Core-collapse supernova simulation of a 3D 25 $M_\odot$ progenitor model

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Purpose

We need ***Realistic*** CCSN models
Comparable to observations.

Realistic model… based on 3D self-consistent simulations without any arbitrary parameters.

Comparable to obs… $E_{\rm exp}$~ 10^{51}erg, $M_{\rm Ni}$~ 0.07$M_\odot$

One of the key inputs is non-spherical structure of initial conditions (CCSN progenitors).

Previous works

2D simulations

Mass accretion is important!

high $\dot{M}$ → high L_ν → high $\dot{Q}$ → high $E_{\rm exp}$

Progenitors with high $\dot{M}$ can attain 10^{51}erg in 1-2 s after bounce (if they explode).

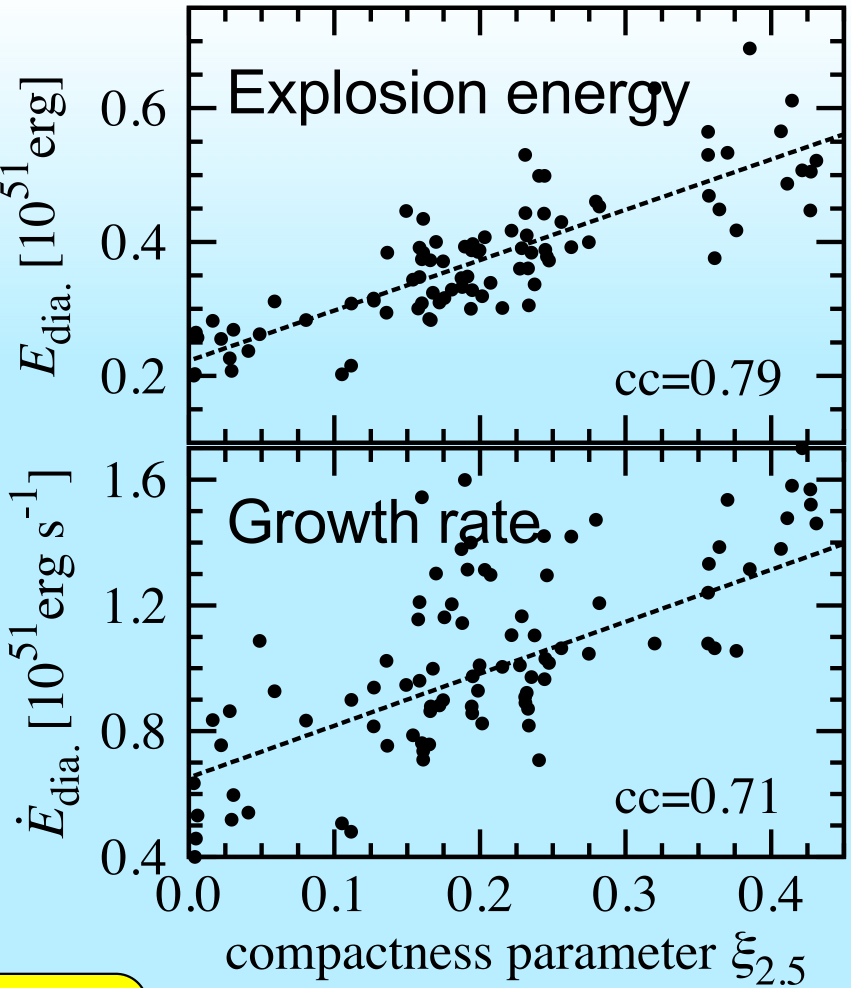
3D simulations

It's not easy to explode high $\dot{M}$ progenitors.

Some small mass (≒ small $\dot{M}$) progenitors can explode, but their $E_{\rm exp}$ is small.

Melson+15: 9.6$M_\odot$ → 10^{50}erg

Mueller+18: 7 progenitors →1-4 x 10^{50}erg



(≒ mass accretion rate)

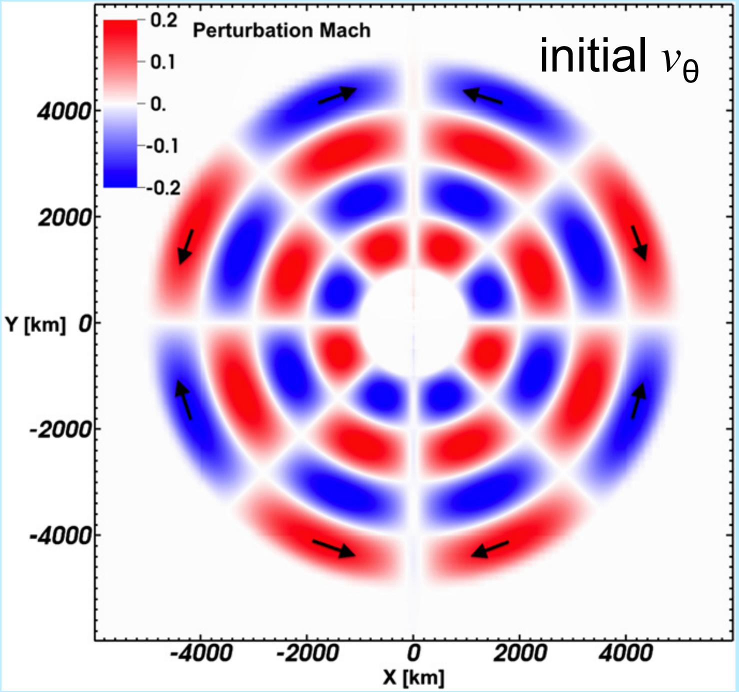
We could obtain $E_{\rm exp}$~ 10^{51}erg (& $M_{\rm Ni}$~ 0.07$M_\odot$) CCSM models if high $\dot{M}$ progenitors explode.

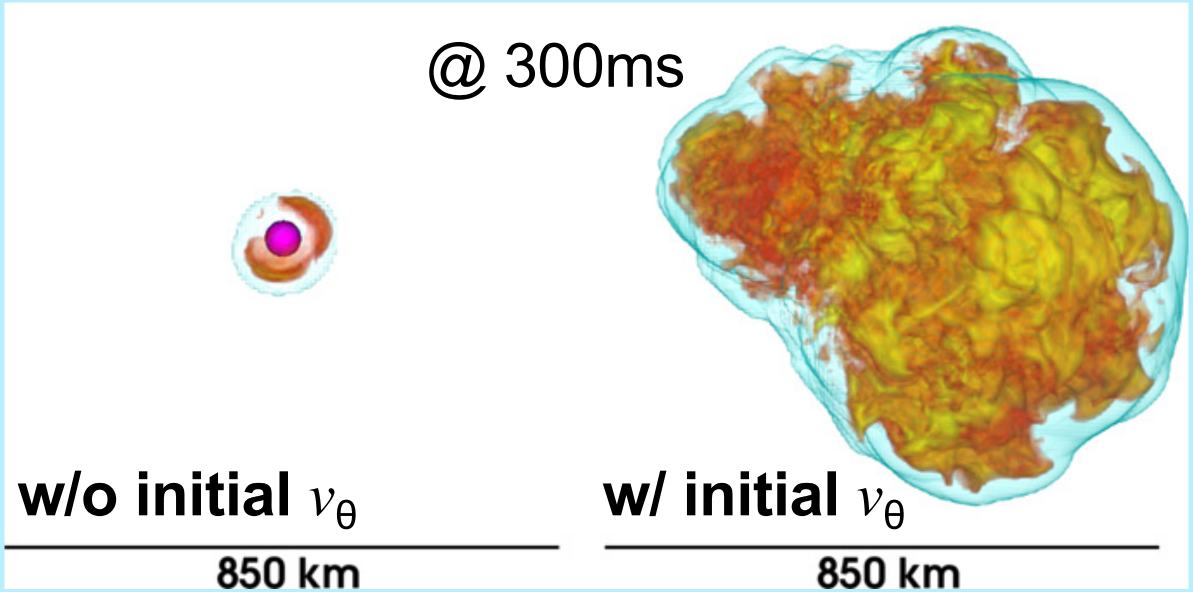
KN+15, PASJ

Previous works

Couch & Ott 13

3D CCSN simulation for a **spherical** $15 M_{\odot}$ progenitor star with a **parametric v_{θ} perturbation** in 1,000 - 5,000 km. → **Shock revival**.





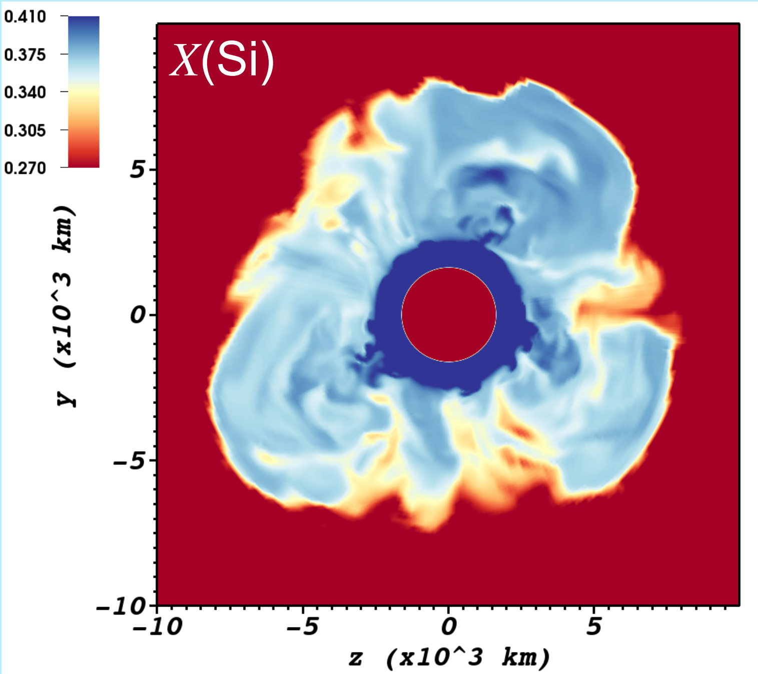
Previous works

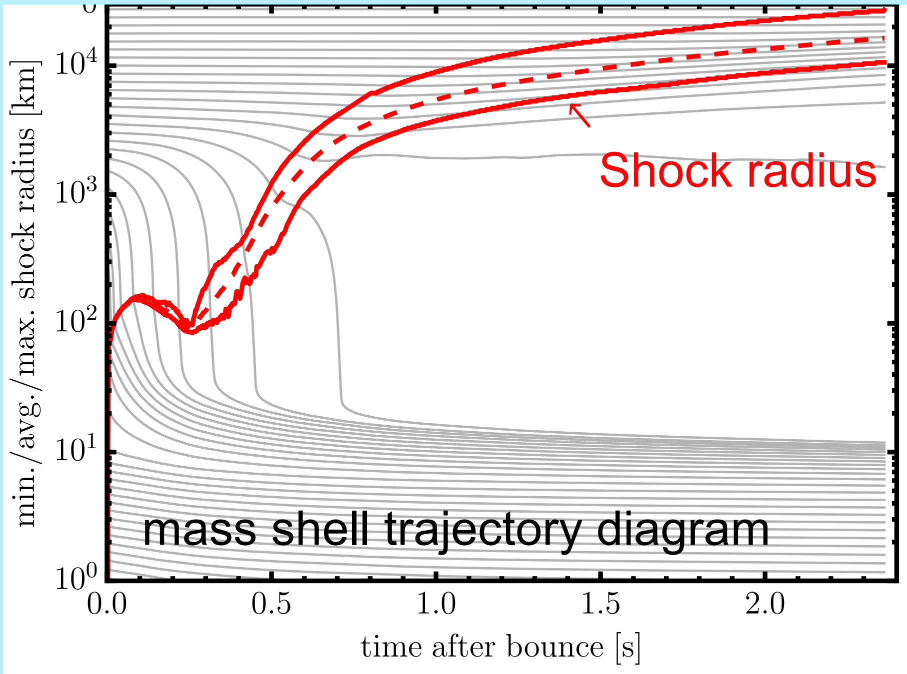
Couch & Ott 13

3D CCSN simulation for a **spherical** 15$M_\odot$ progenitor star with a **parametric v_θ perturbation** in 1,000 - 5,000 km. → **Shock revival**.

Mueller+17

3D CCSN simulation following a **3D stellar evolution** of 18$M_\odot$ progenitor (*Mueller+16*). → E_{exp} ~ 7.7x10^{50} erg @ 2.4 s.





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☆ ***Bollig+21***

"*Self-consistent 3D SN models from -7 min. to +7 sec: a 1-Bethe explosion*"

3D CCSN simulation following a 3D stellar evolution of 18.88$M_\odot$ progenitor (*Yadav+20*). → **E_{exp} ~ 10^{51} erg & M_{Ni} ~ 0.087**$M_\odot$ @ 7 s.

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We want to construct independent 1-Behte CCSN models employing different progenitor models and numerical code.

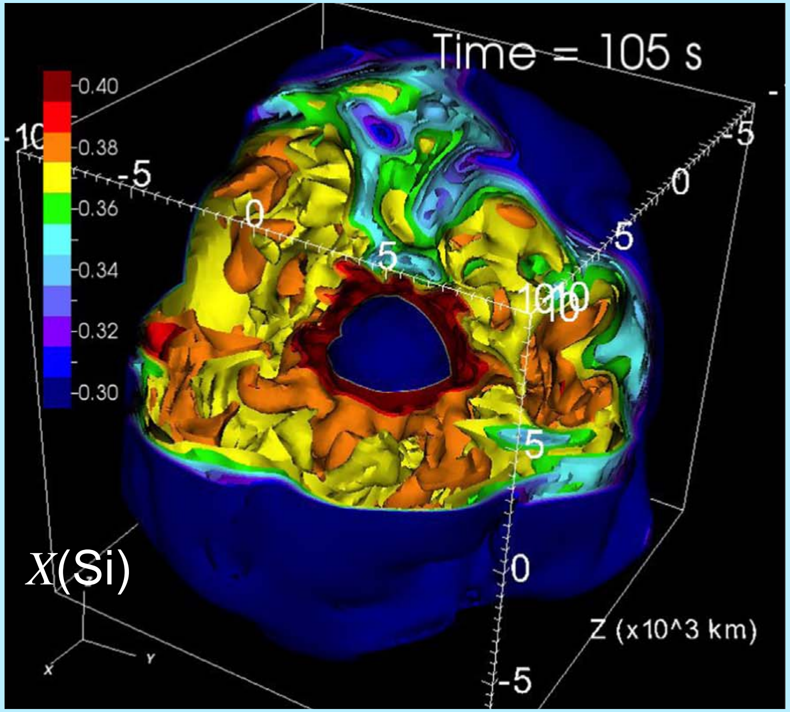
Numerical scheme

Progenitor model（ *Yoshida+19* ）

3D stellar evolution of $25M_\odot$ progenitor for 100 s before collapse.

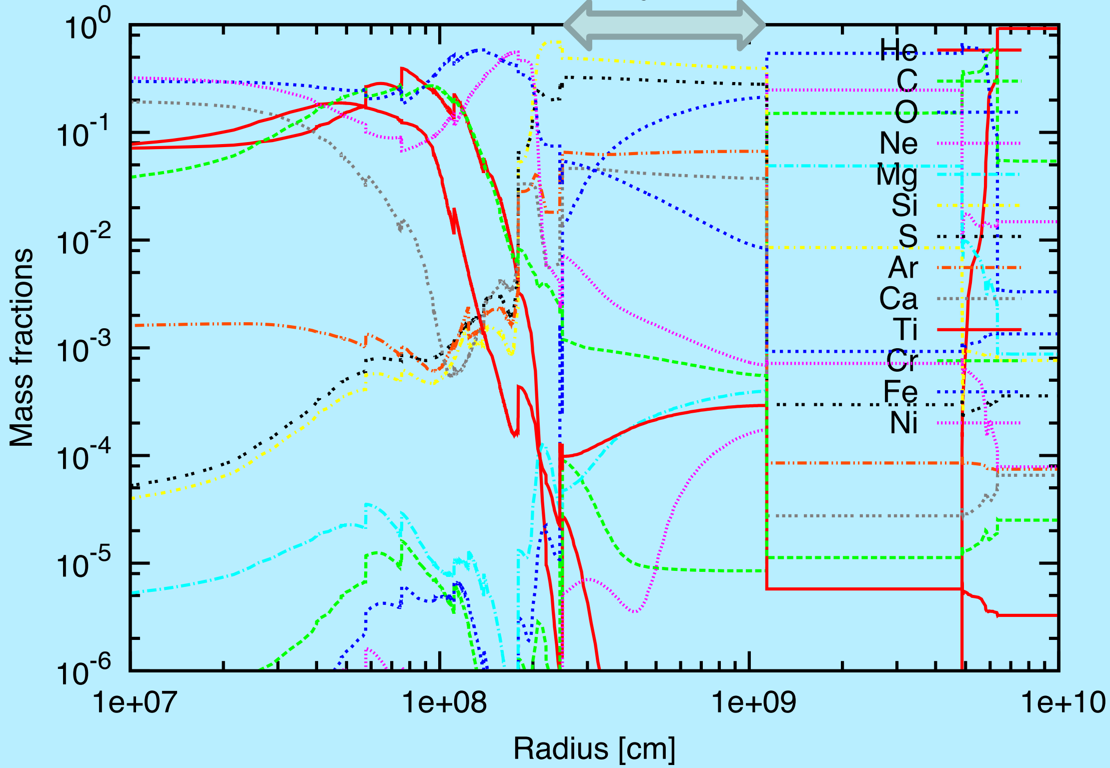
→ O-shell burning drives large convective motions in Si/O layer.

→ Mapping the v_r profile on 1D progenitor for the initial condition.



Yoshida+'19

Si/O layer（2490-11400km）



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Core-collapse simulations

2D/3D simulation by means of **3DnSNE code**（*Takiwaki+18*）.

ν transport : 3-flavor IDSA scheme, 20 energy bins (<300 MeV)

EoS : LS220 + Boltzmann gas

nuclear network : 13-α (He-Ni) simple network calculation

spatial resolution : $0 \leq r \leq 10^4$ km, 600(r)x128(θ) or 600x64x128(φ)

Inputted non-spherical structures

rp: random density perturbation (< 0.01%)

vp: radial velocity perturbation based on 3D stellar evolution.

（$v_{\rm turbl.}$~ ±10^8 cm/s, much smaller than $v_{\rm infall}$~ -10^9cm/s）

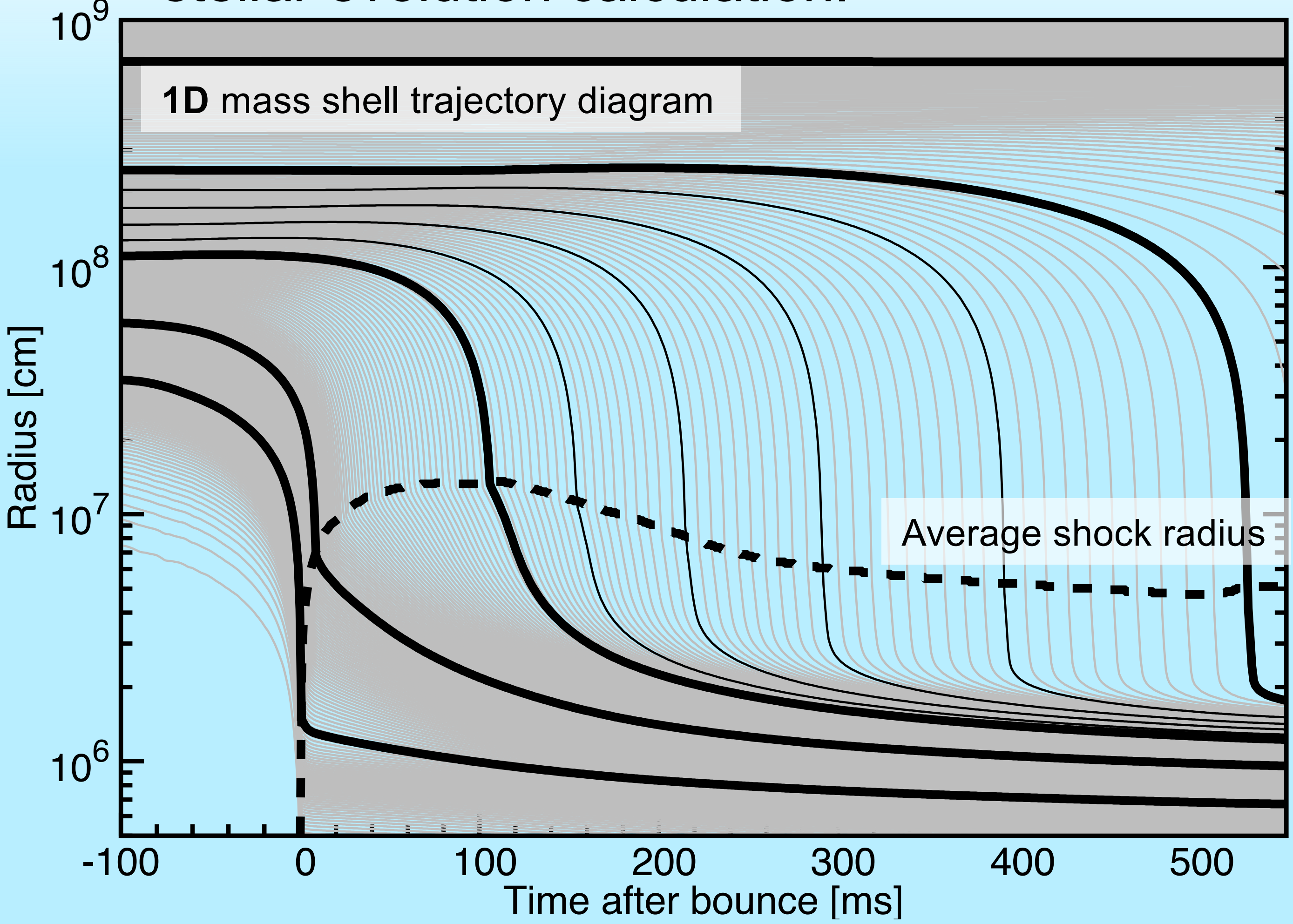
Results - 1D/2D simulations

1D（spherical）

No explosion.

rp: random density perturbation (< 0.01%).

vp: radial velocity perturbation from 3D stellar evolution calculation.



Results - 1D/2D simulations

1D（spherical）
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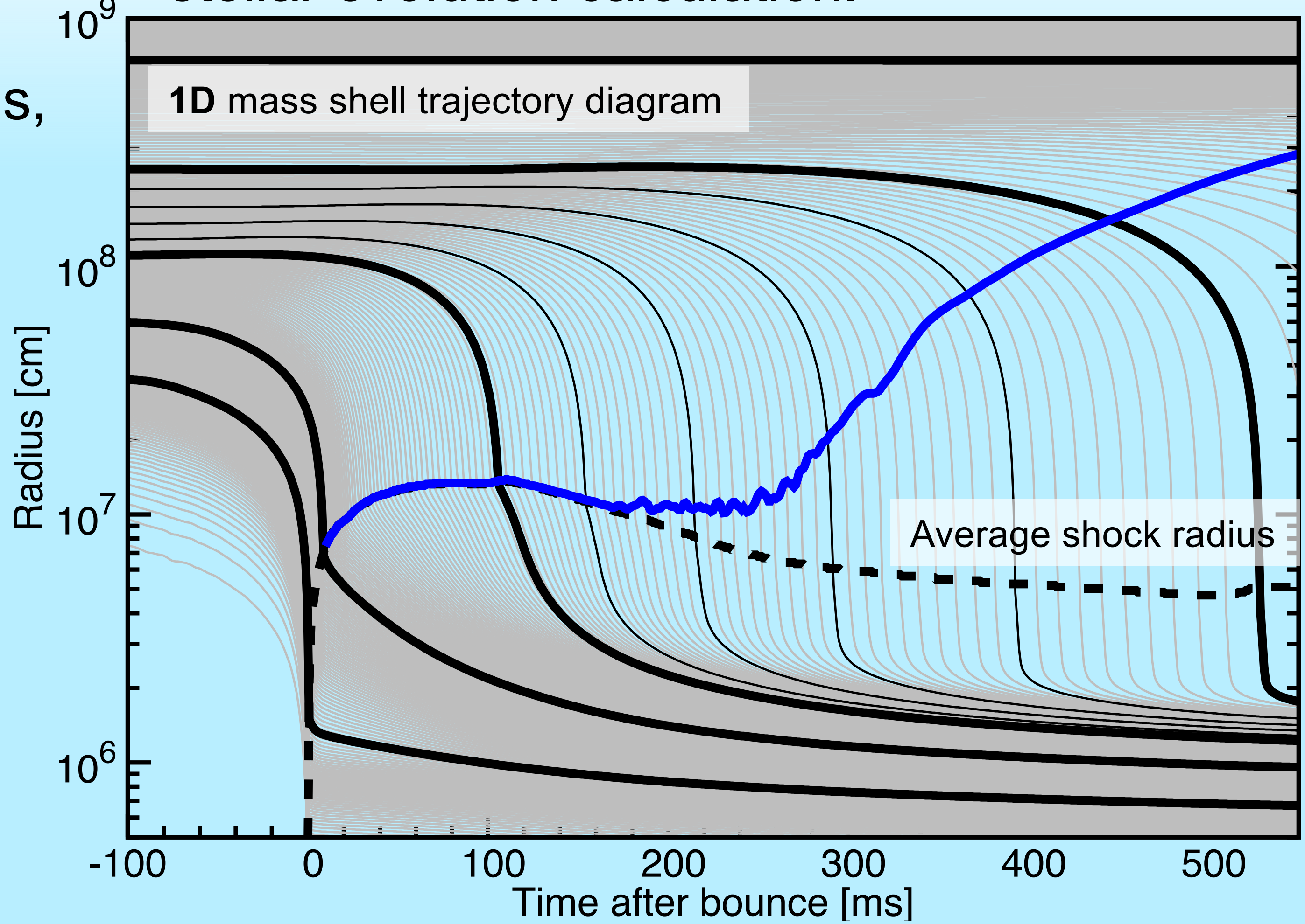
2D with rp
Shock revival at ~ 260ms,

rp: random density perturbation (< 0.01%).
vp: radial velocity perturbation from 3D stellar evolution calculation.



Results - 1D/2D simulations

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2D with rp

Shock revival at ~ 260ms, earlier than the infall time of the convective region.

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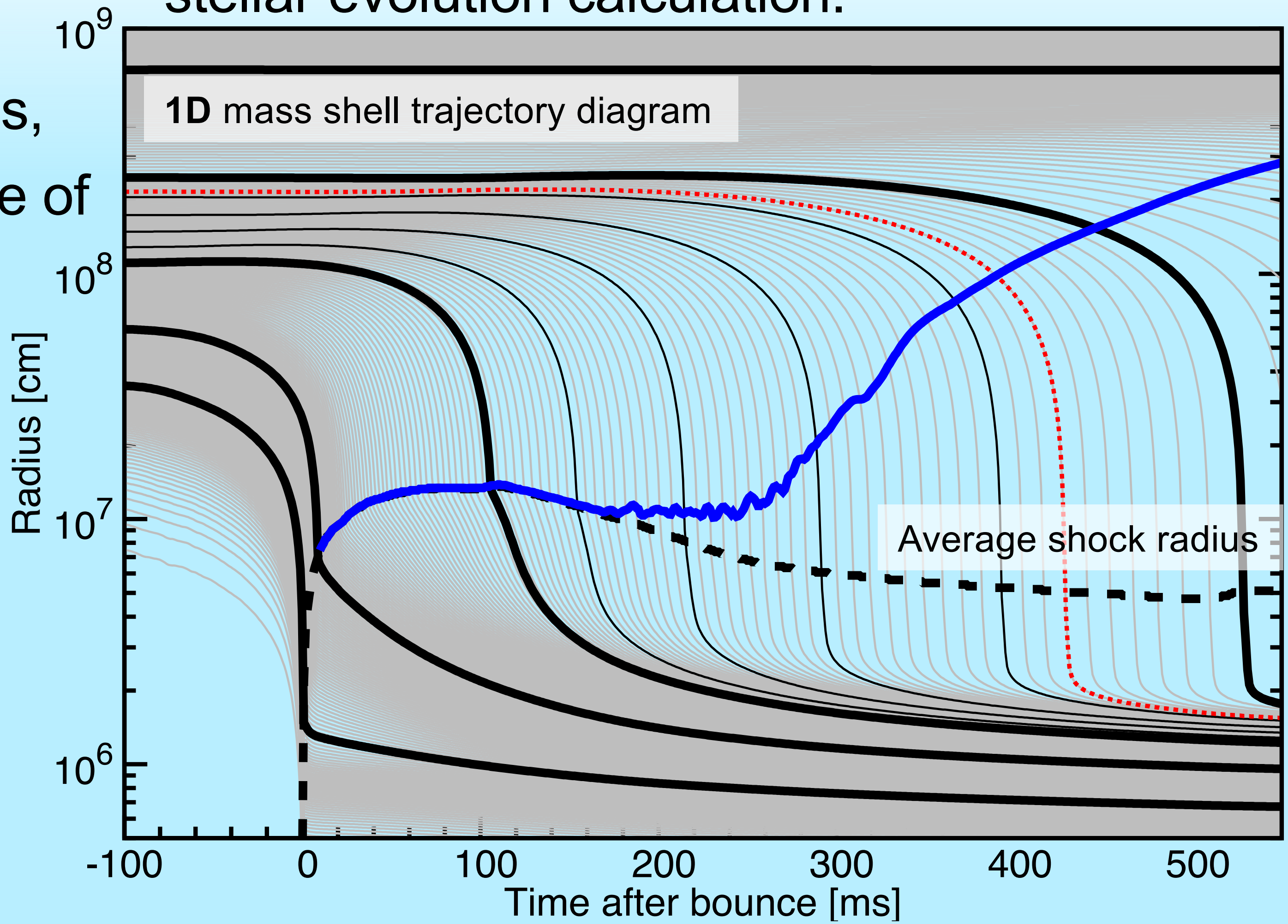


Results - 1D/2D simulations

1D (spherical)

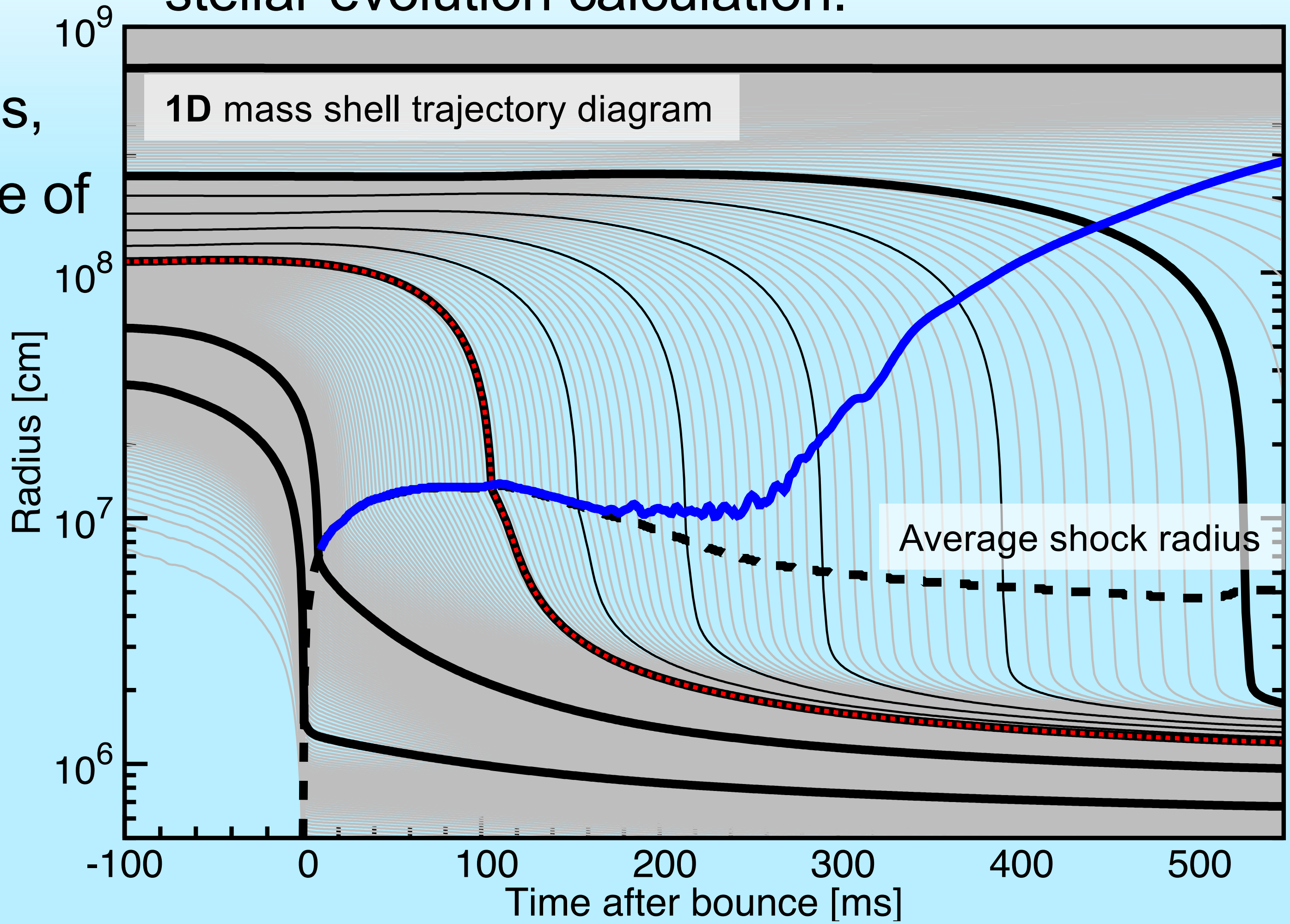
No explosion.

2D with rp

Shock revival at ~ 260ms, earlier than the infall time of the convective region.

We shift the inner radius of the region inward.

rp: random density perturbation (< 0.01%).
vp: radial velocity perturbation from 3D stellar evolution calculation.



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2D with rp

Shock revival at ~ 260ms, earlier than the infall time of the convective region.

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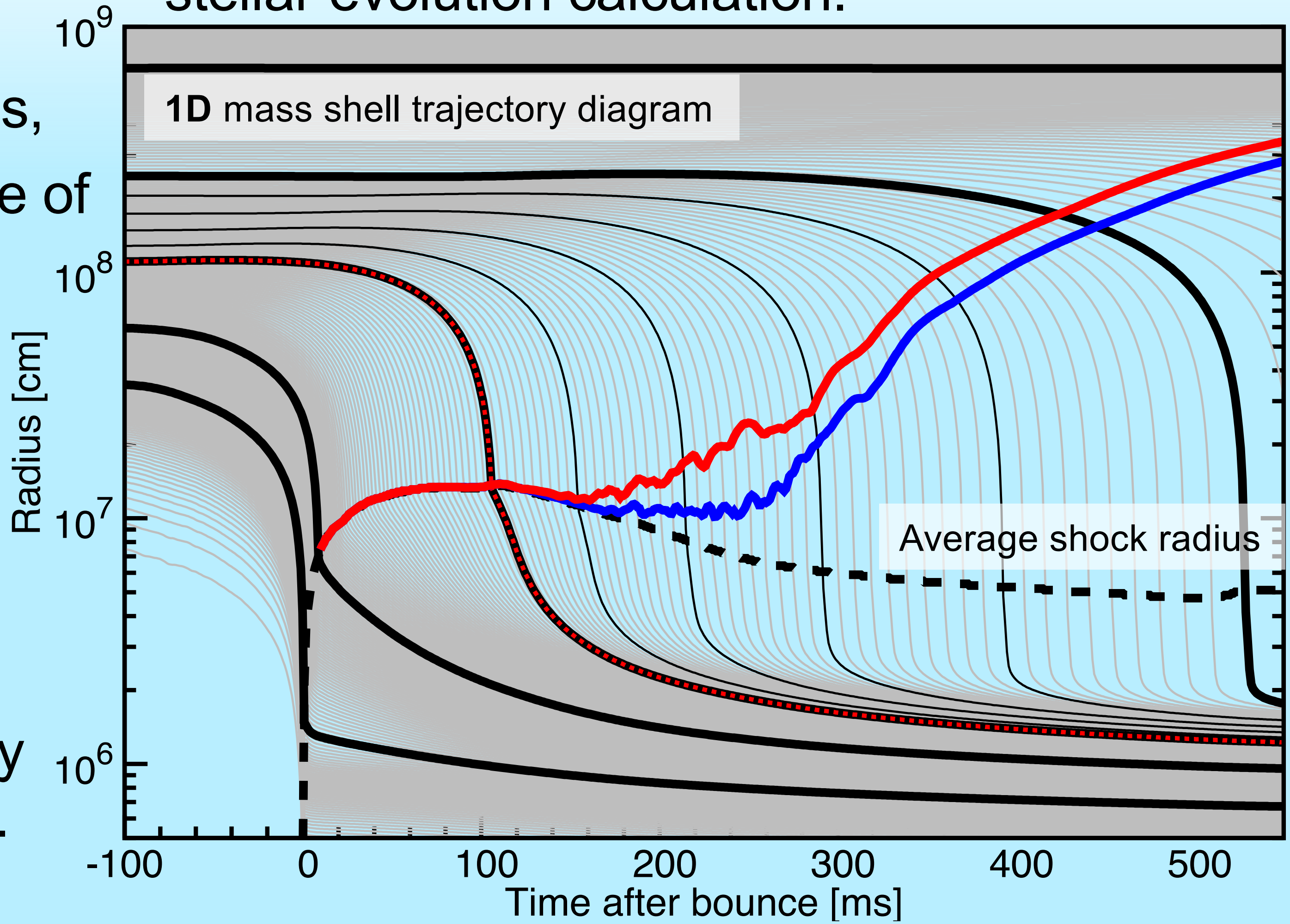
2D with rp+vp

Inputted velocity perturbation assists early shock revival (~ 150ms).

rp: random density perturbation (< 0.01%).

vp: radial velocity perturbation from 3D stellar evolution calculation.



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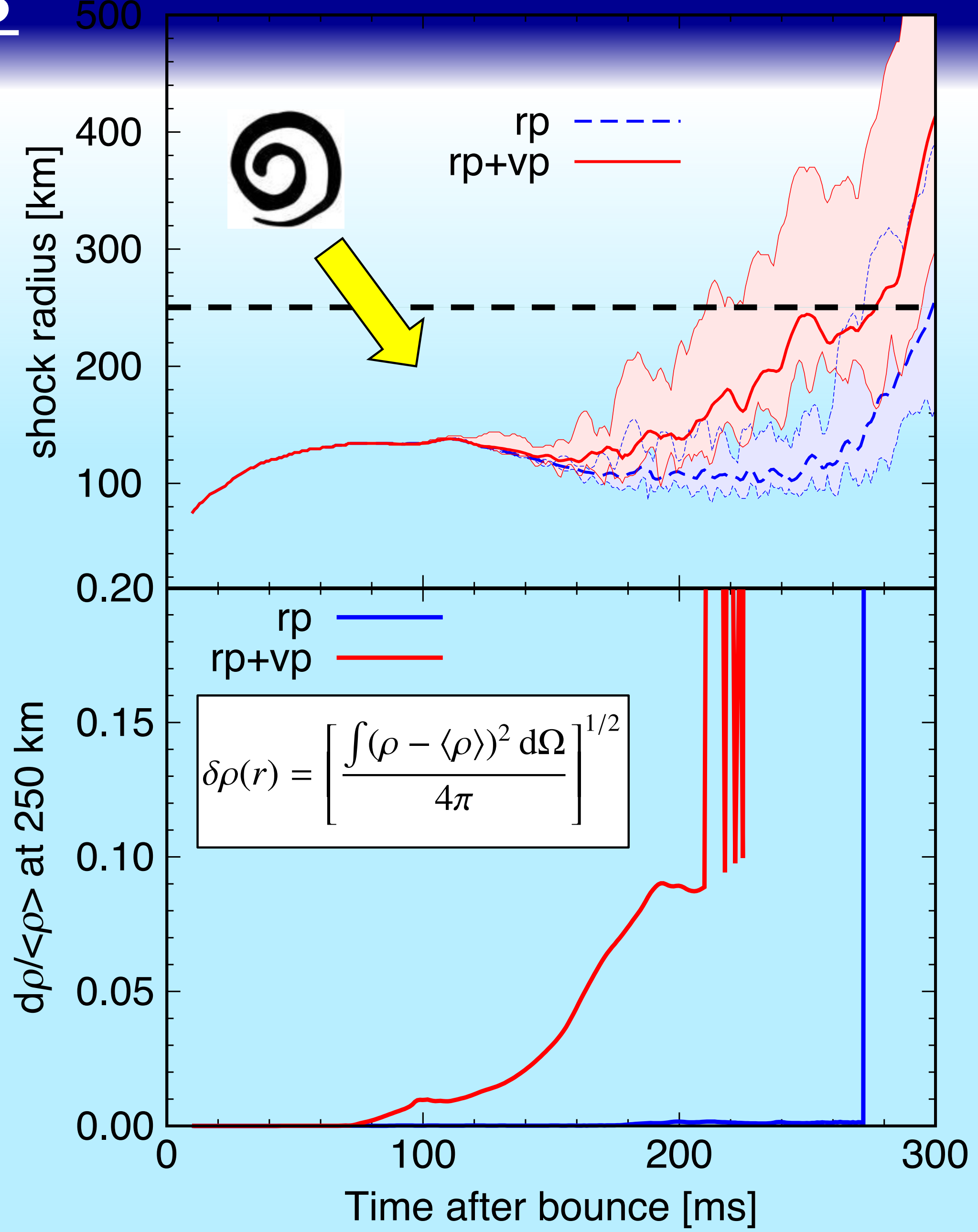
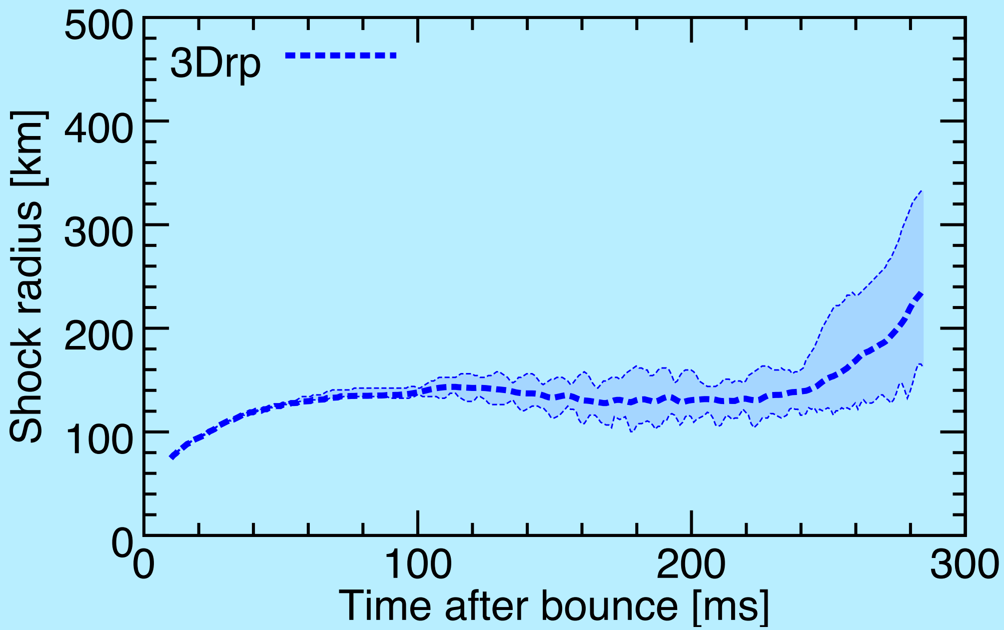


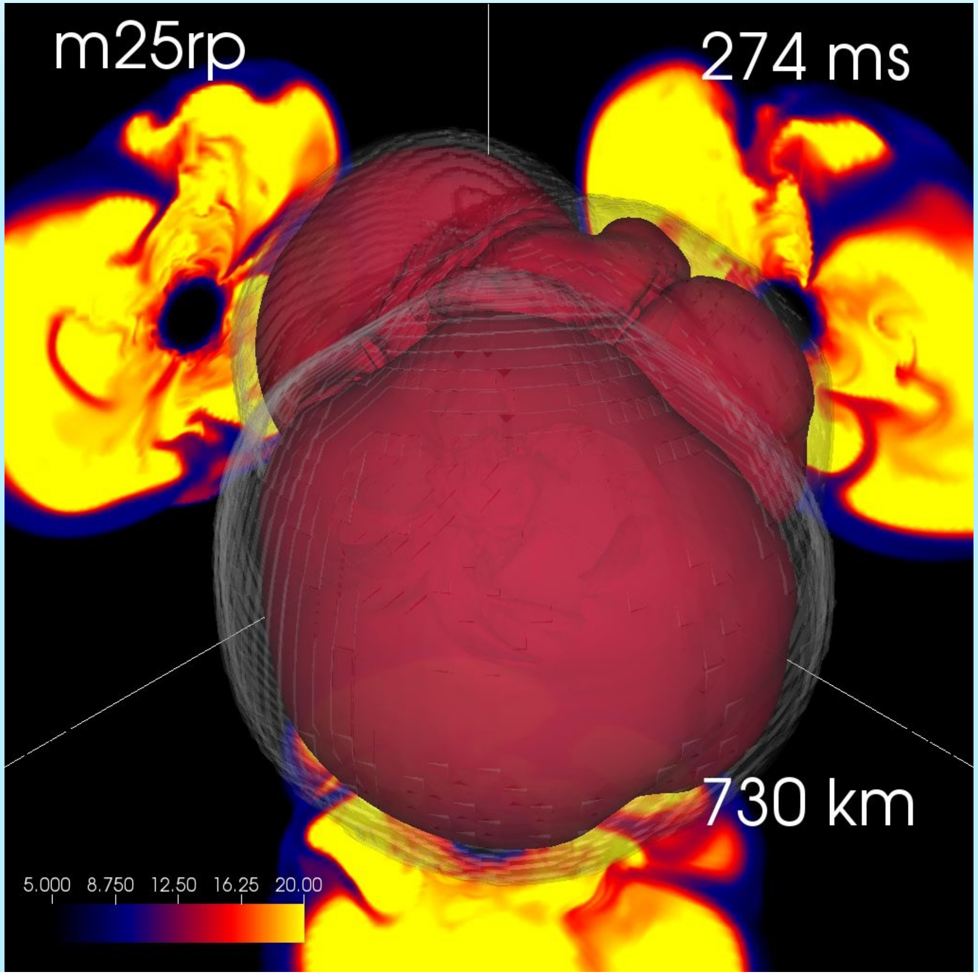
Results - 3D simulations

3D with rp

Successful shock revival.

rp: random density perturbation (< 0.01%).
vp: radial velocity perturbation from 3D stellar evolution calculation.





Results - 3D simulations

3D with rp

Successful shock revival.

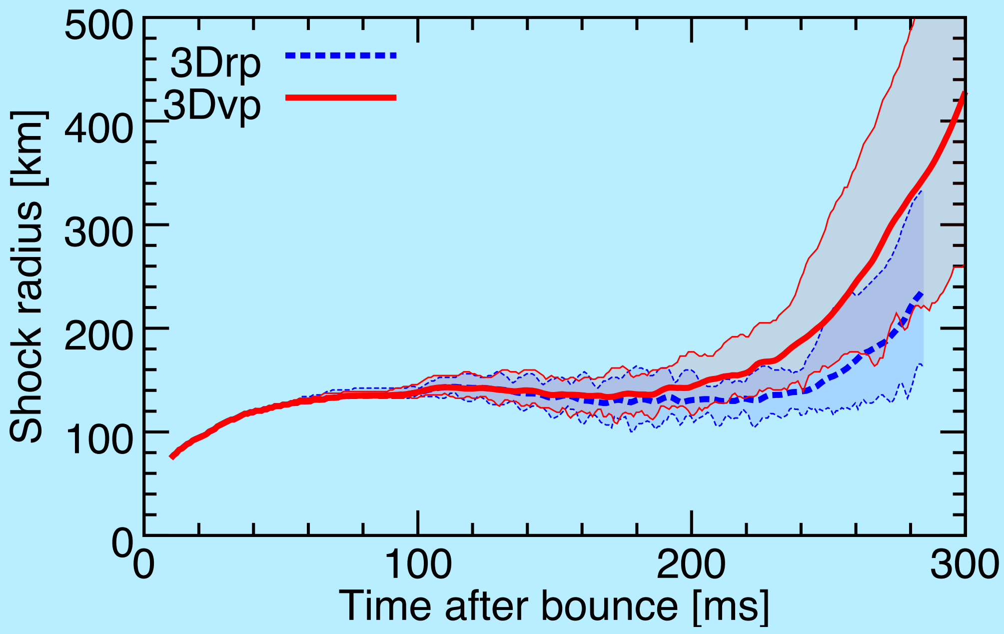
3D with vp

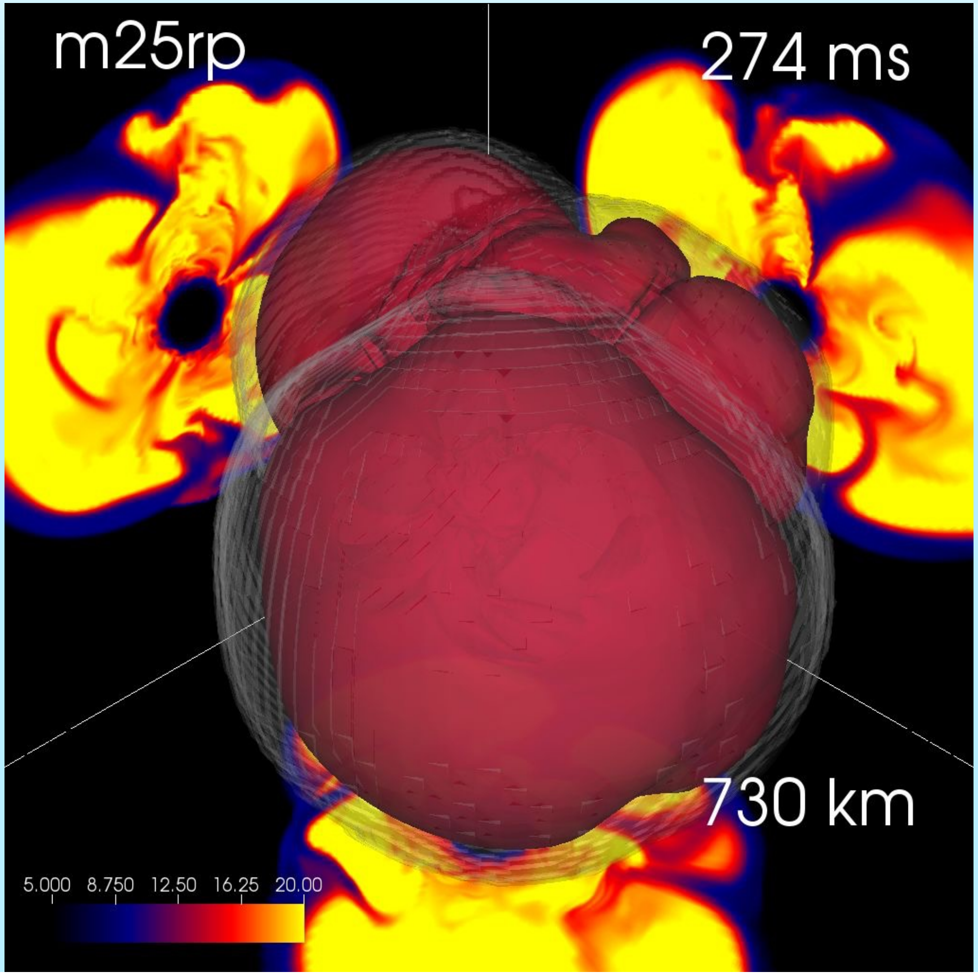
Earlier shock revival,

will be produce more energetic explosion.

rp: random density perturbation (< 0.01%).

vp: radial velocity perturbation from 3D stellar evolution calculation.





Summary

- ✓ Numerical (self-consistent) CCSN models have been suffered from small explosion energy ($<10^{51}$erg).

- ✓ One of the key inputs is non-spherical structure of CCSN progenitors such as a convective motion driven by nuclear shell burning.

- ✓ We perform 3D CCSN simulation for 3D progenitor model and confirm that the non-spherical structure helps shock revival.

- ✓ This mechanism may be effective only when the bottom of the Si/O layer is close to the progenitor core.