Нейтринный сигнал от коллапсирующих сверхновых

А.В. Юдин, ИТЭФ

Дубна, 11.05.2016

Звёзды

Table 10.1: Some integral properties of the cosmic mixture

<u>Mass fraction of</u>			
Hydrogen	X	= 0.707	
Helium	Y	= 0.274	
Metals	Z	= 0.019	
CNOF-isotopes	X_{CNOF}	= 0.0137	=0.726 Z
α-nuclides (^{20}Ne→^{40}Ca)	X_α	$= 3.30\cdot10^{-3}$	=0.175 Z
Iron-56	X_{56}	$= 1.16\cdot10^{-3}$	=0.062 Z
Iron-group (Ti→Fe→Cu)	X_{Fe}	$= 1.38\cdot10^{-3}$	=0.073 Z
Heavies (beyond Iron-group)	X_{h}	$= 2.9\cdot10^{-6}$	
Pure r-nuclides	X_{r}	$= 5.5\cdot10^{-8}$	
Pure s-nuclides	X_{s}	$= 4.0\cdot10^{-8}$	
p-nuclides	X_{p}	$= 3.9\cdot10^{-9}$	
<u>Metals:</u>			
Mean atomic number	$\langle Z\rangle$	= 8.409	
Mean atomic mass number	$\langle \mathcal{A}\rangle$	= 16.94	
Mean molecular weight of the whole mixture	μ	= 0.6176	
Mean molecular weight per electron	μ_e	= 1.179	
Normalizing constant	C	$= 2.515\cdot10^{-11}$	

$$0.08M_\odot \le M \le 200M_\odot$$

$$10^{-4}L_\odot \le L \le 10^{6}L_\odot$$

$$10^{-2}R_\odot \le R \le 10^{3}L_\odot$$

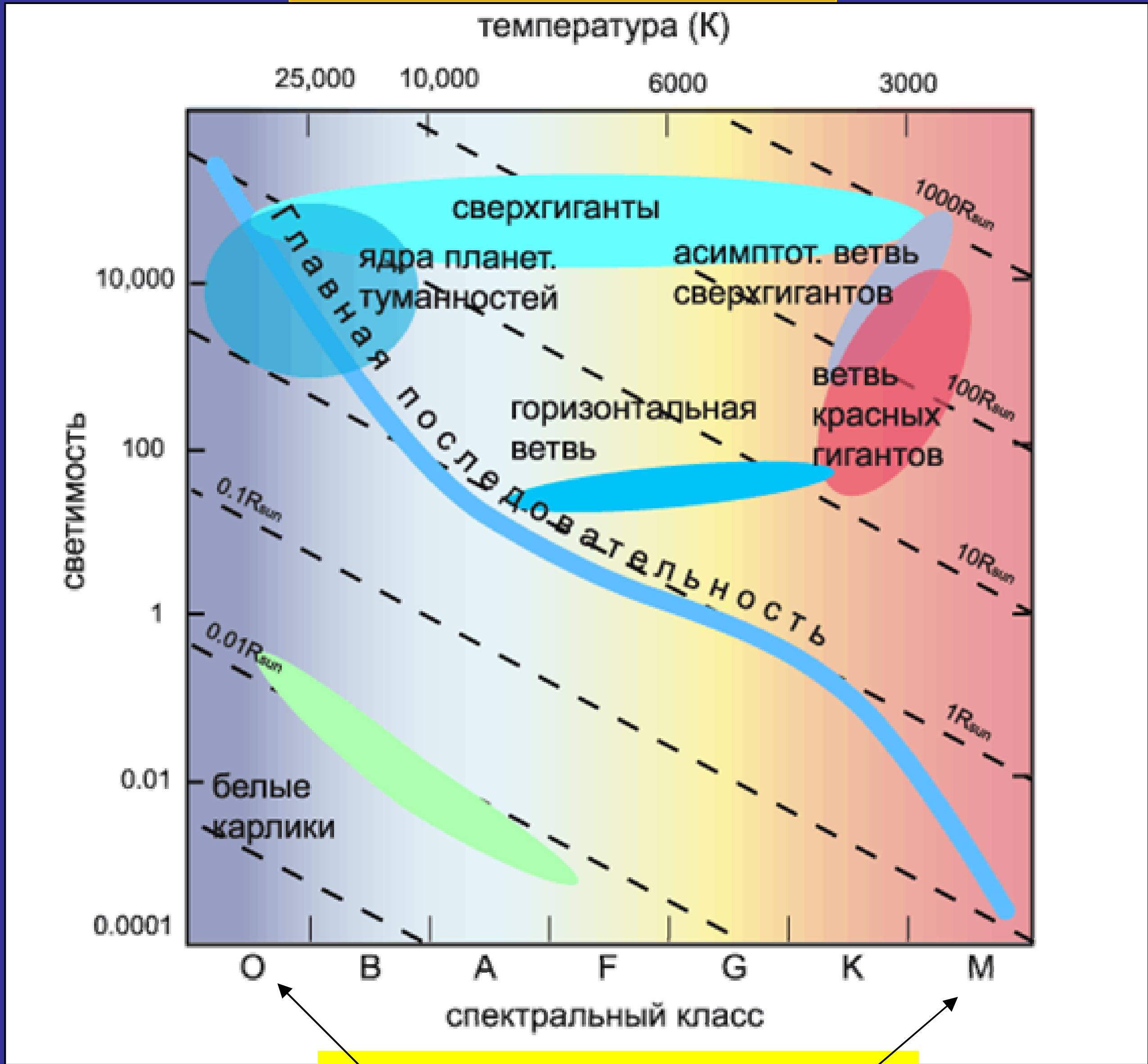
$$M_\odot \approx 2\times10^{33}\,г$$

$$R_\odot \approx 7\times10^{10}\,см \approx 100R_\oplus$$

$$L_\odot \approx 3.8\times10^{33}\,эрг$$

Диаграмма Герцшпрунга-Рассела

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

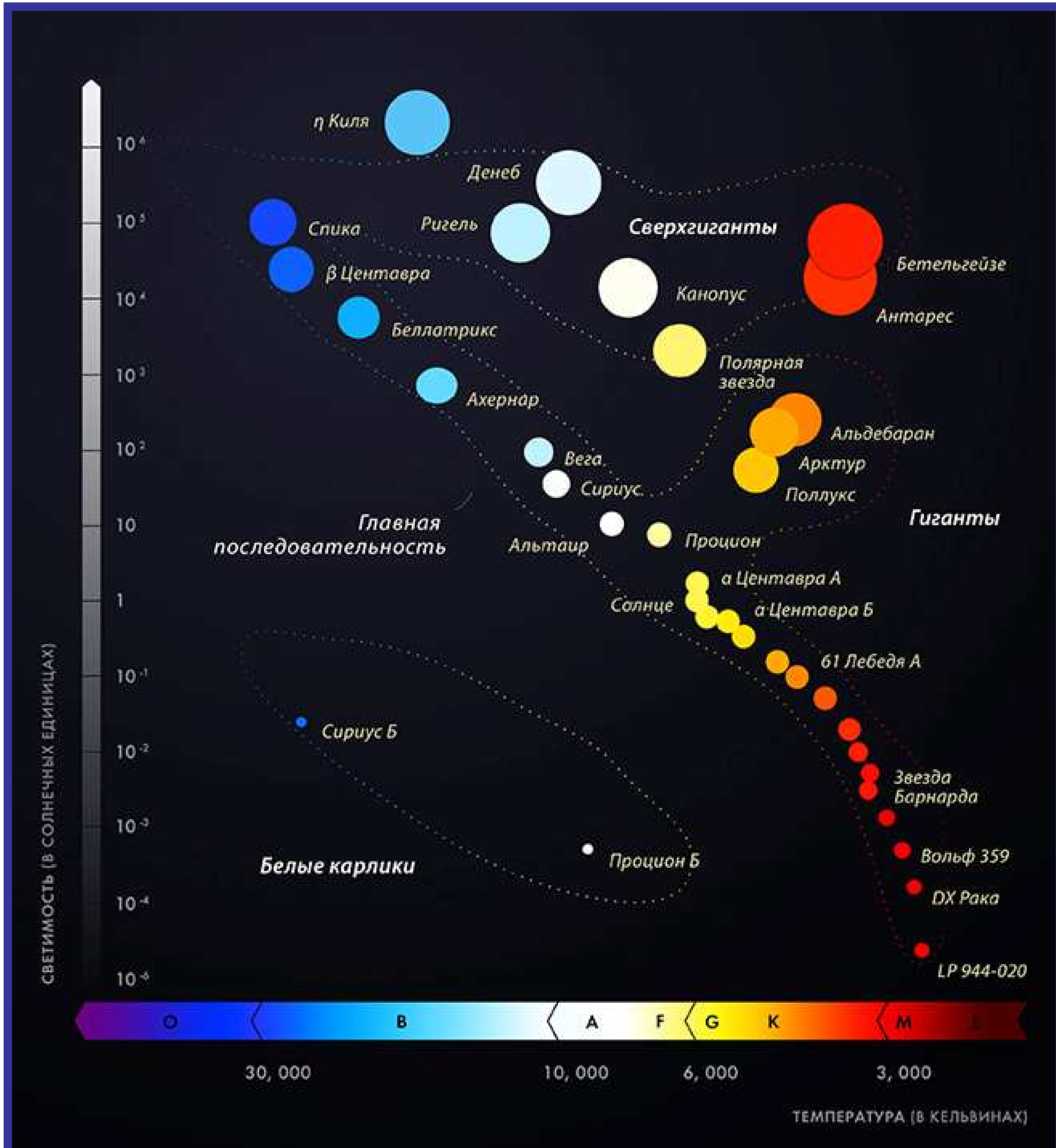


Oh be a fine girl kiss me

$t_H \ll t_{Th} \ll t_n$

Table 2.1: Stellar time scales

Object	t_H	t_T	t_n
The Sun	1000 s	$2\cdot10^7$ y	10^{10} y
Blue Supergiant on the Main Sequence $M = 30M_\odot$	3,500 s	$3\cdot10^4$ y	$5\cdot10^6$ y
Red Supergiant (Betelgeuse) $M = 20M_\odot$	2 months	$1\cdot10^3$ y	$1\cdot10^7$ y
White Dwarf (Sirius B)	0.8 s	$3\cdot10^7$ y	no nuclear burning



$M > 85M_{\odot}$

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

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

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

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

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

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

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

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

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

Эволюция звёзд разных масс на Г-Р диаграмме (I.Iben)

$0.5 \le M / M_{\odot} \le 2.5$

Горение водорода. Красный гигант, сжатие ядра, горение H в слое, растущее He ядро, вспышка гелия в вырожденных условиях, CO-WD, M ~ 0.5 Msun

$2.5 \le M / M_{\odot} \le 8$

На стадии КГ невырожденное He ядро, горение гелия, вырожденное CO ядро, тепловая неустойчивость, сброс оболочки, планетарная туманность. CO-WD с M ~ 0.6-0.7 Msun

$8 \le M / M_{\odot} \le 10 \div 12$

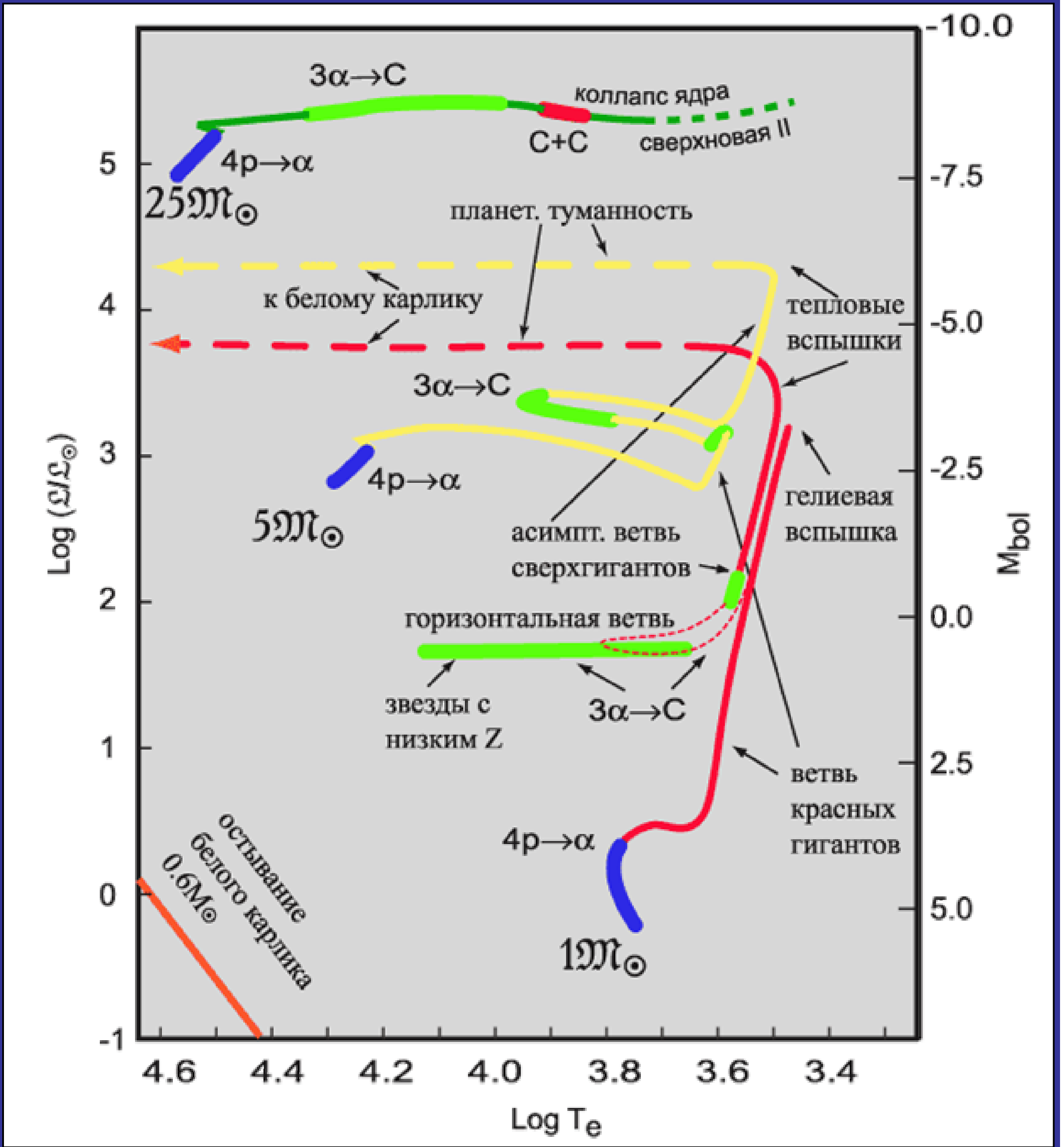
Горение O, Ne, Mg, планетарная туманность. O-Ne-Mg WD с массой M ~ MCh ~ 1.2 Msun

$10 \div 12 \le M / M_{\odot} \le 30 \div 40$

Горение до “железного пика”: Fe, Co, Ni. Mcore ~ 1.5-2 Msun. Коллапс, SN!

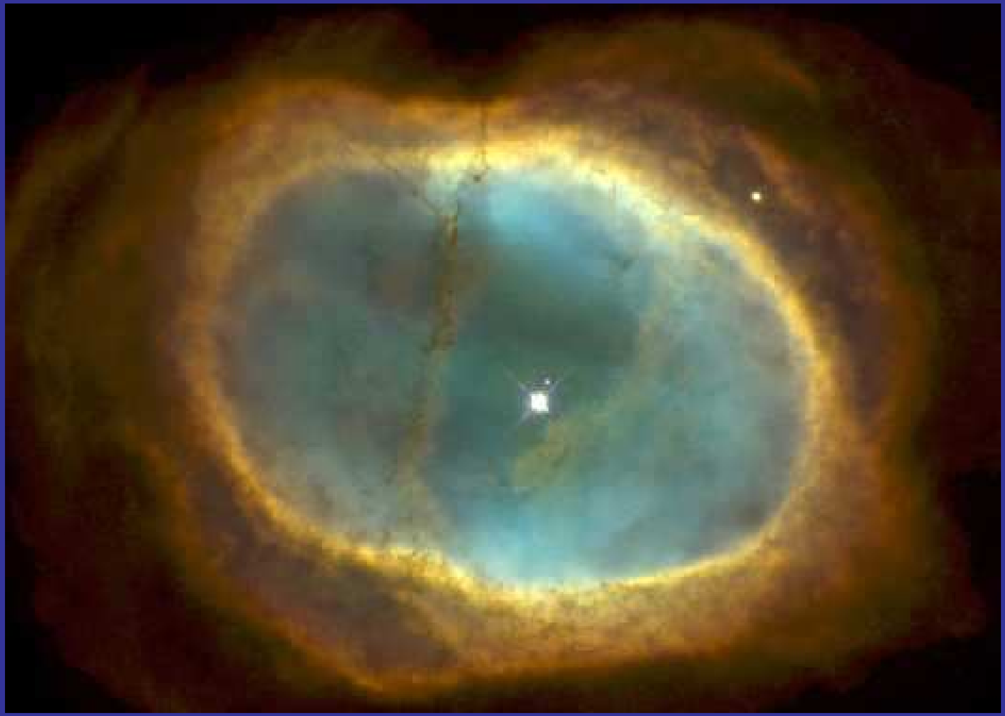
$40 \le M / M_{\odot}$

“Тихий” коллапс? Гипернова?



Планетарные туманности вокруг белых карликов

NGC 6543, Кошачий глаз



NGC 3132
Планетарная туманность
в созвездии Паруса

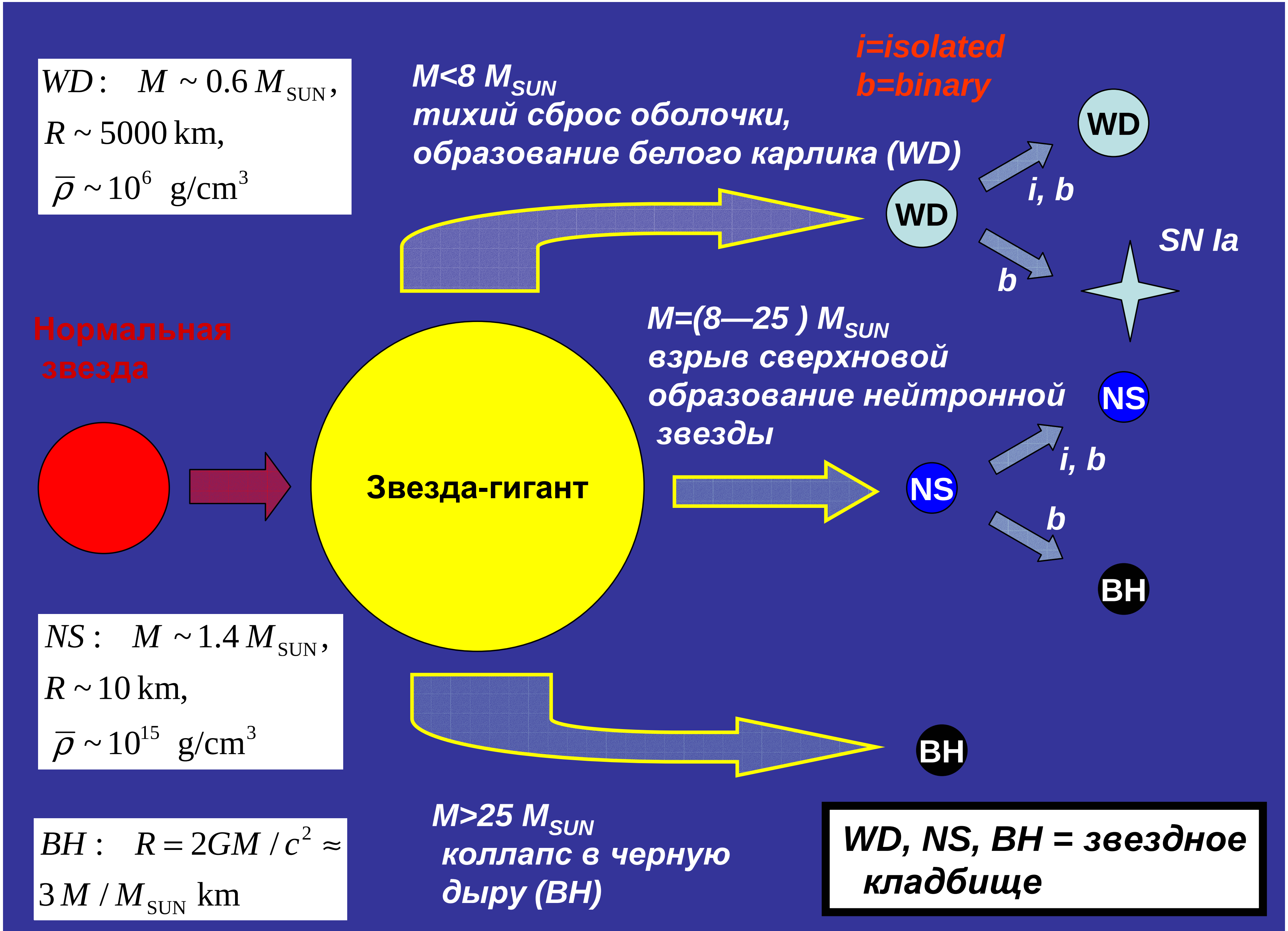
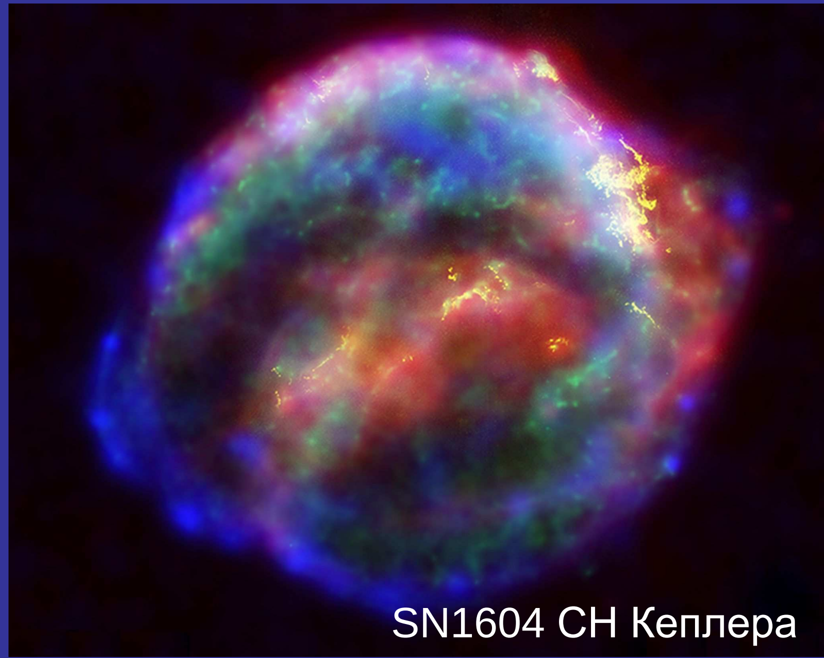
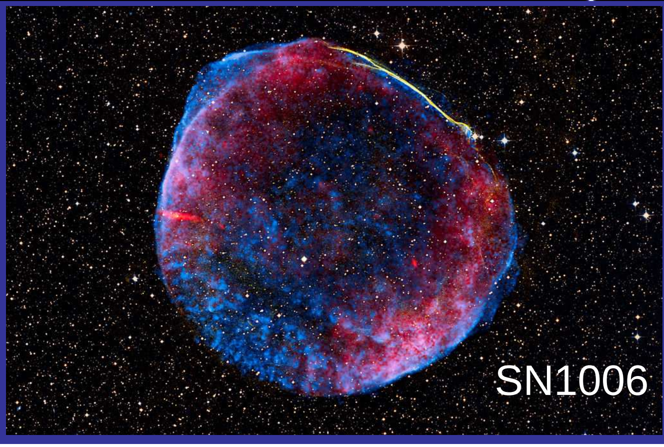
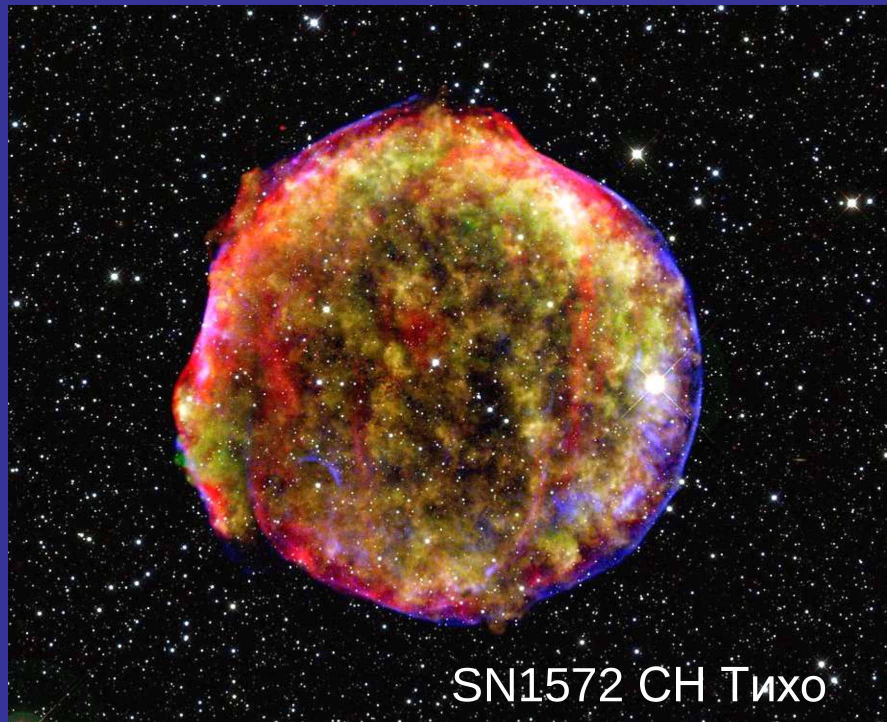


Схема из Д. Г. Яковлев, “Ядерное горение в сверхплотном веществе”

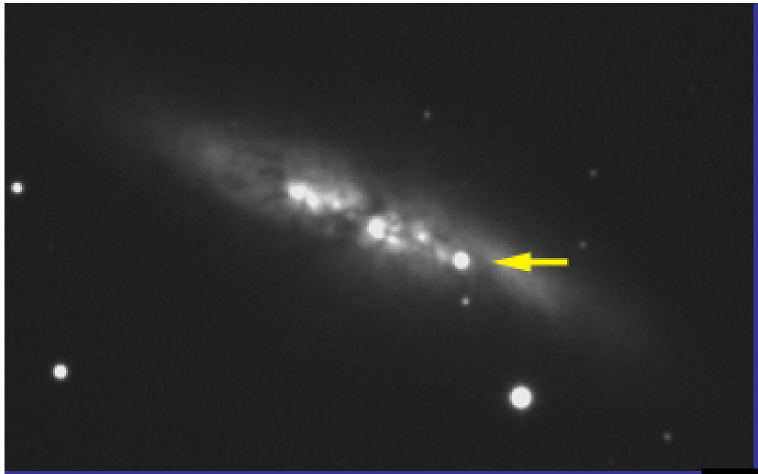

SN1054 Крабовидная туманность

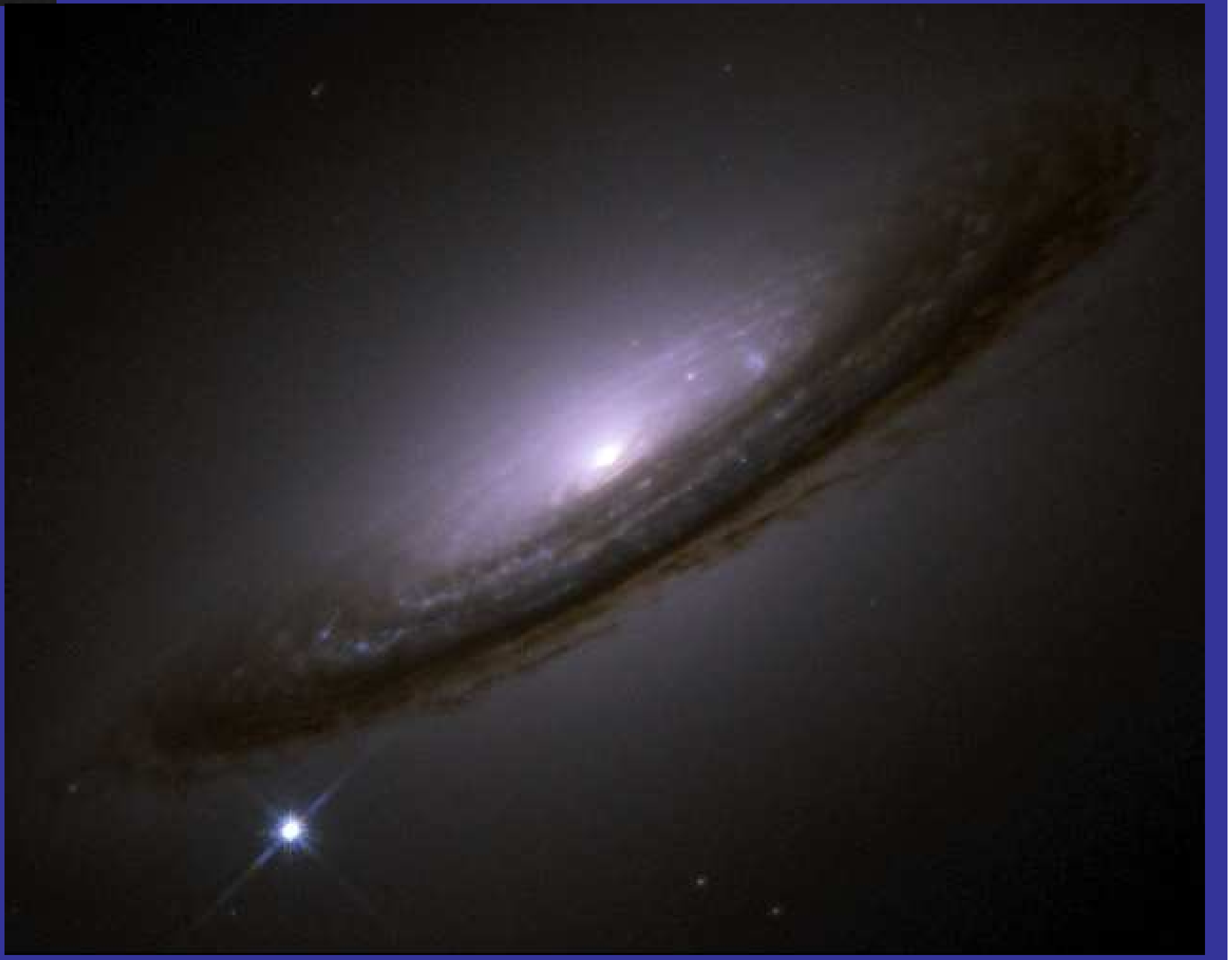

SN1604 СН Кеплера


SN1006


SN1572 СН Тихо

Свехновые звёзды: Стандартная Картина

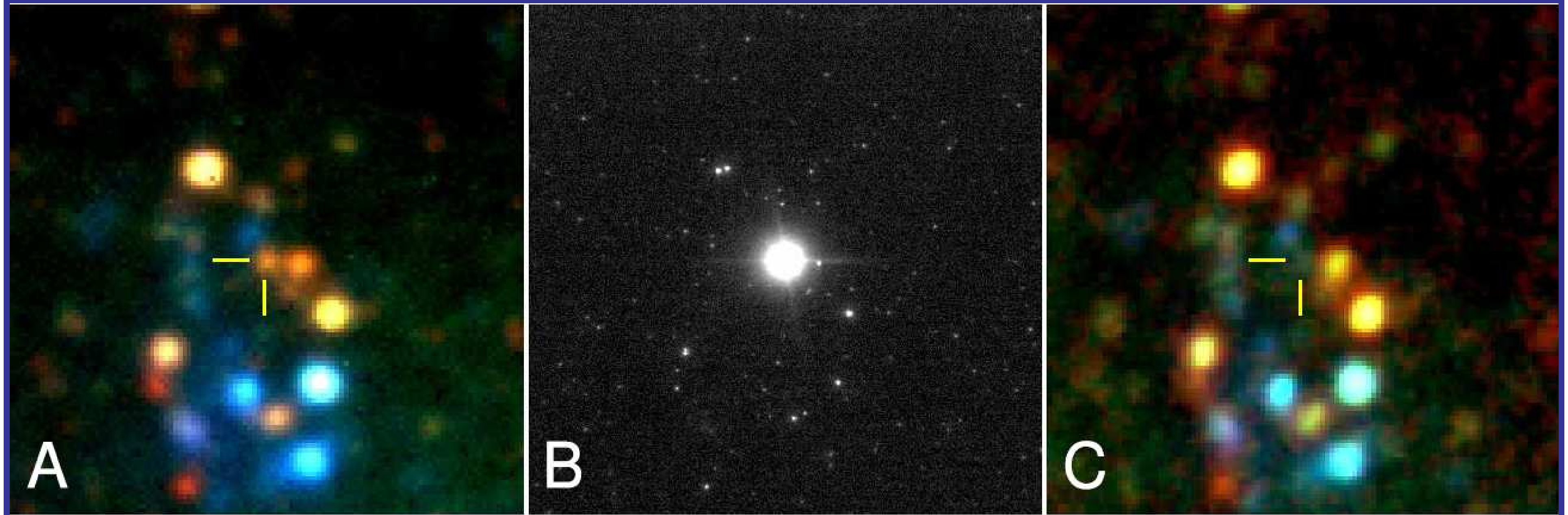




Supernova 1994D in Galaxy NGC 4526

The Disappearance of the Red Supergiant Progenitor of Supernova 2008bk

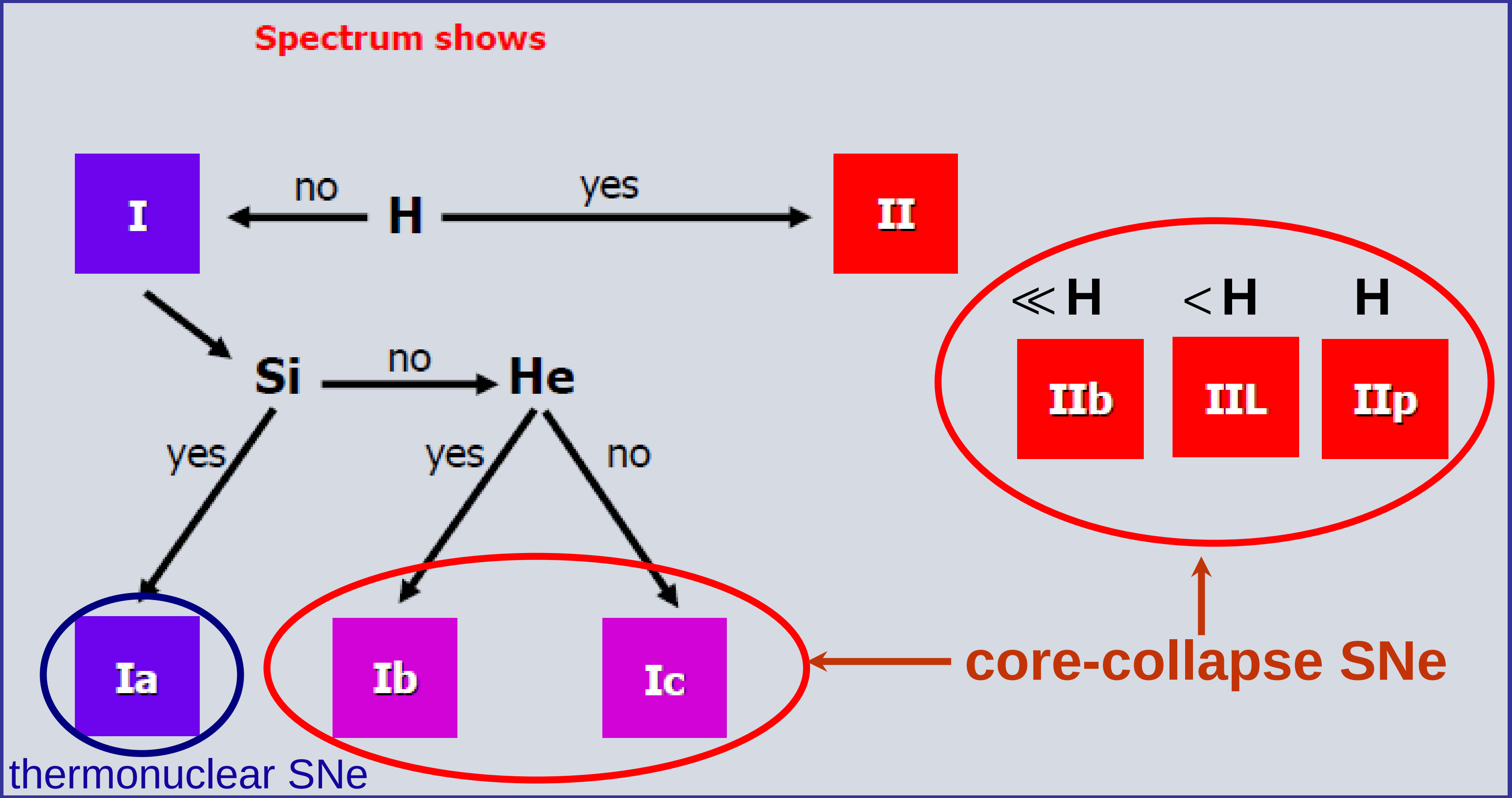
Seppo Mattila,[1,2*] Stephen Smartt,[3] Justyn Maund,[4,5] Stefano Benetti,[6] Mattias Ergon[1]



Type IIP SN 2008bk

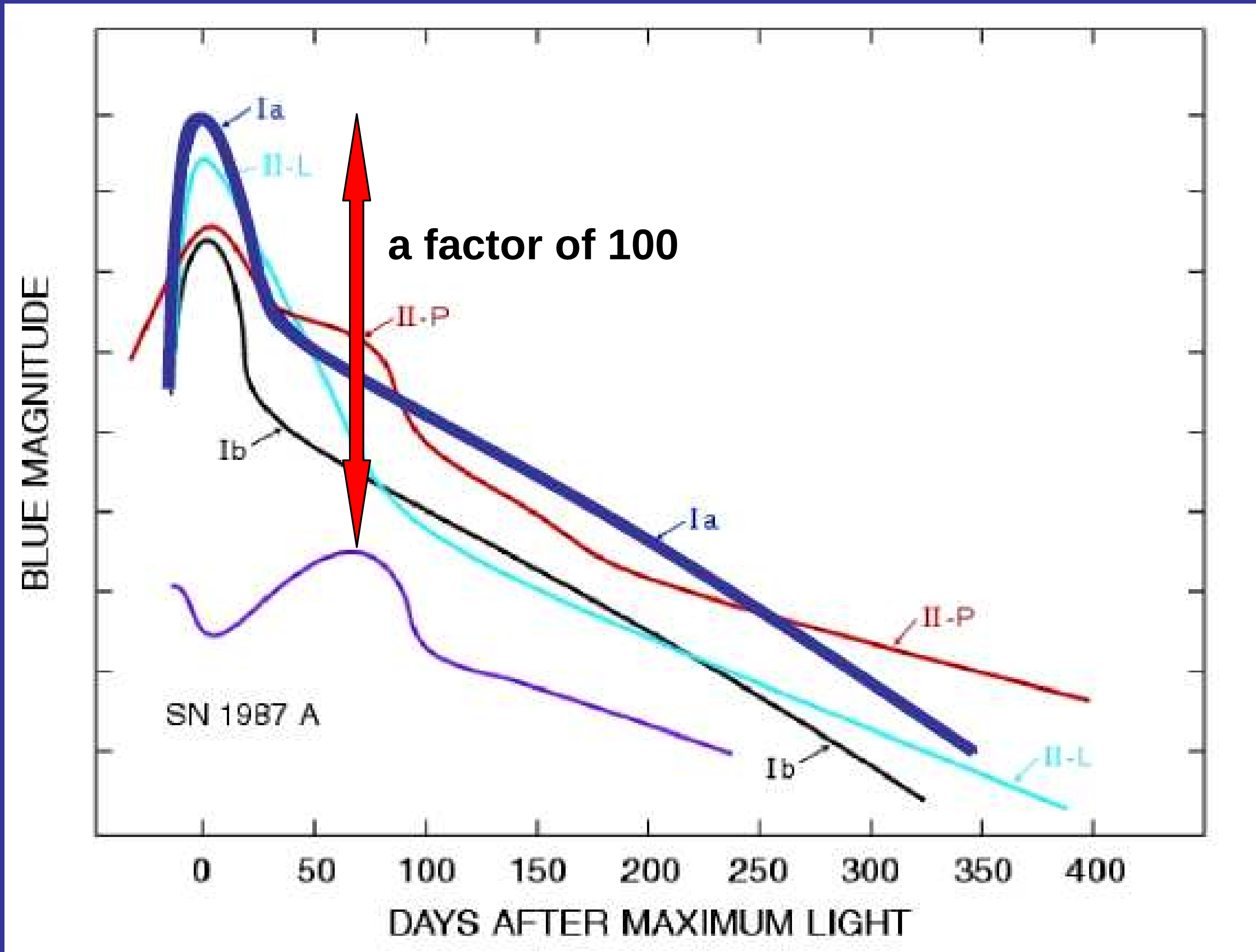
Properties of supernovae and their classification

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)

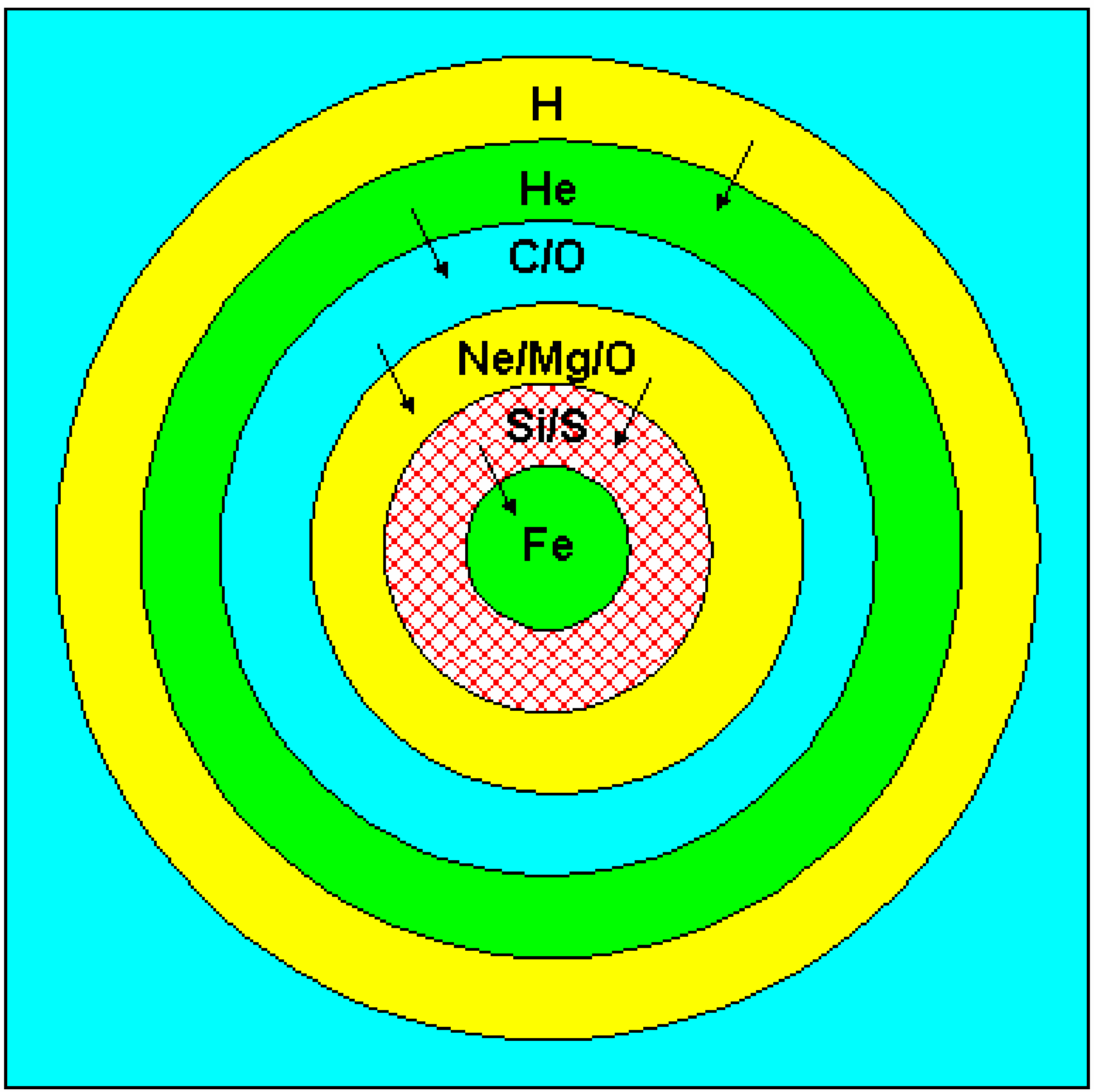
Light curves of supernovae

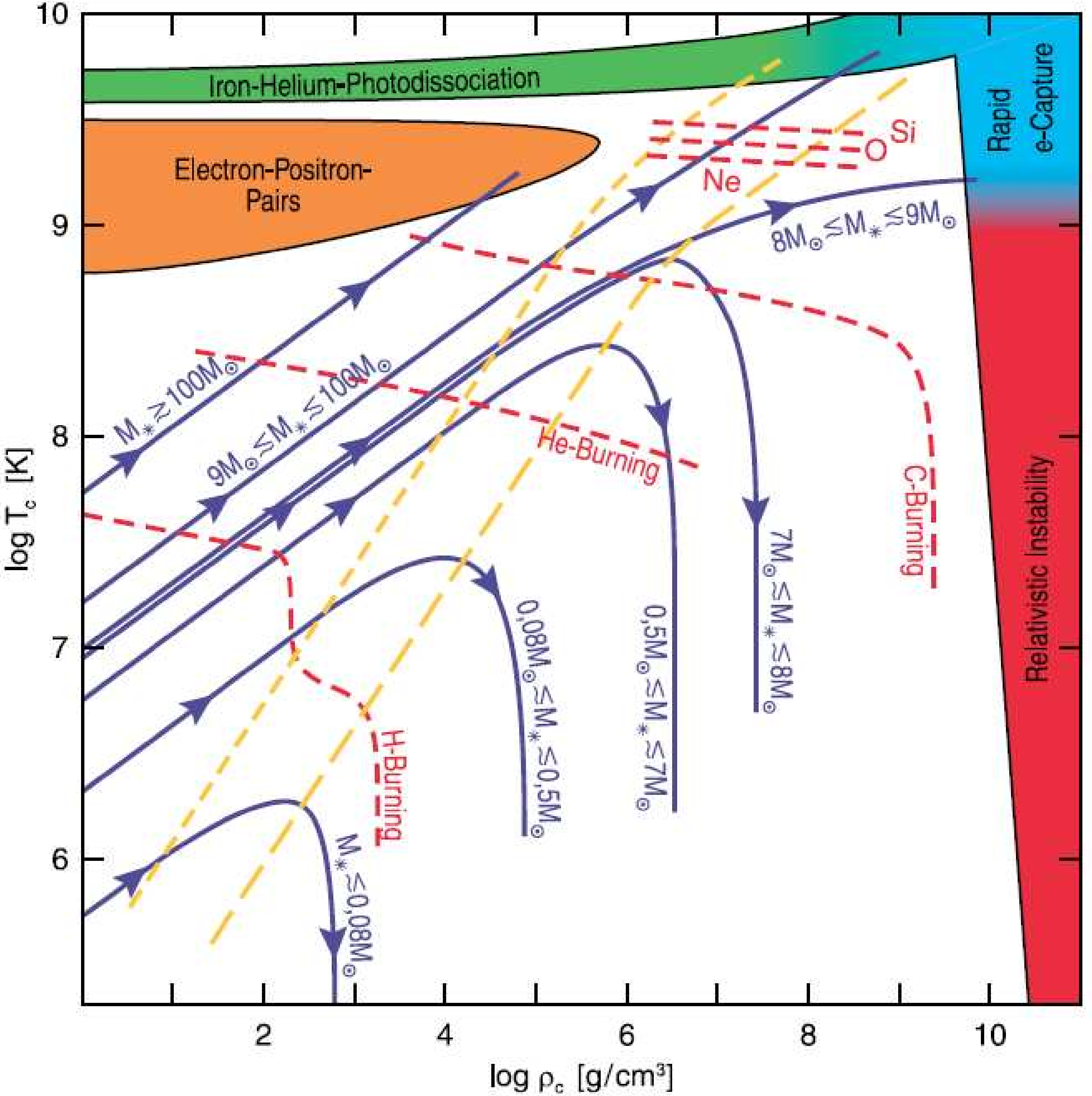


Adapted from: F. Röpke (http://theor.jinr.ru/~ntaa/07/files/program.html)
A. Filippenko (Annu. Rev. Astron. Astrophys. 1997, **35**, 309)

Массивная звезда на последней стадии своей эволюции перед коллапсом

“Луковичная” структура звезды




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]
10
9
8
7
6
2
4
6
8
10

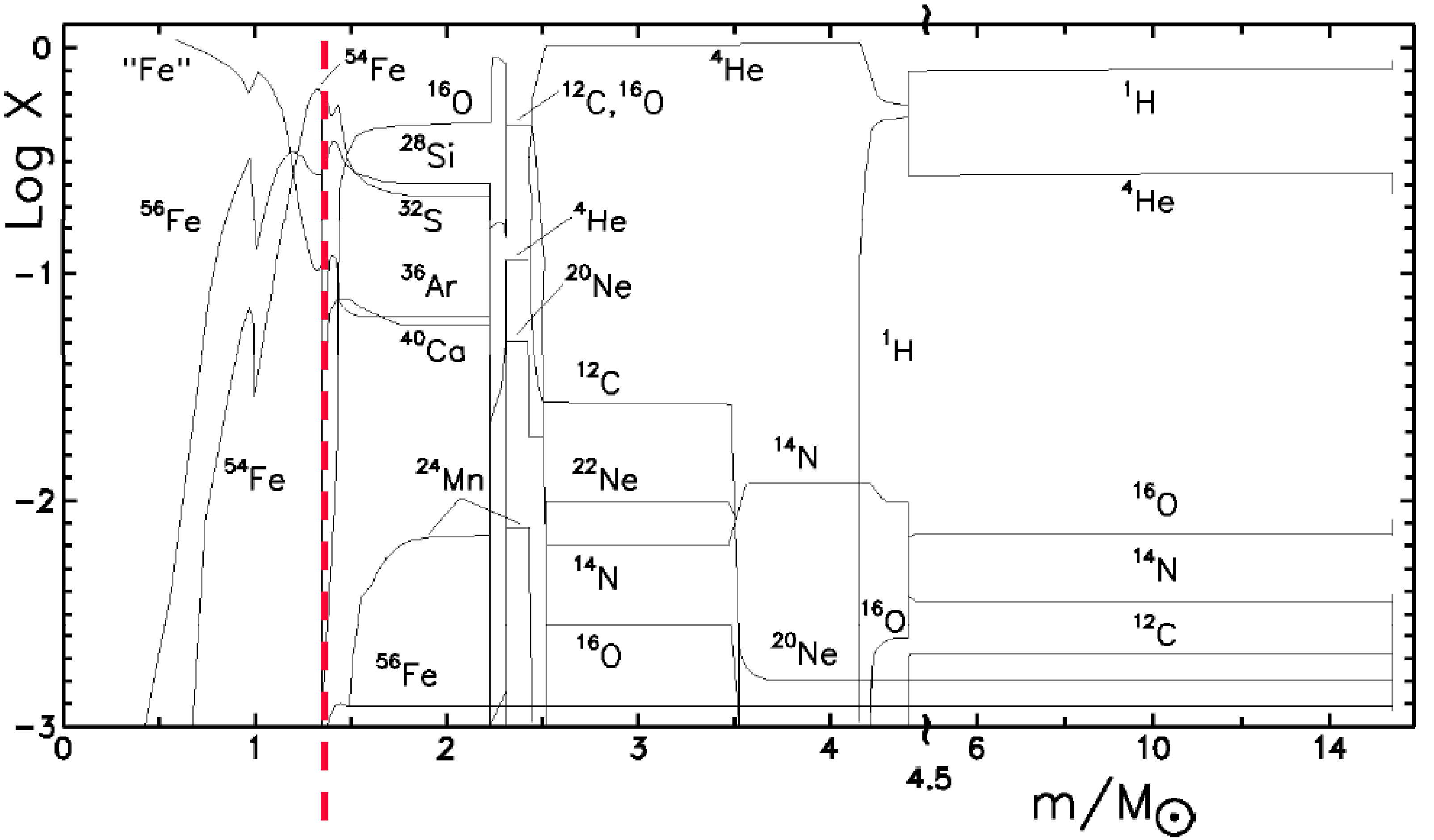
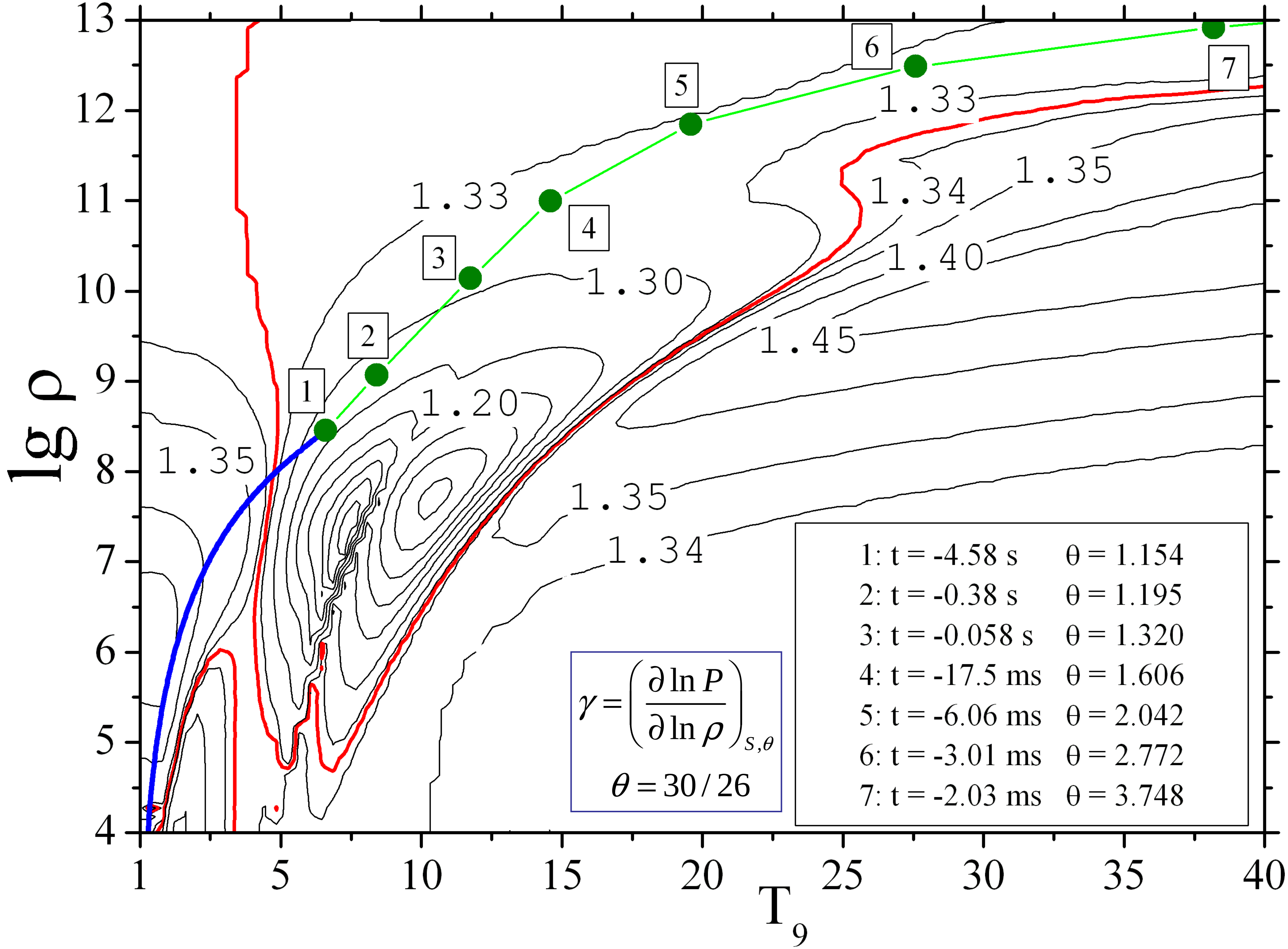
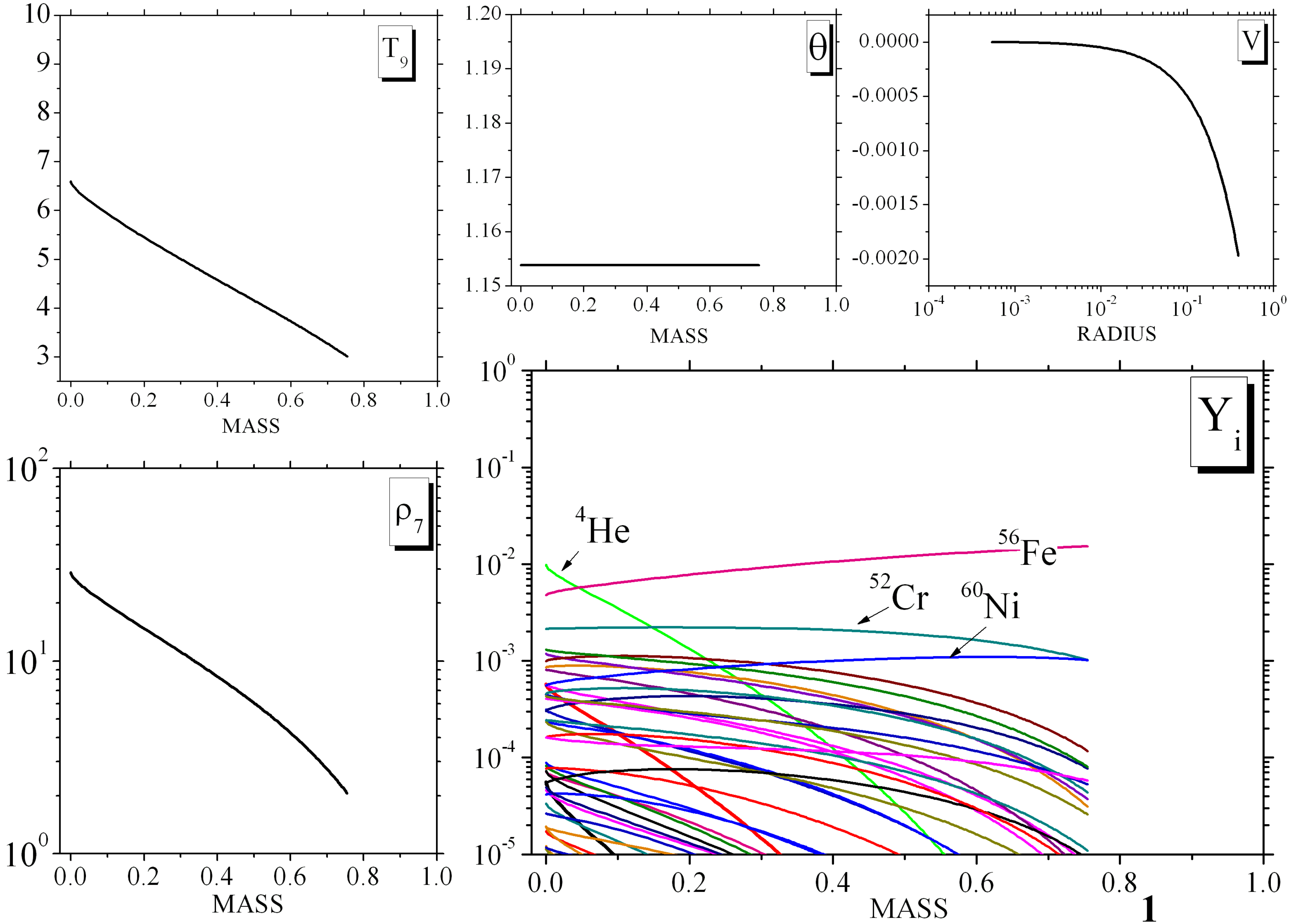


Figure 5.6: Composition versus current mass m for a 15 $M_\odot$ presupernova star just before its iron core collapse shown as the mass fractions X of various nuclear species. The curve labeled by "Fe" includes all nuclides of mass numbers $48 \lesssim A \lesssim 65$ having a neutron excess greater than ^{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]

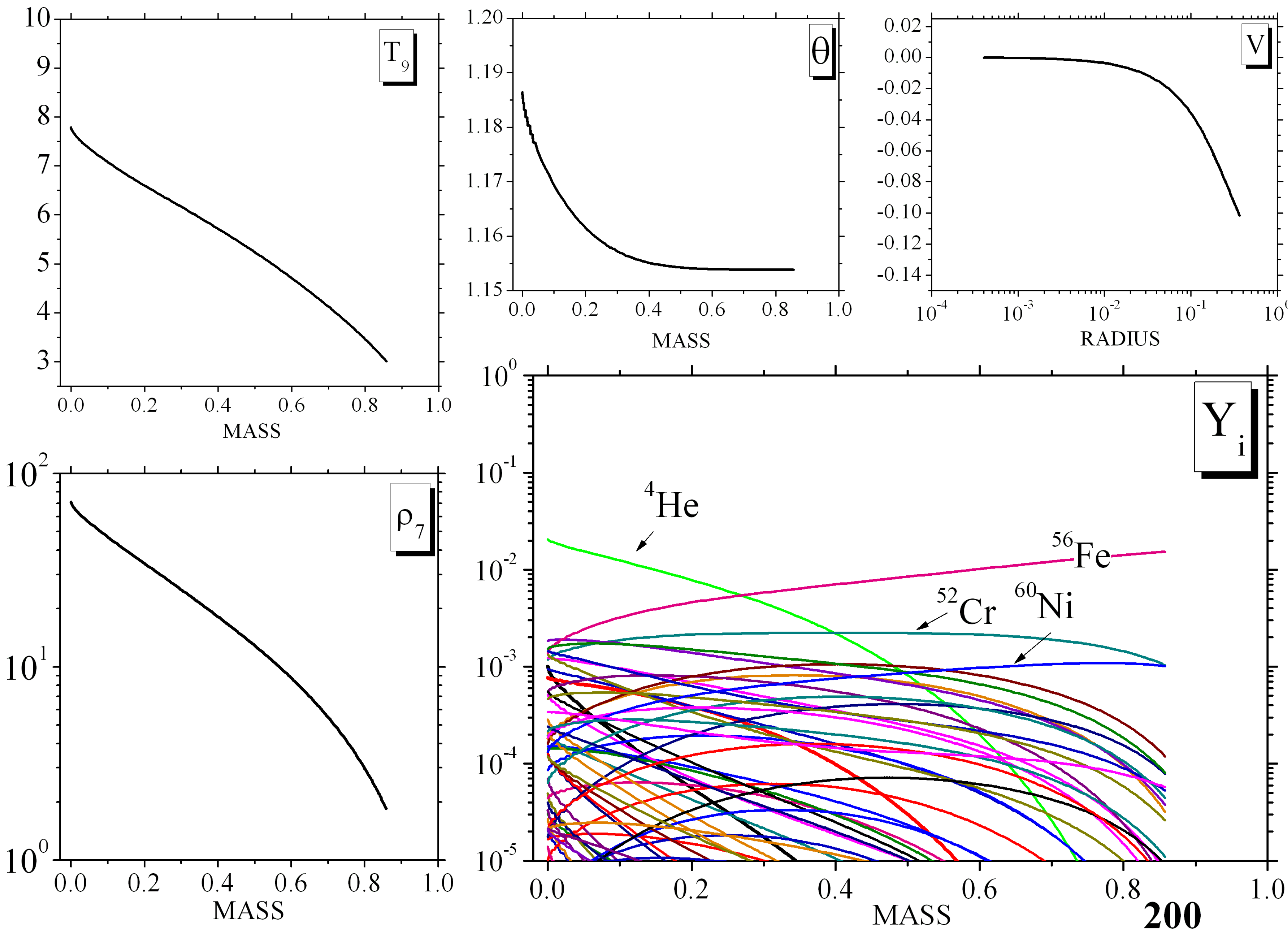
From Woosley & Weaver An.Rev. Astron. Astrophys. v. 24, p. 205 (1986)



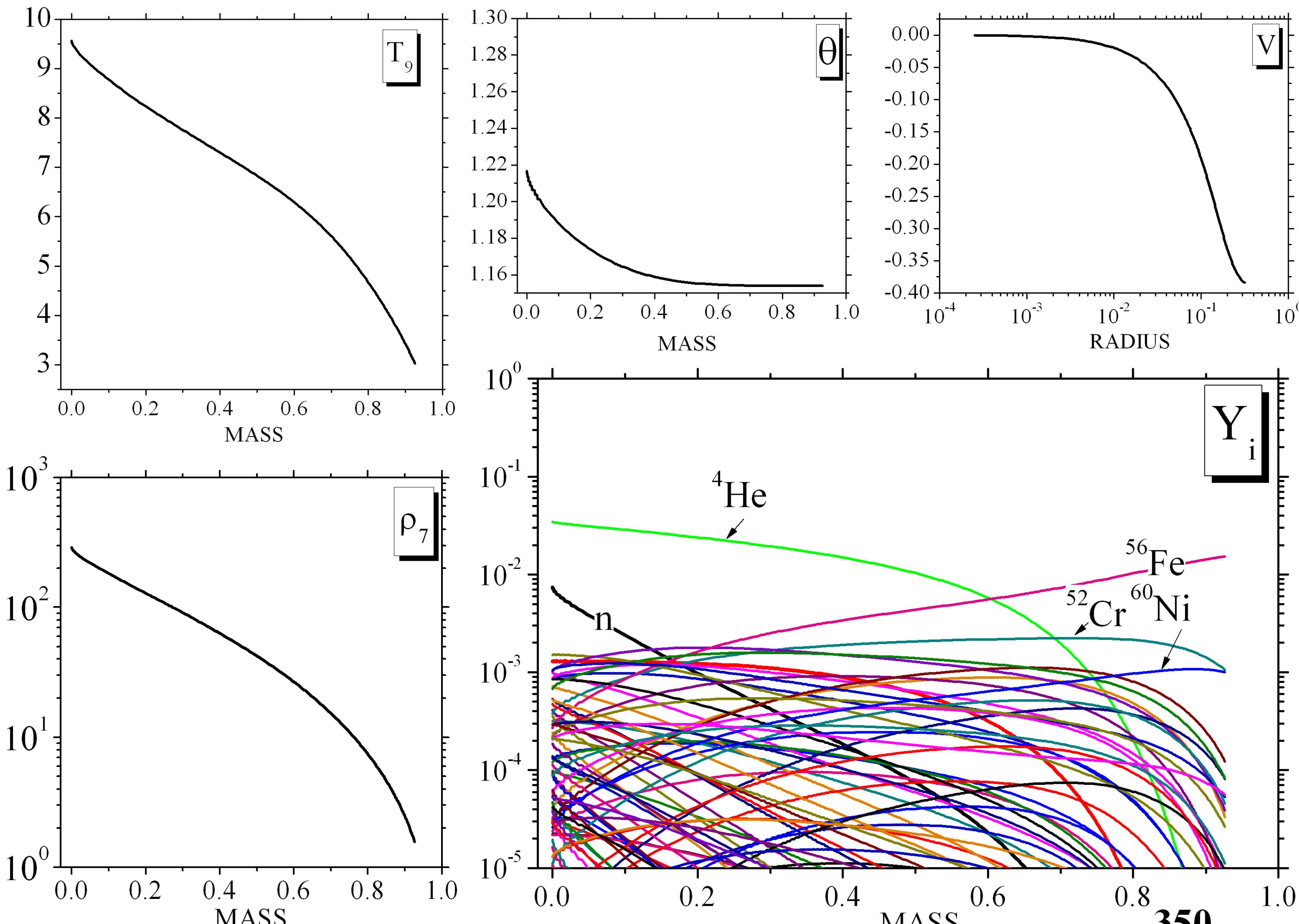
lg ρ
T9
1.35
1.33
1.30
1.20
1.33
1.34
1.35
1.40
1.45
1.35
1.34
$\gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{S,\theta}$
$\theta = 30/26$
1: t = -4.58 s θ = 1.154
2: t = -0.38 s θ = 1.195
3: t = -0.058 s θ = 1.320
4: t = -17.5 ms θ = 1.606
5: t = -6.06 ms θ = 2.042
6: t = -3.01 ms θ = 2.772
7: t = -2.03 ms θ = 3.748



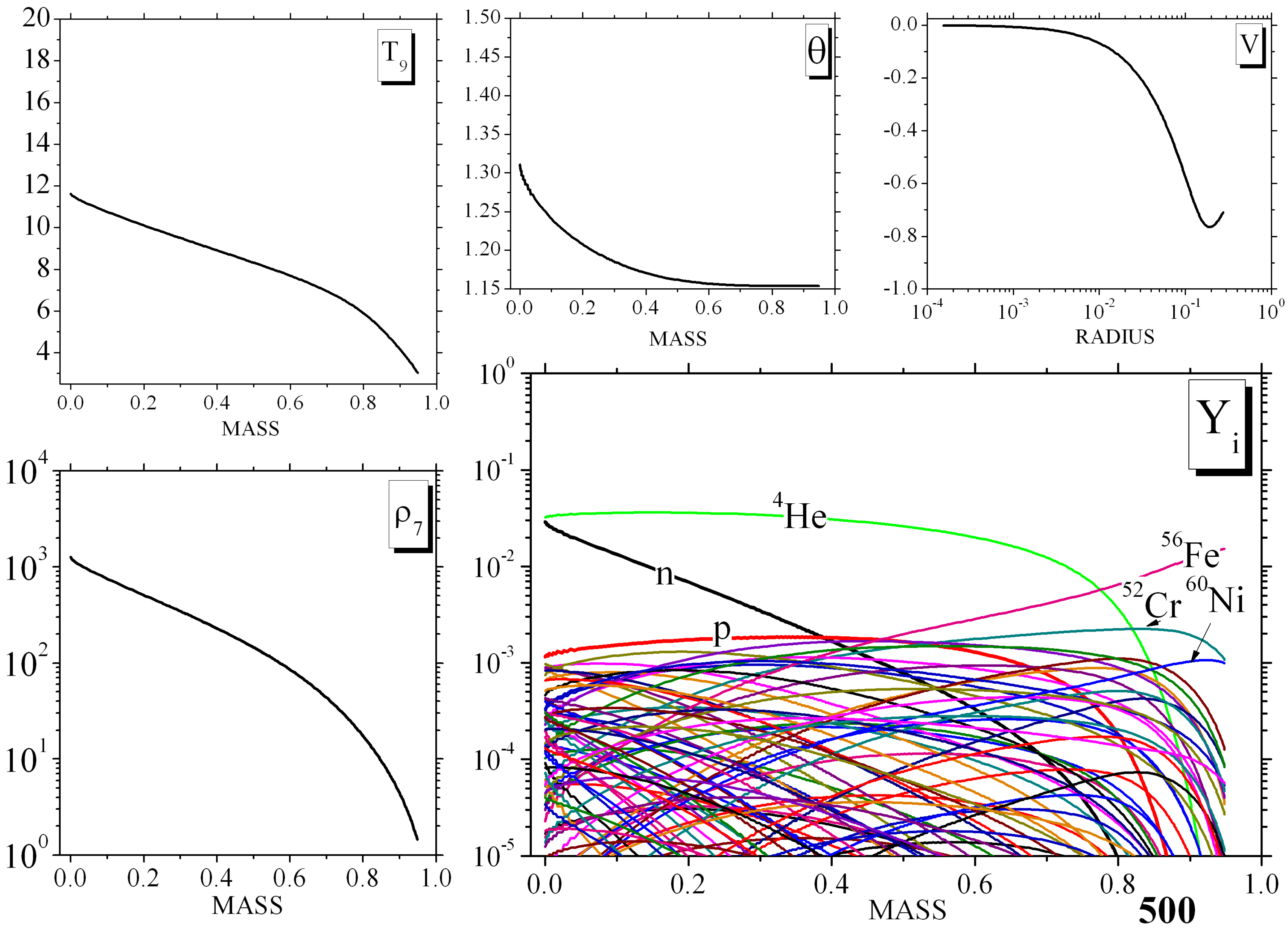
1

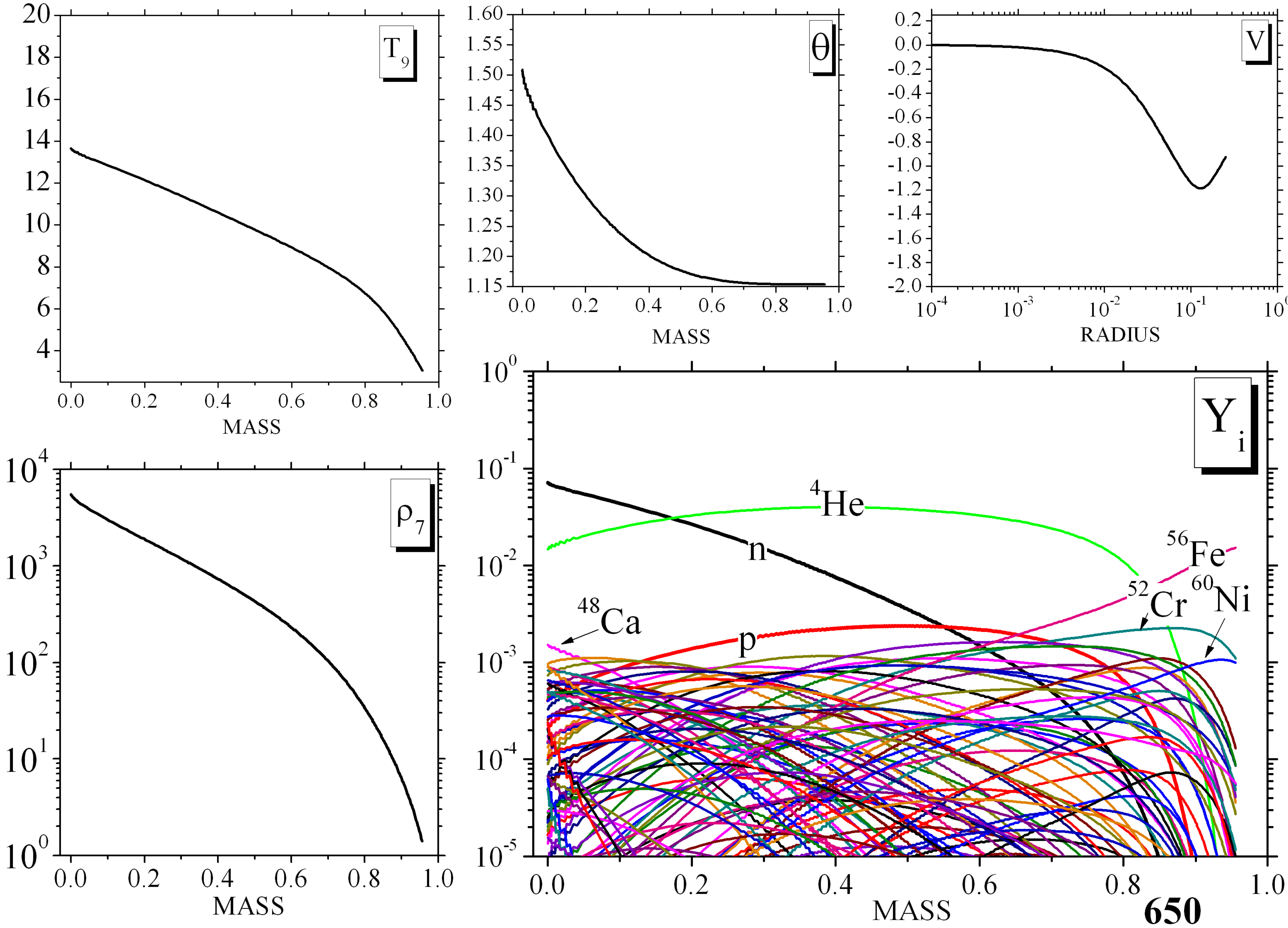


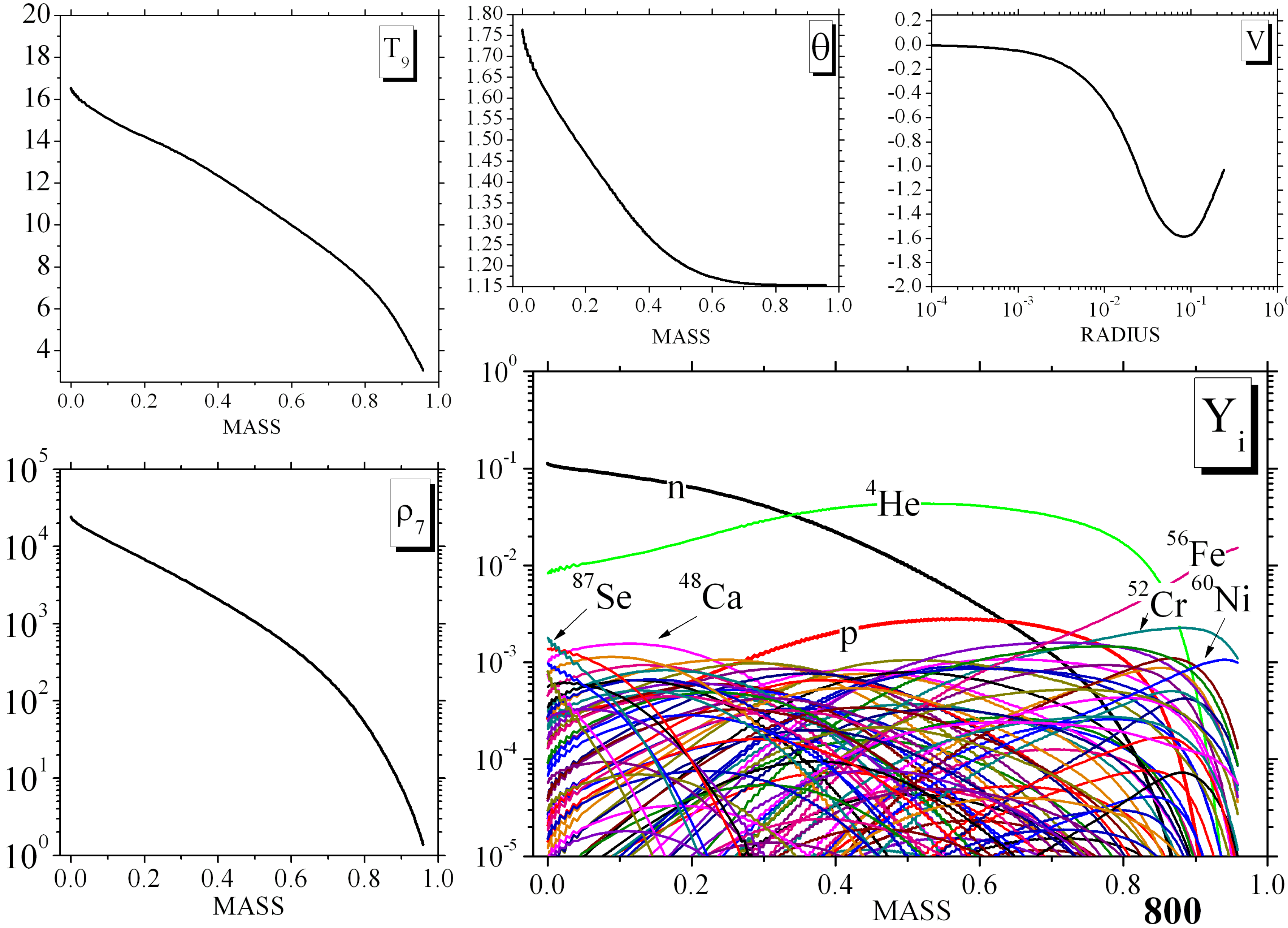
200



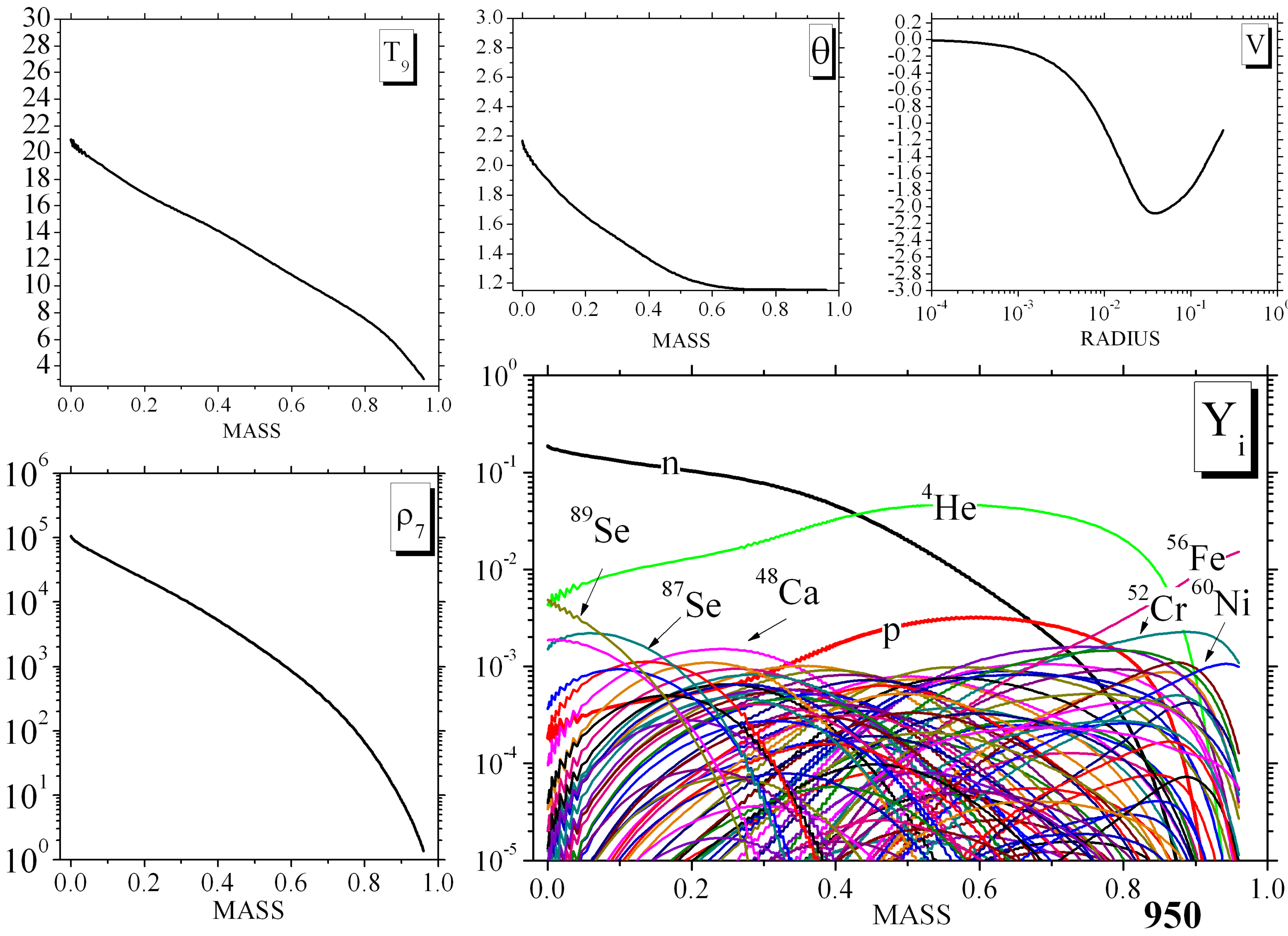
350

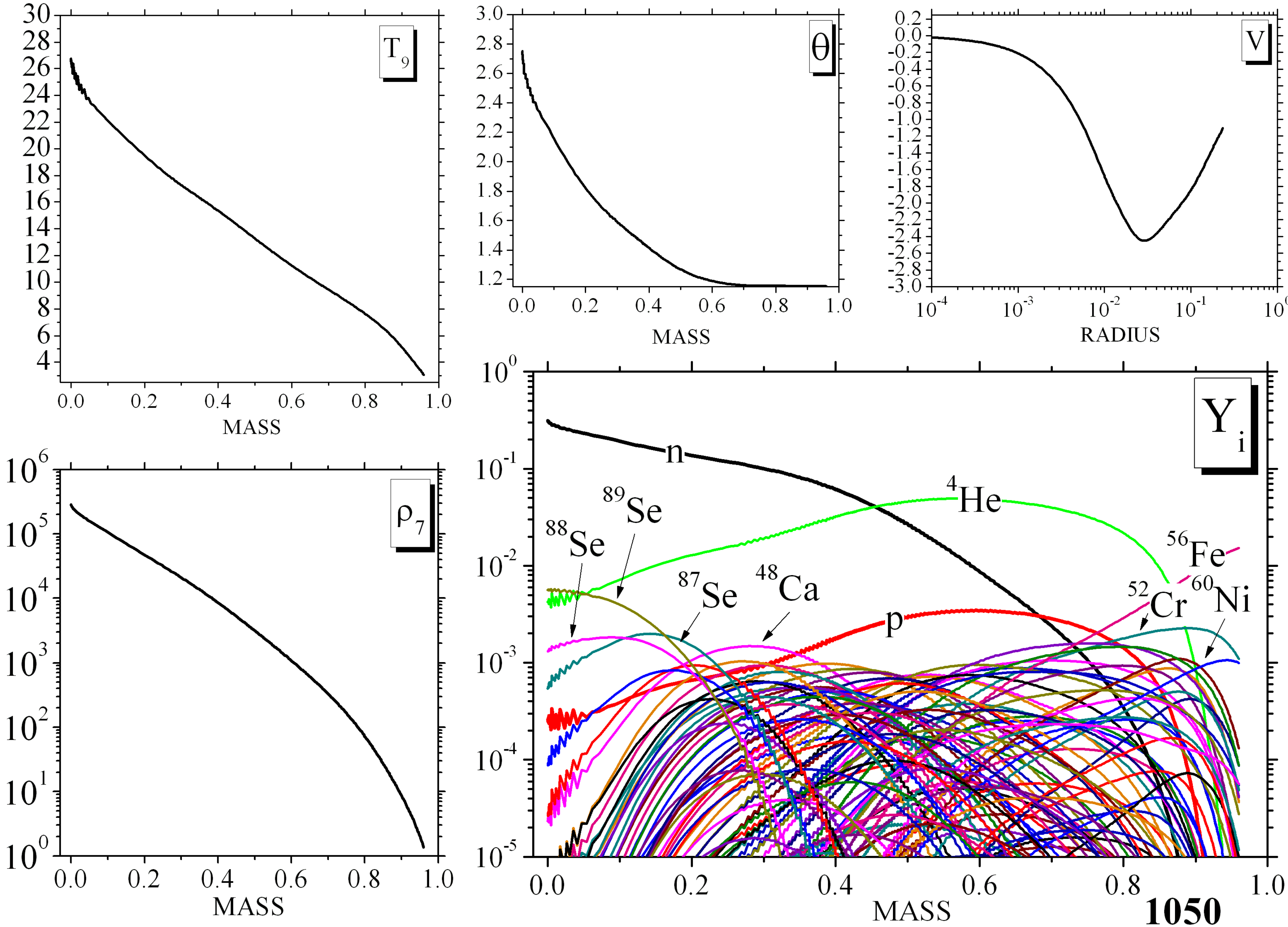

T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
4He
n
p
56Fe
52Cr
60Ni
MASS
500


T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
4He
n
56Fe
52Cr
60Ni
48Ca
p
MASS
650

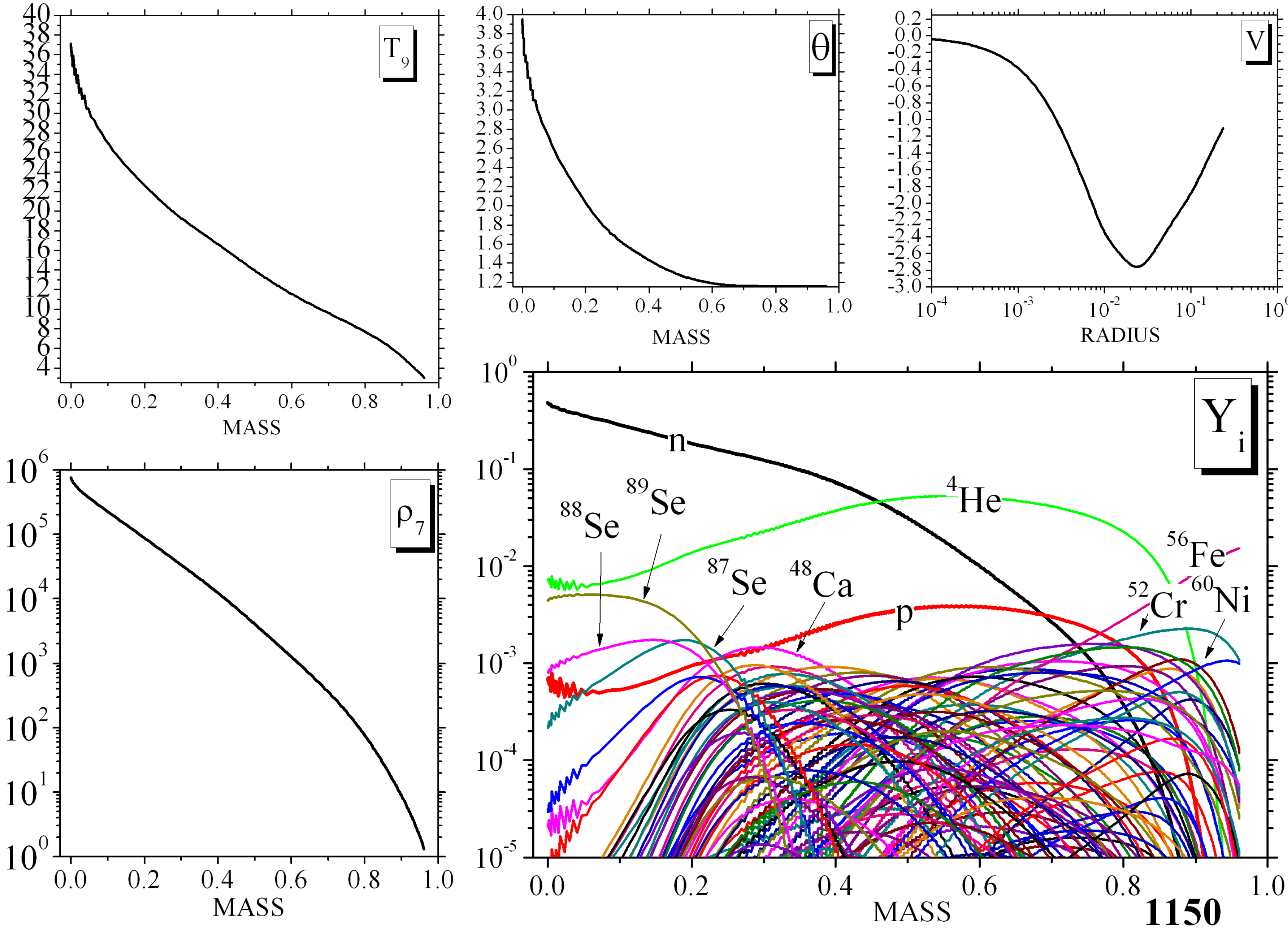


T9
θ
V
ρ7
Yi
MASS
RADIUS
n
4He
56Fe
52Cr
60Ni
87Se
48Ca
p
800


T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
n
4He
89Se
87Se
48Ca
p
56Fe
52Cr
60Ni
MASS
950


T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
n
p
4He
88Se
89Se
87Se
48Ca
56Fe
52Cr
60Ni
MASS

1050



T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
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n
4He
88Se
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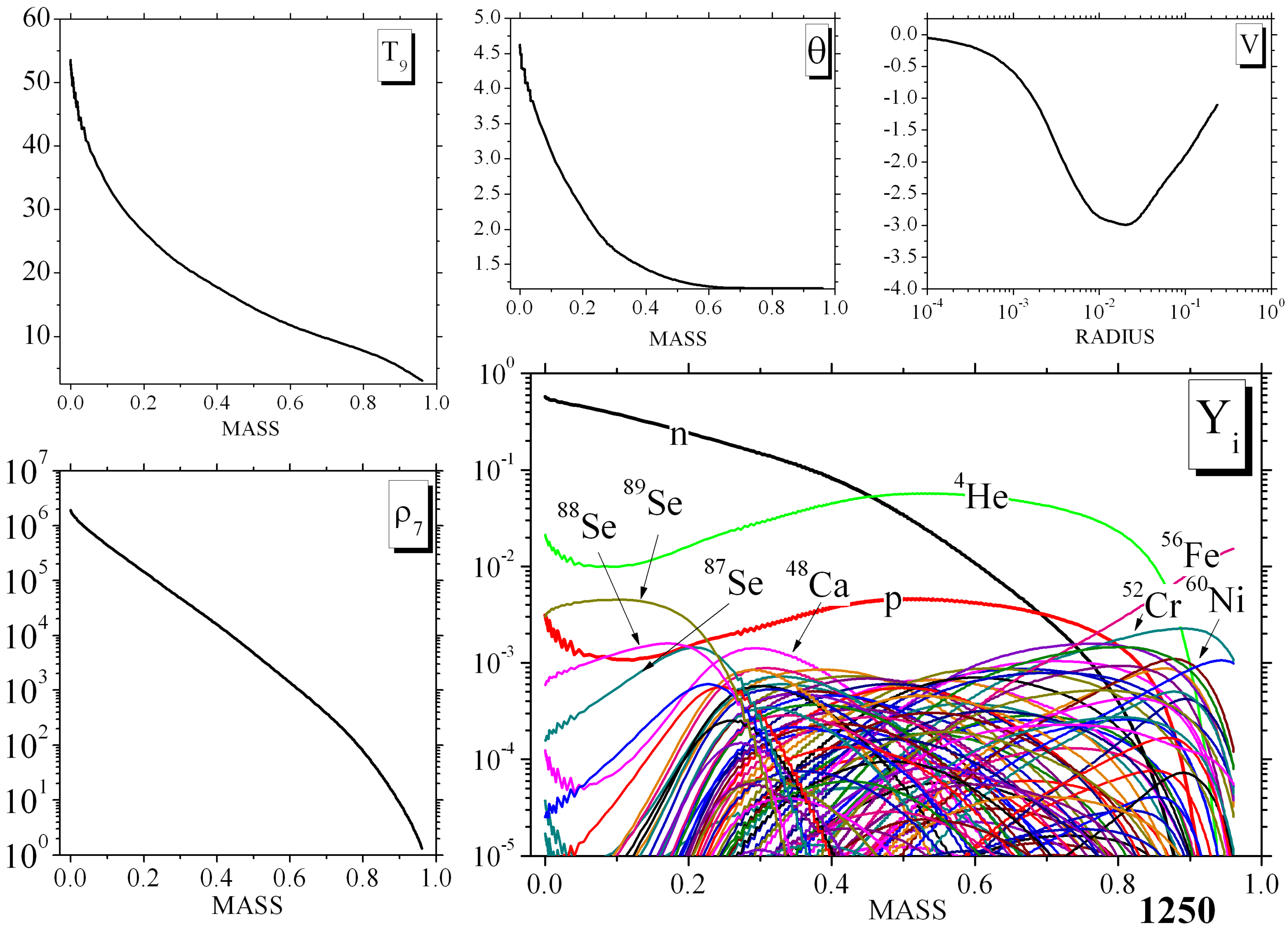
p
56Fe
52Cr
60Ni
MASS
1150



T9
MASS
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MASS
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RADIUS
ρ7
MASS
Yi
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4He
88Se
89Se
87Se
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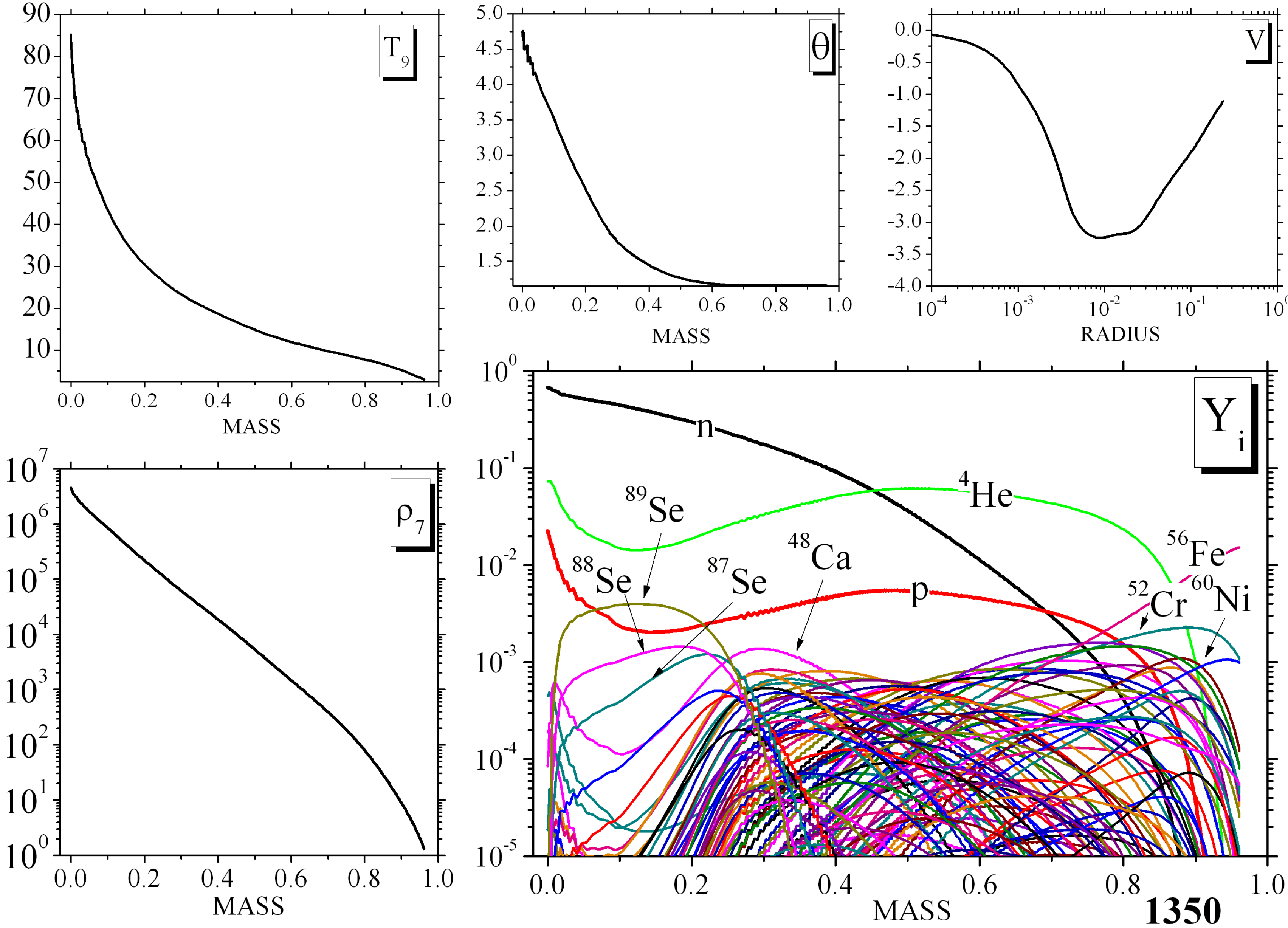
56Fe
52Cr
60Ni
MASS
1250



T9
θ
V
RADIUS
MASS
ρ7
Yi
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89Se
88Se
87Se
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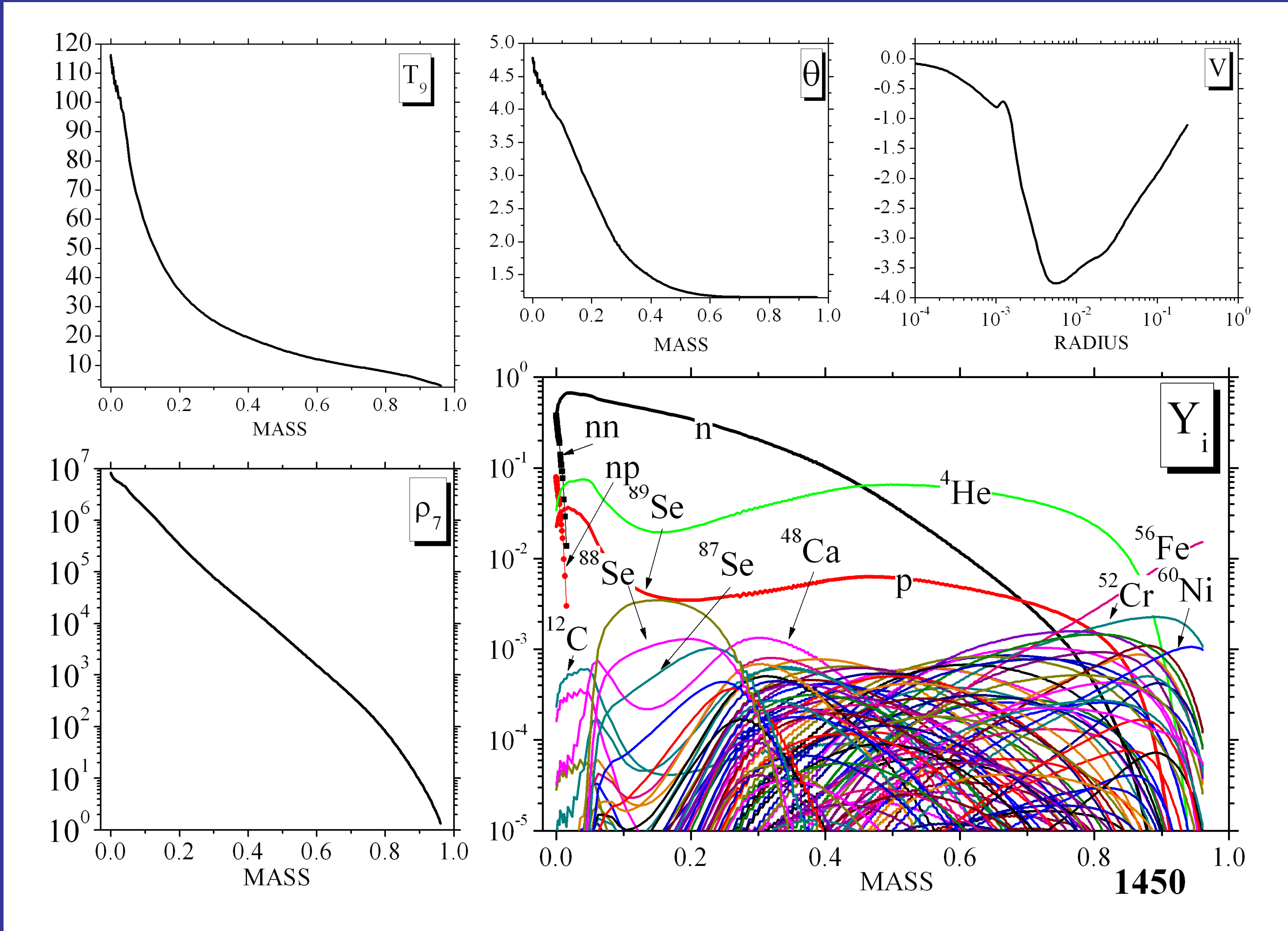
52Cr
60Ni
1350



T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
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52Cr
60Ni
MASS
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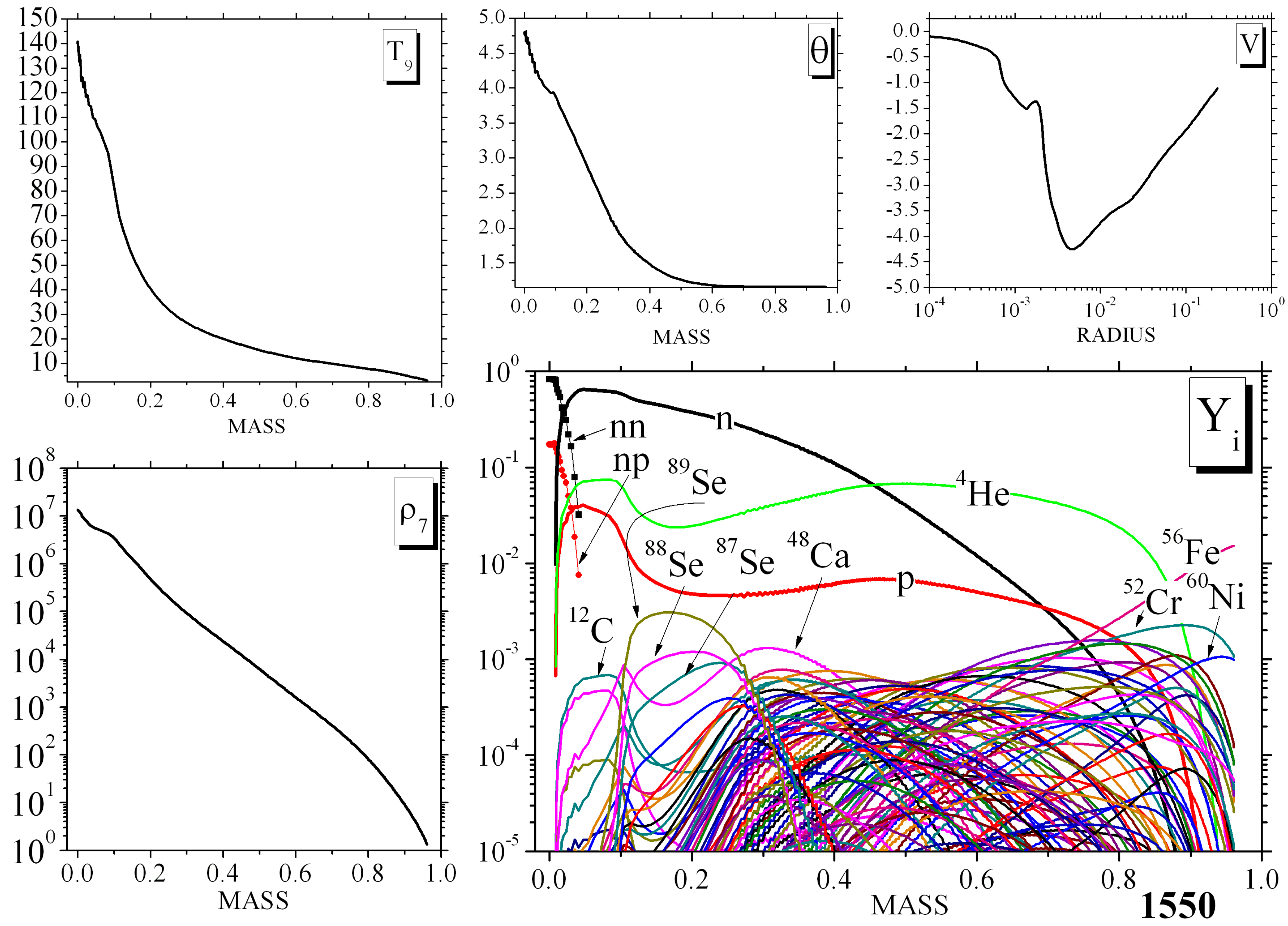
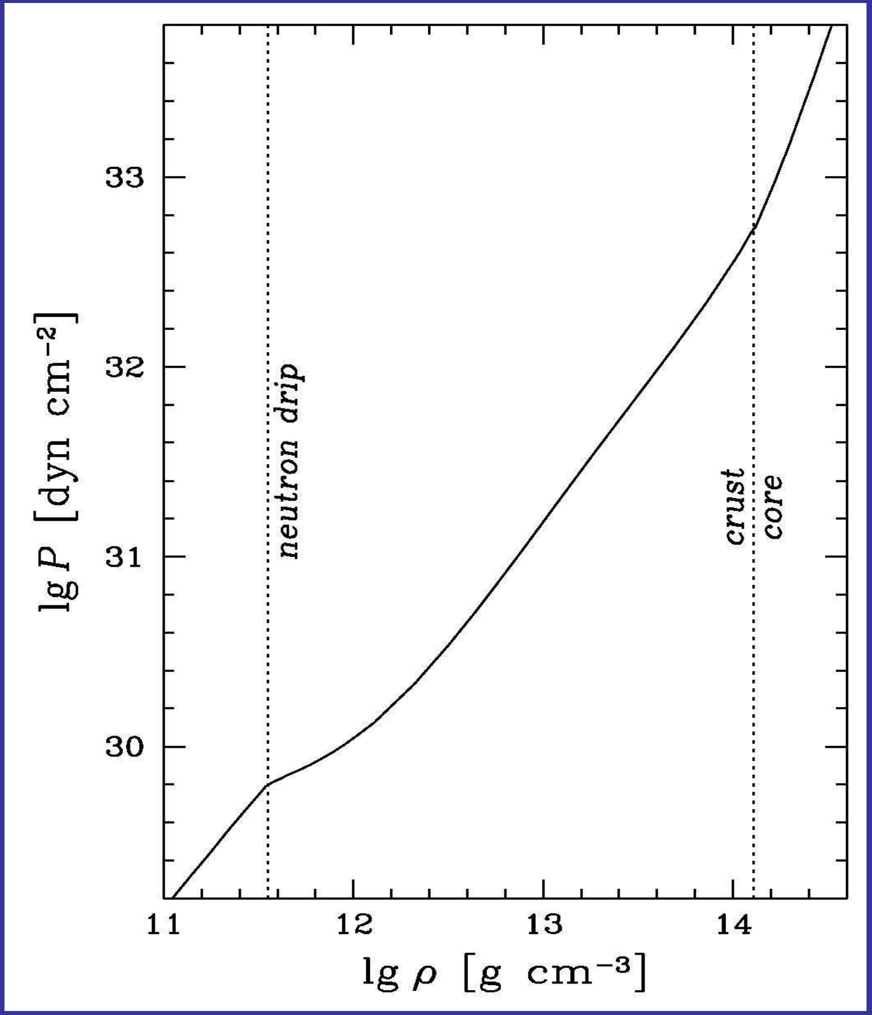
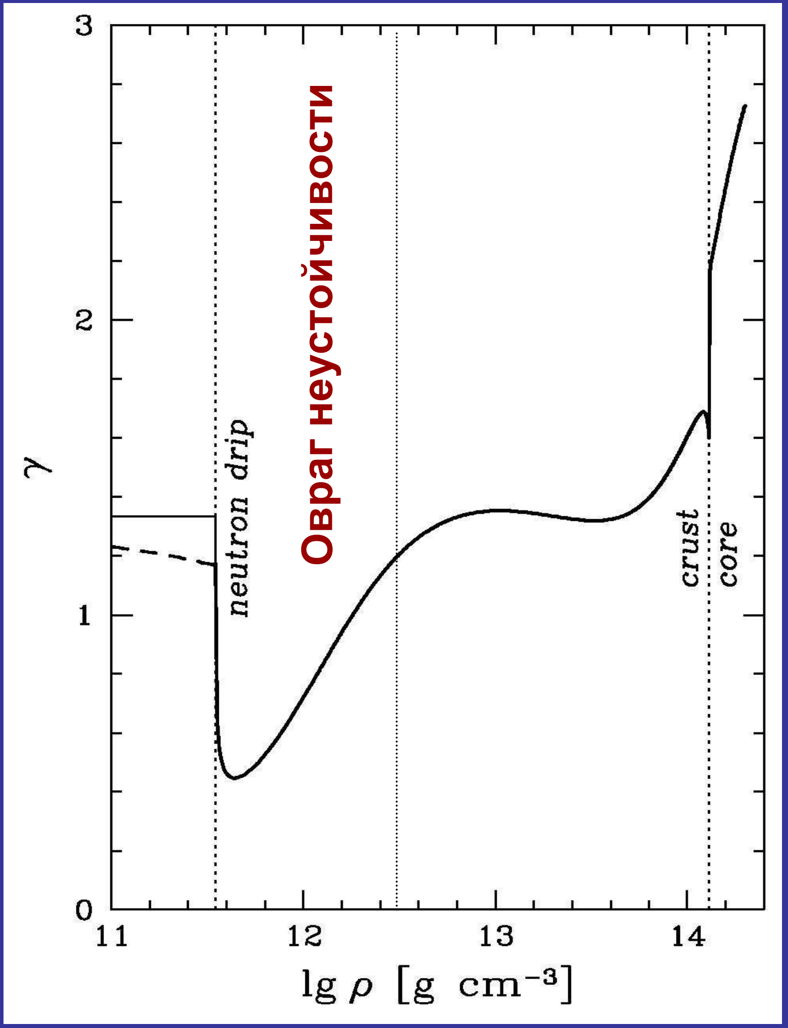


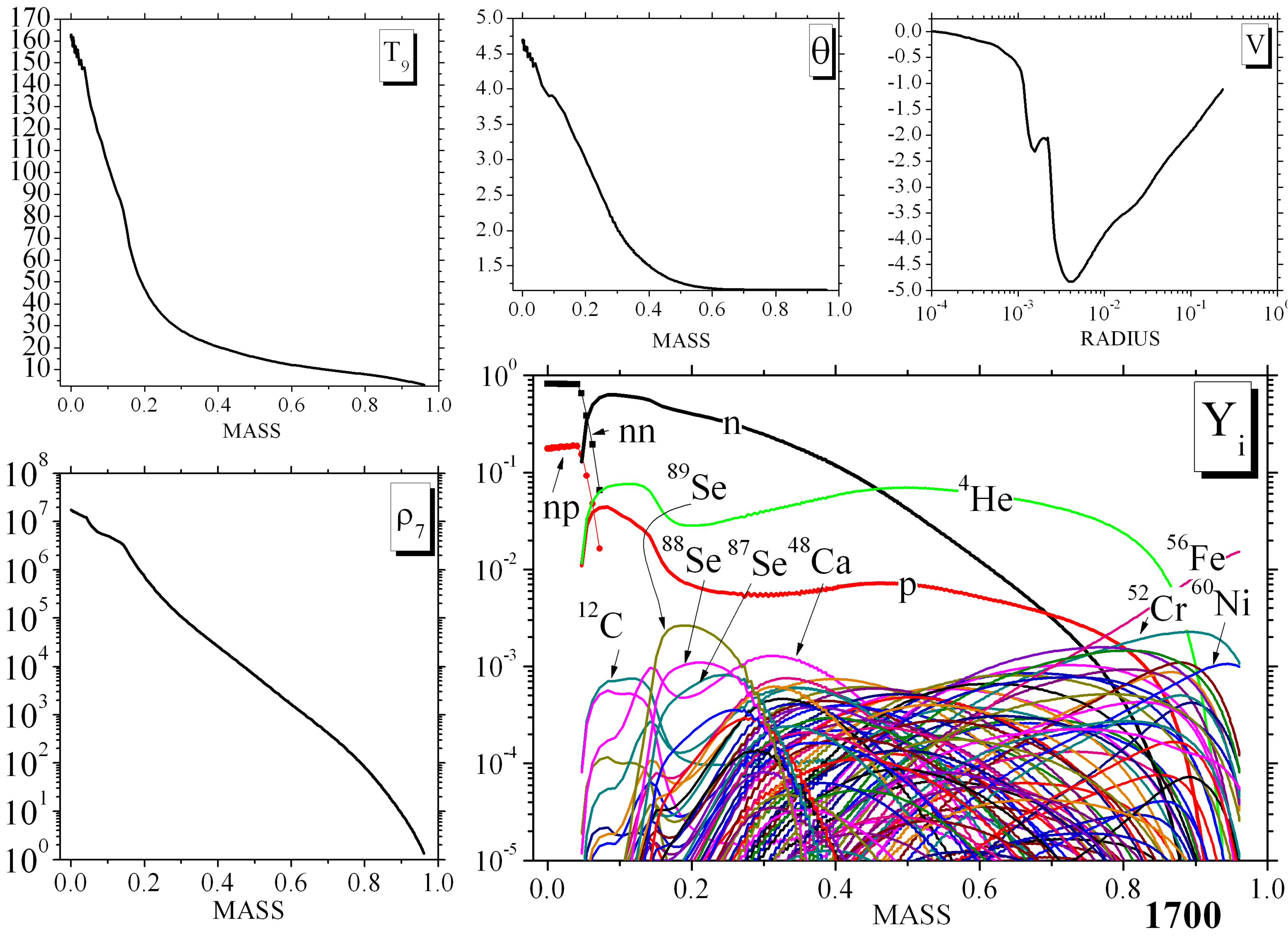
T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
nn
np
n
89Se
4He
88Se
87Se
48Ca
p
56Fe
52Cr
60Ni
12C
MASS
1550

РАВНОВЕСНЫЙ ЯДЕРНЫЙ СОСТАВ
Уравнение состояния в коре нейтронной звезды





Sly EOS; Douchin & Haensel (2001)



T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
n
nn
np
89Se
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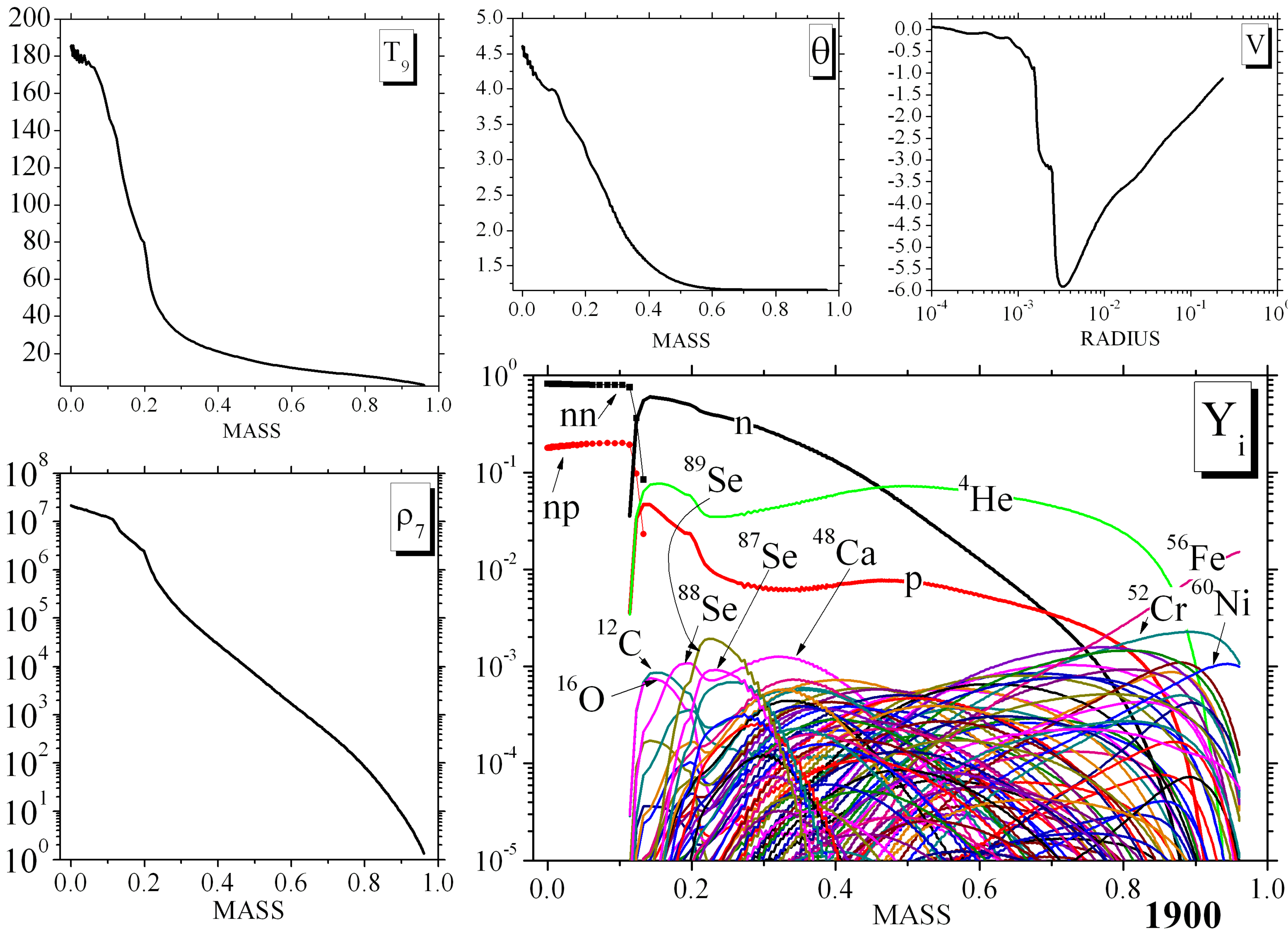
88Se 87Se 48Ca
p
56Fe
52Cr 60Ni
12C
MASS
1700



T9
θ
V
ρ7
Yi
MASS
RADIUS
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p
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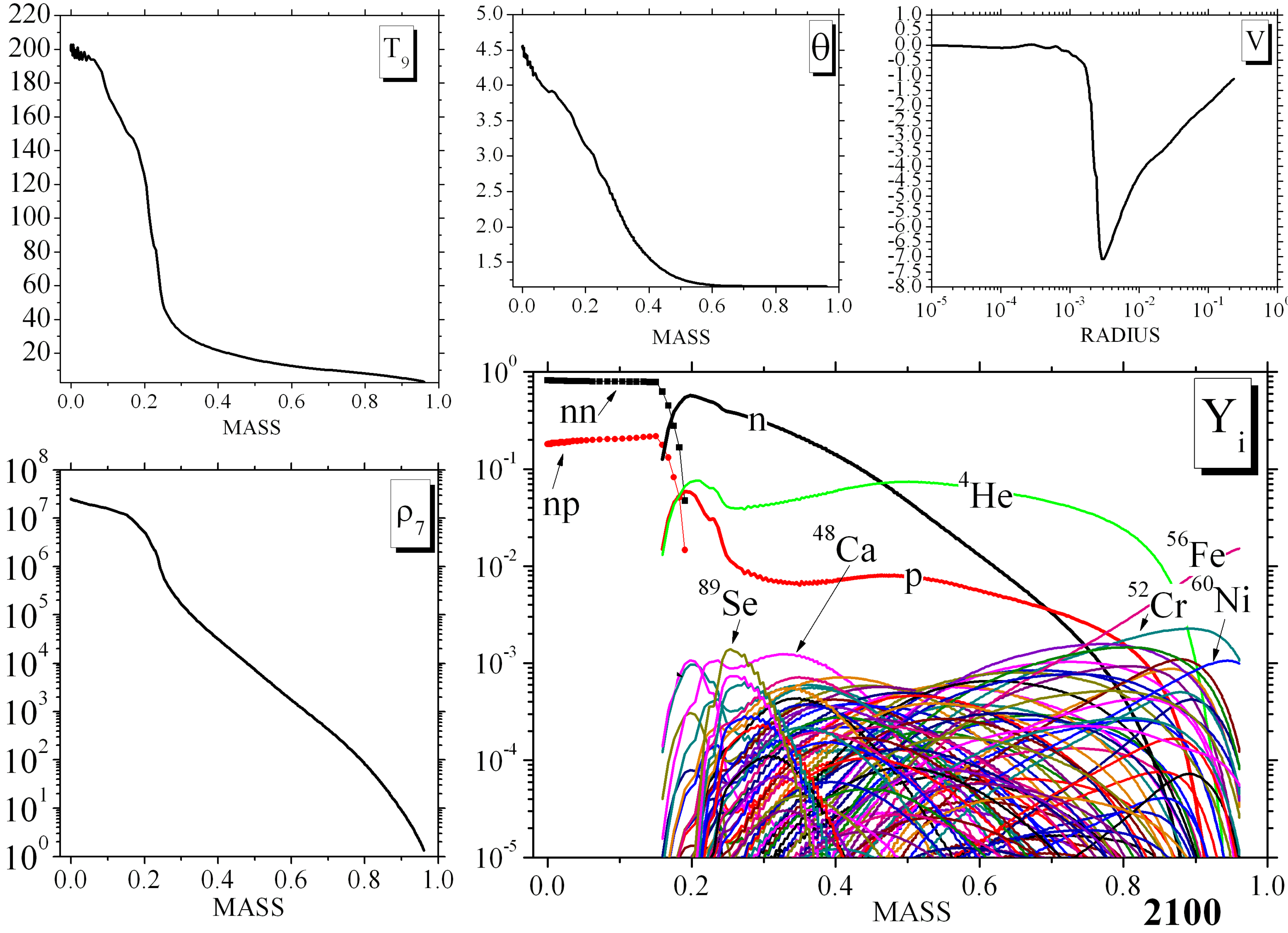
60Ni
12C
16O
1900



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MASS
θ
MASS
V
RADIUS
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52Cr
60Ni
MASS
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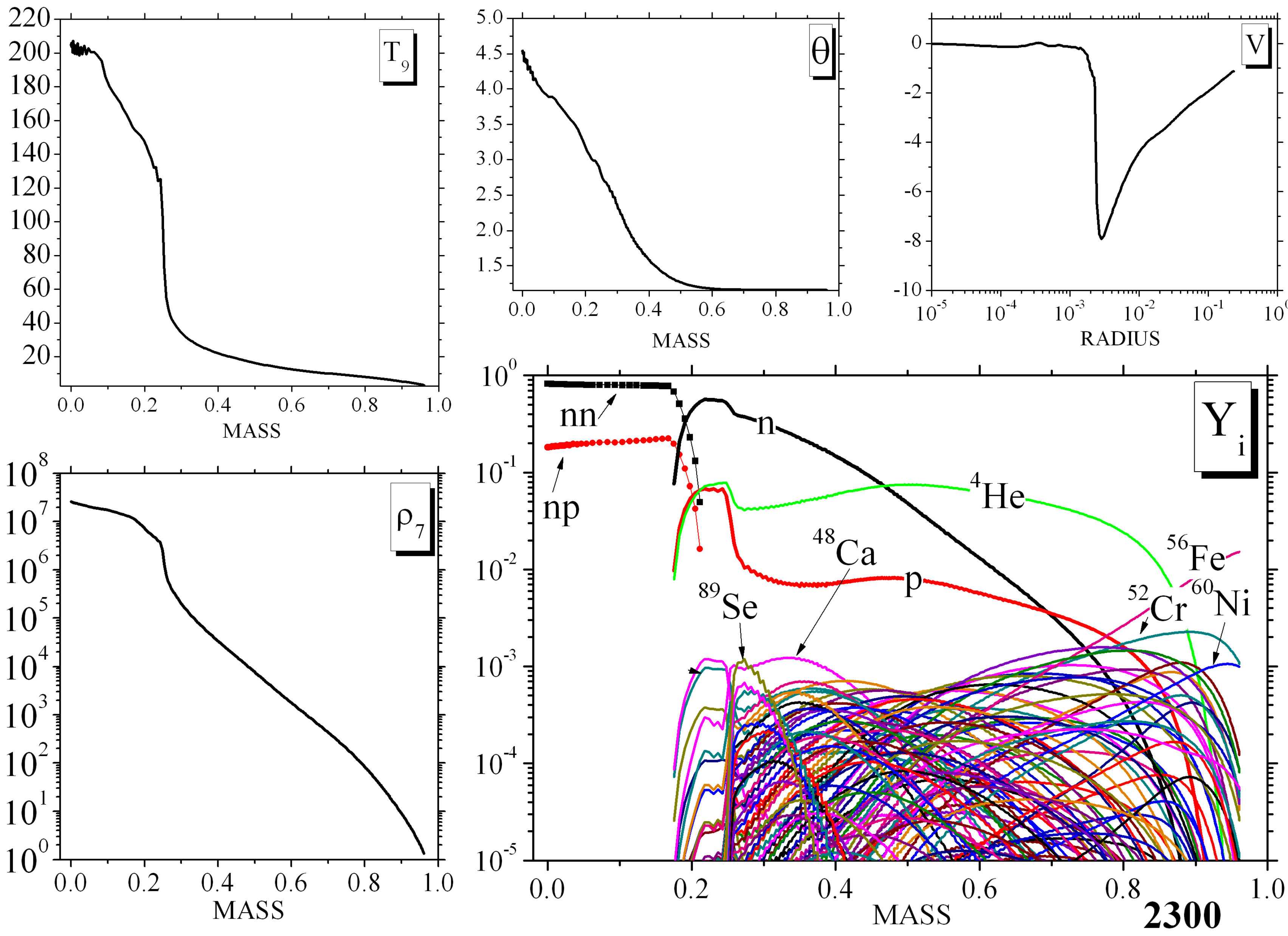
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60Ni
MASS
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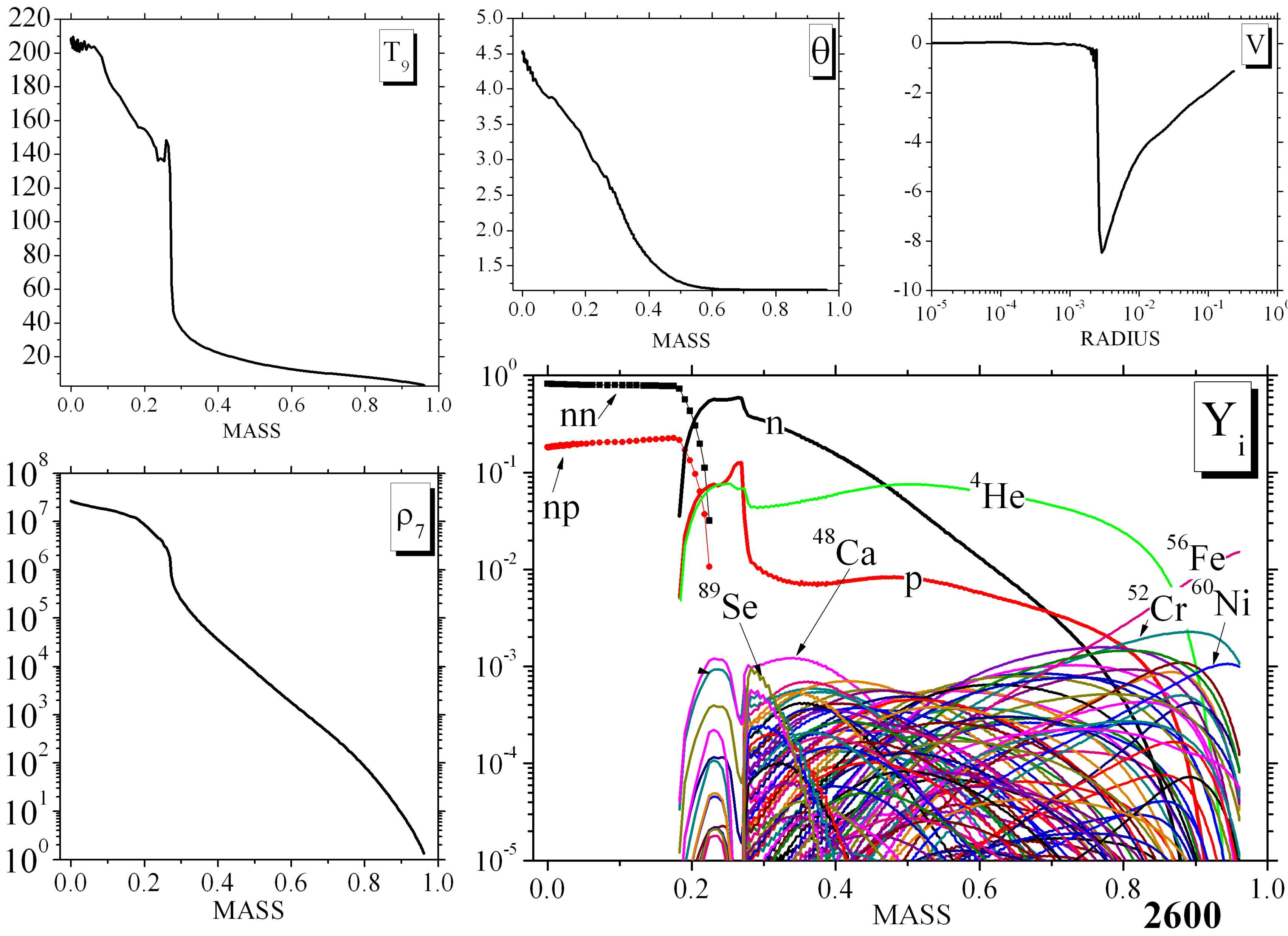

T9
MASS
θ
MASS
V
RADIUS
ρ7
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52Cr
60Ni
MASS
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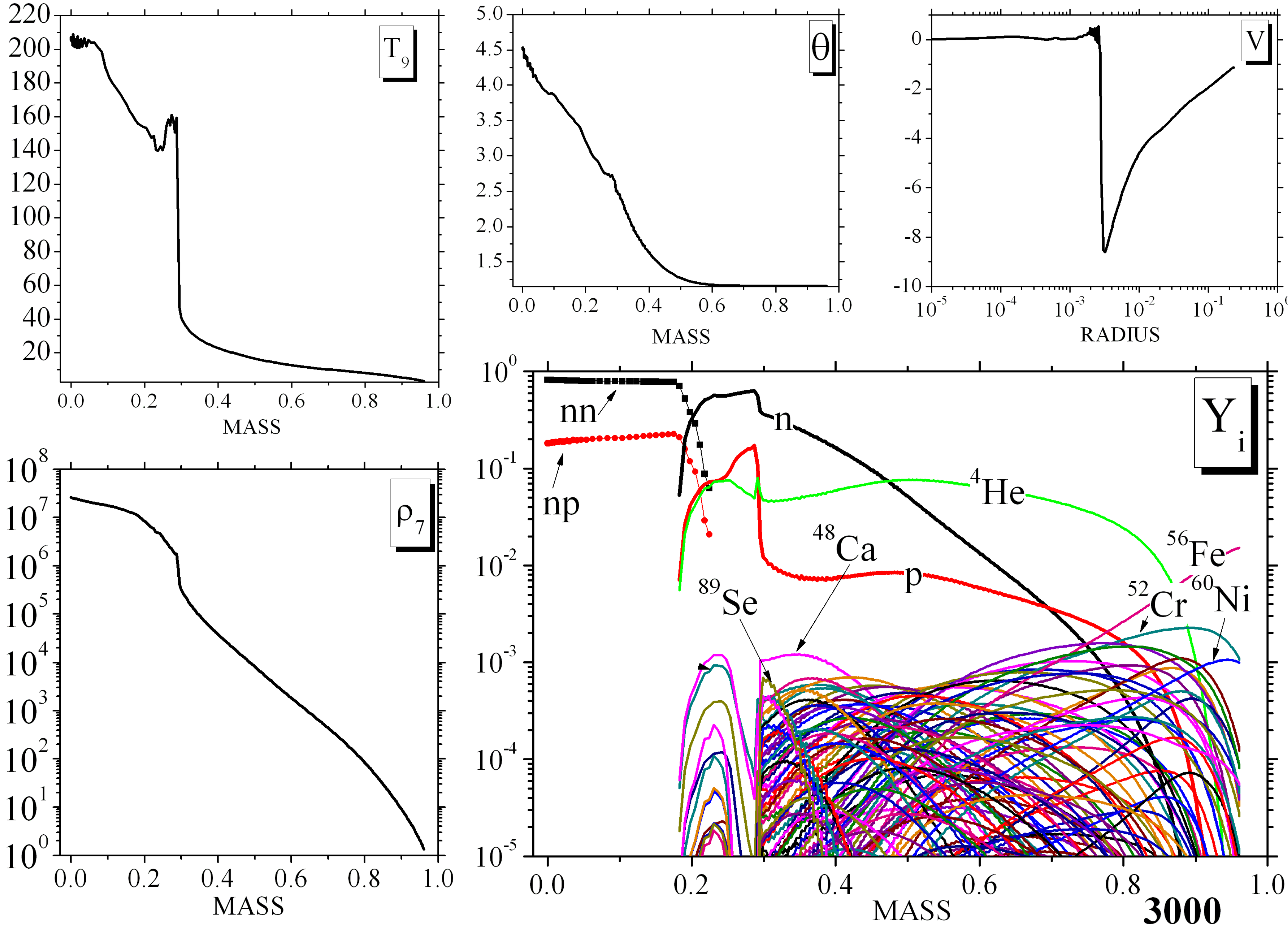
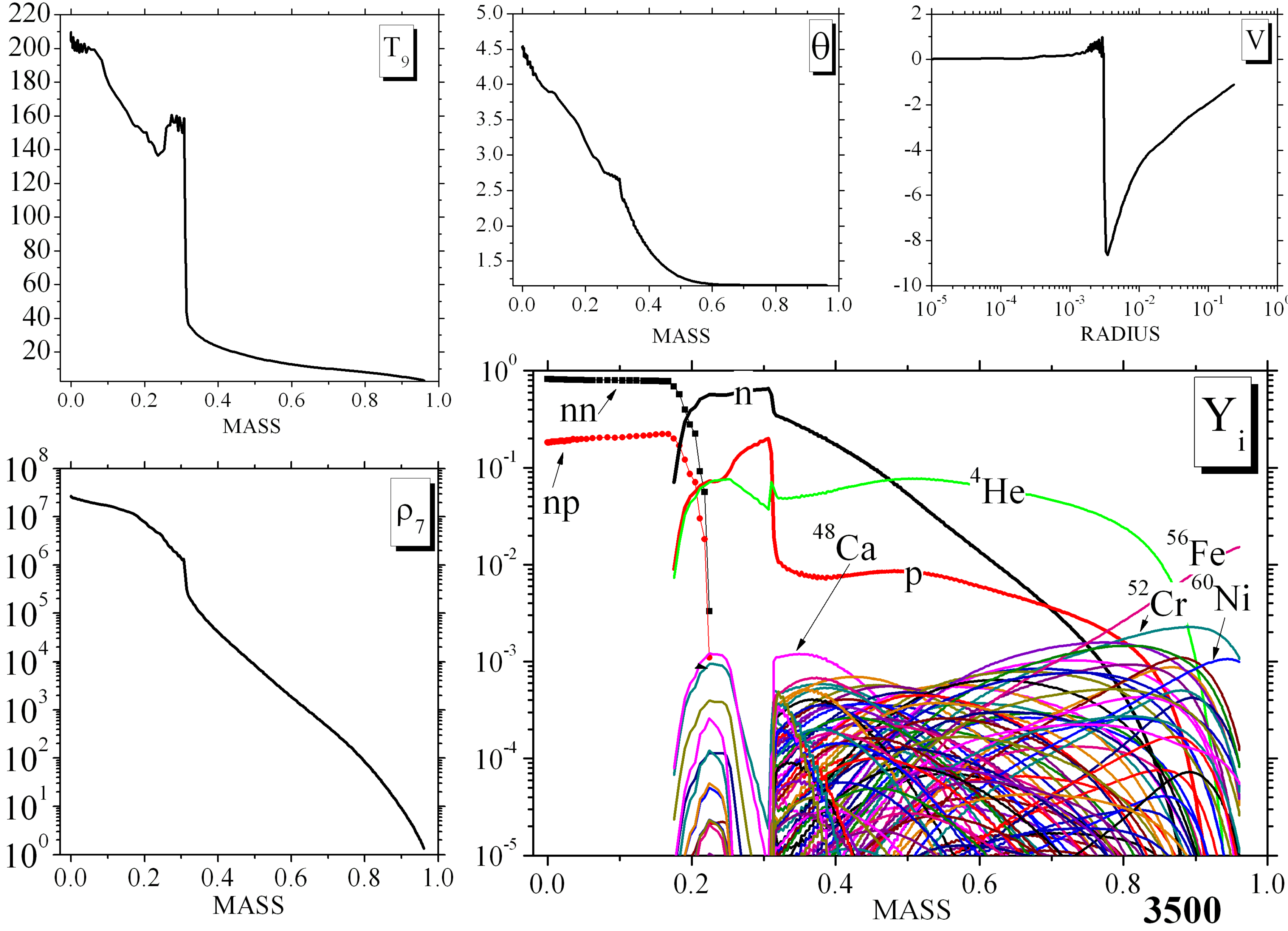
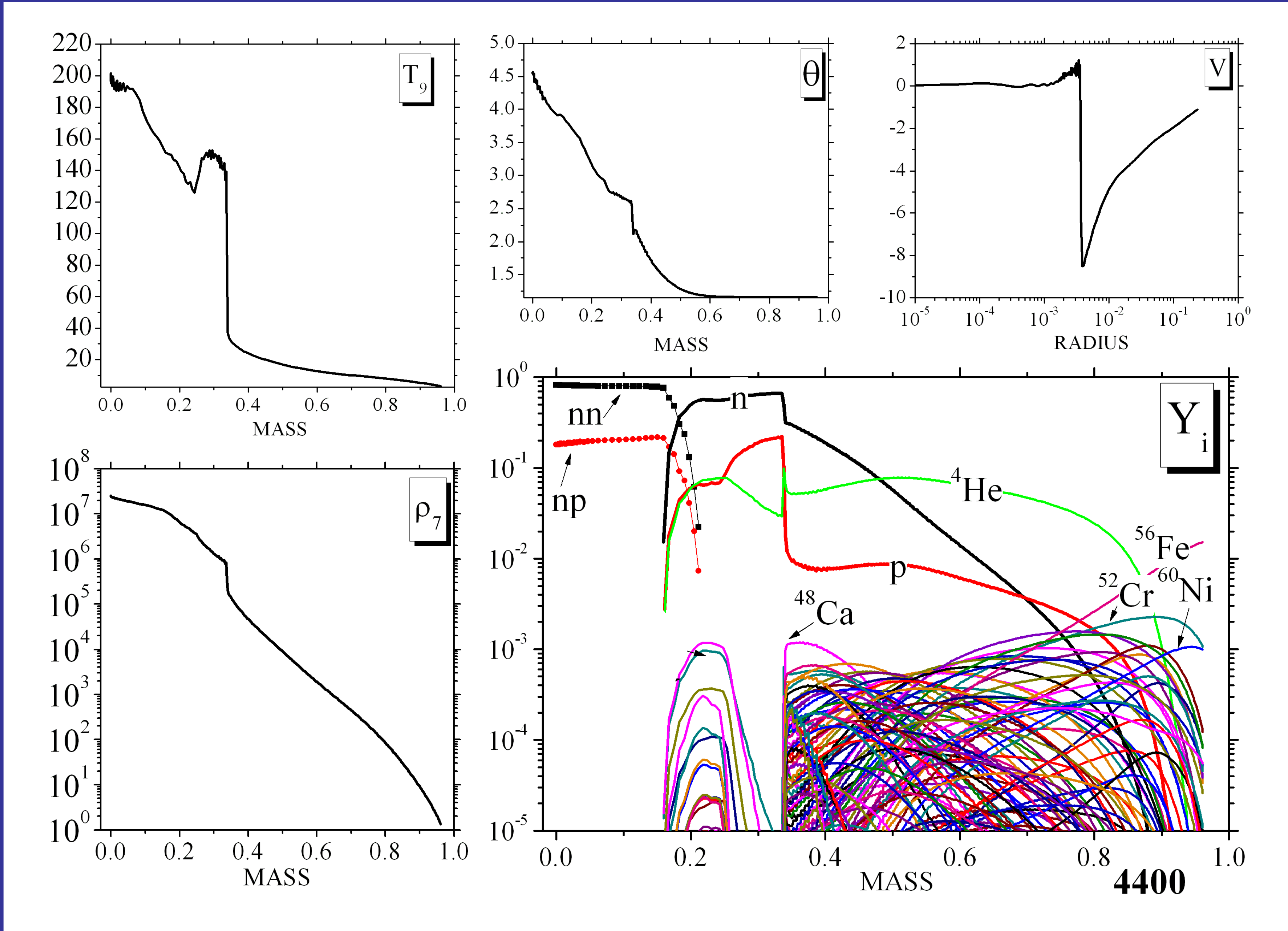


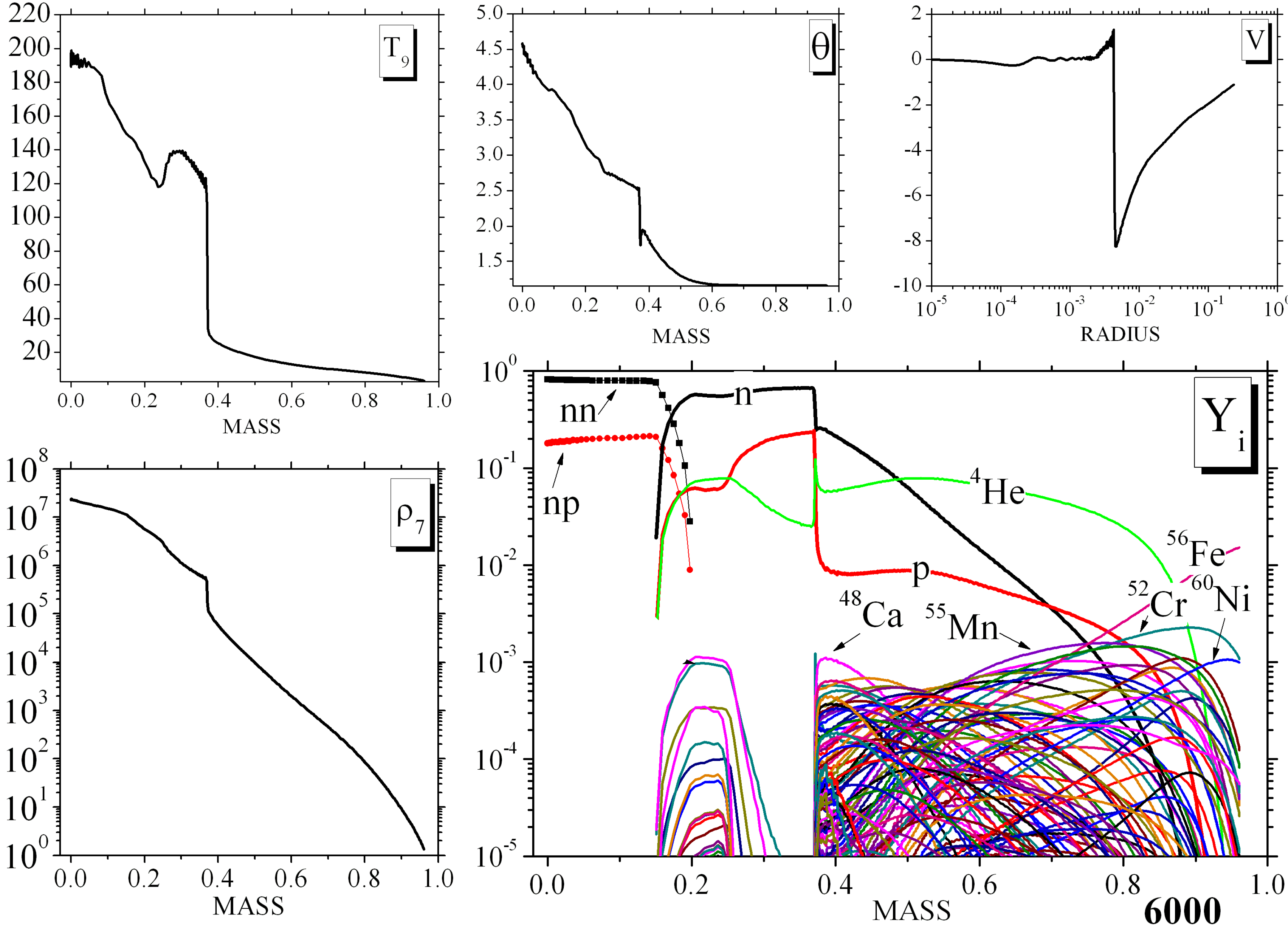
T_9
MASS
θ
MASS
V
RADIUS
ρ_7
MASS
Y_i
nn
np
n
p
^{4}He
^{48}Ca
^{89}Se
^{56}Fe
^{52}Cr
^{60}Ni
MASS
3000



T9
MASS
θ
MASS
V
RADIUS
ρ7
MASS
Yi
nn
n
np
4He
48Ca
p
56Fe
52Cr
60Ni
MASS
3500



T9
θ
V
ρ7
Yi
MASS
RADIUS
nn
n
np
p
4He
56Fe
52Cr
60Ni
48Ca
4400



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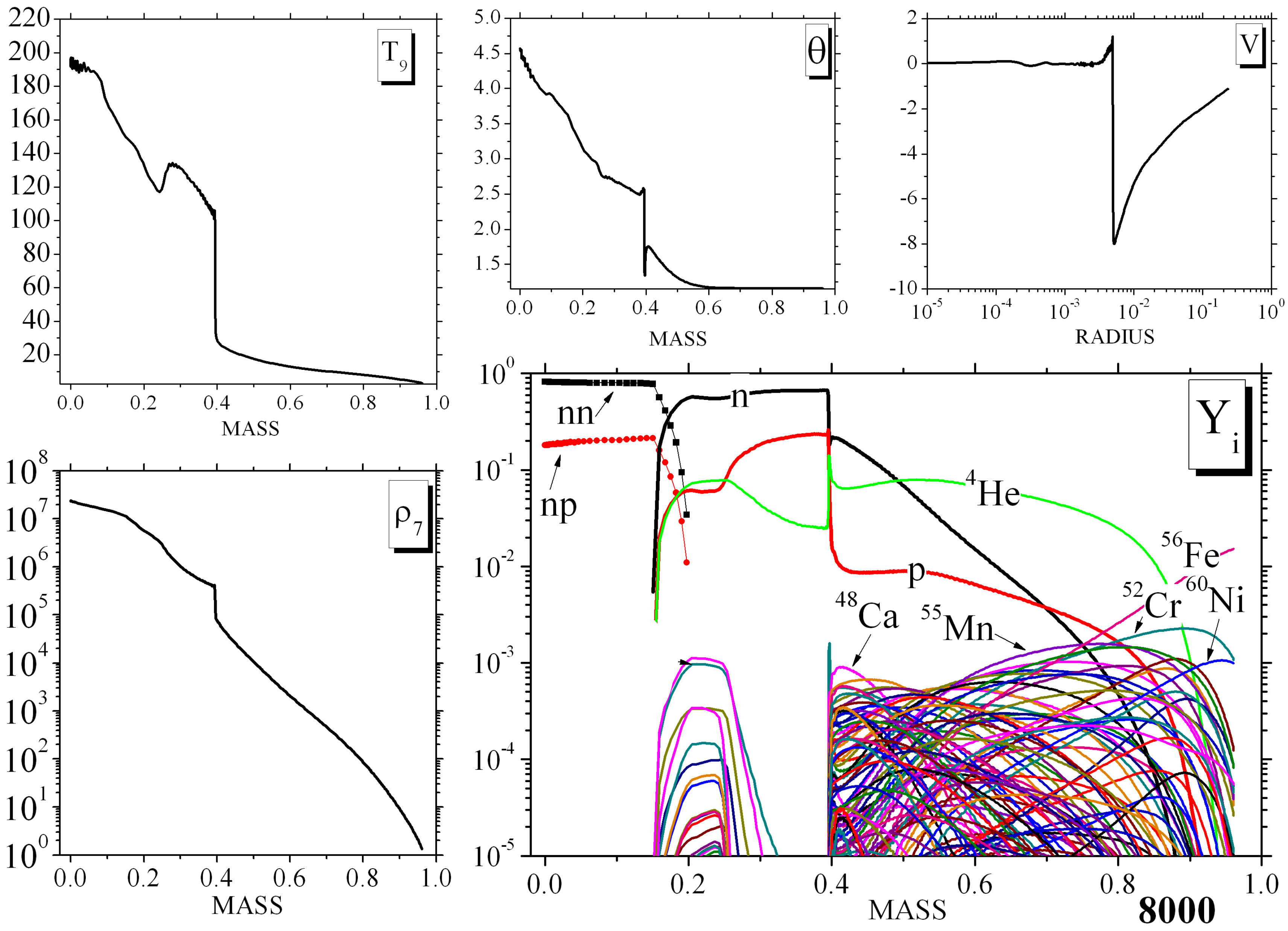
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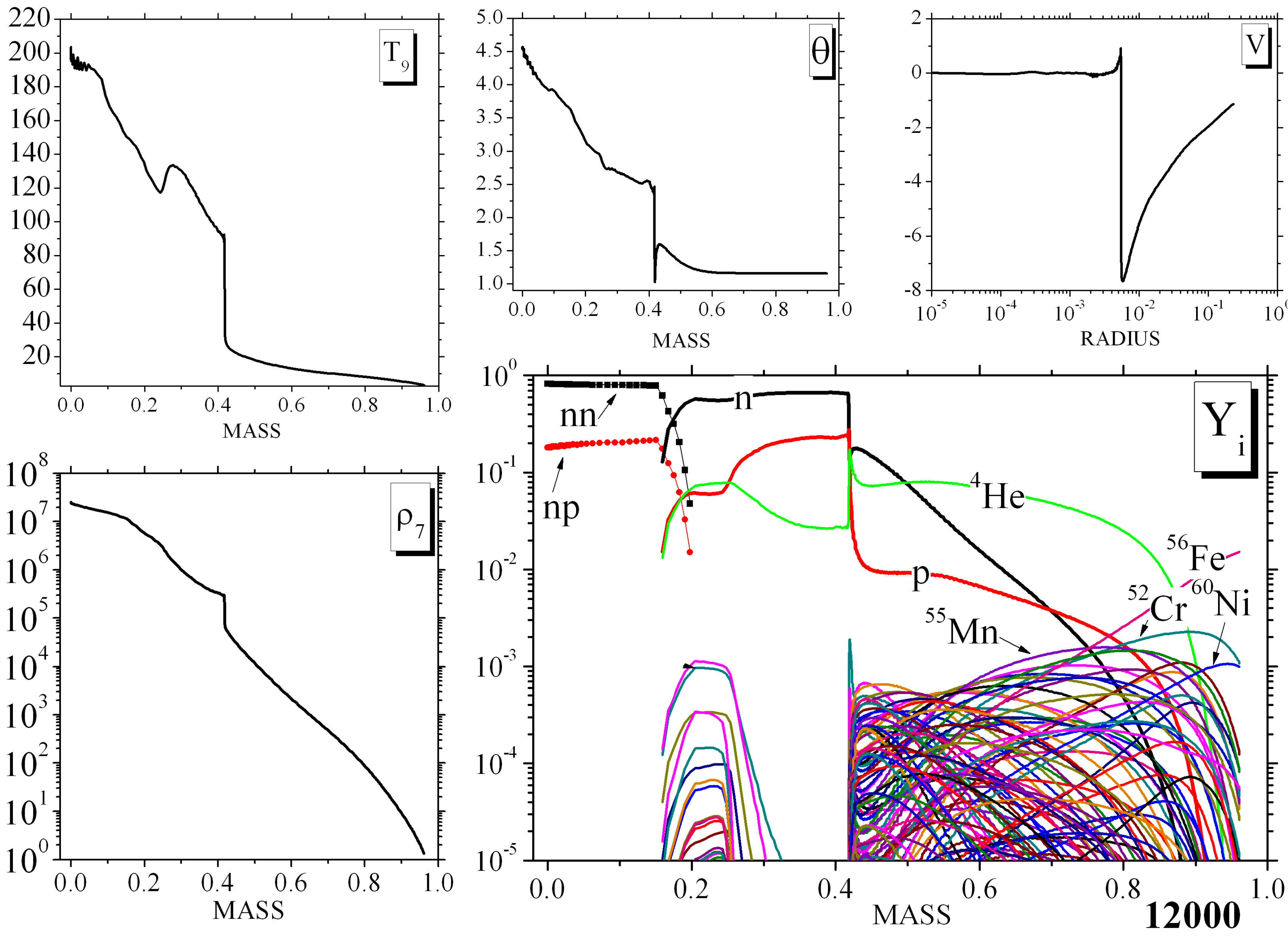

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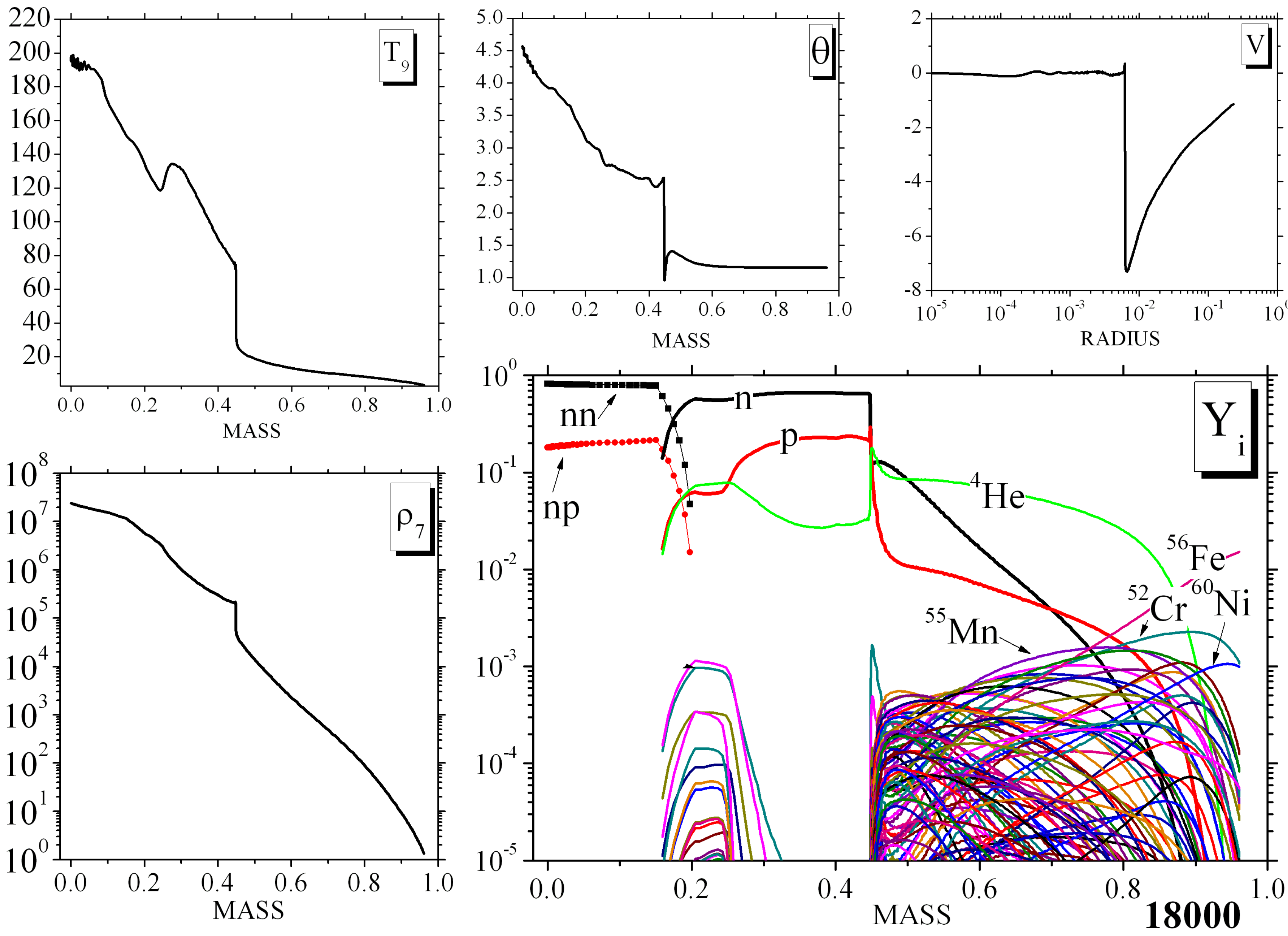

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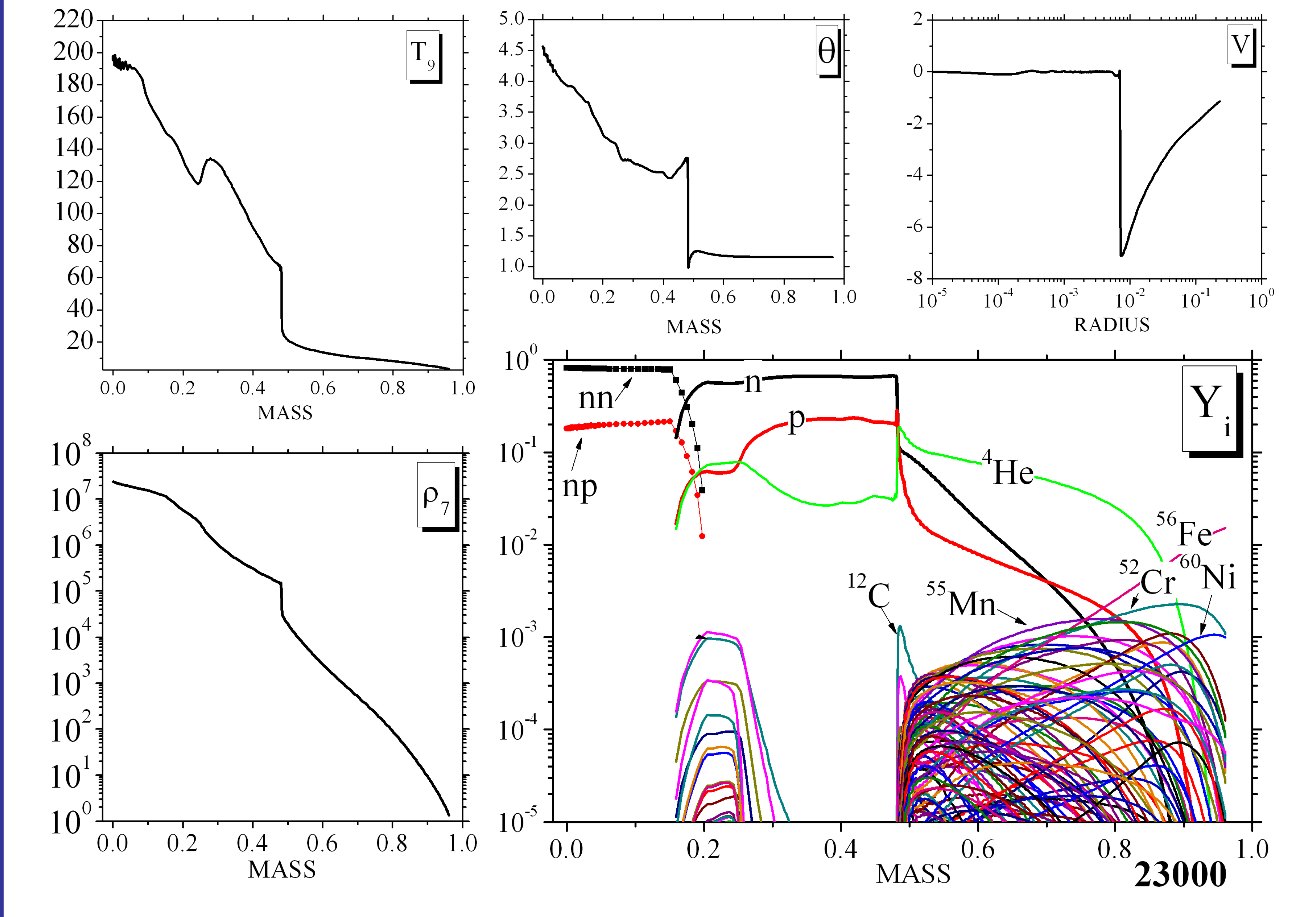

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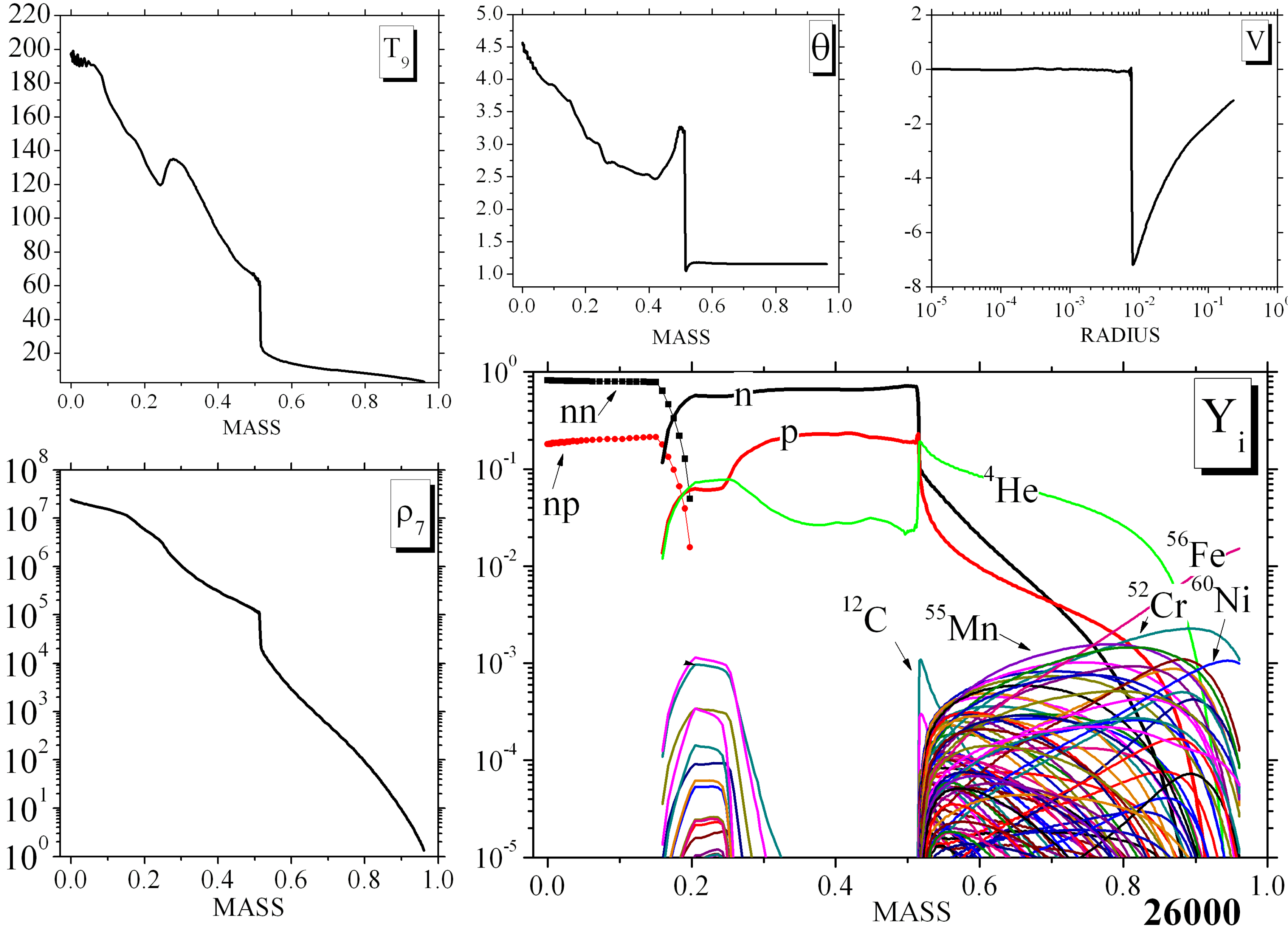
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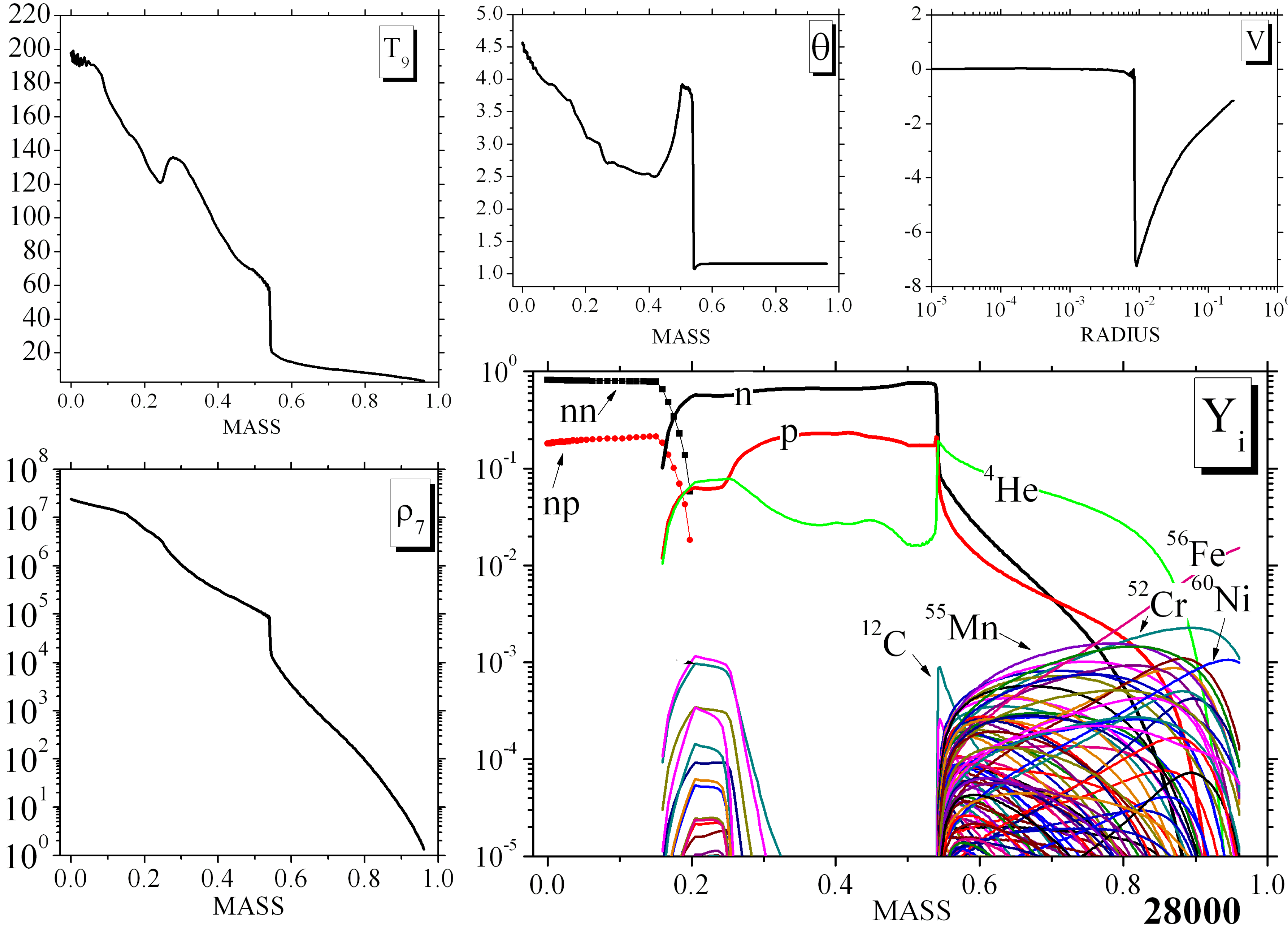

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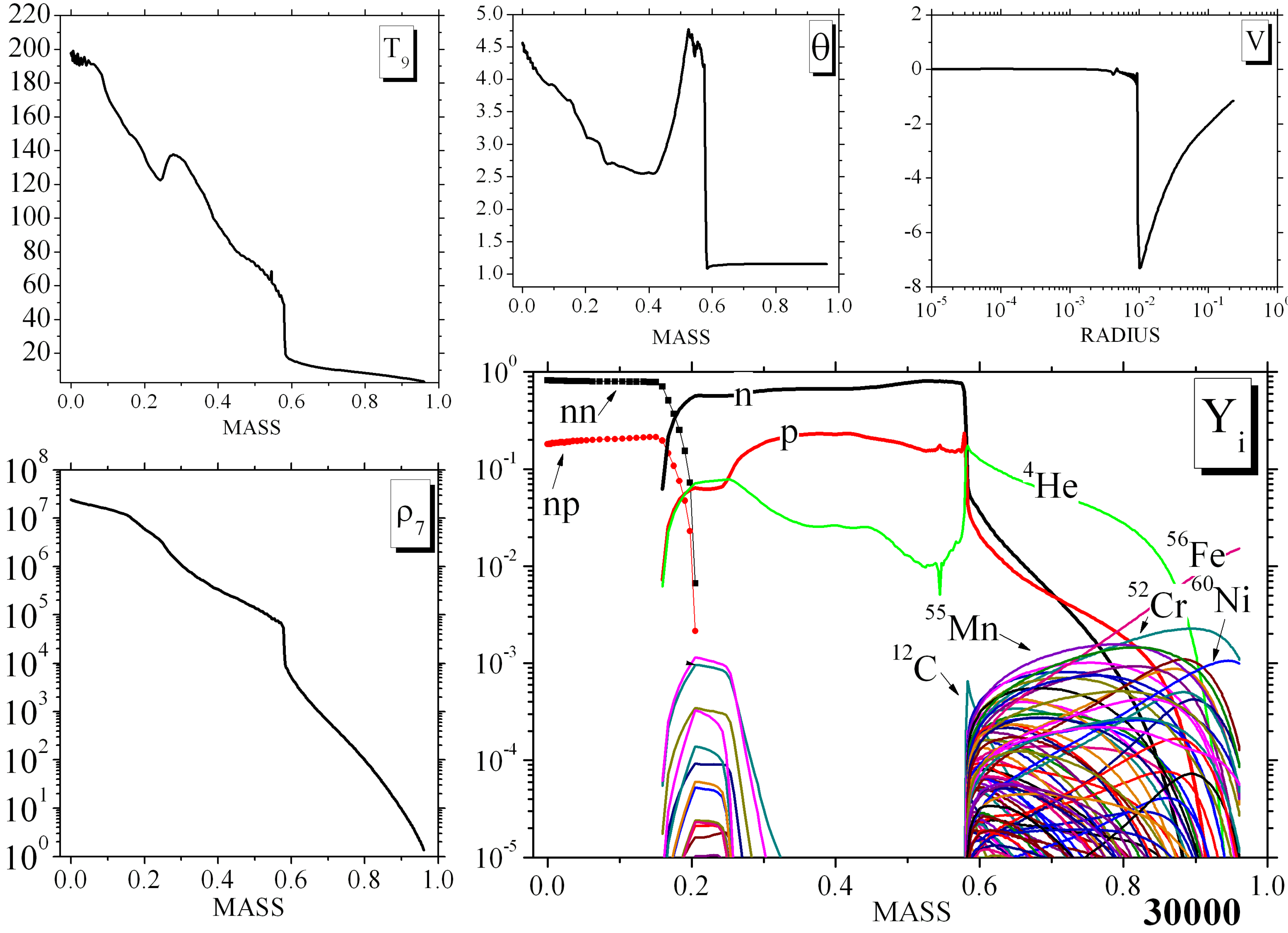

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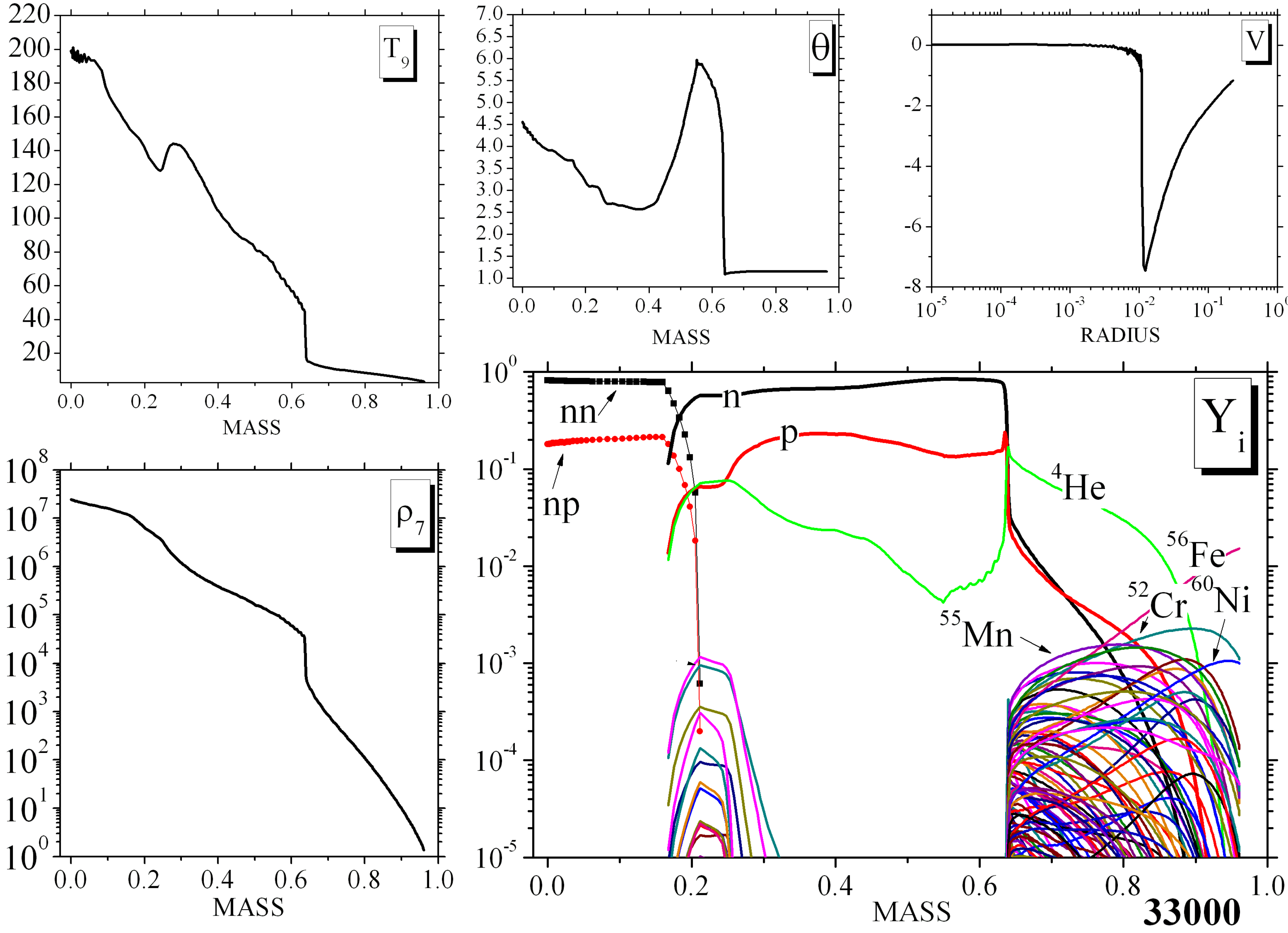

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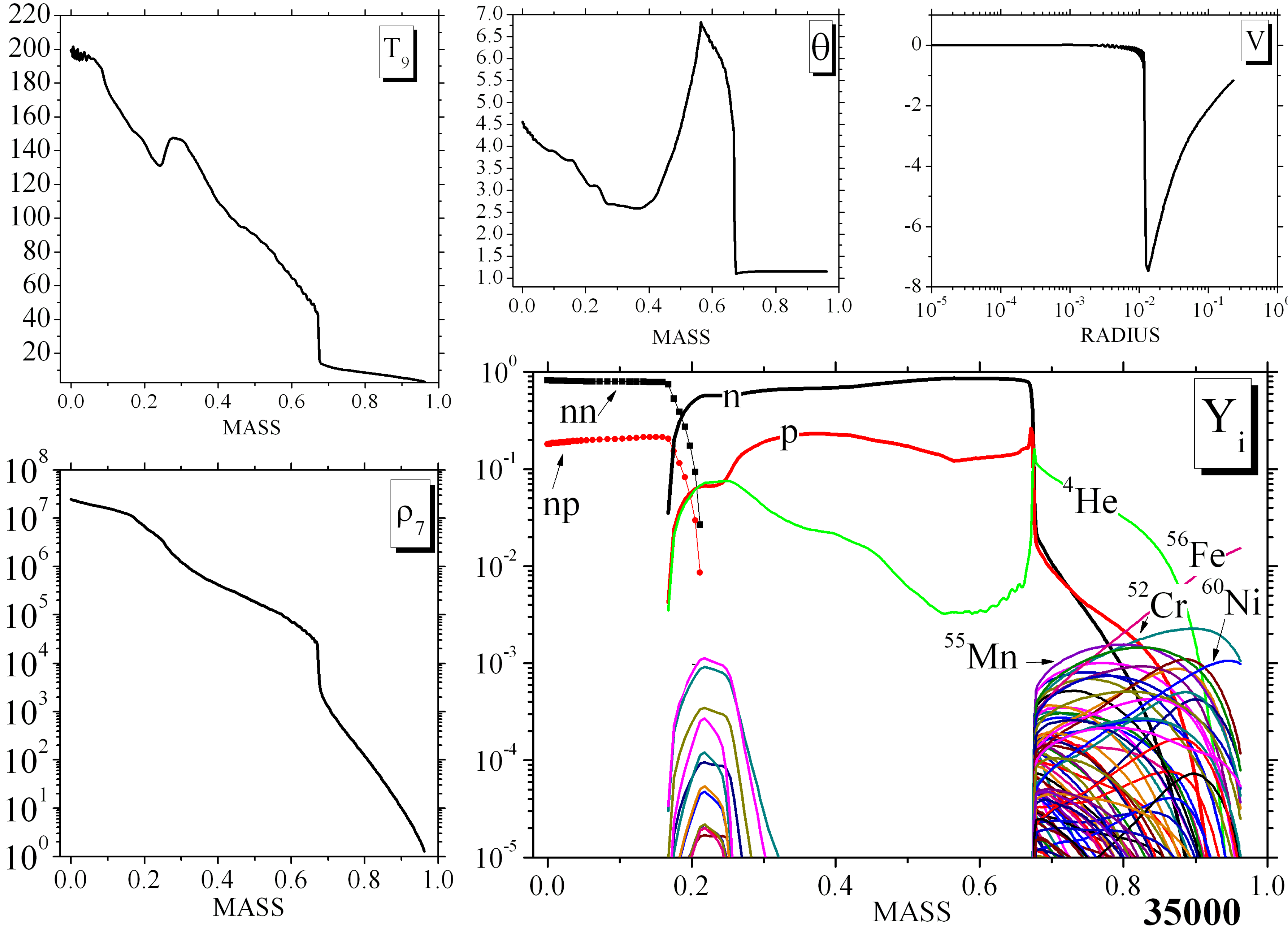

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MASS
RADIUS
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n
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4He
56Fe
52Cr
60Ni
55Mn
35000

$$H_\nu = -\frac{4\pi}{3h^3c^2}\left[(A_\nu + A_{\overline{\nu}})\frac{1}{kT^2}\frac{\partial T}{\partial r} + (B_\nu - B_{\overline{\nu}})\frac{\partial \psi_\nu}{\partial r}\right]$$

$$F_\nu = -\frac{4\pi}{3h^3c^2}\left[(C_\nu - C_{\overline{\nu}})\frac{1}{kT^2}\frac{\partial T}{\partial r} + (D_\nu + D_{\overline{\nu}})\frac{\partial \psi_\nu}{\partial r}\right]$$

$$A = \int_0^\infty \frac{f_\mathrm{e}}{\lambda_\mathrm{m}} g_\mathrm{T}\, \omega^3 d\omega\,, \qquad B = \int_0^\infty \frac{f_\mathrm{e}}{\lambda_\mathrm{m}} g_\psi\, \omega^3 d\omega$$

$$C = \int_0^\infty \frac{f_\mathrm{e}}{\lambda_\mathrm{m}} g_\mathrm{T}\, \omega^2 d\omega\,, \qquad D = \int_0^\infty \frac{f_\mathrm{e}}{\lambda_\mathrm{m}} g_\psi\, \omega^2 d\omega$$

$$\begin{cases} g_\mathrm{T}(\omega) = \omega(1-f_\mathrm{e}) + \displaystyle\int_0^\infty \Phi_1(\omega,\omega')\, g_\mathrm{T}(\omega')\frac{d\omega'}{\lambda_\mathrm{m}(\omega')} \\ g_\psi(\omega) = (1-f_\mathrm{e}) + \displaystyle\int_0^\infty \Phi_1(\omega,\omega')\, g_\psi(\omega')\frac{d\omega'}{\lambda_\mathrm{m}(\omega')}\,. \end{cases}$$

$$\lambda_\mathrm{m}(\omega) \equiv \tilde{l}^{-1} + l_\mathrm{cs}^{-1}\,(1-\langle\eta\rangle) + \frac{1}{1-f_\mathrm{e}}\int_0^\infty (1-f'_\mathrm{e})\Phi_0(\omega,\omega')\, d\omega'$$

$$R(\omega,\omega',\eta) \;=\; R_\mathrm{nc}(\omega,\omega',\eta) + R_\mathrm{cs}(\omega,\eta)\,\delta(\omega-\omega')$$

$$\langle\eta\rangle \;=\; 2\pi l_\mathrm{cs}\int_{-1}^{1}\eta R_\mathrm{cs}(\omega,\eta)\, d\eta\,, \qquad l_\mathrm{cs}^{-1} \;=\; 2\pi\int_{-1}^{1} R_\mathrm{cs}(\omega,\eta)\, d\eta$$

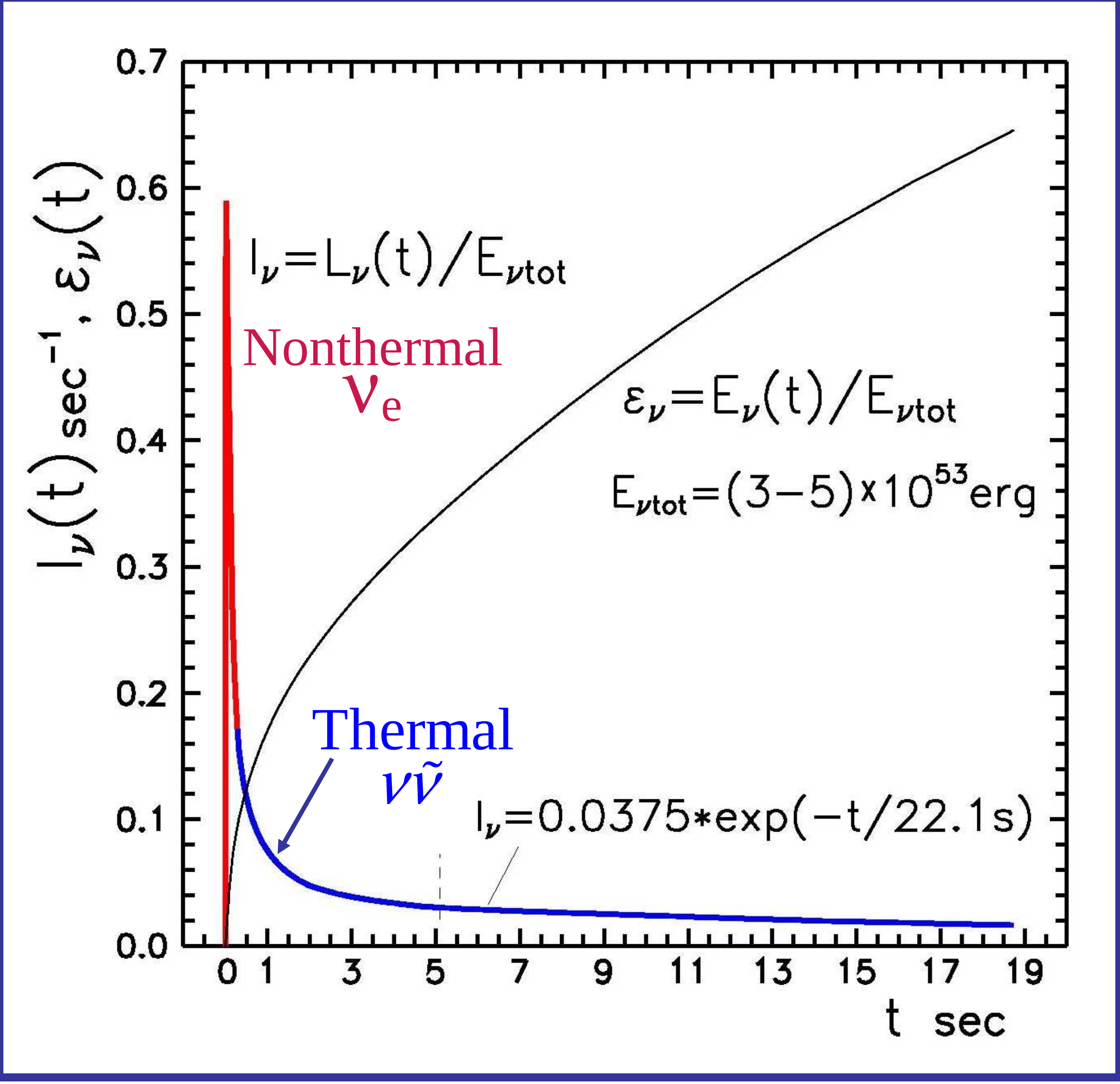
$$\Phi_0(\omega,\omega') = 2\pi\int_{-1}^{1} R_\mathrm{nc}(\omega,\omega',\eta)d\eta \qquad \Phi_1(\omega,\omega') = 2\pi\int_{-1}^{1} \eta R_\mathrm{nc}(\omega,\omega',\eta)d\eta$$

$$\Phi(\omega,\omega') = \Phi(\omega',\omega)\left(\frac{\omega'}{\omega}\right)^2 e^{\frac{\omega-\omega'}{kT}}$$

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

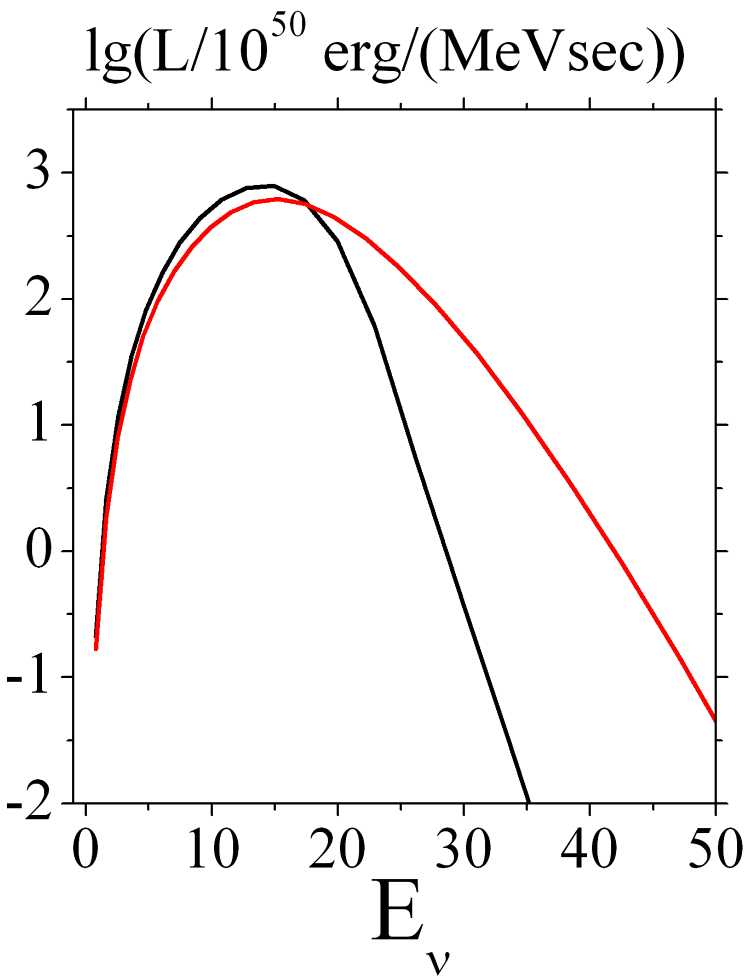
The properties of the Neutrino flux

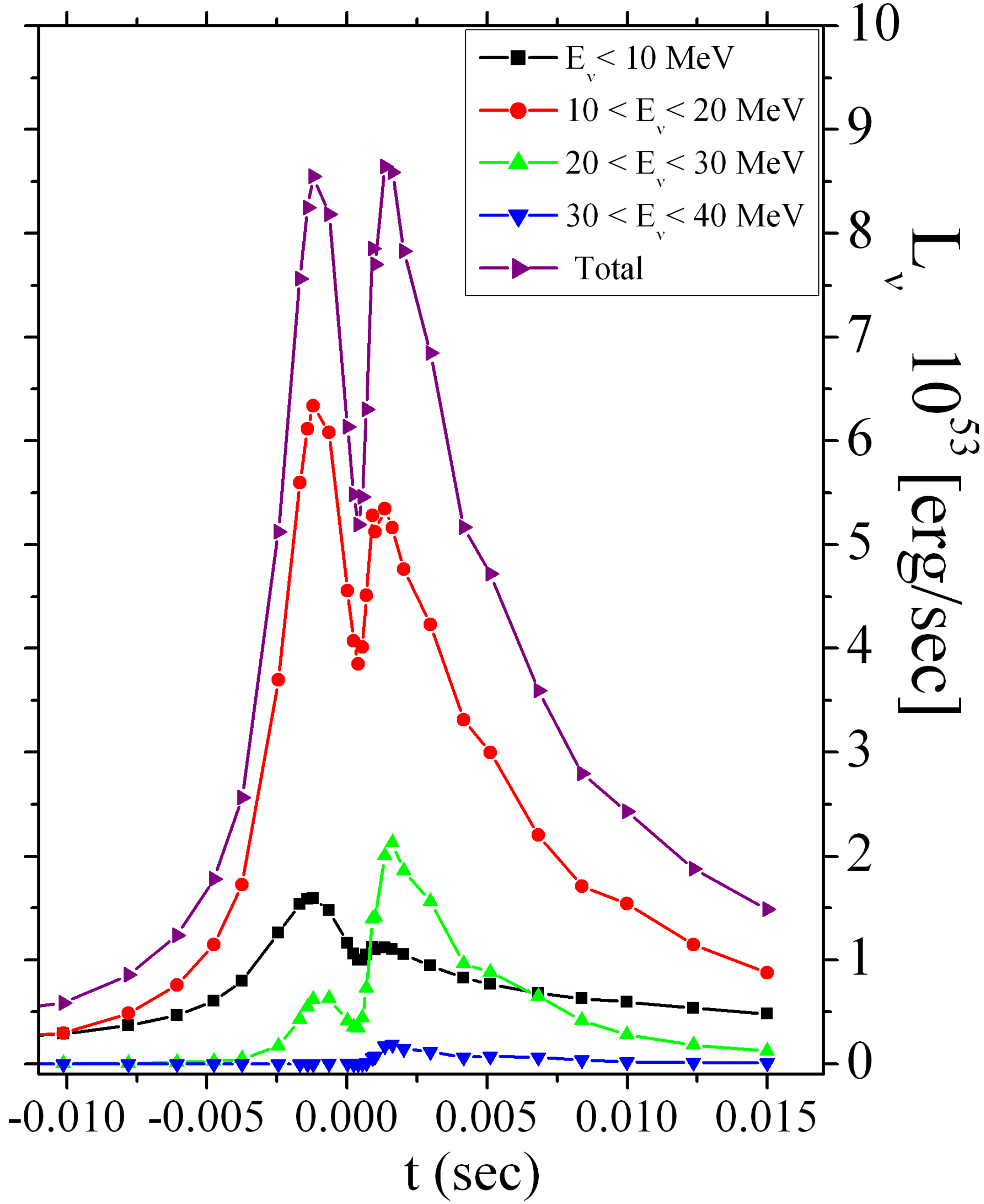
Cumulative neutrino "light" curve (based on Nadyozhin 1978)



t = -1.2 ms, $\langle E_\nu \rangle$ = 12.3 MeV

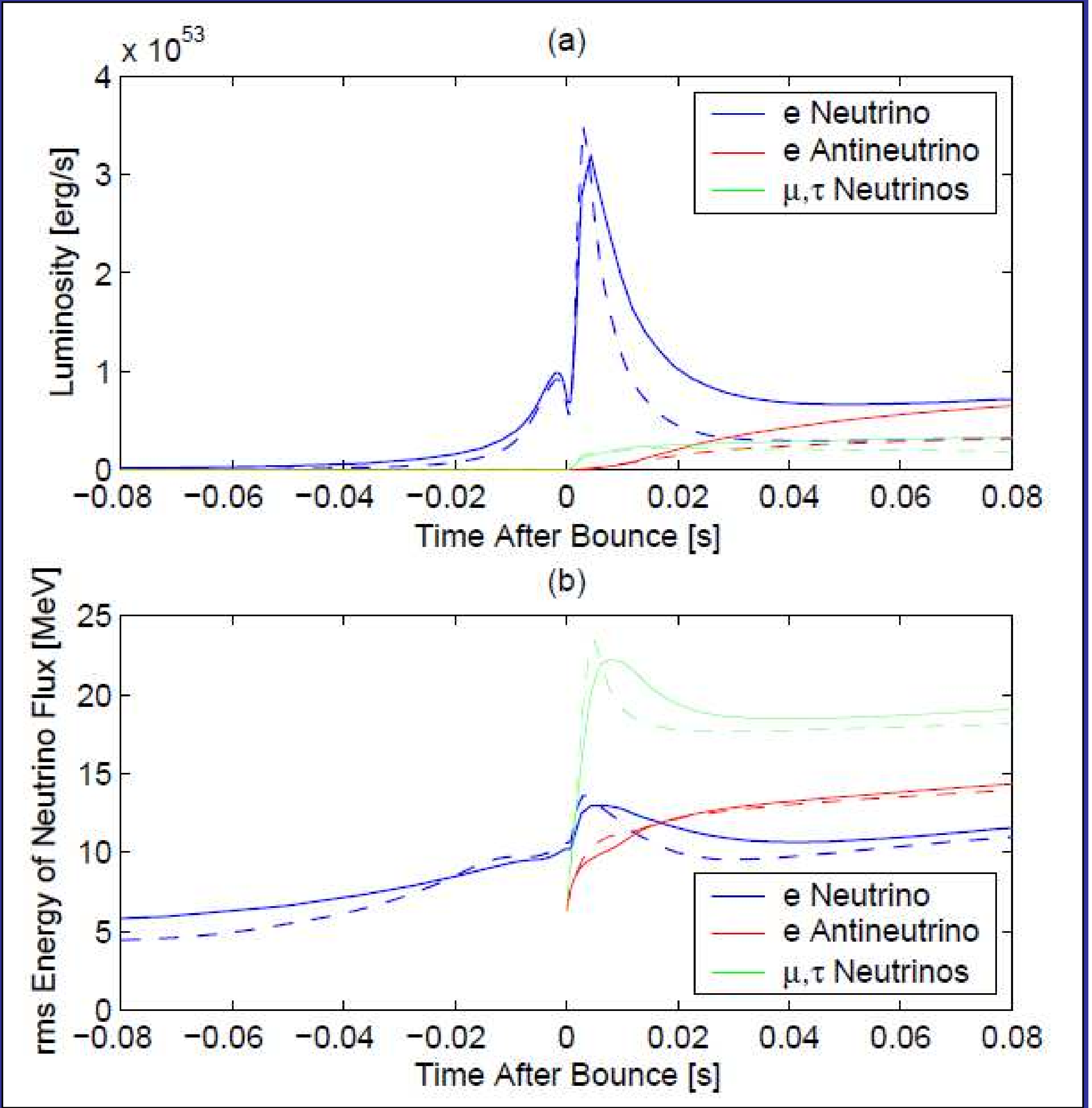
t = 1.35 ms, $\langle E_\nu \rangle$ = 14.1 MeV





Liebendoerfer et al. 2003

Solid lines:
40 M_{Sun} progenetor
dashed:
13 M_{Sun} progenetor



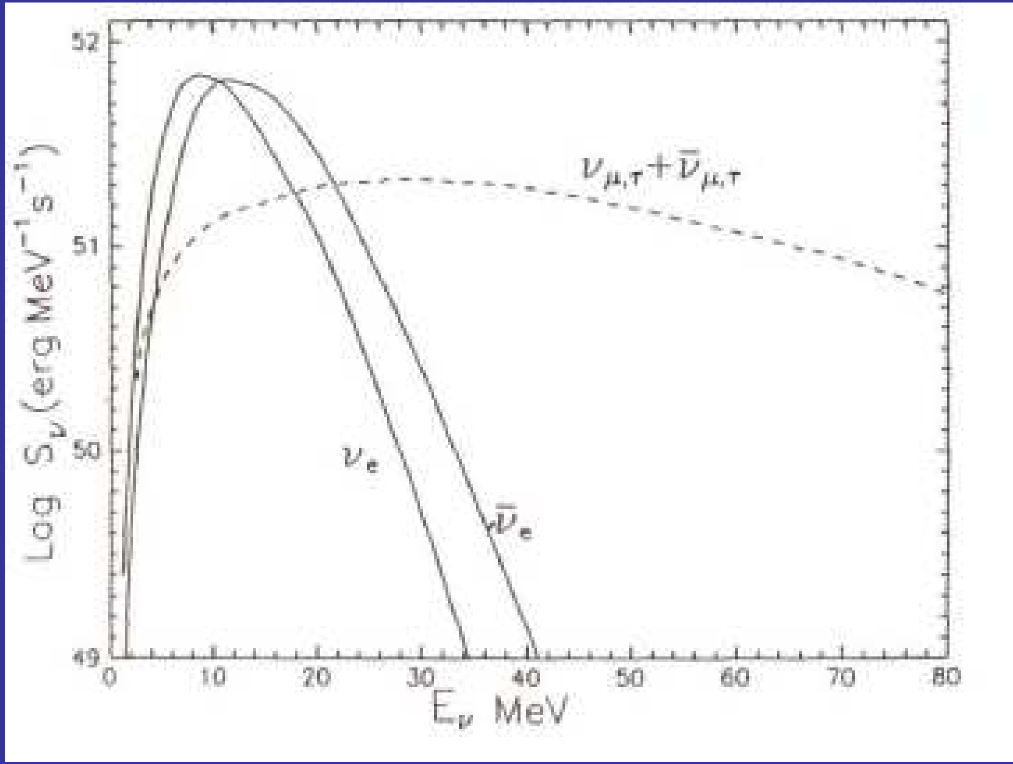
Neutrino spectra for thermal phase

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

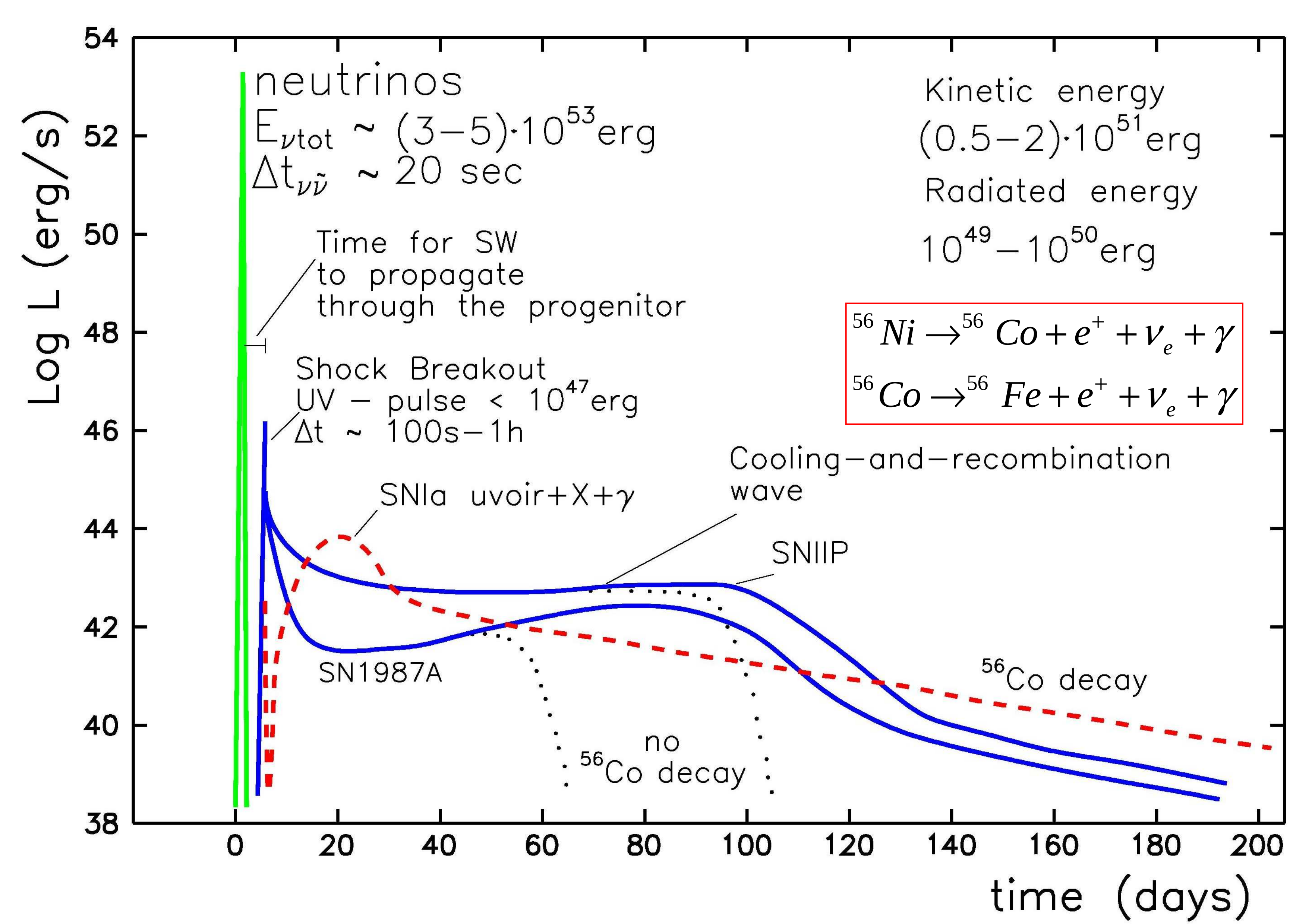
(*relevant to* $\nu_\mathrm{e}, \tilde{\nu}_\mathrm{e}$):

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

$T_{\nu\mathrm{ph}} \approx 4$ 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):

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

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

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

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

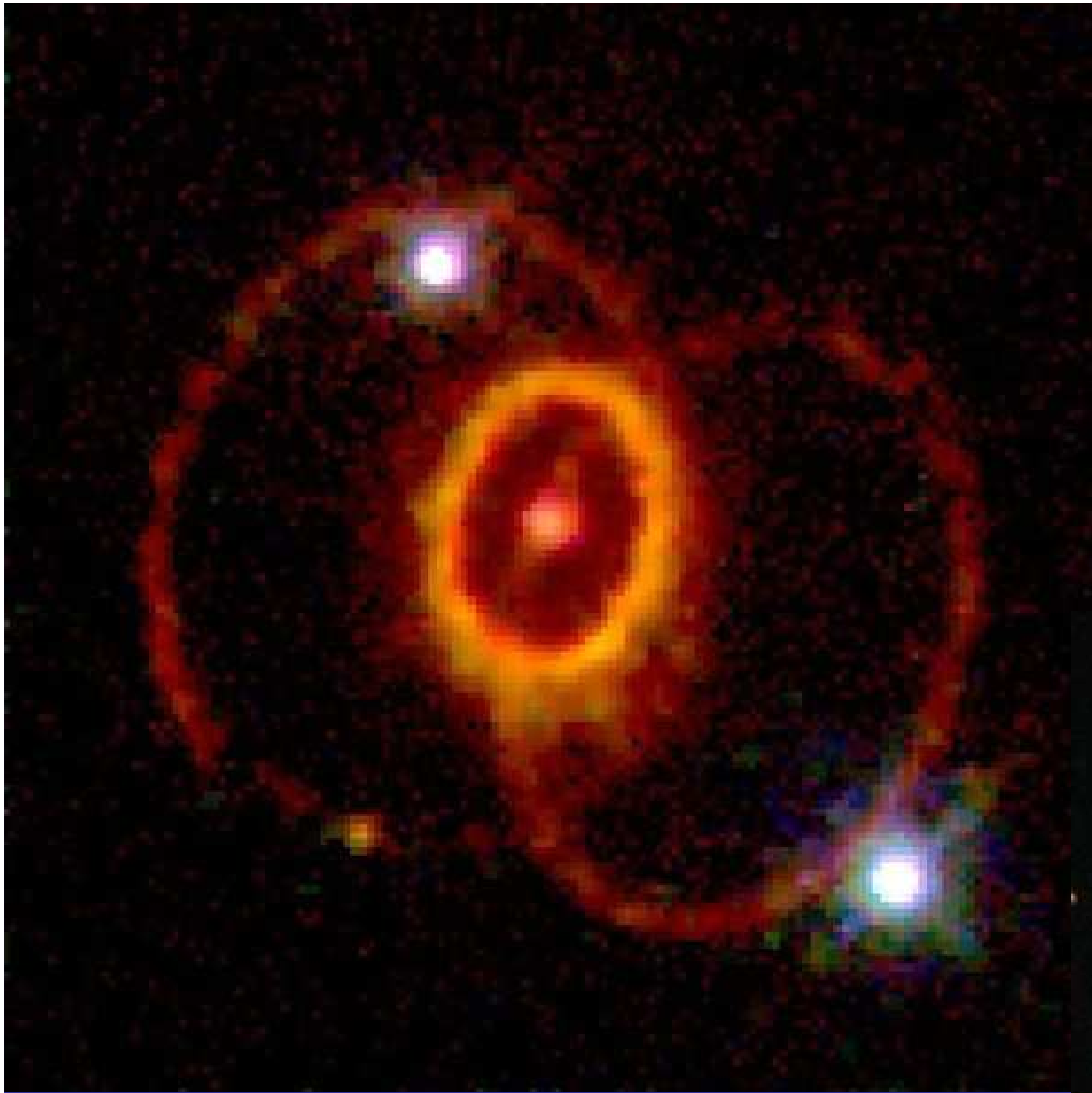
→ Low-mass neutron star explosion + second collapse

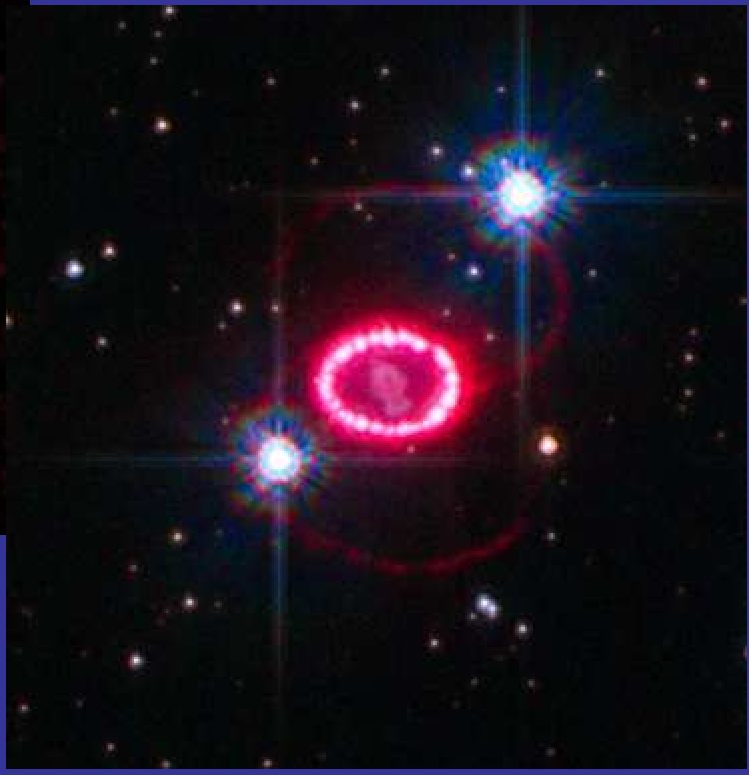
$\nu\nu$ of all flavours; IMB, Kamioka, Baksan signals; SN otburst

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

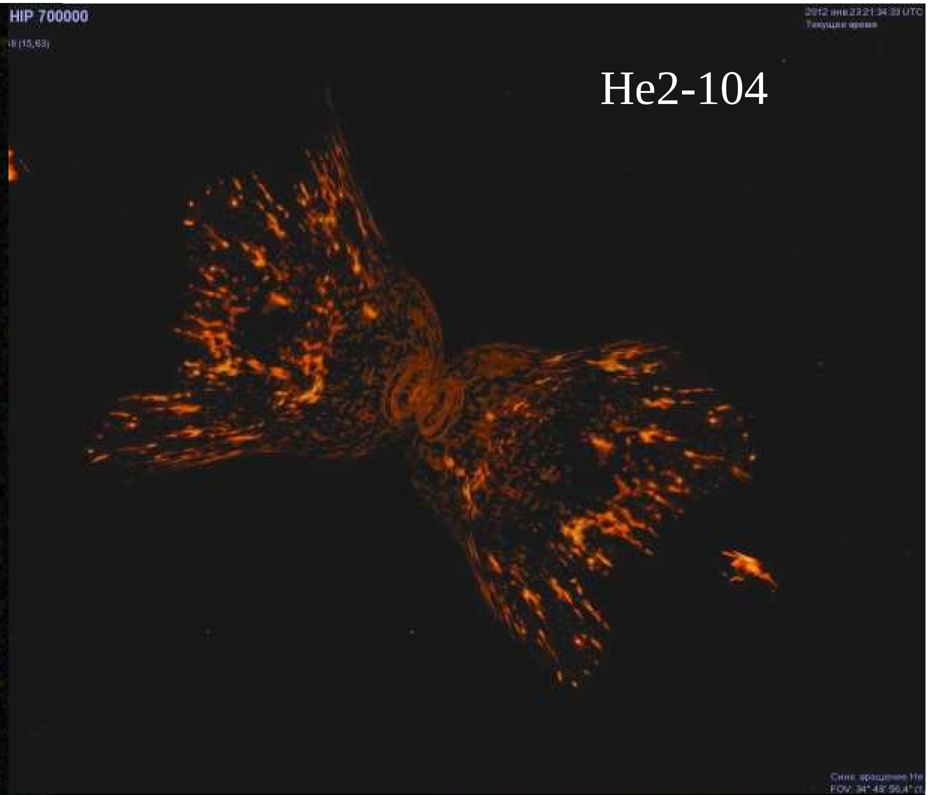
Загадка SN1987A

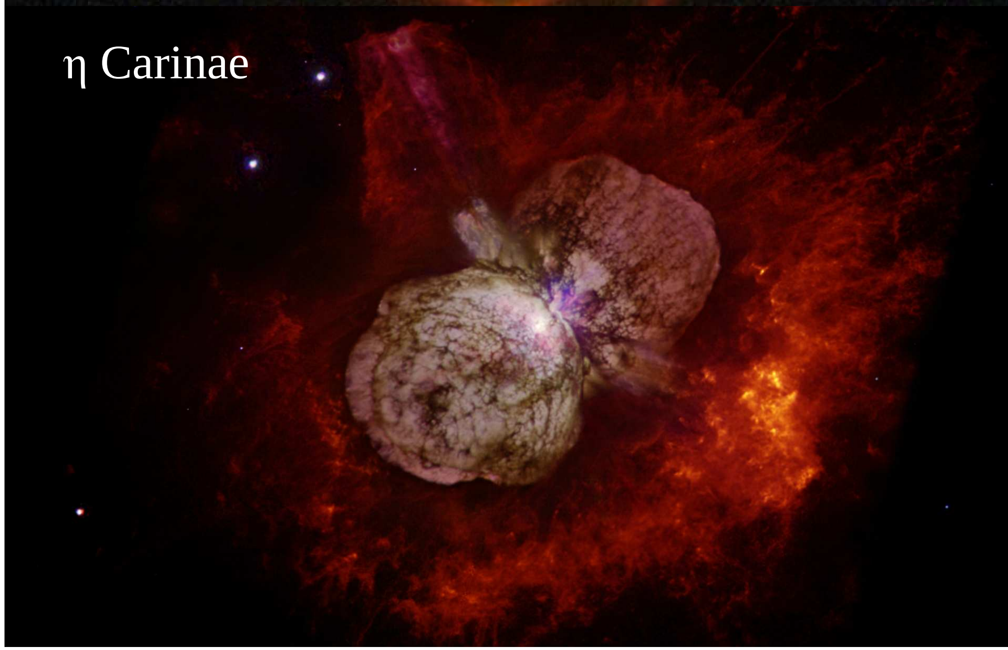
Сверхновая 1987A

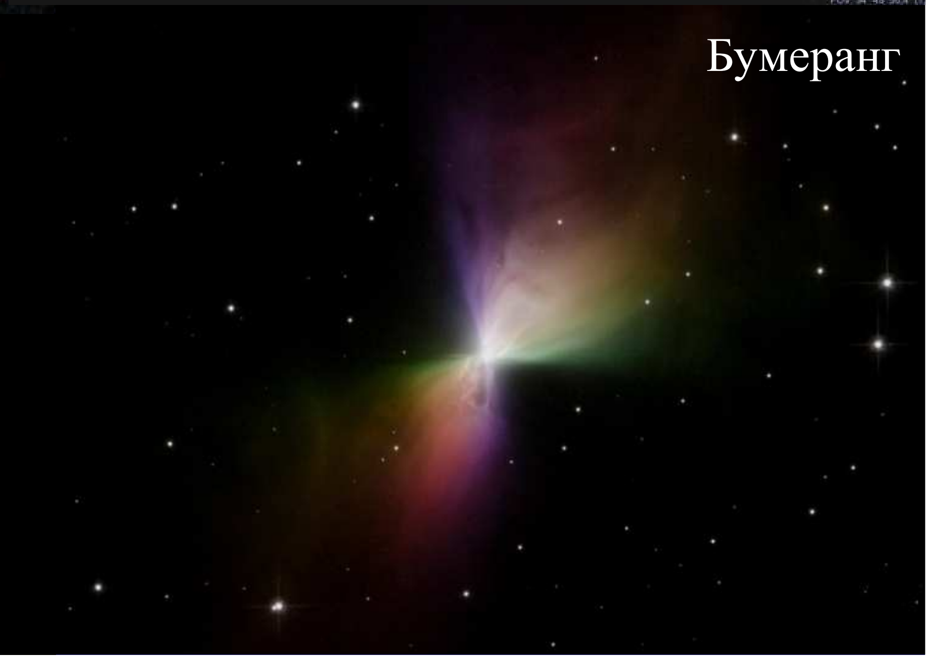


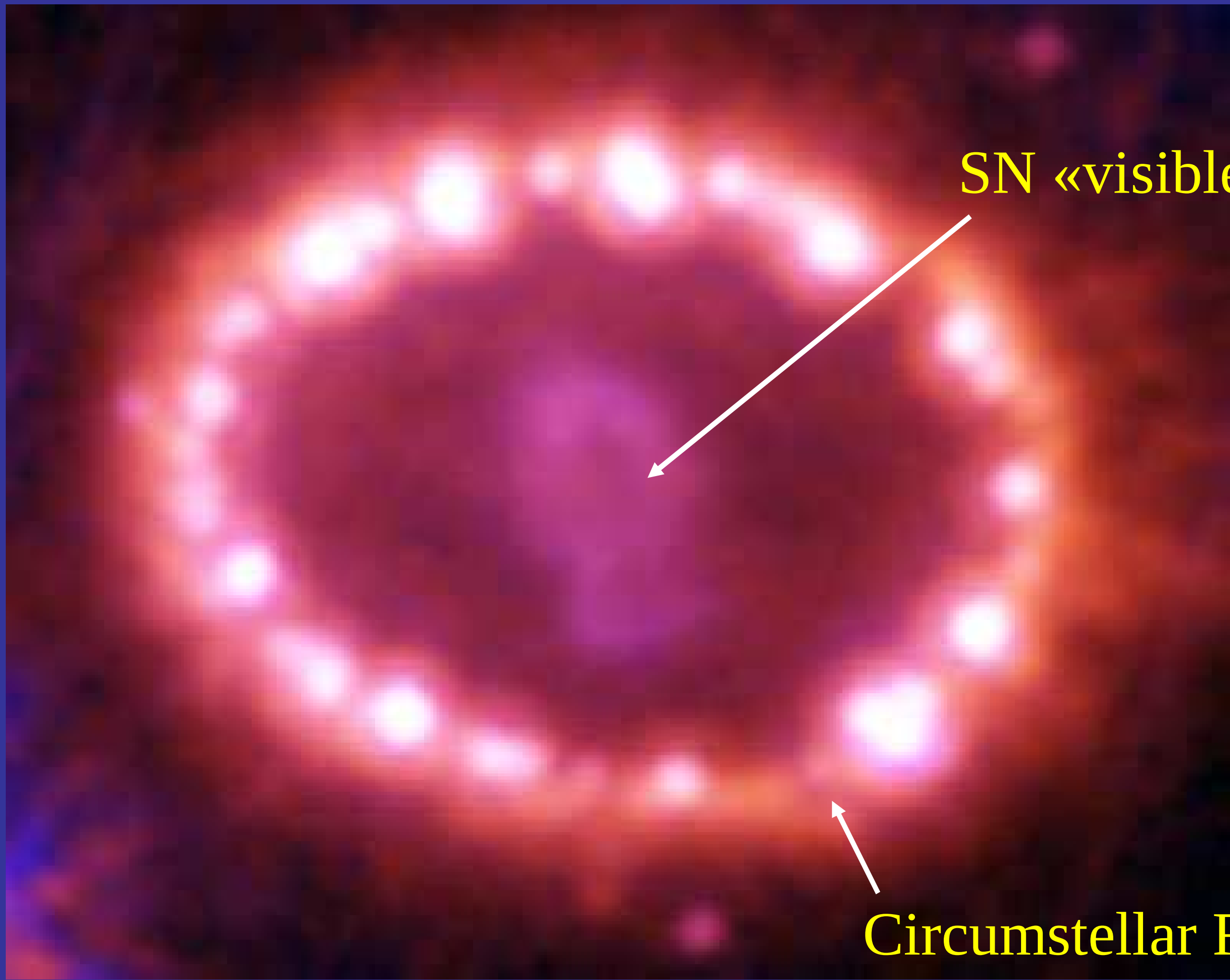



Песочные часы


HIP 700000
He2-104

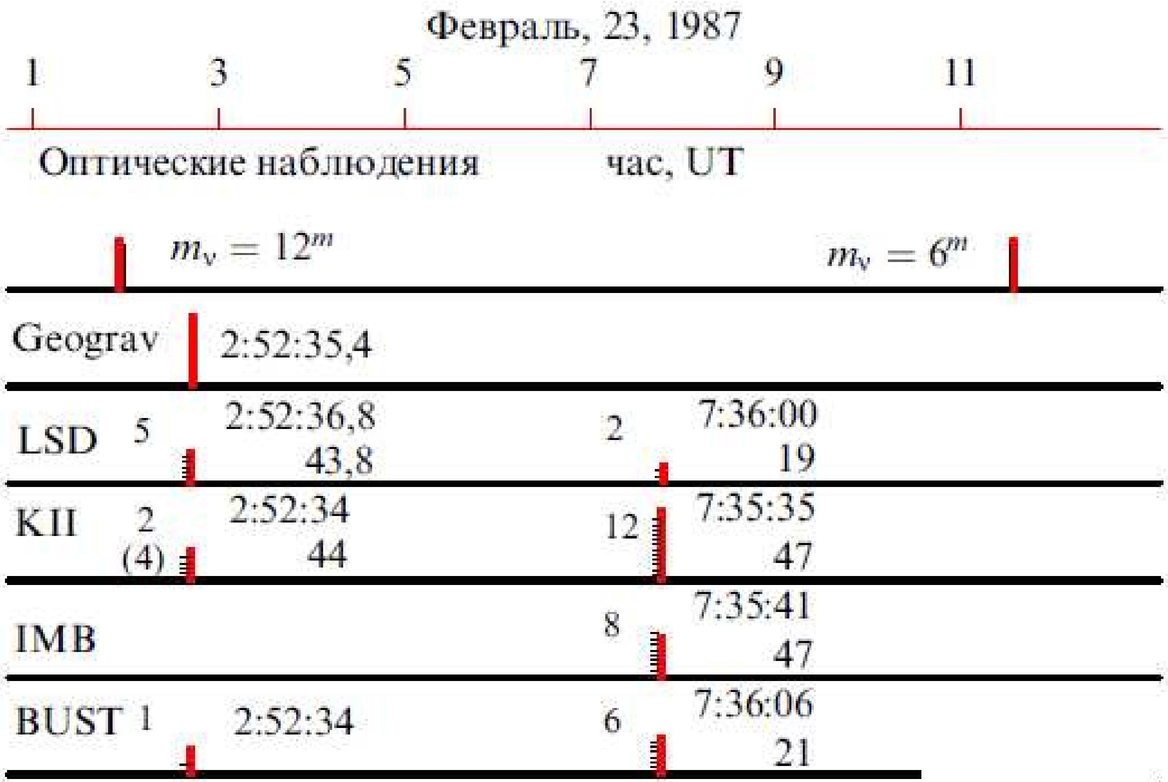

η Carinae

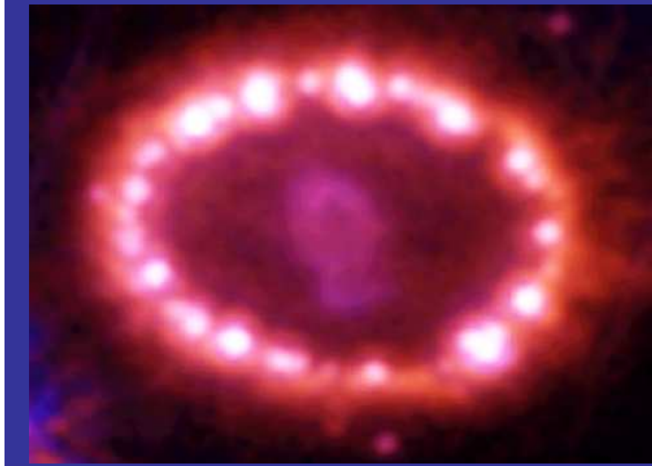

Бумеранг



SN 1987A 16 years old (HST Nov. 28, 2003)

Interaction of shock wave with the circumstellar ring

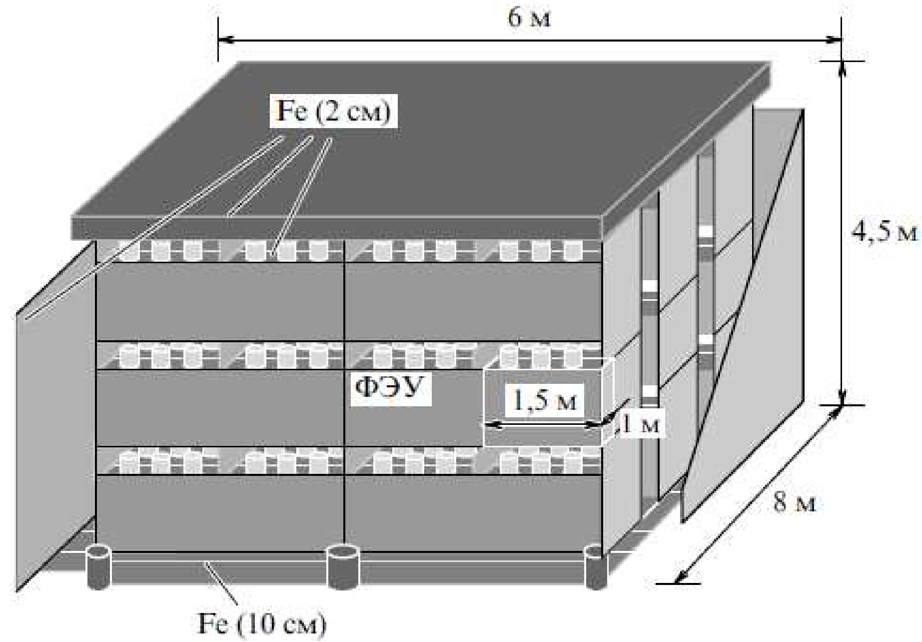




$$\nu_e + (A, Z) \to e^- + (A, Z+1)\,,$$
$$\nu_e + (A, Z) \to \nu'_e + (A, Z)^*\,,$$

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

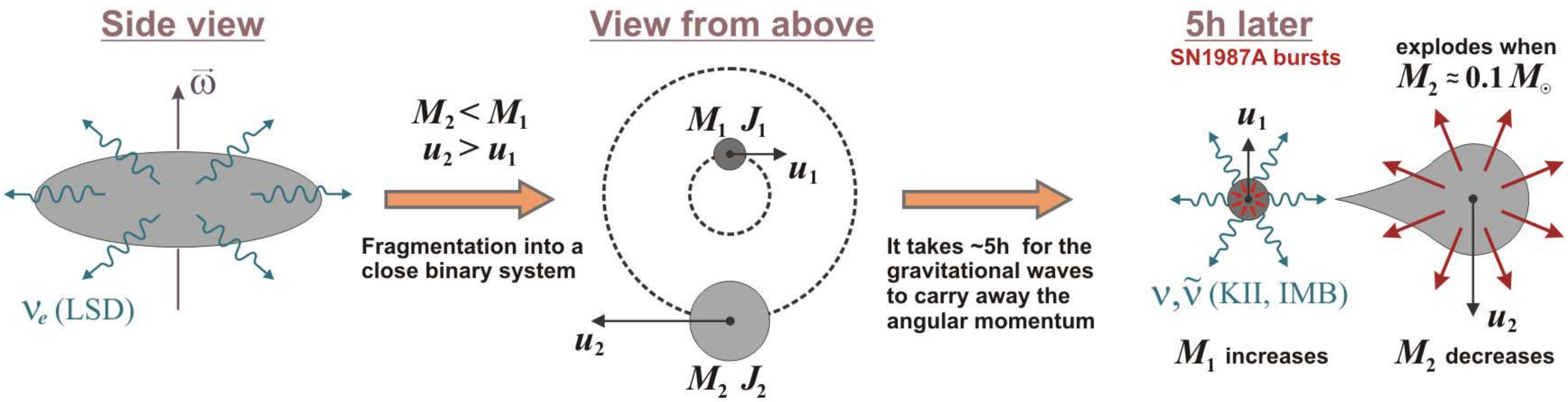
$$n + p \to d + \gamma\,(2{,}2\ \text{МэВ})$$



О.Г. Ряжская, УФН 176, №10, 2006

Rotational breakup –
neutron star explosion scenario

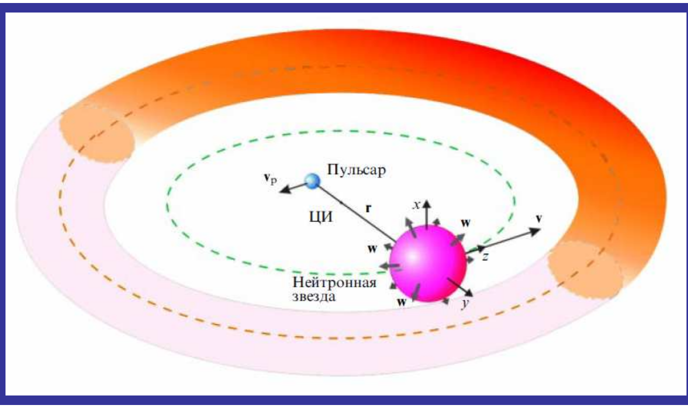
Imshennik, *Sov. Astron. Lett.* 18, 194 (1992)



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)

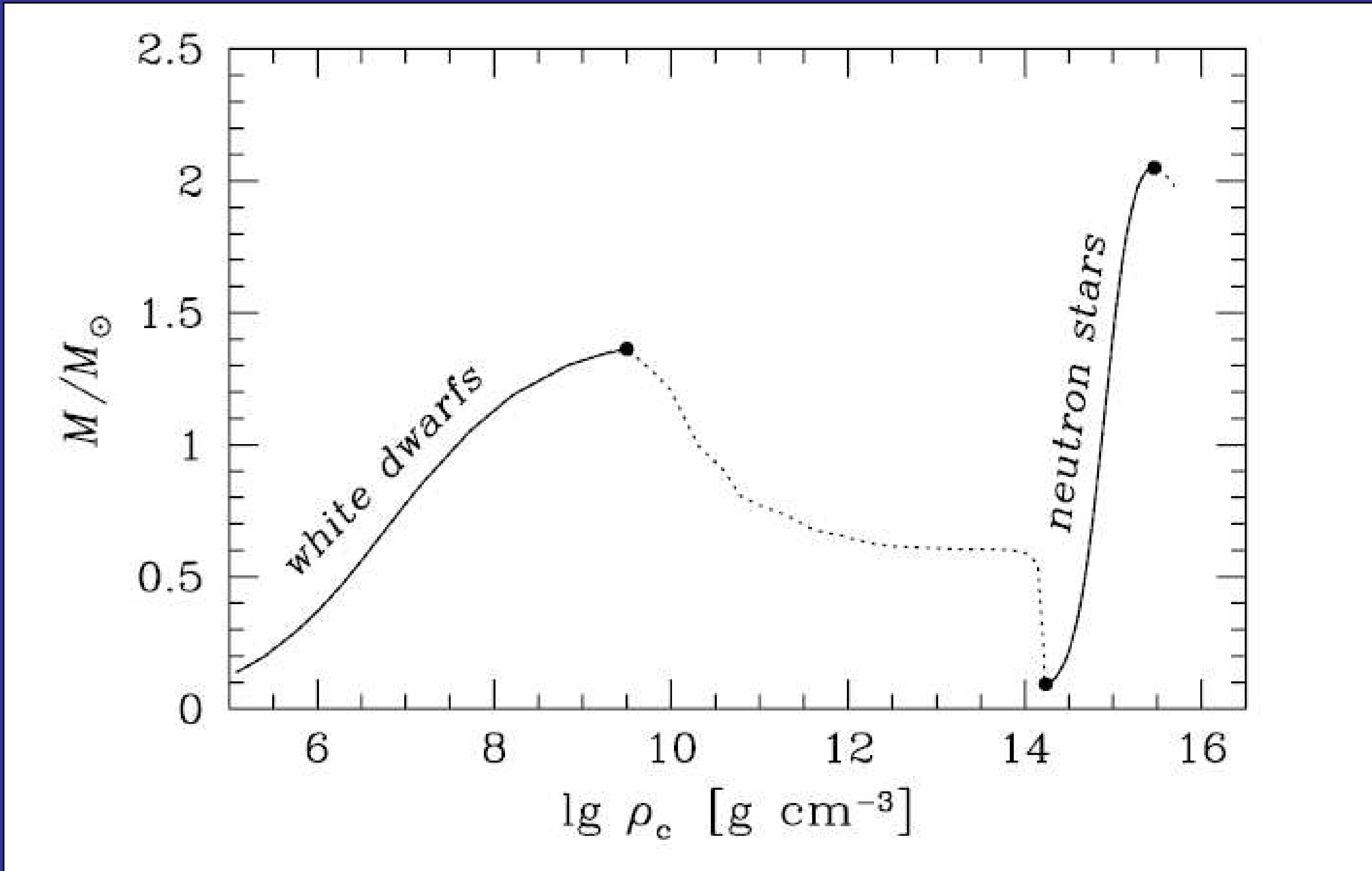
The binary components begin to approach each other due to the loss of total angular momentum and kinetic energy of orbital motion through the radiation of gravitational waves.

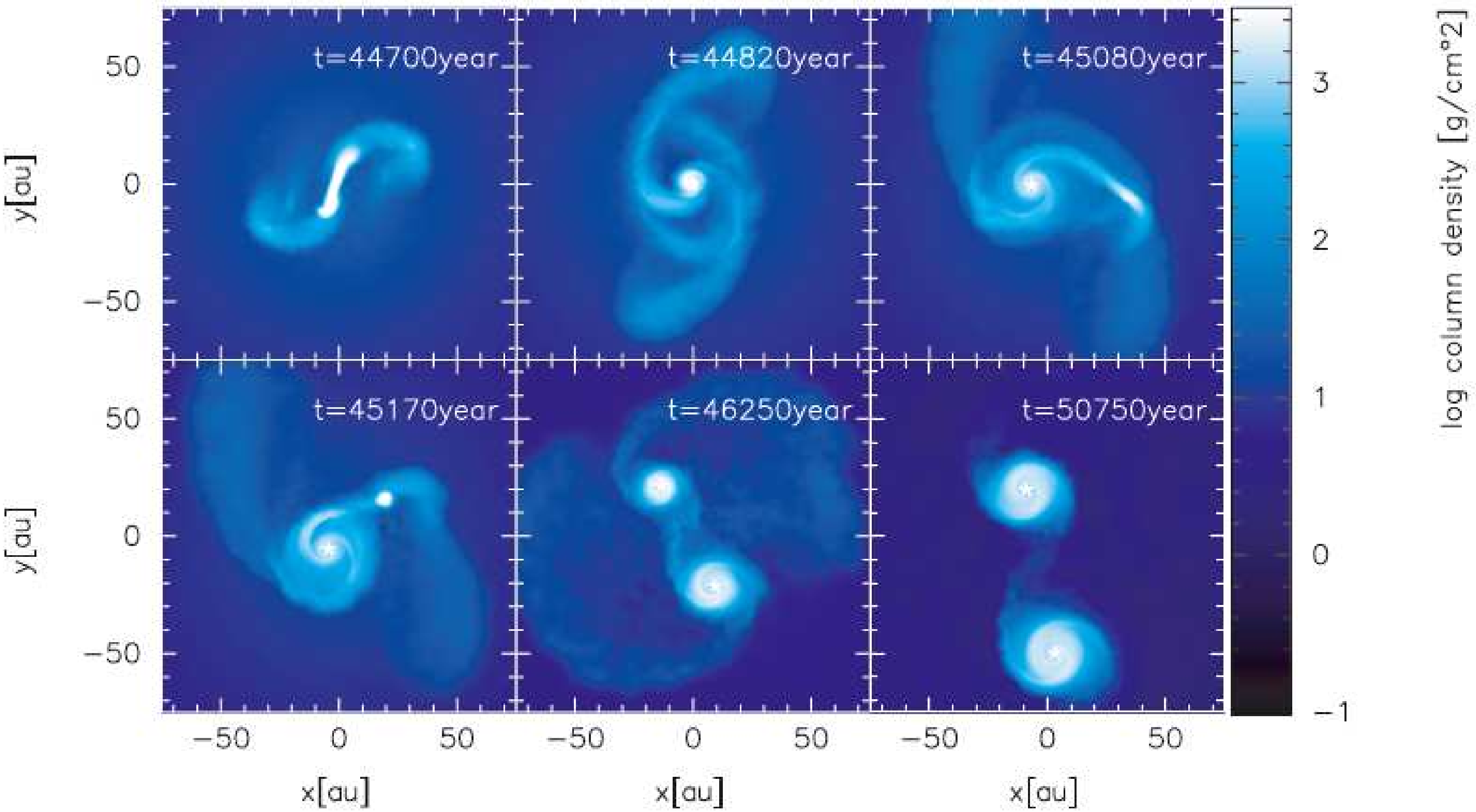
Less massive component fills its Roche lobe. There begins a rapid mass transfer from the component M_2 to the component M_1. Low-mass NS explodes when its mass decreases to the minimum possible mass of a NS.



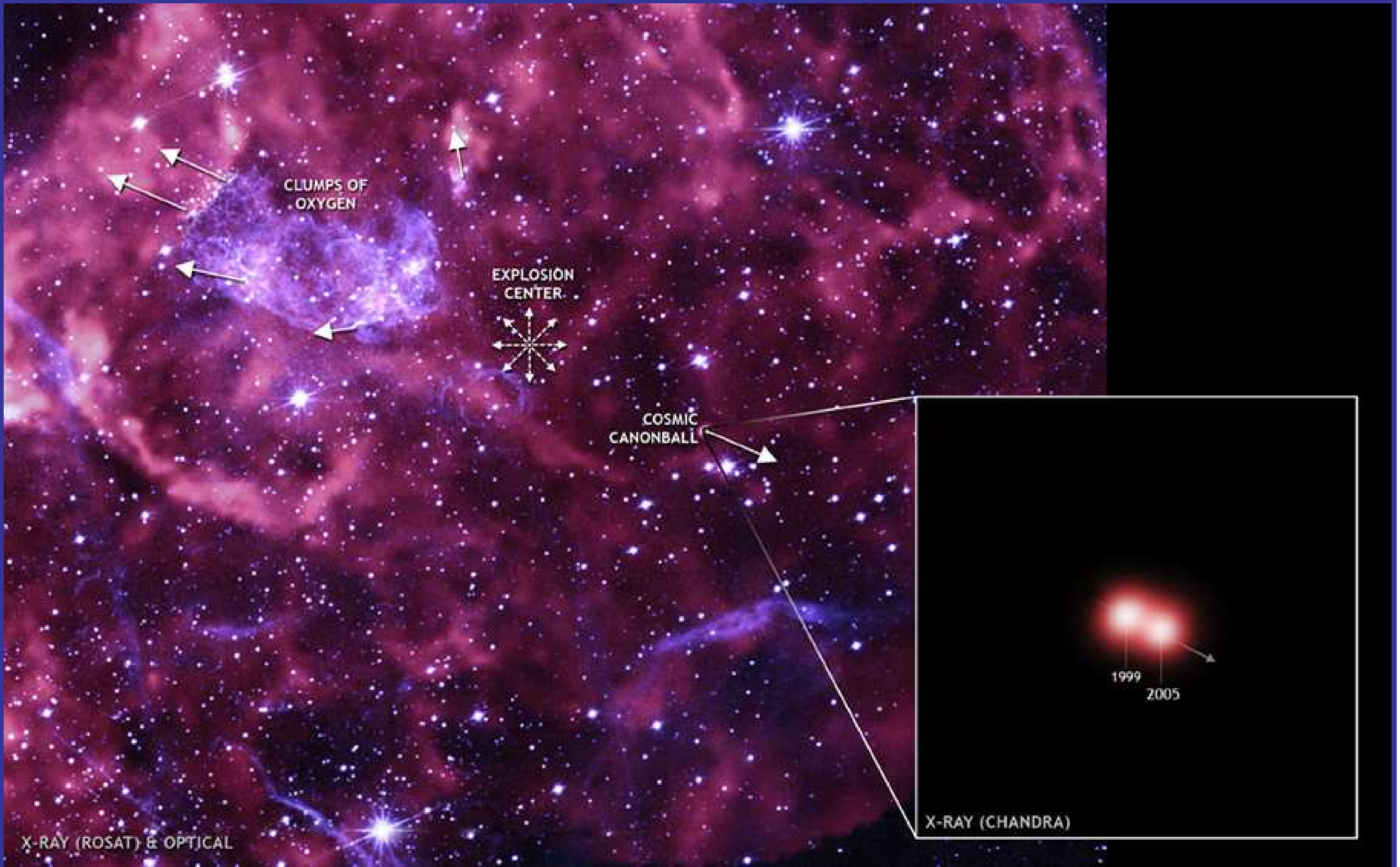
Модель* / Параметры и результаты	M4	M7	M8	M6
M/m	18	18	18,	12
V_{po}, 10^3 км с$^{-1}$	1	0,5	1,5	1
E_{exp}, 10^{51} эрг	0,67	0,76	0,45	0,77
V_{pf}, 10^3 км с$^{-1}$	0,56	0,48	0,39	0,85

Зависимость масса – центральная плотность для компактных объектов

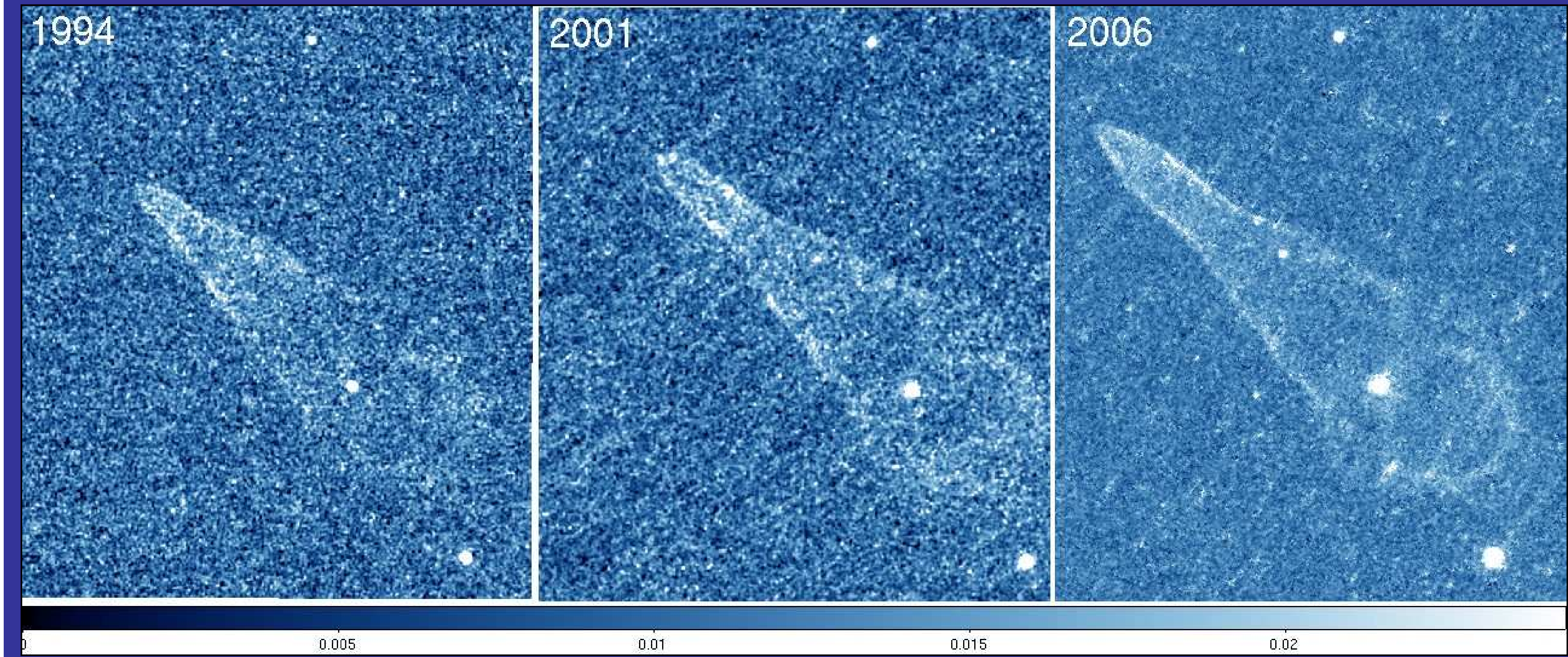



t=44700year
t=44820year
t=45080year
t=45170year
t=46250year
t=50750year
y[au]
x[au]
log column density [g/cm^2]
50
0
−50
3
2
1
0
−1

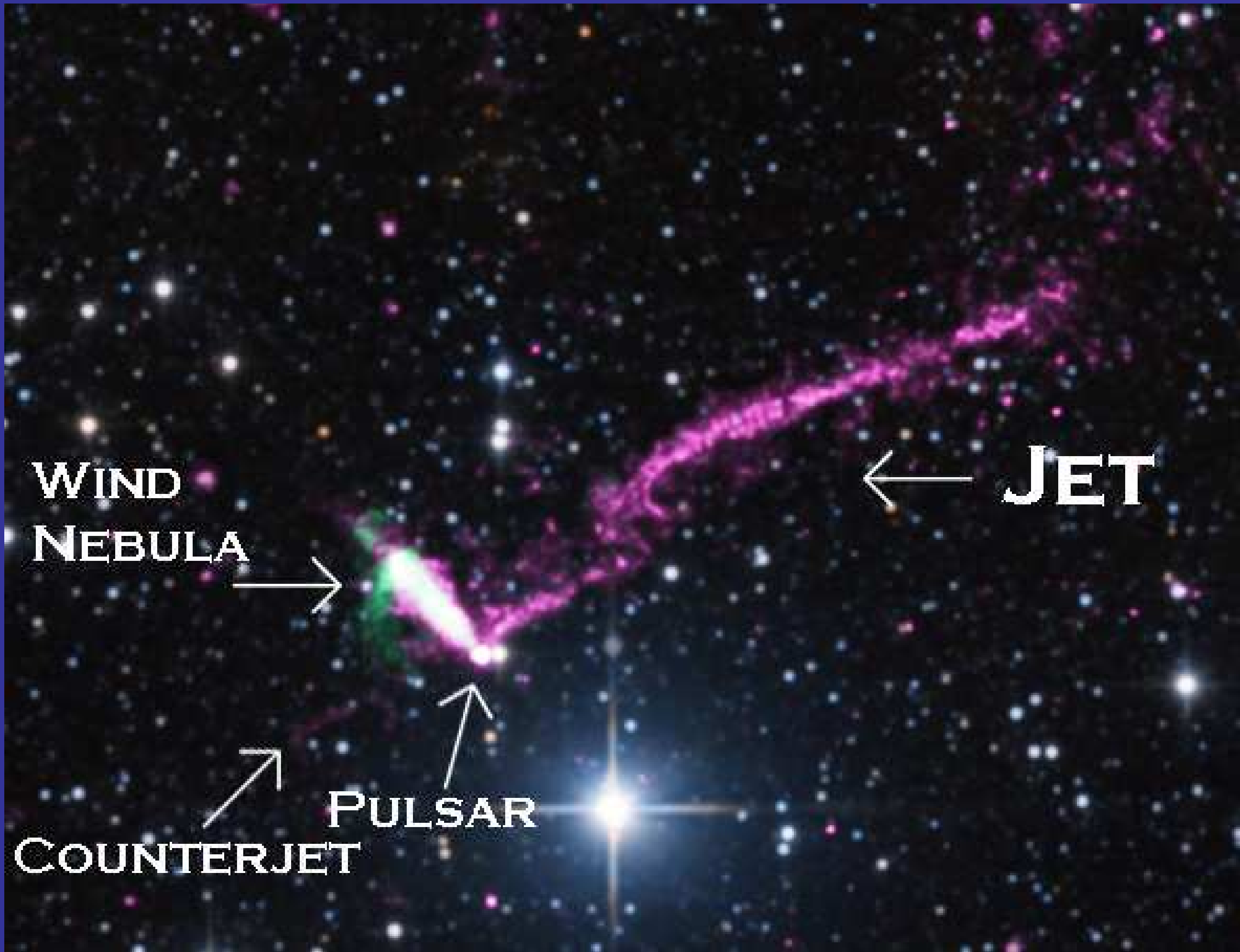
Fast Facts for RX J0822-4300 in Puppis A:



Guitar nebula

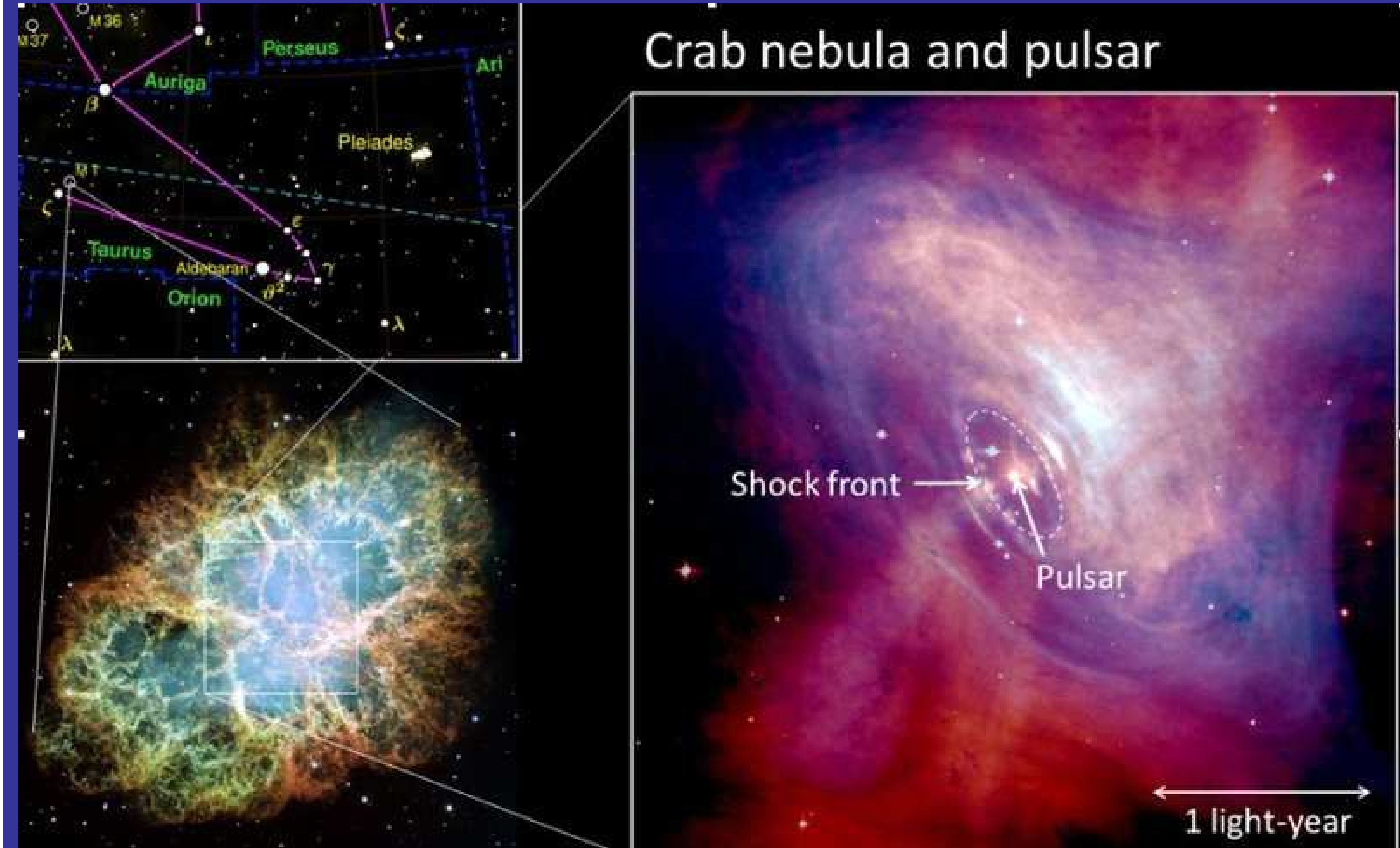


Runaway pulsar by Chandra



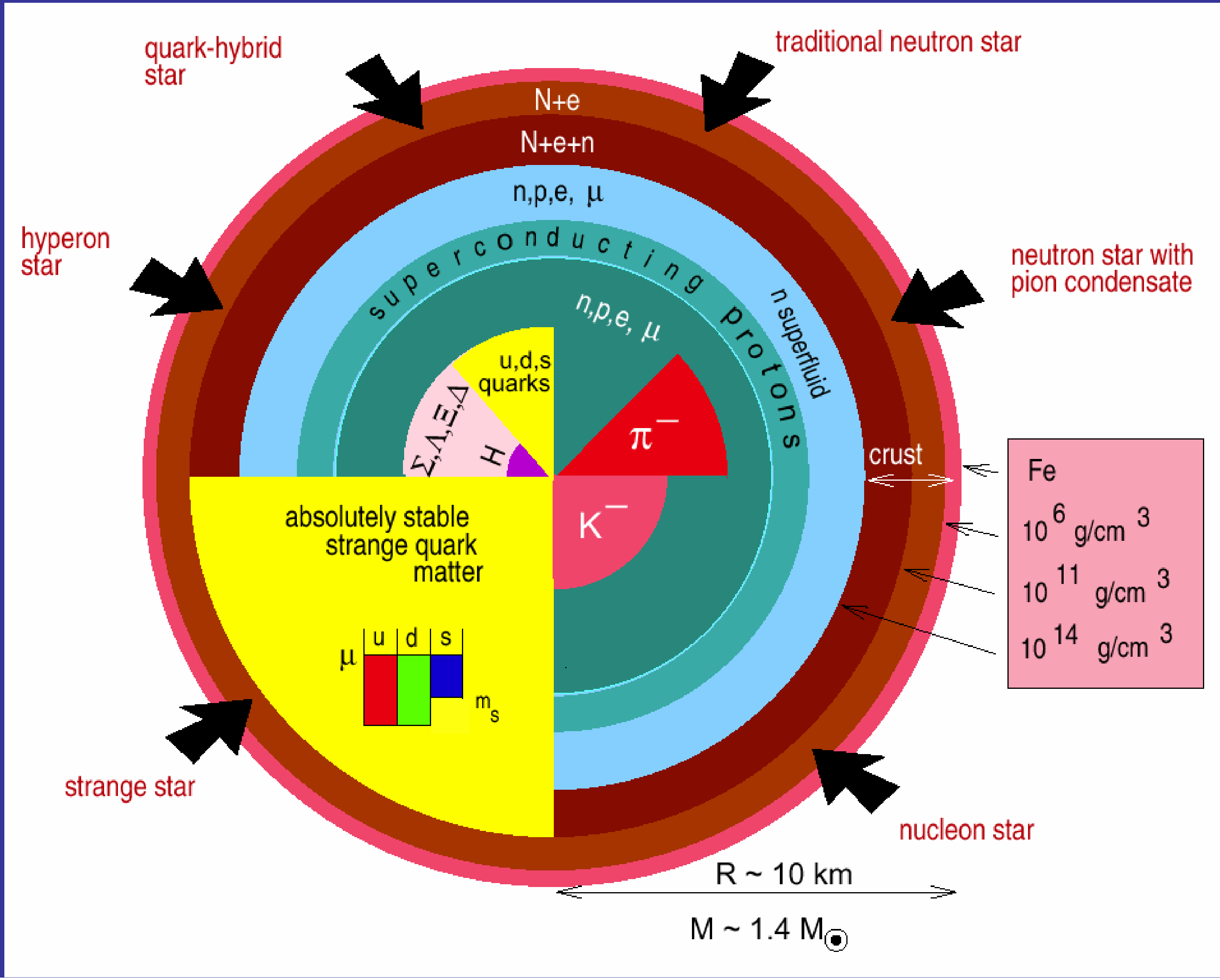
Механизмы с “экзотикой”:

1. Кварковые и гибридные звёзды

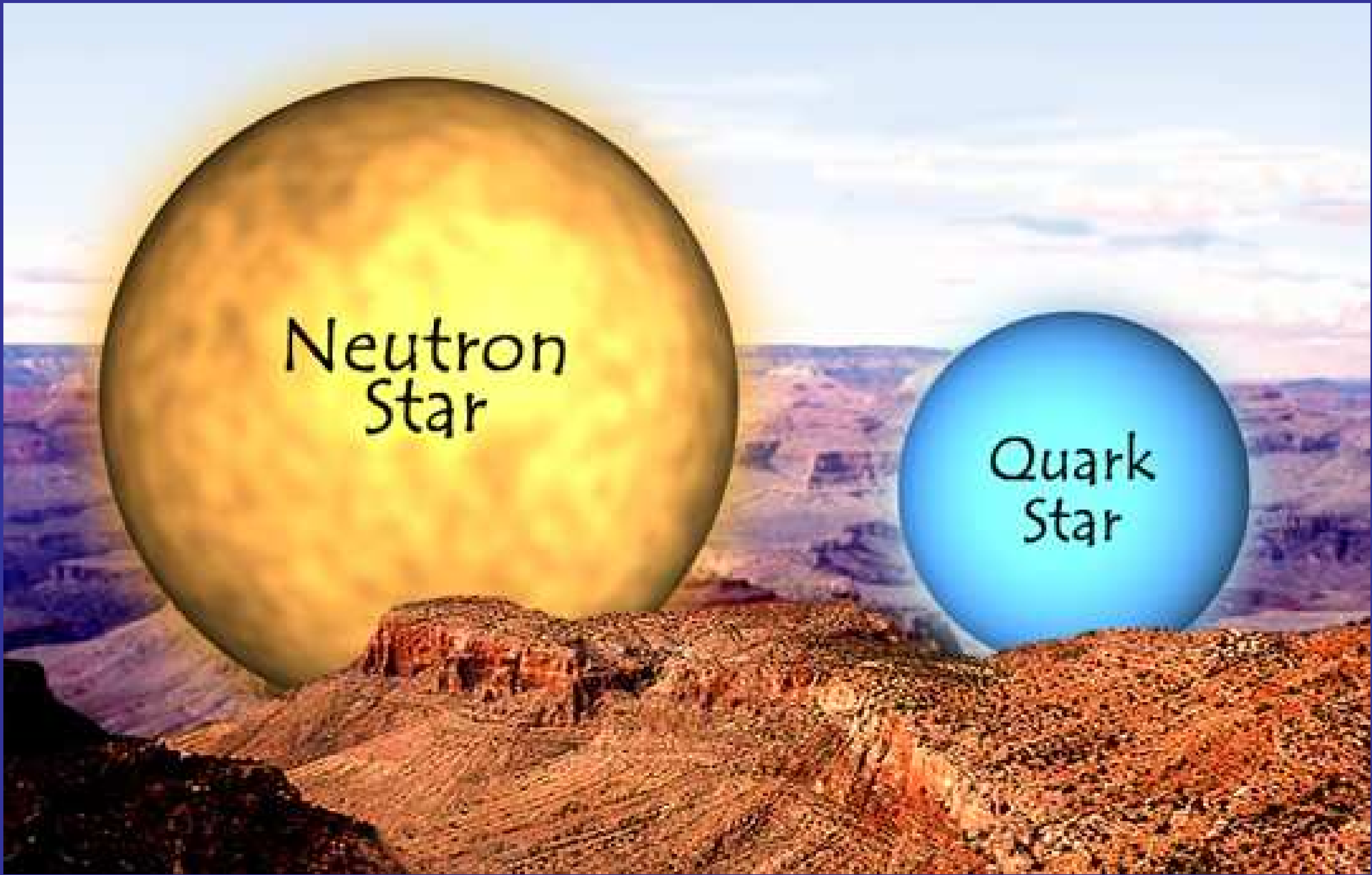

Crab nebula and pulsar
M36
M37
Perseus
Ari
Auriga
Pleiades
Taurus
Aldebaran
Orion
Shock front
Pulsar
1 light-year


Neutron Star
Vancouver
www.kindaroomy.com

Composition of a Neutron Star



Neutron star, quark star or hybrid?



Ordinary Phase Transition

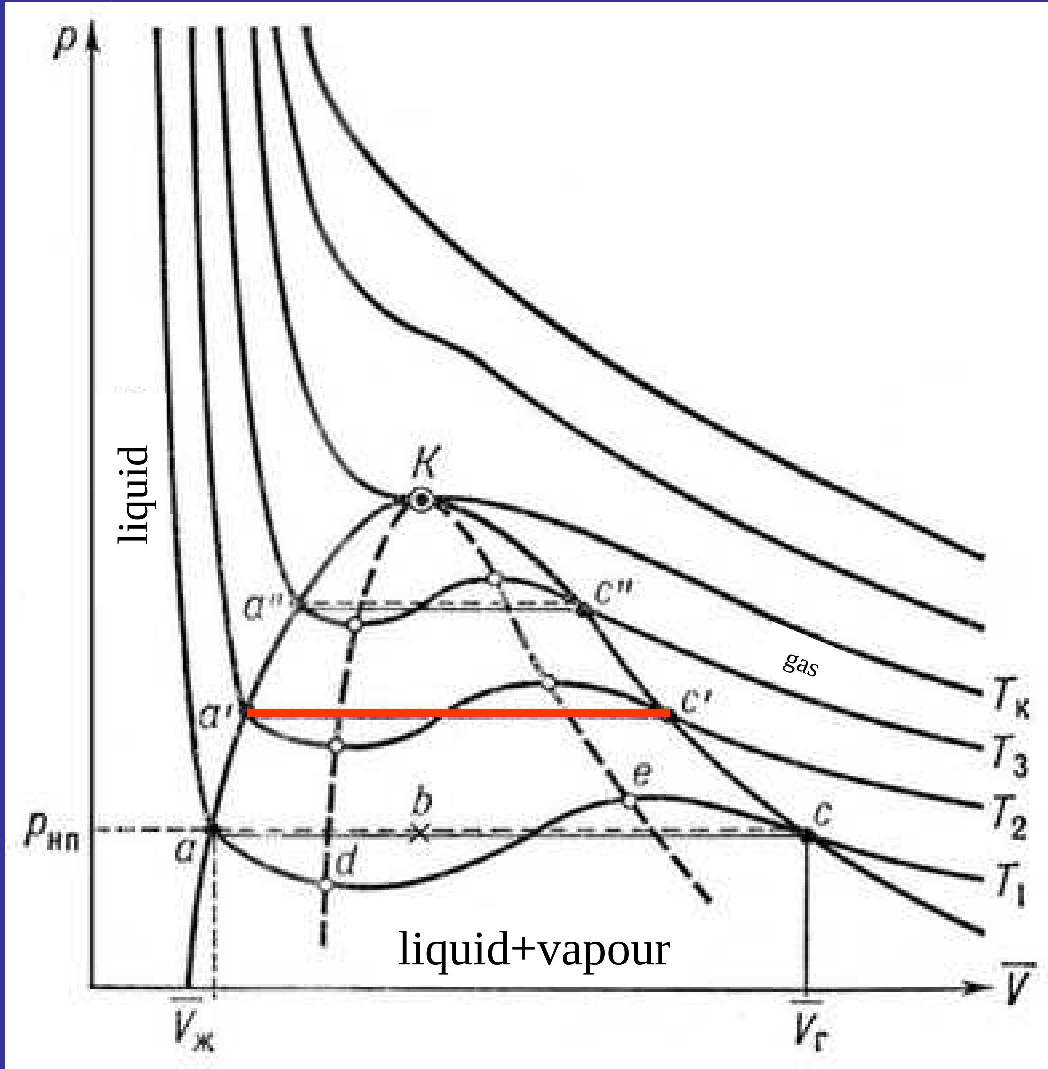
One-component matter
Maxwell-type PT

Phase coexistence conditions:

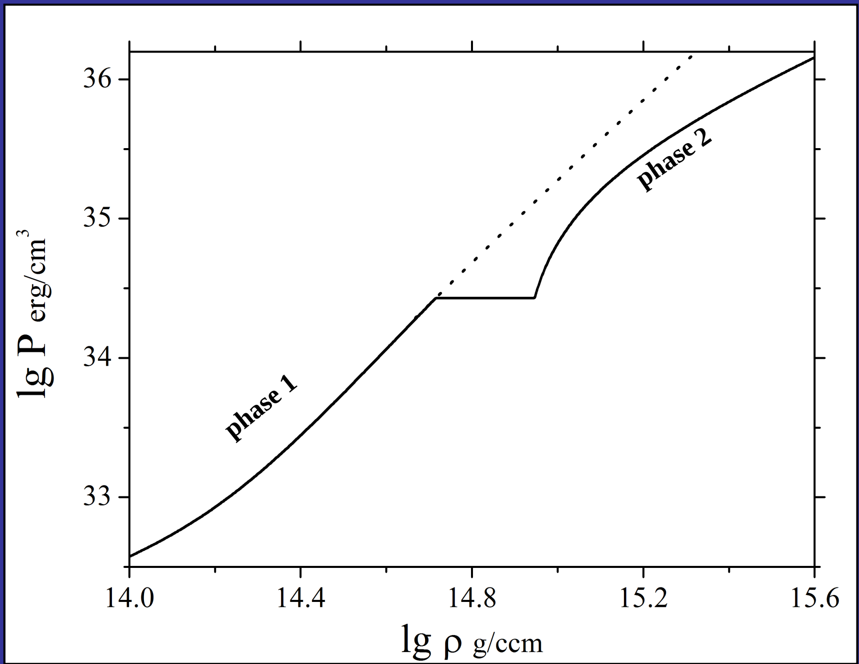
$$\begin{cases} P_I(\rho_I, T) = P_{II}(\rho_{II}, T) \\ \mu_I(\rho_I, T) = \mu_{II}(\rho_{II}, T) \end{cases}$$

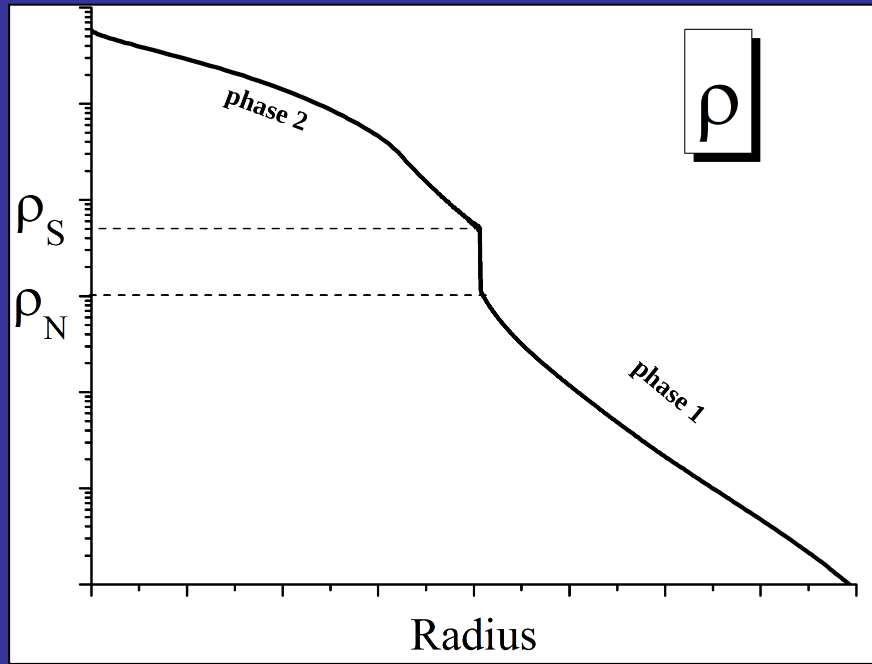
$$\rho = \chi\rho_I + (1-\chi)\rho_{II}$$

$$\chi = \frac{V_I}{V}, \quad V = V_I + V_{II}$$



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





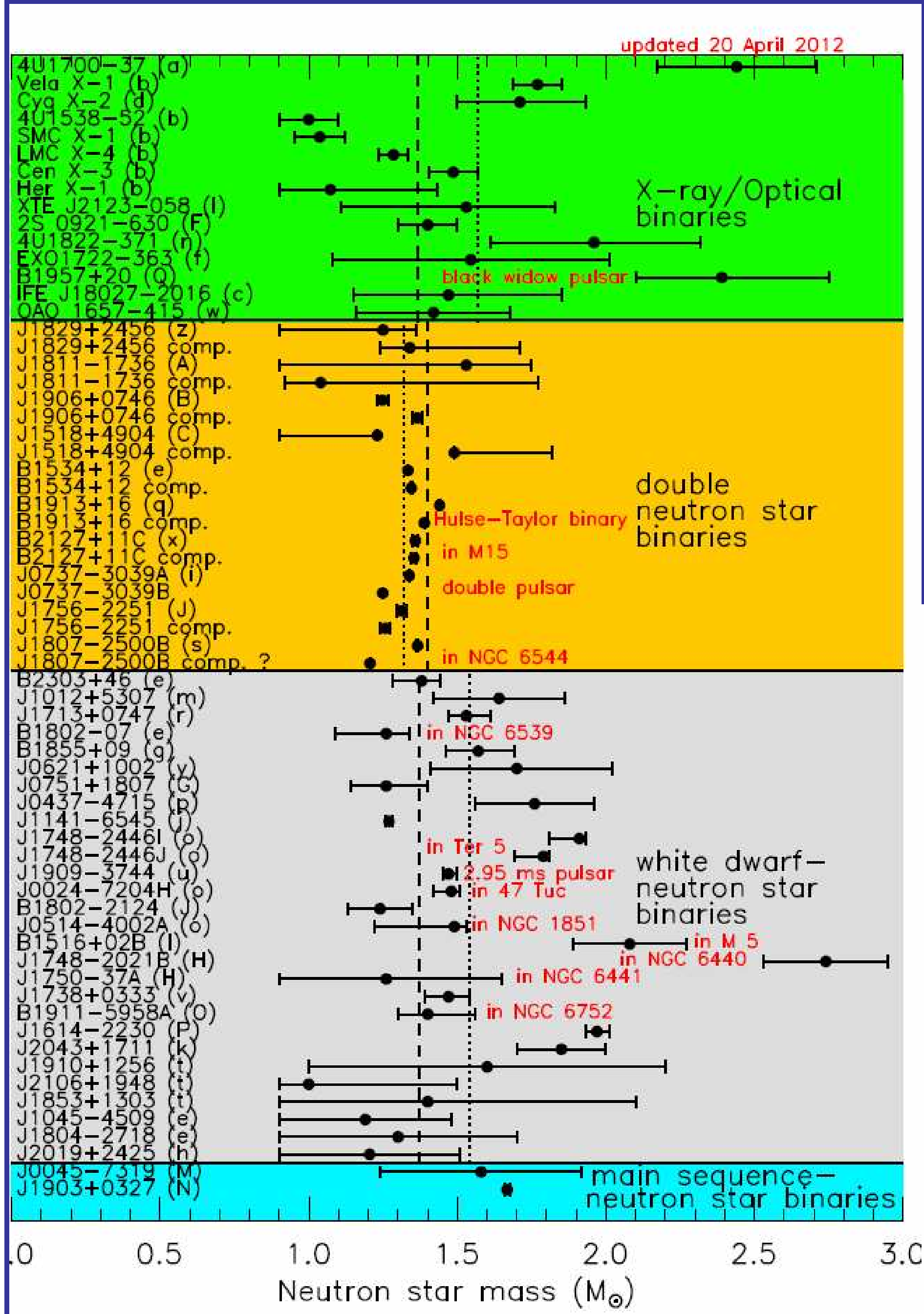
$$\lambda_c = \frac{\rho_S}{\rho_N} = \frac{3}{2}$$

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

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

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

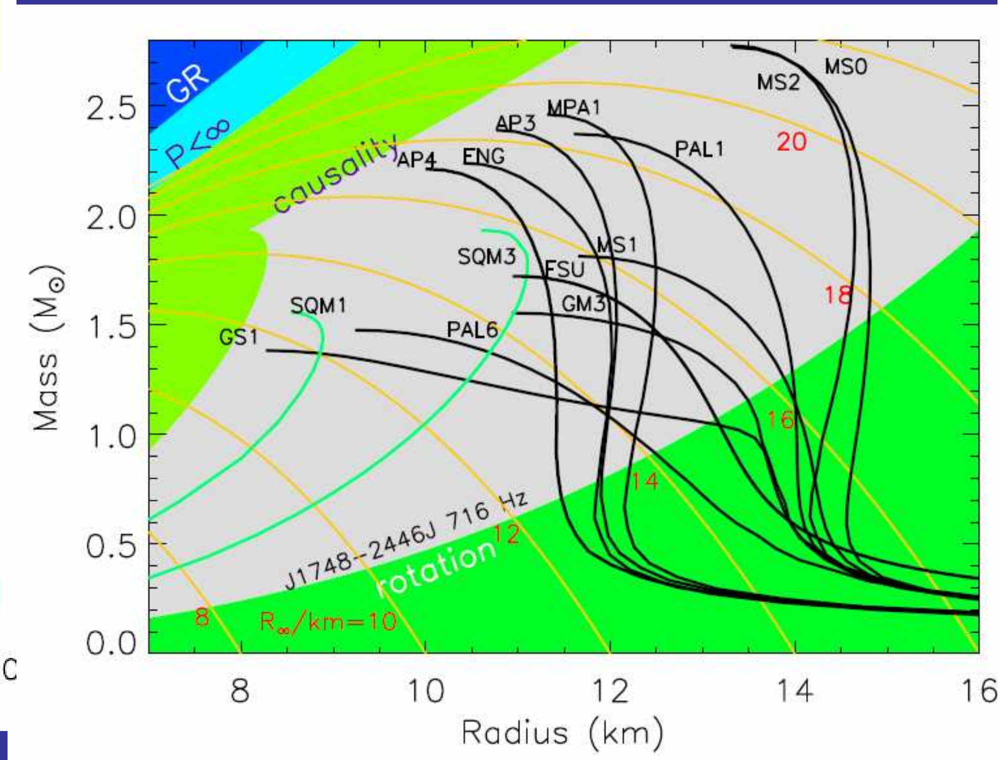
Z.F. Seidov (1971)



Maximum neutron star mass

J.M. Lattimer

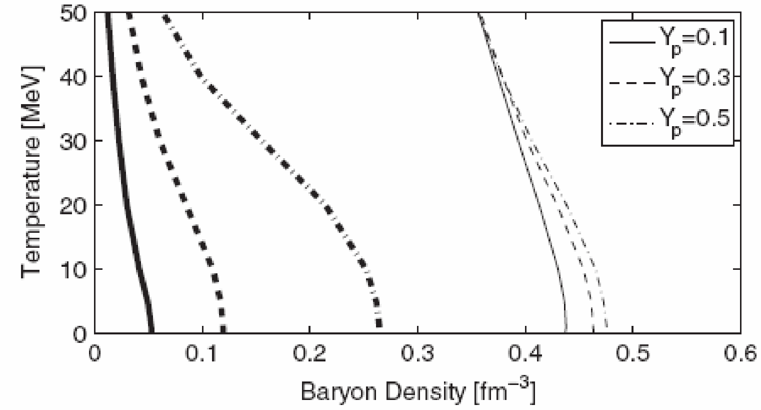
Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

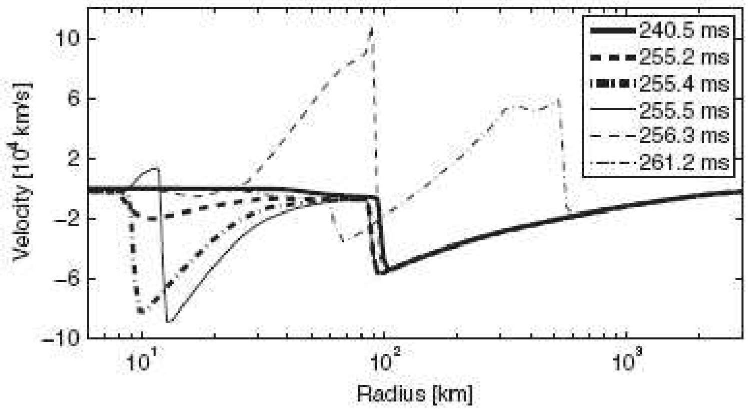


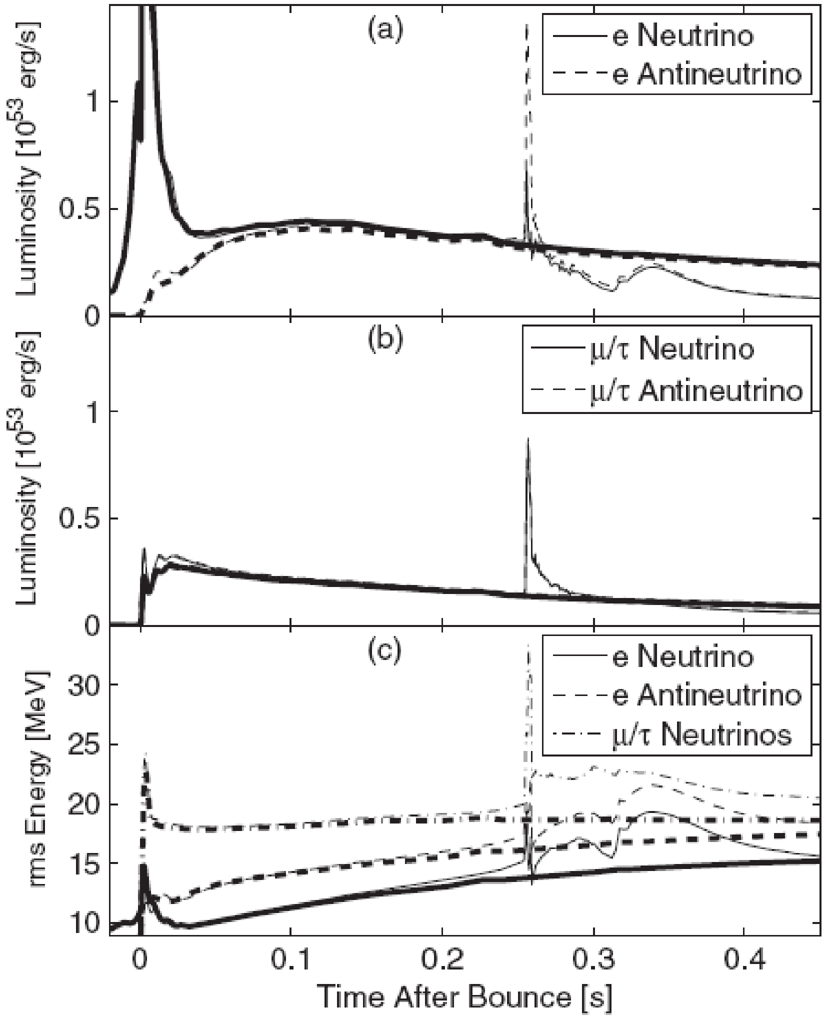
PRL **102,** 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

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]



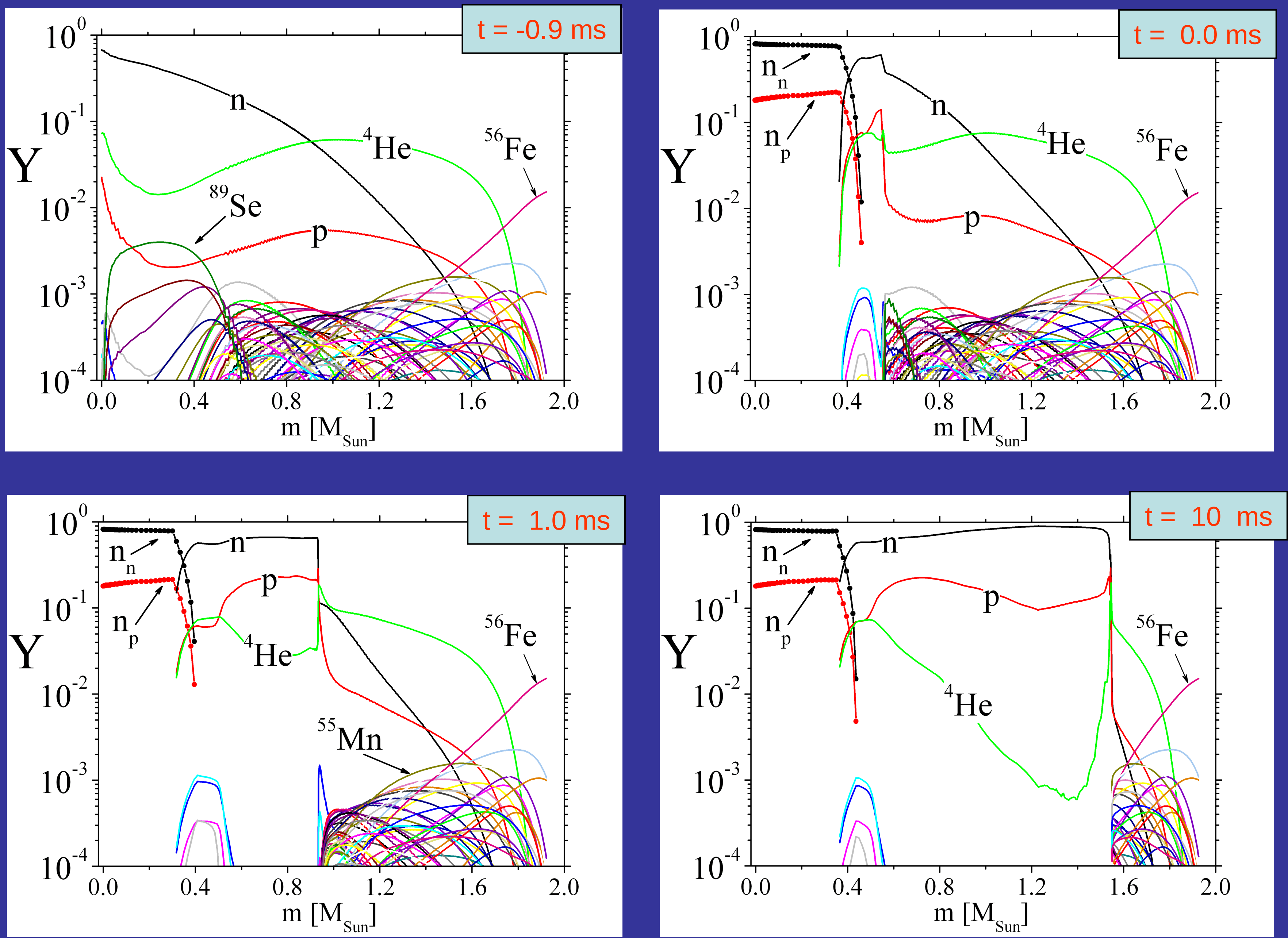


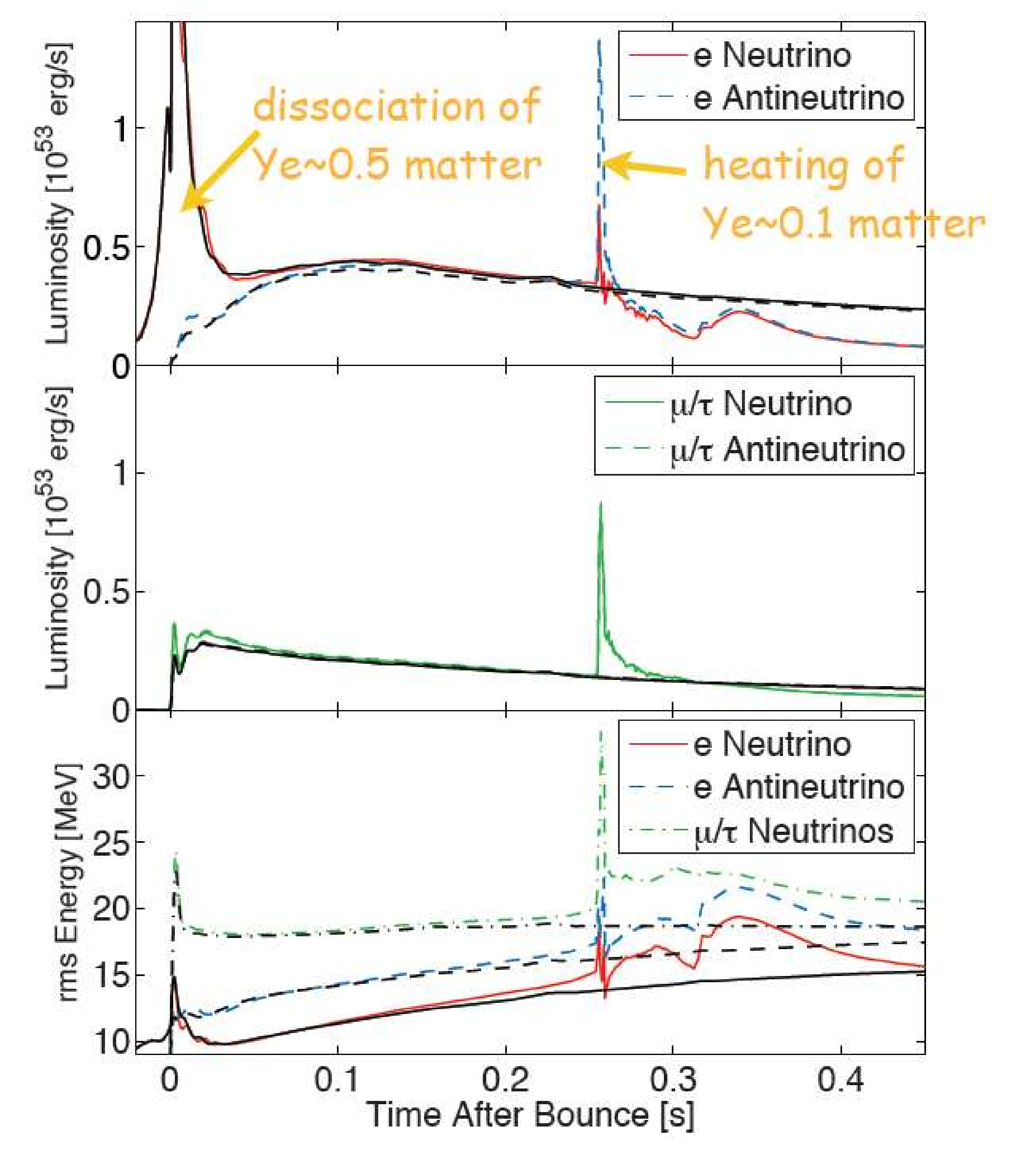


Prog.	EOS	t_{pb}	M_Q	M_{mix}	M_{pns}	E_{expl}	BE	M_G
[$M_\odot$]		[*ms*]	[$M_\odot$]	[$M_\odot$]	[$M_\odot$]	[10^{51}erg]	[10^{53}erg]	[$M_\odot$]
10	*eos*1	255	0.850	0.508	1.440	0.44	3.40	1.25
10	*eos*2	448	1.198	0.161	1.478	1.64	3.19	1.30
15	*eos*1	209	1.146	0.320	1.608	0.42	4.08	1.38
15	*eos*2	330[a]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

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

Образование ударной волны в коллапсирующем ядре звезды




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

Механизмы с “экзотикой”:

2. Стерильные нейтрино

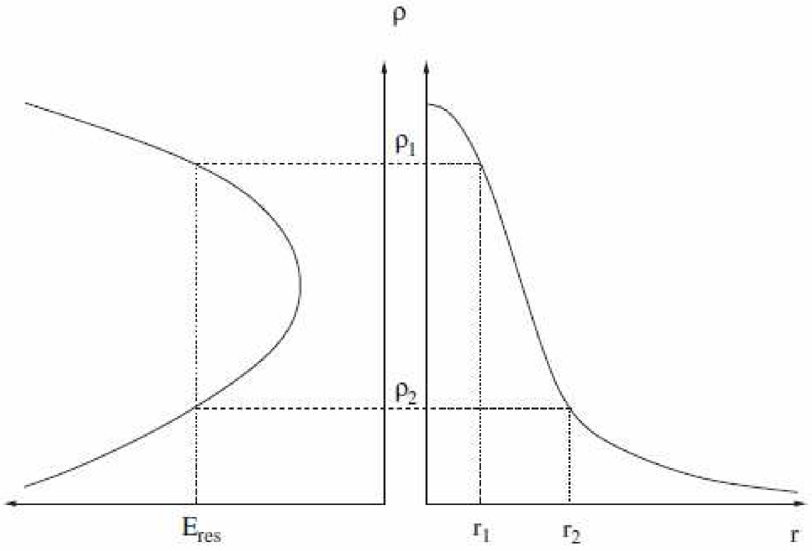


FIG. 7. Resonance energy (left) and radius parameter r (right) in the in-falling, prebounce core are shown back-to-back as functions of density ρ (vertical axes). An example given resonance energy E_{res} corresponds to two locations, r_1 and r_2, and two corresponding densities, ρ_1 and ρ_2.

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Sterile neutrino-enhanced supernova explosions

Jun Hidaka* and George M. Fuller†

$$E_{res} = \frac{\delta m^2 \cos 2\theta}{2V} \approx \frac{m_s^2}{2V},$$

$$V = \frac{3\sqrt{2}}{2} G_F n_b \left(Y_e - \frac{1}{3} + \frac{4}{3} Y_{\nu_e} + \frac{2}{3} Y_{\nu_\mu} + \frac{2}{3} Y_{\nu_\tau} \right),$$

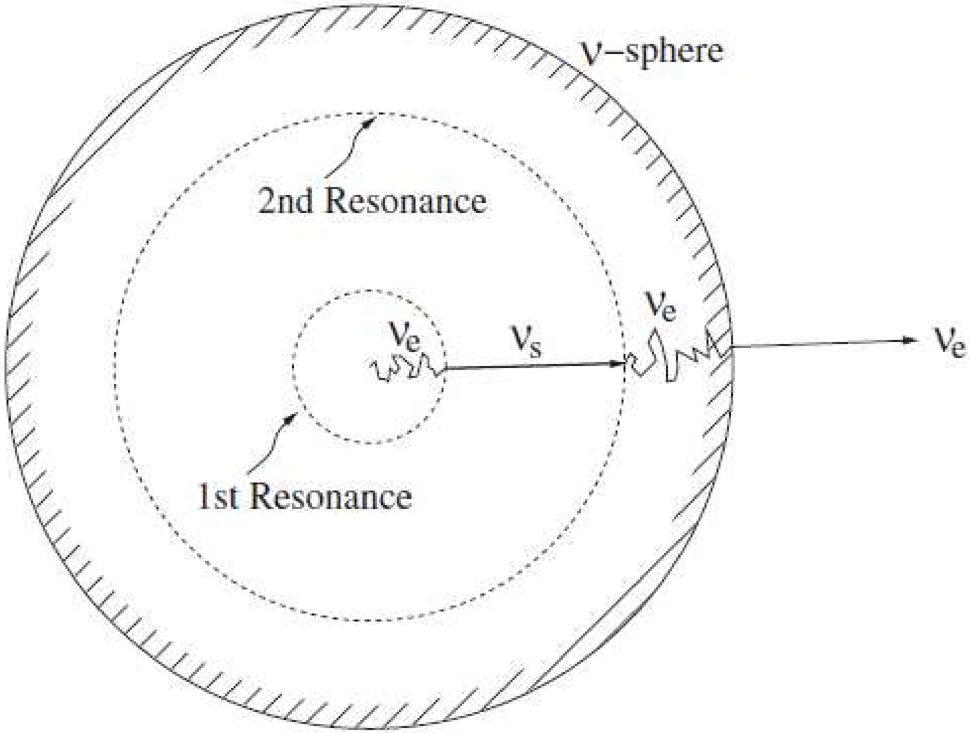
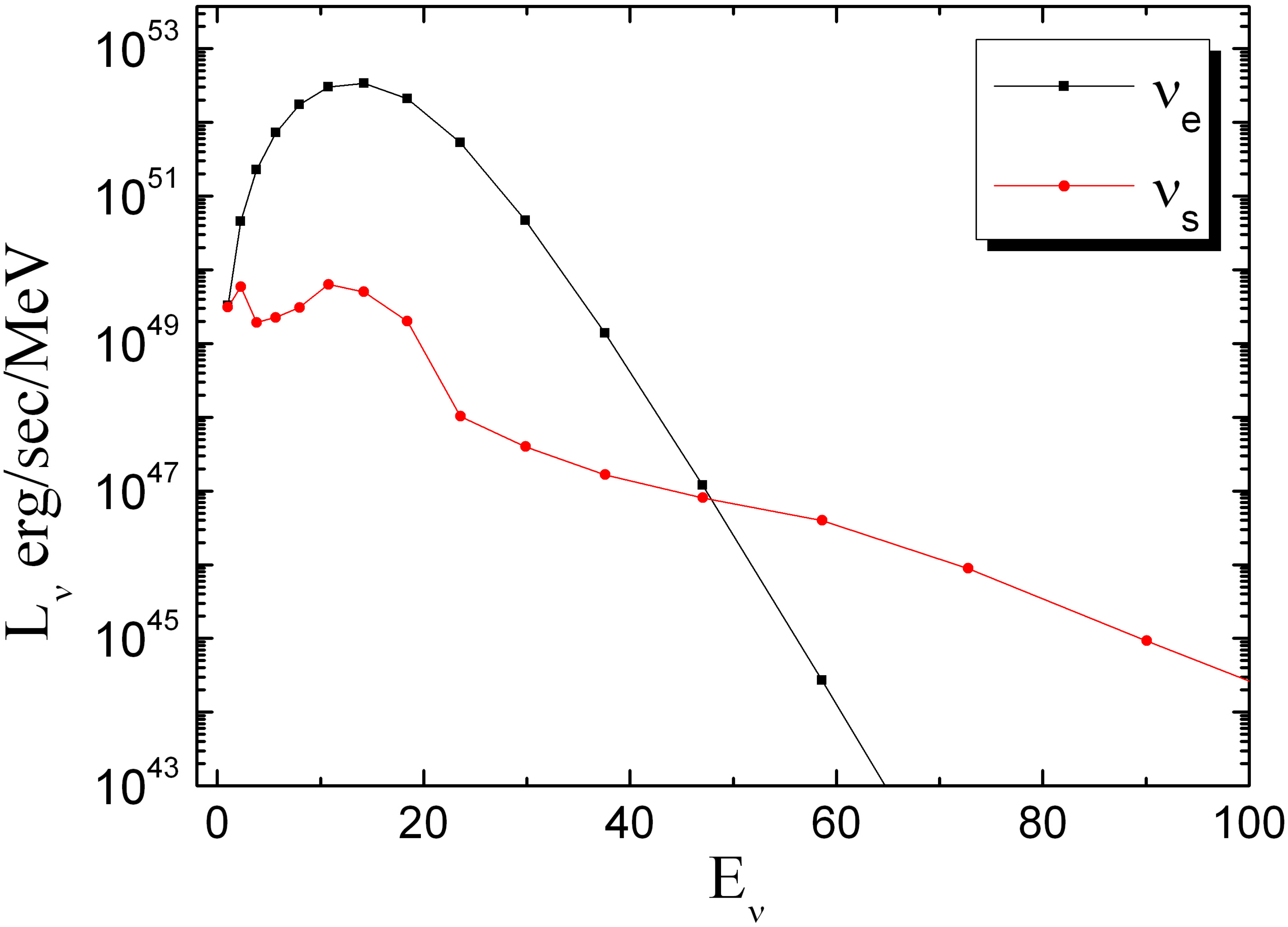
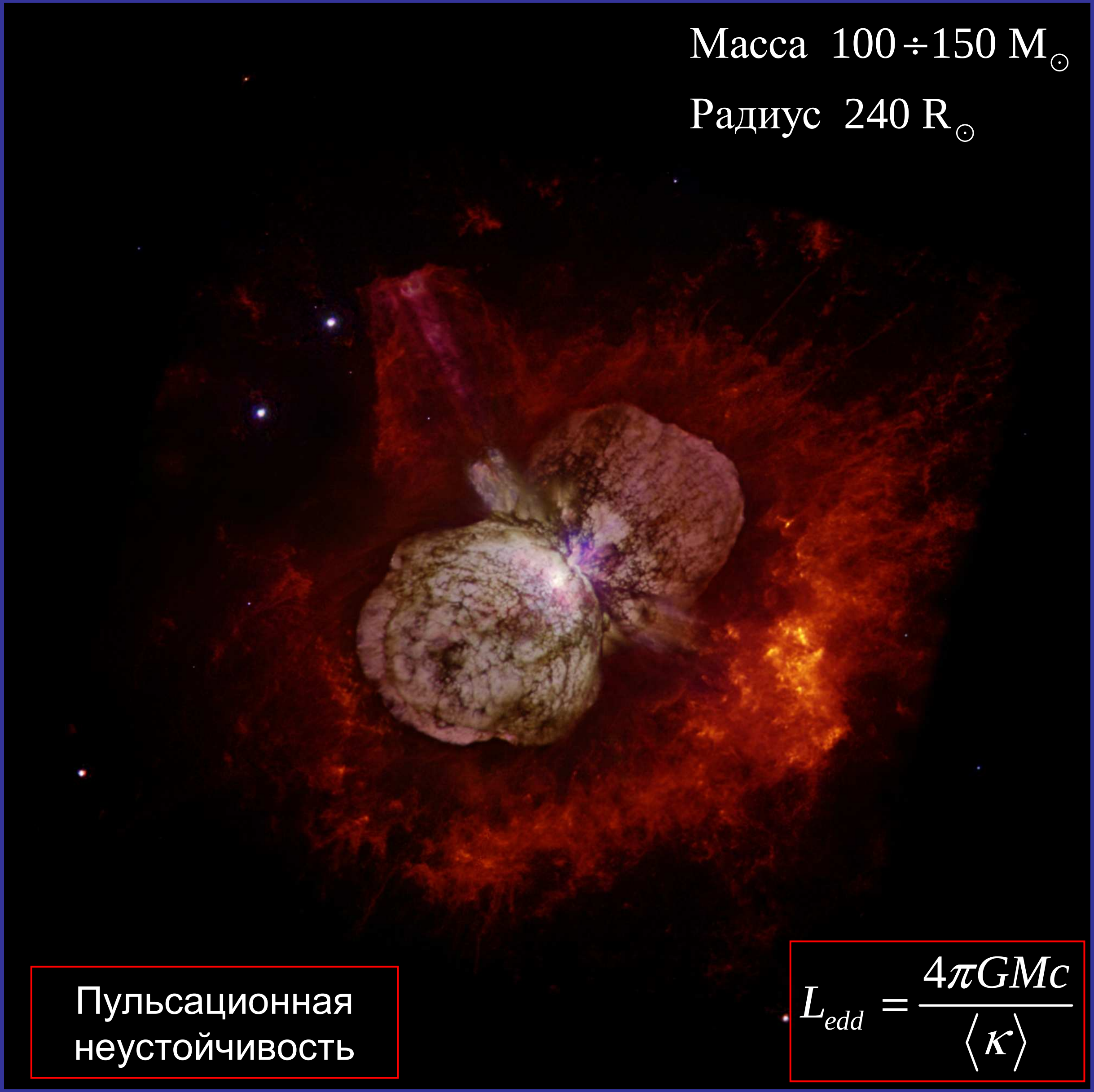


FIG. 8. High energy ν_e's could be converted to sterile neutrinos deep in the core and then regenerated as ν_e further out, nearer the neutrino sphere (edge of core).

t=3 ms after bounce



Массивные звёзды на последних стадиях эволюции



Эта Киля (η Carinae)

1600 - 2÷4^m

1837 - 0÷-1^m

~1900 - 8^m

~2000 - 6

Расстояние 2.3 кпк

Тип – LBV
Large Blue Variable

$T \sim 15 \div 30 \times 10^3\ K$

$L \sim 10^6 L_\odot$

$V \sim 650$ Km/c

$\dot{M} \sim 10^{-3} M_\odot$/год

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
	3.7 (7)	3.8 (0)	2.0 (37)	3.1 (38)	3.98 (4)	6.0 (0)	7.3 (6)y
Helium	1.6 (8)	1.3 (3)	3.9 (33)	2.3 (38)	1.59 (4)	3.2 (1)	1.3 (6)y
	1.8 (8)	6.2 (2)	7.3 (34)	9.5 (38)	1.58 (4)	6.8 (1)	6.7 (5)y
Carbon	6.2 (8)	1.7 (5)	3.4 (38)	3.3 (38)	4.26 (3)	5.3 (2)	6.3 (3)y
	7.2 (8)	6.4 (5)	1.0 (40)	1.2 (39)	4.36 (3)	9.6 (2)	1.6 (2)y
Neon	1.3 (9)	1.6 (7)	6.7 (41)	3.7 (38)	4.28 (3)	5.6 (2)	7.0 (0)y
	1.4 (9)	3.7 (6)	7.8 (42)	1.2 (39)	4.36 (3)	9.6 (2)	1.2 (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
	1.8 (9)	1.3 (7)	2.3 (43)	1.2 (39)	4.36 (3)	9.6 (2)	0.5 (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
	3.4 (9)	1.1 (8)	3.8 (45)	1.2 (39)	4.36 (3)	9.6 (2)	1.4 (0)d
Collapse	8.3 (9)	6.0 (9)	6.8 (48)	3.7 (38)	4.28 (3)	5.6 (2)	0.30 s
	8.3 (9)	3.5 (9)	8.1 (48)	1.2 (39)	4.36 (3)	9.6 (2)	0.35 s

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

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

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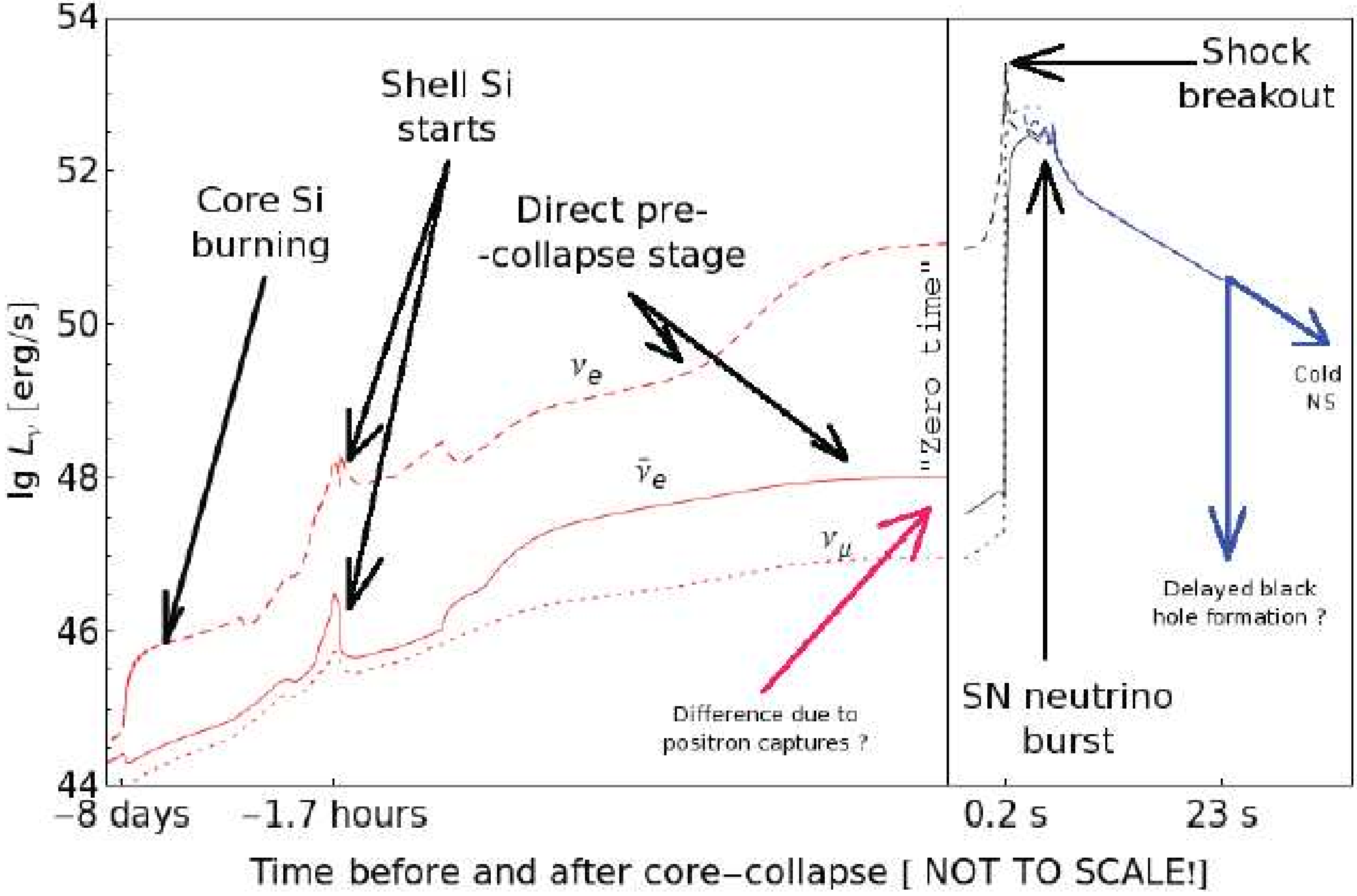
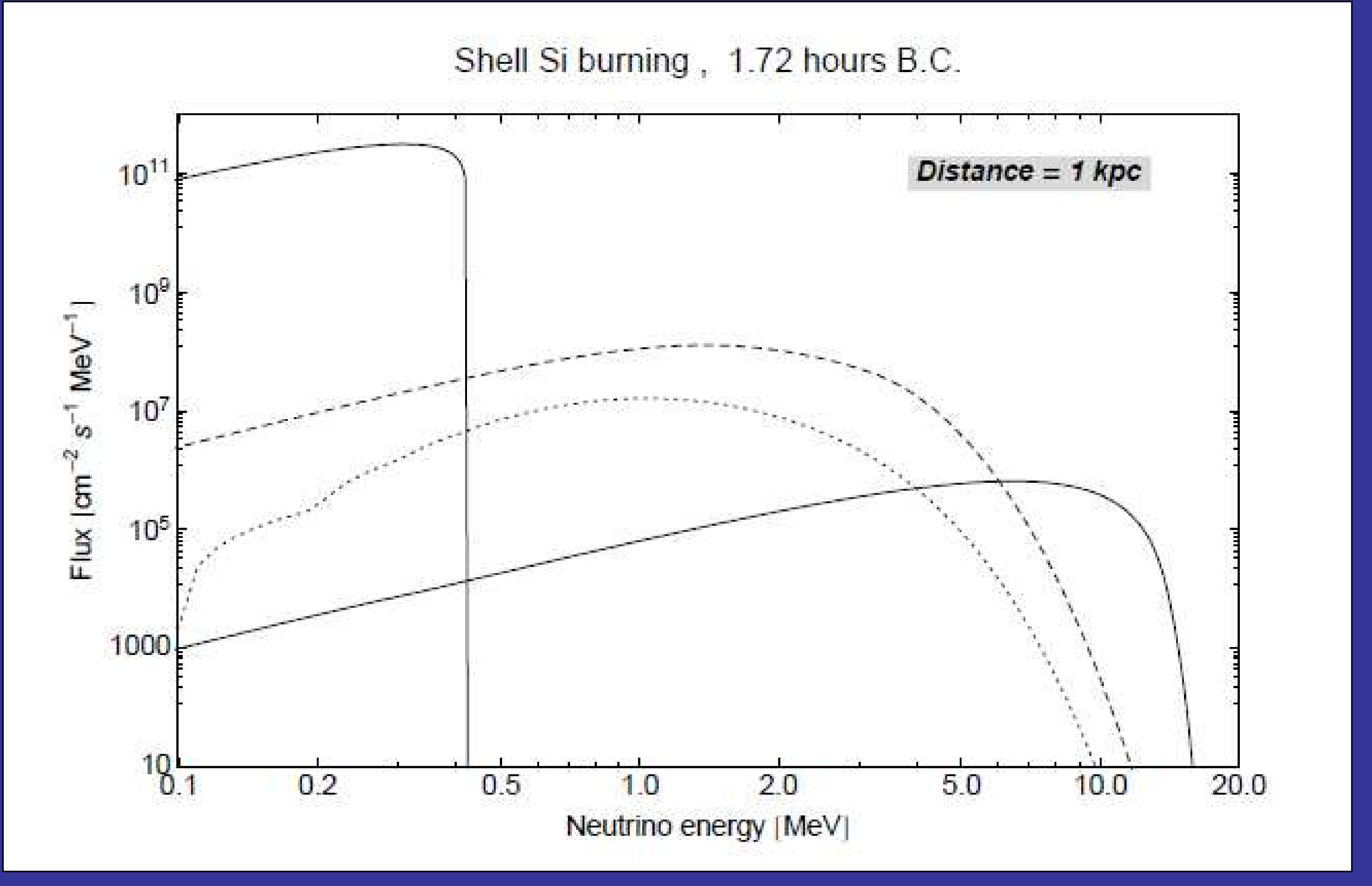
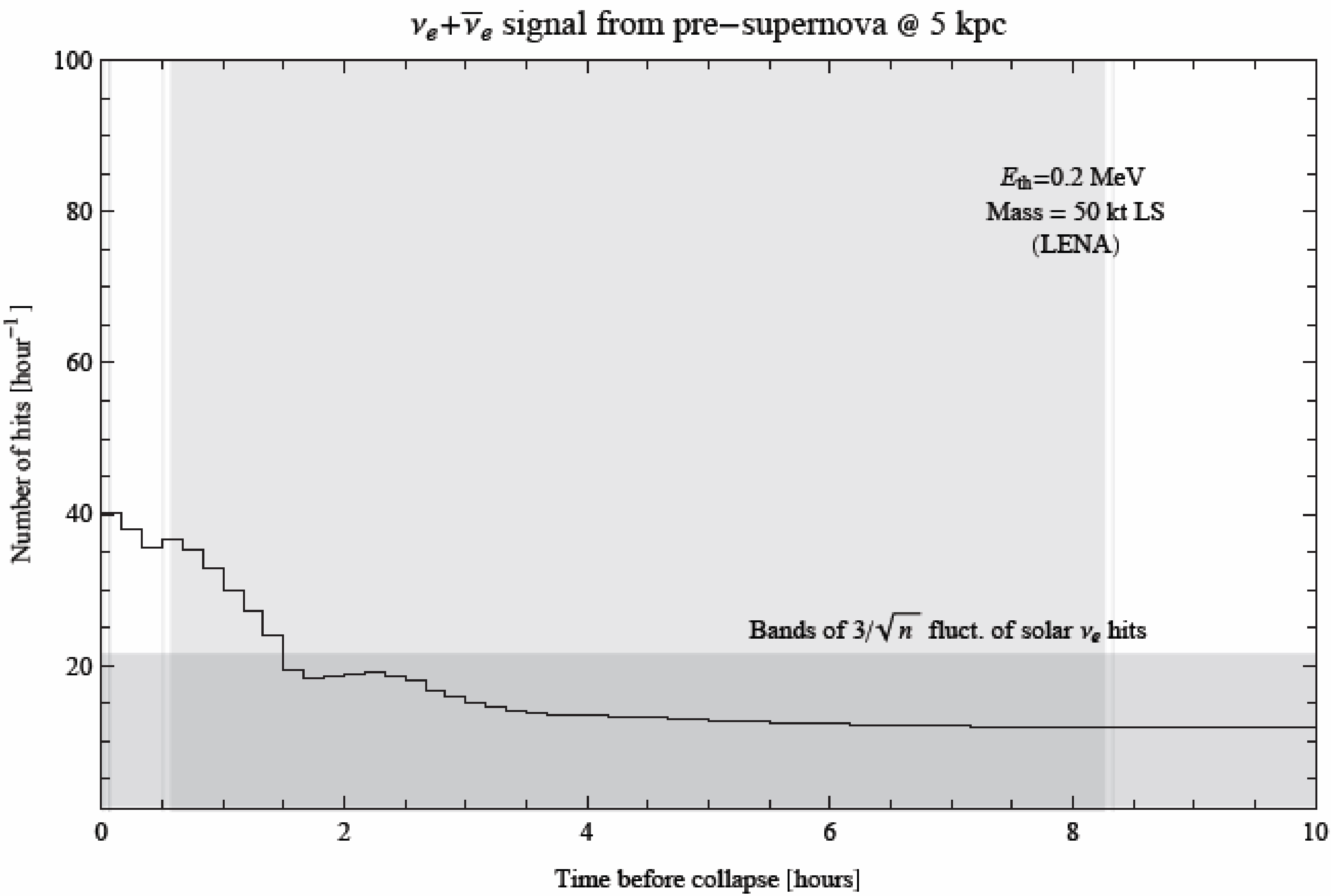
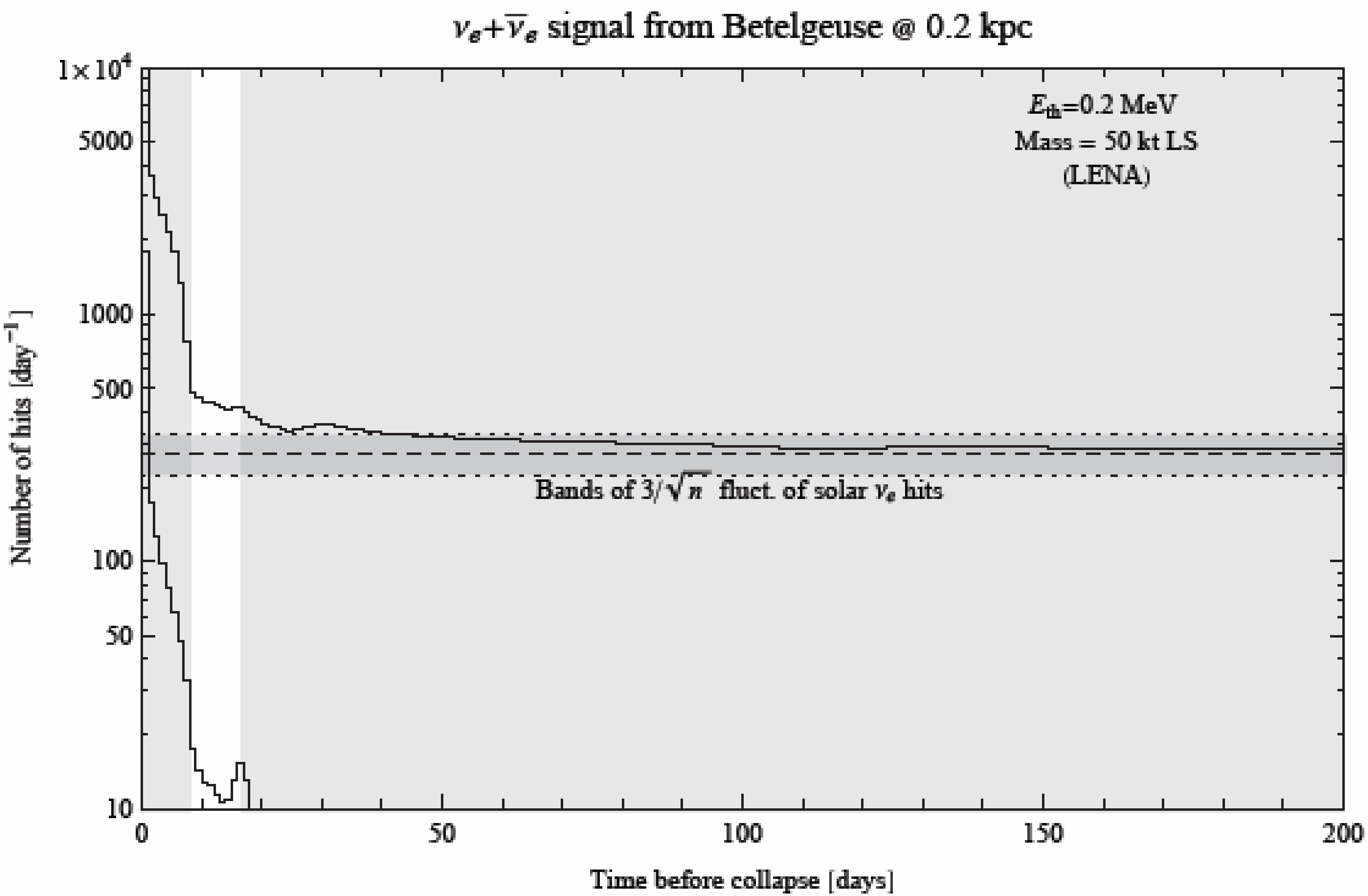


During Si-burning phase 1 neutron/day/kiloton of water 1kpc distance





$\nu_e+\bar{\nu}_e$ signal from pre−supernova @ 5 kpc
E_{th}=0.2 MeV
Mass = 50 kt LS
(LENA)
Bands of $3/\sqrt{n}$ fluct. of solar ν_e hits
Number of hits [hour^{-1}]
Time before collapse [hours]
0
2
4
6
8
10
20
40
60
80
100



$\nu_e+\overline{\nu}_e$ signal from Betelgeuse @ 0.2 kpc
E_{th}=0.2 MeV
Mass = 50 kt LS
(LENA)
Bands of $3/\sqrt{n}$ fluct. of solar ν_e hits
Number of hits [day^{-1}]
1×10^4
5000
1000
500
100
50
10
0
50
100
150
200
Time before collapse [days]

Спасибо за внимание!

Бетельгейзе