MAGNETOROTATIONAL SUPERNOVAE AND GRAVITATIONAL WAVES

S.G.Moiseenko(1), G.S.Bisnovatyi-Kogan(1,2),

(1)Space Research Institute of RAS, Moscow, Russia,

and

(2)National Research Nuclear University "MEPhI", Moscow, Russia

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

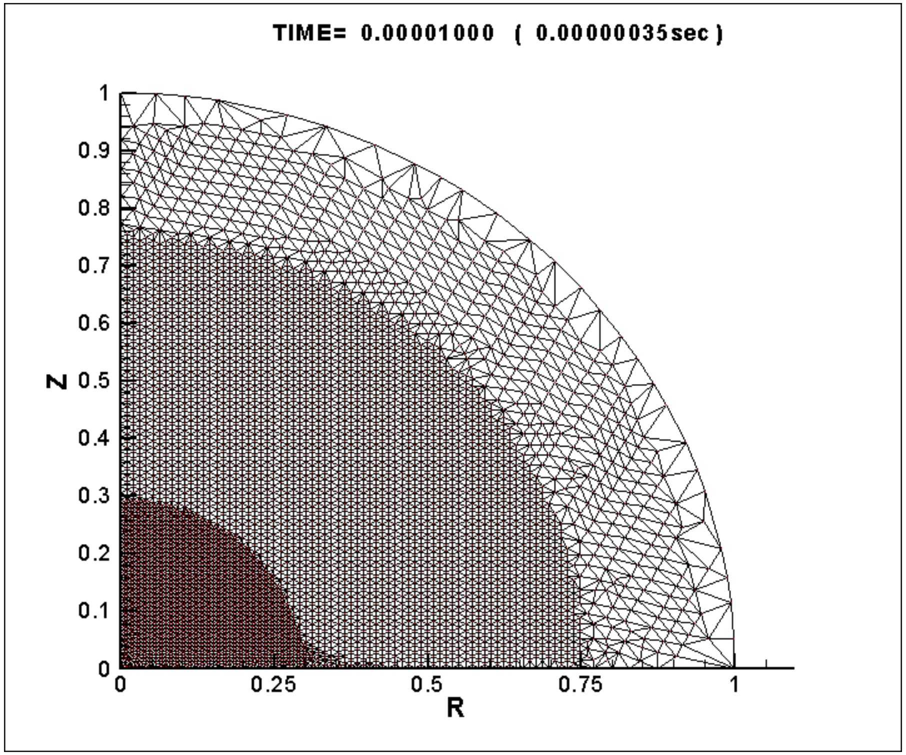
Amplification of magnetic fields due to differential rotation, angular momentum transfer by magnetic field. Part of the rotational energy is transformed to the energy of explosion.

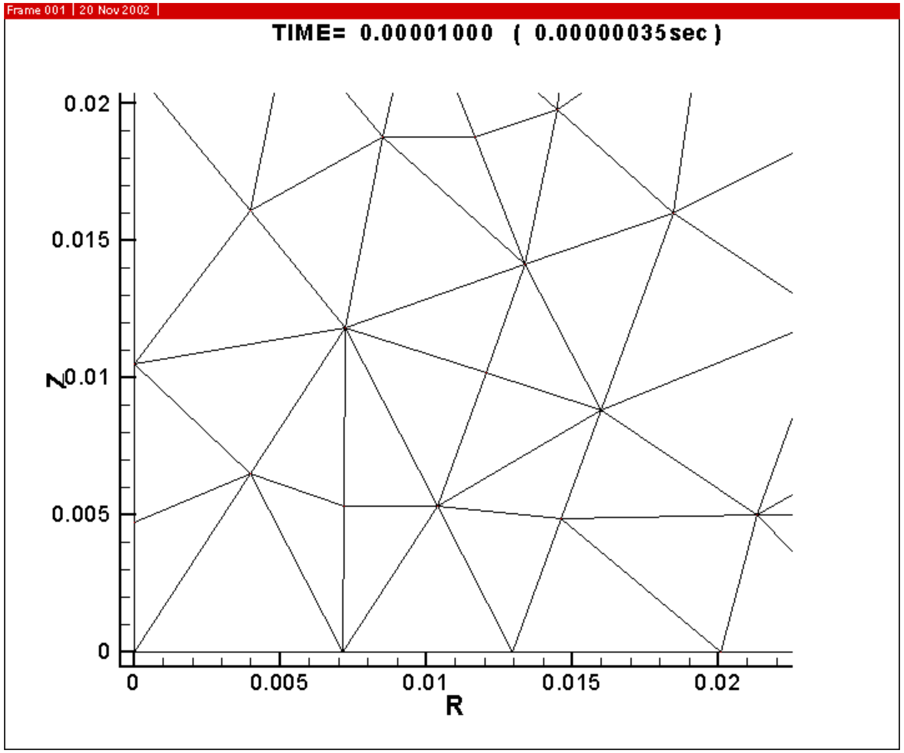
First 2D calculations: LeBlanck&Wilson (1970))(original article was submitted: September 25, 1969) ->too large initial magnetic fields. $E_{mag0} \sim E_{grav} \Rightarrow$ axial jet

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, Moesta 2015…

Magnetorotational mechanism for core-collapsed supernova is one of the most realistic.

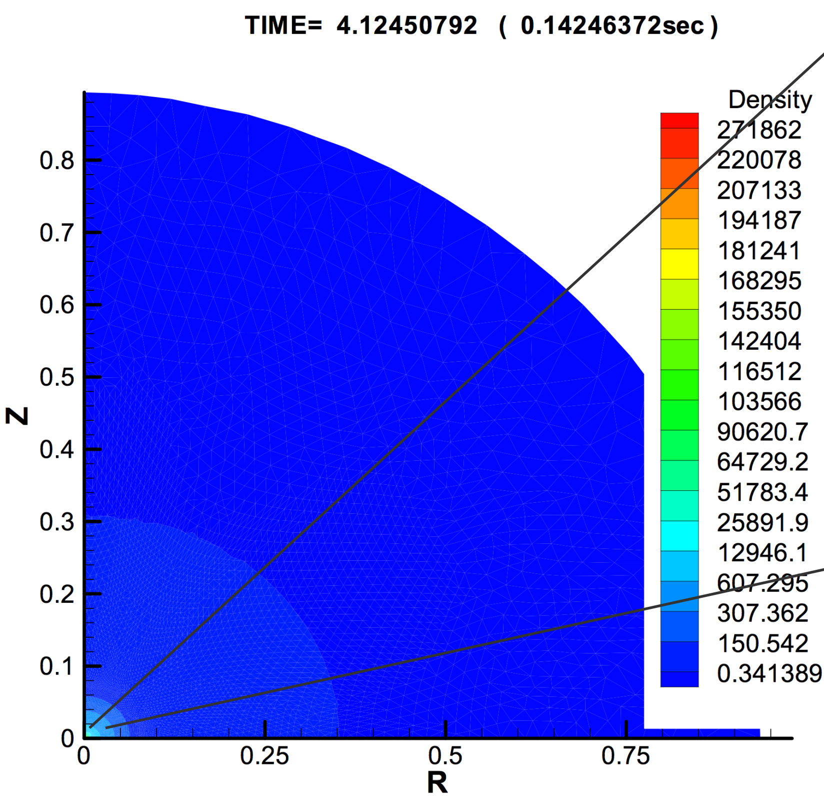
Triangular grid evolution example (Ardelyan et.al.)

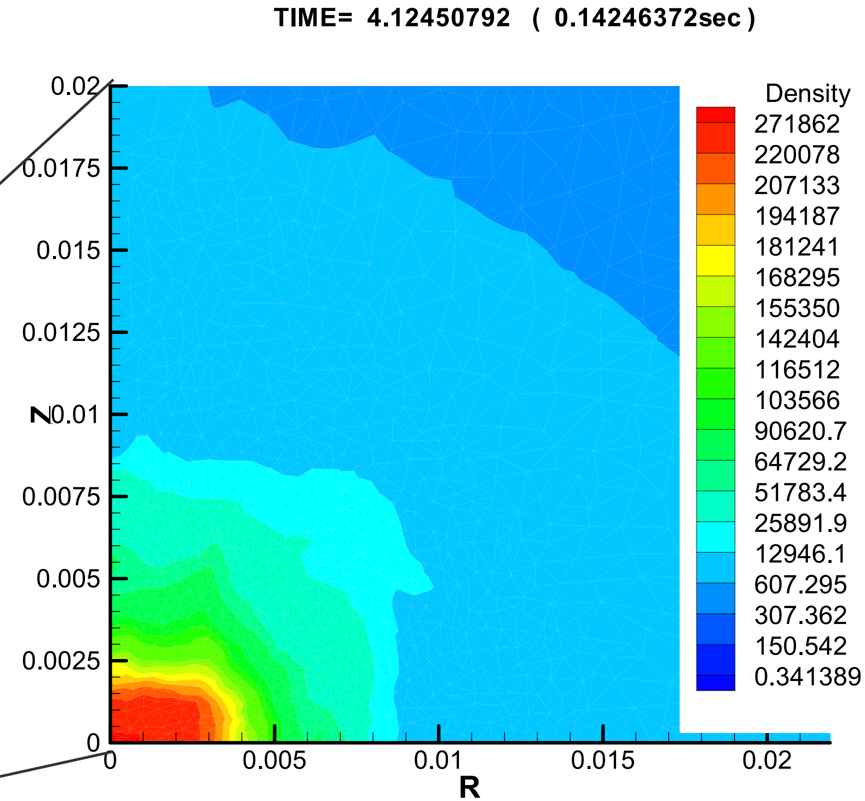




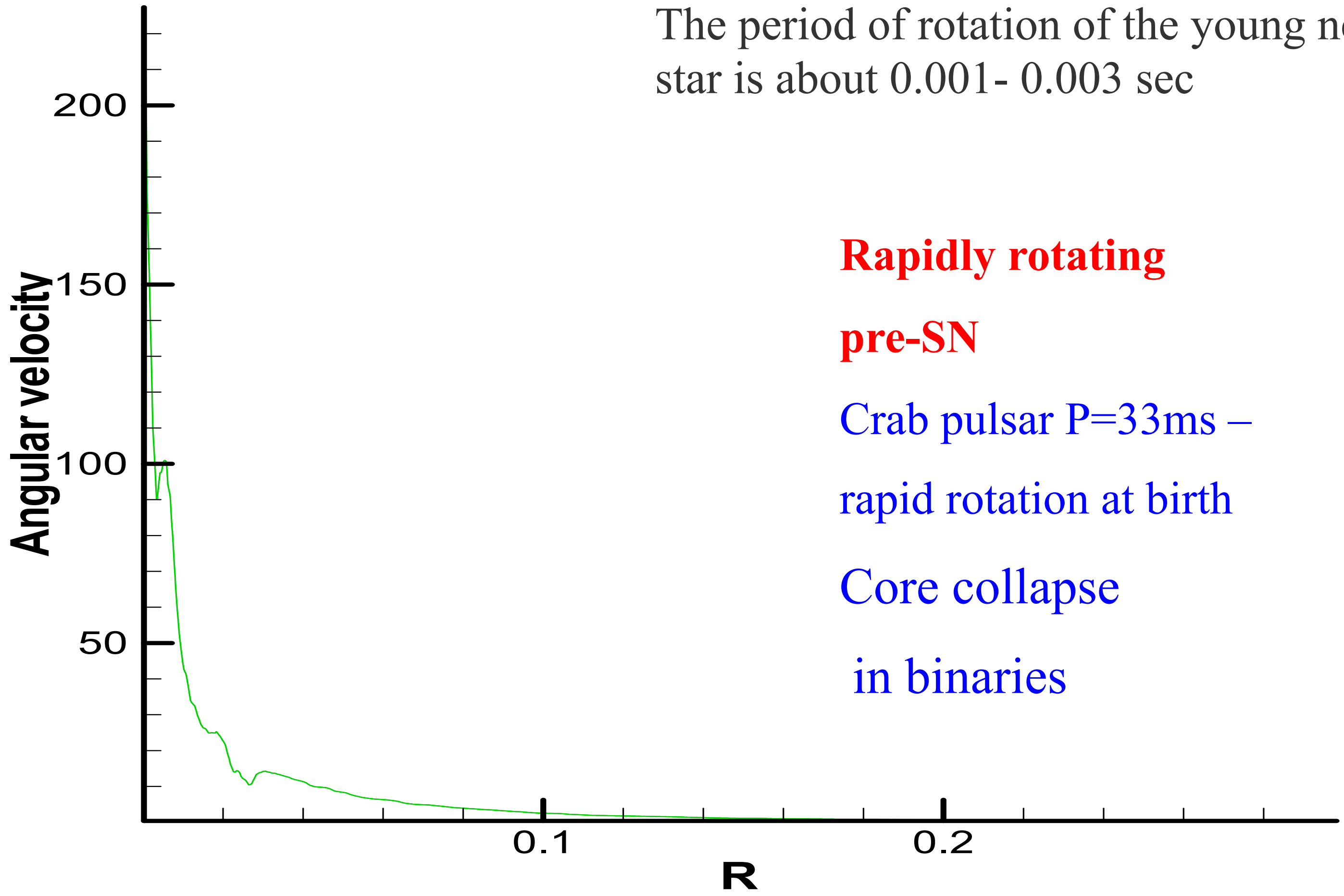
Maximal compression state

Max. density = $2.5 \cdot 10^{14} g/cm^3$





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

Crab pulsar P=33ms –

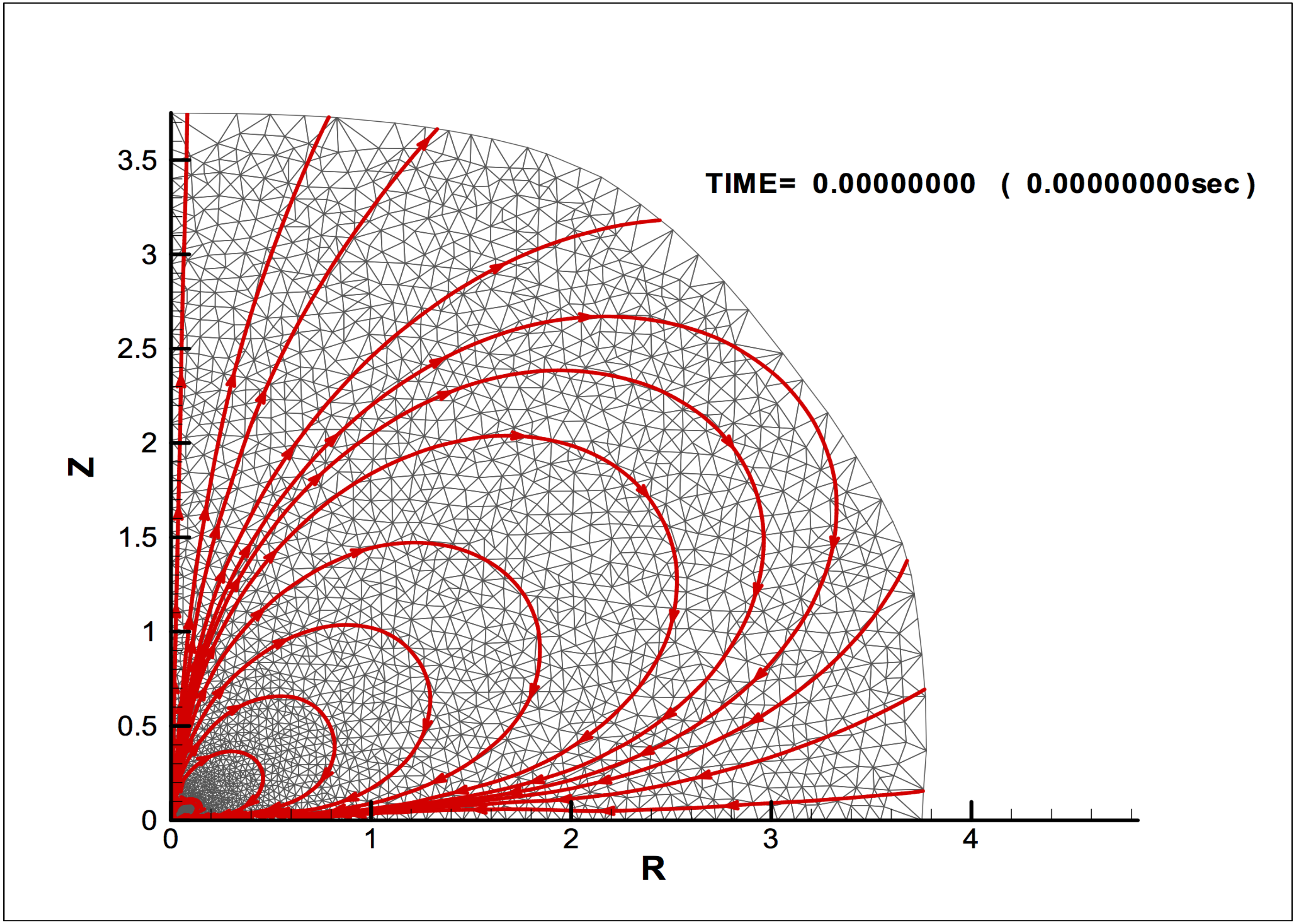
rapid rotation at birth

Core collapse

in binaries

Initial magnetic field –quadrupole-like symmetry

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



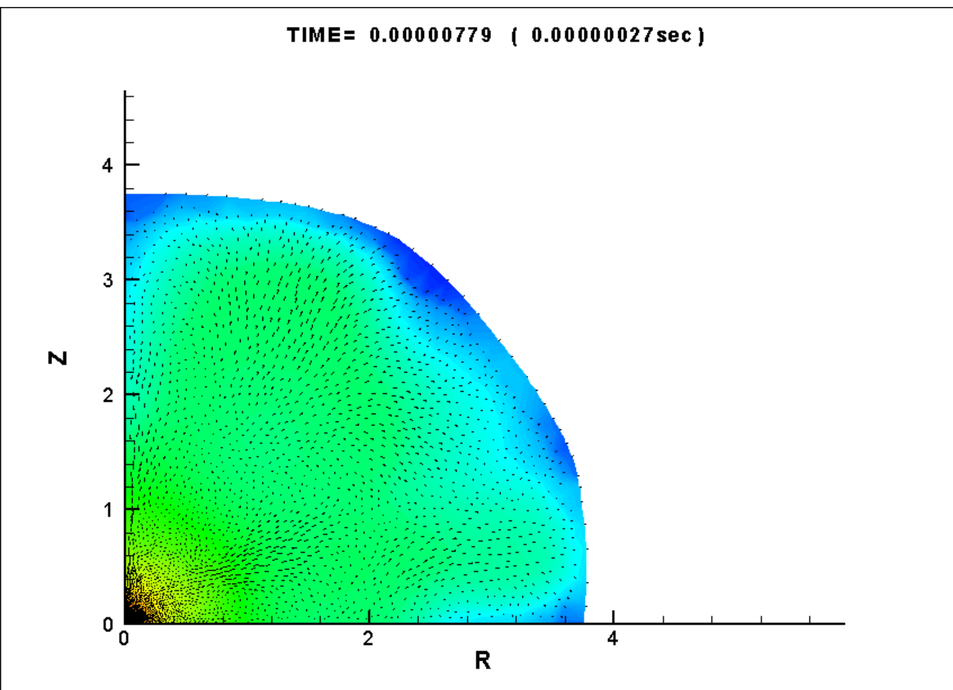
Magnetorotational supernova explosion

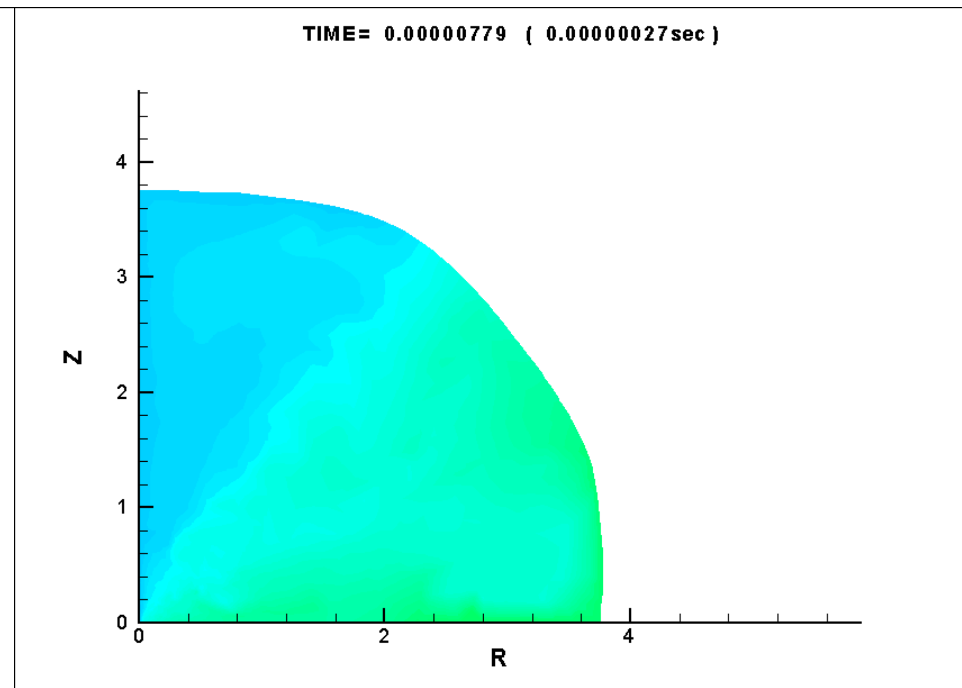
quadruple field

N.V.Ardeljan, SM, G.S.Bisnovatyi-Kogan MNRAS, 2005, 359, 333

Temperature and velocity field

Specific angular momentum rV_{φ}

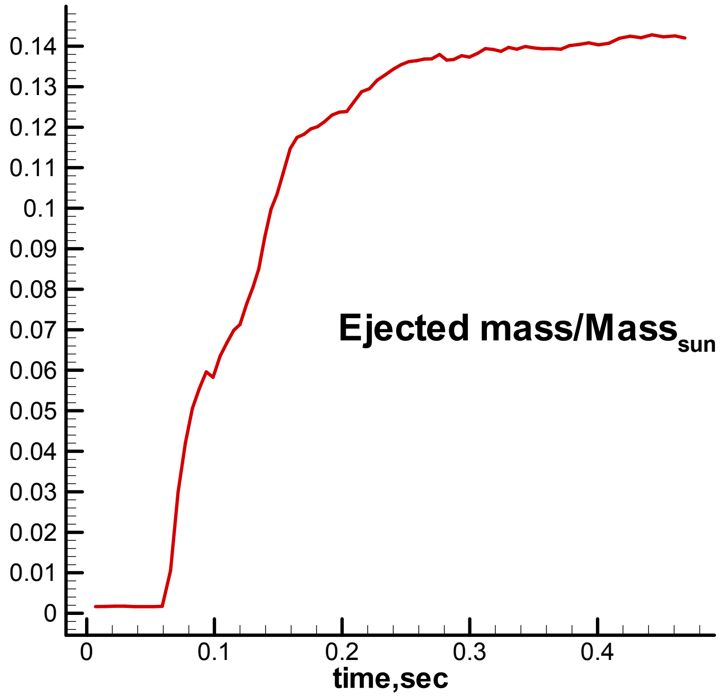


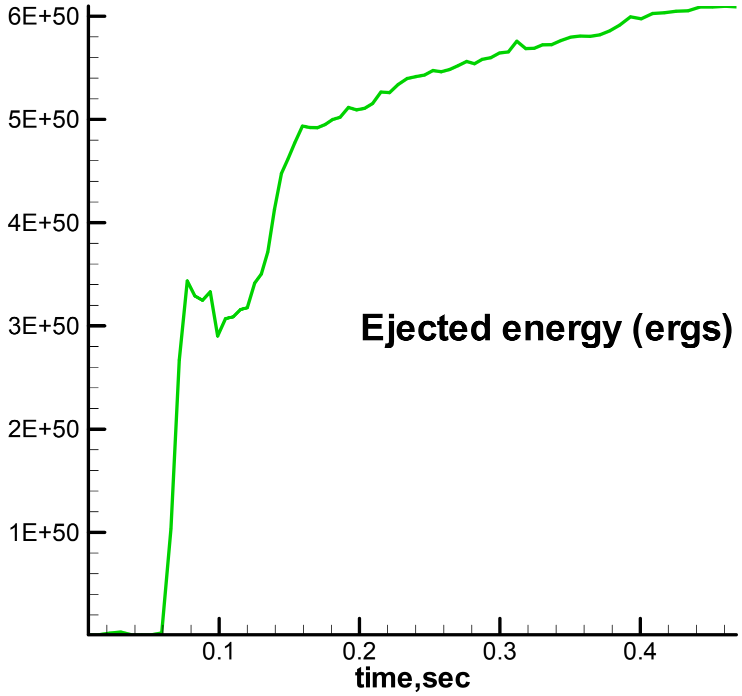


Ejected energy and mass

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

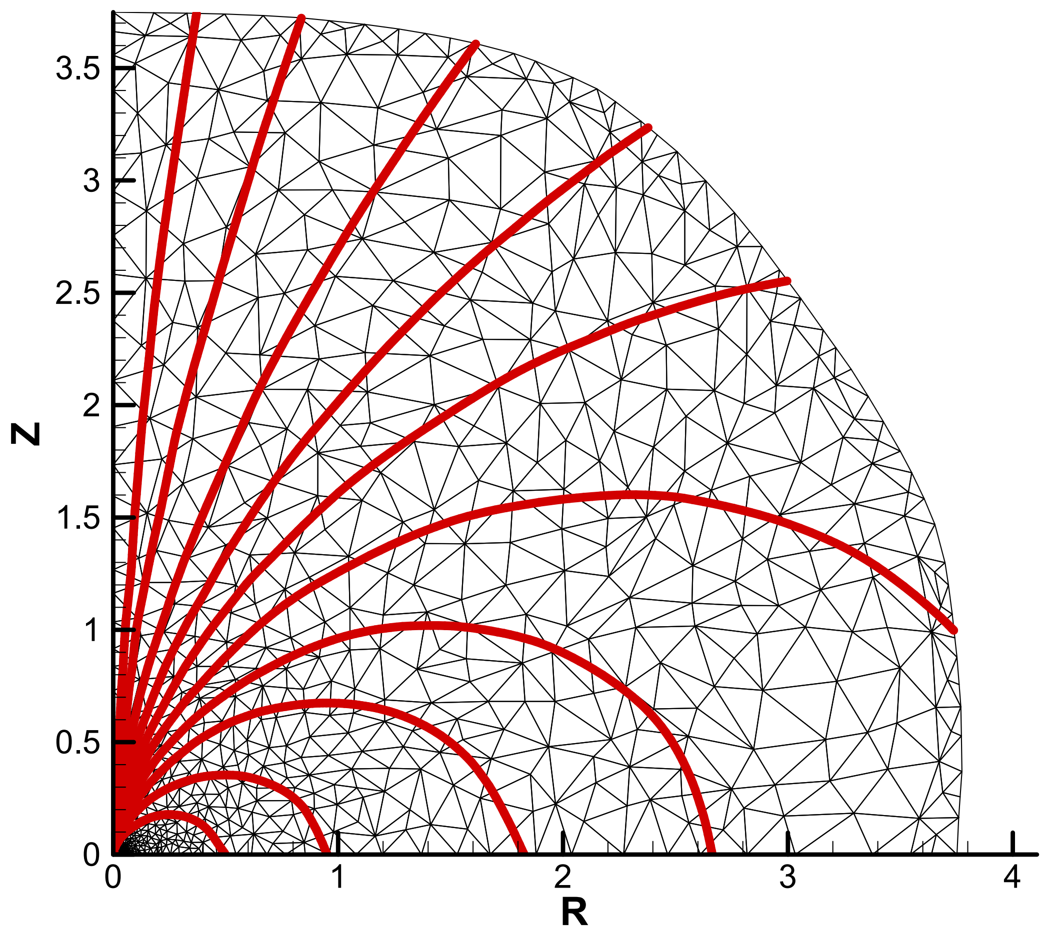
Particle is considered "ejected" –
if its kinetic energy is greater than its potential energy





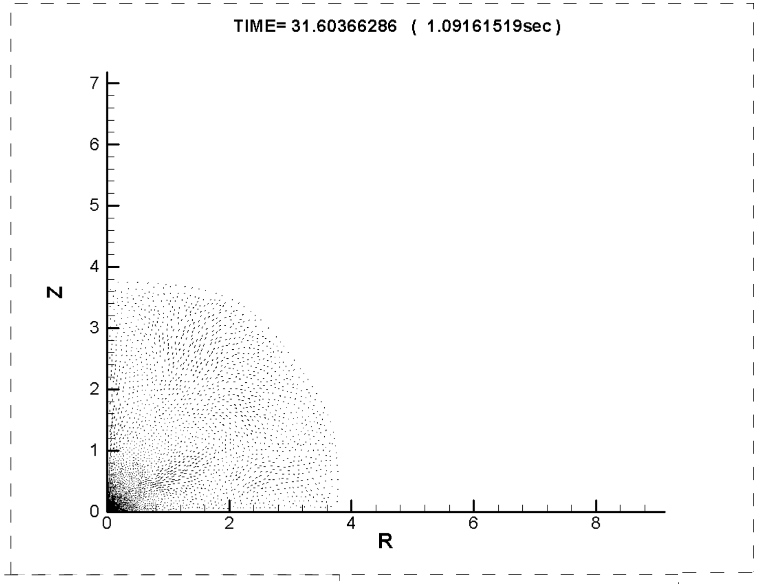
Initial magnetic field – dipole-like symmetry

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



Magnetorotational supernova explosion quadruple field

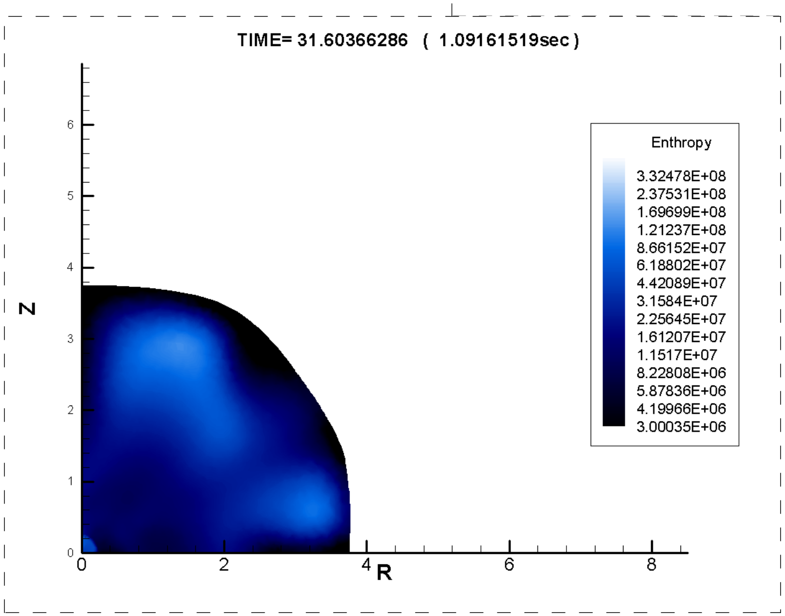
jet formation

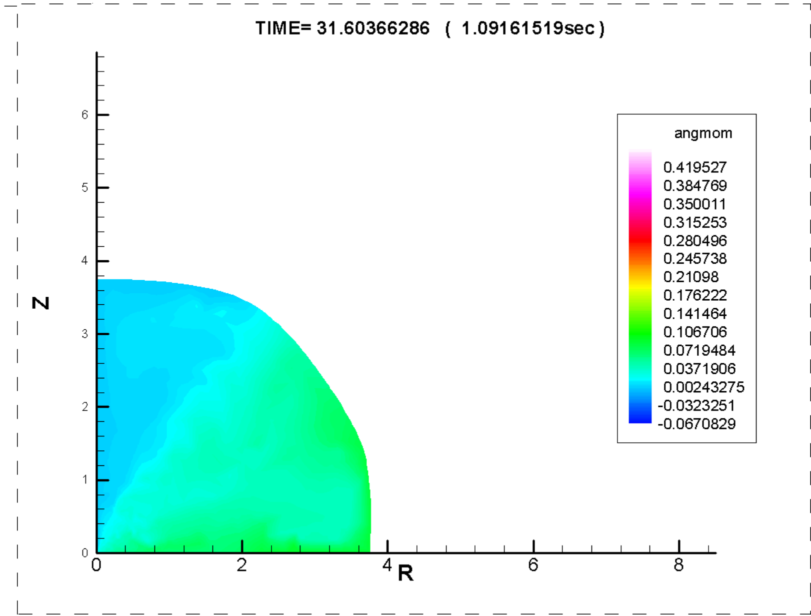


Velocity field

Entropy

Specific angular momentum



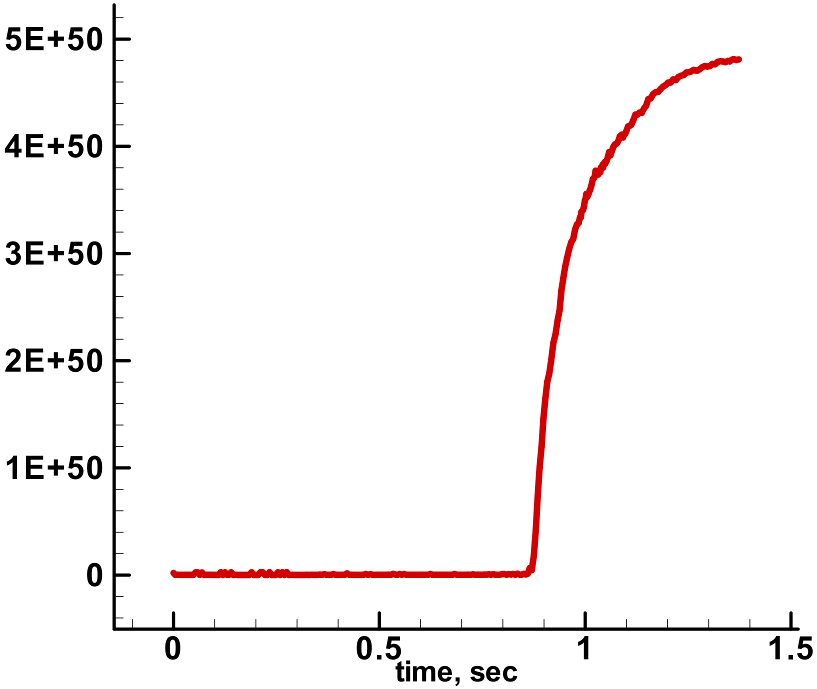


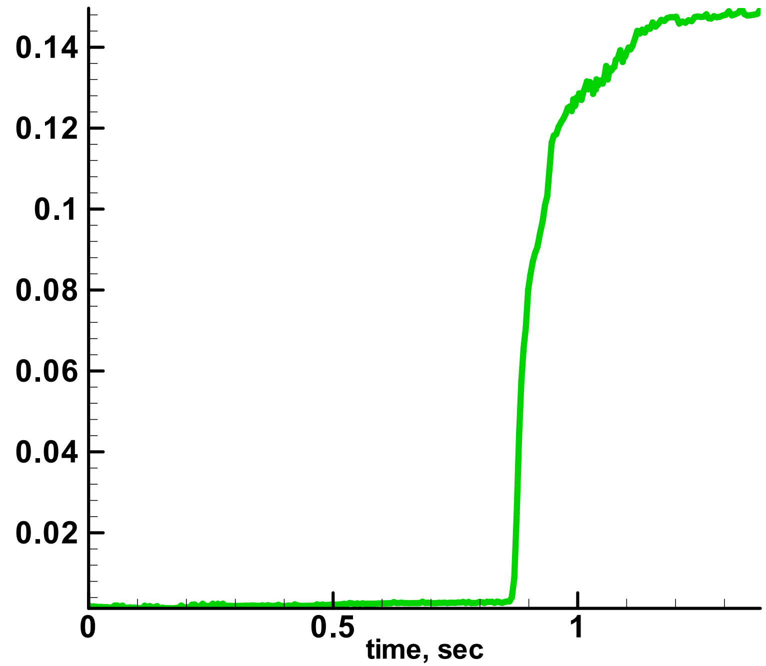
Ejected energy and mass (dipole)

Ejected energy $\approx 0.5 \cdot 10^{51}\, erg$

Ejected mass $\approx 0.14 M_{\odot}$

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

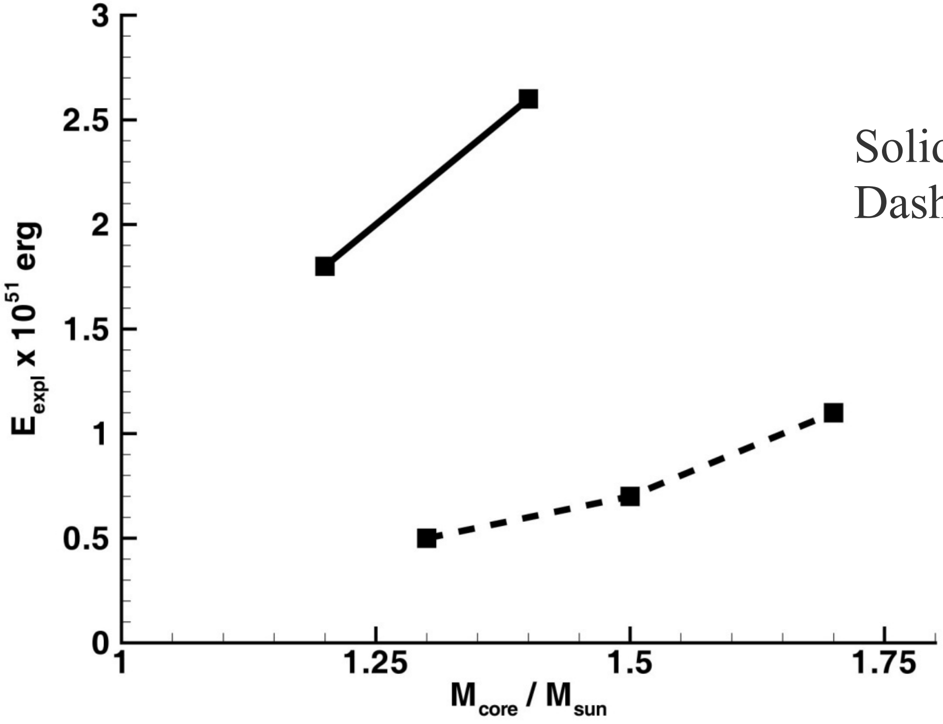




MR supernova – different core masses

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

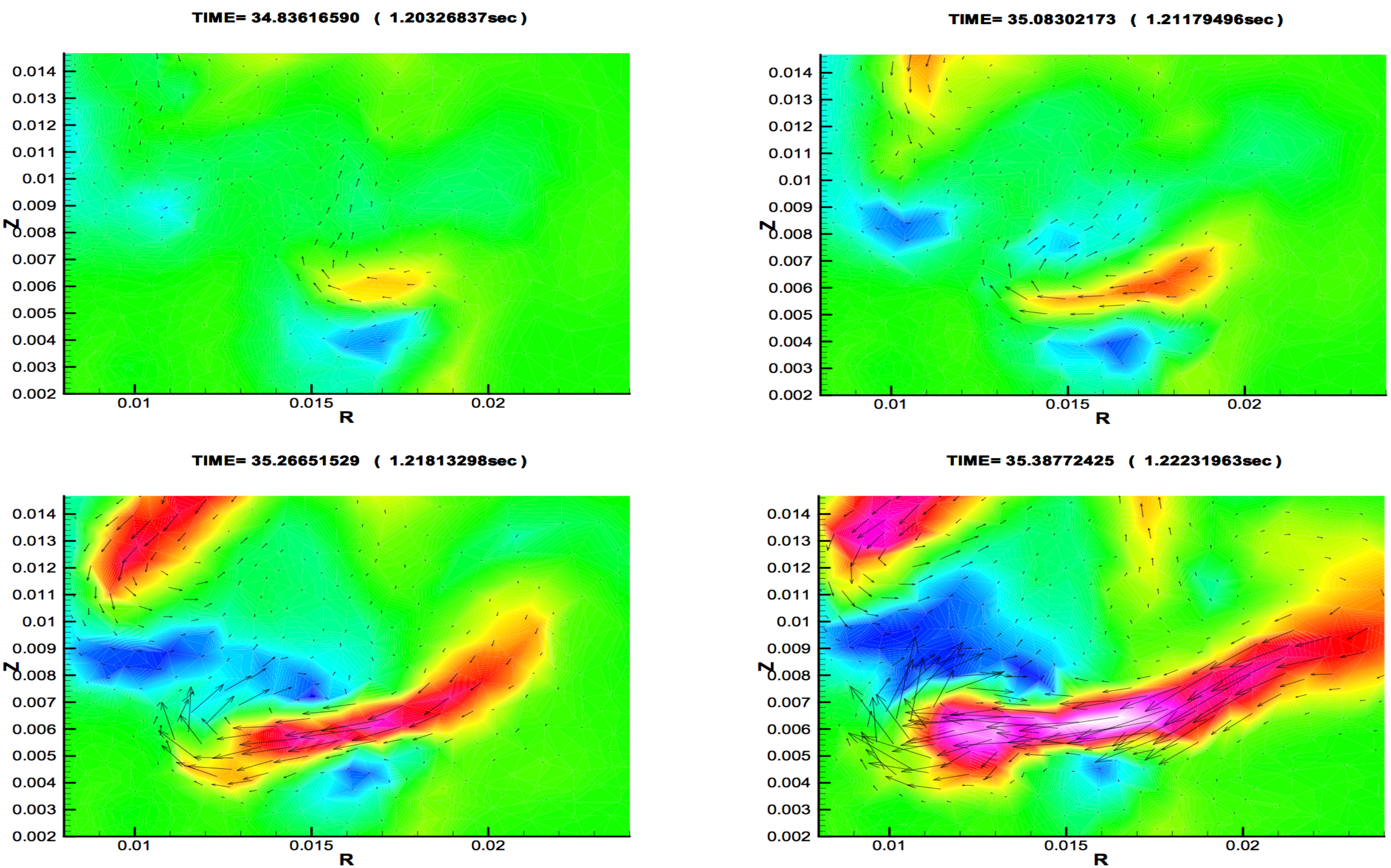
Dependence of the MR supernova explosion energy on the core mass and initial angular momentum



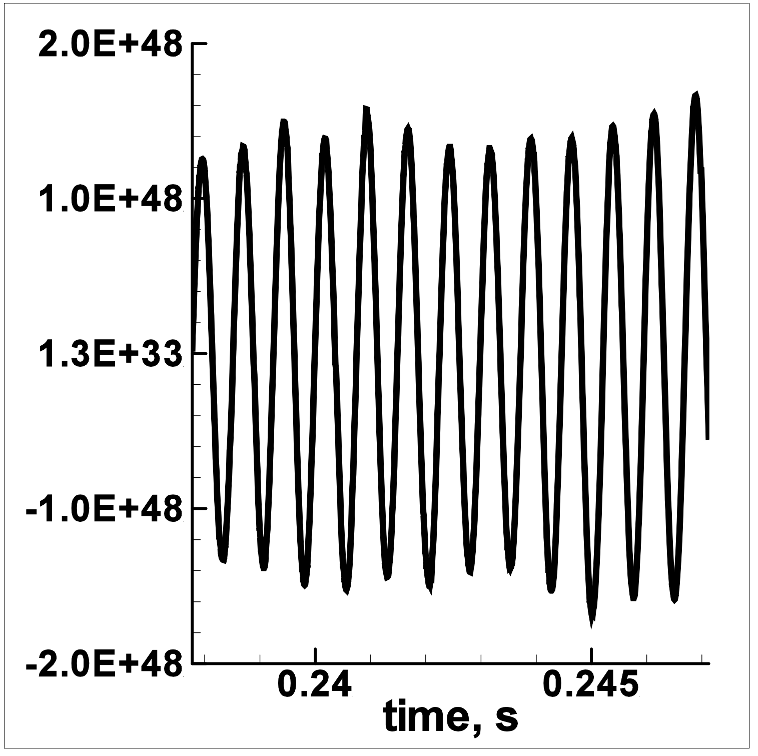
Solid line – initial angular velocity = 3.53s^{-1}
Dashed line - initial angular velocity = 2.52s^{-1}

Magnetorotational instability

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



Time evolution of poloidal kinetic core energy
in MR supernova explosion



Quadrupole moment of the collapsing star

$$D_{\alpha\beta} = \int \rho(\mathbf{r}, t)(3r_\alpha r_\beta - \delta_{\alpha\beta} r^2)$$

The gravitational waves power can be calculated as

$$\dot{E} = \frac{G}{45c^5} \dddot{D}_{\alpha\beta} \dddot{D}^{\alpha\beta}$$

GENERIC GRAVITATIONAL WAVE SIGNALS FROM THE COLLAPSE OF ROTATING STELLAR CORES

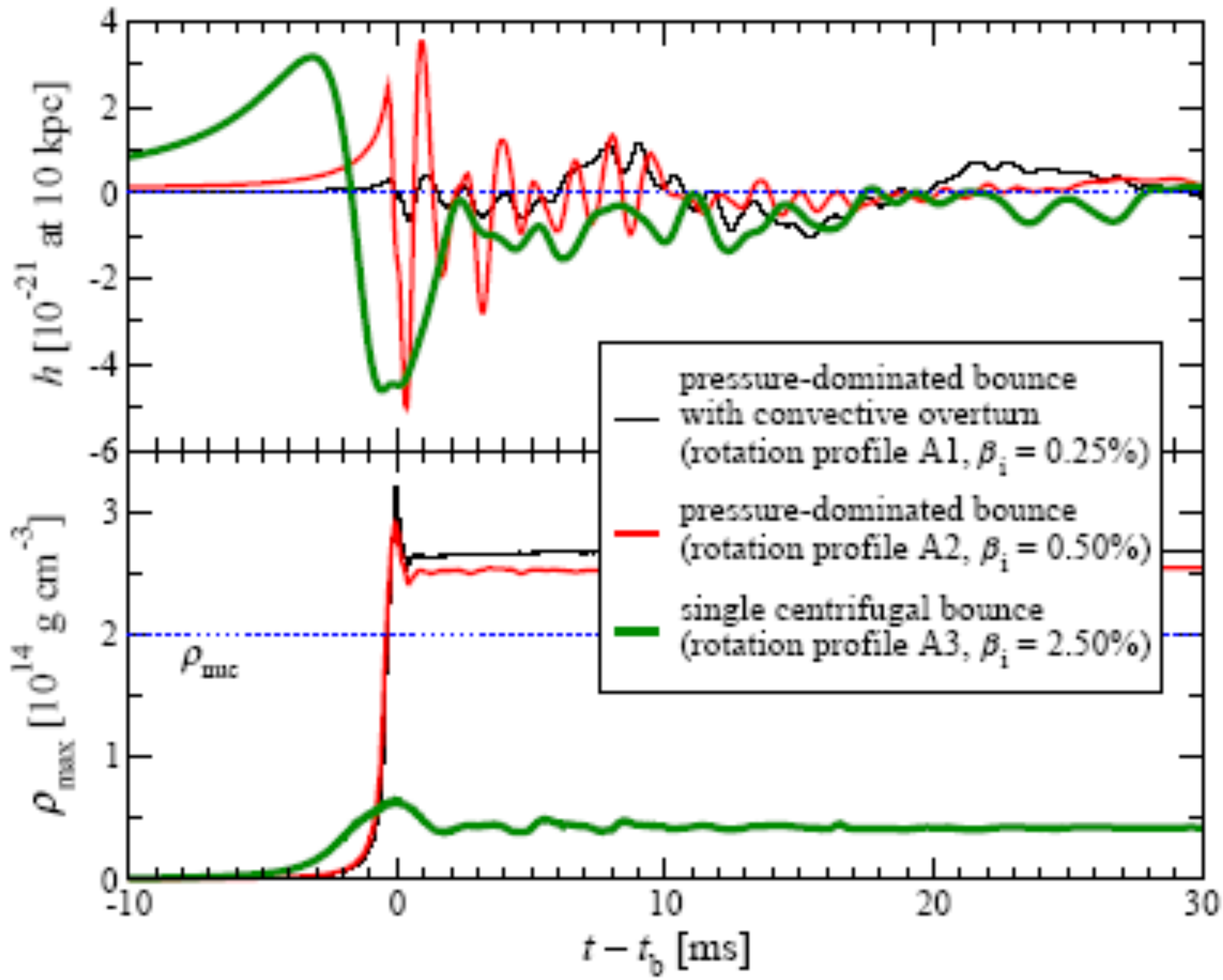
H. DIMMELMEIER
Department of Physics, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece

C. D. OTT
Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ 85721, U.S.A.

H.-T. JANKA, A. MAREK, E. MÜLLER
Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany

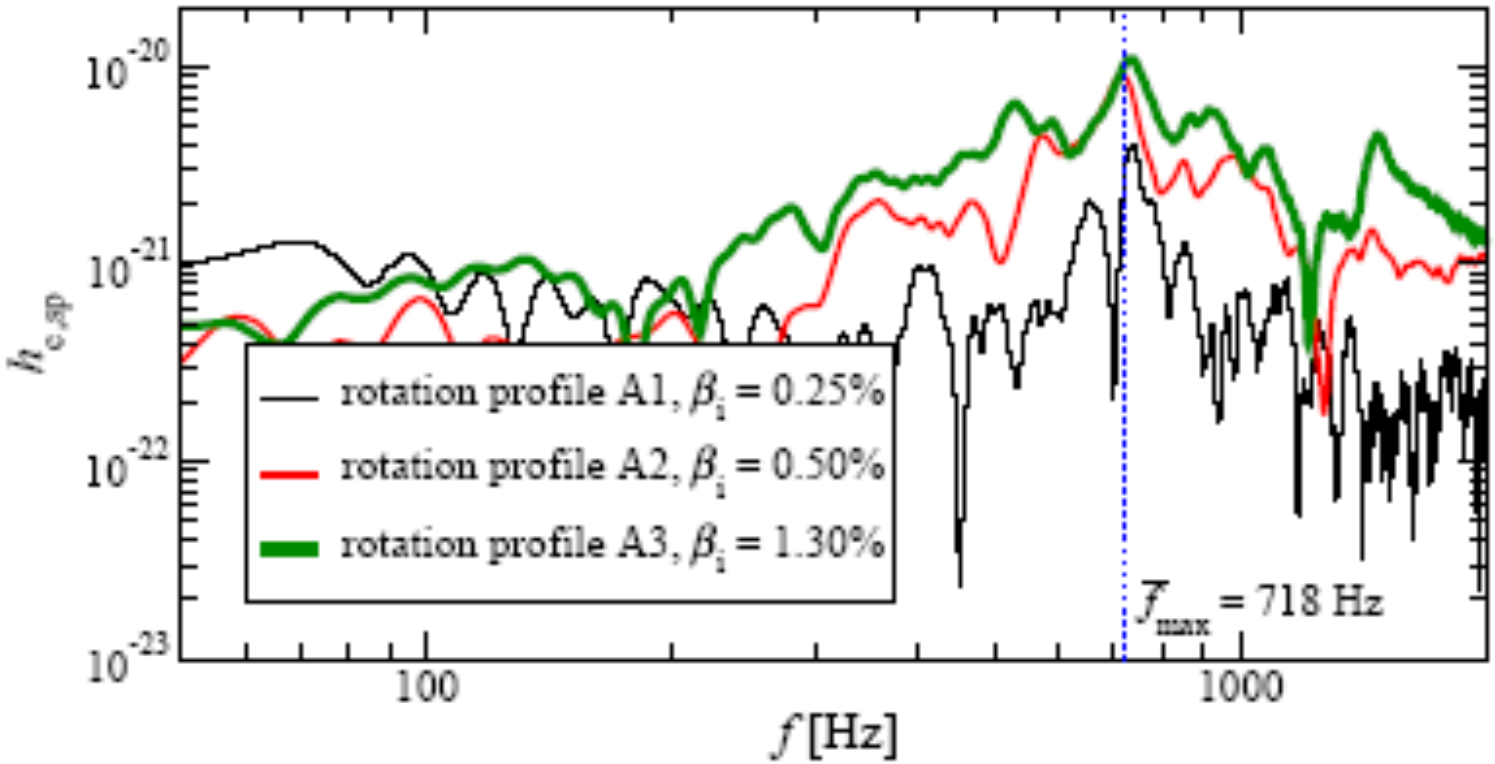
arXiv:070526755

Inferring the core-collapse supernova explosion mechanism with gravitational waves
Jade Powell, Sarah E. Gossan, Joshua Logue, Ik Siong Heng
arXiv:1610.05573



Dimmelmeier et al., 2007

Time evolution of the GW amplitude h and maximum density for three representative models with different rotation profiles and initial rotation rates β i, at a distance d = 10 kpc .



Dimmelmeier et al., 2007

Characteristic GW strain spectra h_c,sp at a distance d = 10 kpc to the source for three representative models in GR with microphysical EoS and deleptonization that do not undergo centrifugal bounce. As for most other models the individual maxima f_max of their frequency spectrum is very close to fmax ≃ 718 Hz.

For the simplicity one can consider the collapse of homogeneous rigidly rotating dust cloud

The GW power from an oblate spheroid with a mass M, a major semi-axis A, and a minor semi-axis C can be written as [17, 18]

$$L_{\mathrm{GW}} = \frac{2}{375}\frac{GM^2}{c^2}(\dddot{A^2} - \dddot{C^2})^2 . \qquad (1)$$

In the case of collapse of a nonrotating body, the emitted GW energy is given in [16] as

$$E_{\mathrm{GW}} = 0.0370\left(\frac{r_{\mathrm{g}}}{A_{\mathrm{min}}}\right)^{7/2} Mc^2 \lesssim 10^{51}\ \mathrm{erg}. \qquad (2)$$

Here, $r_{\mathrm{g}} = 2GM/c^2$ is the Schwarzschild radius and A_{min} is the minimal value of the major semi-axis. In the case of rapid rotation, less energy is emitted because the rotation leads to a bounce (at $C = 0$) with a lower surface density and higher value of A_{min}:

$$E_{\mathrm{GW}} = 0.109\left(\frac{r_{\mathrm{g}}}{A_{\mathrm{min}}}\right)^{7/2} Mc^2 \gtrsim 10^{45}\ \mathrm{erg}. \qquad (3)$$

GRAVITATIONAL RADIATION FROM STELLAR COLLAPSE

T. X. Thuan and J. P. Ostriker

The Astrophysical Journal, 191:L105–L107, 1974 August 1

Gravitational radiation from a star collapsing into a disk

I. D. Novikov

Astron. Zh. 52, 657–659 (May–June 1975)

Maximum GW radiation is during the bounce

$$E_{GW} \approx kMc^2 \left(\frac{r_g}{A_{min}}\right)^{7/2} \frac{A_{min}}{C_{min}} .$$

A- the large axis, C_{min} – minimal value of C, A/C_{min} may be >> 1, K~0.01

The formal upper limit:

$$\Delta\varepsilon_{max} \approx M(dC/dt)^2 \approx Mc^2 r_S/A,$$

Never reached

We estimated energy of GW at the bounce stage in our simulations

G.S. Bisnovatyi-Kogan, SM, Physics Uspekhi, (2017)

M – is the mass
Of the star inside
isodense specified

$$
\begin{aligned}
&A_{\min} = 5.5 \times 10^5\ \text{cm}\,, \quad \frac{C_{\min}}{A_{\min}} = 0.50 \quad \text{for} \quad M = 0.24 M_{\odot}\,, \\
&\qquad E_{\text{GW}} = 1.3 \times 10^{49}\ \text{erg}\,, \\
&A_{\min} = 5.3 \times 10^6\ \text{cm}\,, \quad \frac{C_{\min}}{A_{\min}} = 0.79 \quad \text{for} \quad M = 0.3 M_{\odot}\,, \\
&\qquad E_{\text{GW}} = 1.2 \times 10^{46}\ \text{erg}\,, \\
&A_{\min} = 9.5 \times 10^6\ \text{cm}\,, \quad \frac{C_{\min}}{A_{\min}} = 0.83 \quad \text{for} \quad M = 0.5 M_{\odot}\,, \\
&\qquad E_{\text{GW}} = 5.4 \times 10^{45}\ \text{erg}\,, \qquad (9) \\
&A_{\min} = 3 \times 10^7\ \text{cm}\,, \quad \frac{C_{\min}}{A_{\min}} = 0.89 \quad \text{for} \quad M = 0.8 M_{\odot}\,, \\
&\qquad E_{\text{GW}} = 7.4 \times 10^{44}\ \text{erg}\,, \\
&A_{\min} = 4.2 \times 10^7\ \text{cm}\,, \quad \frac{C_{\min}}{A_{\min}} = 0.94 \quad \text{for} \quad M = M_{\odot}\,, \\
&\qquad E_{\text{GW}} = 5.9 \times 10^{44}\ \text{erg}\,.
\end{aligned}
$$

Grav. Energy
is defined by the mass
inside the isodense
with max. compression

The related amplitude of GW at distance r from collapsing object
(Landau L D, Lifshitz E M The Classical Theory of Fields,
Saenz R A, Shapiro S L Astrophys. J. 221 286 (1978))

$$h_{\phi\phi} = -h_{\theta\theta} = \frac{GM}{5rc^4}\frac{A_{\min}^2}{(\Delta t)^2}$$

The characteristic bounce time is about $\Delta t \sim 0.7-0.8$ms

For the maximum GW flux corresponding to M=0.24Msun we can get:

$$h = h_{\phi\phi} = -h_{\theta\theta} = \frac{6.7\times10^{-8}(0.48\times10^{33})}{5rc^4}$$

$$\times\frac{(5.5\times10^5)^2}{(0.75\times10^{-3})^2} \approx 1.4\times10^{-22}\,\frac{10\ \text{kpc}}{r}\,.$$

Conclusions

1. Core-collapsed supernovae can explode as magnetorotational supernovae.
2. In addition to merging, GW are radiated during the first bounce in non-spherical core collapse (e.q. supernovae), frequency 100-1000 Hz.