Core-collapse Supernova Simulations with the Boltzmann-neutrino-transport

Akira Harada (UTAP)

Core-collapse supernovae

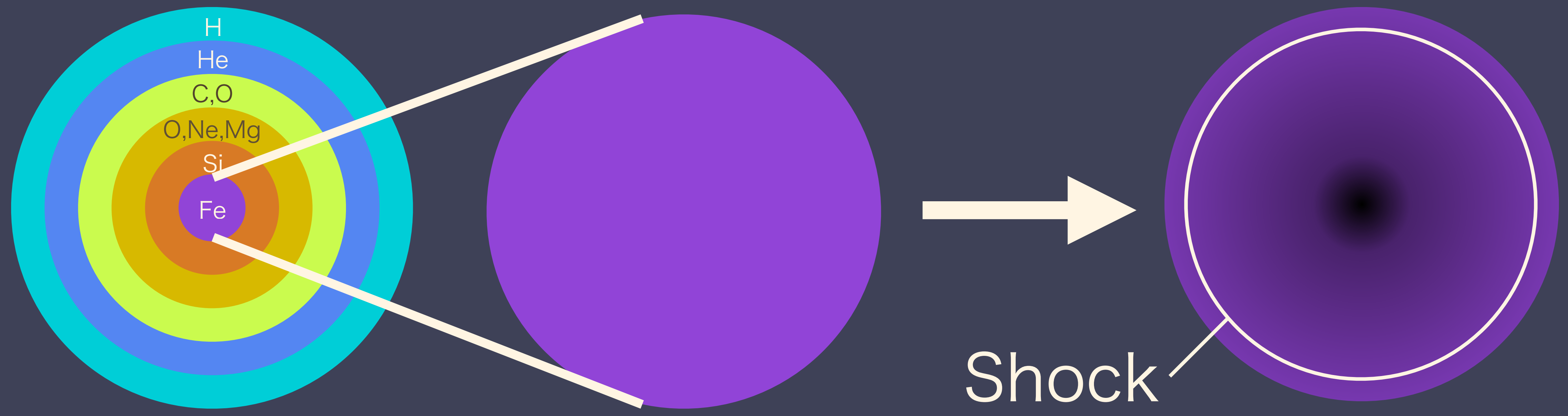
- Core-collapse Supernovae:
  explosive death of massive star
- Stellar core-collapse
  → explosion by released gravitational energy

SN1987A

Stellar core bounce

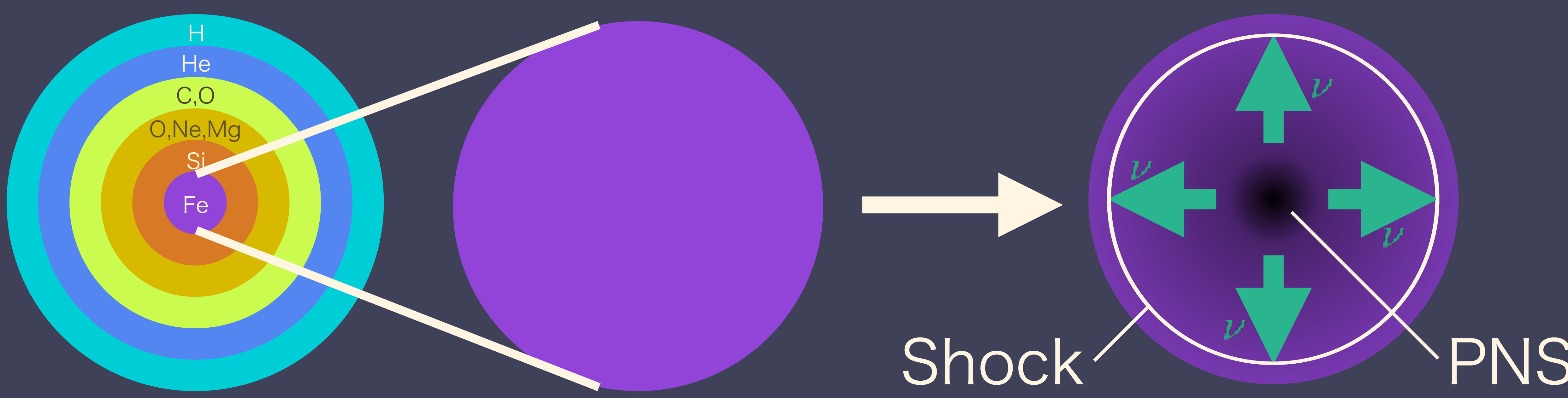
- Core-collapse by iron photodissociation/electron capture reactions
- Finally, the collapse is stopped by nuclear force
- The bounce shock is launched
- The energy of the shock is lost by photodissociation

→The shock stalls



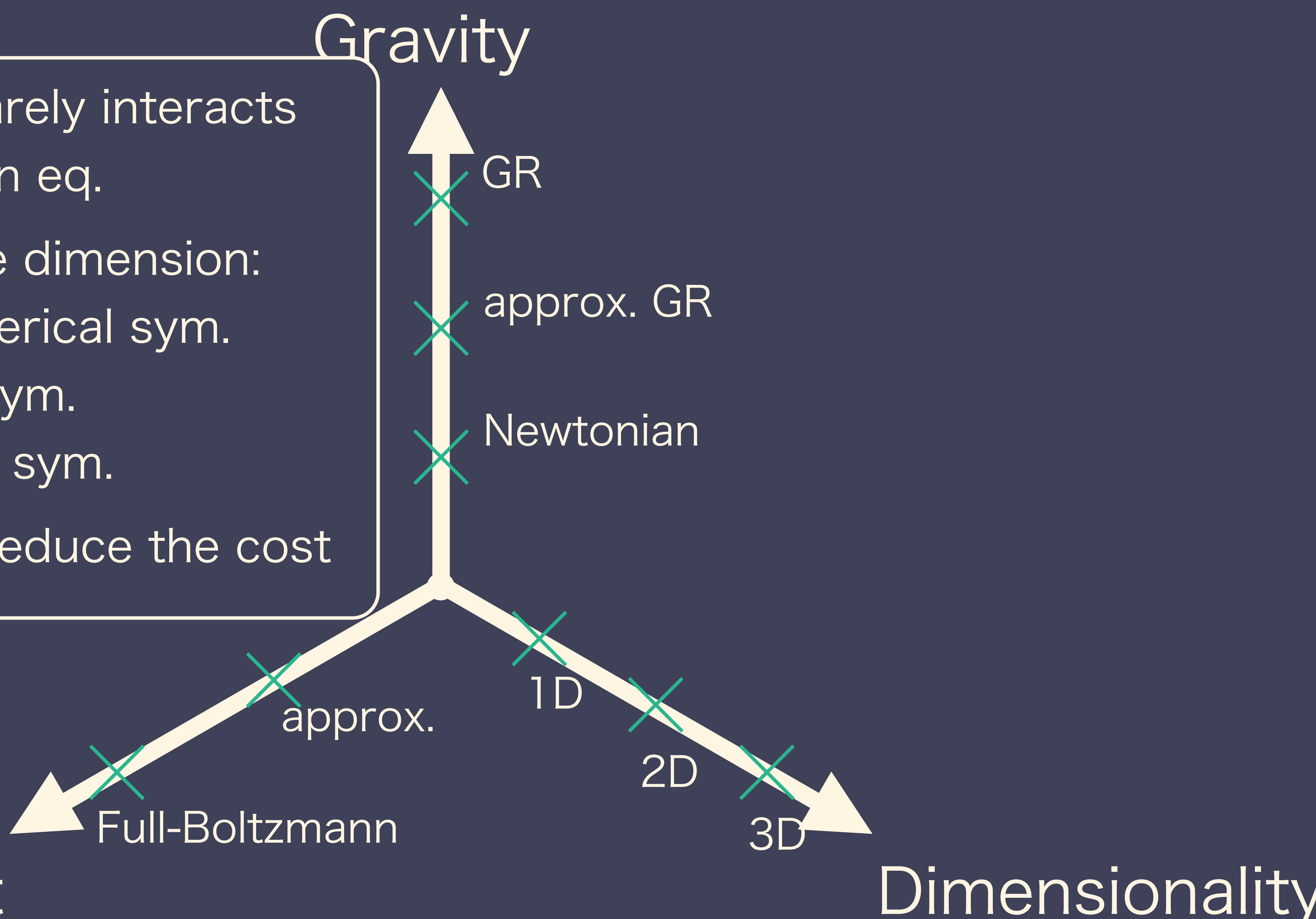
Neutrino heating mechanism

- How to revive the shock?
- The gravitational energy is contained in proto-neutron star.
- PNS evolves to be NS with emitting neutrinos
- The neutrino heating mechanism: emitted neutrinos heat the shock to revive.



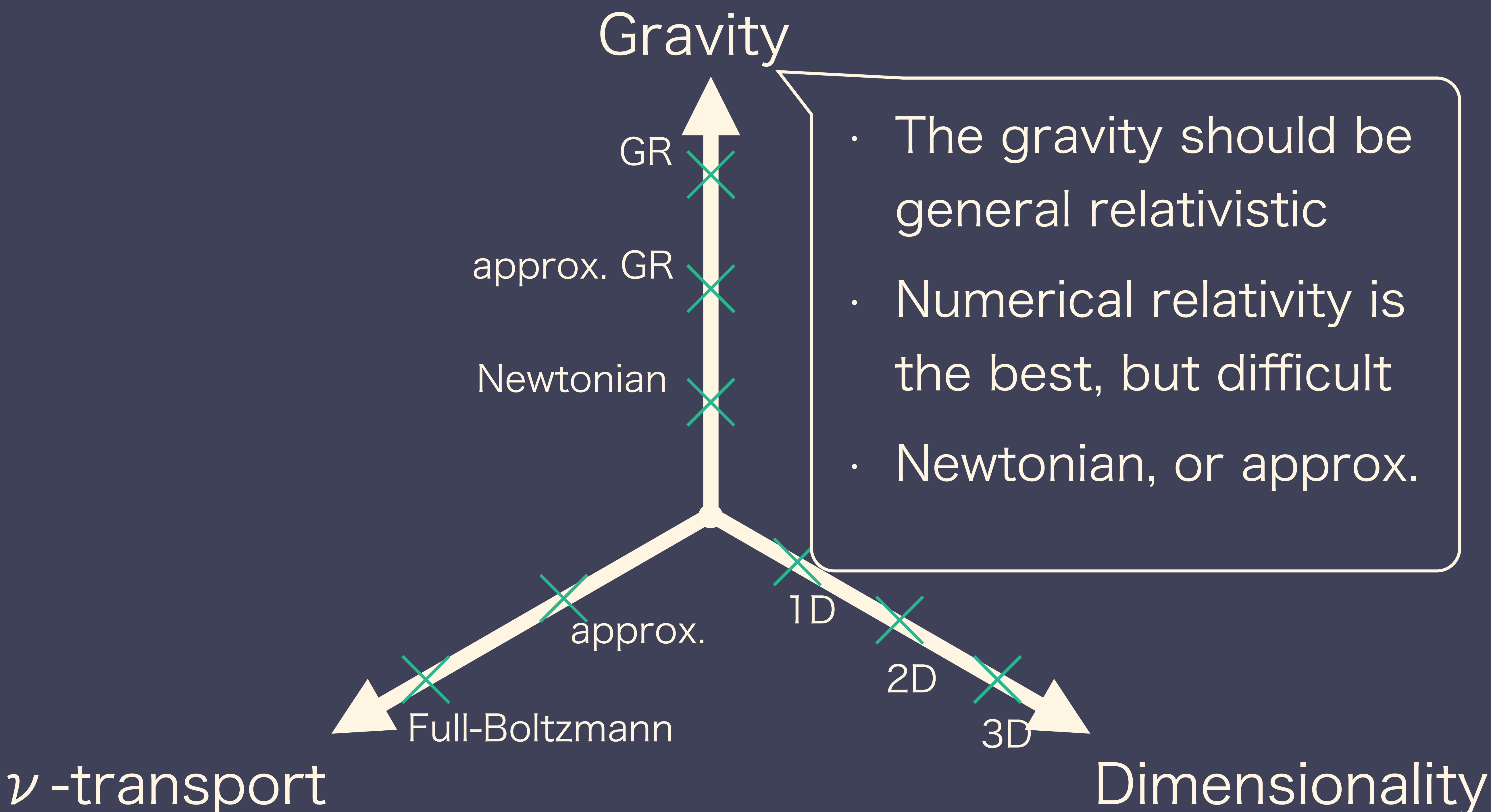
The progress in CCSNe sim.

- Neutrinos rarely interacts
  → Boltzmann eq.
- Phase space dimension:
  - 3 for spherical sym.
  - 5 for axisym.
  - 6 without sym.
- Approx. to reduce the cost



Microphysics is also important, but neglected here.

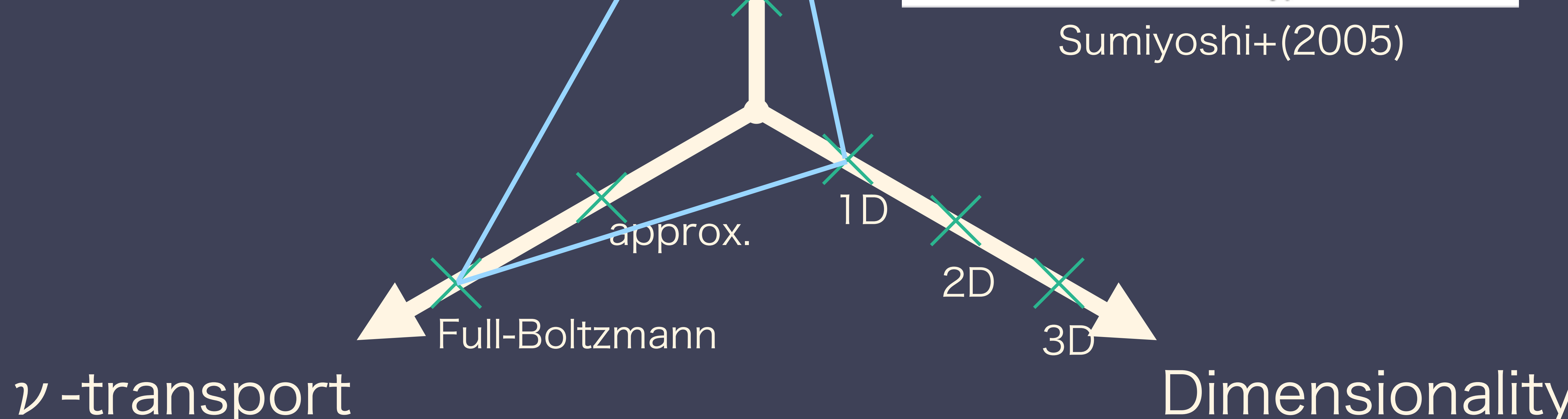
The progress in CCSNe sim.

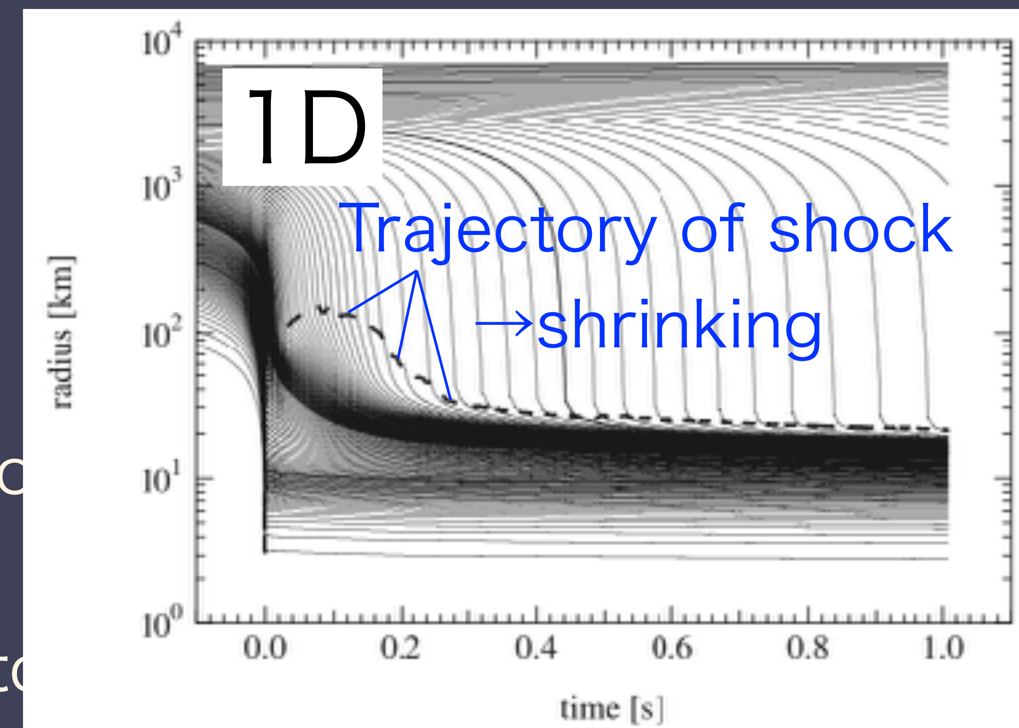


Microphysics is also important, but neglected here.

The progress in CCSNe sim.

1D: fail to explode



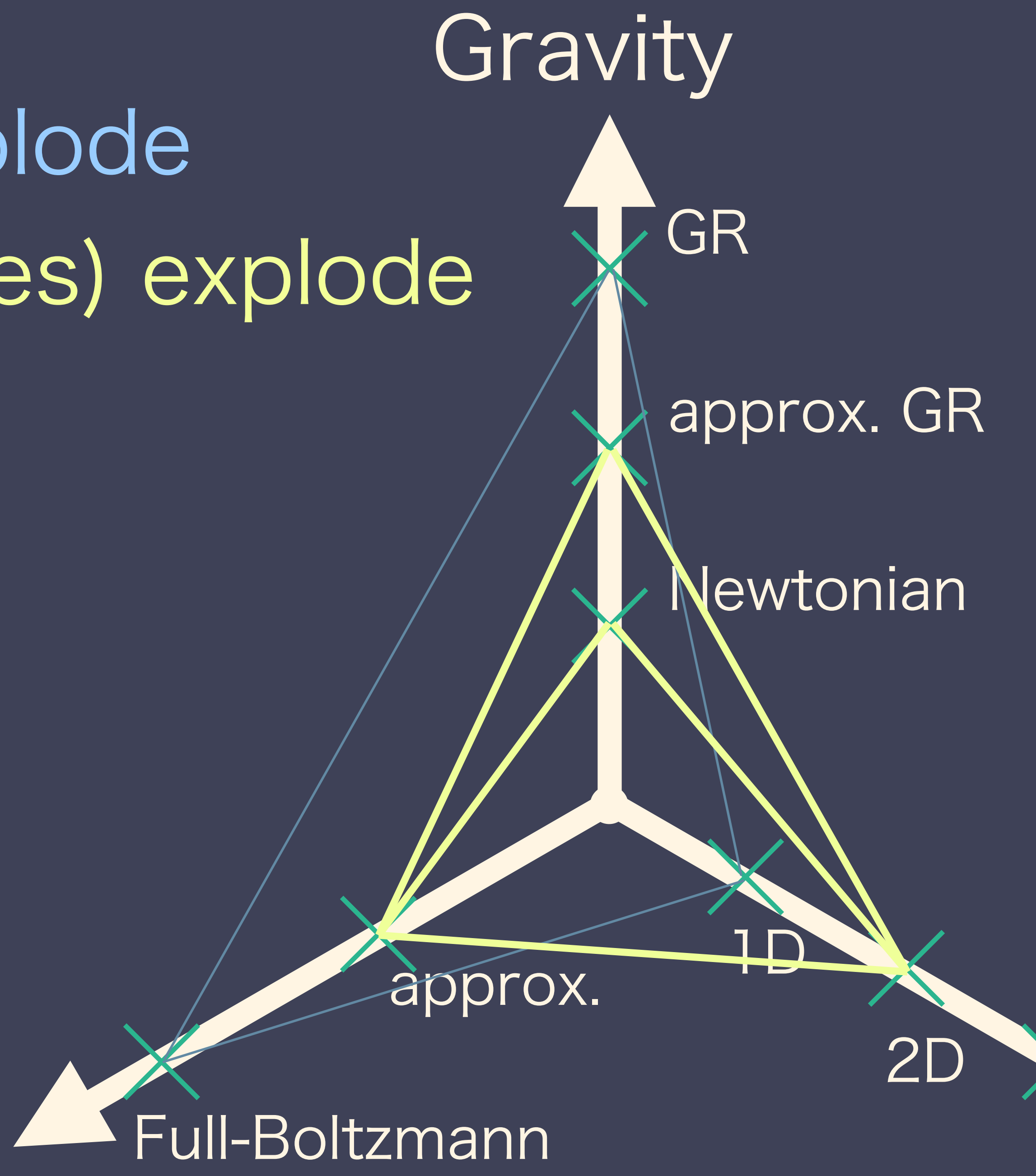


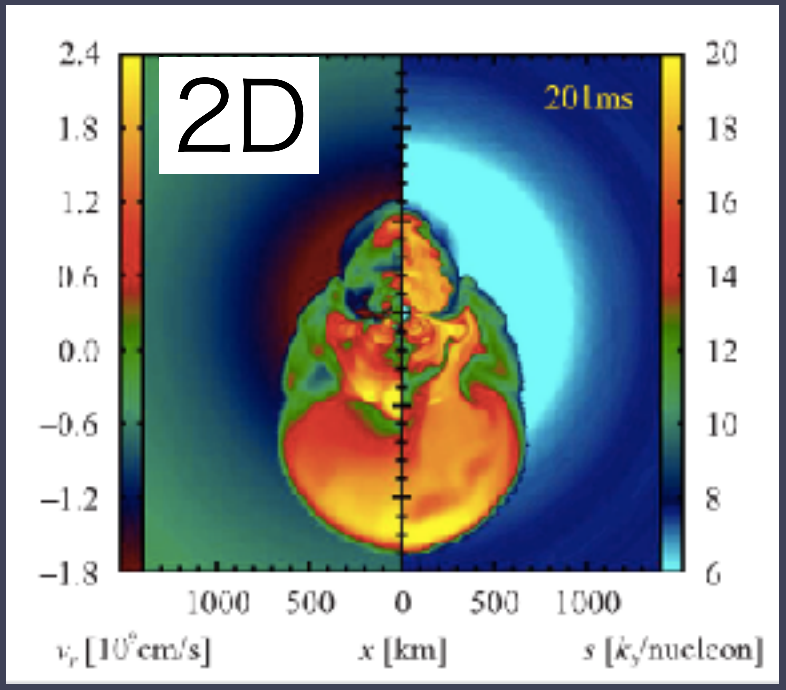
Sumiyoshi+(2005)

The progress in CCSNe sim.

1D: fail to explode

2D: (sometimes) explode





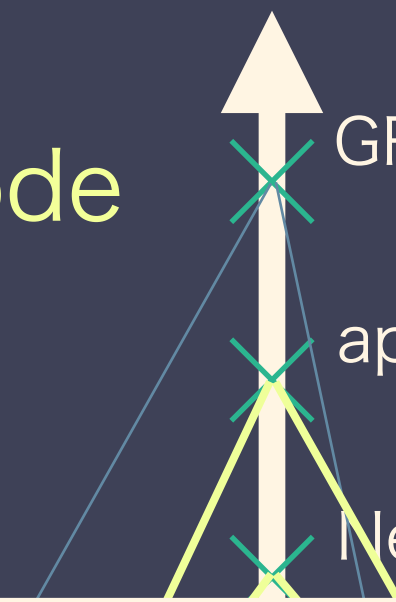
MPA (Mueller+ 2012)

The progress in CCSNe sim.

1D: fail to explode

2D: (sometimes) explode

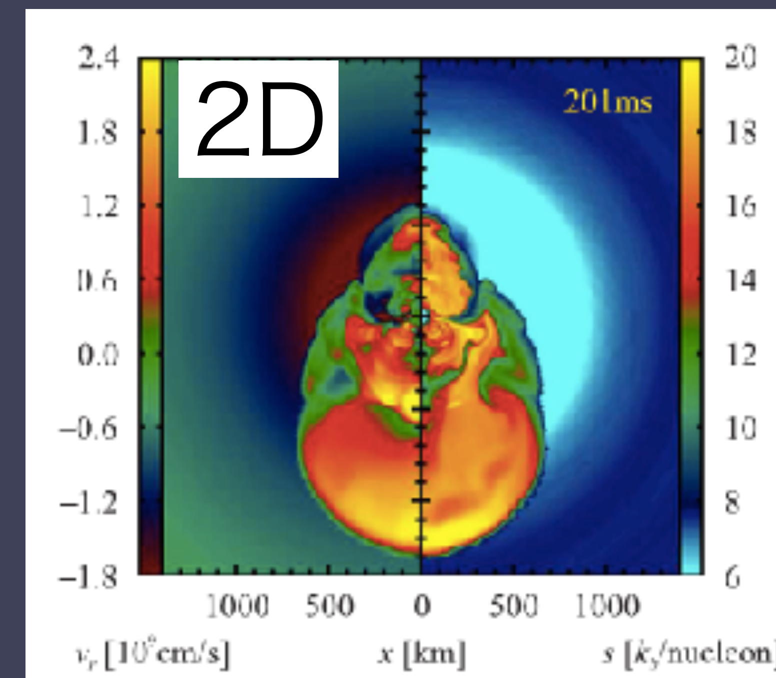
Gravity



GR

approx. GR

Newtonian



MPA (Mueller+ 2012)

- observed energy: 10^{51} erg, simulated energy: 10^{50} erg
- neutrino transport: not Boltzmann eq., but approx. eq.
- even qualitatively different results
  - Observed explosion is not yet reproduced

ν-transport

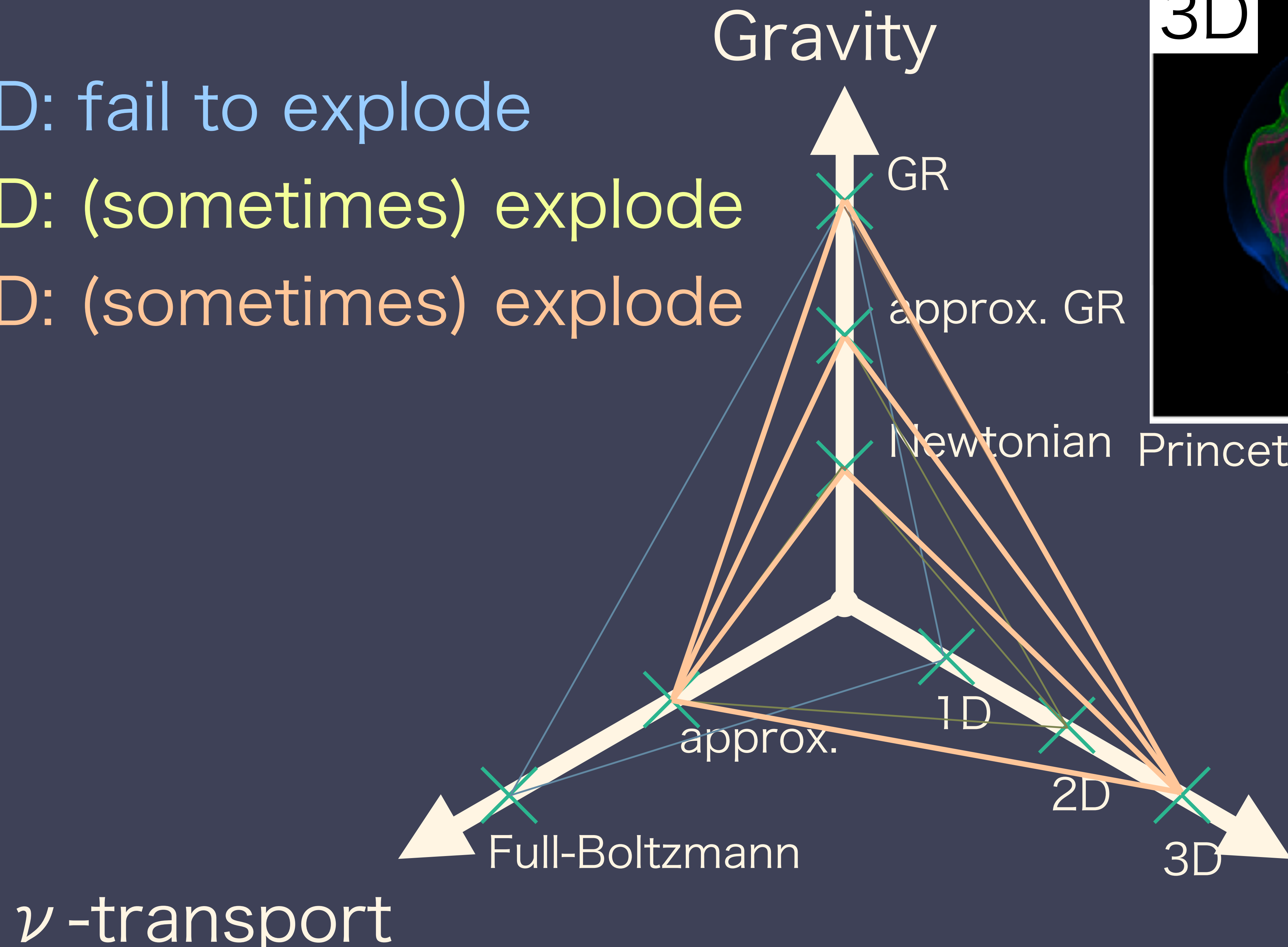
Dimensionality

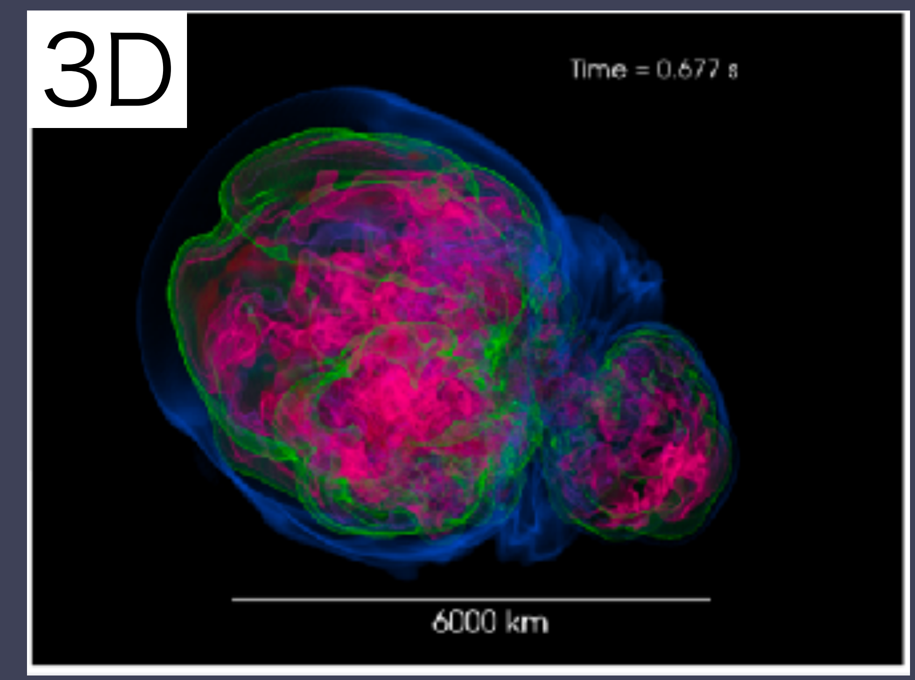
The progress in CCSNe sim.

1D: fail to explode

2D: (sometimes) explode

3D: (sometimes) explode





Princeton (Vartanyan+ 2018)

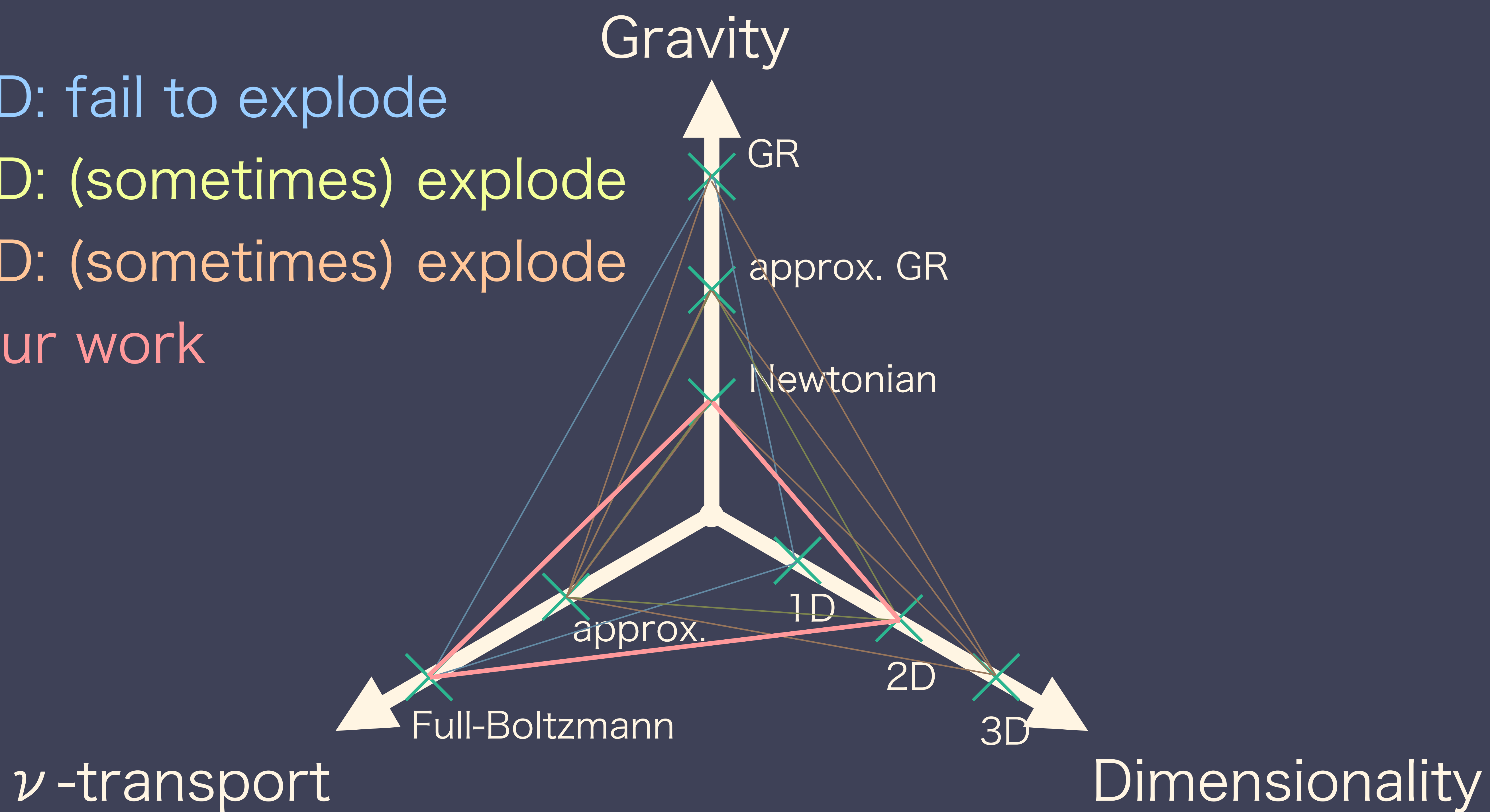
Our work

1D: fail to explode

2D: (sometimes) explode

3D: (sometimes) explode

Our work



Our work

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

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

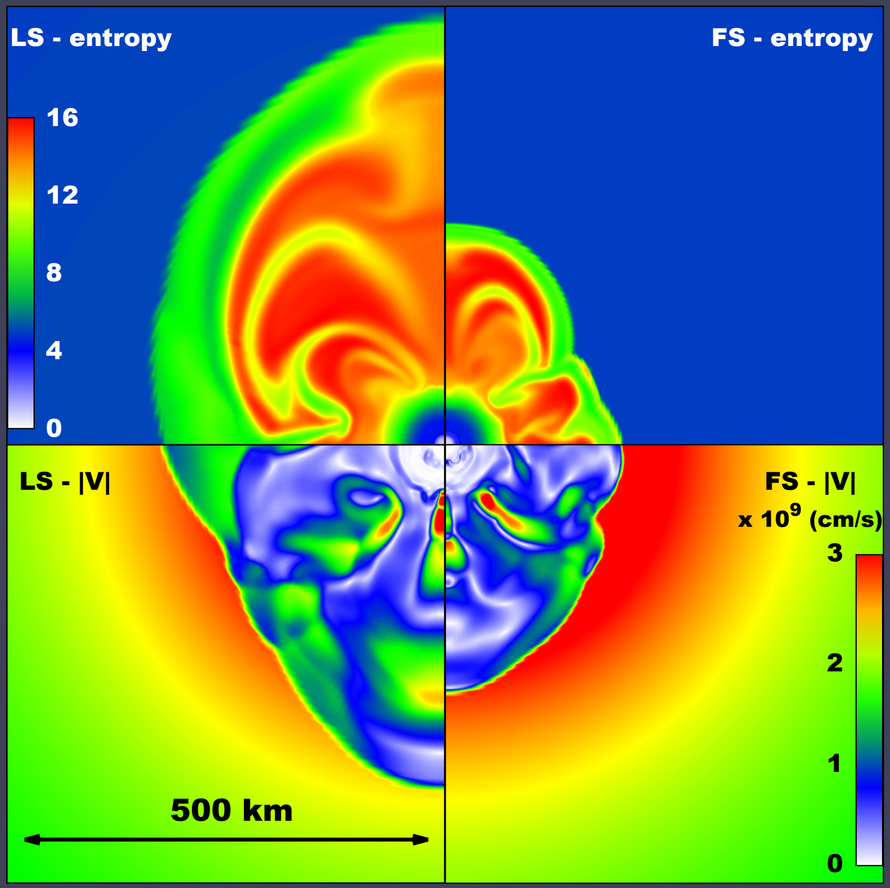
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + P\boldsymbol{I}) = -\rho \nabla \Phi + \boldsymbol{M}^i + \rho \dot{\beta}$$

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

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

Our work

LS EOS
Explode



Nagakura+(2018)

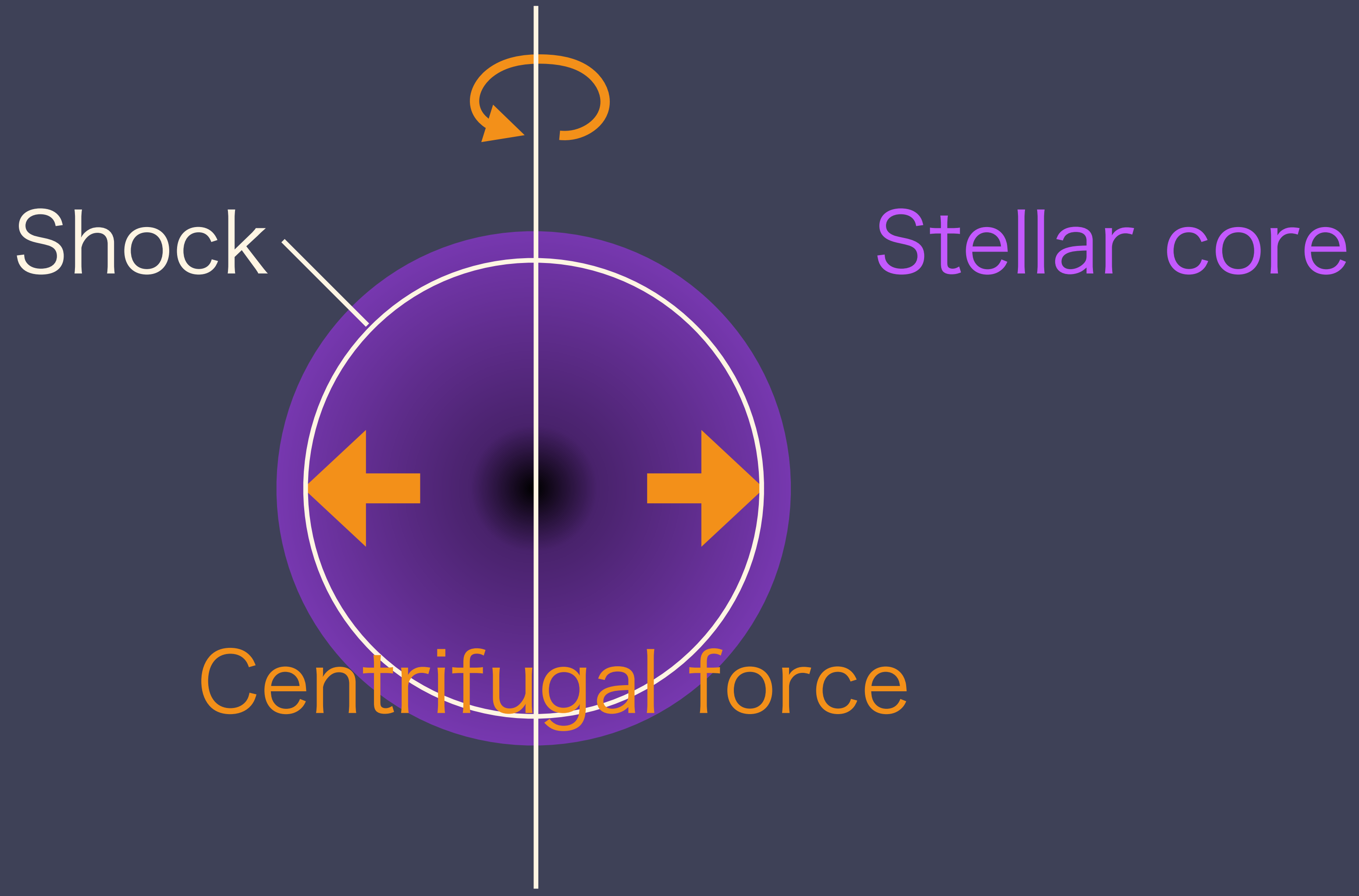
FS EOS
Fail

- The Boltzmann-radiation-hydrodynamics code
- There are several EOS models
  - EOS comparison paper: LS VS FS
- The simulation with LS EOS shows shock revival, but probably due to an artifact of the single-nuclear approximation
- Detailed analysis will appear (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.

- Presented in Harada+ (2019)



Setup

- 11.2 M$_\odot$ progenitor of Woosley+ (2002)
- Shellular rotation (almost the fastest according to current stellar evolution theory)

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

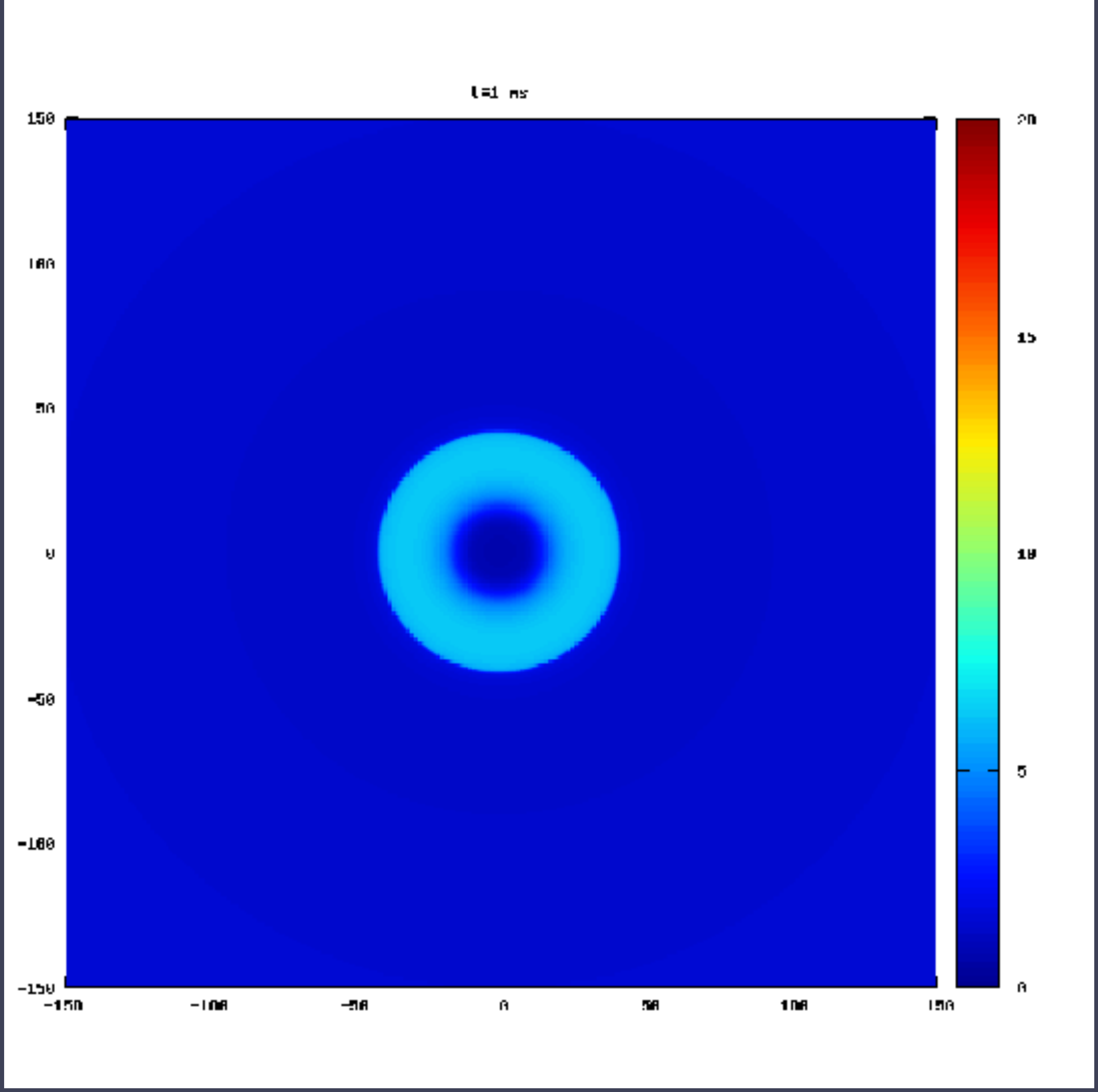
- Furusawa-Shen equation of state
- Neutrino reactions

$$\begin{array}{lllllll}
\nu_\mathrm{e} + \mathrm{n} & \leftrightarrow & \mathrm{e}^- + \mathrm{p} & \quad & \nu + A & \leftrightarrow & \nu + A \\
\bar{\nu_\mathrm{e}} + \mathrm{p} & \leftrightarrow & \mathrm{e}^+ + \mathrm{n} & & \nu + \mathrm{e}^- & \leftrightarrow & \nu + \mathrm{e}^- \\
\nu_\mathrm{e} + A & \leftrightarrow & \mathrm{e}^- + A' & & \nu + \bar{\nu} & \leftrightarrow & \mathrm{e}^- + \mathrm{e}^+ \\
\nu + N & \leftrightarrow & \nu + N & & N + N & \leftrightarrow & N + N + \nu + \bar{\nu}
\end{array}$$

- Notation: $\nu_x = \nu_\mu, \bar{\nu_\mu}, \nu_\tau, \bar{\nu_\tau}$

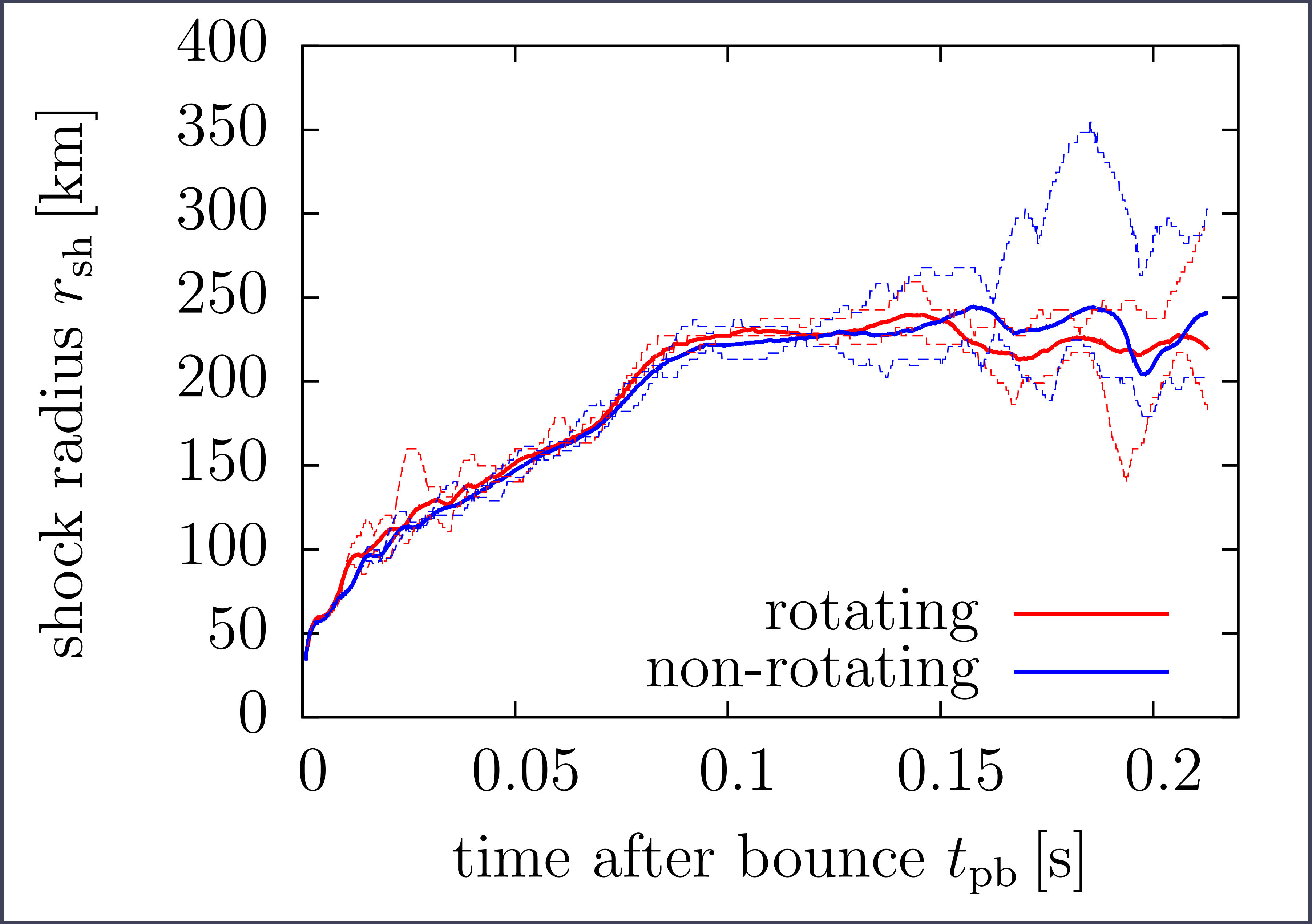
Entropy distribution

- Time evolution until ~200 ms after bounce.



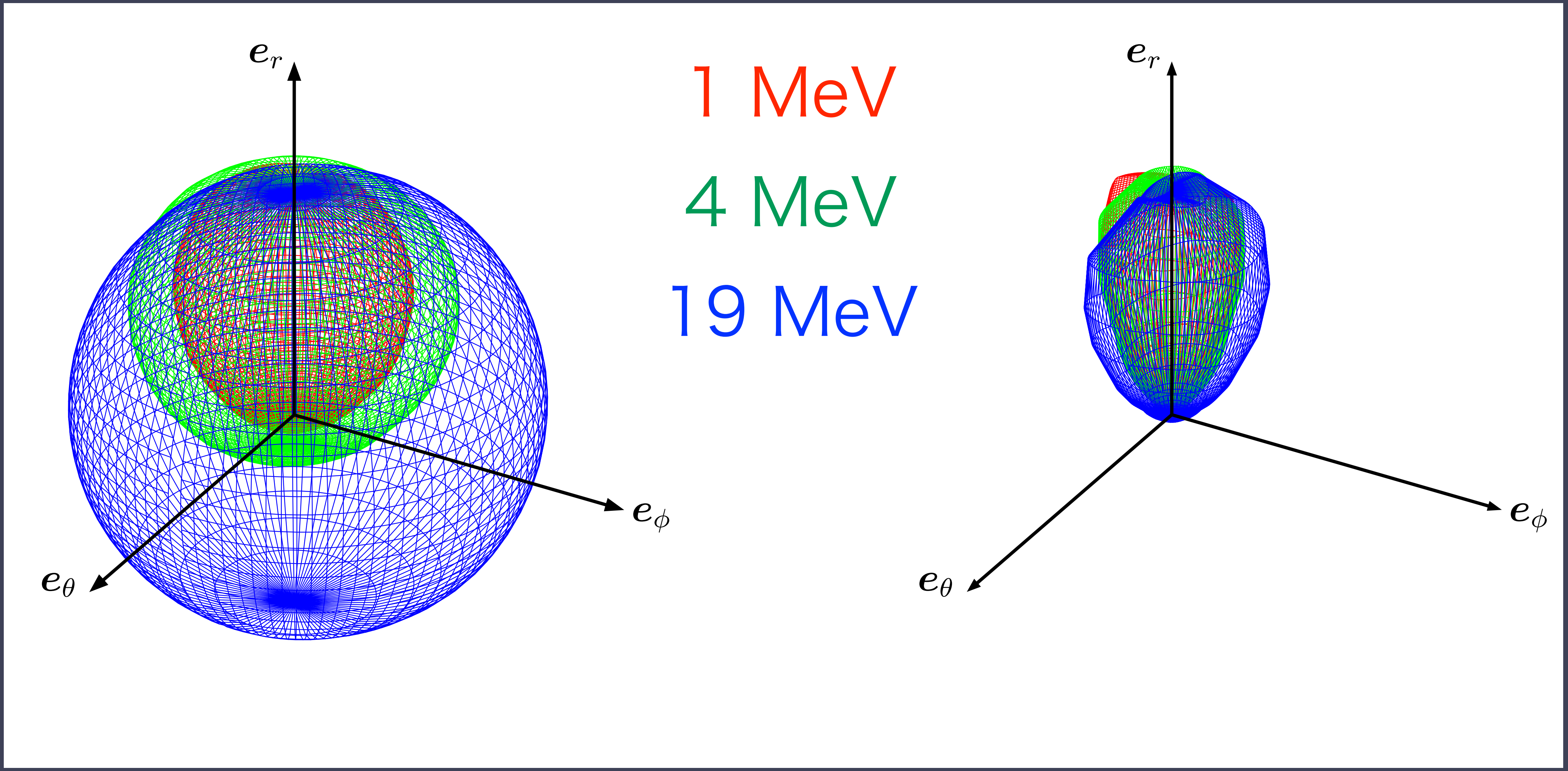
Shock evolution

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



Neutrino ang. distribution

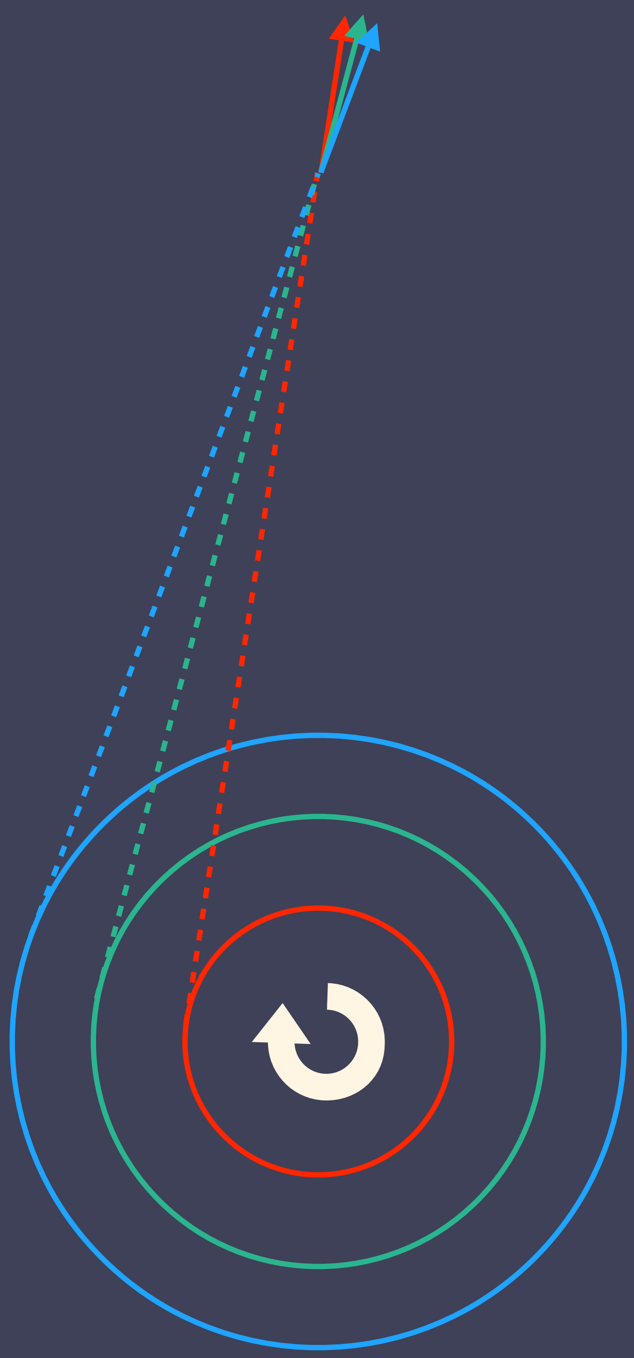
- Distribution functions at ~10 ms after bounce.

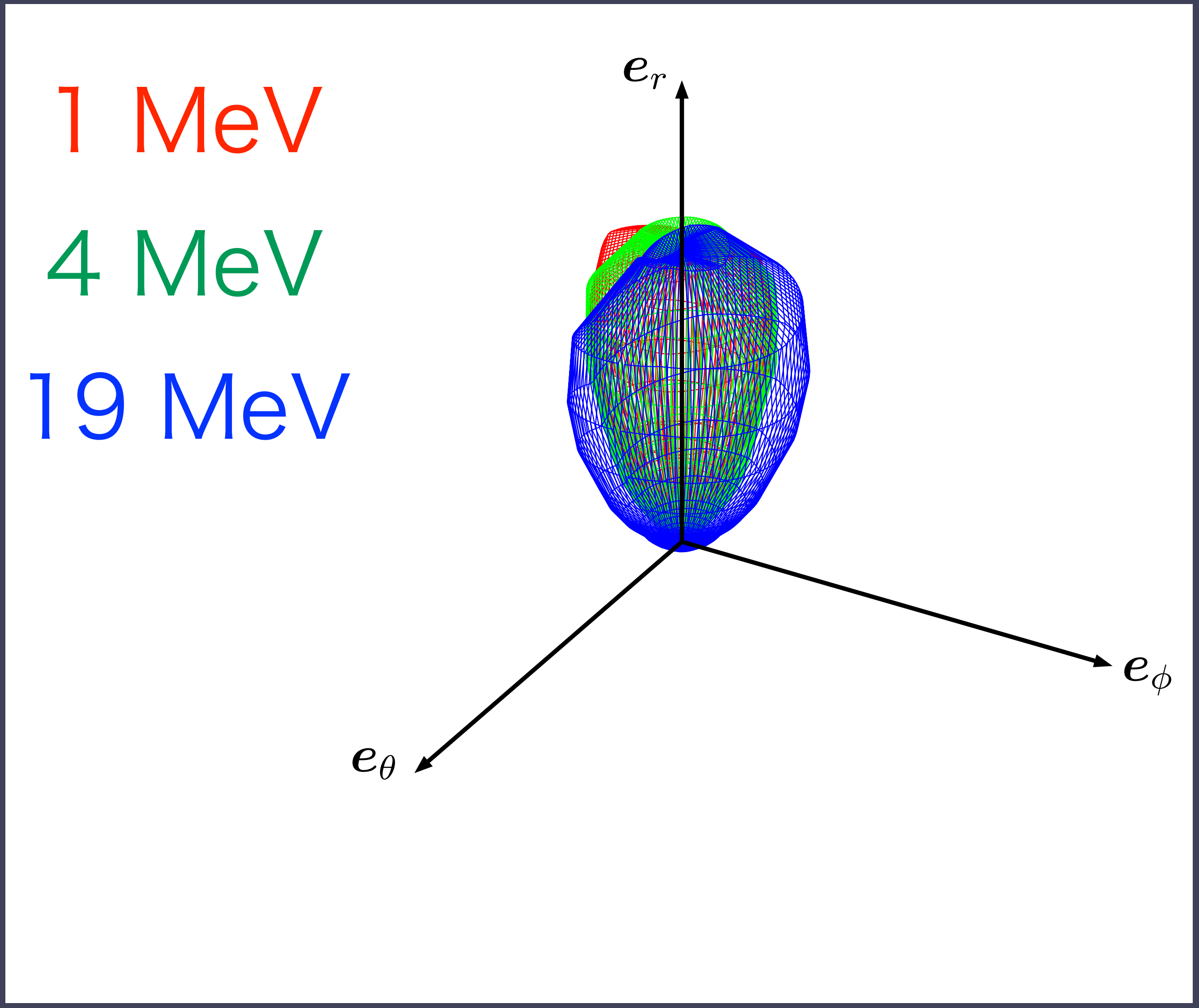


~60 km ~170 km

Neutrino ang. distribution

- Distribution functions at ~10 ms after bounce.





~170 km

Moment formalism

- Boltzmann equation

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

zero-th moment $\int \mathrm{d}\Omega$

$$\frac{\partial E}{\partial t} + \frac{\partial F^i}{\partial x^i} = S_0$$

first moment $\int \mathrm{d}\Omega p^i$

$$\frac{\partial F^i}{\partial t} + \frac{\partial P^{ij}}{\partial x^j} = S_1^i$$

$$E \sim \int \mathrm{d}\Omega p^0 f \qquad F^i \sim \int \mathrm{d}\Omega p^i f \qquad P^{ij} \sim \int \mathrm{d}\Omega p^i p^j f$$

Eddington tensor

- Evaluation of M1-closure scheme-Eddington tensor

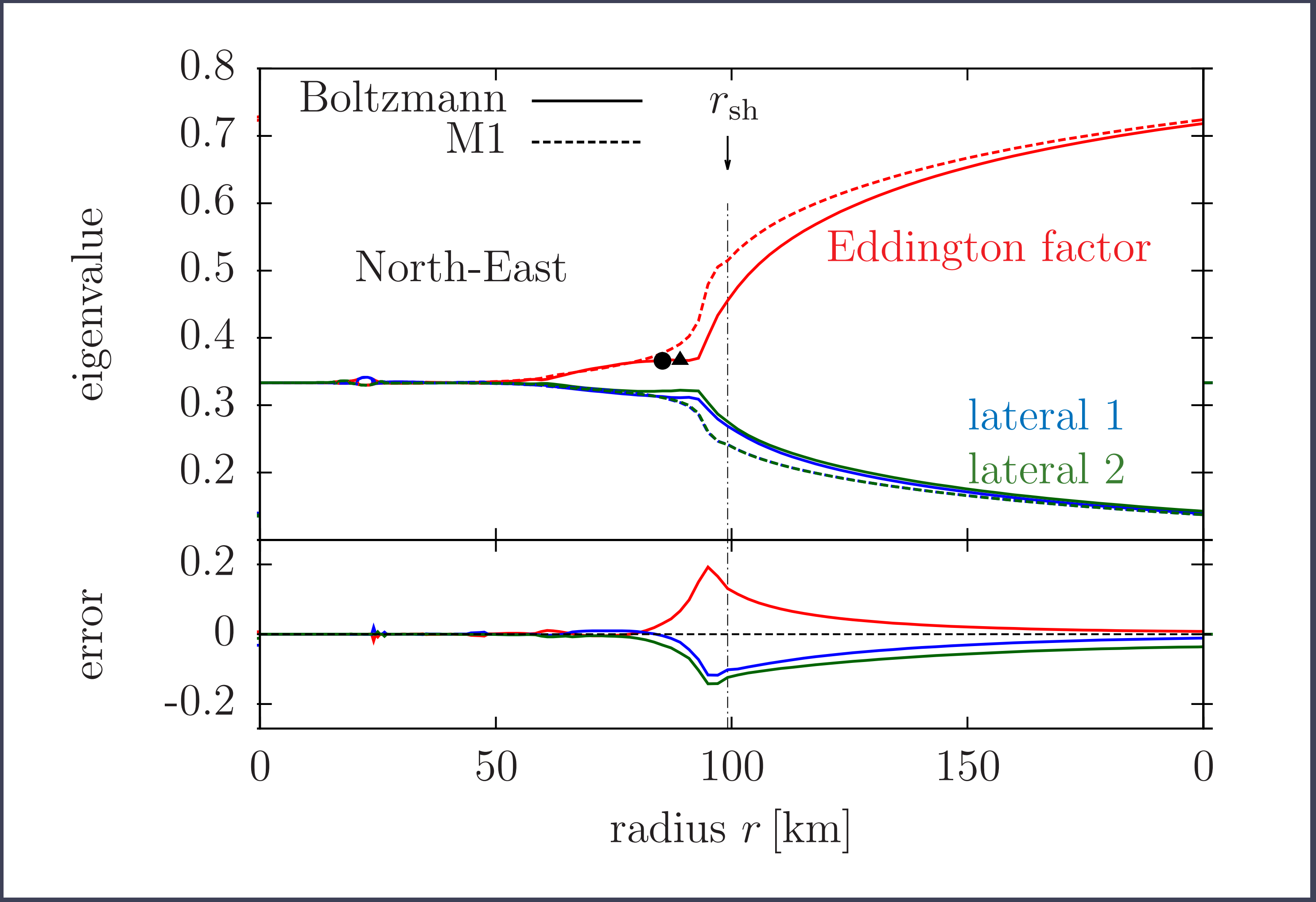
$$E^{ij} = \begin{cases} \dfrac{P^{ij}}{E} & \text{Boltzmann-Eddington tensor} \\[2ex] \dfrac{3\chi - 1}{2}\delta^{ij} + \dfrac{1-\chi}{2}\dfrac{F^i F^j}{F^2} & \text{M1-Eddington tensor} \end{cases}$$

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

Eddington fac. Flux fac.

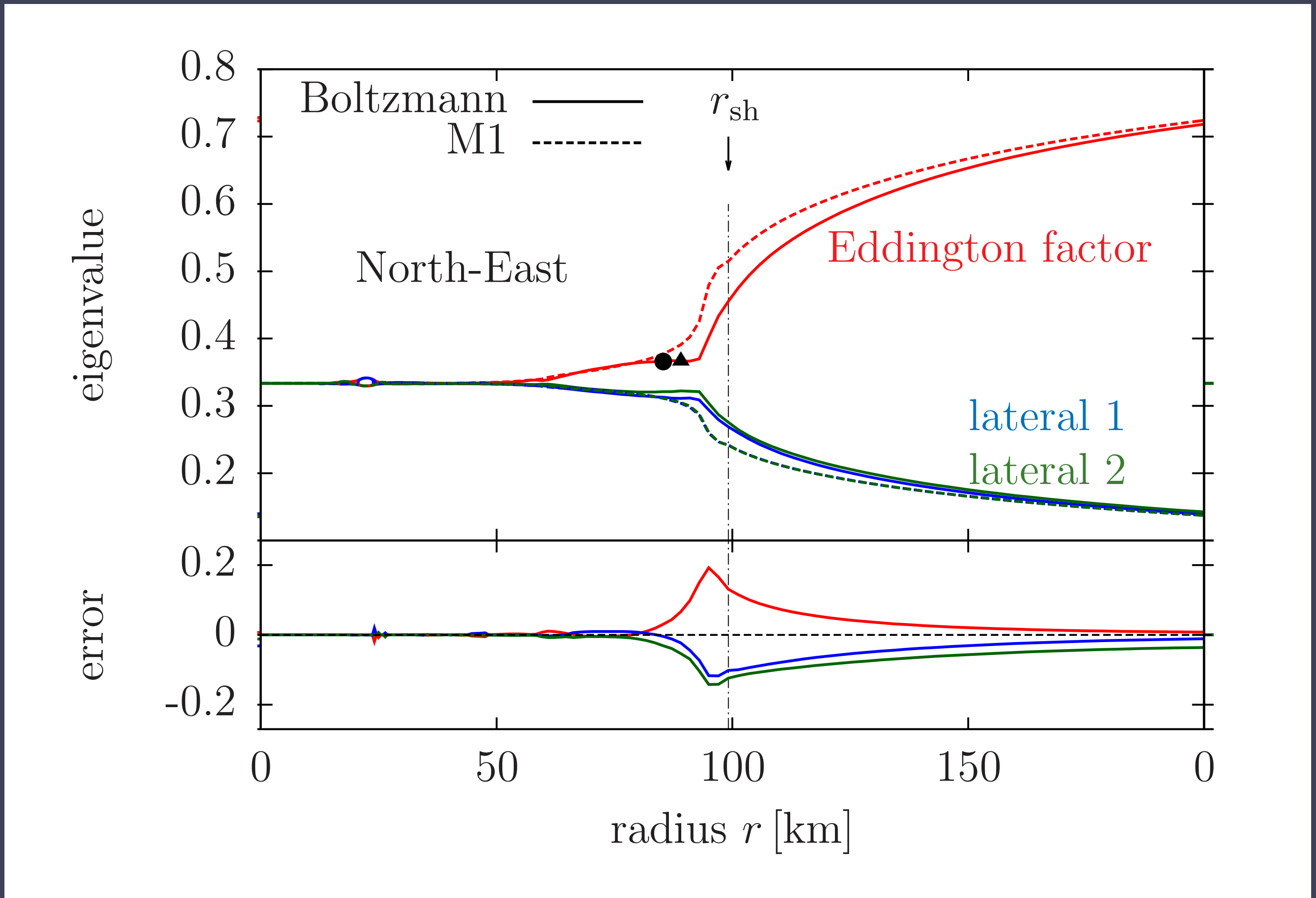
Eddington factor

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

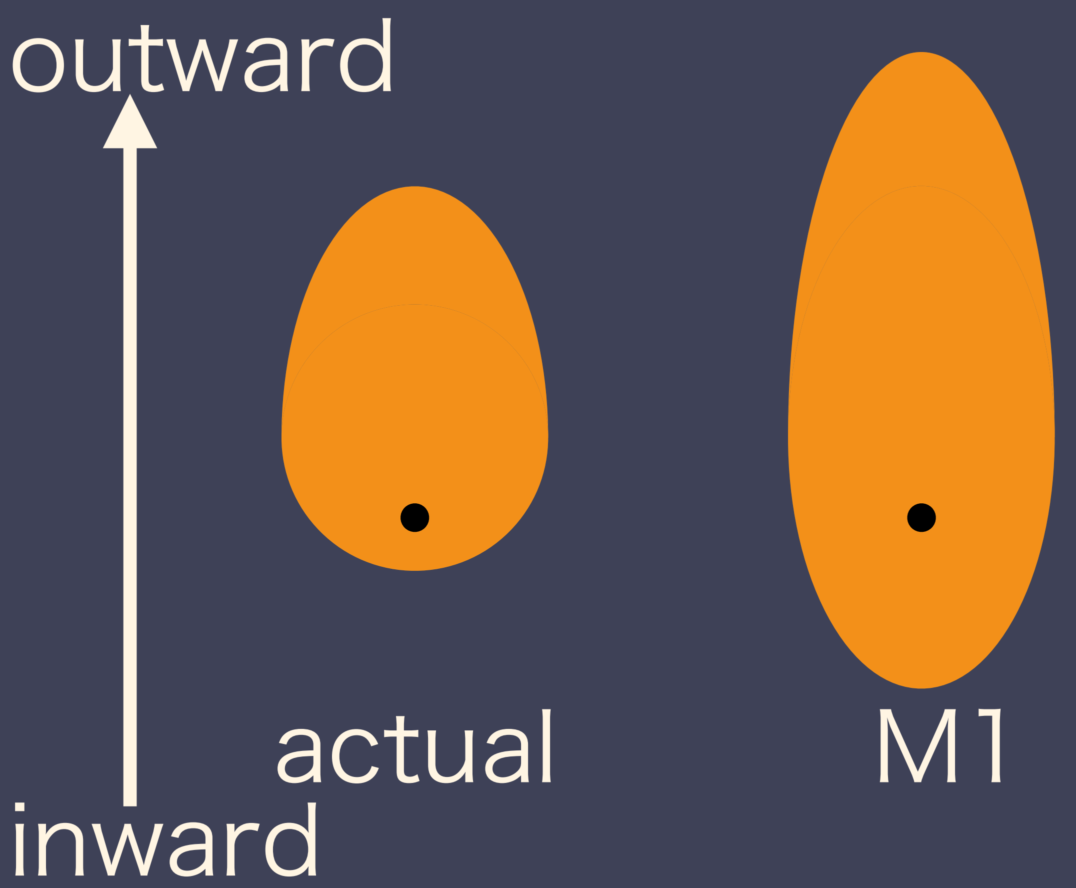


Eddington factor

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

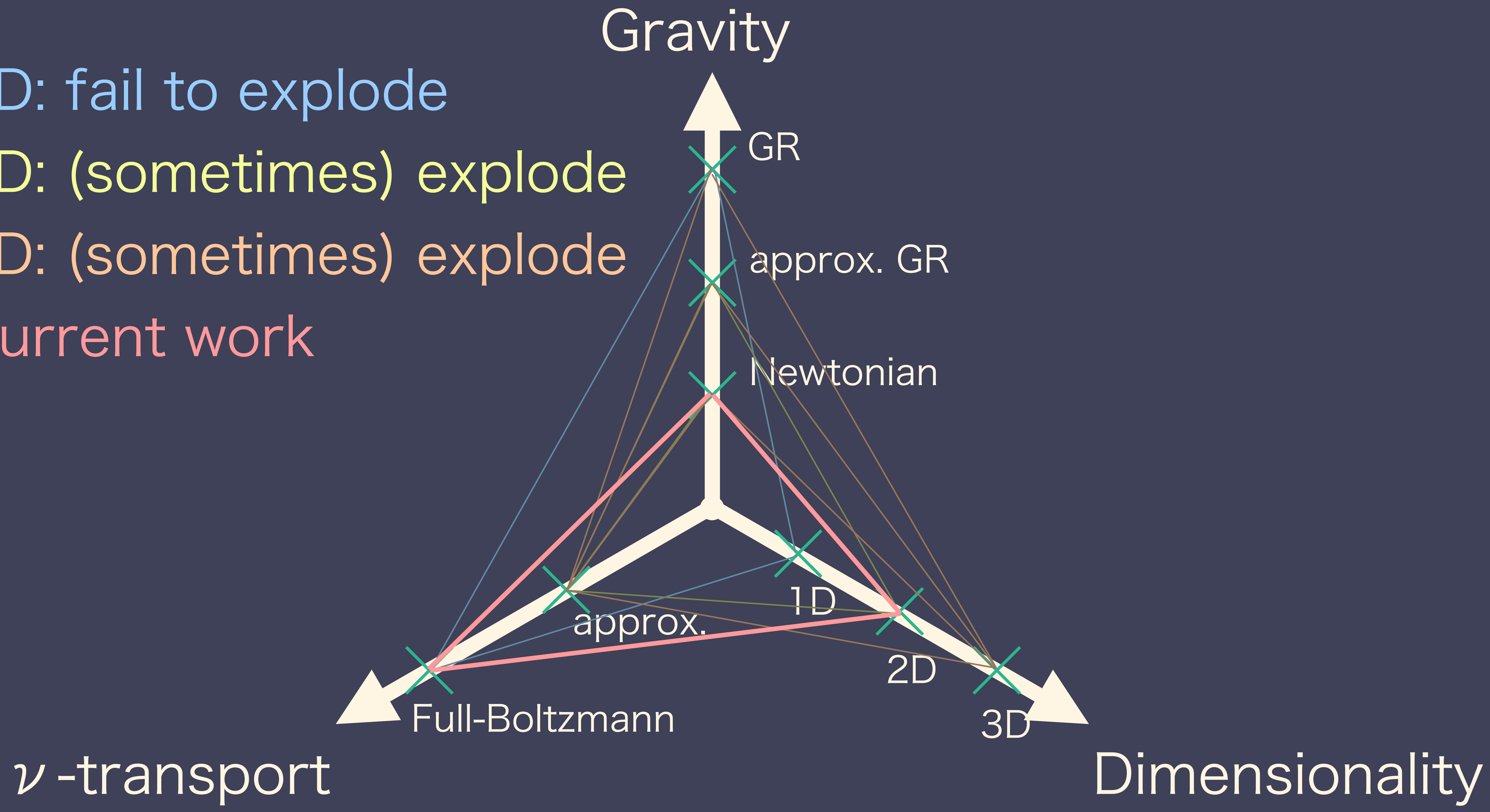


- Prolateness of distribution
- M1: estimated from deviation



Future prospects

1D: fail to explode
2D: (sometimes) explode
3D: (sometimes) explode
Current work



Future prospects

1D: fail to explode

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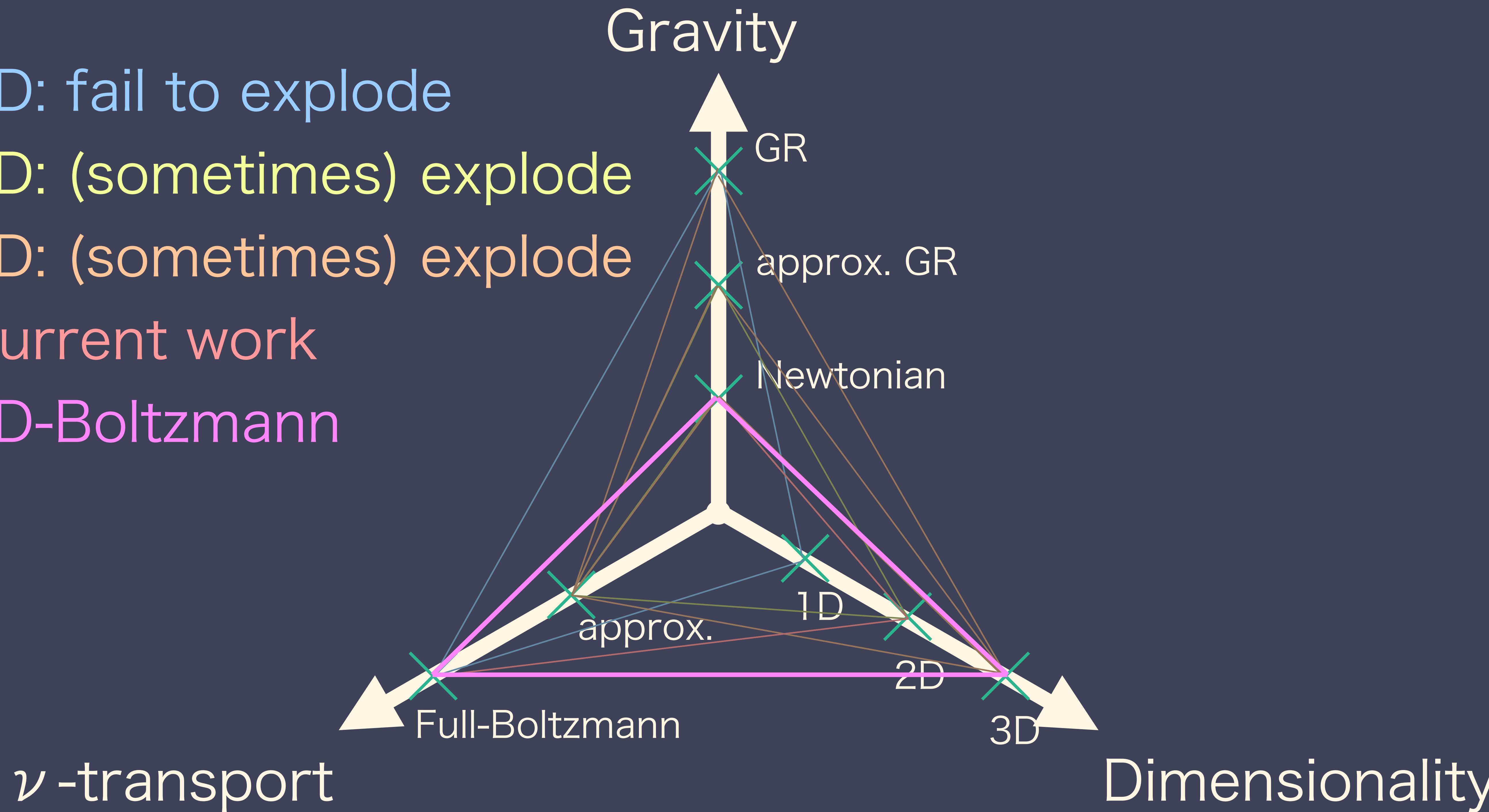
Current work

3D-Boltzmann



Future prospects

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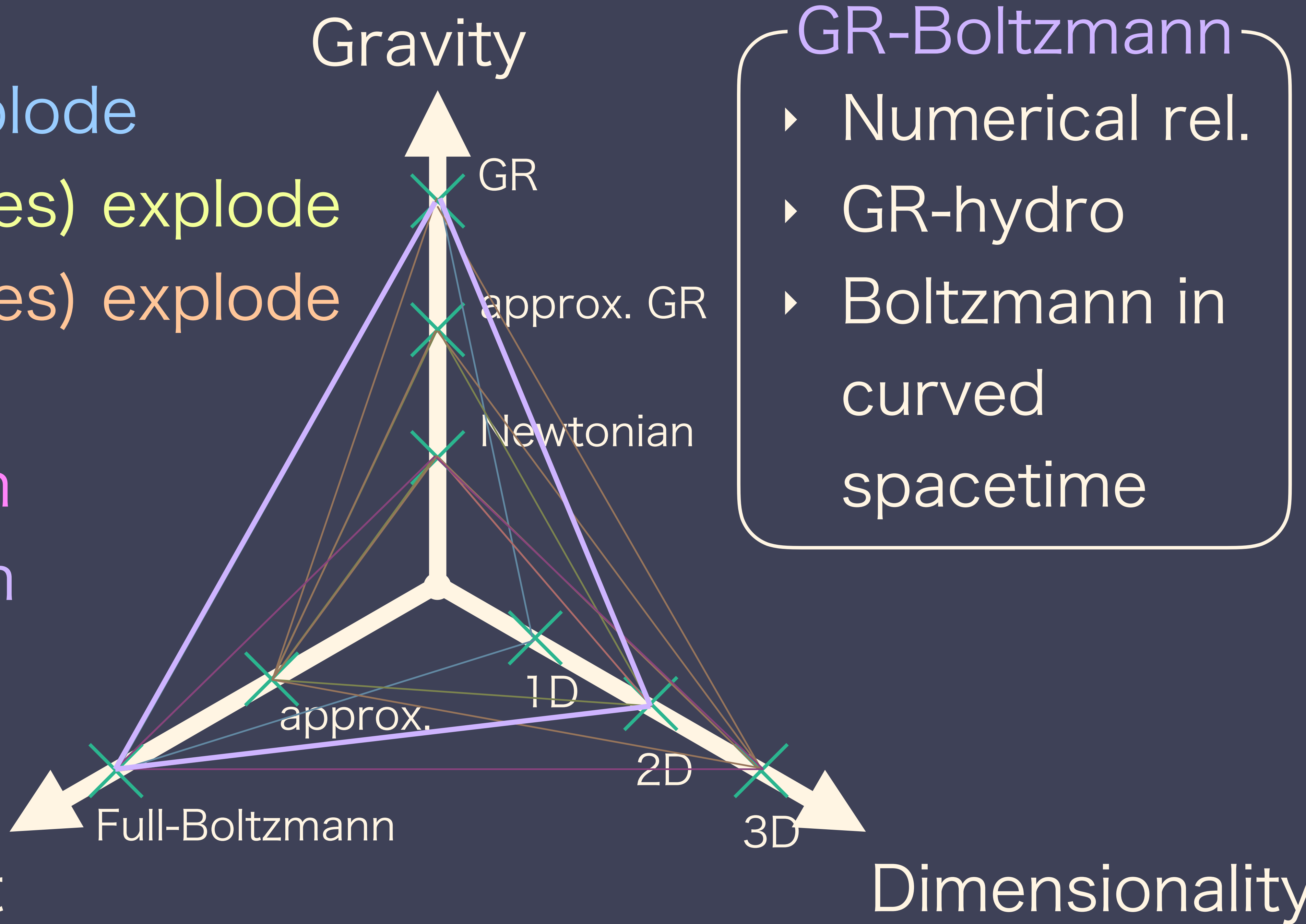
Current work
3D-Boltzmann
GR-Boltzmann



GR-Boltzmann

- Numerical rel.
- GR-hydro
- Boltzmann in curved spacetime

Future prospects

1D: fail to explode

2D: (sometimes) explode

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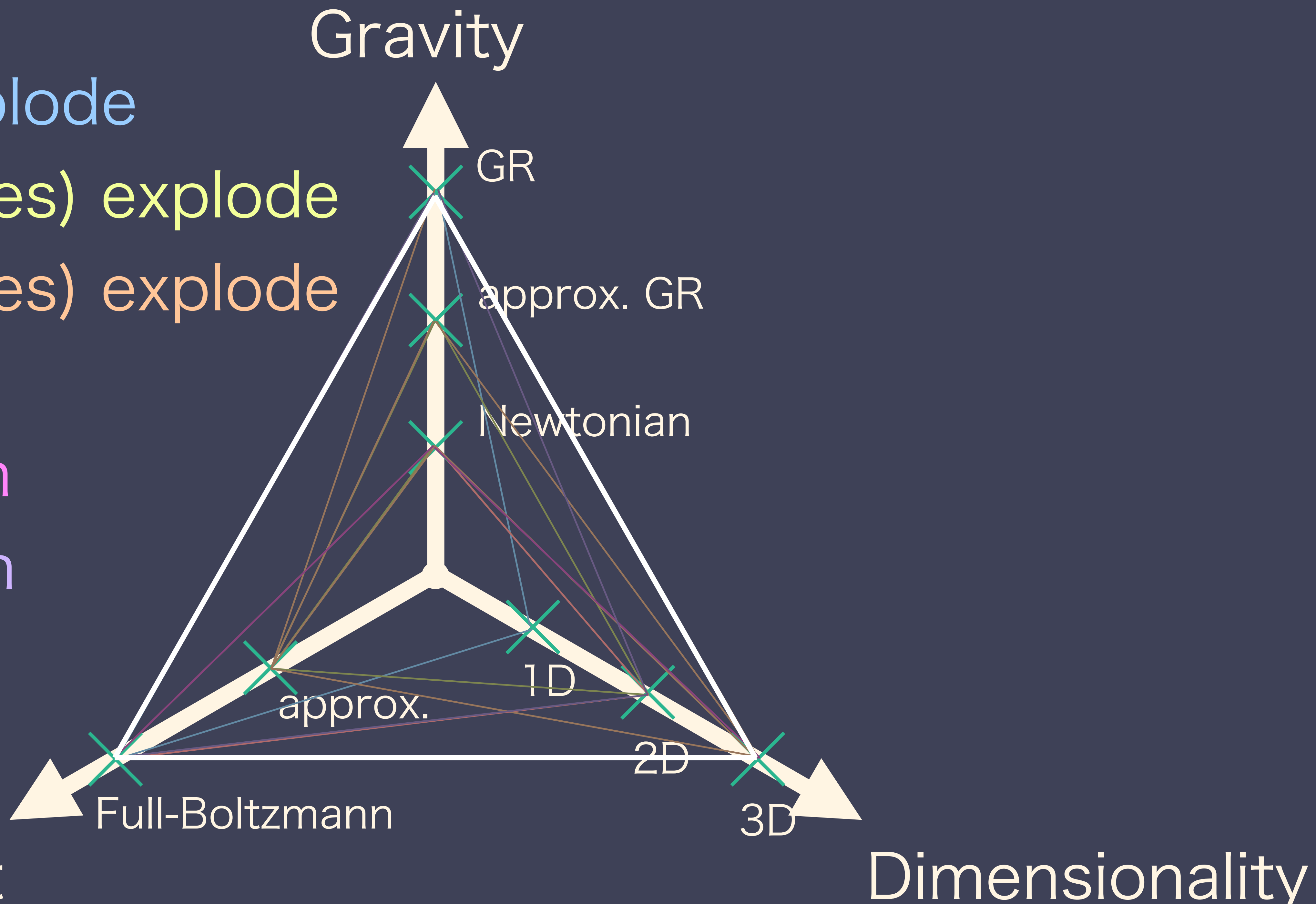
Current work

3D-Boltzmann

GR-Boltzmann

Final goal



Summary

- Simulations for the neutrino heating mechanism of CCSNe have been performed.
- The Boltzmann-radiation-hydrodynamics code is one of the most sophisticated code.
- Unique feature is obtained by using the Boltzmann code.