NEW INTERPRETATION OF THE AMATI RELATION

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Abstract

We present an analysis of pair-instability supernovae explosions as possible candidates for Gamma-Ray Bursts. Results of our analysis show that pair-instability supernovae provide necessary energy budget, timescale and peak energy of emission. Moreover a correlation between total nuclear energy release and maximum temperature was found. Basing on this correlation we propose a new physical interpretation of the Amati relation and conclude that the key parameter of Gamma-Ray burst phenomenon is the mass of the progenitor.

Gamma-Ray Bursts and Pair-Instability Supernovae

GRBs

Timescale	1–100 seconds
Origin	Extragalactic (cosmological) phenomenon
Energy budget	10^{51}–10^{54} ergs
Environment	Host galaxies of GRBs have been found to be faint irregular galaxies. GRBs are concentrated on bright regions of host galaxies with intense star formation and low metallicity.
Metallicity	GRB hosts are low in luminosity and low in metal abundances.

GRB-SN connection

Some GRBs were associated with supernovae Ibc.

Rate	The rate of GRBs is 1000–10000 times lower than the rate of core collapse supernovae.
Environment	Long GRB and core-collapse supernovae have different environments [1].
Metallicity	The environment of *every* broad-lined SN Ic that had no GRB is more metal rich than the site of any broad-lined SN Ic where a GRB was detected [2]

Original model of GRBs

All these observational facts indicate that GRBs are related to explosive processes in massive stars in specific environment with limited chemical evolution. Such event already exists in theory of stellar evolution: it is explosion of very massive star on-going pair-instability. Recently the original model of **GRBs as pair-instability supernovae explosions** was proposed [3]. It is well-known that stars with masses between 100 $M_\odot$ and 260 $M_\odot$ explode without leaving a remnant. High mass of these stars provides necessary energy budget. Although the detailed theory of evolution of very massive is still an open issue, it is believed that they form in low metallicity environment.

Main equations

Hydrodynamical equations in the Lagrangian variables in spherical symmetry:

$$dr/dt = v,$$

$$dv/dt = -Gm/r^2 - 4\pi r^2(\partial P/\partial m),$$

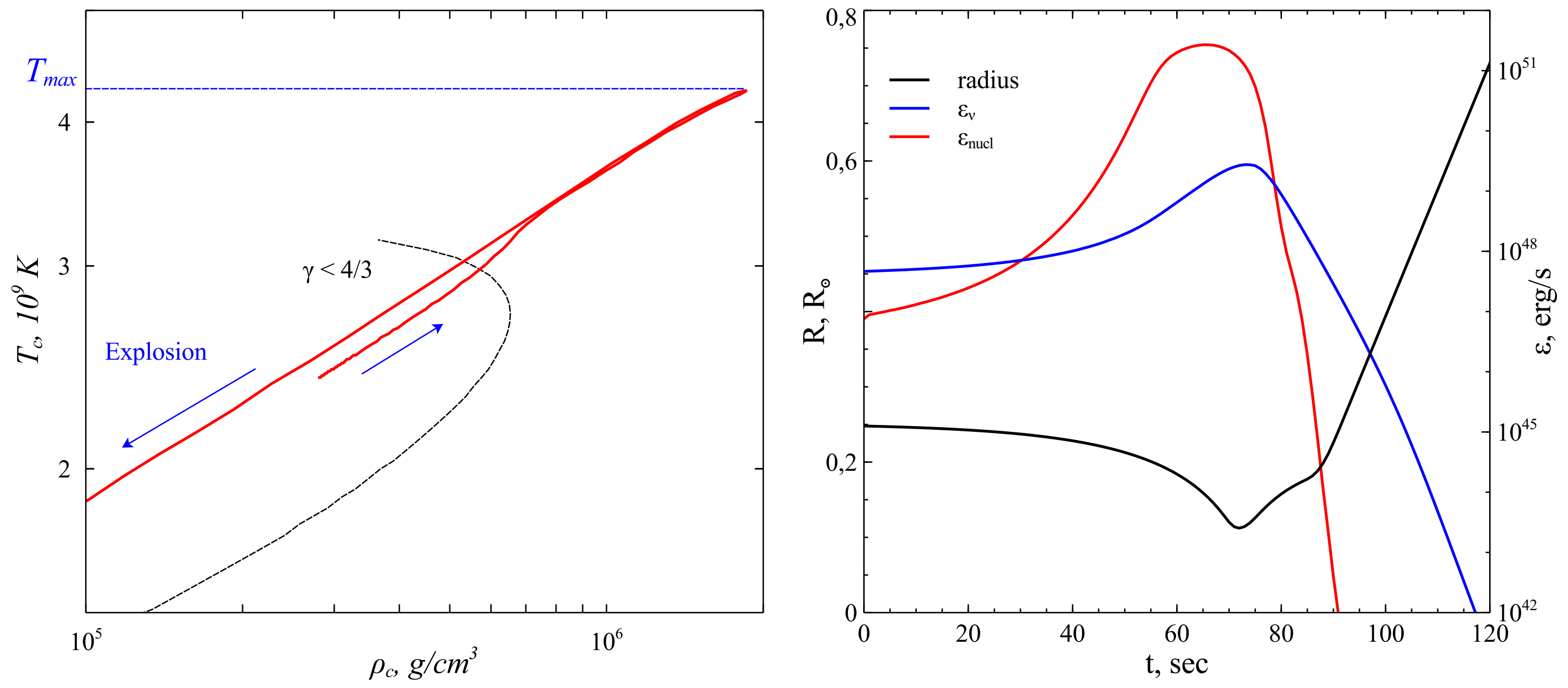
$$dT/dt = (-4\pi\frac{\partial(r^2 v)}{\partial m}T(\partial P/\partial T)_\rho + \varepsilon_{\rm nucl} - \varepsilon_\nu)/(\partial E/\partial T)_\rho,$$

$$dY_j/dt = \rho Y_k Y_l R_{kl,j} - \rho Y_j Y_l R_{jl,m} + Y_n\lambda_{n,j} - Y_j\lambda_{j,k}, \quad j = \overline{1,13}.$$

Here m is the mass Lagrangian coordinate, r is the radial distance, t is the time, v is the velocity of the element of fluid, P is the total pressure, T is the temperature and E is the specific internal energy. Terms ε_ν and $\varepsilon_{\rm nucl}$ correspond to the rates of neutrino losses and nuclear energy production. Y_j are the abundances of chemical elements, nuclear burning has been computed according to the simplified network of reactions, consisting of the 13 isotopes from ^{4}He to ^{56}Ni.

Results

Explosion of 100 $M_\odot$ star

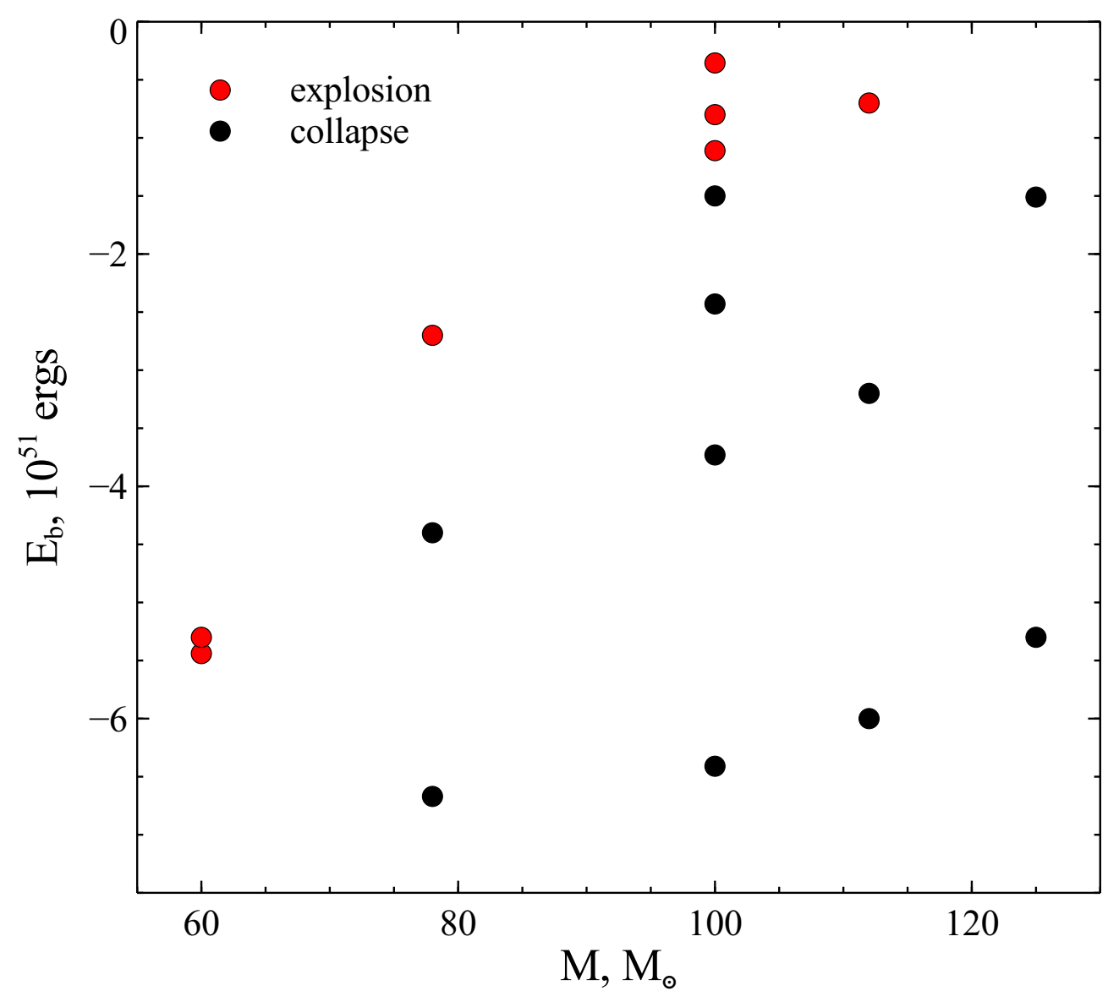


Dynamics of explosion of 100 $M_\odot$ oxygen core. Trajectory in ρ_c–T_c plane is shown on the left. Rates of nuclear energy production and neutrino losses and radius of the core are shown on the right.

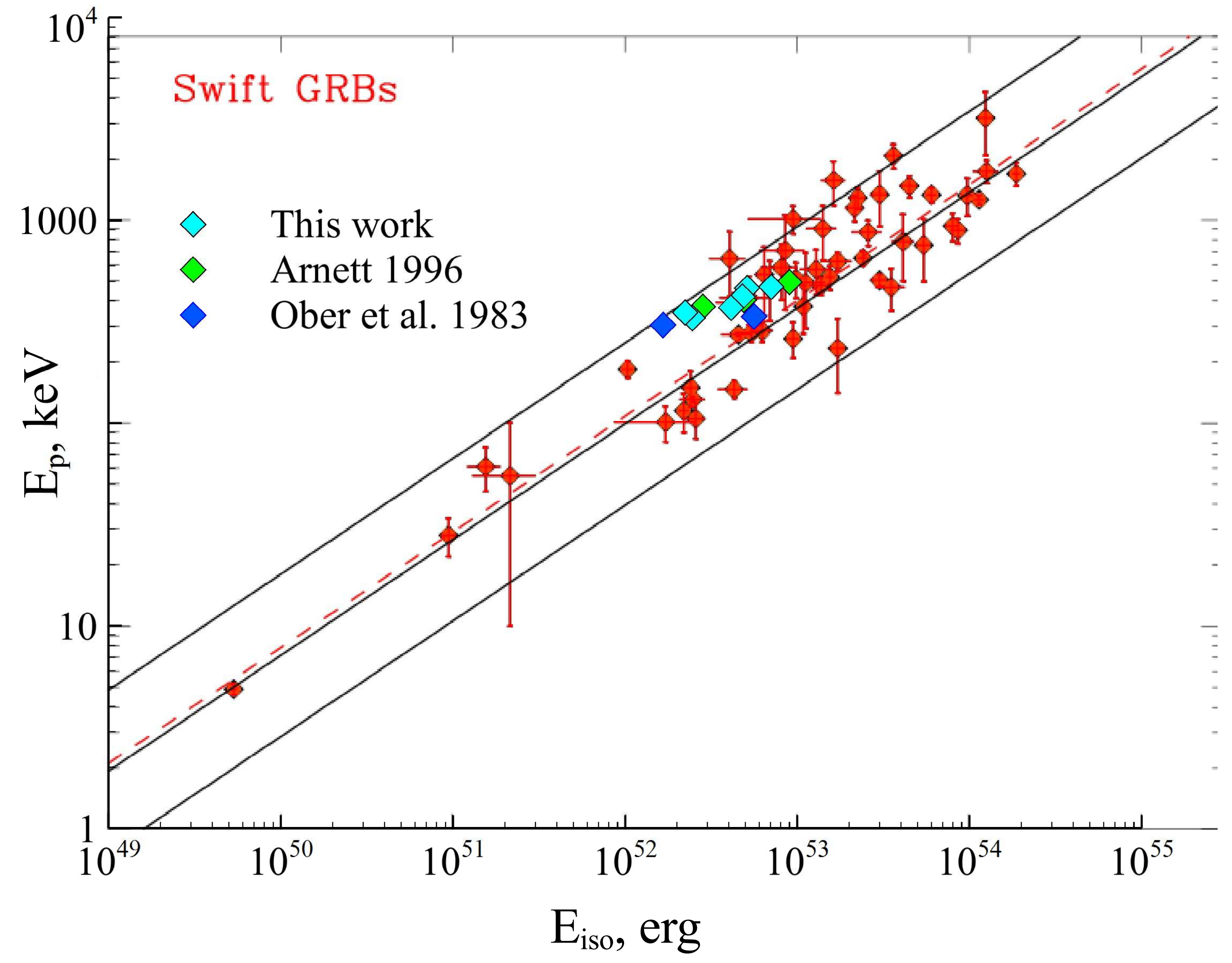
Explosion vs collapse

It was found that for the cores with the same mass final stage of evolution could be either collapse or explosion depending on initial central density and temperature, which define the whole initial configuration. We have investigated dependence of the fate of the cores on the initial binding energy:

$$E_b = \int_0^M (-Gm/r + E)dm.$$



We propose the mass limit for the explosion of non-rotating oxygen core at $\sim$ 120–130 $M_\odot$.



Summarized results of computations. M is the mass of the core, T_{max} is the maximum temperature reached in the center at the moment of reversal of collapse, E_{nucl} is the total nuclear energy release. In the case of total disruption of the star hot matter of the core could be ejected outside. And energy gathered from nuclear burning will be emitted by electromagnetic radiation with the same characteristic energies. The efficiency of transformation of the nuclear energy into emission should be high, since there are no intermediate processes of transformation and redistribution of energy.

Assuming that the progenitor of GRB is pair-instability explosion of a very massive star, it is natural to associate the peak energy E_p with the T_{max}, and the total isotropic energy E_{iso} with the nuclear energy reservoir E_{nucl}.

$M/M_\odot$	T_{max}, keV	$E_{nucl}, 10^{52}$ ergs	fate
60	352	2.23	explosion
60	351	2.25	explosion
78	—	—	collapse
78	—	—	collapse
78	330	2.46	explosion
100	—	—	collapse
100	—	—	collapse
100	—	—	collapse
100	—	—	collapse
100	463	5.11	explosion
100	421	4.80	explosion
100	371	4.12	explosion
112	—	—	collapse
112	—	—	collapse
112	470	5.46	explosion
125	—	—	collapse
125	—	—	collapse

In our interpretation the distribution of the points on E_p–E_{iso} diagram corresponds to window of physical parameters of a massive star required for pair-instability explosion.

References

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