Gravitational waves and core-collapse supernovae

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

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

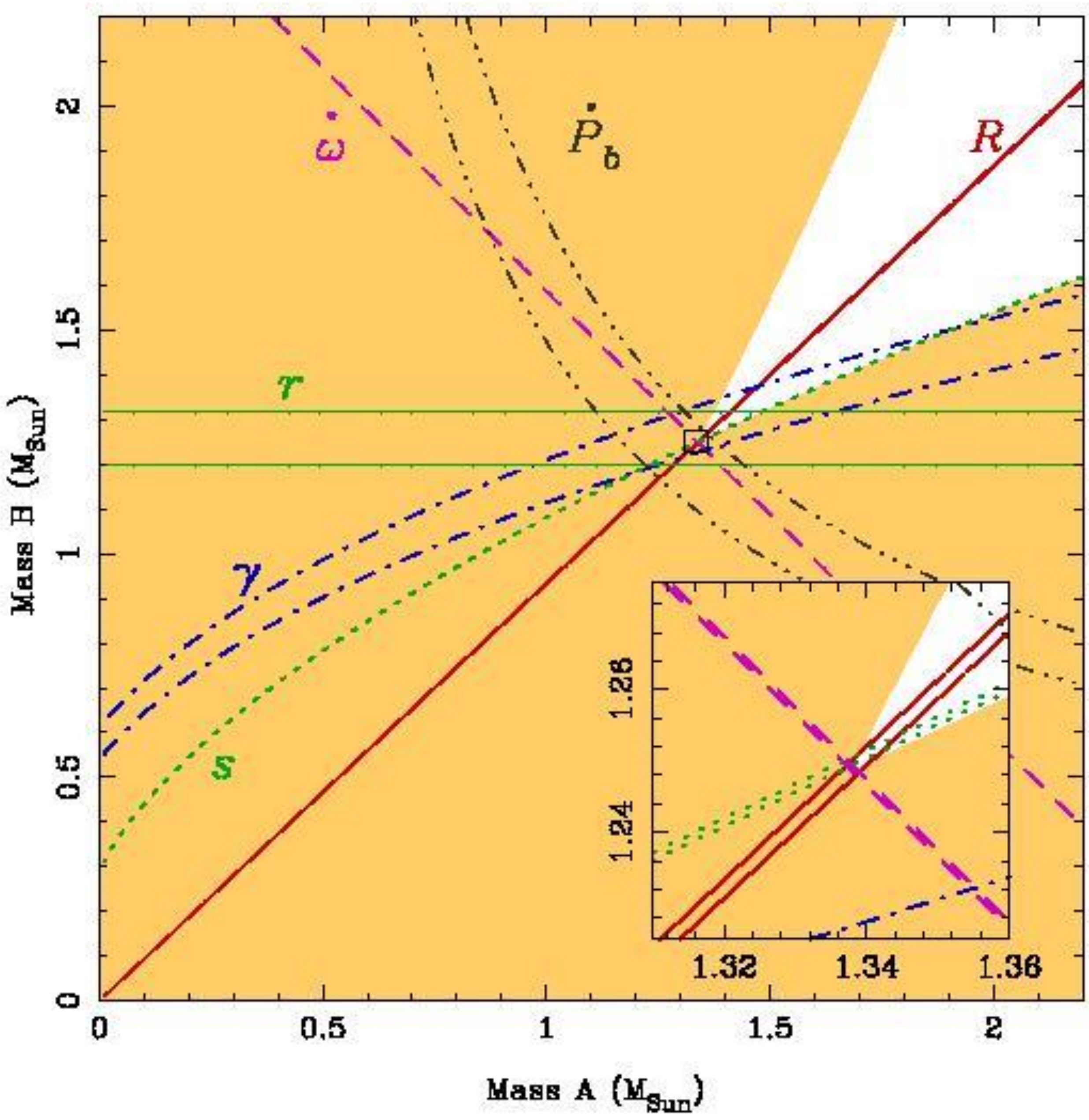
(2)National Research Nuclear University “MEPhI”, Moscow, Russia

In collaboration with

S.G.Moiseenko, N.V. Argelyan

GRBs and other transient sources:
25 Years of Konus-Wind Experiment
(KW25)
9-13 September 2019

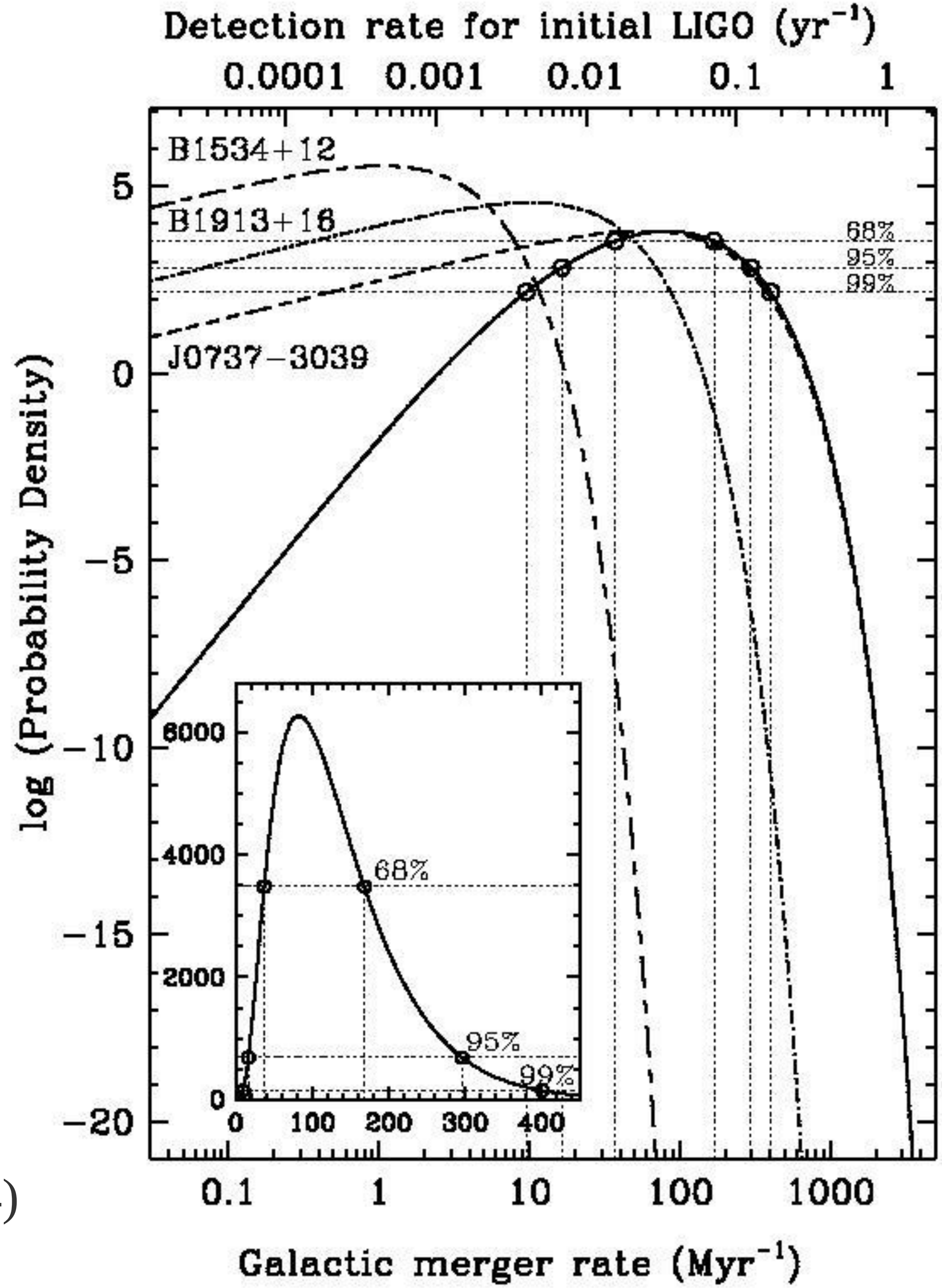
Binary pulsars diagram



MERGING of COMPACT STARS in CLOSE BINARIES (LIGO-VIRGO)

Probability density function that represents our expectation that the actual DNS binary merger rate in the Galaxy (bottom axis) and the predicted initial LIGO rate (top axis) take on particular values, given the observations. The solid line shows the total probability density along with those obtained for each of the three binary systems (dashed lines). **Inset**: Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale.

Kalogera V et al. Astrophys. J. Lett. 601 L179; 614 L137 (2004)

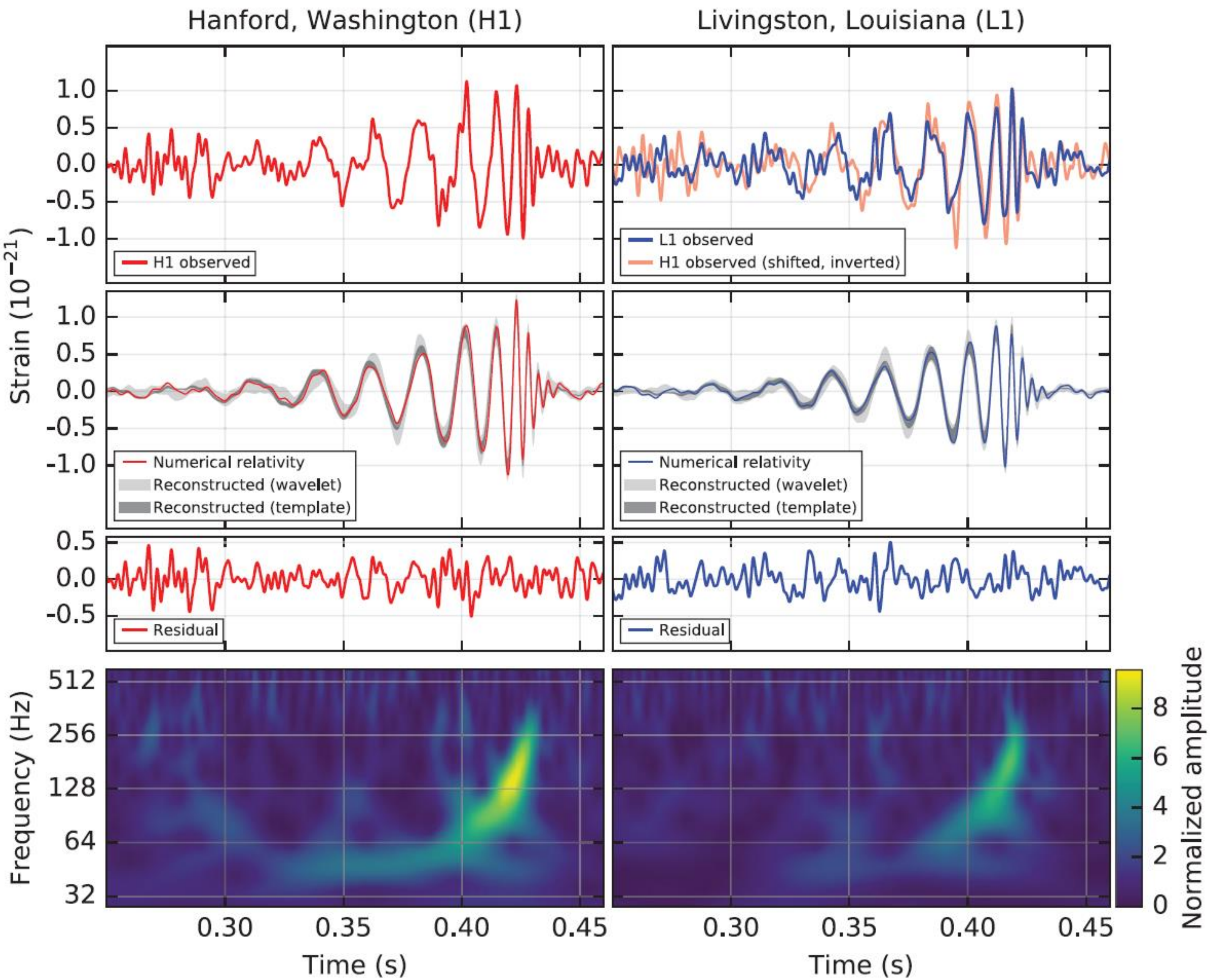


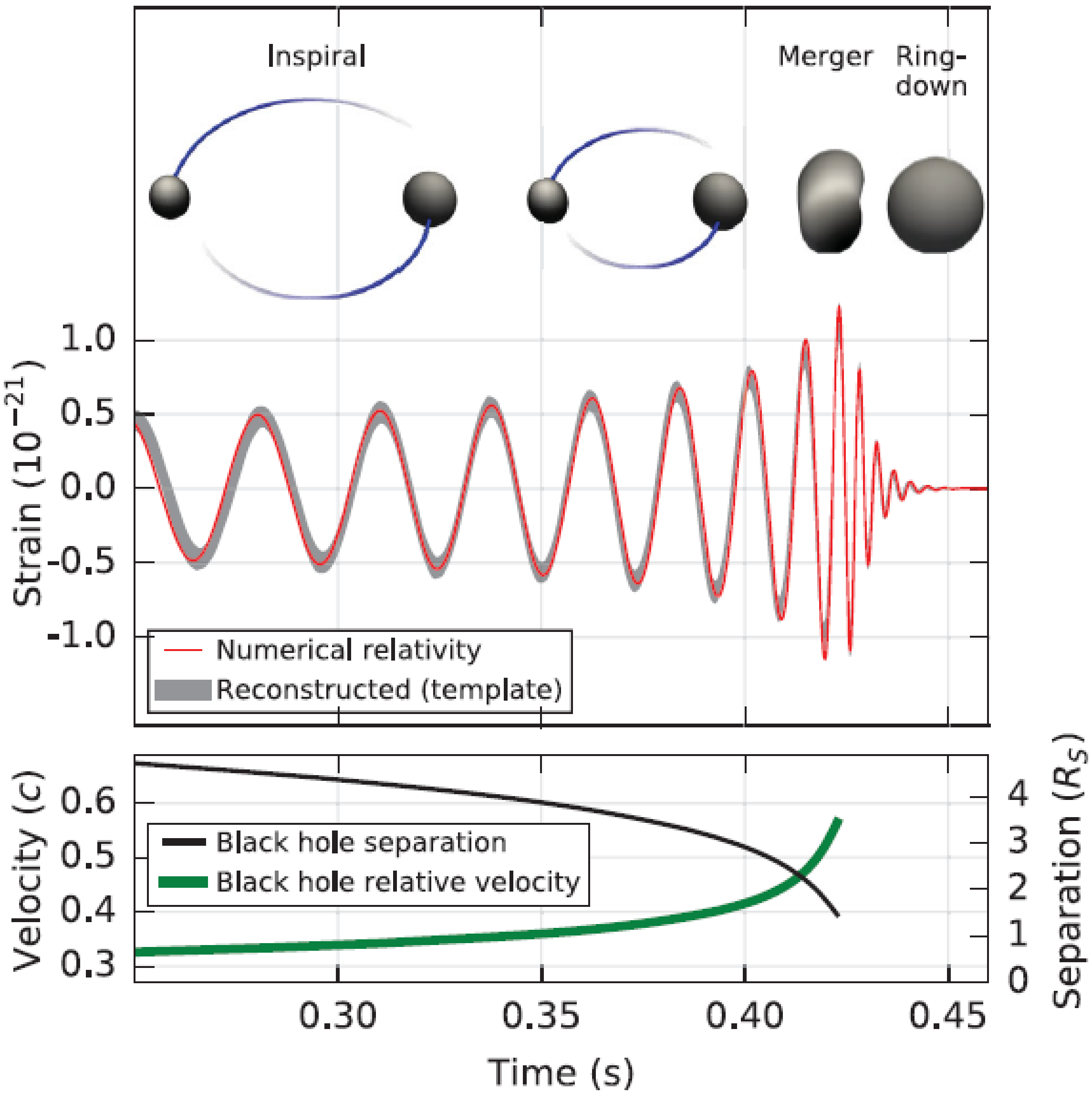
For the model of pulsar evolution, the mean galactic merging rate of BNS systems is **R~83/ Myr**. The 68%- and 95%-confidence level intervals are 40 ± 140 and 20 ± 290 /Myr, respectively. The expected detection rate of a gravitational-wave pulse from neighboring galaxies is **0.035** and **190** events per year for the initial (the detection limit **20 Mpc**) and advanced (the detection limit 350 Mpc) LIGO interferometers, respectively. The corresponding 95%-confidence intervals are **0.007 ± 0.12 and 40 ± 660** events per year, respectively. The discovery of the double pulsar J0737-3039 increased **R** by **6.4 times** compared to earlier calculations, because it dominates in computing the total probability, as seen in Fig.

Examination of a broader class of evolutionary models of pulsars showed that in all cases, accounting for the double pulsar J0737 ± 3039 increases the BNS merging rate by 6 - 7 times, although the rates can differ by more than **50 times** in individual cases

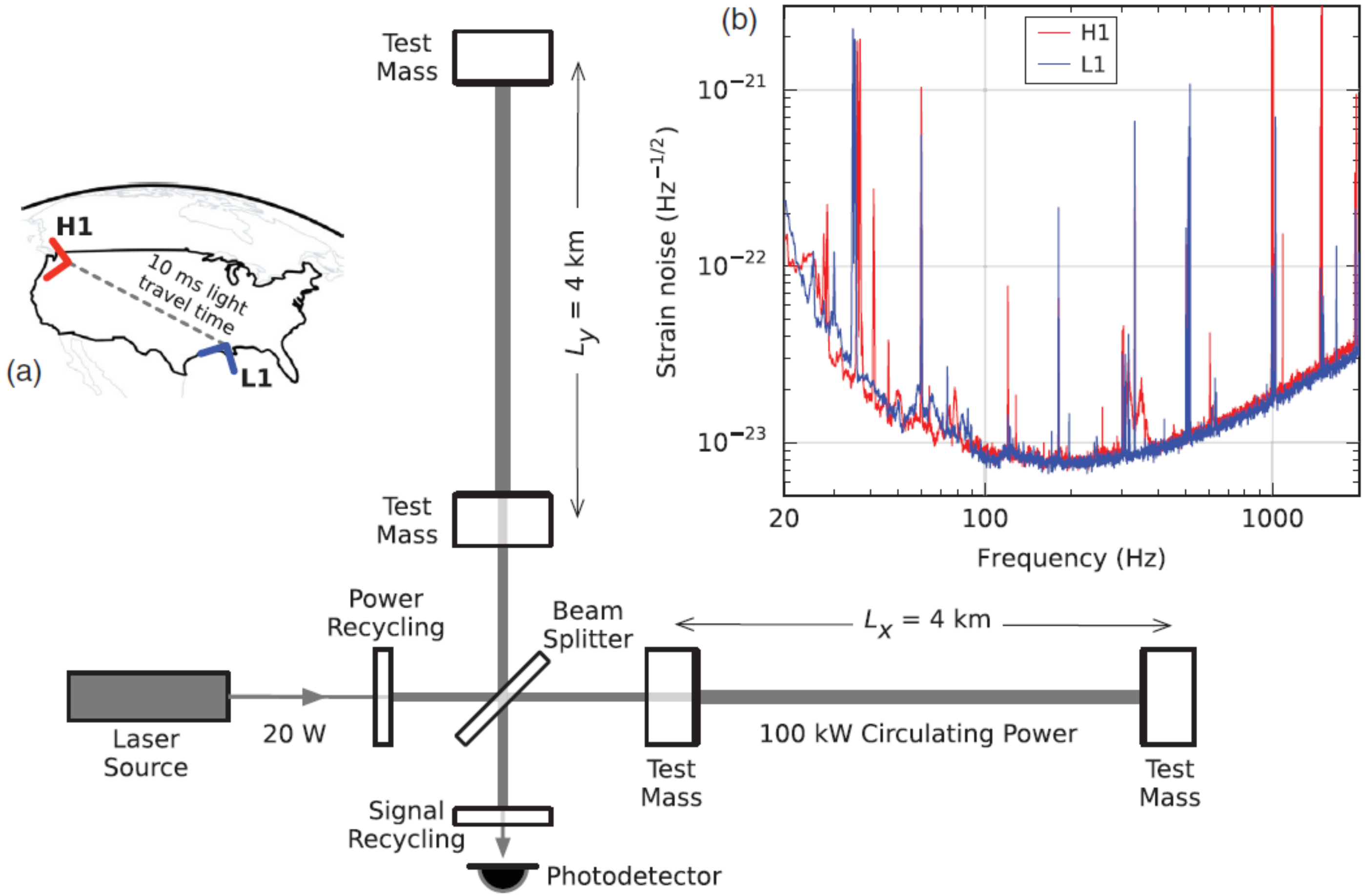
Observed **2017-08-17, 12:41:04**

First announced discovery: 2 massive BH merging 2015-09-14, 5:1sigma





Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)



(a)
H1
10 ms light travel time
L1
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector

Nonspherical Gravitational Collapse

Core-collapsed supernovae

Supernovae type Ib, Ic, II

Supernova explosion – star’s death.

Supernova remnant – neutron star, black hole.

Iron core collapse. Neutronization.

Neutrino radiation.

Supernova observed (kinetic + radiation)

explosion energy ~ 10(51) erg(!)

GRAVITATIONAL RADIATION FROM STELLAR COLLAPSE

T. X. THUAN AND J. P. OSTRIKER

THE ASTROPHYSICAL JOURNAL, 191:L105–L107, 1974 August 1

$$E(\mathrm{RAD}) = \frac{2}{375}\frac{GM^2}{c^2}(\dddot{A}^2 - \dddot{C}^2)^2$$

Uniform collapse without rotation

$$\Delta E(\mathrm{RAD}) = 0.0370(r_{\mathrm{Sch}}/r_{\mathrm{min}})^{7/2}Mc^2 \quad <\sim 10^{51} \text{ erg}$$

0.109 >~ $2\ 10^{45}$ erg **for rapid rotation**

Radiated during the collapse to maximal compression

Schwarzschild radius, **min**imal value of large semi-axis

Gravitational radiation from a star collapsing into a disk

I. D. Novikov

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

GW radiation during the bounce at finite entropy

$$\Delta\varepsilon \approx KMc^2 \left(\frac{r_S}{A}\right)^{7/2} \cdot \frac{A}{C_f}$$

A- the large axis, C_f – minimal value of C, A/C_f < ~10, K~0.01

The formal upper limit:

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

Never reached

Magnetorotational mechanism for the supernova explosion Bisnovatyi-Kogan (1970)

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.

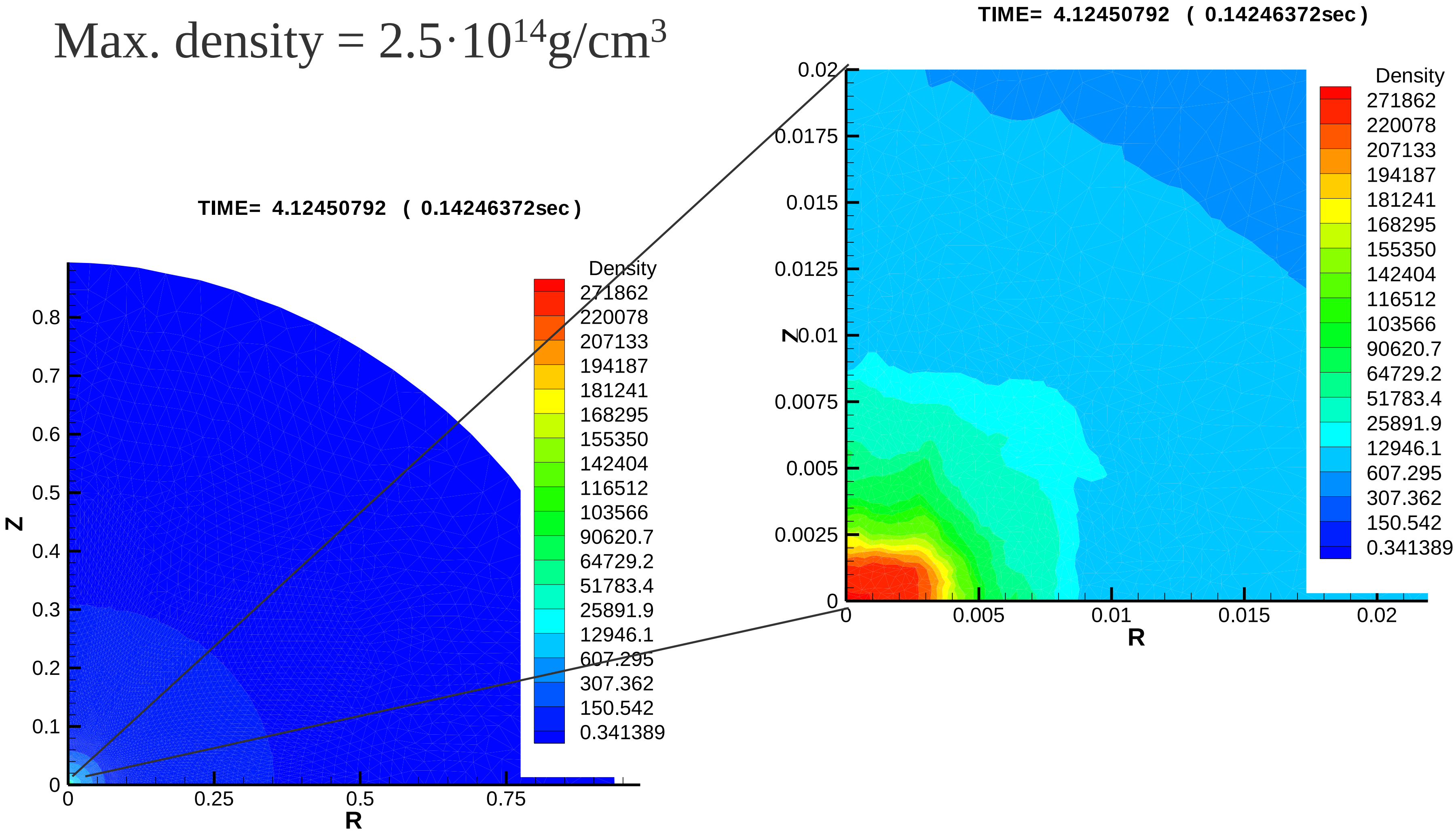
NUMERICAL SMULATIONS

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 and many others

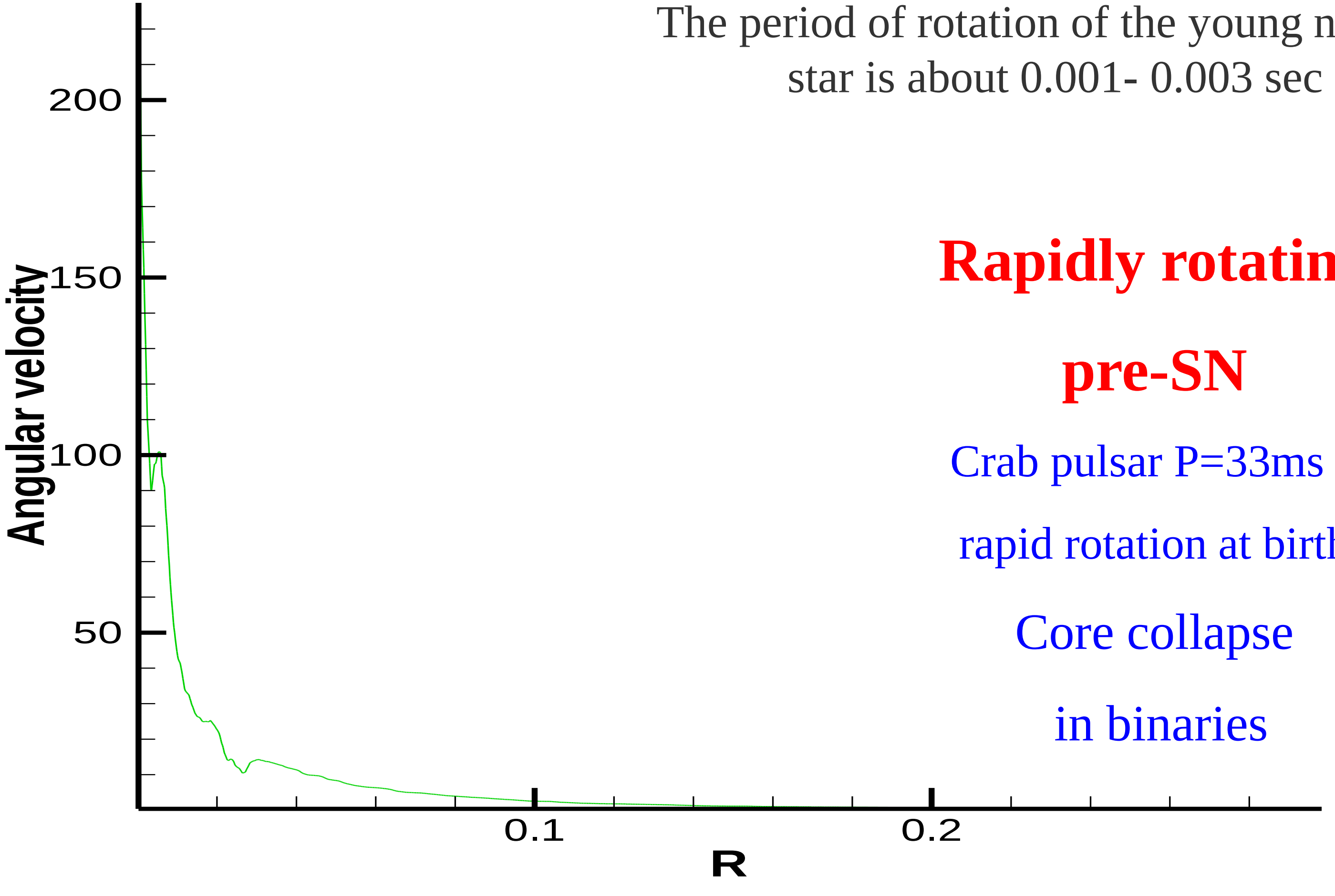
Magnetorotational mechanism for core-collapsed supernova is one of the most reliable for energy production.

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 –

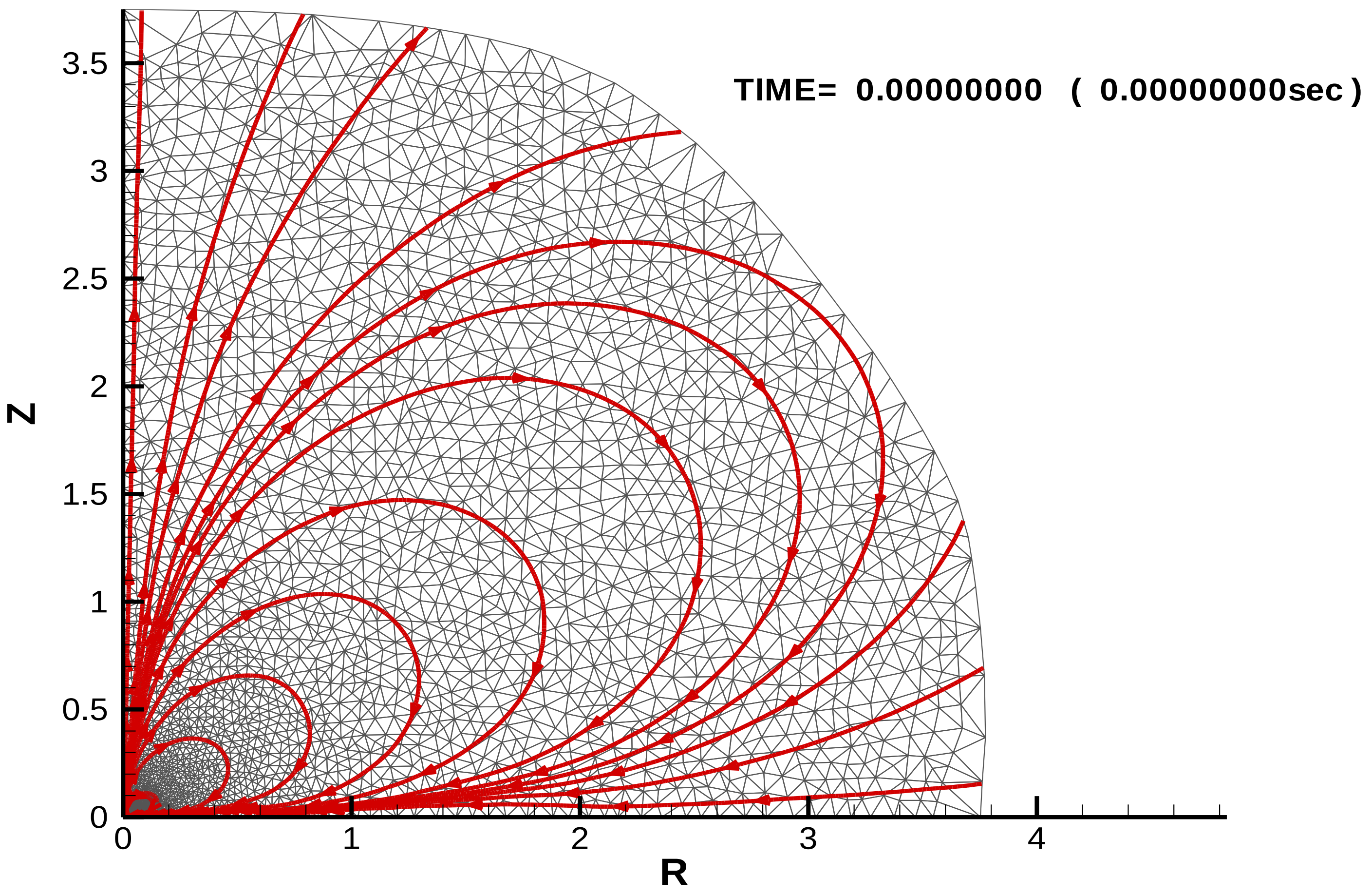
rapid rotation at birth

Core collapse

in binaries

Initial magnetic field –quadrupole-like symmetry

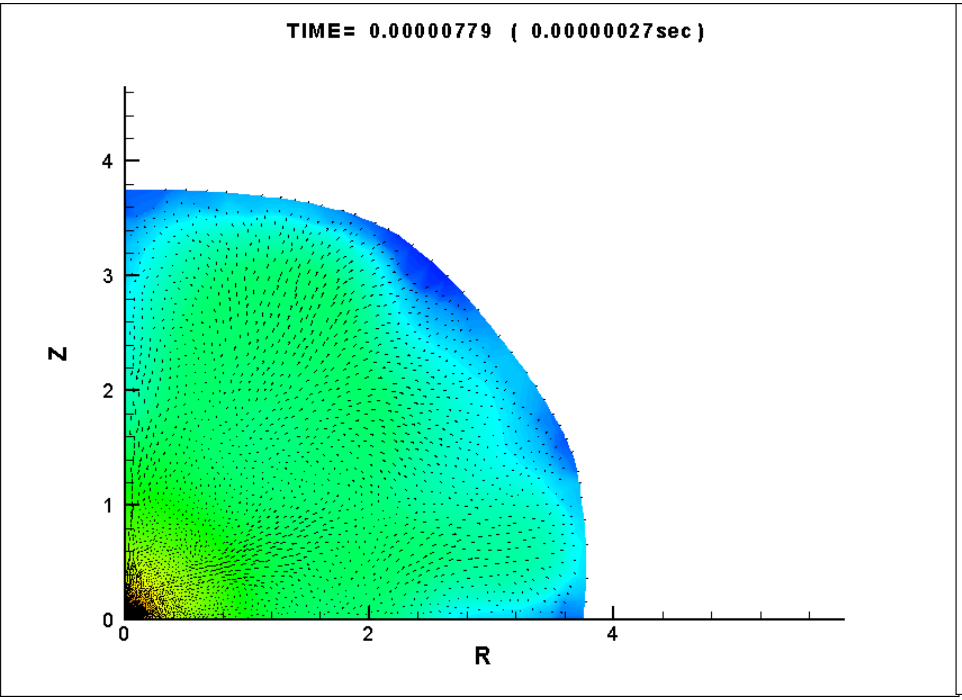
N.V.Ardeljan, S.G. Moiseenko, G.S.Bisnovatyi-Kogan MNRAS, 2005, 359, 333
S.G.Moiseenko, G.S.Bisnovatyi-Kogan, Astronomy Reports, 2015, 59, 7, 573-580



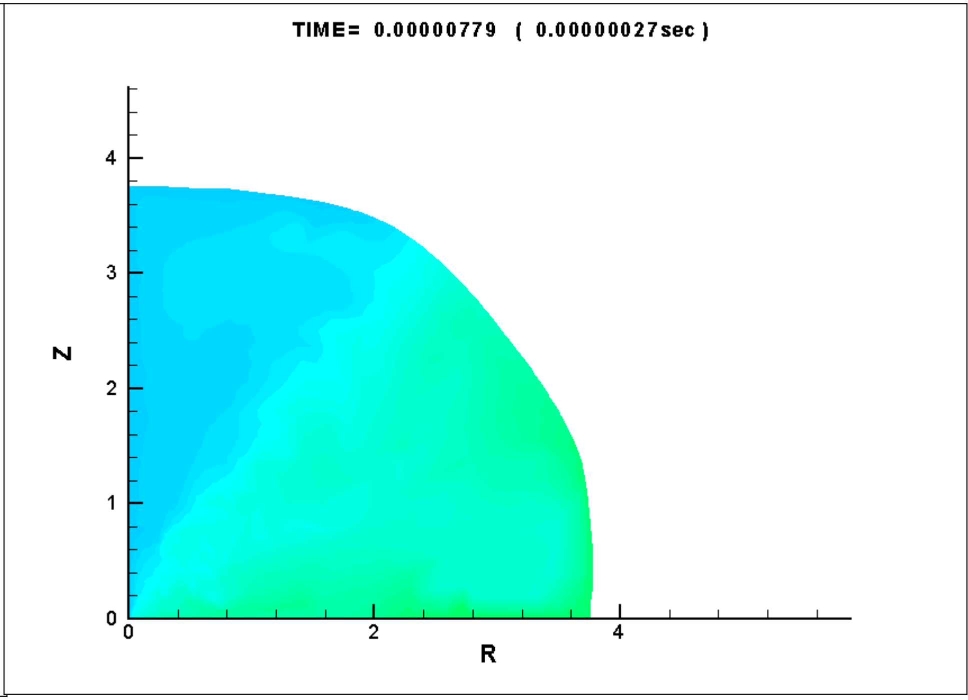
Magnetorotational supernova explosion

quadruple field

Temperature and velocity field



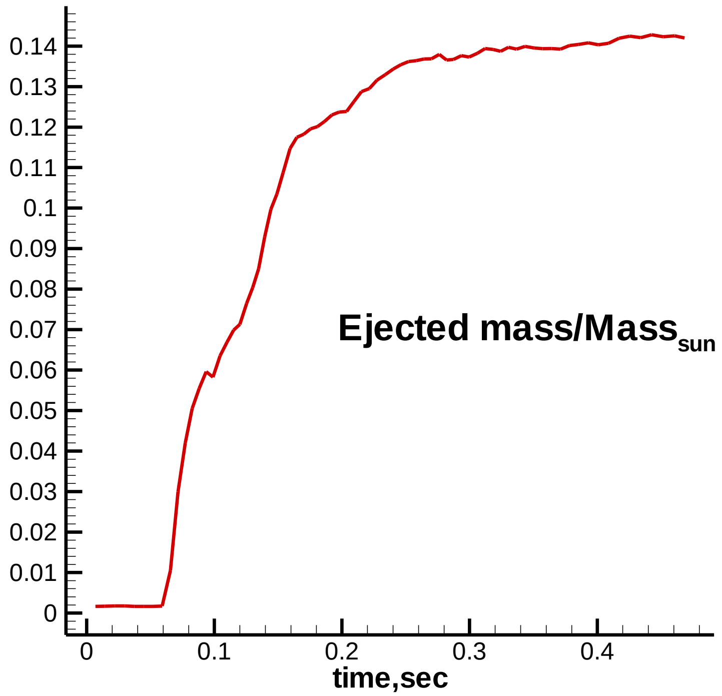
Specific angular momentum rV_{φ}

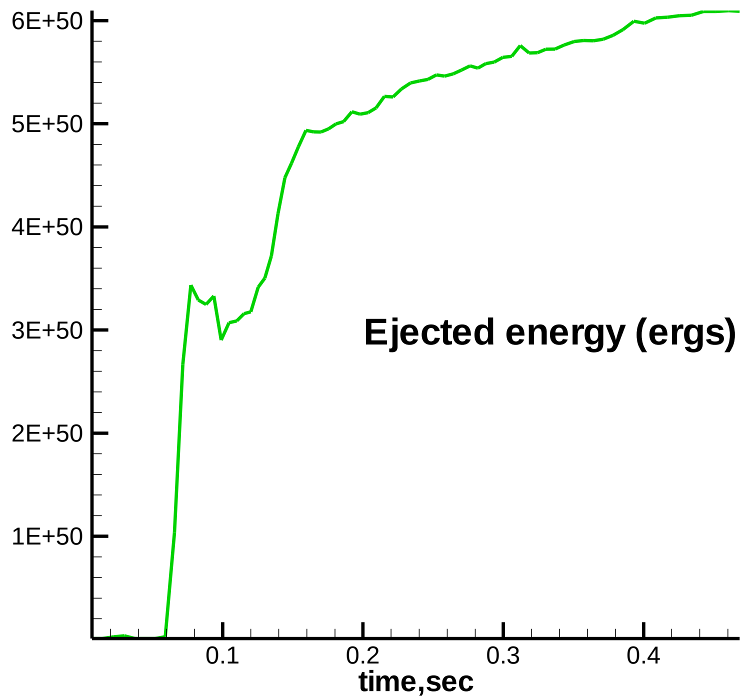


Ejected energy and mass

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

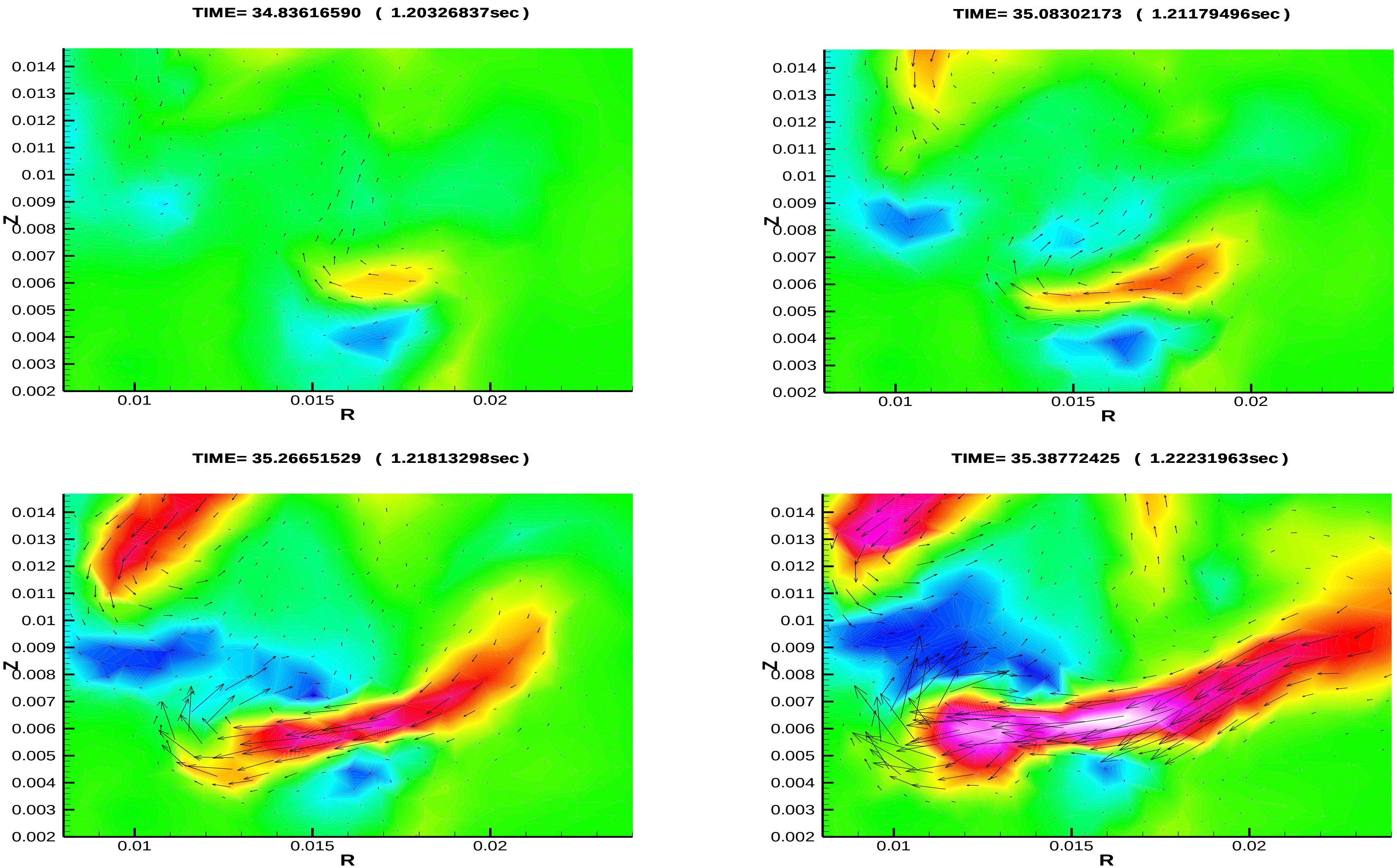
Particle is considered "ejected" –
if its kinetic energy is greater than its potential energy





Magnetorotational instability

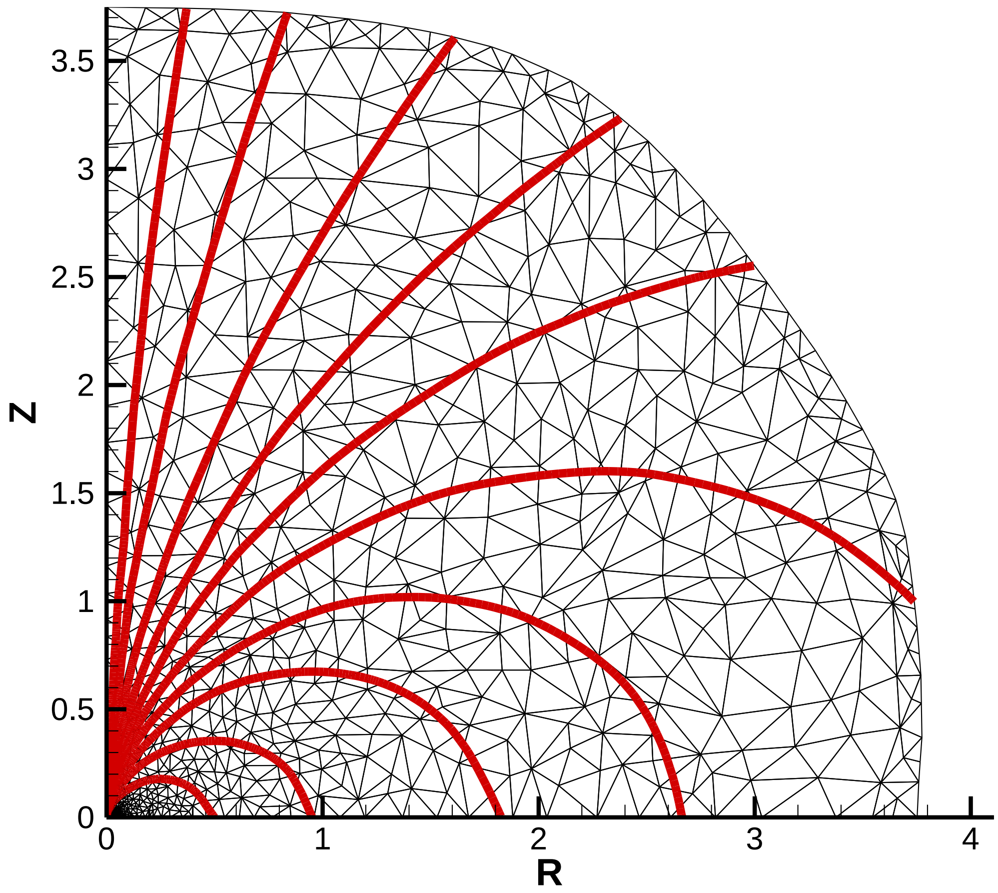
Central part of the computational domain . Formation of the MRI.



Initial magnetic field – dipole-like symmetry

Moiseenko, Ardeljan & Bisnovatyi-Kogan MNRAS 2006, 370, 501

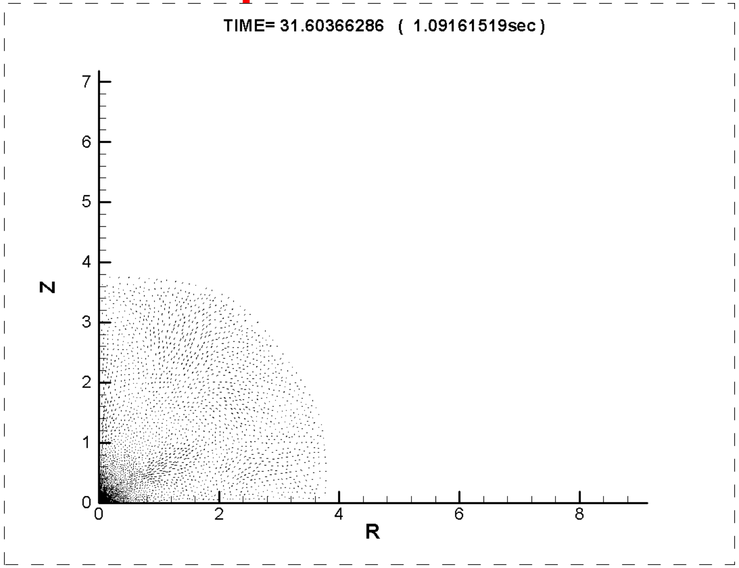
S.G.Moiseenko, G.S.Bisnovatyi-Kogan, Astronomy Reports, 2015, 59, 7, 573-580



Magnetorotational supernova explosion

dipole-like field

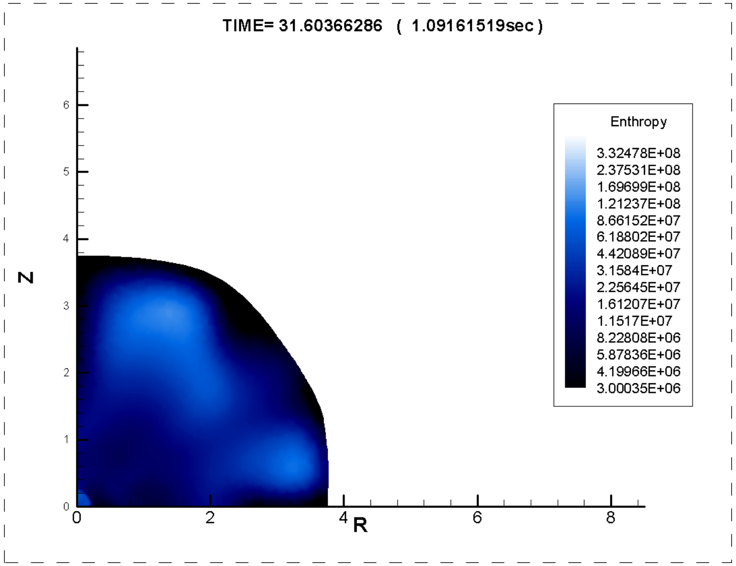
jet formation

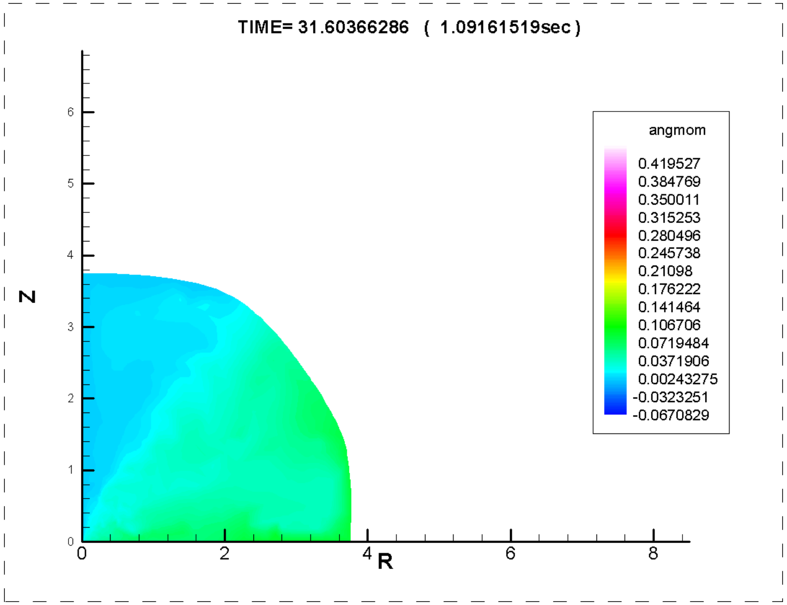


Velocity field

Entropy

Specific angular momentum

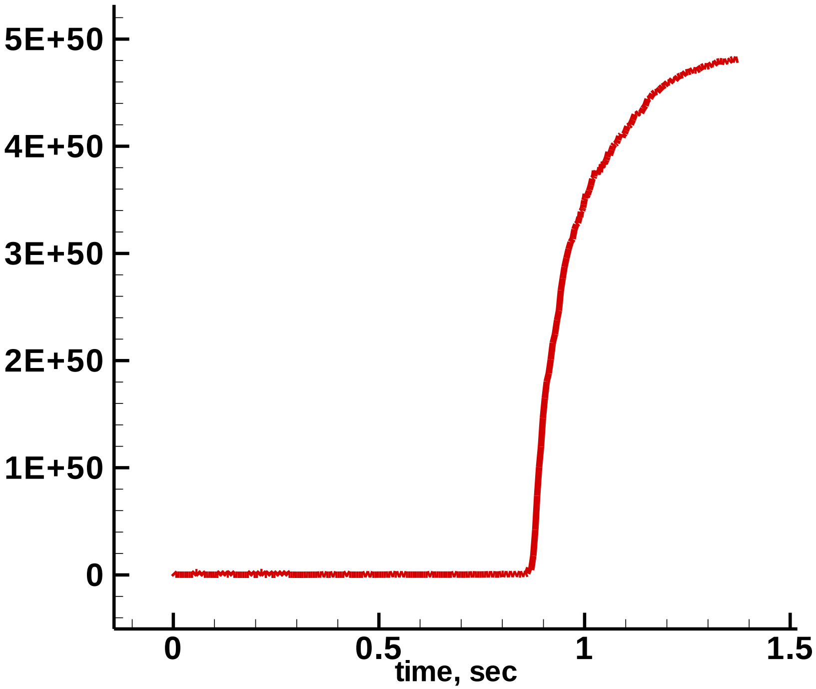


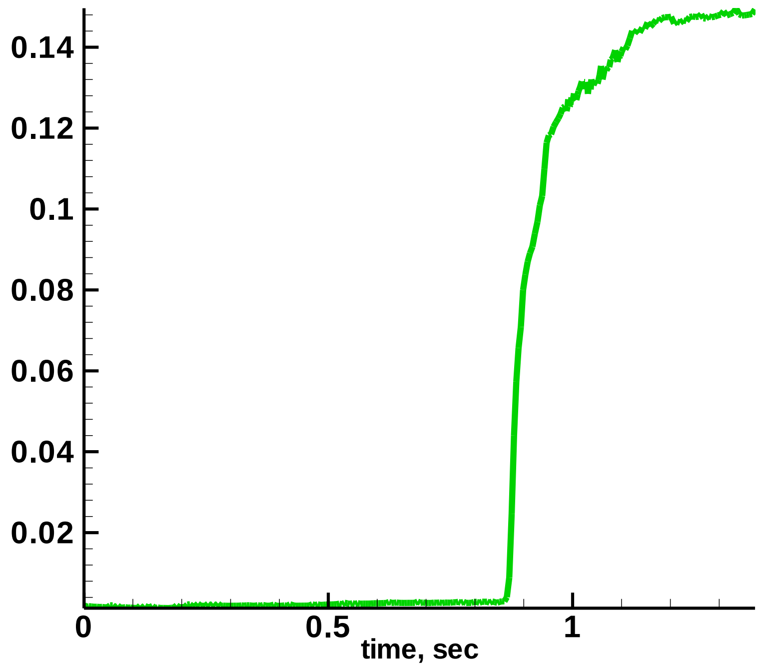


Ejected energy and mass (dipole)

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





GENERIC GRAVITATIONAL WAVE SIGNALS FROM THE COLLAPSE OF ROTATING STELLAR CORES

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

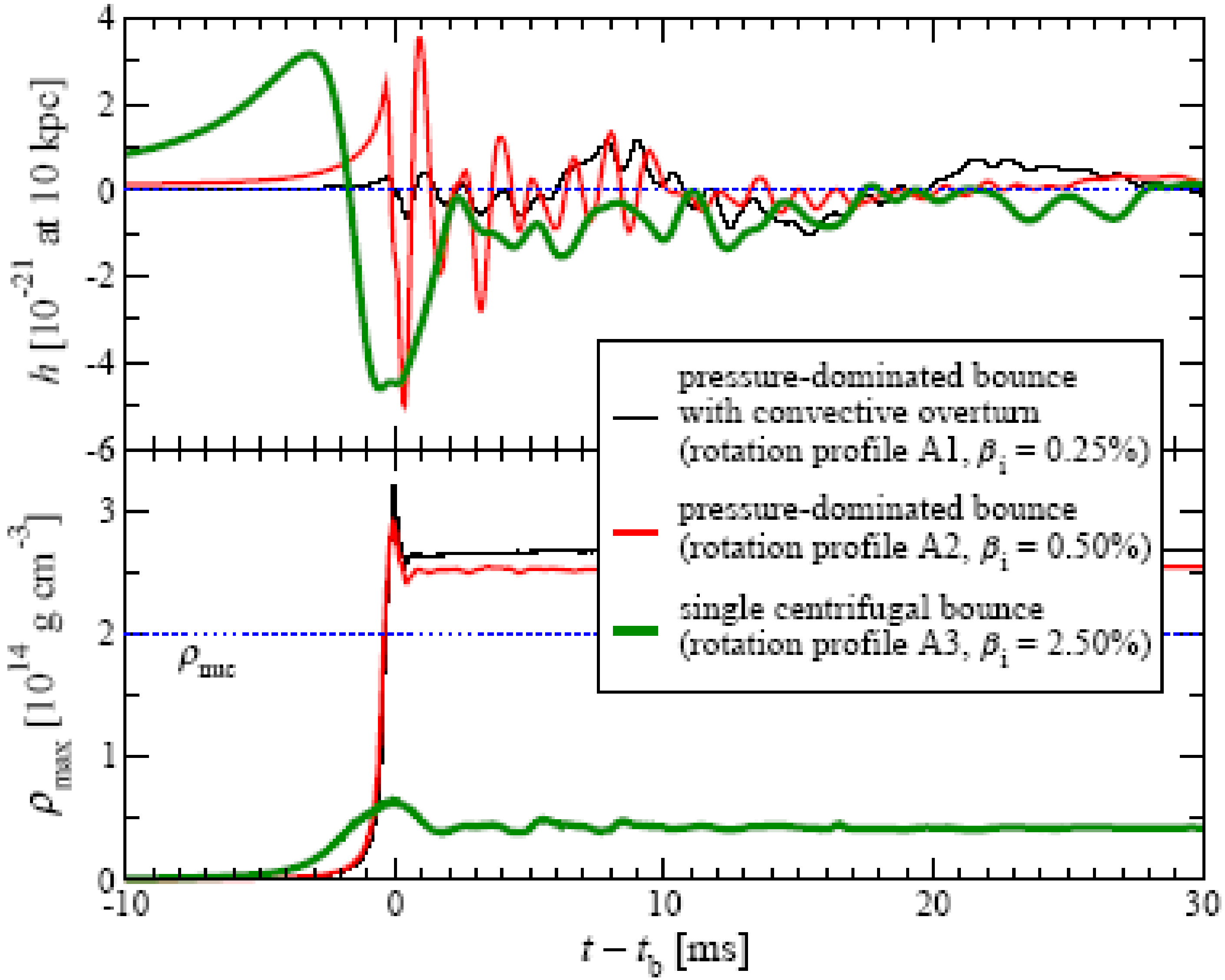
C. D. OTT
Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ 85721, U.S.A.

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

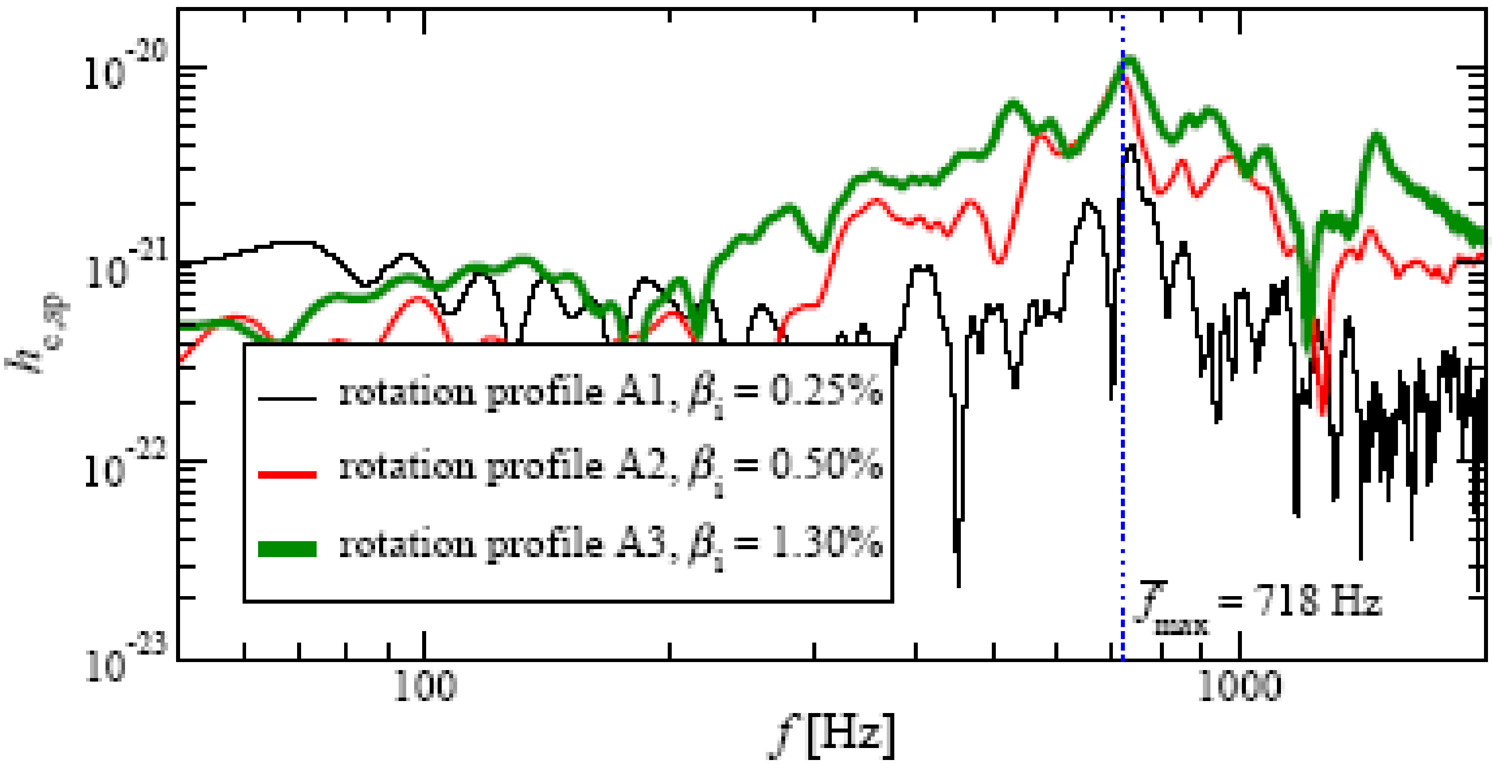
arXiv:070526755

Inferring the core-collapse supernova explosion mechanism with gravitational waves
Jade Powell, Sarah E. Gossan, Joshua Logue, Ik Siong Heng
PHYSICAL REVIEW D **94**, 123012 (2016)

GW signal from magneto-rotational and neutrino modeling of CCSE



Time evolution of the GW amplitude h and maximum density for three representative models with different rotation profiles and initial rotation rate $\beta_{\rm i} = T_{\rm i}/|W|_{\rm i}$, at a distance d = 10 kpc .



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.

Estimations of GW signal from non-spherical collapse

G.S. Bisnovatyi-Kogan, S.G. Moiseenko "**Gravitational waves and core-collapse supernovae**"
***Phys. Usp.* 60** (8) (2017)

Collapse of rotating WD with

$1{,}2\, M_\odot$

Collapse is bounced at formation of a hot neutron star

M is a mass inside a given iso-density

$$
\begin{aligned}
& A_{\min} = 5{,}5 \times 10^5\ \text{см}\,, \quad \frac{C_{\min}}{A_{\min}} = 0{,}50 \quad \text{при} \quad M = 0{,}24 M_\odot\,, \\
& \qquad E_{\mathrm{GW}} = 1{,}3 \times 10^{49}\ \text{эрг}\,, \\
& A_{\min} = 5{,}3 \times 10^6\ \text{см}\,, \quad \frac{C_{\min}}{A_{\min}} = 0{,}79 \quad \text{при} \quad M = 0{,}3 M_\odot\,, \\
& \qquad E_{\mathrm{GW}} = 1{,}2 \times 10^{46}\ \text{эрг}\,, \\
& A_{\min} = 9{,}5 \times 10^6\ \text{см}\,, \quad \frac{C_{\min}}{A_{\min}} = 0{,}83 \quad \text{при} \quad M = 0{,}5 M_\odot\,, \\
& \qquad E_{\mathrm{GW}} = 5{,}4 \times 10^{45}\ \text{эрг}\,, \qquad\qquad (9) \\
& A_{\min} = 3 \times 10^7\ \text{см}\,, \quad \frac{C_{\min}}{A_{\min}} = 0{,}89 \quad \text{при} \quad M = 0{,}8 M_\odot\,, \\
& \qquad E_{\mathrm{GW}} = 7{,}4 \times 10^{44}\ \text{эрг}\,, \\
& A_{\min} = 4{,}2 \times 10^7\ \text{см}\,, \quad \frac{C_{\min}}{A_{\min}} = 0{,}94 \quad \text{при} \quad M = M_\odot\,, \\
& \qquad E_{\mathrm{GW}} = 5{,}9 \times 10^{44}\ \text{эрг}\,.
\end{aligned}
$$

$$h_{\phi\phi} = -h_{\theta\theta} = \frac{GM}{5rc^4} \sin^2 \theta_0 (\ddot{A}^2 - \ddot{C}^2) , \quad h_{\theta\phi} = 0 .$$

Approximately:

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

The GW amplitude: $\beta_b \approx 0{,}028.$ f_max ~ 1200

$$h = h_{\phi\phi} = -h_{\theta\theta} = \frac{6{,}7 \times 10^{-8} (0{,}48 \times 10^{33})}{5rc^4} \times$$

$$\times \frac{(5{,}5 \times 10^5)^2}{(0{,}75 \times 10^{-3})^2} \approx 1{,}4 \times 10^{-22} \frac{10 \text{ кпк}}{r} .$$

Joke about GW registration
(information for consideration)

2015-09-14 09:50:45
2015-10-12 09:54:43
2015-12-26 03:38:53
2017-01-04 10:11:58
2017-06-08 02:01:16
2017-08-14 10:30:43
2017-08-17 12:41:04

100 Hz corresponds to 3000 rot/min
Rotation rate of a powerful auto

2015-09-14 09:50:45 5:1s
2015-10-12 09:54:43 S/N9:7 1:7s
2017-01-04 10:11:58 S/N13
2017-08-14 10:30:43 S/N18
2017-06-08 02:01:16 S/N13
2015-12-26 03:38:53 5:3s
2017-08-17 12:41:04 S/N32:4

4 bursts during 3 years are inside 40 minutes of the day

Police inspecting the area

From Wikipedia:

Modern automobile engines are typically operated around 2,000–3,000 rpm **(33–50 Hz)** when cruising, with a minimum (idle) speed around 750–900 rpm (12.5–15 Hz), and an upper limit anywhere from 4500 to 10,000 rpm **(75–166 Hz)** for a road car

GW frequency is doubled!

Conclusions

1. GW have been discovered indirectly 25 years ago in observations of binary pulsar.

2. In addition to merging, GW are radiated during the first bounce in non-spherical core collapse (e.q. supernovae), frequency ~1000 Hz. This GW signal may be registered from core-collapse SN in our Galaxy