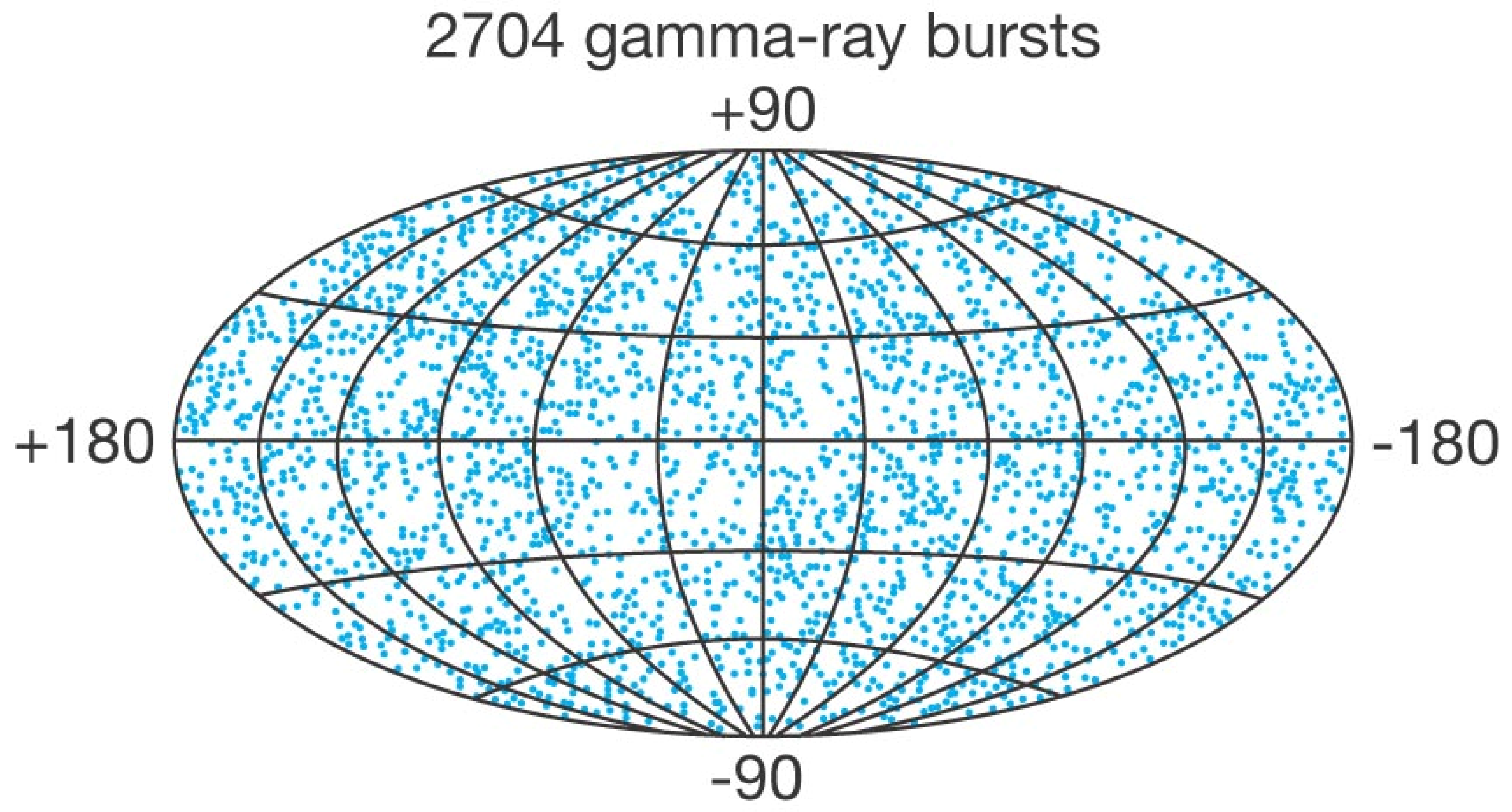
Слияние нейтронных звёзд и гамма-всплески: модель обдирания

С.И. Блинников, Д.К. Надёжин и <u>А.В. Юдин</u>

Десятые Зацепинские чтения, 7 июня 2019 г.

Gamma-Ray Bursts

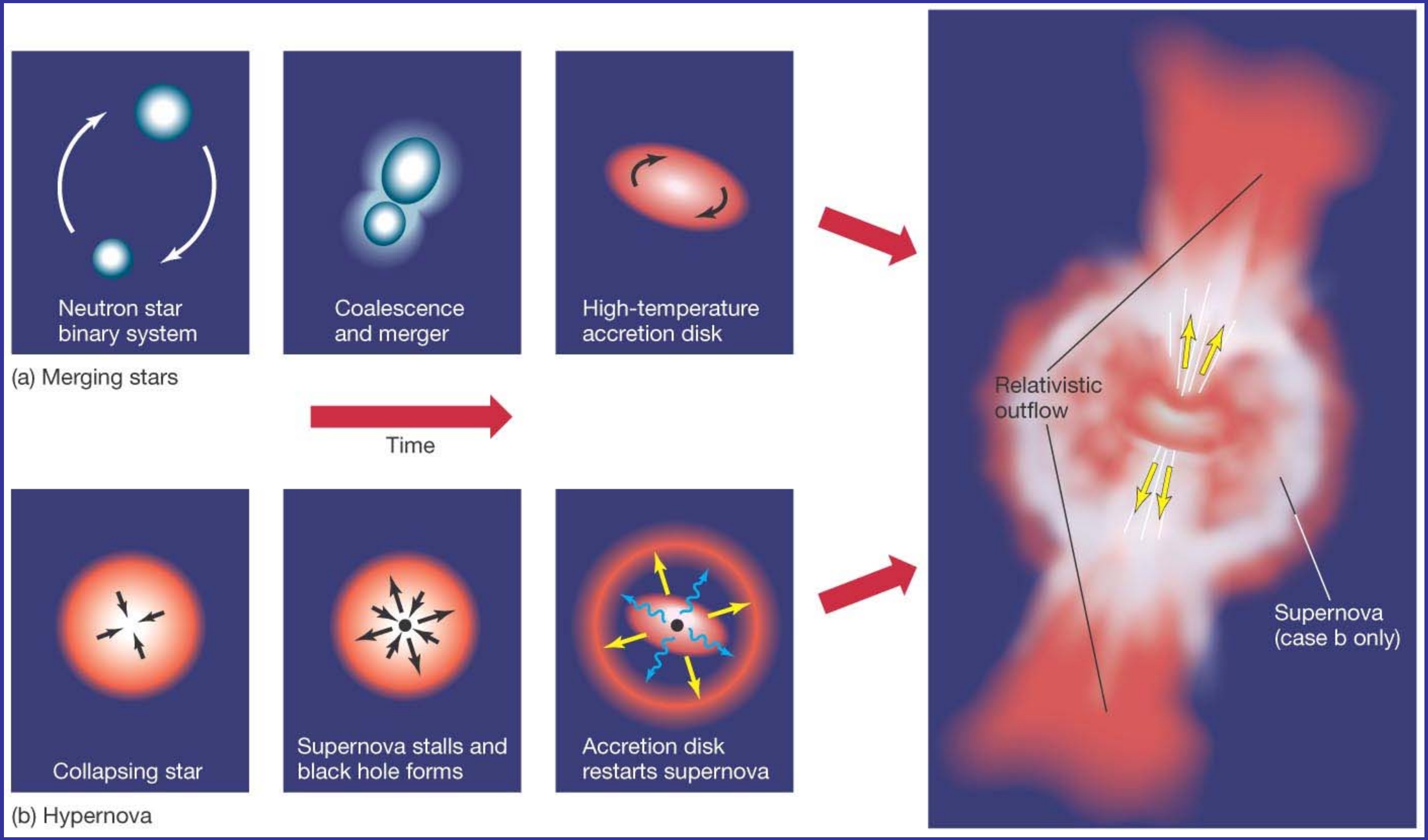


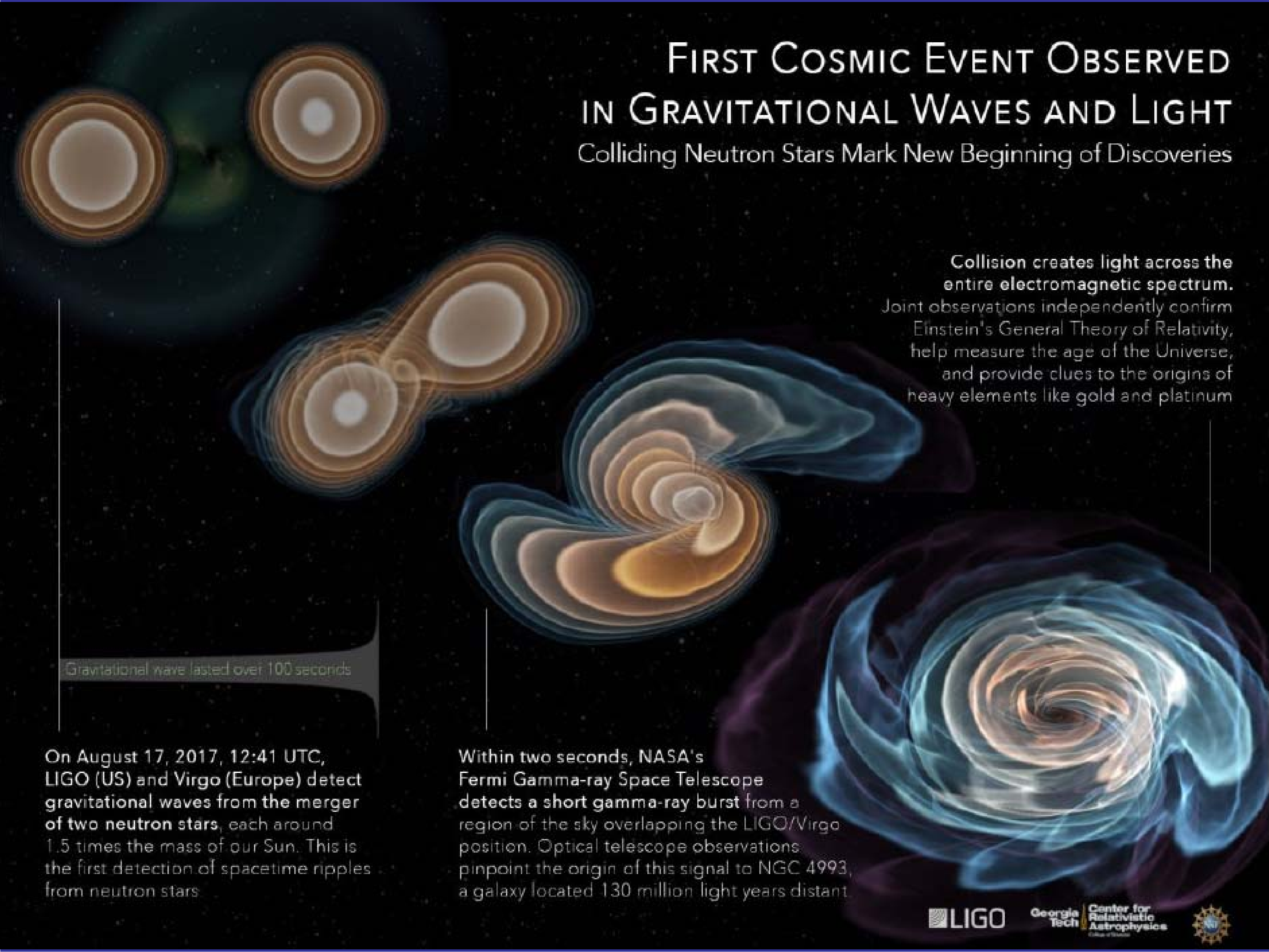
GRB (гамма-всплески): вспышки с энергией от нескольких десятков кэВ до МэВ (иногда и более жесткие). Вспышки длятся от нескольких долей секунд до минут, а иногда и часов.

<u>Короткие гамма-всплески</u> (меньше 2 сек) – слияние нейтронных звёзд.
<u>Длинные</u> – Гипернова?

Gamma-Ray Bursts

Two models—merging Neutron Stars or a “Hypernova” – have been proposed as the source of Gamma-Ray Bursts (“GRB’s”):





FIRST COSMIC EVENT OBSERVED
IN GRAVITATIONAL WAVES AND LIGHT
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant
LIGO
Georgia Tech
Center for Relativistic Astrophysics

https://www.nature.com/news/rumours-swell-over-new-kind-of-gravitational-wave-sighting-1.22482

NATURE | EXPLAINER

Rumours swell over new kind of gravitational-wave sighting

Gossip over potential detection of colliding neutron stars has astronomers in a tizzy.

Davide Castelvecchi

24 August 2017 | Updated: 25 August 2017, 25 August 2017

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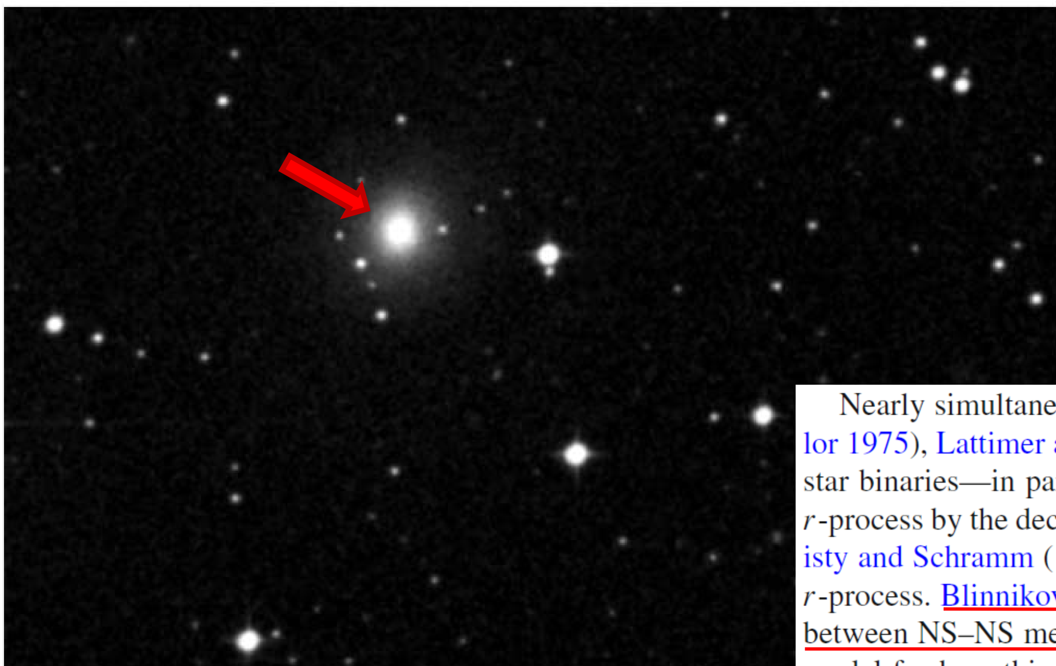


The galaxy NGC 4993 (fuzzy bright spot) in the constellation Hydra, where dete... have spotted gravitational waves from a neutron star merger.

Событие GW170817

Галактика NGC 4993
Расстояние 40 млн пс

Гамма-всплеск
GRB 170817A

Living Rev Relativ (2017) 20:3
DOI 10.1007/s41114-017-0006-z

REVIEW ARTICLE

Kilonovae

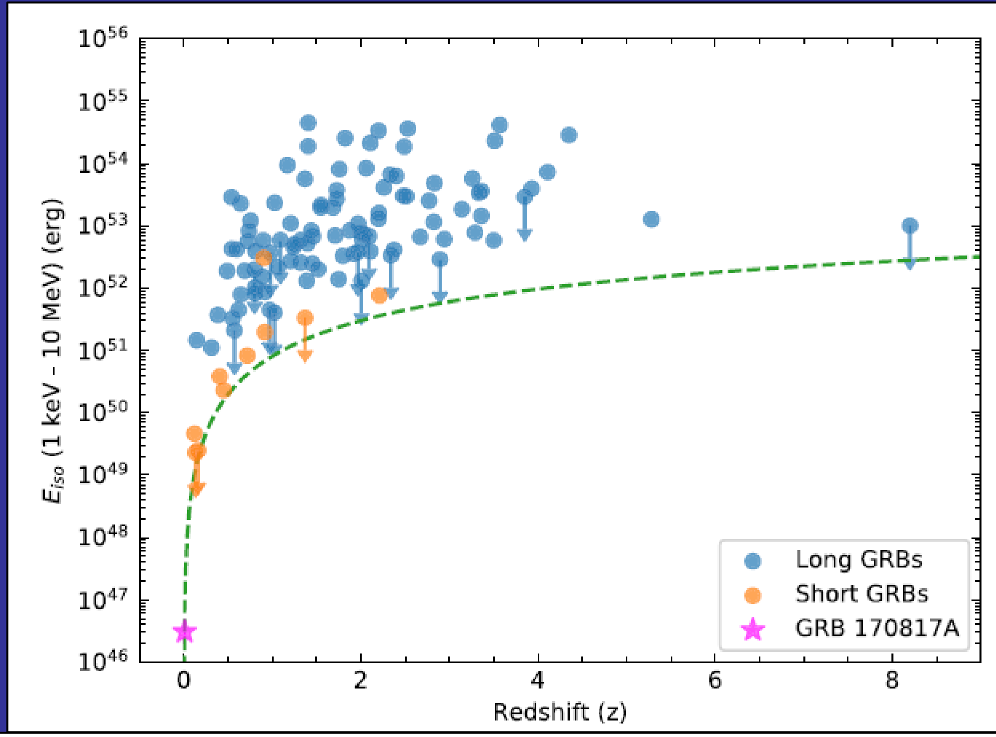
Brian D. Metzger[1]

Nearly simultaneous with the discovery of the first binary pulsar (Hulse and Taylor 1975), Lattimer and Schramm (1974, 1976) proposed that the merger of compact star binaries—in particular the collision of BH–NS systems—could give rise to the r-process by the decompression of highly neutron-rich ejecta (Meyer 1989). Symbalisty and Schramm (1982) were the first to suggest NS–NS mergers as the site of the r-process. Blinnikov et al. (1984) and Paczyński (1986) first suggested a connection between NS–NS mergers and GRBs. Eichler et al. (1989) presented a more detailed model for how this environment could give rise to a GRB (albeit one which differs significantly from the current view). Davies et al. (1994) performed the first numerical simulations of mass ejection from merging neutron stars, finding that ~2% of the binary mass was unbound during the process. Freiburghaus et al. (1999) presented the first explicit calculations showing that the ejecta properties extracted from a hydro-

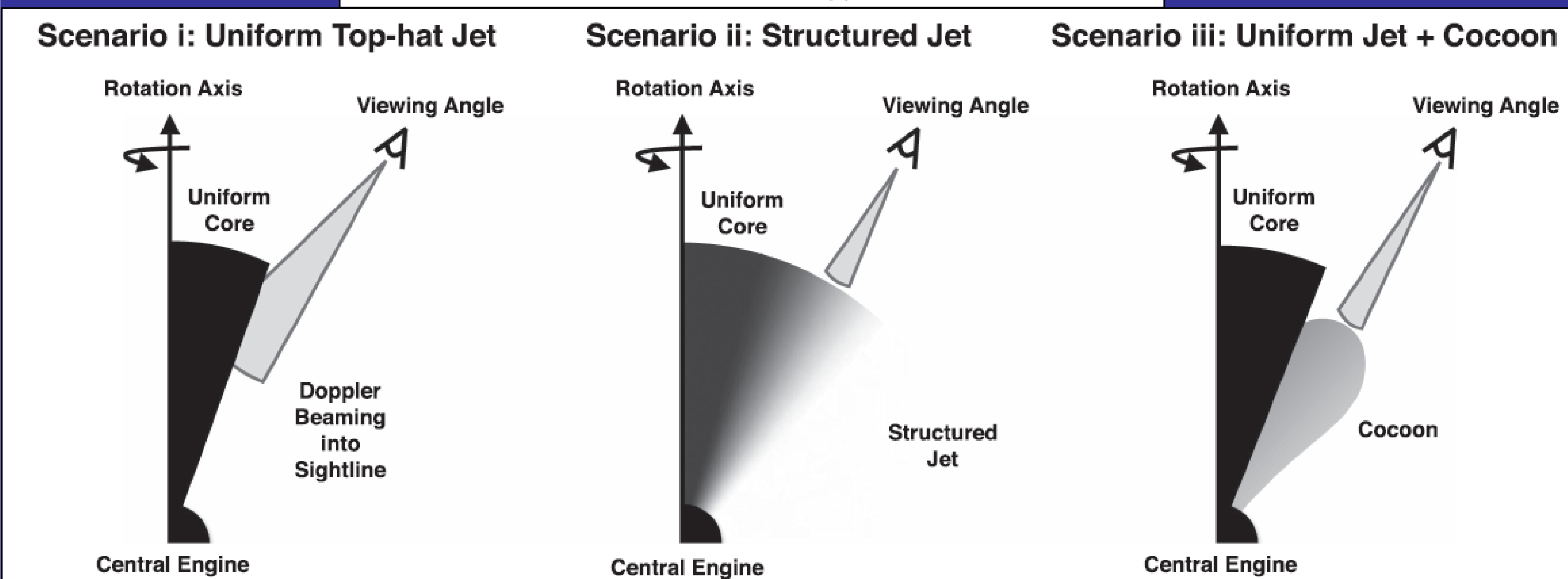
Важное о GW170817

- GW170817 — 6-е гравитационно-волновое событие и 1-ое наблюдение слияния объектов с массами нейтронных звезд.
- Гамма-всплеск GRB170817A наблюдался спустя 1.7 сек. после потери сигнала GW170817.
  - Подтверждена связь коротких GRB со сливающимися NS
  - Ограничения на гравитацию: скорость распространения ($\Delta v/c \lesssim 10^{-15}$), лоренц-инвариантность, принцип эквивалентности
- Спустя 11 часов открыт источник в видимом свете в NGC 4993
  - Кривые блеска и спектры соответствуют килоновой
  - Синтез тяжелых элементов в r-процессе
  - Космология: независимое измерение расстояний, параметра Хаббла
- Впервые выполнены наблюдения одного объекта в грав.волновом и эл.-маг. (гамма, рентген, ультрафиолет, видимый и инфракрасный свет, радио) канале. Для нейтрино далеко

Начало эры многодиапазонной (многоканальной) астрономии – multi-messenger astronomy



10^{56}
10^{55}
10^{54}
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
E_{iso} (1 keV - 10 MeV) (erg)
0
2
4
6
8
Redshift (z)
Long GRBs
Short GRBs
GRB 170817A



Scenario i: Uniform Top-hat Jet
Rotation Axis
Viewing Angle
Uniform Core
Doppler Beaming into Sightline
Central Engine
Scenario ii: Structured Jet
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Central Engine
Scenario iii: Uniform Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Cocoon
Central Engine

Exploding neutron stars in close binaries

S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev

Institute of Theoretical and Experimental Physics, Moscow and Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted January 27, 1984)

Pis'ma Astron. Zh. **10**, 422–428 (June 1984)

A close binary system comprising a neutron star and another neutron star (or a black hole) will evolve so that the less massive component sheds mass, passing through a series of quasiequilibrium states, until it achieves its minimum possible mass $m_{\min} \approx 0.09\ M_{\odot}$ and explodes. In a compact globular cluster or the nucleus of a galaxy, such evolution can terminate in an explosion in less than the Hubble time.

Explosion of a low-mass neutron star

S. I. Blinnikov, V. S. Imshennik, D. K. Nadezhin, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev

Institute of Theoretical and Experimental Physics, Space Research Institute, USSR Academy of Sciences

(Submitted April 4, 1990)

Astron. Zh. **67**, 1181–1194 (November–December 1990)

The process of hydrodynamic destruction of a neutron star that occurs when its mass becomes somewhat less than the minimum mass $M_{\min} \approx 0.1\ M_{\odot}$ is calculated. It is shown that this process occurs explosively and results in the complete dispersal of the neutron star with a kinetic energy ~ 4.8 MeV per nucleon. The calculated results hardly depend on the means by which the mass of the neutron star is reduced to less than $M_{\min}$ (transfer to a companion in a binary system, decay of nucleons, an equivalent mass decrease due to a decrease in the gravitational constant). Destruction of the neutron star should be accompanied by a short (hundredths of a second) burst of hard thermal x rays and soft gamma rays ($kT \approx 10$–100 keV), which should be followed by the considerably longer "tail" of x rays and gamma rays associated with a decay of long-lived radioactive nucleons. Some fraction of the explosive energy is carried off in the form of neutrinos.

Exploding neutron stars in close binaries

S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev

Once having achieved $m_2 = m_{min}$, star 2 will lose its hydrostatic stability and will begin to expand at a rate determined by t_{hyd} and the amended equation of state. Clark and Eardley[6] estimate that perhaps one neutron star may undergo tidal disruption every 100 yr within a 15-Mpc radius; thus the event would not be exceedingly rare. Notonly should a burst of gravitational waves be produced,[6] but also a powerful electromagnetic flare (most likely x rays and γ rays). Page[2] believes that the explosion may attain an energy of supernova scale, but the problem awaits a detailed analysis. We intend to consider this process further in a separate paper.

We also have omitted discussion here of the physical processes that will accompany the mass transfer, such as the stripping from the star of material with nuclei having excess neutrons; as these nuclei later decay, γ-ray burster phenomena might occur (like the processes that Bisnovatyi-Kogan and Checkëtkin[13] have discussed).

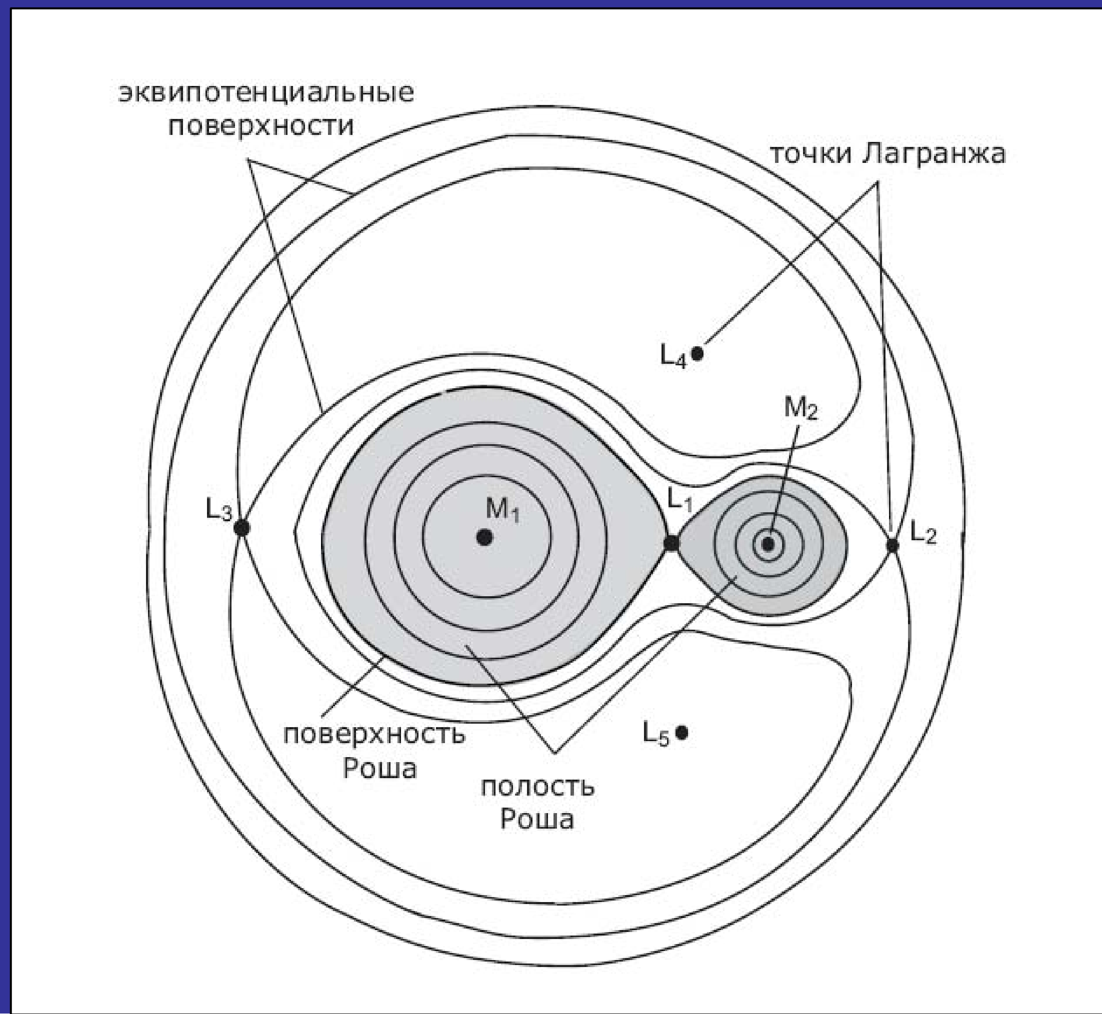
$$t_{\rm grav} \approx (10^{10}\ {\rm yr}) \left(\frac{m_1}{10^{33}\,{\rm g}}\right)^{-1} \left(\frac{m_2}{10^{33}\,{\rm g}}\right)^{-1} \left(\frac{m_1}{10^{33}\,{\rm g}} + \frac{m_2}{10^{33}\,{\rm g}}\right)^{-1} \left(\frac{a}{R_\odot}\right)^4$$

$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{1}{2}\omega^2\left[(x-\mu a)^2 + y^2\right]$$

$$\omega = \sqrt{\frac{G(M_1+M_2)}{a^3}}$$

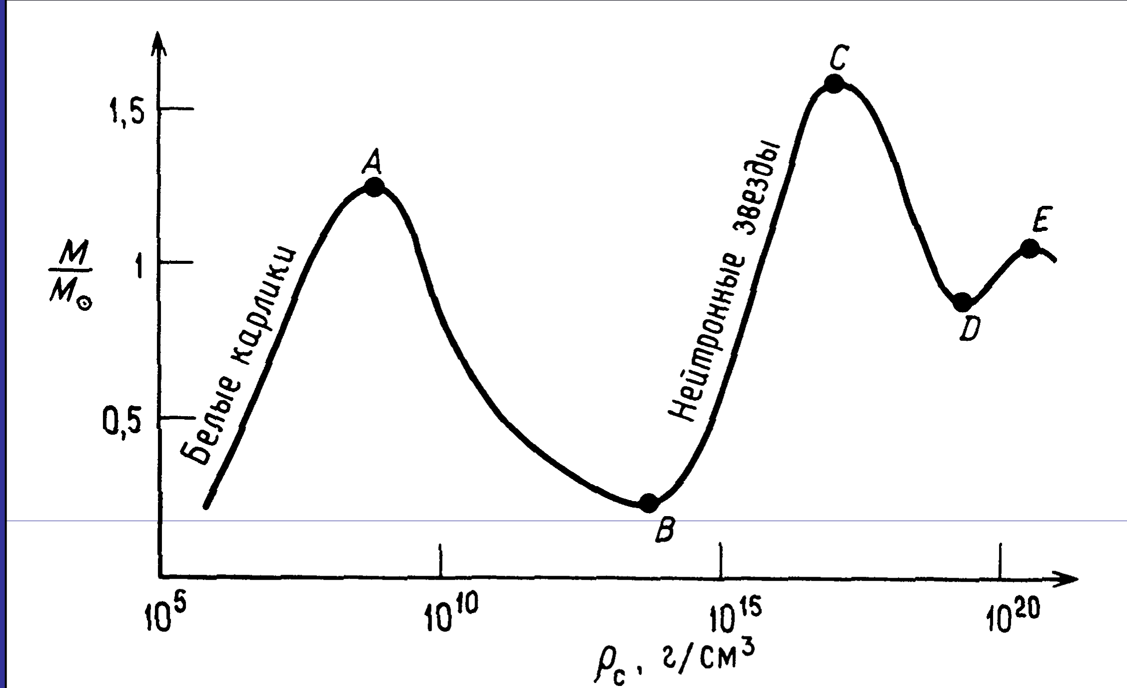
$$L = \sqrt{G\frac{M_1^2 M_2^2}{M_1+M_2}a}$$

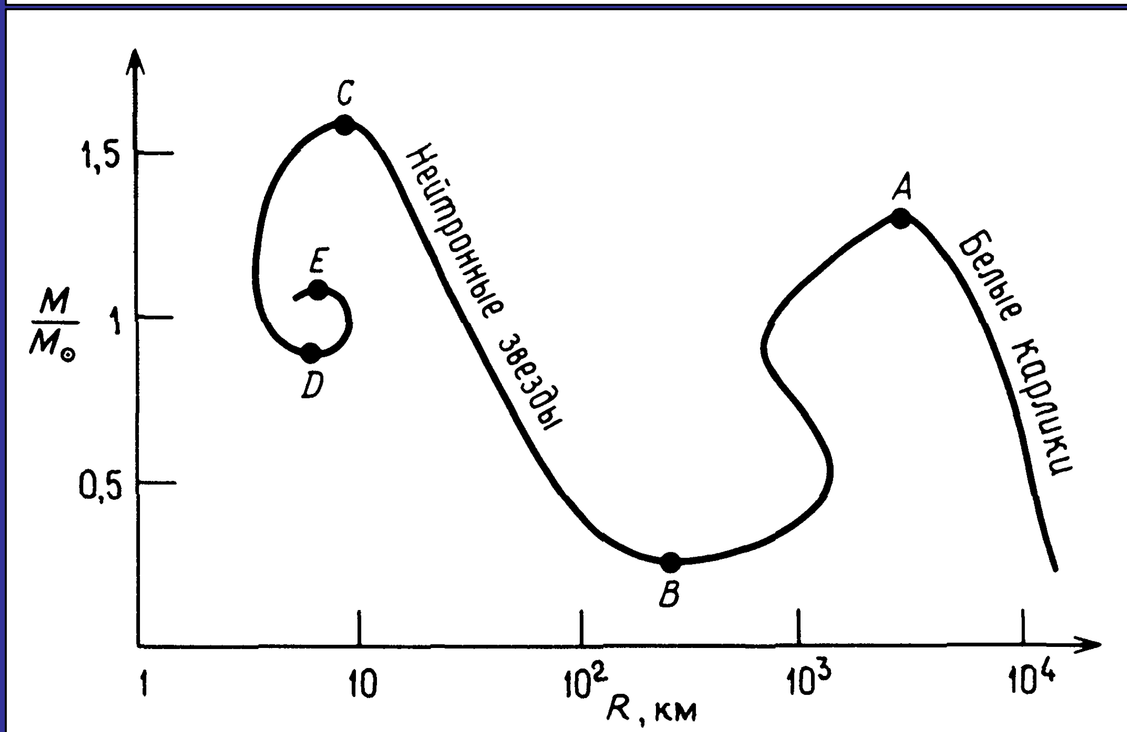
$$\frac{d\ln R_2}{d\ln M_2} > 2\frac{M_2}{M_1} - \frac{5}{3}$$



Stuart L. Shapiro
Saul A. Teukolsky

Black Holes, White Dwarfs, and Neutron Stars





THE ASTROPHYSICAL JOURNAL, 215:311–322, 1977 July 1

EVOLUTION OF CLOSE NEUTRON STAR BINARIES

JOHN PAUL ADRIAN CLARK* AND DOUGLAS M. EARDLEY†
Observatory and Department of Physics, Yale University
Received 1976 November 11; revised 1976 December 17

ABSTRACT

In binary systems consisting of two neutron stars, the orbit decays by gravitational radiation. A crude model shows that the less massive star may suffer either immediate tidal disruption or slow mass stripping when it reaches its Roche radius, depending on the initial masses and on the details of mass exchange or mass loss. Typical energy releases are 4×10^{52} ergs in gravitational waves before the onset of stripping, 2×10^{52} ergs in gravitational waves after the onset of stripping, 2×10^{53} ergs in neutrinos after the onset of stripping. The stripping process always ends in tidal disruption of the less massive star after a few seconds or a few hundred revolutions.

As the endpoint of binary stellar evolution, such events are estimated to occur only every ~ 100 yr out to a radius of 15 Mpc, and are thus less important than supernovae as sources of gravitational waves; the observed wave amplitude would be $h \sim 10^{-21}$. Such events may occur in Type II supernovae, if the collapsing stellar core rotates rapidly enough to fission into two neutron stars.

Subject headings: gravitation — stars: binaries — stars: evolution — stars: neutron

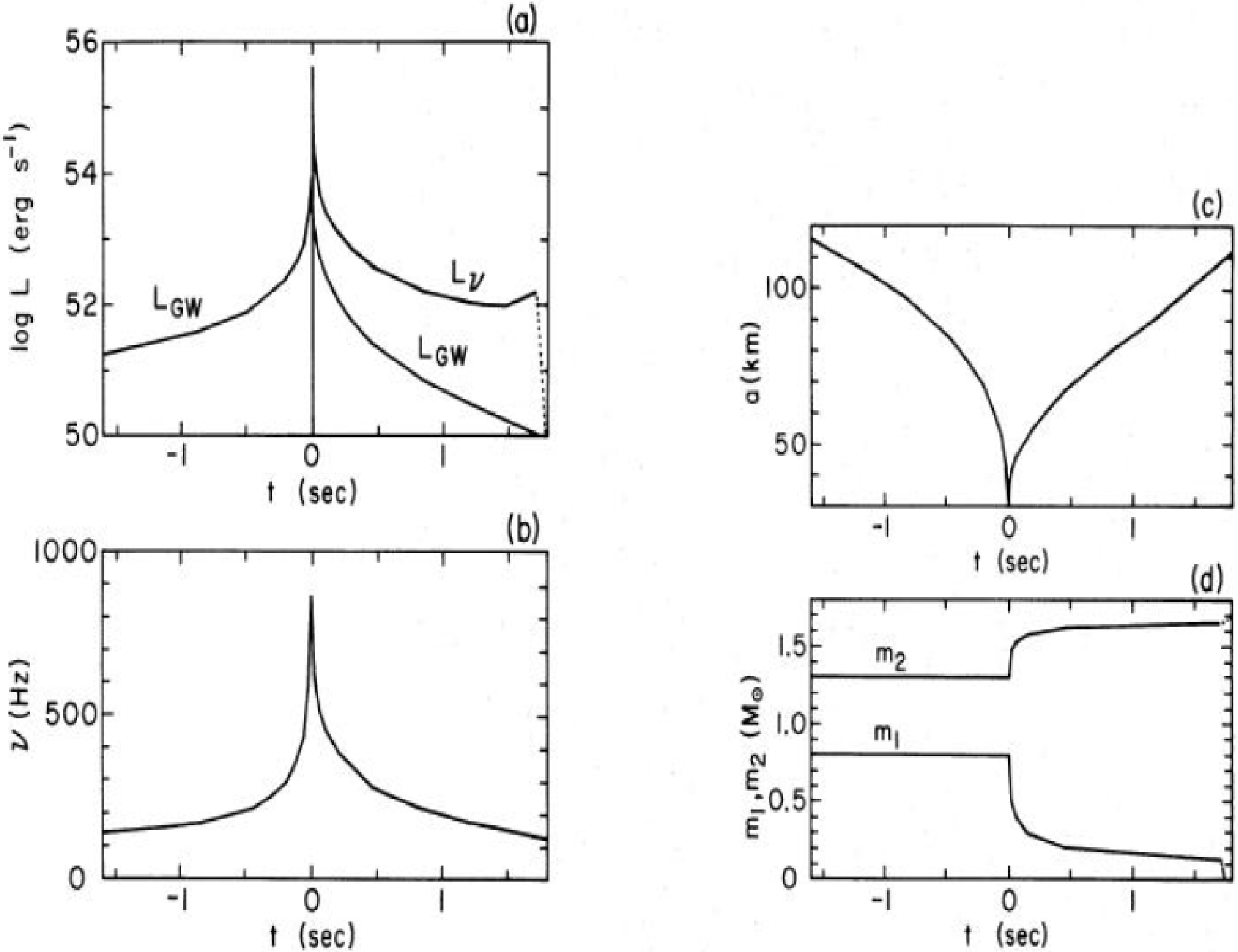
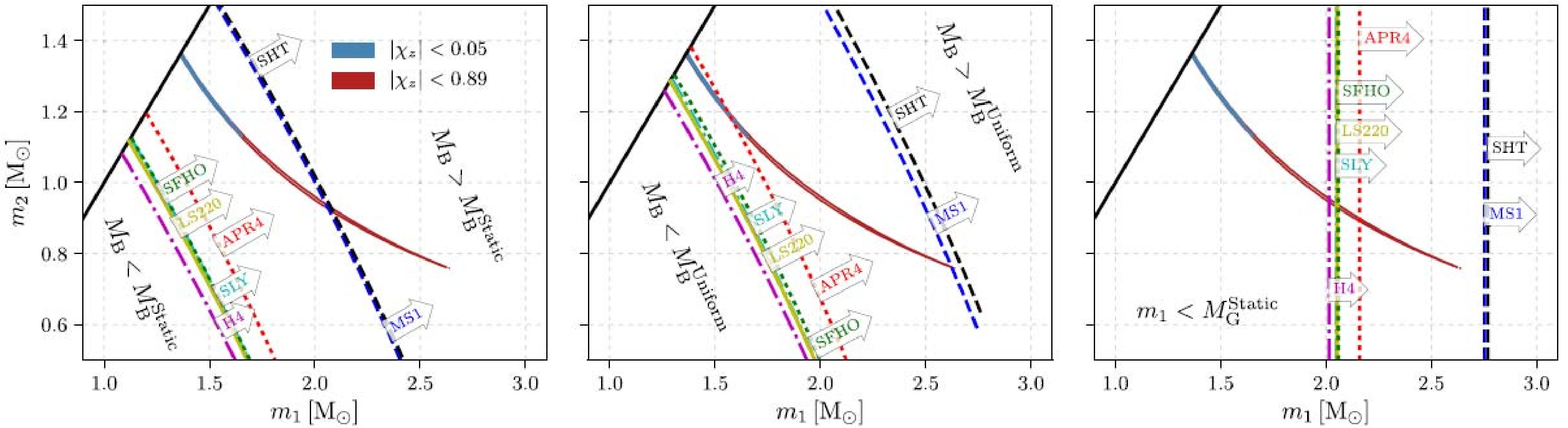
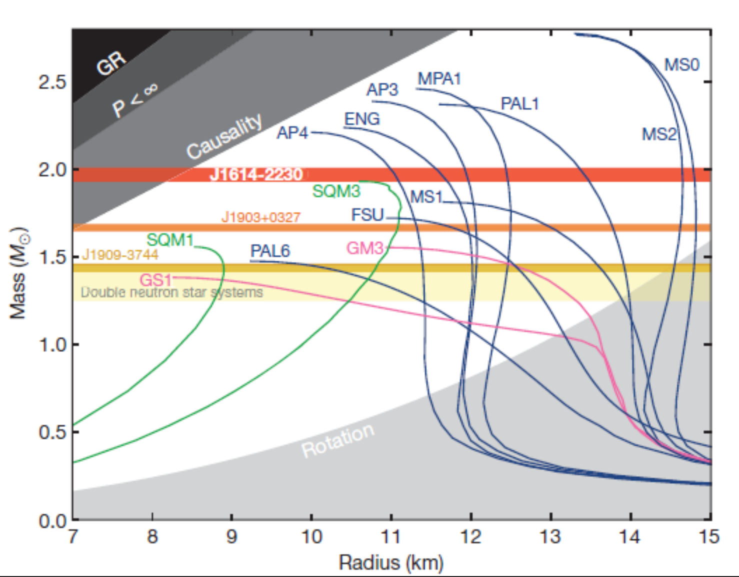


FIG. 7—Time evolution of a system with initial masses 0.8 and 1.3 $M_\odot$. (*a*) Neutrino and gravitational wave luminosities. (*b*) Frequency of gravitational wave. (*c*) Separation of components. (*d*) Masses of stars.



$$M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp mass



high-spin:

$m_1 \in (1.36 \div 2.26) M_\odot$

$m_2 \in (0.86 \div 1.36) M_\odot$

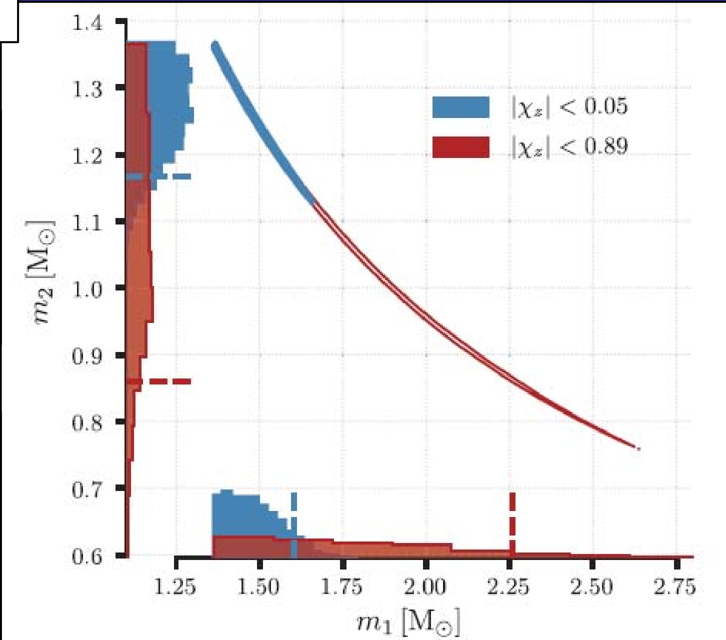
$m_{tot} = 2.82^{+0.47}_{-0.09} M_\odot$

low-spin:

$m_1 \in (1.36 \div 1.60) M_\odot$

$m_2 \in (1.17 \div 1.36) M_\odot$

$m_{tot} = 2.74^{+0.04}_{-0.01} M_\odot$

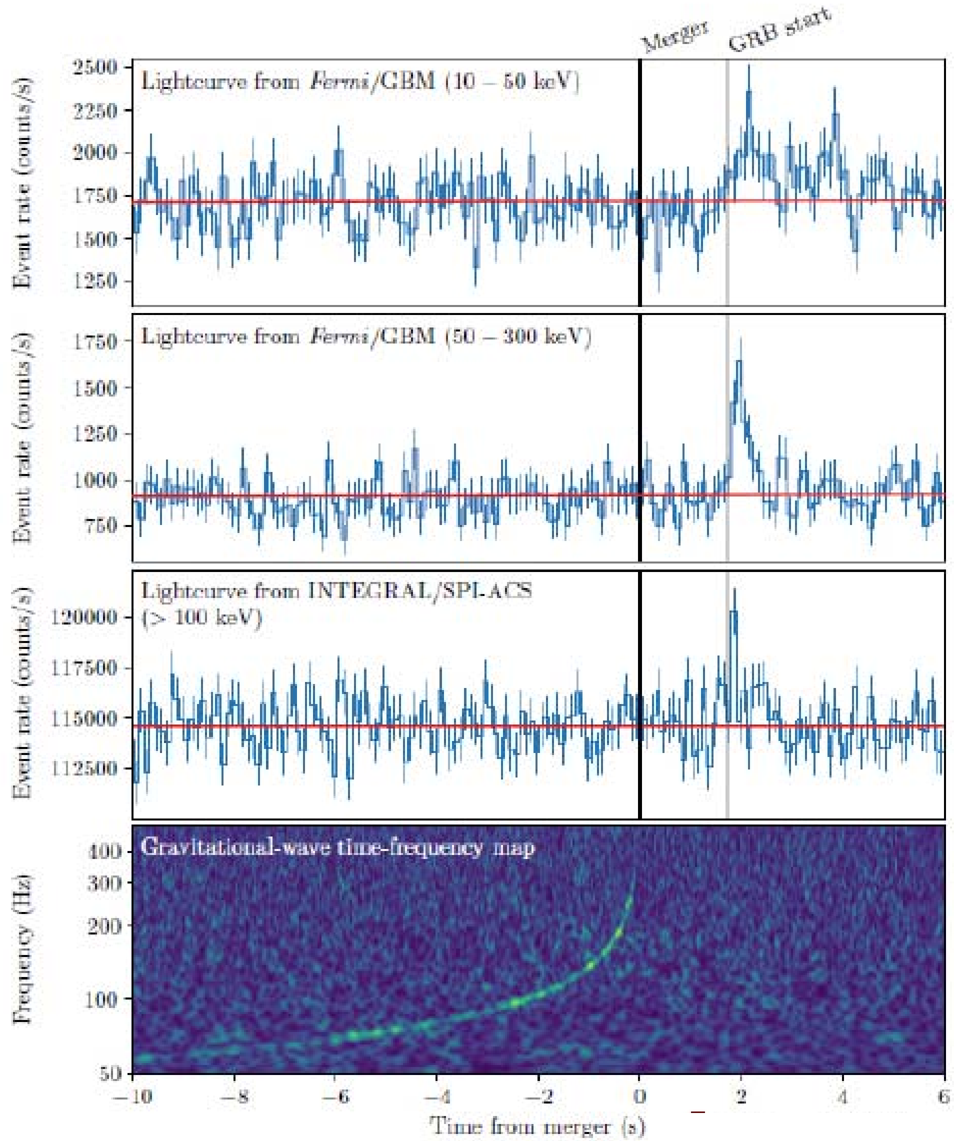


INTEGRAL and NASA's Fermi satellite

INTErnational
Gamma-Ray
Astrophysics
Laboratory

(INTEGRAL)

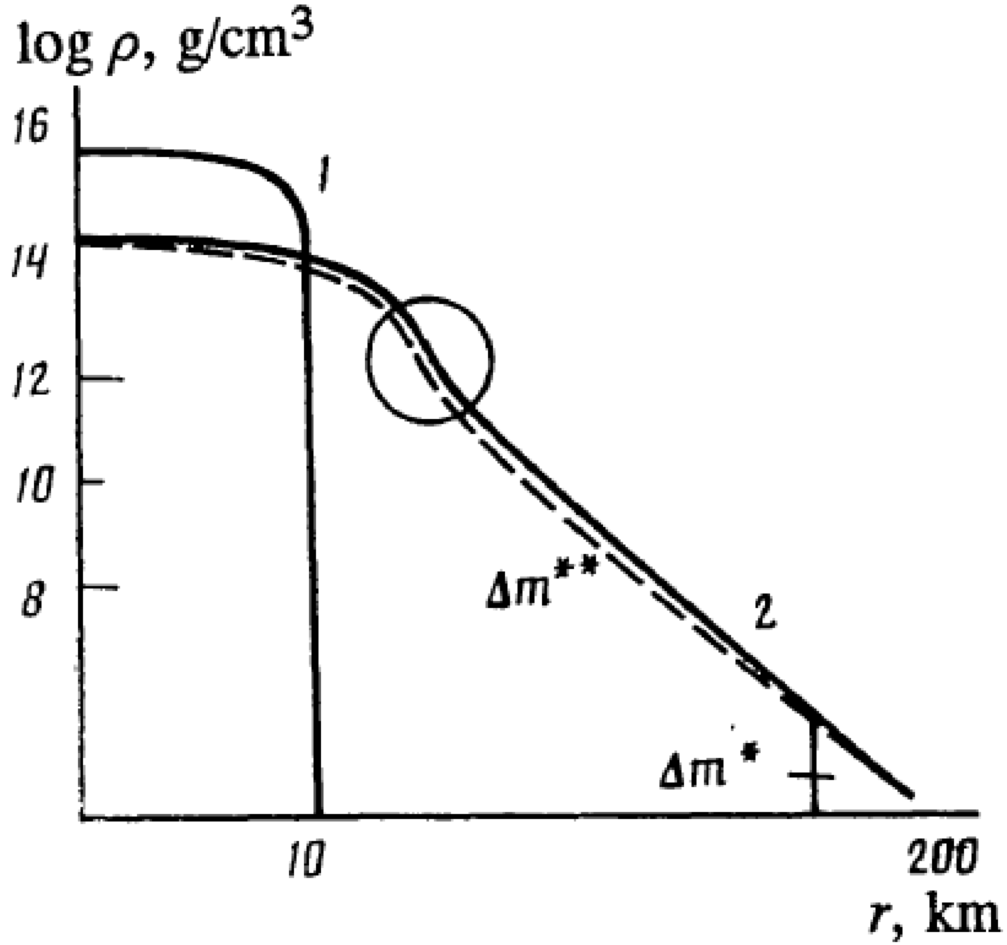
The Fermi
Gamma-ray
Space
Telescope



Постановка задачи о взрыве

Explosion of a low-mass neutron star

S. I. Blinnikov, V. S. Imshennik, D. K. Nadezhin, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev

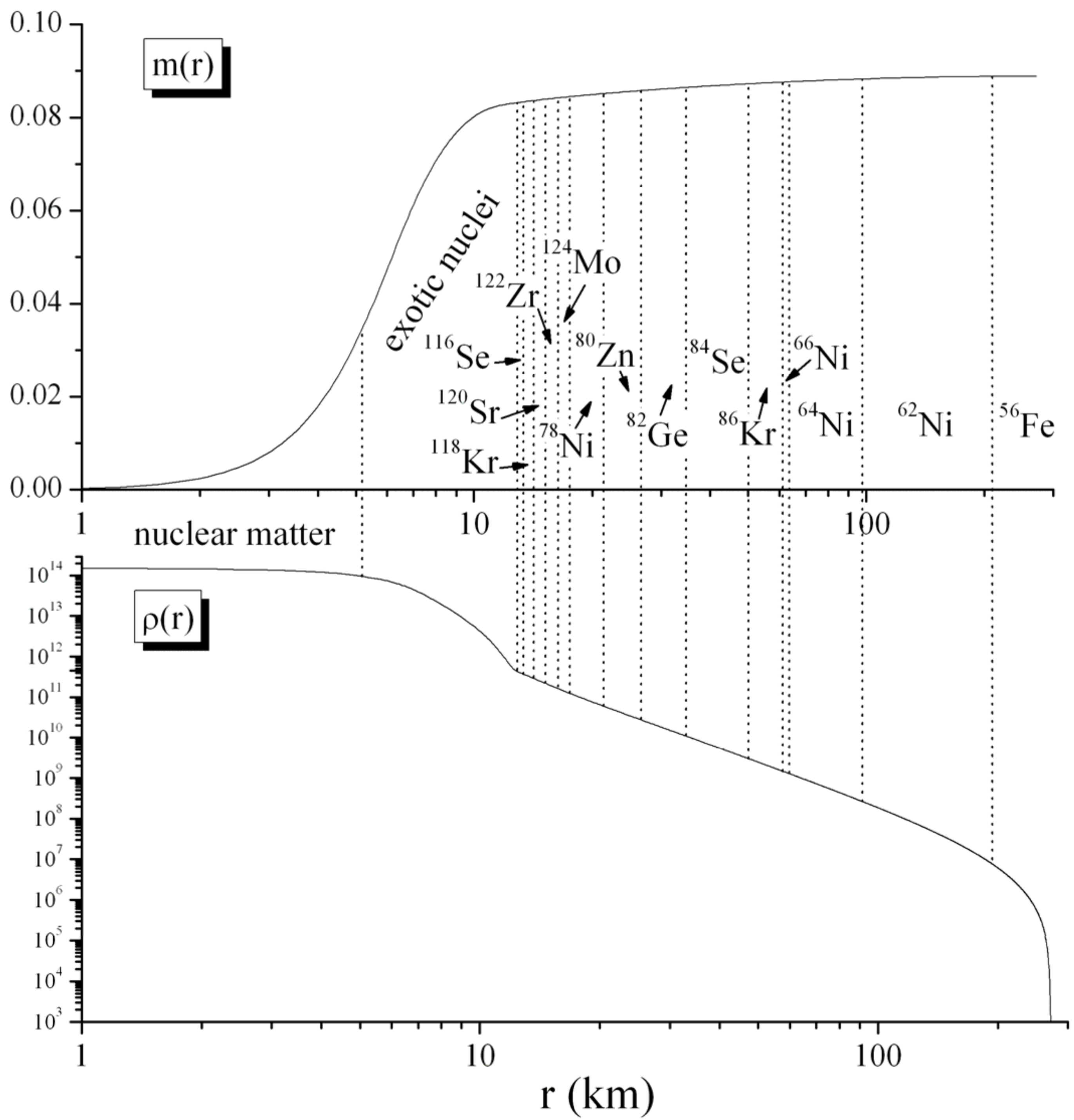


$$P = P_0(\rho) + \rho \tilde{R} T + \frac{1}{3} a T^4,$$

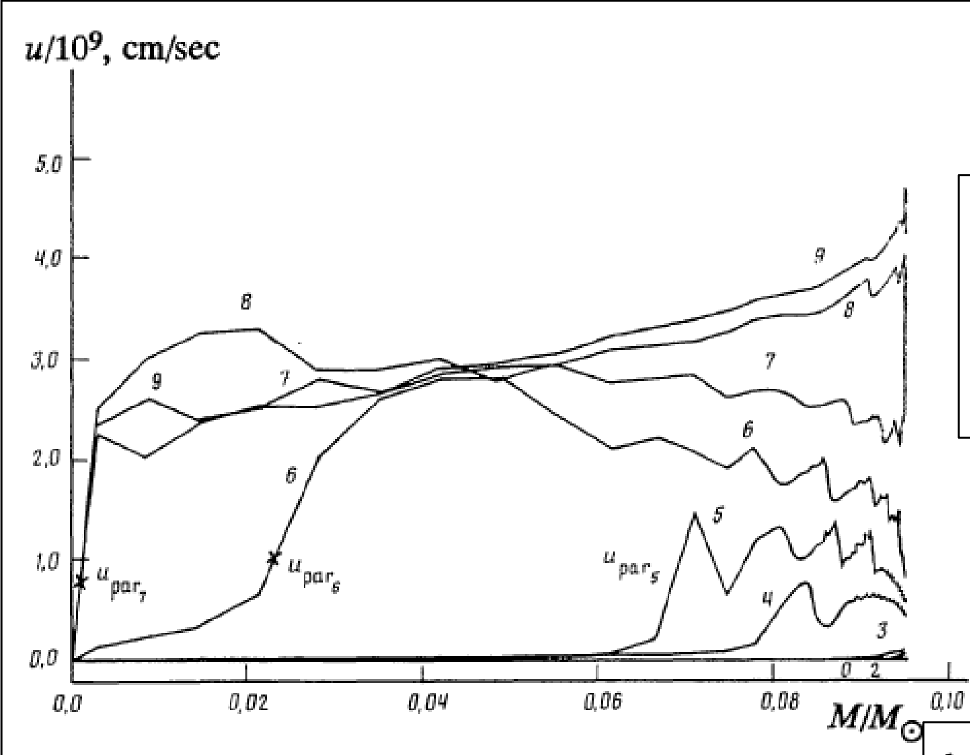
$$E = E_0(\rho) + \frac{3}{2} \tilde{R} T + \frac{a T^4}{\rho}.$$

$$t_{\text{hyd}} \approx \frac{1}{\sqrt{6\pi G \bar{\rho}}} \approx 0.3 \text{ msec}$$

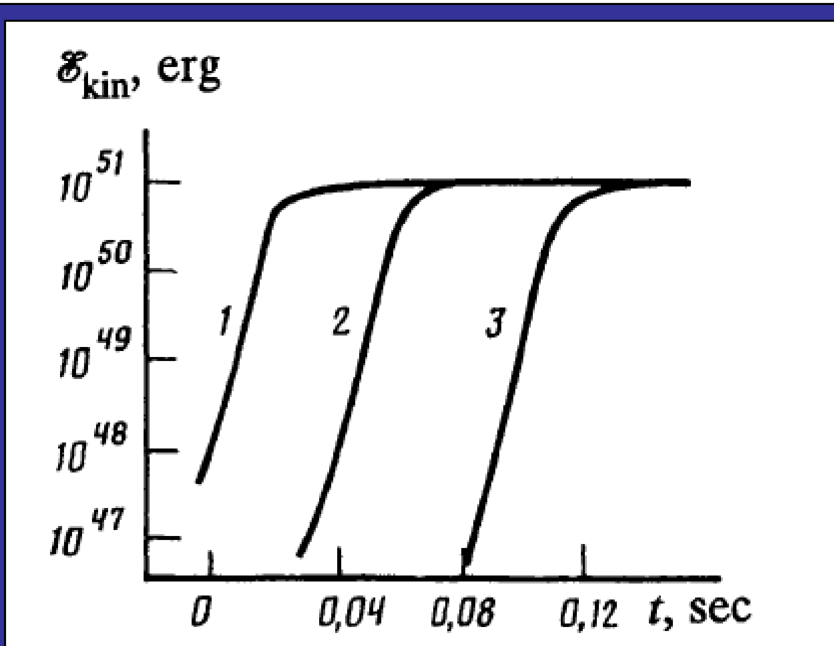
$$\begin{cases} \dfrac{\partial r}{\partial t} = u, \\ \dfrac{\partial u}{\partial t} = -4\pi r^2 \dfrac{\partial P}{\partial m} - \dfrac{Gm}{r^2}, \\ \dfrac{1}{\rho} = \dfrac{4\pi}{3} \dfrac{\partial r^3}{\partial m}, \\ \dfrac{\partial E}{\partial t} + P \dfrac{\partial 1/\rho}{\partial t} = 0. \end{cases}$$

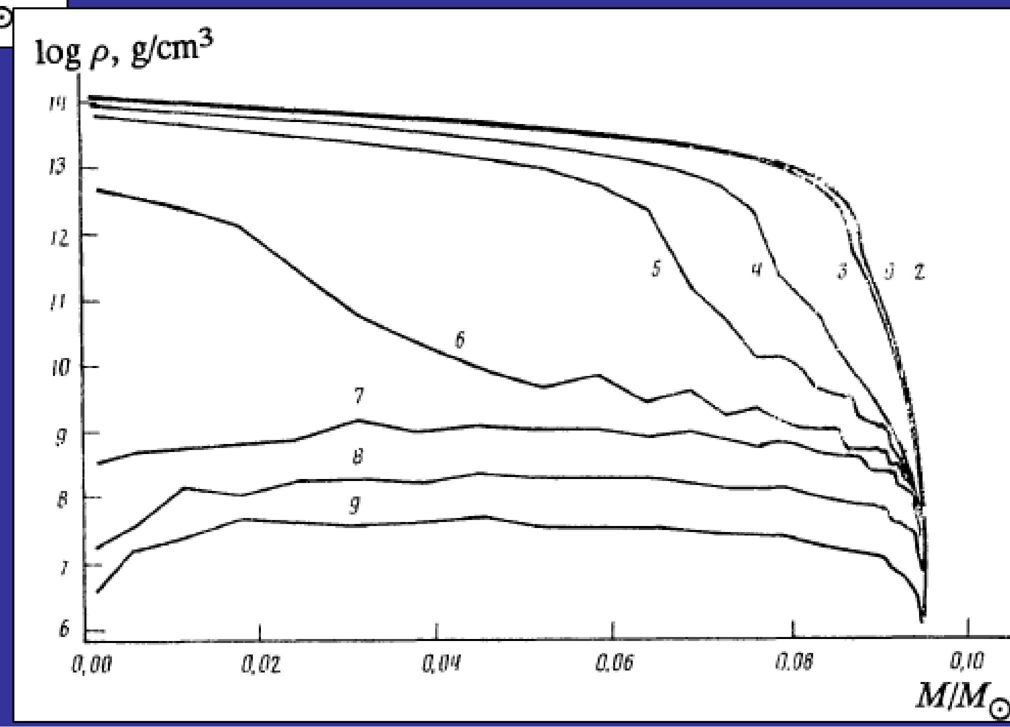


m(r)
ρ(r)
0.10
0.08
0.06
0.04
0.02
0.00
1
10
100
nuclear matter
exotic nuclei
124Mo
122Zr
116Se
80Zn
84Se
66Ni
120Sr
78Ni
82Ge
86Kr
64Ni
62Ni
56Fe
118Kr
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
r (km)



Curve No. in the figures	Curve No. in the figures	Curve No. in the figures	Time, sec	Curve No. in the figures	Time, sec
0	0	4	$9{,}70\cdot10^{-2}$	7	$1{,}20\cdot10^{-1}$
1	$5{,}60\cdot10^{-3}$	5	$1{,}03\cdot10^{-1}$	8	$1{,}31\cdot10^{-1}$
2	$2{,}63\cdot10^{-2}$	6	$1{,}11\cdot10^{-1}$	9	$1{,}44\cdot10^{-1}$
3	$5{,}52\cdot10^{-2}$				





surface layers can be maintained at 10^8-10^9 K. This should lead to a burst of hard thermal x rays and soft gamma rays with a total energy of 10^{43}-10^{47} erg.

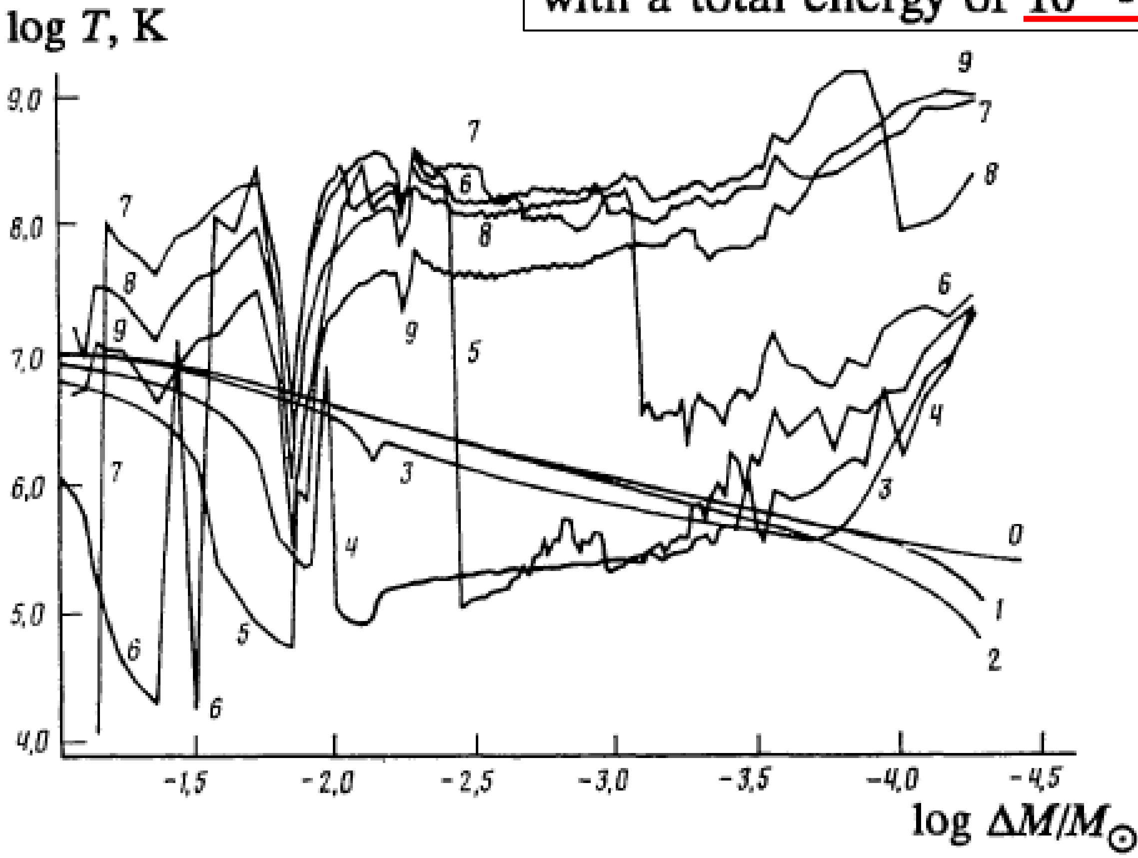
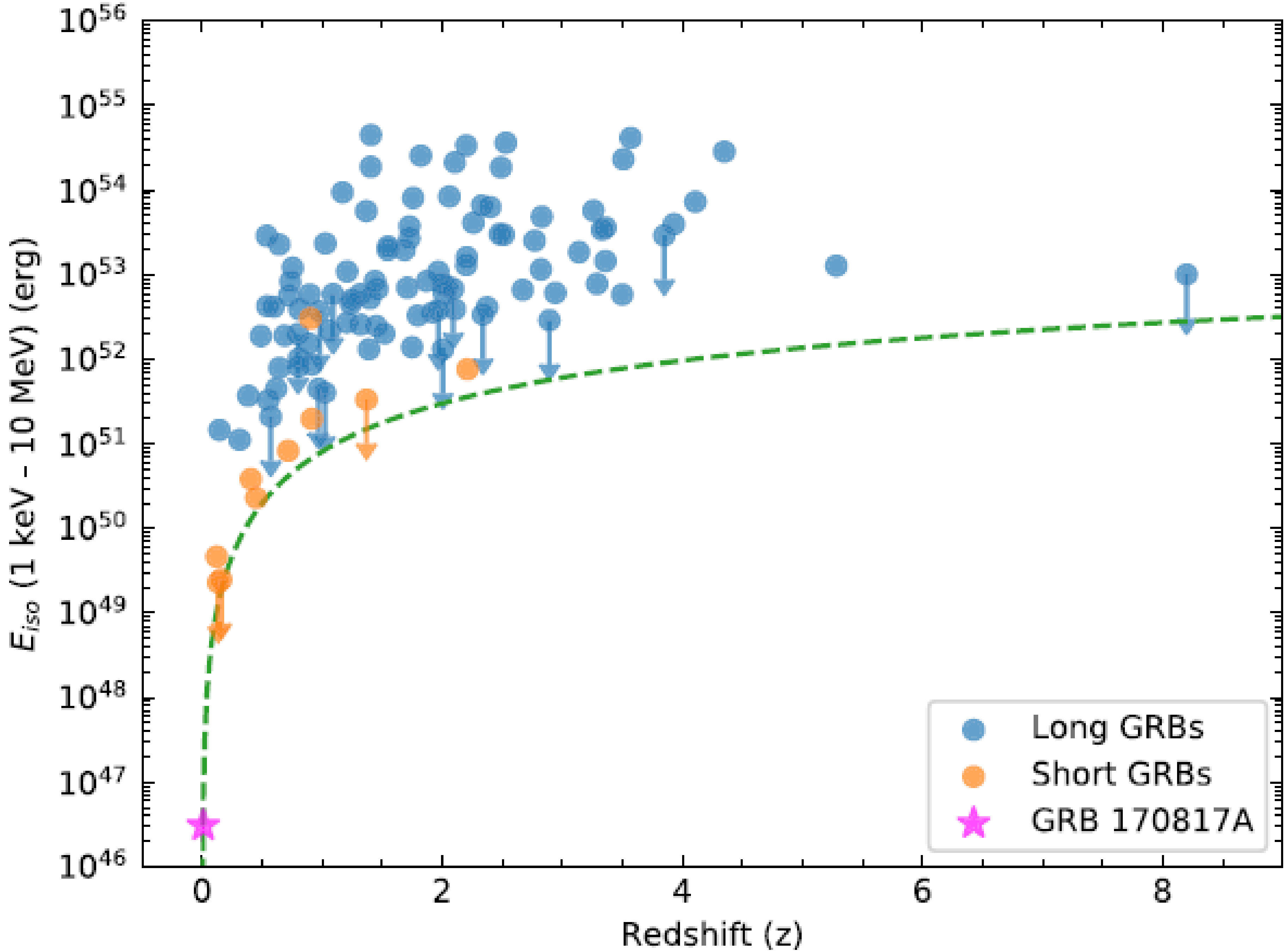


FIG. 12. Temperature distributions along the Lagrangian coordinate (ΔM is the mass reckoned from the surface) in the course of the explosion of a neutron star of mass $M = 0.09499\ M_\odot$ at different times (Table I). The temperature increase to 10^8-10^9 K at the surface indicates the possibility of thermal x-ray and gamma-ray bursts accompanying the explosions of neutron stars.



10^{56}
10^{55}
10^{54}
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
E_{iso} (1 keV - 10 MeV) (erg)
0
2
4
6
8
Redshift (z)
Long GRBs
Short GRBs
GRB 170817A

GW170817–the first observed neutron star merger and its kilonova: implications for the astrophysical site of the r-process

Daniel M. Siegel[1,2]

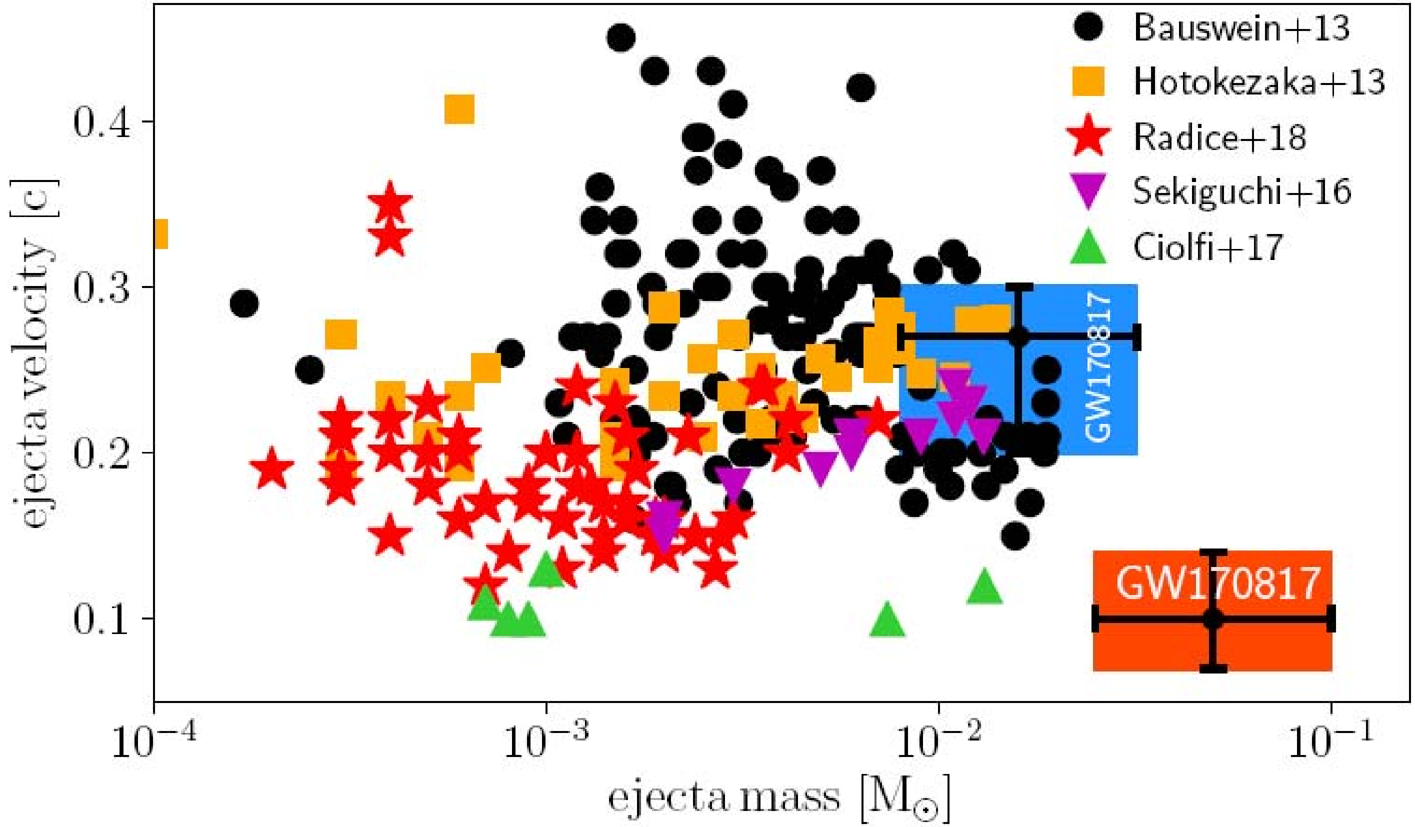
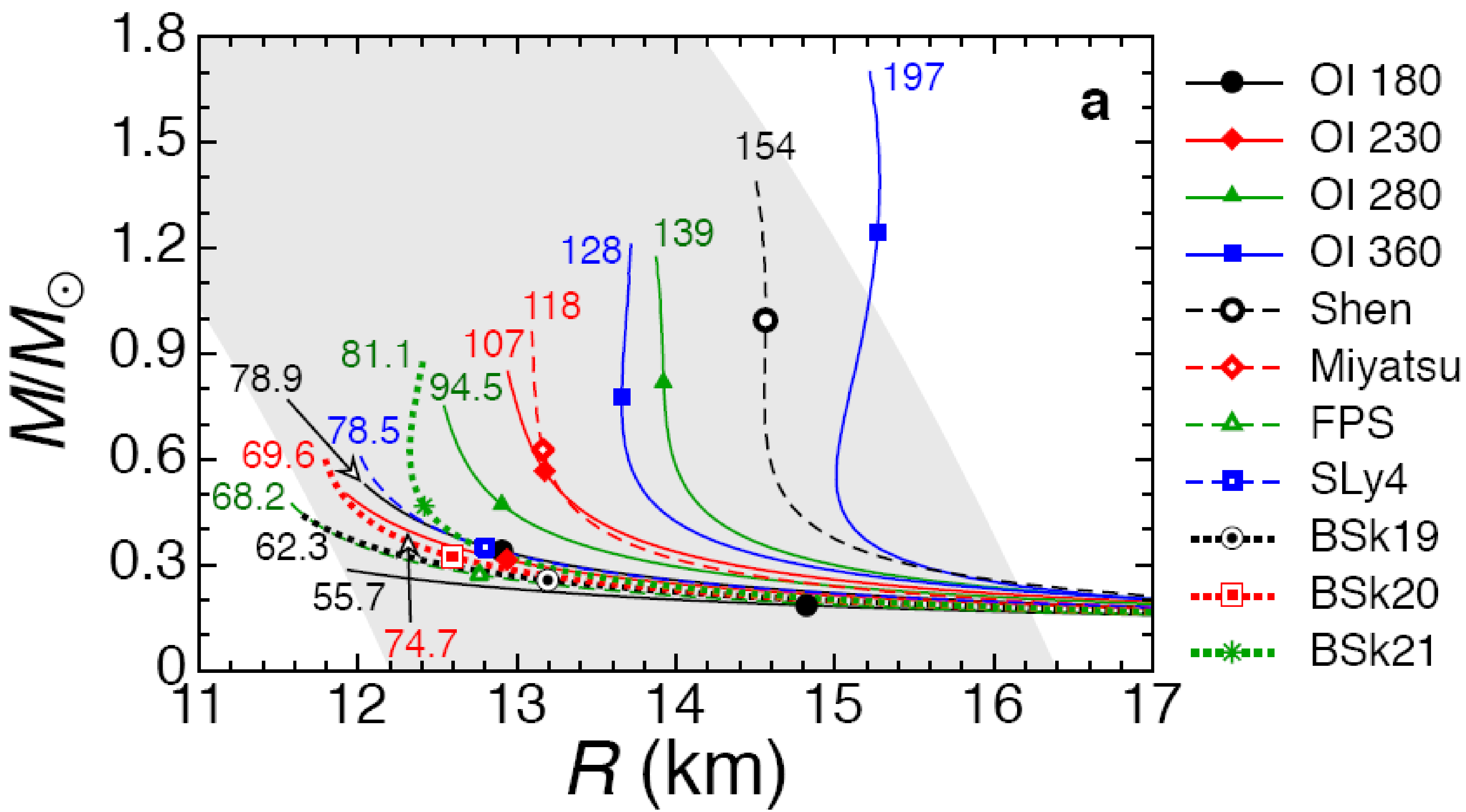


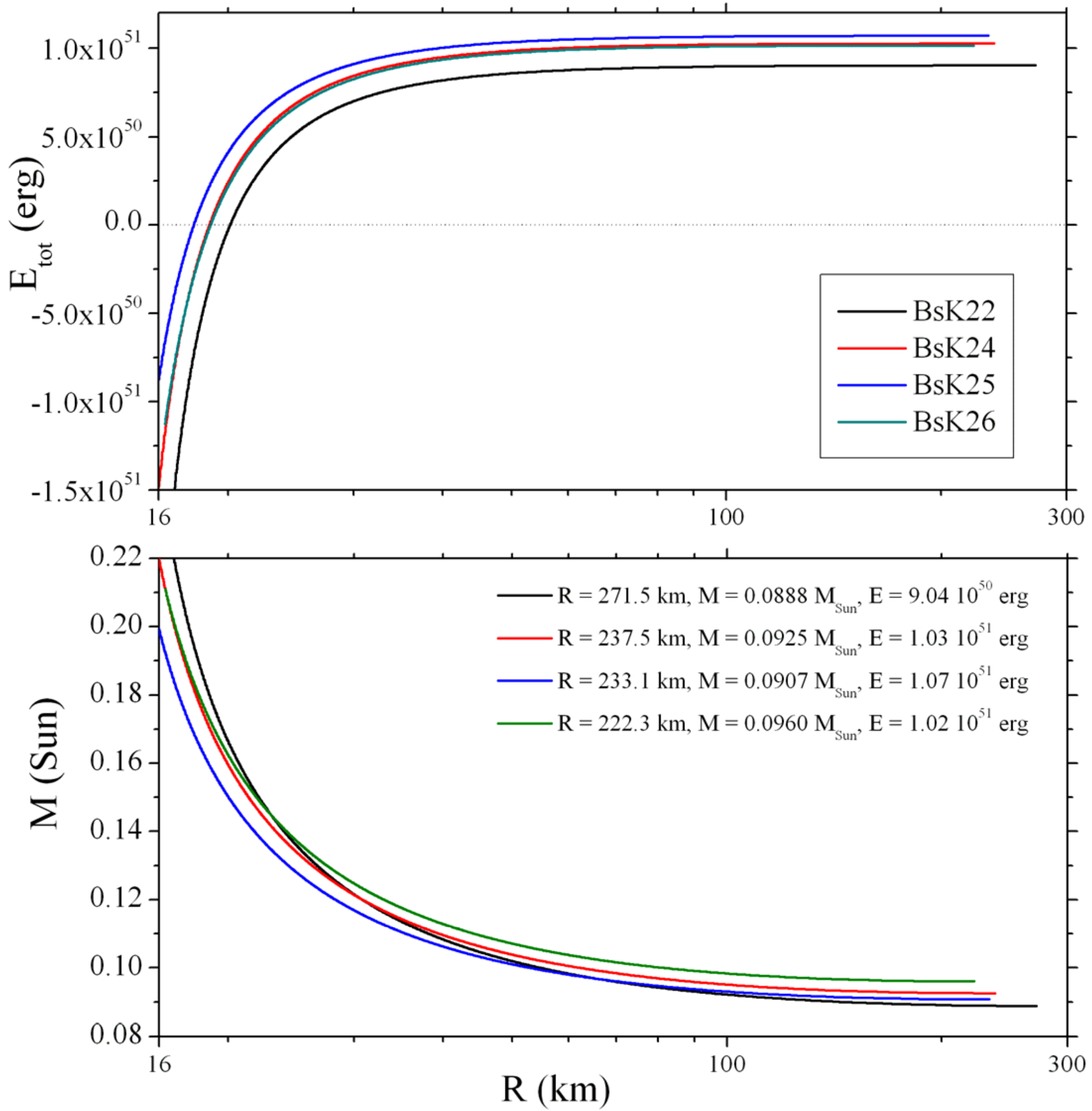
Figure 1. Dynamical ejecta masses and velocities from various binary neutron star merger simulations encompassing different numerical techniques, various equations of state, binary binary mass ratios 0.65 – 1.0, effects of neutrinos and magnetic fields [77, 78, 64, 73, 65], together with the corresponding ejecta parameters inferred from the 'blue' and 'red' kilonova of GW170817 (see the text for details).

PTEP
Prog. Theor. Exp. Phys. **2012**, 00000 (9 pages)
DOI: 10.1093/ptep/0000000000

Mass and radius formulas for low-mass neutron stars

Hajime Sotani[1,*], Kei Iida[2], Kazuhiro Oyamatsu[3], and Akira Ohnishi[1]





1.0x10^51
5.0x10^50
0.0
-5.0x10^50
-1.0x10^51
-1.5x10^51
E_tot (erg)
BsK22
BsK24
BsK25
BsK26
16
100
300
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
M (Sun)
R = 271.5 km, M = 0.0888 M_Sun, E = 9.04 10^50 erg
R = 237.5 km, M = 0.0925 M_Sun, E = 1.03 10^51 erg
R = 233.1 km, M = 0.0907 M_Sun, E = 1.07 10^51 erg
R = 222.3 km, M = 0.0960 M_Sun, E = 1.02 10^51 erg
16
100
300
R (km)

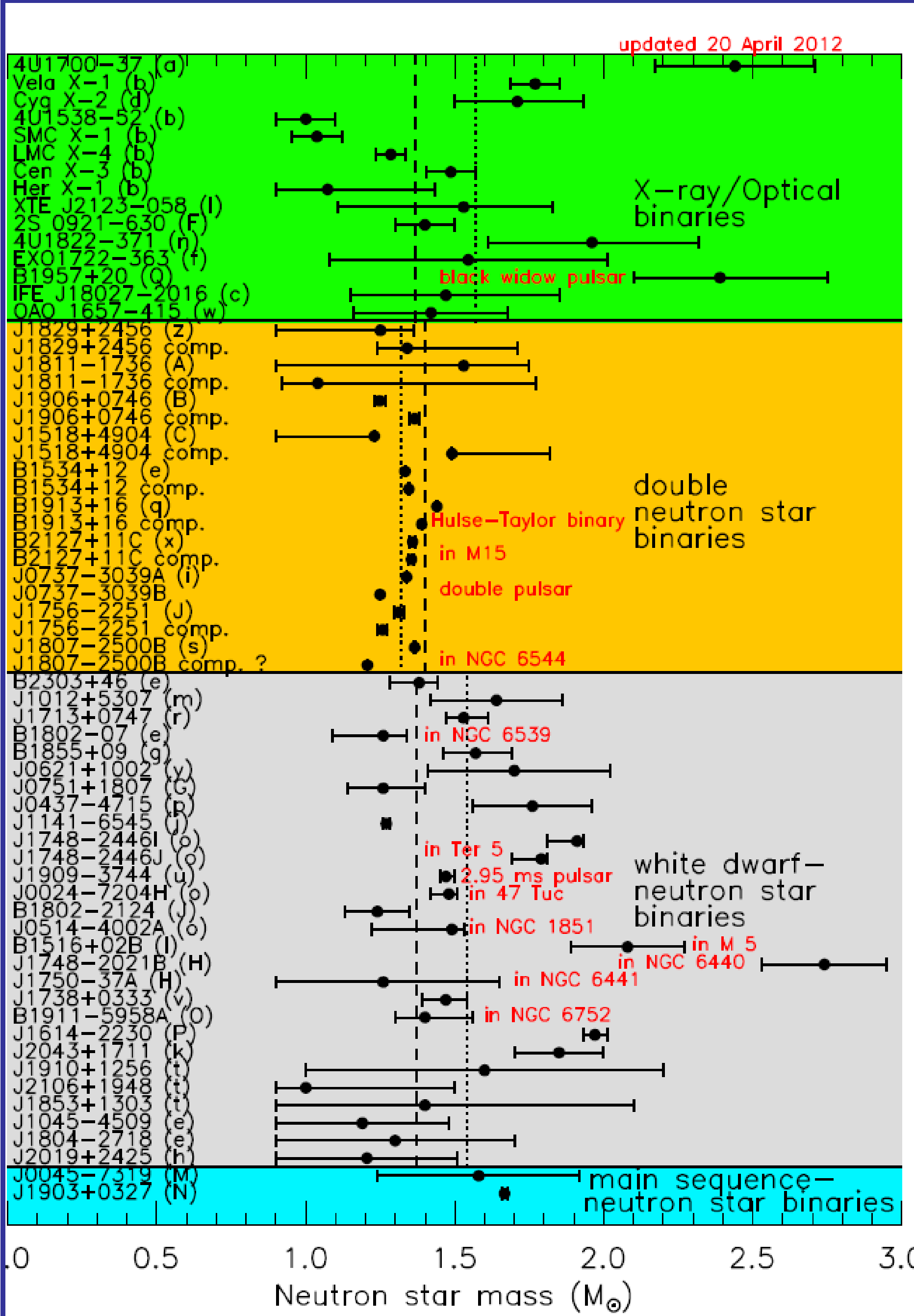
Спасибо за внимание!

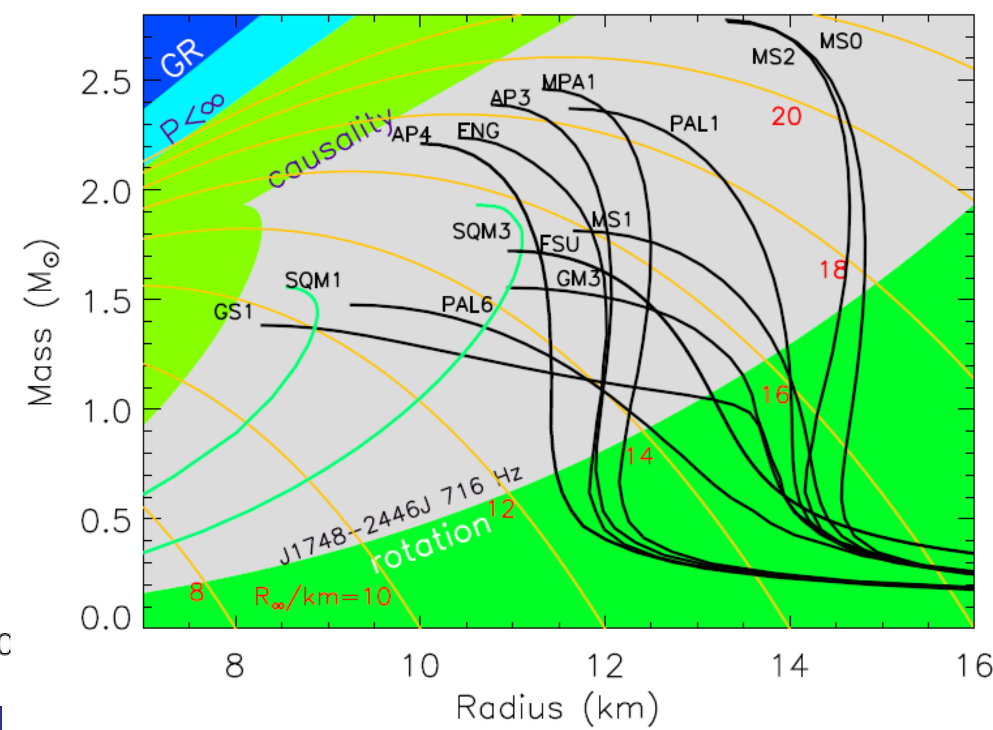
Caption: Artist's concept of the explosive collision of two neutron stars. Illustration by Robin Dienel courtesy of the Carnegie

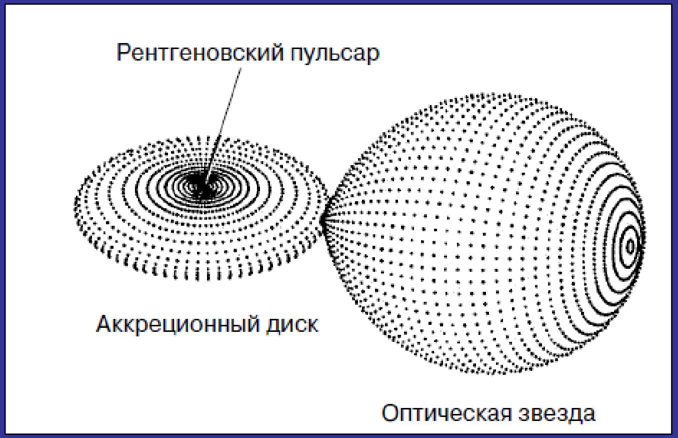
Maximum neutron star mass

J.M. Lattimer

Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

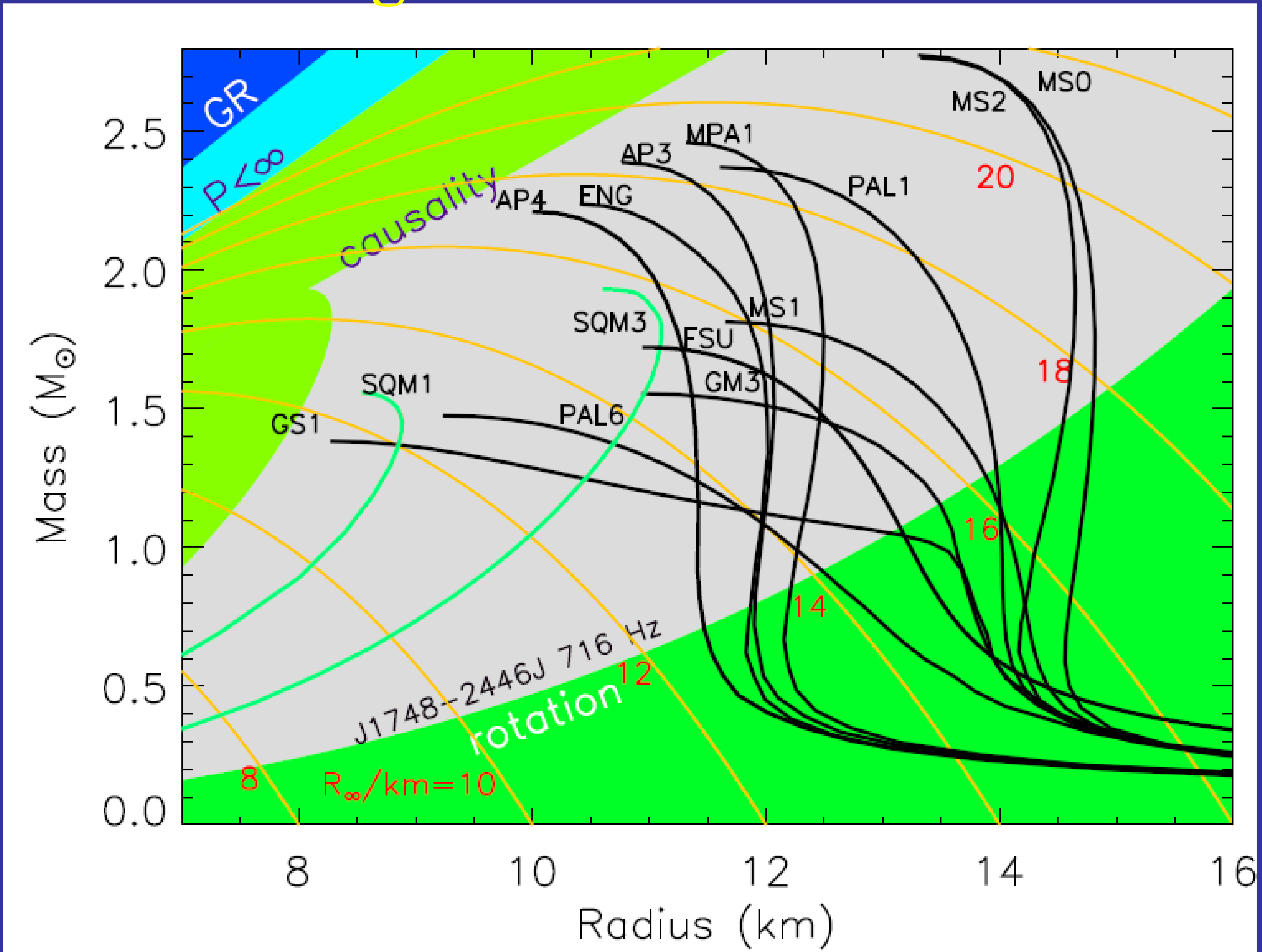






А.В. Тутуков и Л.Р. Юнгельсон, Научные информ. Астросовета АН СССР. Т. 27. 1973

M-R diagram for neutron stars



J.M. Lattimer Ann. Rev. of Nucl. and Part. Sci., 62, 1, 485-515 (2012)