Neutrino Heating-Driven Explosion Aided by Magnetorotational Instability

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Sawai & Yamada 2014, ApJ, 784, L10
Sawai & Yamada 2014, in prep
Nishimura, Sawai, Yamada 2014, in prep

SNGRB2014, RIKEN 2014/08/25

1. Introduction

Recent numerical simulations show …

The neutrino heating succeeds in the shock revival.

But, some problems …

The Explosion energy is small.   <~ 10^50 erg

← Sumiyoshi, Nagakura, Takiwaki's Talk

A factor to boost the explosion seems necessary.

Aim of This Work

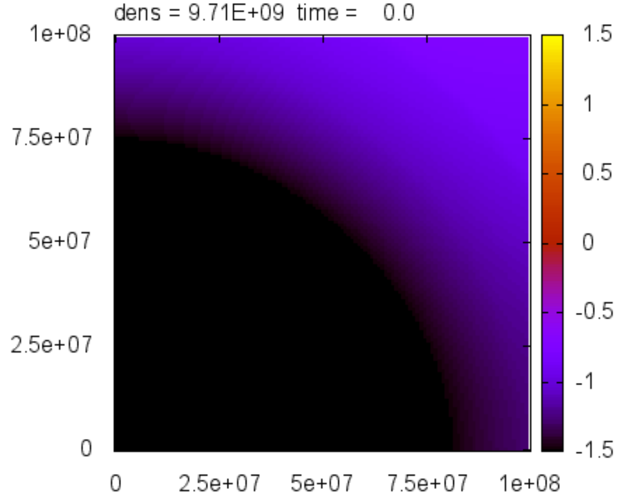
Studying the impact of ***weak*** pre-collapse B-fields on the explosion.

ϖ cm

Core-collapse supernovae (CCSNe)
with ***strong*** pre-collapse B-fields
(with magnetar-class B-fluxes)
are well studied for the decade.

→ The B-field amplified due to differential rotation in PNS drives the explosion.
(Symbalisity 84, Yamada & Sawai 04)

B-field direction & Pm/P



ϖ cm

Sawai+13

Although observations implies
some OB stars with magnetar-class B-fluxes
(Donati+02,06, Hubrig+06, Neiner+03),
They may not be quite popular.

Studying CCSNe with ***weak*** pre-collapse field is important.
Weakly magnetized progenitors have ***not*** been studied well so far.

Winding by diff. rotation: Burrows+06, Takiwaki+09

MRI: Obergaulinger+09, Masada+12, Sawai+ 13, 14
Convection, SASI: Endeve+12, Obergaulinger+14

◆Weakly magnetized, rapidly rotating progenitors

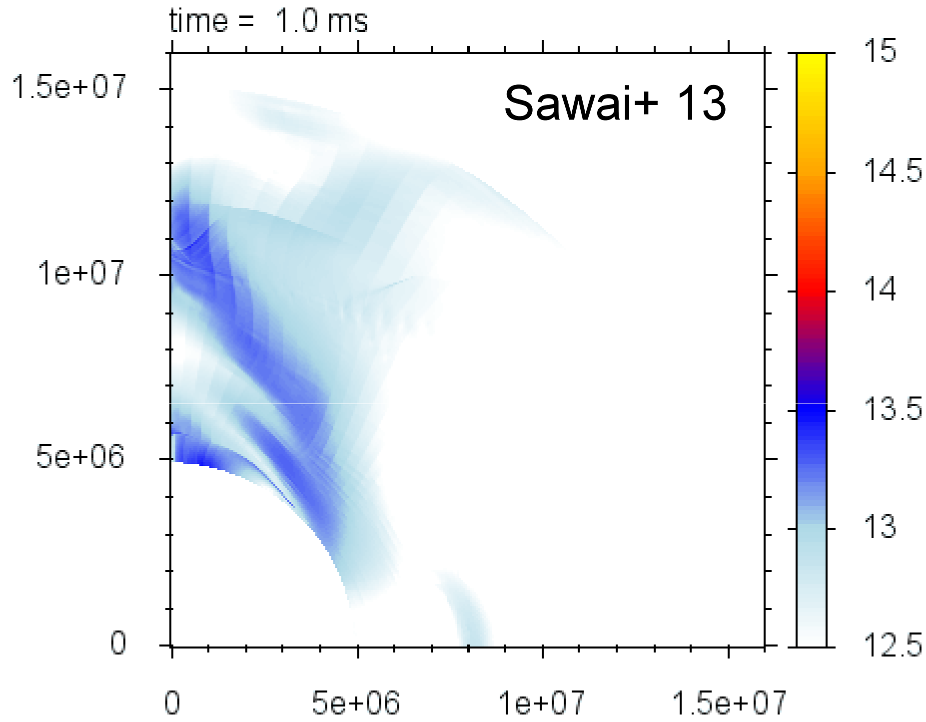
Magnetorotational Instability (MRI)

may be important.

✔The MRI occurs magnetized, differentially rotating system.

✔The MRI leads to the amplification of the B-field, and angular momentum transfer.

Sawai +13 found the efficient amplification of B-field by global simulations.



<u>This work</u>

✔ Long term, global simulations of weakly-magnetized, rapidly rotating SNe with simplified neutrino treatment.

✔ pays attention to the SN dynamics under the occurrence of MRI.

2. Numerical Procedure and Model

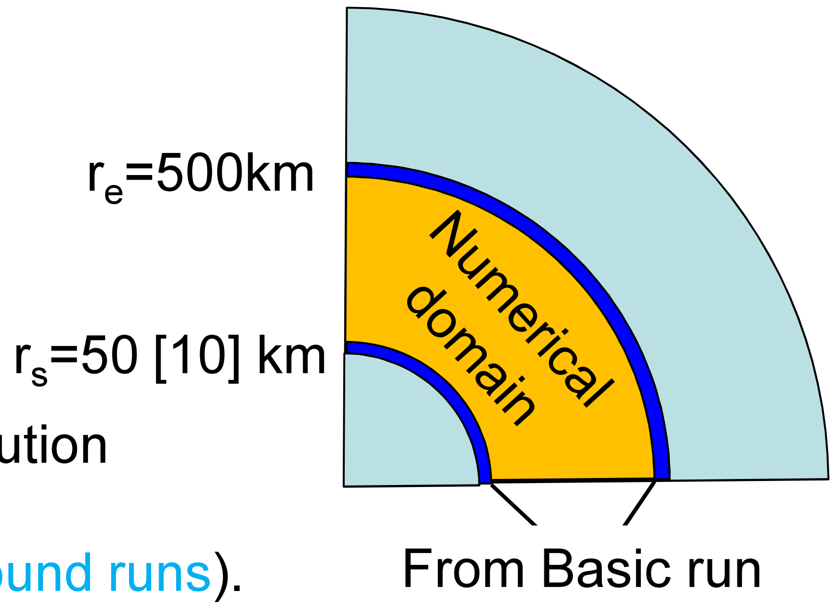
◆Very high spatial resolution is required for simulations of MRI

$$\lambda_{MRI} \sim \sqrt{\frac{\pi}{\rho}}\frac{B}{\Omega} \sim 500\,m \times \left(\frac{\rho}{10^{11}\,g/cm^3}\right)^{-\frac{1}{2}}\left(\frac{B}{10^{13}\,G}\right)\left(\frac{\Omega}{10^3\,rad/s}\right)^{-1} \Rightarrow \Delta r \sim 50\,m << 1000\,km\,(iron \quad core)$$

◆Numerical domain: a part of the core

50 [10] < (r / km) < 500 (MRI runs)

Axisymmetry and equatorial-symmetry are assumed.



◆Procedure

The collapse is first followed with low resolution inside the radius of 4000 km until several 100 ms after bounce (Background runs).

✓The data of a BG run are mapped into the numerical domain of MRI runs at 6 ms after bounce.

✓The data of a BG run are used for the boundary conditions for MRI runs.

✓Ideal MHD eqs. are solved ins axisymmetry

✓Neutrino: Cooling function + Light bulb ($L\nu_e = 1 \times 10^{52}$ erg/s)

✓Progenitor: 15 Msun (Woosley '95)

✓B-field： 3 different strengths, Dipole-like

$B_{c,in} = 5.0 \times 10^{10}$ G
$= 1.0 \times 10^{11}$ G
$= 2.0 \times 10^{11}$ G
→ $B_{PNS} \sim 10^{13}$ G

✓Rotation： rapid, differential

(T/W)in = 0.25 % (Ωin=2.7 rad/s)

Differential rotation

$$\Omega = \Omega_0 \frac{r_0^2}{r_0^2 + r^2}$$

r_0=1000 km

✓ MRI runs with 3 different resolutions

		Number of grids
Δr_{min} =	12.5 m	(9250 × 6400)
Δr_{min} =	25 m	(4700 × 3200)
Δr_{min} =	50 m	(2500 × 1600)
Δr_{min} =	100 m	(1200 × 800)

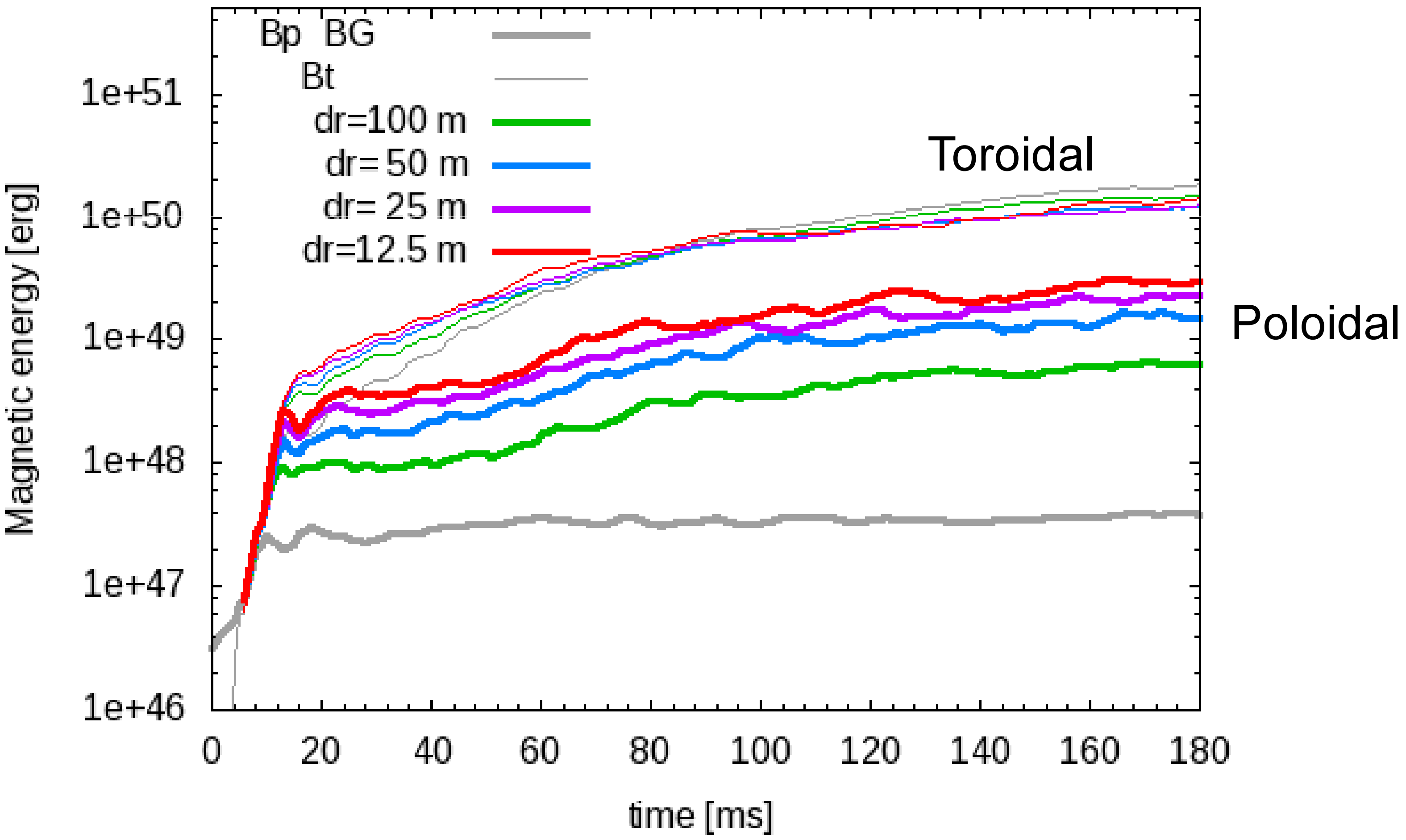
3. Result

Evolutions of magnetic energy

The amplification of B-field due to MRI

NOTE: In the highest resolution runs, maximum wave length of MRI is mostly resolved with > 100 grids.

Strongest B-field model $B_{c,in} = 2.0 \times 10^{11}$ G

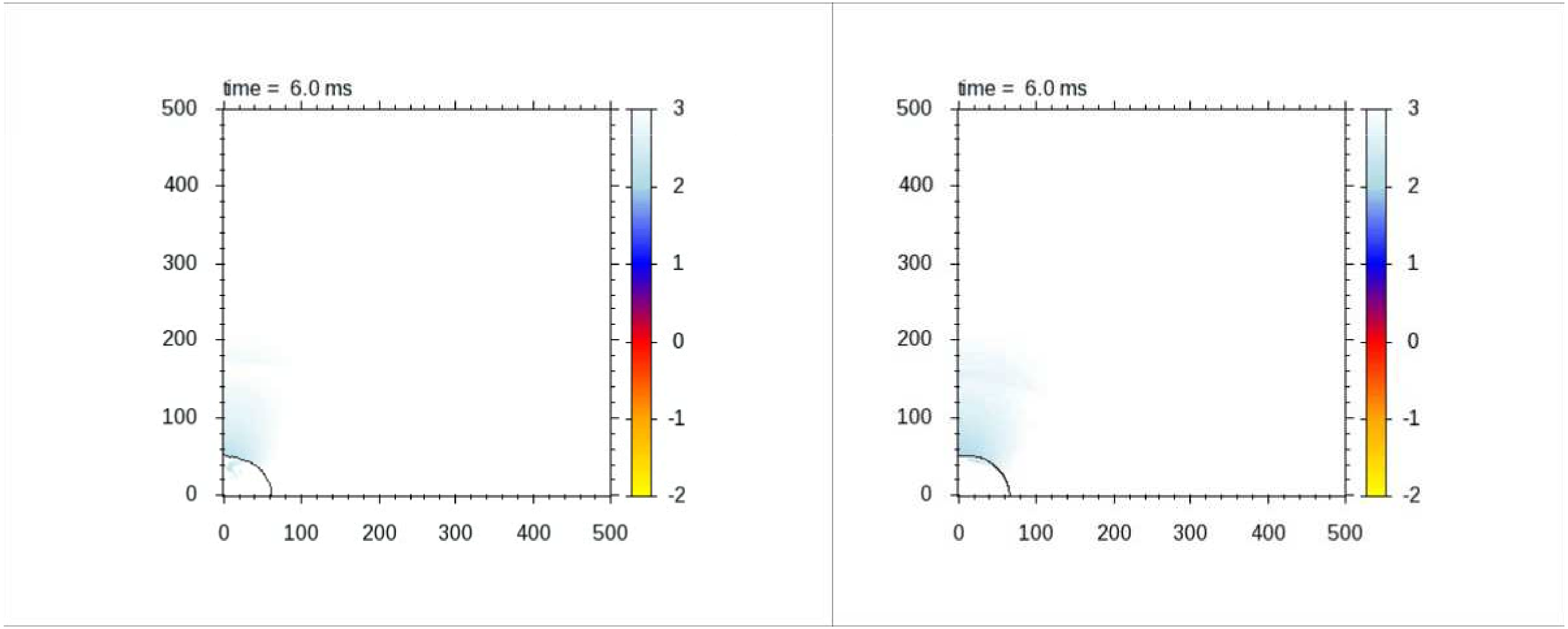


Plasma beta p/p_B Log[β]

Strongest B-field model
$B_{c,in} = 2.0 \times 10^{11}$ G

Lowest resolution
MRI unresolved

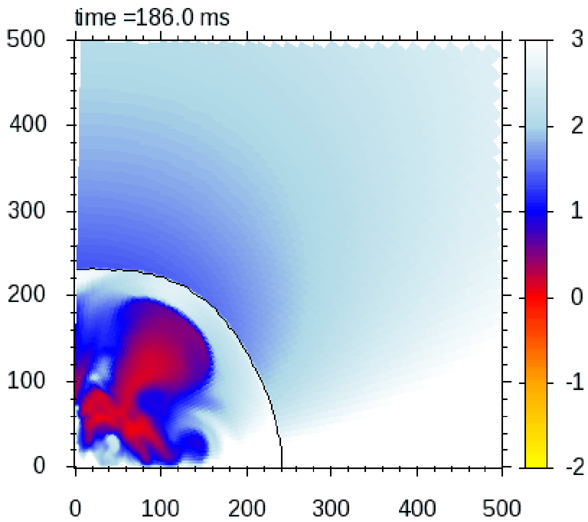
Highest resolution
MRI resolved



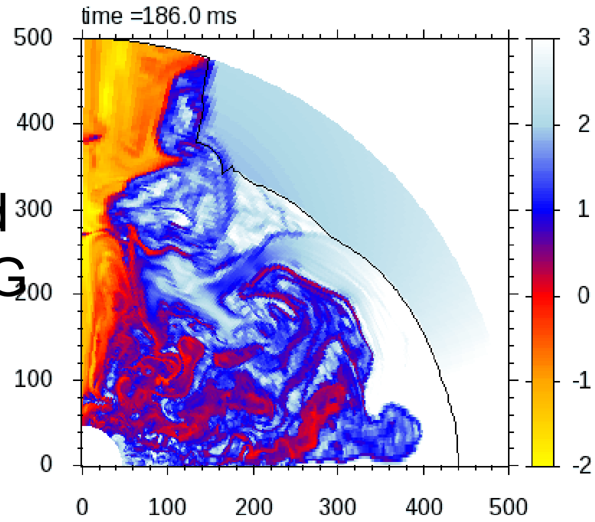
km

km

Plasma beta p/p_B Log[β]

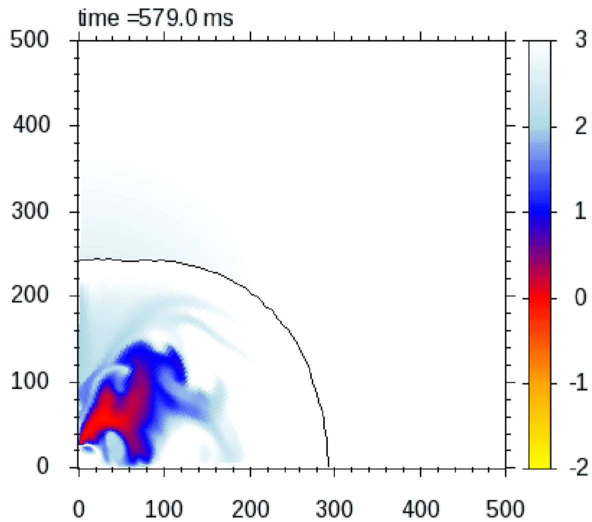


Strongest B-field
$B_{c,in} = 2.0 \times 10^{11}$ G

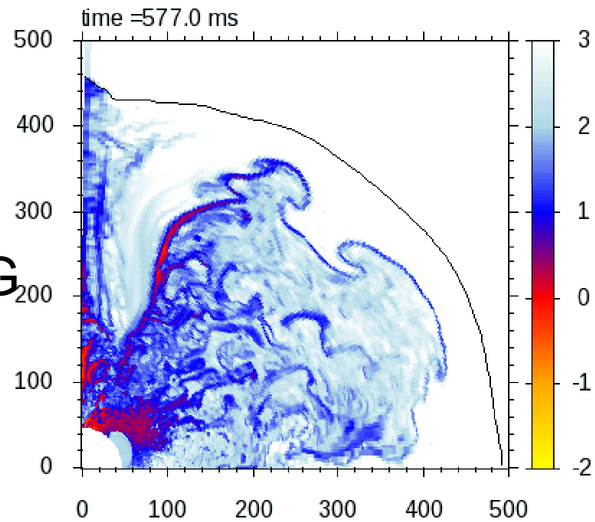


Lowest resolution
MRI unresolved

Highest resolution
MRI resolved



Weakest B-field
$B_{c,in} = 5.0 \times 10^{10}$ G



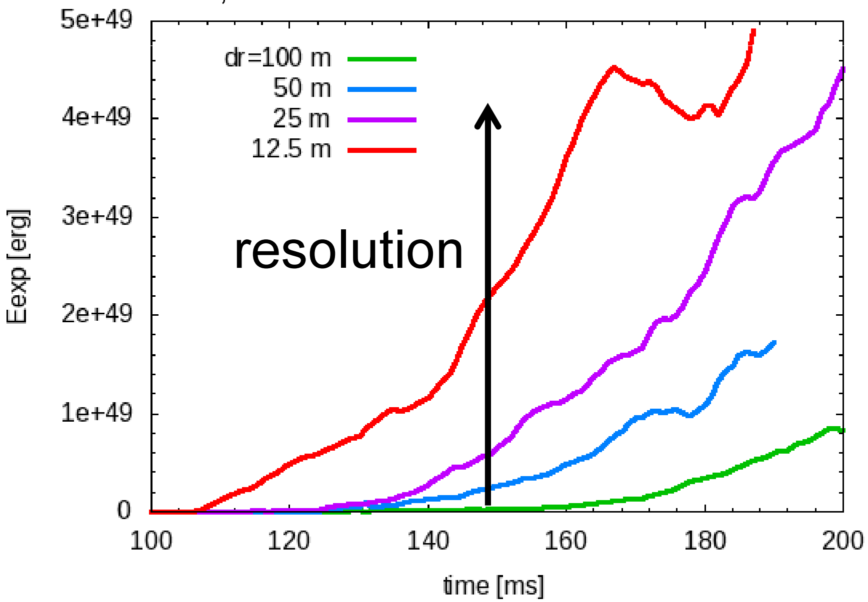
◆Evolutions of diagnostic explosion energy

Higher resolution → Larger explosion energy.

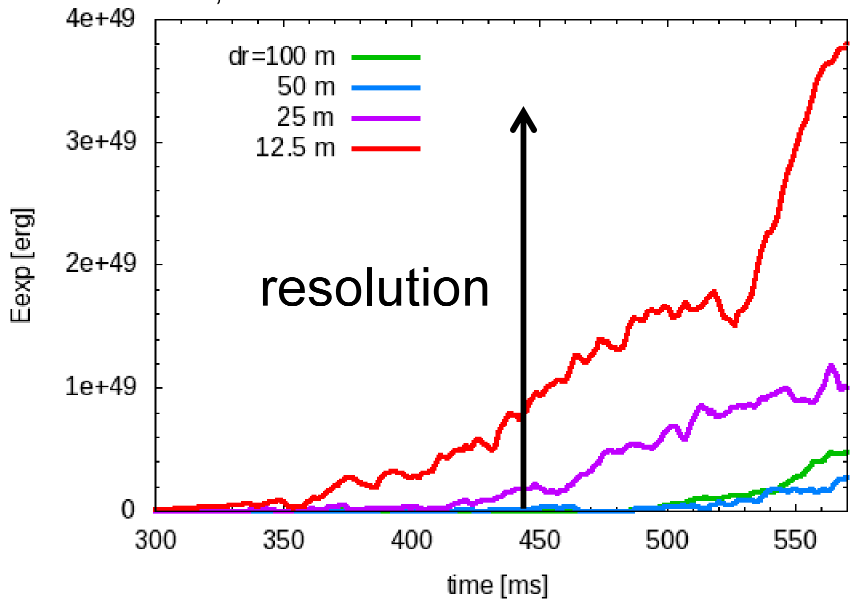
(still small, < 10^51 erg, due to low Lnu assumed)

Still No Convergence

$B_{c,in} = 2.0 \times 10^{11}$ G

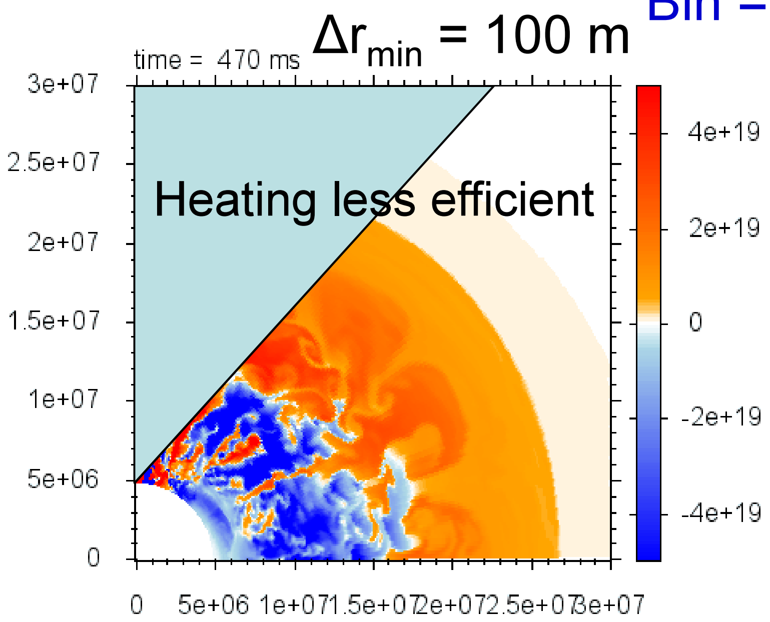


$B_{c,in} = 5.0 \times 10^{10}$ G

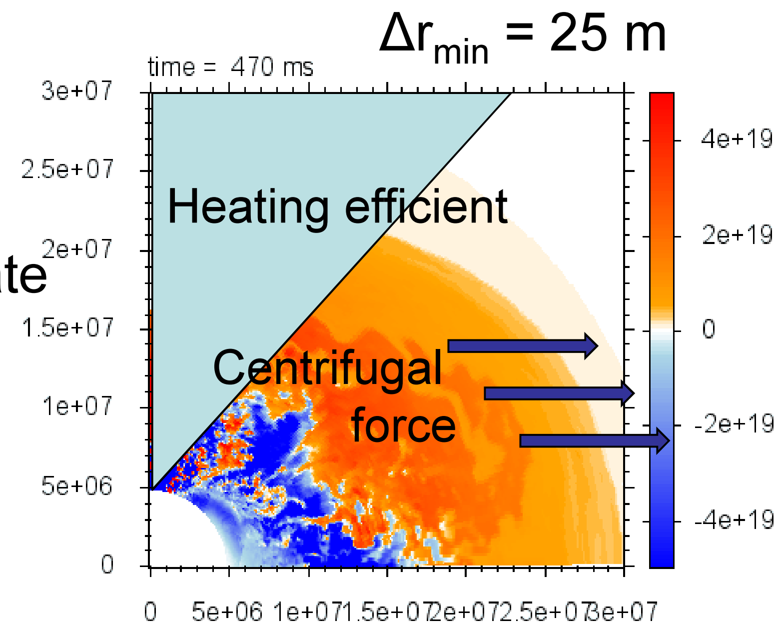


The weakest B-field case

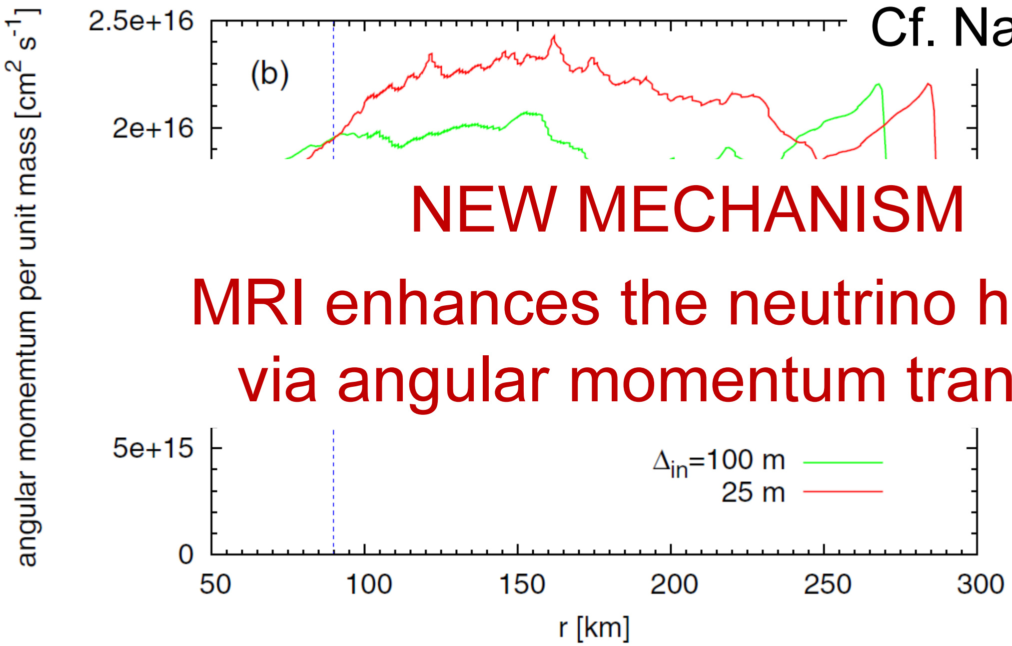
Bin = 5×10^{10} G



Net heating rate [erg/g.s]



Cf. Nakamura+14, Iwakami+14



NEW MECHANISM

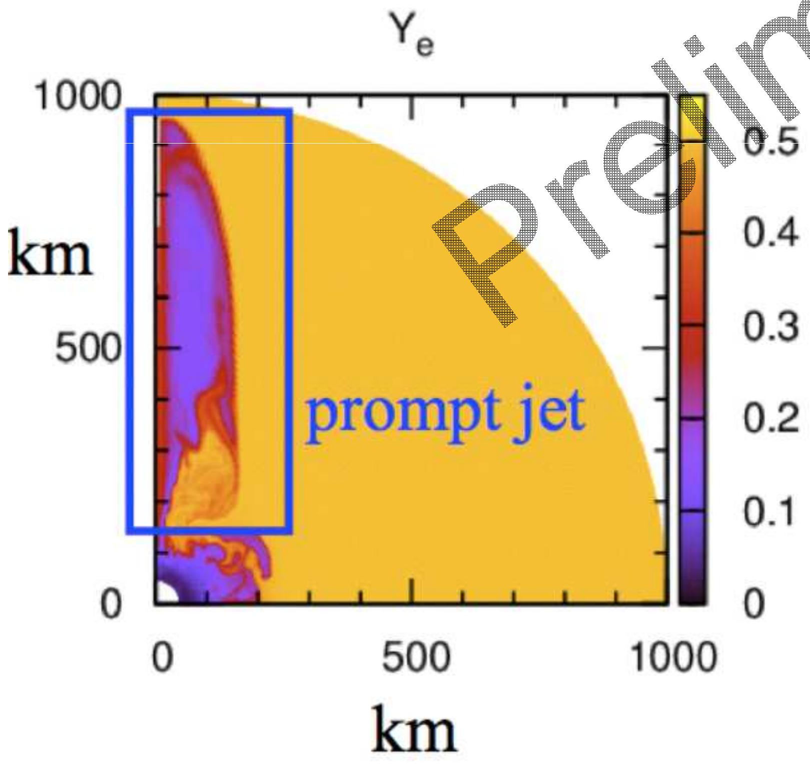
MRI enhances the neutrino heating via angular momentum transfer.

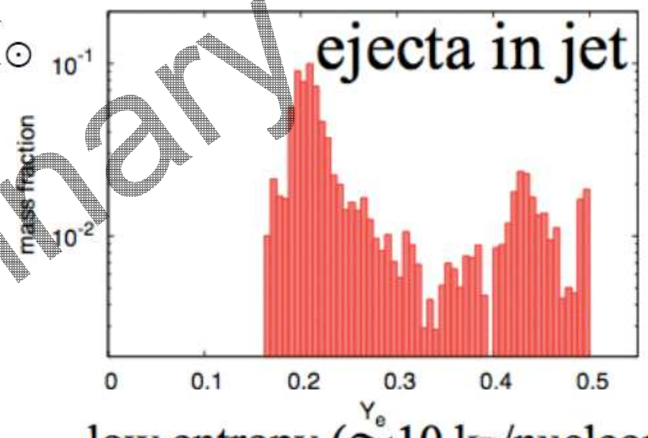
◆r-process nucleosynthesis in MRI-neutrino SN

Neutron-rich ejecta in the Jet-like explosion

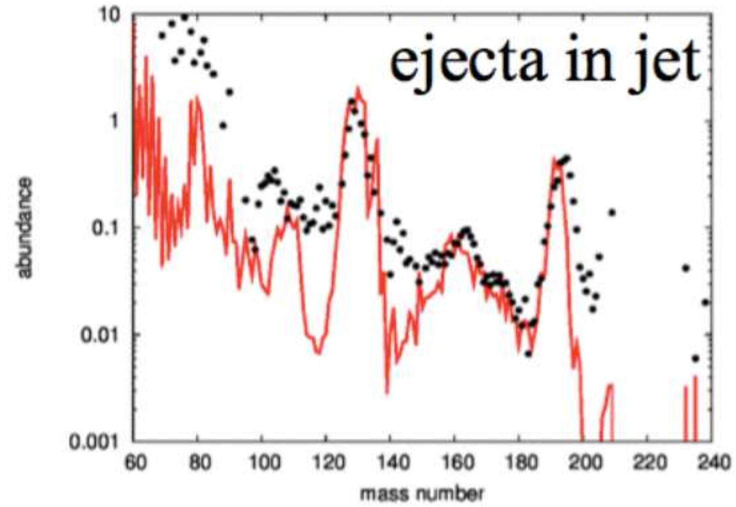
ejected mass by jet = $2.0\times10^{-3}\ M_\odot$

t=325ms (after collapse)



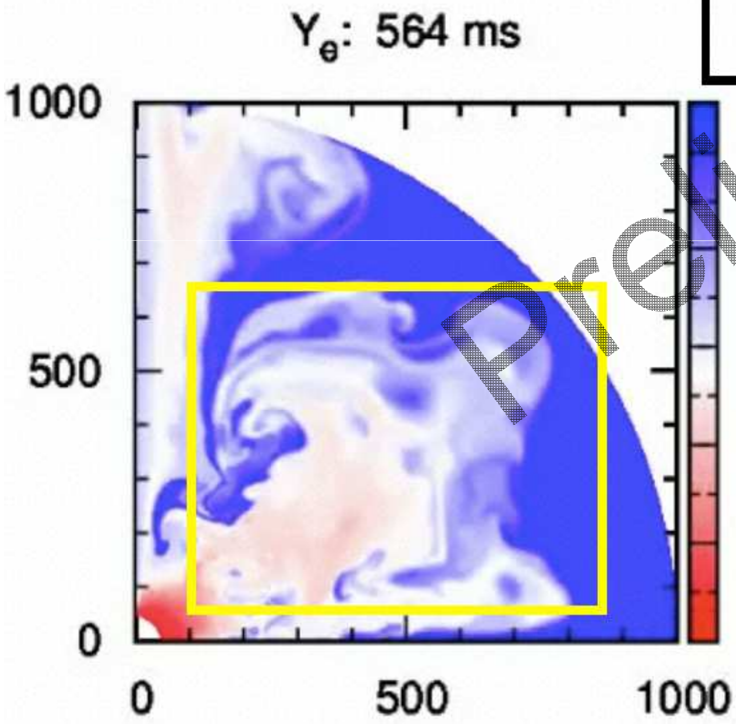


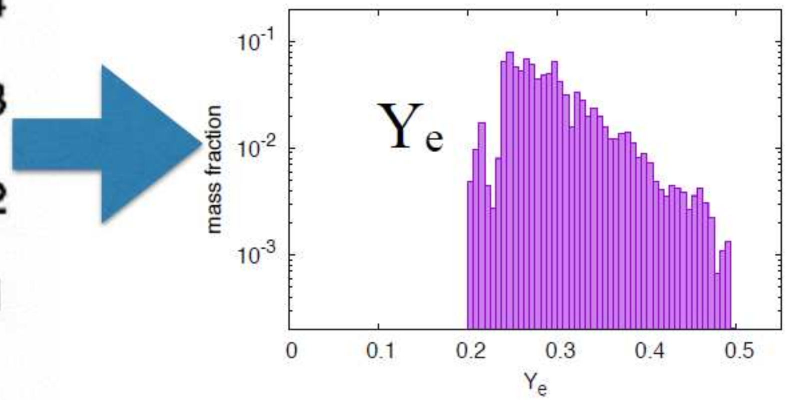
low entropy (~10 kB/nucleon)



non-jet ejecta

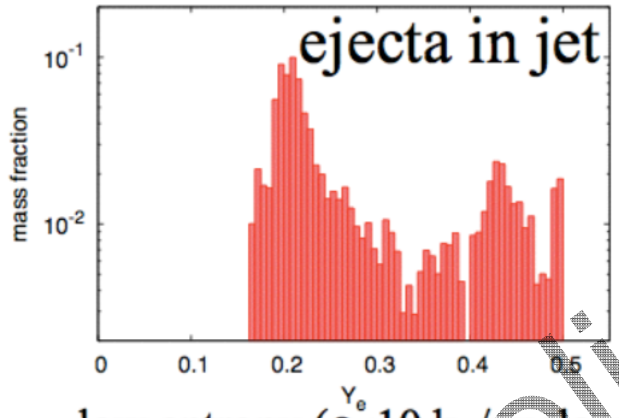
criterion:
- non-jet component
- radius > 400 km (at 564 ms)
- Y_e must be under estimate (ignored ν-captures)



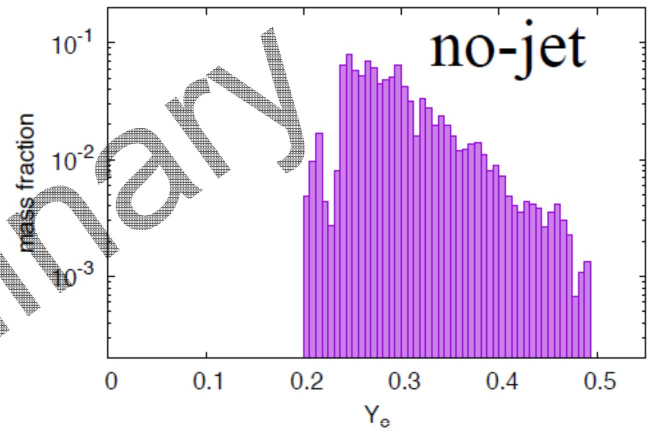


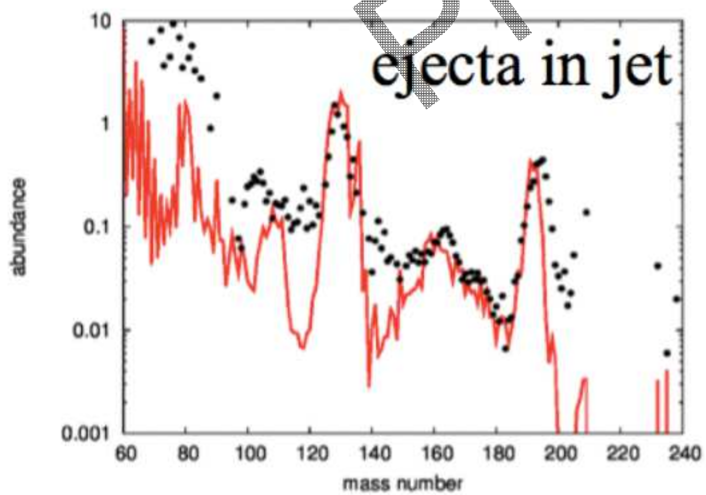
The peak of Y_e is higher than ejecta in Jet

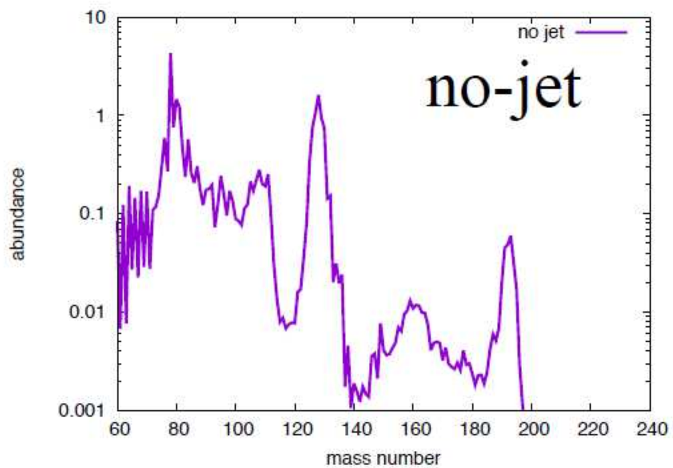
Comparison: jet vs ν-heating(w MRI) ejecta



low entropy (~10 k_B/nucleon)







4. Summary

We have performed 2D-axisymmetric MHD simulations of CCSNe of weakly magnetized, rapidly rotating progenitors.

- ✓ MRI amplifies the B-field to a dynamically important strength.
  - ✓ A relatively strong B-field leads to the jet formation.
  - ✓ MRI enhances the neutrino heating via angular momentum transfer.

    ← A New Mechanism.
- ✓ Not only the jet component but also the non-jet component have low Ye ejecta. → r-process nucleosynthesis up the 3^{nd} peak.

Future works

- ✔Slower rotation model (MRI-SASI interaction)
- ✔Higher resolution simulations/ less diffusive schemes
- ✔ Non-axisymmetric simulations（3D-simulations）