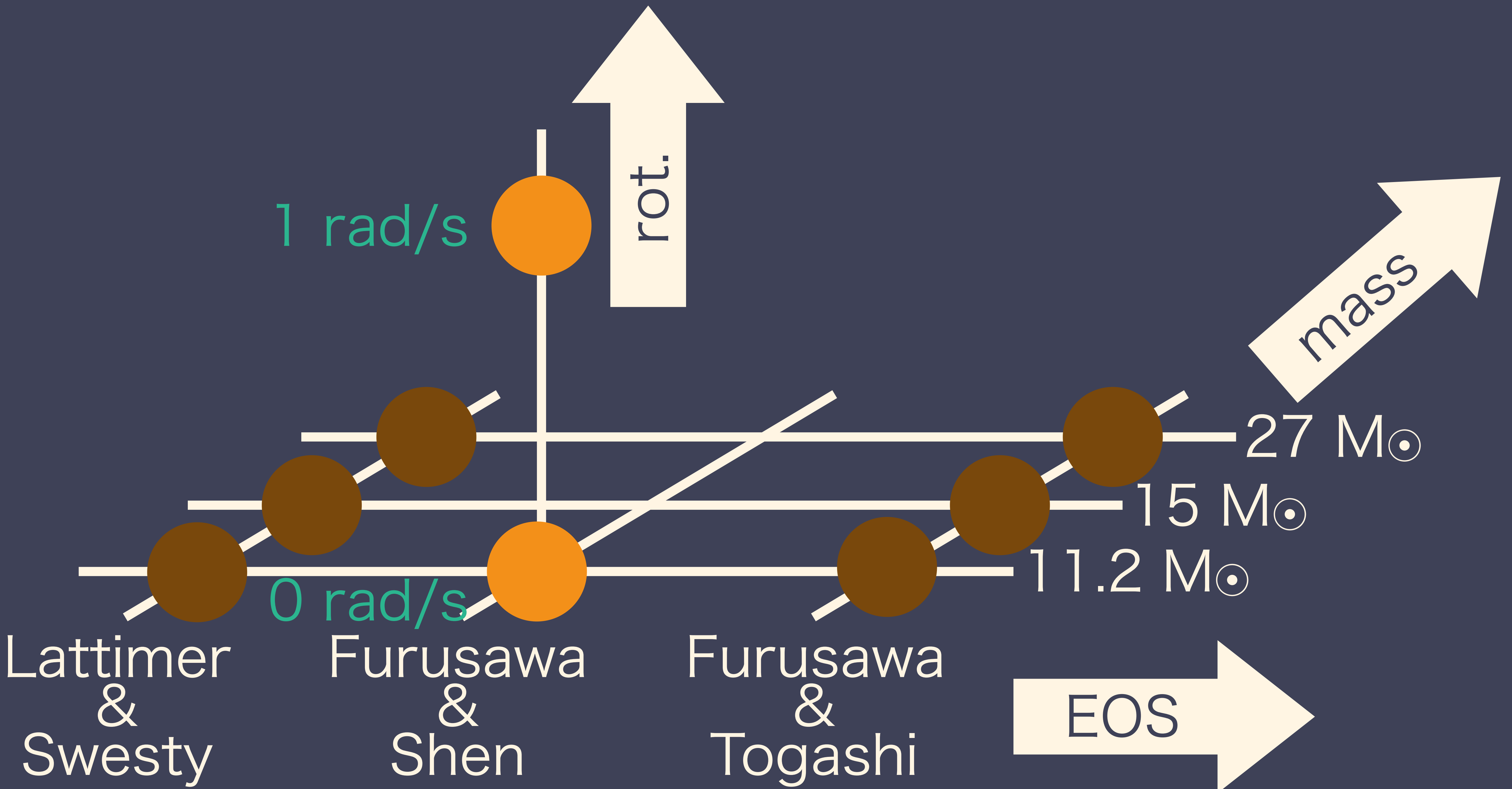
Difference in composition

- 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

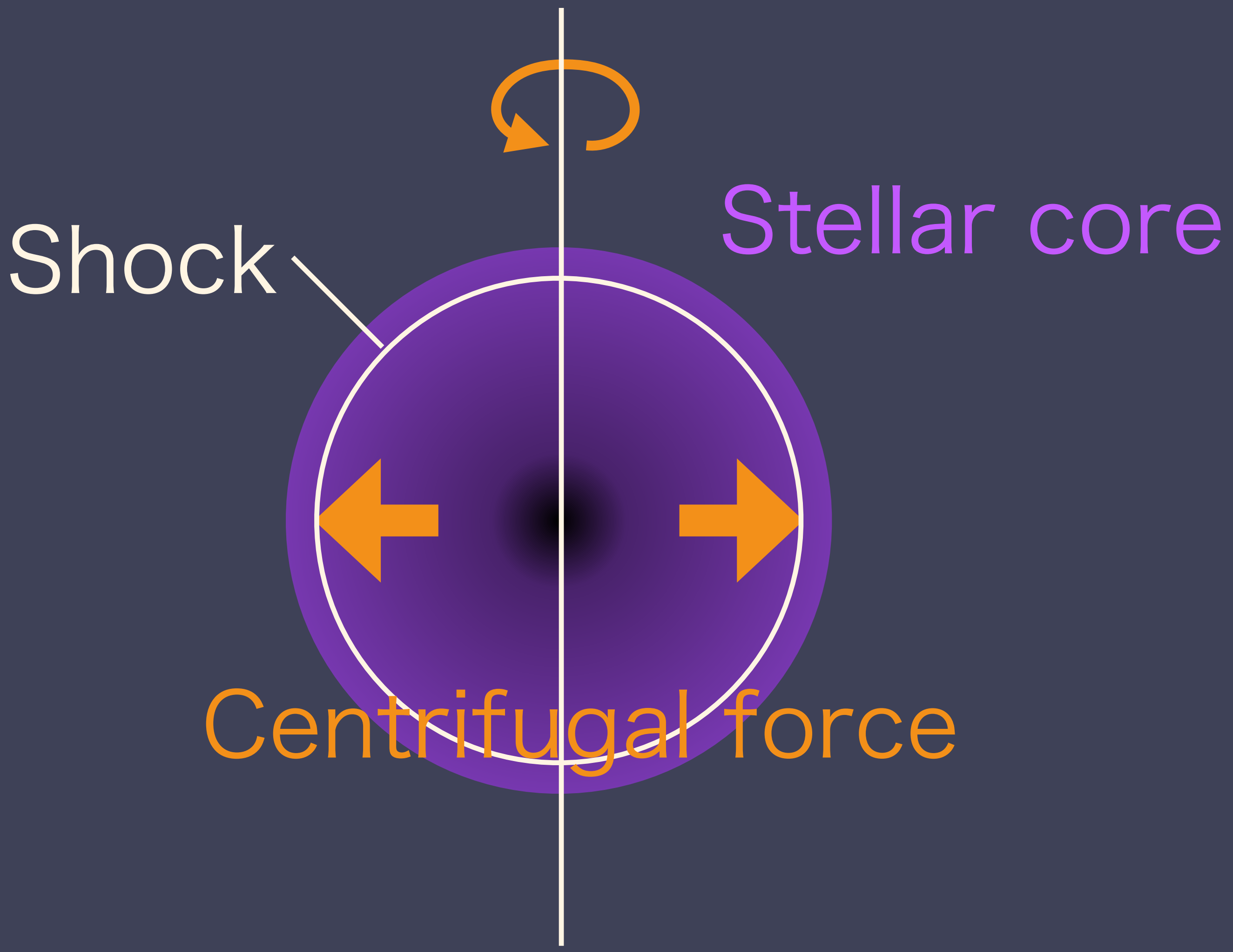


rot.
1 rad/s
mass
27 M⊙
15 M⊙
11.2 M⊙
0 rad/s
Lattimer & Swesty
Furusawa & Shen
Furusawa & Togashi
EOS

Rotation

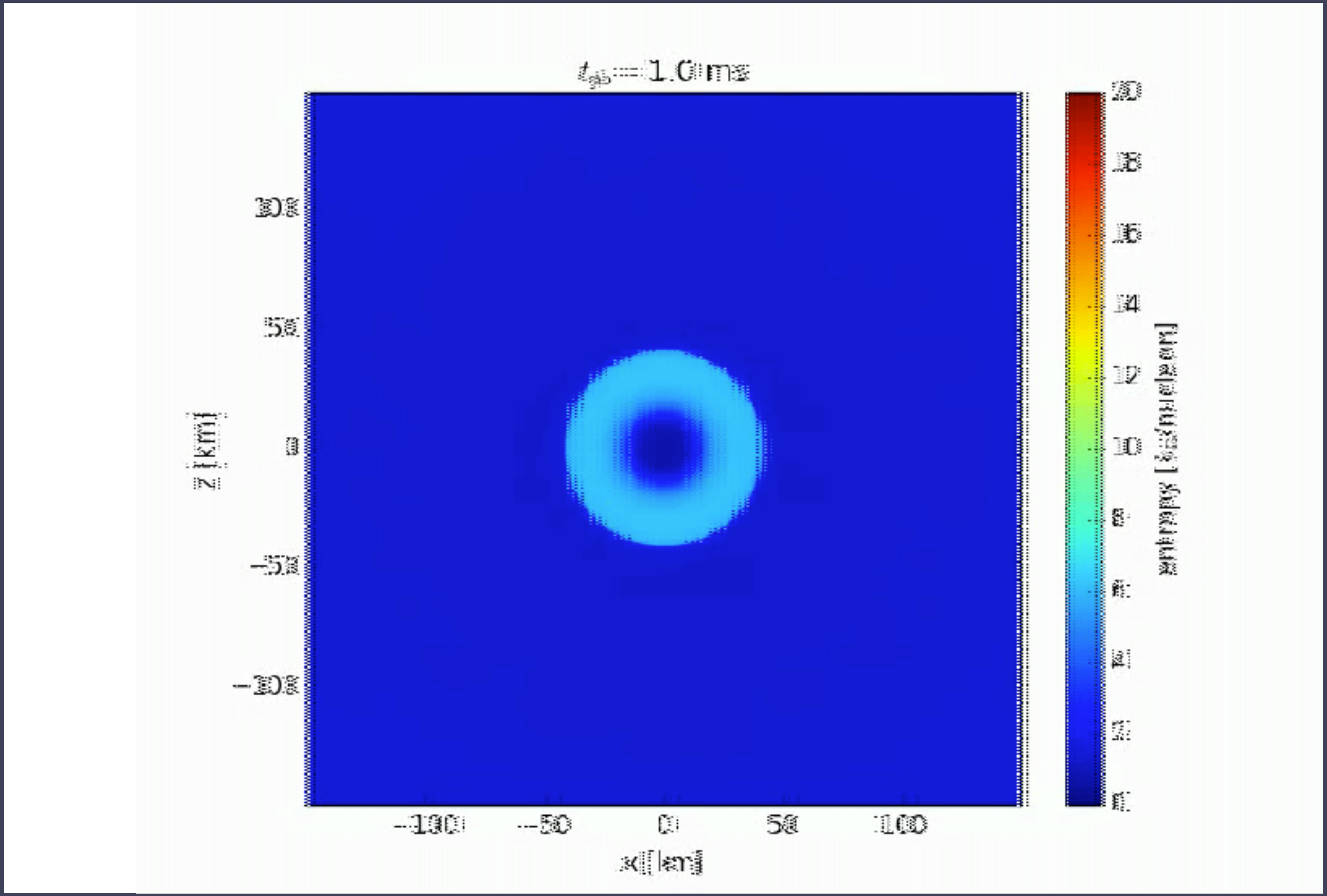
- Both positive and negative effects on shock revival
- Neutrino distributions are distorted
- (Thanks to the Boltzmann solver,) The accuracy of approximation is checked.
- Imposed rotation:

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



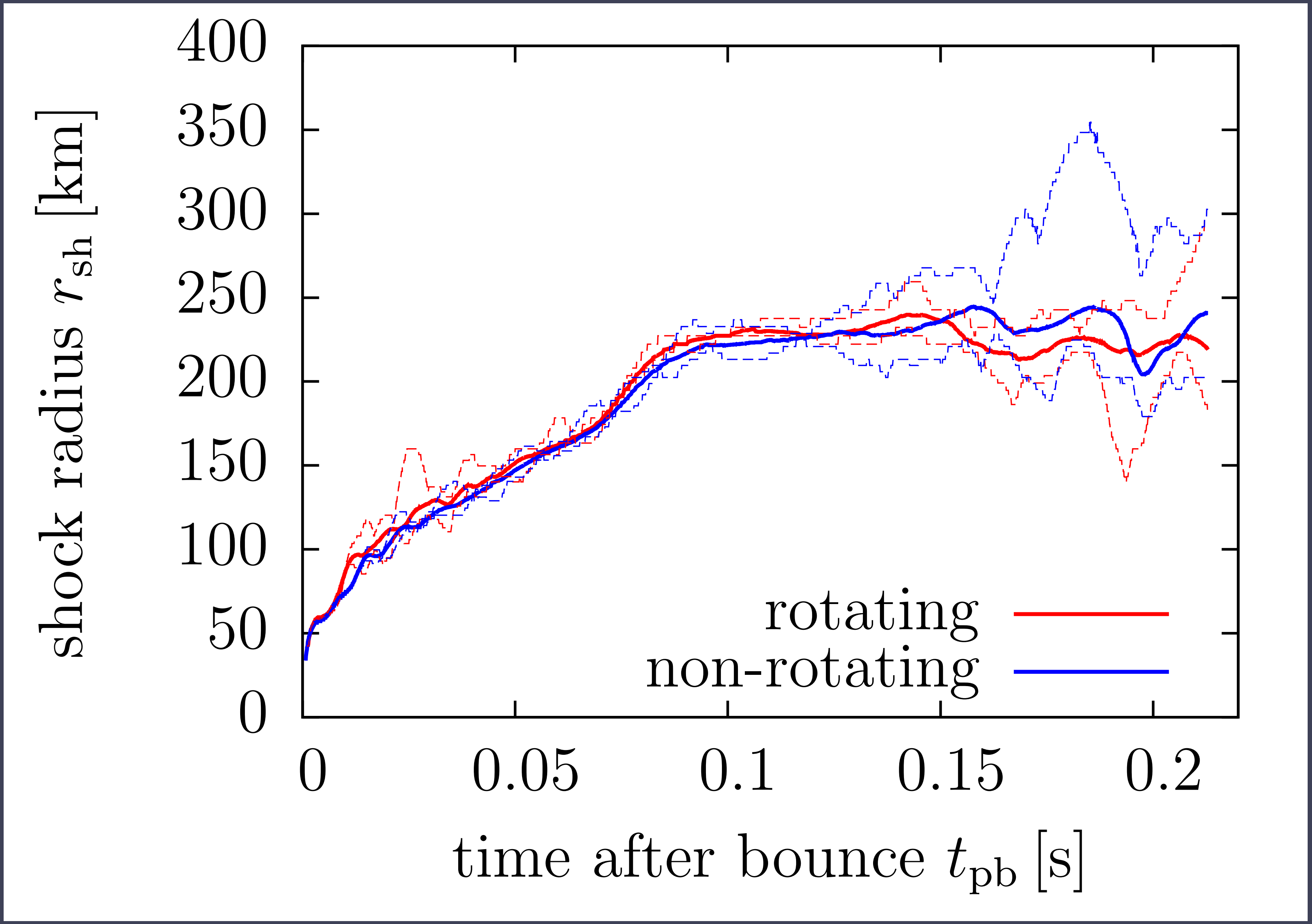
Entropy distribution

- Time evolution until ~200 ms after bounce.



Shock evolution

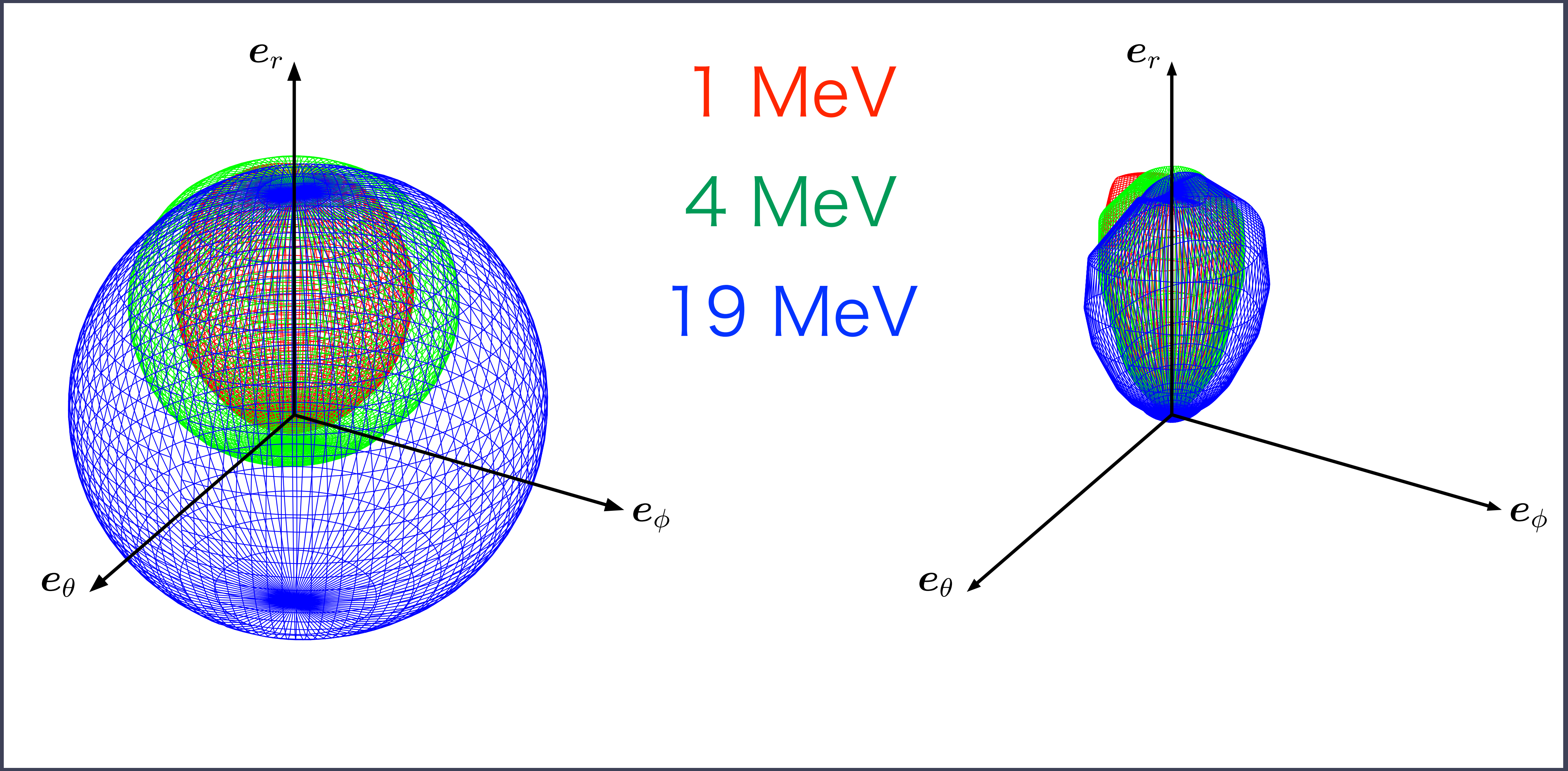
- Postbounce evolution until ~200 ms
- The difference between rotating & non-rotating model



AH+(2019)

Neutrino ang. distribution

- Distribution functions at ~10 ms after bounce.

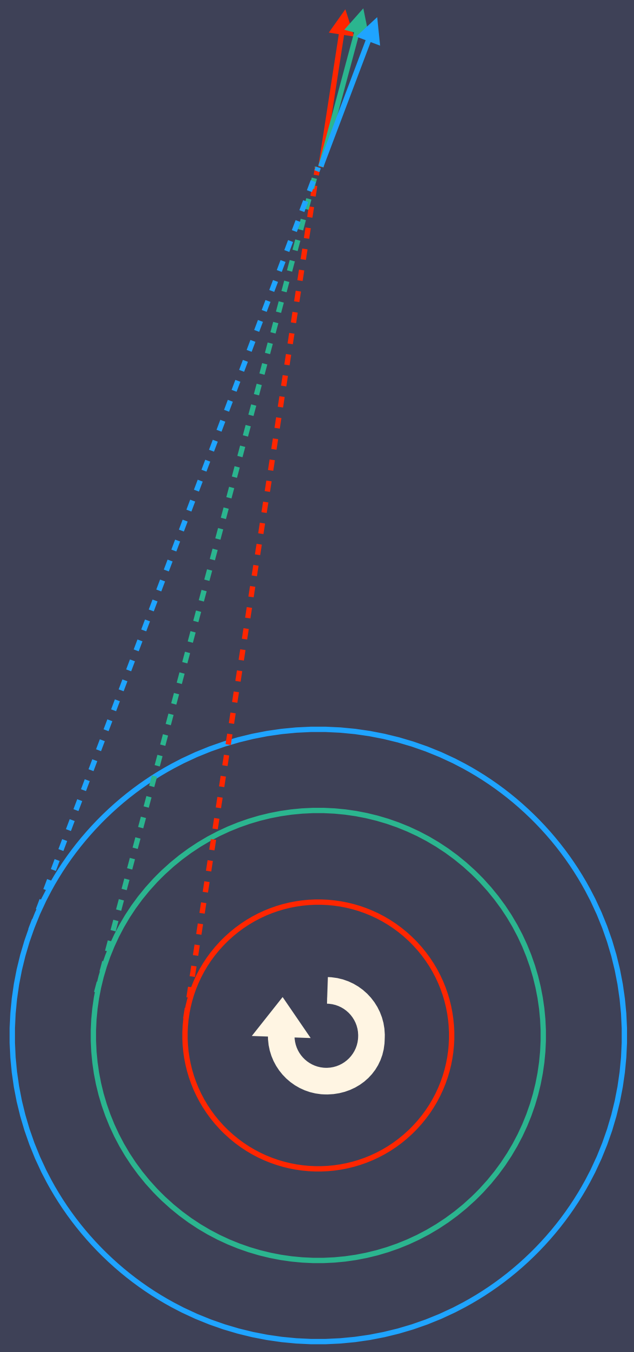


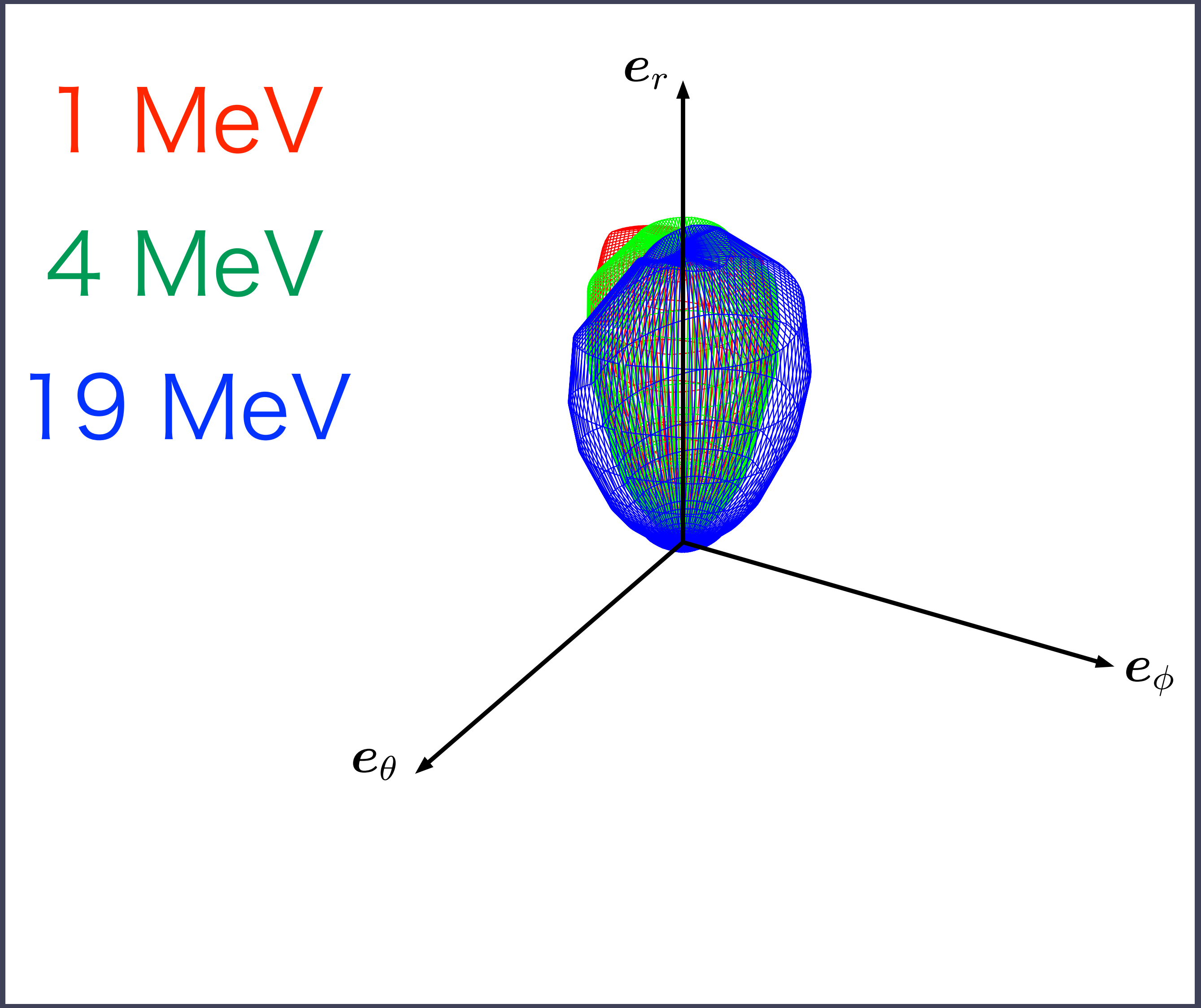
~60 km ~170 km

AH+(2019)

Neutrino ang. distribution

- Distribution functions at ~10 ms after bounce.



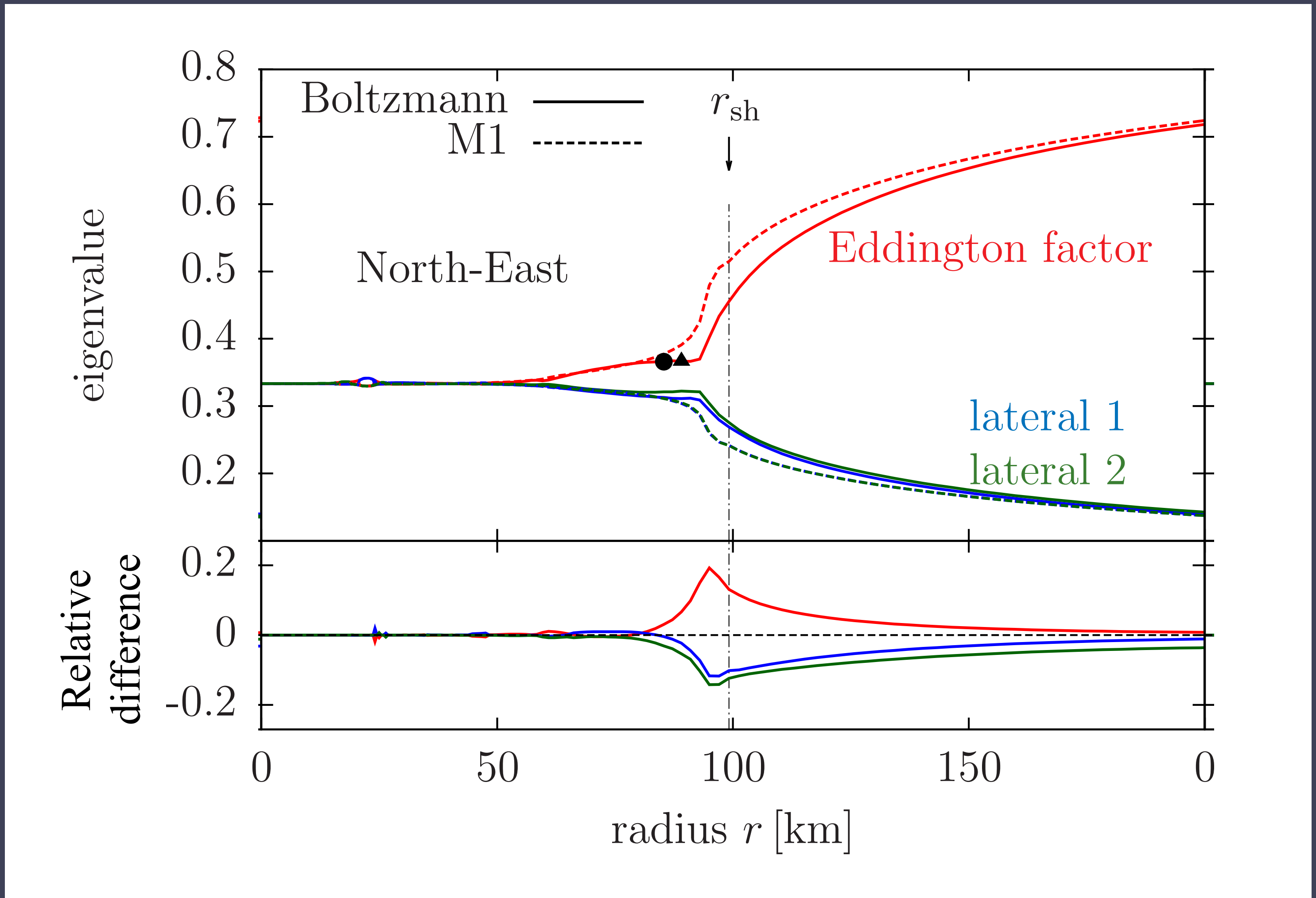


~170 km

AH+(2019)

Eddington factor

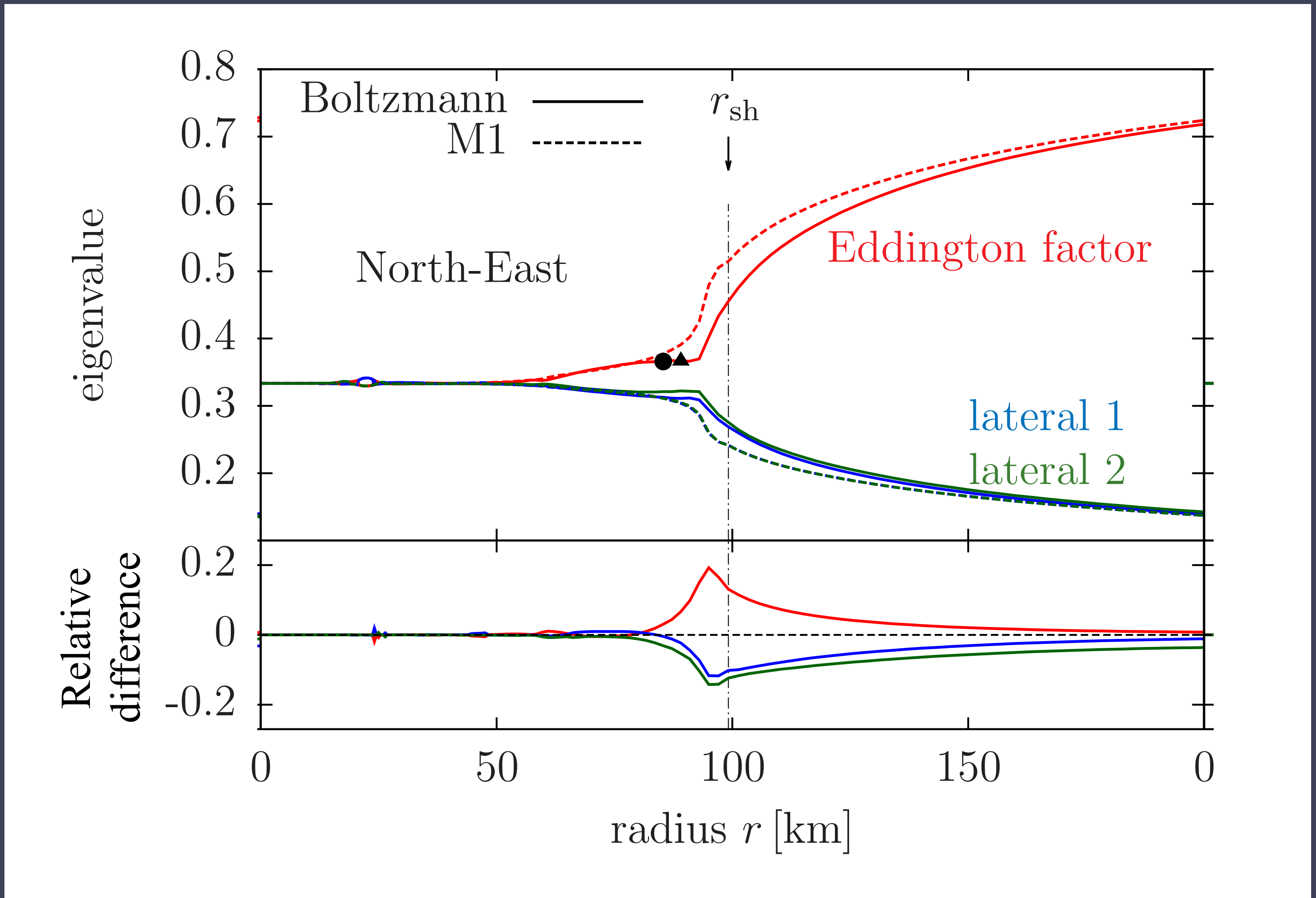
- Eddington tensor at ~10 ms after bounce
- spatial distribution of eigenvalues
- ~20% difference in M1-closure scheme



AH+(2019)

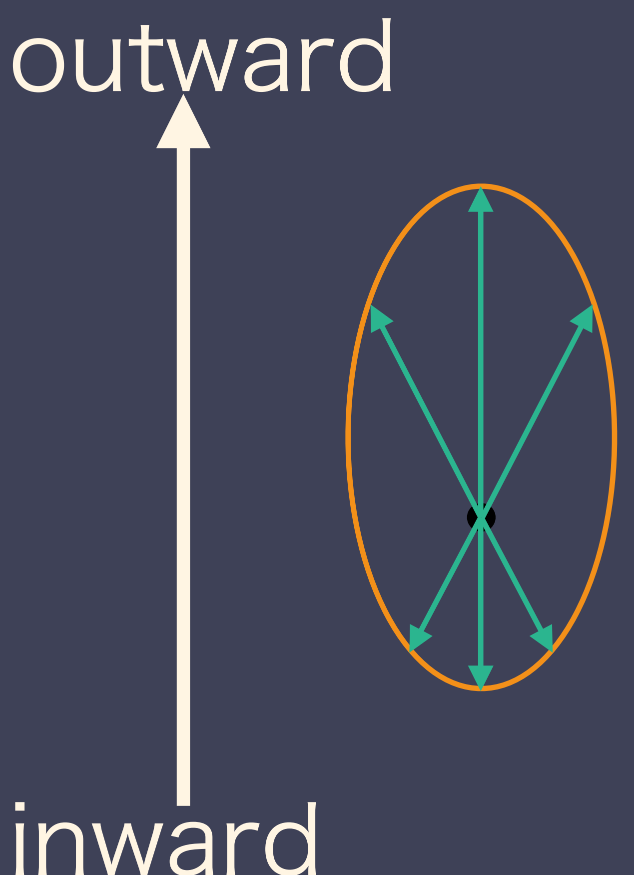
Eddington factor

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



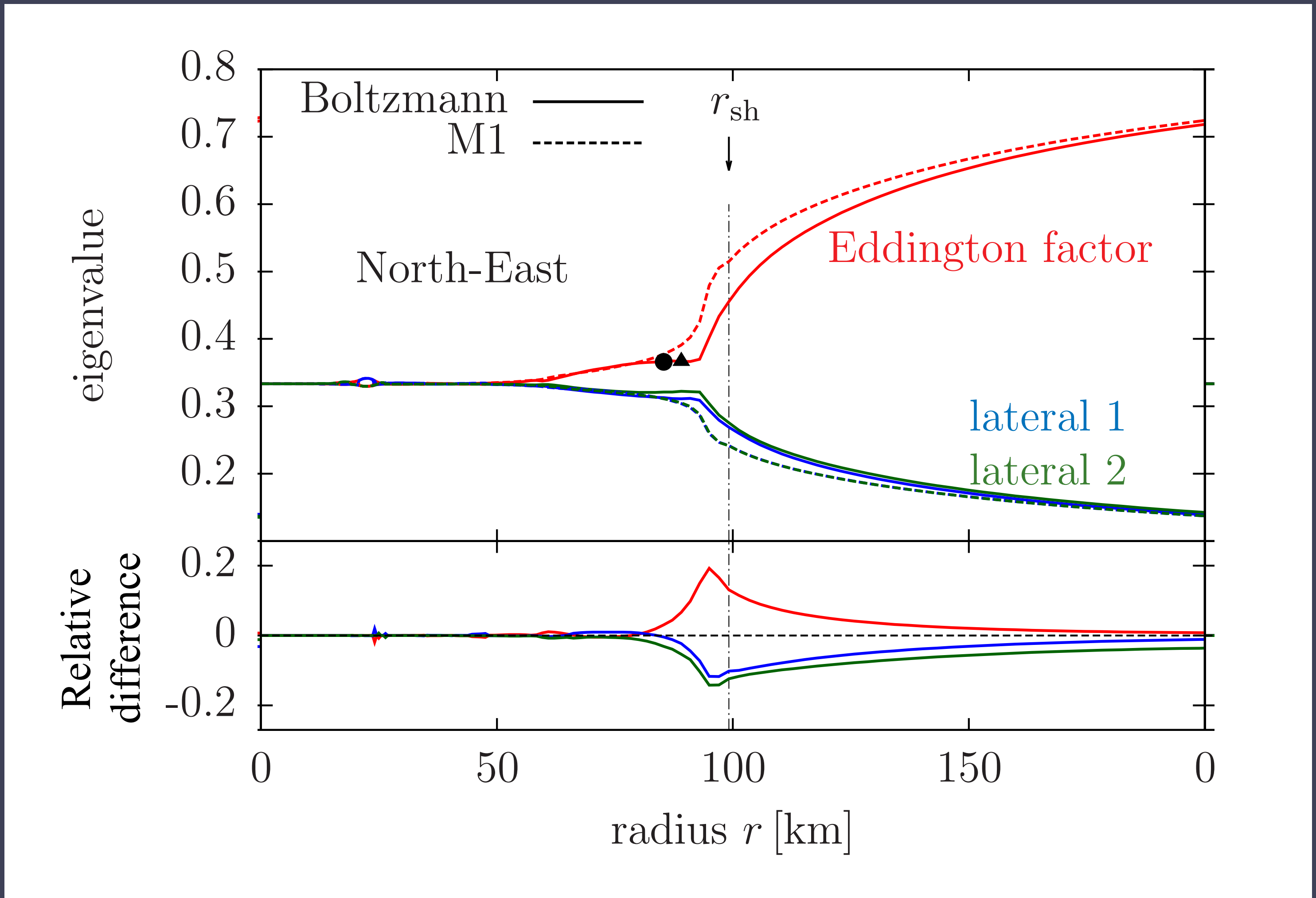
AH+(2019)

- Prolateness of distribution
- M1: estimated from deviation

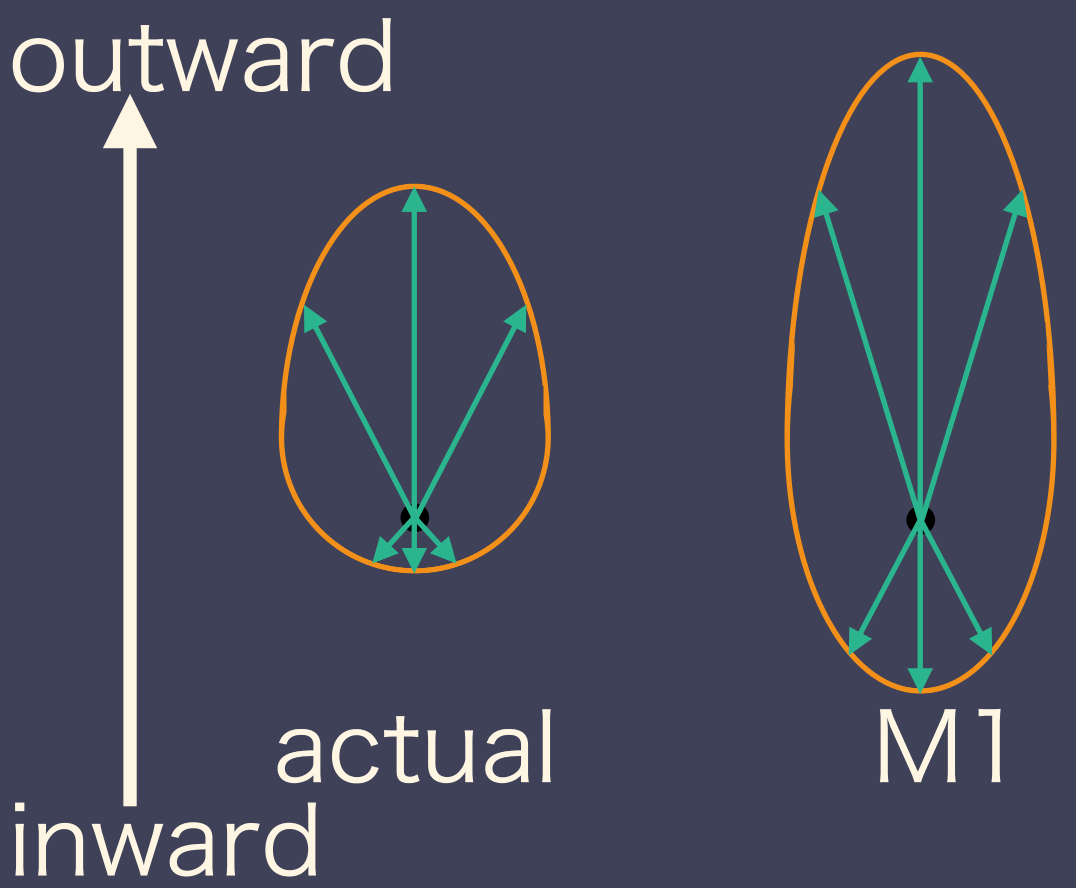


Eddington factor

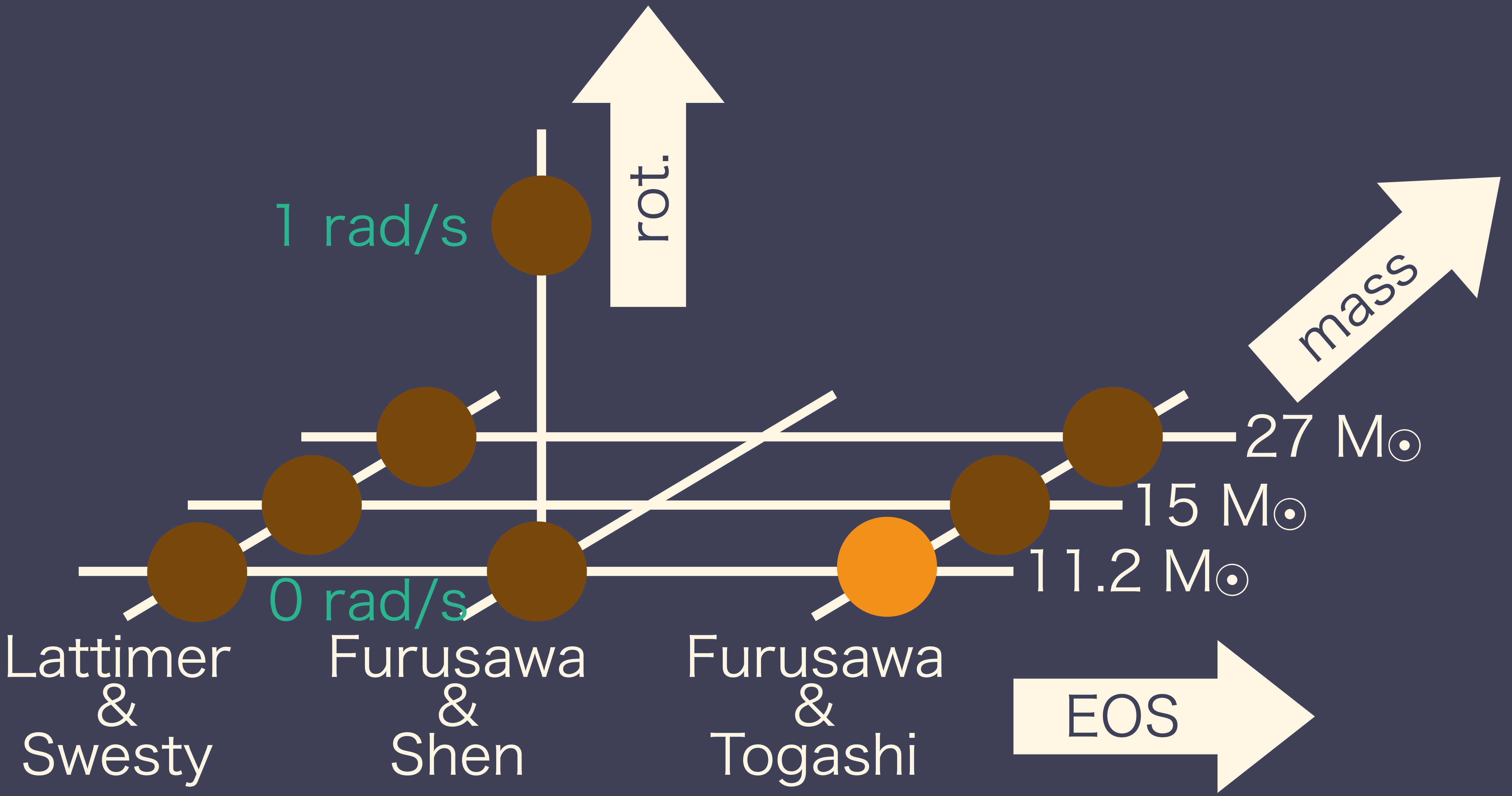
- Eddington tensor at ~10 ms after bounce
- Comparison between Boltzmann- and M1-Edd. factors
- Information which distinguish these situations may improve the approximation



AH+(2019)



PNS kick



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27 M⊙
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Lattimer & Swesty
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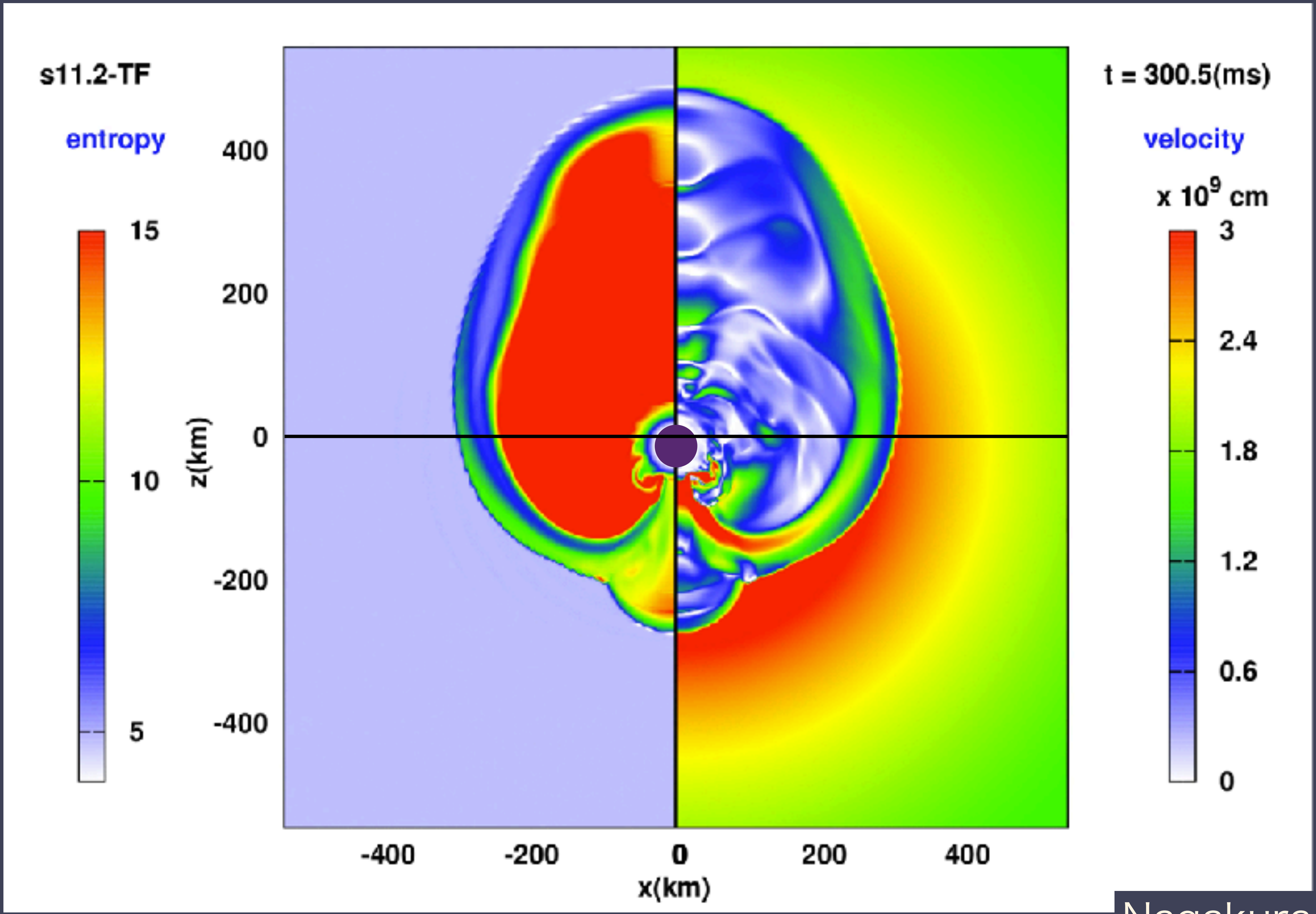
EOS

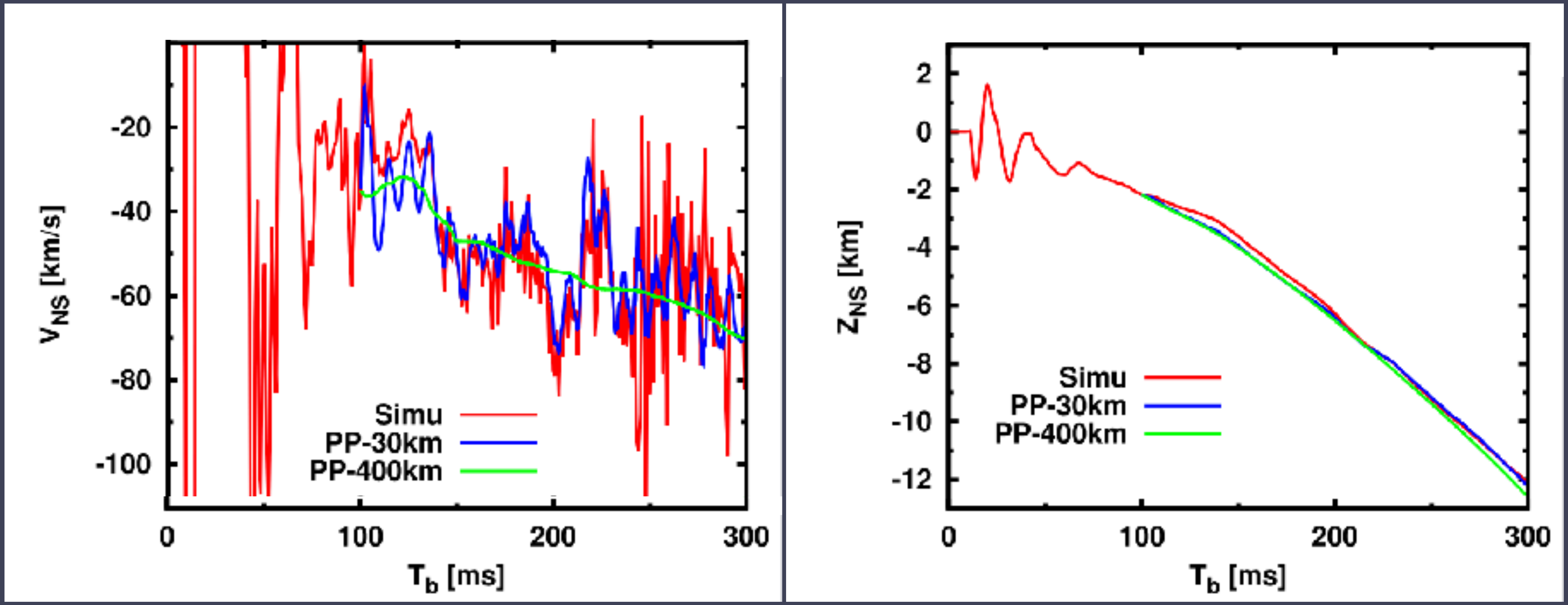
Entropy distribution

- PNS moves from its initial position.



Nagakura+(2019)

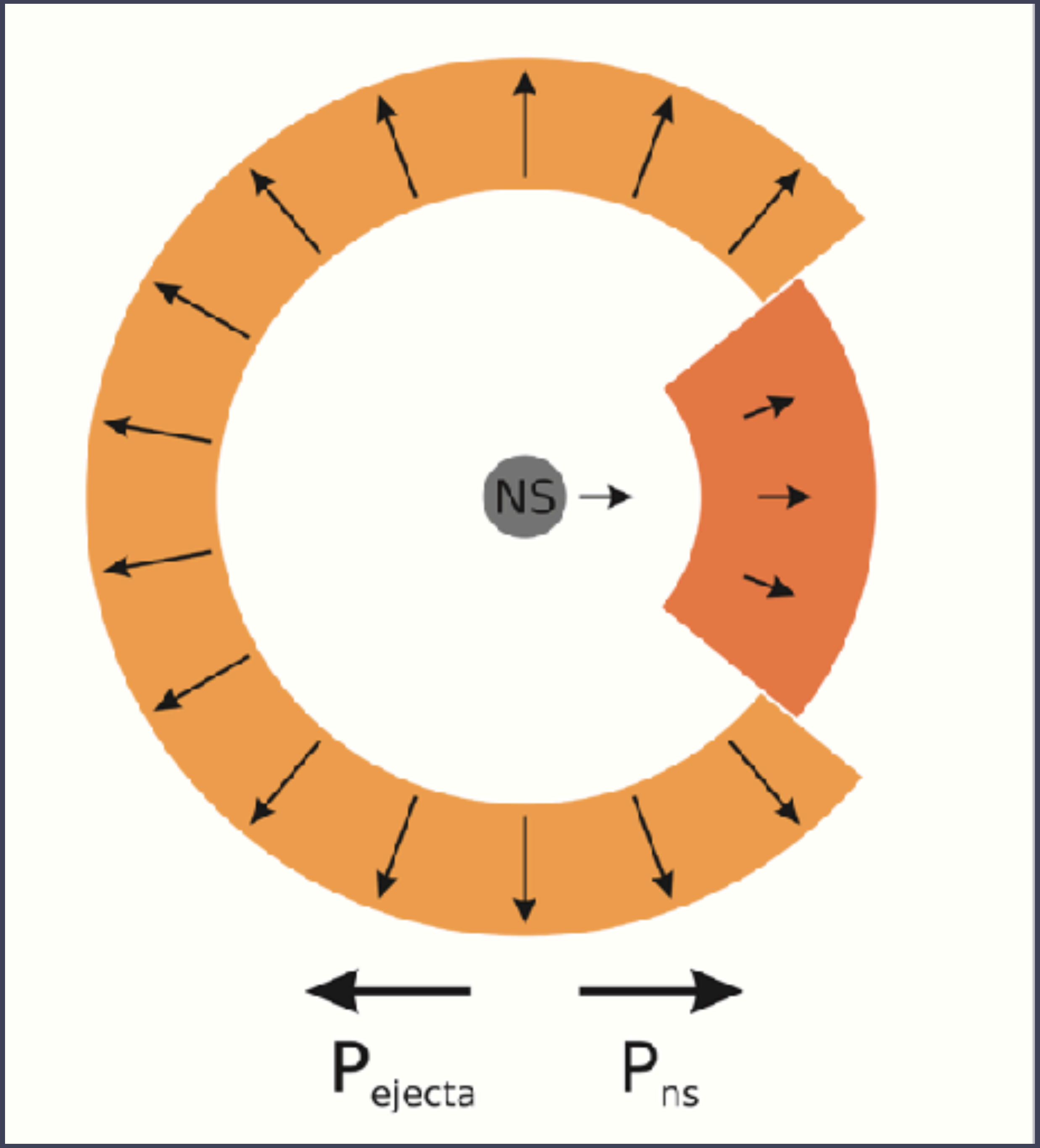
Proper motion of PNS after 100 ms



Nagakura+(2019)

- PNS kick after T_b = 100 ms is observed.

PNS kick mechanism (at late phase): gravitational tug boat?



Scheck+(2006)

Gravitational tug boat mechanism:

- Anisotropic explosion

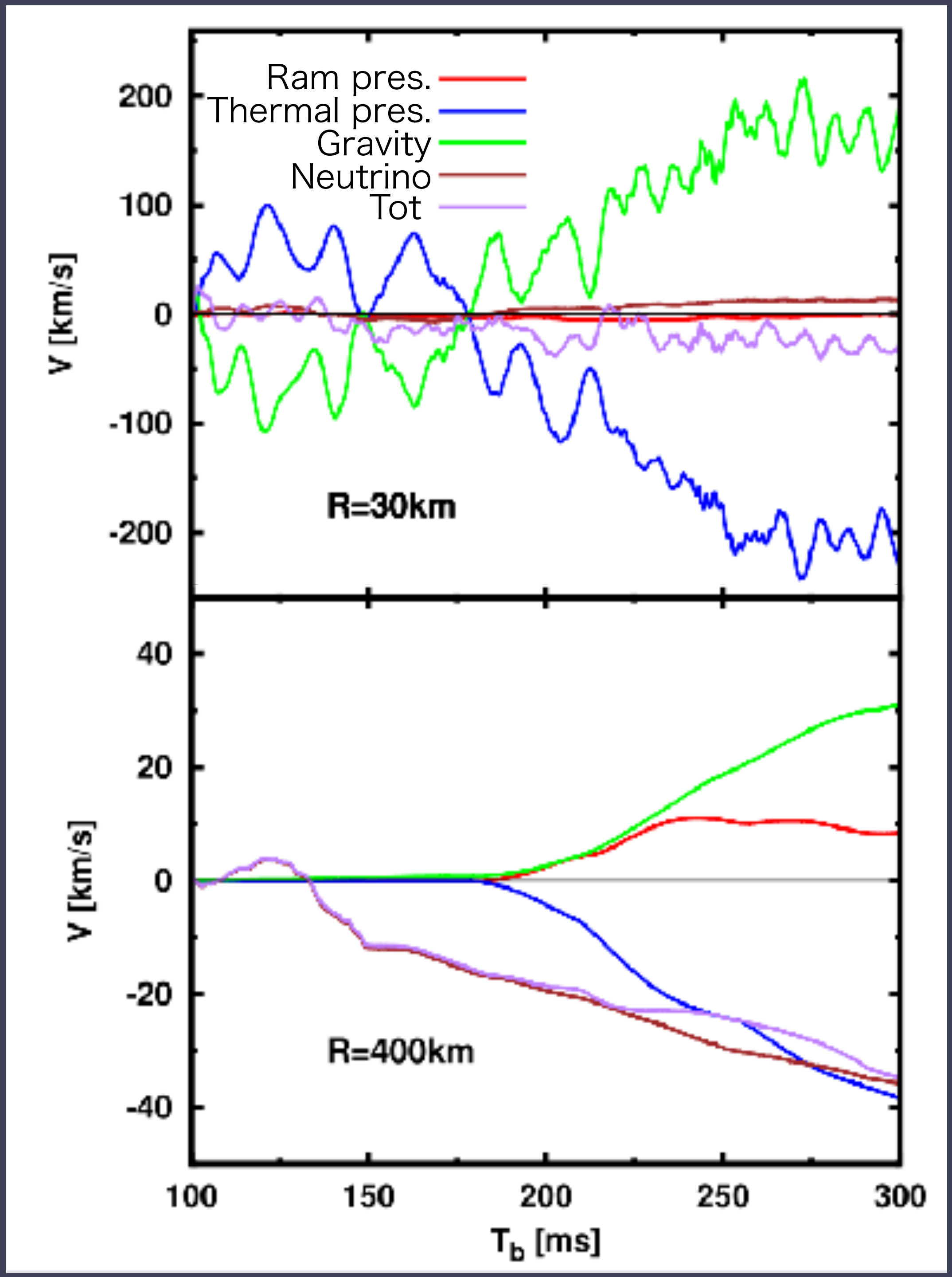
↓

- slower side is closer to the PNS and more dense

↓

- PNS is attracted to this side

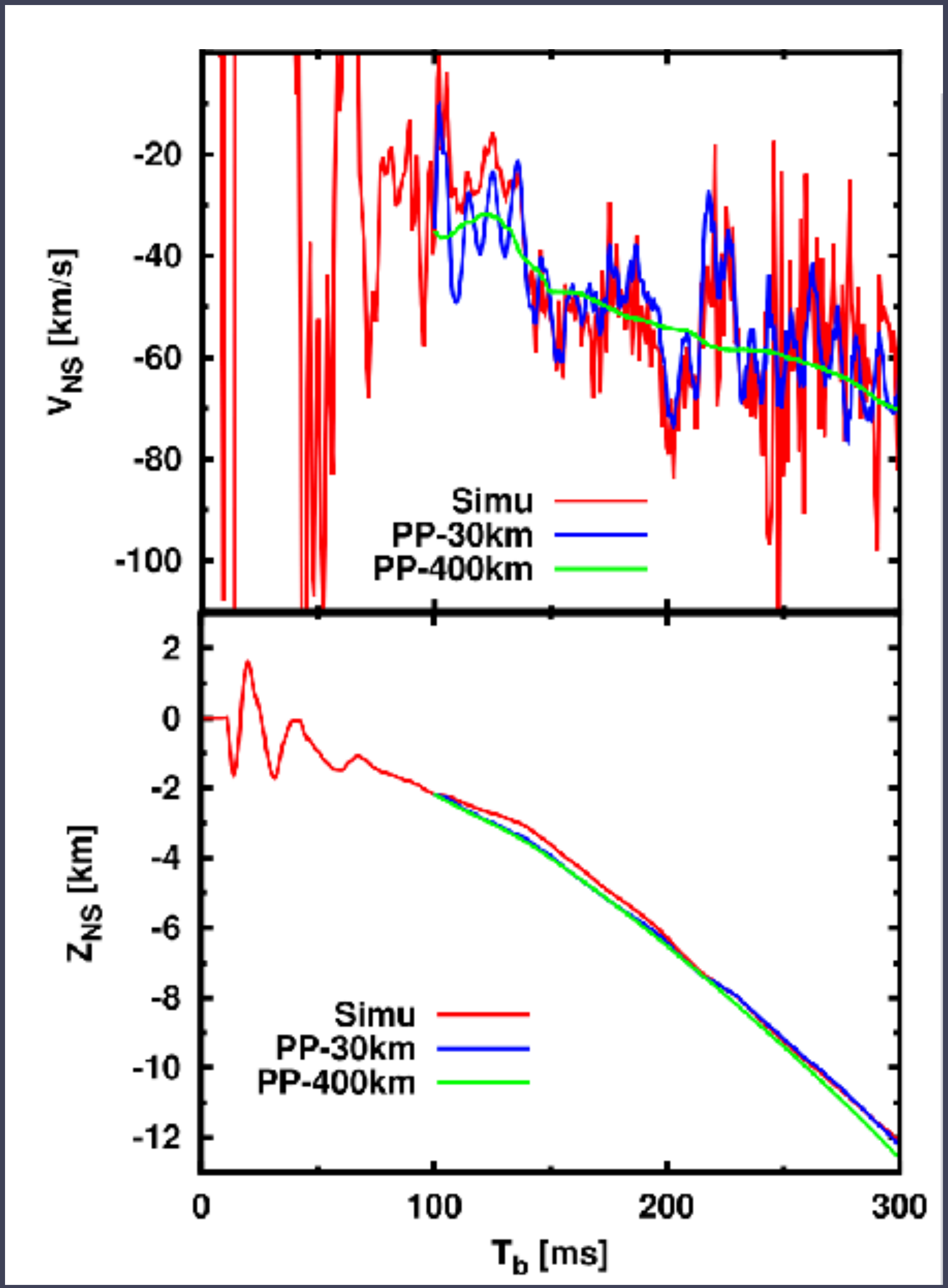
PNS kick mehanism (at early phase): gravity? pressure? neutrino force?



Nagakura+(2019)

- What kind of force is important?
- Velocity originated from each force (time integrated acceleration)
- Inside 30 km: thermal pressure exceeds gravity
- Inside 400 km: neutrino force is dominant

Radiation force of neutrinos may play a role

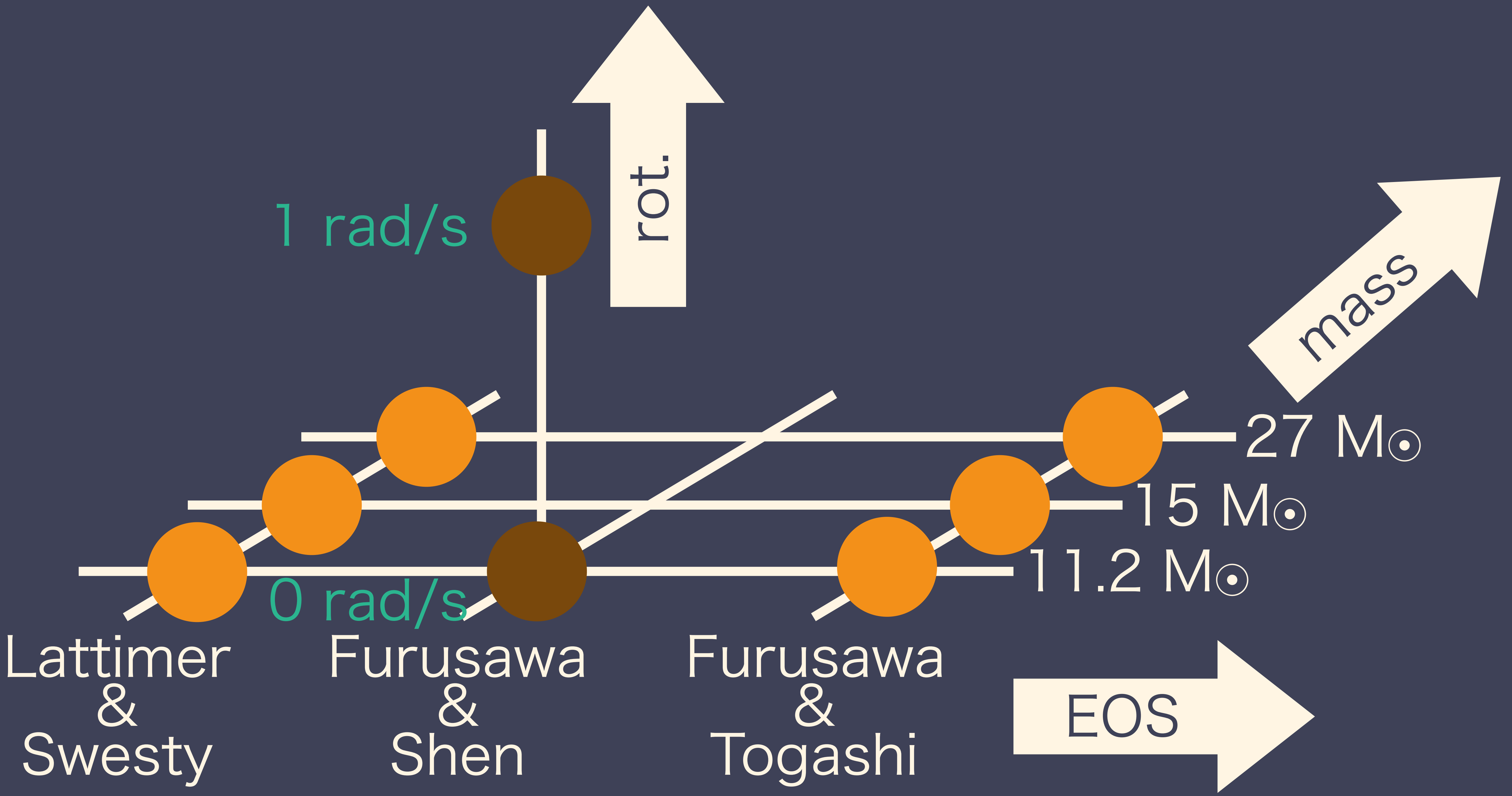


Nagakura+(2019)

- Force applied inside 30 km (thermal pressure + gravity) reproduces the PNS kick.
- Force inside 400 km (neutrino force) also reproduces the PNS kick.

- Neutrino force may play an important role.

Progenitor



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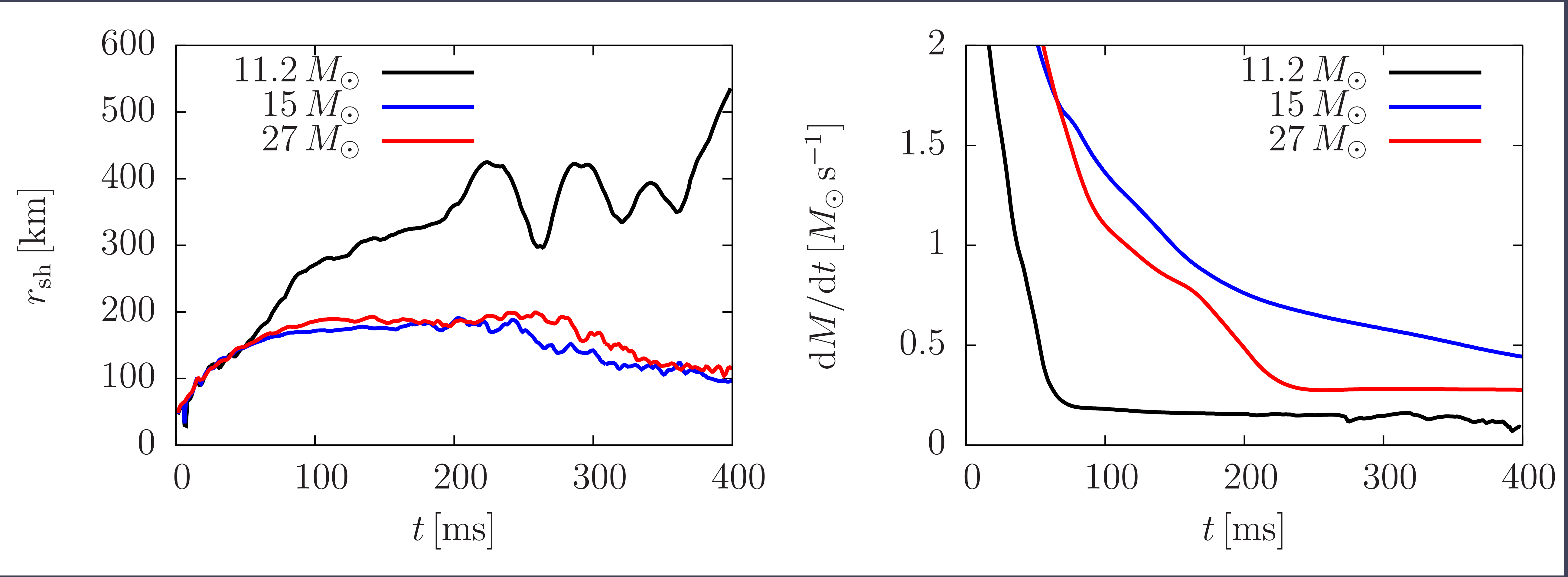
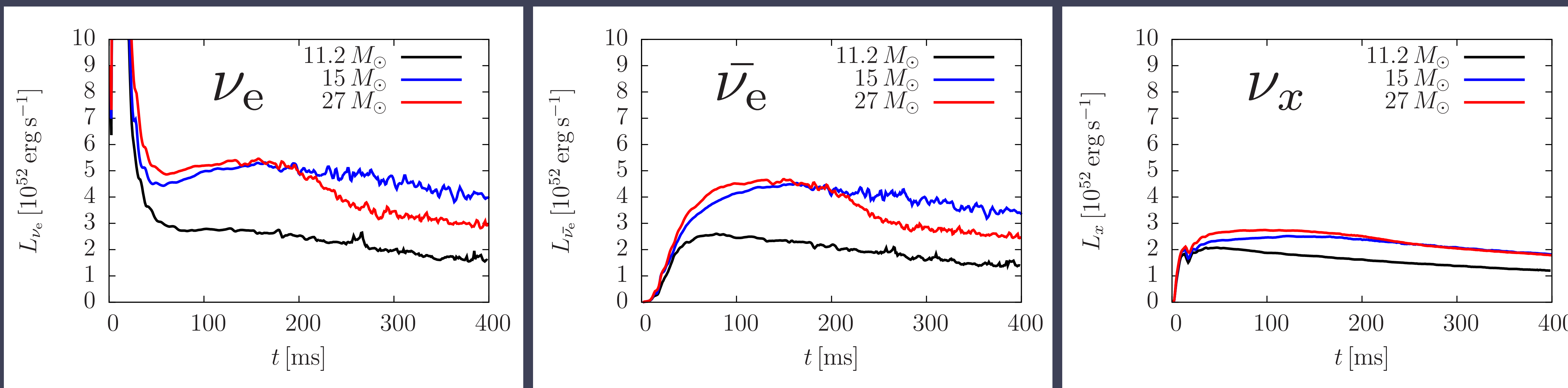
Shock evolution of different progenitor models with LS EOS



Iwakami+ in prep.

- Only 11.2 M⊙ model shows shock revival beginning with the rapid drop of mass accretion rate
- The others do not explode even when the mass accretion rates drop.

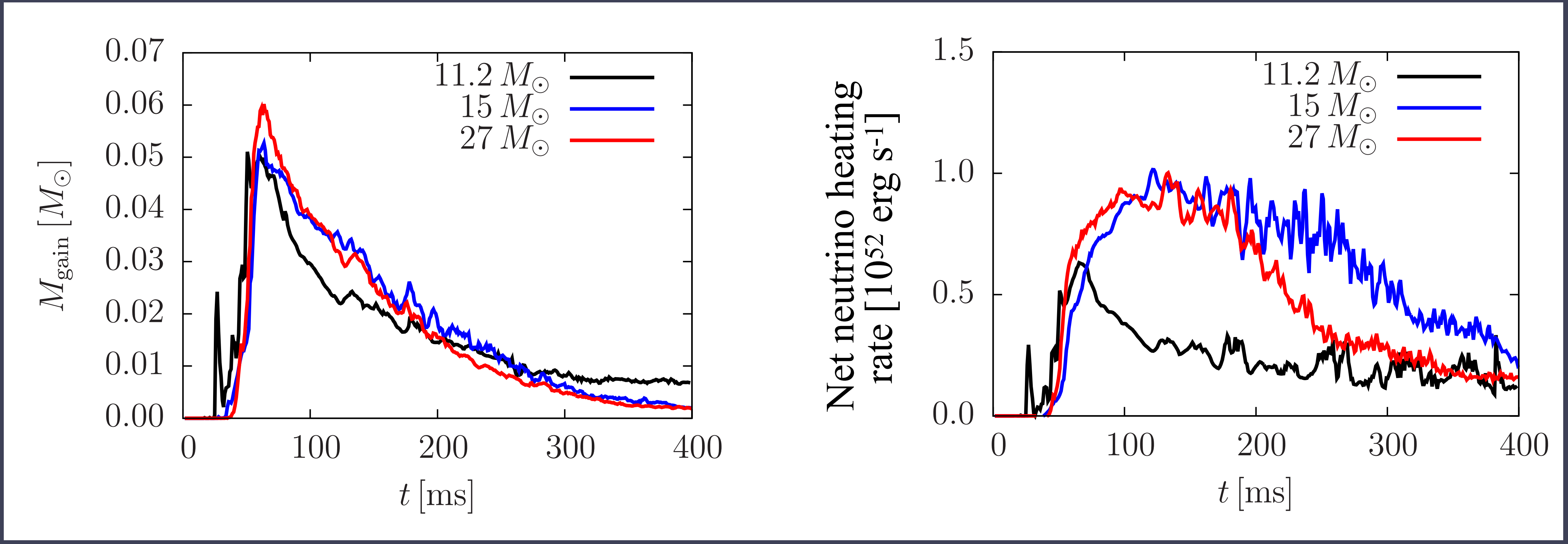
Higher neutrino heating rate for non-explosive models



Iwakami+ in prep.

- Since the mass accretion onto the PNS for non-explosive models is high, neutrino luminosities are large.
- Non-explosive models are dense inside the shock → gain mass is large.
- Neutrino heating rate is high for non-explosive models.

Higher neutrino heating rate for non-explosive models



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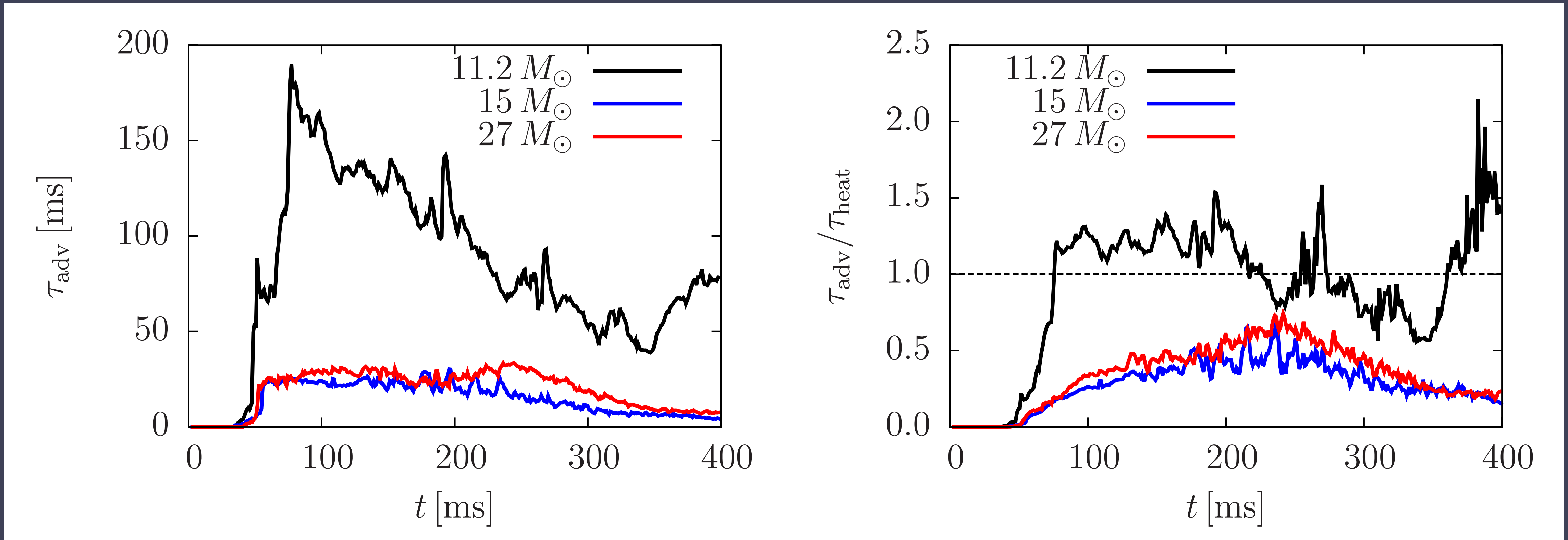
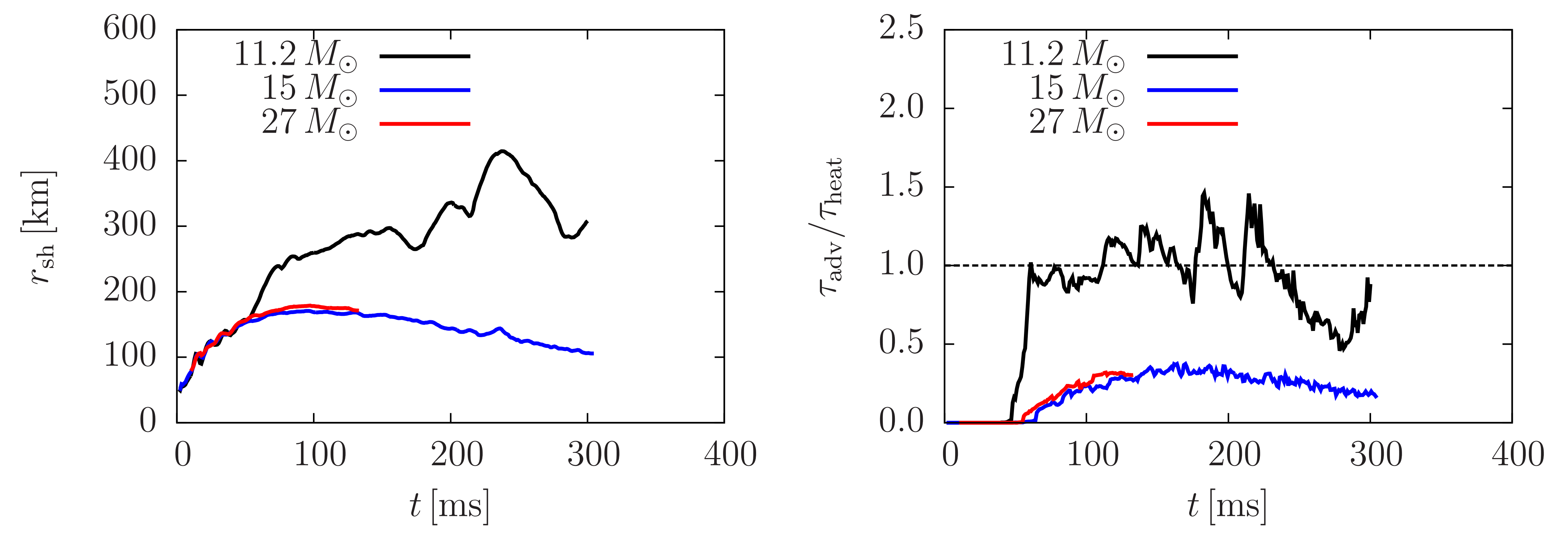
Advection timescale is long for the explosive model



Iwakami+ in prep.

- The heating timescale does not differ so much, but the advection timescale differs significantly due to the mass accretion rate
- Timescale ratio only for 11.2 M$_\odot$ model exceeds unity.

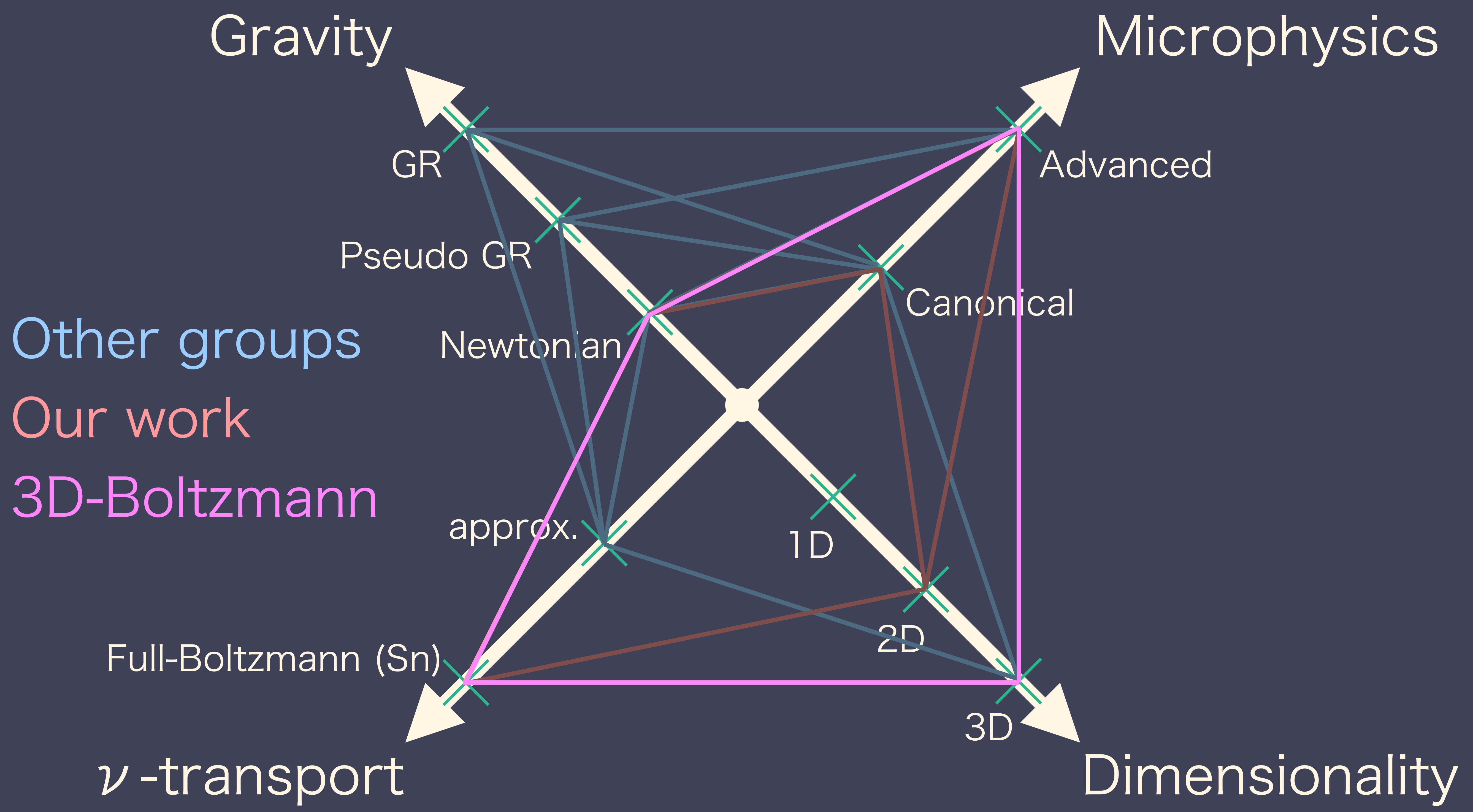
Similar properties for FT models



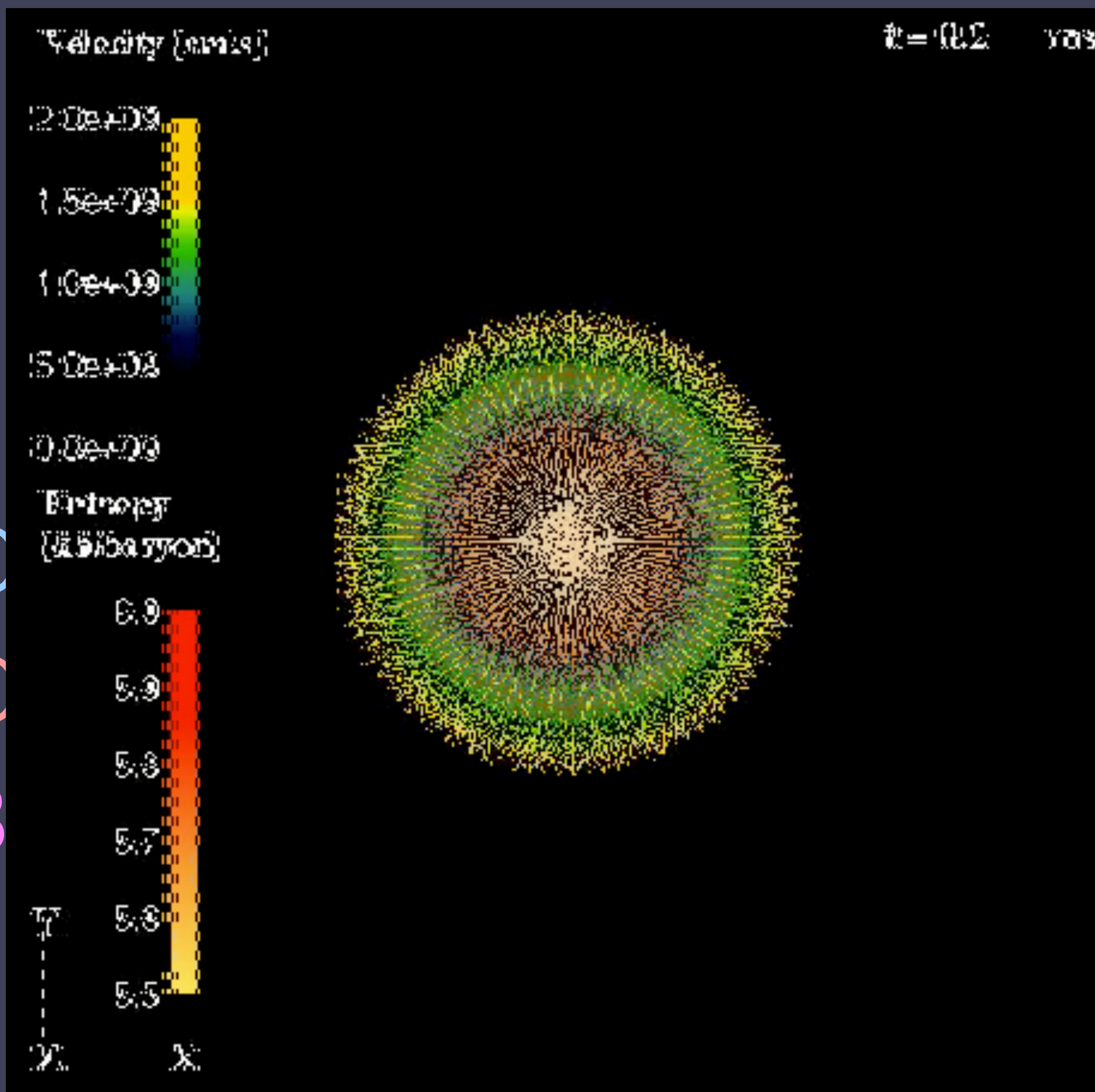
Iwakami+ in prep.

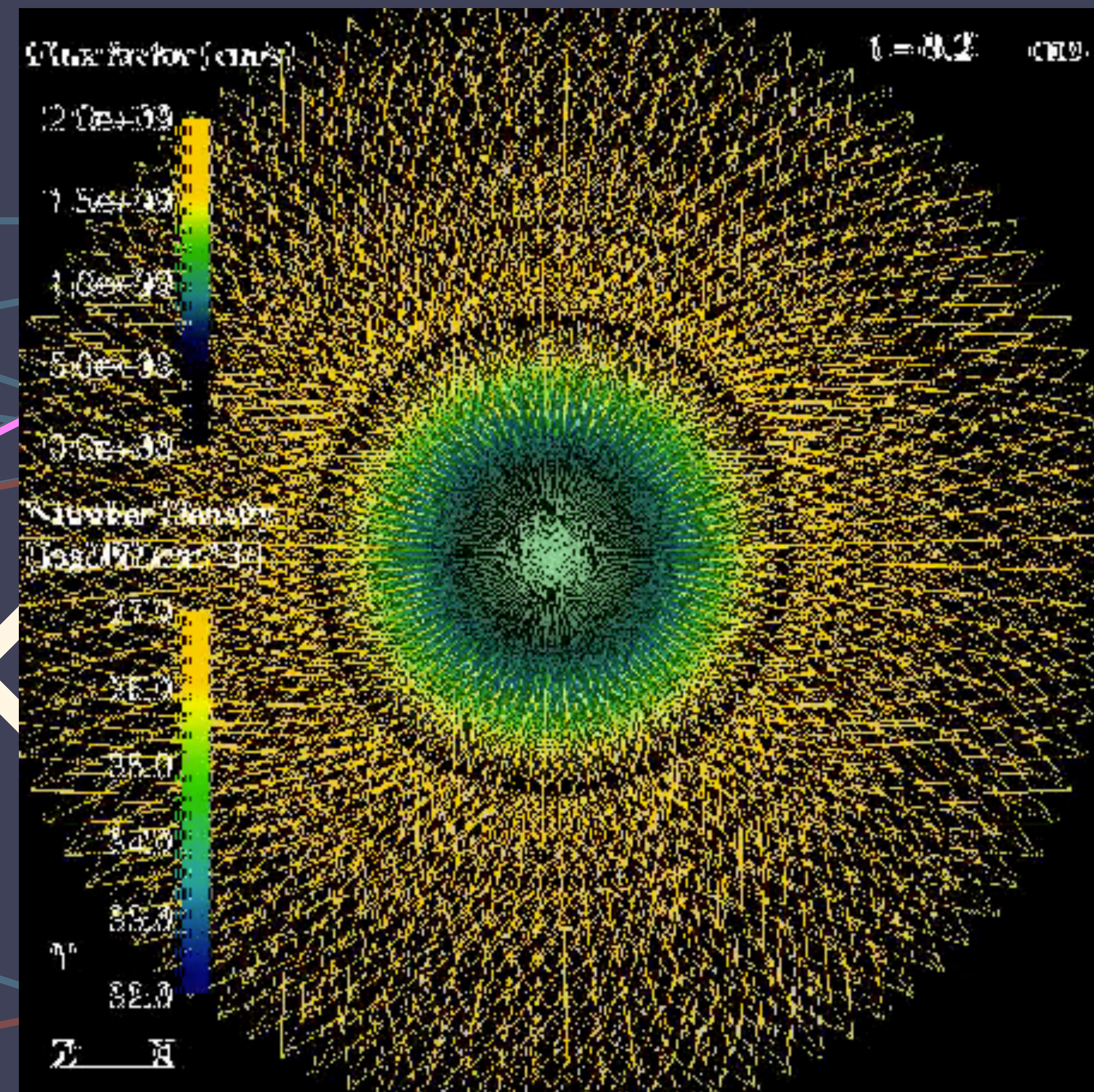
- Results using the FT EOS are similar.
- Longer simulations are required to judge whether the FT models explode or not.

Future prospects: 3D simulations and general relativistic simulations



Future prospects: 3D simulations and general relativistic simulations





Iwakami+ in prep.

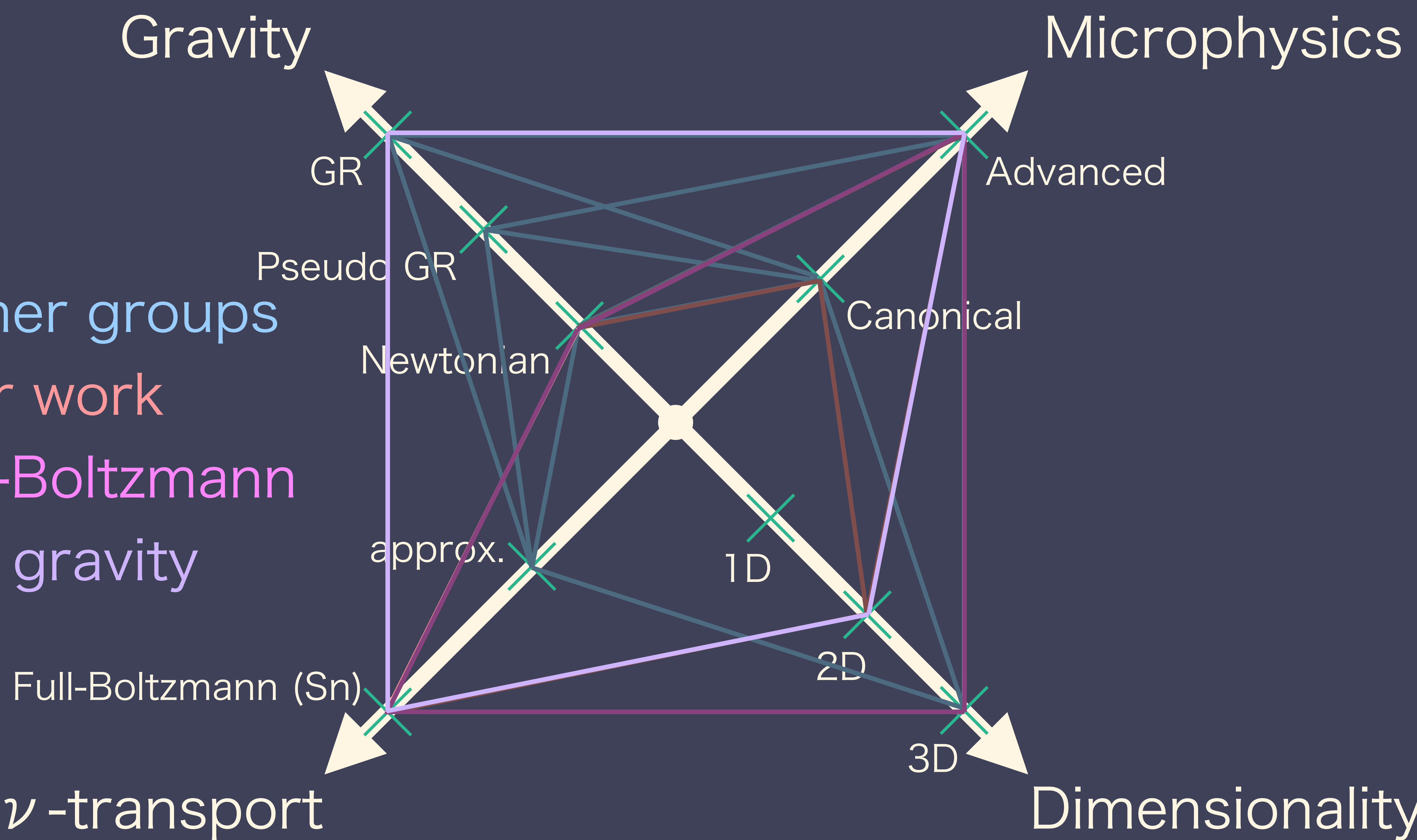
3D

ν-transport

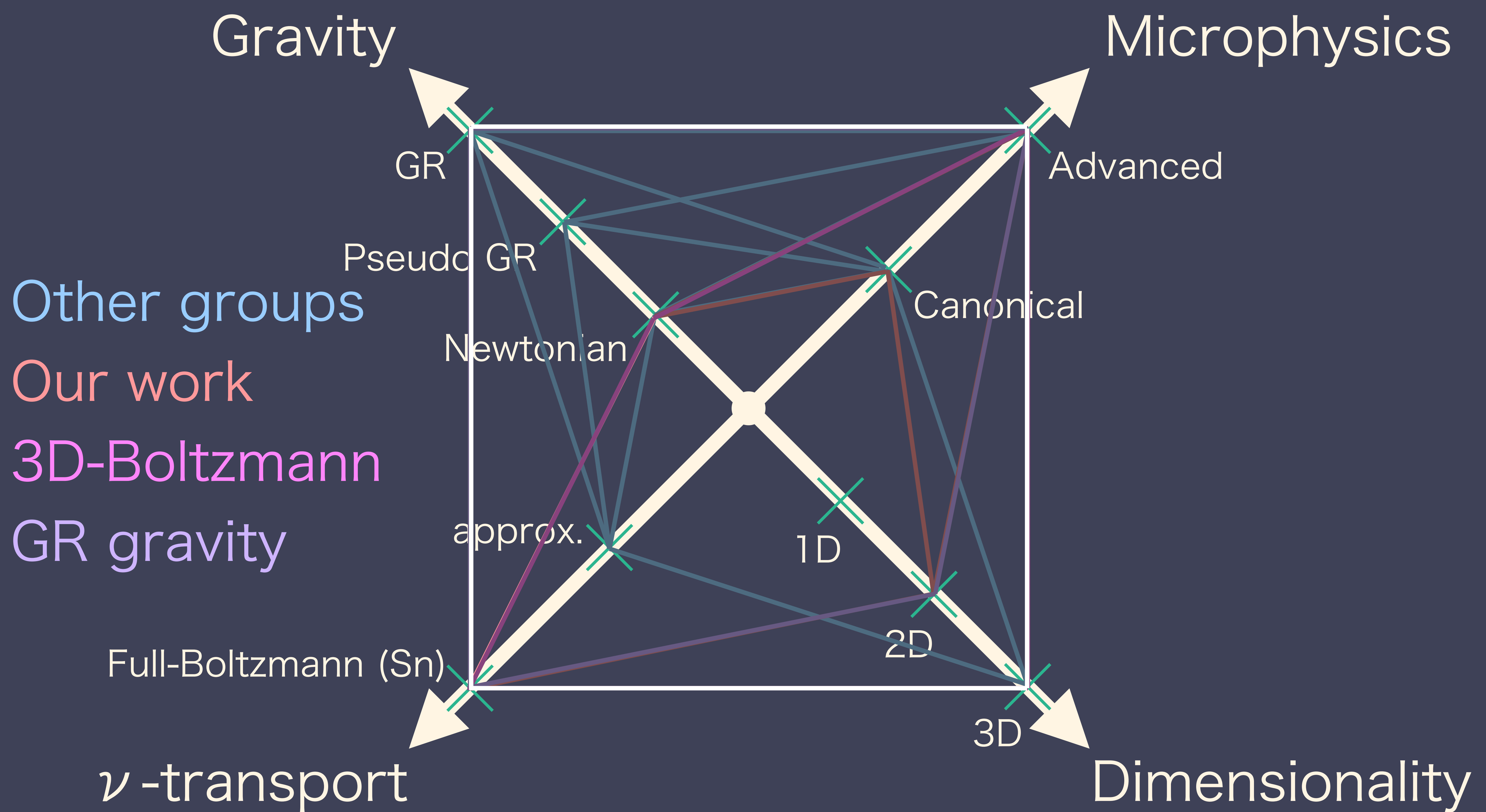
Dimensionality

Future prospects: 3D simulations and general relativistic simulations

Other groups
Our work
3D-Boltzmann
GR gravity



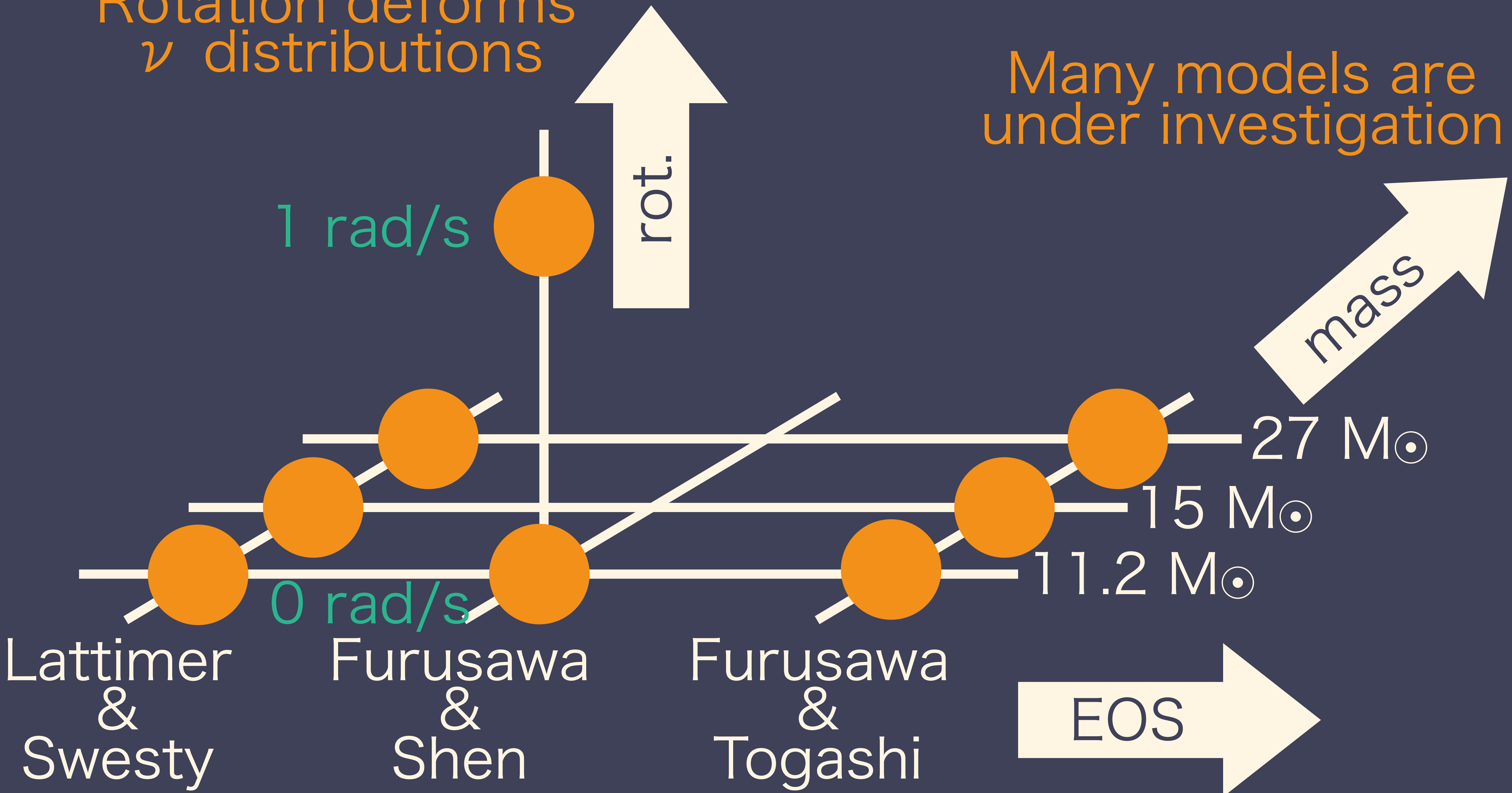
Future prospects: 3D simulations and general relativistic simulations



Summary

Rotation deforms
ν distributions

Many models are
under investigation



Composition may
be important

ν may be not negligible
for PNS kick