There was Light: on Pair Instabilities Supernovae Explosion (PISNe)

P. Chardonnet
Université de Savoie, LAPTH Annecy

With:
V. Chechetkin, M. Popov Moscou
A. Baranov & A. Filina Annecy

15-16 January 2015
Institut Henri Poincaré, Paris

THE ASTROPHYSICAL JOURNAL, 641:293–301, 2006 April 10

THE OBSERVED GALACTIC ANNIHILATION LINE: POSSIBLE SIGNATURE OF ACCRETING SMALL-MASS BLACK HOLES IN THE GALACTIC CENTER

LEV TITARCHUK[1,2] AND PASCAL CHARDONNET[3]
Received 2005 March 30; accepted 2005 November 6

ABSTRACT

Various balloon and satellite observatories have revealed what appears to be an extended source of 0.511 MeV annihilation radiation with a flux of $\sim 10^{-3}$ photons cm^{-2} s^{-1} centered on the Galactic center. Positrons from radioactive products of stellar explosions can account for a significant fraction of the emission. We discuss an additional source for this emission: namely, e^+e^- pairs produced when X-rays generated from the $\sim 2.6 \times 10^6\ M_\odot$ Galactic center black hole interact with ~ 10 MeV temperature blackbody emission from 10^{17} g black holes within 10^{14}–10^{15} cm of the center. The number of such small-mass black holes (SMMBHs) can account for the production of the $10^{42}\ e^+$ s^{-1} that produces the observed annihilation in the inner Galaxy when transport effects are taken into account. We consider the possibility for confirming the presence of these SMMBHs in the Galactic center region with future generations of γ-ray instruments if a blackbody-like emission of ~ 10 MeV temperature would be detected by them. SMMBHs can be a potential candidate for the dark (invisible) matter halo.

Subject headings: accretion, accretion disks — black hole physics — Galaxy: center — radiation mechanisms: nonthermal

1. INTRODUCTION

The Galactic center (GC), found in 1974 as a strong radio source called Sgr A*, is where a supermassive black hole with $2.6 \times 10^6\ M_\odot$ is present (e.g., Melia & Falcke 2001). Moreover,

et al. 1994; Cheng et al. 1997; Share et al. 1990; Teegarden et al. 1996; Gehrels et al. 1991; Niel et al. 1990; Chapuis et al. 1991).

Recently new measurements of the 511 keV line emission from the GC region have been performed with the spectrometer SPI on the space observatory *INTEGRAL* (Jean et al. 2003). The

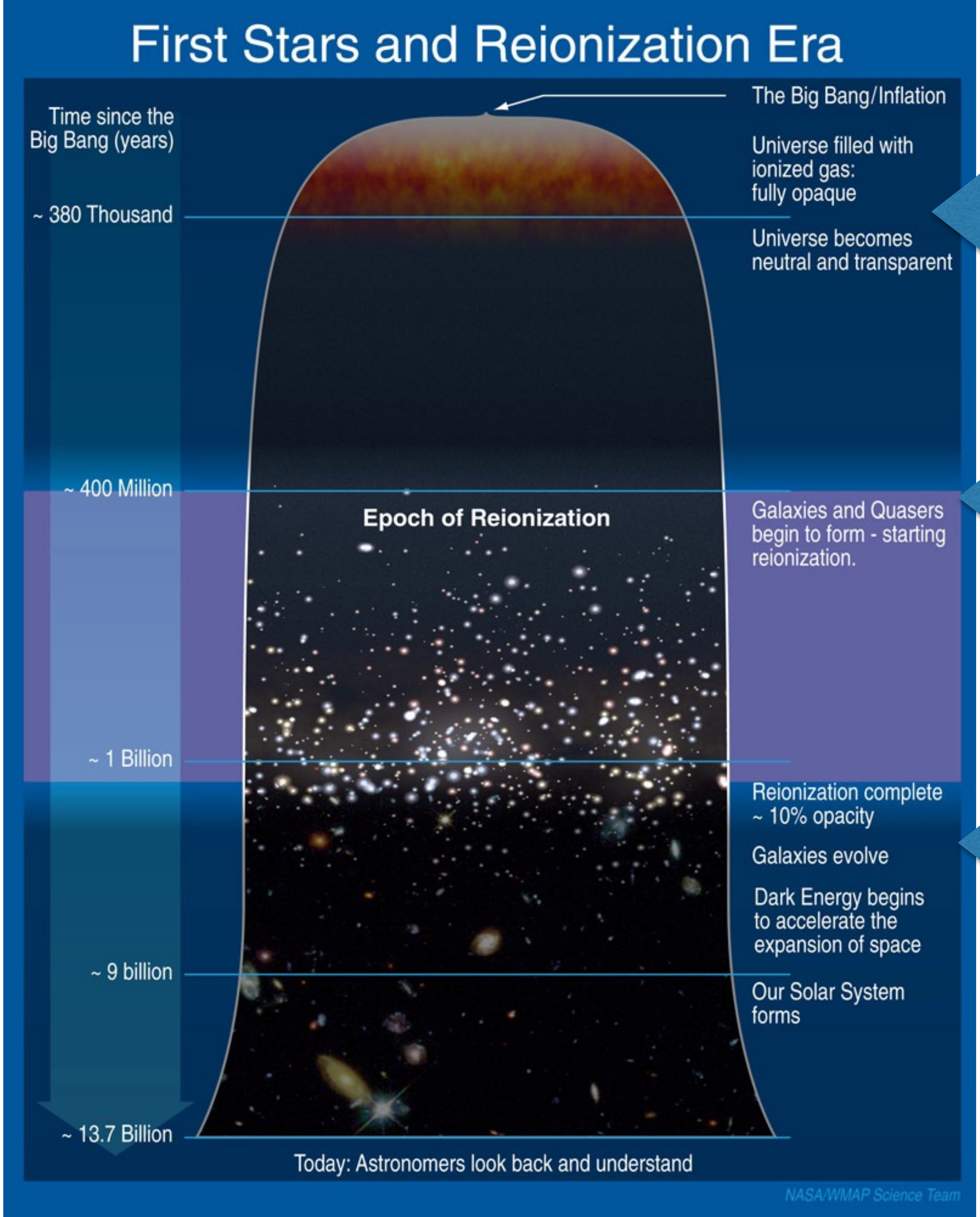
Outlines

- Introduction
- Simulation setup
- Results
- Conclusions

**Multidimensional simulations of pair-instability supernovae,
Astronomy & Astrophysics, Volume 558, id.A10, 5 pp**

Introduction

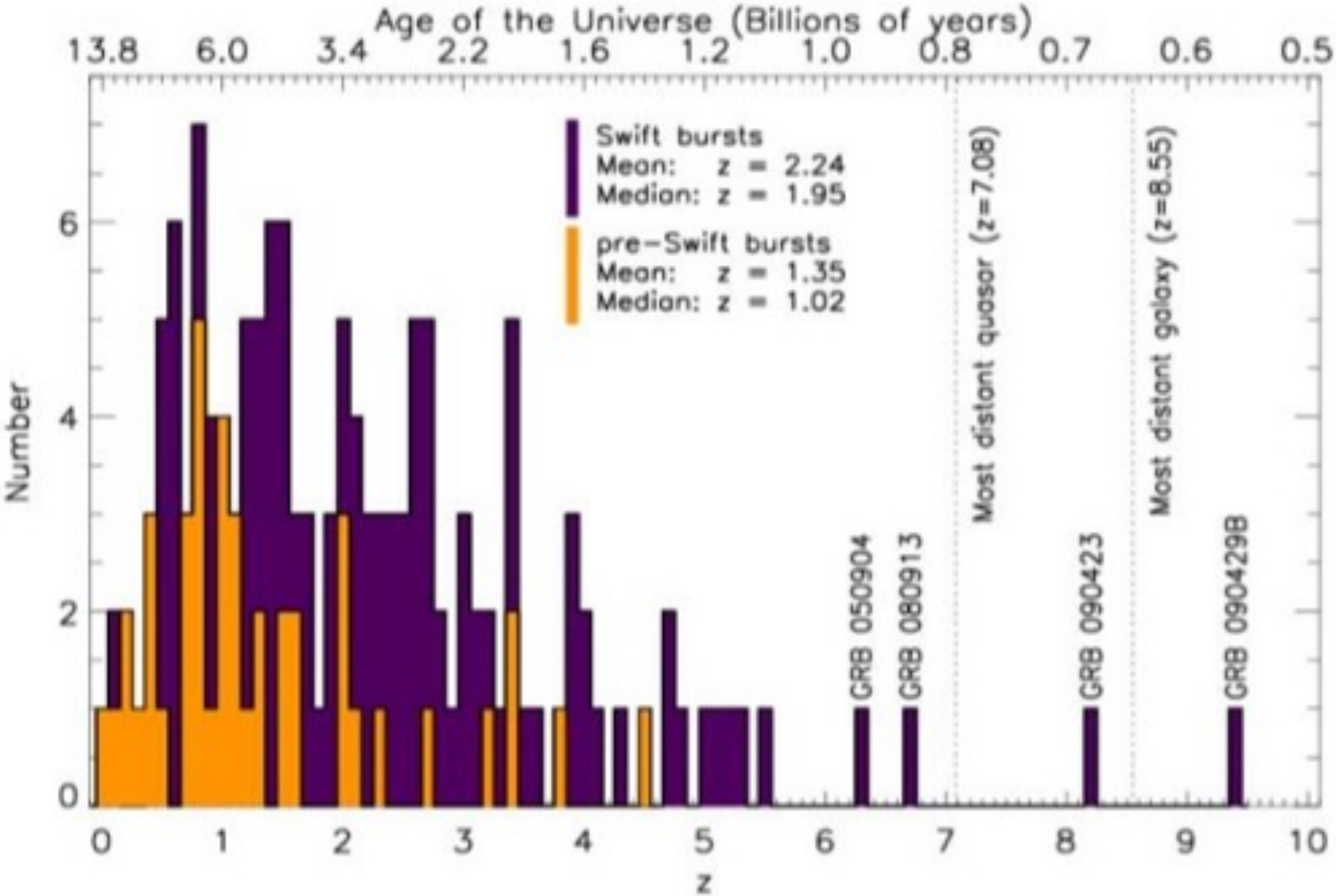
- Introduction: general context
- What is a pair instability supernovae explosion?
- References



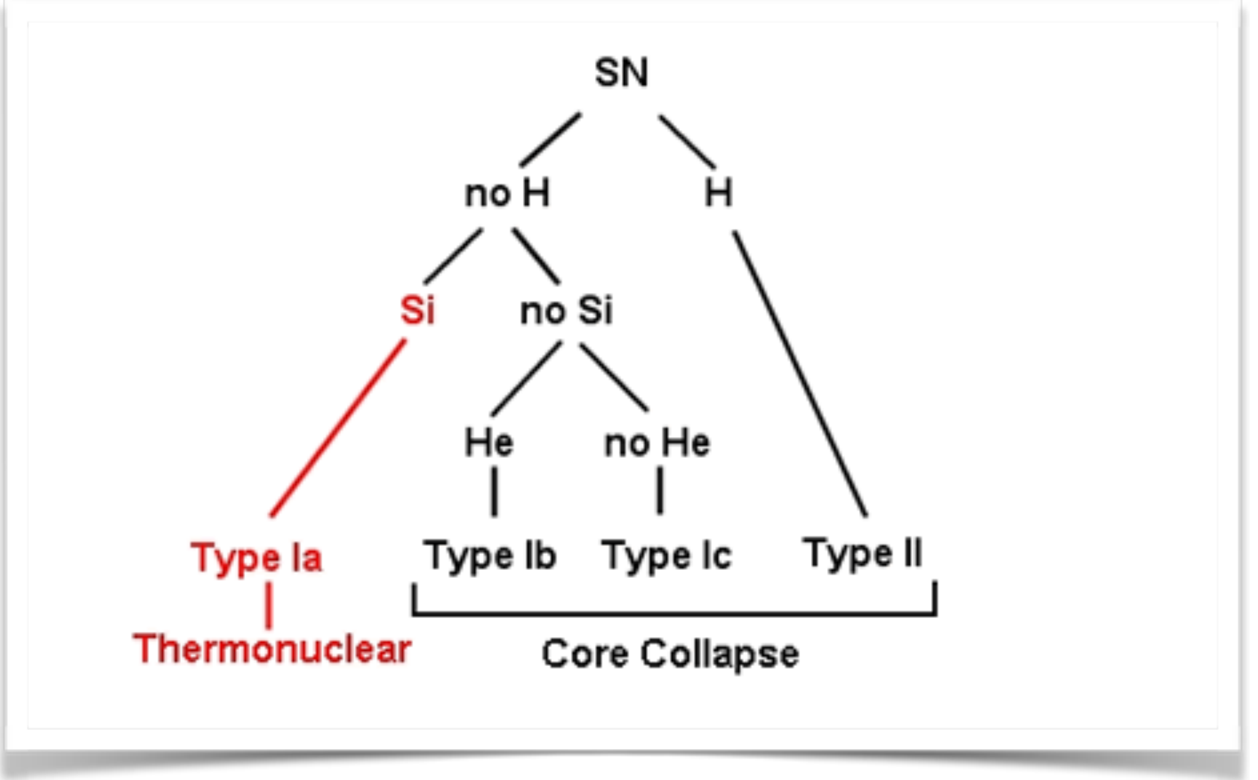
Planck

THESEUS ?

EUCLID


Age of the Universe (Billions of years)
13.8
6.0
3.4
2.2
1.6
1.2
1.0
0.8
0.7
0.6
0.5
Swift bursts
Mean: z = 2.24
Median: z = 1.95
pre-Swift bursts
Mean: z = 1.35
Median: z = 1.02
Most distant quasar (z=7.08)
Most distant galaxy (z=8.55)
GRB 050904
GRB 080913
GRB 090423
GRB 090429B
Number
0
2
4
6
0
1
2
3
4
5
6
7
8
9
10
z

Classification of SN is based on spectral characteristic



I will not speak about spectra

SN Ia: mass overcomes the Chandrasekhar mass, **losses the stability** and start to contract

SN II: main trigger is the **gravitational instability of the iron core.**

PISNe: pair creation reduces internal pressure and leads to rapid contraction of the star. **An instability regime.**

This type of instability was predicted by Rakavy & Shaviv (1967)

Because of the huge mass of the star that encounters pair creation, energy release during PISN explosion is tremendous

Energy released: $\simeq \mathbf{3.5 \times 10^{52}}\ \boldsymbol{ergs}$

to be compared to the binding energy $\simeq \mathbf{0.5 \times 10^{52}}\ \boldsymbol{ergs}$

Bond, Arnett and Carr (1984)

Role of temperature

When central temperature in the core of the star reaches a few 10^9 K : possibility of pair creation

Planck spectrum

Wien Law

$$\lambda_{max} T = 0.2898\ cm.K$$

$$E_\gamma \simeq 1\ MeV$$

$$T \simeq 2 \times 10^9\ K$$

First computation: Koppe (1948), See also: Fowler & Hoyle (1964)

For massive stars, they reach high value of T at relatively **low value of central density**

This can be understood by some basic equations of standard stellar physics

$$\rho_c \simeq \frac{T_c^3}{M^2}$$

(formulation of Fowler and Hoyle $\rho_c \simeq \frac{T_c^3}{M^{1/2}}$)

Example of typical central density : few 10^5 g.cm-3

Effect of pair creation

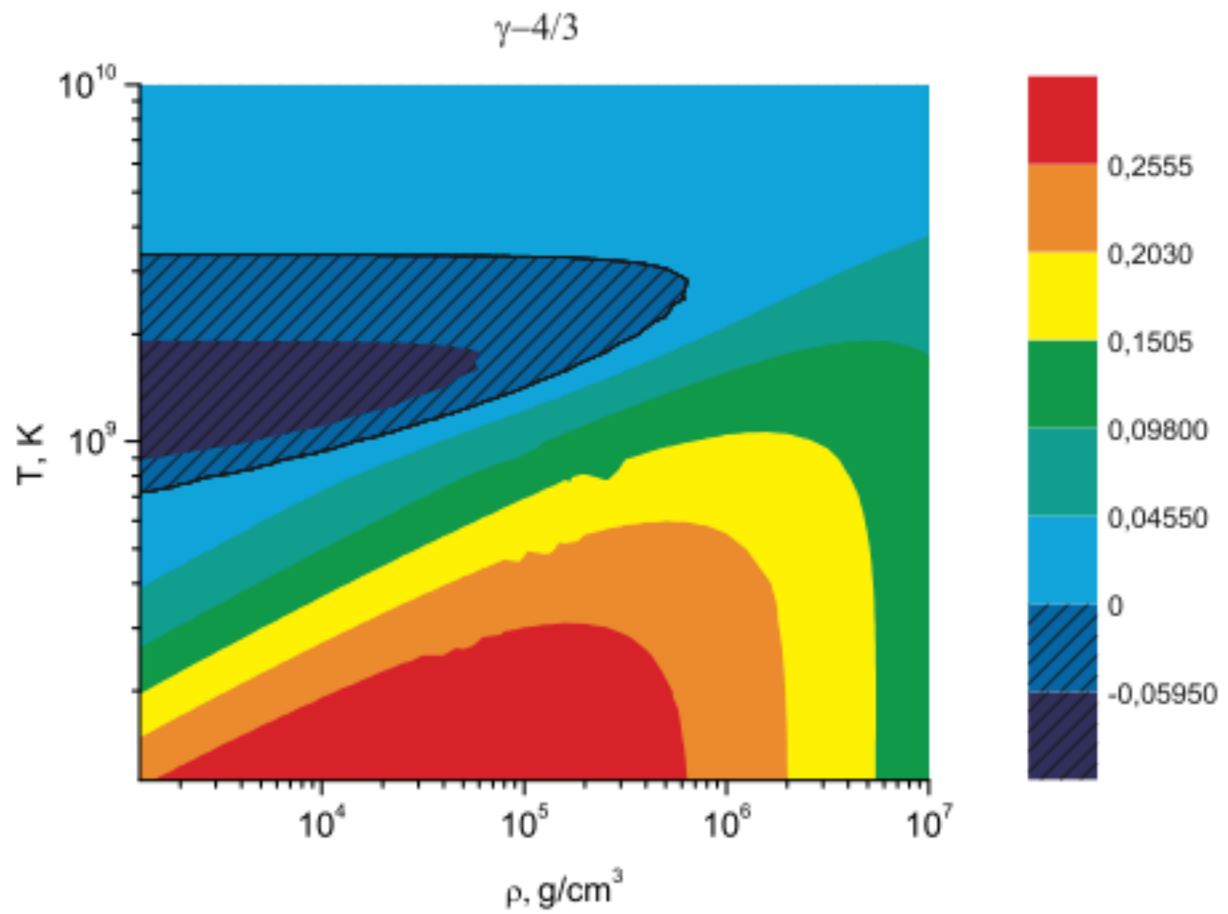
Fowler and Hoyle discovered that when the central temperature of a star reaches value 2 10 9 K, intensive pair creation occurs.

the consequence is to increase the energy losses by neutrinos

$$e^+ + e^- \rightarrow \nu_e + \nu_e$$

This accelerate the contraction of the star and rise the temperature and create new pairs.

Model of Pair-instability SN



Absorption of energy to create rest mass of the pairs
When a sufficient amount of the star entered in this area it becomes
dynamically unstable

A recent history

The first evolutionary calculations were performed by Rakavy and Shaviv (1967). Computation of a 30 solar oxygen core.

The first dynamical computation of explosion was performed by Barkat et al. (1967): 40 solar mass oxygen core. They have found the limit of mass for PISNe of 30 solar mass oxygen core.

First detailed evolution of helium core were performed by Arnett (1972). He demonstrated that the core were composed mainly of oxygen when reaching the pair instability zone.

El Eid et al (1983) have studied evolution of 80-500 solar mass.

Glatzel et al (1985) have studied the effect of rotation. This could extend the region of mass

Woosley & Heger (2002) The evolution and explosion of massive stars

Woosley,Blinnikov, Heger (2007) SN 2006gy

also Binsnovatyi-Kogan, Nomoto, Gal-Yam

Yusof et al (2013) Evolution and fate of very massive stars

KEPLER code: Woosley CASTRO code Almgren et al

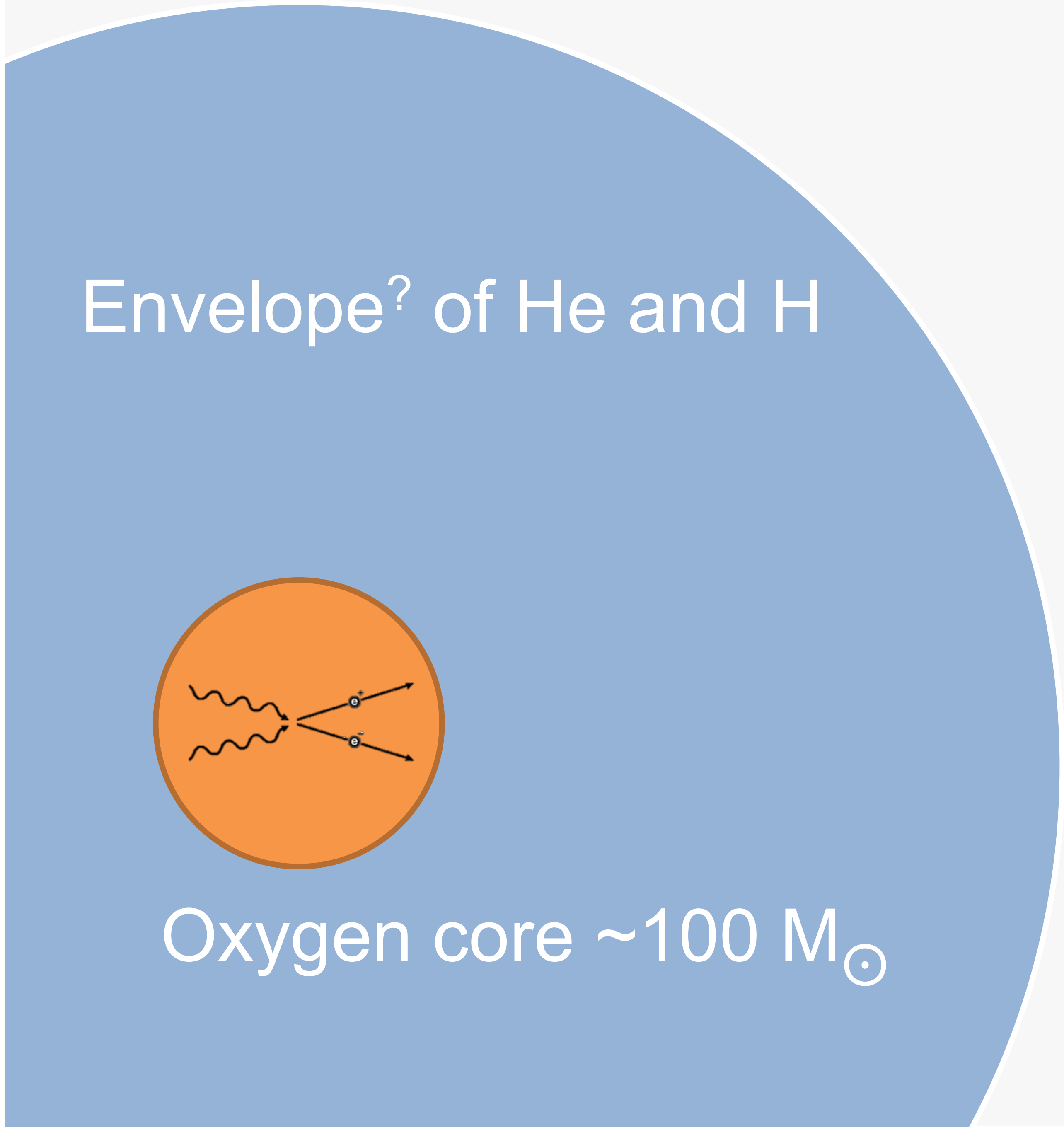
MESA code: Paxton et al 2010, 2013

Multidimensional simulations: Chen et al. 2011,Joggerst et Whalen 2011

Simulation setup

- Computational Grid
- Initial Model
- Equation of State
- Simulation runs

Numerical simulations



- Spherical symmetry
- Computation of the core only
- Polytrope with γ=4/3

  $P=K\rho^{\gamma}$

Numerical simulations

$$
\left\{
\begin{aligned}
\partial r/\partial t &= v \\
\partial v/\partial t &= -Gm/r^2 - 4\pi r^2(\partial P/\partial m) \\
\partial T/\partial t &= \left[- 4\pi \frac{\partial(r^2 v)}{\partial m}(T(\partial P/\partial T)_\rho) + \varepsilon_{\mathrm{nucl}} - \varepsilon_\nu\right] / (\partial E/\partial T)_\rho
\end{aligned}
\right.
$$

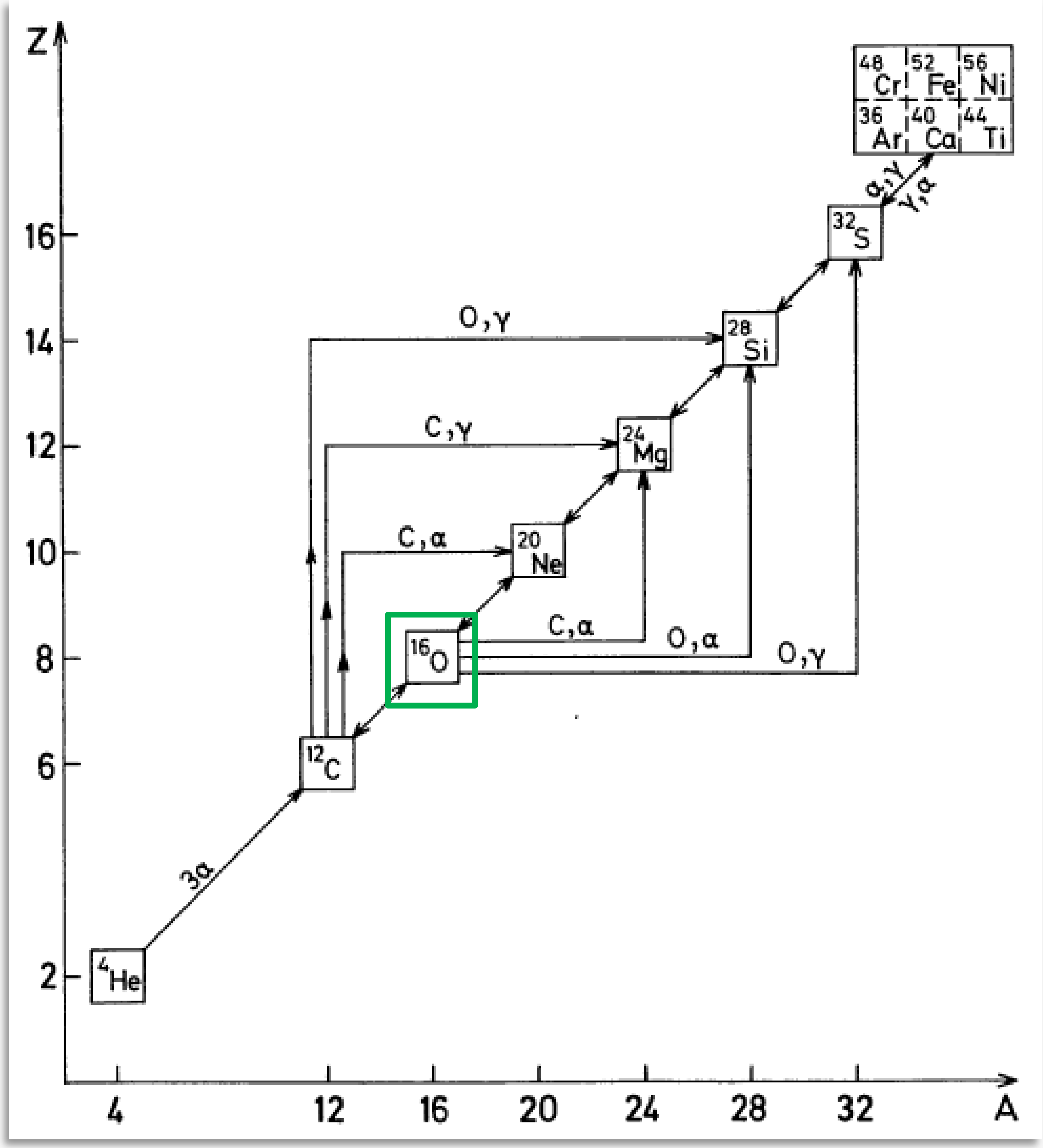
Nuclear burning

Neutrino losses

System of equations

$$
\begin{cases}
\partial r/\partial t & = v \\
\partial v/\partial t & = -Gm/r^2 - 4\pi r^2(\partial P/\partial m) \\
\partial T/\partial t & = (-4\pi \frac{\partial(r^2 v)}{\partial m} T(\partial P/\partial T)_\rho + \varepsilon_{nucl} - \varepsilon_\nu)/(\partial E/\partial \rho)_\rho \\
P(\rho, T, Y_i) & = EOS(\rho, T, Y_i) \\
... & \\
dY_j/dt & = Y_k Y_l \rho R_{jk,l} - Y_j Y_l \rho R_{jl,m} + Y_i \lambda_{i,j} - Y_j \lambda_{j,k} \\
... &
\end{cases}
$$

Nuclear reactions

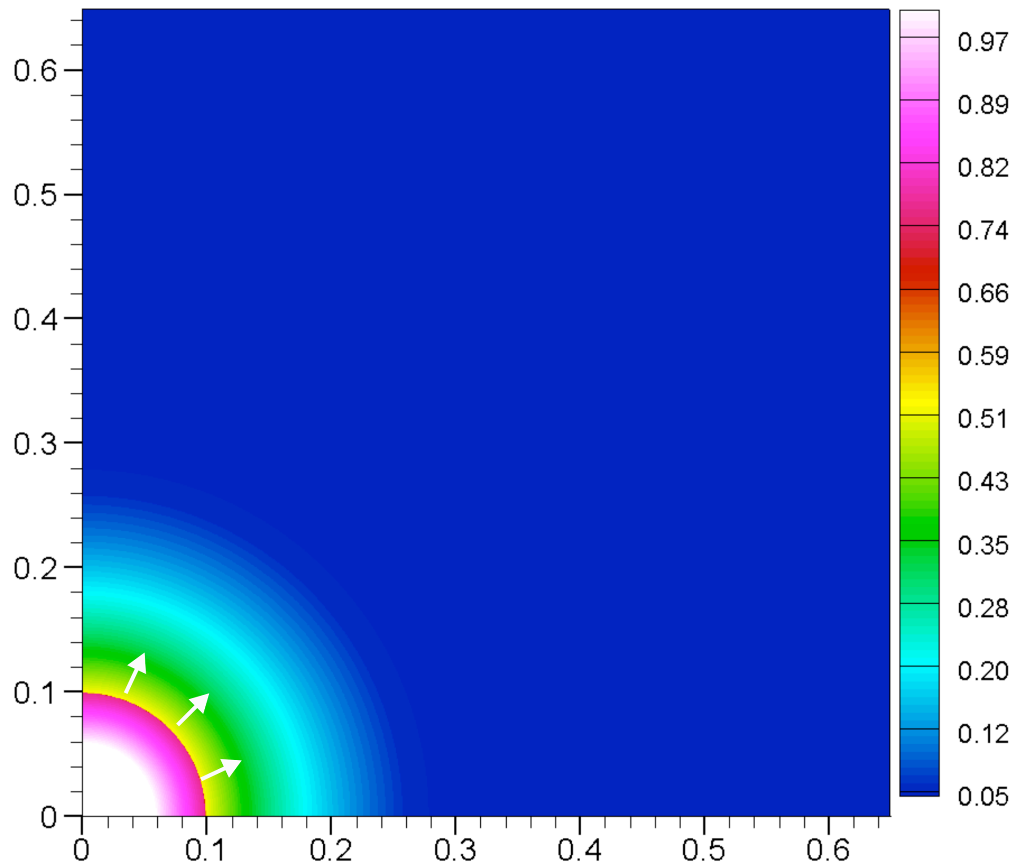


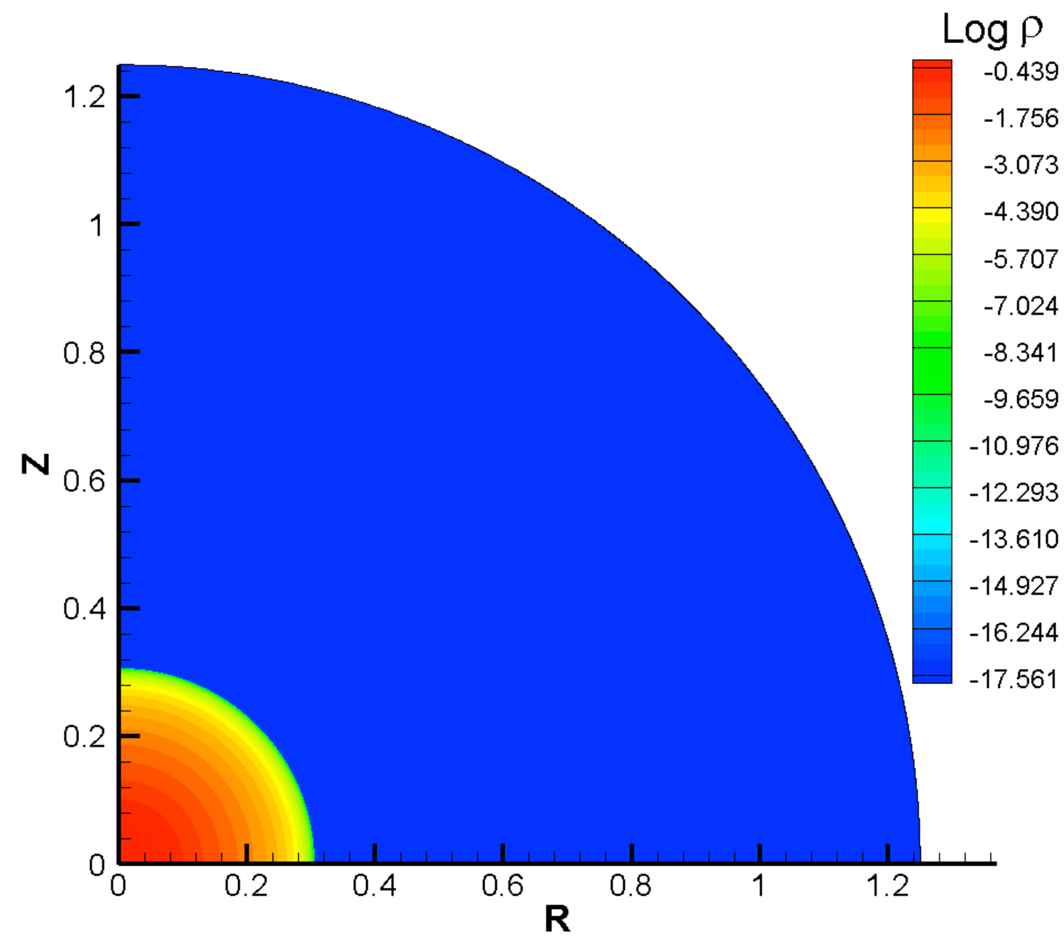
Multidimensional approach

- Oxygen core : 100 solar mass
- Radius of the core : 0.3 solar radius
- Central density : $\rho_c \sim 2 \times 10^5 g/cm^{-3}$
- Central Temperature : $Tc \sim 2 \times 10^9 K$

Hydrodynamics simulations were performed with a numerical code based on PPML algorithm Popov & Ustyugov (2007); Popov (2012)

Initial conditions



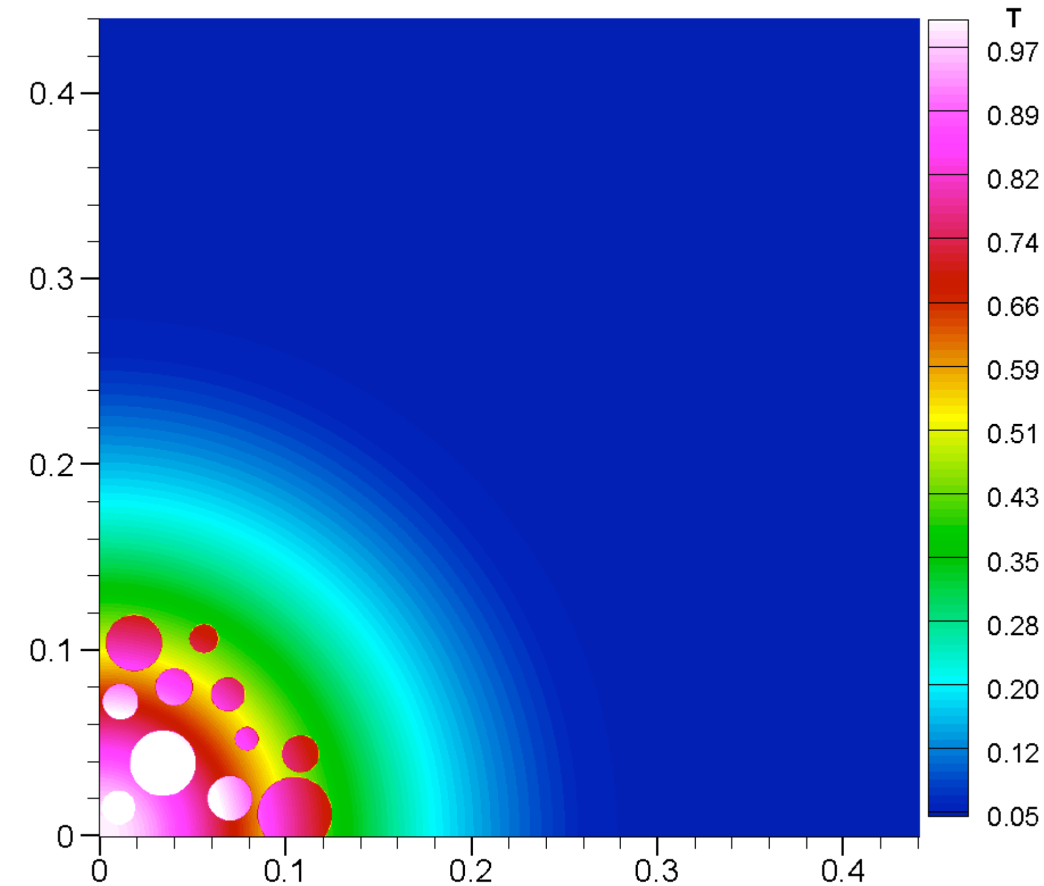


The energy 5. 10^52 ergs was deposited in the central region . This region contains 60 solar mass.

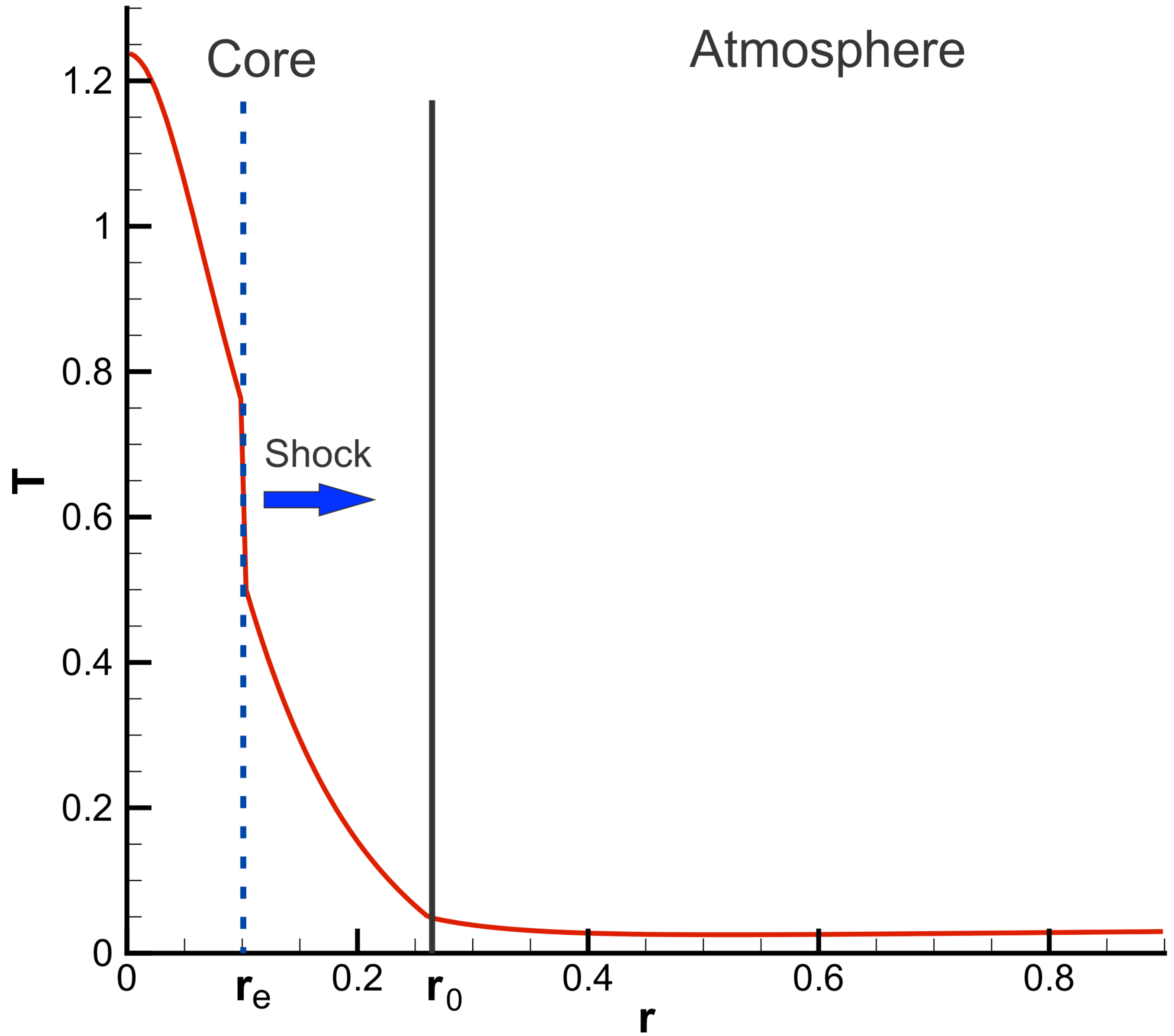
The pictures were obtained with 2D PPML code in cylindrical geometry (r,z) on 1600 1600 grid.

Multi-explosion core

- The fragmentation could be related with instabilities of the burning front.
- The front could propagate in different directions with different velocities. If there are some inhomogeneities in density, for example, some dense fragments in the central core, they could give several ignition points.
- Explosion was set by 11 ignition areas, which were distributed randomly. Total energy inserted into these areas is 5. 10^52 ergs



Nuclear burning in the center of a star could cause the development of large-scale convection (Arnett 2011) if convention occurs prior the moment of pair instability the contraction and explosion could be non symmetrical. Inhomogeneities in T and rho could cause ignition of spots to occur in the core.

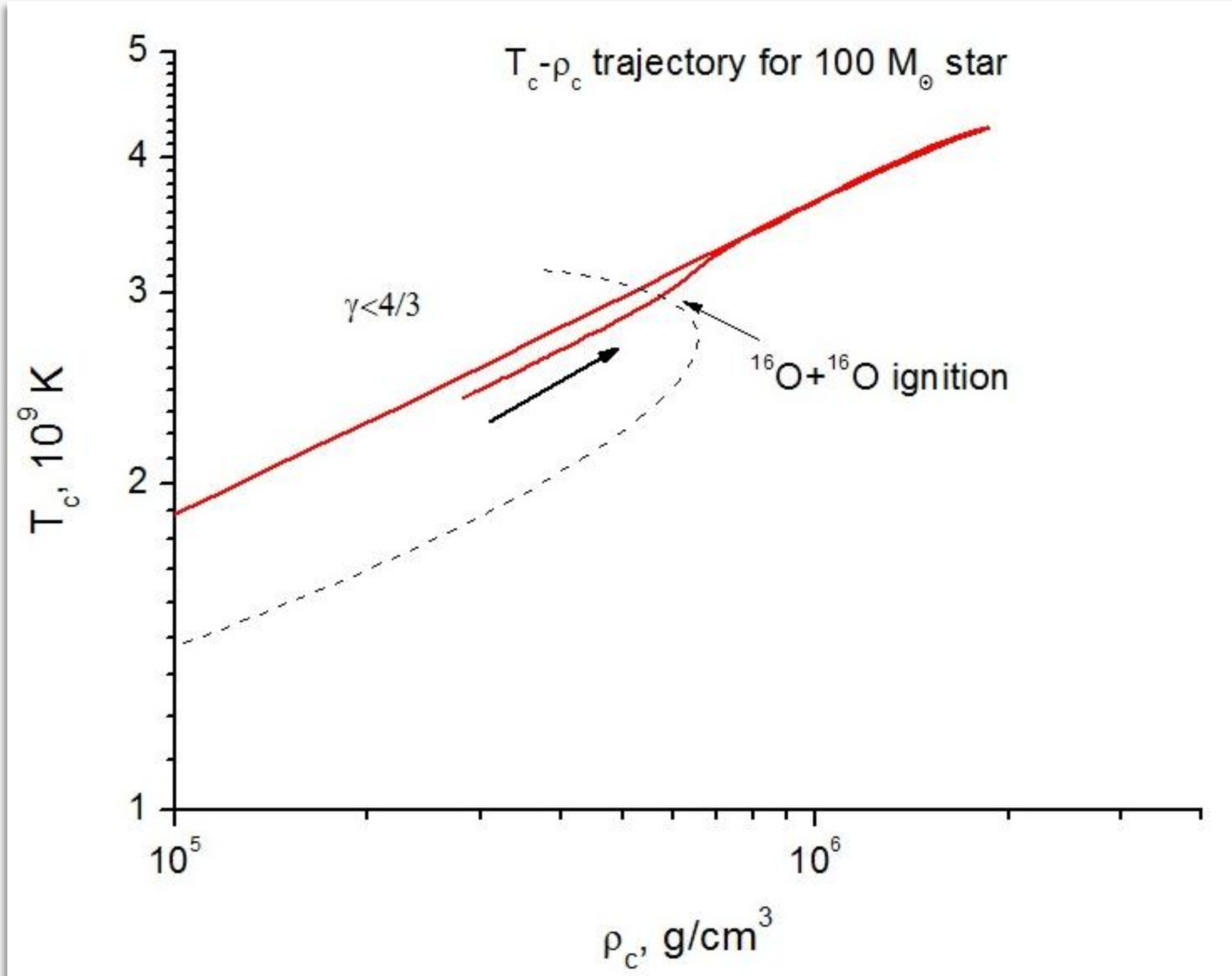


The energy deposition, which produces the shock, is shown
Temperature profile at the moment of explosion in the units of 2.36 10**9K
The values for the atmosphere: order of 10**8 K

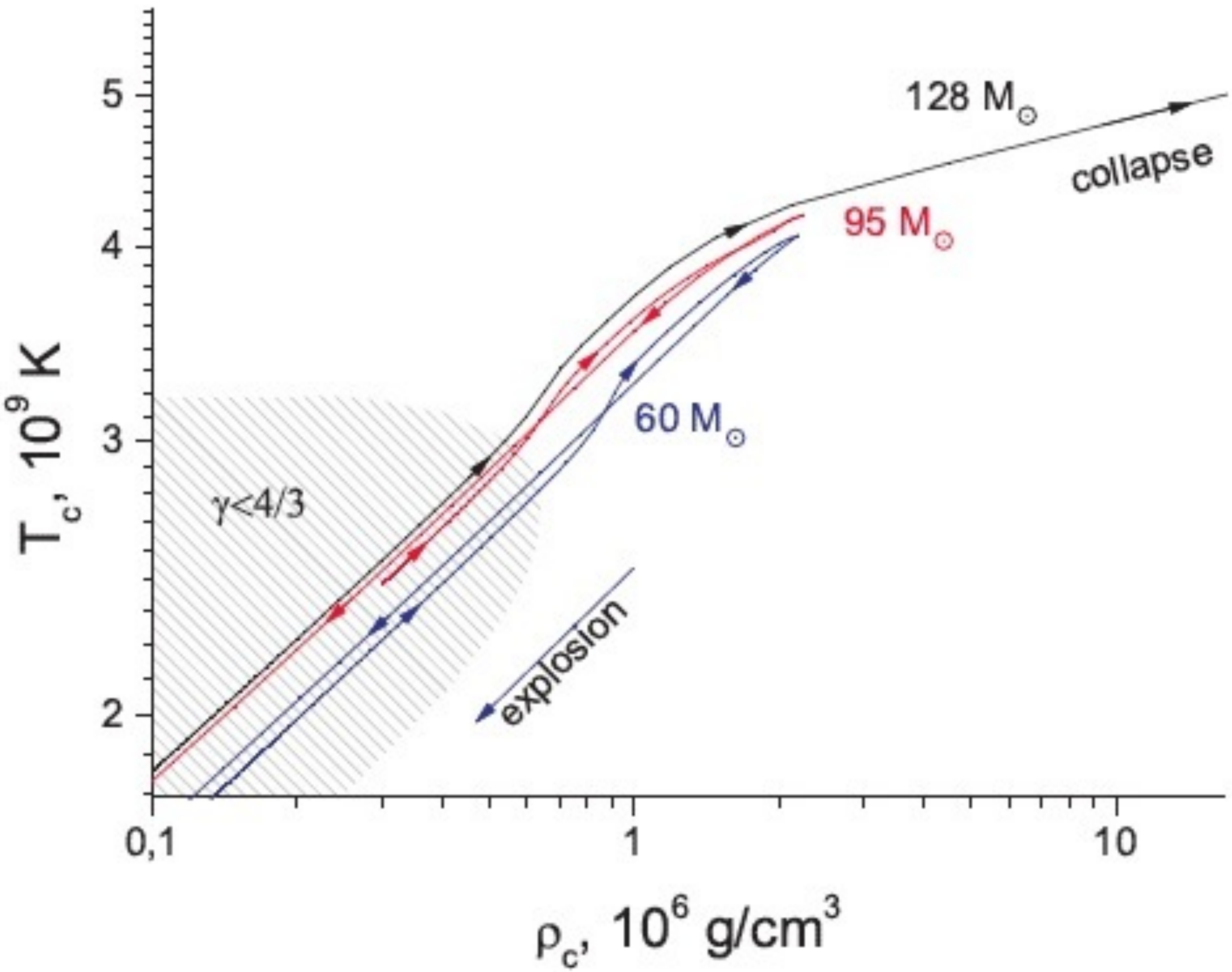
Results

- 1D code: dynamical evolution
- Scaling relation between Enuc and T
- fate of stars depending on Binding energy
- 2D code: symmetrical explosion
- 2D code : multicore explosion. Fragmentation of the core

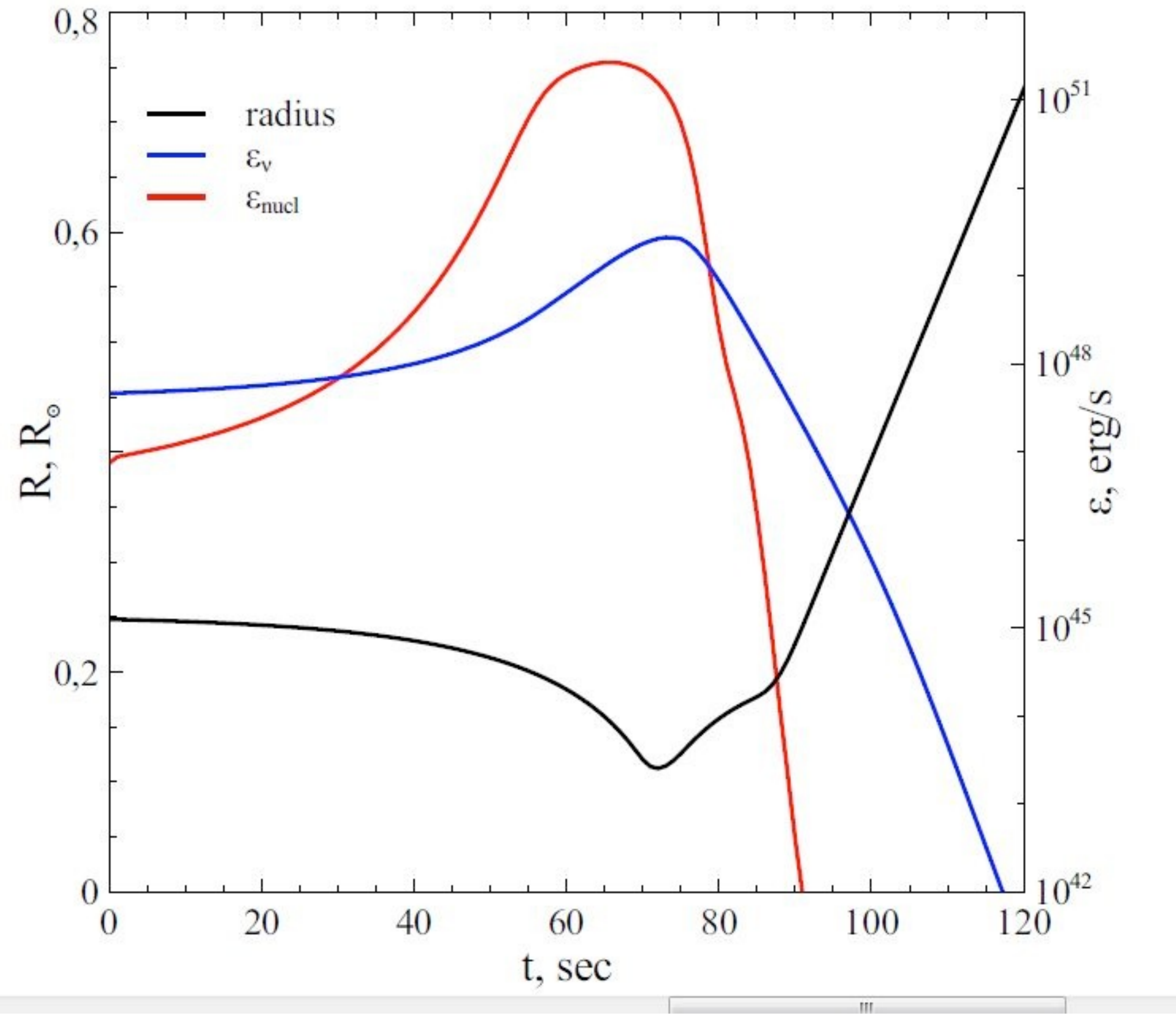
Results



T_c-ρ_c trajectory for 100 $M_\odot$ star
γ<4/3
$^{16}O+^{16}O$ ignition
T_c, 10^9 K
ρ_c, g/cm^3
5
4
3
2
1
10^5
10^6



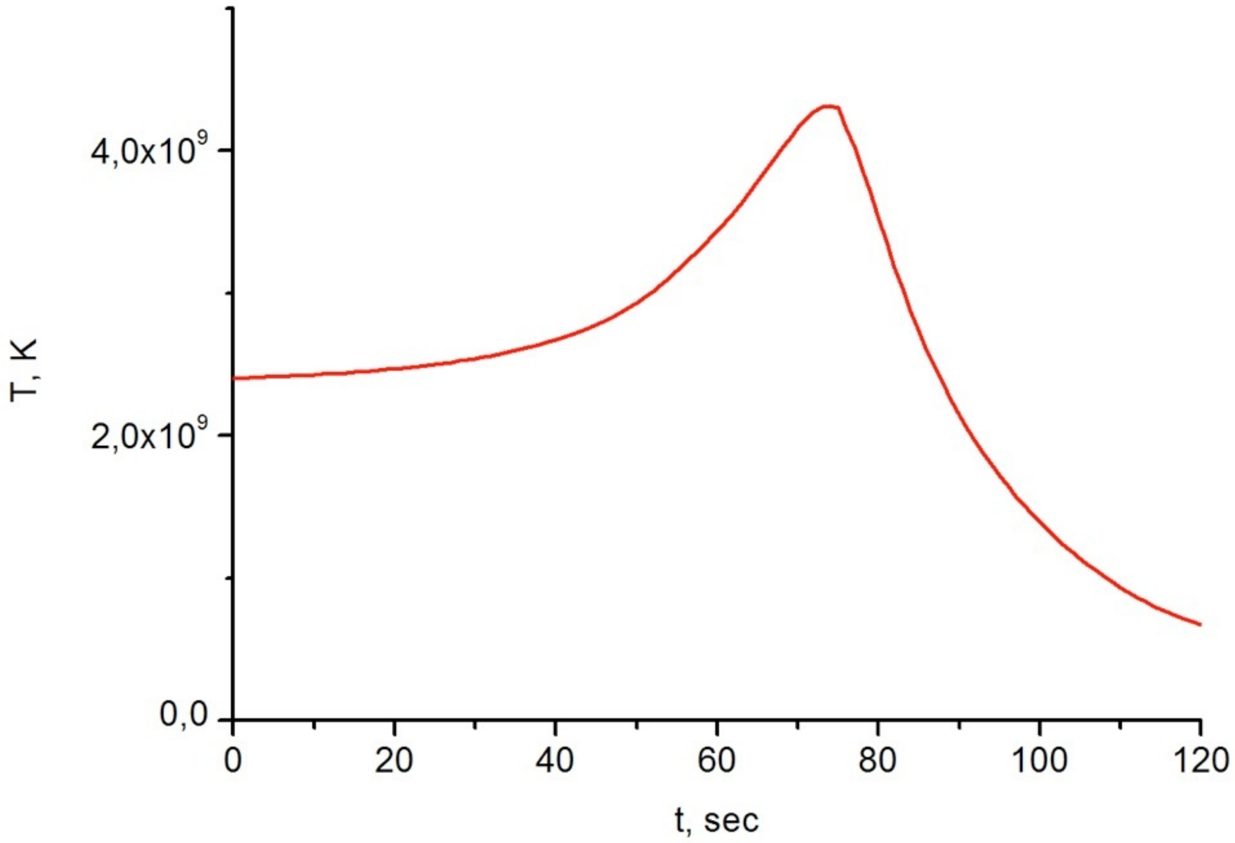
128 M⊙
collapse
95 M⊙
60 M⊙
γ<4/3
explosion
5
4
3
2
T_c, 10^9 K
0,1
1
10
ρ_c, 10^6 g/cm^3



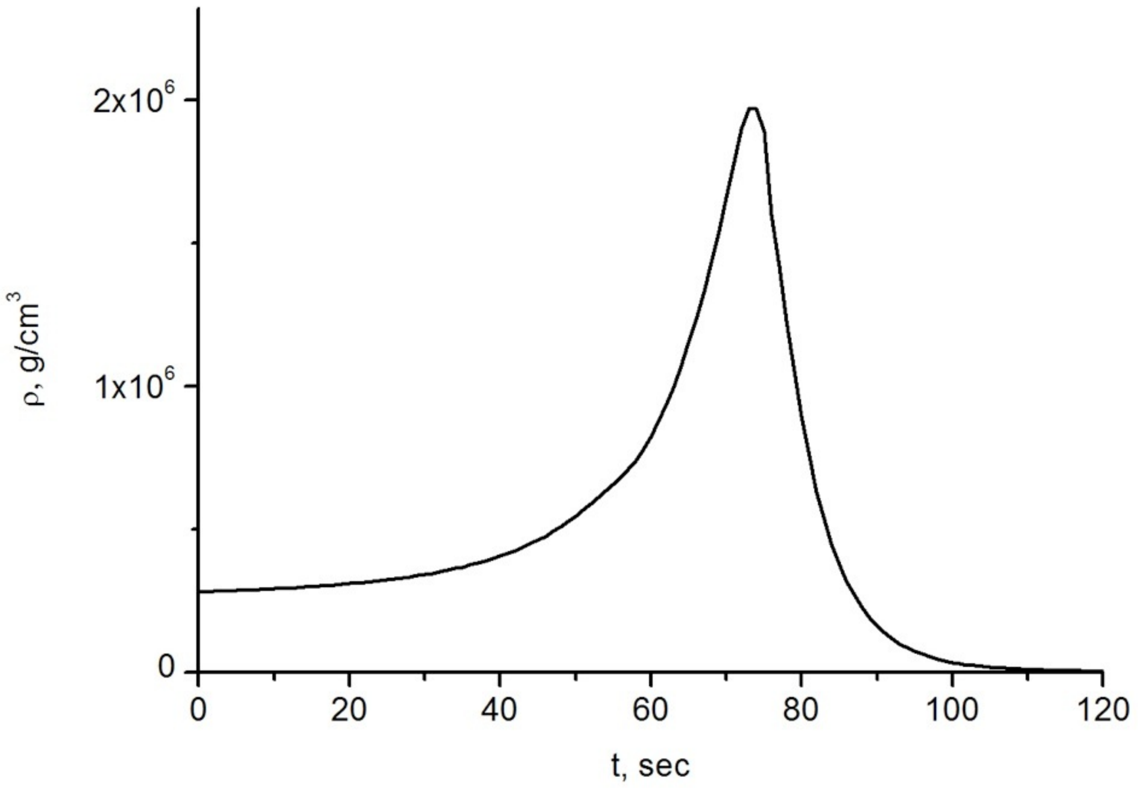
radius
ε_ν
ε_{nucl}
0,8
0,6
0,2
0
$R, R_\odot$
10^{51}
10^{48}
10^{45}
10^{42}
ε, erg/s
0
20
40
60
80
100
120
t, sec

Results: density – temperature

Central temperature

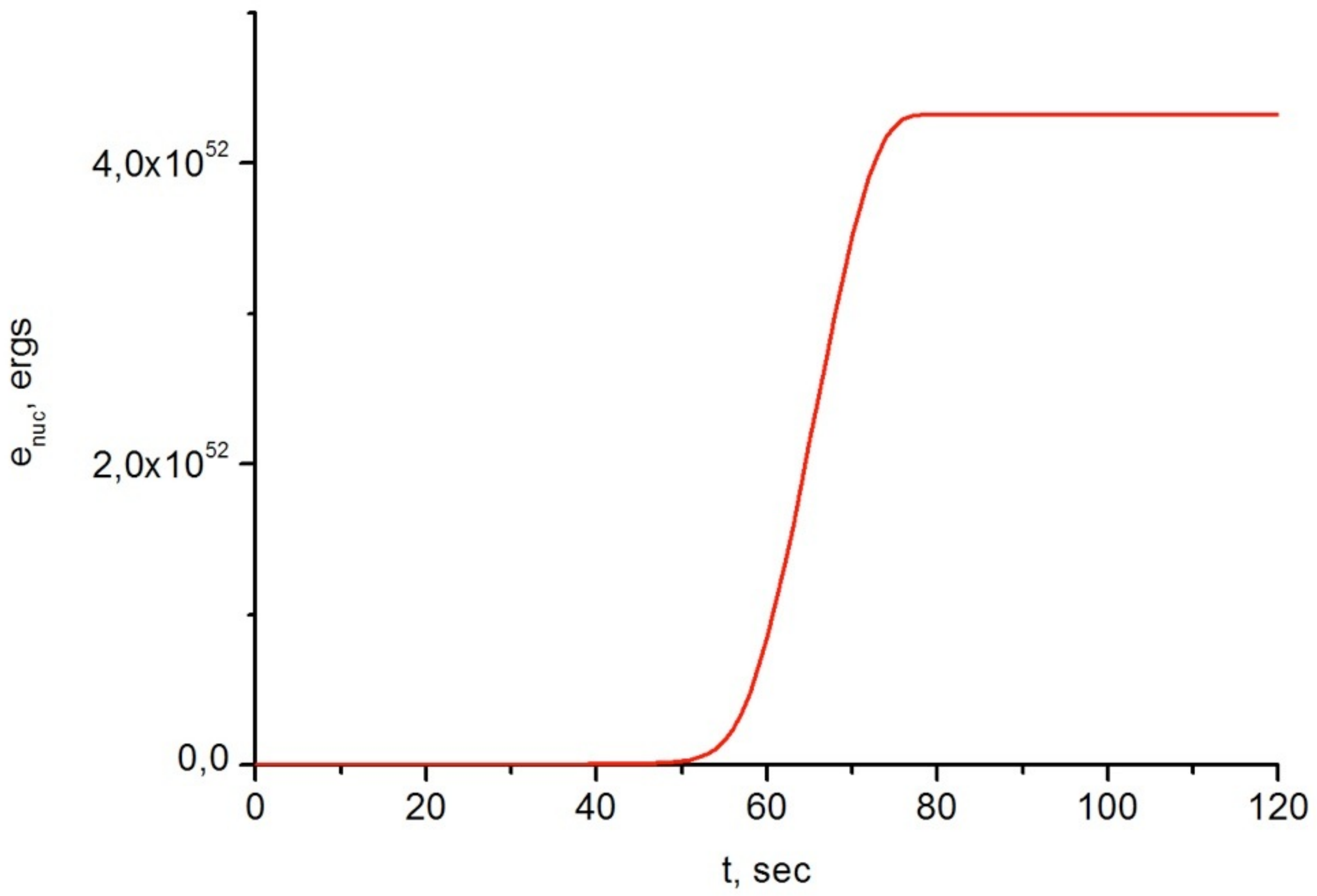


Central density



Results: timescale

Nuclear burning energy



Results

$M/M_{\odot}$	$\rho_c, 10^5 g/cc$	T_{max}, keV	$E_{nucl}, 10^{52}$ ergs	fate
60	0.87	352	2.23	explosion
60	1.15	351	2.25	explosion
78	0.60	—	—	collapse
78	2.00	—	—	collapse
78	3.00	330	2.46	explosion
100	1.00	—	—	collapse
100	1.65	—	—	collapse
100	2.00	—	—	collapse
100	2.25	—	—	collapse
100	2.40	463	5.11	explosion
100	2.50	421	4.80	explosion
100	2.65	371	4.12	explosion
112	1.00	—	—	collapse
112	1.50	—	—	collapse
112	2.00	470	5.46	explosion
125	1.00	—	—	collapse
125	1.50	—	—	collapse

Results

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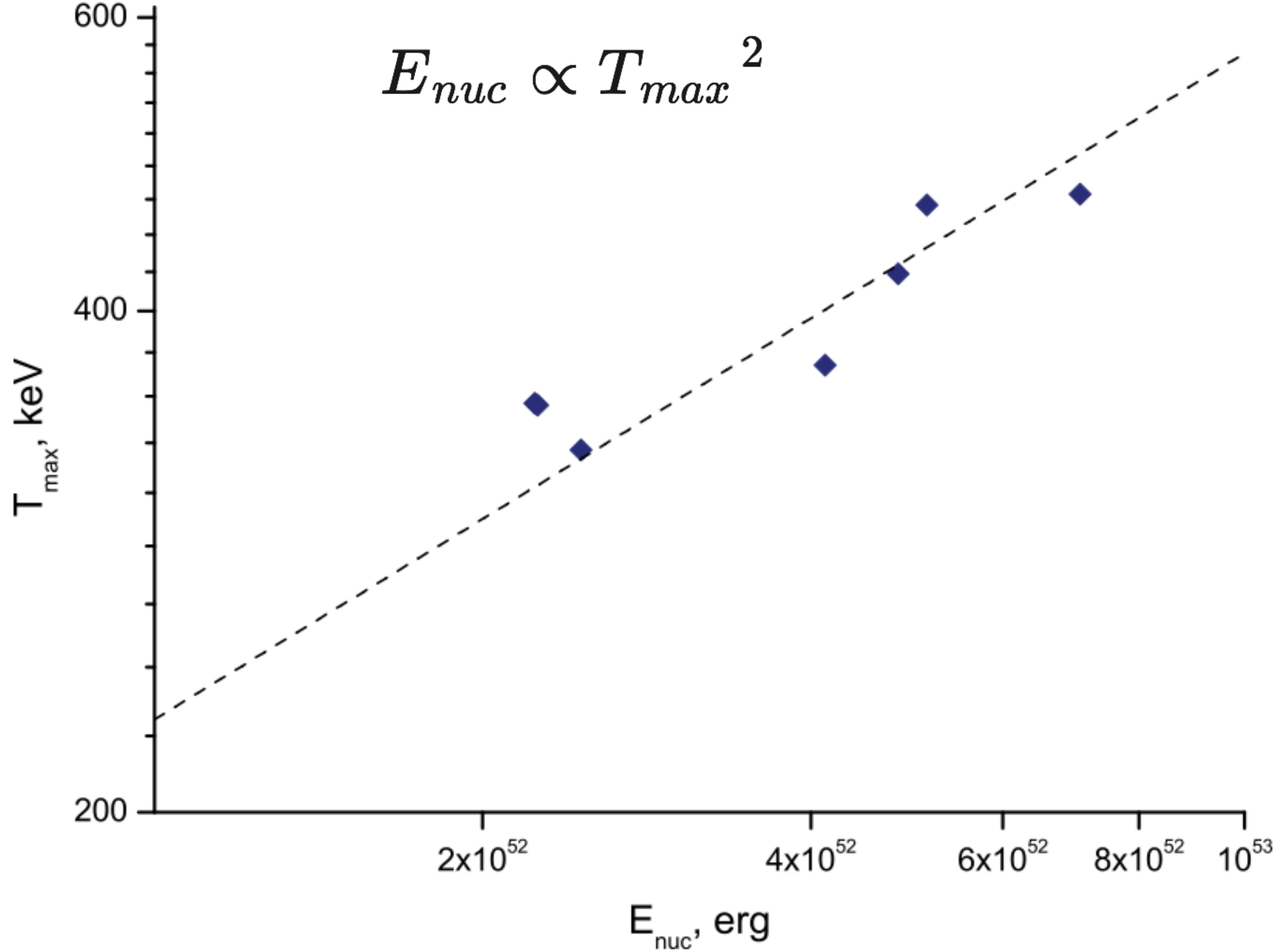
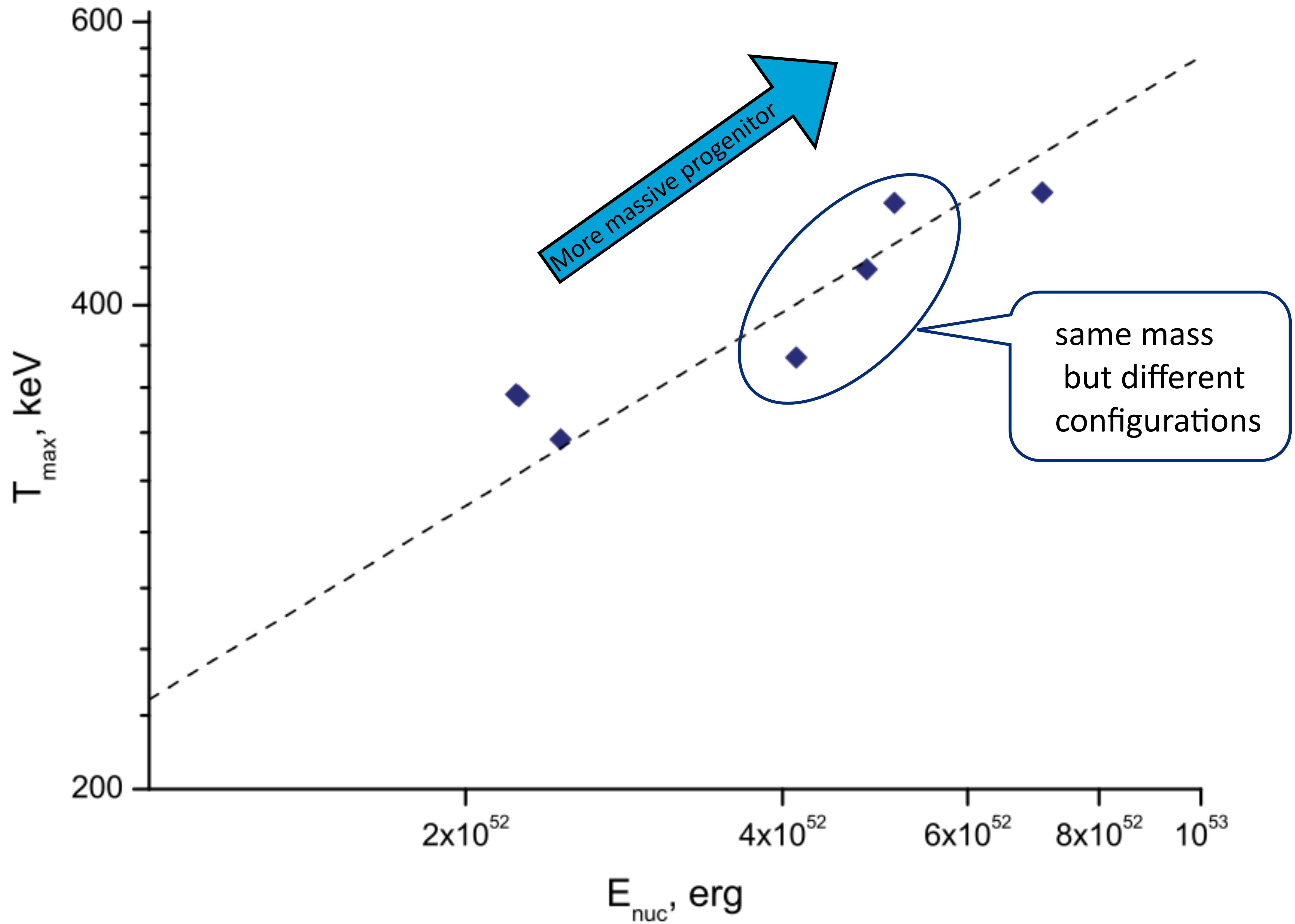
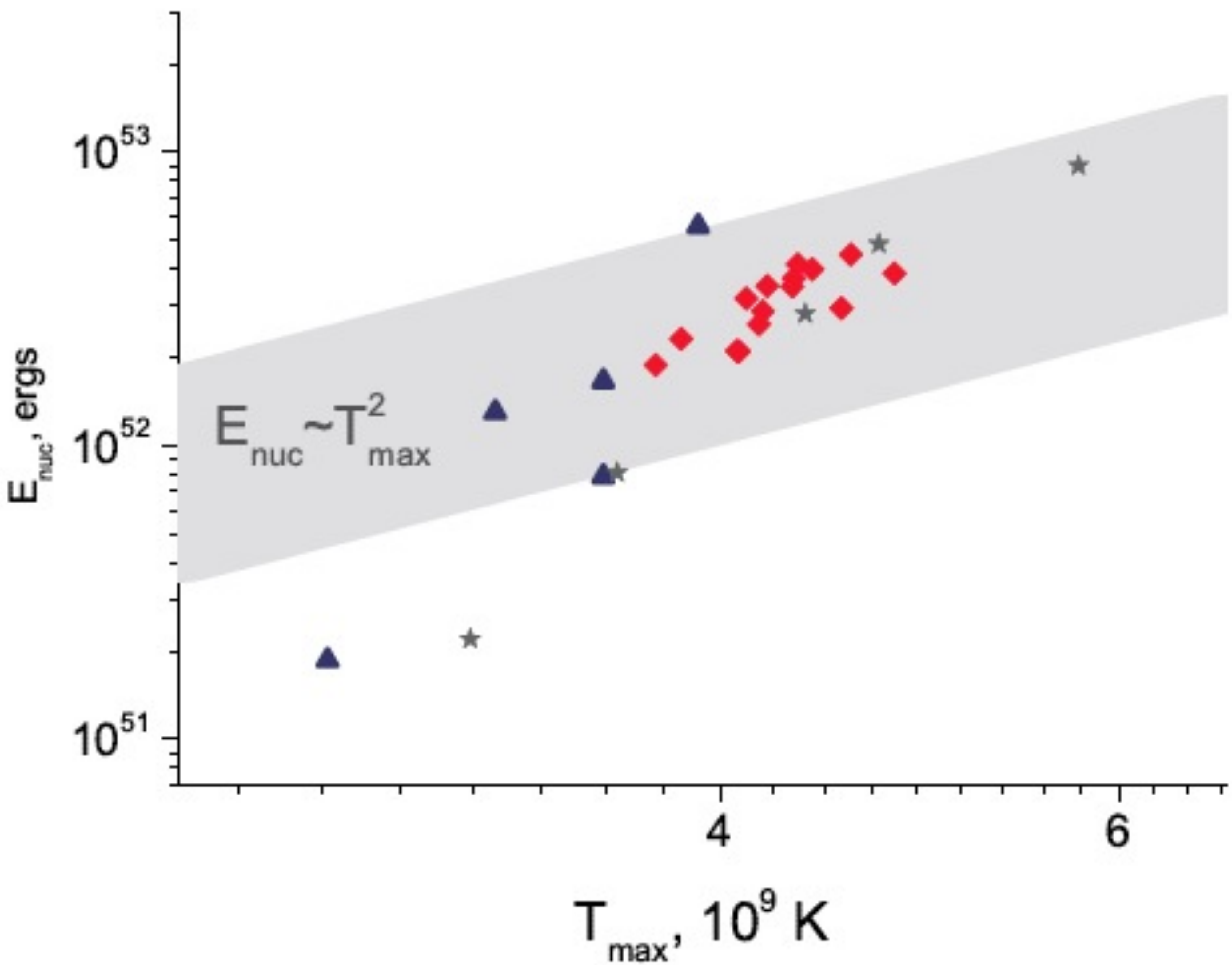
125	1.50	—	—	collapse


$E_{nuc} \propto T_{max}{}^2$
600
400
200
T_{max}, keV
2x10^52
4x10^52
6x10^52
8x10^52
10^53
E_{nuc}, erg



600
400
200
T_{max}, keV
2x10^52
4x10^52
6x10^52
8x10^52
10^53
E_{nuc}, erg
More massive progenitor
same mass
but different
configurations



10^{53}
10^{52}
10^{51}
E_{nuc}, ergs
$E_{nuc} \sim T^2_{max}$
4
6
T_{max}, 10^9 K

Since source of energy is nuclear burning

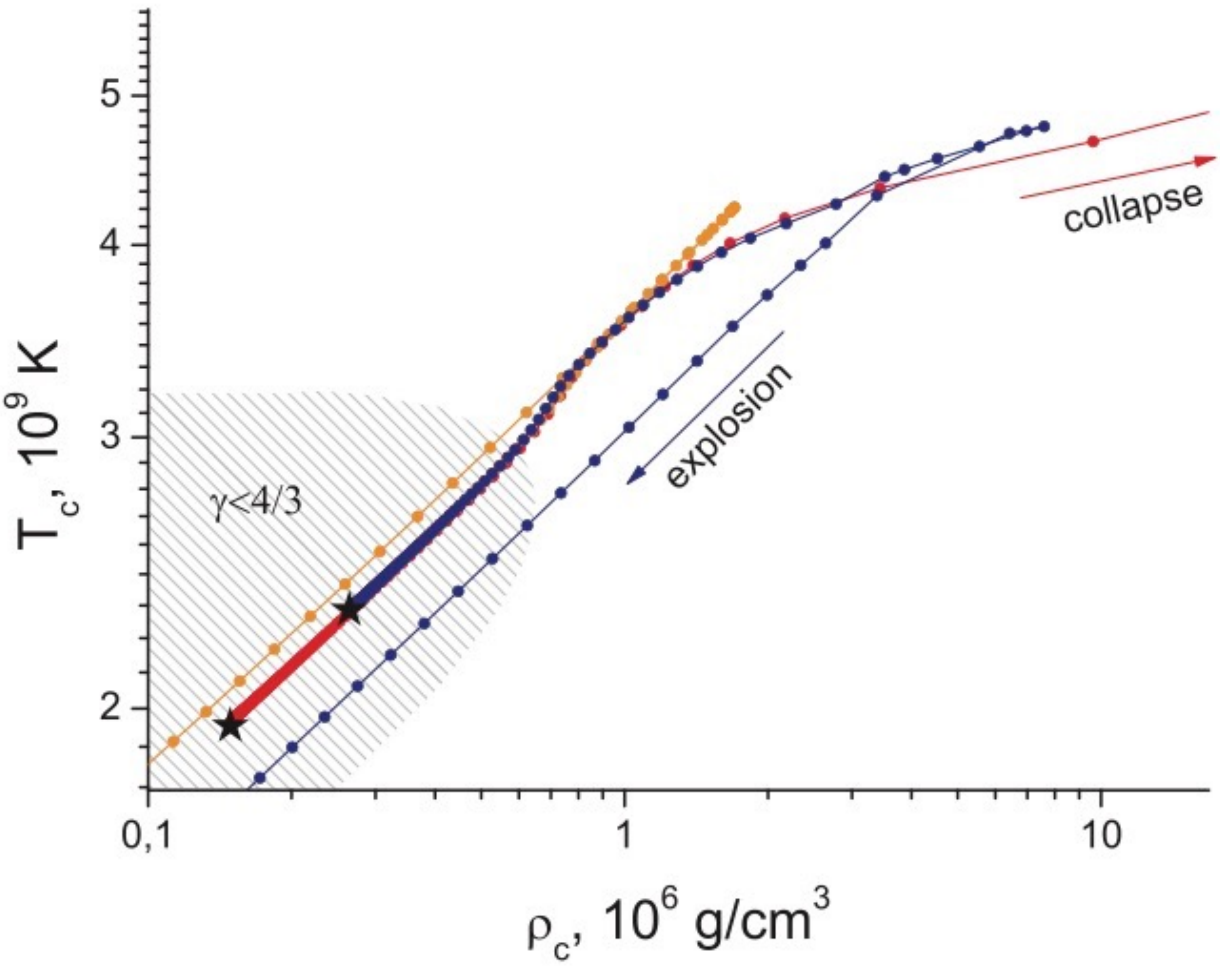
$$L \sim E_{Nucl} \sim M \cdot q, \quad [q] = \frac{ergs}{g \cdot s}$$

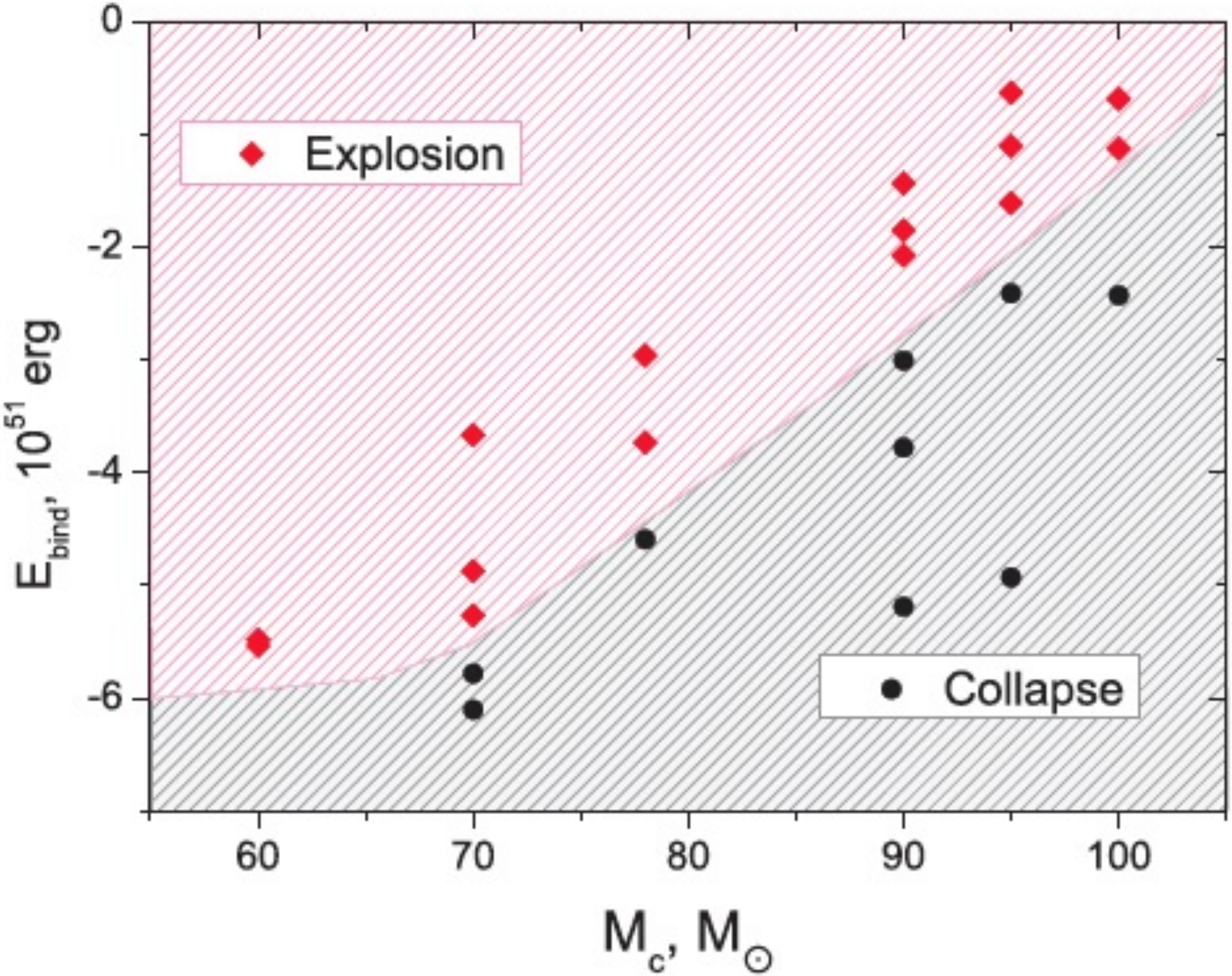
$$\frac{dT}{dR} = \frac{3\kappa\rho L}{16\pi a c T^3 R^2}$$

$$\frac{dT}{dR} \rightarrow \frac{T}{R}, \quad \rho \rightarrow \frac{M}{R^3}$$

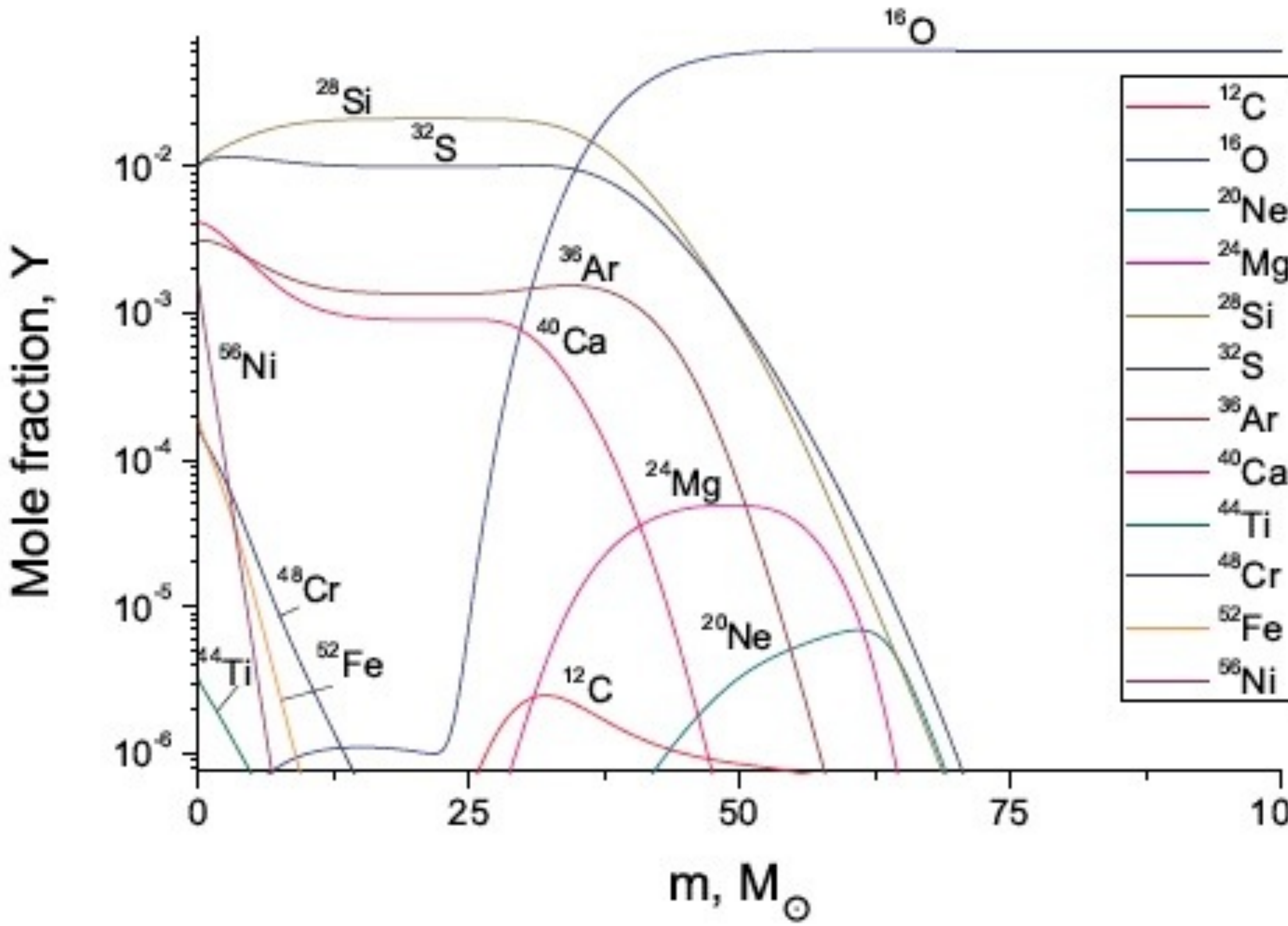
$$T^4 \sim \frac{ML}{R^4} \sim E_{Nucl}^2$$

$$\boxed{T^2 \sim E_{Nucl}}$$

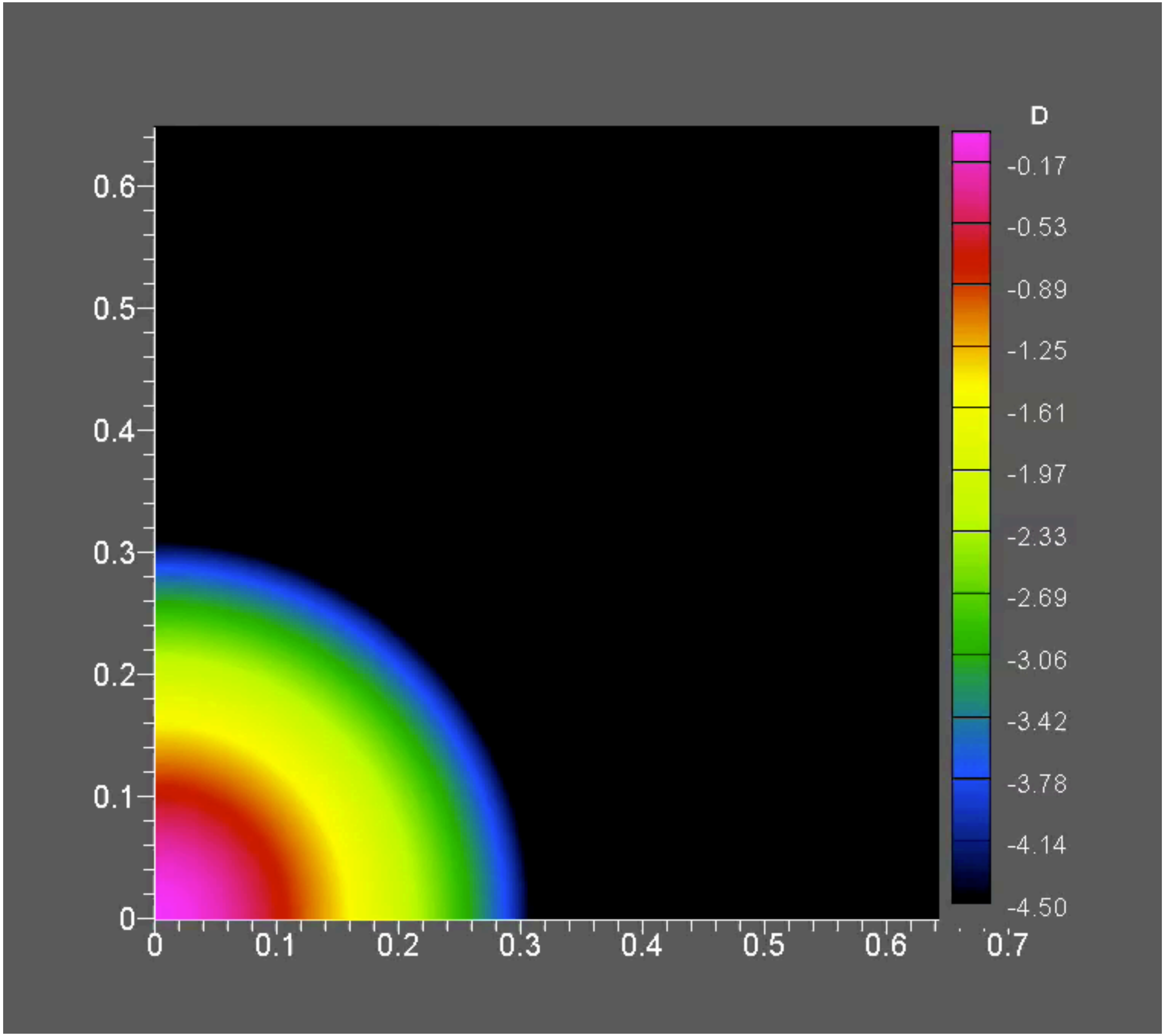

5
4
3
2
T_c, 10^9 K
γ<4/3
explosion
collapse
0,1
1
10
ρ_c, 10^6 g/cm^3



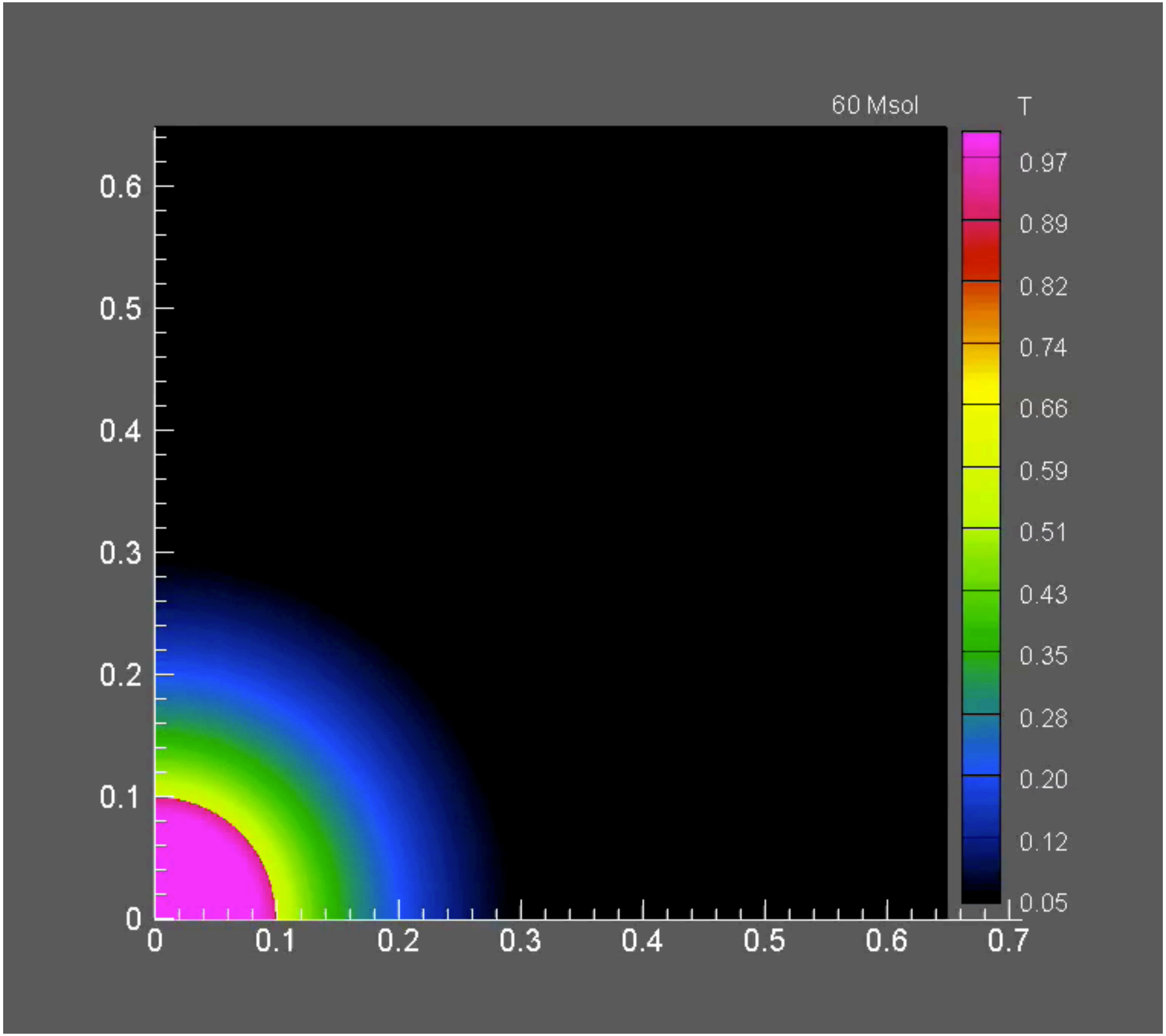
0
-2
-4
-6
60
70
80
90
100
E_{bind}, 10^{51} erg
M_c, $M_\odot$
Explosion
Collapse



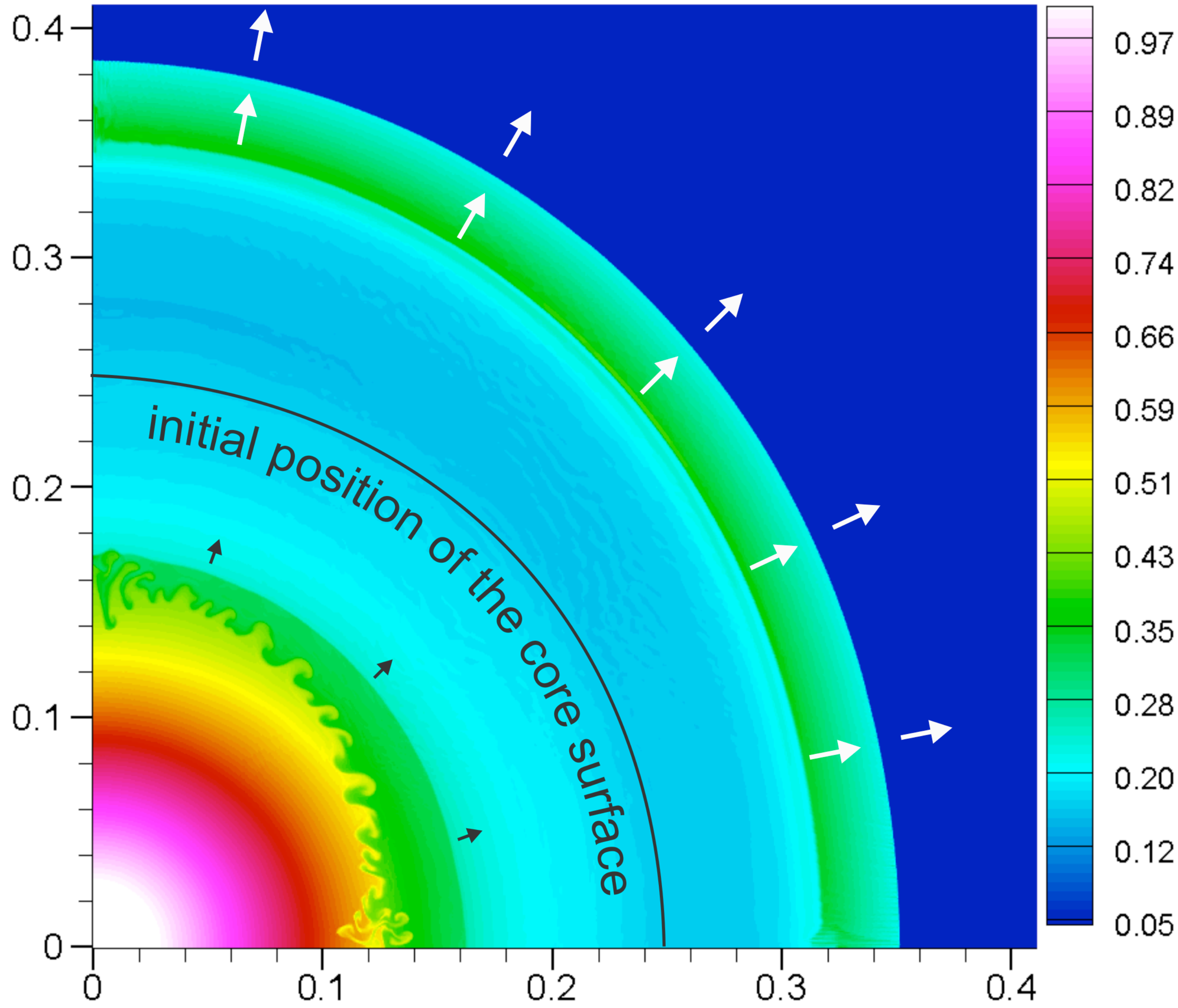
In the central region where the temperature is higher the elements are transformed by further reactions of capturing alpha-particles to the elements of the iron group up to Ni56 (example with 90 solar mass).



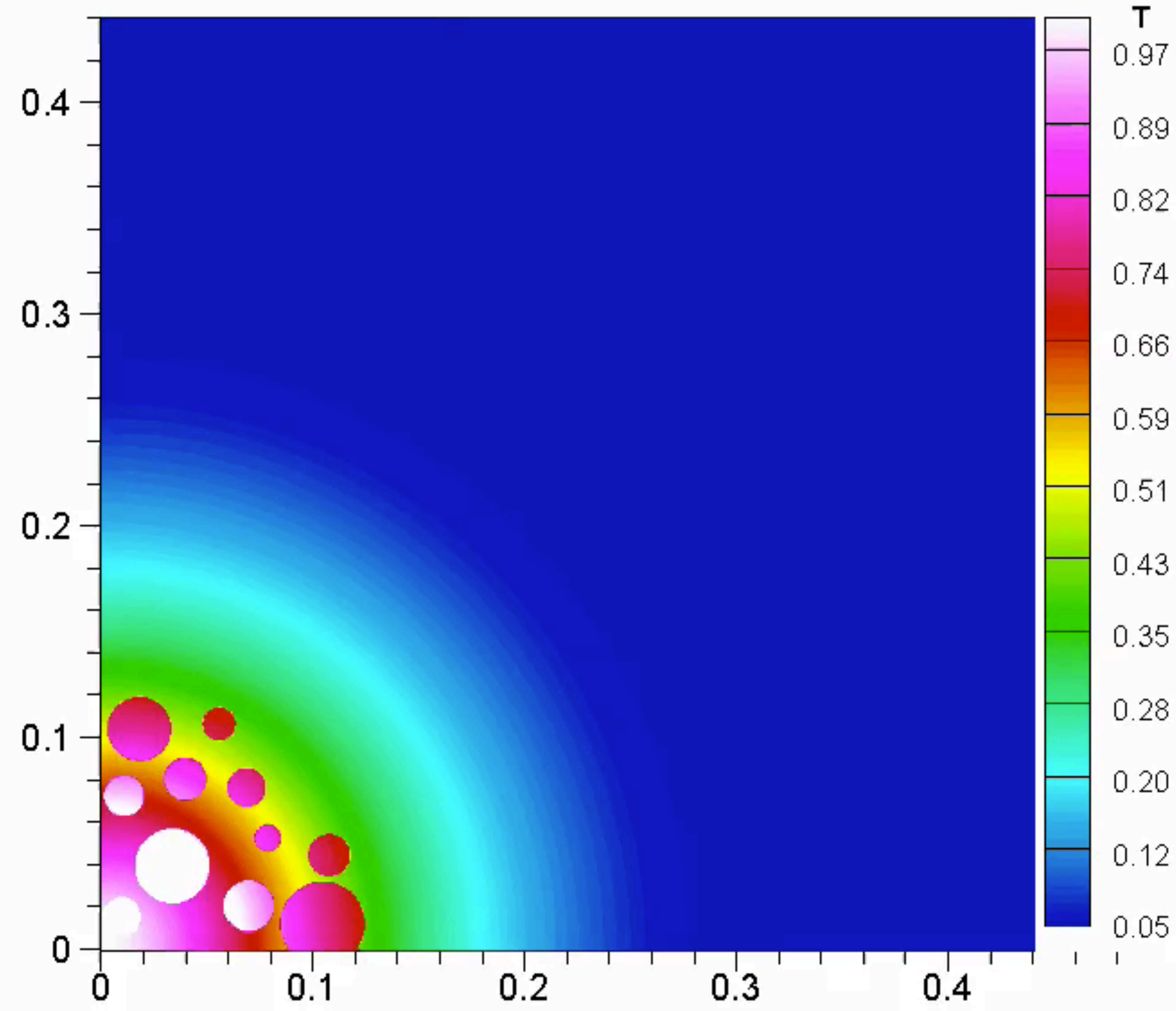
D
-0.17
-0.53
-0.89
-1.25
-1.61
-1.97
-2.33
-2.69
-3.06
-3.42
-3.78
-4.14
-4.50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

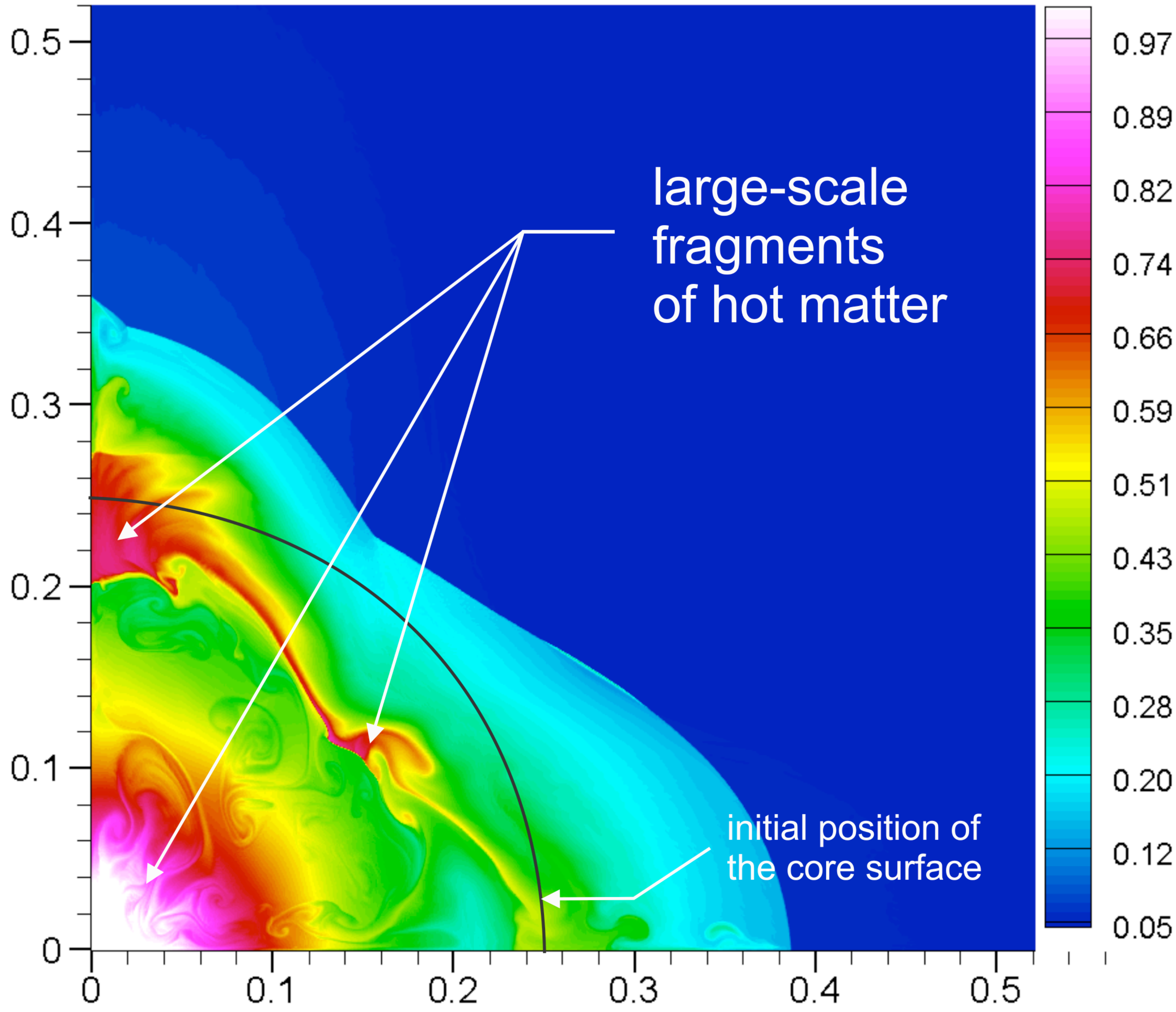


60 Msol
T
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7



at t=25 s, in the central part of the core there is a region where a Rayleigh Taylor instability occurs. The radius we found is very similar to the one obtained by Chen with Castro Code

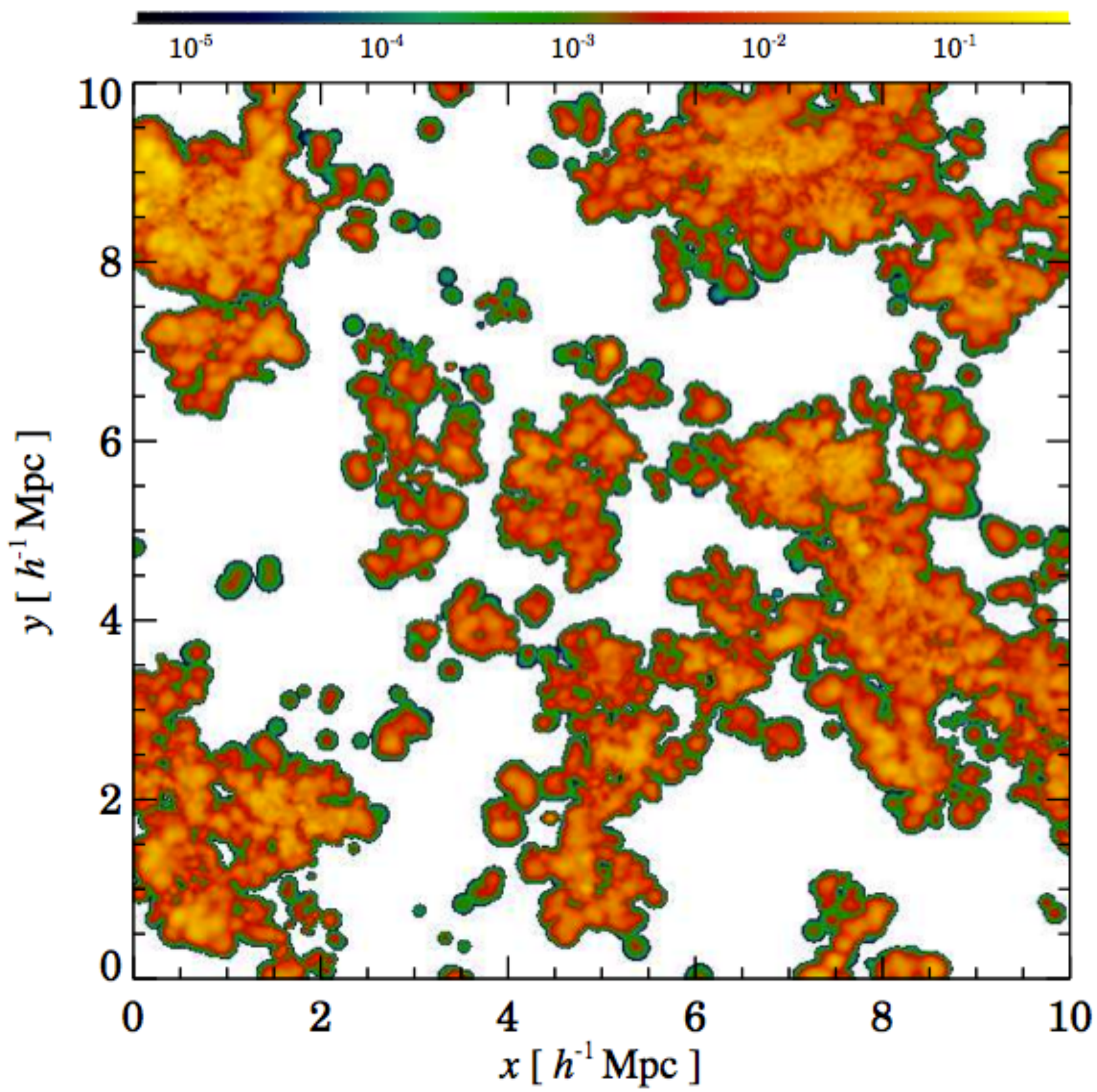

T
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4


large-scale
fragments
of hot matter
initial position of
the core surface
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0
0.1
0.2
0.3
0.4
0.5

Are PISNe too massive to be observed in our local Universe ?

From L.Tornatore et al. 2007
Mont. Not. R. Astron. Soc 382, 945

Population III stars: hidden or disappeared



Pockets of almost pristine gas (Z<Zcr) continue to exist

" At the metallicity of the LMC, only stars more massive than 300 M are expected to explode as PCSNe.At the SMC metallicity, the mass range for the PCSN progenitors is much larger and comprises stars with initial masses between about 100 and 290 M …
All VMS stars in the metallicity range studied here produce either a type Ib or a type Ic SN but not a type II SN. We estimate that the progenitor of SN2007bi, assuming a SMC metallicity, had an initial mass between 160 and 175 M . None of models presented in this grid (the initial mass range from 120 to 500 M) produce GRBs or magnetars. They lose too much angular momentum by mass loss or avoid the formation of a BH by producing a completely disruptive PCSN."

Yusof et al. 2013 Monthly Notices of the Royal Astronomical Society, Volume 433, Issue 2, p.1114-1132

Conclusions

- Interesting results in 1D and 2D
- We are working to improve: 3D
- Ongoing work to compute nuclear abundances
- Ongoing work to compute N(z) for cosmological purpose.
- Collaboration: EJD + Ferrara/Bologna

Thank you for your attention

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A&A (2013) 558, 10

Aspherical Nucleosynthesis in core-collapse supernovae
M. V. Popov, A. A. Filina, A.A. Baranov, P. Chardonnet, V. M. Chechetkin
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