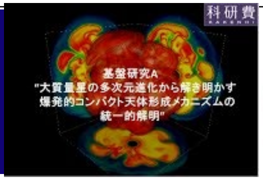
Gravitational Wave Physics and Astronomy Genesis

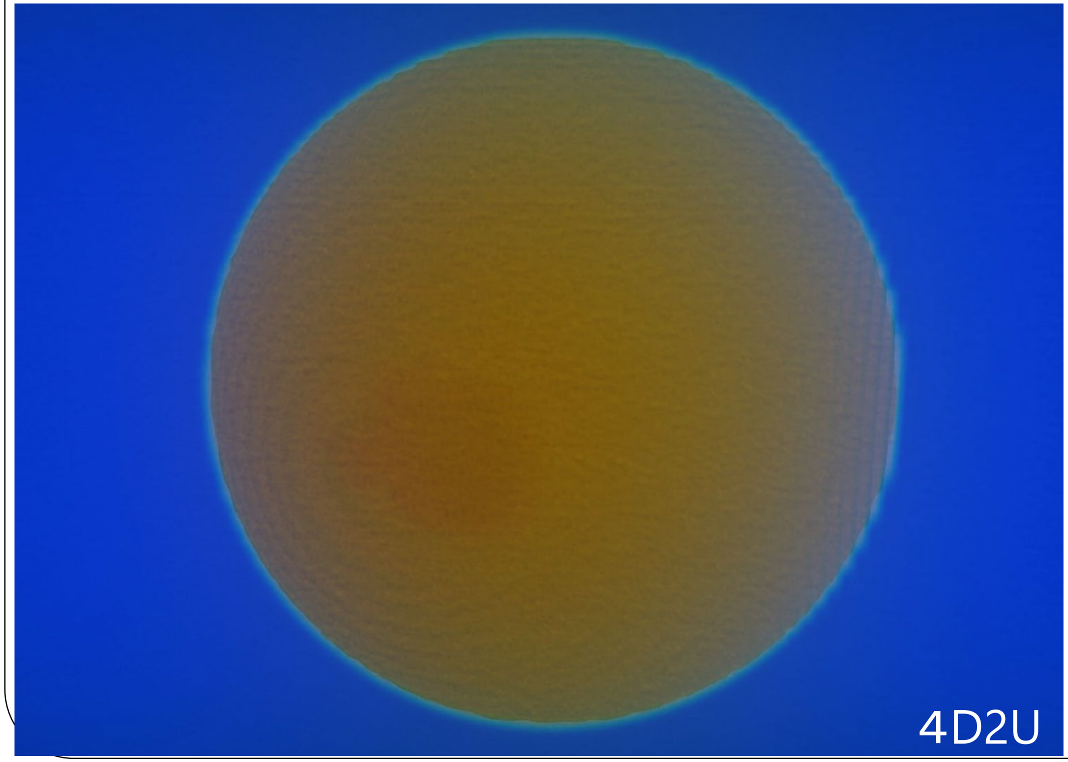


CfCA
Center for Computational Astrophysics

京
K computer

2019/7/4, OMEG15

Explosion mechanism of core-collapse supernovae and recent progress in nuclear physics


4D2U

Tomoya Takiwaki

(National Astronomical Observatory of Japan)

Supernovae teach us Nuclear physics

Supernova explosions provide densest and most extreme environments in Universe.

⇒ Good site to investigate nuclear physics: e.g.

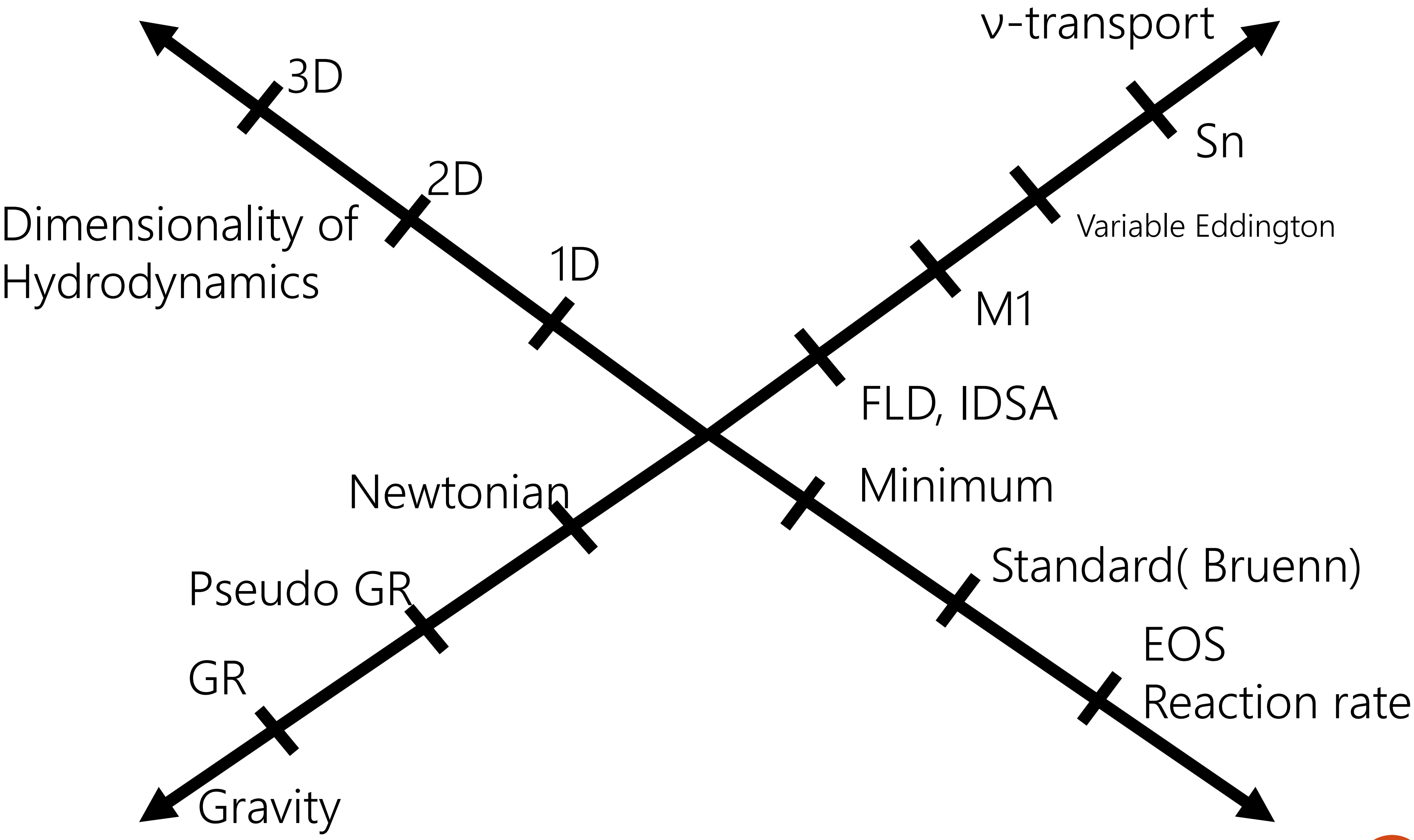
- Nucleosynthesis
- Neutrino nucleon (nuclei) interactions
- Neutron star equation of state and nuclear forces

Very rich physics can be investigated potentially.

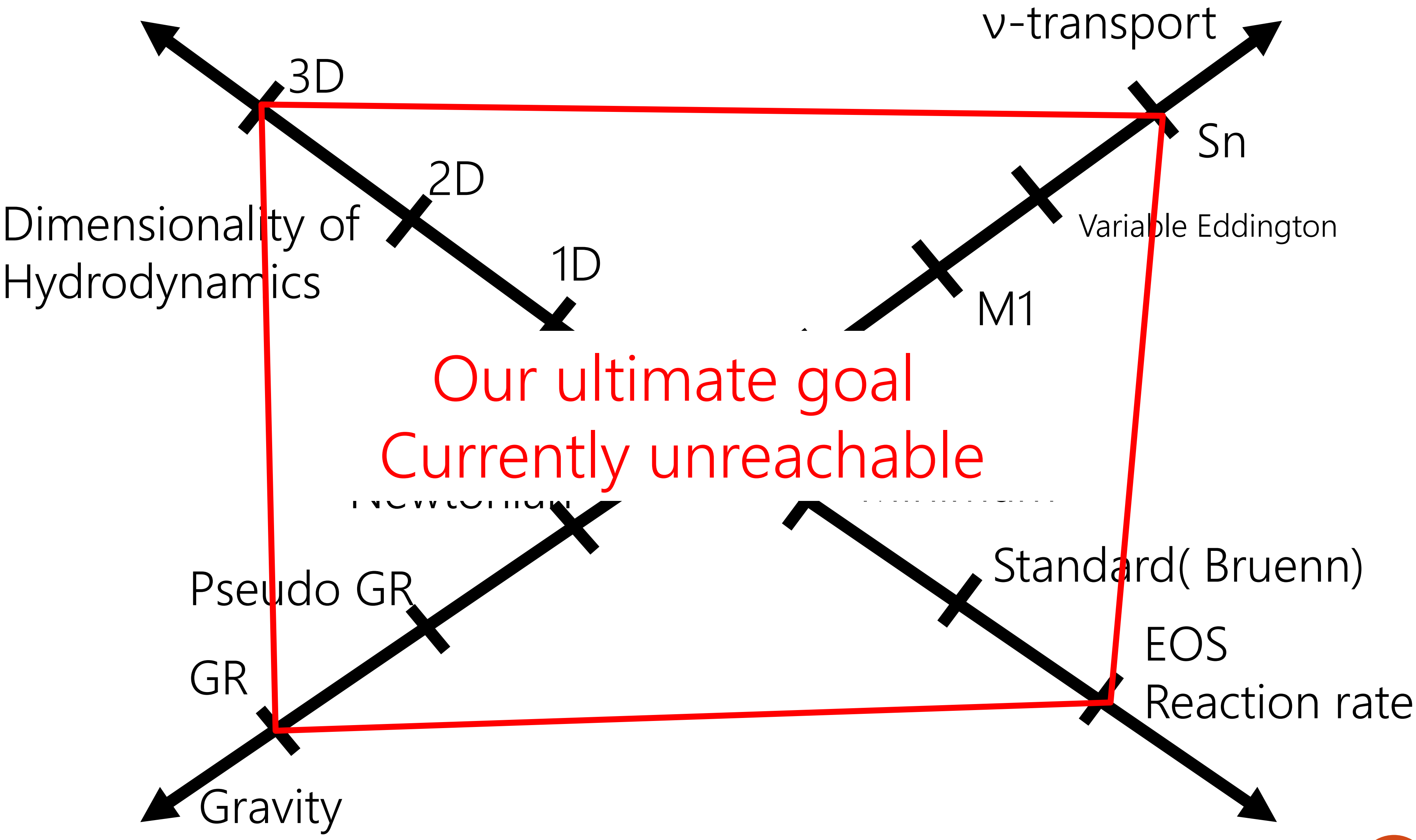
But, simulations with our best knowledge, CANNOT reproduce the energetic explosion!

Q: What ingredients are missing?

Evaluation and Comparison of the methods



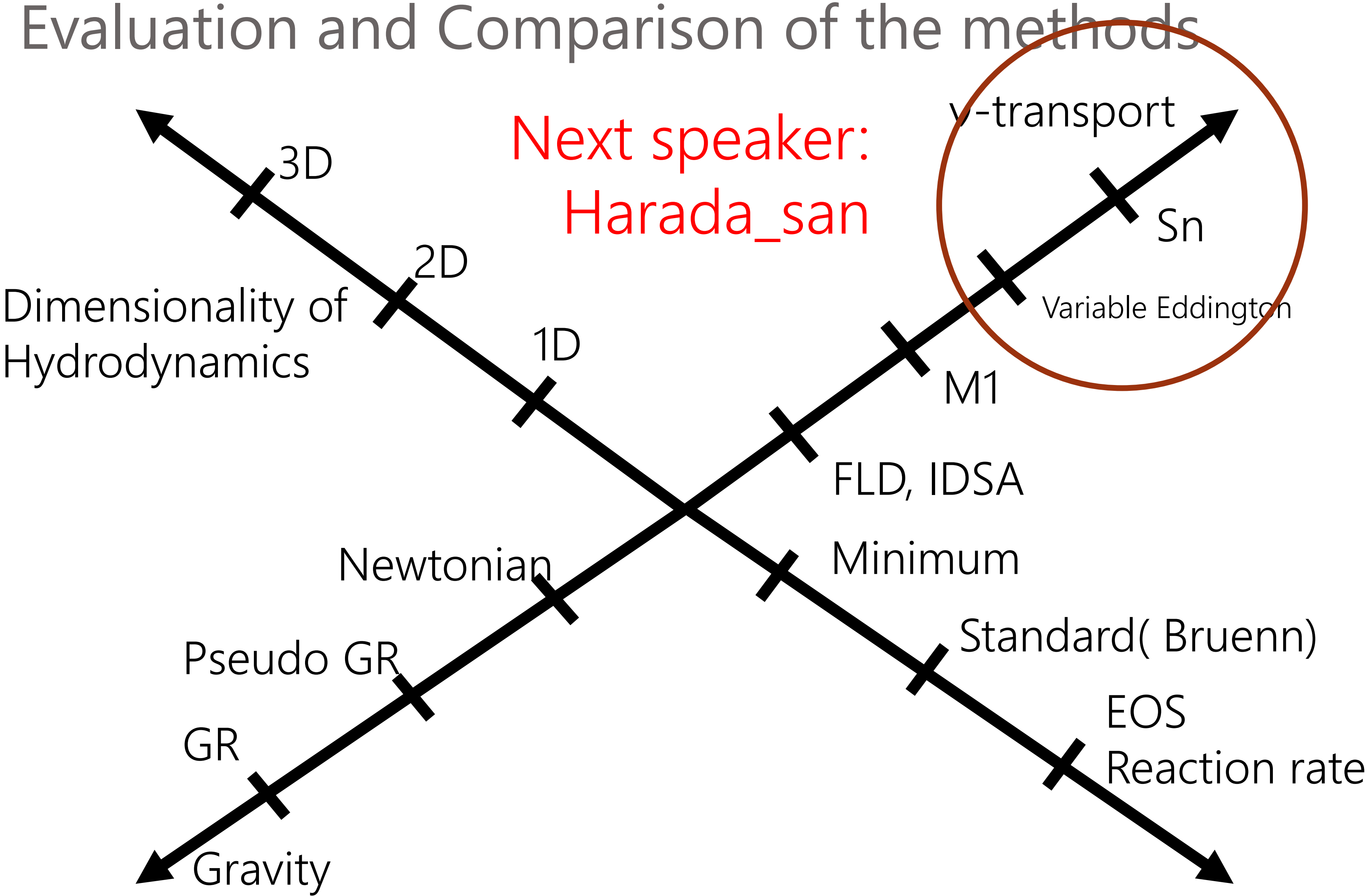
Evaluation and Comparison of the methods



Our ultimate goal
Currently unreachable

Evaluation and Comparison of the methods

Next speaker:
Harada_san



ν-transport

Sn

Variable Eddington

M1

FLD, IDSA

3D

2D

1D

Dimensionality of
Hydrodynamics

Minimum

Standard(Bruenn)

EOS
Reaction rate

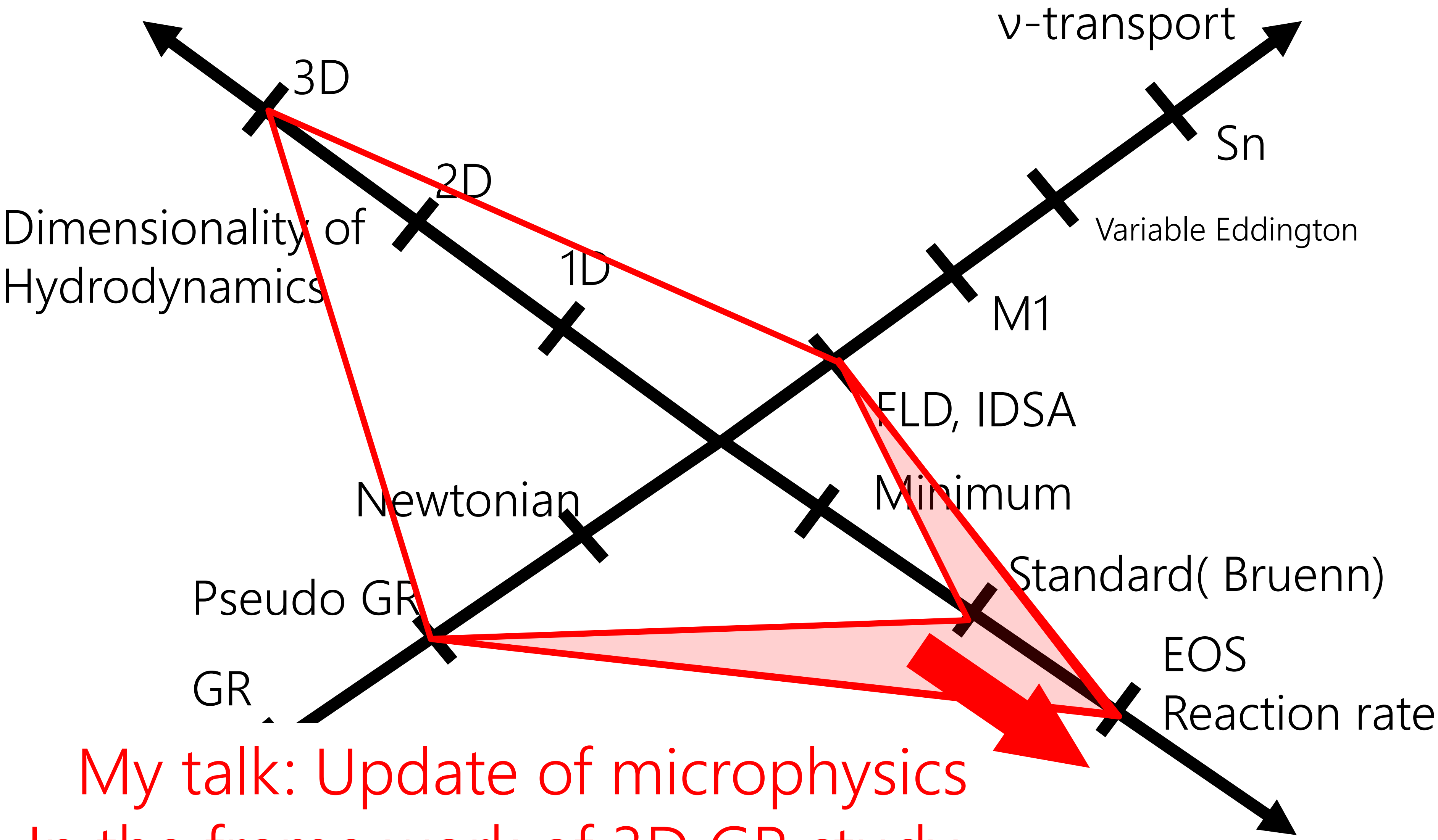
Newtonian

Pseudo GR

GR

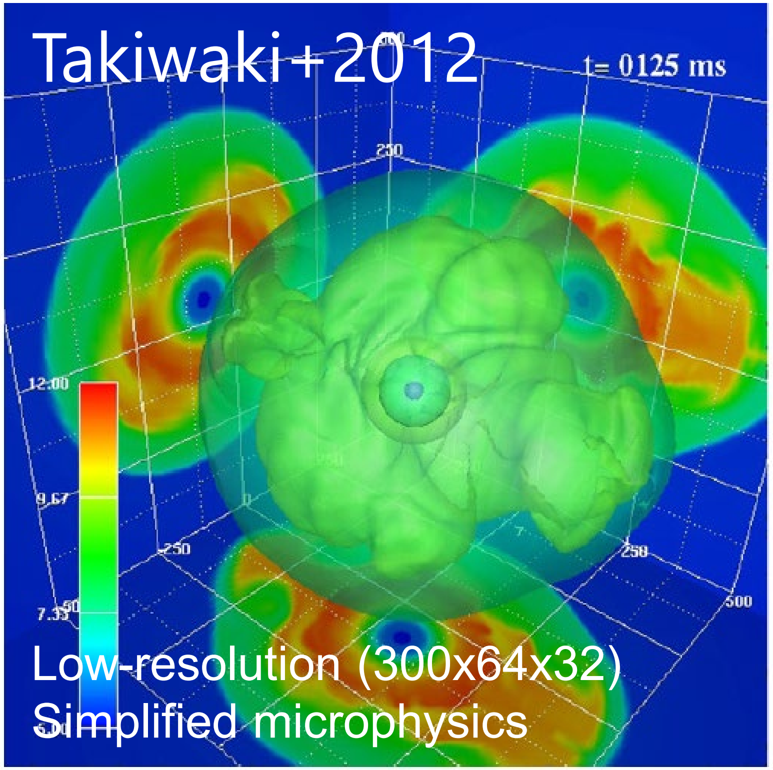
Gravity

Evaluation and Comparison of the methods



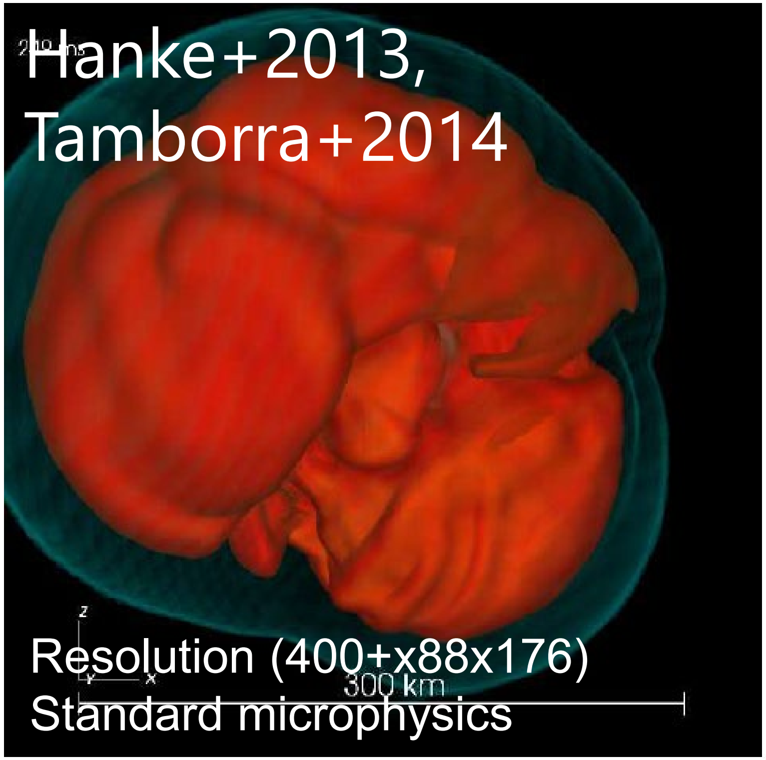
My talk: Update of microphysics
In the frame work of 3D GR study.

Pioneering work => Fiducial work



Takiwaki+2012

Low-resolution (300x64x32)
Simplified microphysics



Hanke+2013,
Tamborra+2014

Resolution (400+x88x176)
Standard microphysics

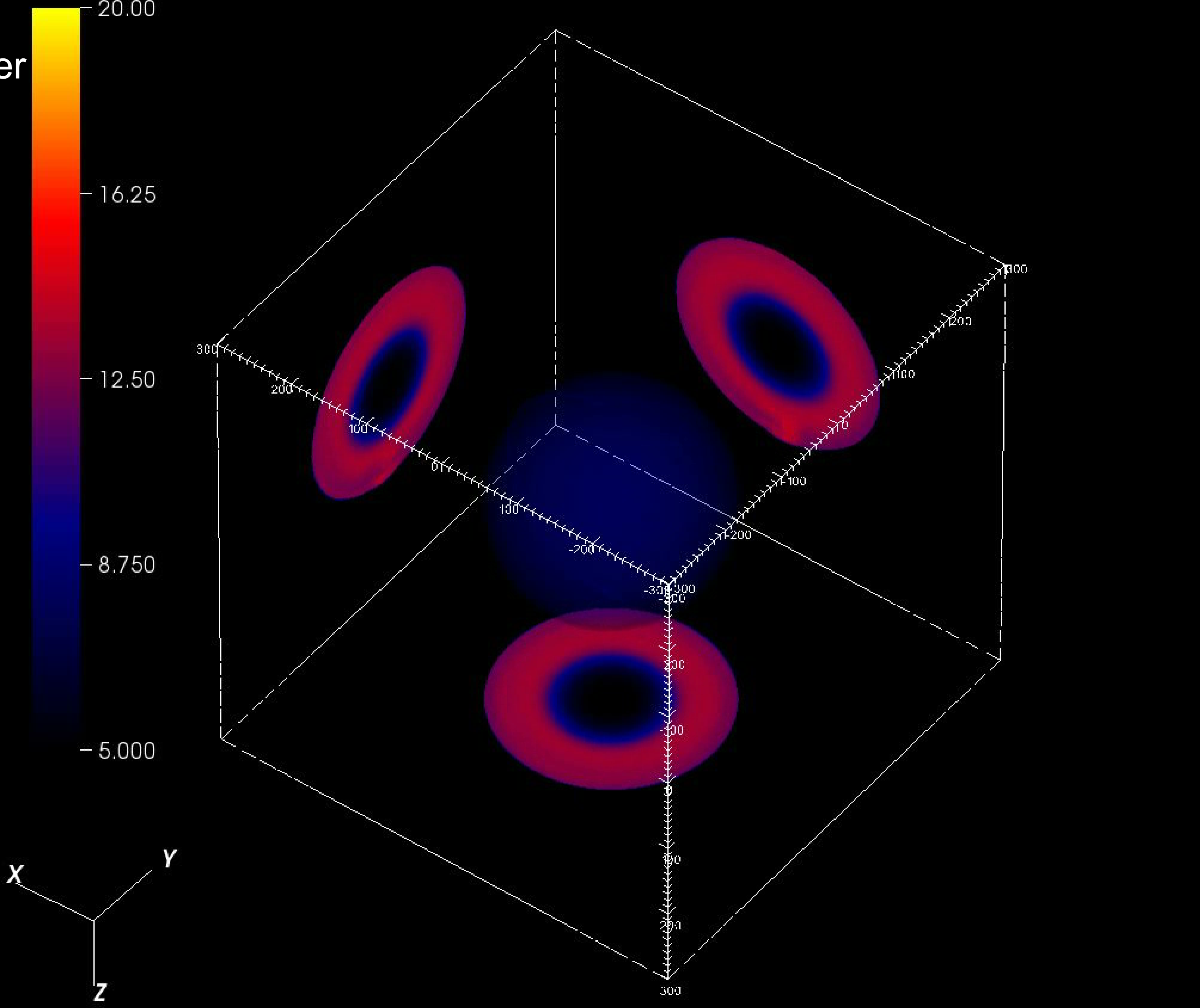
An explosion found in 11.2M_s(WH02)

Explosions not found in 11.2 M_s and 27M_s(WH02)

Inconsistent at the era, but now it become consistent.

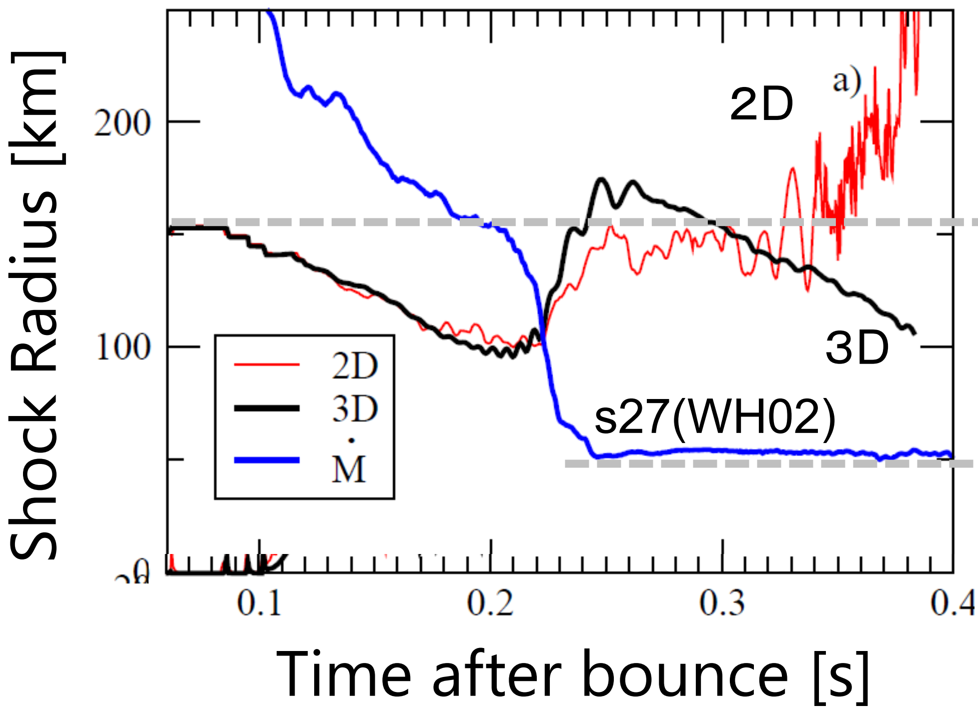
s27(WHW02)
Togashi,TF
WM
2^{nd} order
HLLE

139 ms

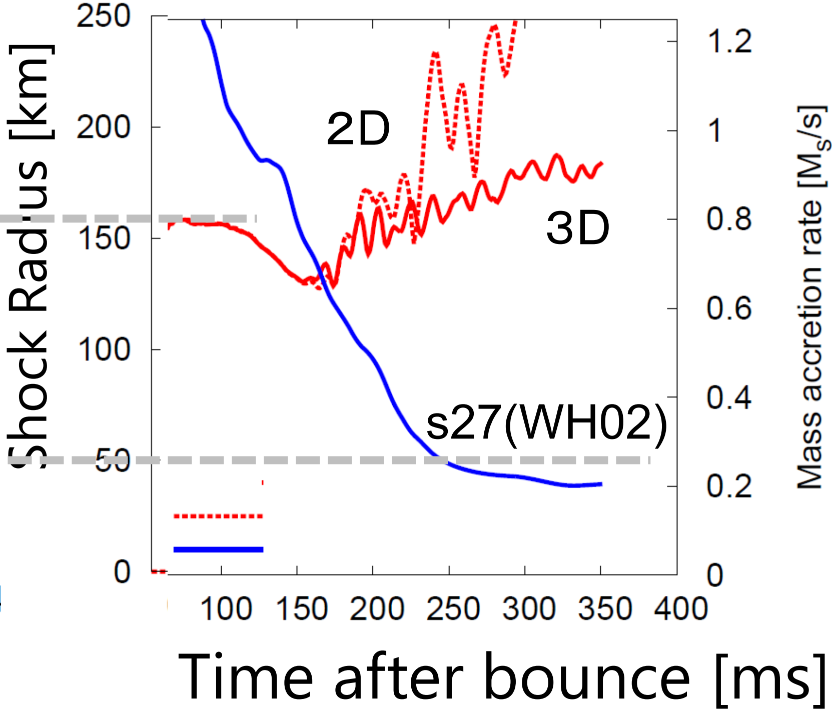


Comparison of 2D and 3D

Hanke+2013



Takiwaki+ in prep.



We employ similar set of microphysics.

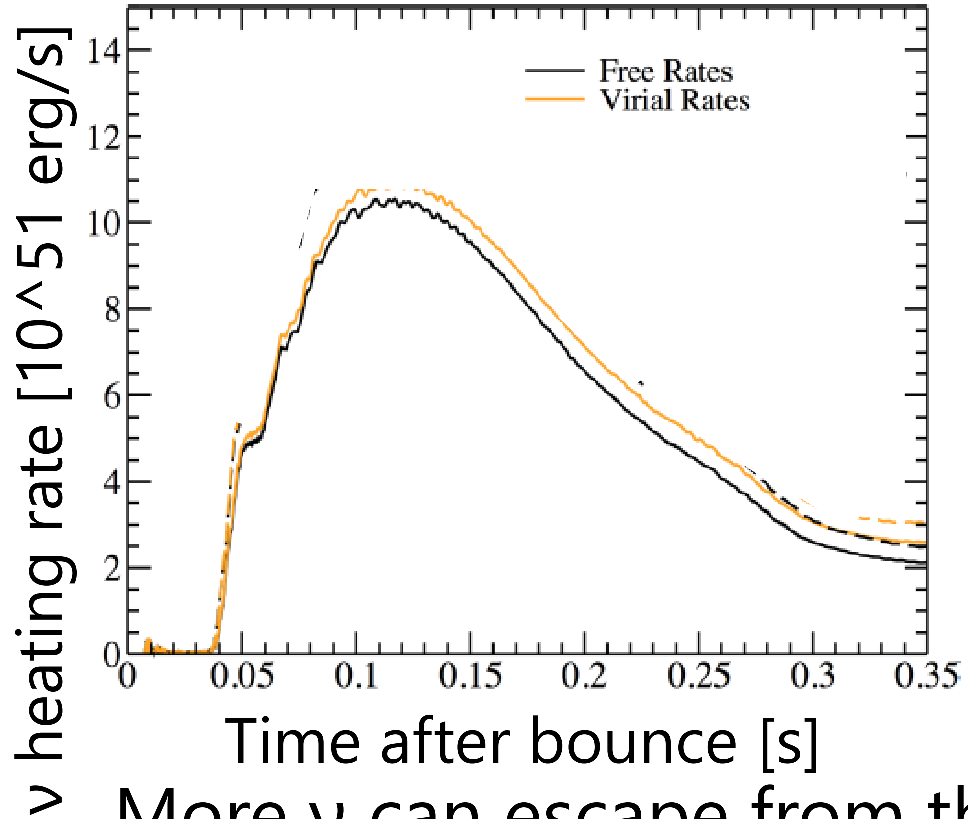
The dynamics is roughly consistent:

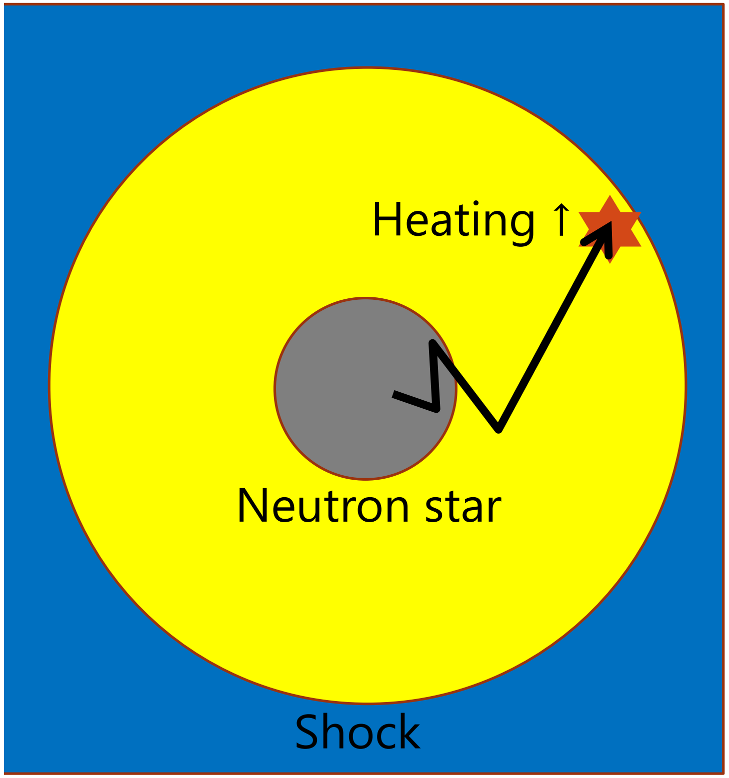
e.g. 2D explode and 3D not. SASI is found.

Explosion in 3D geometry is still difficult to achieve.

Hopeful Effects

Reaction Rate of $n + \nu \rightarrow n + \nu$ in dense region decreased by a nucleon correlation effect!

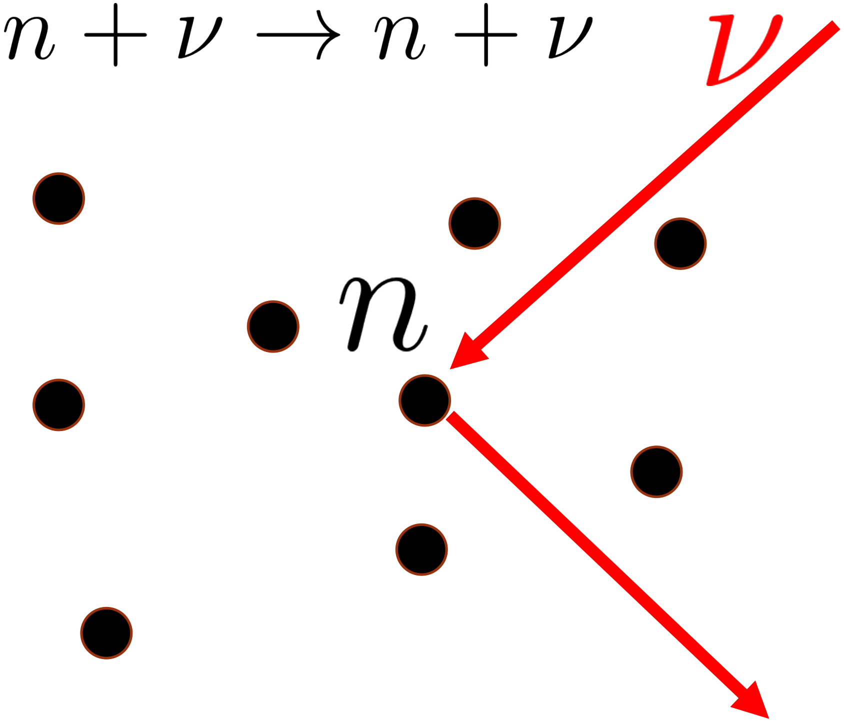




More ν can escape from the center and can heat the matter more.

Previous Assumption on the reaction

$$n + \nu \rightarrow n + \nu$$



Distribution function

$$R \propto 2 \int \frac{\mathrm{d}^3 \boldsymbol{p}}{(2\pi\hbar c)^3} F_n$$
$$\sim n_n$$

Pauli blocking

$$R \propto 2 \int \frac{\mathrm{d}^3 \boldsymbol{p}}{(2\pi\hbar c)^3} F_n (1 - F_n)$$
$$\sim n_n \frac{3\mu_n}{2k_B T}$$

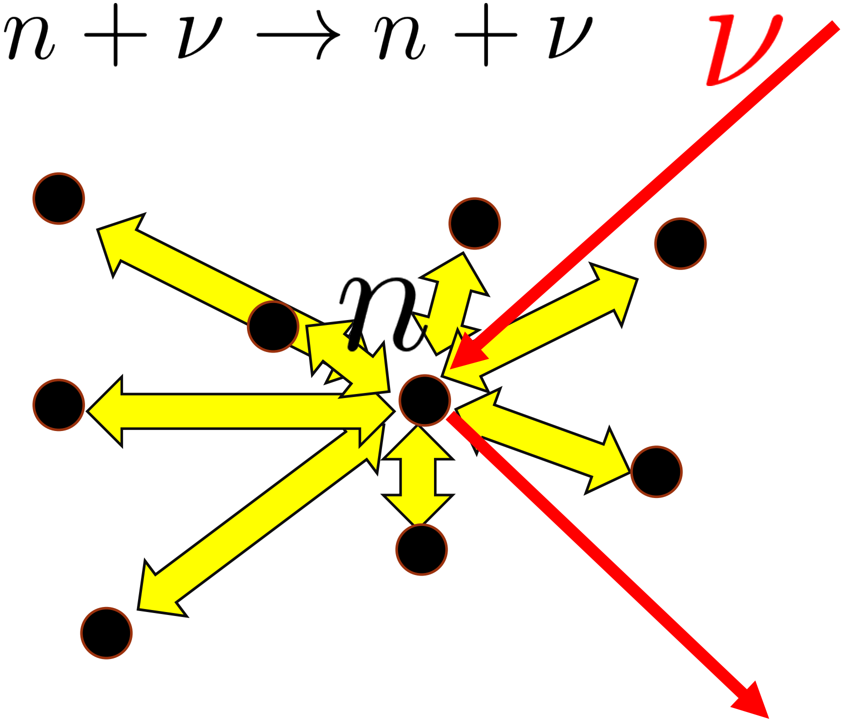
Previous studies assumed that nucleon is ideal Fermi gas.

There is no interaction between nucleons.

Bruenn 1985, Rampp+2002

Correlation Effect

$n + \nu \rightarrow n + \nu$



$$\xcancel{R \propto 2\int \frac{\mathrm{d}^3 \boldsymbol{p}}{(2\pi\hbar c)^3} F_n (1 - F_n)}$$

First correction can be evaluated by the two body interactions (data of phase shift of the scattering).

Repulsive force of spin-spin interaction decreases the reaction rate.

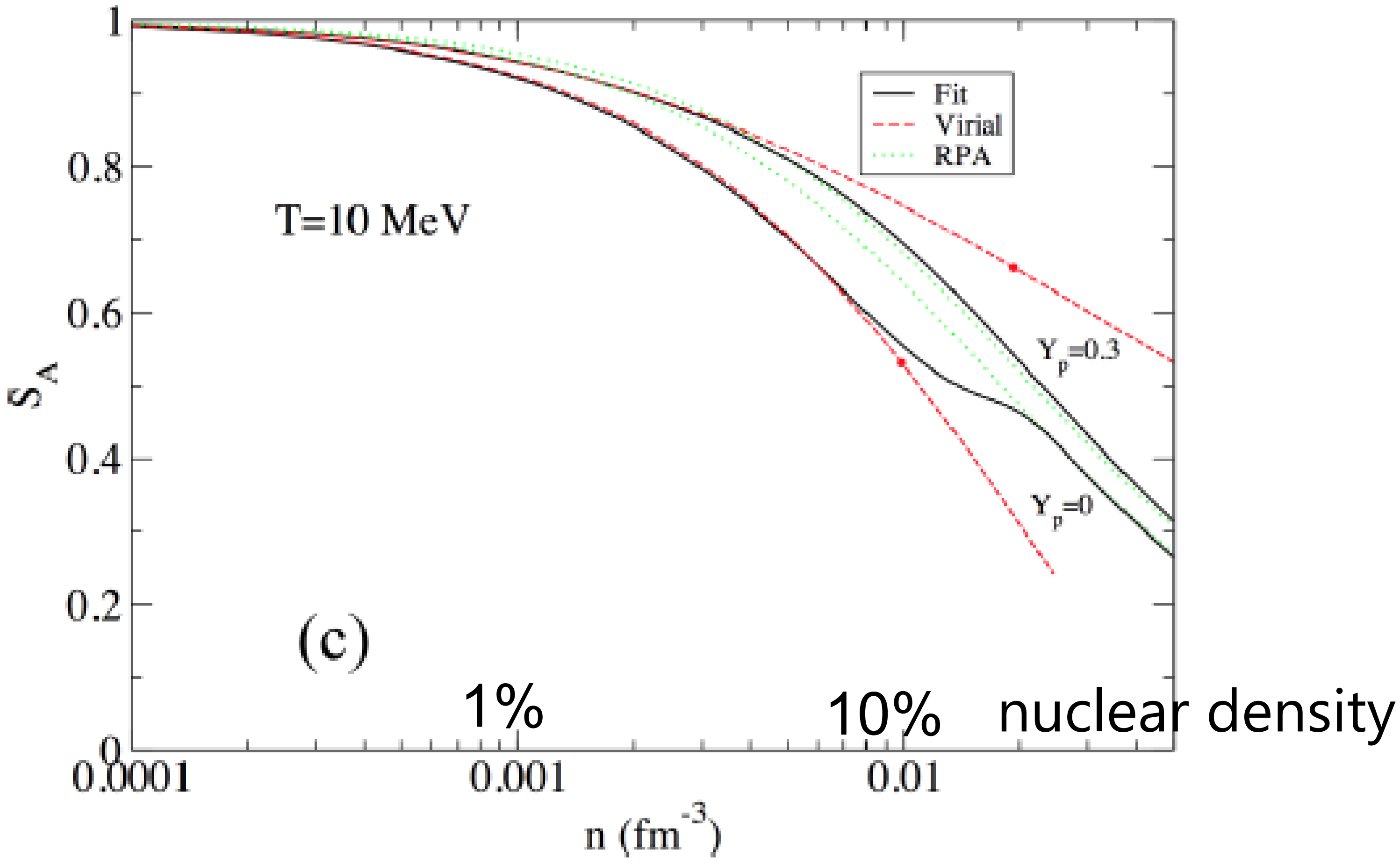
In reality, interaction between nucleon cannot be ignored.

The correction to the ideal case should be included.

Burrows and Sawer 1998, Horowitz+2017

Correlation Effect

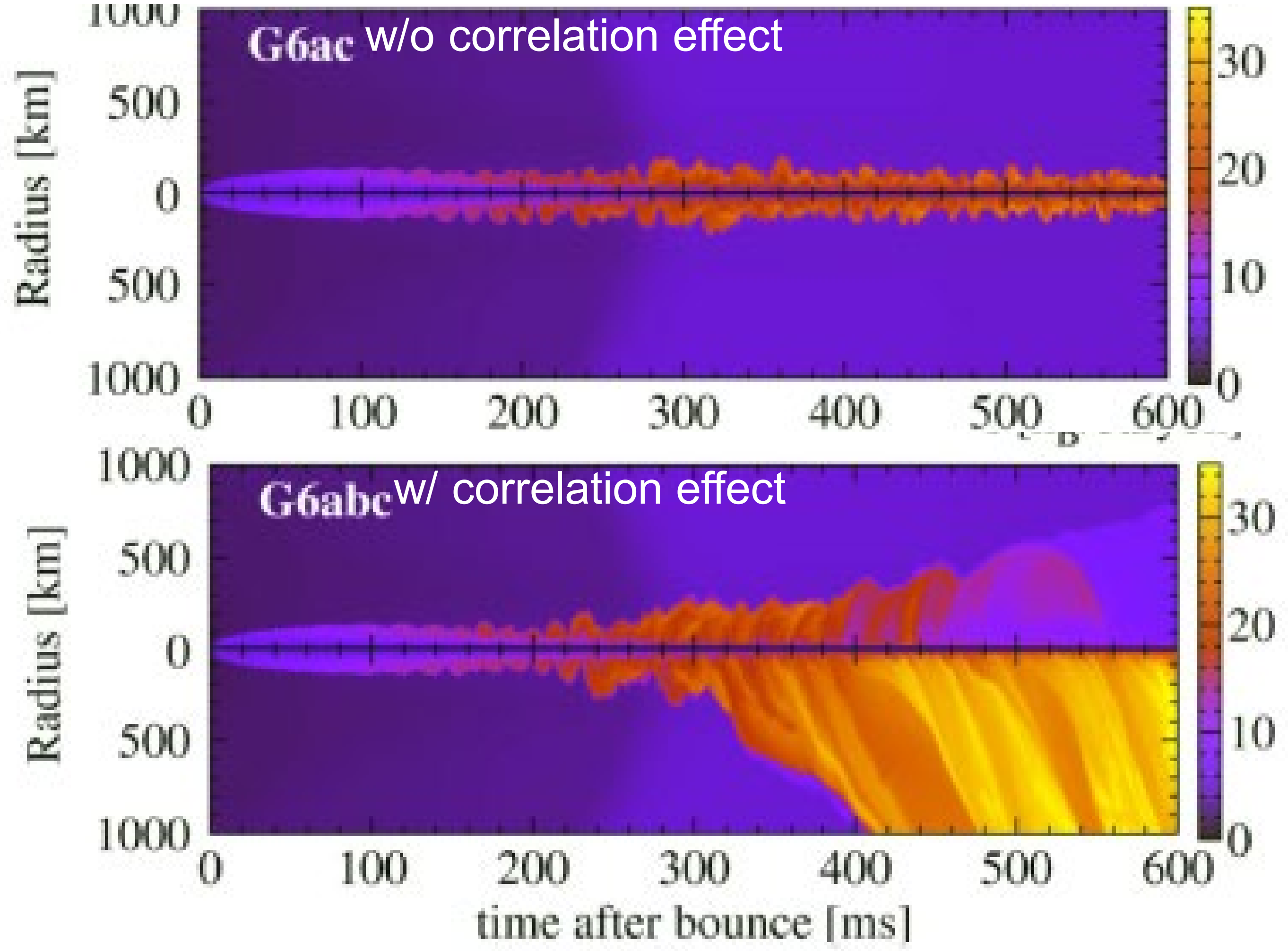
How small the reaction rare becomes compare to its density



The reaction rate become 50% in nuclear density and in the region of 1-10% nuclear density, the effect is still significant!

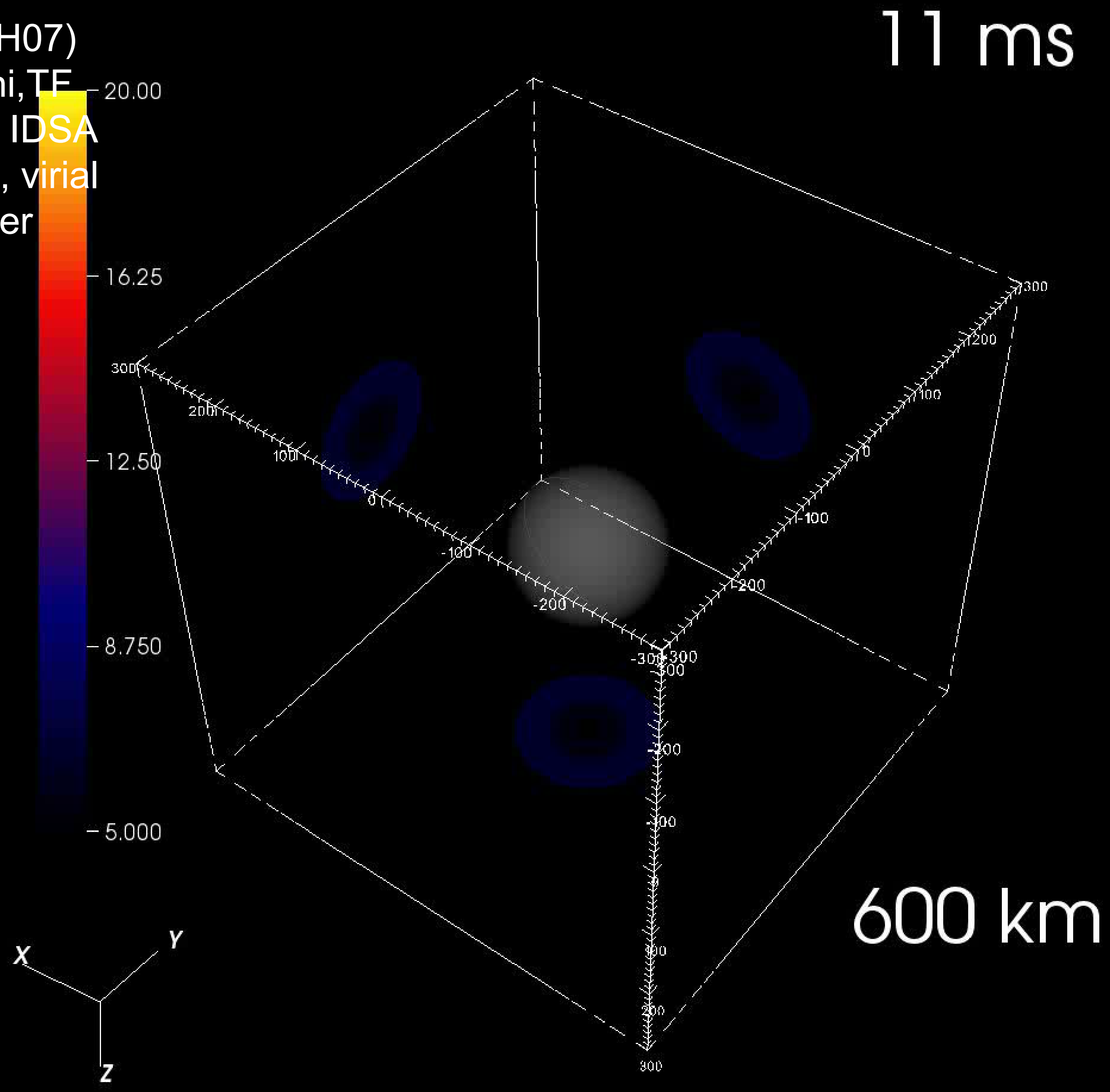
Horowitz+2017

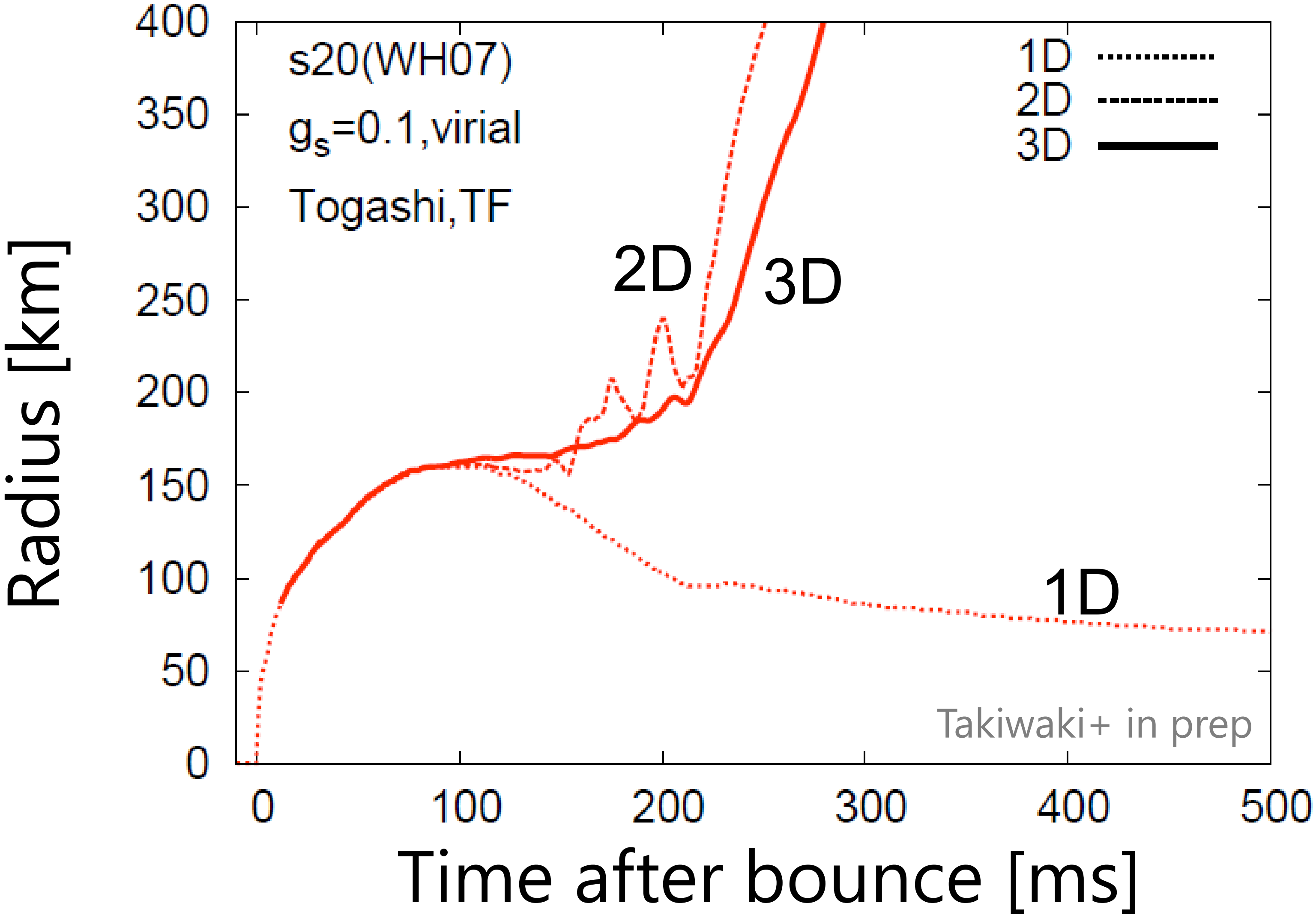
Impact of the reaction



Kotake+ 2018 investigates the impact of the effect in 2D simulation.
We found significant difference. How about 3D?

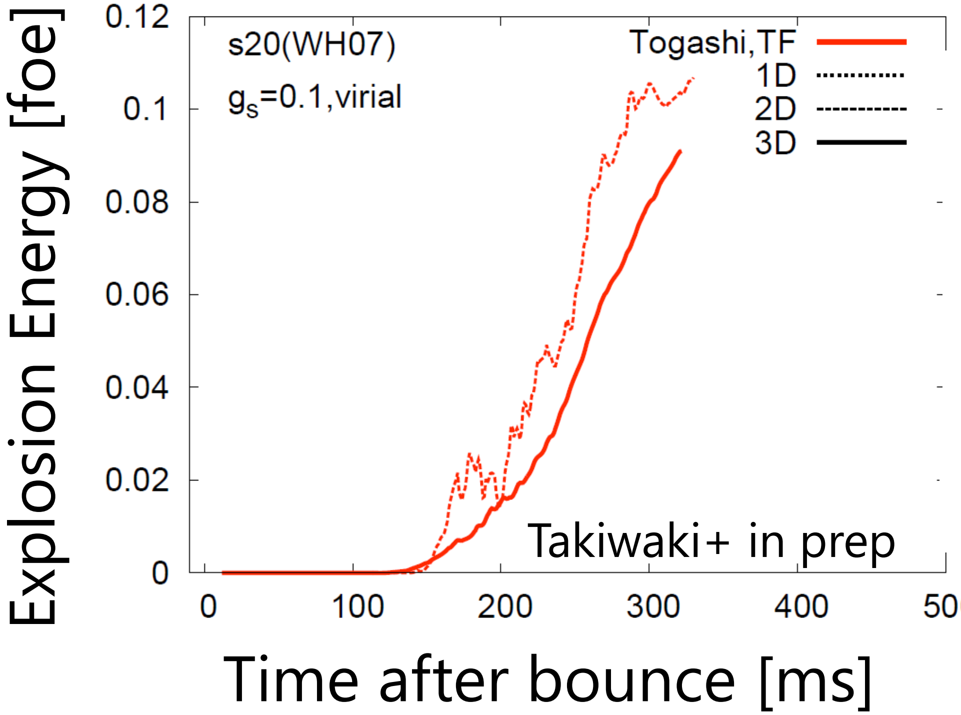
s20(WH07)
Togashi,TF
3flavor IDSA
gs=0.1, virial
2nd order
HLLC

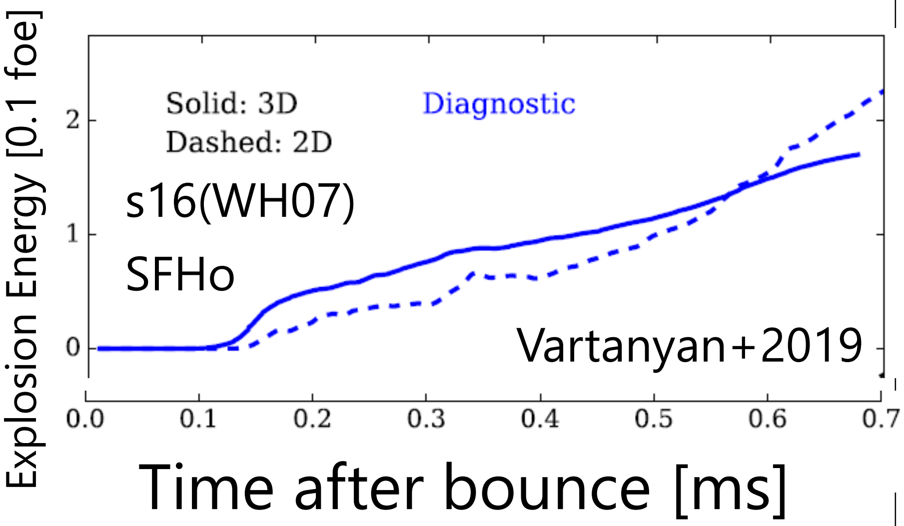




Explodability: 1D << 3D (< 2D)
(how easily the shock revives.)

Explosion Energy





$$\frac{\mathrm{d}E_{\mathrm{exp}}}{\mathrm{d}t} \sim 0.7 \times 10^{51}[\mathrm{erg/s}] \qquad \frac{\mathrm{d}E_{\mathrm{exp}}}{\mathrm{d}t} \sim 0.3 \times 10^{51}[\mathrm{erg/s}]$$

The slope of the energy is similar to recent study (Suwa+2019)

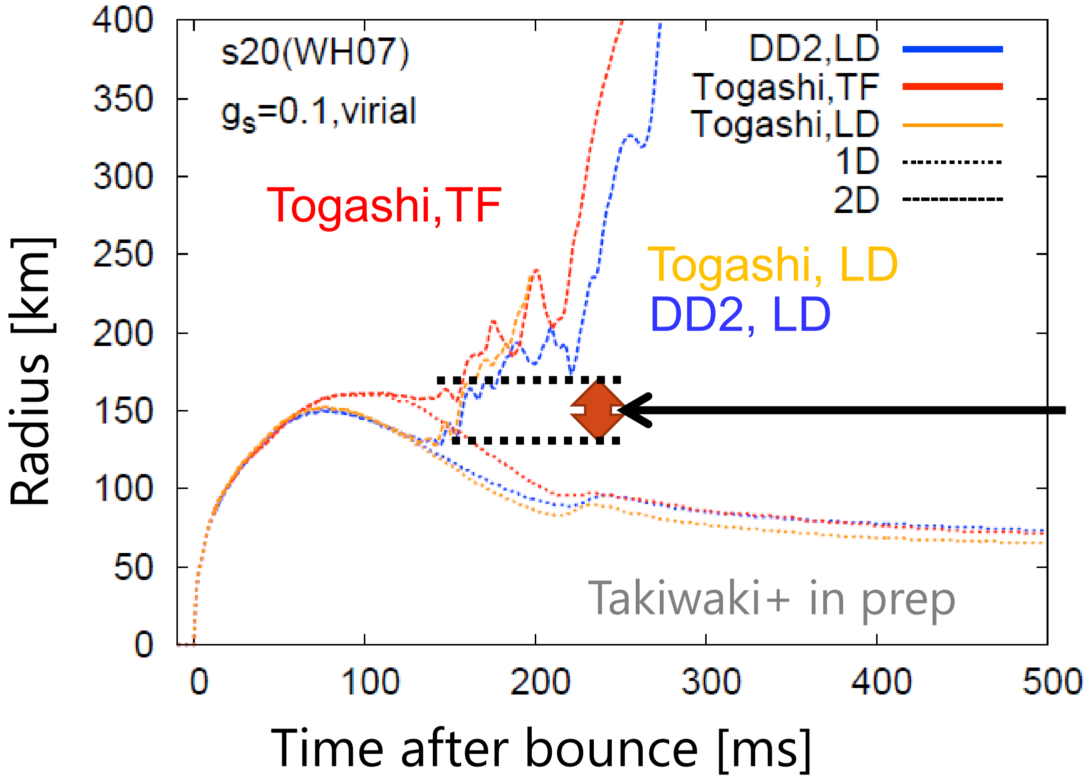
It's difficult to estimate the final energy. However,

the explosion energy might not reach the fiducial 10^51 erg.

Caveat: Nuclear burning, initial anisotropy … is not employed.

Effect of EOS

EOS NAME	Uniform matter	Non uniform matter
DD2, LD	Stiff	Multi nuclei, Liquid Drop
Togashi, TF	Soft	Single nuclei, Thomas Fermi
Togashi, LD	Soft	Multi nuclei, Liquid Drop



Takiwaki+ in prep

Togashi,LD vs DD2, LD:
=>Dif. of Uniform matter
Insignificant for explodability

Togashi, LD vs Togashi,TF:
⇒Dif. of non-uniform matter
Significant for explodability

Effect of EOS

EOS NAME	Uniform matter	Non uniform matter
DD2, LD	Stiff	Multi nuclei, Liquid Drop
Togashi, TF	Soft	Single nuclei, Thomas Fermi
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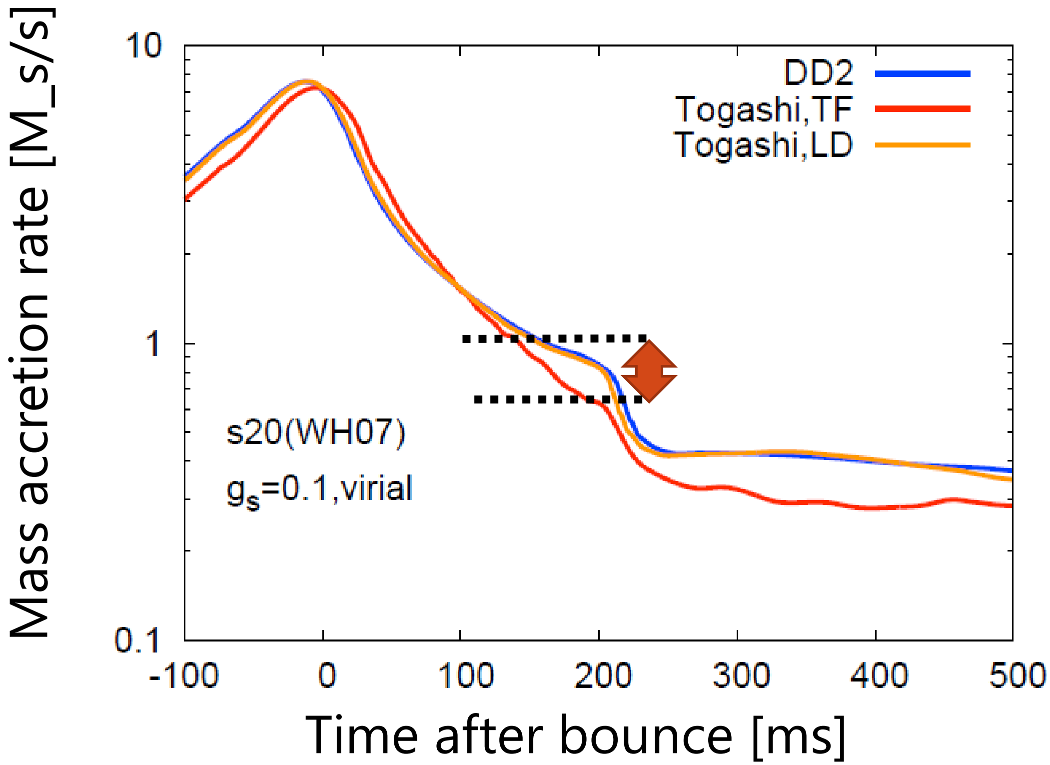

The origin of difference come from the nuclei in the pre-bounce phase.

In Togashi, TF, cooling by the electron capture in heavy nuclei is surpressed.
⇒ Less cooling
⇒ Delay core bounce
⇒ Small mass accretion in the post bounce phase.

Summary

We performed 3D neutrino radiation hydrodynamic simulations and investigated the impact of the update of microphysical processes.

- My results are roughly consistent with the results of other group.
- With the effect of nucleon correlation, we found shock revivals in 3D.
- Treatment of sub-nuclear part in EoS, changes the bounce time and accretion rates.

Message:

- Some important effects of microphysics is still not sufficiently employed in the simulation and that could be gradients to make a strong explosion.