Machine-learned Closure Relation for the Core-collapse Supernova Neutrino Transport

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What is the supernova ?

The explosion phenomenon that occurs at the end of the evolution of massive star.

The Collapse due to self-gravity.

The explosion is affected by neutrino transport.

→ Accurate handing of neutrino radiation transport is essential.

Radiation transport equation and closure relation.

Radiation transport equation

$$\frac{\partial f}{\partial t} + \boldsymbol{P} \cdot \frac{\partial f}{\partial \boldsymbol{r}} + \dot{\boldsymbol{P}} \frac{\partial f}{\partial \boldsymbol{P}} = \left(\frac{df}{dt}\right)_{\text{collision}}$$

A simulation is spend a lot of time.

Approximate equation.

Moment method

$$M^{i_1 i_2 \ldots i_n} = \int f l^{i_1} l^{i_2} \ldots l^{i_n} d^2\Omega \quad \left(l = \frac{\boldsymbol{P}}{|\boldsymbol{P}|}\right)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \boldsymbol{F} = Q$$

$$\frac{\partial \boldsymbol{F}}{\partial t} + \nabla \cdot \boldsymbol{K} = \boldsymbol{Q'}$$

$$E = \epsilon \int f d^2\Omega$$

$$F^{i_1} = \int f l^{i_1} d^2\Omega$$

$$K^{i_1 i_2} = \int f l^{i_1} l^{i_2} d^2\Omega$$

$$Q = \int S_{rad} d^2\Omega$$

$$Q'^{i_1} = \int S_{rad} l^{i_1} d^2\Omega$$

This equation is not closure.

Assume $\boldsymbol{K} = \boldsymbol{K}(E, \boldsymbol{F})$

This equation is close.

Closure relation

Eddington tensor

$$\boldsymbol{K} = E\boldsymbol{T}(E, \boldsymbol{F})$$

Energy density

$$T^{ij} = \frac{3\chi - 1}{2} \frac{F^i F^j}{F^2} + \frac{1 - \chi}{2} \delta^{ij}$$

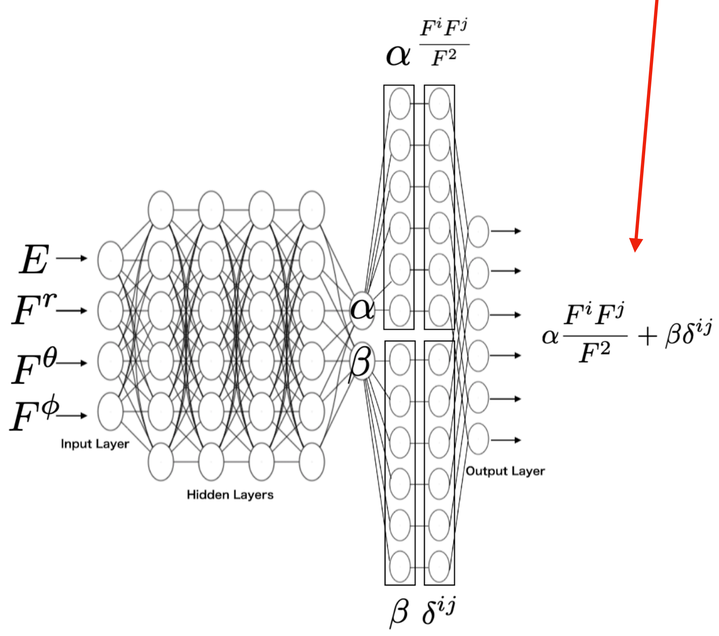
$$\chi = \frac{3 + 4\tilde{f}^2}{5 + 2\sqrt{4 - 3\tilde{f}^2}}$$

$$\tilde{f} = \frac{|\boldsymbol{F}|}{cE}$$

This relation is named M1 closure.

↓

Will improve using deep learning.



Result and discussion.

Output of the NN

M1 closure

Eddington tensor obtained by directly solving the Boltzmann equation.

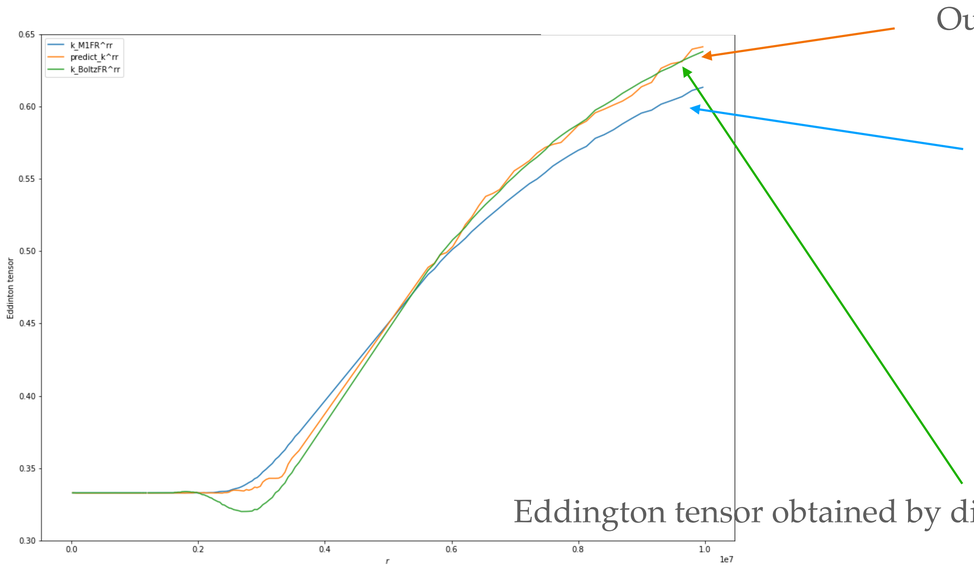


Fig.1 the diagonal component of Eddington tensor

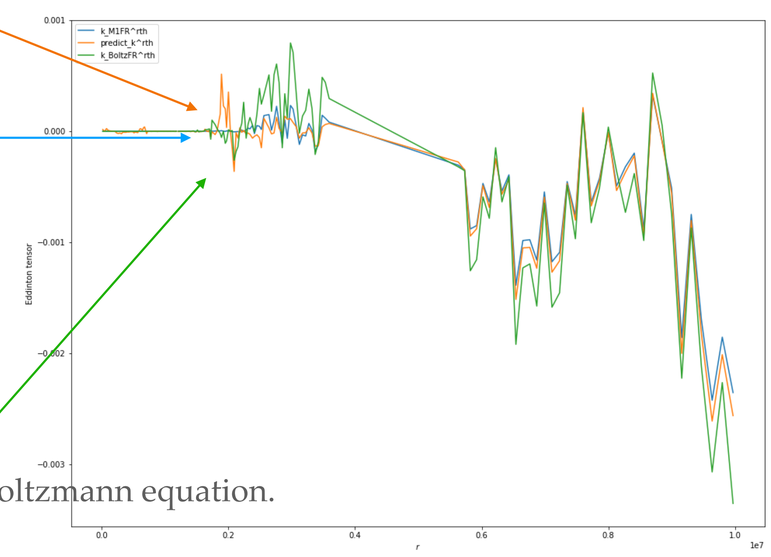


Fig.2 the off-diagonal component of Eddington tensor

- It was shown to be more reproducible than existing approximation methods.
- Adapt to verification and simulation at various time steps.
- Verification of higher moments.