Magnetically Assisted Explosions of Weakly Magnetized Stars

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SN 1987A, 30 years later, IAU Symposium 331
La Réunion Island, France, 20-24 February 2017

Neutrino-driven explosion

- A promising scenario for Core-Collapse Supernovae
- Some problems such as small explosion energy

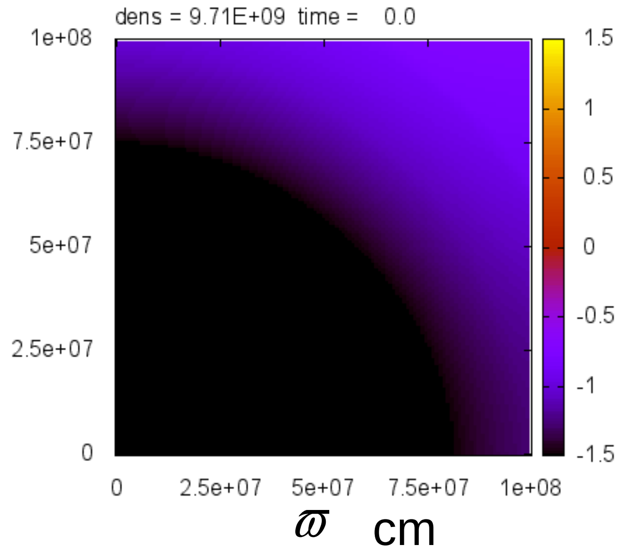
Roles of Magnetic field and Rotation?

Strong B field & Rapid Rotation
lead to a strong explosion

Strong B field : $B_{PNS} \sim \mathbf{10^{15}}$ G
Rapid Rotation : $P_{PNS} \sim \mathbf{1\ ms}$

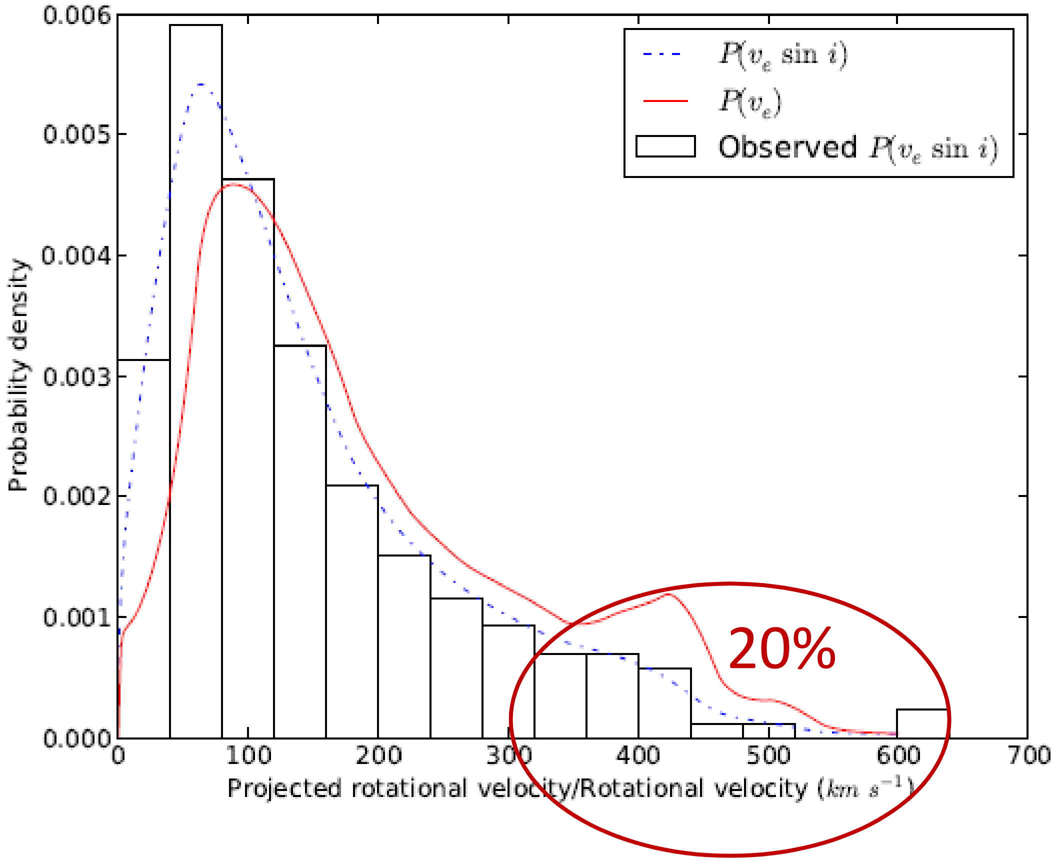
How common are they?

B-field direction & Pm/P



Distribution of Surface Rotation

Optical Observations of 216 O stars (Ramirez-Agudelo+13)



Stellar Evolution Calculations

The Faster the surface rotation, the faster the NS rotation.

(Woosley&Heger06)

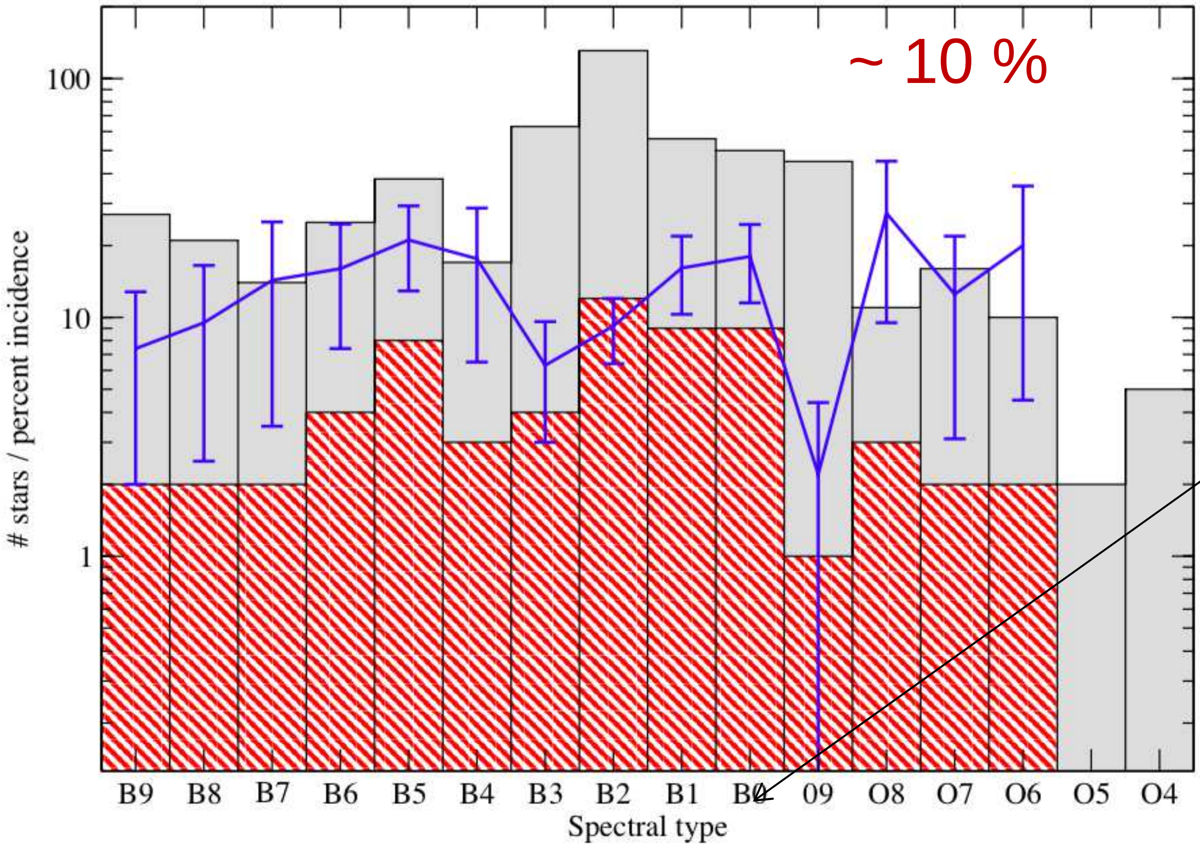
Ex. for 16M star of v_surf=360 km/s & solar metallicity

P_NS=2.3-9.7 ms

We consider both Fast (ms) and Slow Rotation Cases

Magnetic Fields of Progenitors

Purple line: the fraction of stars with surface B field more than ~100 G.



Magnetar-class B-flux

$$B_{surf} \sim 300 \left(\frac{R_*}{8\,R_\odot}\right)^{-2} \mathrm{G}$$

M ~ 17 Msun

R ~ 8 Rsun

MiMes survey

Wade+14

Majority involves sub-magnetar-class (weak) B fields.

We only consider weak B field cases.

Numerical Model

✓Ideal MHD eqs. are solved in Axisymmetry.

✓Neutrino: Light bulb approximation ($L\nu_e = 1\times10^{52}$ erg/s)

✓Progenitor: 15 Msun (Woosley & Weaver 95)

✓EOS: Shen+(1998)

✓B-field: "Weak" Dipole-like

$B_{c,in} = 5.0\times10^{10}$ -- 2.0×10^{11} G → $B_{PNS} \sim 10^{13}$ -- 10^{14} G

✓Rotation： shellular differential

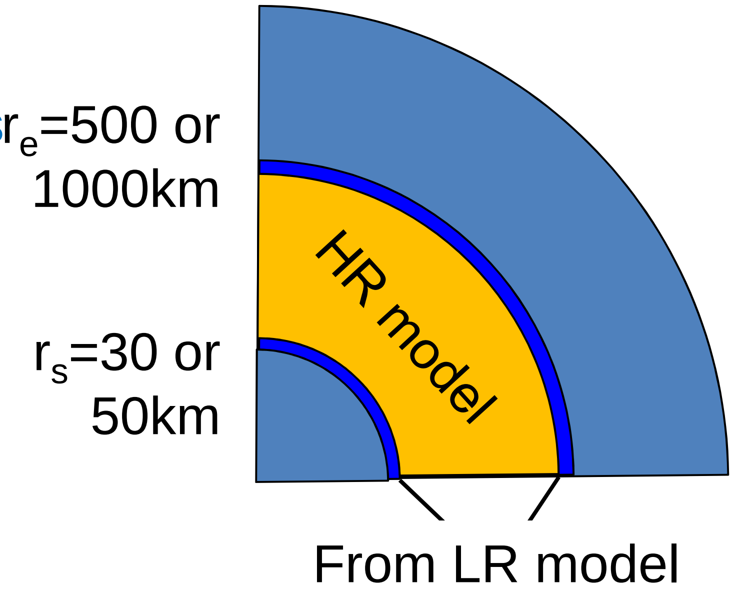
Rapid Ωin≈3 rad/s or Slow Ωin≈0.3 rad/s

✓ For the highest resolution

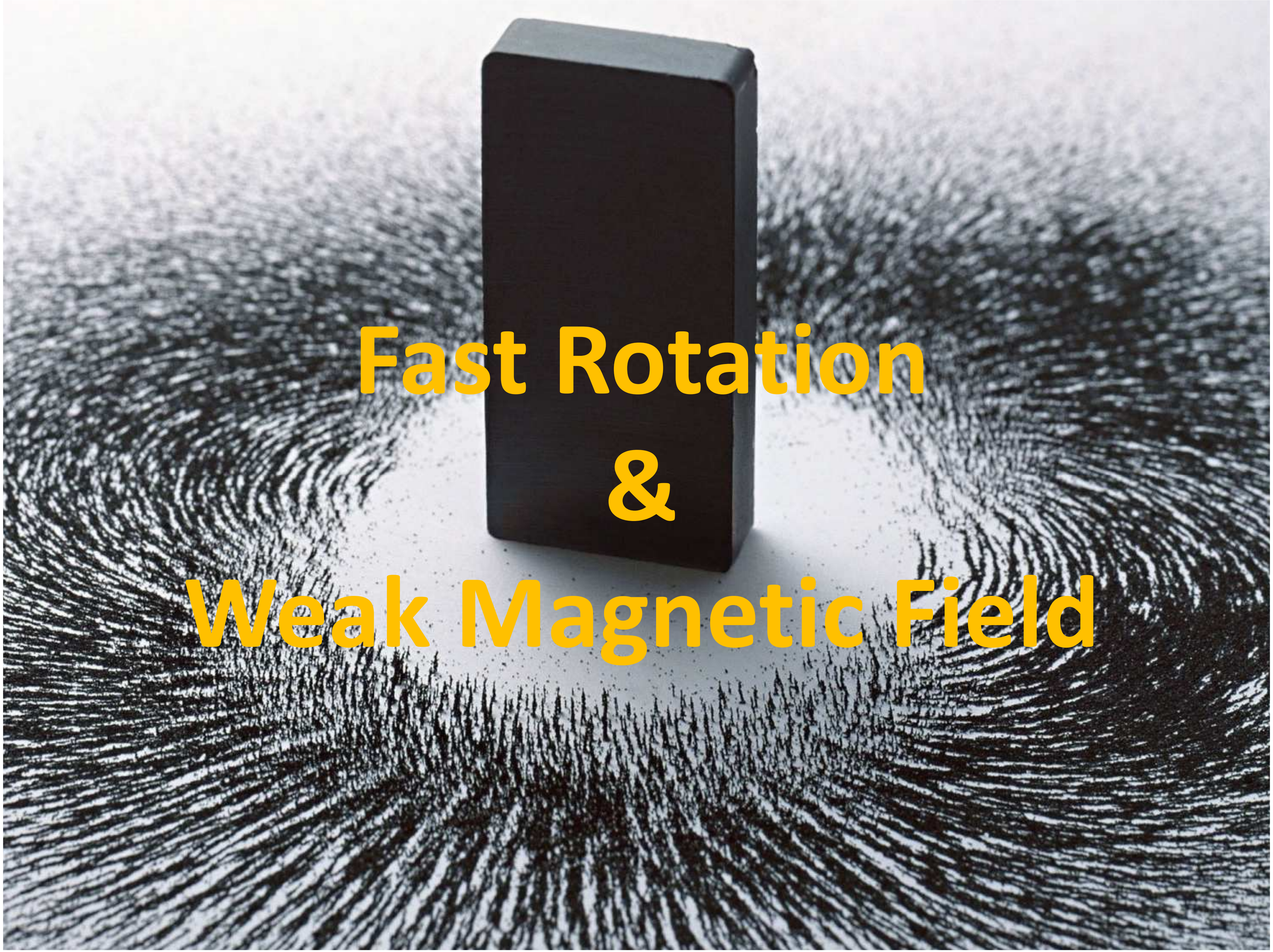
Δr_{min} = 12.5 m (9250×6400)

✓ Computation

at XC40 (NAOJ) & SR1600 (YITP)



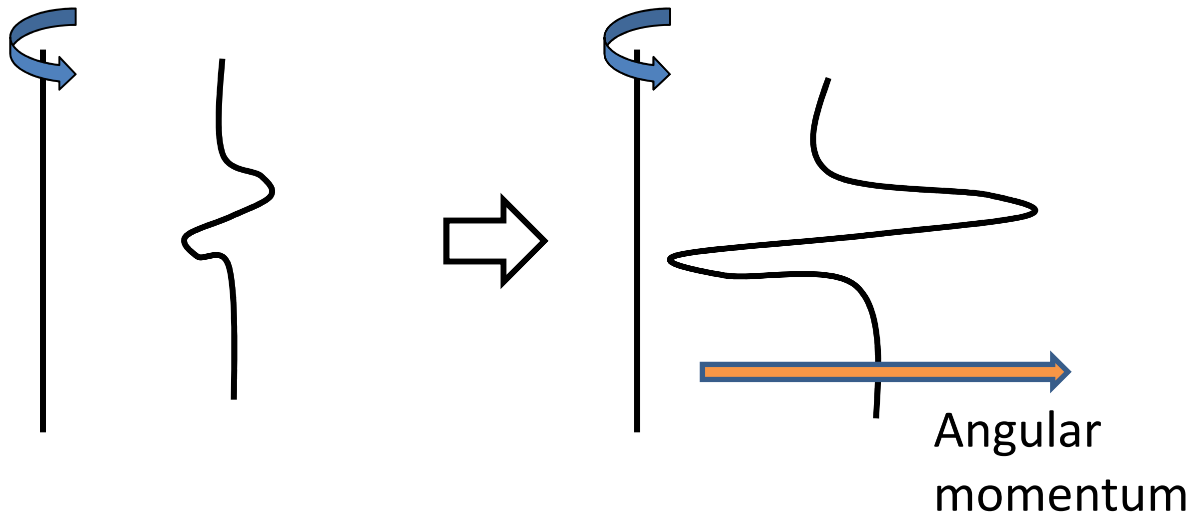
Fast Rotation
&
Weak Magnetic Field



Magnetorotational Instability (MRI) Balbus & Hawley 91, 95

occurs in magnetized differentially-rotating system

SNe are favorable site for MRI (Akiyama+03)



MRI simulations with weak B field demand high spatial resolutions

$$\lambda_{MRI} \sim \sqrt{\frac{\pi}{\rho}}\frac{B}{\Omega} \sim 500\,m \times \left(\frac{\rho}{10^{11}\,g/cm^3}\right)^{-\frac{1}{2}}\left(\frac{B}{10^{13}\,G}\right)\left(\frac{\Omega}{10^3\,rad\ /\,s}\right)^{-1}$$

$$\Rightarrow \Delta r \sim 50\,m << 1000\,km\,(iron\quad core)$$

Simulations of MRI in CCSNe for "weak" B fields

3D Local

Obergaulinger+09 | Guilet+15

Masada+12 | Rembiasz+16, 16

Global

HS+13, 14, 16 (2D, ~500km^2, ~100-600 ms)

Masada+15 (3D, ~200km^2*1km, ~50 ms)

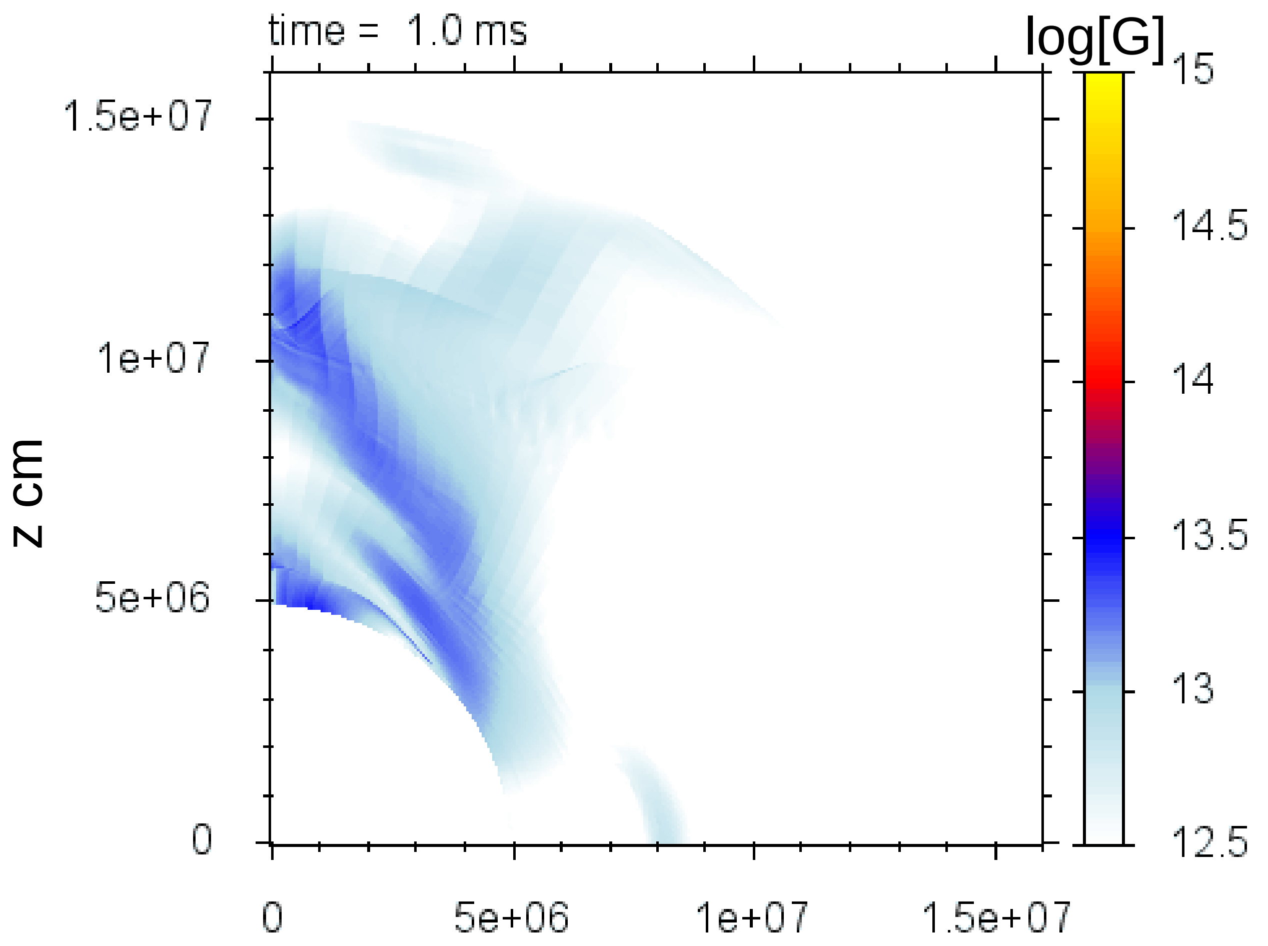
Moesta+15 (3D, ~100km^3, ~10ms)

Although 2D, ours have large numerical domain, and follow long time evolution.

These enable studying impact of the MRI on the CCSNe.

B field amplification by MRI HS+13

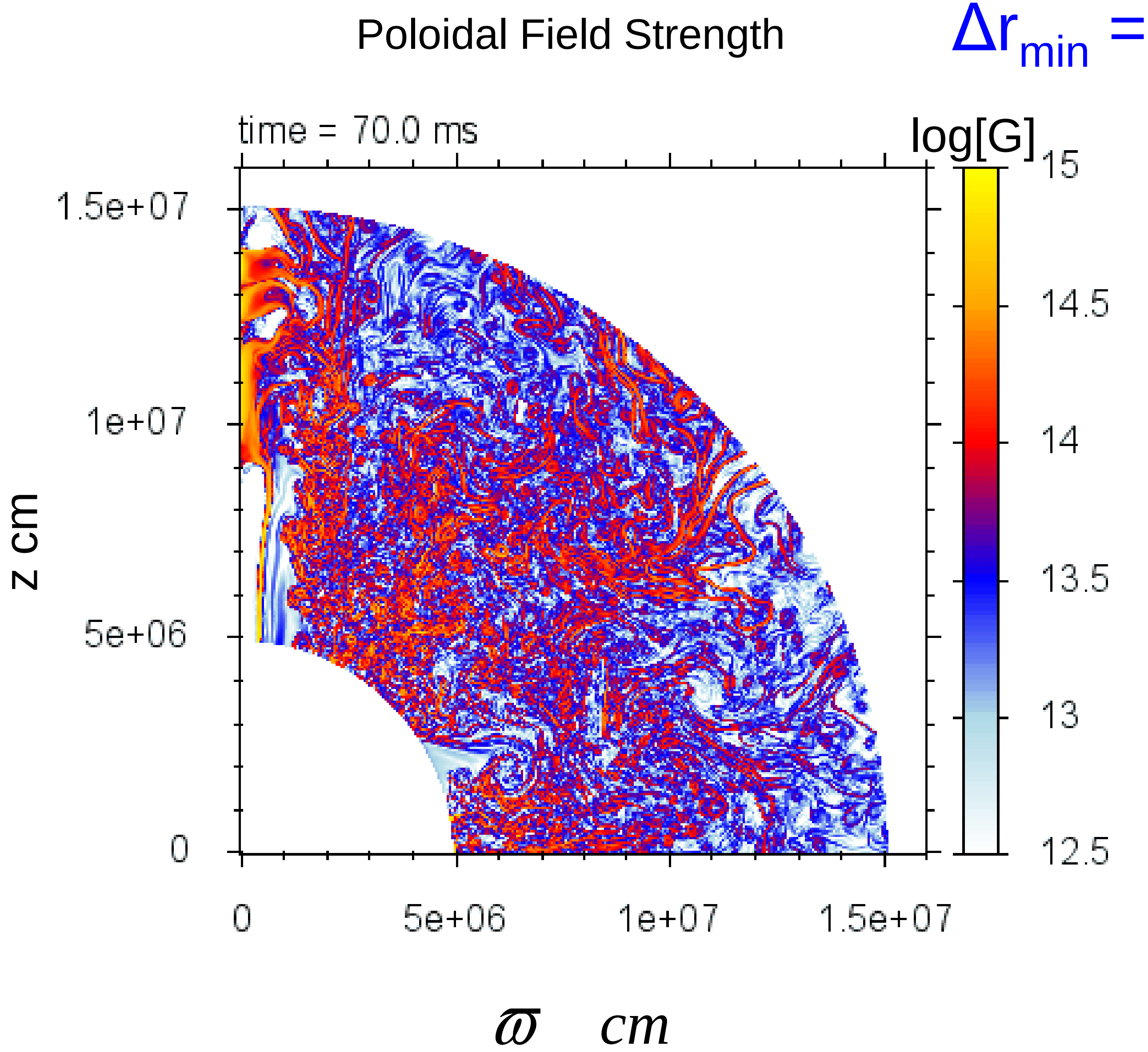
Poloidal Field Strength Δr_{min} = 25 m



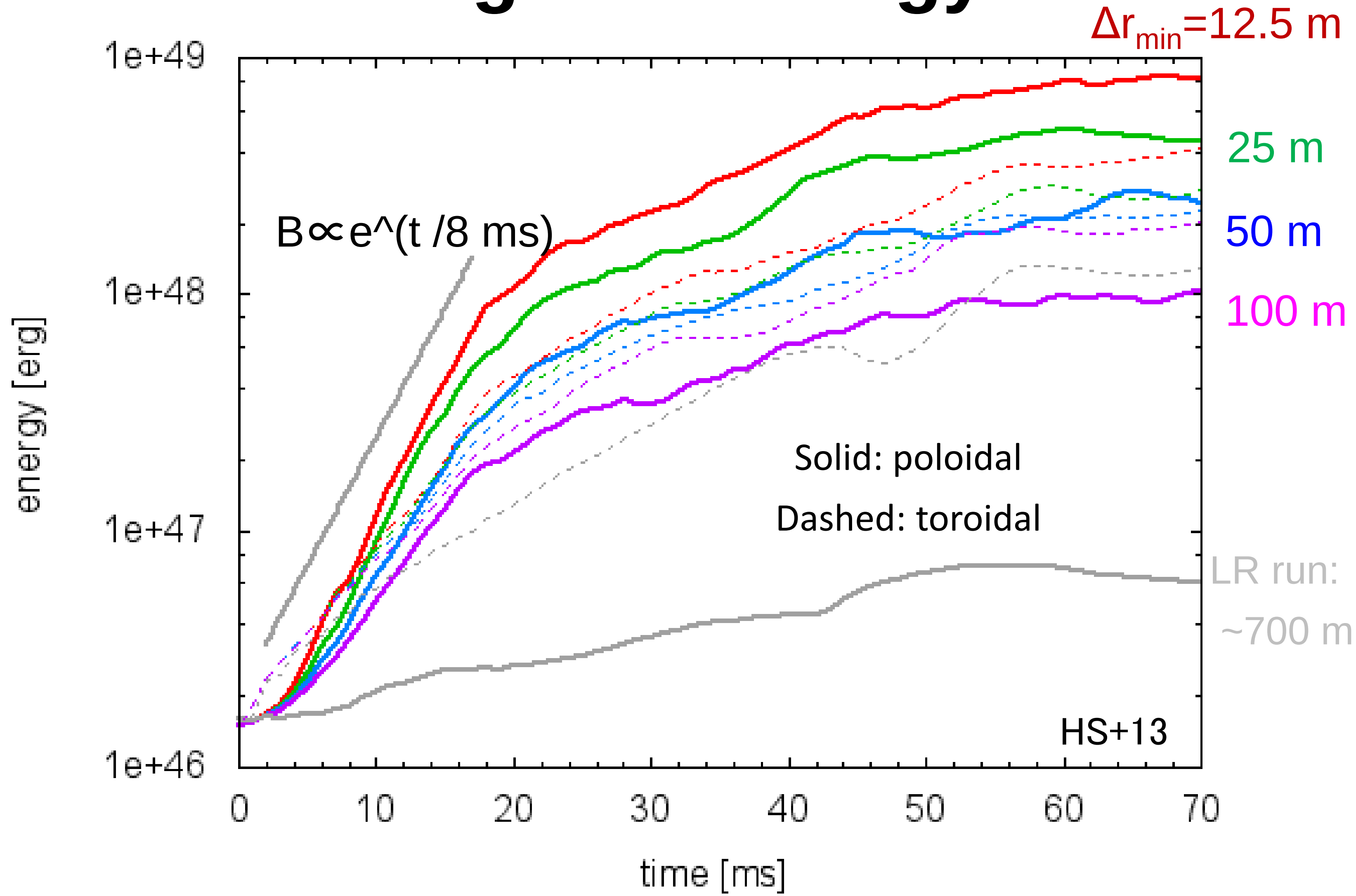
ϖ cm

B field amplification by MRI HS+13

$\Delta r_{min} = 25$ m



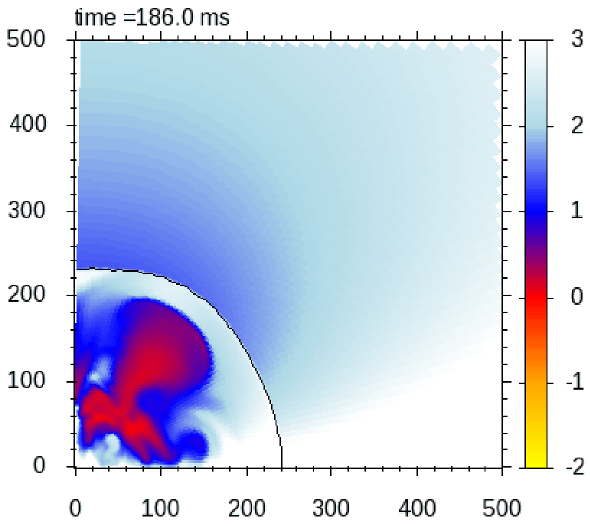
Evolution of the poloidal magnetic energy



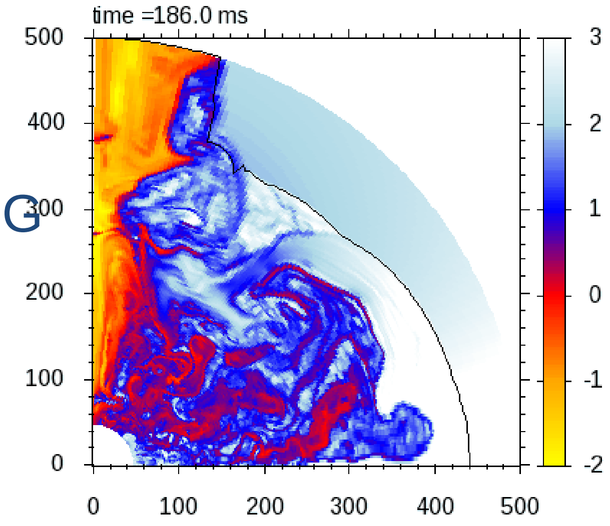
The exponential growth due to MRI

Dynamics

Log[p/pB]

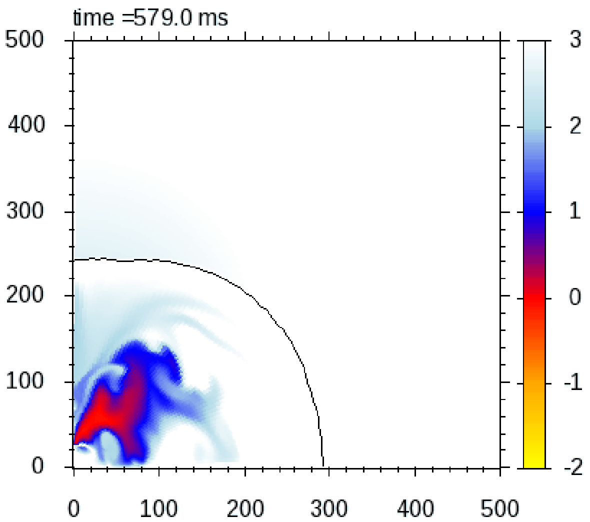


$B_{c,in} = 2.0 \times 10^{11}$ G

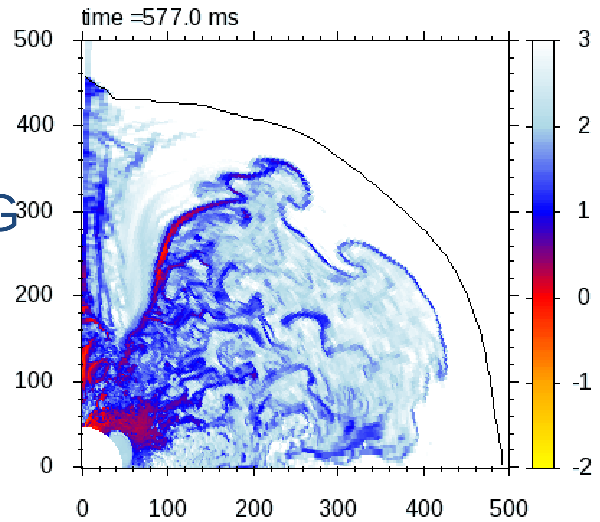


Lowest resolution
MRI unresolved

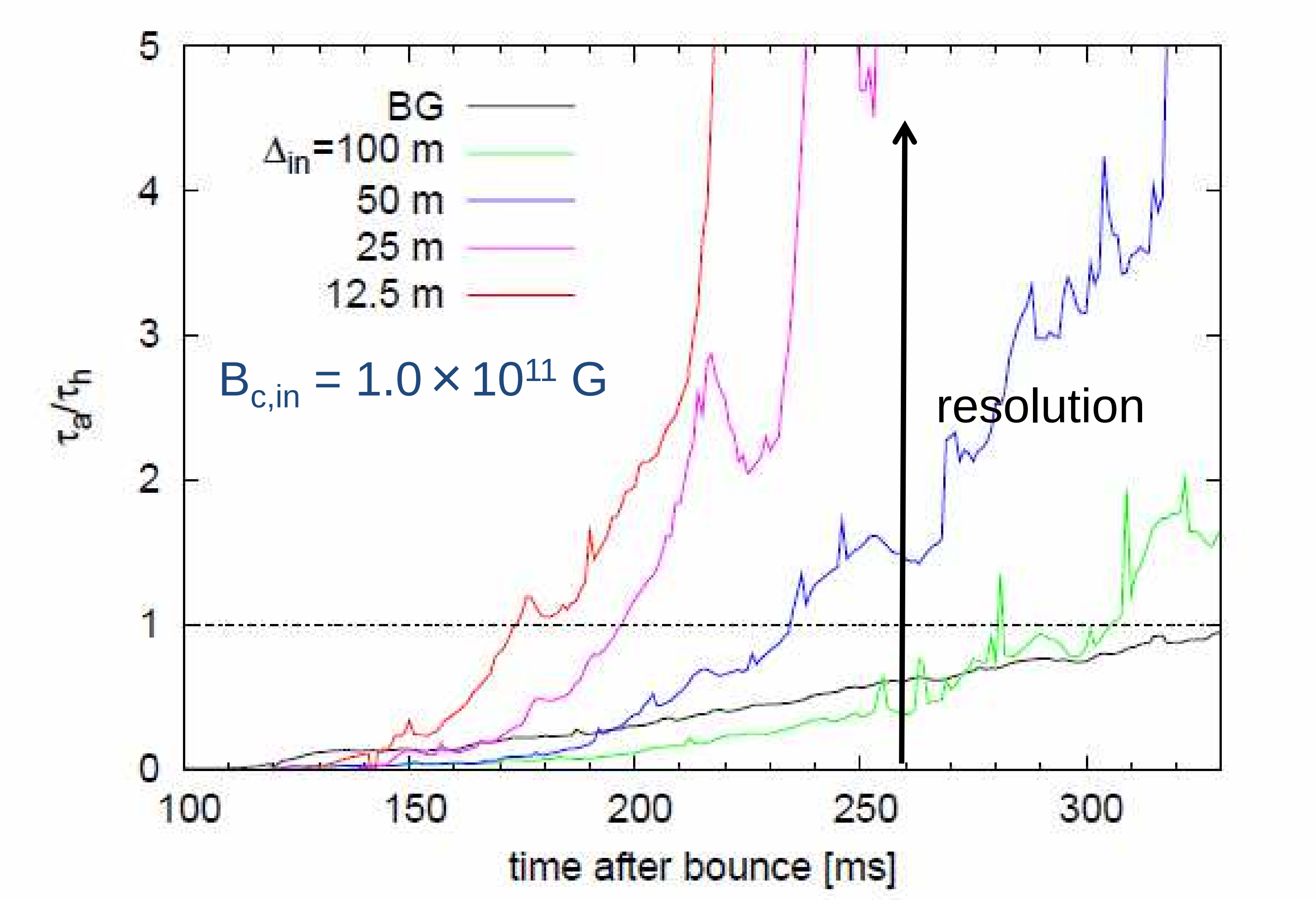
Highest resolution
MRI resolved



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

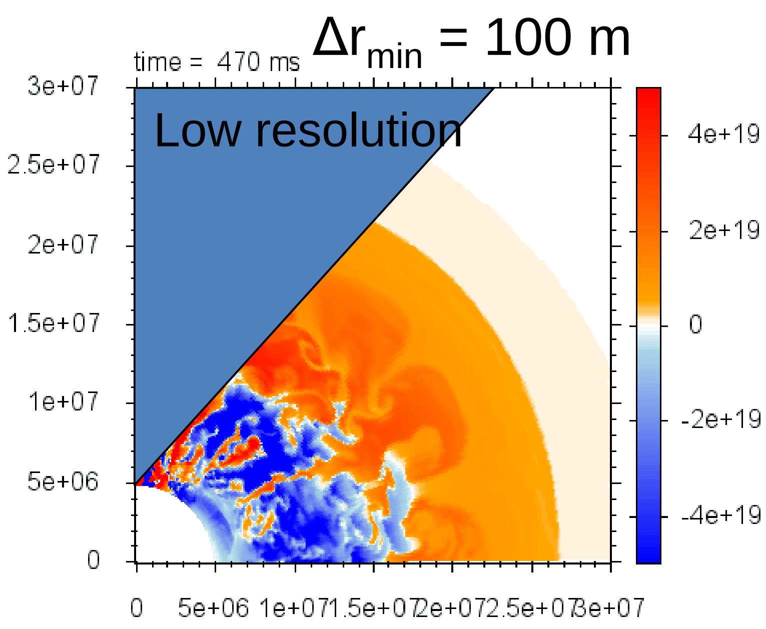


Advection time/ heating time

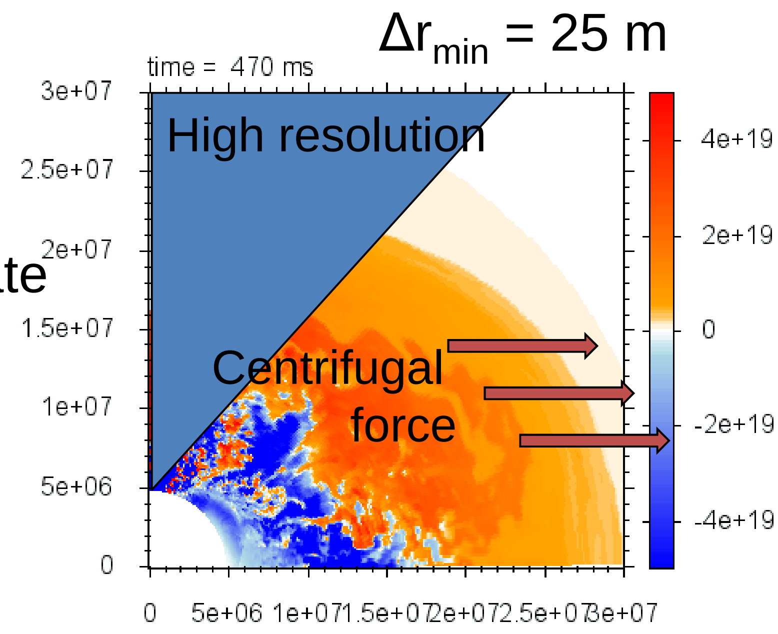


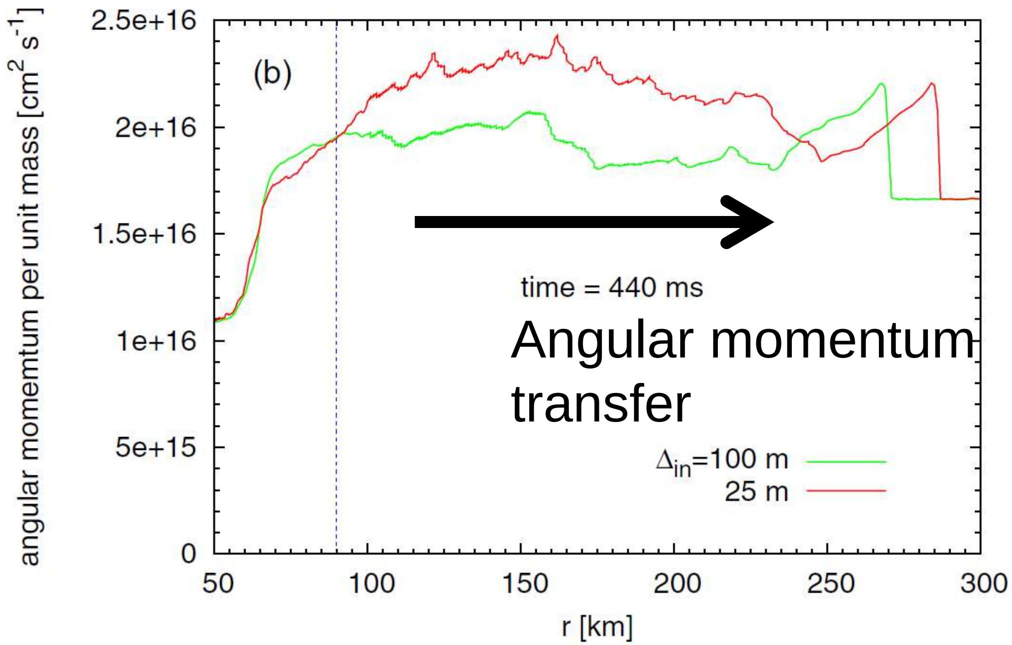
Higher resolution models show more efficient neutrino heating.

Boost of Explosion by MRI



Net heating rate [erg/g.s]

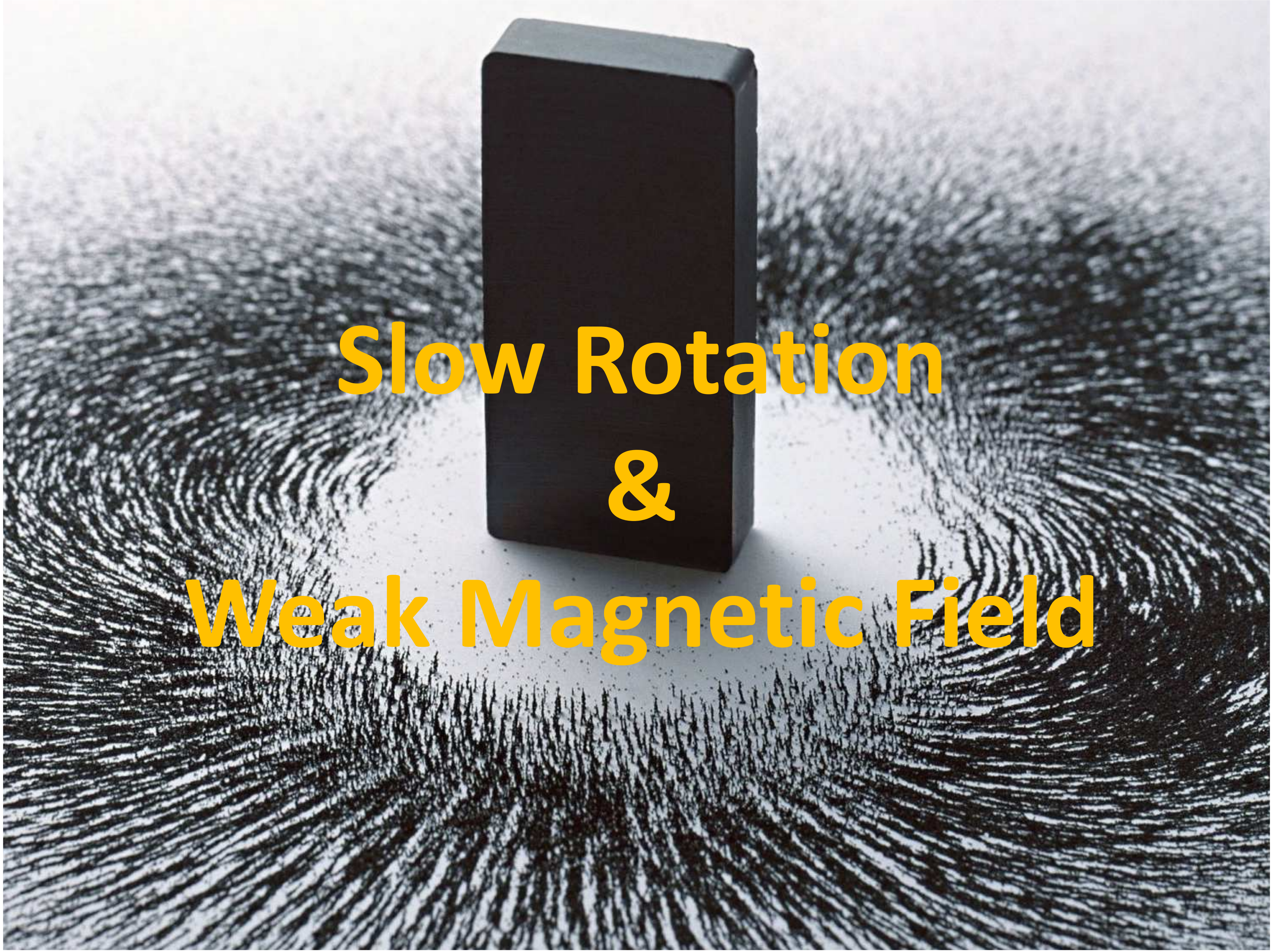




The MRI enlarges the heating region

→ More strong neutrino heating

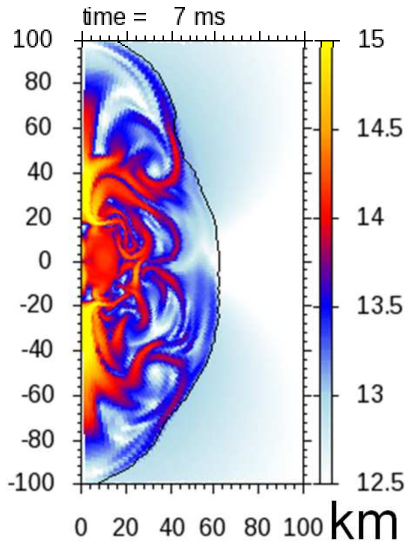
→ Boost of explosion


Slow Rotation
&
Weak Magnetic Field

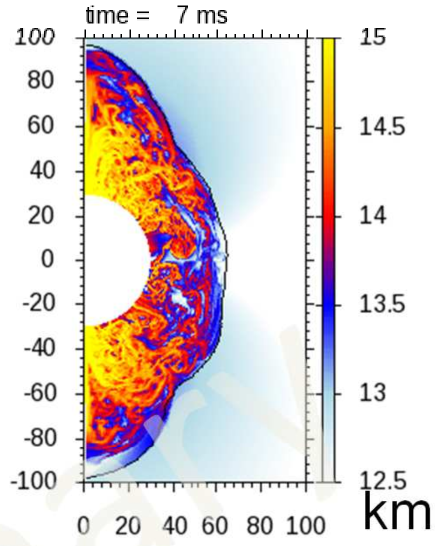
Explosion in High resolution model

Bin=1e11 G
Ωin=0.1 pi

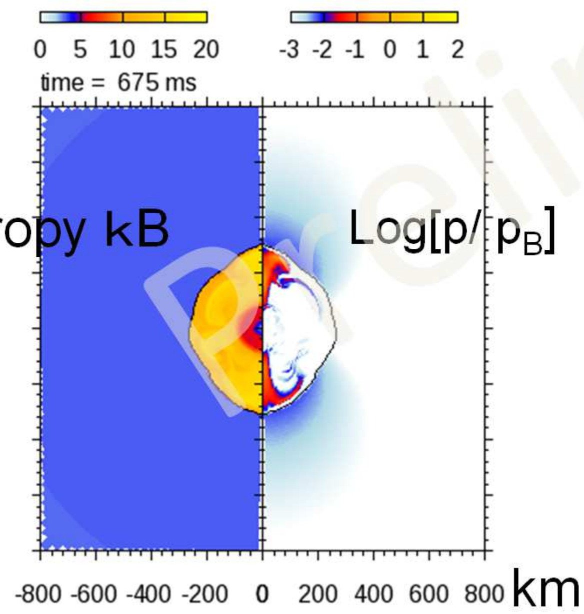
Poloidal B field [G]

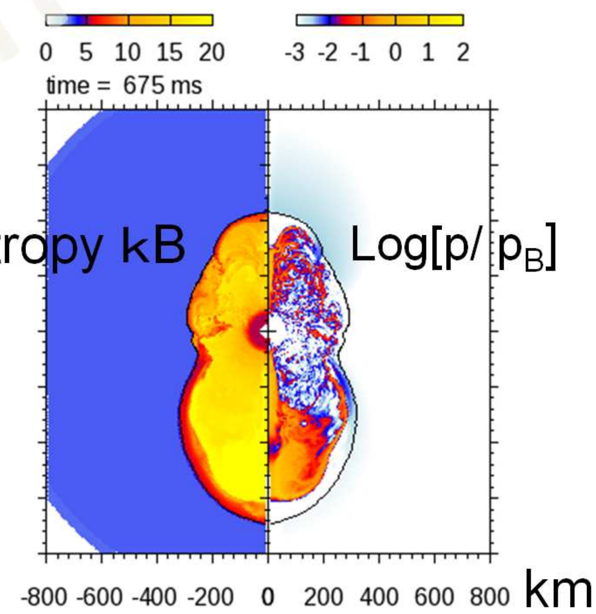


Low resolution



High resolution

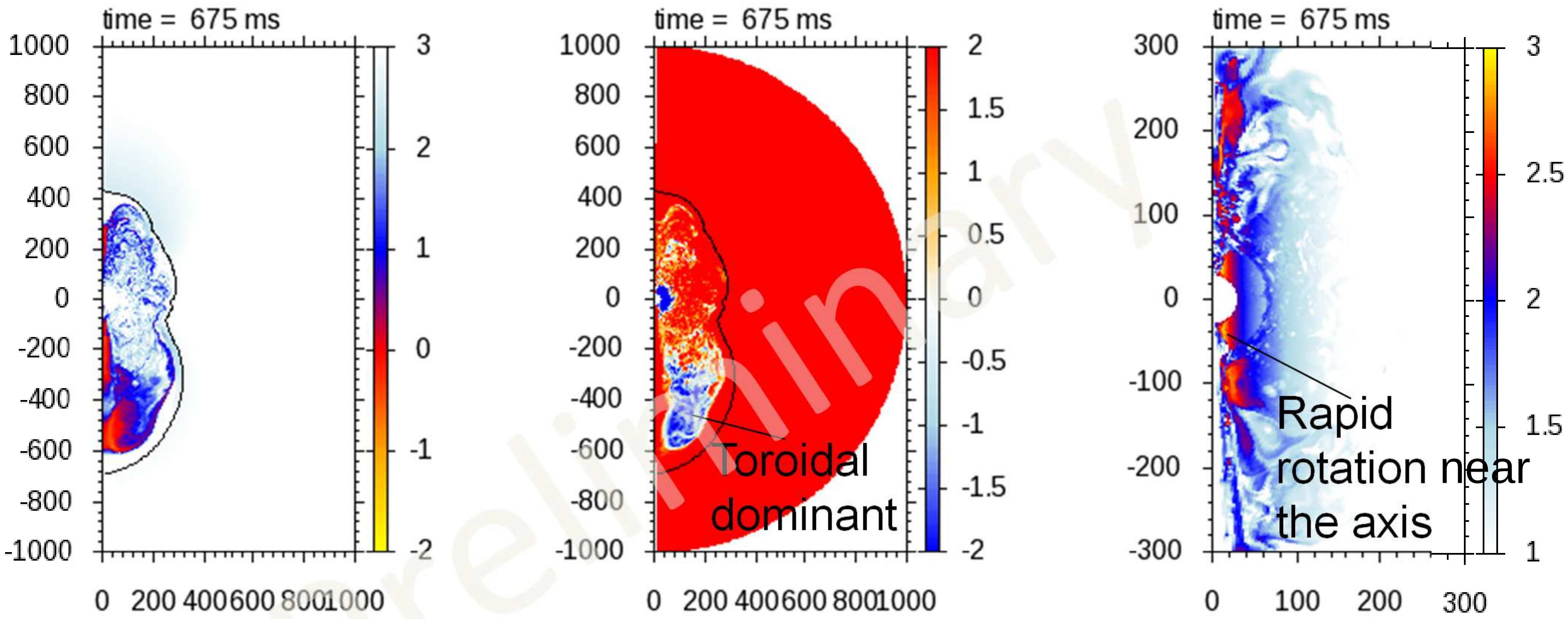




Weak mass ejection by the toroidal B field

High resolution model

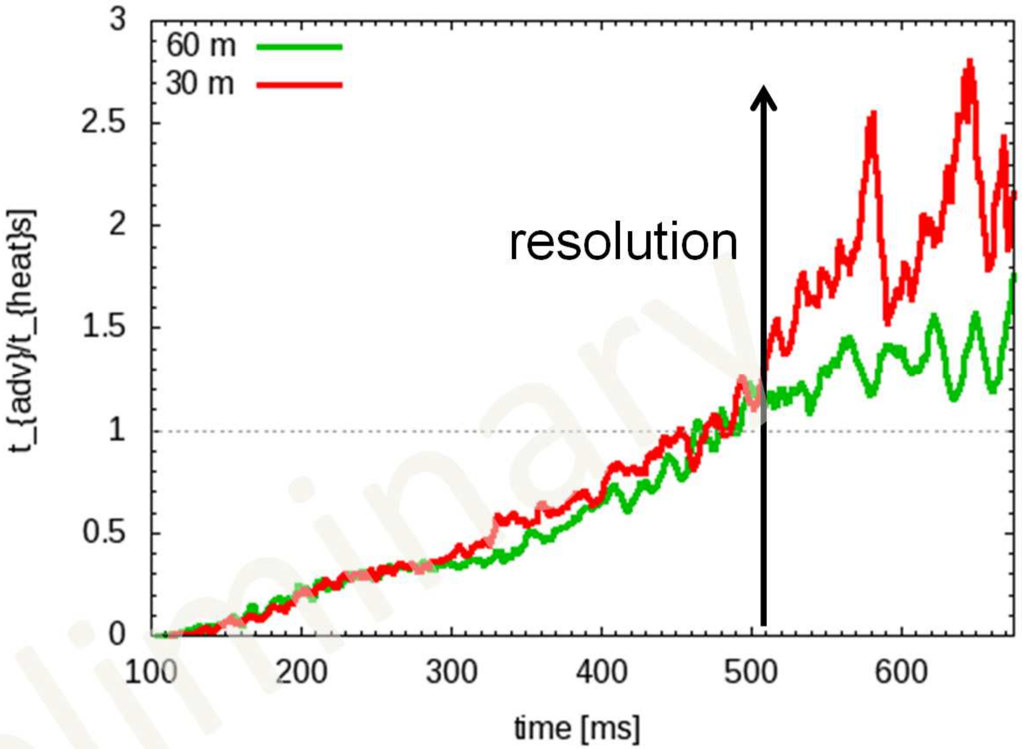
Log(p/pB) | Bpol/Btor | Angular velocity rad/s



Although Weak & Slow B fields & Rotation still Important

Boost of Neutrino Heating

Advection time
―――――――――
Heating time



Magnetically-driven weak mass ejection

→ Long advection time

→ Stronger neutrino heating

Summary

We have performed 2D-axisymmetric MHD simulations of CCSNe for ”weakly” magnetized progenitors, for both rapidly and slowly rotating cases.

➢ Rapid rotation cases:

- MRI amplifies the B-field to a dynamically important strength.

- Boosts of the explosion in high resolution models.

Efficient angular momentum transfers due to MRI enlarge the heating region.

➢ Slow rotation cases:

- Boosts of the explosion in high resolution models.

Magnetically-driven mass ejections lead to efficient neutrino heating due to long advection time.

Future

- Seeking minimum B field affecting the dynamics (“Weak” B fields are still strong.)

- Long term 3D simulations are desired. (Exa-scale or more is required)