Magnetorotational mechanism of core-collapse supernova explosion

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Outline of the talk

- Magnetorotational(MR) mechanism of supernova explosion.
- MR supernova with initial quadrupole field, dipole field.
- Magnetorotational instability(MRI) in MR supernova.
- MR supernova with different core masses and rotation rates.
- Recent results
- Conclusions.

Magnetorotational mechanism for the supernova explosion Bisnovatyi-Kogan (1970) (original article was submitted: September 3, 1969)

Amplification of magnetic fields due to differential rotation, angular momentum transfer by magnetic field. Part of the rotational energy is transformed to the energy of explosion

First 2D calculations: LeBlanck&Wilson (1970))(original article was submitted: September 25, 1969) ->too large initial magnetic fields. $E_{mag0} \sim E_{grav} \Rightarrow$ axial jet

Bisnovatyi-Kogan et al 1976, Meier et al. 1976, Ardeljan et al.1979, Mueller & Hillebrandt 1979, Symbalisty 1984, Ardeljan et al. 2000, Wheeler et al. 2002, 2005, Yamada & Sawai 2004, Kotake et al. 2004, 2005, 2006, Burrows et al.2007, Sawai, Kotake, Yamada 2008,Barkov, Komissarov 2008…

It is popular now!

The realistic values of the magnetic field are: $E_{mag} << E_{grav}$ ($E_{mag}/E_{grav} = 10^{-8}$-$10^{-12}$)

Small initial magnetic field -is the main difficulty for the numerical simulations.

The problem has 2 different time scales.

The hydrodynamic time scale is much smaller than the magnetic field amplification time scale (*if magnetorotational instability is neglected*).

Explicit difference schemes require very big number of timesteps. (CFL restriction on the time-step).

Implicit schemes should be used.

The main difference between bounce shock, neutrino driven mechanisms and MR supernovae: the magnetic field works like a piston. This MHD piston supports the supernova MHD shock wave for some time.

Basic equations: MHD +self-gravitation, infinite conductivity:

$$
\begin{cases}
\dfrac{dx}{dt} = \mathbf{u}, \quad \dfrac{d\rho}{dt} + \rho \operatorname{div}\mathbf{u} = 0, \\
\rho \dfrac{du}{dt} = -\operatorname{grad}\left(p + \dfrac{\mathbf{H}\cdot\mathbf{H}}{8\pi} \right) + \dfrac{1}{4\pi}\operatorname{div}(\mathbf{H} \otimes \mathbf{H}) - \rho \operatorname{grad}\Phi \\
\rho \dfrac{d\varepsilon}{dt} + p \operatorname{div}\mathbf{u} + \rho F(\rho, T) = 0, \quad p = P(\rho, T), \varepsilon = \mathrm{E}(\rho, T), \\
\Delta\Phi = 4\pi G\rho, \\
\rho \dfrac{d}{dt}\left(\dfrac{\mathbf{H}}{\rho} \right) = \mathbf{H} \cdot \nabla \mathbf{u}.
\end{cases}
$$

Additional condition div**H**=0

Axis symmetry ($\dfrac{\partial}{\partial \phi} = 0$) and equatorial symmetry (z=0) are supposed.

Notations:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla, \mathbf{x} = (\mathrm{r}, \varphi, \mathrm{z}), \mathbf{u} - \text{velocity}, \rho - \text{density}, p - \text{pressure},$$

$$\mathbf{H} - \text{magnetic field}, \Phi - \text{gravitational potential}, \varepsilon - \text{internal energy},$$

$$\mathrm{G} - \text{gravitational constant}.$$

Presupernova Core Collapse

Equations of state take into account degeneracy of electrons and neutrons, relativity for the electrons, nuclear transitions and nuclear interactions. Temperature effects were taken into account approximately by the addition of radiation pressure and an ideal gas

.

Neutrino losses were taken into account in the energy equations.

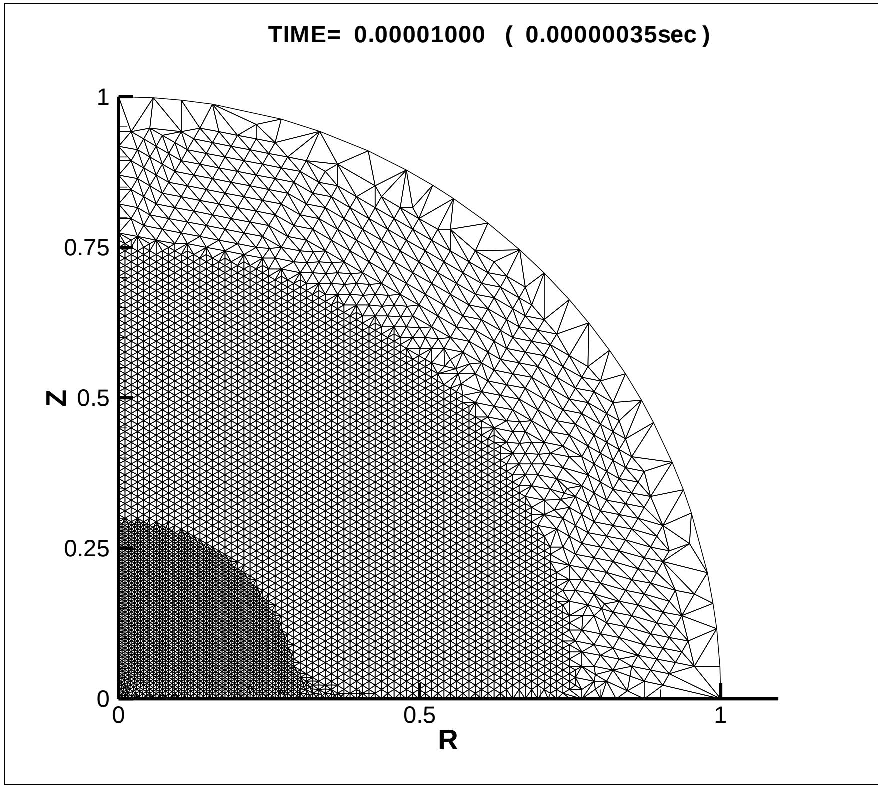
A cool white dwarf was considered at the stability limit with a mass equal to the Chandrasekhar limit.

To obtain the collapse we increase the density at each point by 20% and we also impart uniform rotation on it.

Initial state

$M = 1.2042$ BM_{sun} , spherically symmetrical stationary state, initial angular velocity 2.519 (1/sec)

Initial temperature distribution $T = \delta\rho^{2/3}$



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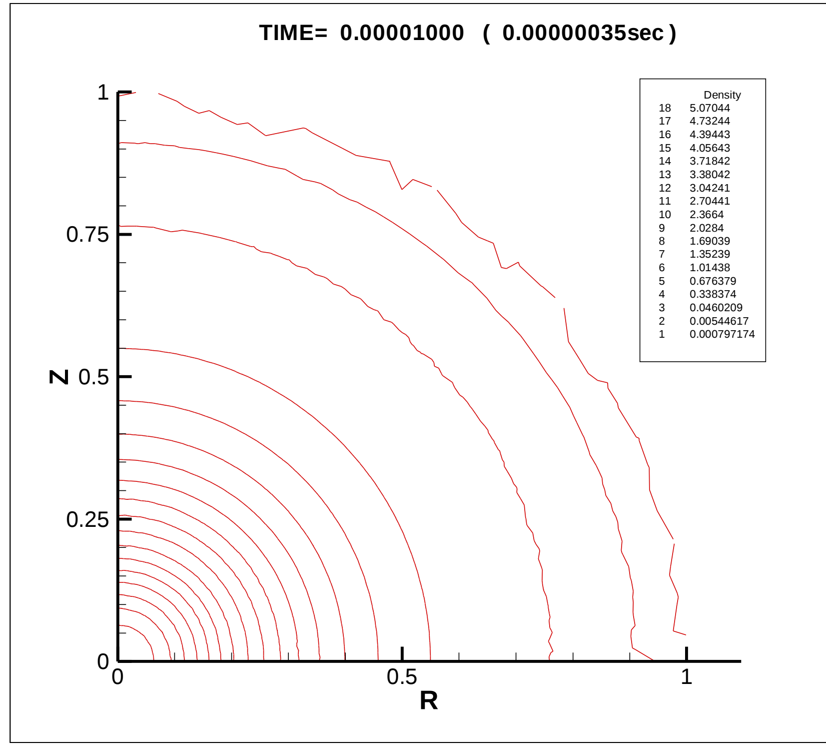
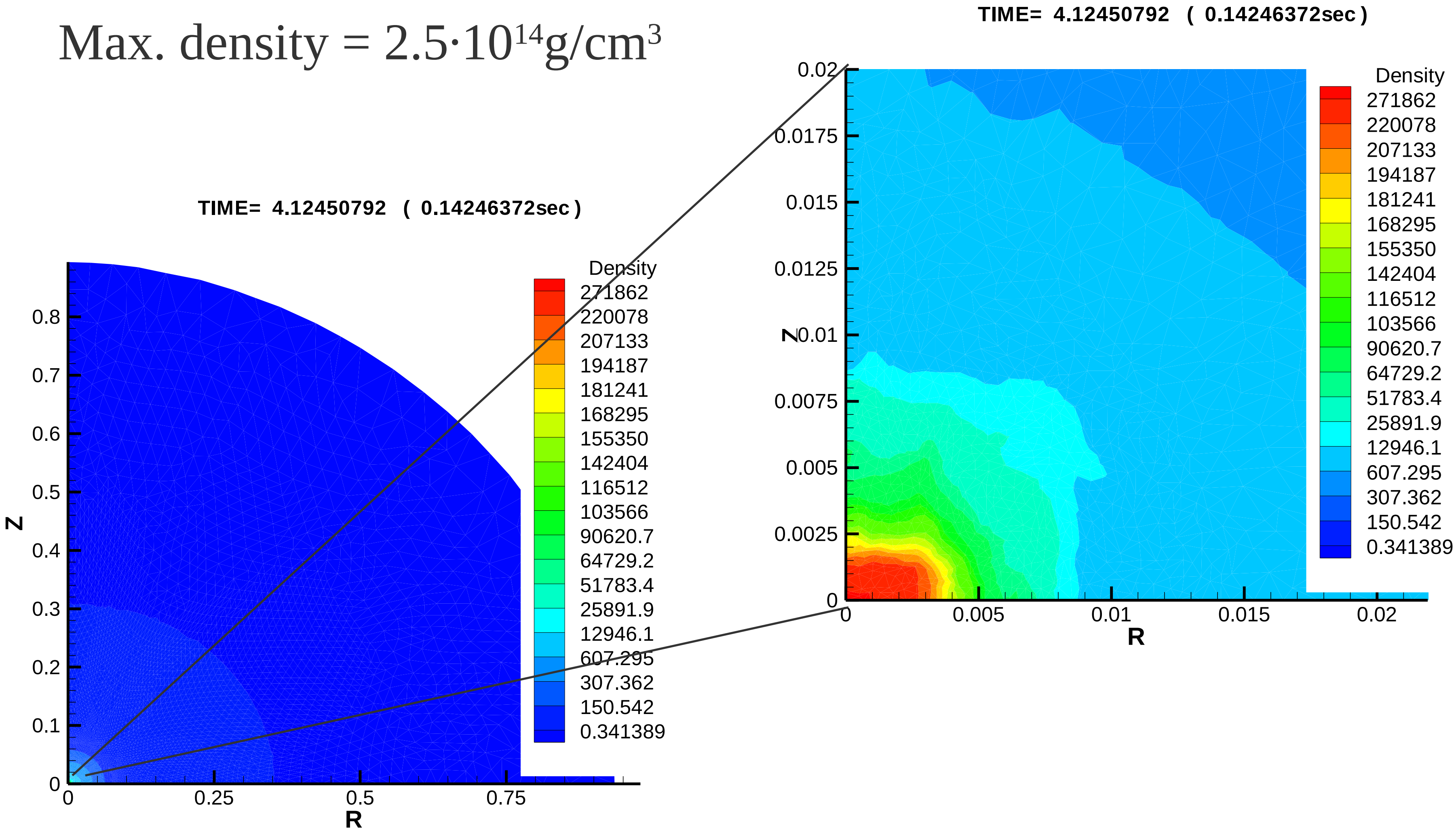


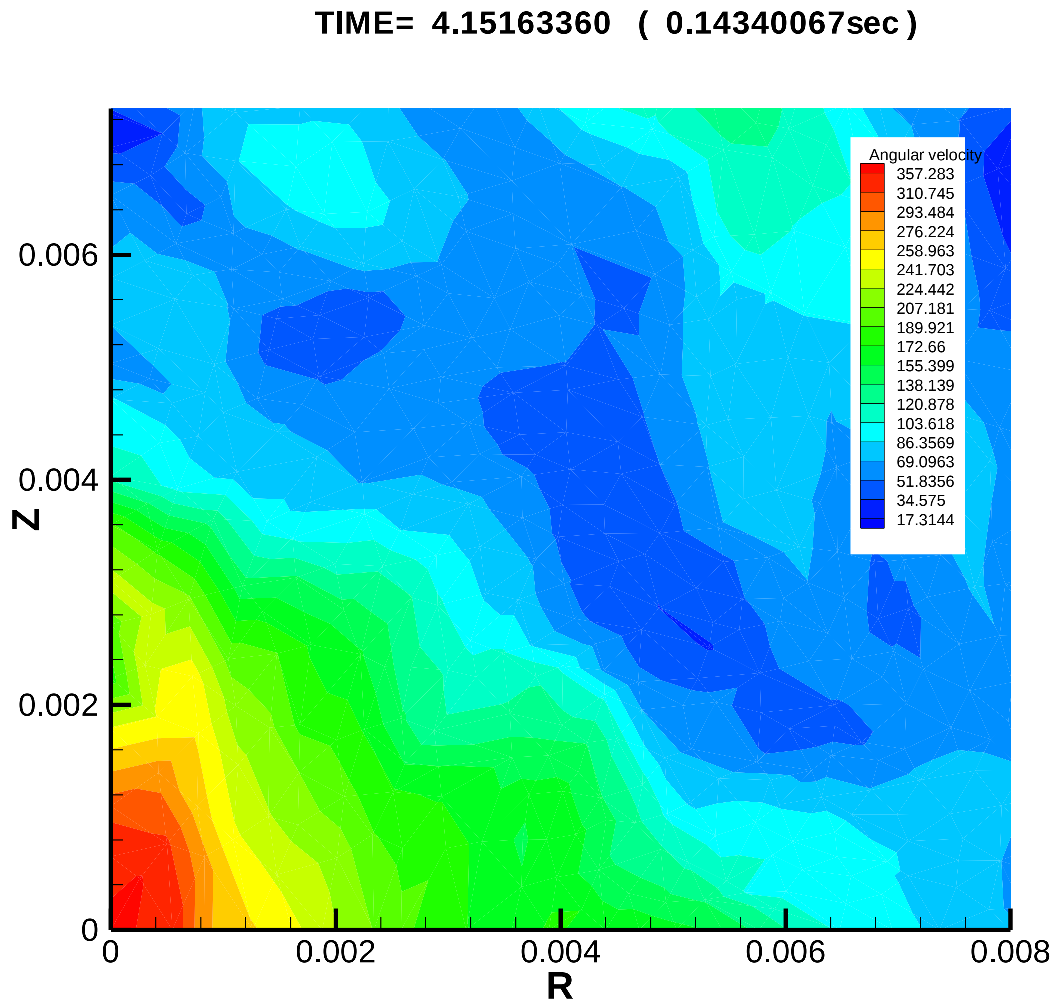
$$\frac{E^{rot}}{E^{grav}} = 0.571\% \qquad \frac{E^{int}}{E^{grav}} = 72.7\%$$

Maximal compression state

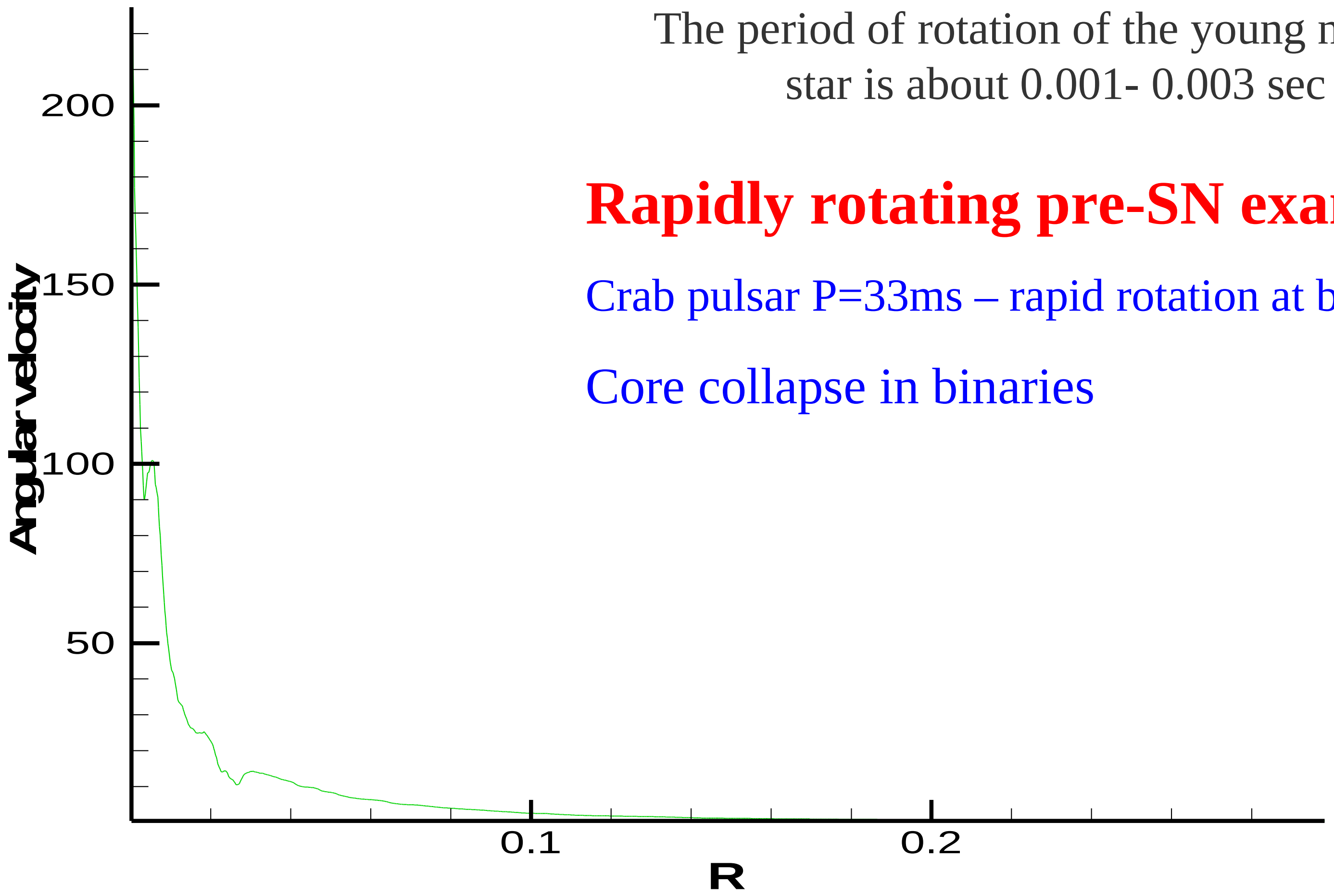
Max. density = $2.5\cdot10^{14}$g/cm^3



Angular velocity (central part of the computational domain). Rotation is differential.



Distribution of the angular velocity



The period of rotation of the young neutron star is about 0.001- 0.003 sec

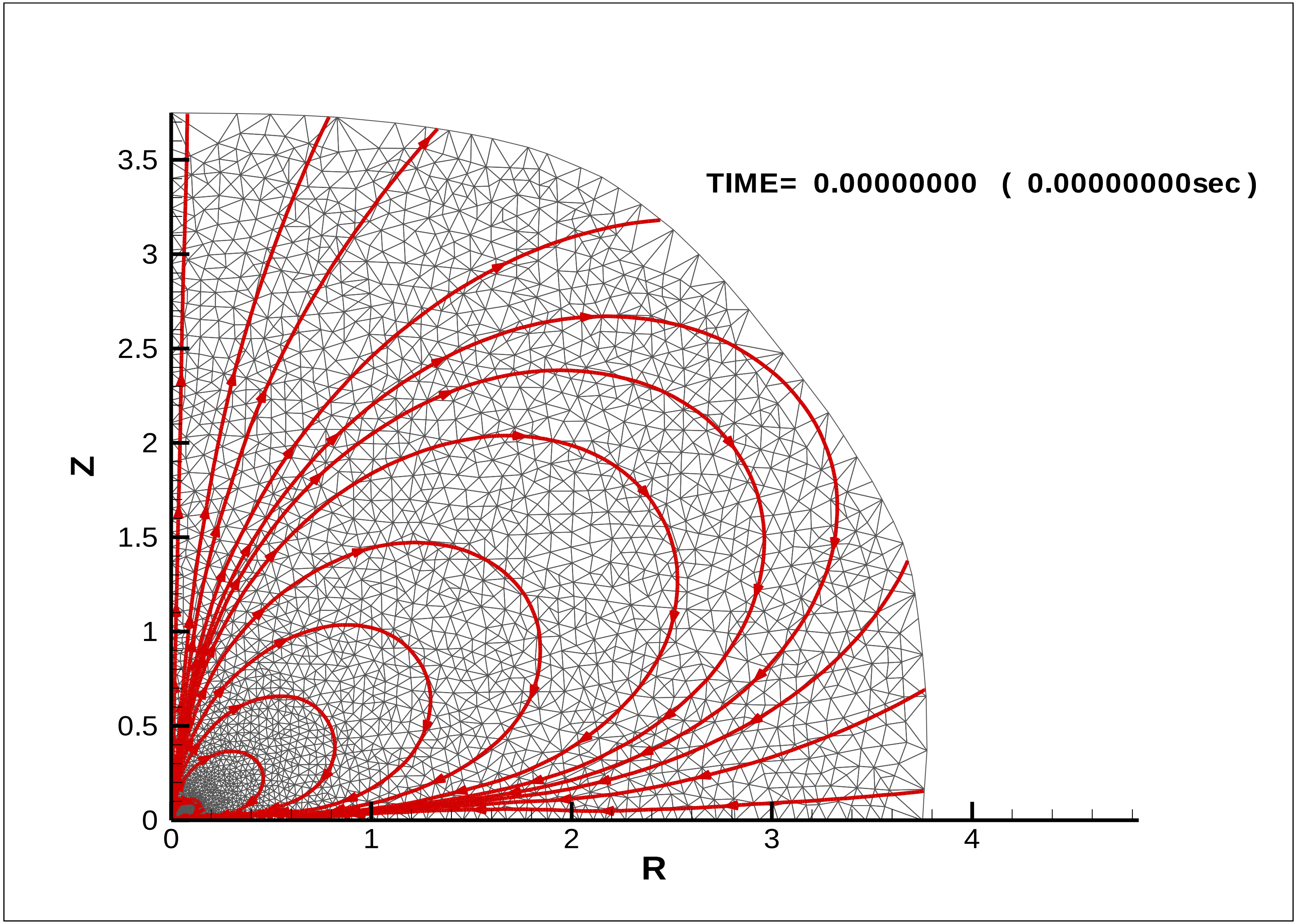
Rapidly rotating pre-SN examples:

Crab pulsar P=33ms – rapid rotation at birth

Core collapse in binaries

Initial magnetic field –quadrupole-like symmetry

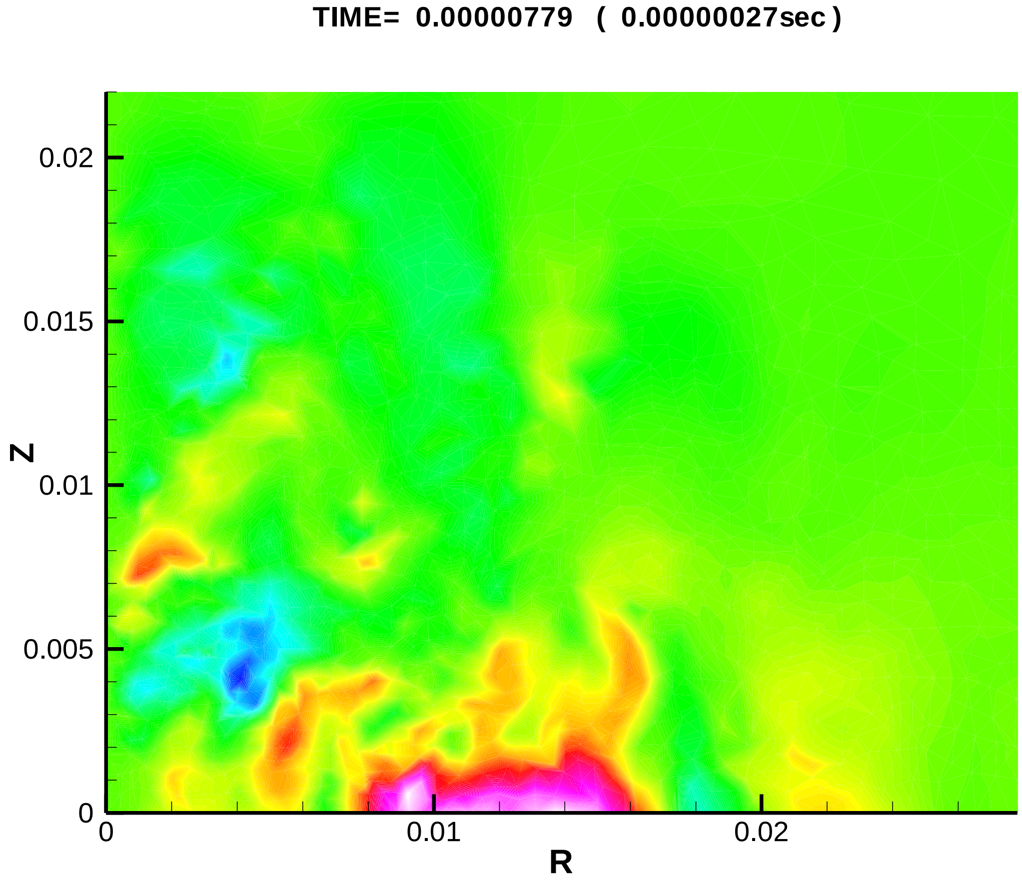
Ardeljan, Bisnovatyi-Kogan, SM, MNRAS 2005, 359, 333



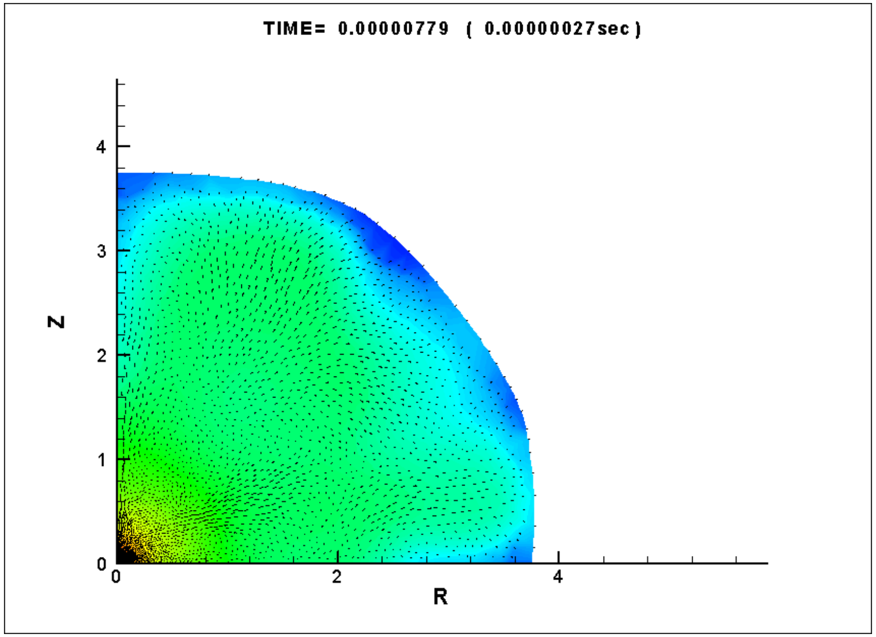
Toroidal magnetic field amplification.

pink – maximum_1 of Hf^2 blue – maximum_2 of Hf^2

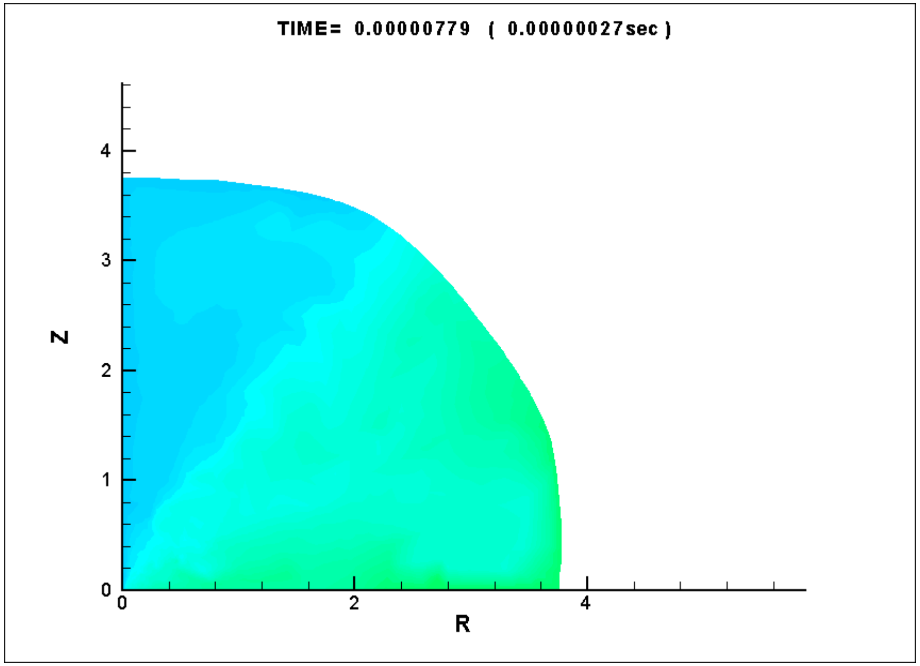
Maximal values of Hf=2.5 ·10(16)G



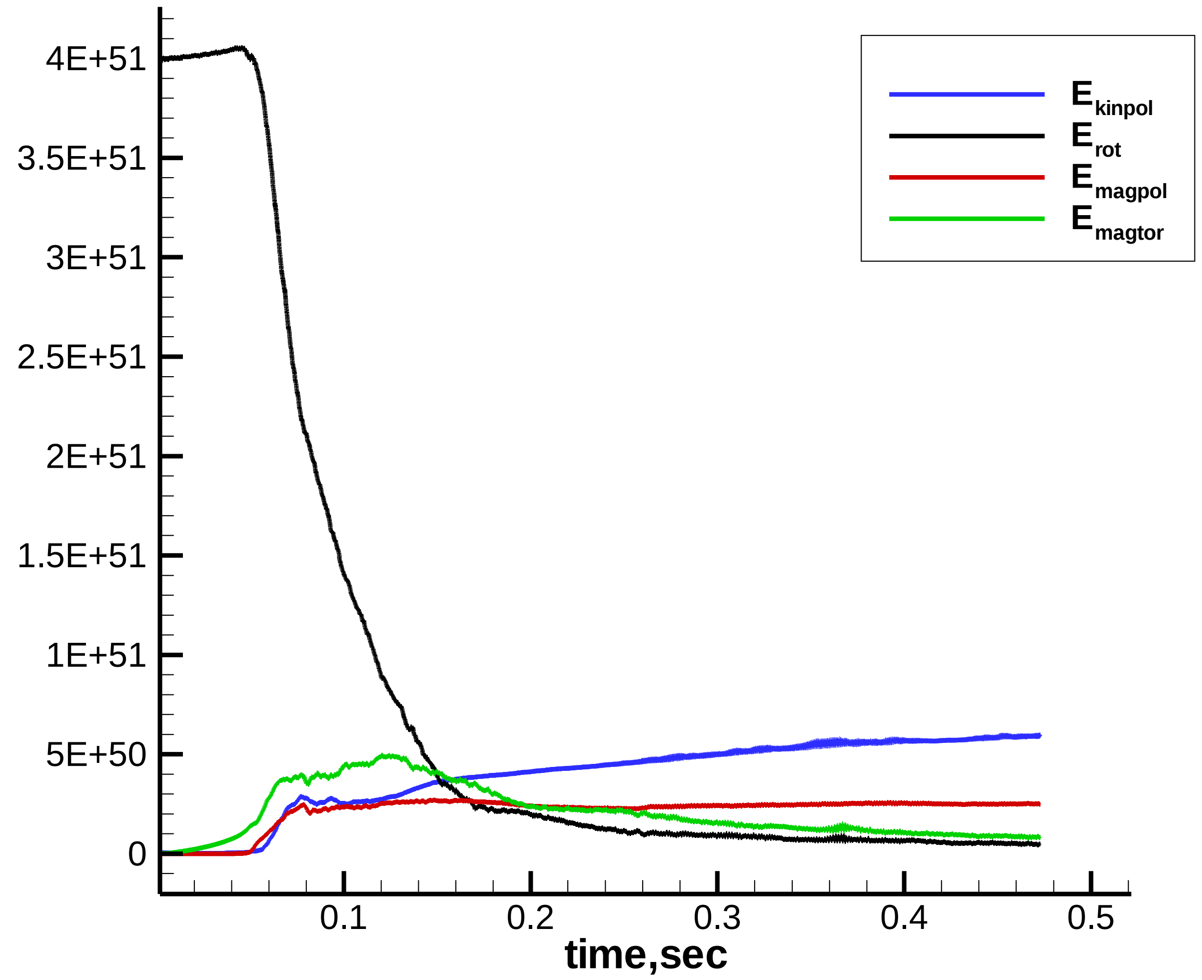
Temperature and velocity field



Specific angular momentum

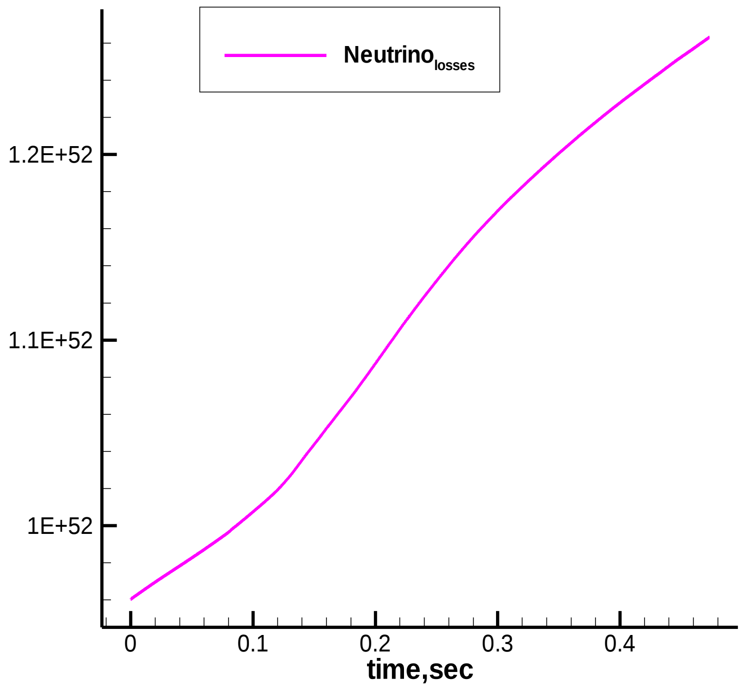


Time evolution of different types of energies

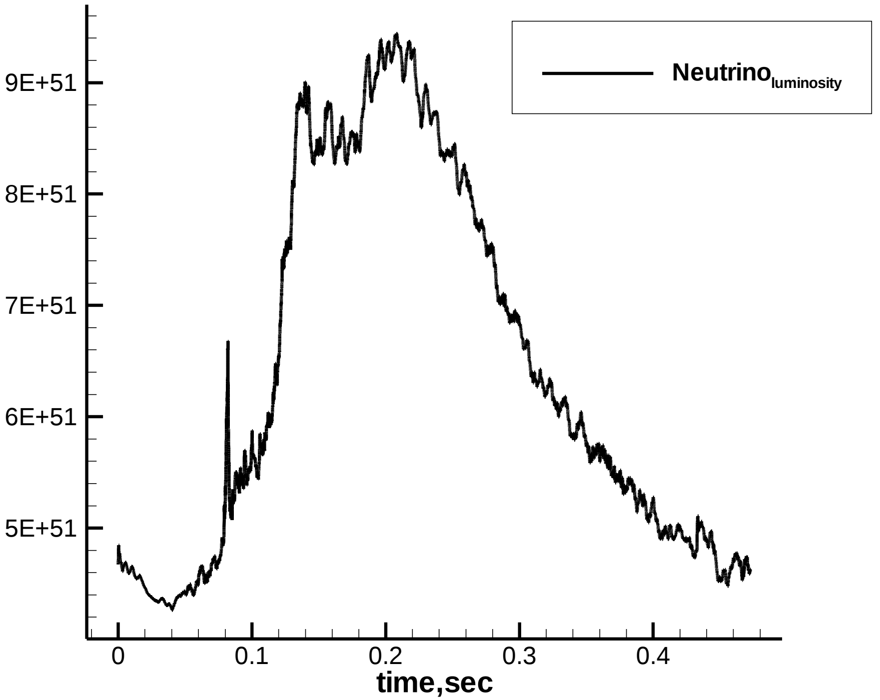


Time evolution of the energies

Neutrino losses (ergs)



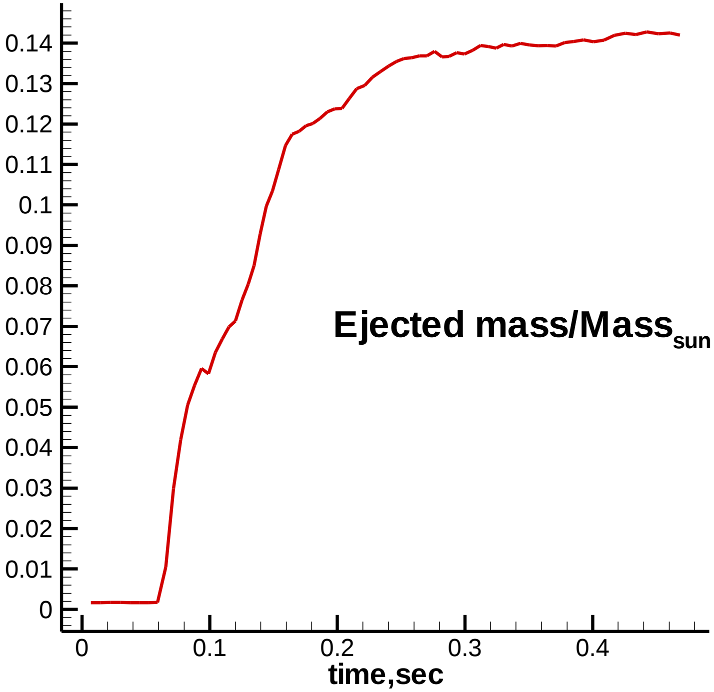
Neutrino luminosity (ergs/sec)

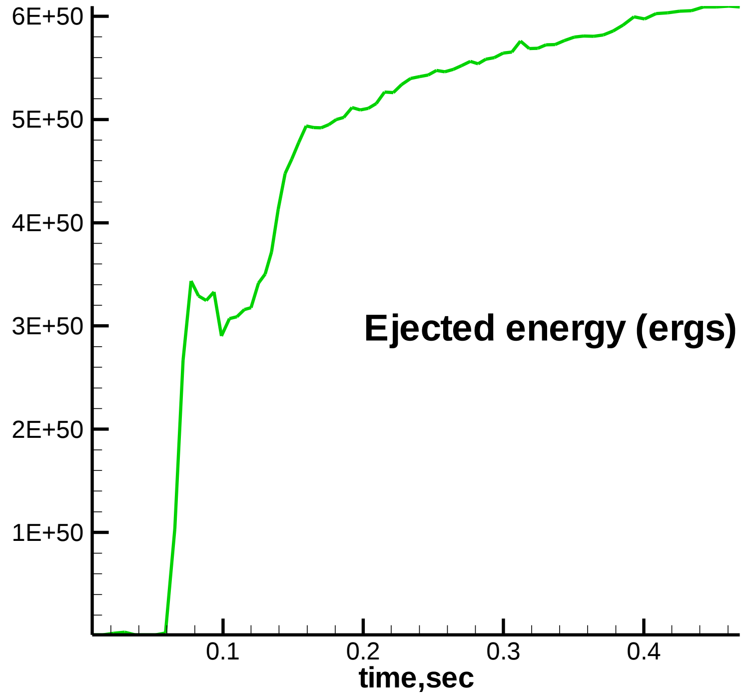


Ejected energy and mass

Ejected energy $0.6 \times 10^{51} erg$ Ejected mass $0.14M_{\odot}$

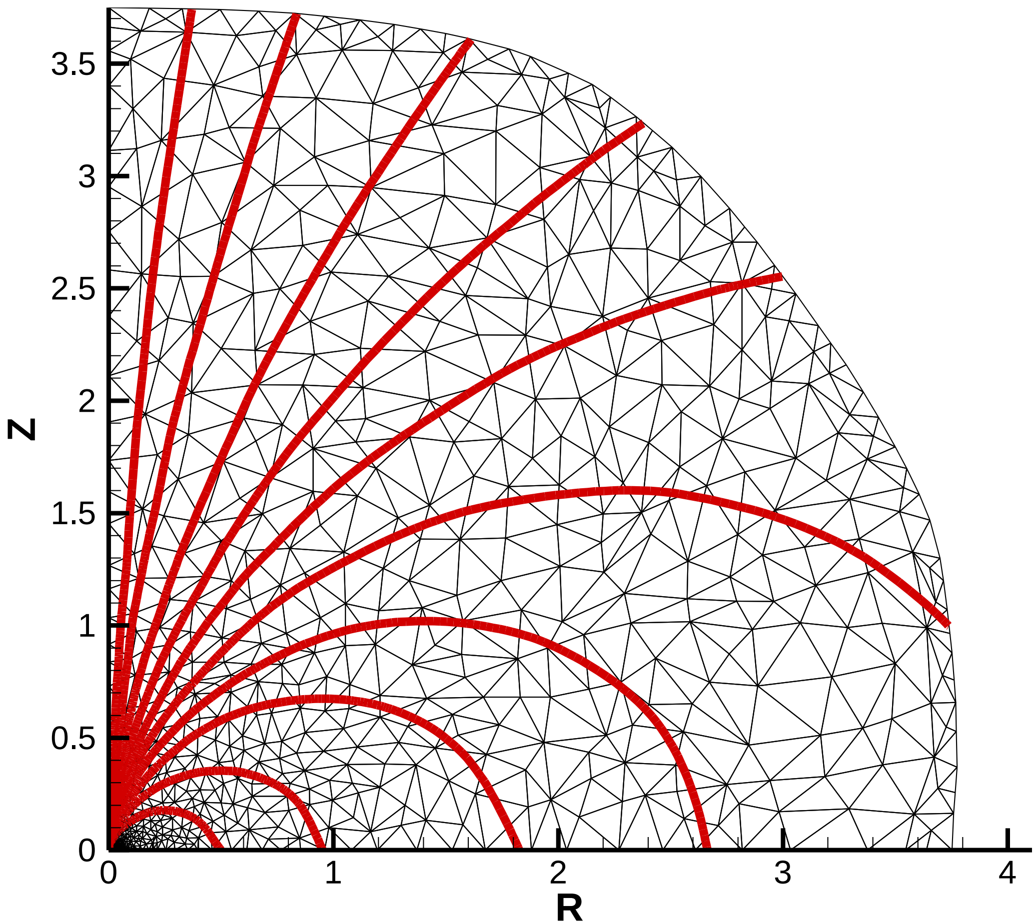
Particle is considered "ejected" –
if its kinetic energy is greater than its potential energy



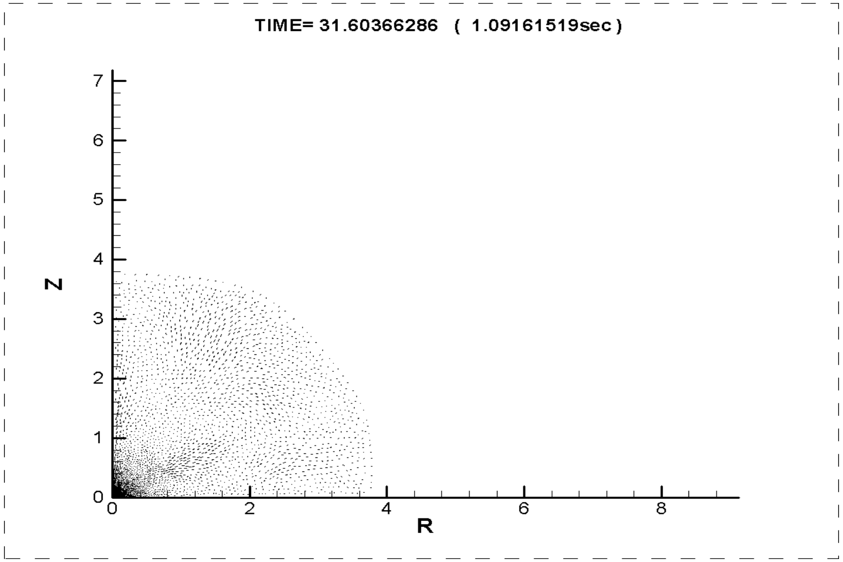


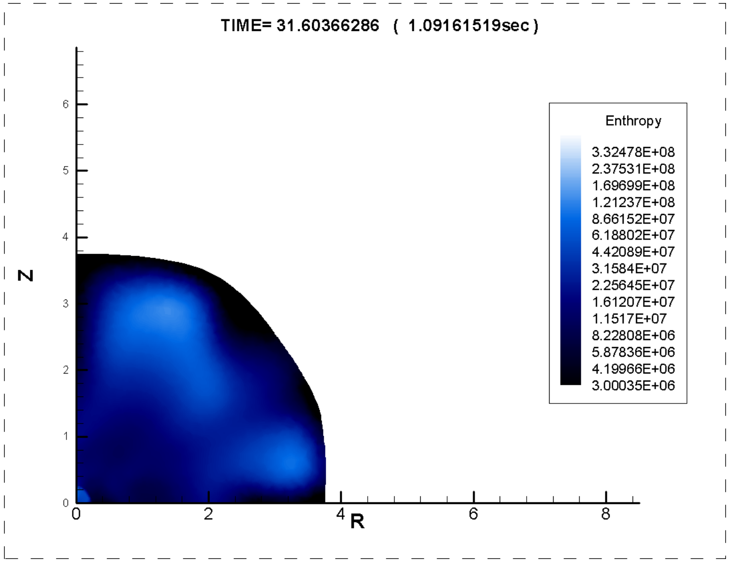
Initial magnetic field – dipole-like symmetry

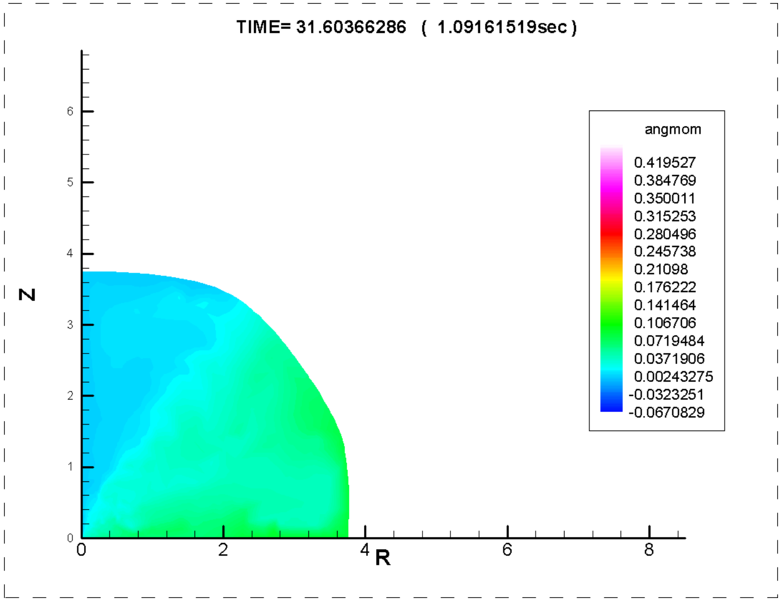
SM., Ardeljan & Bisnovatyi-Kogan MNRAS 2006, 370, 501



Magnetorotational explosion for the dipole-like magnetic field



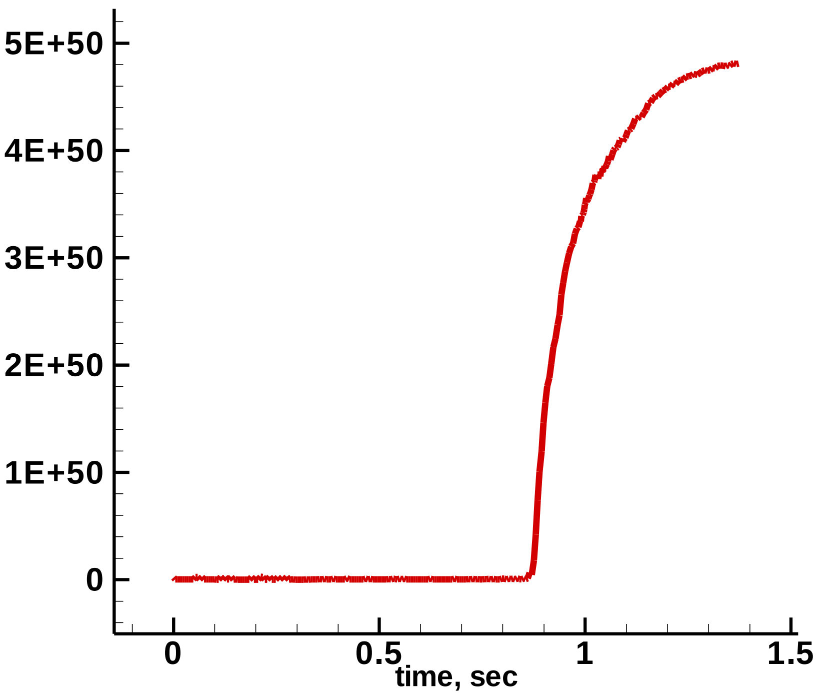


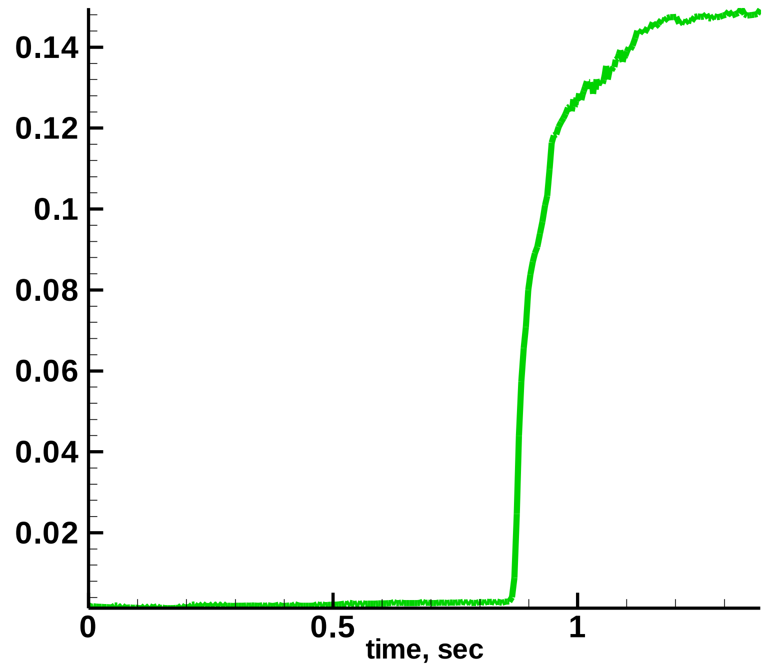


Ejected energy and mass (dipole)

Ejected energy $\approx 0.5 \times 10^{51}\, erg$ Ejected mass $\approx 0.14 M_{\odot}$

Particle is considered "ejected" –
if its kinetic energy is greater than its potential energy

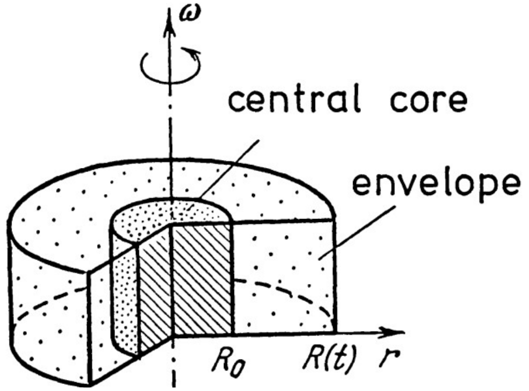




Magnetorotational supernova in 1D

Bisnovaty-Kogan et al. 1976, Ardeljan et al. 1979

$$t_{\text{explosion}} : \frac{1}{\sqrt{\alpha}}, \qquad \left(\alpha = \frac{E_{\text{mag0}}}{E_{\text{grav0}}}\right)$$



Example: $\alpha = 10^{-2}$ ч $t_{\text{explosion}} = 10,$

$\alpha = 10^{-12}$ ч $t_{\text{explosion}} = 10^{6}$!!!

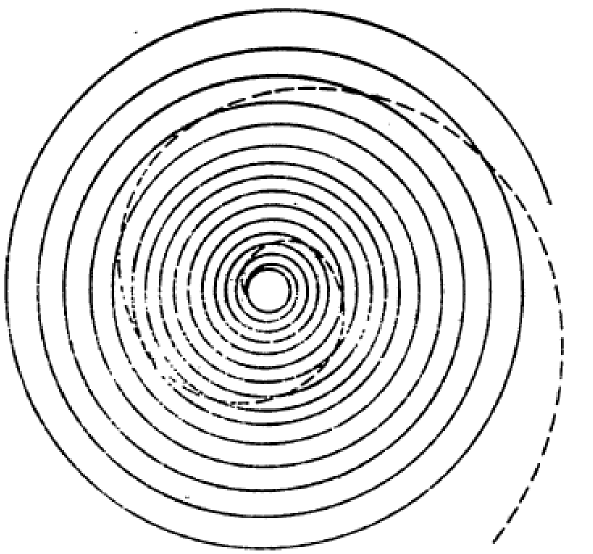
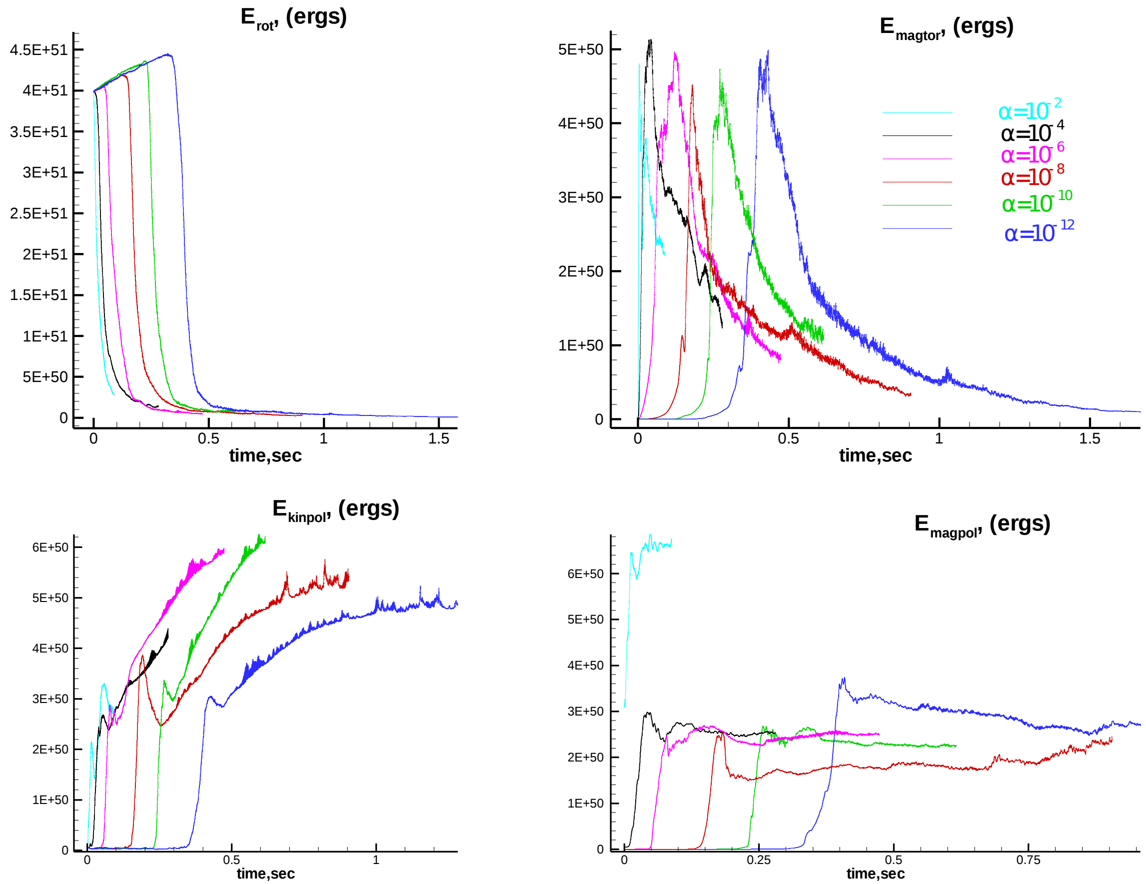


FIG. 3. Shape of a field line in the region near the core at the time $t_\alpha = 7$ for $\alpha = 10^{-2}$ (dashed line) and $\alpha = 10^{-4}$ (solid line).

Magnetorotational explosion for the different $\alpha = \frac{E_{mag\,٠}}{E_{grav\,٠}} = ١٠^{-٢} - ١٠^{-١٢}$

Magnetorotational instabilityÆmag. field grows exponentially
(Dungey 1958,Velikhov 1959, Chandrasekhar, Balbus & Hawley 1991,
Spruit 2002, Akiyama et al. 2003…)



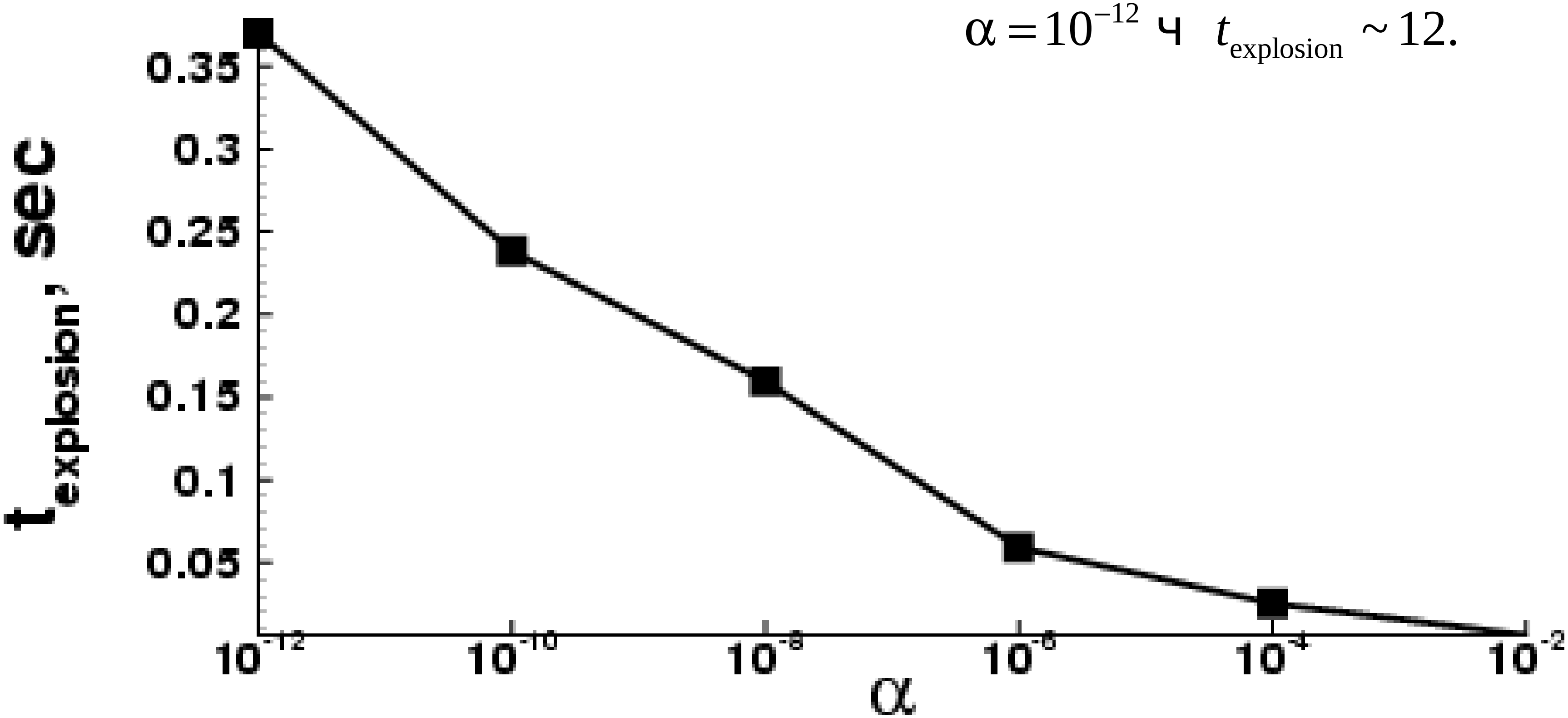
Dependence of the explosion time from $\alpha = \frac{E_{mag0}}{E_{grav0}}$

$t_{explosion} \sim -\log(\alpha)$ (for small α)

Example:

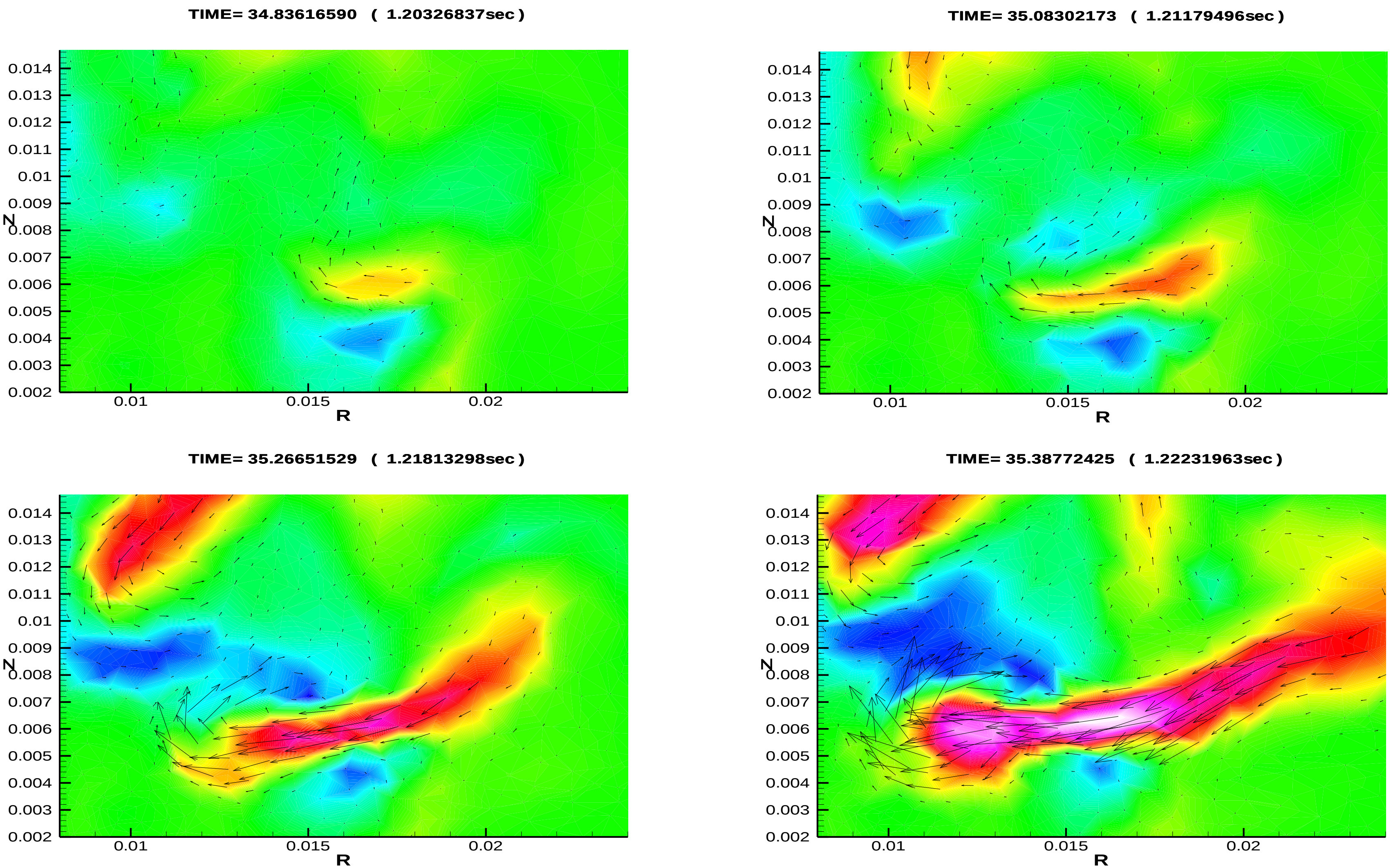
$\alpha = 10^{-6}$ Ч $t_{explosion} \sim 6,$

$\alpha = 10^{-12}$ Ч $t_{explosion} \sim 12.$



Magnetorotational instability

Central part of the computational domain . Formation of the MRI.



Toy model for MRI in the magnetorotational supernova

$\frac{dH_\varphi}{dt} = H_r\left(r\frac{d\Omega}{dr}\right)$ at the initial stage of the process $H_\varphi < H_\varphi^*$: $H_r\left(r\frac{d\Omega}{dr}\right) \approx \text{const},$

beginning of the MRI => formation of multiple *poloidal* differentially rotating

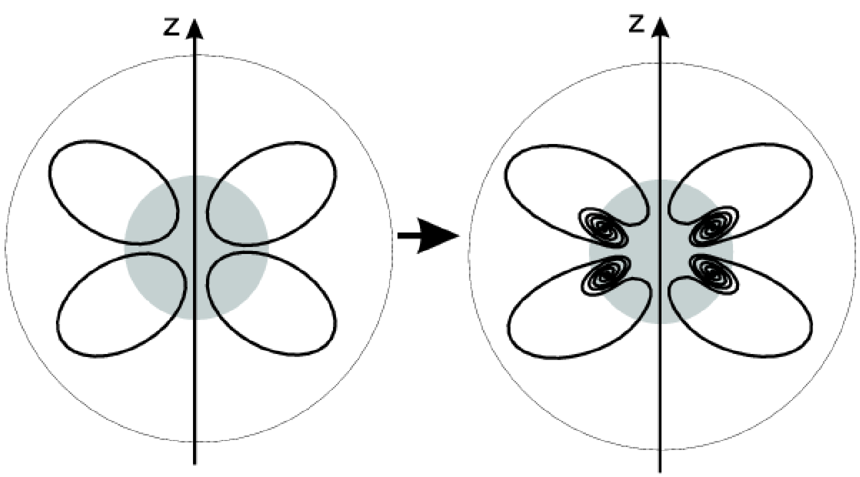
vortexes $\frac{dH_r}{dt} = H_{r0}\left(\frac{d\omega_v}{dl}l\right)$ in general we may approximate: $\left(\frac{d\omega_v}{dl}l\right) \approx \alpha(H_\varphi - H_\varphi^*).$

Assuming for the simplicity that $\left(r\frac{d\Omega}{dr}\right) = A$ is a constant during the first stages of MRI, and taking H_φ^* as a constant we come to the following equation:

$$\frac{d^2}{dt^2}\left(H_\varphi - H_\varphi^*\right) = AH_{r0}\alpha(H_\varphi - H_\varphi^*)$$

$$\Rightarrow$$

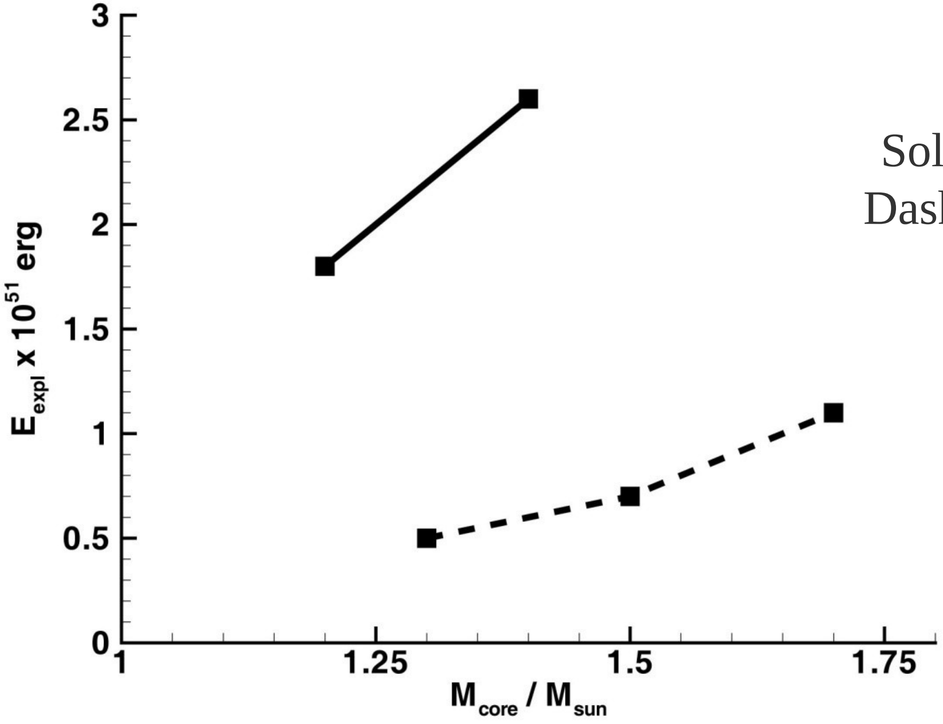
$$\begin{cases} H_\varphi = H_\varphi^* + H_{r0}e^{\sqrt{A\alpha H_{r0}}\,(t-t^*)}, \\ H_r = H_{r0} + \frac{H_{r0}^{3/2}\alpha^{1/2}}{\sqrt{A}}\left(e^{\sqrt{A\alpha H_{r0}}\,(t-t^*)} - 1\right). \end{cases}$$



MR supernova – different core masses

Bisnovatyi-Kogan, SM, Ardeljan Astron.Rep. 2008, 52, 997

Dependence of the MR supernova explosion energy on the core mass and initial angular momentum



Solid line – initial angular velocity = $3.53 s^{-1}$
Dashed line - initial angular velocity = $2.52 s^{-1}$

The magnetorotational supernova explosion is always asymmetrical.

but

Jet, kick and axis of rotation are **aligned** in MR supernovae.

Evidence for alignment of the rotation and velocity vectors in pulsars

S. Johnston et al. MNRAS, 2005, 364, 1397

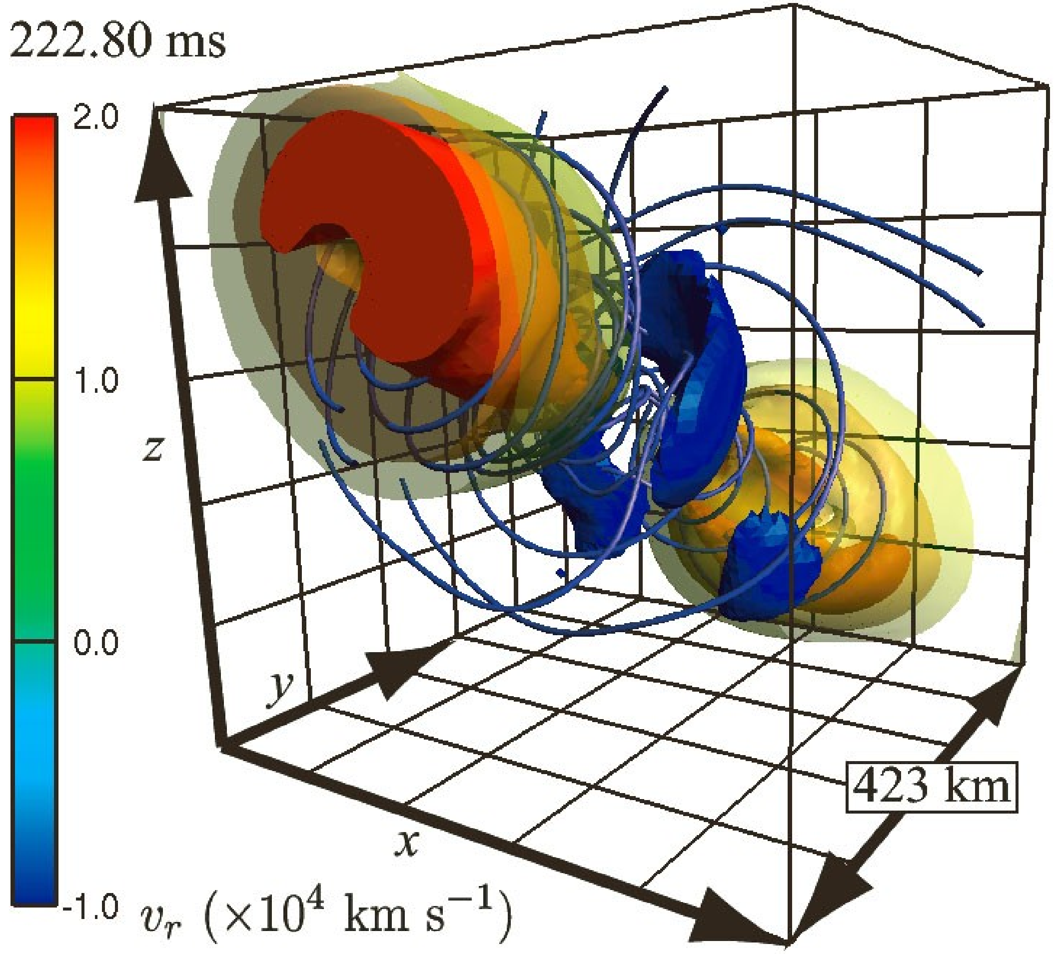
“We present strong observational evidence for a relationship between the direction of a pulsar's motion and its rotation axis. We show carefully calibrated polarization data for 25pulsars, 20 of which display linearly polarized emission from the pulse longitude at closest approach to the magnetic pole…

we conclude that the velocity vector and the rotation axis are aligned at birth“.

First 3D simulations of MR supernova (simplified)

Hanawa et al. ApJ 2008

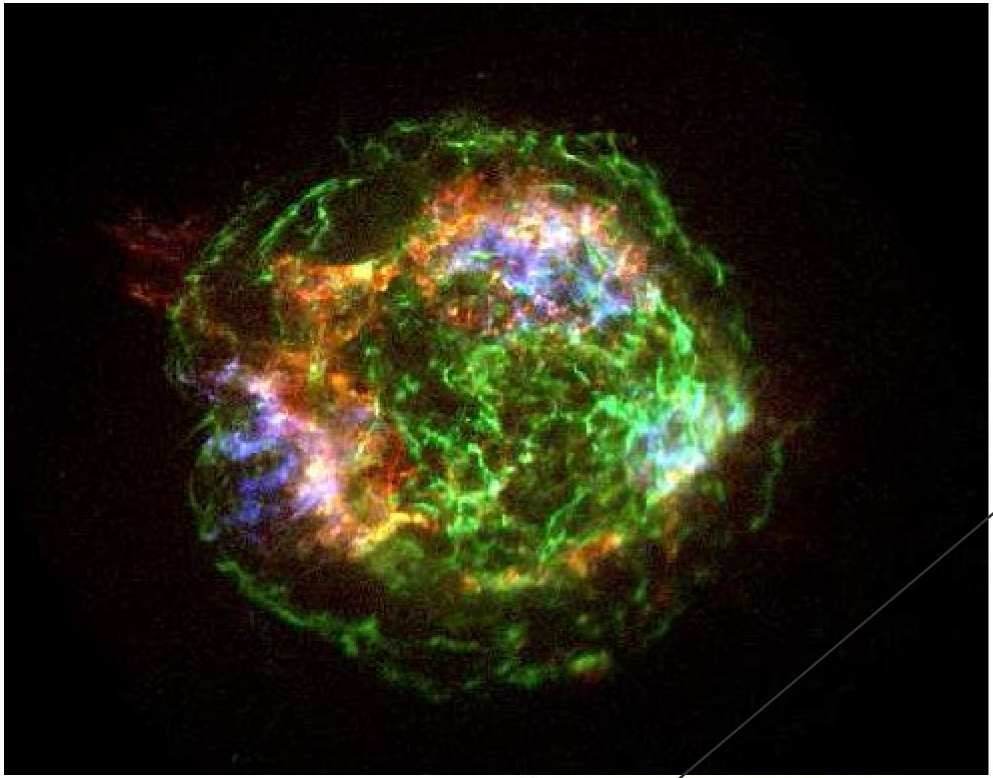
(strong initial magnetic field, simple EoS, no neutrino transport



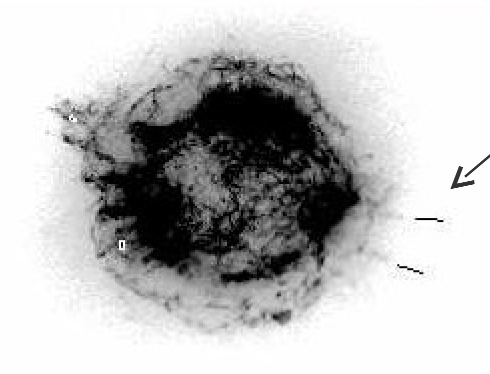
Rotational axis and jet axes are aligned!

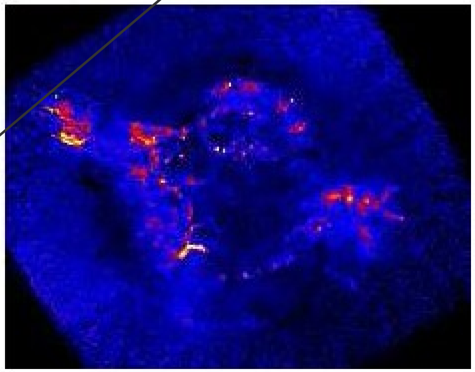
Cassiopea A- supernova with jets-an example of the magnetorotational supernova

(Hwang et al. ApJL, 2004, 615, L117)



1 million seconds Chandra servey of Cas A.
Second jet was found.





Recent results

(in collaboration with K.Sato&K.Kotake)

Implementation of modified (Shen et al., 1998) equation of state.

Approximate treatment of electron captures and neutrino transport. (Kotake et.al.2003) . Neutrino leakage scheme.

$$Y_l = Y_e + Y_\nu$$

$$\frac{dY_e}{dt} = -\gamma_e$$ Equation for electron fraction

$$\frac{dY_l}{dt} = -\frac{Y_\nu}{\tau_{esc}}$$ Equation for lepton fraction

$$L_\nu = \int dV \left(\epsilon_\nu \frac{Y_\nu}{\tau_{esc}} \frac{\rho}{m_u} + \epsilon_\nu \gamma_e \frac{\rho}{m_u} \right)$$ - neutrino luminosity

Neutrino pressure was taken into account.

Recent results

(in collaboration with K.Sato&K.Kotake)

- Neutrino burst during core-collapse stage is very similar to previous result.

- Maximum neutrino luminosity is ~2.5 10(53) erg/sec at t~0.17sec.

- After core collapse angular velocity steeply decreases outwards.

- The MRI is developed as it was for ‘old’ equation of state.

- The MR supernova explosion energy is ~ 0.6 10(51) erg.

Conclusions

- Magnetorotational mechanism (MRM) produces enough energy for the core collapse supernova.
- The MRM is weakly sensitive to the equation of state and details of neutrino cooling mechanism.
- MR supernova shape depends on the configuration of the magnetic field and is always asymmetrical.
- MRI developes in MR supernova explosion.
- One sided jets and rapidly moving pulsars can appear due to MR supernovae.
- 3D simulations of MR supernova with full physics are necessary.

Thank you!