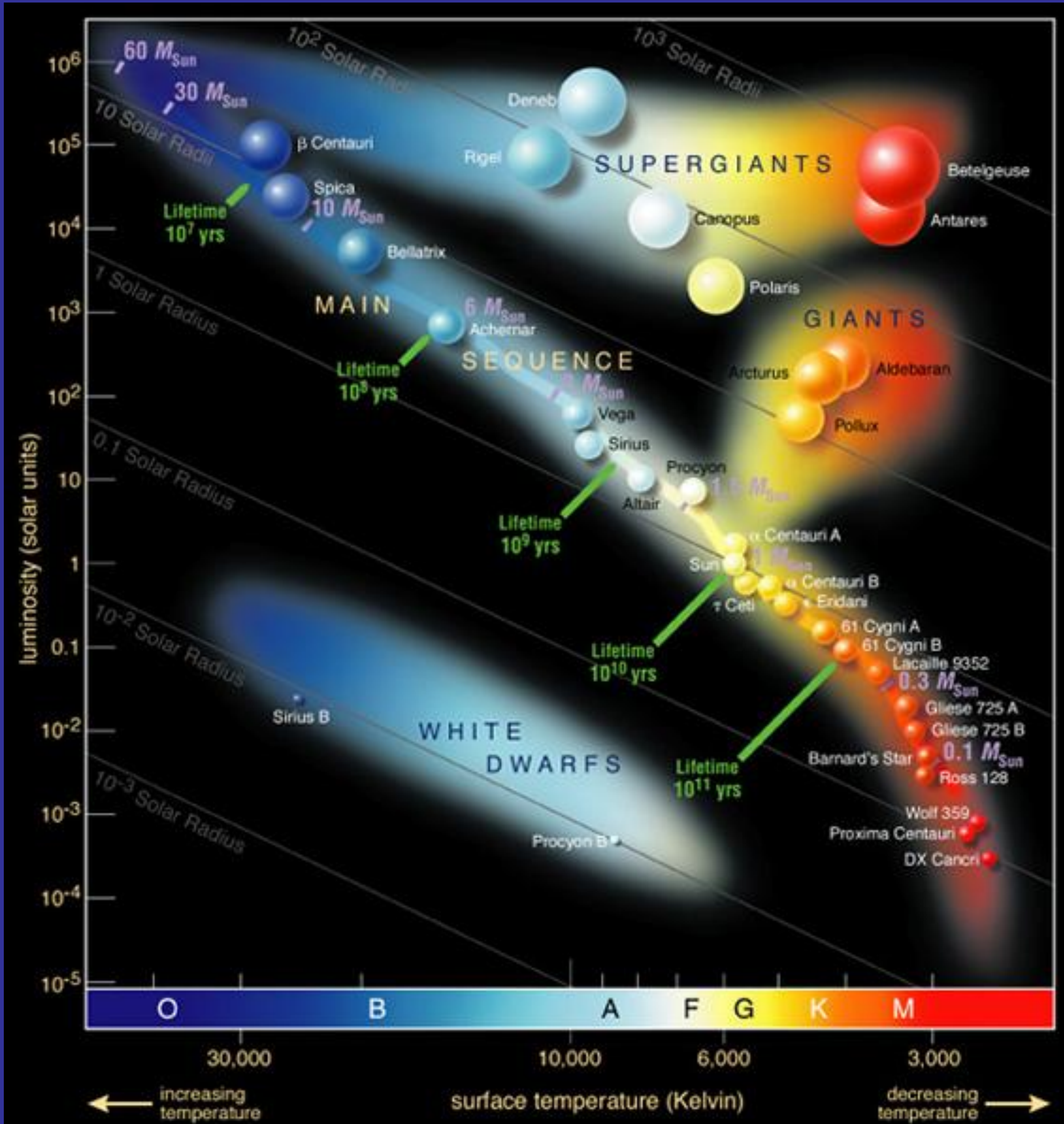
Neutrinos from supernova: status and prospects

A.V. Yudin, ITEP

International Session-Conference of the Section of Nuclear Physics of the Physical Sciences Department of the Russian Academy of Sciences "Physics of fundamental interactions" dedicated to 50th anniversary of Baksan Neutrino Observatory June 6-8, 2017



Hertzsprung-Russell diagram

$$L = 4\pi R_s^2 \times \sigma_{SB} T_{eff}^4$$

$M > 85M_\odot$

$O \rightarrow Of \rightarrow LBV \rightarrow WN \rightarrow WC \rightarrow SN$

$85M_\odot > M > 40M_\odot$

$O \rightarrow Of \rightarrow WN \rightarrow WC \rightarrow SN$

$40M_\odot > M > 25M_\odot$

$O \rightarrow RSG \rightarrow WN \rightarrow WC \rightarrow SN$

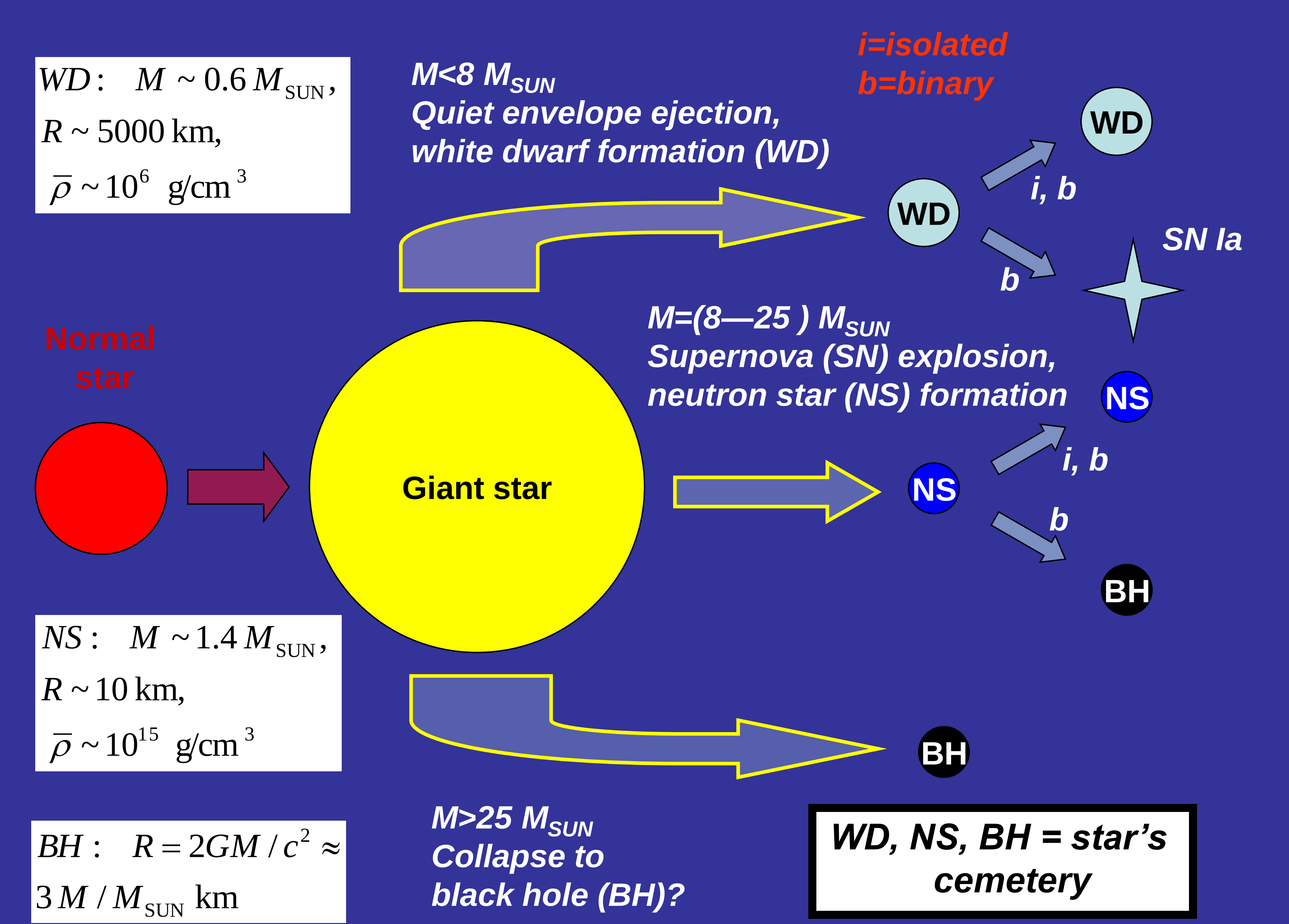
$25M_\odot > M > 20M_\odot$

$O \rightarrow RSG \rightarrow WN \rightarrow SN$

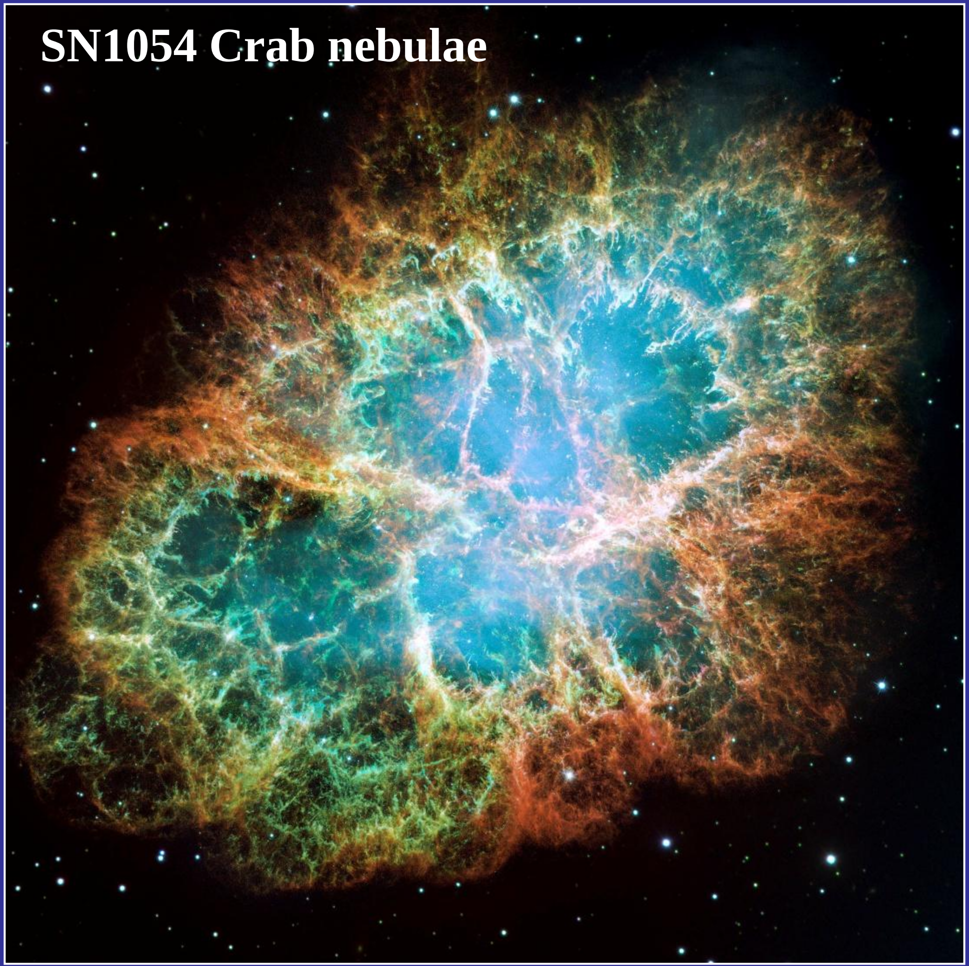
$20M_\odot > M > 10M_\odot$

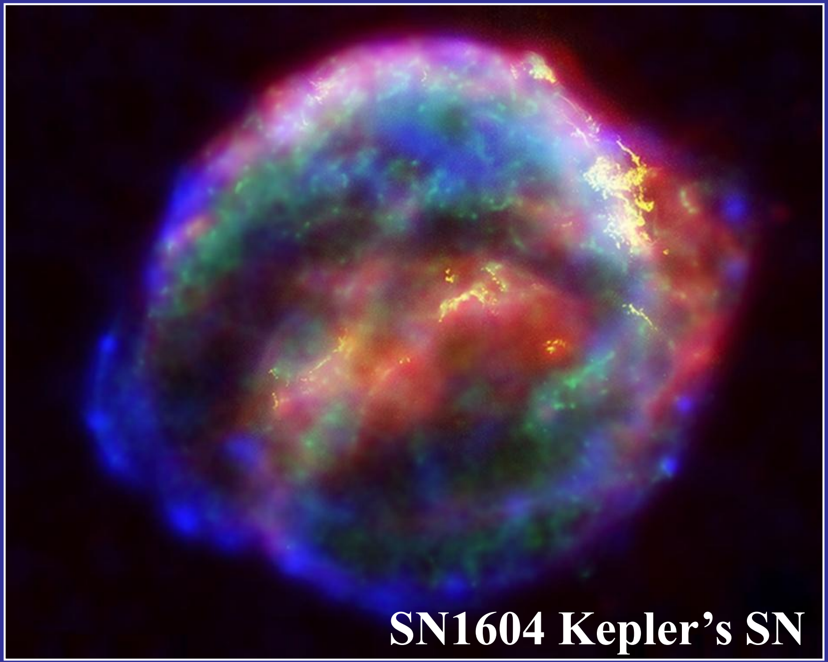
$O \rightarrow RSG \rightarrow BSG \rightarrow SN$

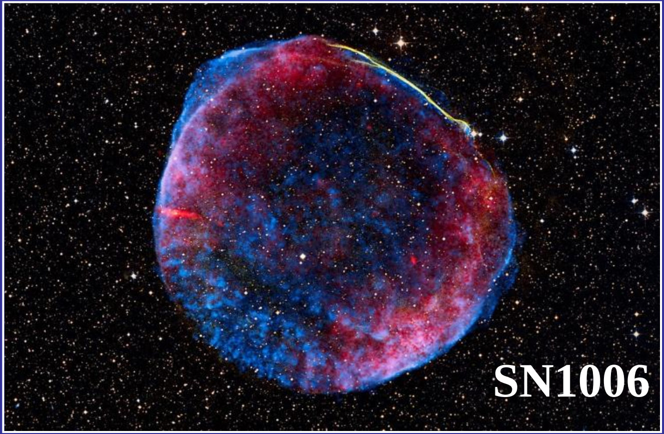
Image: Wiki, credits ESO https://www.eso.org/public/images/eso0728c/

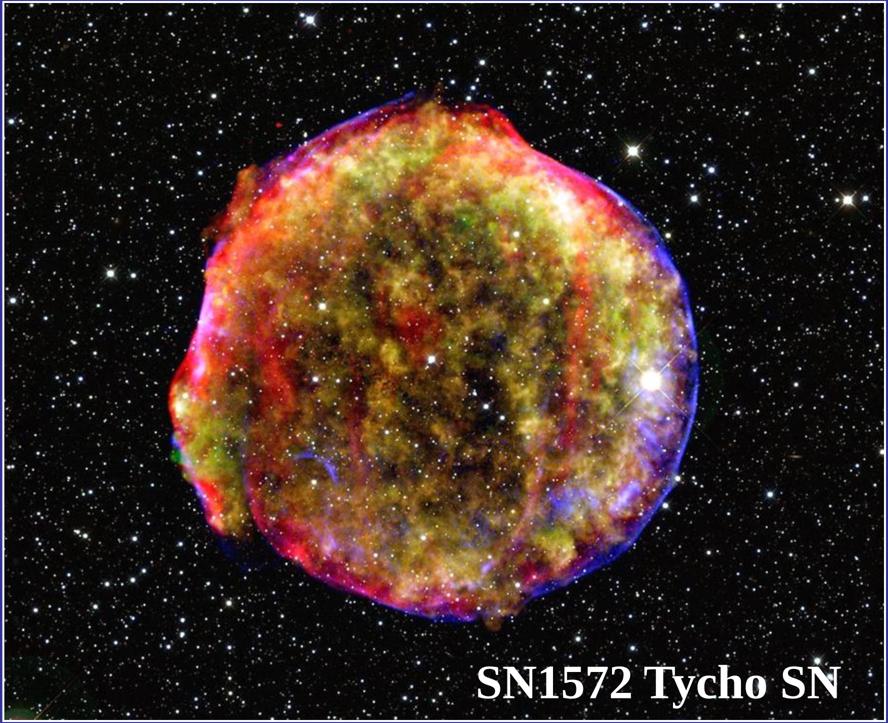


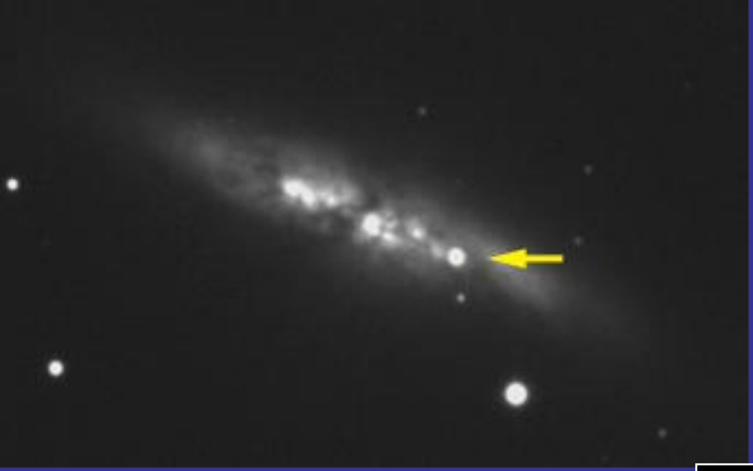
Adapted from D.G. Yakovlev, "Nuclear burning in superdense matter", Pushino (2010)


SN1054 Crab nebulae


SN1604 Kepler’s SN


SN1006

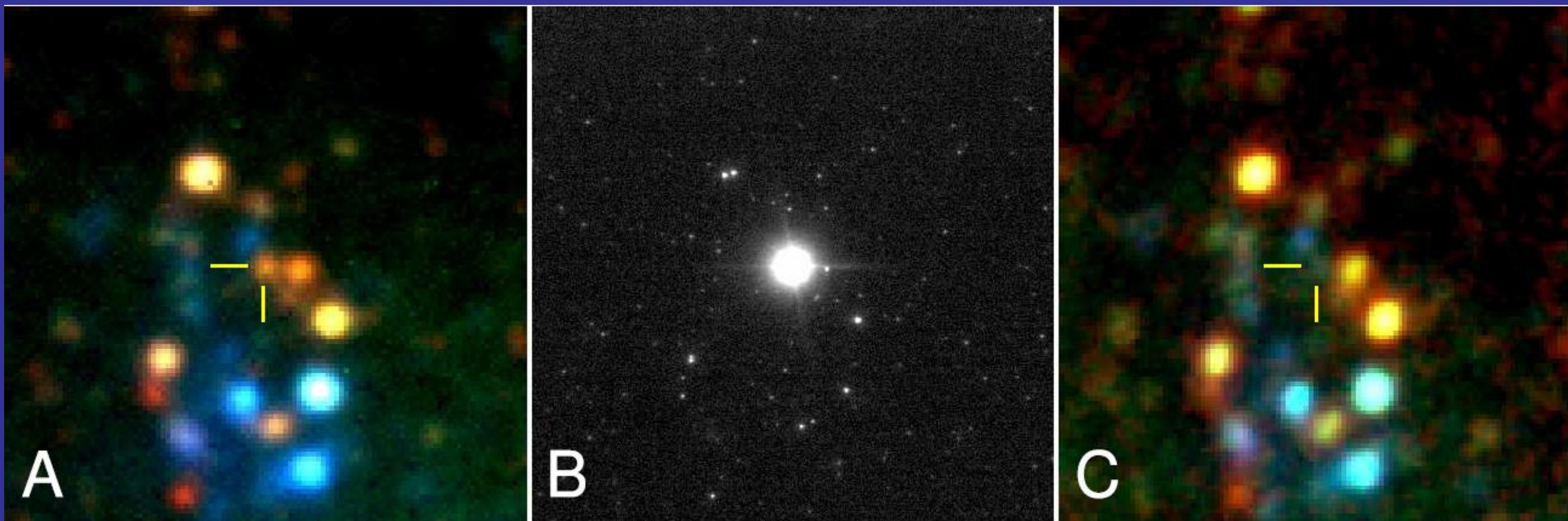

SN1572 Tycho SN



Supernova 1994D in
Galaxy NGC 4526

The Disappearance of the Red Supergiant Progenitor of Supernova 2008bk

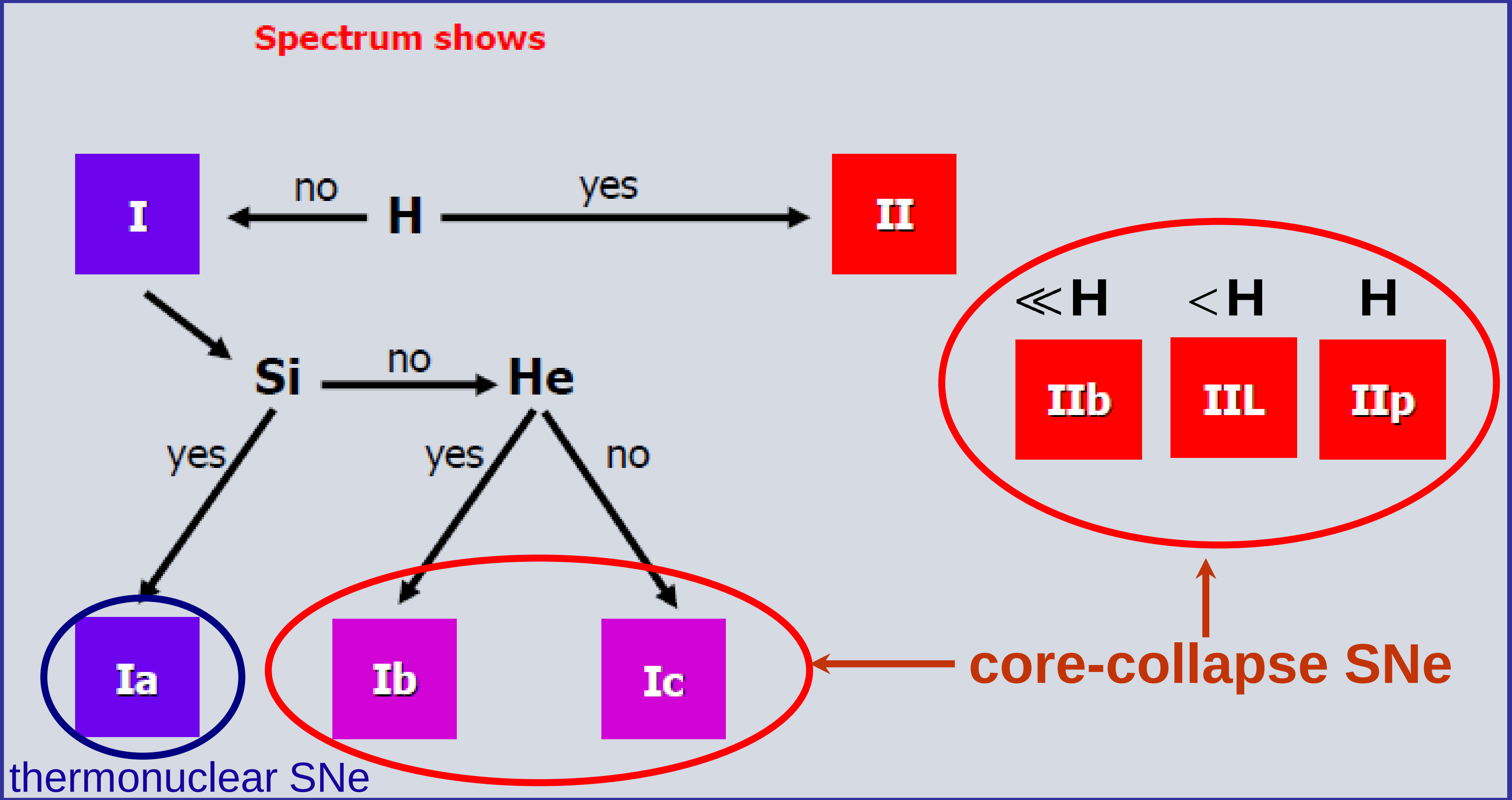
Seppo Mattila,[1,2*] Stephen Smartt,[3] Justyn Maund,[4,5] Stefano Benetti,[6]
Mattias Ergon[1]



Type IIP SN 2008bk

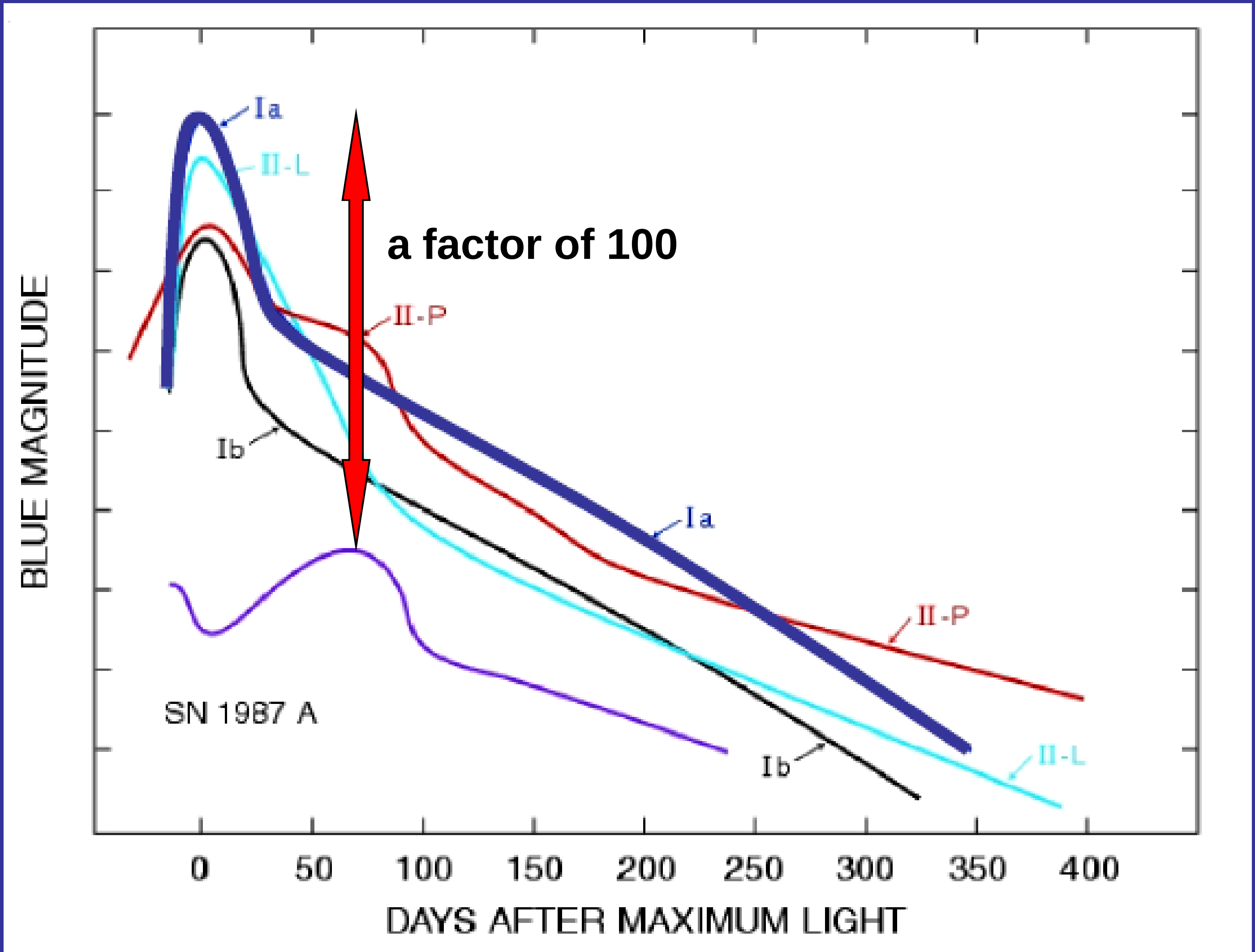
Properties of supernovae and their classification

Overwhelming majority of information on SNe comes from observations of their spectra:
fluxes, colors, doppler shift and width of spectral lines

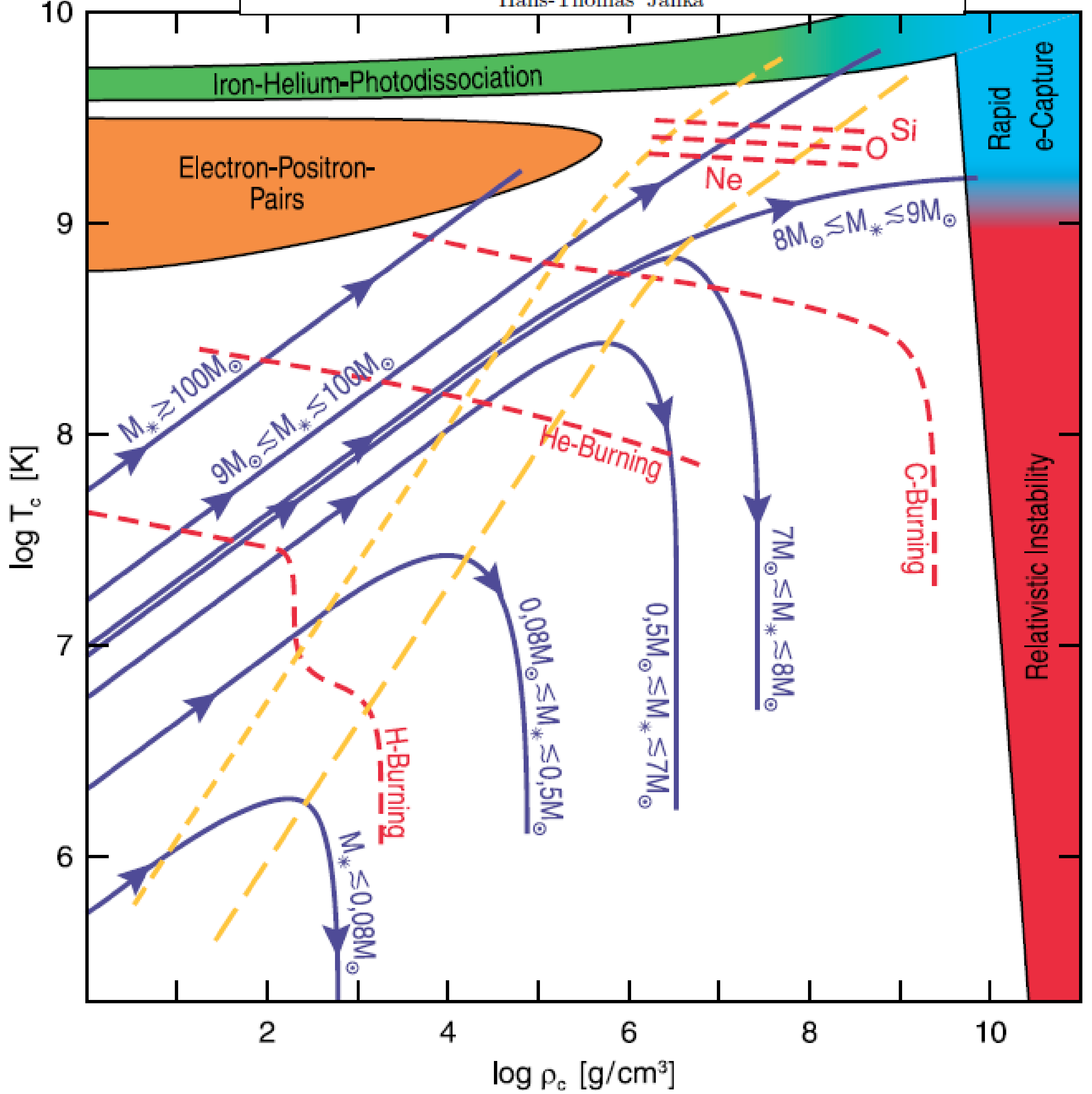


Adapted from: F. Röpke (http://theor.jinr.ru/~ntaa/07/files/program.html)

Light curves of supernovae

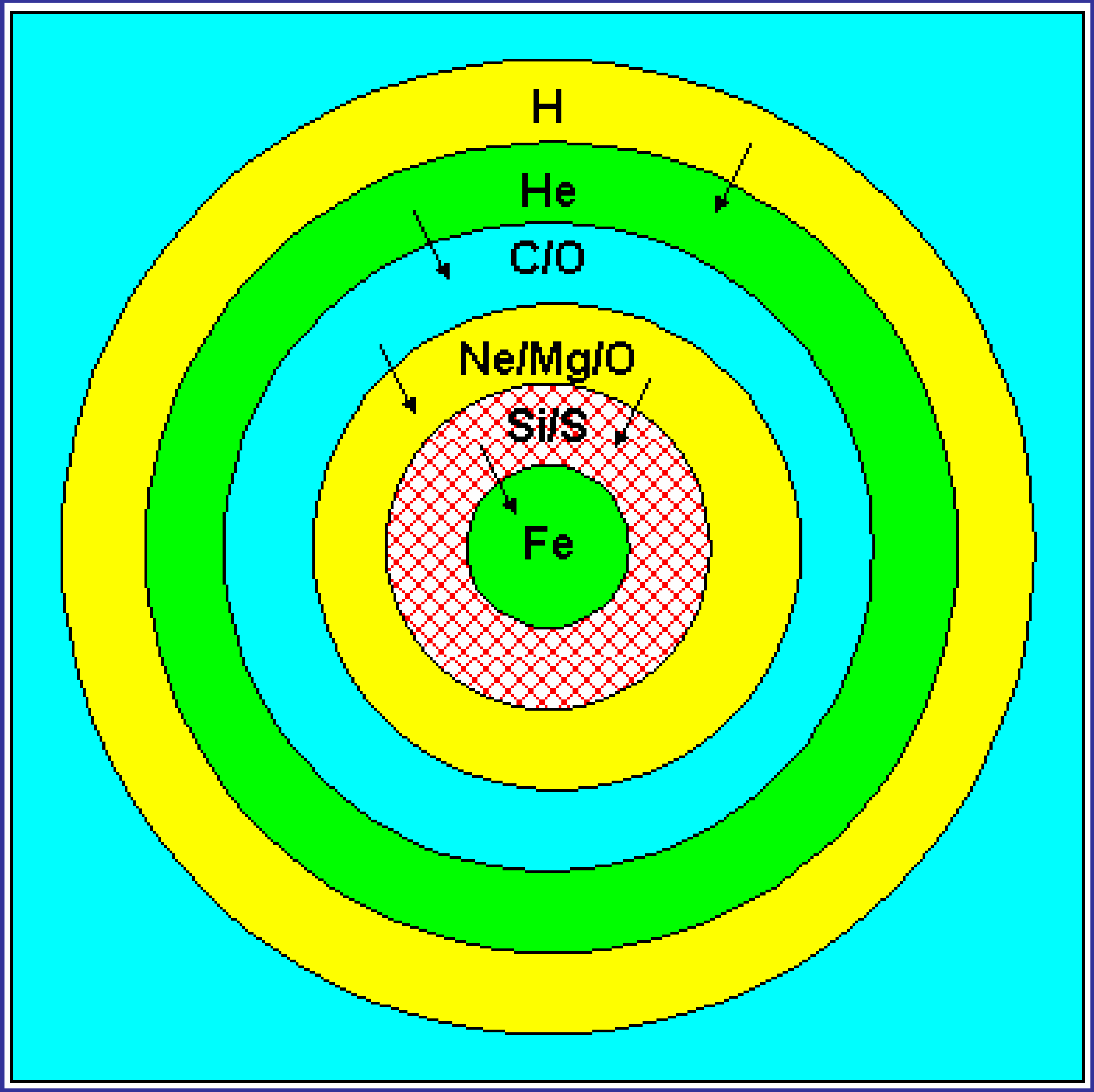


Adapted from: F. Röpke (http://theor.jinr.ru/~ntaa/07/files/program.html)
A. Filippenko (Annu. Rev. Astron. Astrophys. 1997, **35**, 309)


Iron-Helium-Photodissociation
Electron-Positron-Pairs
Rapid e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
M* ≳100M⊙
9M⊙≲M*≲100M⊙
8M⊙≲M*≲9M⊙
7M⊙≲M*≲8M⊙
0,5M⊙≲M*≲7M⊙
0,08M⊙≲M*≲0,5M⊙
M*≲0,08M⊙
log Tc [K]
log ρc [g/cm³]

Massive star before collapse

Onion-like structure of the star



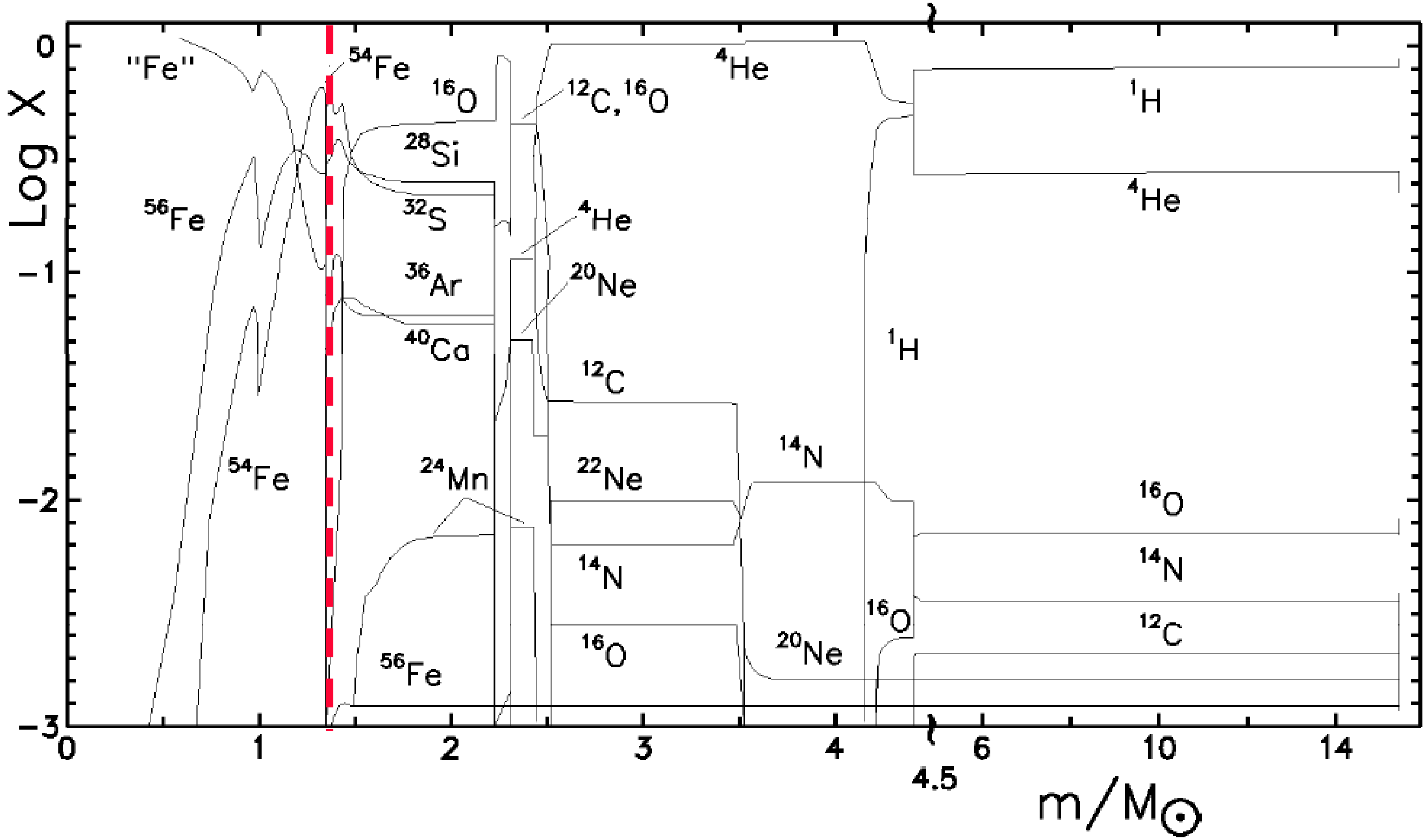
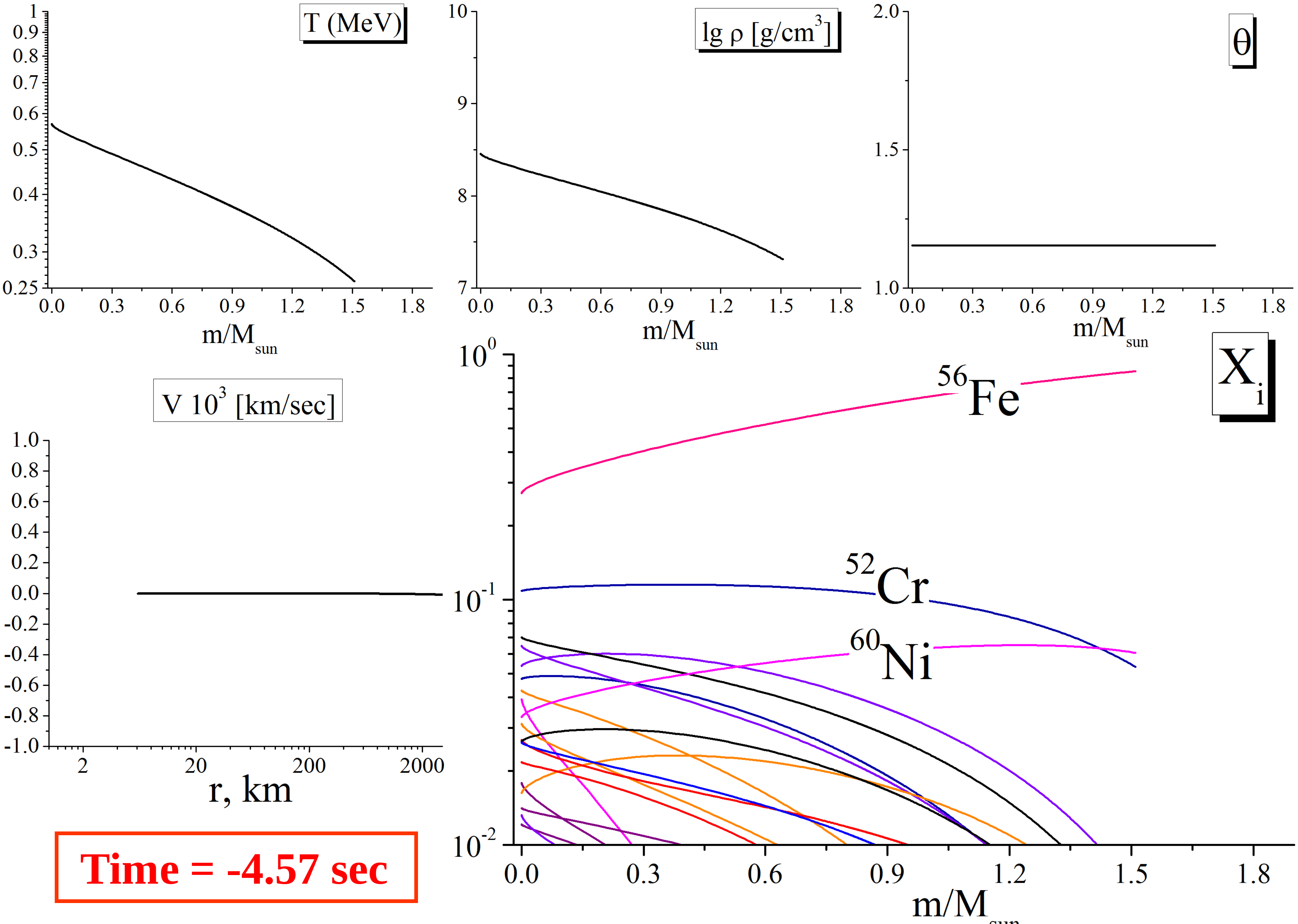


Figure 5.6: Composition versus current mass m for a 15 $M_{\odot}$ presupernova star just before its iron core collapse shown as the mass fractions X of various nuclear species. The curve labeled by "Fe" includes all nuclides of mass numbers $48 \lesssim A \lesssim 65$ having a neutron excess greater than ^{56}Fe (such as ^{48}Ti, ^{51}V, ^{52}Cr, ^{57,58}Fe, ^{59}Co, ^{62}Ni, ^{63}Cu, and several other species). Note a scale break at 4.5 $M_{\odot}$. Adapted from [32]

From Woosley & Weaver An.Rev. Astron. Astrophys. v. 24, p. 205 (1986)



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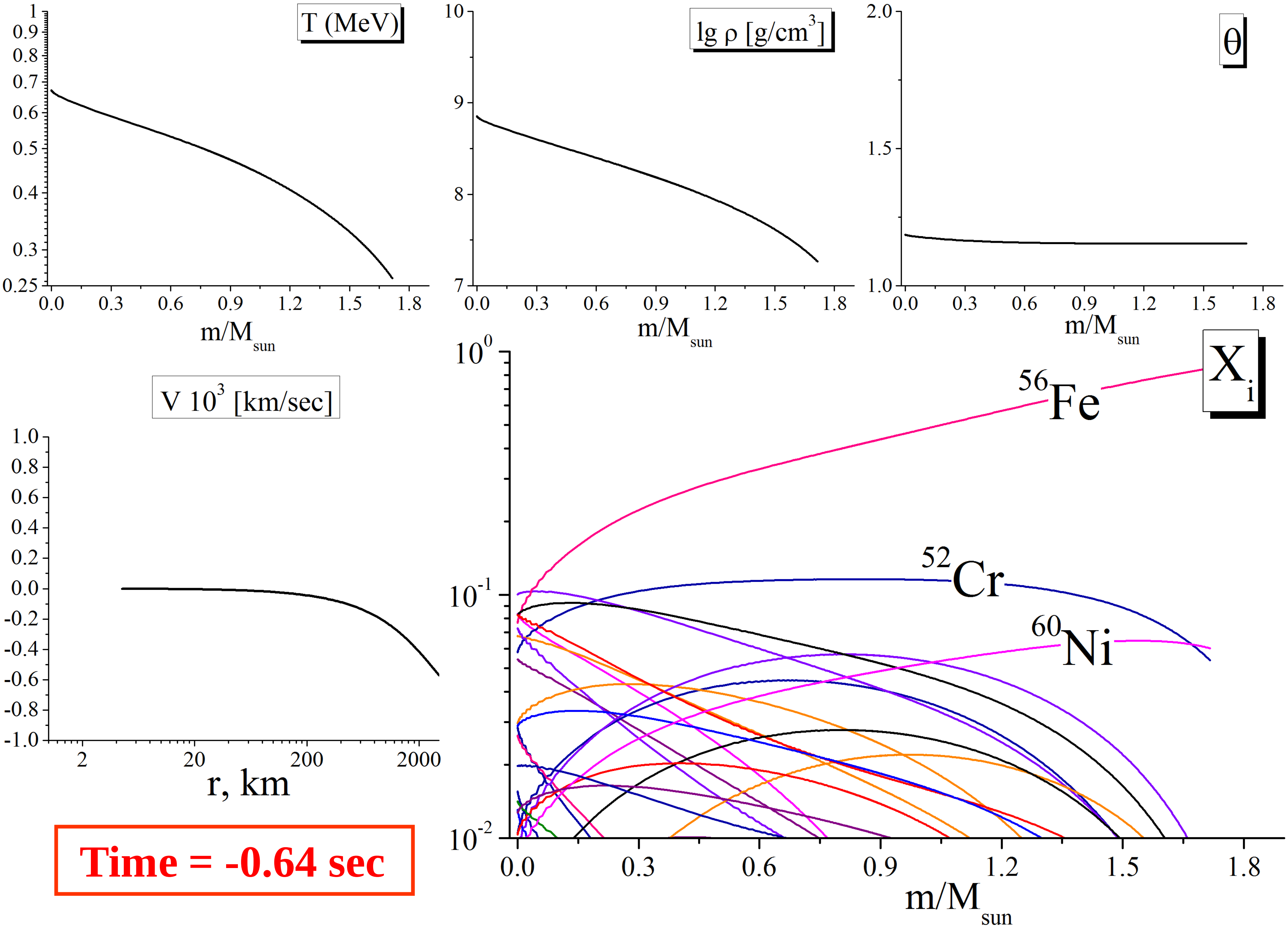
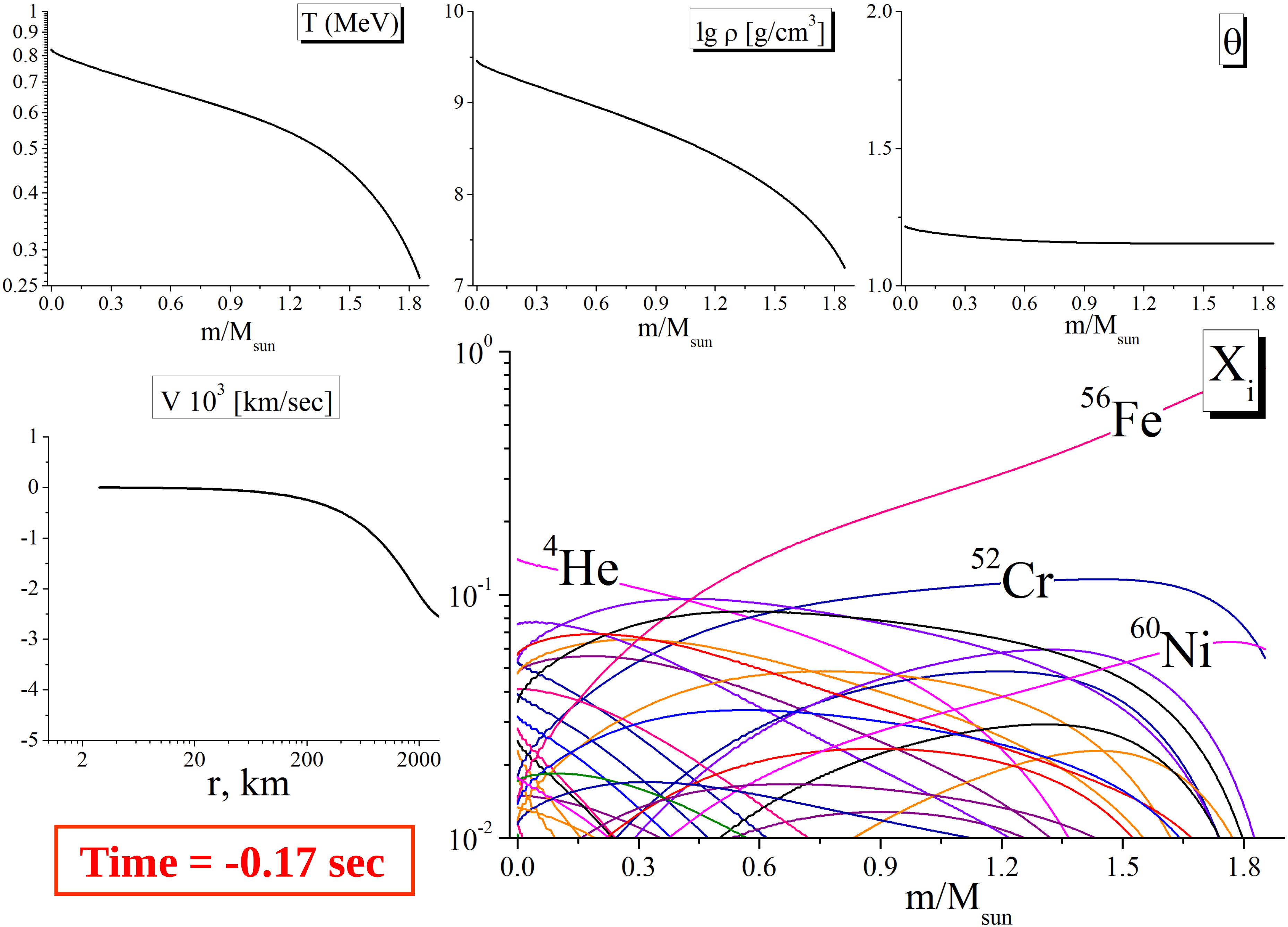
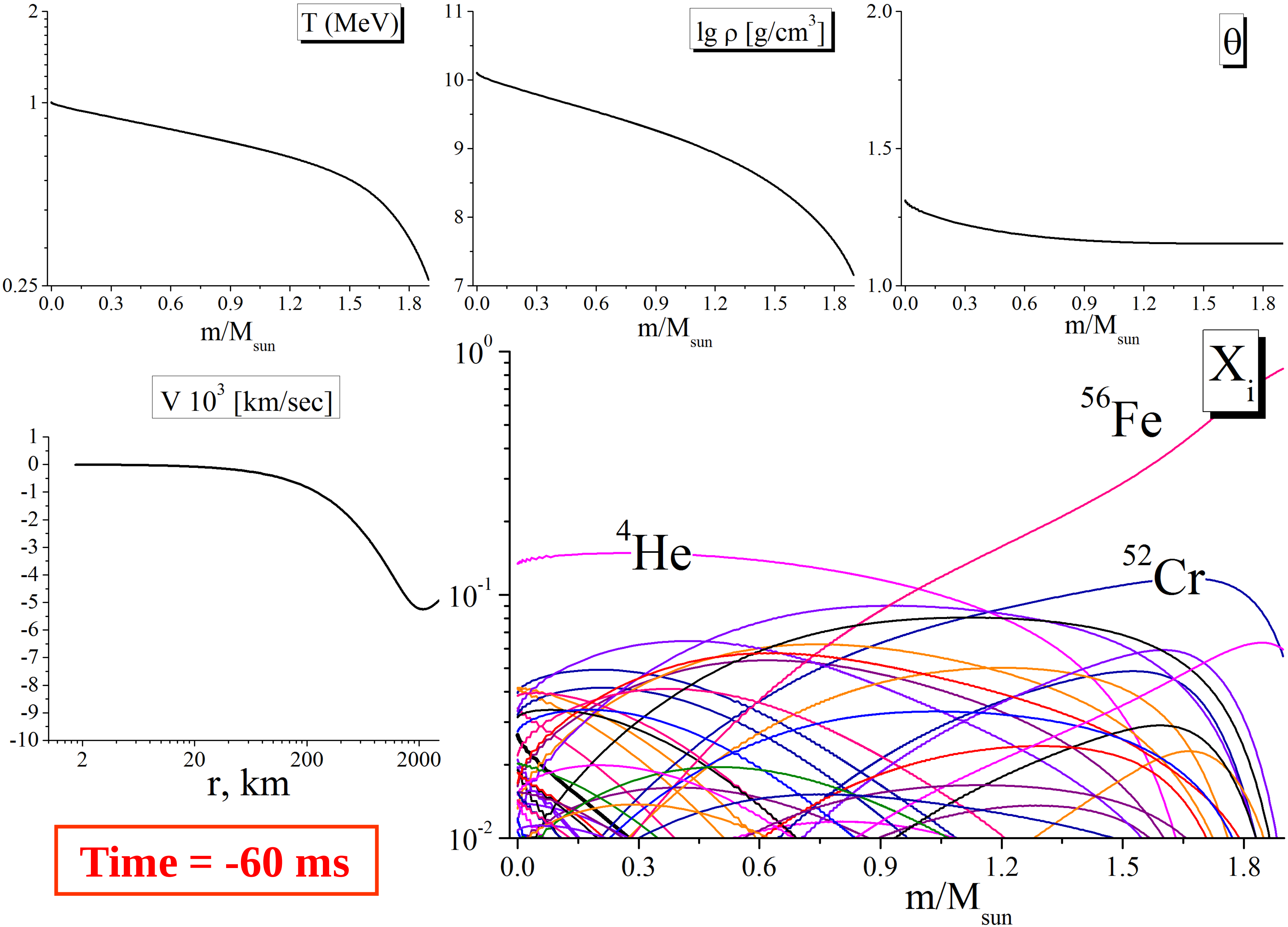
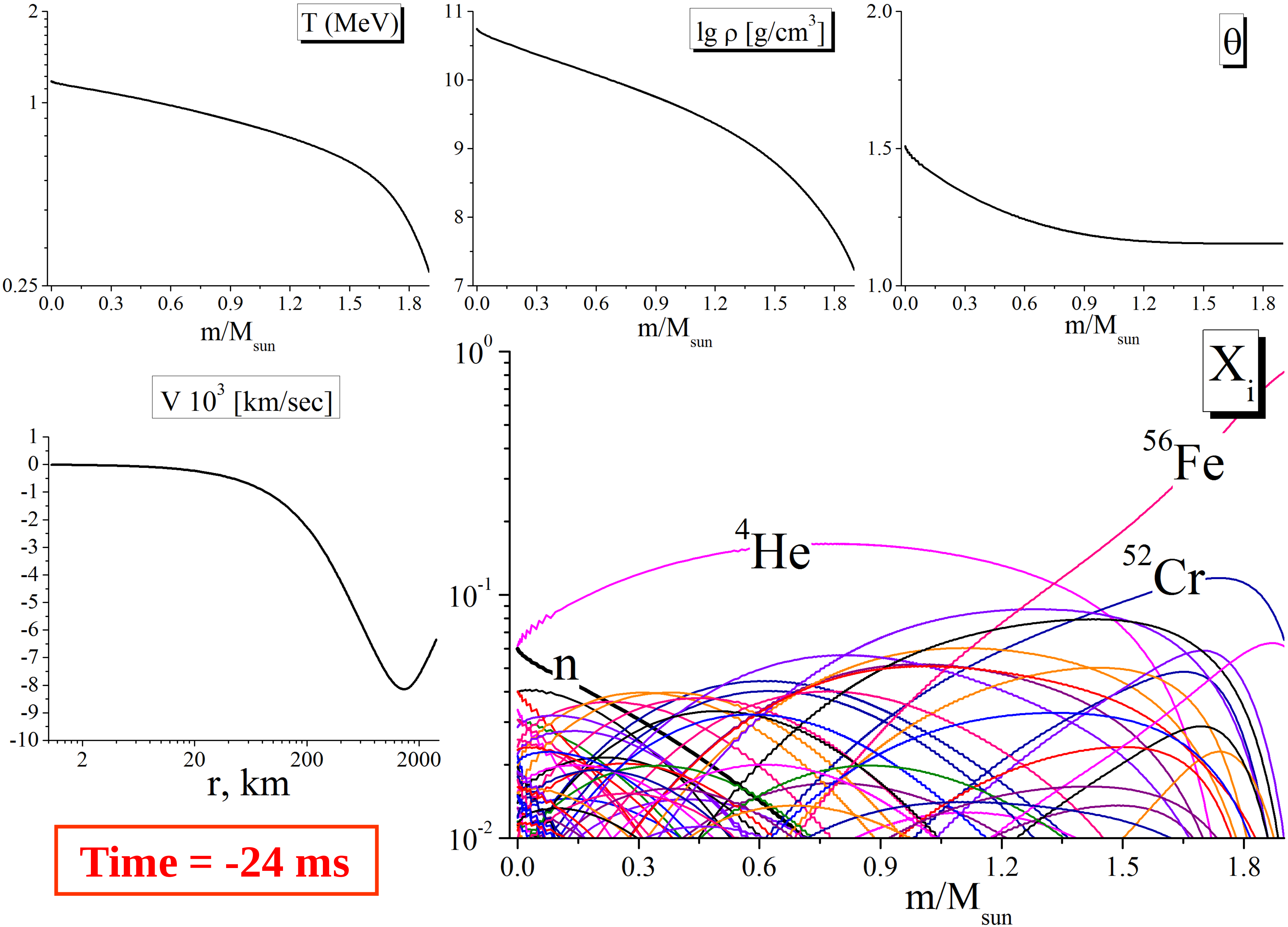


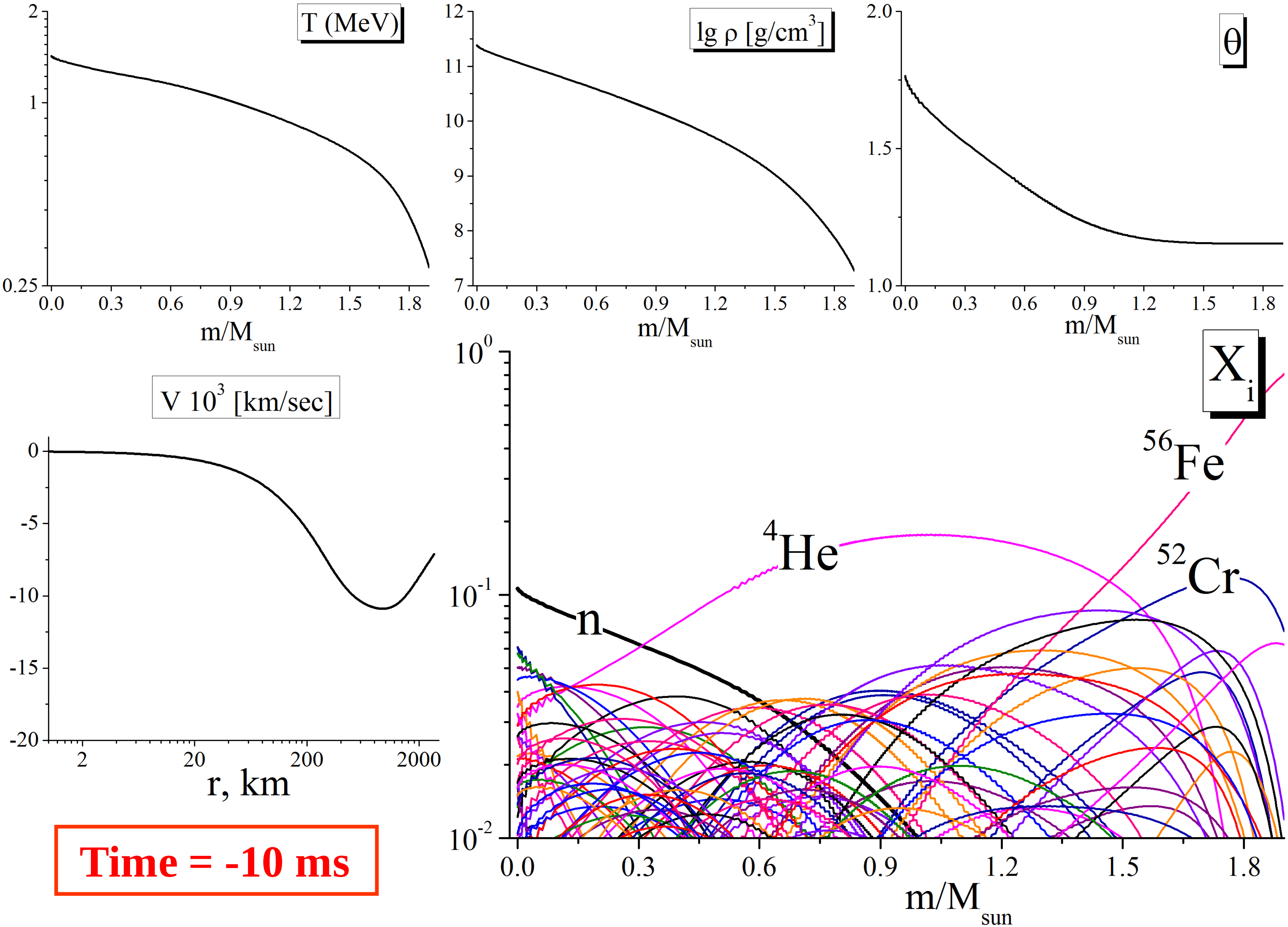
T (MeV)
m/M_sun
lg ρ [g/cm^3]
m/M_sun
θ
m/M_sun
V 10^3 [km/sec]
r, km
X_i
56Fe
52Cr
60Ni
m/M_sun
Time = -0.64 sec


T (MeV)
m/M_sun
lg ρ [g/cm³]
m/M_sun
θ
m/M_sun
V 10³ [km/sec]
r, km
X_i
⁵⁶Fe
⁴He
⁵²Cr
⁶⁰Ni
m/M_sun

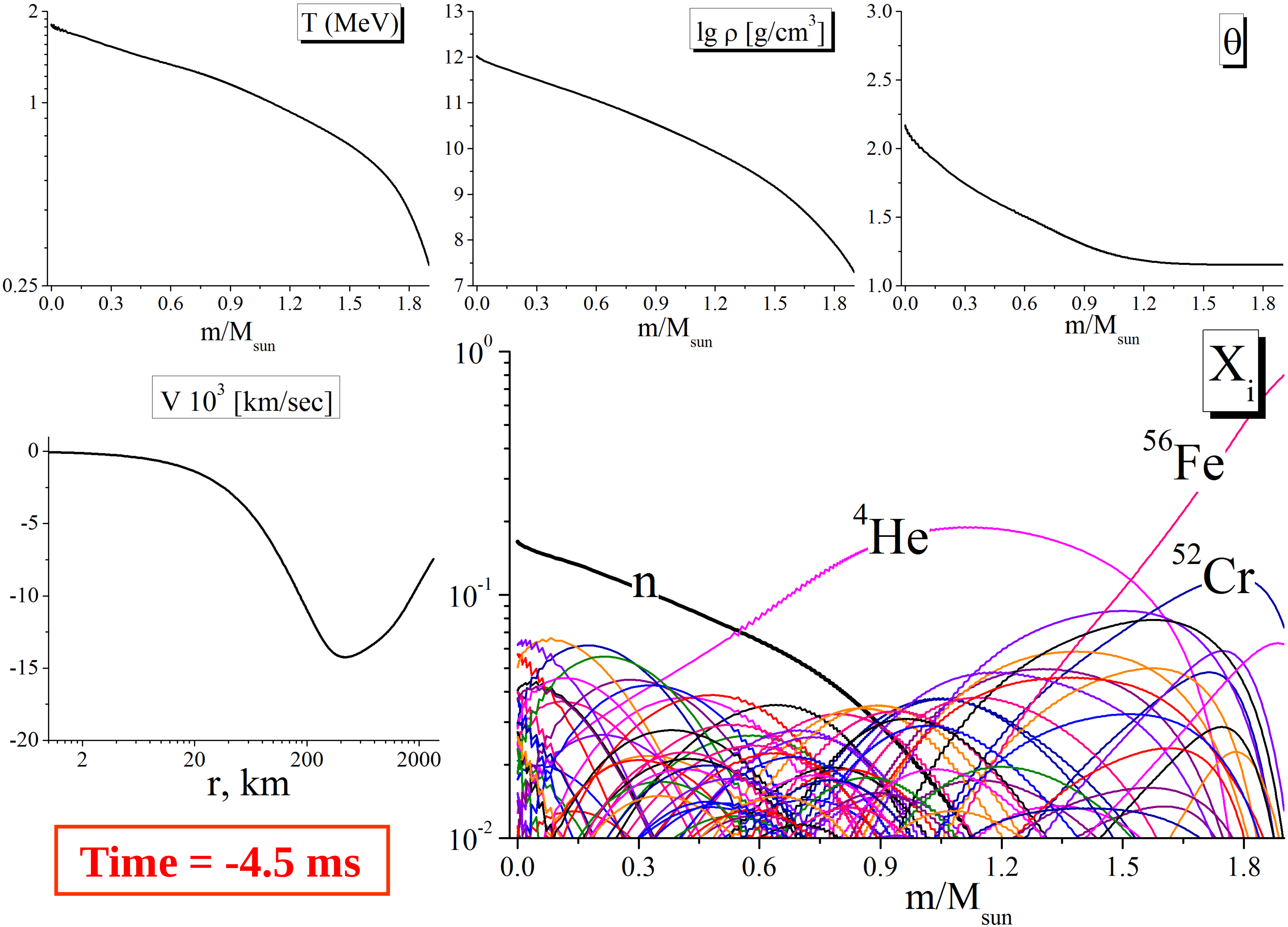
Time = -0.17 sec


T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10³ [km/sec]
r, km
Xi
56Fe
4He
52Cr
Time = -60 ms

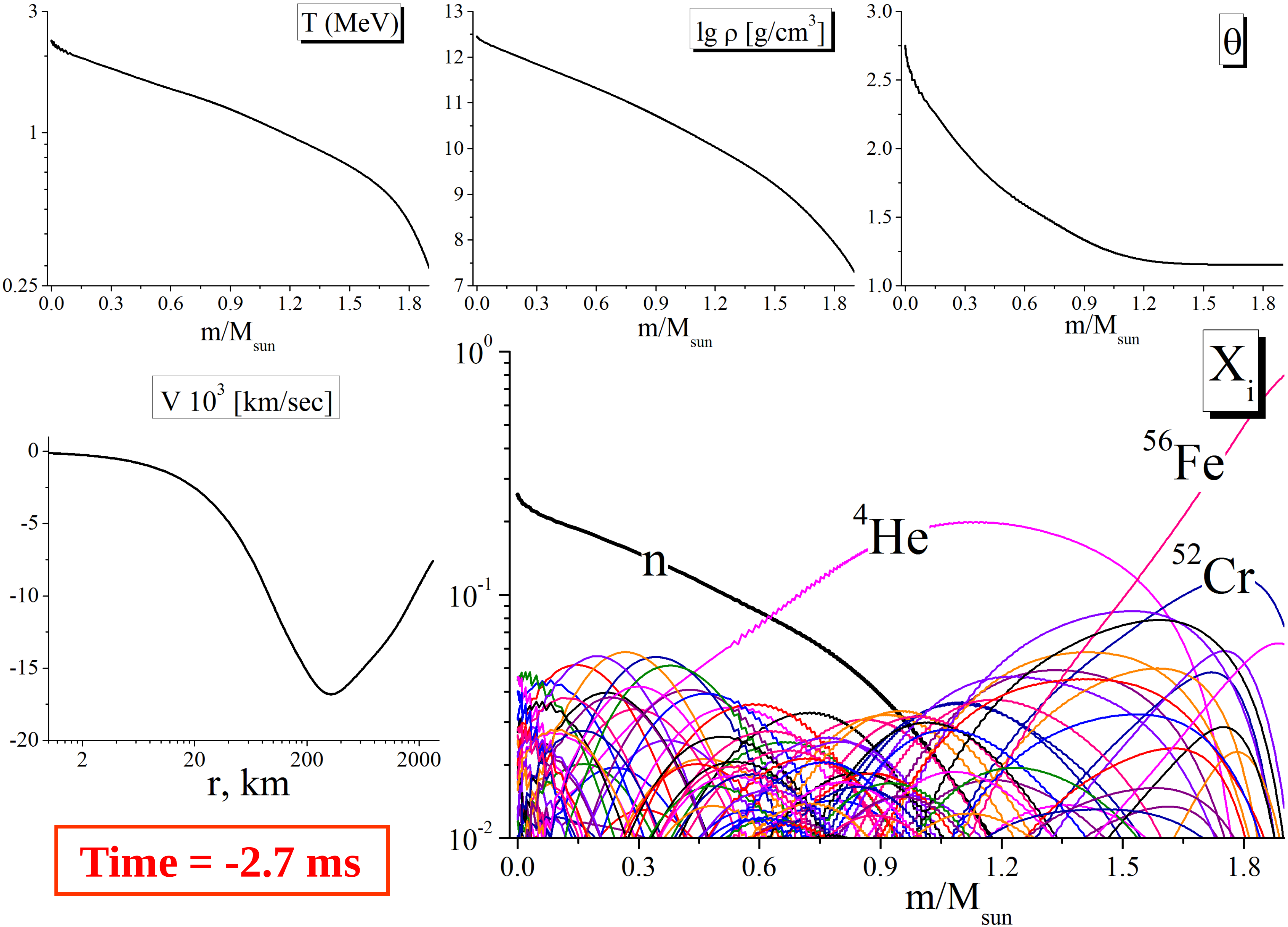

T (MeV)
2
1
0.25
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun
lg ρ [g/cm3]
11
10
9
8
7
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun
θ
2.0
1.5
1.0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun
V 10³ [km/sec]
1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9 -10
2 20 200 2000
r, km
Xi
56Fe
4He
52Cr
n
10⁰
10⁻¹
10⁻²
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun
Time = -24 ms



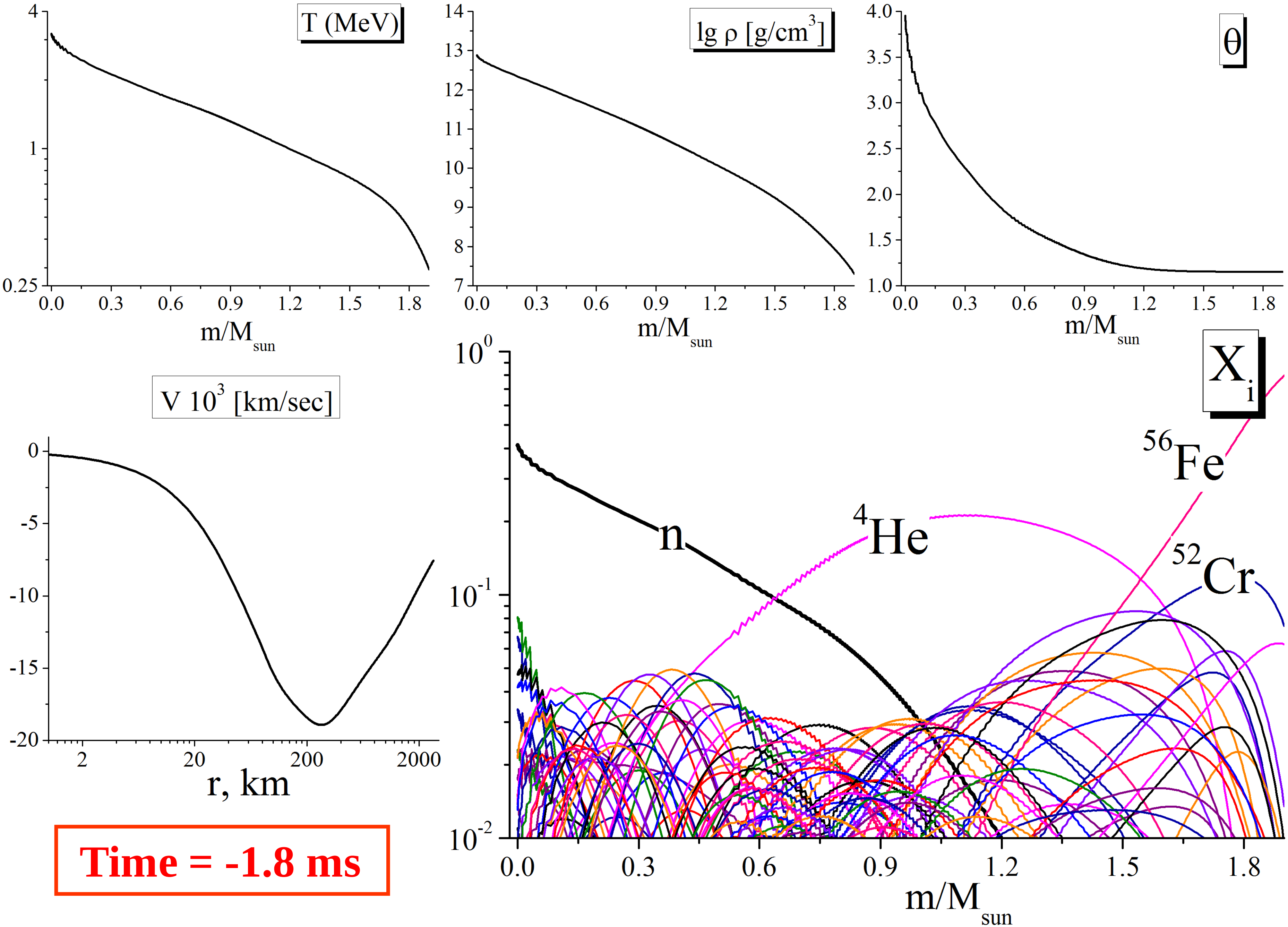
Time = -10 ms

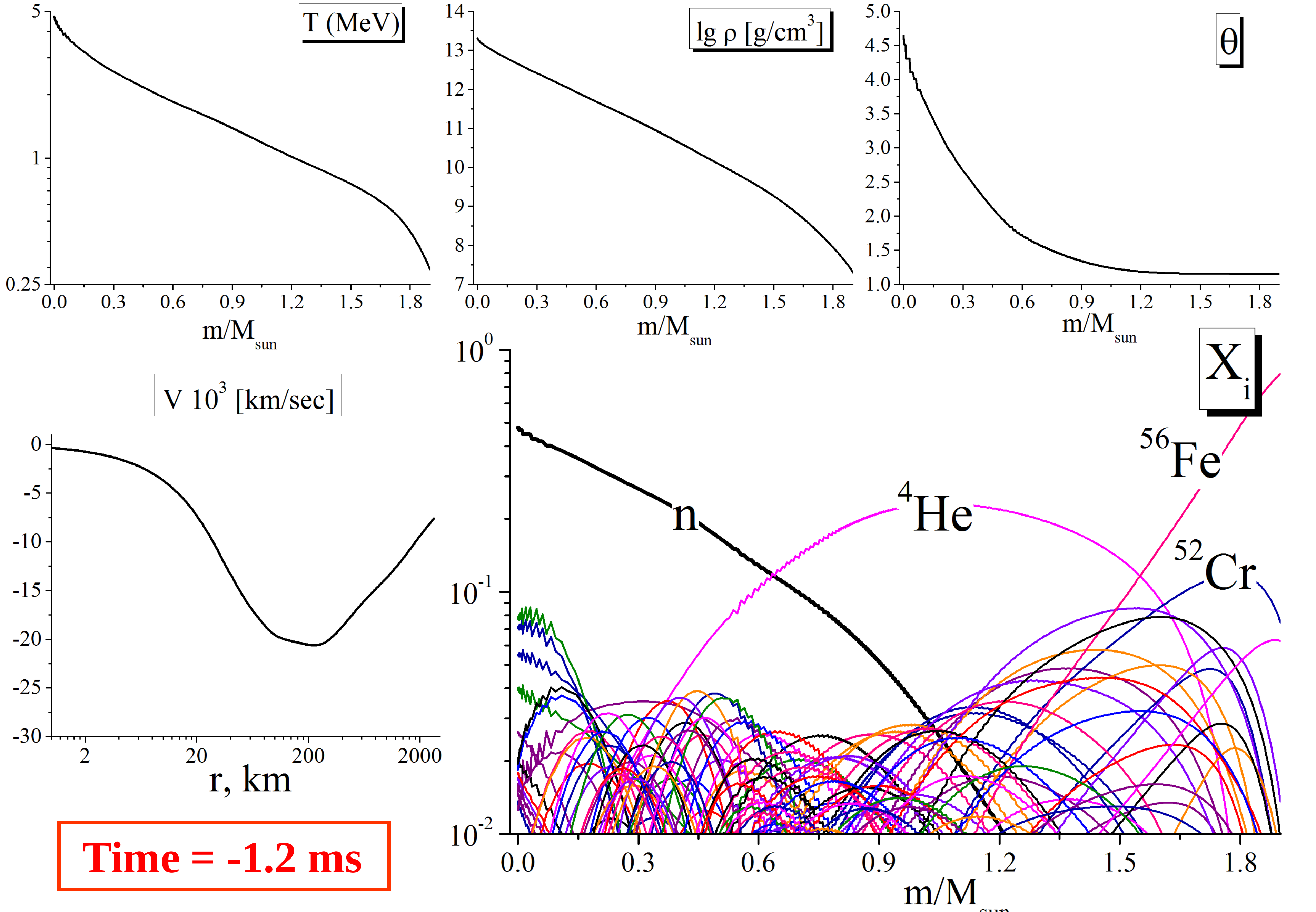


T (MeV)
m/M_sun
lg ρ [g/cm^3]
θ
V 10^3 [km/sec]
r, km
X_i
56Fe
4He
52Cr
n
Time = -4.5 ms

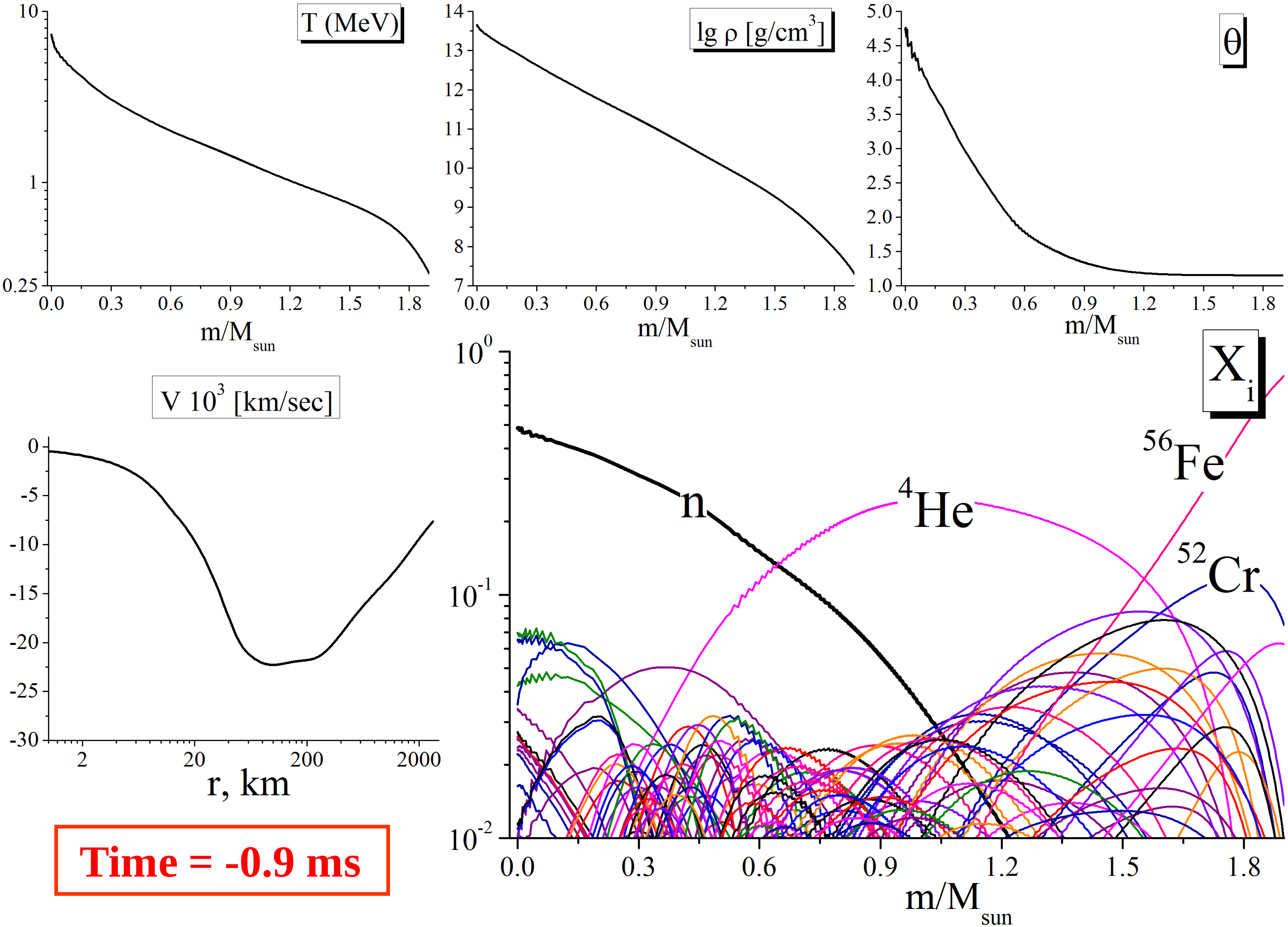


T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
n
4He
56Fe
52Cr
Time = -2.7 ms

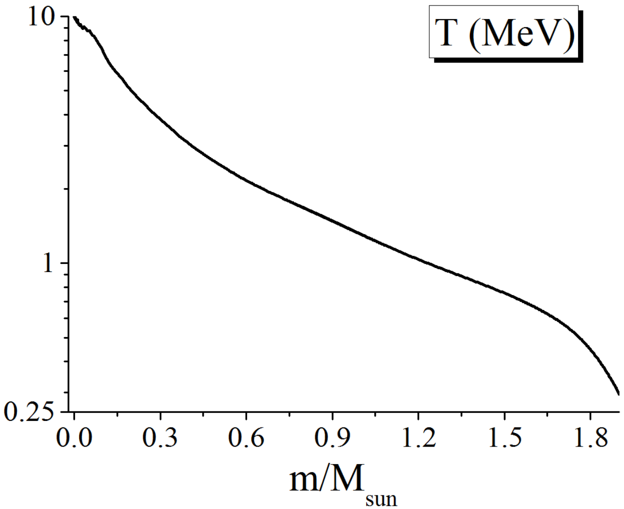

T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
n
4He
56Fe
52Cr
Time = -1.8 ms

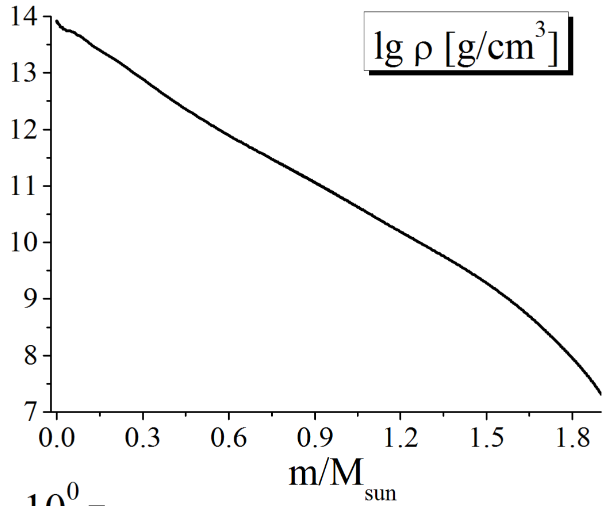


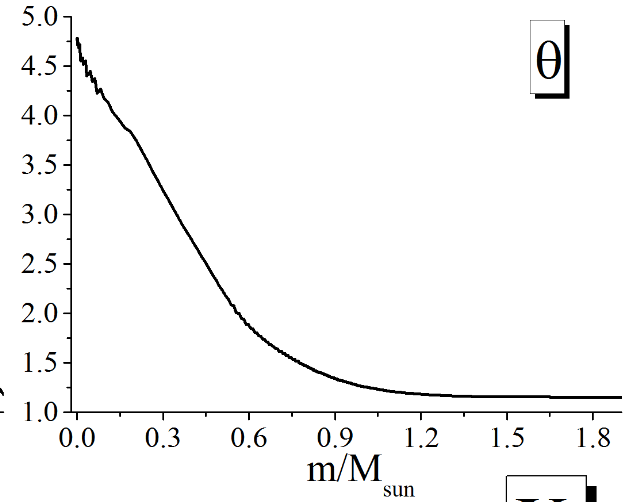
T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
n
4He
56Fe
52Cr
Time = -1.2 ms

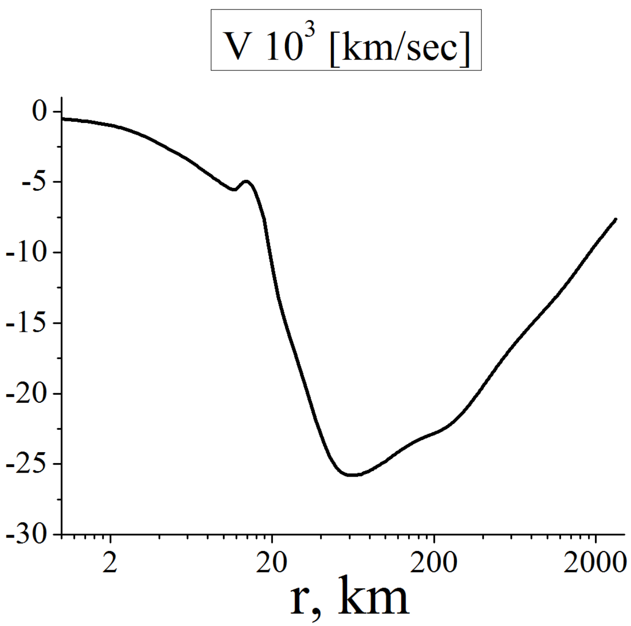

T (MeV)
m/M_sun
lg ρ [g/cm^3]
m/M_sun
θ
m/M_sun
V 10^3 [km/sec]
r, km
X_i
n
^4He
^56Fe
^52Cr
m/M_sun

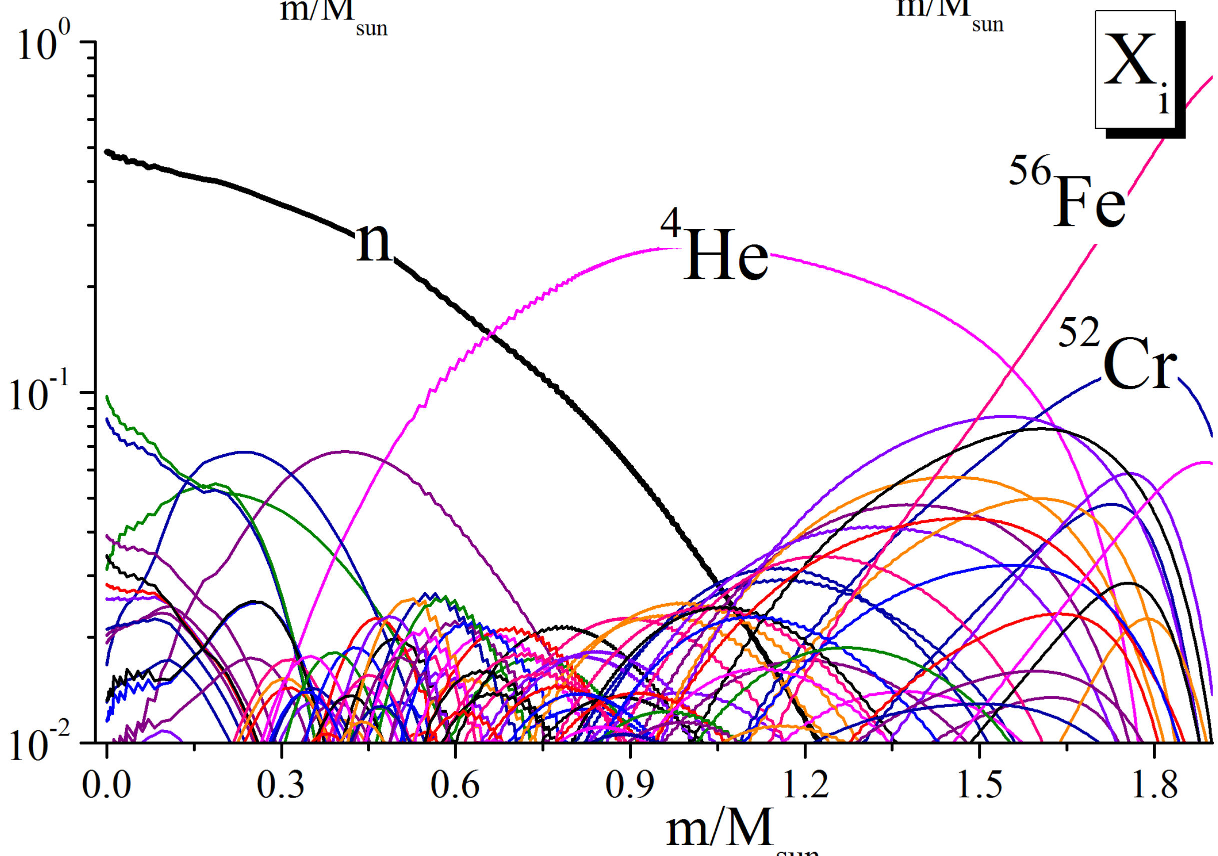
Time = -0.9 ms


T (MeV)
10
1
0.25
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun

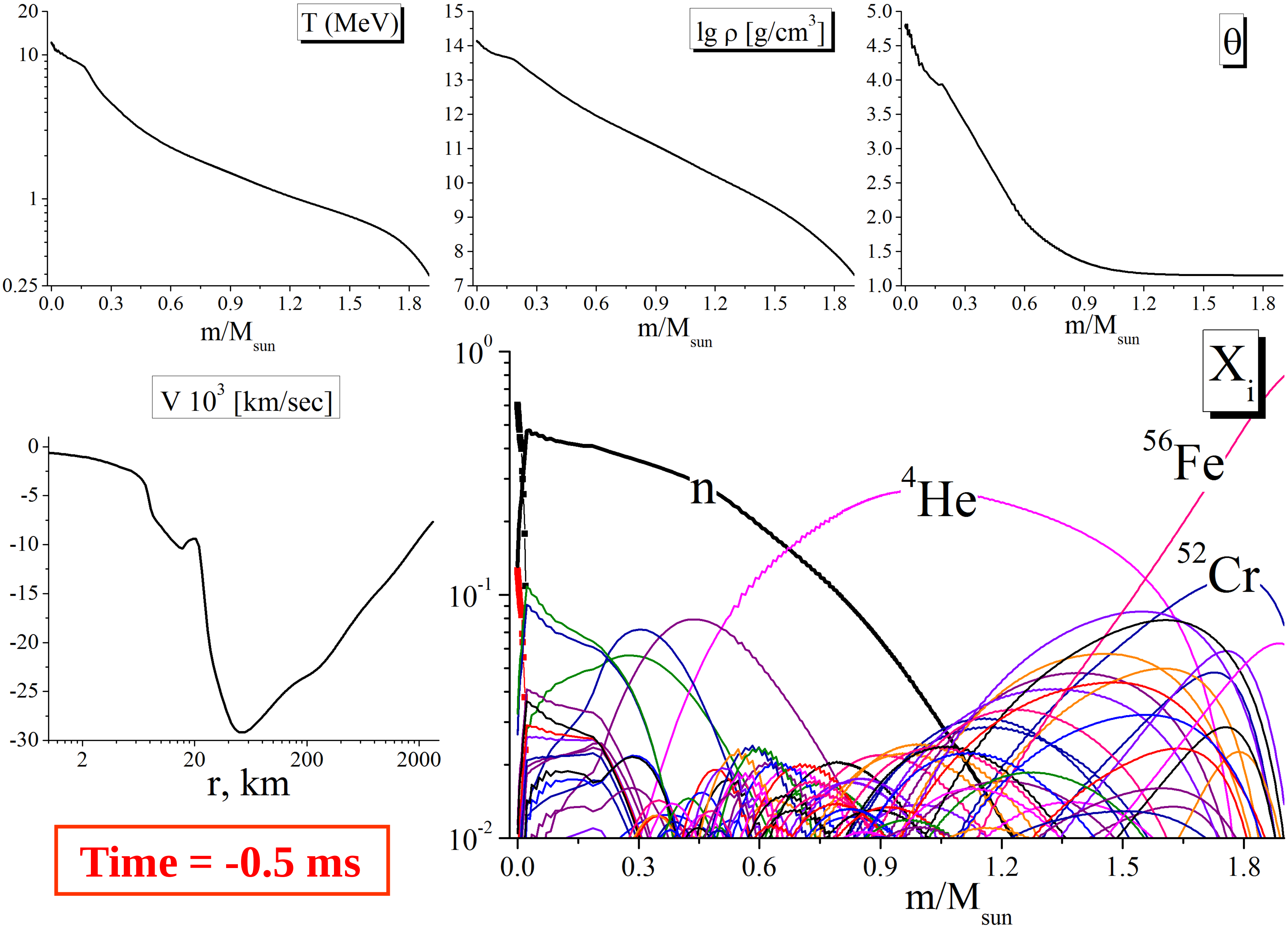

lg ρ [g/cm3]
14 13 12 11 10 9 8 7
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun


θ
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun

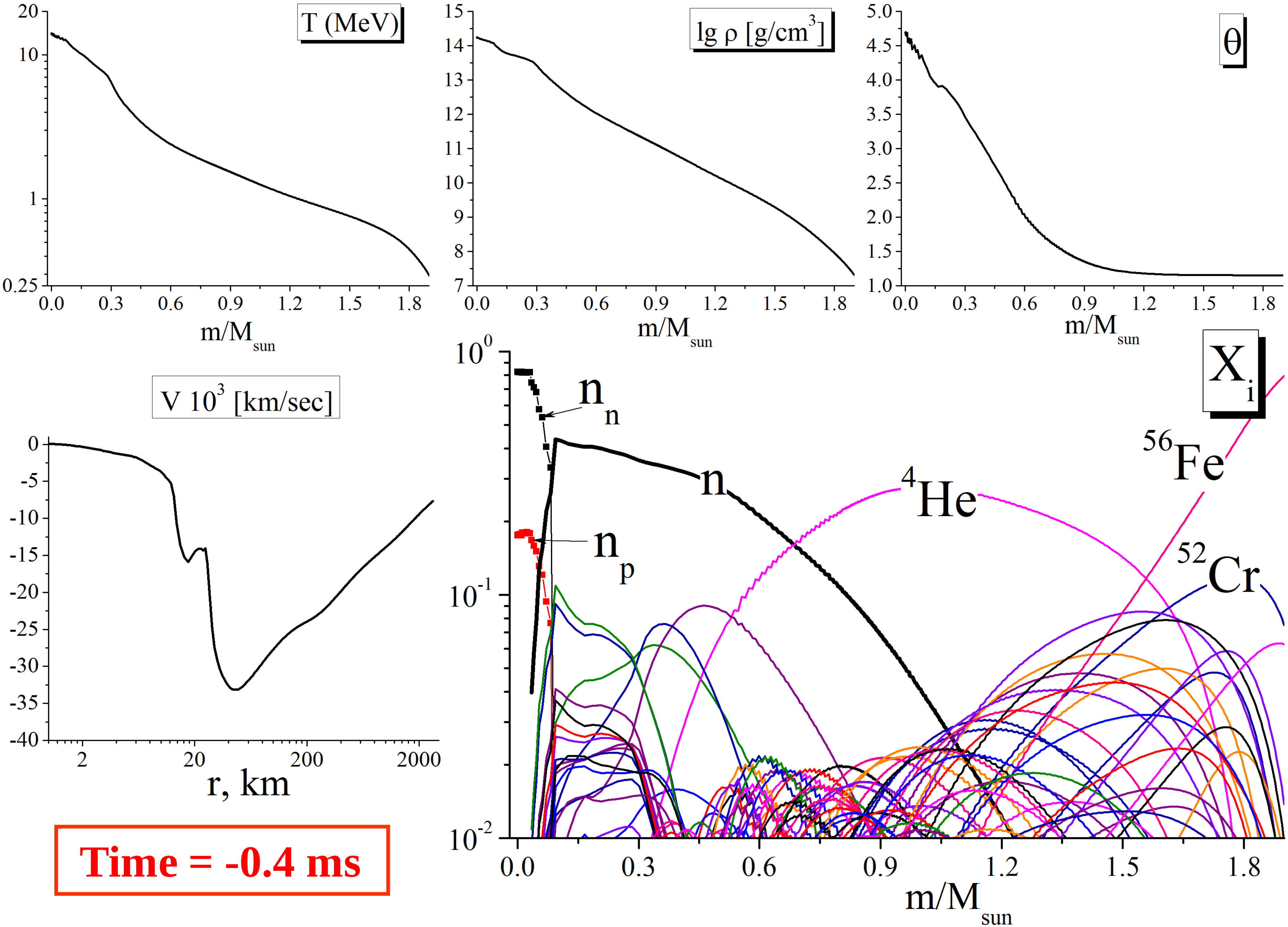

V 10^3 [km/sec]
0 -5 -10 -15 -20 -25 -30
2 20 200 2000
r, km


X i
10^0
10^-1
10^-2
n
4He
56Fe
52Cr
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M sun

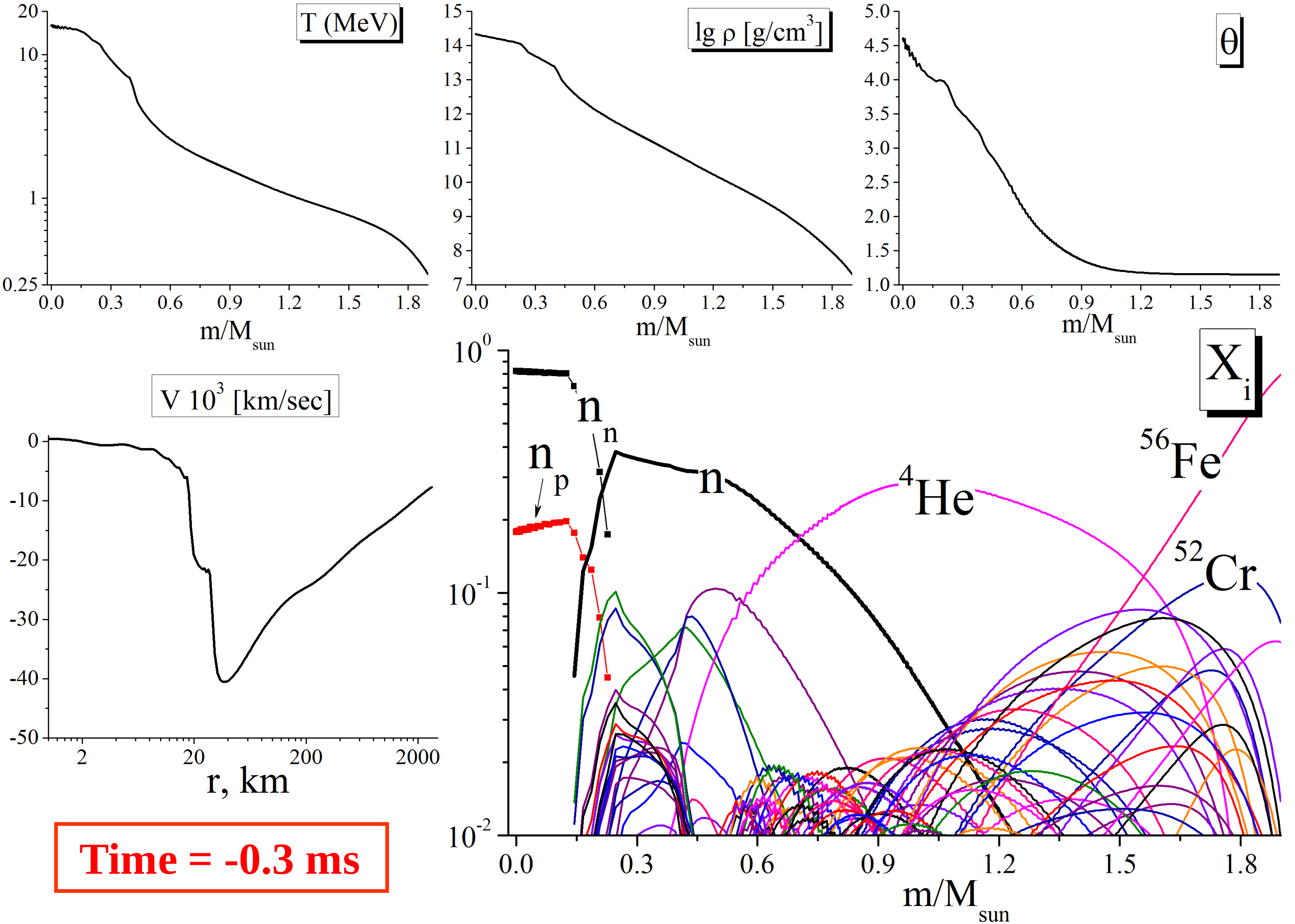
Time = -0.7 ms



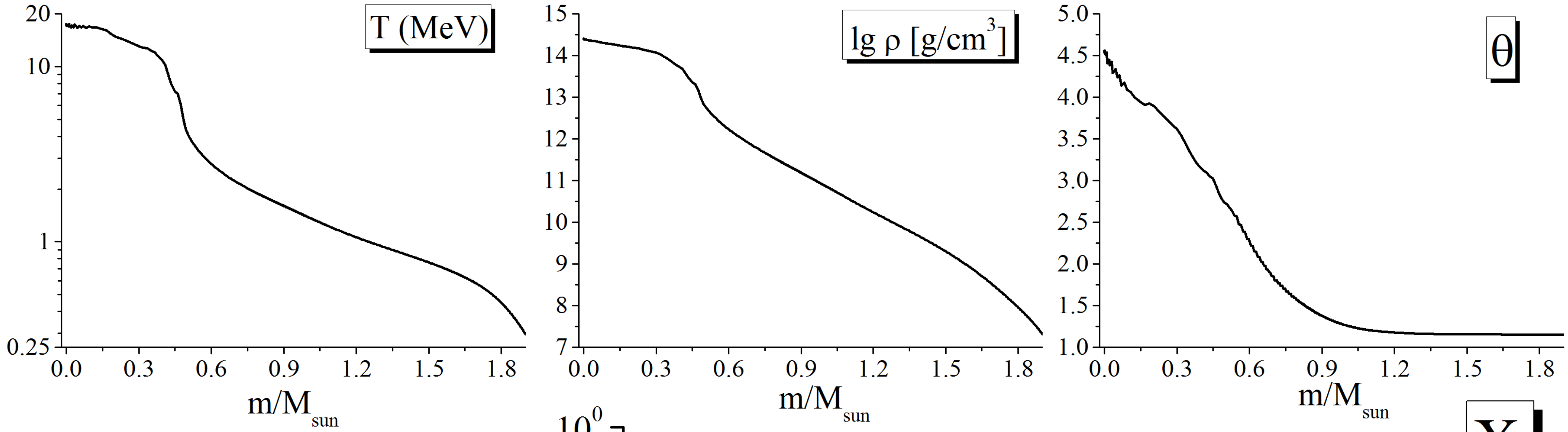
Time = -0.5 ms

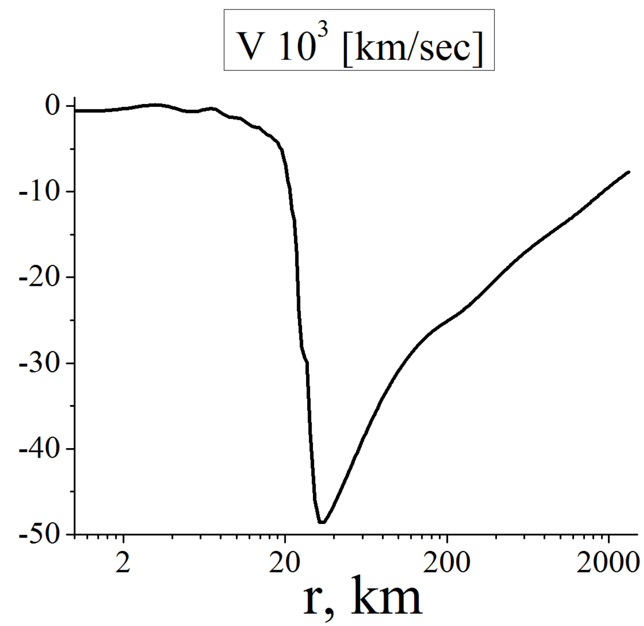


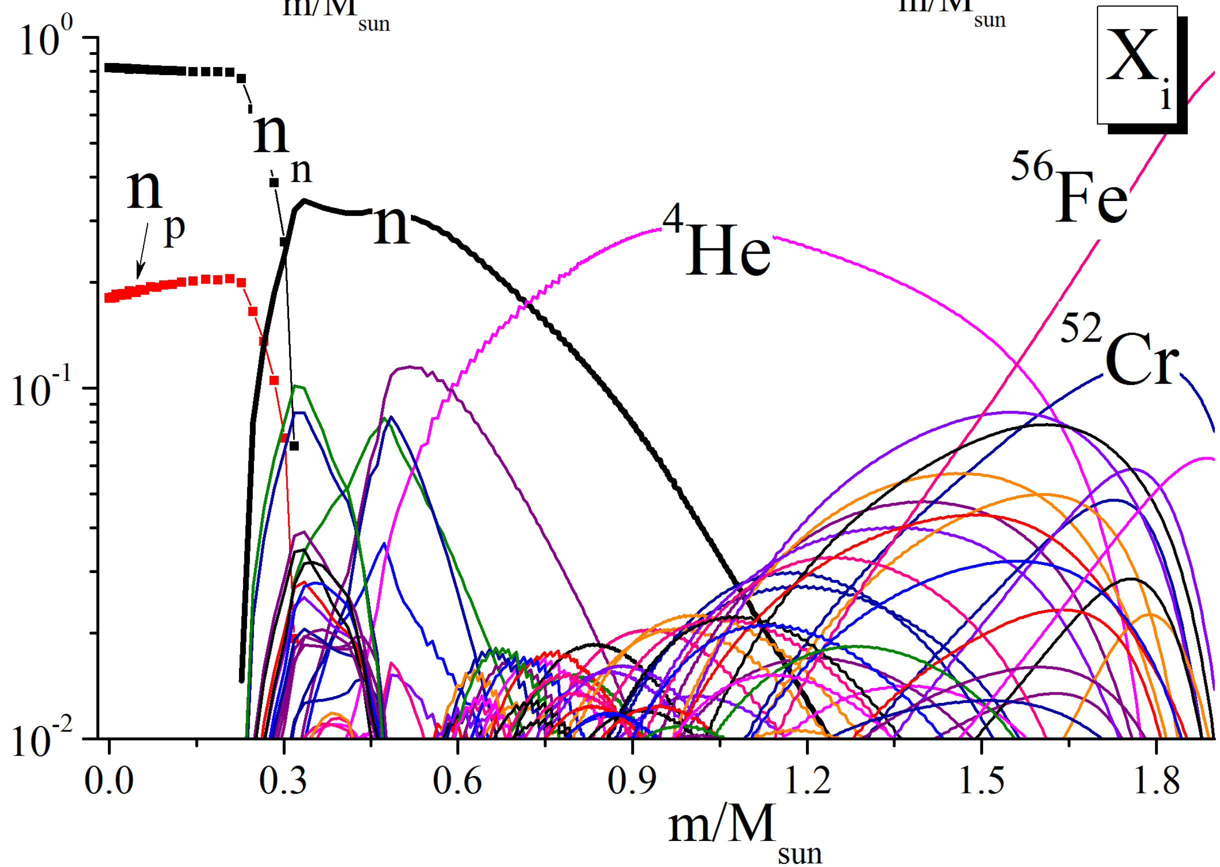
Time = -0.4 ms



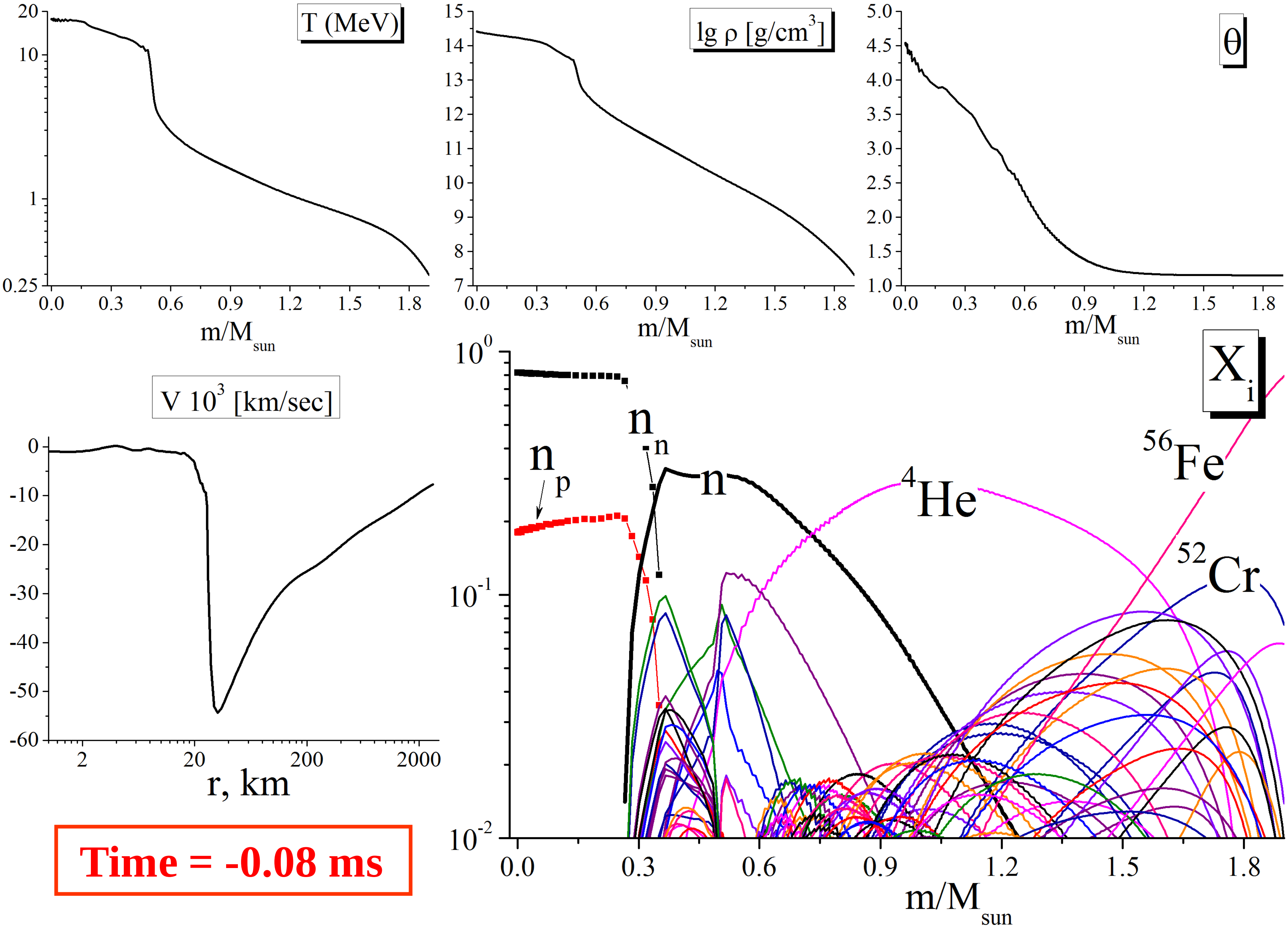
T (MeV)
20
10
1
0.25
lg ρ [g/cm³]
15
14
13
12
11
10
9
8
7
θ
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M_sun
V 10³ [km/sec]
0
-10
-20
-30
-40
-50
2 20 200 2000
r, km
X_i
10^0
10^-1
10^-2
n_n
n_p
n
⁴He
⁵⁶Fe
⁵²Cr
Time = -0.3 ms


T (MeV)
20
10
1
0.25
lg ρ [g/cm3]
15
14
13
12
11
10
9
8
7
θ
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/Msun

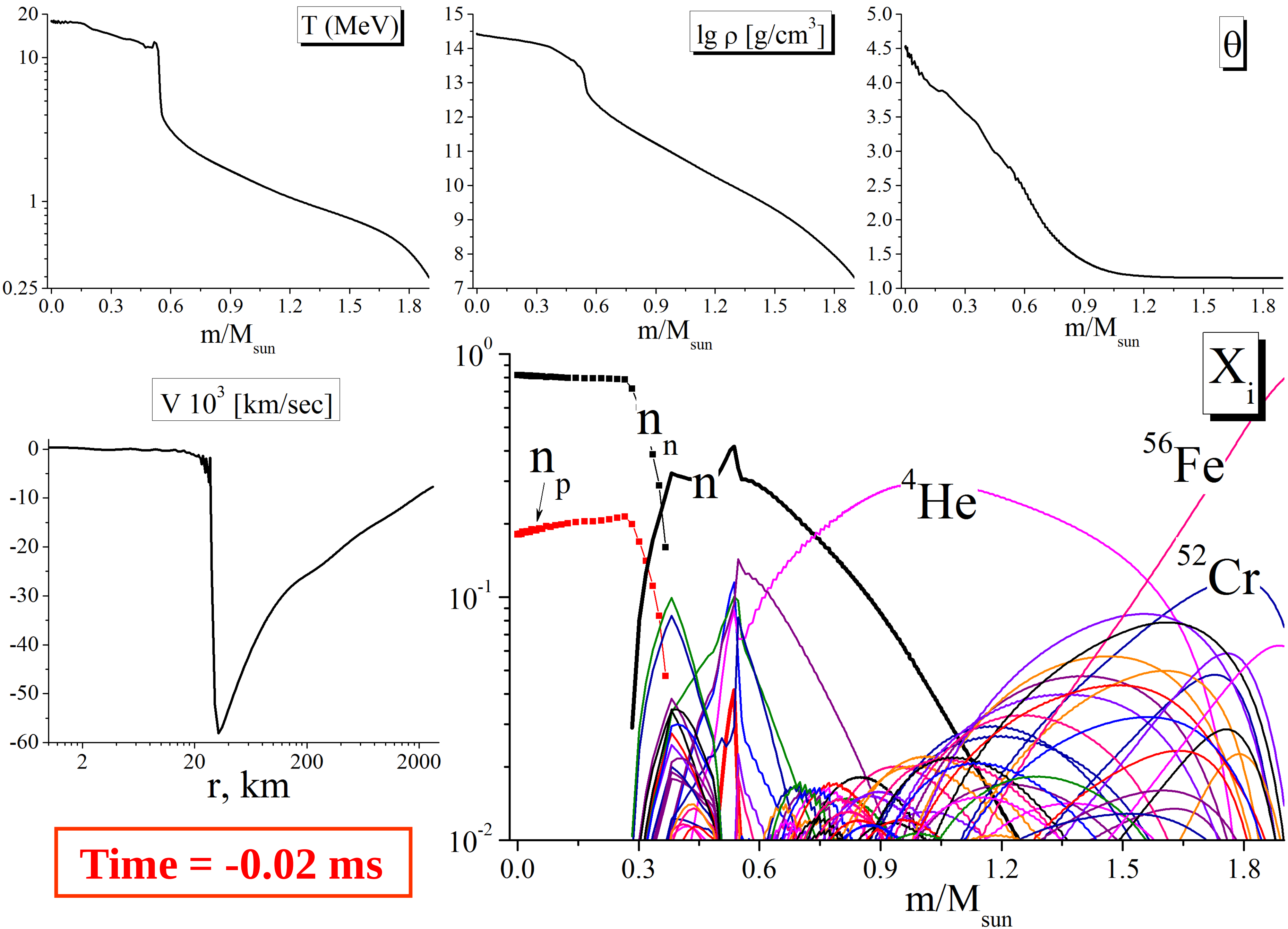

V 103 [km/sec]
0
-10
-20
-30
-40
-50
2
20
200
2000
r, km


Xi
100
10-1
10-2
nn
np
n
4He
56Fe
52Cr
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/Msun

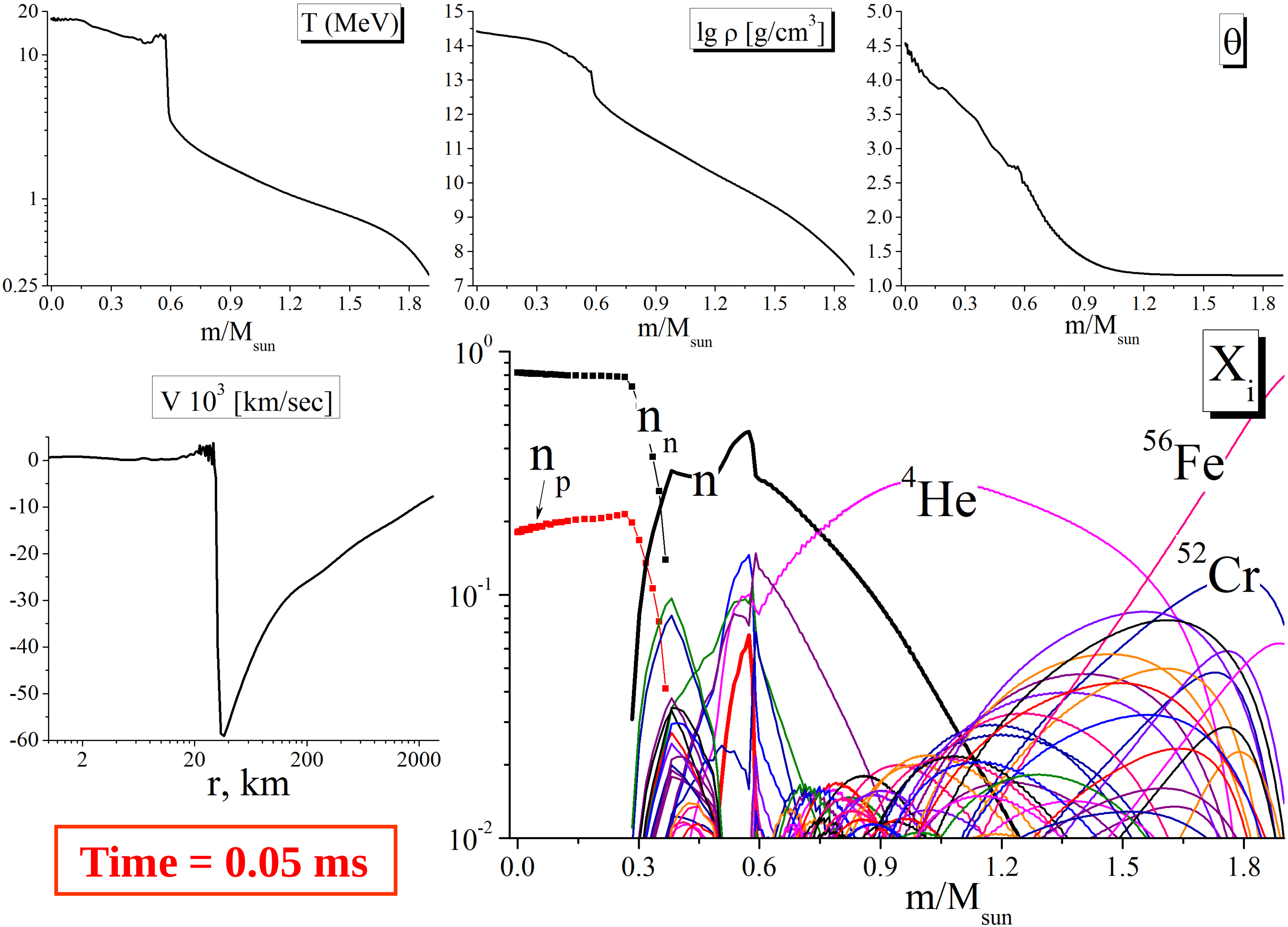
Time = -0.1 ms



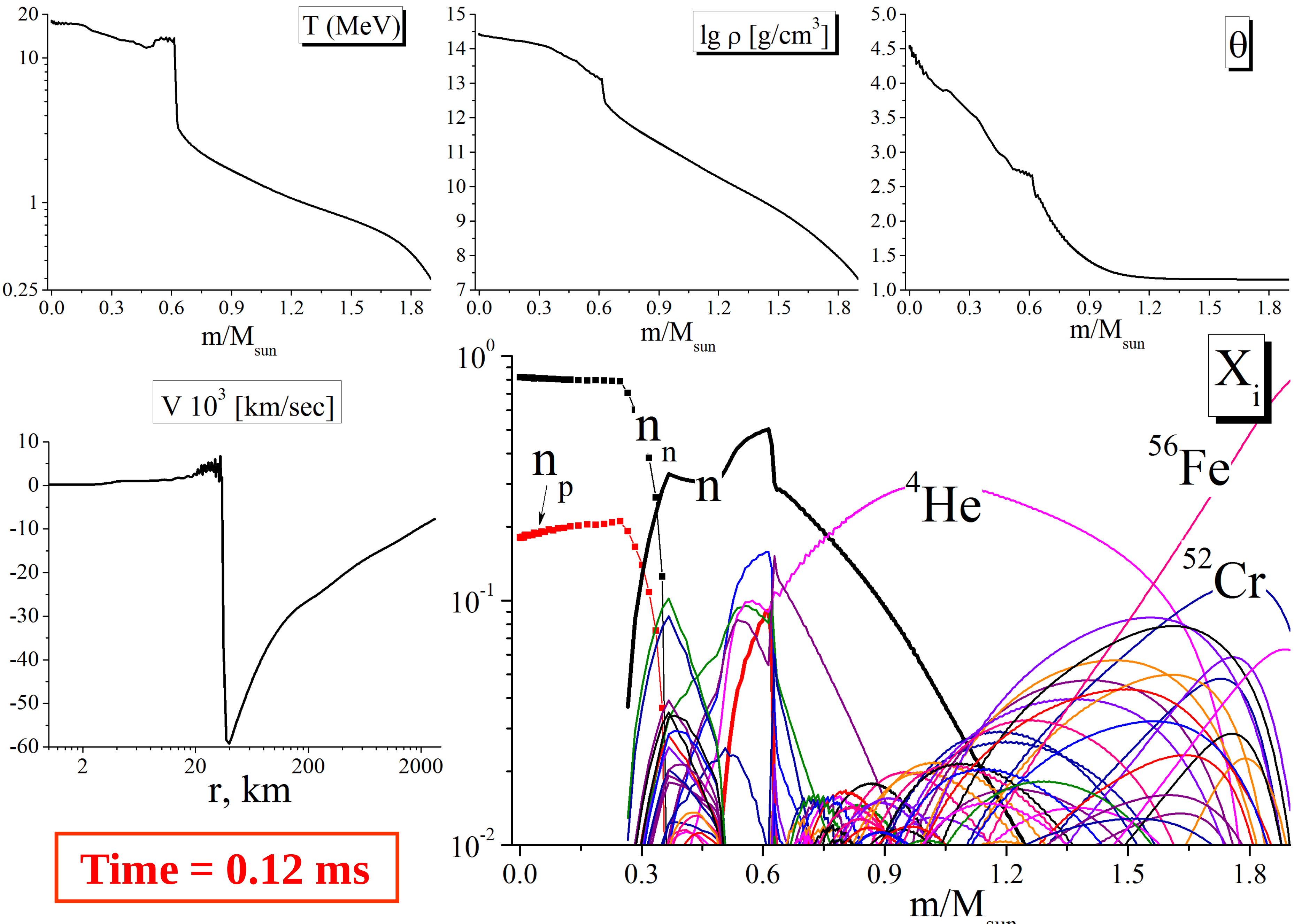
T (MeV)
20
10
1
0.25
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M$_{sun}$
lg ρ [g/cm^3]
15 14 13 12 11 10 9 8 7
m/M$_{sun}$
θ
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0
m/M$_{sun}$
V 10^3 [km/sec]
0 -10 -20 -30 -40 -50 -60
2 20 200 2000
r, km
X$_i$
10^0
10^{-1}
10^{-2}
n
n$_p$
n$_n$
n
^{4}He
^{56}Fe
^{52}Cr
m/M$_{sun}$
Time = -0.08 ms

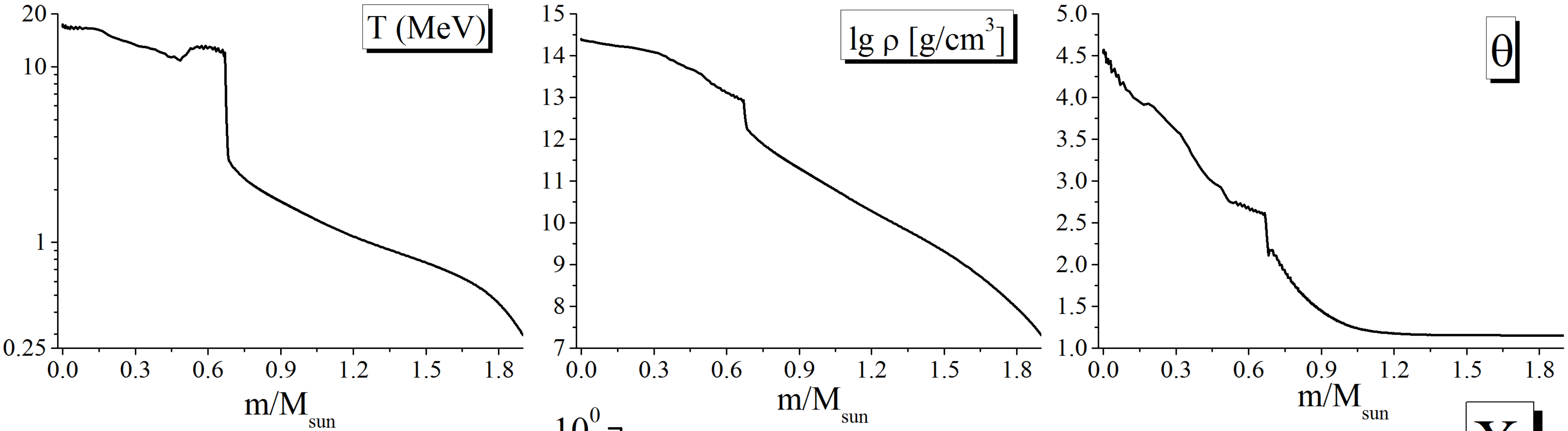


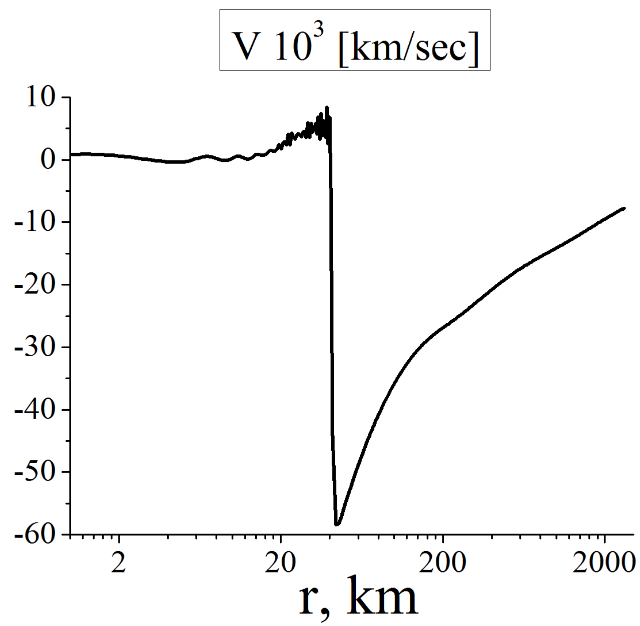
T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
nn
np
n
4He
56Fe
52Cr
Time = -0.02 ms

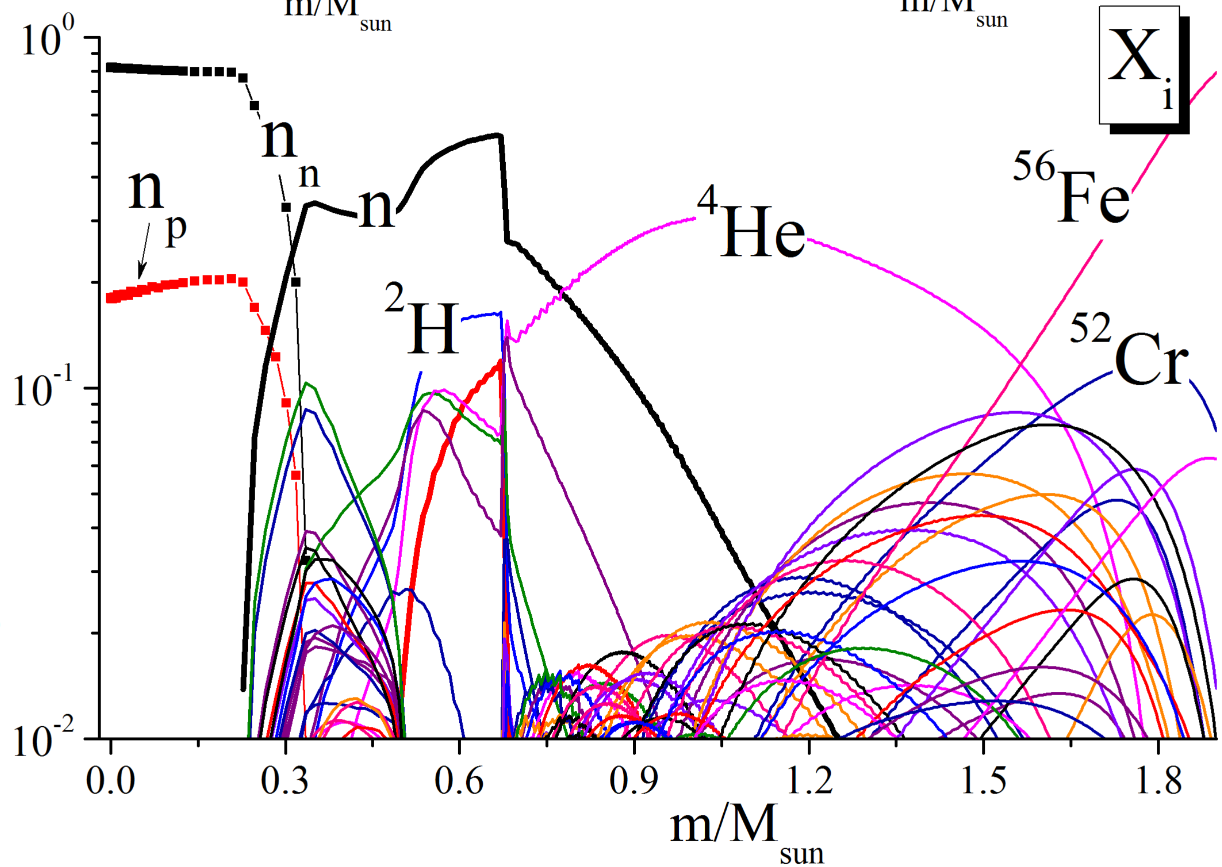


Time = 0.05 ms

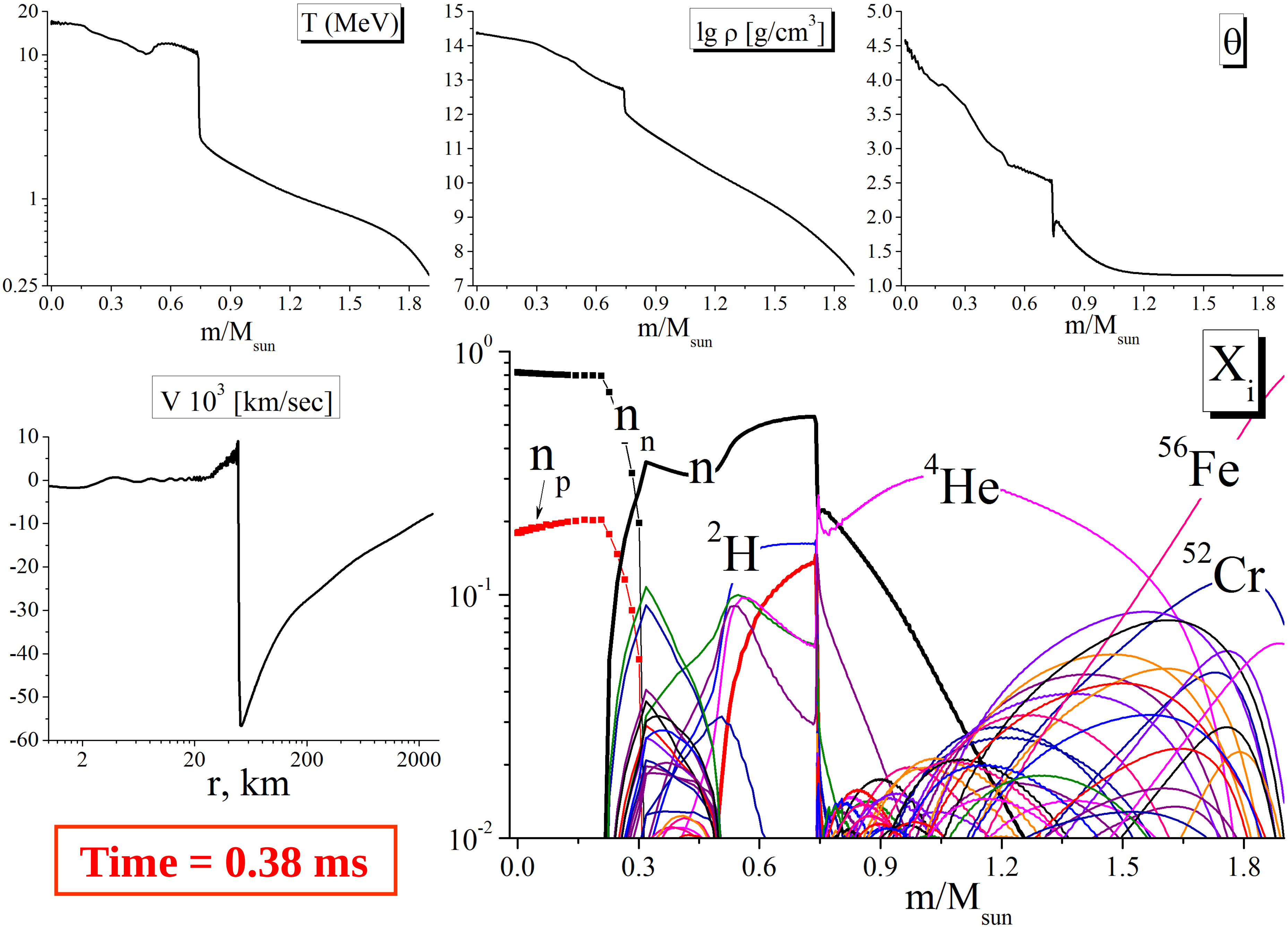

T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
nn
np
n
4He
56Fe
52Cr
Time = 0.12 ms


T (MeV)
m/M$_{sun}$
lg ρ [g/cm^3]
m/M$_{sun}$
θ
m/M$_{sun}$

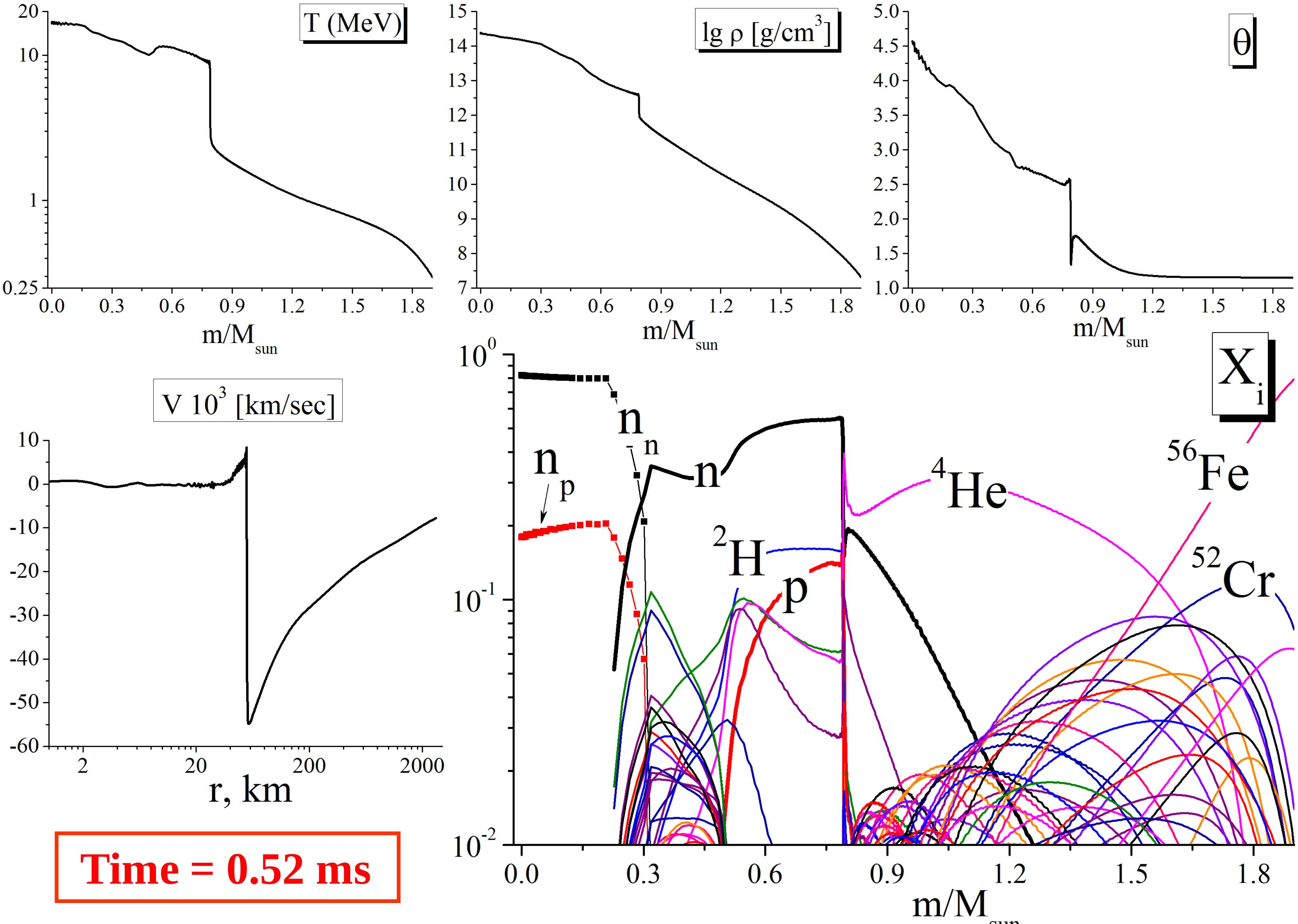

V 10^3 [km/sec]
r, km


X$_i$
n_n
n_p
n
^{4}He
^{56}Fe
^{52}Cr
^{2}H
m/M$_{sun}$

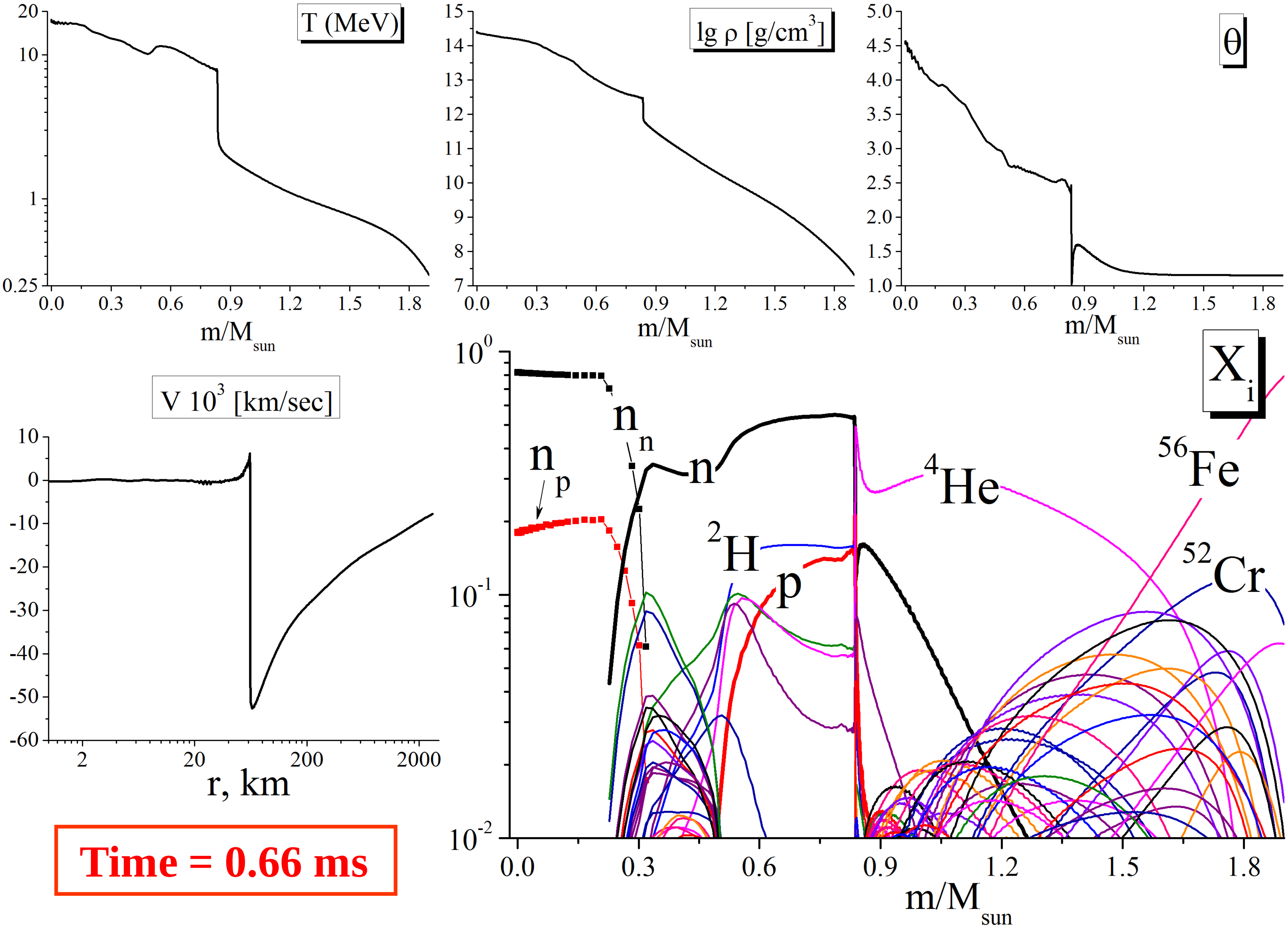
Time = 0.23 ms



Time = 0.38 ms

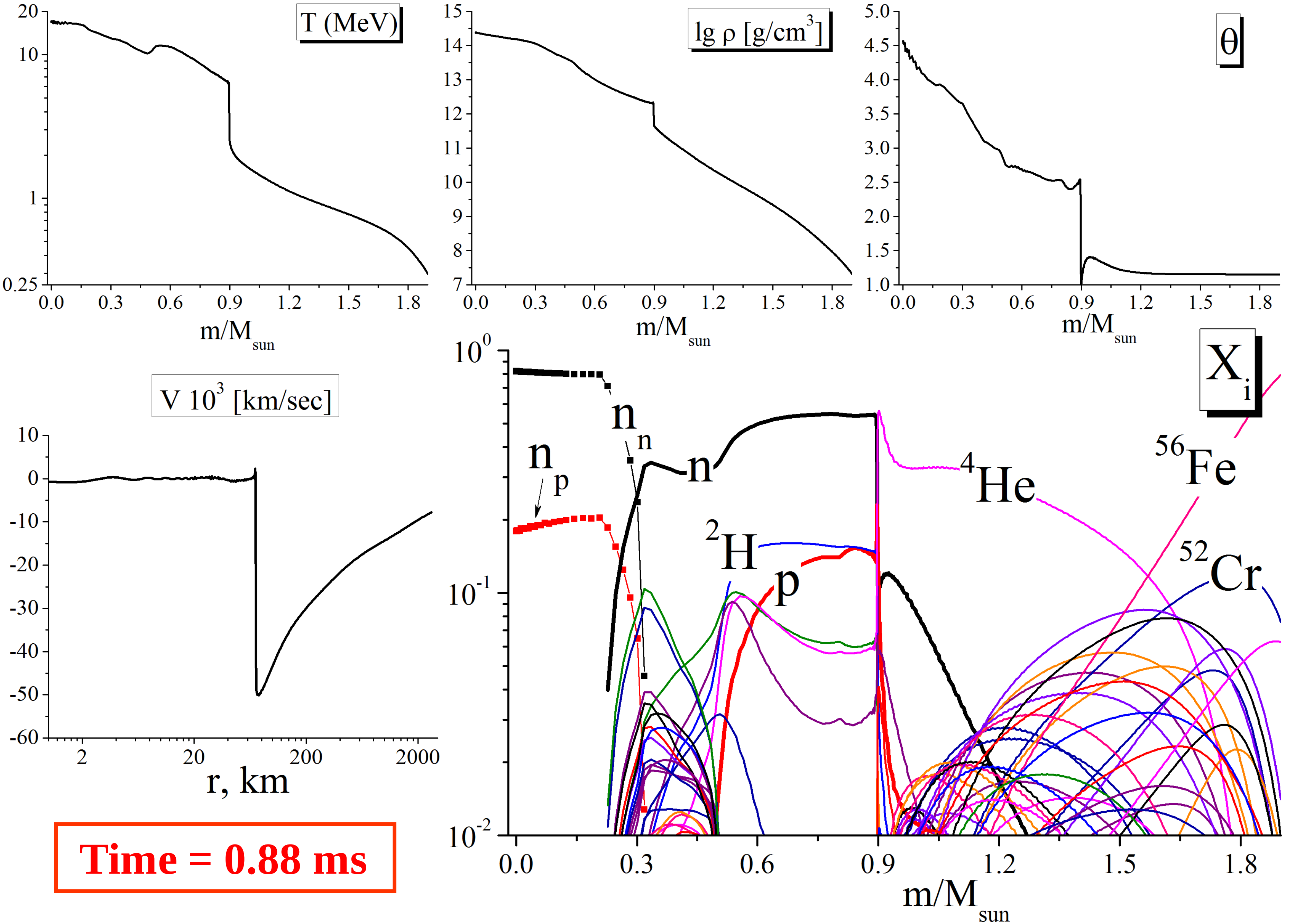


T (MeV)
20
10
1
0.25
0.0 0.3 0.6 0.9 1.2 1.5 1.8
m/M_sun
lg ρ [g/cm^3]
15 14 13 12 11 10 9 8 7
m/M_sun
θ
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0
m/M_sun
V 10^3 [km/sec]
10 0 -10 -20 -30 -40 -50 -60
2 20 200 2000
r, km
X_i
10^0
10^-1
10^-2
n_n
n_p
n
p
^4He
^2H
^56Fe
^52Cr
m/M_sun
Time = 0.52 ms

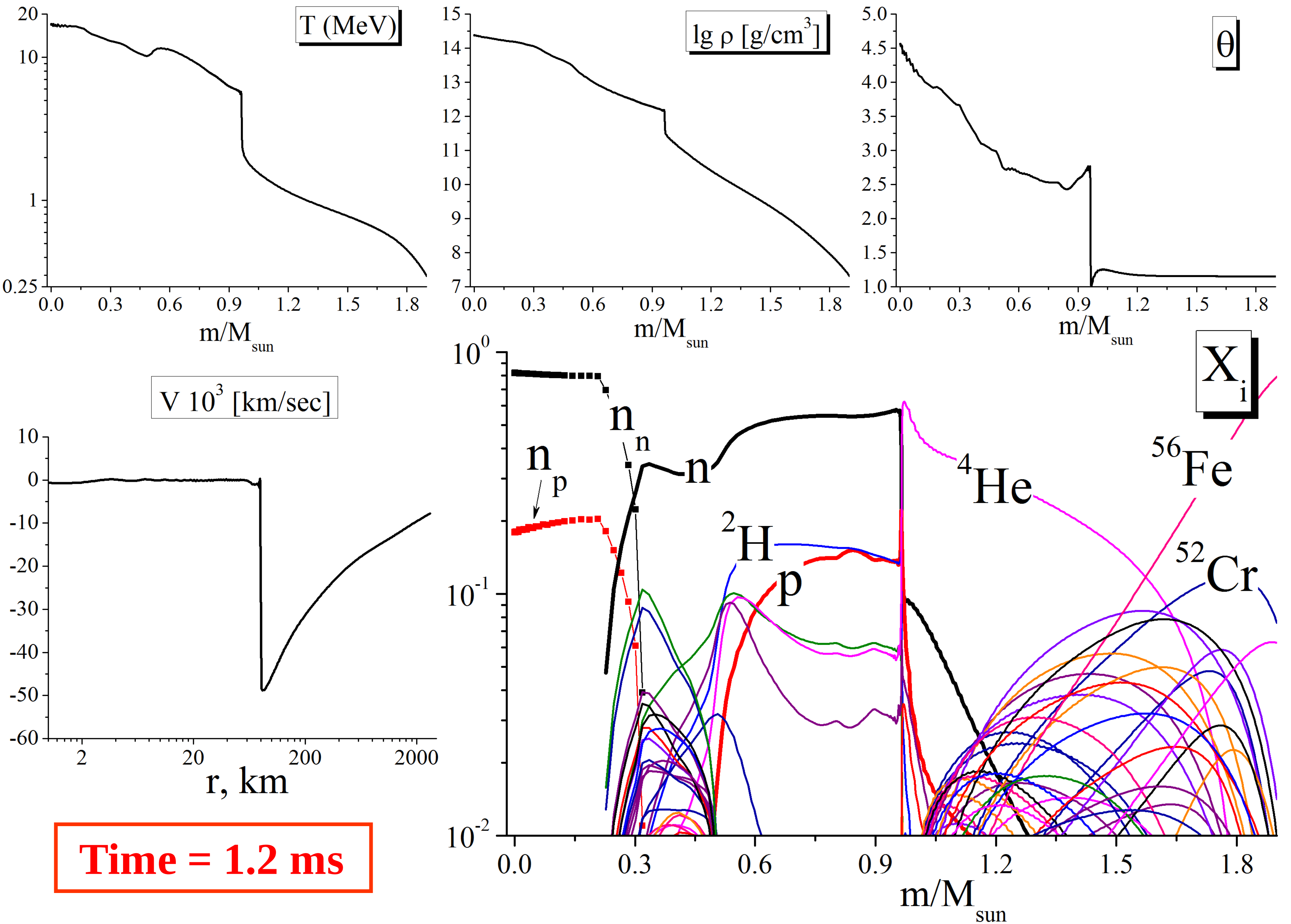


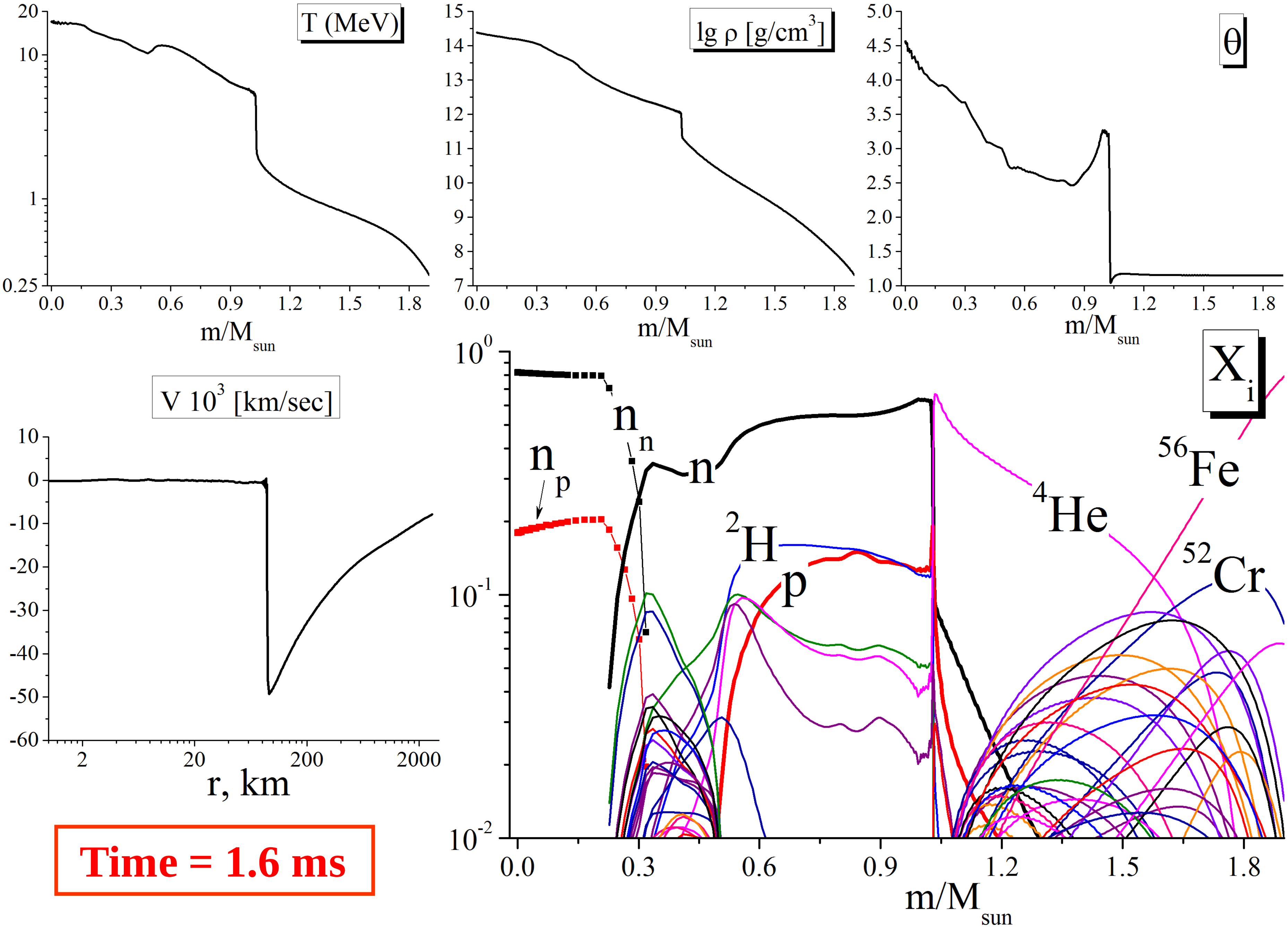
T (MeV)
lg ρ [g/cm³]
θ
m/M sun
V 10³ [km/sec]
r, km
X i
n n
n p
n
⁴He
²H
p
⁵⁶Fe
⁵²Cr
m/M sun

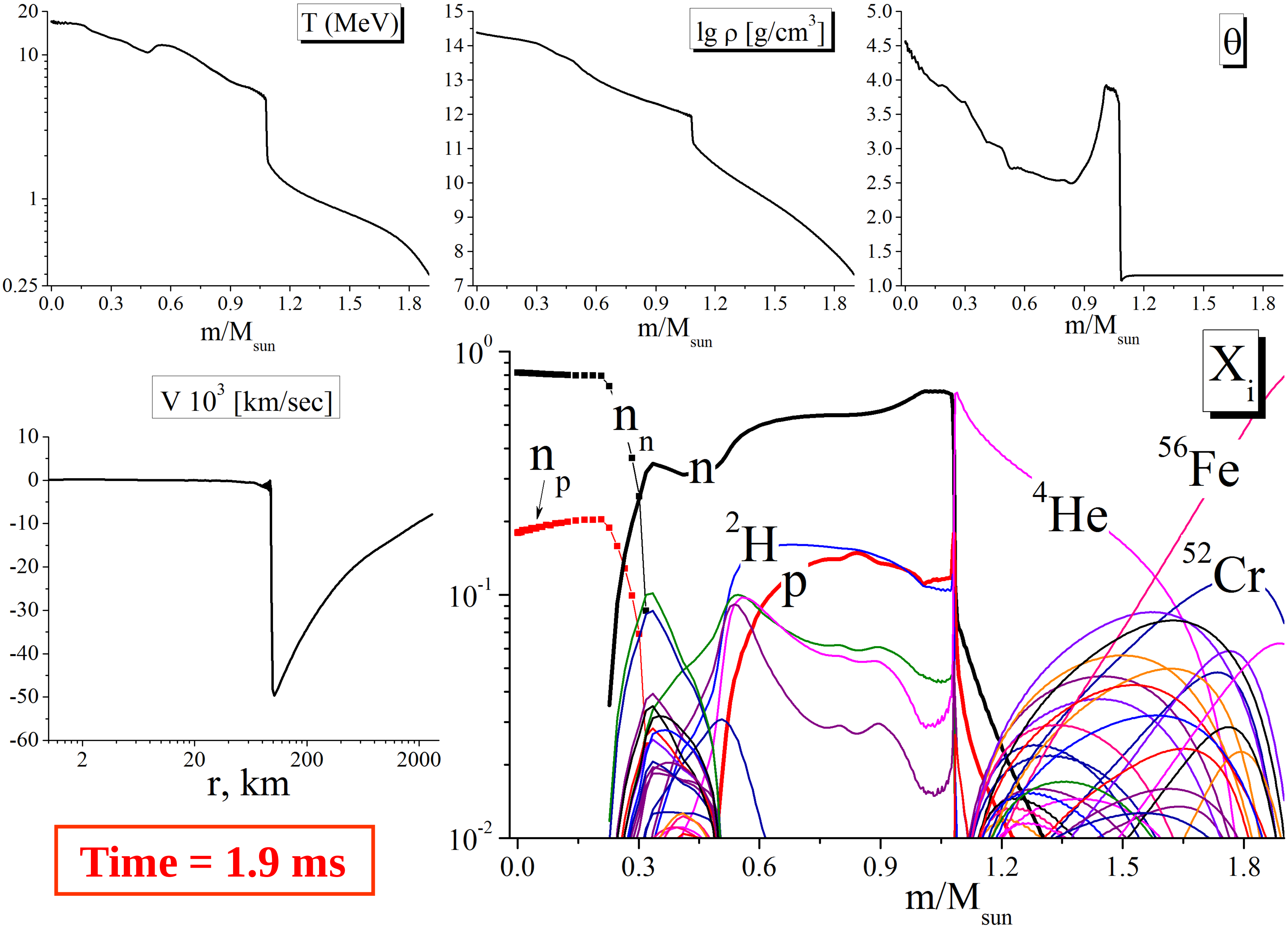
Time = 0.66 ms



T (MeV)
m/M sun
lg ρ [g/cm3]
m/M sun
θ
m/M sun
V 10^3 [km/sec]
r, km
X i
n p
n n
n
2H
p
4He
56Fe
52Cr
m/M sun
Time = 0.88 ms

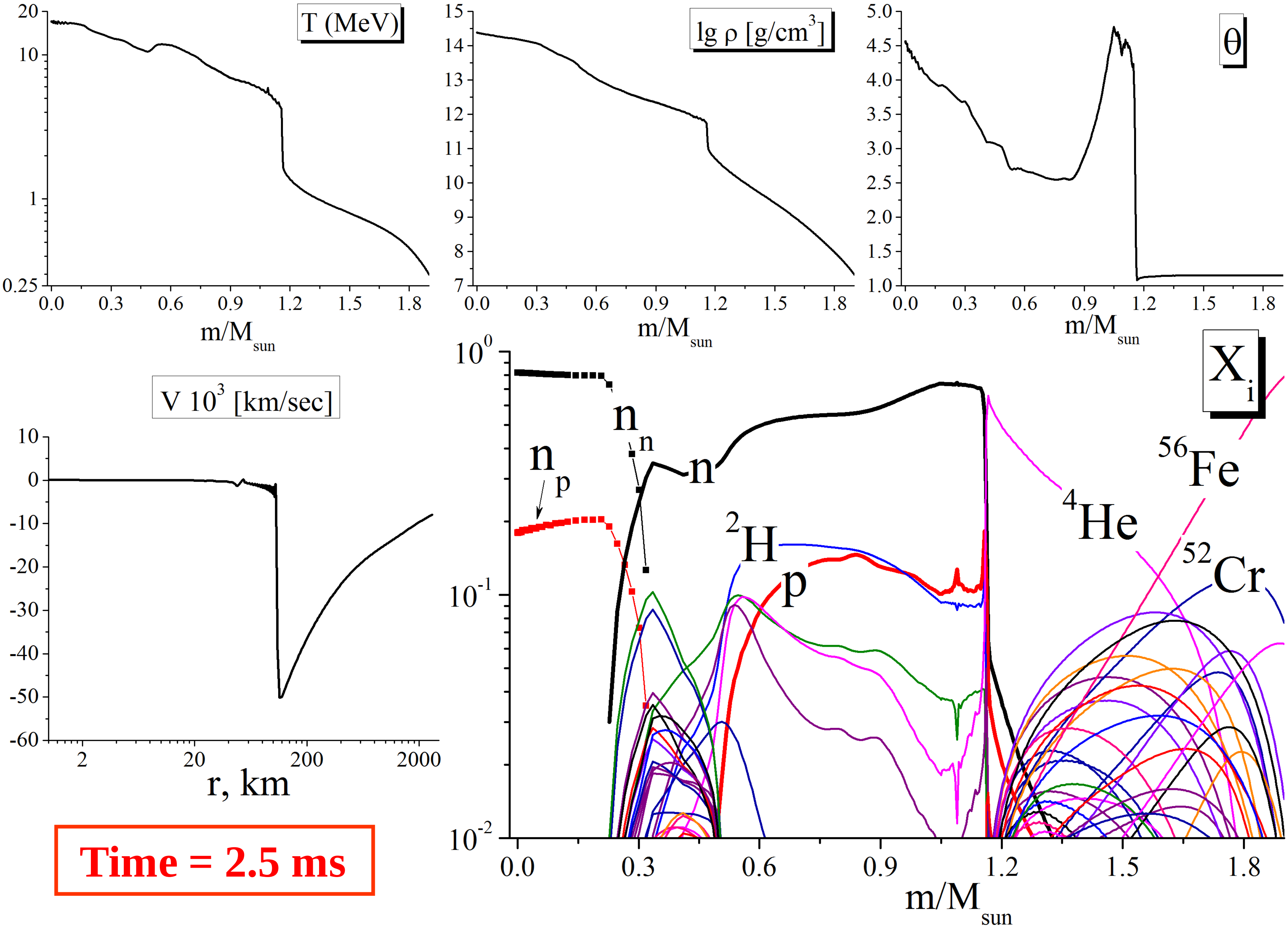

T (MeV)
m/M_sun
lg ρ [g/cm^3]
m/M_sun
θ
m/M_sun
V 10^3 [km/sec]
r, km
X_i
n_n
n_p
n
4He
56Fe
52Cr
2H
p
m/M_sun
Time = 1.2 ms


T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
nn
np
n
p
2H
4He
56Fe
52Cr
Time = 1.6 ms

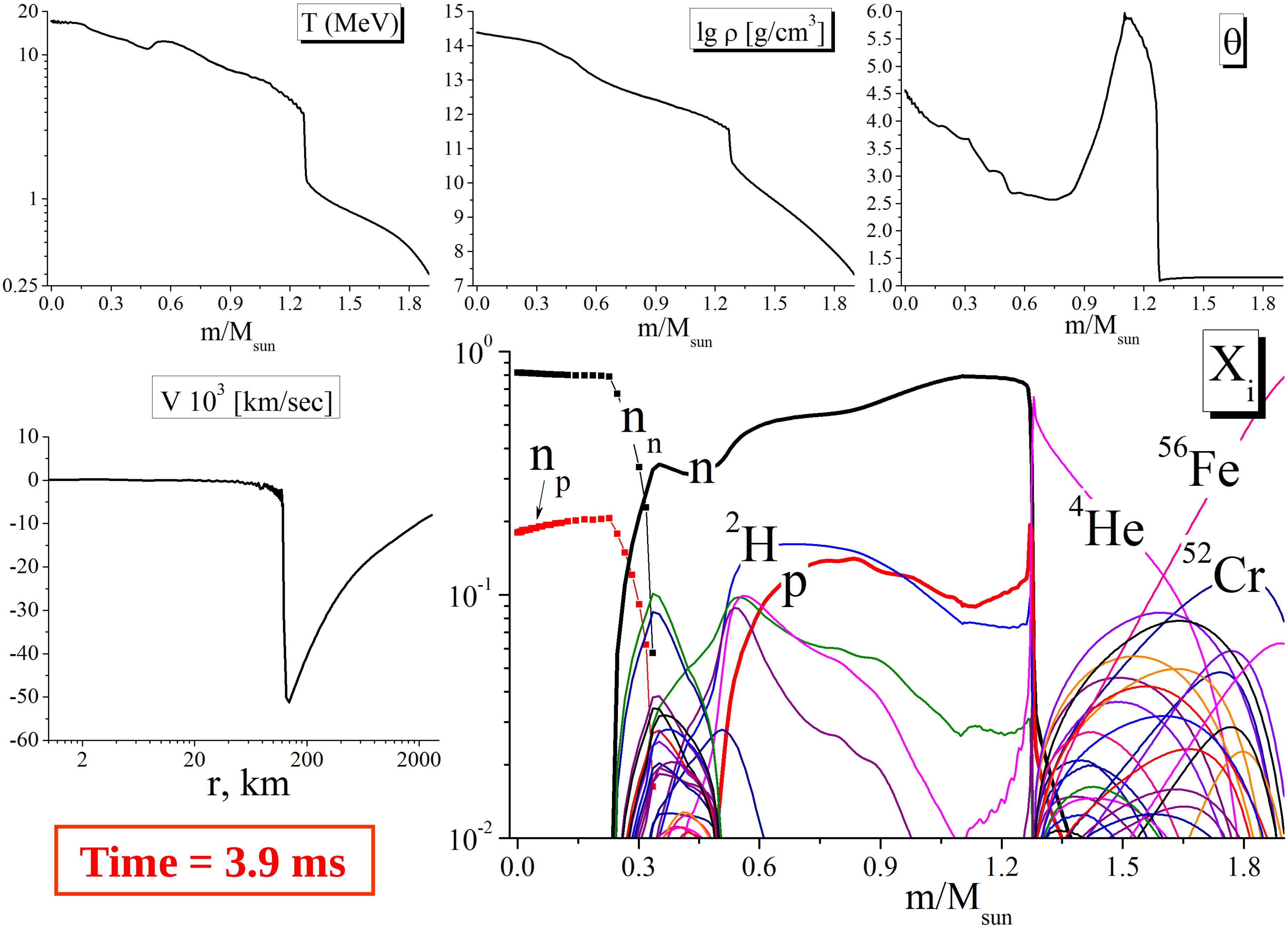


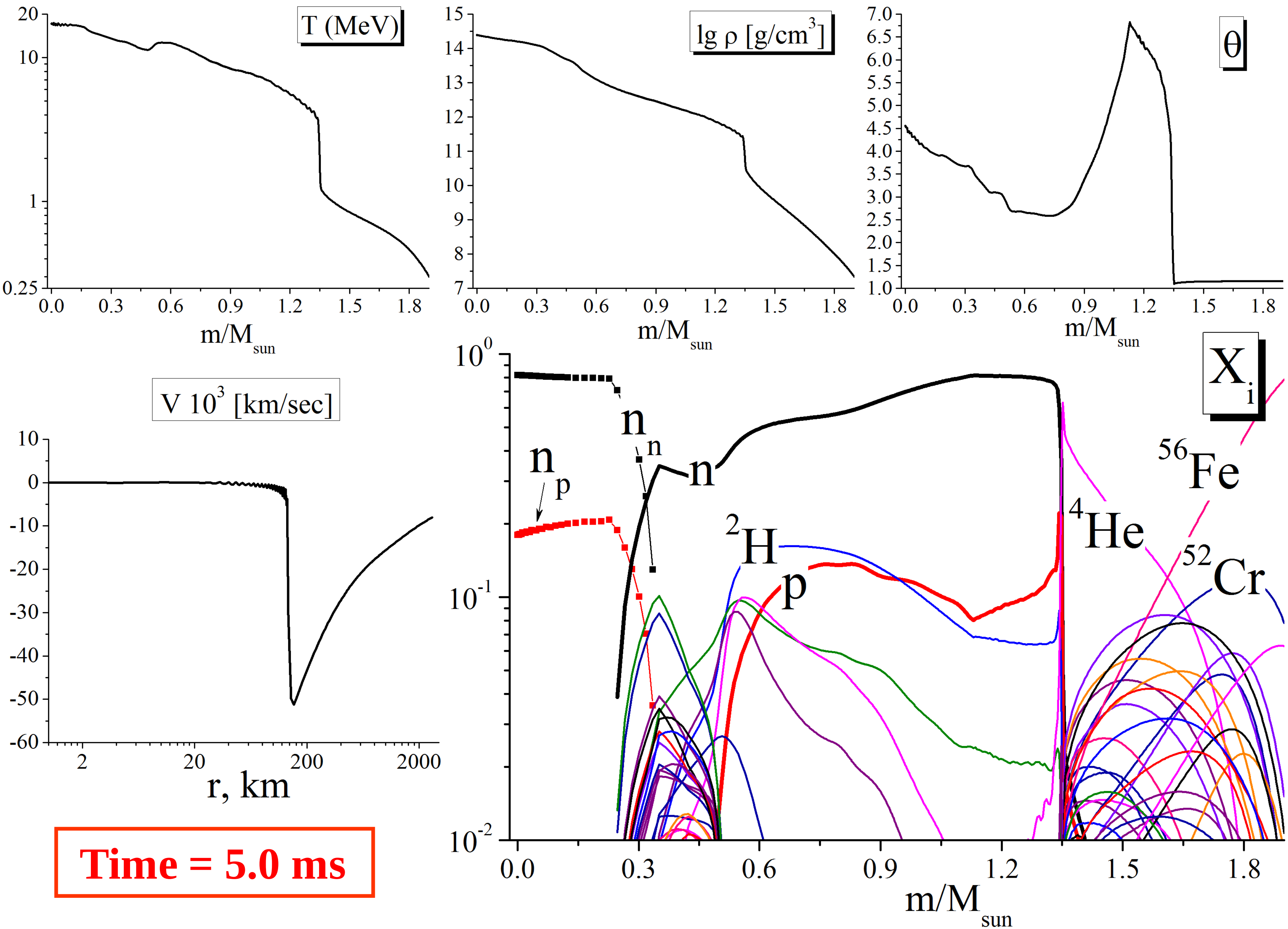
T (MeV)
lg ρ [g/cm³]
θ
V 10³ [km/sec]
r, km
m/M_sun
X_i
n_p
n_n
n
p
²H
⁴He
⁵⁶Fe
⁵²Cr

Time = 1.9 ms



T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
nn
np
n
p
2H
4He
56Fe
52Cr
Time = 2.5 ms


T (MeV)
m/M_sun
lg ρ [g/cm^3]
m/M_sun
θ
m/M_sun
V 10^3 [km/sec]
r, km
X_i
n_n
n_p
n
^2H
p
^4He
^56Fe
^52Cr
m/M_sun
Time = 3.9 ms

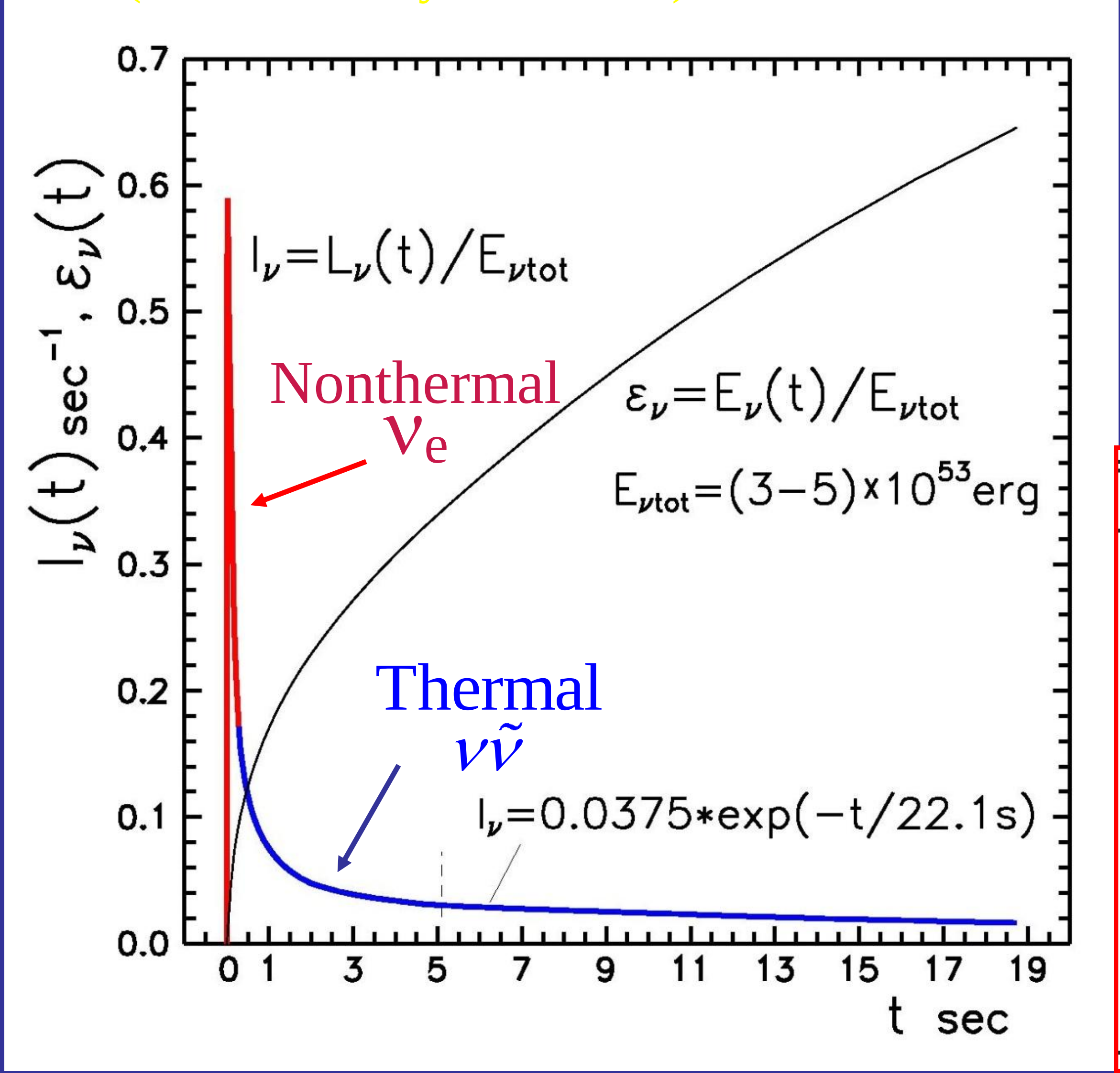

T (MeV)
lg ρ [g/cm3]
θ
m/Msun
V 10^3 [km/sec]
r, km
Xi
np
nn
n
2H
p
4He
56Fe
52Cr

Time = 5.0 ms

The properties of the Neutrino flux

Cumulative neutrino "light" curve

(based on Nadyozhin 1978)

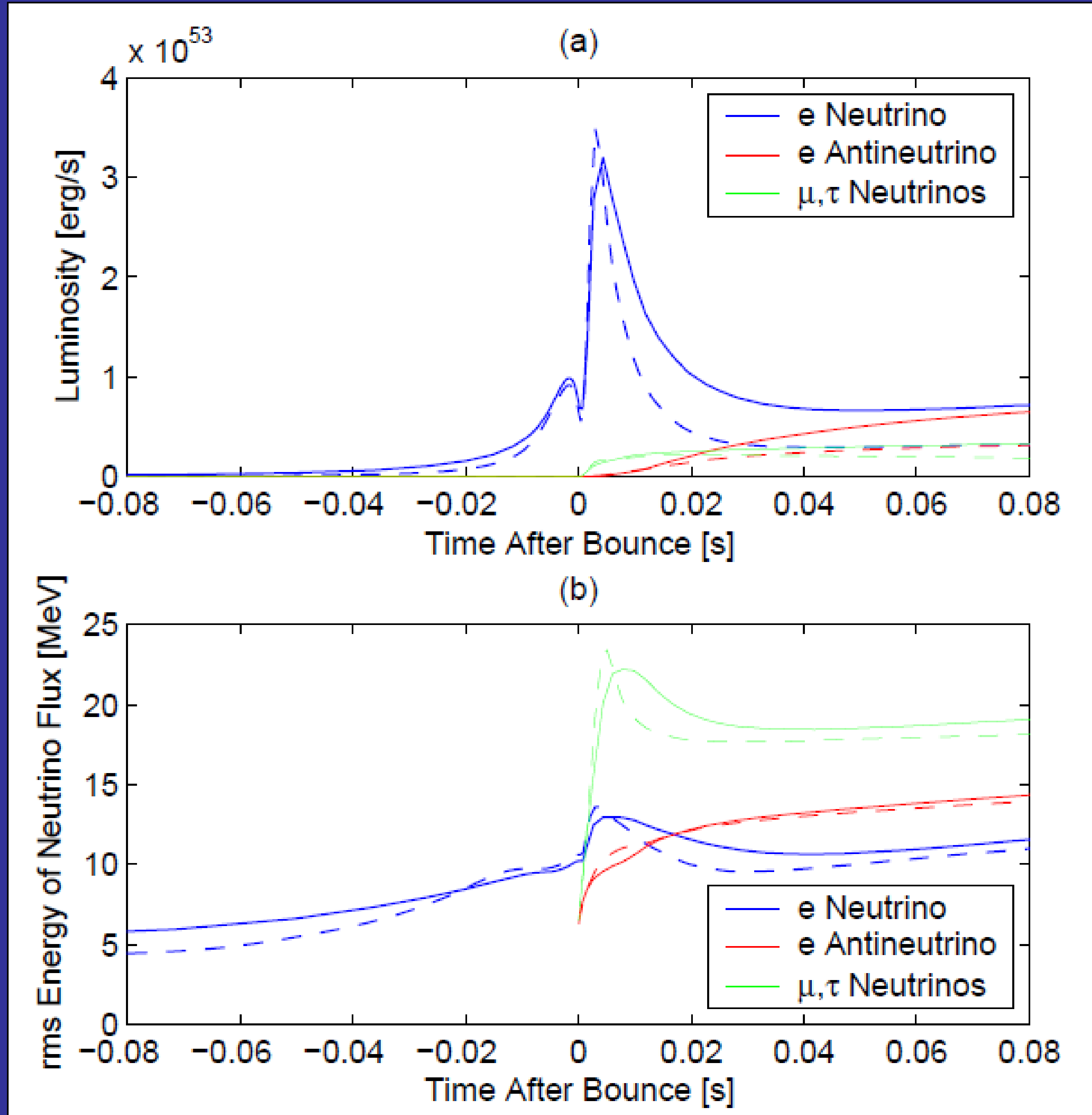


Neutrino reaction
$e^- + p \rightleftarrows n + \nu_e$
$e^+ + n \rightleftarrows p + \bar{\nu}_e$
$e^- + \langle A, Z\rangle \rightleftarrows \langle A, Z-1\rangle + \nu_e$
$\nu + N \rightleftarrows \nu' + N$
$\nu + \langle A, Z\rangle \rightleftarrows \nu' + \langle A, Z\rangle$
$\nu + e^\pm \rightleftarrows \nu' + e^\pm$
$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$
$N + N \rightleftarrows N + N + \nu + \bar{\nu}$
$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$

Liebendoerfer et al.
ApJS 150, 1 (2004)

Solid lines:
$40\ M_{Sun}$
progenetor

Dashed:
$13\ M_{Sun}$
progenetor



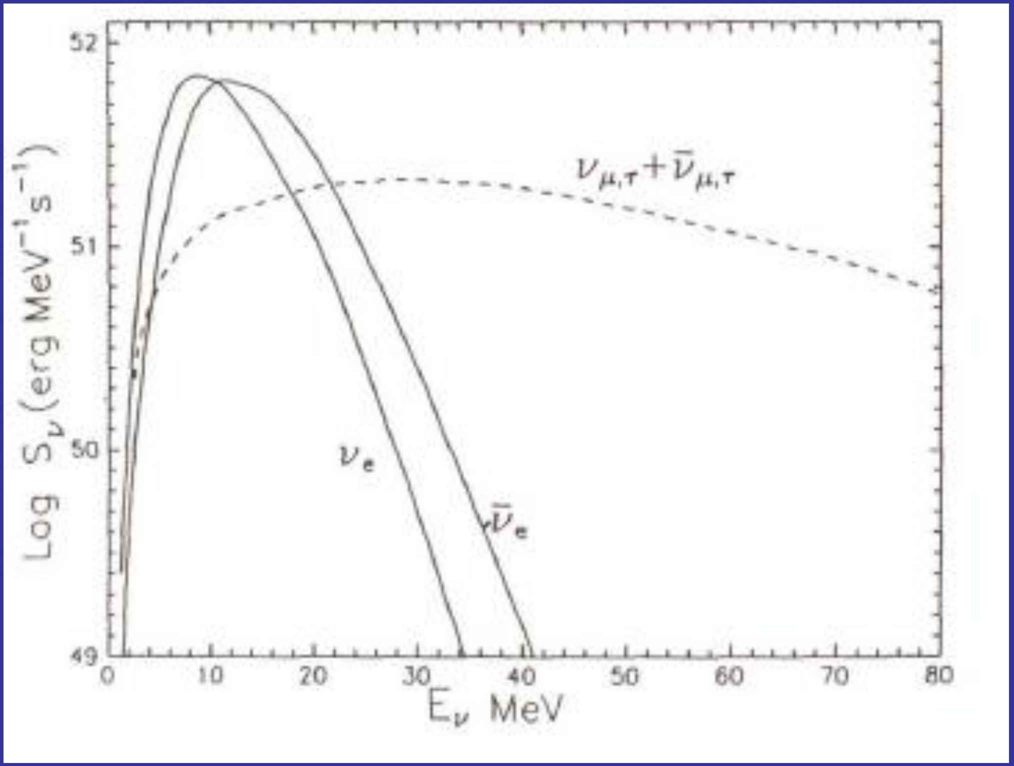
Neutrino spectra for thermal phase

Energy spectra.

Fermi–Dirac law:

$$S_\nu \sim \frac{\varepsilon_\nu^3}{1+\exp\left(\dfrac{\varepsilon_\nu}{kT_{\nu \mathrm{ph}}}-\psi_{\nu \mathrm{ph}}\right)},$$

$(\psi_{\nu \mathrm{ph}} \approx 0)$.



High-energy cutoff

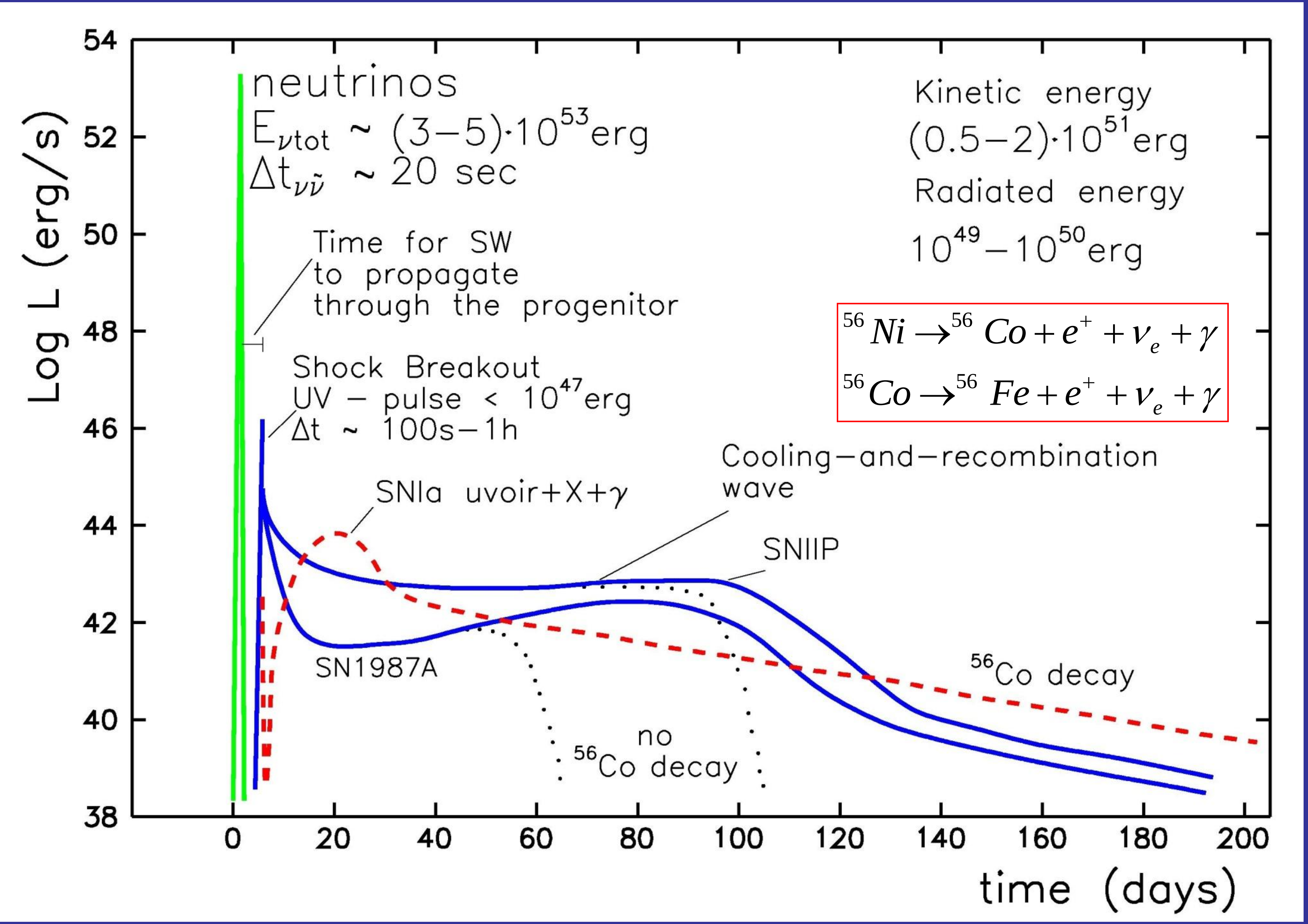
(*relevant to* $\nu_\mathrm{e}, \tilde{\nu}_\mathrm{e}$):

$$S_\nu \sim \frac{\varepsilon_\nu^3 \exp\left[-\alpha\left(\dfrac{\varepsilon_\nu}{kT_{\nu \mathrm{ph}}}\right)^2\right]}{1+\exp\left(\dfrac{\varepsilon_\nu}{kT_{\nu \mathrm{ph}}}\right)}, \quad (\alpha \approx 0.02-0.04).$$

$T_{\nu \mathrm{ph}} \approx 4$ MeV for $\nu_\mathrm{e}, \tilde{\nu}_\mathrm{e}$

$T_{\nu \mathrm{ph}} \approx 8$ MeV for ν_μ, ν_τ

Schematic Supernova «light curves»



Core-collapse SNe (all other Types but Ia)

The SN outburst is triggered by the gravitational collapse of the "iron" core of a mass M_{Fe}=(1.2–2) $M_{\odot}$ into a neutron star. About (10–15)% $M_{Fe}c^2$ is radiated in the form of neutrinos and antineutrinos of all the flavors (e, μ, τ):

$$E_{\nu\tilde{\nu}} = (3-5)\times 10^{53}\,\text{erg}$$

The explosion energy (kinetic energy of the envelope expansion):

$$E_{exp} = (0.5\text{–}2)\times 10^{51}\,\text{erg}$$

it comes from the shock wave created at the boundary between a new-born neutron star and the envelope to be expelled.

$$E_{exp}/E_{\nu\tilde{\nu}} \sim 3\times 10^{-3}\ !!$$

Rich nucleosynthesis — from neutrino-induced creation of light element in C-O and He shells through synthesis of heavy nuclides by neutron capture at the bottom of expelled envelope

The mechanism of the core-collapse SNe

is still under detailed study

Spherically-symmetrical collapse.

An empirical theorem:

Spherically-symmetrical models do not result in expulsion of an envelope;
the SN outburst does not occur:
the envelope falls back on the collapsed core.

Corollary:

One has to address to 2- and, perhaps, 3-dimensional models to convert the stalled accreting shock into an outgoing blast wave.

Multi-dimensional collapse.

- Large-scale neutrino-driven convection

A. Burrows' group (Arisona); E. Müller, T. Janka (MPA, Garching)

- Interaction between rotation and magnetic field

G.S. Bisnovatyi-Kogan's group (ICR, Keldysh IPM, Moscow)

- Massive fast-rotating collapsed core followed by rotational fission resulting in formation of a close neutron-star binary that evolves being driven by the emission of gravitational waves and mass-exchange and ends with the explosion of a low-mass neutron star ($M \approx 0.1 M_{\odot}$). V.S. Imshennik (Alikhanov ITEP, Moscow)

First collapse + Rotational fission → Neutron-star binary evolution

energetic ν_e ; LSD signal

4.7 hour

→ Low-mass neutron star explosion + second collapse

$\nu\nu$ of all flavours; IMB, Kamioka, Baksan signals; SN otburst

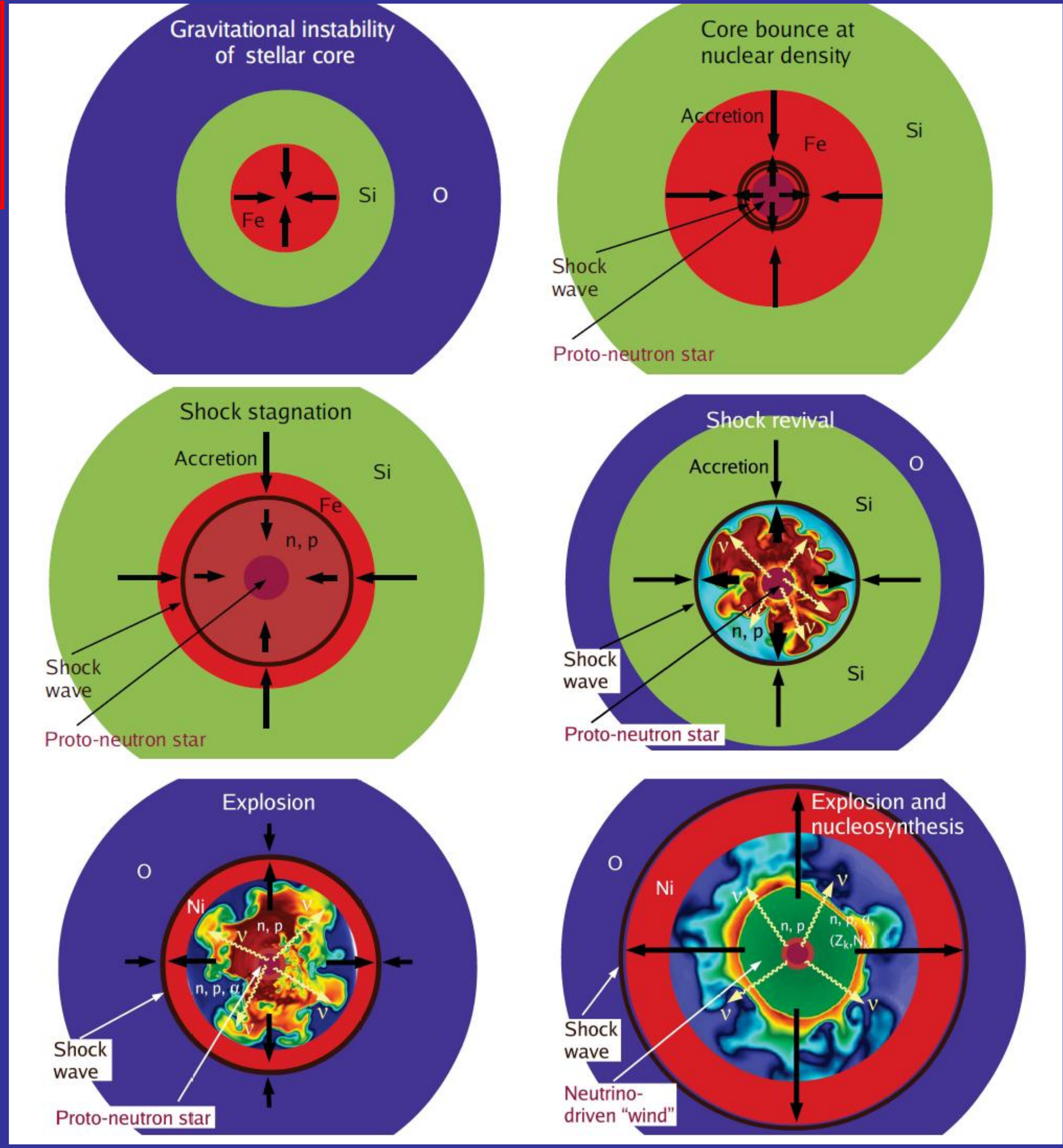
V.S. BEREZINSKY et al**,** Nuovo Cimento, v. **11**, p. 287, (1988).

Neutrino-convective mechanism of supernova explosion

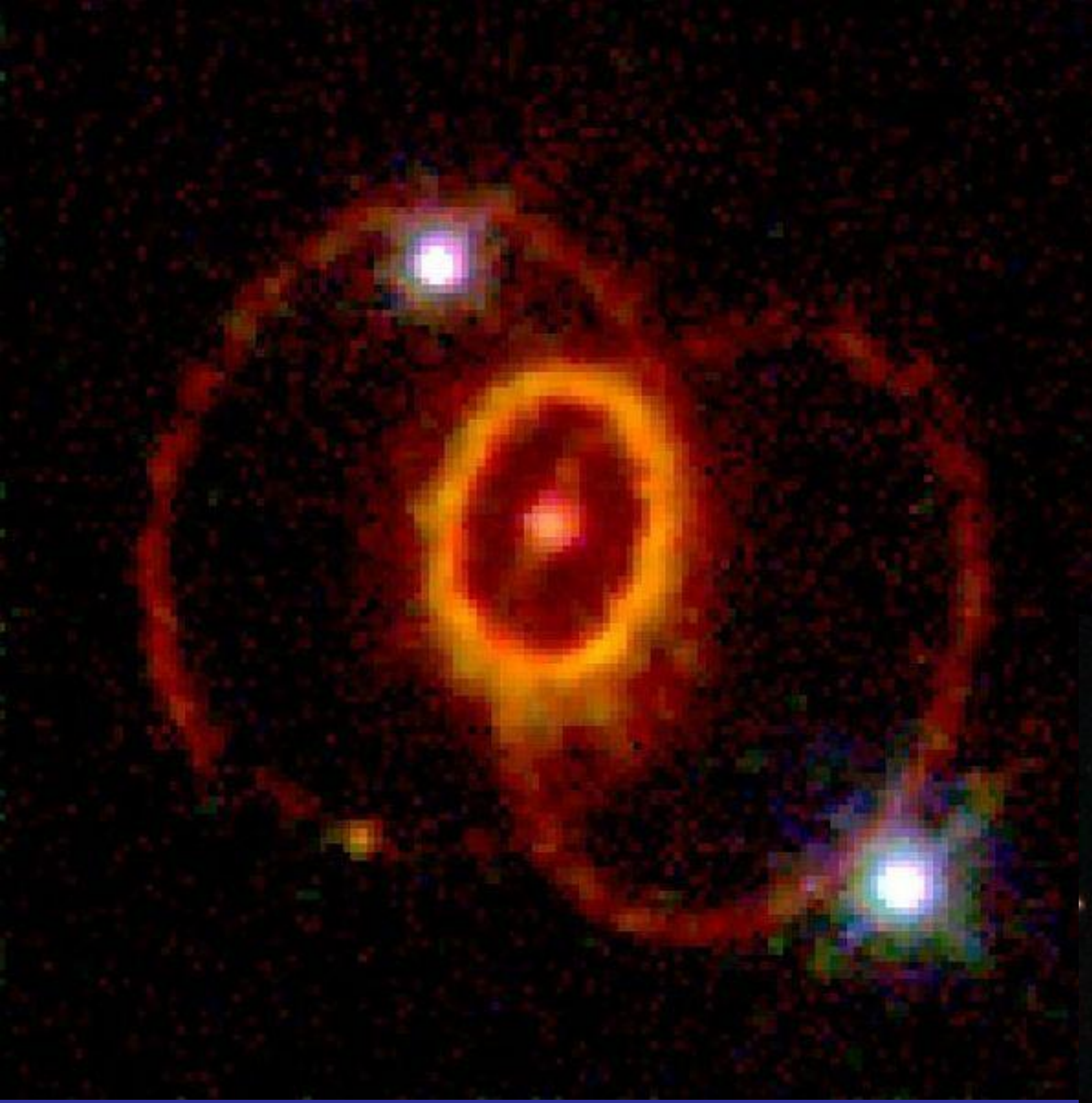
From: Janka H.-T. et al.

«Core-collapse supernovae: Reflections and directions»

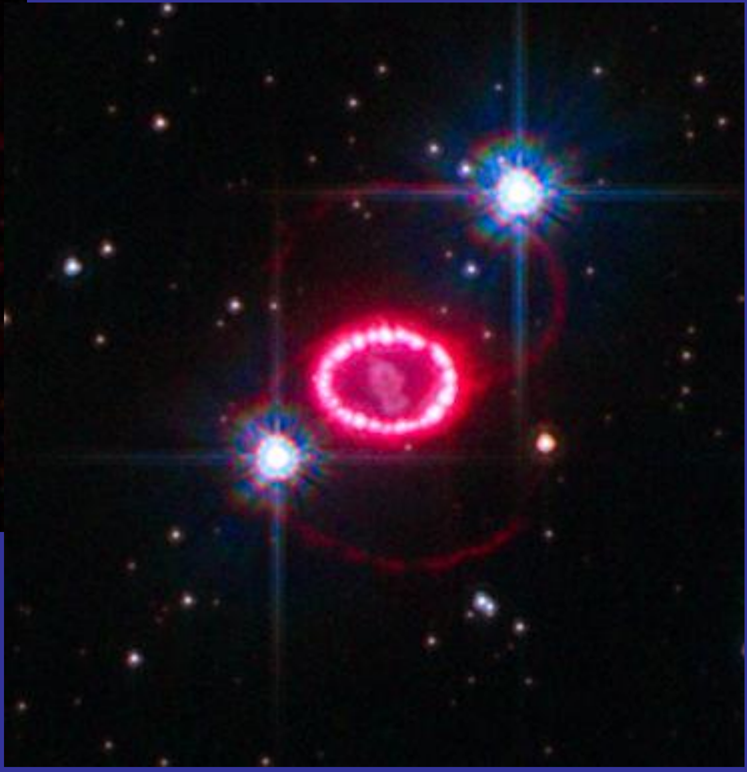
Progress of Theoretical and Experimental Physics, Volume 2012, Issue 1



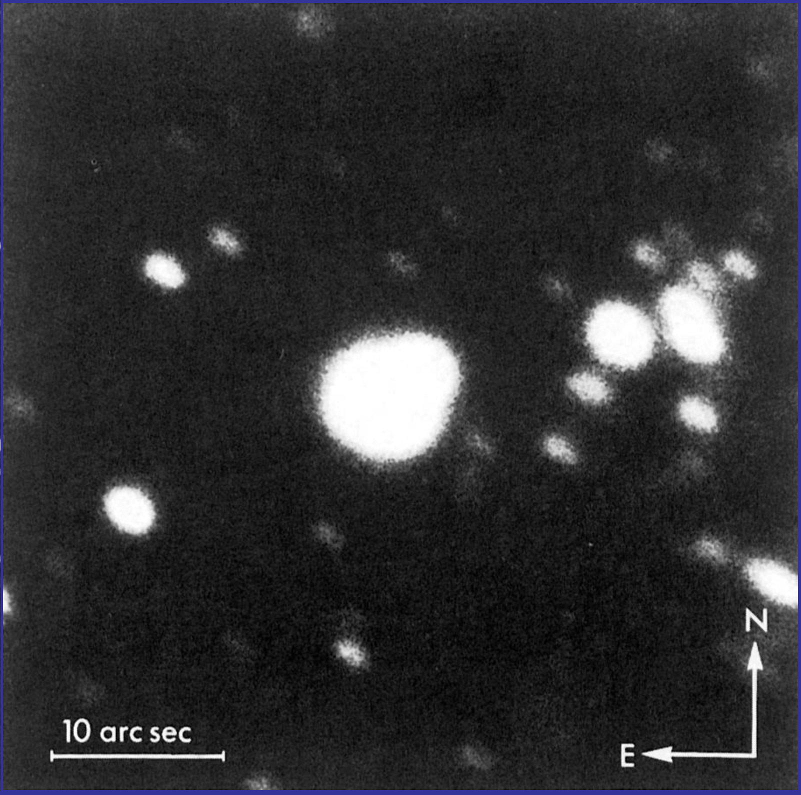
The Puzzle of SN1987A

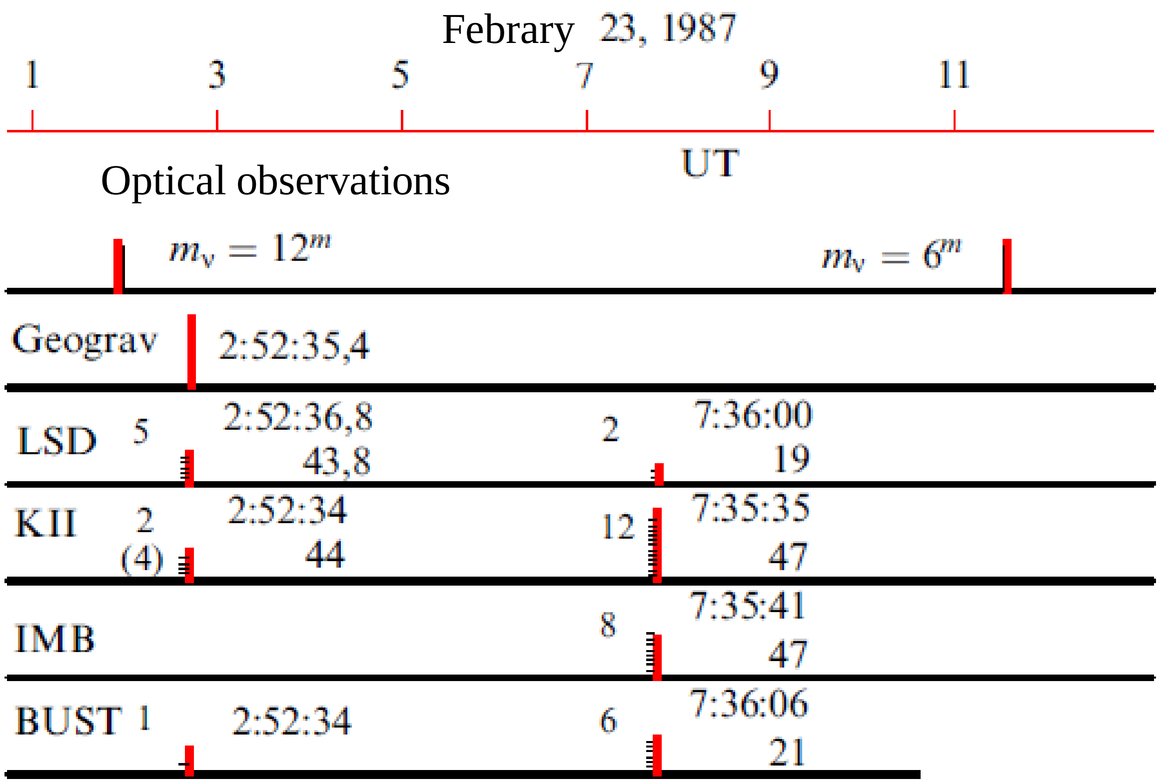


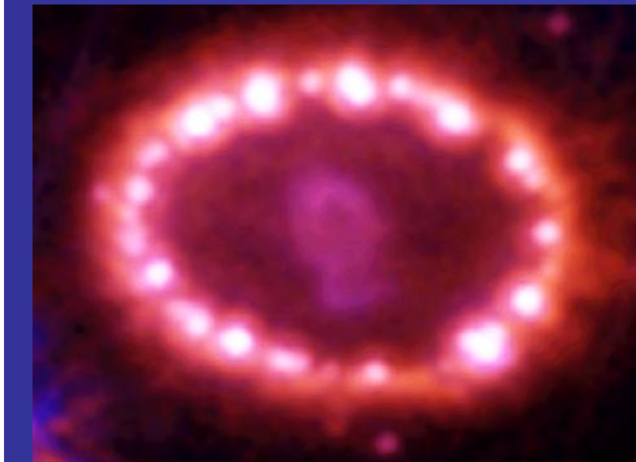
SN 1987A



The star that exploded on February 23 in the Large Magellanic Cloud (the progenitor of supernova 1987A) has now been identified. It was catalogued by in 1969 as an OB star of 12th magnitude and given the designation **Sanduleak-69 202**. Observations at the European Southern Observatory in the mid-1970's allowed to classify it as of spectral type B3 I, that is a very hot, supergiant star. **Credit:** ESO







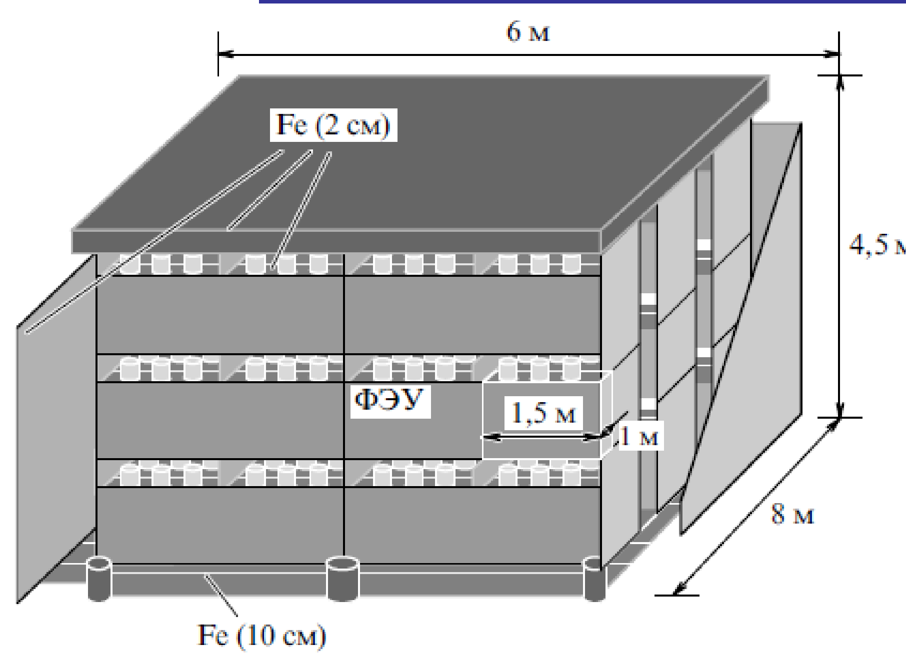
$$\nu_e + (A, Z) \rightarrow e^- + (A, Z+1)\,,$$

$$\nu_e + (A, Z) \rightarrow \nu_e' + (A, Z)^*\,,$$

$$\tilde{\nu}_e + p \rightarrow n + e^+\,,$$

$$E_{e^+} = E_{\tilde{\nu}} - 1{,}3\ \text{МэВ}\,,$$

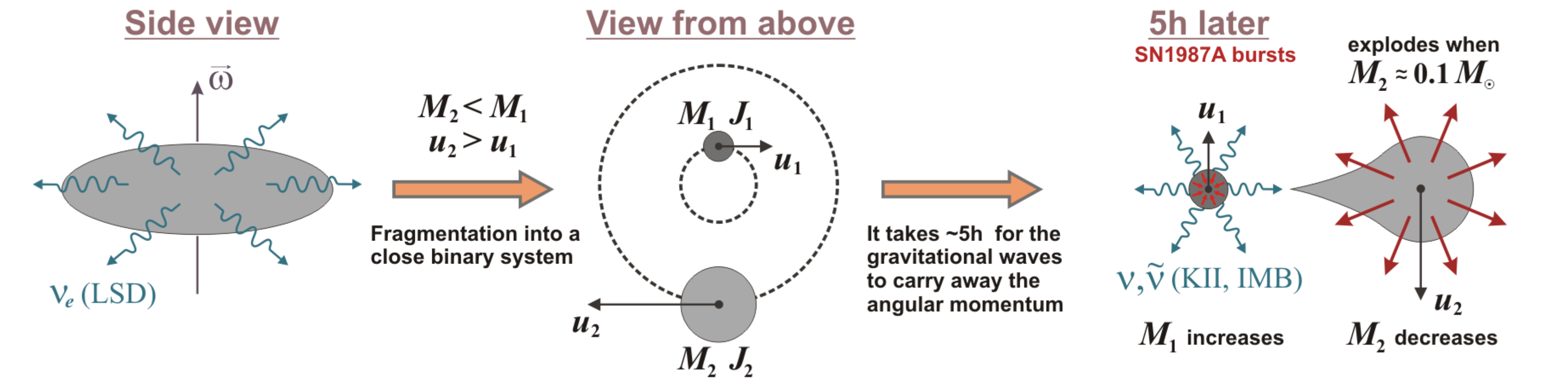
$$n + p \rightarrow d + \gamma\,(2{,}2\ \text{МэВ})$$



O.G. Ryazhskaya, UFN 176, №10, 2006

Rotational breakup neutron star explosion scenario

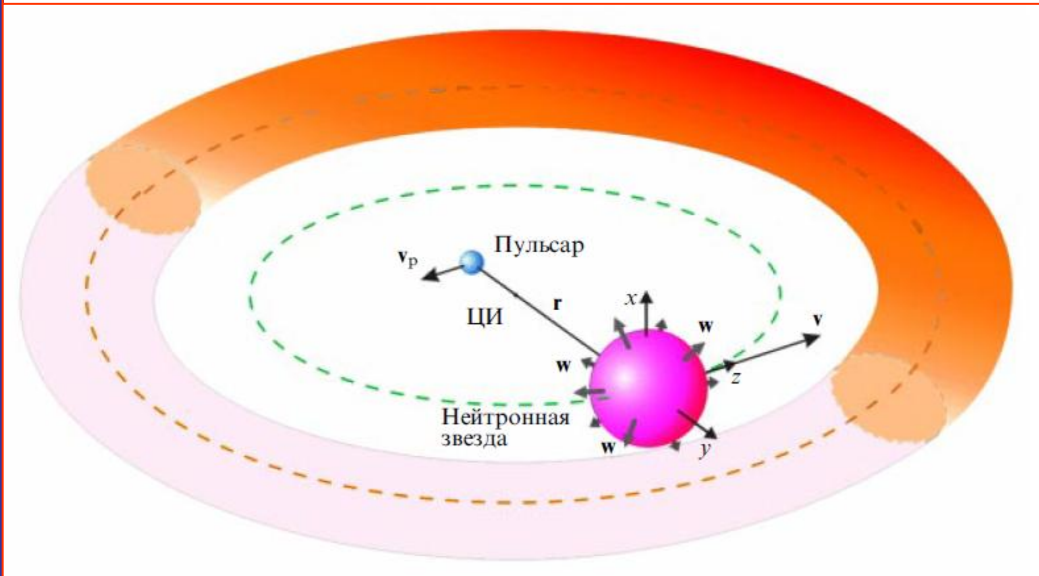
Imshennik, *Sov. Astron. Lett.* 18, 194 (1992)

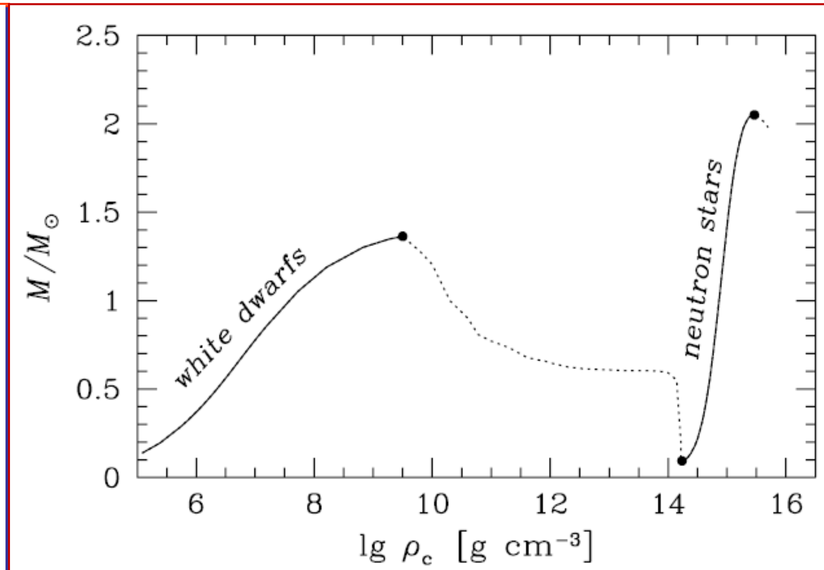


The rotational energy of the collapsing core E_{rot} reaches the limit of stability with respect to fragmentation: $E_{rot}/|E_g| > 0.27$ (E_g is the core gravitational energy)

The binary components begin to approach each other due to the loss of total angular momentum and kinetic energy of orbital motion through the radiation of gravitational waves.

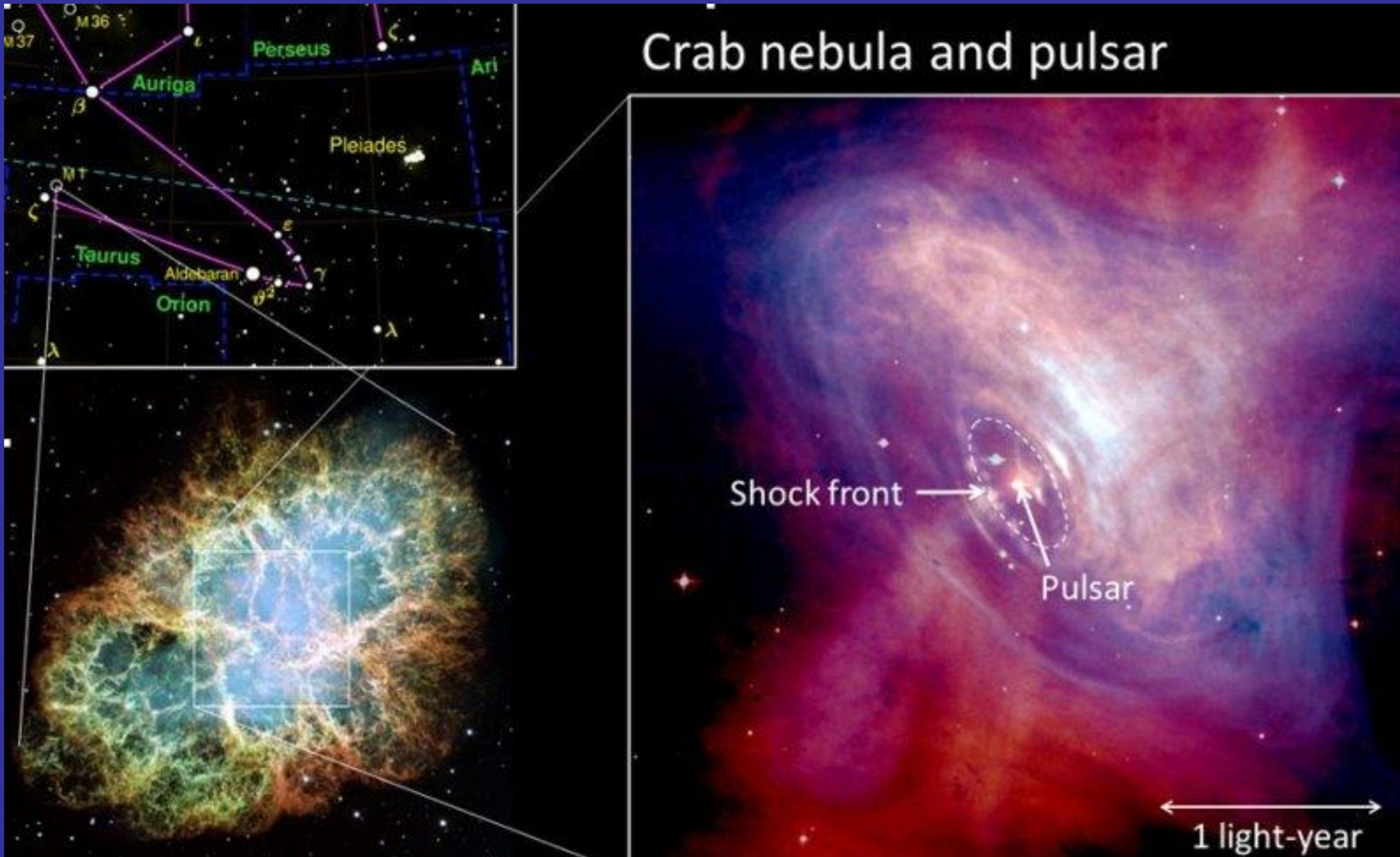
Less massive component fills its Roche lobe. There begins a rapid mass transfer from the component M_2 to the component M_1. Low-mass NS explodes when its mass decreases to the minimum possible mass of a NS.





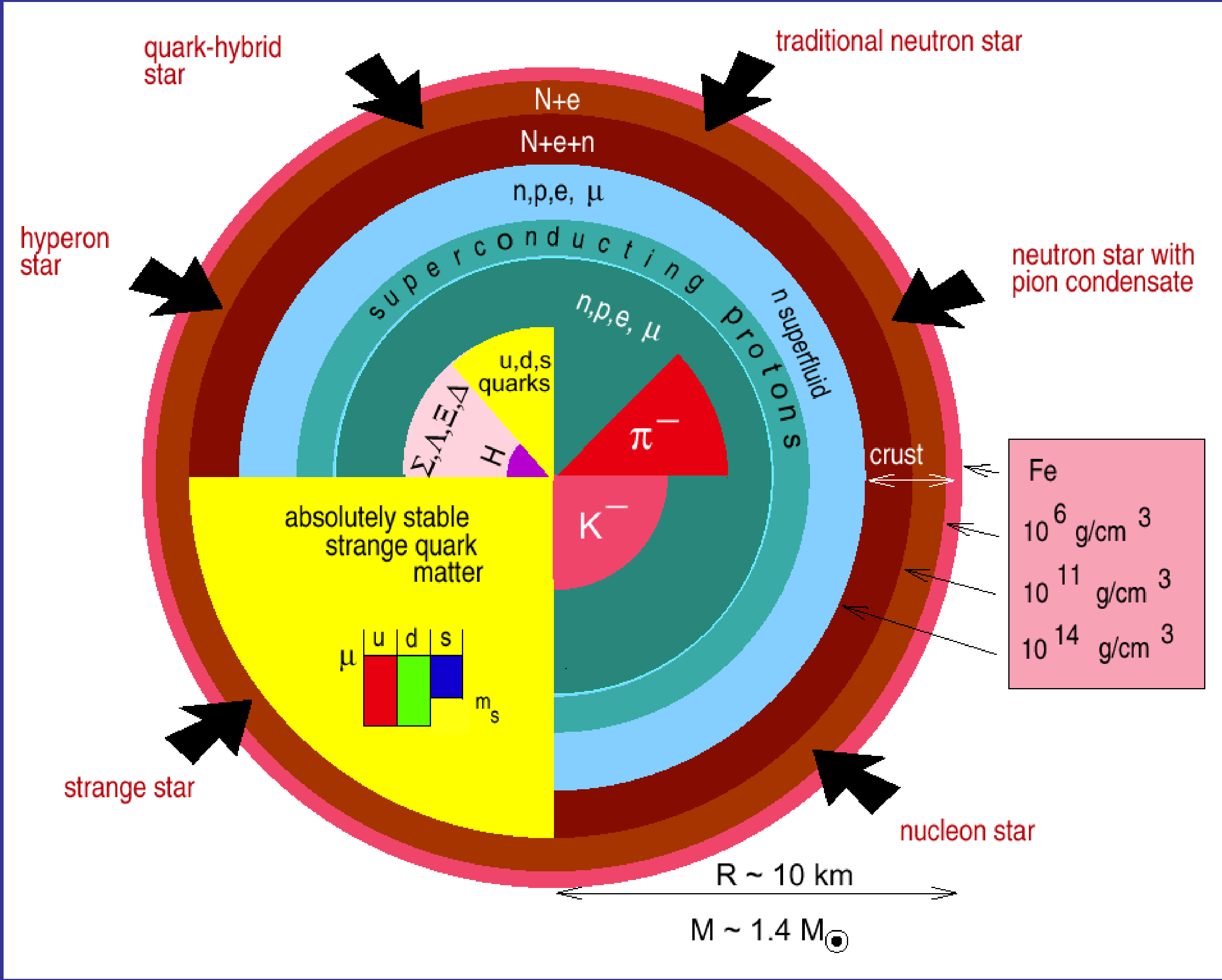
Exotic mechanisms:

Quark and hybrid stars

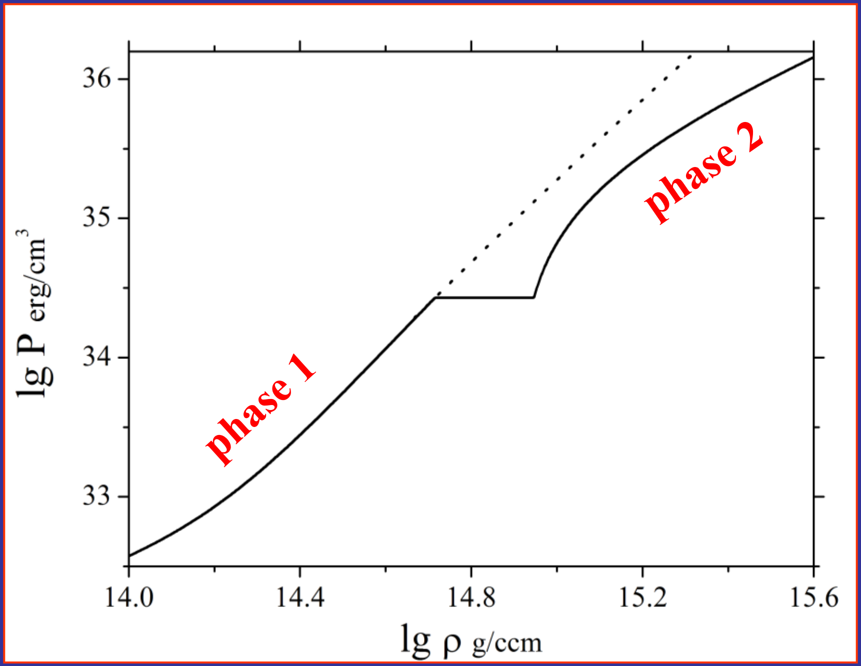

Crab nebula and pulsar
M36
M37
Perseus
Ari
Auriga
Pleiades
M1
Taurus
Aldebaran
Orion
Shock front
Pulsar
1 light-year

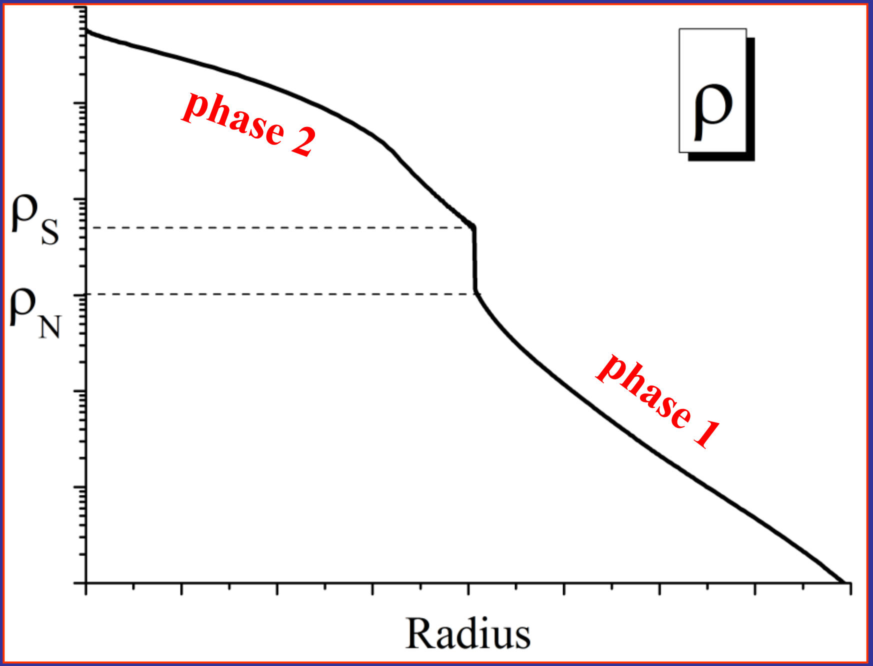

Neutron Star
Vancouver
www.kindaroomy.com

Composition of a Neutron Star



Maxwellian-type phase transition causes a density jump inside the star





$$\lambda_c = \frac{\rho_S}{\rho_N} = \frac{3}{2}$$

W.H. Ramsey, MNRAS 110 (1950) 325
M.J. Lighthill, MNRAS 110 (1950) 339

$$\lambda^{rel} = \frac{\varepsilon_2}{\varepsilon_1}$$

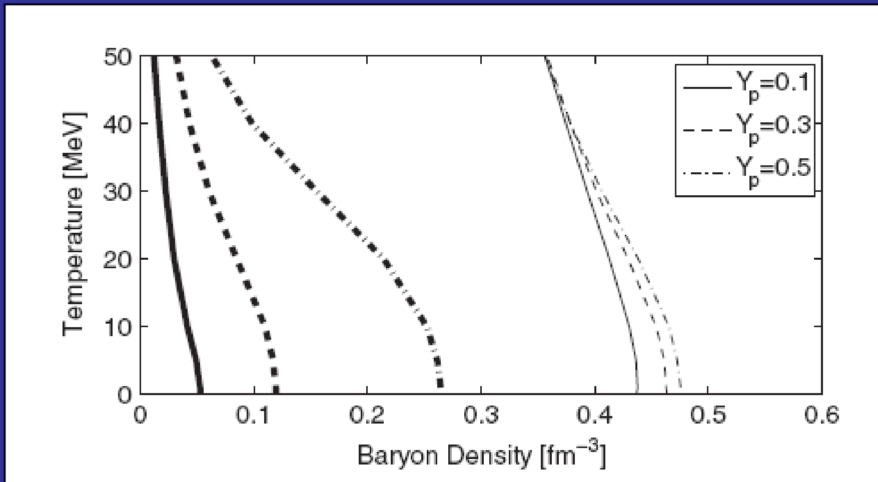
$$\lambda_c^{rel} = \frac{3}{2}\left(1 + \frac{P_*}{\varepsilon_1}\right)$$

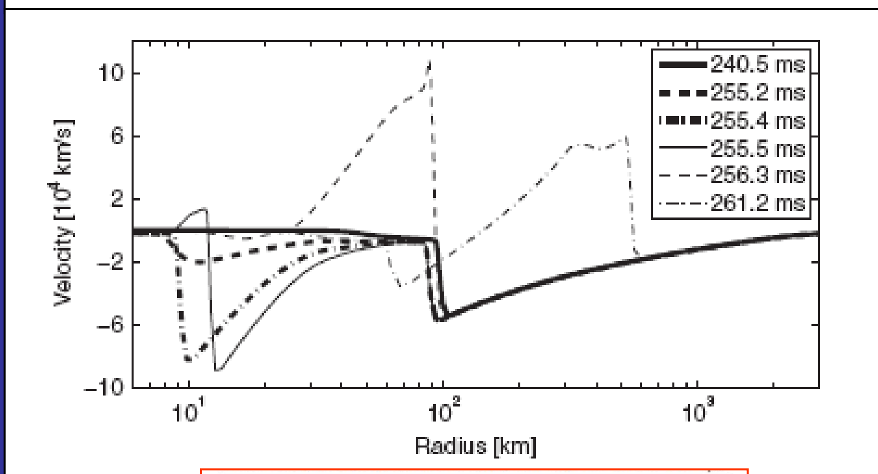
Z.F. Seidov (1971)

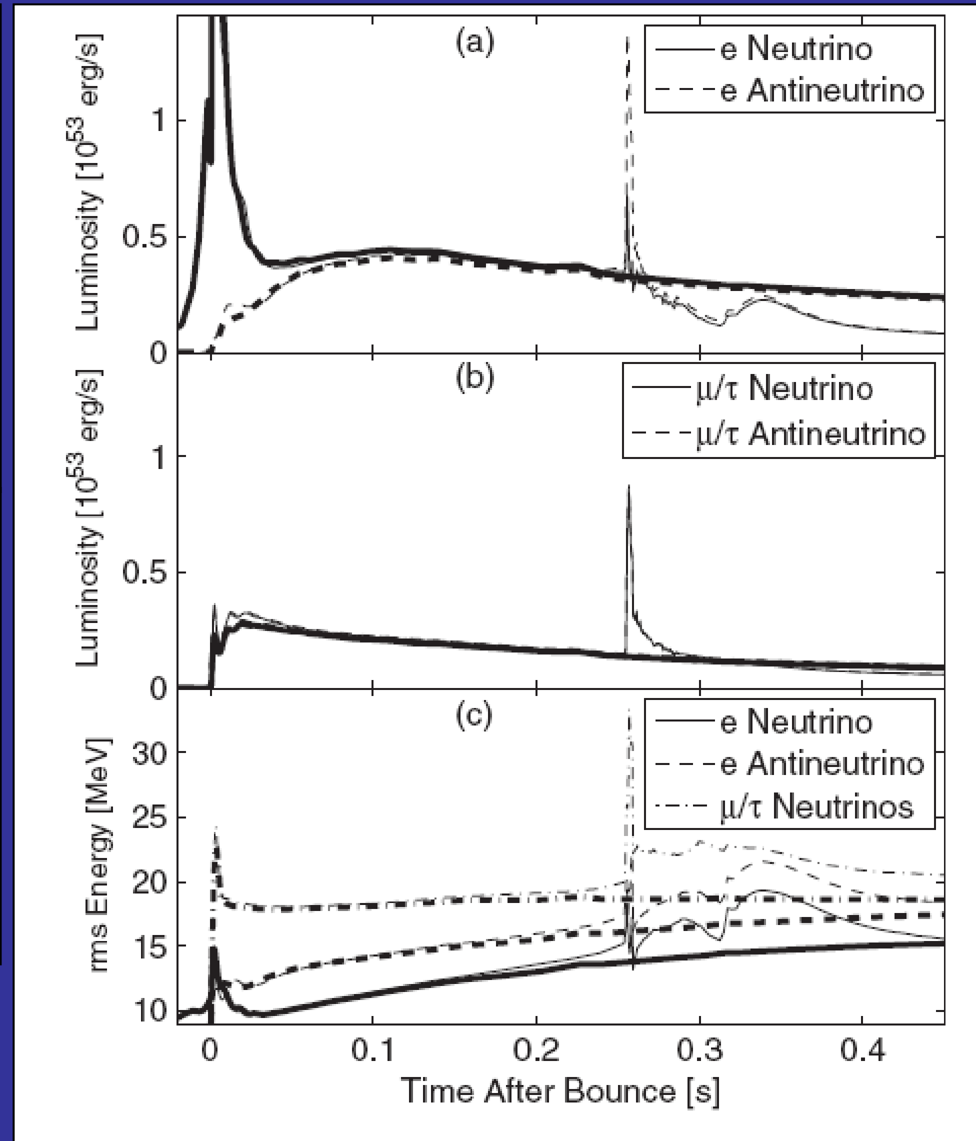
PRL **102,** 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Signals of the QCD Phase Transition in Core-Collapse Supernovae

I. Sagert,[1] T. Fischer,[3] M. Hempel,[1] G. Pagliara,[2] J. Schaffner-Bielich,[2] A. Mezzacappa,[4]
F.-K. Thielemann,[3] and M. Liebendörfer[3]



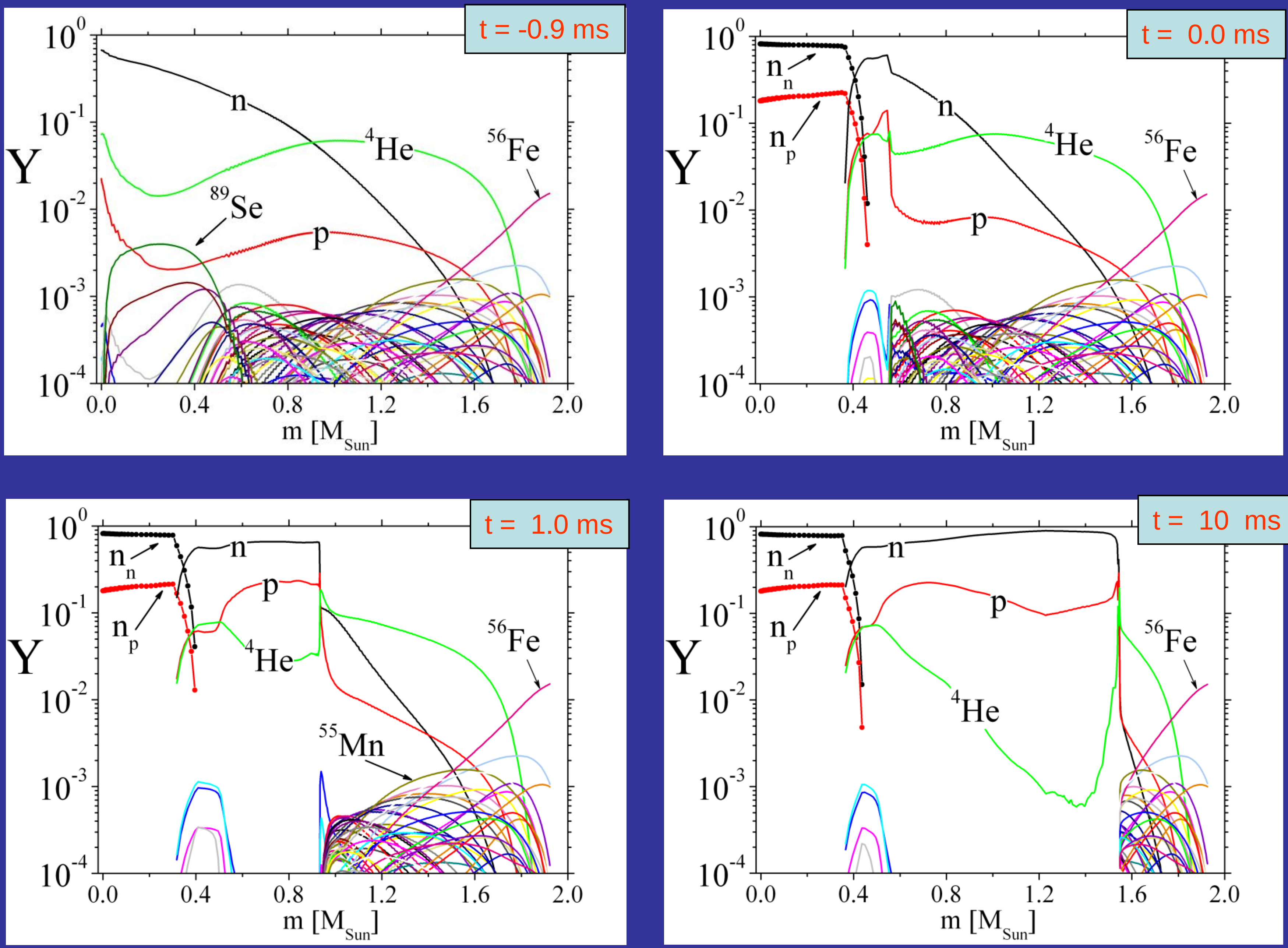


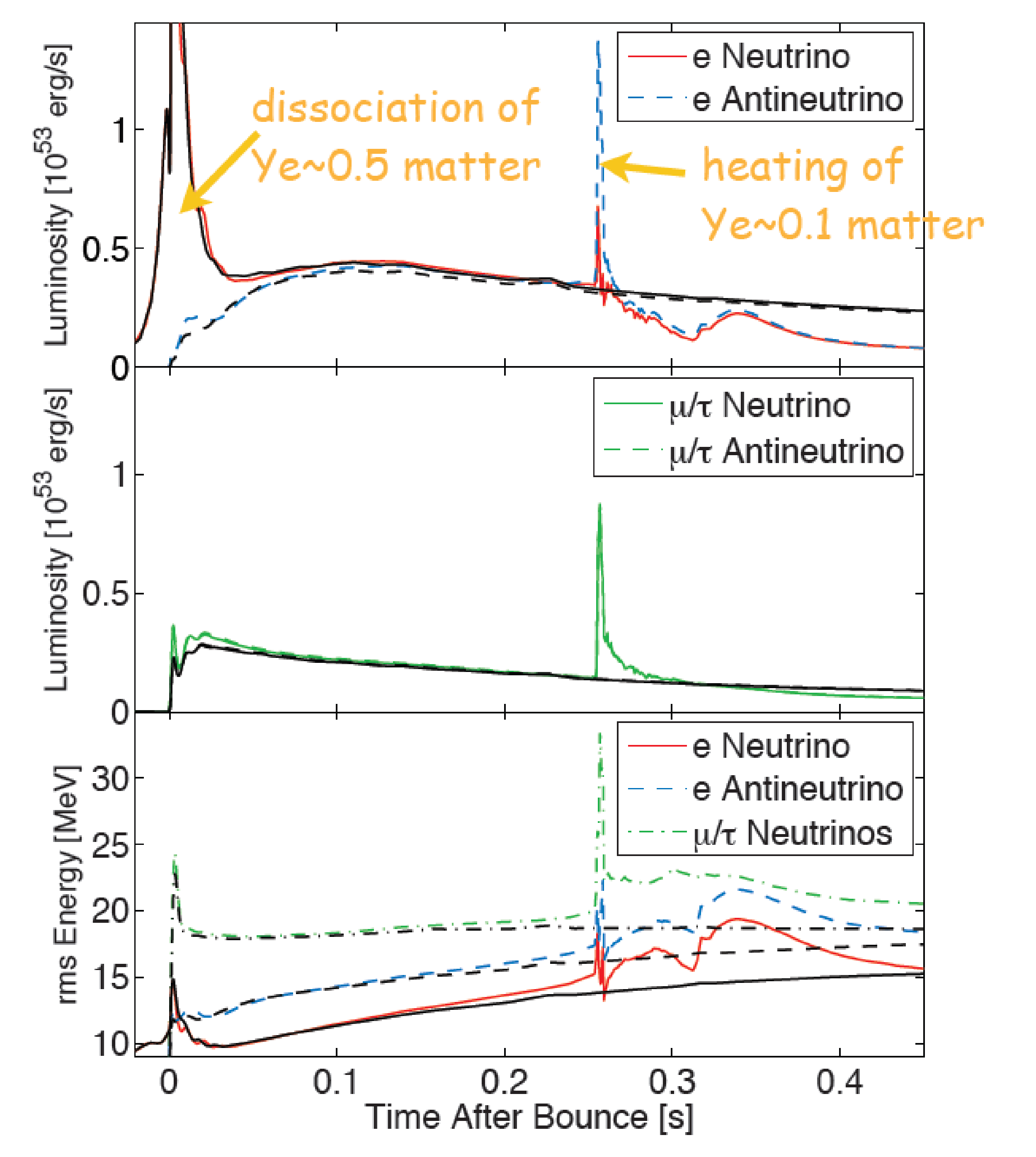


Prog. [$M_\odot$]	EOS	t_{pb} [ms]	M_Q [$M_\odot$]	M_{mix} [$M_\odot$]	M_{pns} [$M_\odot$]	E_{expl} [10^{51}erg]	BE [10^{53}erg]	M_G [$M_\odot$]
10	*eos*1	255	0.850	0.508	1.440	0.44	3.40	1.25
10	*eos*2	448	1.198	0.161	1.478	1.64	3.19	1.30
15	*eos*1	209	1.146	0.320	1.608	0.42	4.08	1.38
15	*eos*2	330[a]	1.496	0.116	1.700	...[b]	4.28	1.46

[a]moment of black hole formation
[b]black hole formation before explosion

Shock wave propagation inside a collapsing stellar core



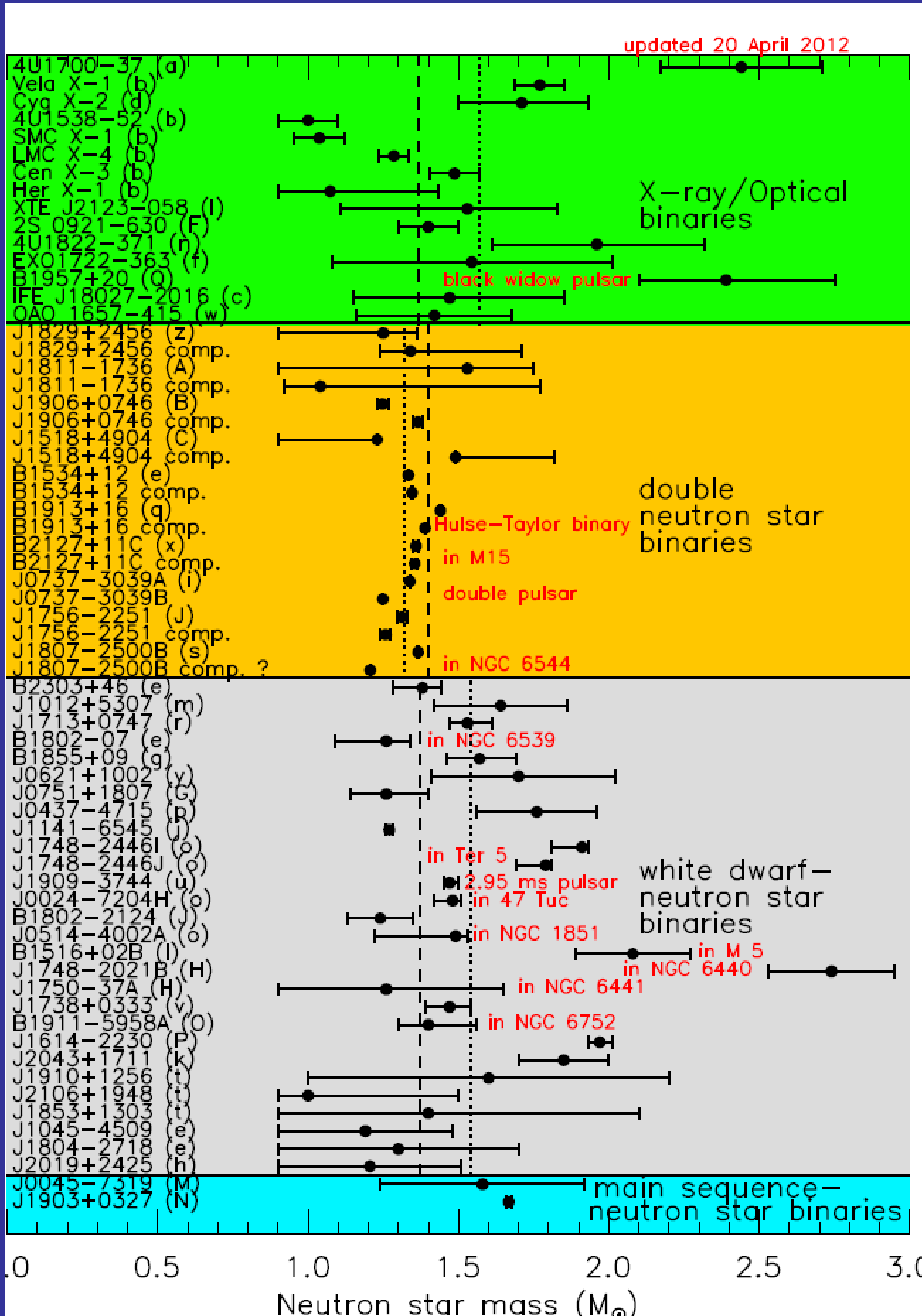


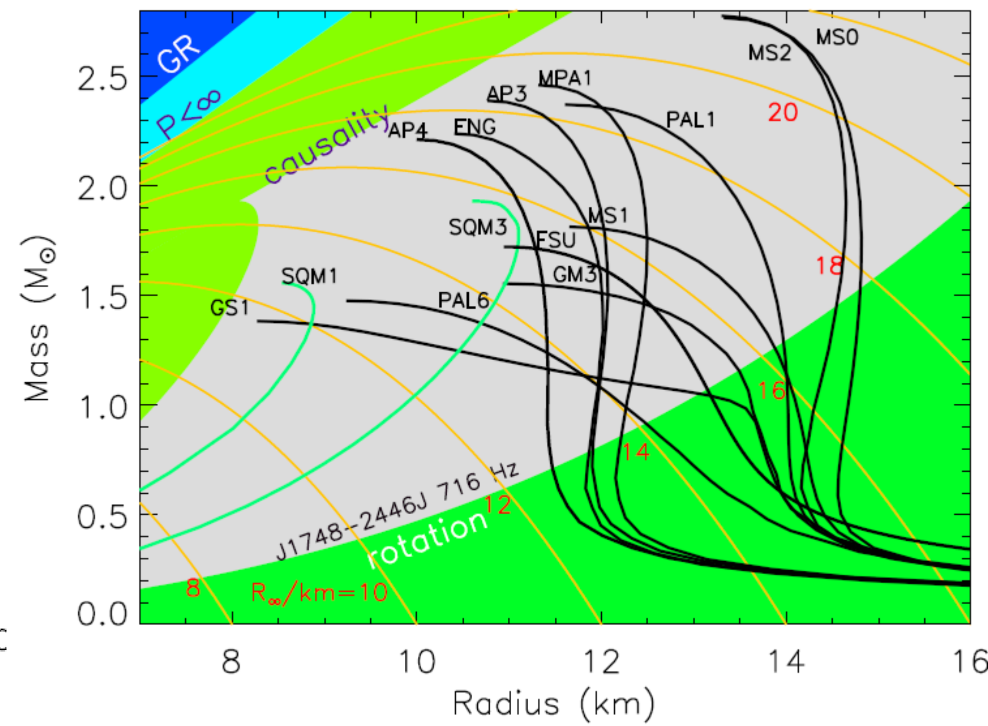
e Neutrino
e Antineutrino
dissociation of
Ye~0.5 matter
heating of
Ye~0.1 matter
Luminosity [10^{53} erg/s]
1
0.5
0
μ/τ Neutrino
μ/τ Antineutrino
Luminosity [10^{53} erg/s]
1
0.5
0
e Neutrino
e Antineutrino
μ/τ Neutrinos
rms Energy [MeV]
30
25
20
15
10
0
0.1
0.2
0.3
0.4
Time After Bounce [s]

Maximum neutron star mass

J.M. Lattimer

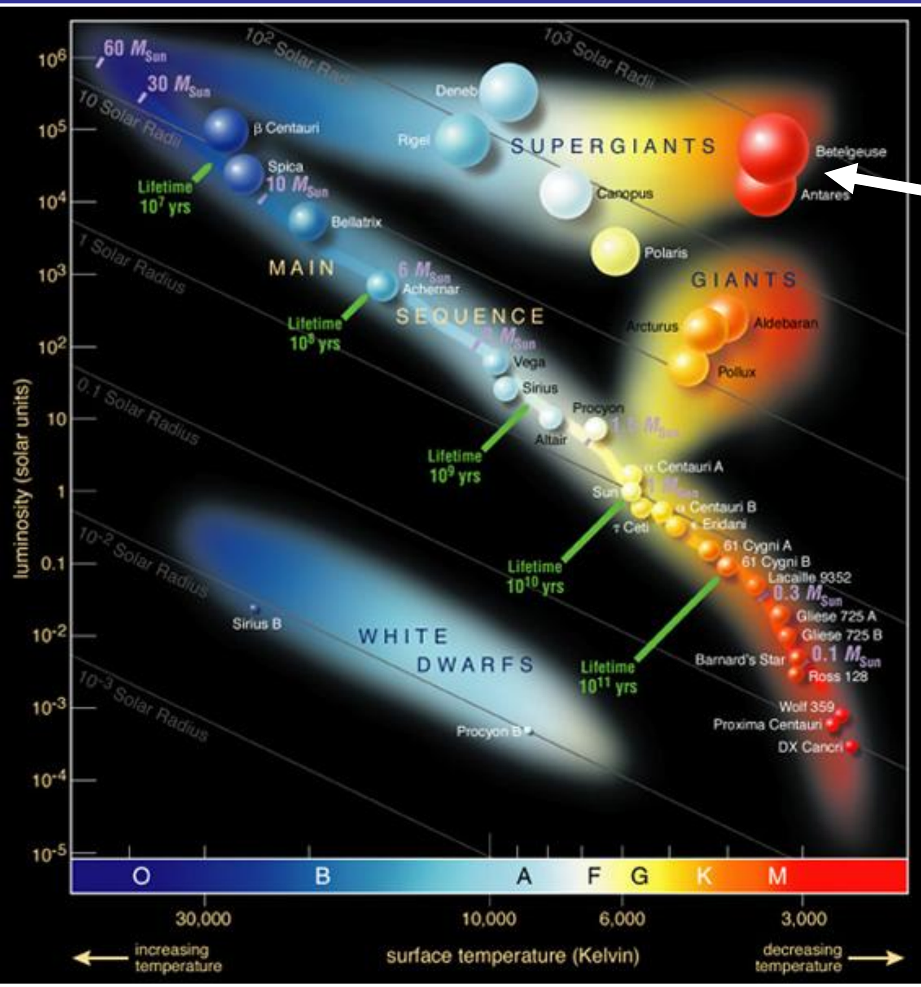
Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

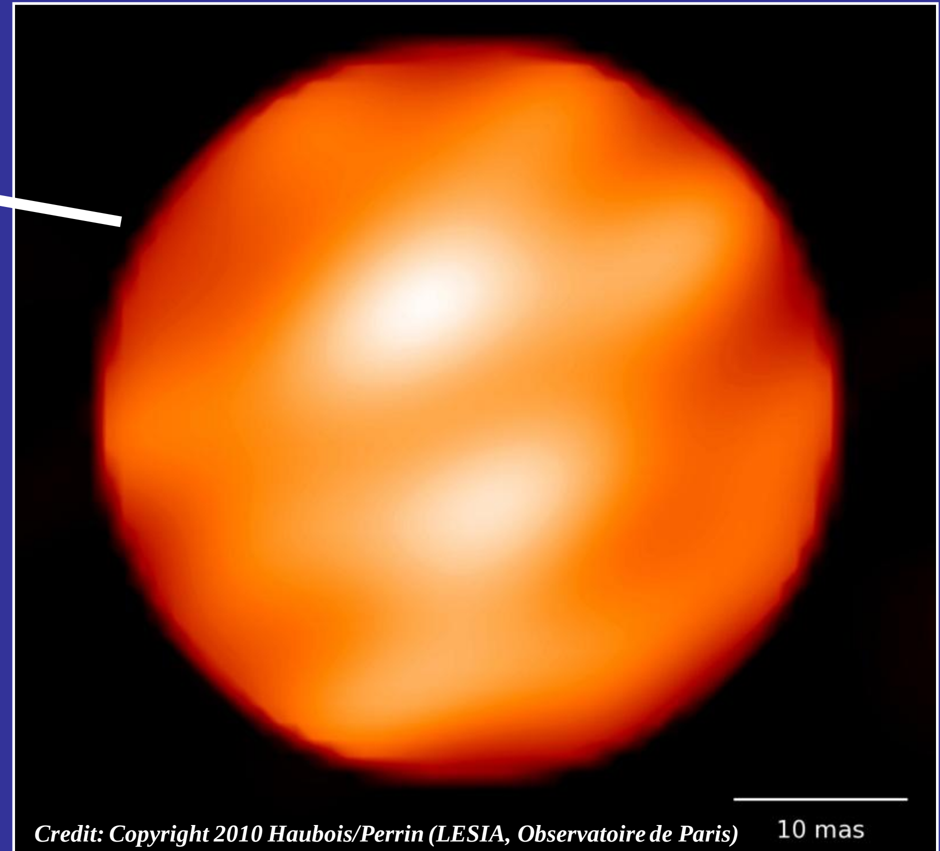




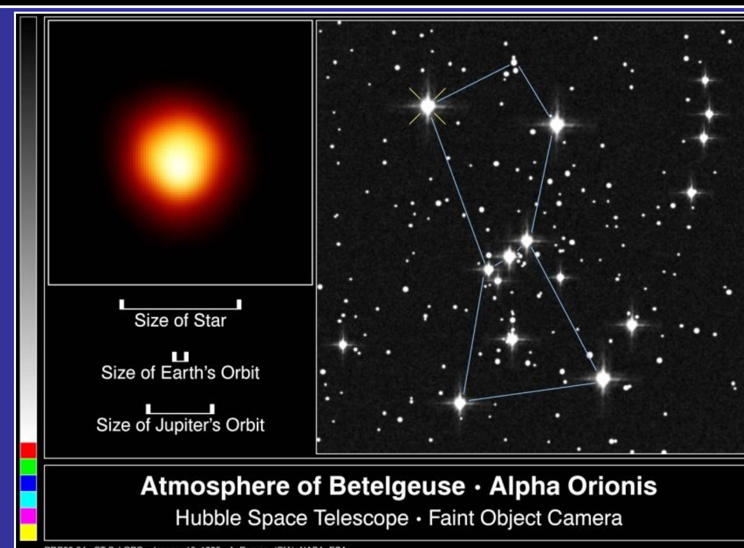
Neutrino signal:

Star death alert





Credit: Copyright 2010 Haubois/Perrin (LESIA, Observatoire de Paris)



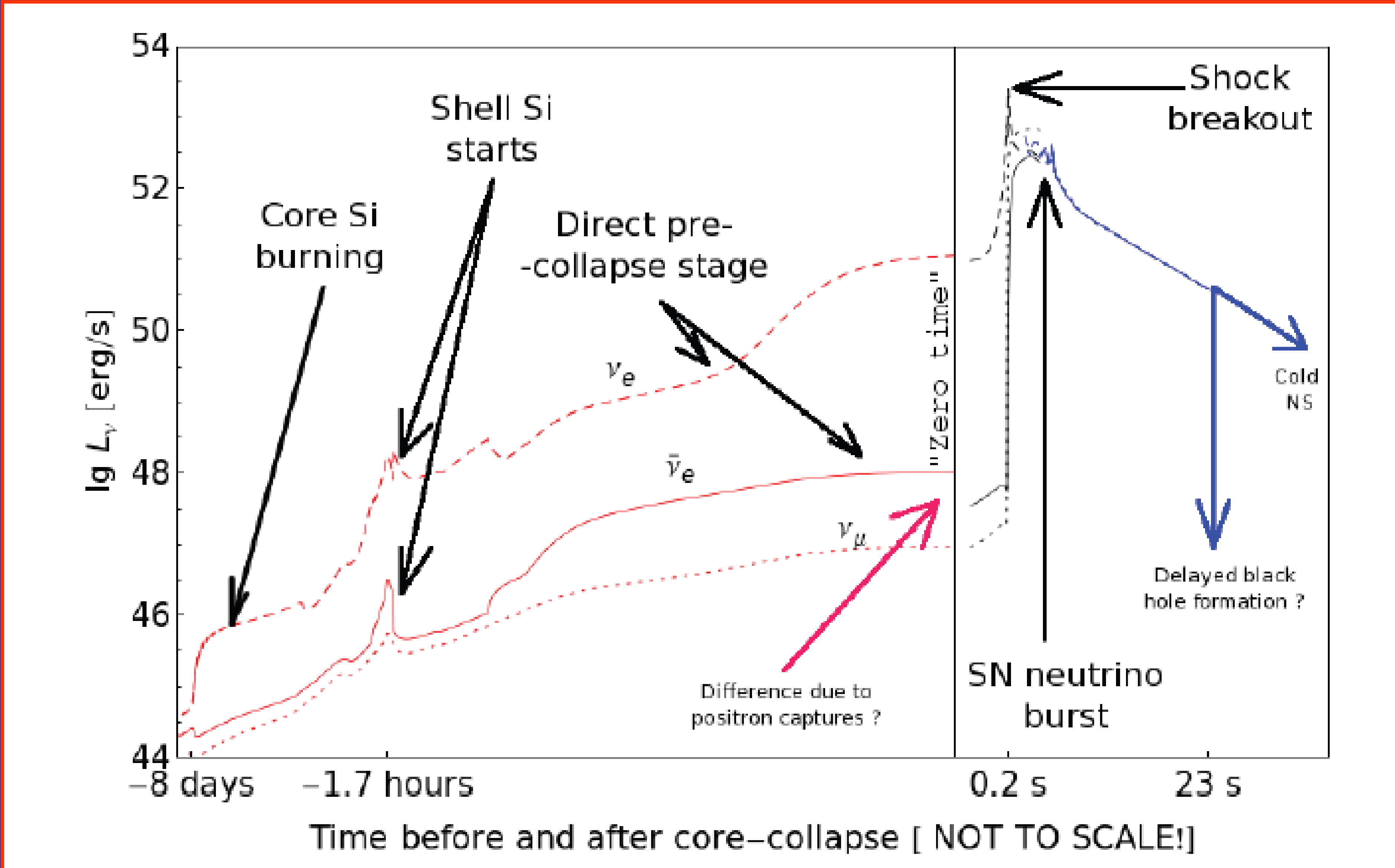
Red Supergiant
Distance ~ 200 pc
Mass ~ 12 Solar
Radius ~ 800 Solar
Luminosity ~ 100 000 Solar

Table 5.1: Major nuclear burning stages for 15 $M_\odot$ and ~~25 $M_\odot$~~ stars (Adapted from [33])*

Burning Stage	T_c (K)	ρ_c (g/cm^3)	$L_{\nu\bar{\nu}}$ (erg/s)	L (erg/s)	$T_{\rm eff}$ (K)	$R_{\rm ph}$ ($R_\odot$)	Time Scale
Hydrogen	3.4 (7)	5.9 (0)	5.3 (36)	8.1 (37)	3.26 (4)	4.6 (0)	1.2 (7)y
Helium	1.6 (8)	1.3 (3)	3.9 (33)	2.3 (38)	1.59 (4)	3.2 (1)	1.3 (6)y
Carbon	6.2 (8)	1.7 (5)	3.4 (38)	3.3 (38)	4.26 (3)	5.3 (2)	6.3 (3)y
Neon	1.3 (9)	1.6 (7)	6.7 (41)	3.7 (38)	4.28 (3)	5.6 (2)	7.0 (0)y
Oxygen	1.9 (9)	9.7 (6)	7.9 (42)	3.7 (38)	4.28 (3)	5.6 (2)	1.7 (0)y
Silicon	3.1 (9)	2.3 (8)	3.4 (44)	3.7 (38)	4.28 (3)	5.6 (2)	6.0 (0)d
Collapse	8.3 (9)	6.0 (9)	6.8 (48)	3.7 (38)	4.28 (3)	5.6 (2)	0.30 s

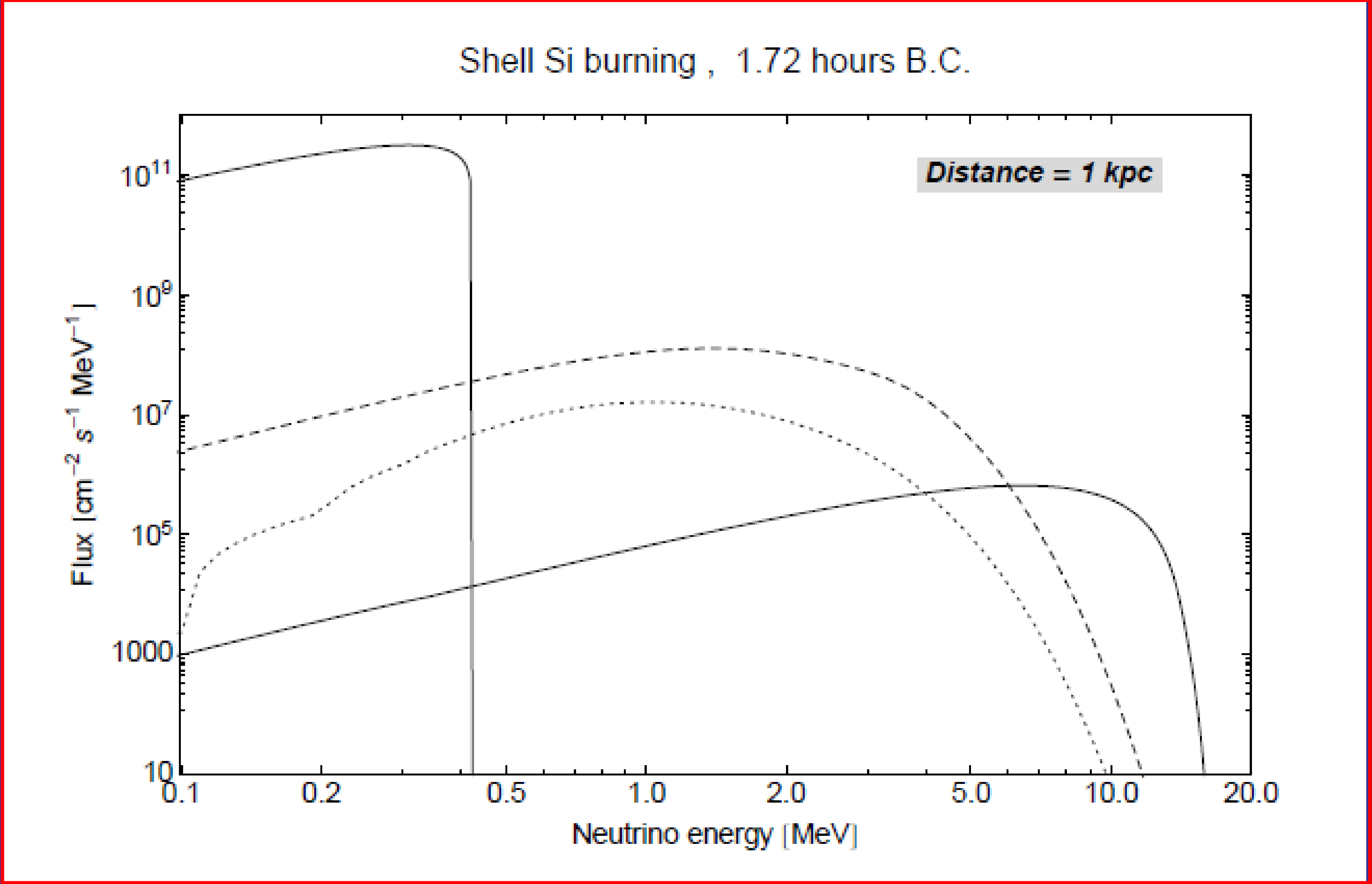
*Notation: 3.4 (7)$\equiv 3.4 \cdot 10^7$ etc.

Weaver, Zimmerman, Woosley ApJ v. 225, p. 1021 (1978)

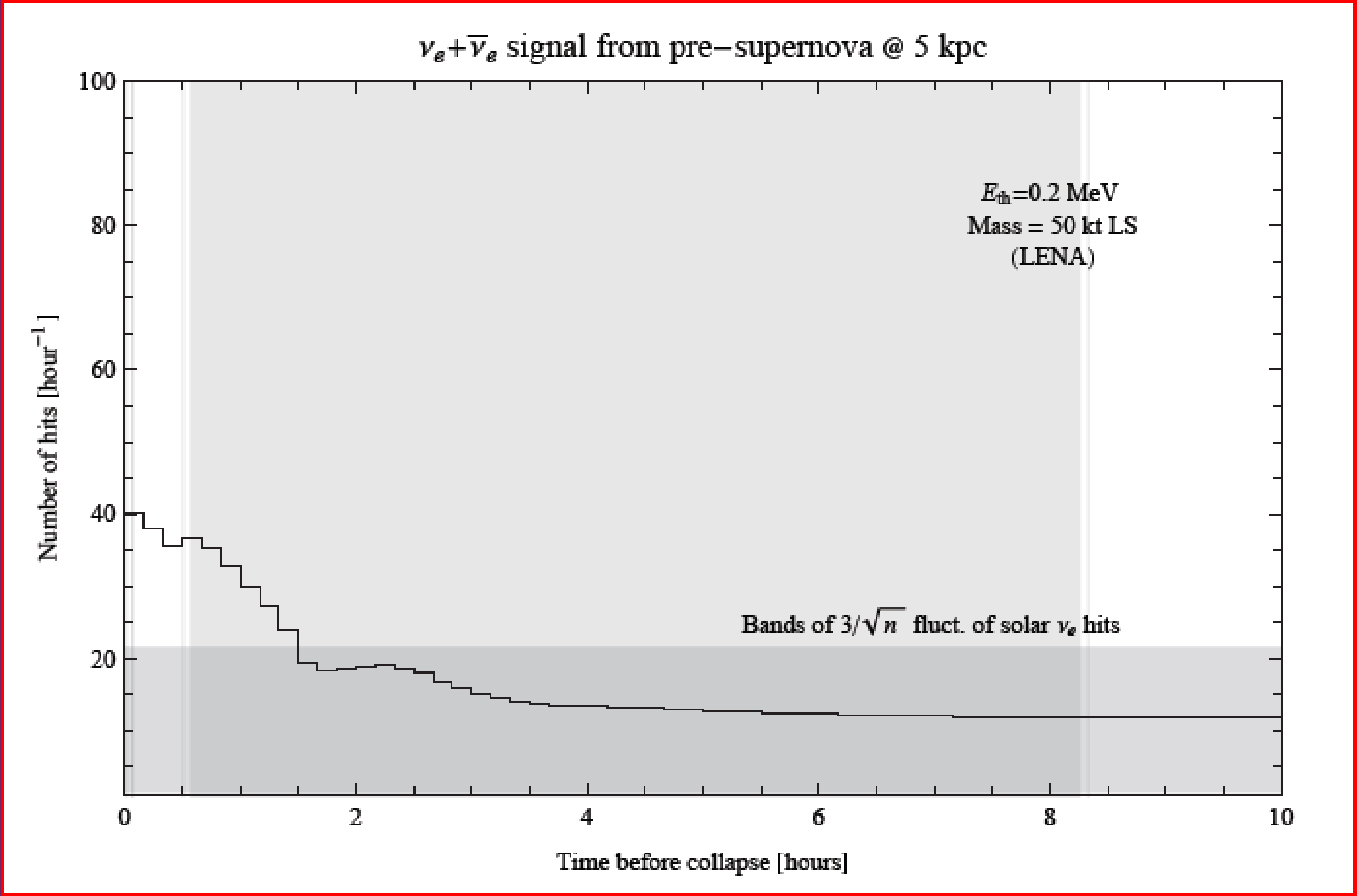


From: A. Odrzywolek

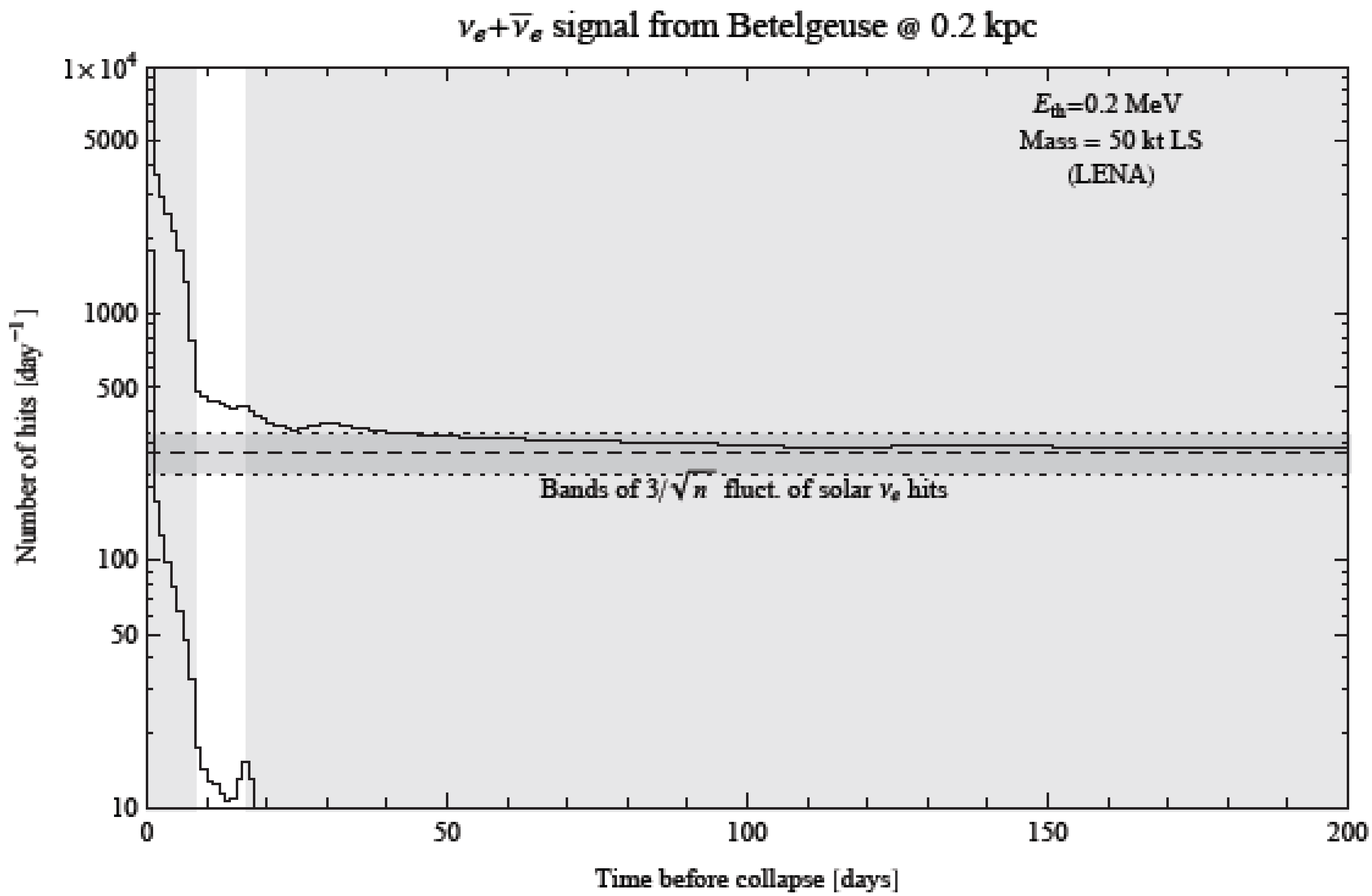
During Si-burning phase 1 neutron/day/kiloton of water 1kpc distance



Kutschera, Odrzywolek, Misiaszek. Acta Phys. Pol. B, 40, 11 (2009)

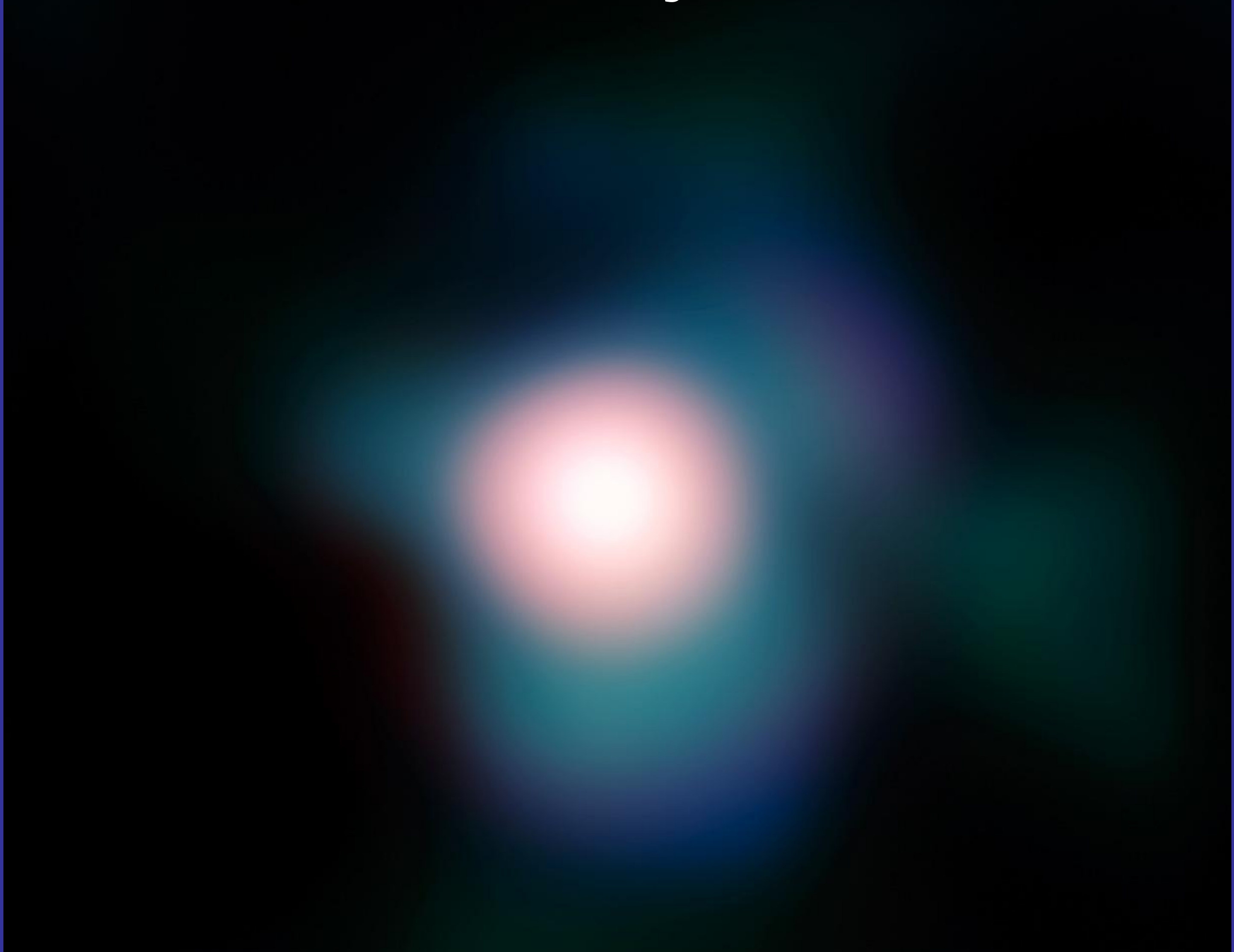


Kutschera, Odrzywolek, Misiaszek. Acta Phys. Pol. B, 40, 11 (2009)



Kutschera, Odrzywolek, Misiaszek. Acta Phys. Pol. B, 40, 11 (2009)

Thank you!



Betelgeuse

Image by ESO/P. Kervella - http://www.eso.org/public/images/eso0927b/