Alikhanov Institute for Theoretical and Experimental Physics
Russian Federation State scientific center

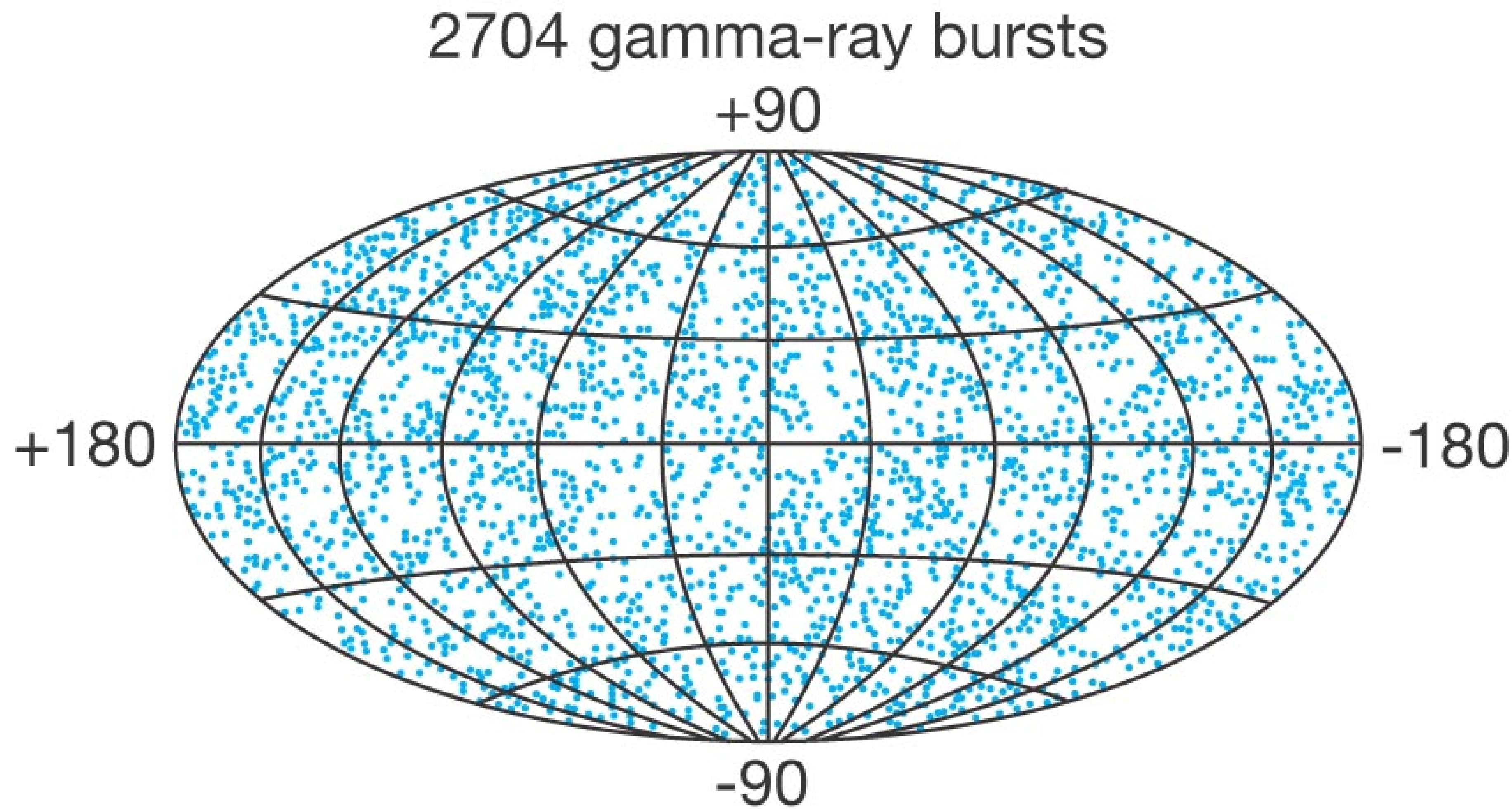
Модель обдирания для коротких гамма-всплесков

<u>А.В. Юдин, ИТЭФ</u>

совместно с С.И. Блинниковым и И.В. Пановым

Семинар отдела релятивистской астрофизики
26 января 2021 г.

Gamma-Ray Bursts

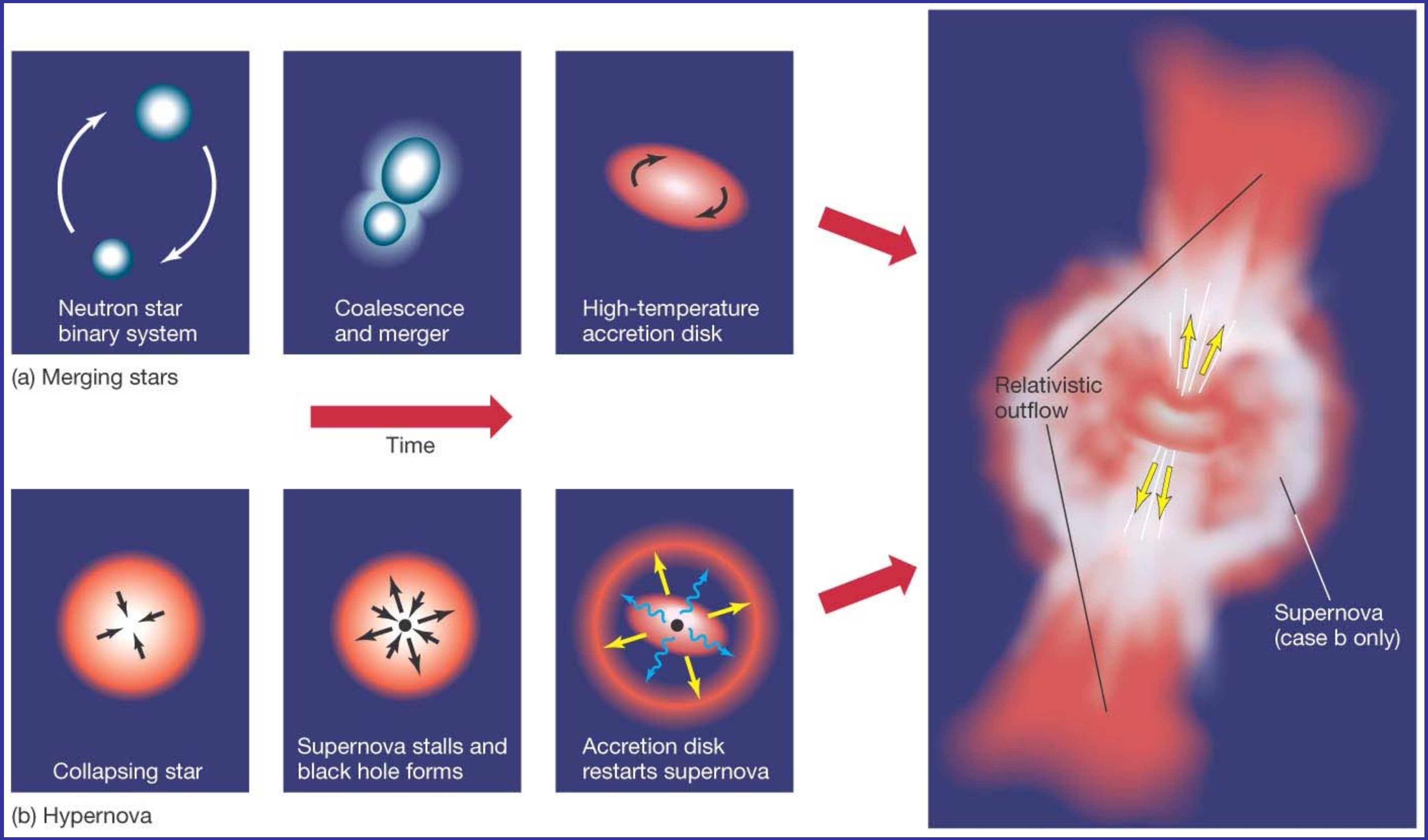


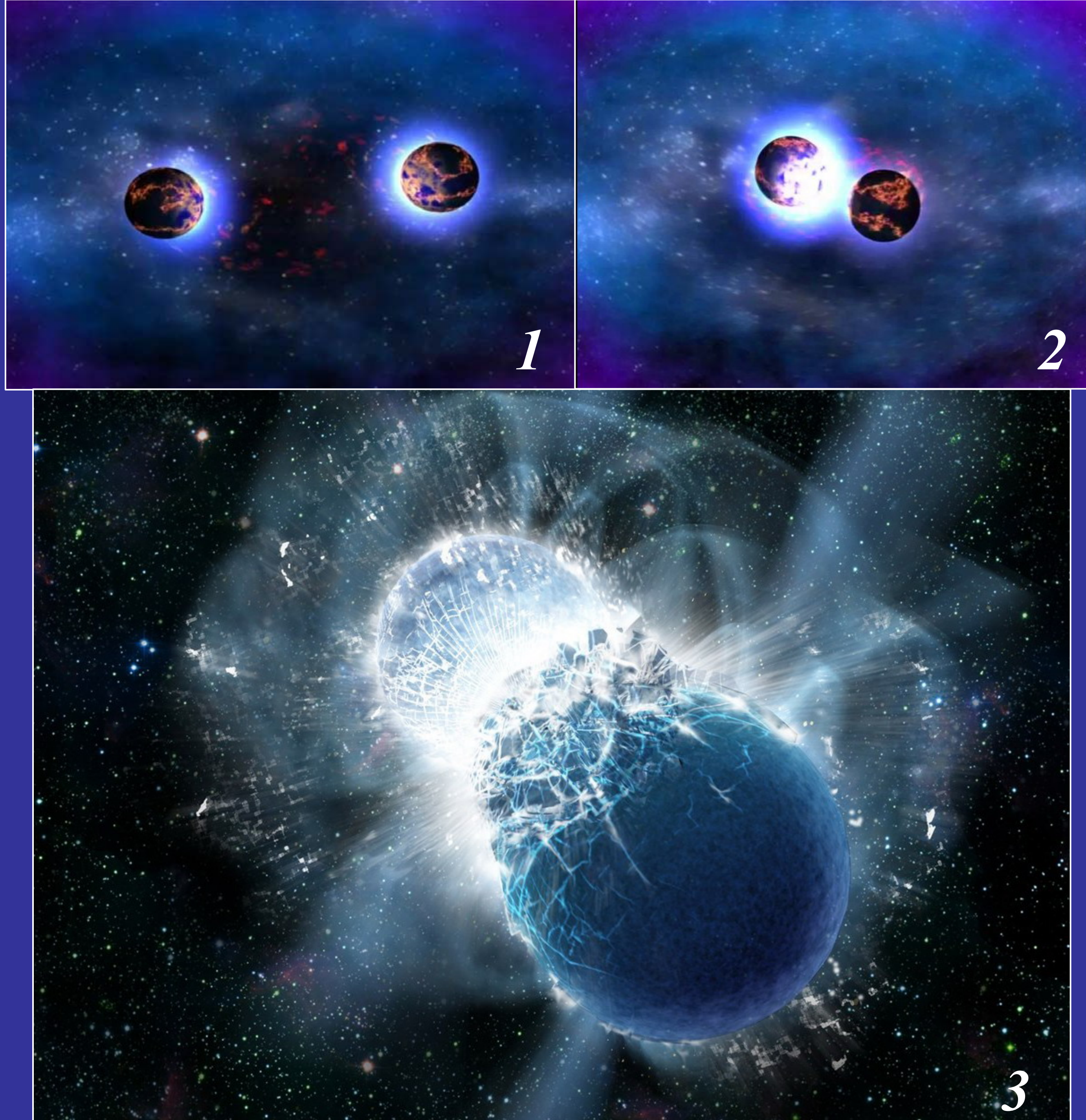
GRB (гамма-всплески): вспышки с энергией от нескольких десятков кэВ до МэВ (иногда и более жесткие). Вспышки длятся от нескольких долей секунд до минут, а иногда и часов.

<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"):

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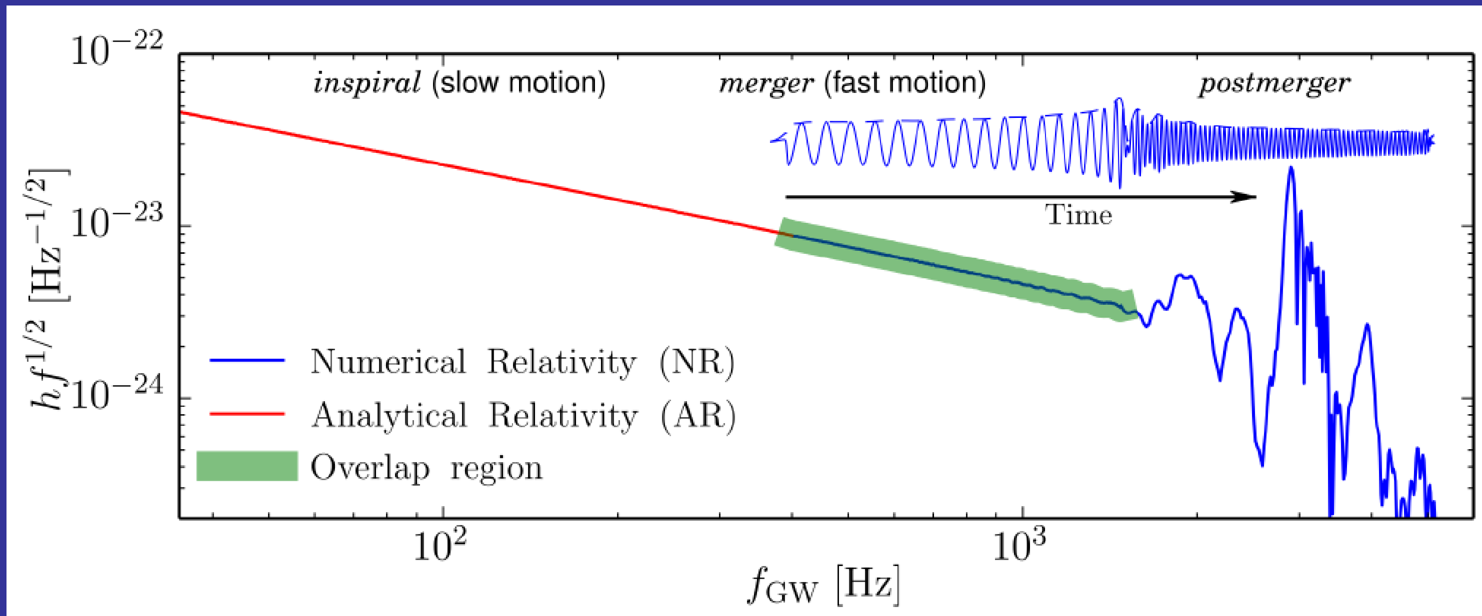
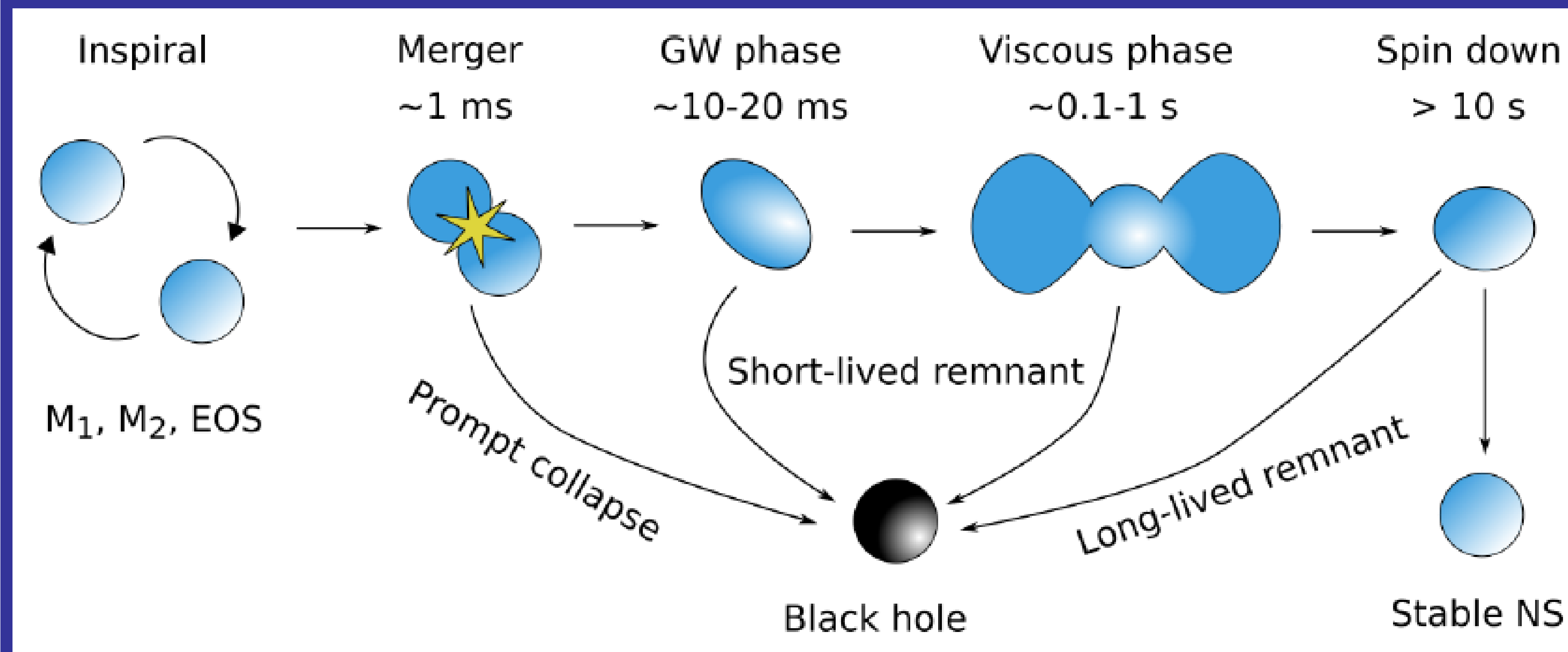
D.Radice, S. Bernuzzi, A. Perego
Annual Reviews of Nuclear and Particle Science





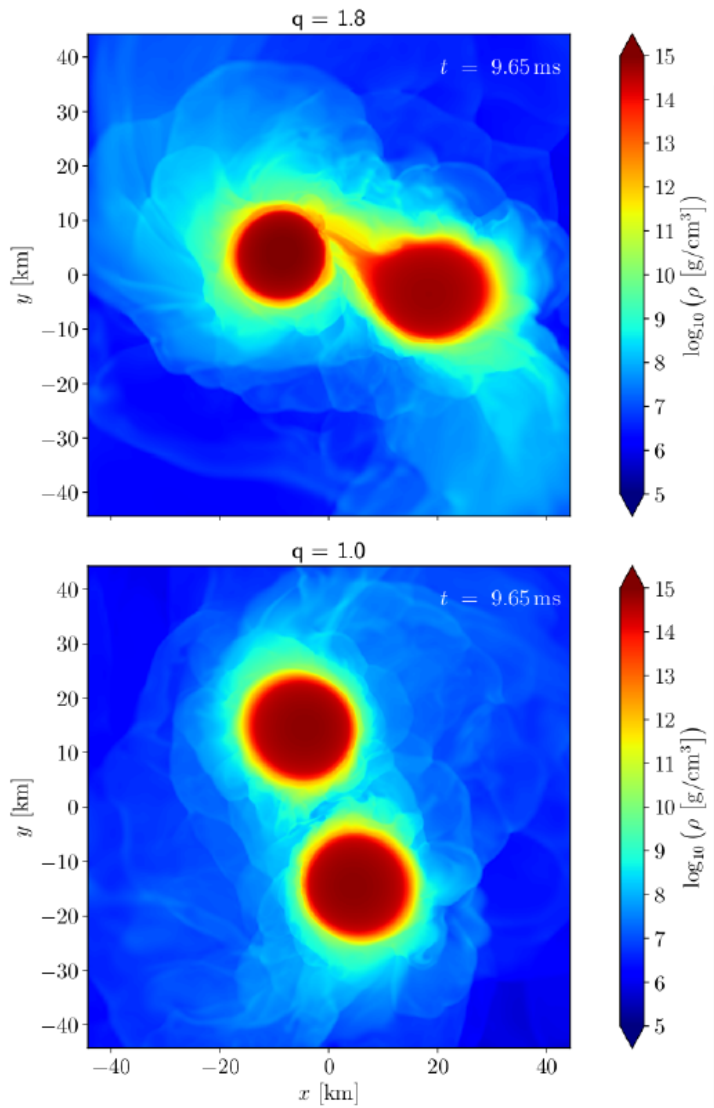


Figure 3. Snapshots of premerger dynamics for BLh $q = 1.8$ (top) and $q = 1.0$ (bottom) simulations. Shown is the rest-mass density in the orbital plane at ∼9 ms corresponding to the third orbit from the beginning of the simulations and 2 orbits to the moment of merger. The companion in the $q = 1.8$ BNS is tidally disrupted and a significant accretion onto the primary is taking place. Accretion starts approximately after one orbits from the beginning of the simulations.

8 *S. Bernuzzi et al.*

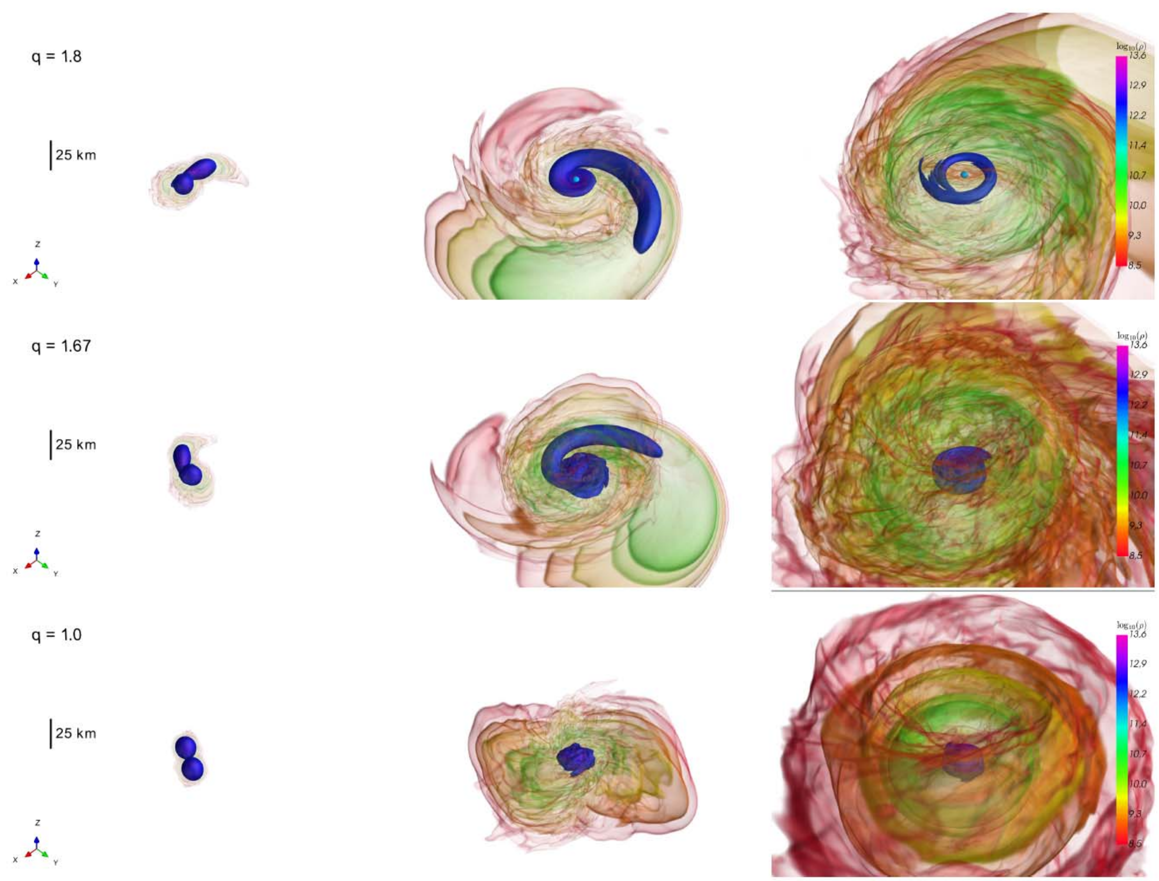


Figure 4. 3D volume rendering of the rest mass density ρ in g cm^{-3} expressed in logarithmic scale for the BLh models. Each column represen time inside the simulation: merger time (left), early postmerger (∼ 2ms, middle) and later stages (∼ 10ms, right). In each row we show a differe $q = M_A/M_B$: $q = 1.8$ (top), $q = 1.67$ (middle) and $q = 1.0$ (bottom). The BH apparent horizon is shown as a bright green isosurface of the l $\alpha = \alpha_{AH}$.

S.Bernuzzi et al., arXiv:2003.06015v1

D.Radice, F. Galeazzi, J. Lippuner, L.F. Roberts, C. D. Ott, L. Rezzolla
MNRAS **460, 3255–3271 (2016)**

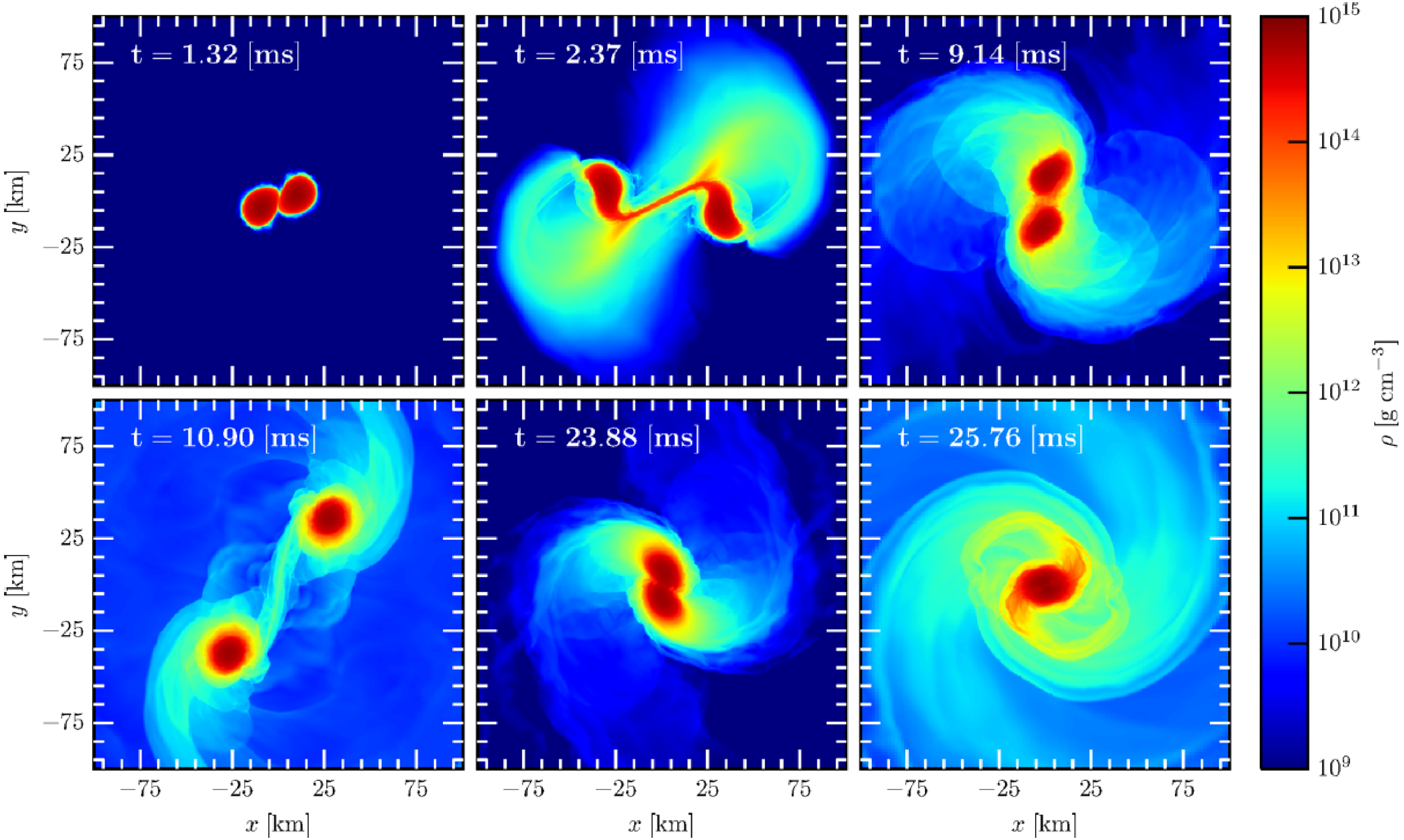


Figure 1. Rest-mass density (equation 4) in the orbital plane for the parabolic encounter simulation `LK_RP10` at six different times. The NSs undergo three close encounters before merging. The panels show snapshots of the two stars immediately before and after each encounter. Tidal torques at the periastron result in large mass ejection and trigger oscillations in the NSs, cf. Fig. 2.

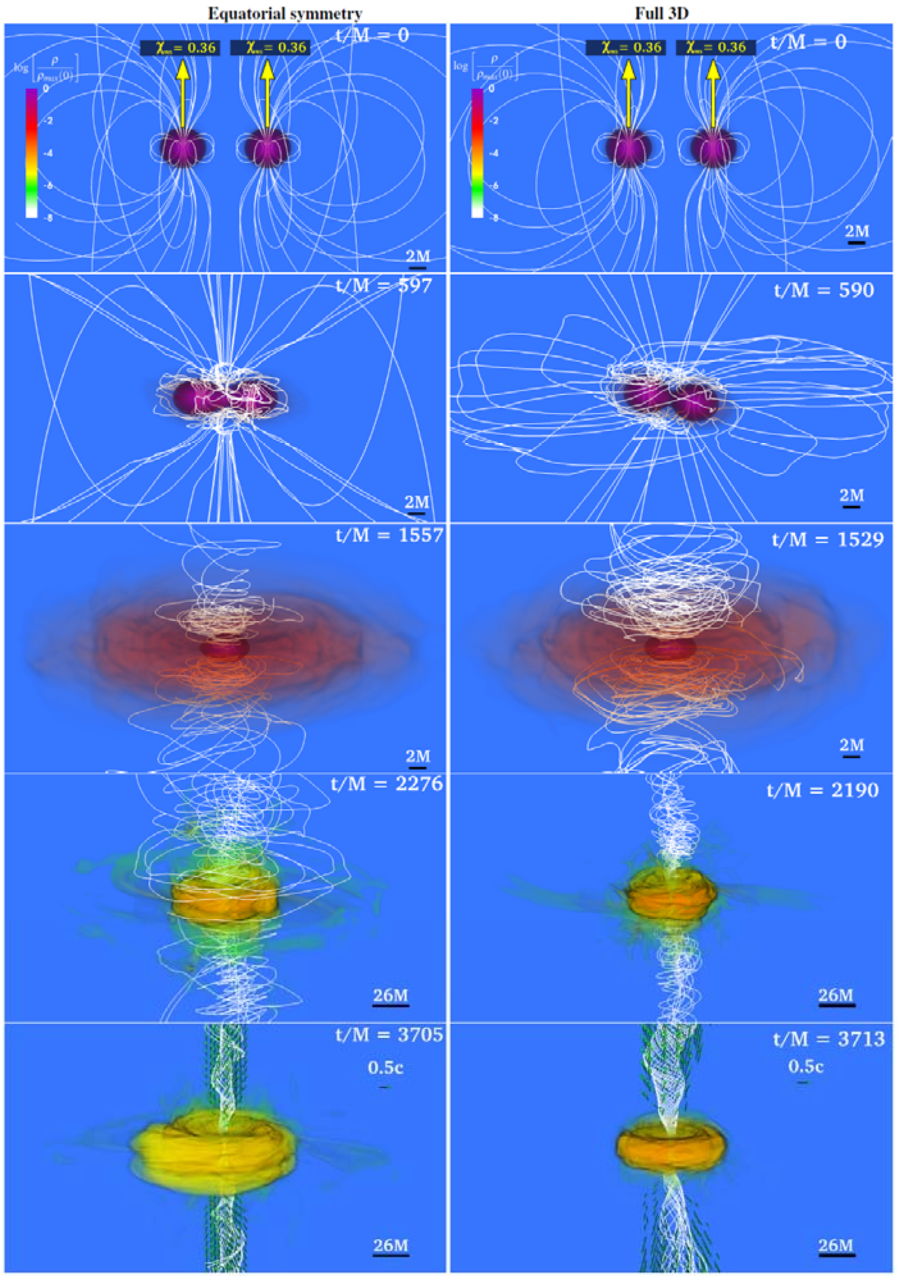
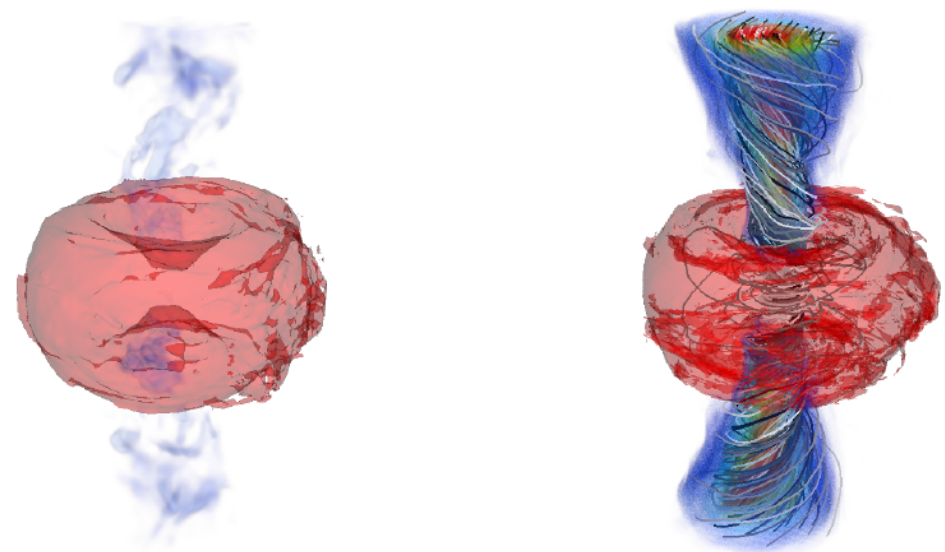


FIG. 1. Volume rendering of rest-mass density ρ_0, normalized to the initial maximum value $\rho_0^{\max} = 10^{14.78}(1.625\,M_\odot/M_{NS})^2 \mathrm{g/cm^3}$ (log scale), at selected times for the Ali-Ali (Eq) case (left column) and the Ali-Ali case (right column). White lines represent the magnetic field lines, while arrows indicate plasma velocities. Bottom panels highlight the final configuration of the BH + disk remnant after an incipient jet has been launched. Here $M = 1.47 \times 10^{-2}(M_{NS}/1.625M_\odot)$ms= $4.4288(M_{NS}/1.625M_\odot)$km.

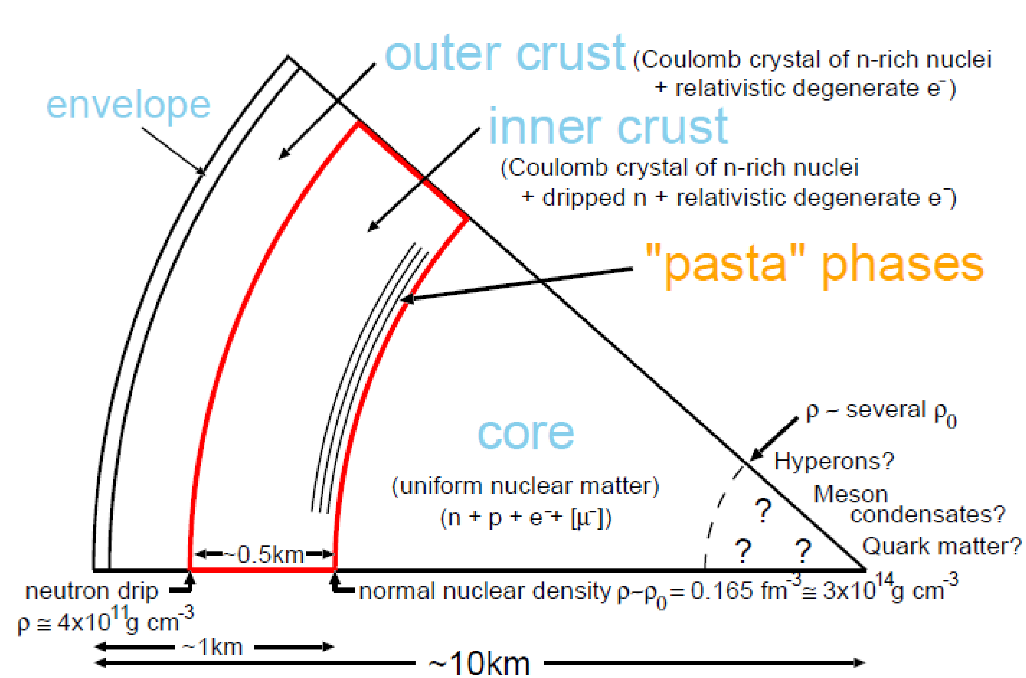
M. Ruiz, A. Tsokaros, S. L. Shapiro
arXiv:2001.09153v1

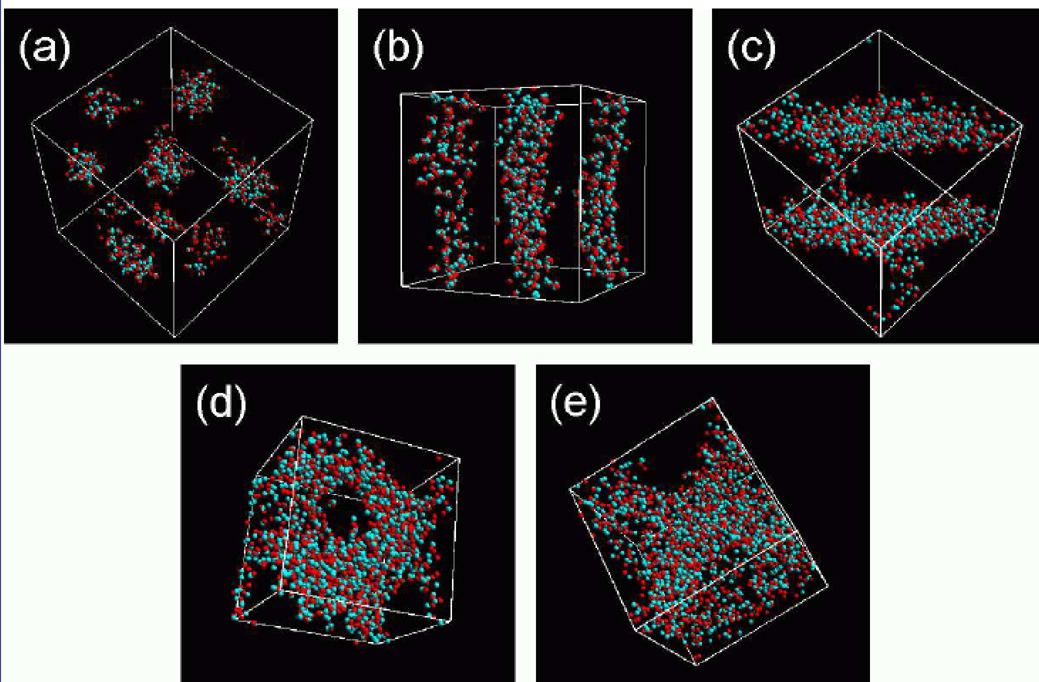
A MAGNETAR ENGINE FOR SHORT GRBS AND KILONOVAE

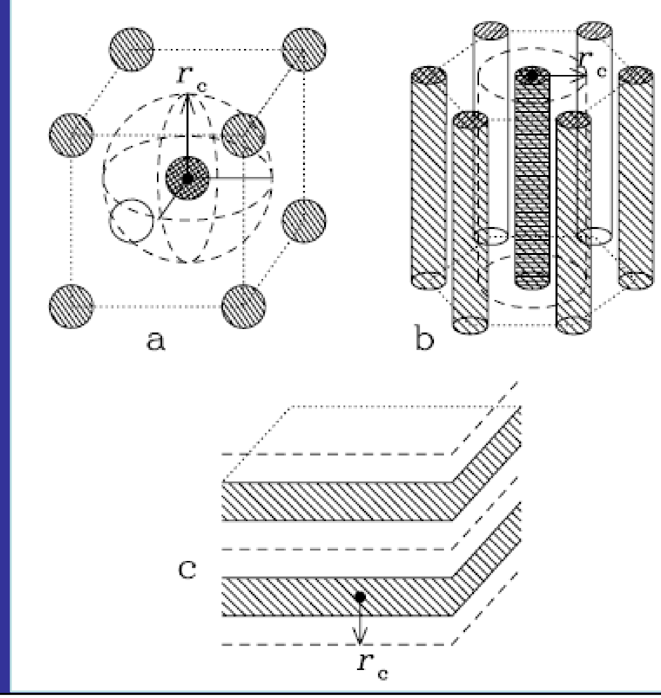


P. Mosta, D. Radice, R. Haas,
E. Schnetter, S. Bernuzzi
ApJL, 901, L37 (2020)

Gentaro Watanabe and Hidetaka Sonoda







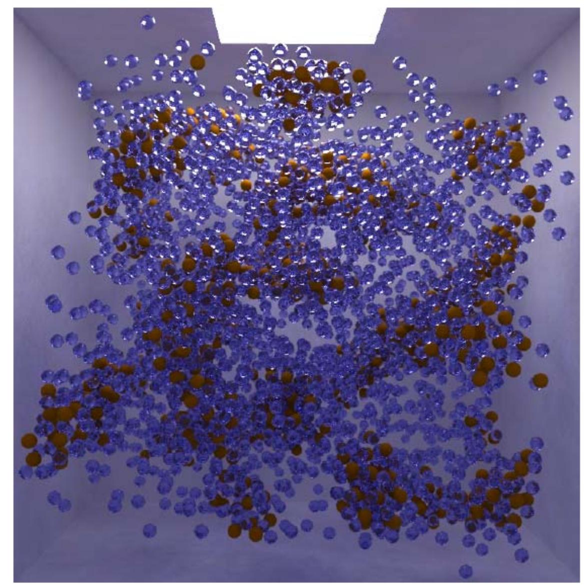
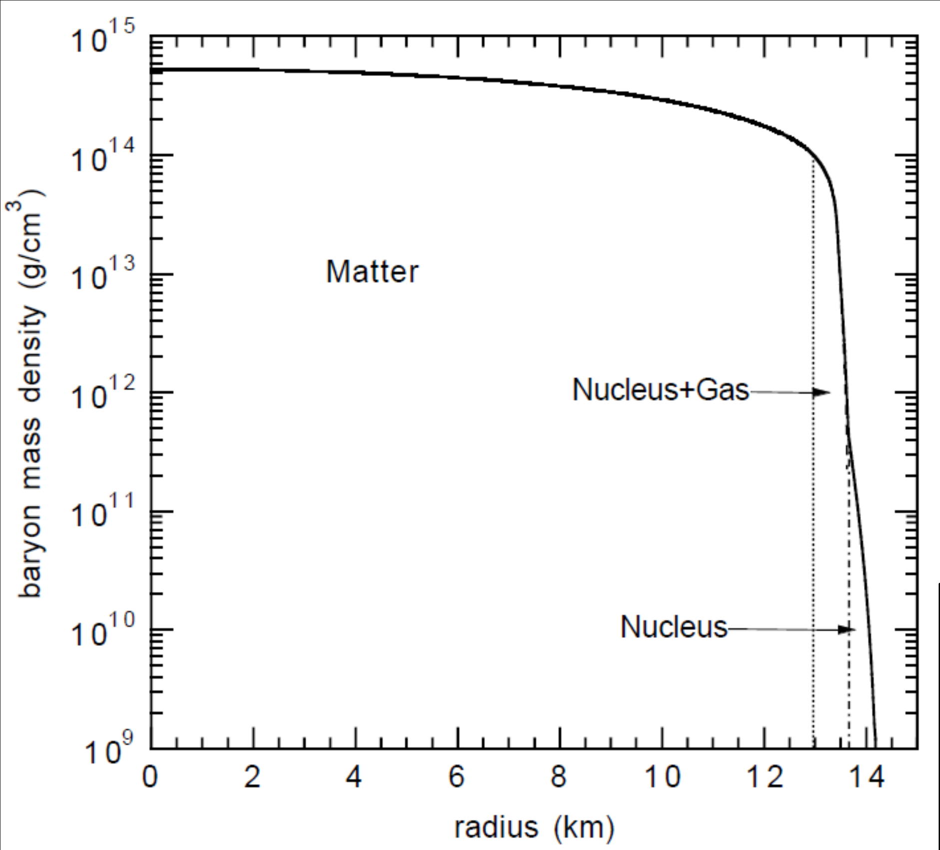
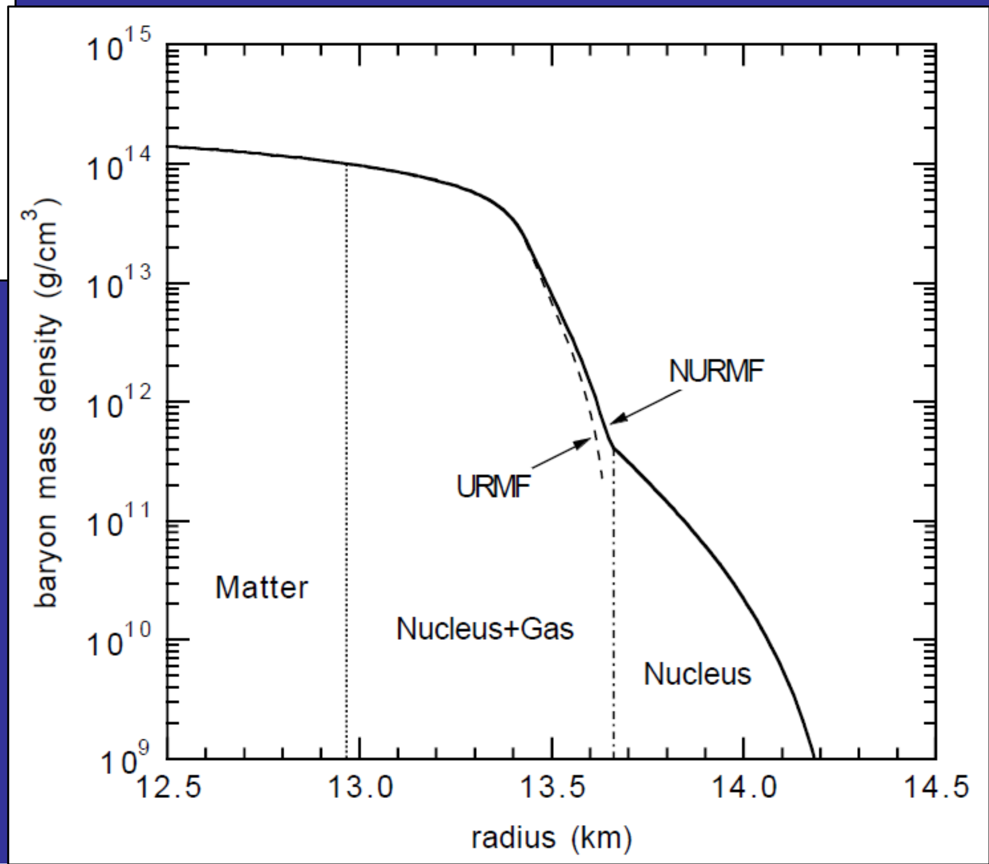
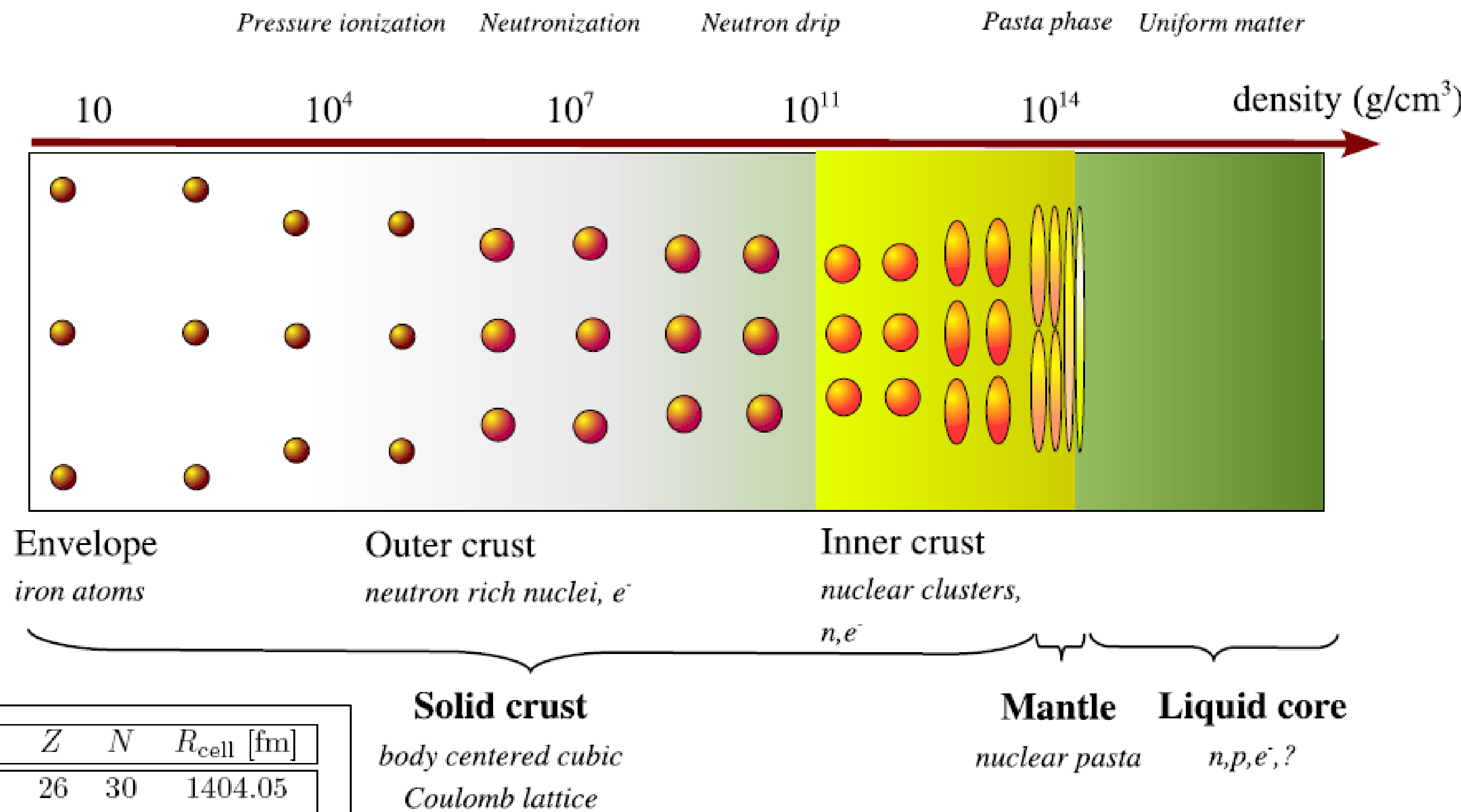


FIG. 5: A snapshot of a Monte-Carlo simulation for a system consisting of 4000 nucleons at a baryon density of $\rho = \rho_{sat}/6$, a proton fraction of $Z/A = 0.2$, and an "effective" temperature of $T = 1$ MeV [47, 48].

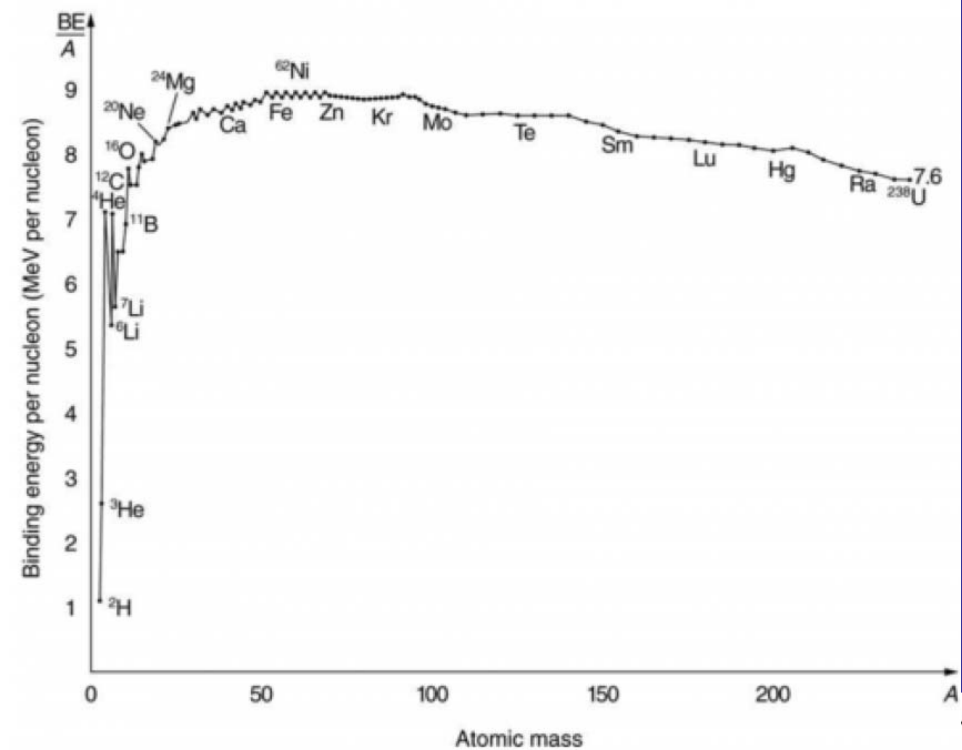


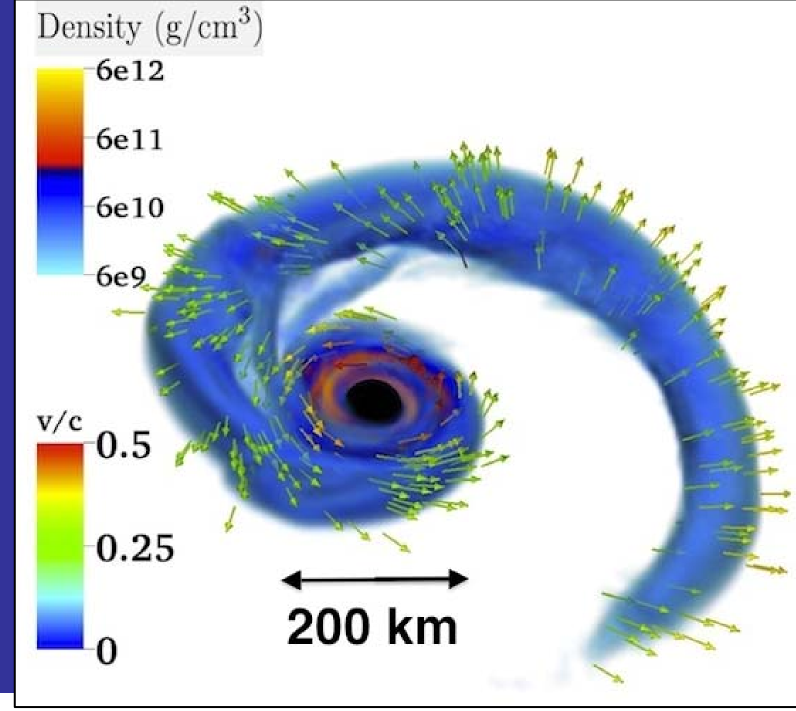


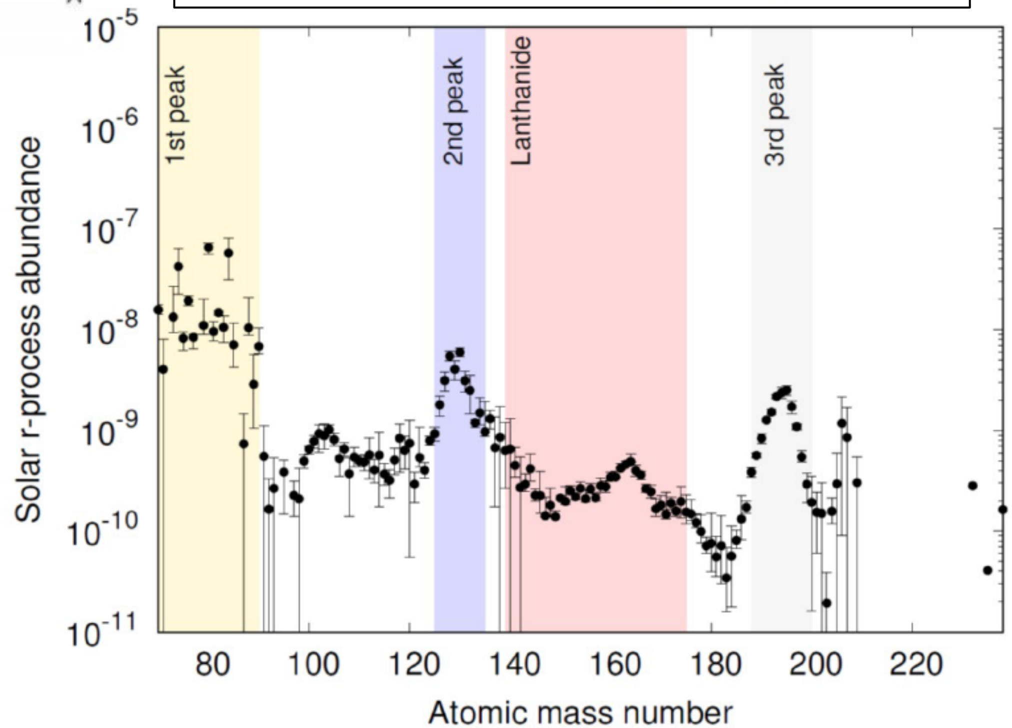
Shen, Toki, Oyamatsu, Sumiyoshi



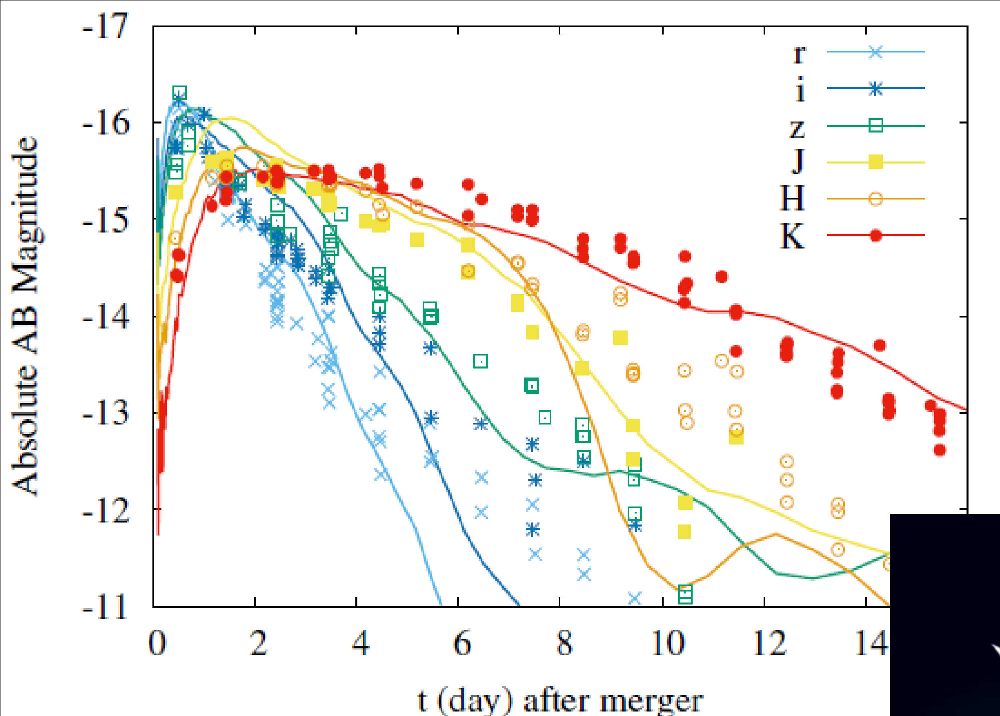
$\rho_{\max}$ [g/cm^3]	Element	Z	N	R_{cell} [fm]
8.02×10^6	^{56}Fe	26	30	1404.05
2.71×10^8	^{62}Ni	28	34	449.48
1.33×10^9	^{64}Ni	28	36	266.97
1.50×10^9	^{66}Ni	28	38	259.26
3.09×10^9	^{86}Kr	36	50	222.66
1.06×10^{10}	^{84}Se	34	50	146.56
2.79×10^{10}	^{82}Ge	32	50	105.23
6.07×10^{10}	^{80}Zn	30	50	80.58
8.46×10^{10}	^{82}Zn	30	52	72.77
9.67×10^{10}	^{128}Pd	46	82	80.77
1.47×10^{11}	^{126}Ru	44	82	69.81
2.11×10^{11}	^{124}Mo	42	82	61.71
2.89×10^{11}	^{122}Zr	40	82	55.22
3.97×10^{11}	^{120}Sr	38	82	49.37
4.27×10^{11}	^{118}Kr	36	82	47.92



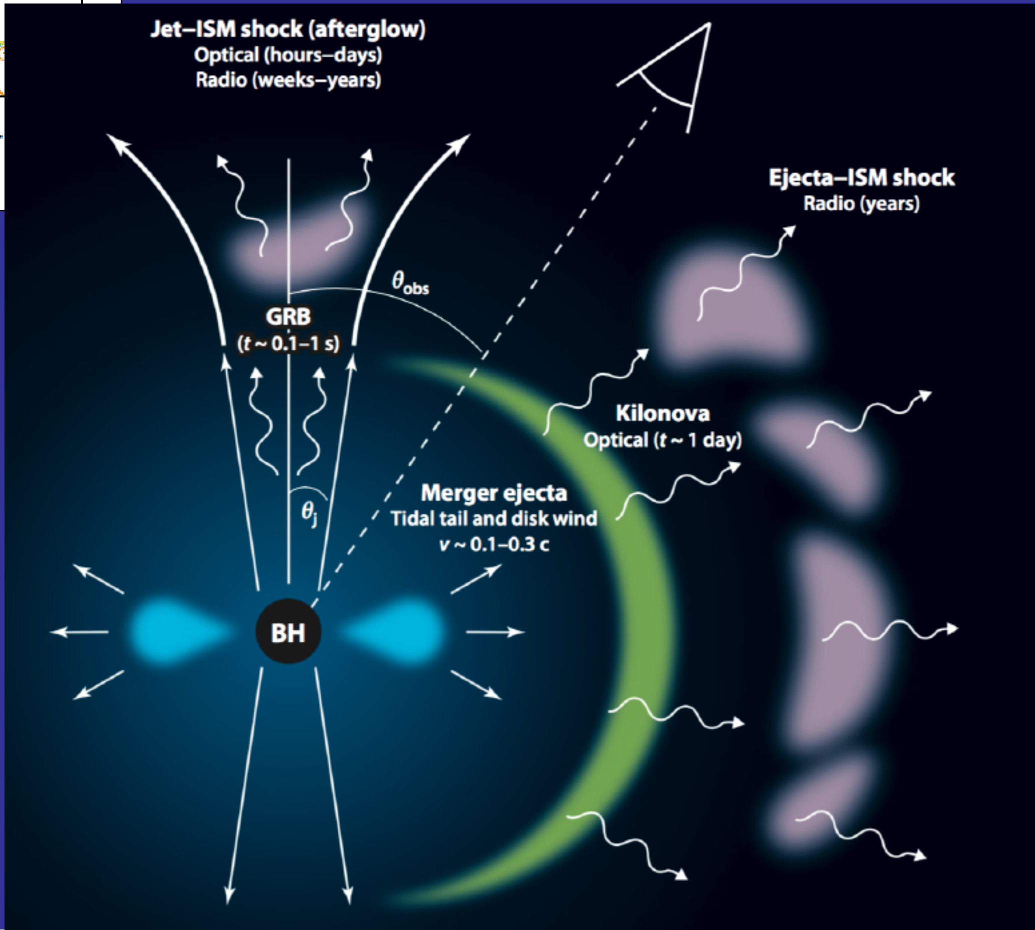




JOHN L. FRIEDMAN
International Journal of Modern Physics D
Foucart et al



Living Rev. Relativ.
Kilonovae
Brian D. Metzger



Annu. Rev. Nucl. Part. Sci. 2019. 69:126
M. Shibata and K. Hotokezaka

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.

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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).

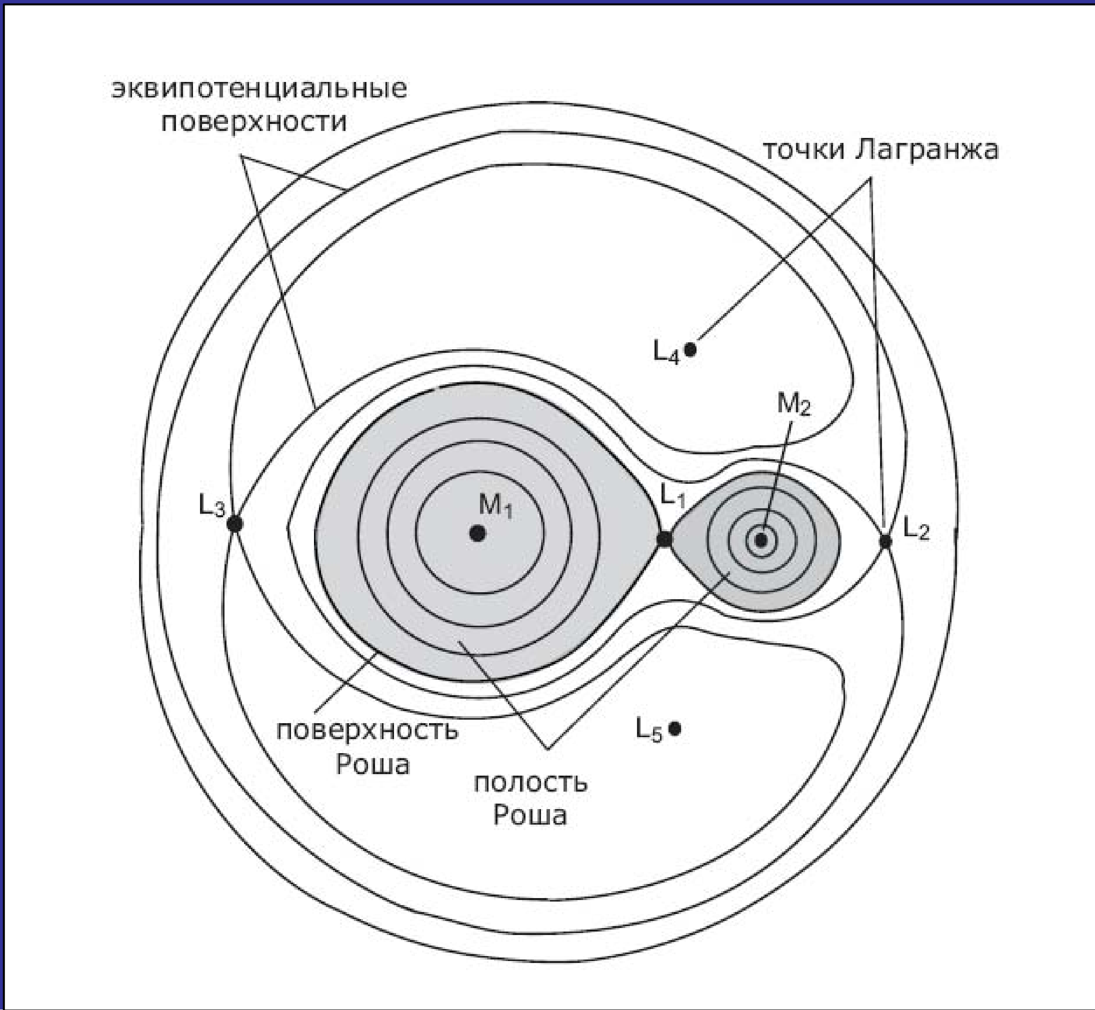
$$t_{\rm grav} \approx (10^{10}\ \text{yr}) \left(\frac{m_1}{10^{33}\,\text{g}}\right)^{-1} \left(\frac{m_2}{10^{33}\,\text{g}}\right)^{-1} \left(\frac{m_1}{10^{33}\,\text{g}} + \frac{m_2}{10^{33}\,\text{g}}\right)^{-1} \left(\frac{a}{R_\odot}\right)^{4}$$

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

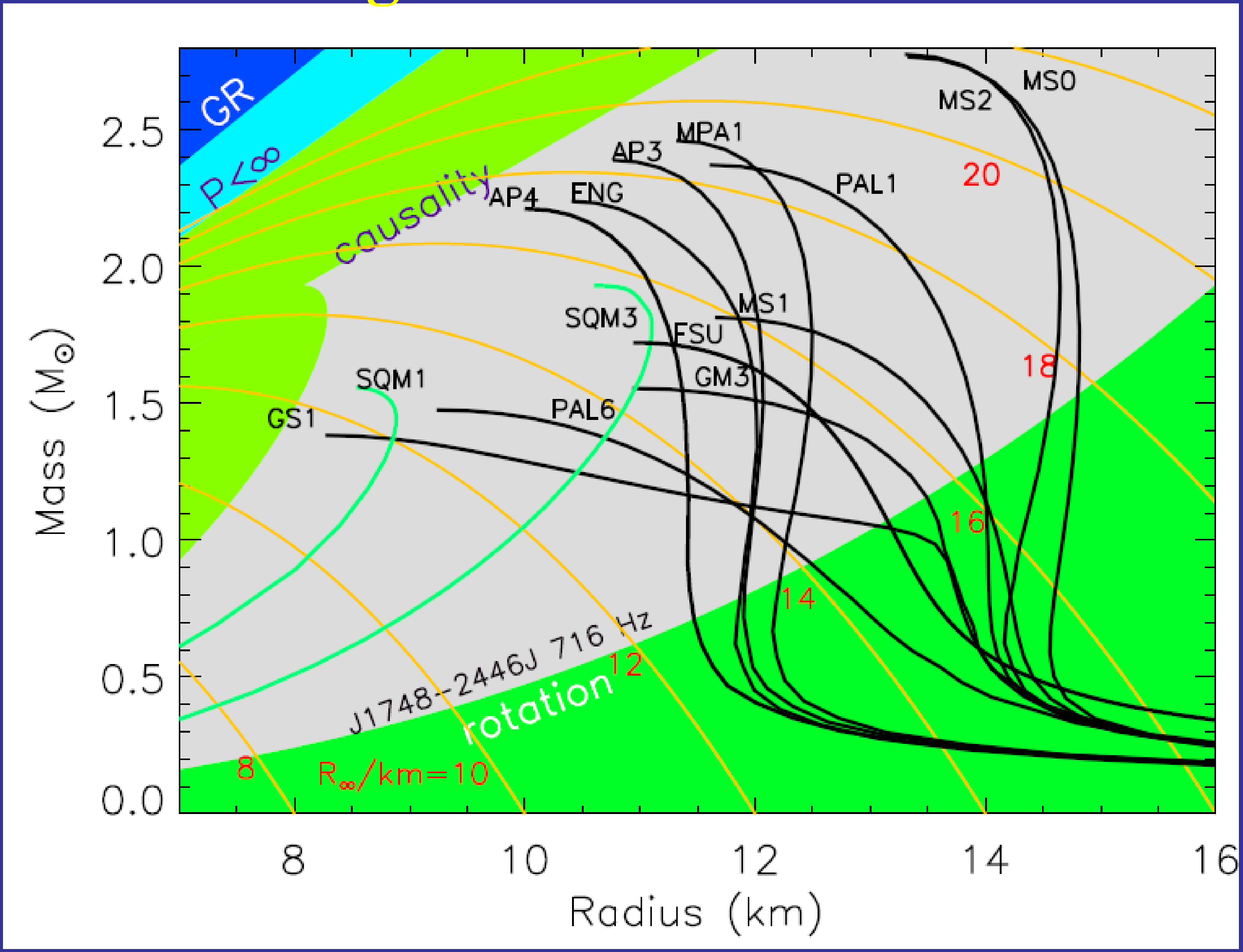
$$\omega = \sqrt{\frac{G(M_1+M_2)}{a^3}}$$

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

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



M-R diagram for neutron stars



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

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

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

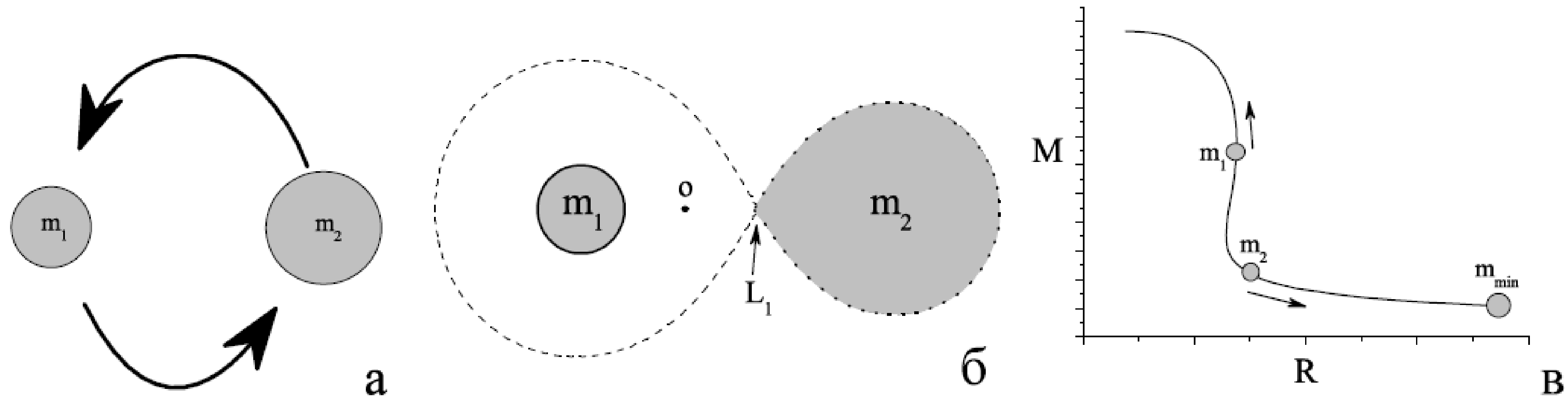


Рис. 1. Сценарий обдирания (схематично): а) две НЗ сближаются из-за гравитационного излучения; б) МНЗ переполняет свою полость Роша и начинается перетекание; в) в результате этого на диаграмме масса-радиус компоненты двойной системы m_1 и m_2 движутся в направлении стрелок.

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

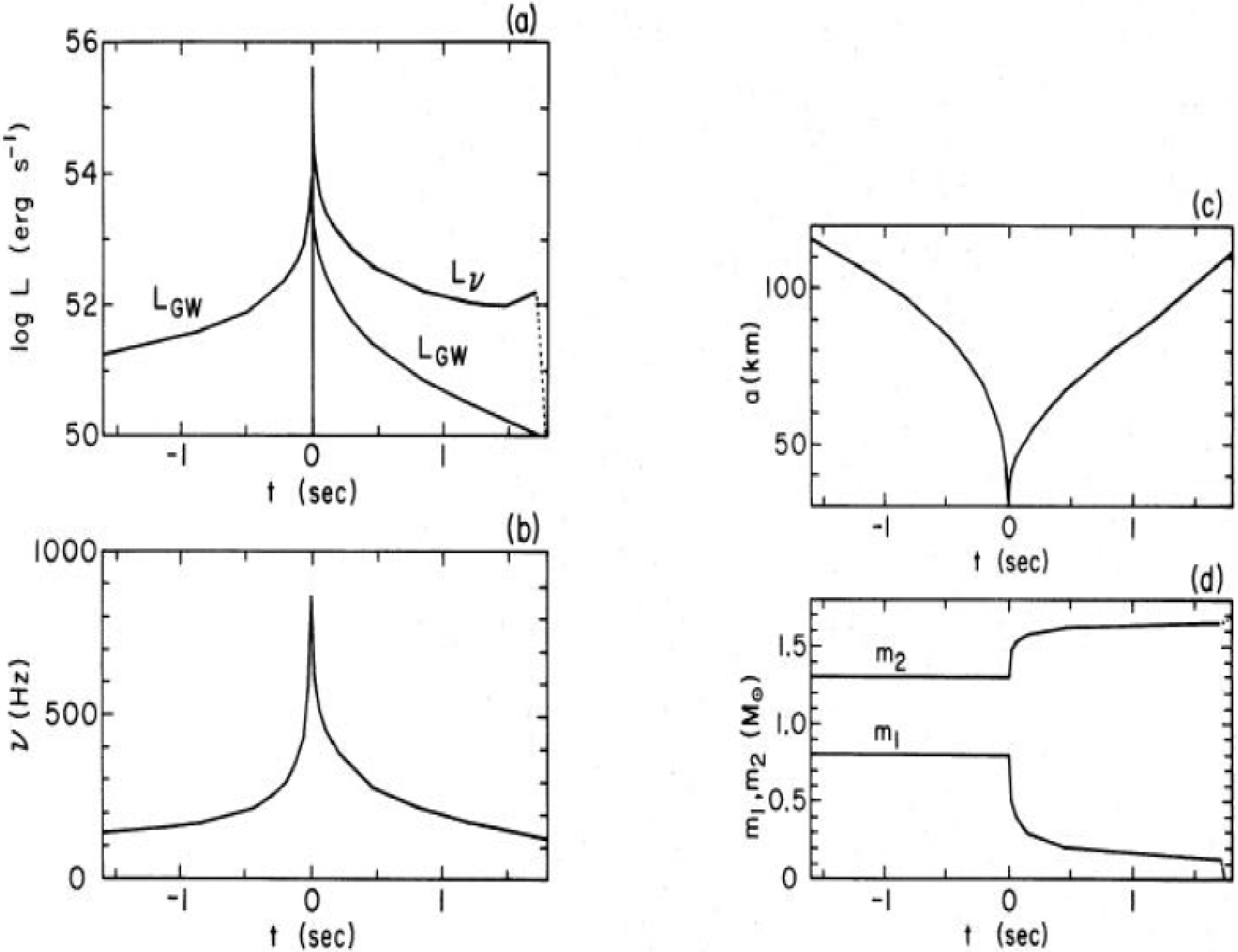
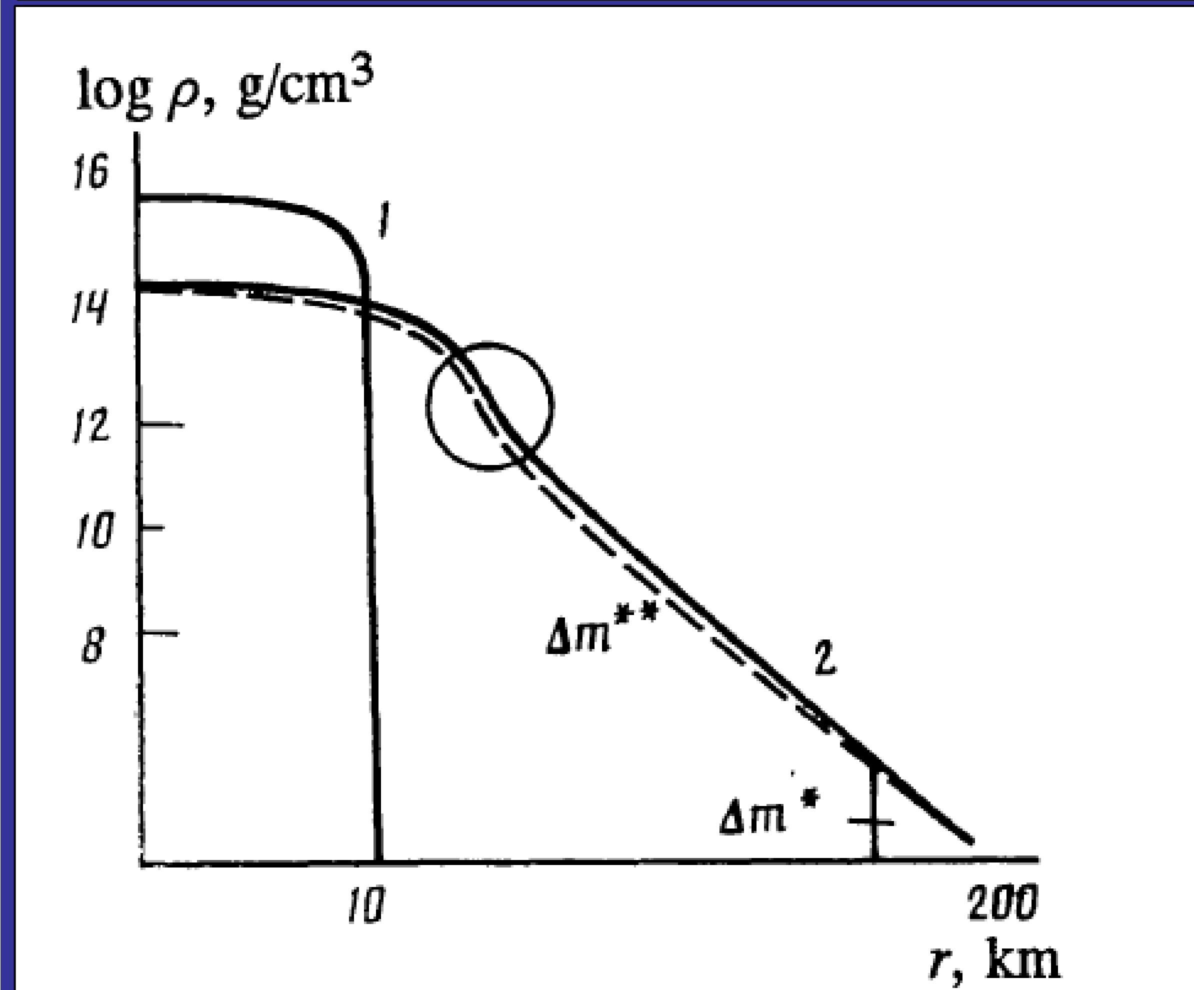


FIG. 7—Time evolution of a system with initial masses 0.8 and 1.3 $M_\odot$. (*a*) Neutrino and gravitational wave luminosities. (*b*) Frequency of gravitational wave. (*c*) Separation of components. (*d*) Masses of stars.

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

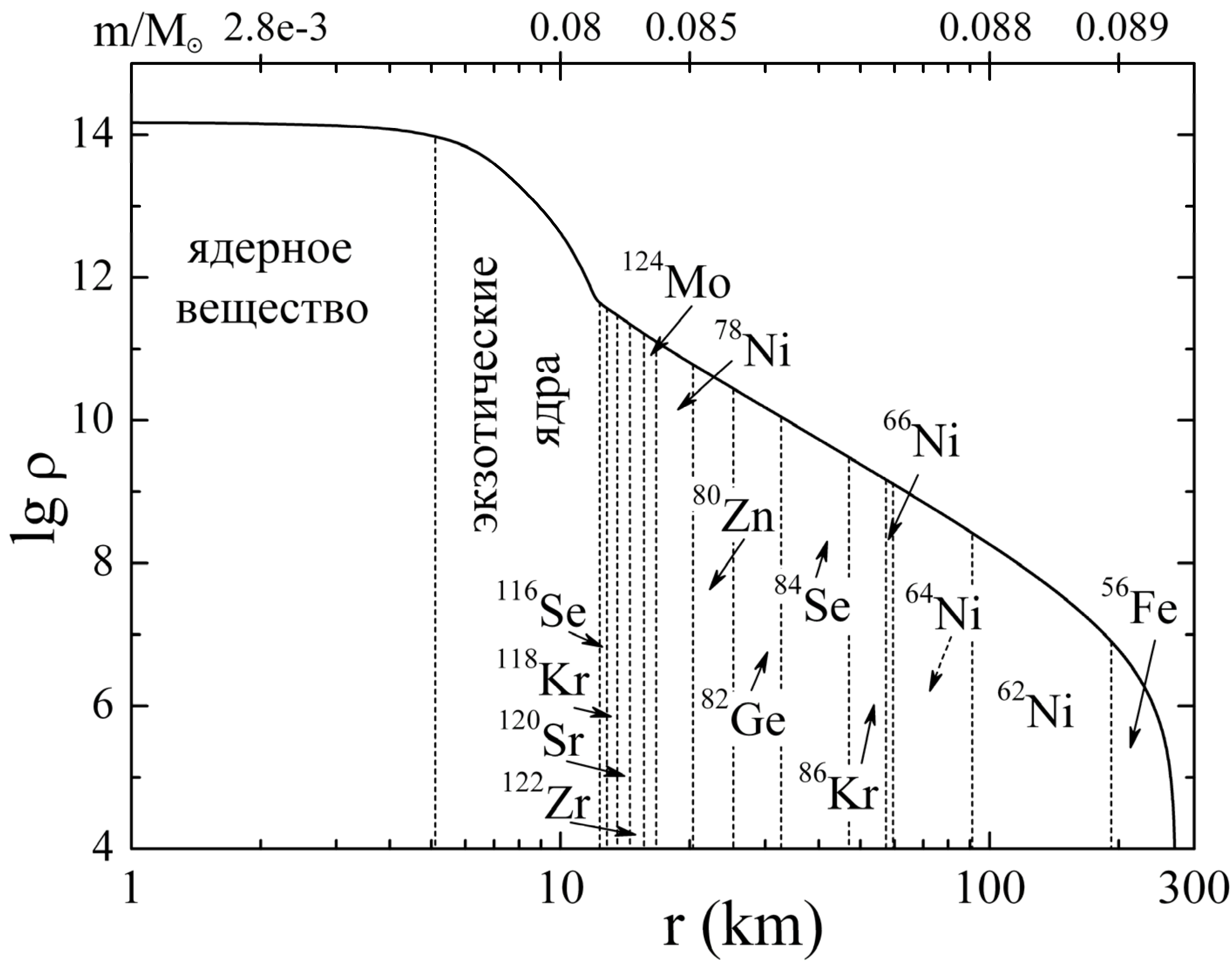


$$P = P_0(\rho) + \rho \tilde{R} T + \frac{1}{3} a T^4,$$

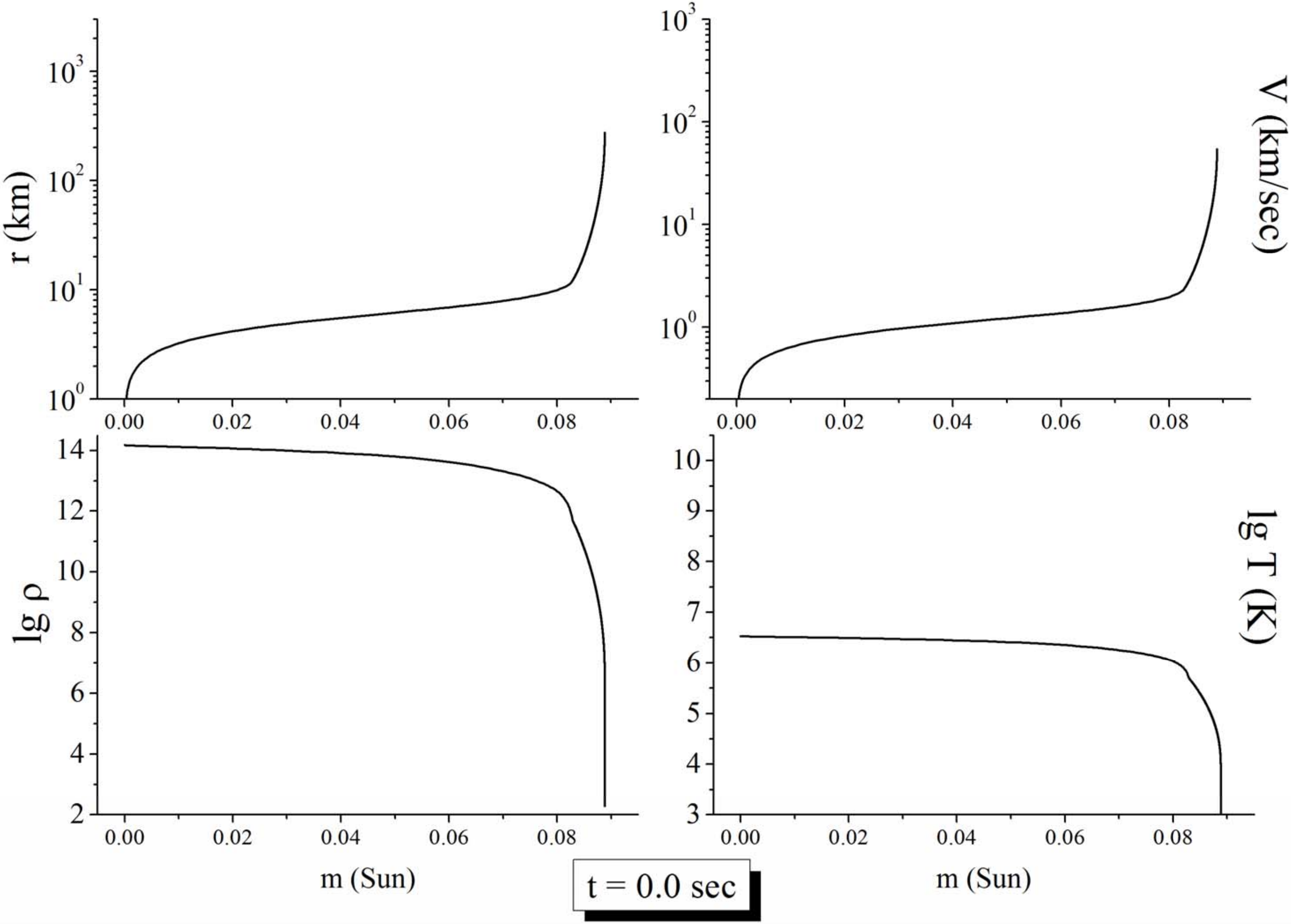
$$E = E_0(\rho) + \frac{3}{2} \tilde{R} T + \frac{a T^4}{\rho}.$$

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

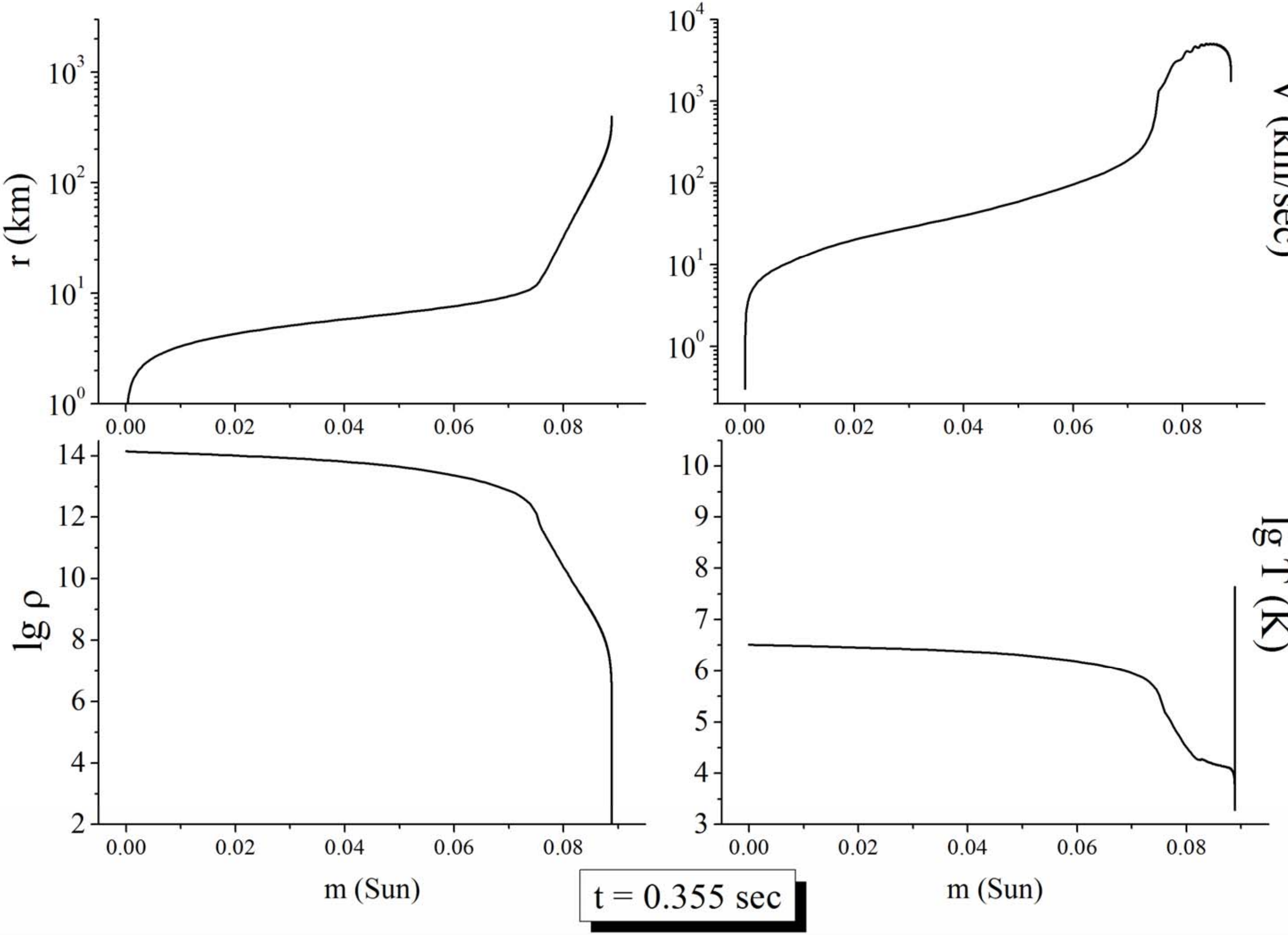
$$\begin{cases} \dfrac{\partial r}{\partial t} = u, \\[2mm] \dfrac{\partial u}{\partial t} = -4\pi r^2 \dfrac{\partial P}{\partial m} - \dfrac{Gm}{r^2}, \\[2mm] \dfrac{1}{\rho} = \dfrac{4\pi}{3} \dfrac{\partial r^3}{\partial m}, \\[2mm] \dfrac{\partial E}{\partial t} + P \dfrac{\partial 1/\rho}{\partial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

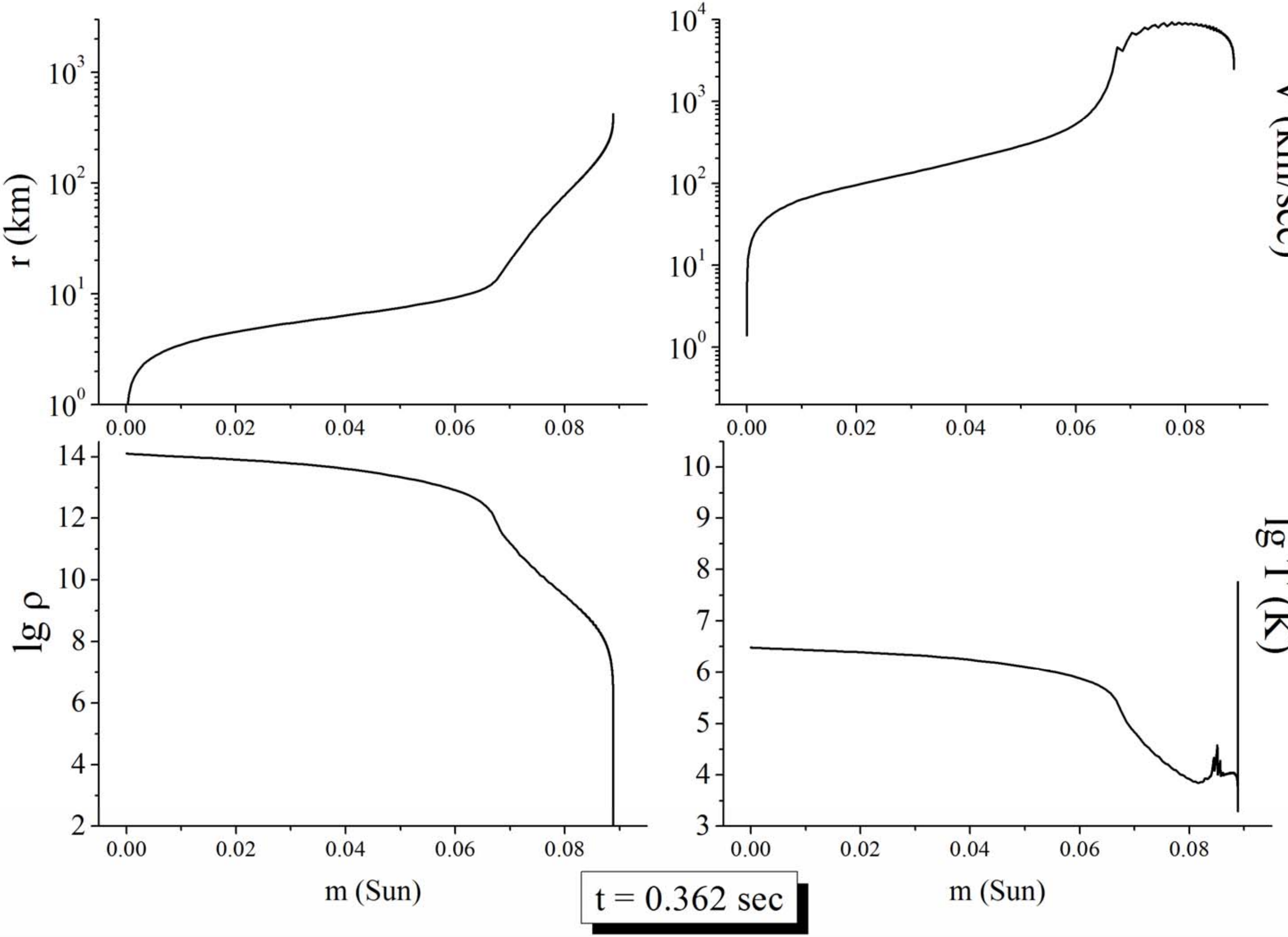


m/M⊙ 2.8e-3 0.08 0.085 0.088 0.089
lg ρ
14
12
10
8
6
4
1
10
100
300
r (km)
ядерное вещество
экзотические ядра
124Mo
78Ni
66Ni
80Zn
84Se
64Ni
56Fe
116Se
118Kr
120Sr
122Zr
82Ge
86Kr
62Ni

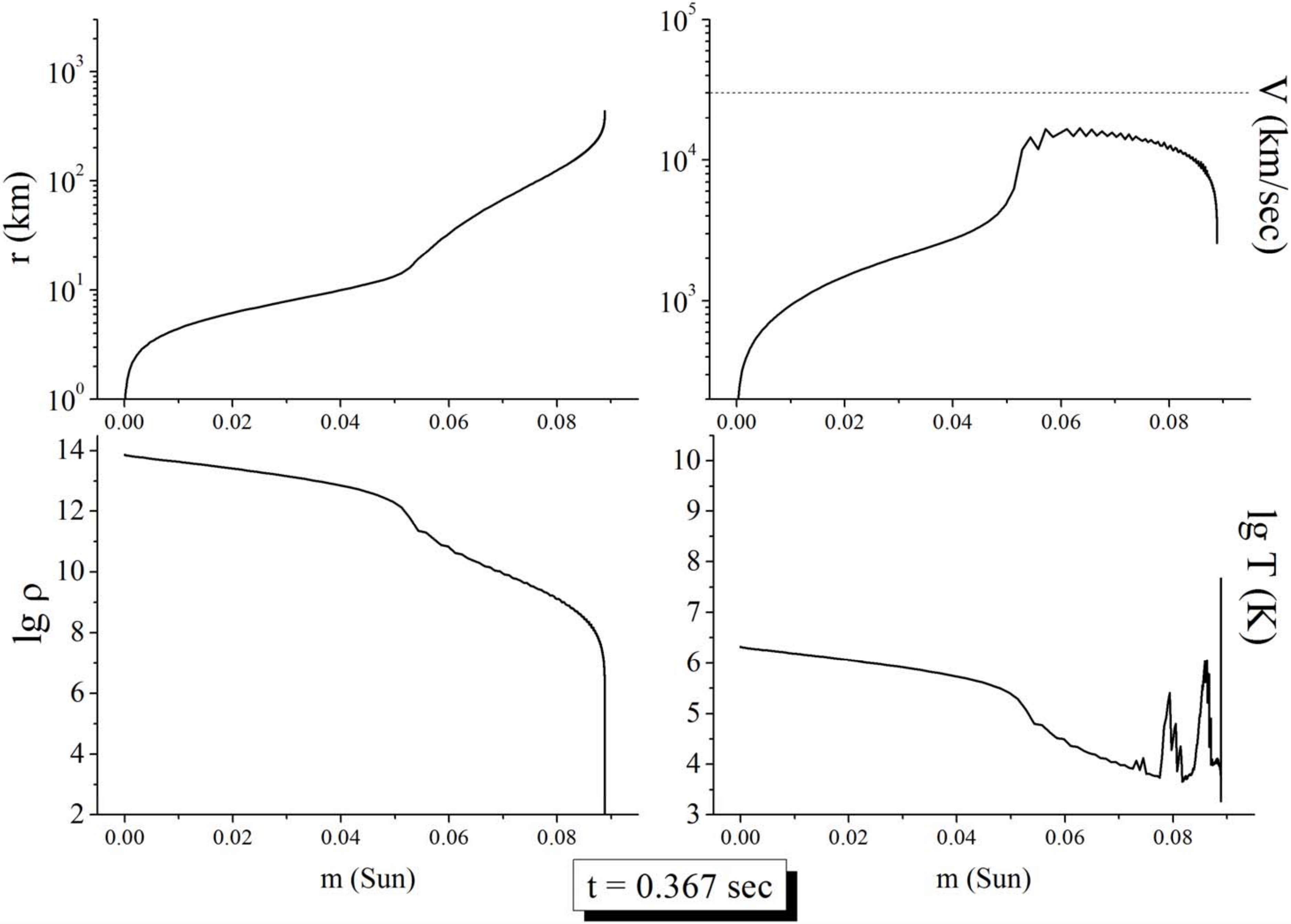


r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.0 sec


r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.355 sec



r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.362 sec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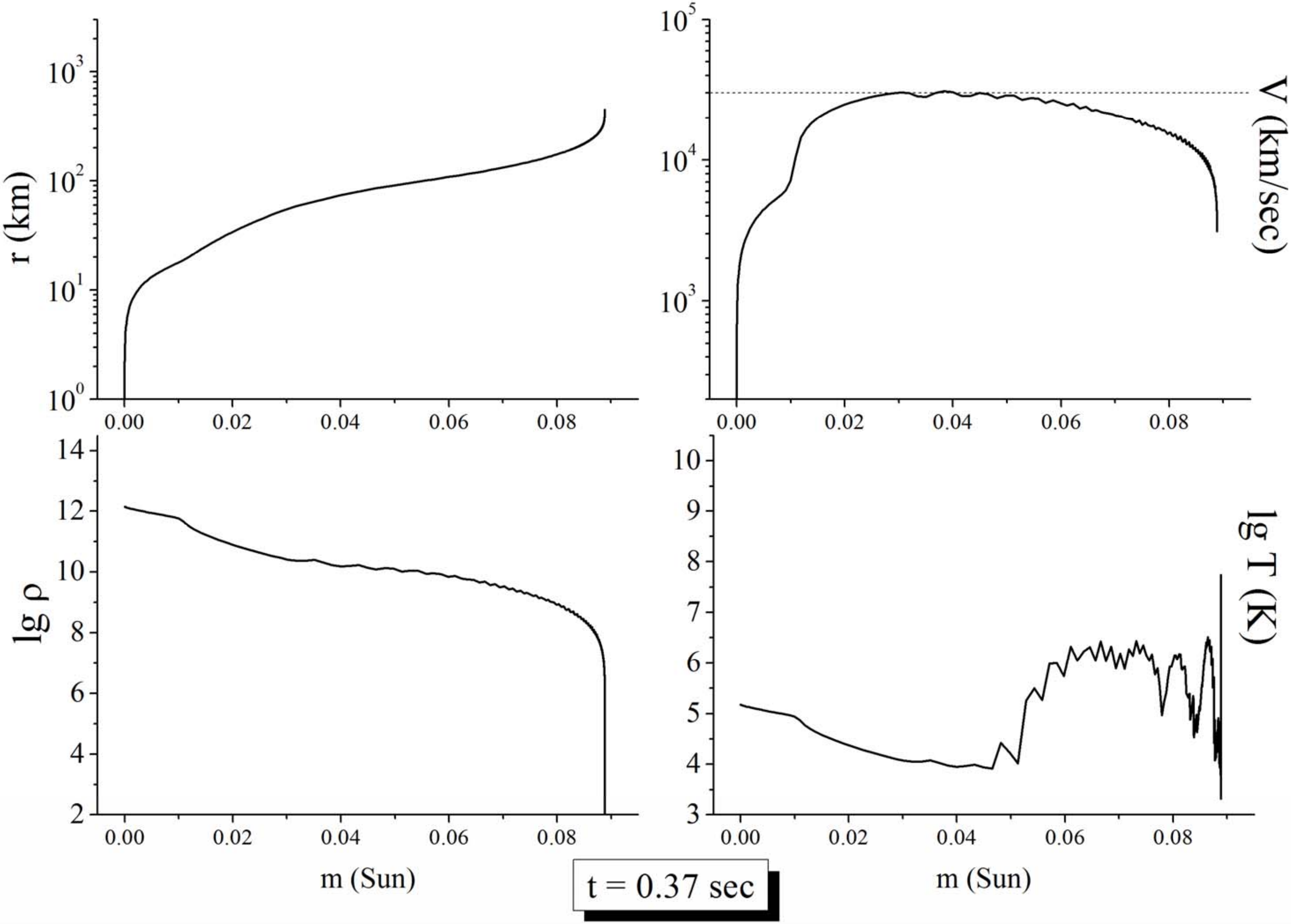

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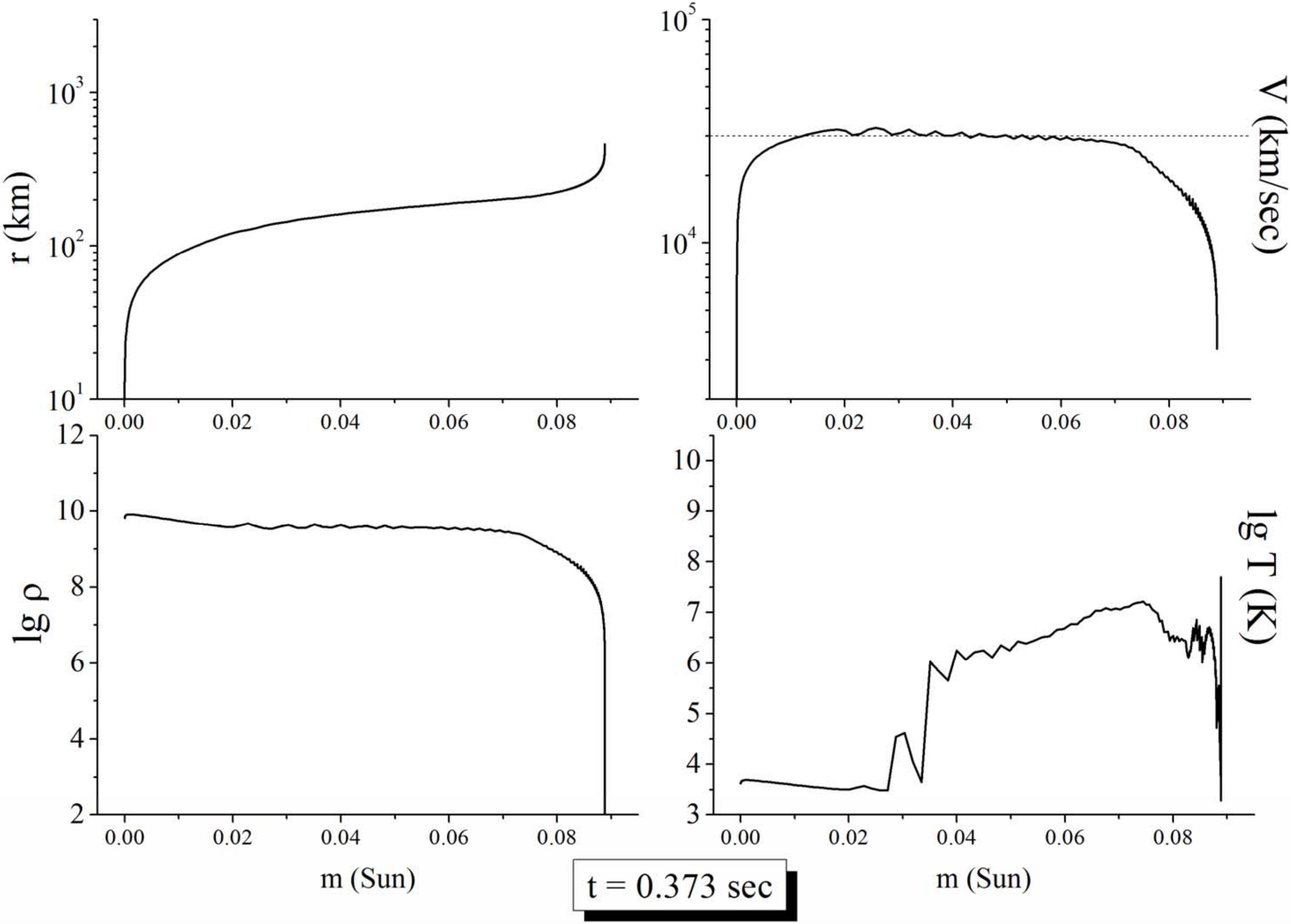
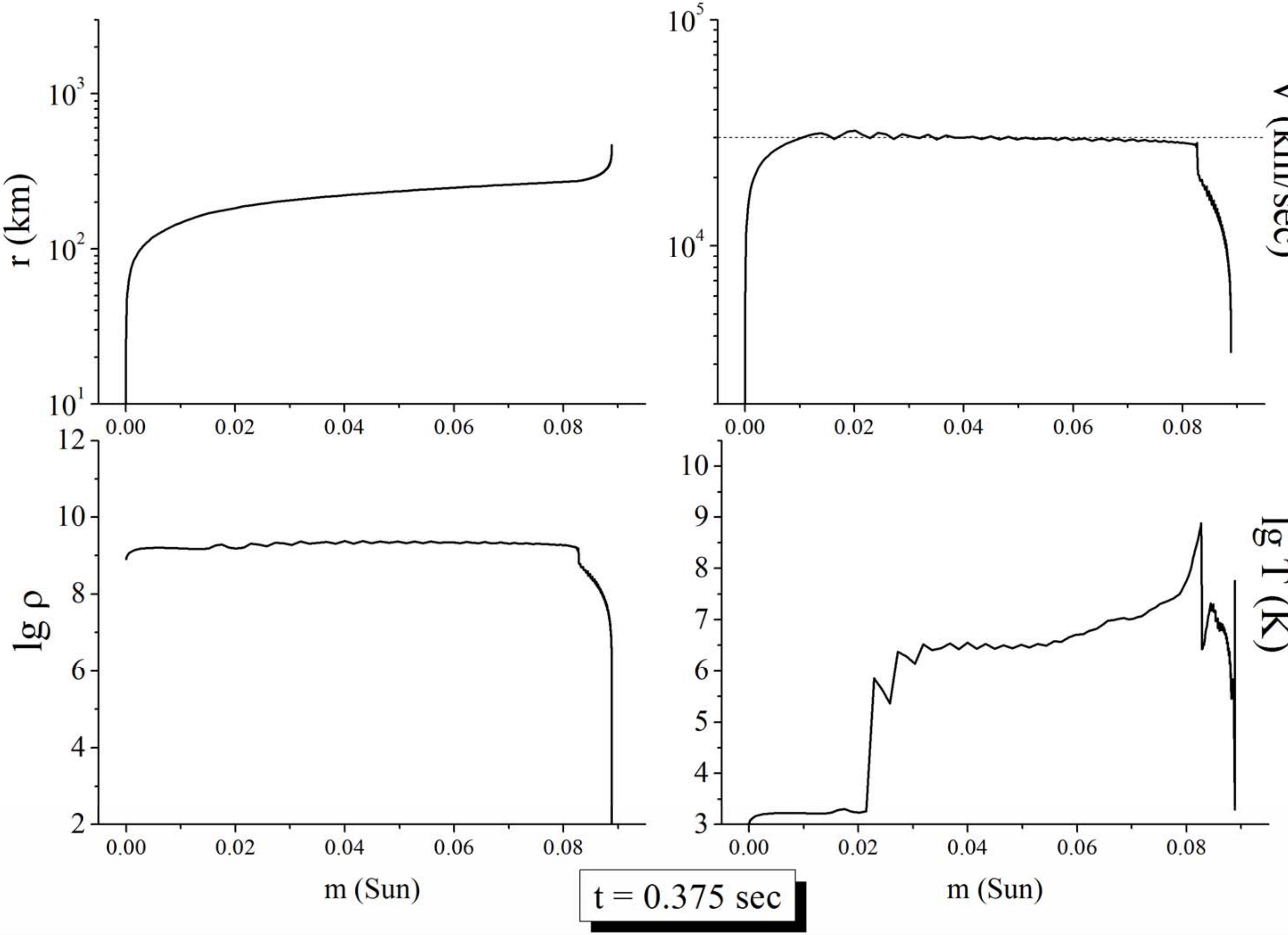
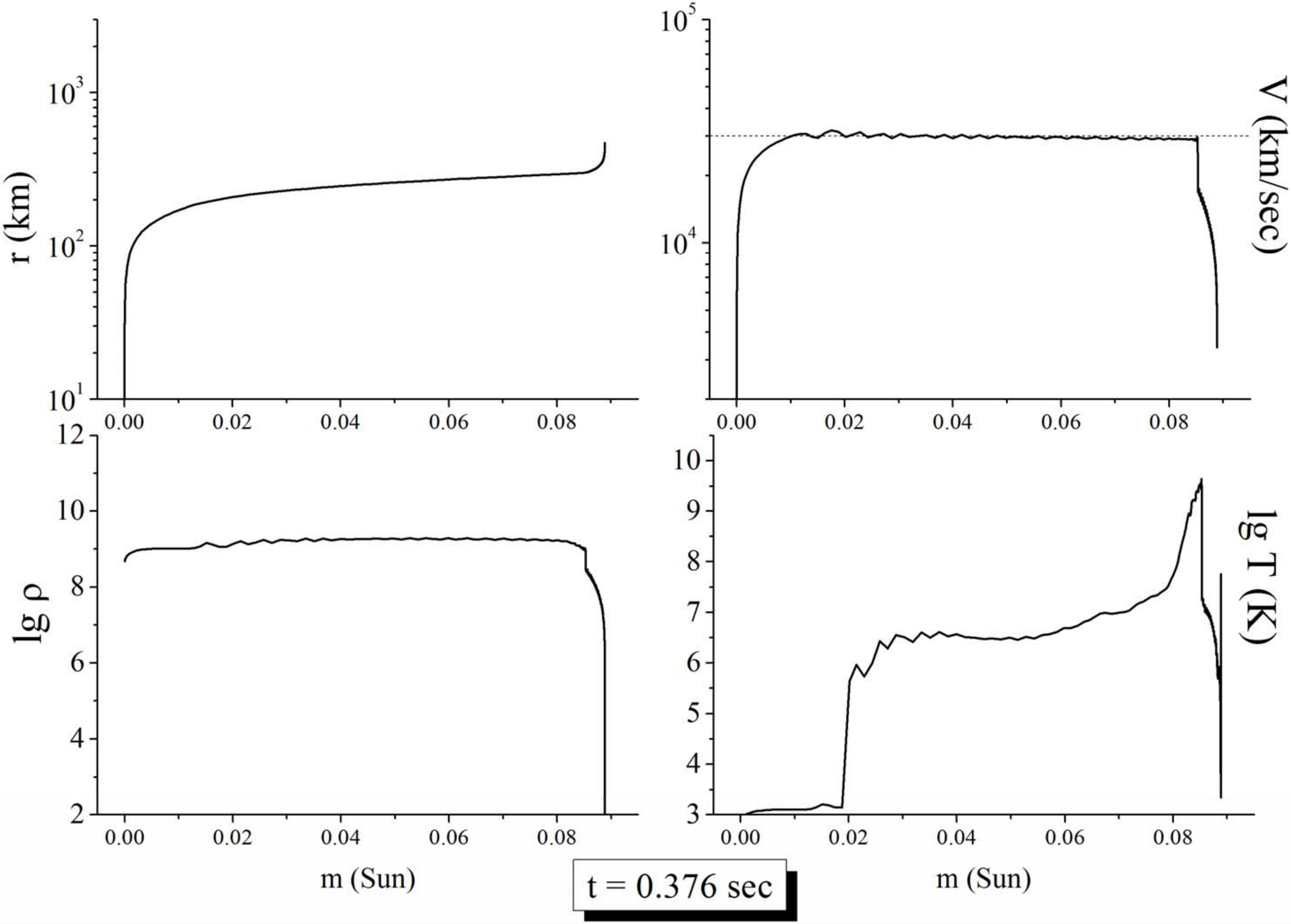
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.37 sec

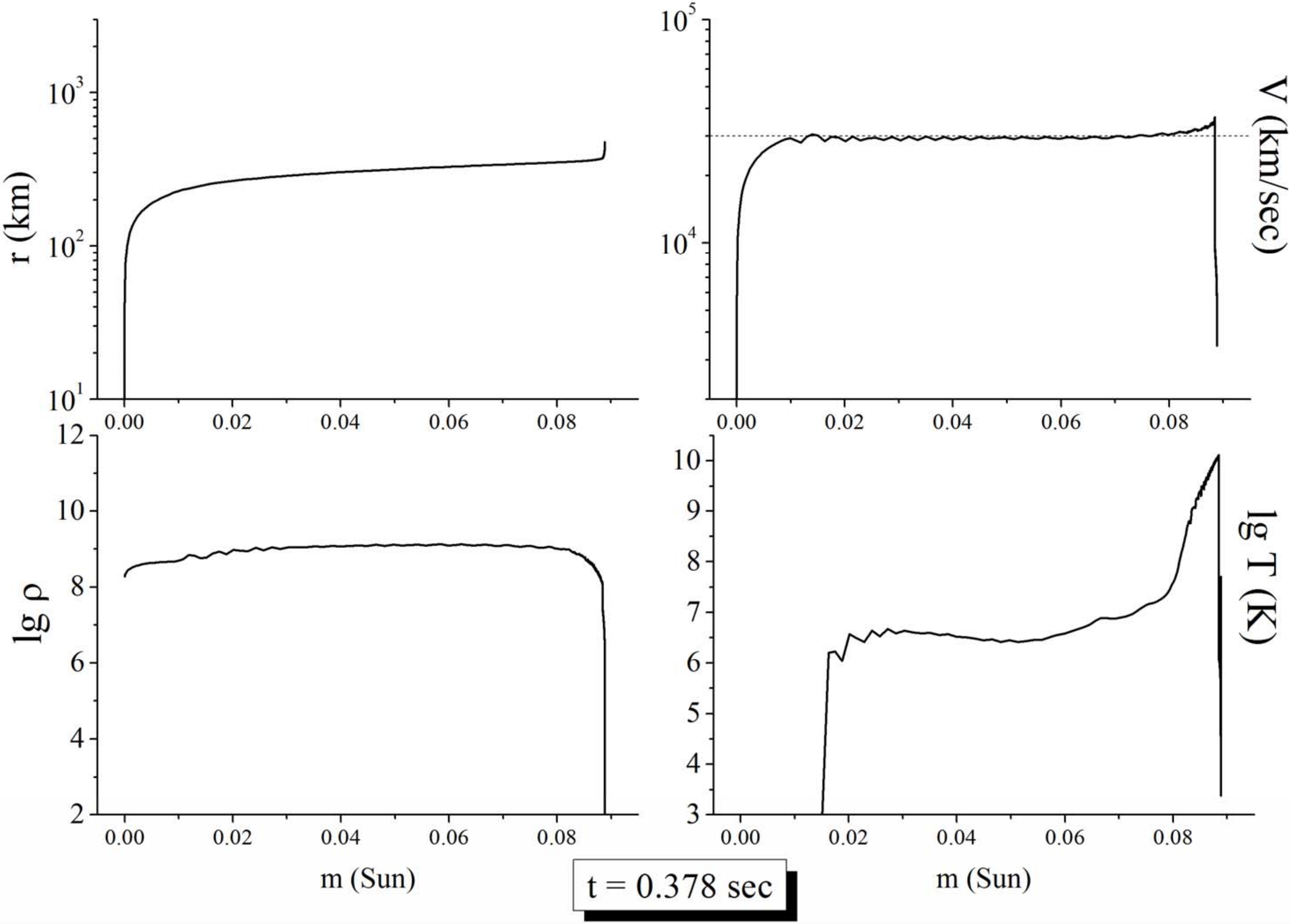


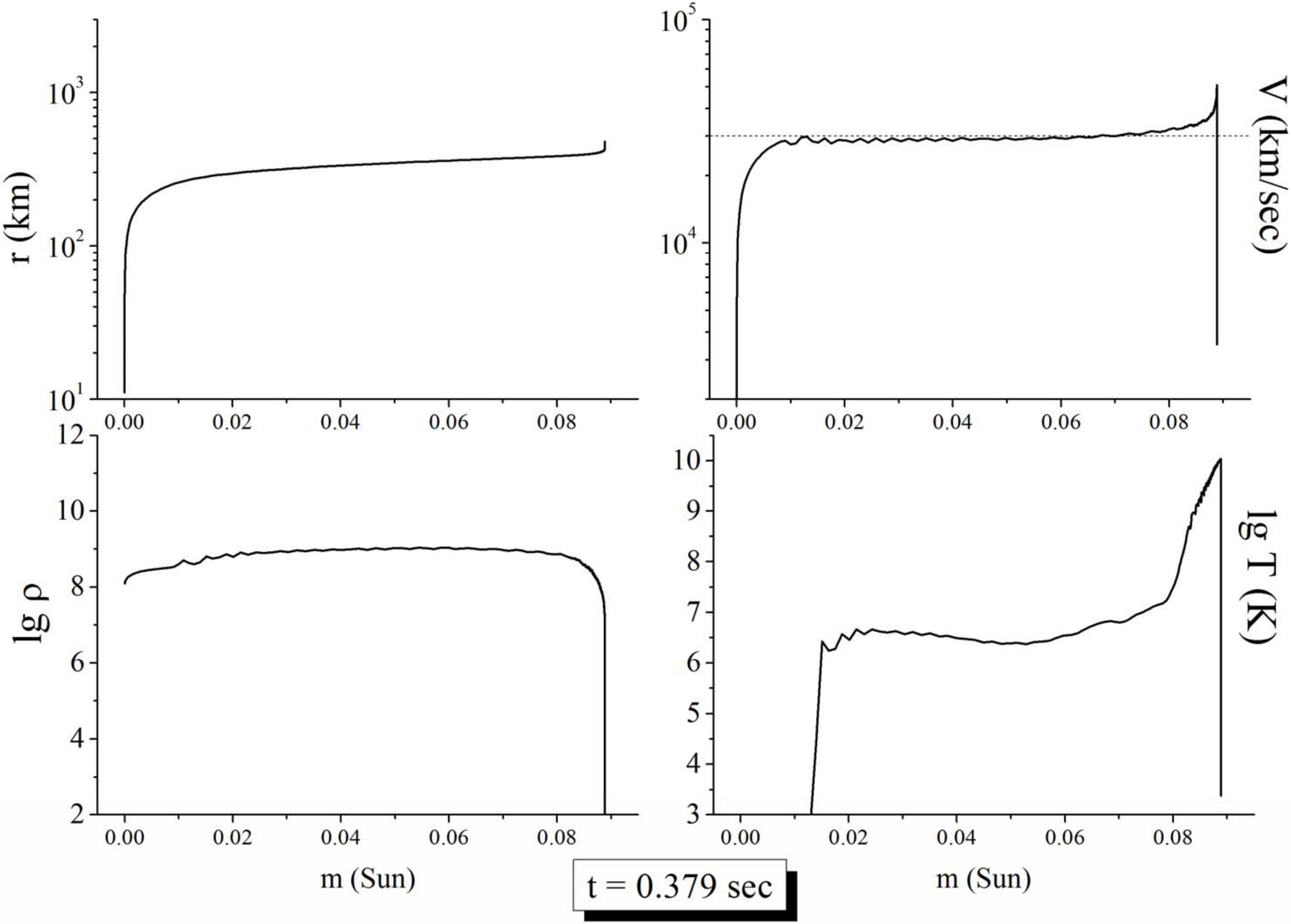
r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.373 sec

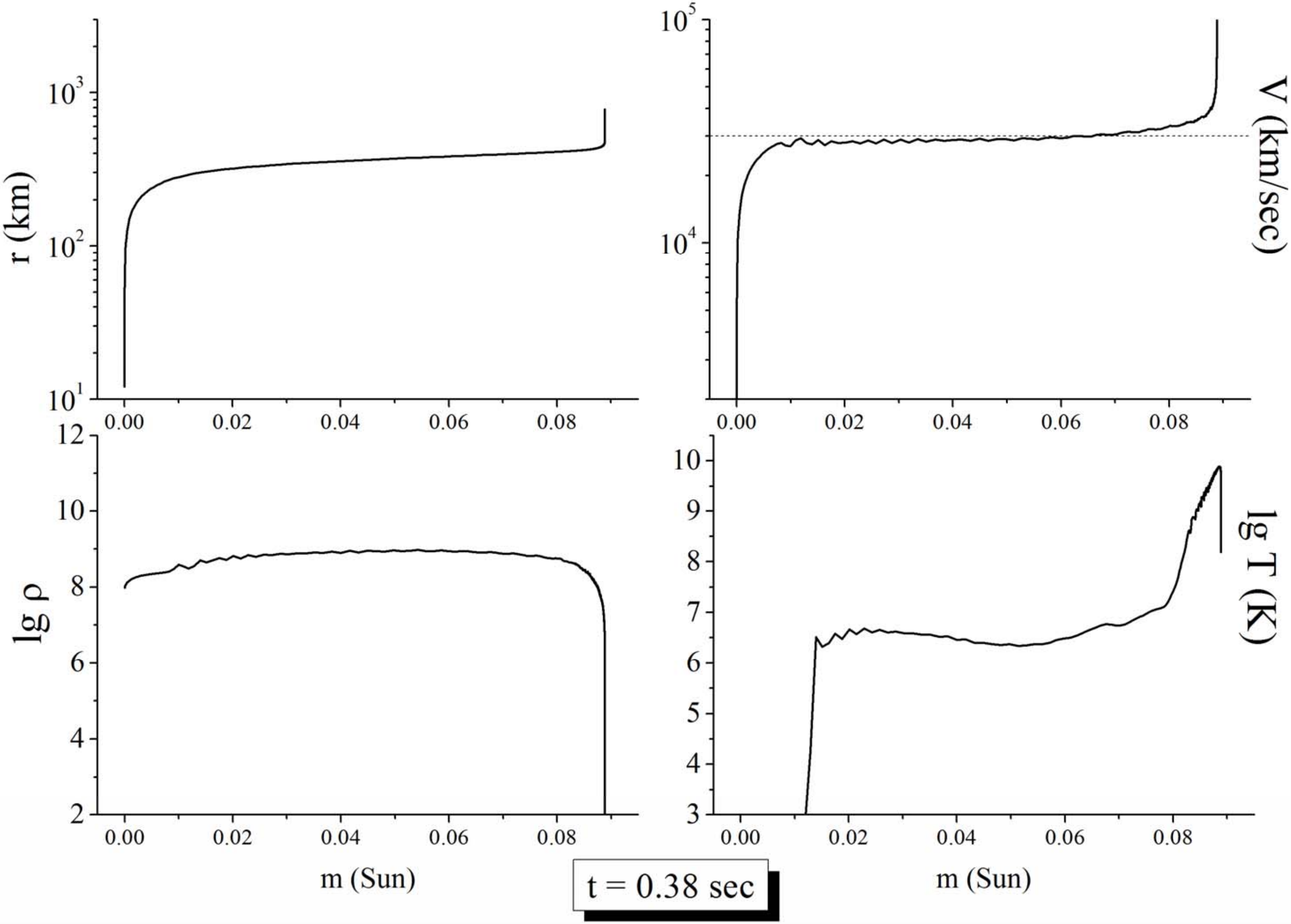


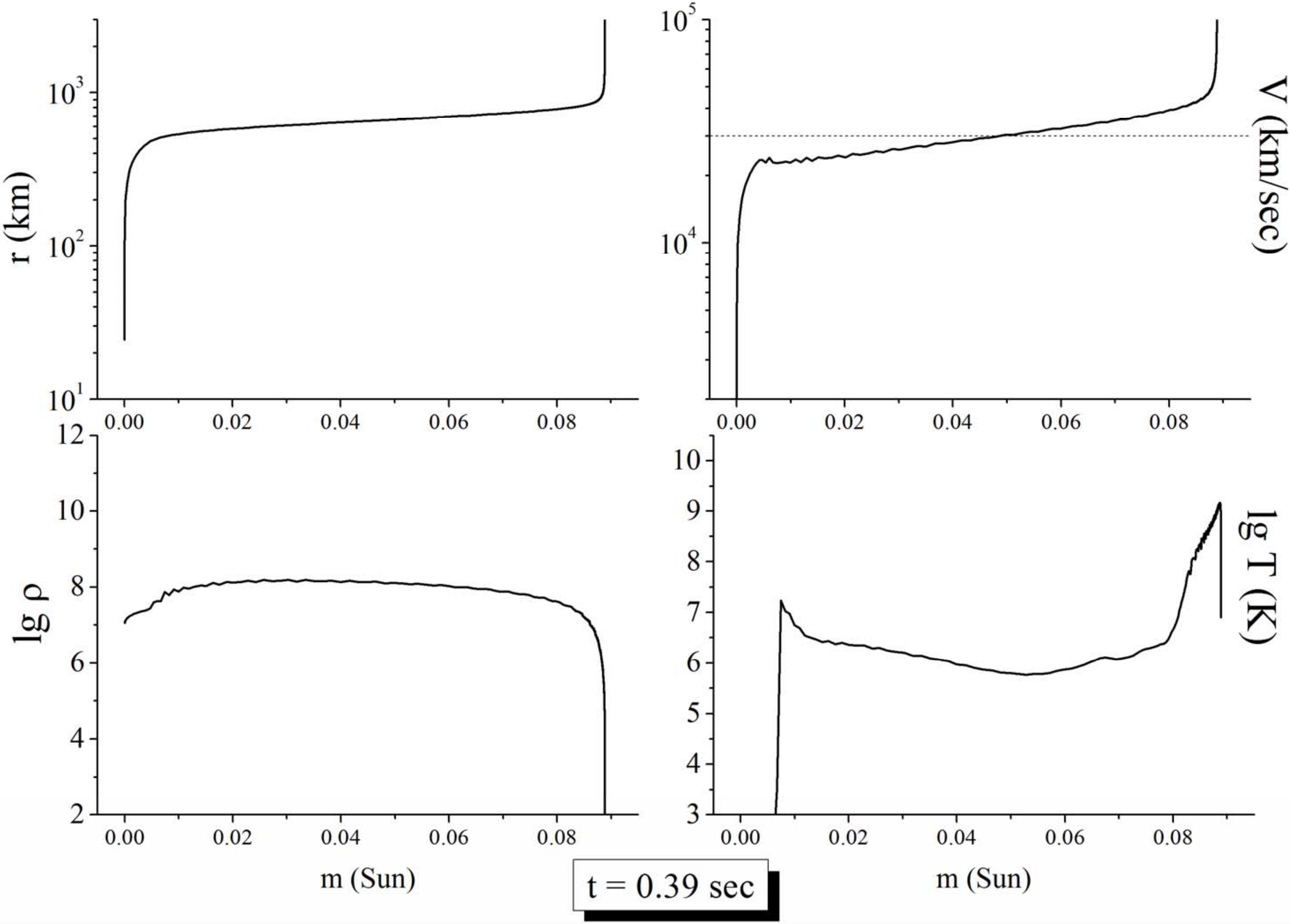
r (km)
10^3
10^2
10^1
V (km/sec)
10^5
10^4
lg ρ
12
10
8
6
4
2
lg T (K)
10
9
8
7
6
5
4
3
0.00
0.02
0.04
0.06
0.08
m (Sun)
m (Sun)
t = 0.375 sec

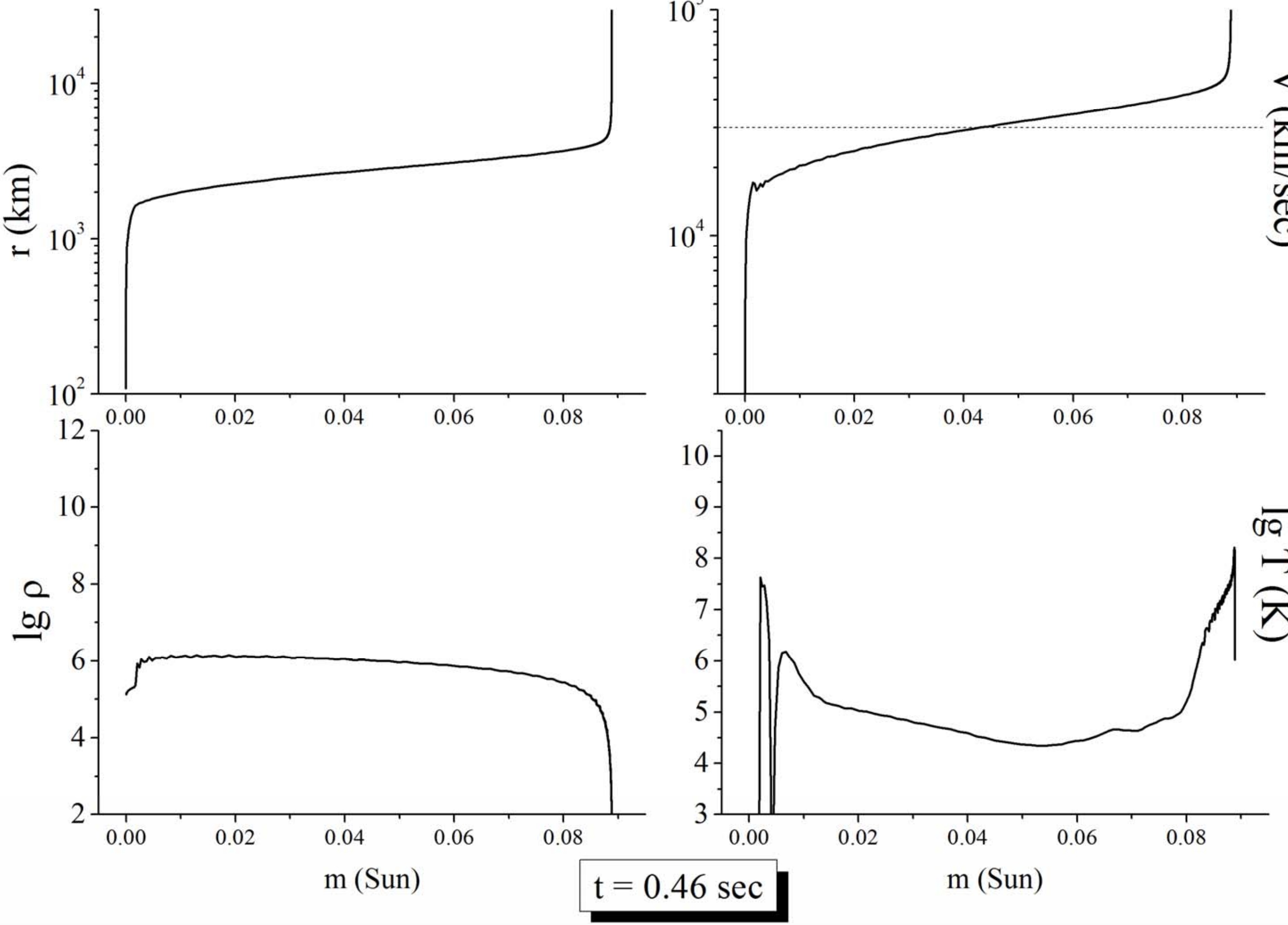

r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.376 sec

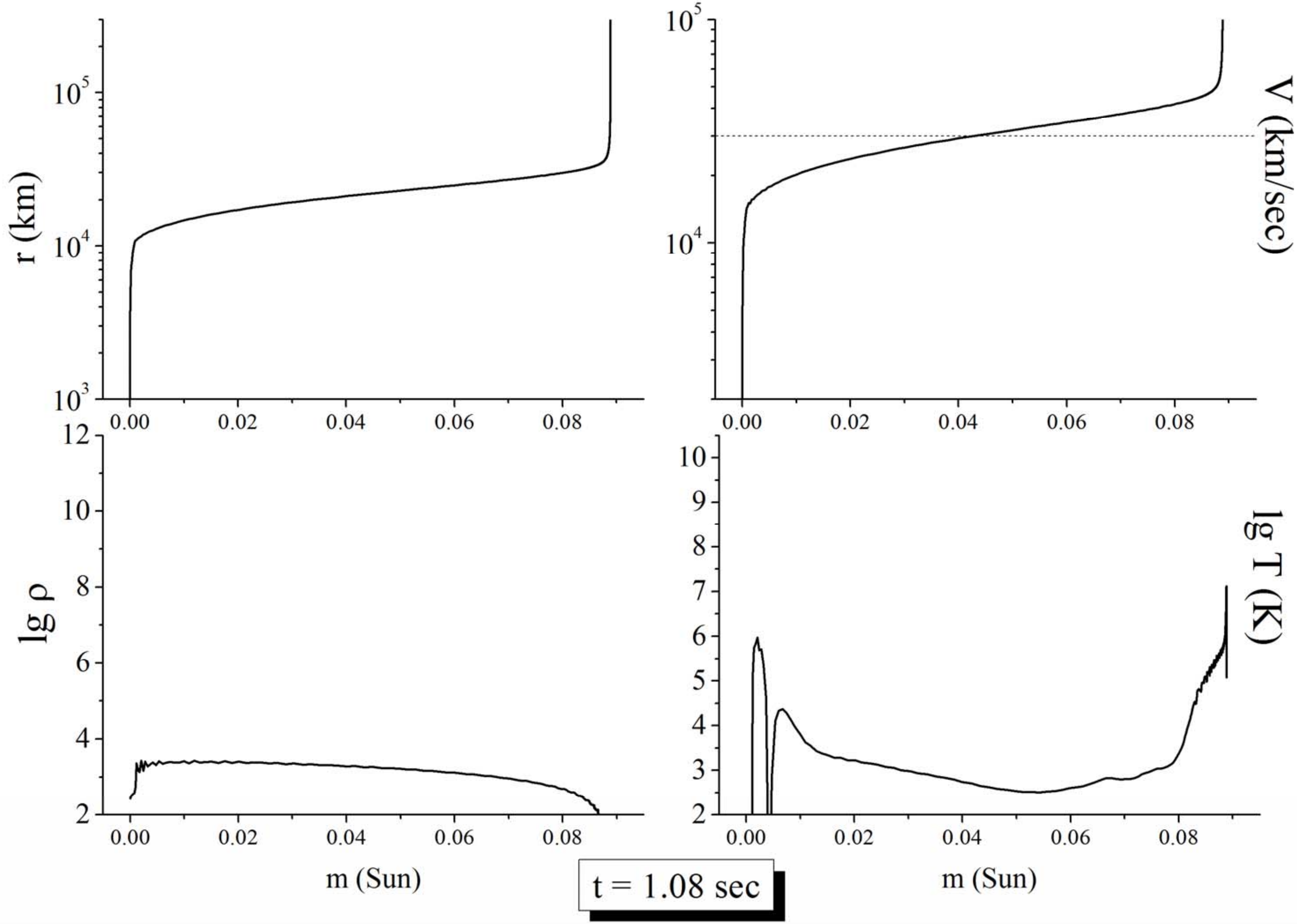

r (km)
10^3
10^2
10^1
V (km/sec)
10^5
10^4
lg ρ
12
10
8
6
4
2
lg T (K)
10
9
8
7
6
5
4
3
0.00
0.02
0.04
0.06
0.08
m (Sun)
m (Sun)
t = 0.378 sec


r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.379 sec

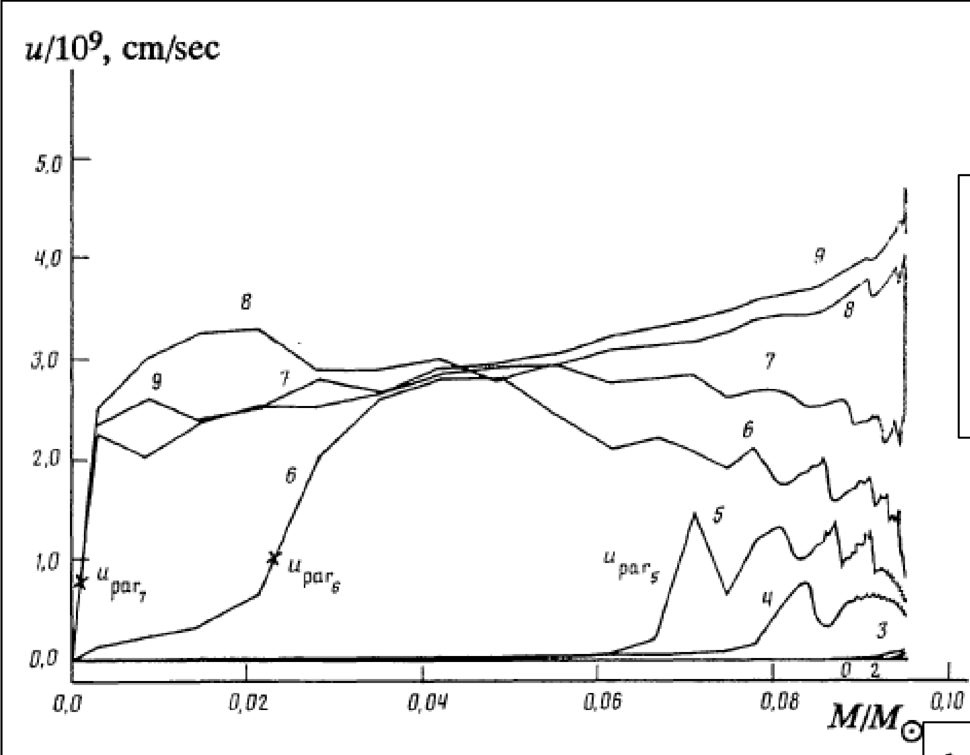

r (km)
10^3
10^2
10^1
V (km/sec)
10^5
10^4
lg ρ
12
10
8
6
4
2
lg T (K)
10
9
8
7
6
5
4
3
0.00
0.02
0.04
0.06
0.08
m (Sun)
m (Sun)
t = 0.38 sec


r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.39 sec

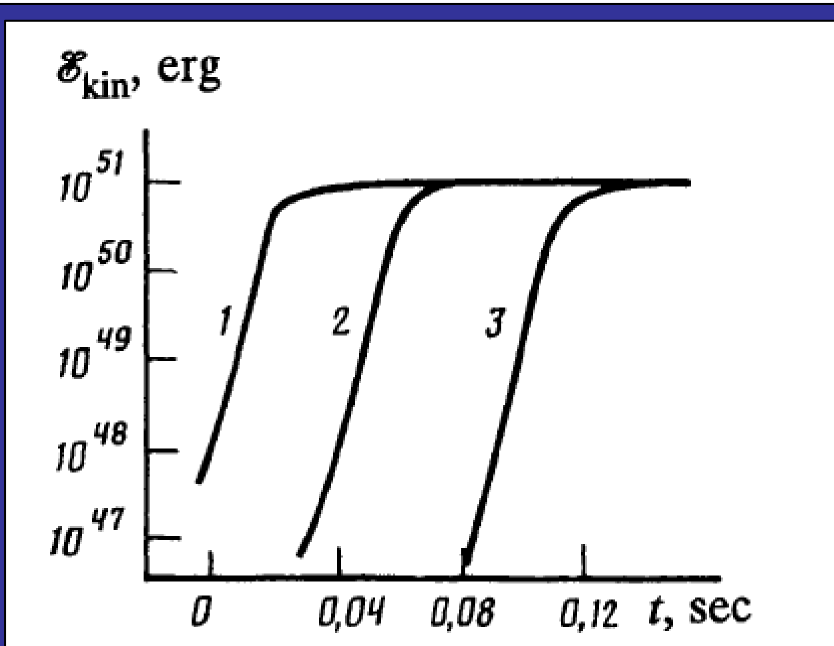

r (km)
V (km/sec)
lg ρ
lg T (K)
m (Sun)
m (Sun)
t = 0.46 sec

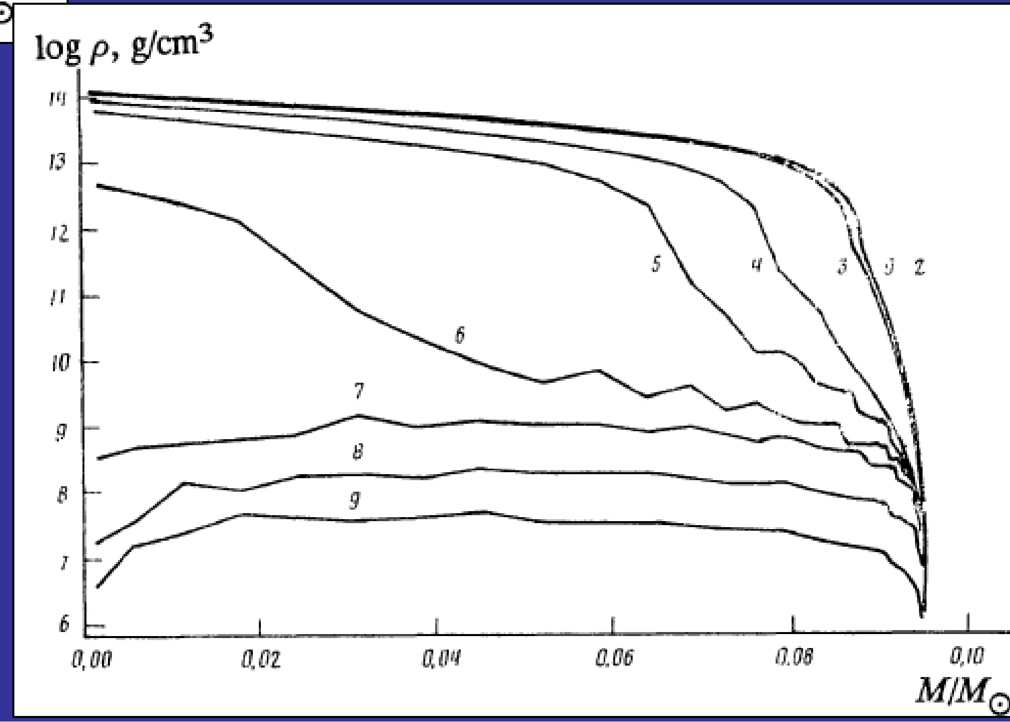


r (km)
10^3
10^4
10^5
V (km/sec)
10^4
10^5
lg ρ
2
4
6
8
10
12
lg T (K)
2
3
4
5
6
7
8
9
10
0.00
0.02
0.04
0.06
0.08
m (Sun)
m (Sun)
t = 1.08 sec



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.

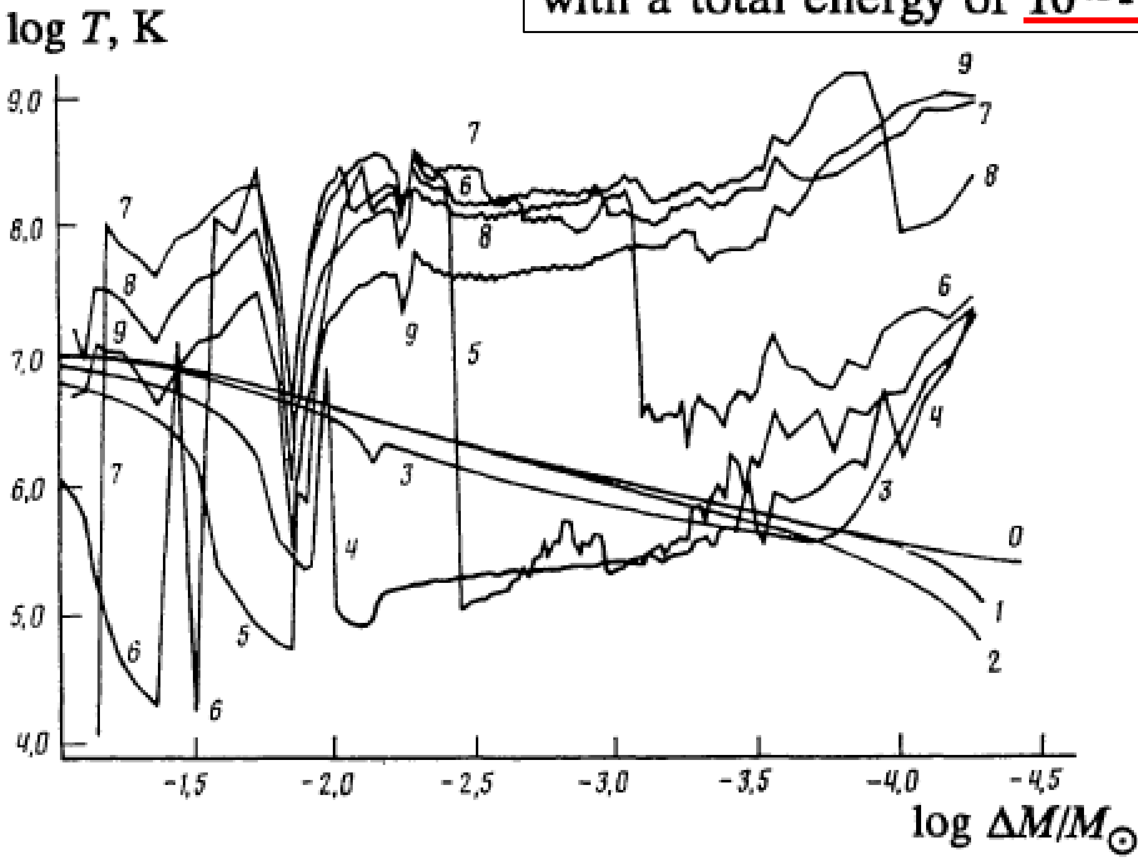


FIG. 12. Temperature distributions along the Lagrangian coordinate (ΔM is the mass reckoned from the surface) in the course of the explosion of a neutron star of mass $M = 0.09499\ M_\odot$ at different times (Table I). The temperature increase to 10^8-10^9 K at the surface indicates the possibility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

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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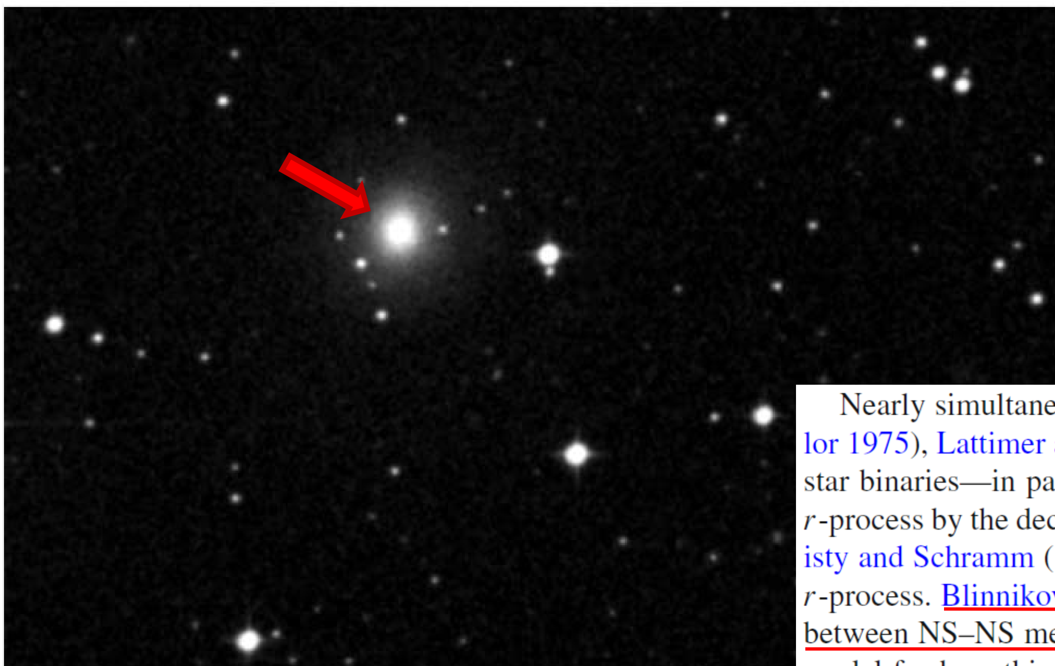


The galaxy NGC 4993 (fuzzy bright spot) in the constellation Hydra, where dete
have spotted gravitational waves from a neutron star merger.

Событие GW170817

Галактика NGC 4993
Расстояние 40 млн пс

Гамма-всплеск
GRB 170817A

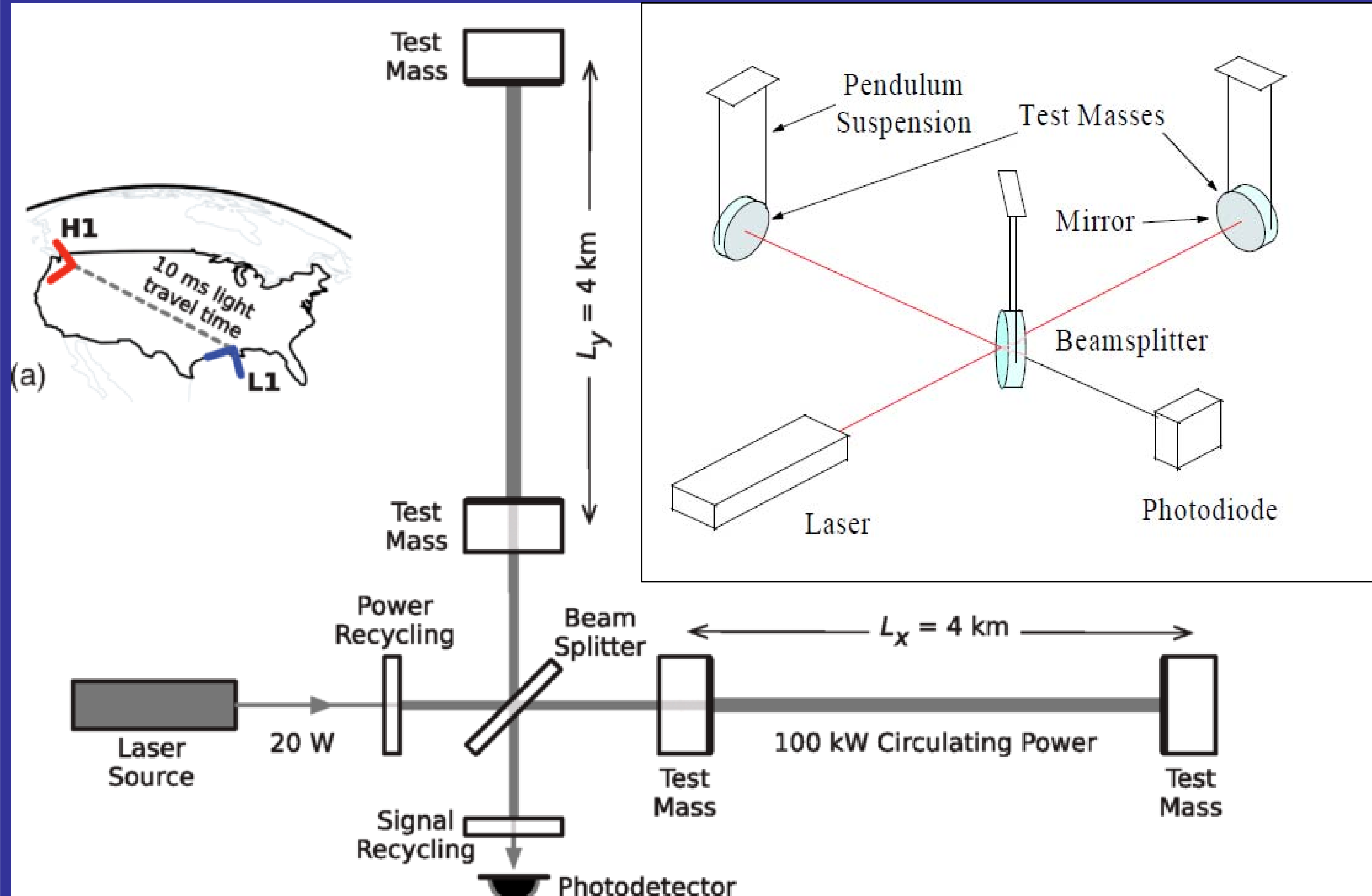
Living Rev Relativ (2017) 20:3
DOI 10.1007/s41114-017-0006-z

REVIEW ARTICLE

Kilonovae

Brian D. Metzger[1]

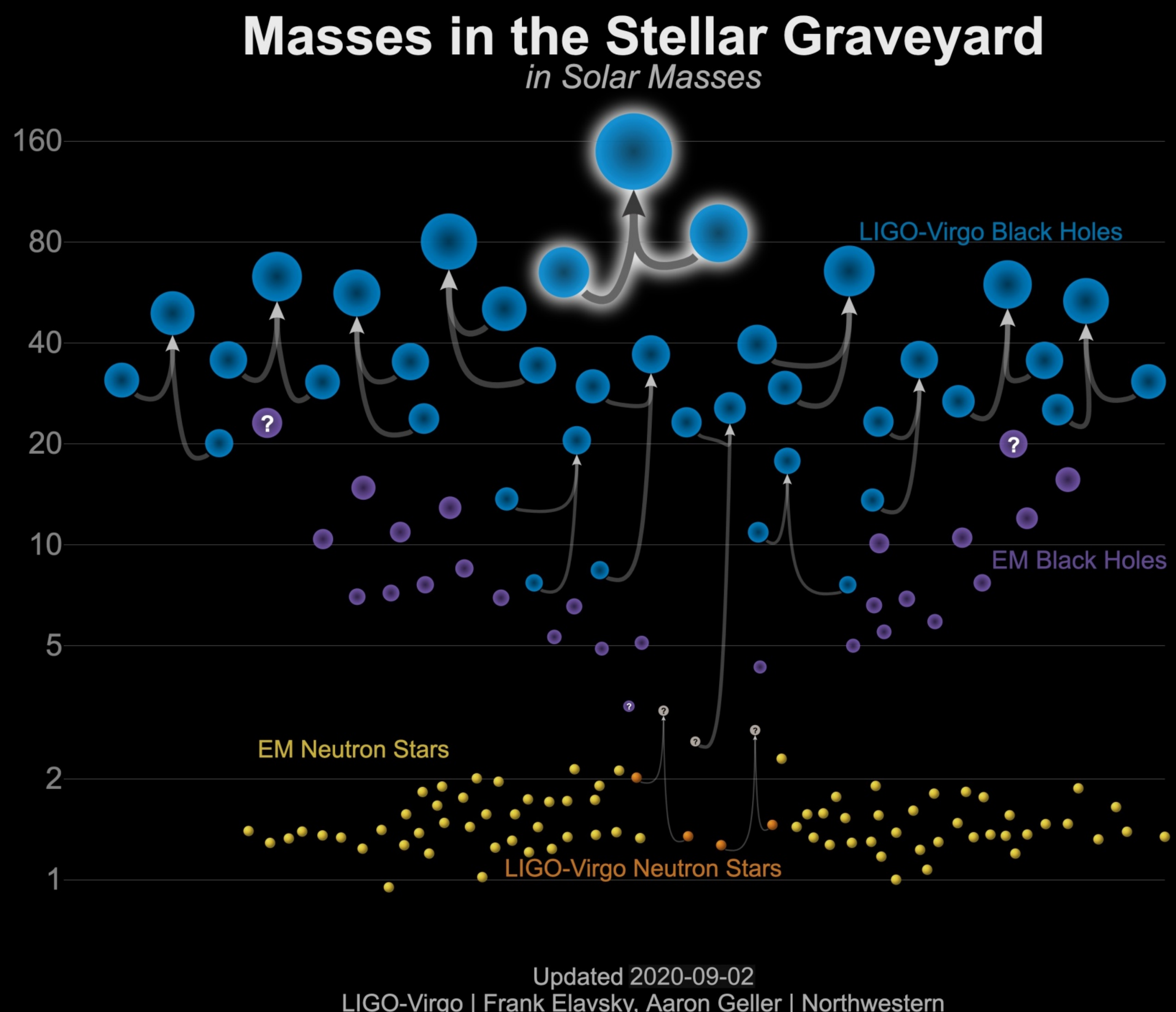
Nearly simultaneous with the discovery of the first binary pulsar (Hulse and Taylor 1975), Lattimer and Schramm (1974, 1976) proposed that the merger of compact star binaries—in particular the collision of BH–NS systems—could give rise to the r-process by the decompression of highly neutron-rich ejecta (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-



H1
10 ms light travel time
L1
(a)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
Pendulum Suspension
Test Masses
Mirror
Beamsplitter
Laser
Photodiode


Virgo

LIGO



14 сентября 2015 года - первое детектирование ГВ: слияние черных дыр по 30 Ms

GW170817

Слияние двух нейтронных звезд

Наблюдалось детекторами гравитационных волн LIGO / Virgo и более 70 электромагнитными обсерваториями.

H L V

Росстояние
130 млн. световых лет

Произошло
17 Августа 2017

Тип
Слияние нейтронных звезд

12:41:04 UTC
Детектирована гравитационная волна от слияния нейтронных звезд

Гравитационная волна
Две нейтронные звезды, каждая размером с город, но с массой не меньше массы Солнца

+ 2 секунды
Детектирована выспышка гамма излучения.

Гамма излучение
Короткая вспышка гамма-излучения это яркий луч гамма излучения, генерируемый сразу после слияния звезд

+10 часов 52 минуты
Новый яркий источник оптического излучения обнаружен в галактике NGC 4993, в созвездии Гидры.

Килоновая
Эволюция богатого нейтронами вещества вызывает свечение килоновой, происходит синтез тяжелых элементов, таких как золото и платина

+11 часов 36 минут
Наблюдается инфракрасное излучение

+15 часов
Детектировано яркое ультрафиолетовое излучение.

+9 дней
Обнаружено рентгеновское излучение

Остаточное радио-излучение
Выброс материала из звезды приводит к ударной волне в межзвездной среде. Это создает радио-излучение, которое может продолжаться годами.

+16 дней
Обнаружено излучение радио-диапазона

GW170817 позволяет нам впервые измерить скорость расширения вселенной напрямую, используя гравитационные волны.

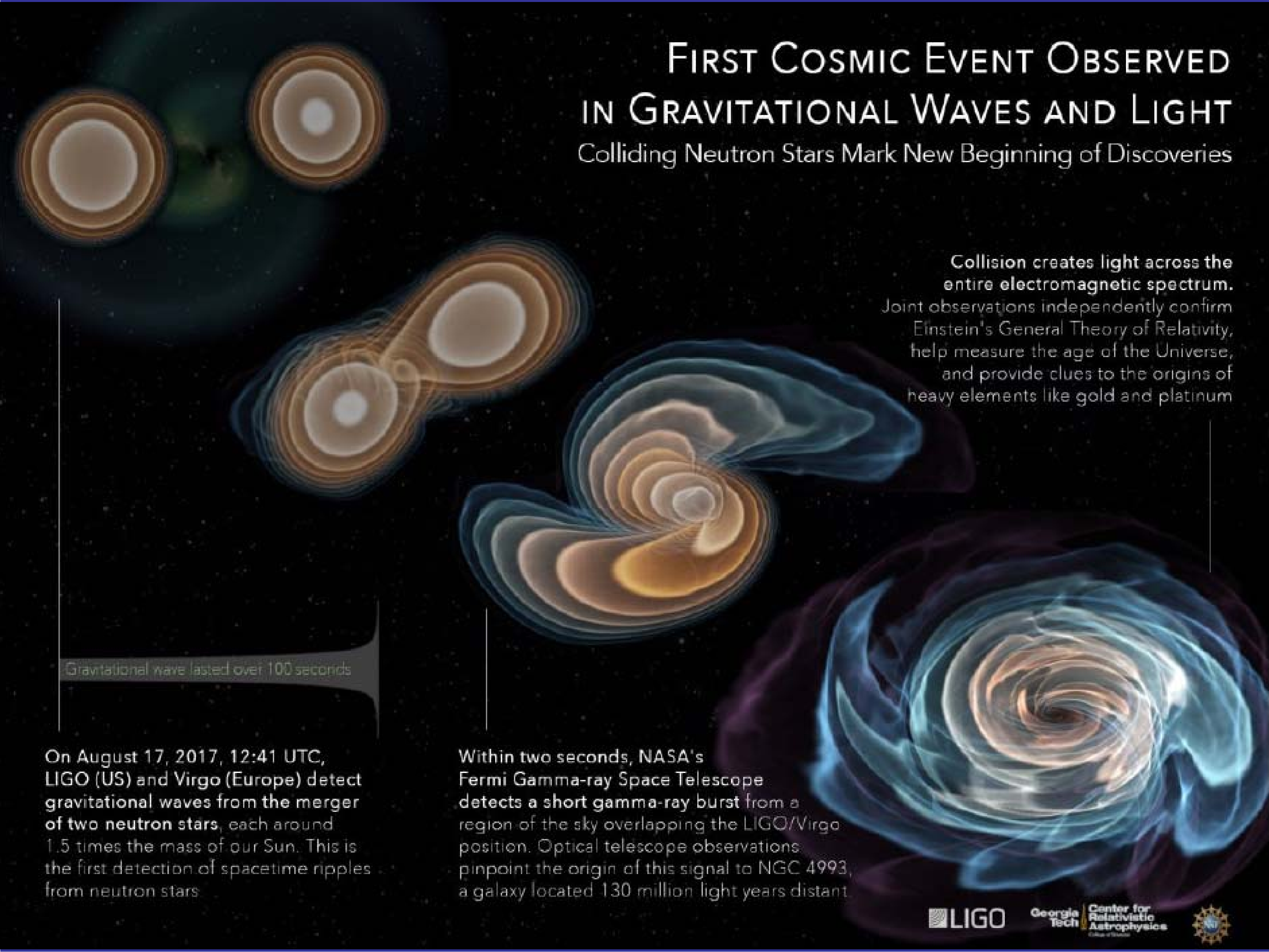
Регистрация гравитационного излучения от слияния нейтронных звезд позволяет нам узнать больше о строении этих необычных объектов

Регистрация этого события различными детекторами подтверждает, что слияние нейтронных звезд может порождать вспышки гамма излучения

Au

Полученные данные о килоновой позволили показать, что столкновения нейтронных звезд могут быть источником большинства тяжелых ядер, например золота, во вселенной.

Наблюдение гравитационных и электромагнитных волн от одного события позволяет уверенно утверждать что гравитационные волны распространяются со скоростью света



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

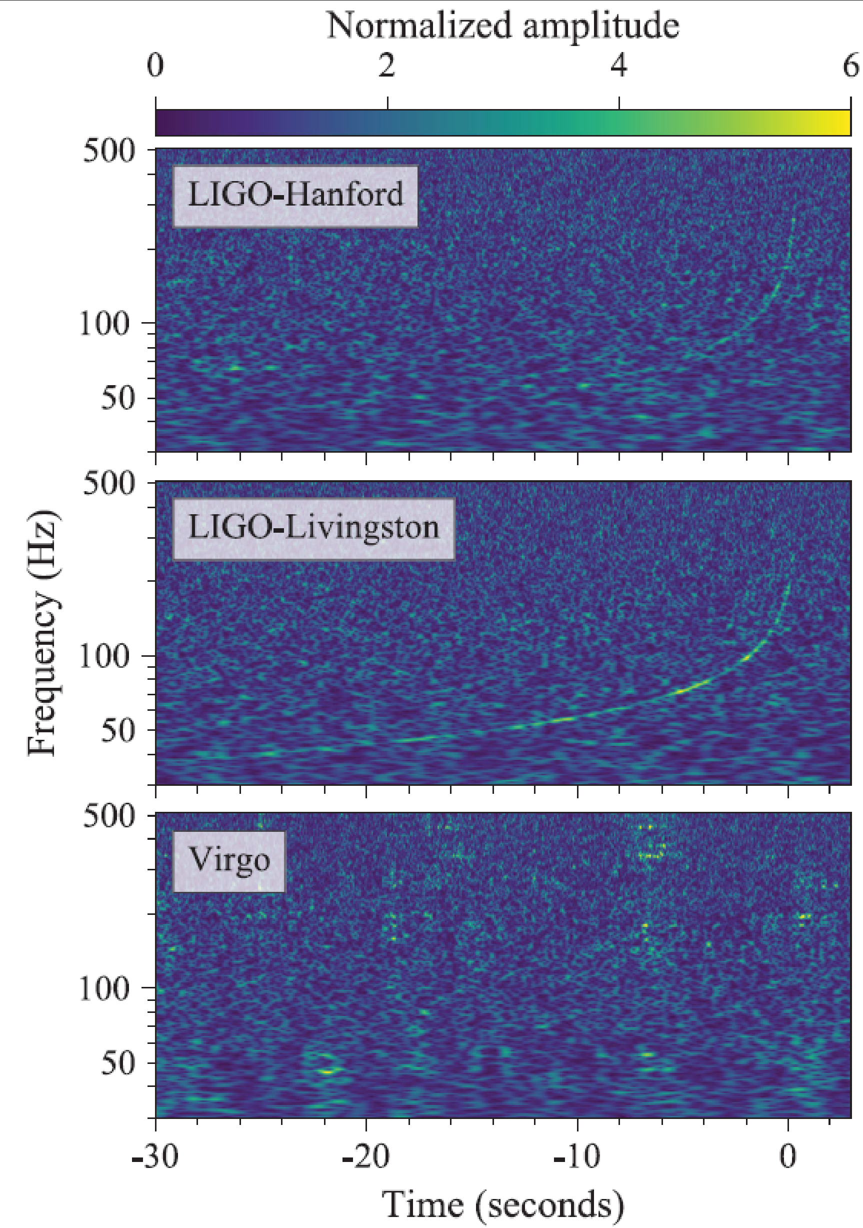
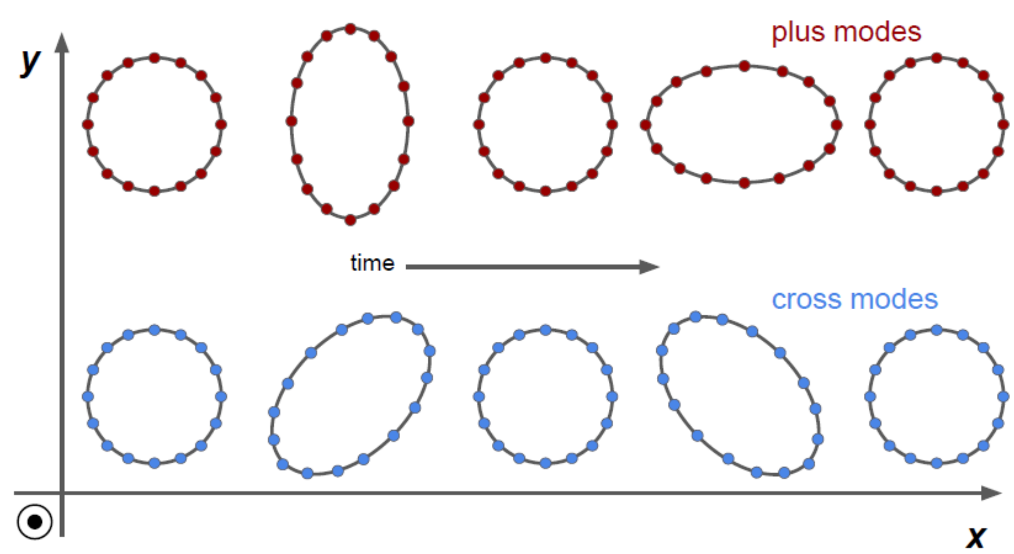
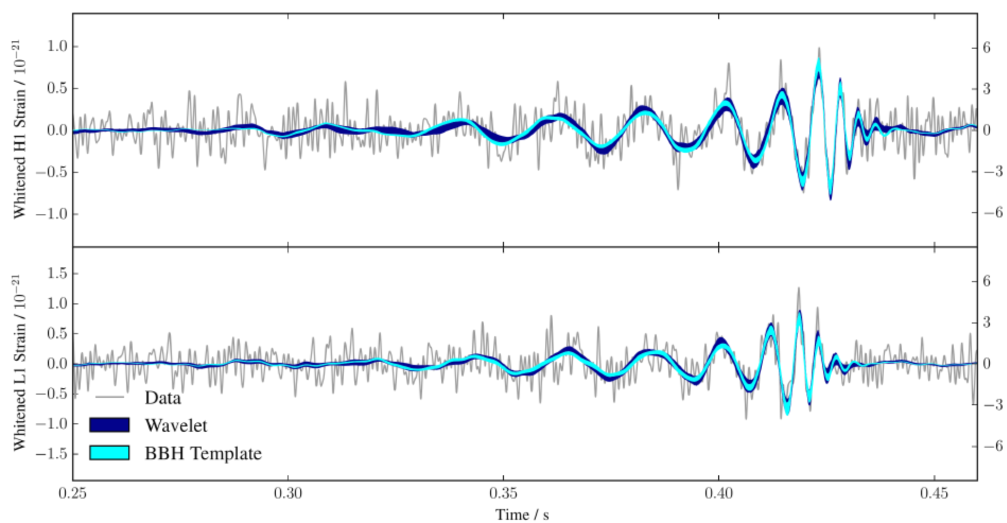


FIG. 1. Time-frequency representations [65] of data containing the gravitational-wave event GW170817, observed by the LIGO-Hanford (top), LIGO-Livingston (middle), and Virgo (bottom) detectors. Times are shown relative to August 17, 2017 12:41:04



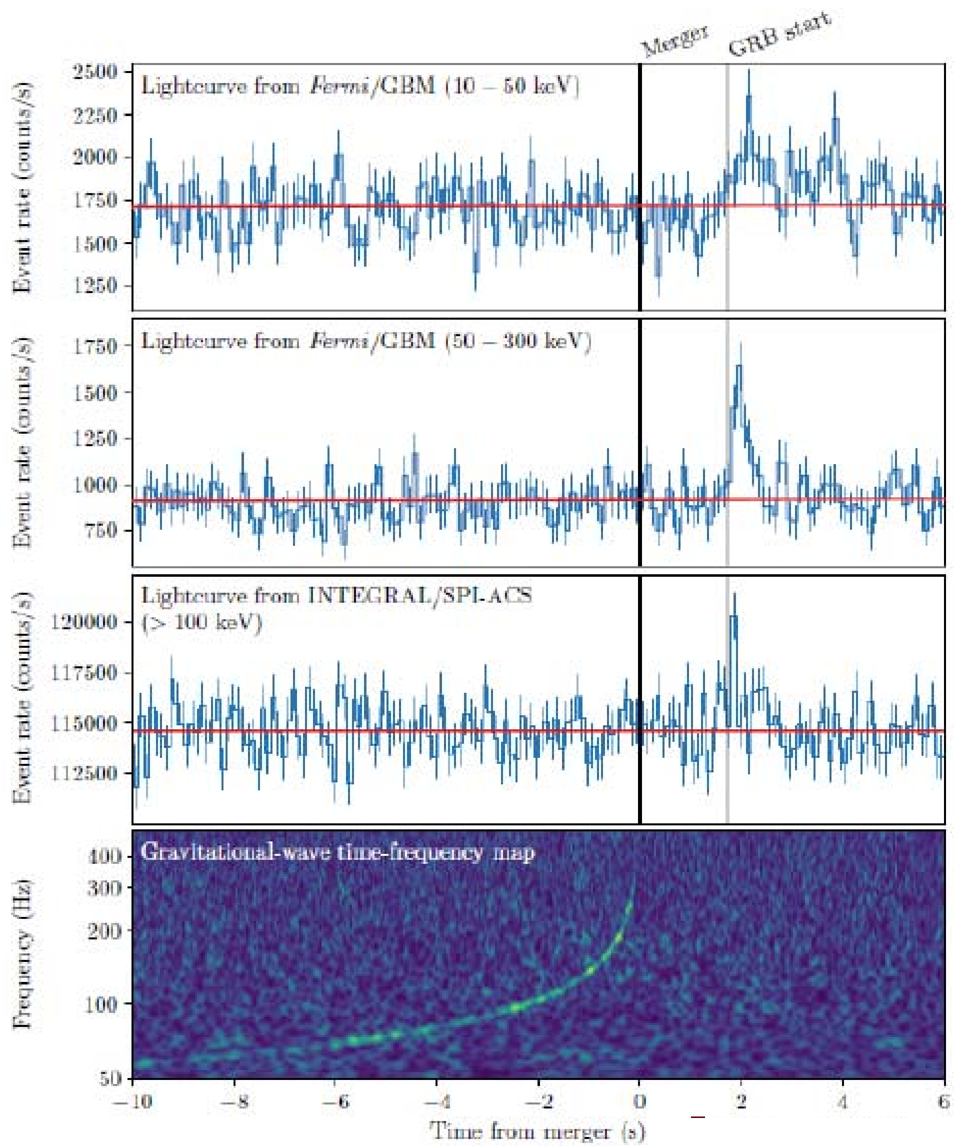


INTEGRAL and NASA's Fermi satellite

INTErnational
Gamma-Ray
Astrophysics
Laboratory

(INTEGRAL)

The Fermi
Gamma-ray
Space
Telescope



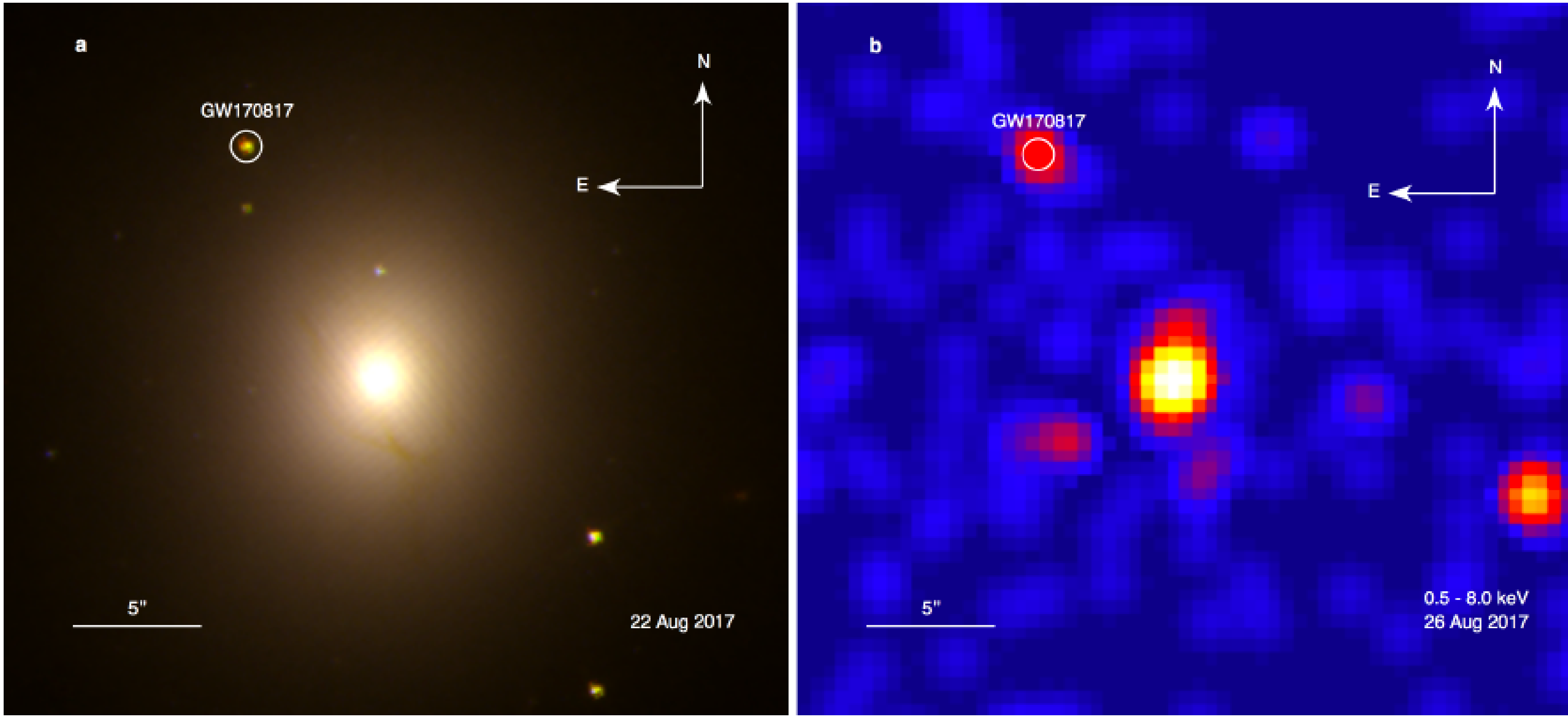
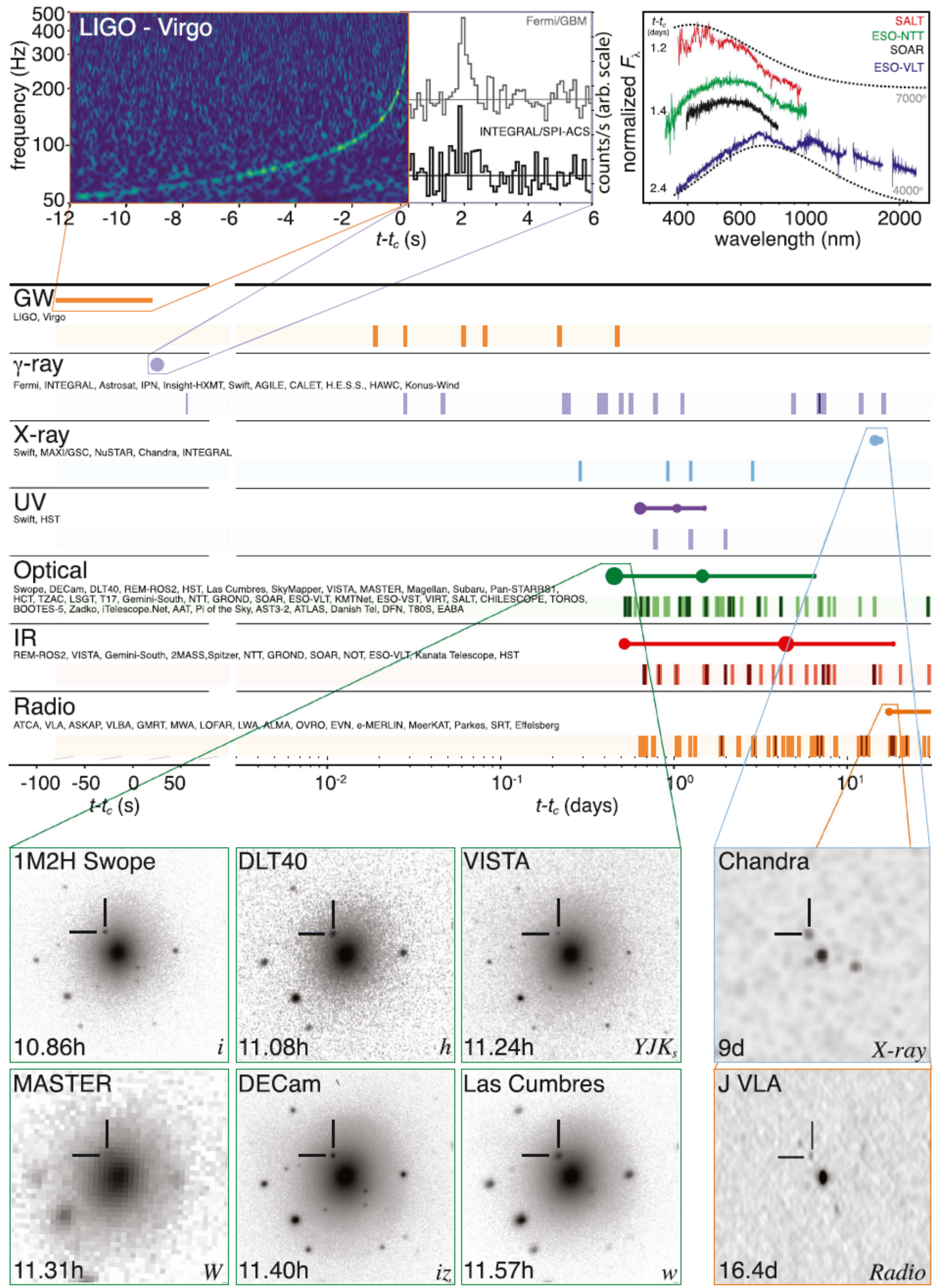


Figure 1: Optical/Infrared and X-ray images of the counterpart of GW170817

a *Hubble Space Telescope* observations show a bright and red transient in the early-type galaxy NGC 4993, at a projected physical offset of ~2 kpc from its nucleus. A similar small offset is observed in some (~25%) short GRBs[5]. Dust lanes are visible in the inner regions, suggestive of a past merger activity (see Methods). **b** *Chandra* observations revealed a faint X-ray source at the position of the optical/IR transient. X-ray emission from the galaxy nucleus is also visible.

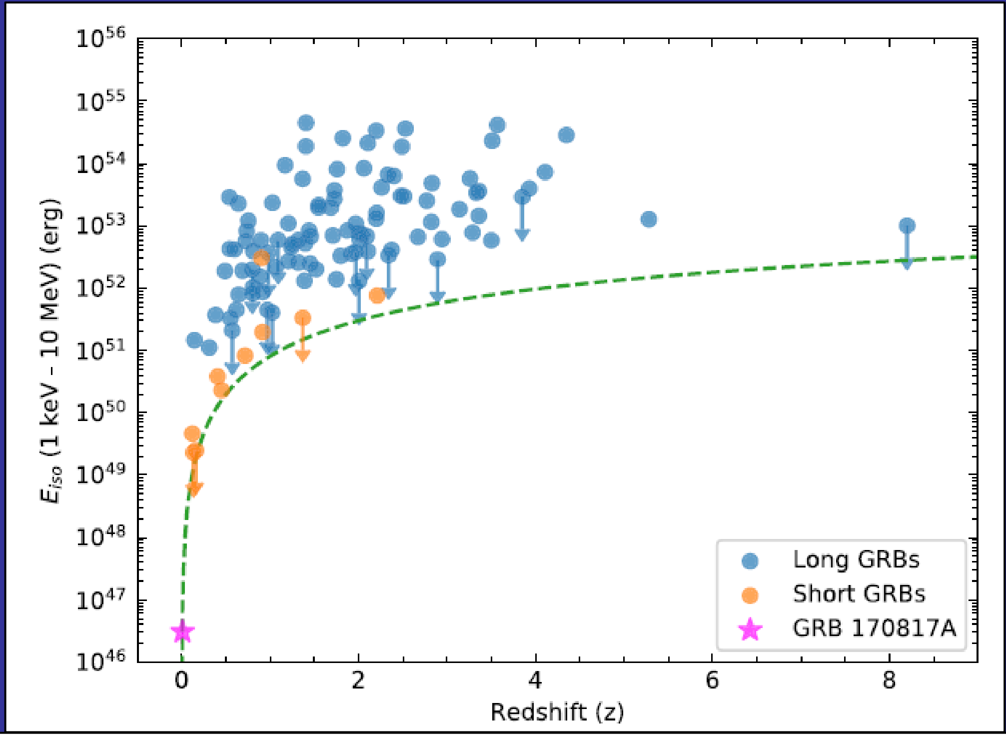


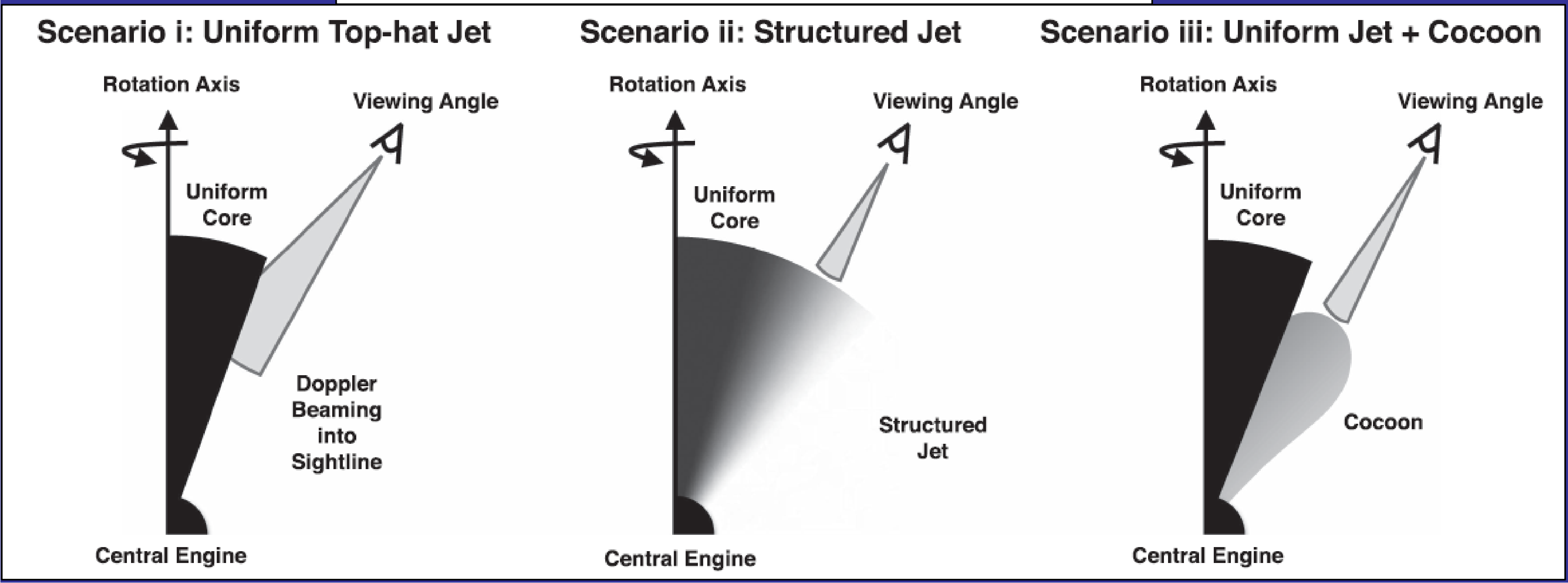
LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized F_λ
wavelength (nm)
7000°
4000°
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1,
HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS,
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope 10.86h i
DLT40 11.08h h
VISTA 11.24h YJK_s
Chandra 9d X-ray
MASTER 11.31h W
DECam 11.40h iz
Las Cumbres 11.57h w
J VLA 16.4d Radio

Важное о GW170817

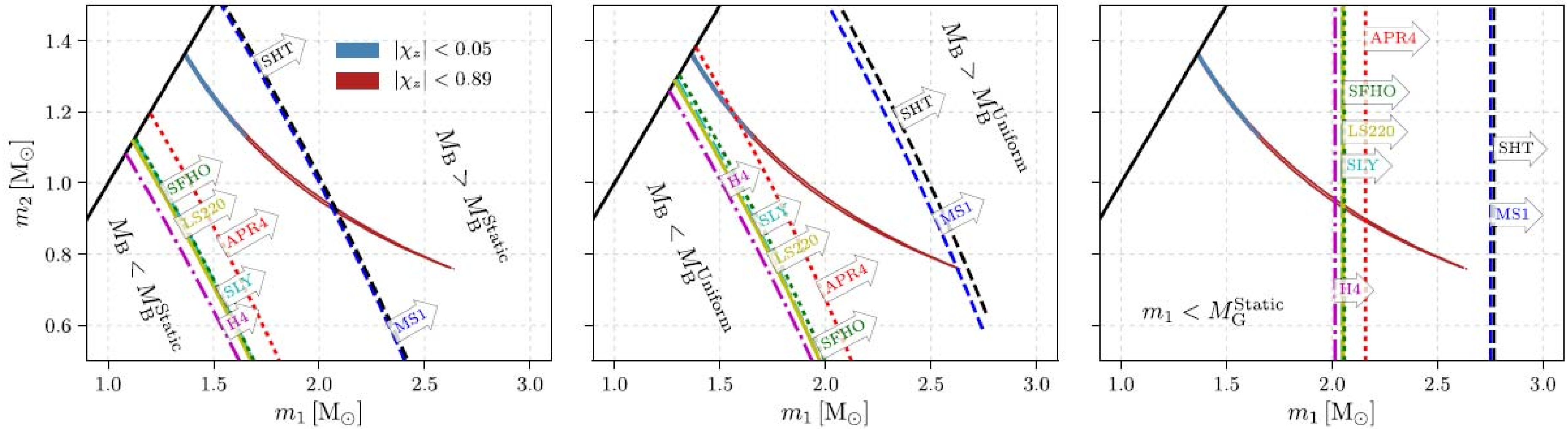
- GW170817 — 6-е гравитационно-волновое событие и 1-ое наблюдение слияния объектов с массами нейтронных звезд.
- Гамма-всплеск GRB170817A наблюдался спустя 1.7 сек. после потери сигнала GW170817.
  - Подтверждена связь коротких GRB со сливающимися NS
  - Ограничения на гравитацию: скорость распространения ($\Delta v/c \lesssim 10^{-15}$), 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
Scenario ii: Structured Jet
Scenario iii: Uniform Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Doppler Beaming into Sightline
Central Engine
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Central Engine
Rotation Axis
Viewing Angle
Uniform Core
Cocoon
Central Engine

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L13 (27pp), 2017 October 20 Abbott et al.



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

Chirp mass

high-spin:

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

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

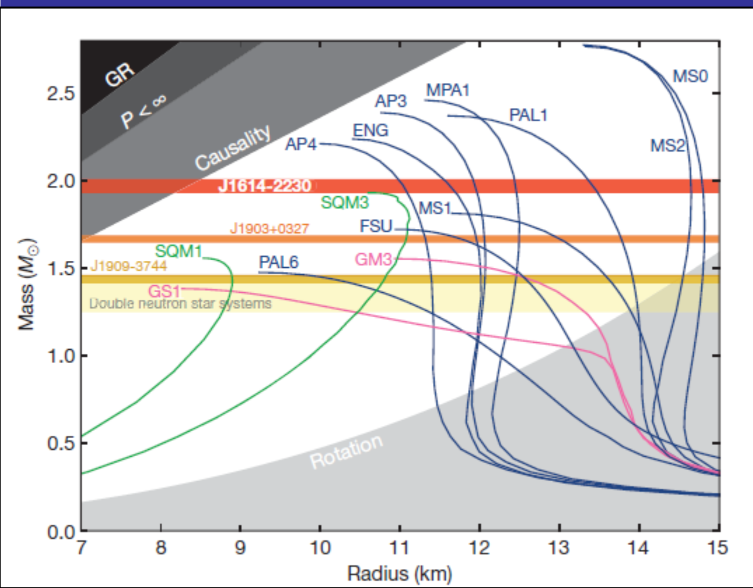
$m_{tot} = 2.82^{+0.47}_{-0.09} M_\odot$

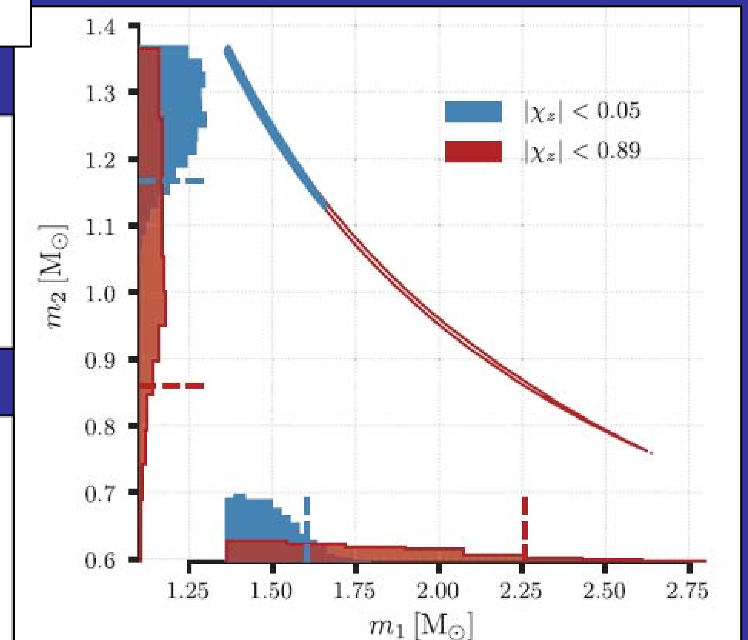
low-spin:

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

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

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





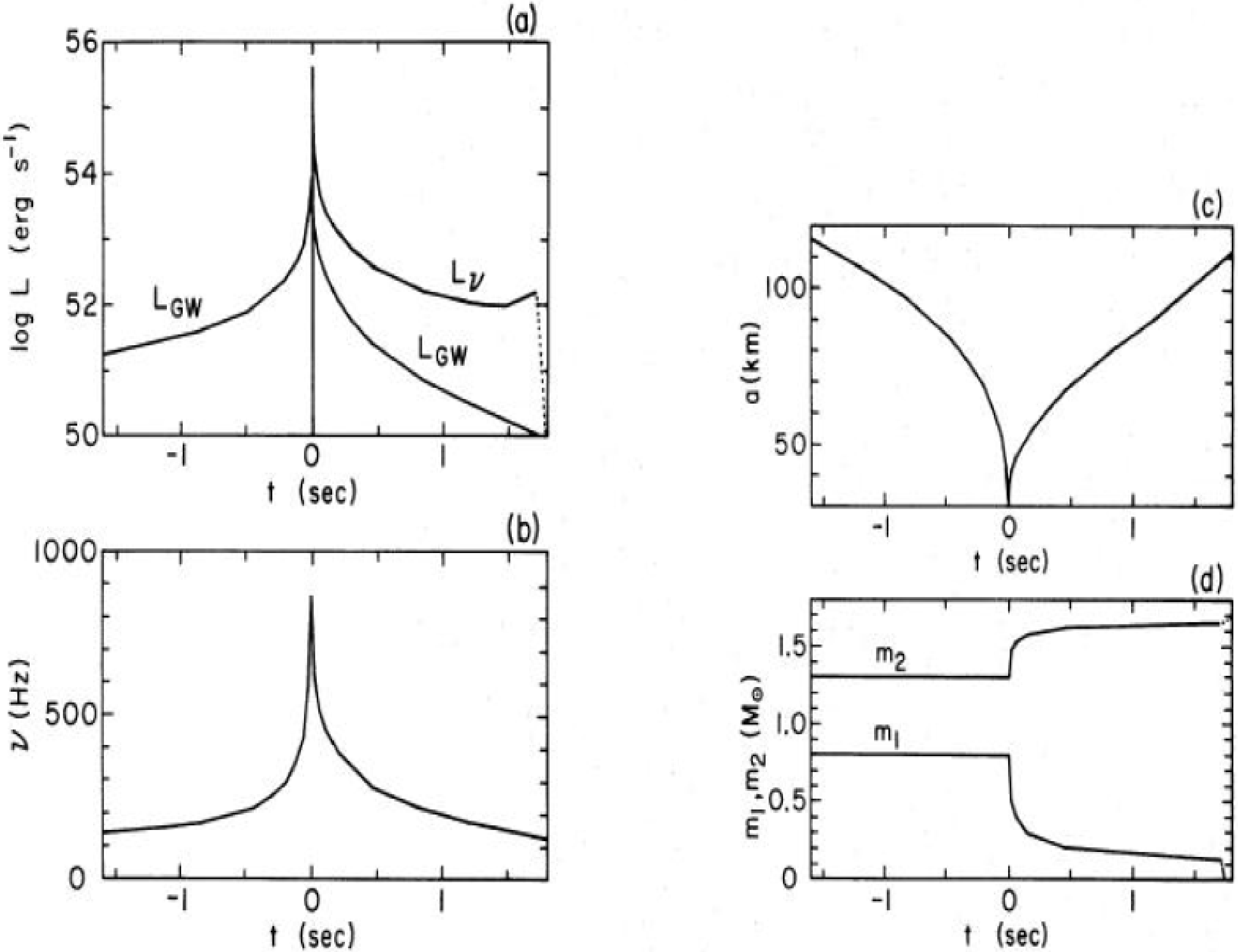
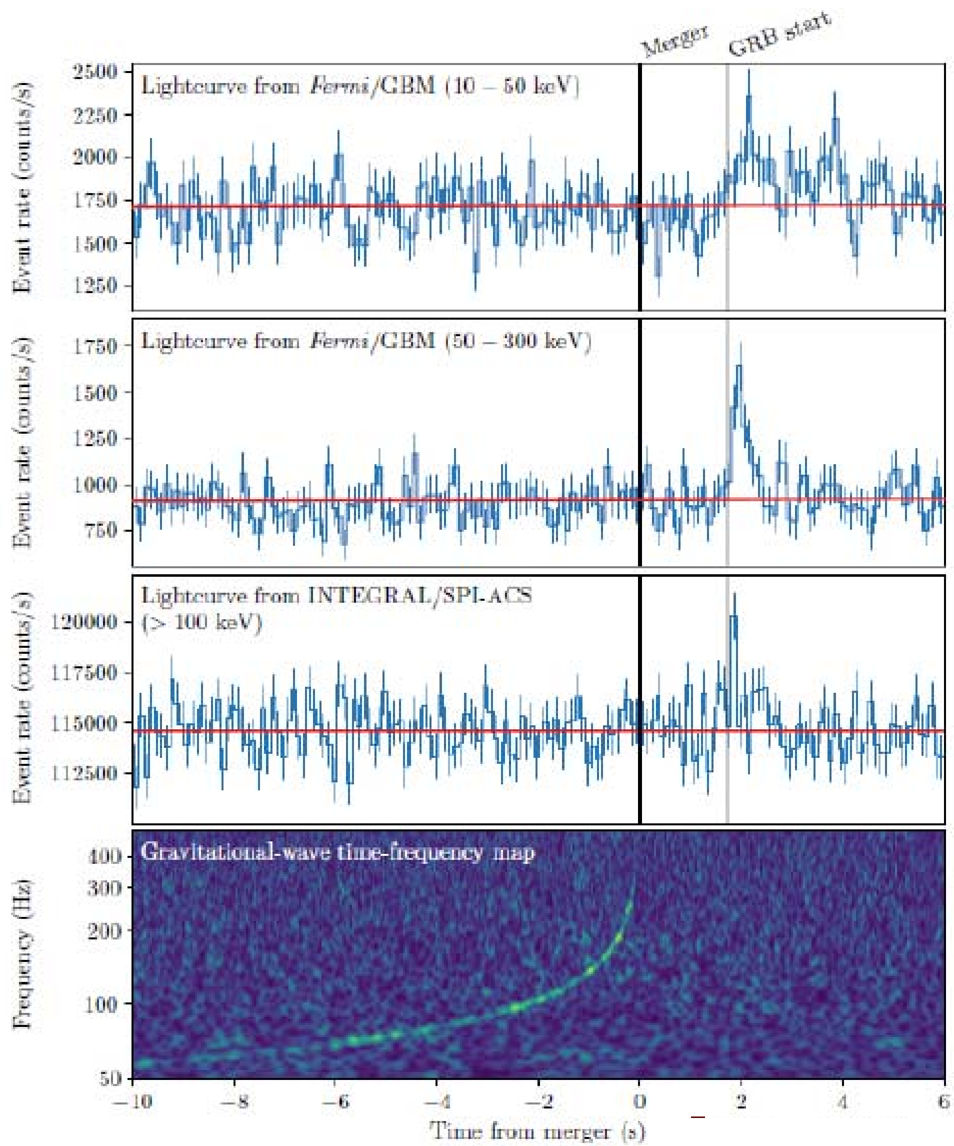


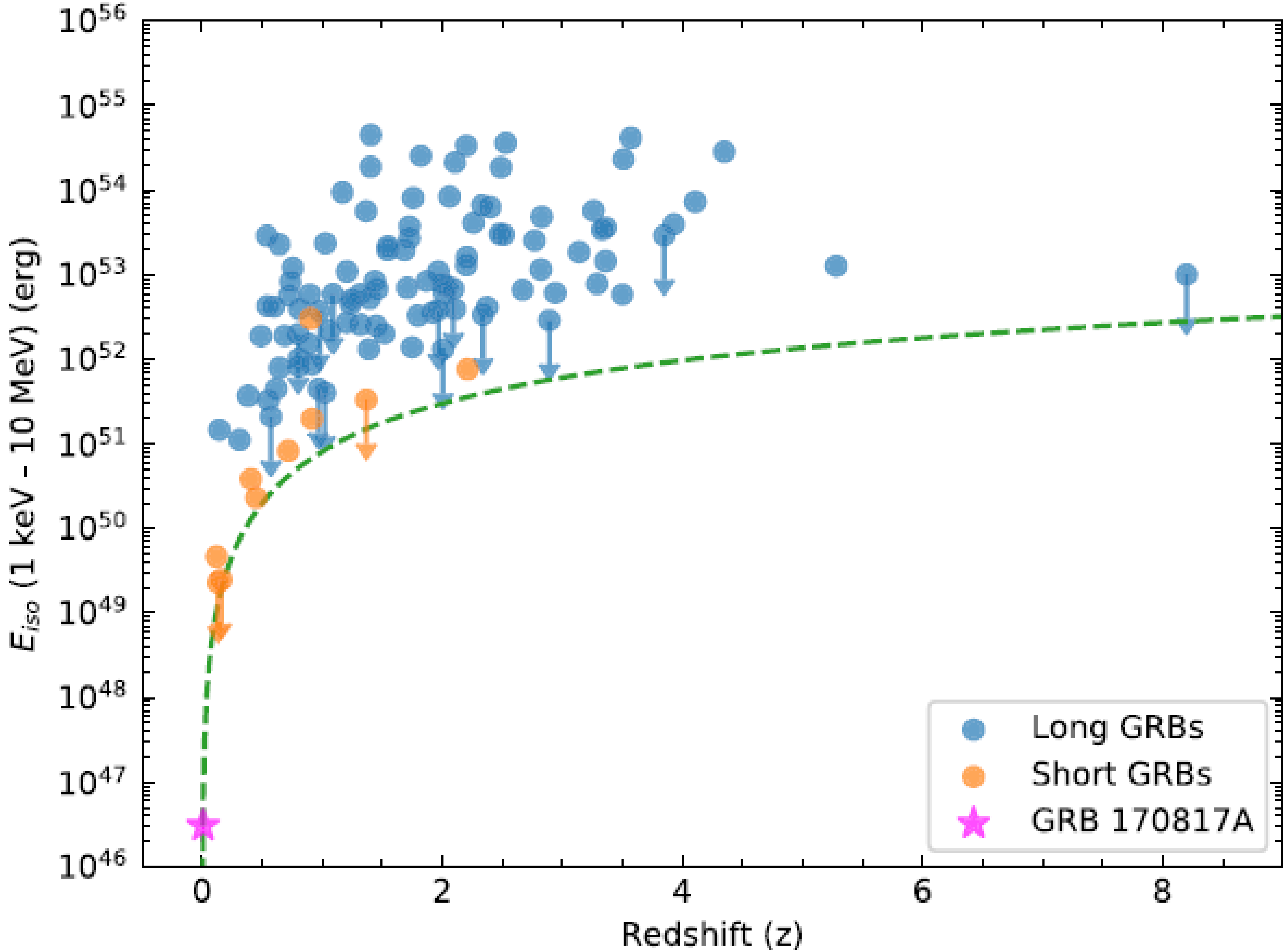
FIG. 7—Time evolution of a system with initial masses 0.8 and 1.3 $M_{\odot}$. (*a*) Neutrino and gravitational wave luminosities. (*b*) Frequency of gravitational wave. (*c*) Separation of components. (*d*) Masses of stars.

INTEGRAL and NASA's Fermi satellite

INTErnational
Gamma-Ray
Astrophysics
Laboratory
(INTEGRAL)

The Fermi
Gamma-ray
Space
Telescope





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

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.

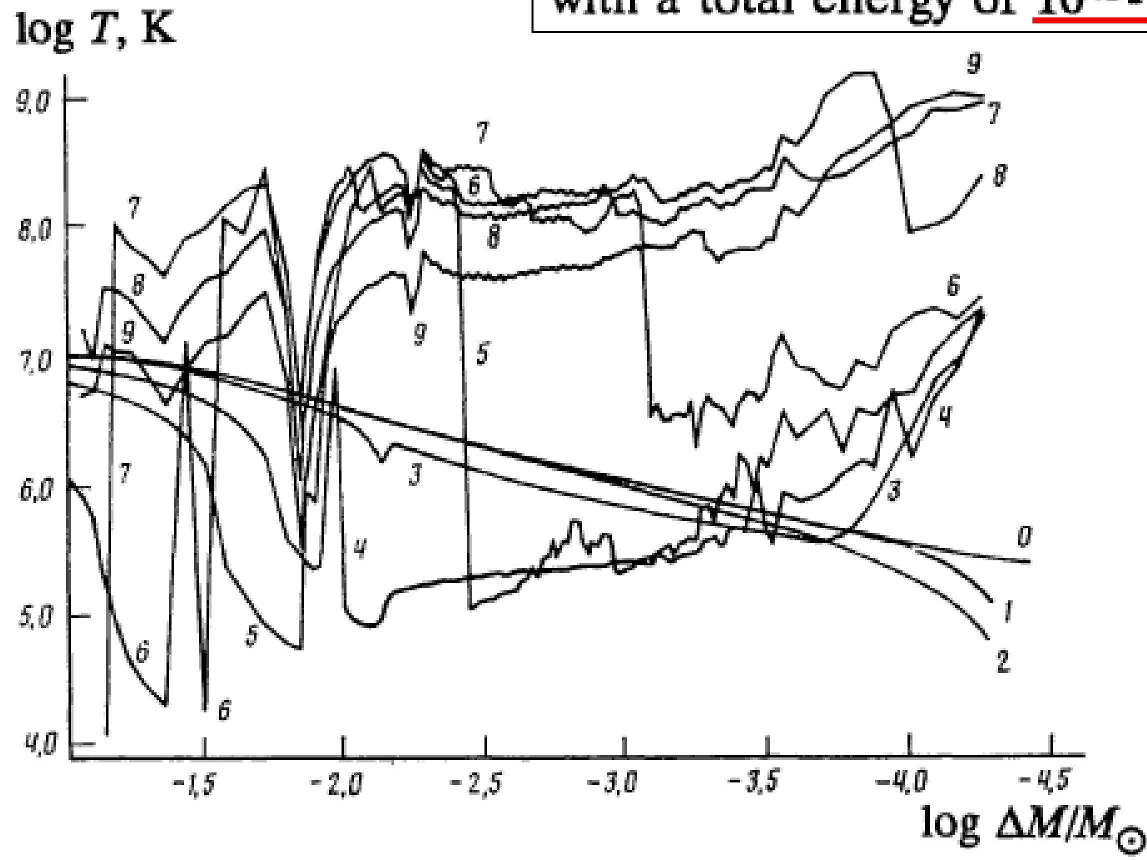


FIG. 12. Temperature distributions along the Lagrangian coordinate (ΔM is the mass reckoned from the surface) in the course of the explosion of a neutron star of mass $M = 0.09499\ M_\odot$ at different times (Table I). The temperature increase to 10^8-10^9 K at the surface indicates the possibility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

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

Daniel M. Siegel[1,2]

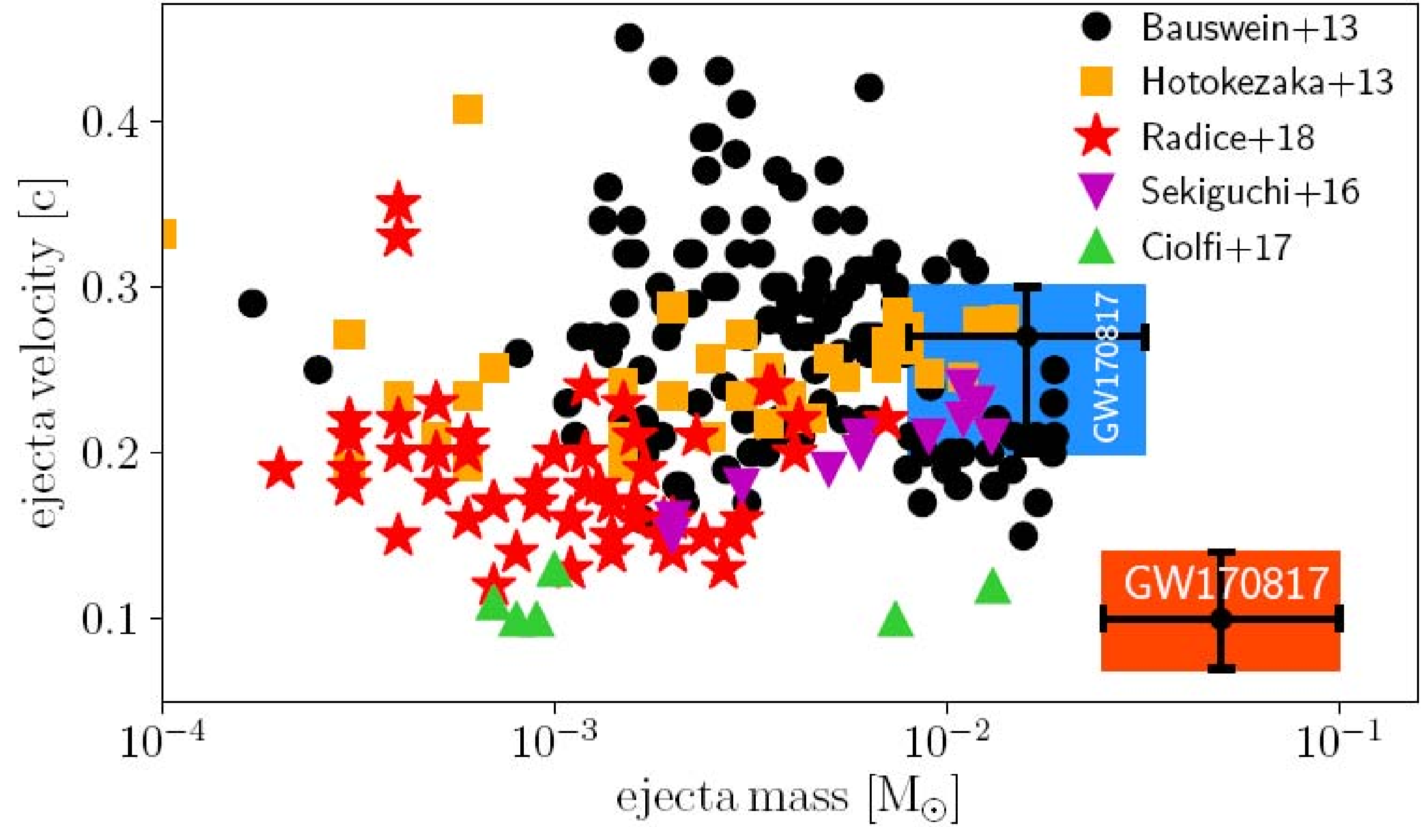
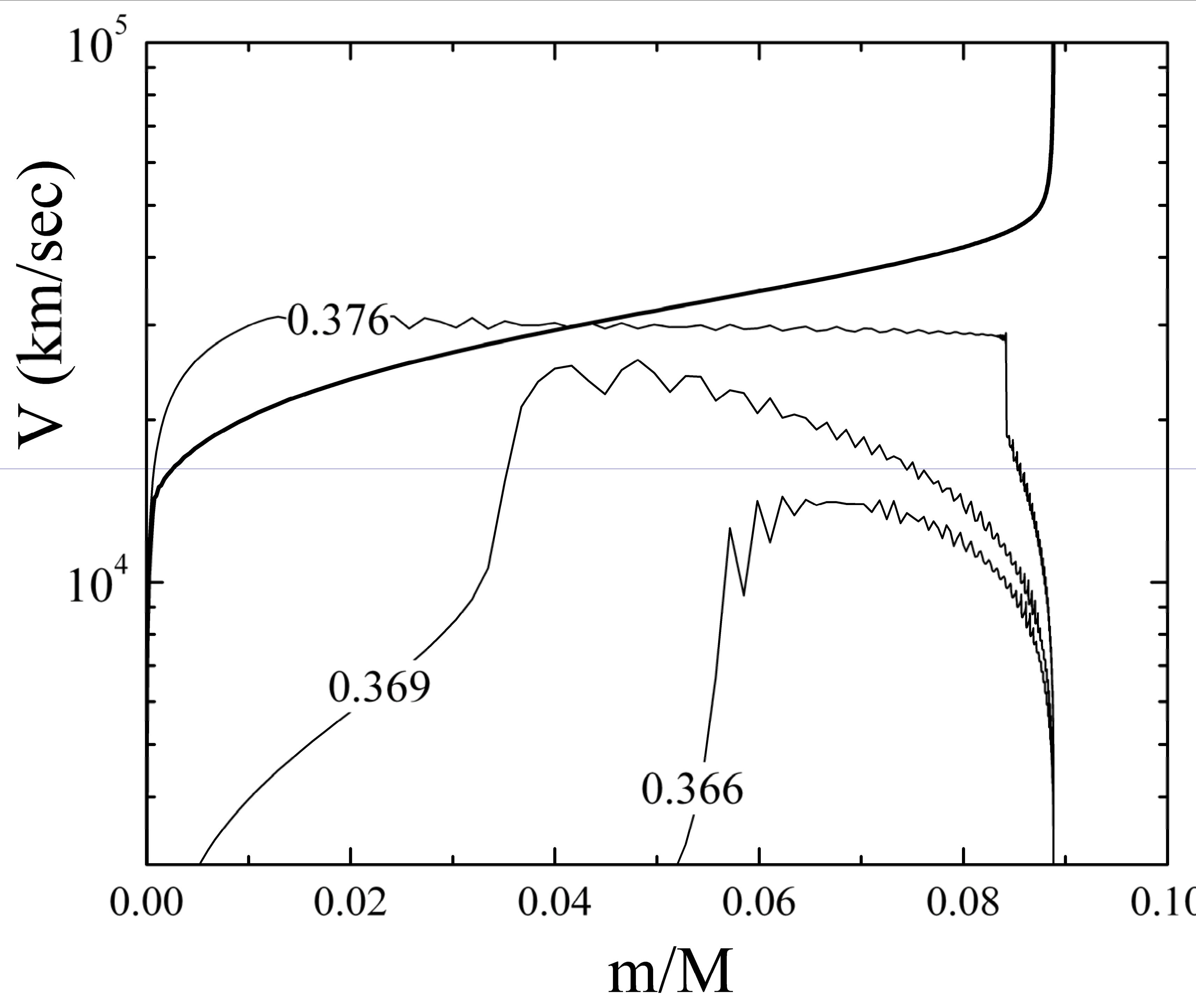
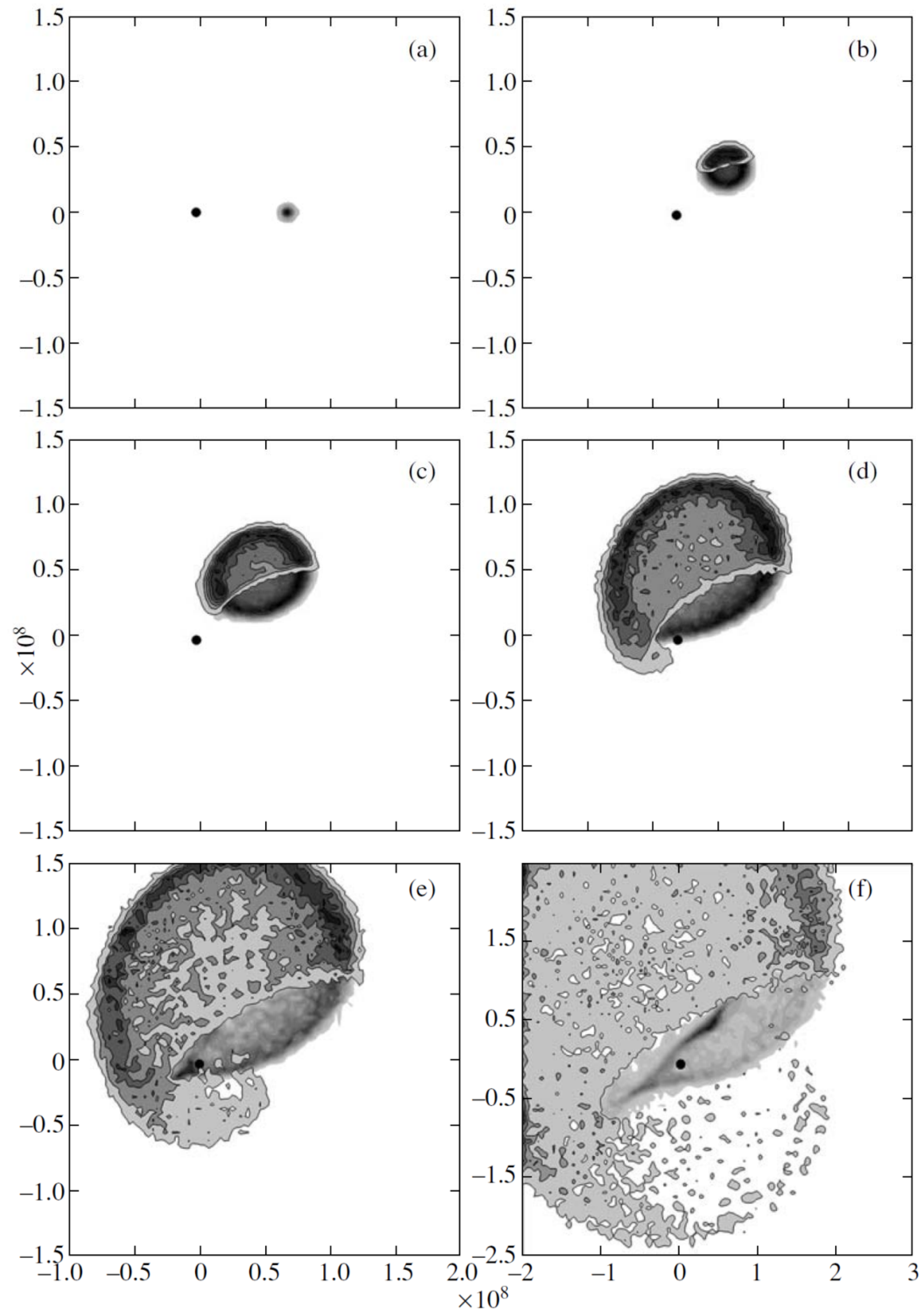


Figure 1. Dynamical ejecta masses and velocities from various binary neutron star merger simulations encompassing different numerical techniques, various equations of state, binary binary mass ratios 0.65 – 1.0, effects of neutrinos and magnetic fields [77,78,64,73,65], together with the corresponding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



10^5
10^4
V (km/sec)
0.376
0.369
0.366
0.00
0.02
0.04
0.06
0.08
0.10
m/M



3D-расчёт взрыва

Model for the Explosion of a Critical-Mass Neutron Star in a Binary System

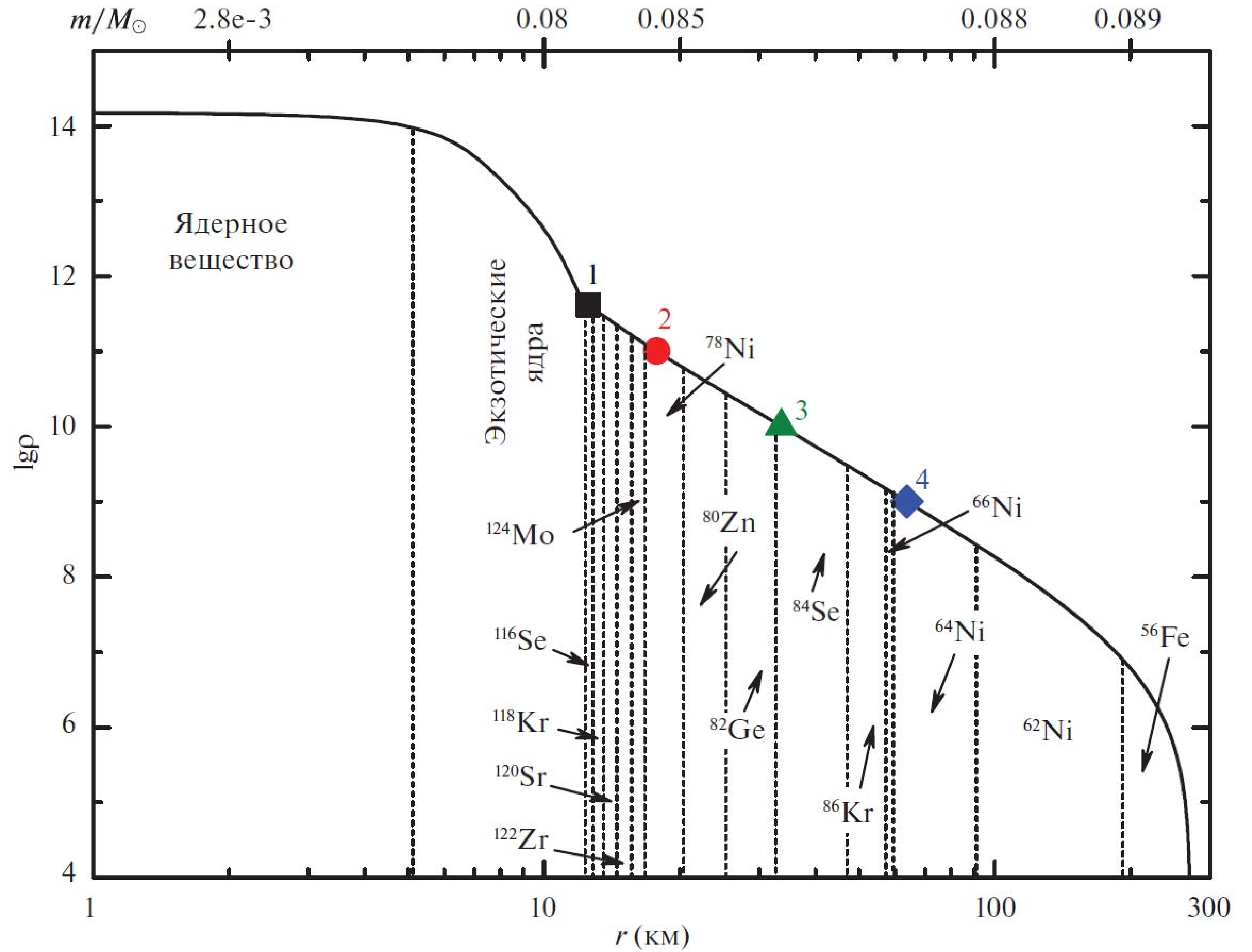
K. V. Manukovskii*

Institute for Theoretical and Experimental Physics, ul. Bol'shaya Cheremushkinskaya 25, Moscow, 117259 Russia

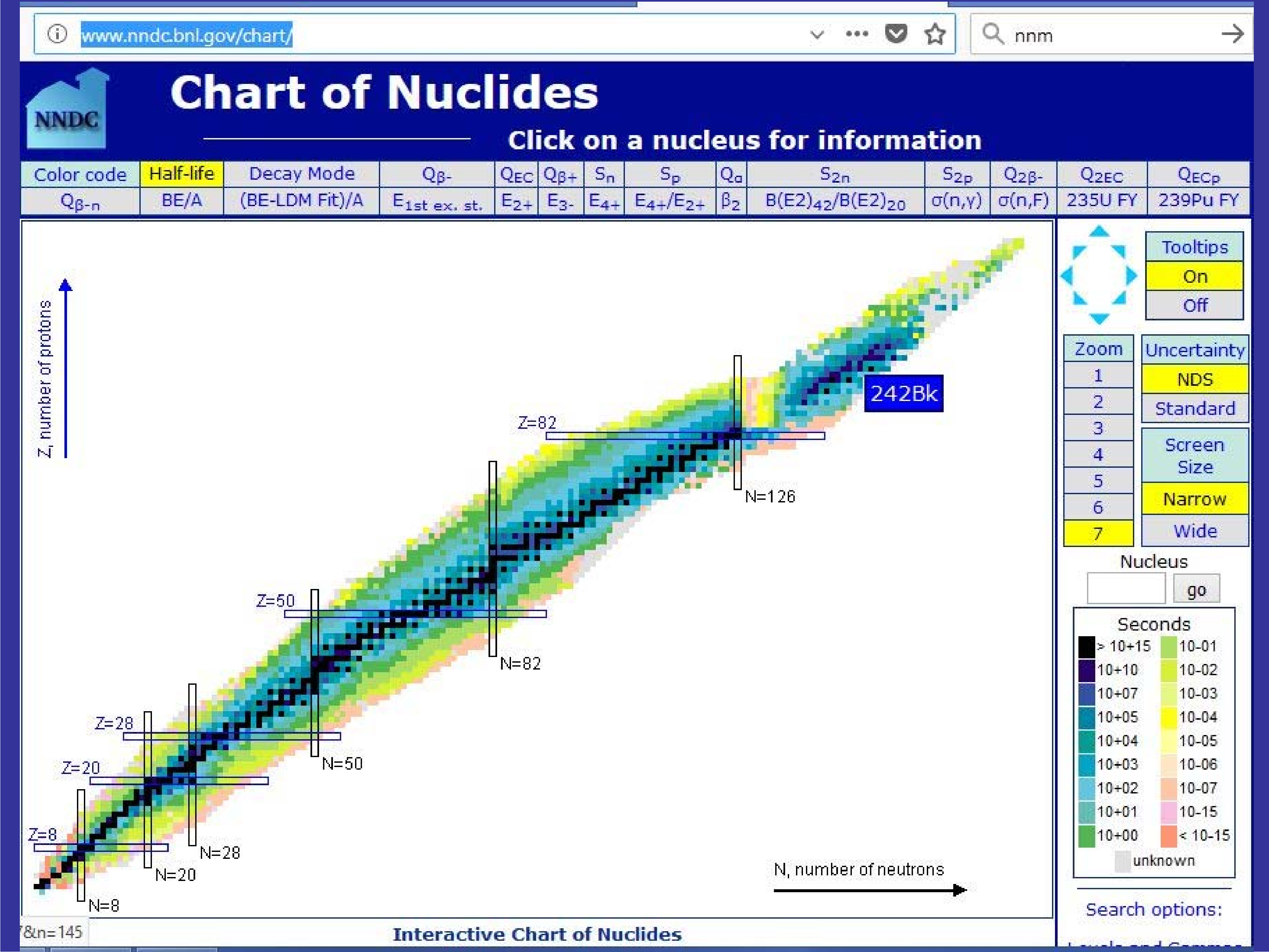
Received August 10, 2009

Model	M1	M2	M3	M4	M5	M6	M7	M8	M9
E_{exp}, 10^{51} erg	0.63	0.66	0.65	0.67	0.72	0.77	0.76	0.45	0.66
V_p, 10^3 km s^{-1}	0.71	0.66	0.59	0.56	0.72	0.85	0.48	0.39	0.60
η	0.23	0.25	0.20	0.23	0.16	0.09	0.03	0.36	0.20

Note. E_{exp} is the total explosion energy, V_p is the final pulsar velocity, and η is the mass fraction of the ejecta's material gravitationally bound to the pulsar.



m/M⊙
2.8e-3
0.08
0.085
0.088
0.089
lgρ
14
12
10
8
6
4
1
10
100
300
r (км)
Ядерное
вещество
Экзотические
ядра
1
2
3
4
78Ni
80Zn
82Ge
84Se
86Kr
66Ni
64Ni
62Ni
56Fe
124Mo
116Se
118Kr
120Sr
122Zr


www.nndc.bnl.gov/chart/
nnm
NNDC
Chart of Nuclides
Click on a nucleus for information
Color code
Half-life
Decay Mode
Qβ-
QEC
Qβ+
Sn
Sp
Qα
S2n
S2p
Q2β-
Q2EC
QECp
Qβ-n
BE/A
(BE-LDM Fit)/A
E1st ex. st.
E2+
E3-
E4+
E4+/E2+
β2
B(E2)42/B(E2)20
σ(n,γ)
σ(n,F)
235U FY
239Pu FY
Z, number of protons
242Bk
Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
Z=8
N=28
N=20
N=8
N, number of neutrons
Tooltips
On
Off
Zoom
1
2
3
4
5
6
7
Uncertainty
NDS
Standard
Screen Size
Narrow
Wide
Nucleus
go
Seconds
> 10+15
10+10
10+07
10+05
10+04
10+03
10+02
10+01
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10-02
10-03
10-04
10-05
10-06
10-07
10-15
< 10-15
unknown
Search options:
7&n=145
Interactive Chart of Nuclides

Chart of Nuclides

NNDC

Click on a nucleus for information

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}
$Q_{\beta-n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U FY	239Pu FY

Z	57Ni 35.60 H ε: 100.00%	58Ni STABLE 68.077%	59Ni 7.6E+4 Y ε: 100.00%	60Ni STABLE 26.223%	61Ni STABLE 1.1399%	62Ni STABLE 3.6346%	63Ni 101.2 Y β-: 100.00%	64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%
27	56Co 77.236 D ε: 100.00%	57Co 271.74 D ε: 100.00%	58Co 70.86 D ε: 100.00%	59Co STABLE 100%	60Co 1925.28 D β-: 100.00%	61Co 1.649 H β-: 100.00%	62Co 1.50 M β-: 100.00%	63Co 27.4 S β-: 100.00%	64Co 0.30 S β-: 100.00%
26	55Fe 2.744 Y ε: 100.00%	56Fe STABLE 91.754%	57Fe STABLE 2.119%	58Fe STABLE 0.282%	59Fe 44.495 D β-: 100.00%	60Fe 2.62E+6 Y β-: 100.00%	61Fe 5.98 M β-: 100.00%	62Fe 68 S β-: 100.00%	63Fe 6.1 S β-: 100.00%
25	54Mn 312.20 D ε: 100.00% β-: 9.3E-5%	55Mn STABLE 100%	56Mn 2.5789 H β-: 100.00%	57Mn 85.4 S β-: 100.00%	58Mn 3.0 S β-: 100.00%	59Mn 4.59 S β-: 100.00%	60Mn 0.28 S β-: 100.00%	61Mn 709 MS β-: 100.00%	62Mn 92 MS β-: 100.00% β-n
24	53Cr STABLE 9.501%	54Cr STABLE 2.365%	55Cr 3.497 M β-: 100.00%	56Cr 5.94 M β-: 100.00%	57Cr 21.1 S β-: 100.00%	58Cr 7.0 S β-: 100.00%	59Cr 1.05 S β-: 100.00%	60Cr 492 MS β-: 100.00%	61Cr 234 MS
	29	30	31	32	33	34	35	36	

Tooltips: On / Off

Zoom: 1 2 3 4 5 6 7

Uncertainty: NDS / Standard

Screen Size: Narrow / Wide

Nucleus [ ] go

Seconds

> 10+15	10-01
10+10	10-02
10+07	10-03
10+00	< 10-15
unknown	

Search options:

60Cr

E(level)	Jπ	$T_{1/2}$	Decay Modes
0.0	0+	492 ms *13*	β^- : 100.00 %
0.0	0+	492 ms *13*	β^-n ?

Ground and isomeric state information for $^{59}_{26}$Fe

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	3/2-	-60.6648046875	44.495 d *9*	β^- : 100.00 %

&n=36

NNDC

Chart of Nuclides

Click on a nucleus for information

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}
$Q_{\beta-n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U FY	239Pu FY

Z	35	36	37	38	39	40	41	42	N
Z	64Cu 12.701 H ε: 61.50% β-: 38.50%	65Cu STABLE 30.85%	66Cu 5.120 M β-: 100.00%	67Cu 61.83 H β-: 100.00%	68Cu 30.9 S β-: 100.00%	69Cu 2.85 M β-: 100.00%	70Cu 44.5 S β-: 100.00%	71Cu 19.4 S β-: 100.00%	72Cu 6.63 S β-: 100.00%
28	63Ni 101.2 Y β-: 100.00%	64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%	66Ni 54.6 H β-: 100.00%	67Ni 21 S β-: 100.00%	68Ni 29 S β-: 100.00%	69Ni 11.4 S β-: 100.00%	70Ni 6.0 S β-: 100.00%	71Ni 2.56 S β-: 100.00%
27	62Co 1.50 M β-: 100.00%	63Co 27.4 S β-: 100.00%	64Co 0.30 S β-: 100.00%	65Co 1.16 S β-: 100.00%	66Co 209 MS β-: 100.00% β-n	67Co 329 MS β-: 100.00% β-n	68Co 99 MS β-: 100.00% β-n	69Co 180 MS β-: 100.00% β-n	70Co 14 MS β-: 100.00% β-n
26	61Fe 5.98 M β-: 100.00%	62Fe 68 S β-: 100.00%	63Fe 6.1 S β-: 100.00%	64Fe 2.0 S β-: 100.00%	65Fe 810 MS β-: 100.00%	66Fe 351 MS β-: 100.00%	67Fe 395 MS β-: 100.00%	68Fe 188 MS β-: 100.00%	69Fe 162 MS β-: 100.00%
25	60Mn 0.28 S β-: 100.00%	61Mn 709 MS β-: 100.00%	62Mn 92 MS β-: 100.00% β-n	63Mn 276 MS β-: 100.00% β-n	64Mn 90 MS β-: 100.00% β-n: 2.00%	65Mn 91.9 MS β-: 100.00% β-n: 7.9%	66Mn 4 MS β-: 100.00% β-n: 4.00%	67Mn 47 MS β-: 100.00%	68Mn 28 MS β-: 100.00% β-n

Tooltips: On | Off

Zoom
1
2
3
4
5
6
7

Uncertainty: NDS | Standard

Screen Size: Narrow | Wide

Nucleus [ ] go

Seconds	
> 10+15	10-01
10+10	10-02
10+07	10-03
10+05	10-04
10+04	10-05
10+03	10-06

68Mn

E(level)	Jπ	$T_{1/2}$
0.0	(>3)	28 ms *4*

Ground and isomeric state information for $^{66}_{27}$Co

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	(3+)	-56.40853125	209 ms *19*	β^- : 100.00 %

&n=43

Chart of Nuclides

NNDC

Click on a nucleus for information

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}
$Q_{\beta-n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	σ(n,γ)	σ(n,F)	235U FY	239Pu FY

Z									
Z	67Ni 21 S β-: 100.00%	68Ni 29 S β-: 100.00%	69Ni 11.4 S β-: 100.00%	70Ni 6.0 S β-: 100.00%	71Ni 2.56 S β-: 100.00%	72Ni 1587 MS β-: 100.00%	73Ni 842 MS β-: 100.00% β-n	74Ni 507.7 MS β-: 100.00% β-n	75Ni 331.8 MS β-: 100.00% β-n: 10.00%
27	66Co 209 MS β-: 100.00% β-n	67Co 329 MS β-: 100.00% β-n	68Co 99 MS β-: 100.00% β-n	69Co 180 MS β-: 100.00% β-n	70Co 14 MS β-: 100.00% β-n	71Co 80 MS β-: 100.00% β-n < 3.60%	72Co 57.3 MS β-: 100.00% β-n > 4.00%	73Co 40.5 MS β-: 100.00% β-n < 7.90%	74Co 31.4 MS β-: 100.00% β-n: 18.00%
26	65Fe 810 MS β-: 100.00%	66Fe 351 MS β-: 100.00%	67Fe 395 MS β-: 100.00%	68Fe 188 MS β-: 100.00%	69Fe 162 MS β-: 100.00%	70Fe 63 MS β-: 100.00%	71Fe 35 MS β-: 100.00% β-n	72Fe 19 MS β-: 100.00% β-n	73Fe >633 NS β-: 100.00% β-n
25	64Mn 90 MS β-: 100.00% β-n: 2.00%	65Mn 91.9 MS β-: 100.00% β-n: 7.9%	66Mn 4 MS β-: 100.00% β-n: 4.00%	67Mn 47 MS β-: 100.00%	68Mn 28 MS β-: 100.00% β-n	69Mn 16 MS β-: 100.00%	70Mn >360 NS β-: 100.00% β-n	71Mn >637 NS β-: 100.00% β-n	
24	63Cr 129 MS β-: 100.00% β-n	64Cr 42.9 MS β-: 100.00%	65Cr 28 MS β-: 100.00%	66Cr 23 MS β-: 100.00% β-n	67Cr β-: 100.00% β-n	68Cr >60 NS β-: 100.00% β-n			
	39	40	41	42	43	44	45	46	N

Tooltips: On / Off

Zoom: 1, 2, 3, 4, 5, 6, 7

Uncertainty: NDS / Standard

Screen Size: Narrow / Wide

Nucleus [ ] go

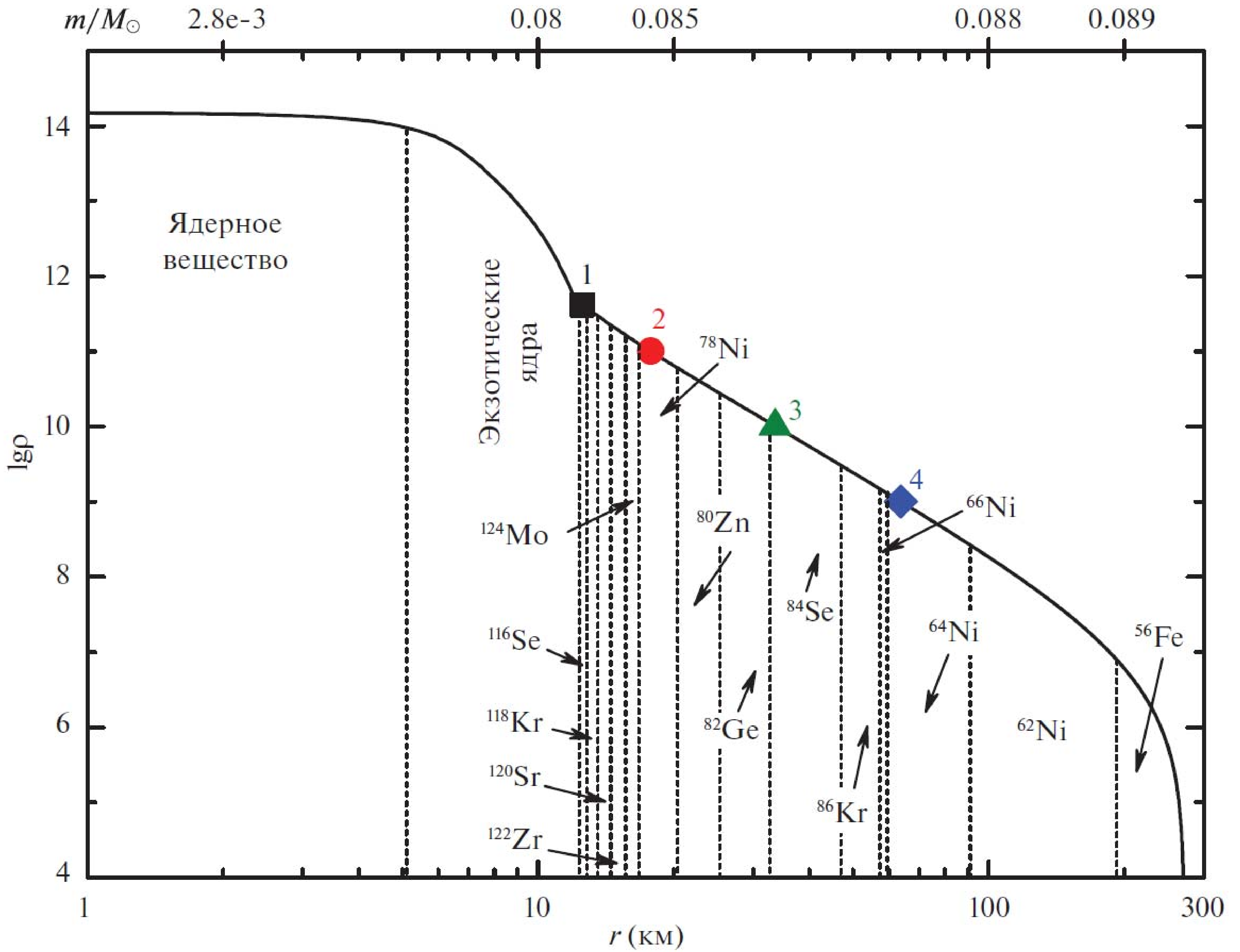
Seconds

> 10+15	10-01
10+10	10-02
10+07	10-03
10+05	10-04
10+04	10-05
10+03	10-06
10+02	10-07
10+01	10-15
10+00	< 10-15
unknown	

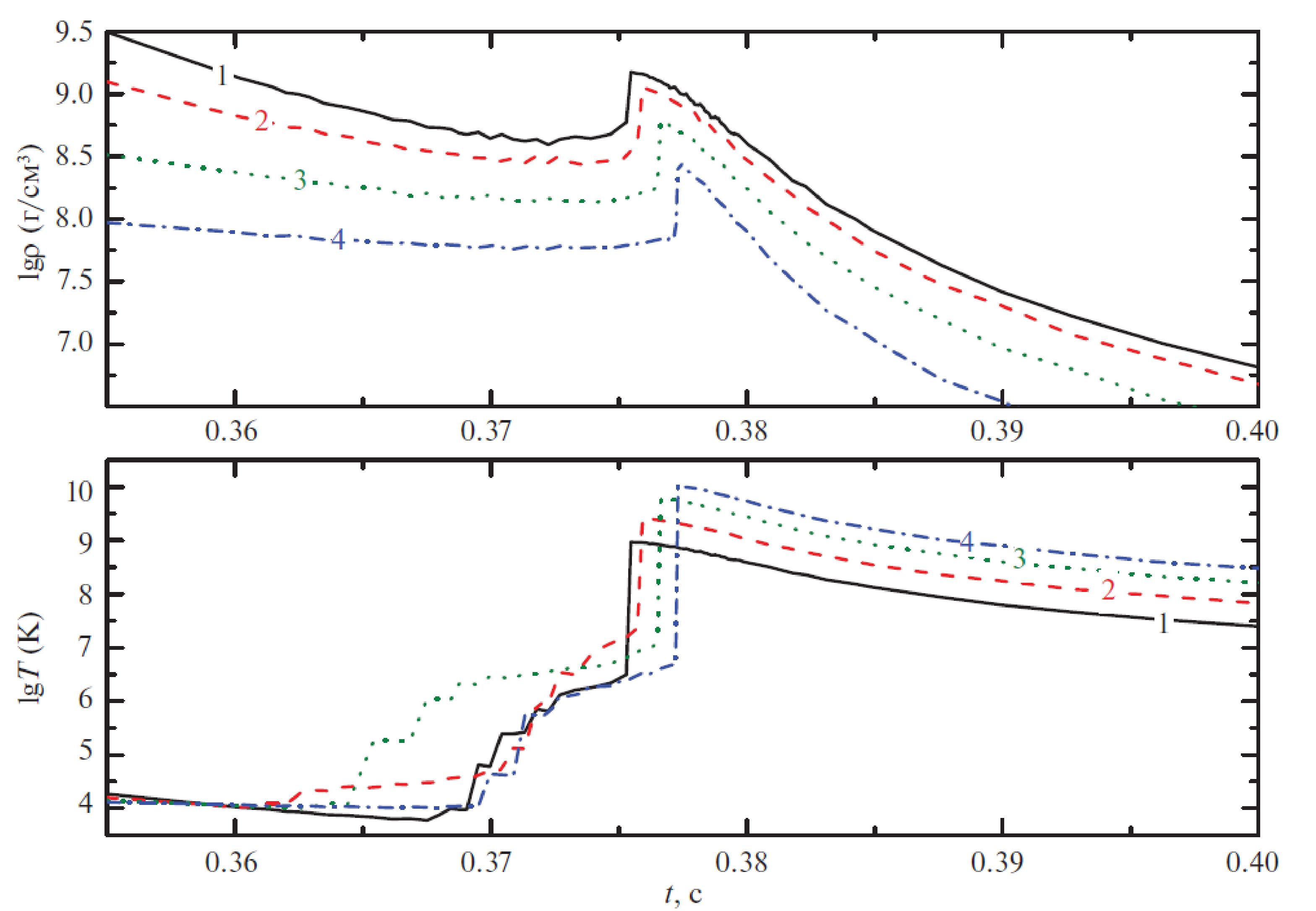
Search options:

Ground and isomeric state information for $^{69}_{26}Fe$

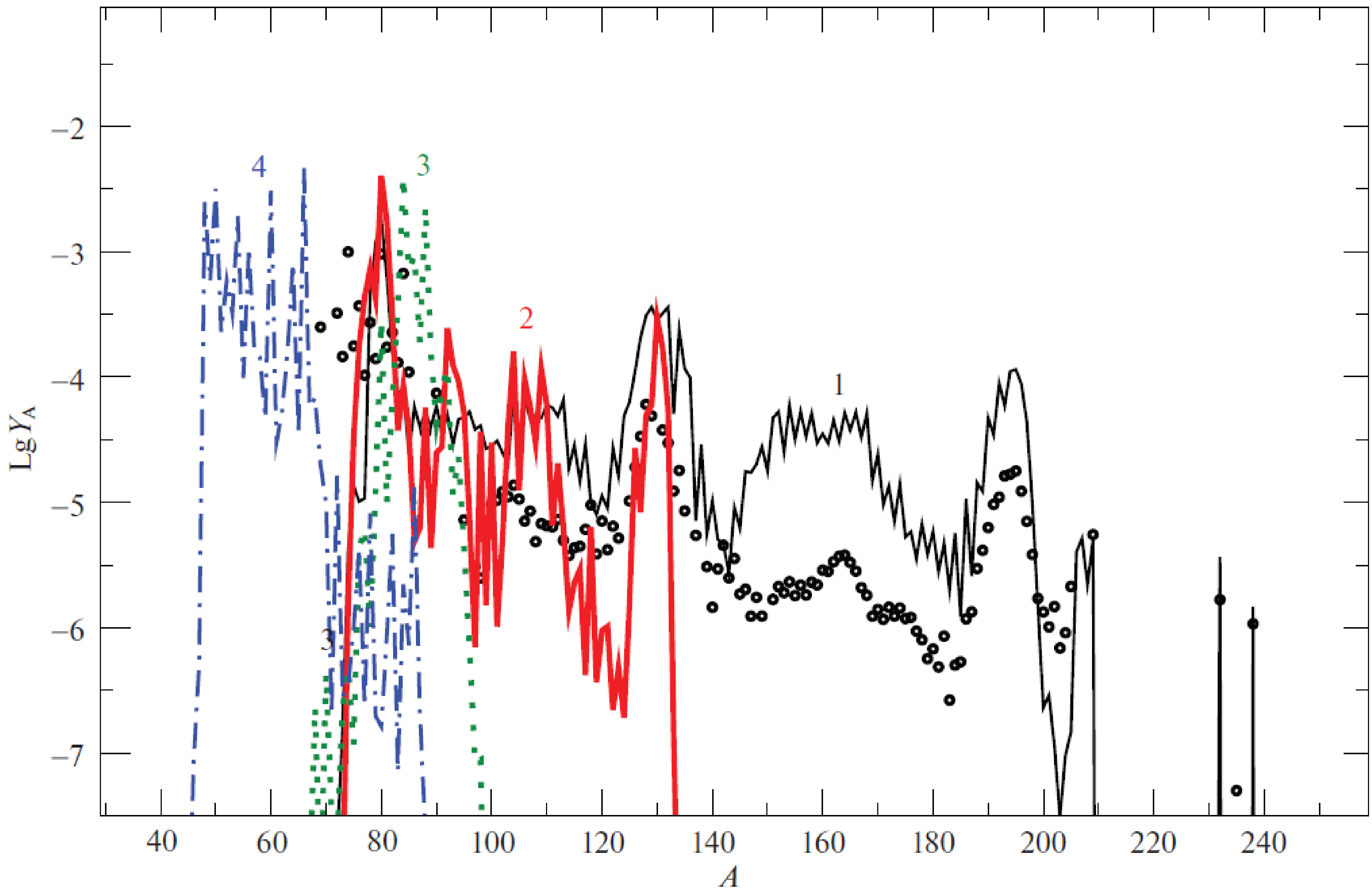
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	1/2-	-39.03	162 ms 7	β^- : 100.00 %



m/M⊙
2.8e-3
0.08
0.085
0.088
0.089
lgρ
14
12
10
8
6
4
1
10
100
300
r (км)
Ядерное
вещество
Экзотические
ядра
1
2
3
4
78Ni
124Mo
80Zn
66Ni
84Se
64Ni
116Se
56Fe
118Kr
82Ge
62Ni
120Sr
86Kr
122Zr



Вариант, №	Исходный состав	T_9^{max}	ρ_0^{max}, г/см^3	r_0, км	Y_e
1	^{116}Se	0.93	4×10^{11}	12.5	0.25
2	^{78}Ni	2.5	10^{11}	17.8	0.335
3	^{84}Se	6.3	10^{10}	33.8	0.405
4	^{64}Ni	10	10^{9}	63.5	0.44



−2
−3
−4
−5
−6
−7
Lg Y_A
40
60
80
100
120
140
160
180
200
220
240
A
1
2
3
4

Phantom documentation

The Phantom SPH code, by Daniel Price.

This code is designed to be an ultra-sleek, ultra-low-memory, code for high resolution SPH simulations.

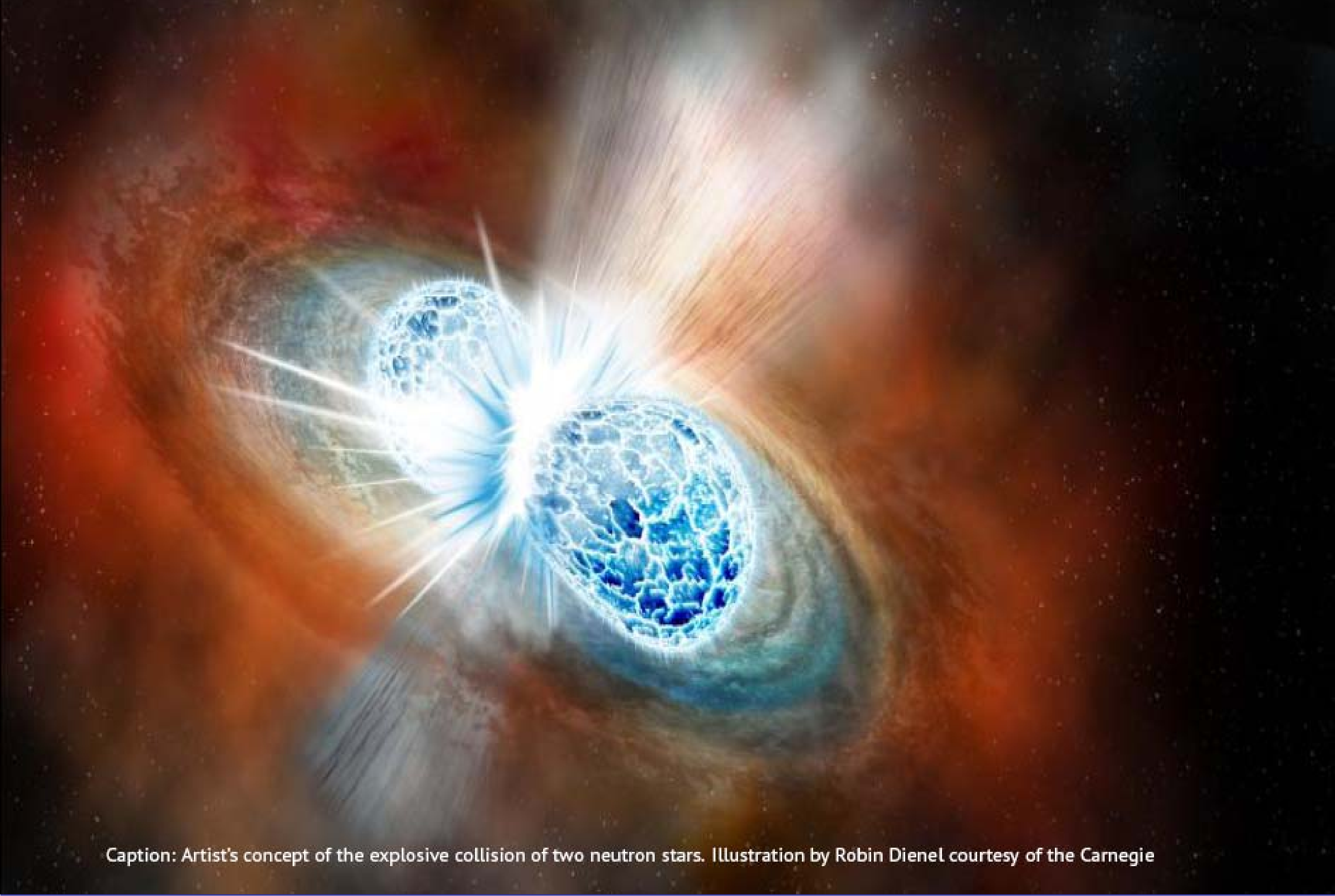
- Project homepage: http://phantomsph.bitbucket.io/
- Code repository: https://bitbucket.org/danielprice/phantom/
- Documentation: https://phantomsph.readthedocs.org/

Contents

Licence

Phantom is available under the GPLv3 licence.

Спасибо за внимание!



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