# On Pair Instability Supernovae and Gamma-ray Bursts

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# Overview

- Introduction: some facts on GRBs
- PISNe
- Results
- conclusions and outlook

# Facts on GRBs

- Extremely high energy budget: $10^{51}$-$10^{54}$ ergs
- Timescale of the prompt emission:1-100 seconds
- Most of energy is emitted in X-rays or gamma-rays within interval of few 10-100 keV
- **Death of massive stars**

# Facts on GRBs

- cosmological phenomenon: **unique picture** (from low to high z)
- order of 1 event every 3 days: **rare event**
- Relative number of GRBs to SN Ibc is about 0.4%-3% (Guetta and Della Valle, 2007)
- Importance for cosmology

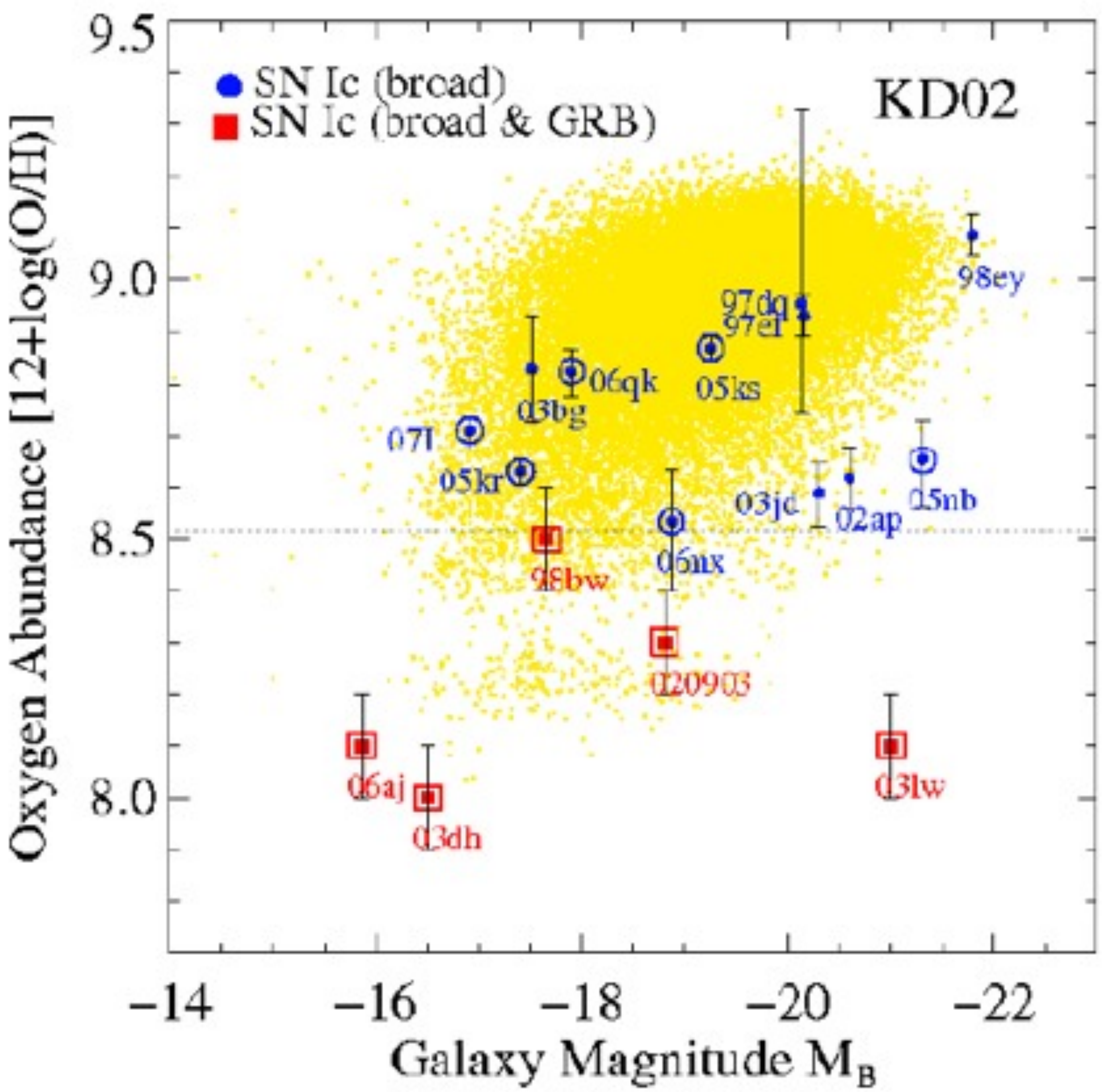
# Environment

- Some GRBs are associated with SN Ibc
- Host environments of GRBs are less metal-rich than host environments of broad-lined SN Ic where no GRB was observed
- Long GRB and core-collapse supernovae have different environments (Fruchter et al. 2006)
- highly ionized gas no explained

**Any study of Gamma-Ray Bursts invites consideration of the factors that produce such exceptional events**

# Metallicity

- GRB hosts are low in luminosity and low in metal abundances (Starling et al. 2005)
- 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 (Modjaz et al. 2008)



# Intermezzo

- Dirac: «I understand what an equation means if I have a way of figuring out the character of its solution without actually solving it»
- In stellar evolution one of the key parameter is the mass of the stars

GRBs are related to the dead of massive stars (true)

Q1: Is the mass of the progenitor a key parameter to understand GRBs ?

# PISNe as possible candidate

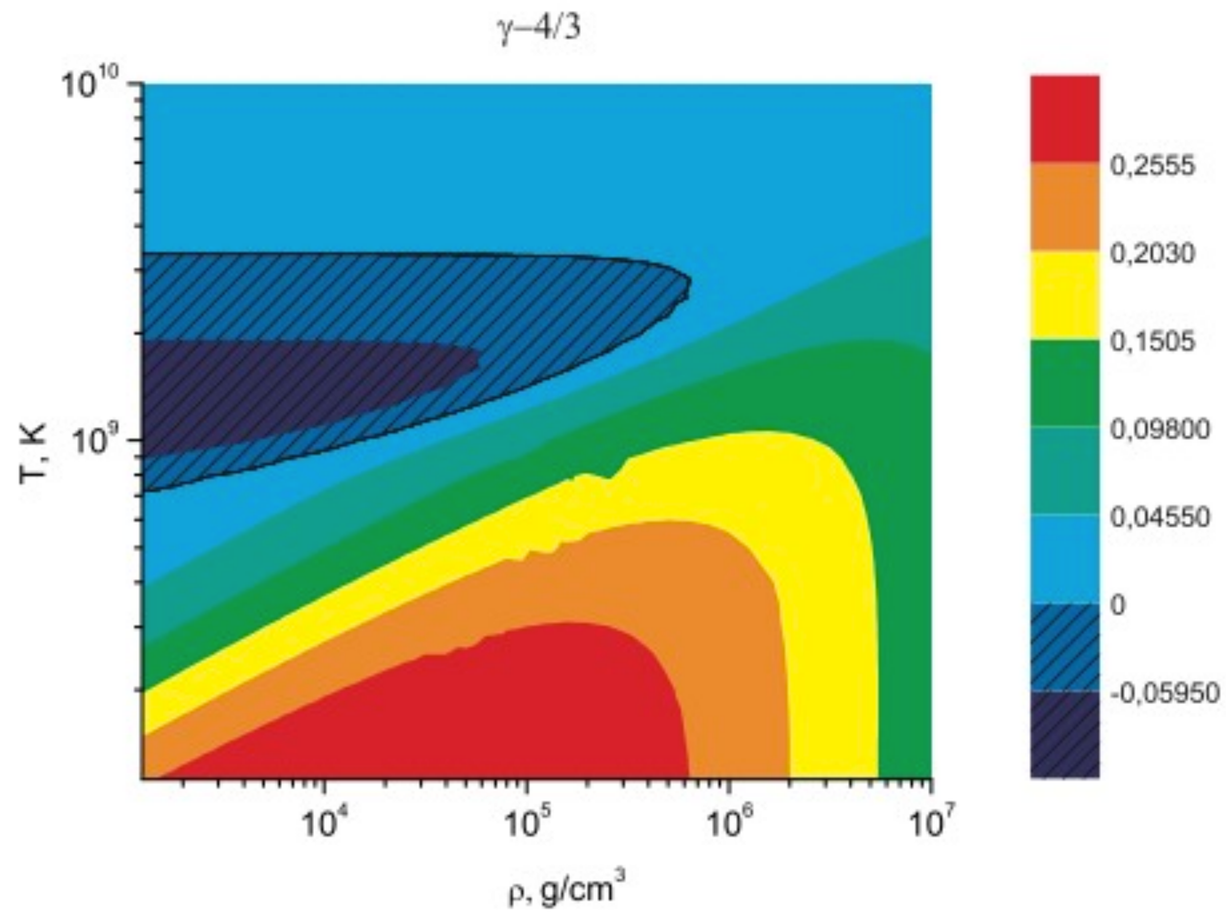
- Explosive process different form the CC SN
- Low metallicity
- High Energy budget

On the pair-instability supernovae and gamma-ray burst phenomenon.

P. Chardonnet, V. Chechetkin and L. Titarchuk

Astrophys.Space Sci.325:153-161,2010.

# Model of Pair-instability SN

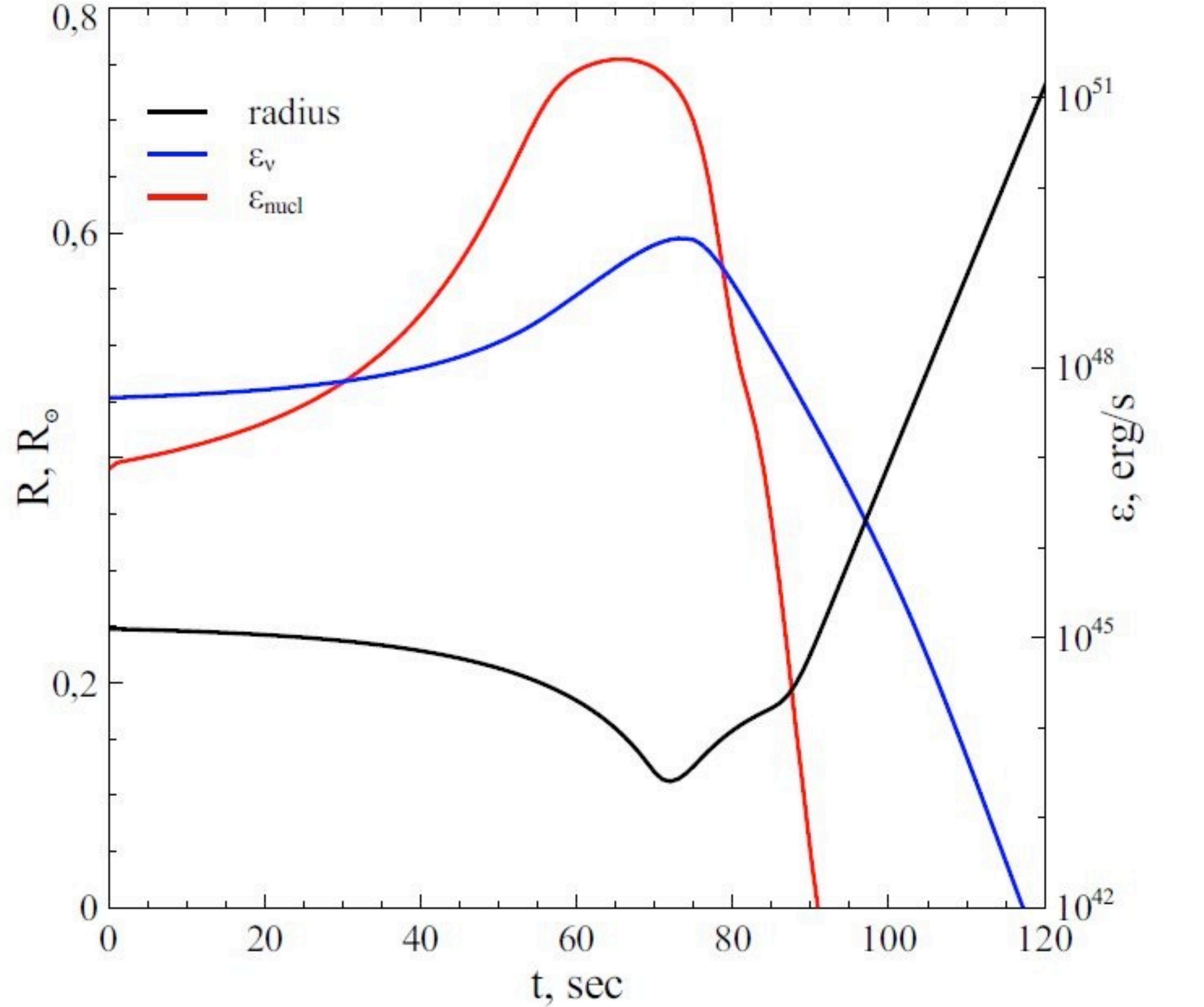

Absorption of energy to create rest mass of the pairs
When a sufficient amount of the star entered in this area it becomes dynamically unstable

# Numerical simulations

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

Nuclear burning — Neutrino losses

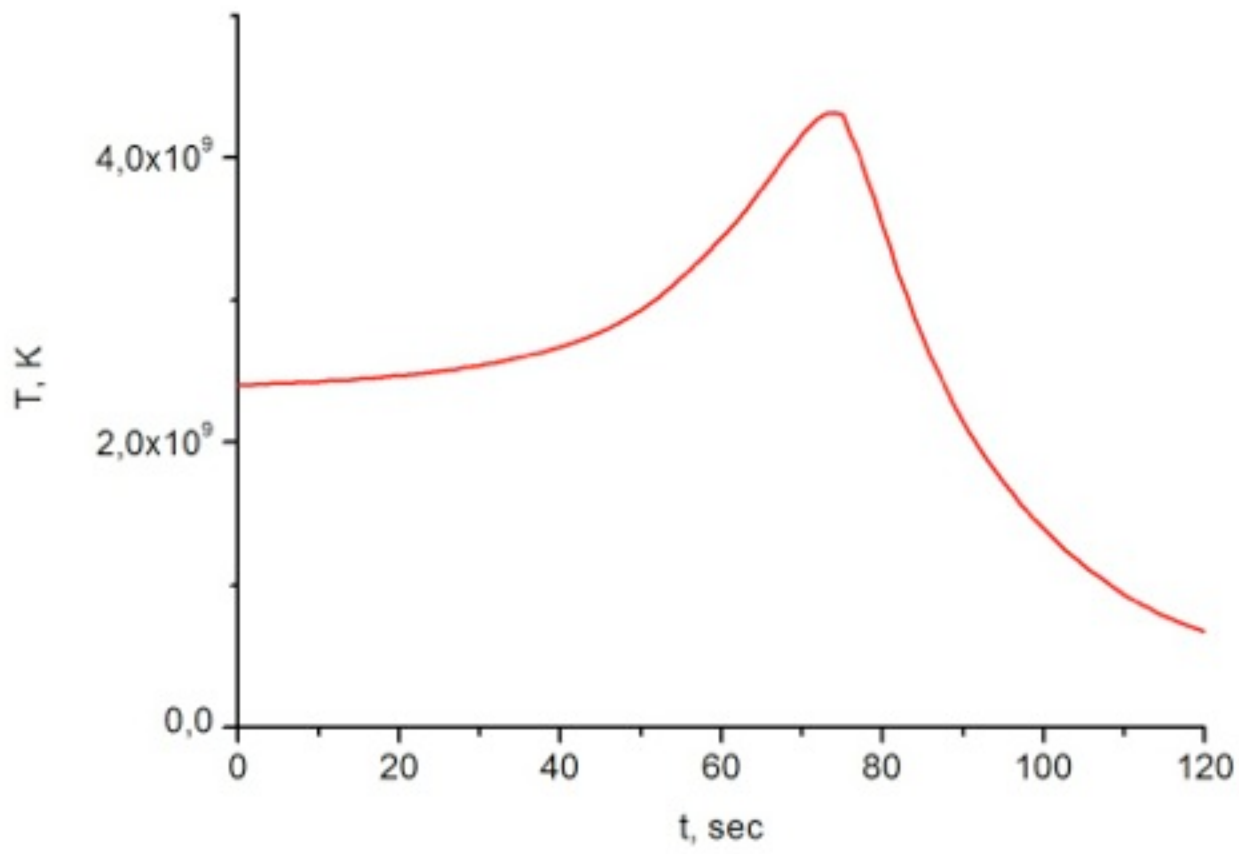
for details see Poster N°4, Baranov



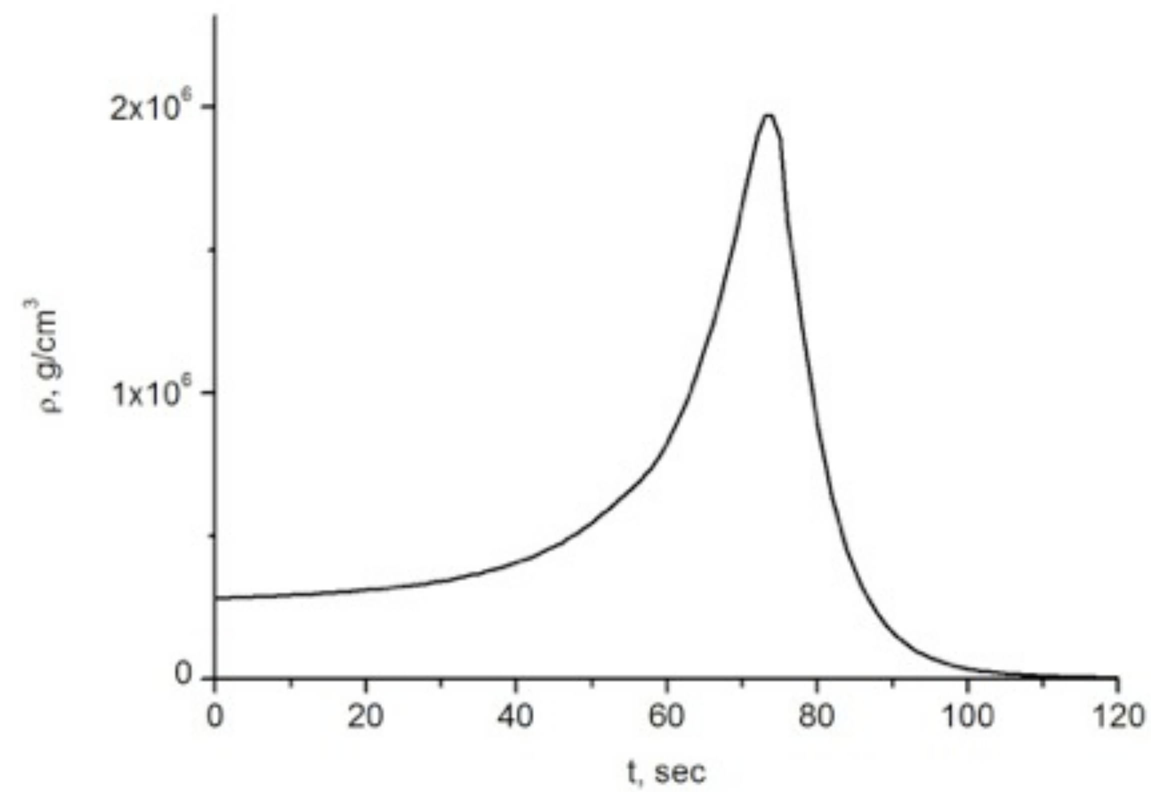
0,8
0,6
0,2
0
R, R⊙
0
20
40
60
80
100
120
t, sec
10^51
10^48
10^45
10^42
ε, erg/s
radius
εν
εnucl

# Results: density – temperature

Central temperature

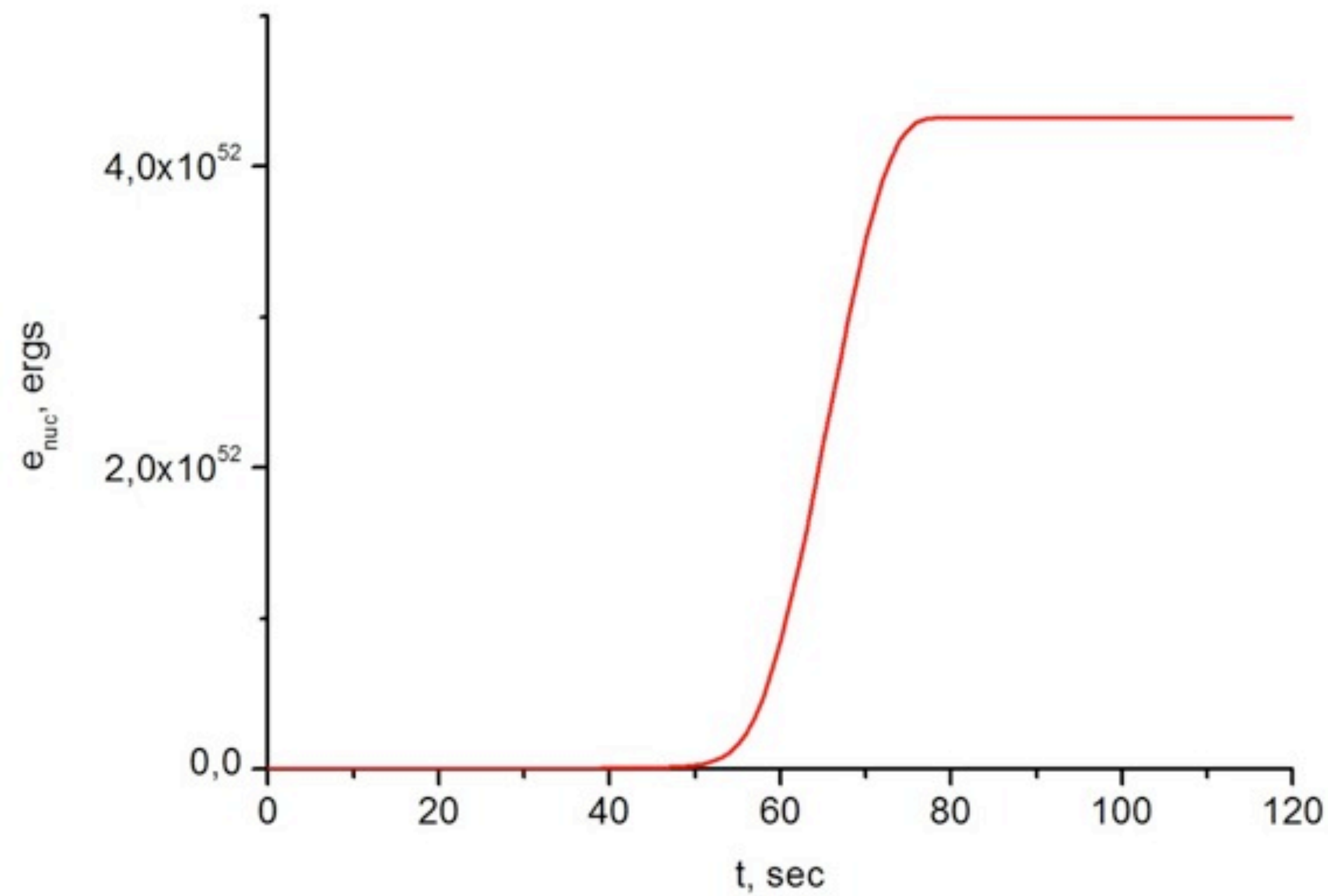



Central density

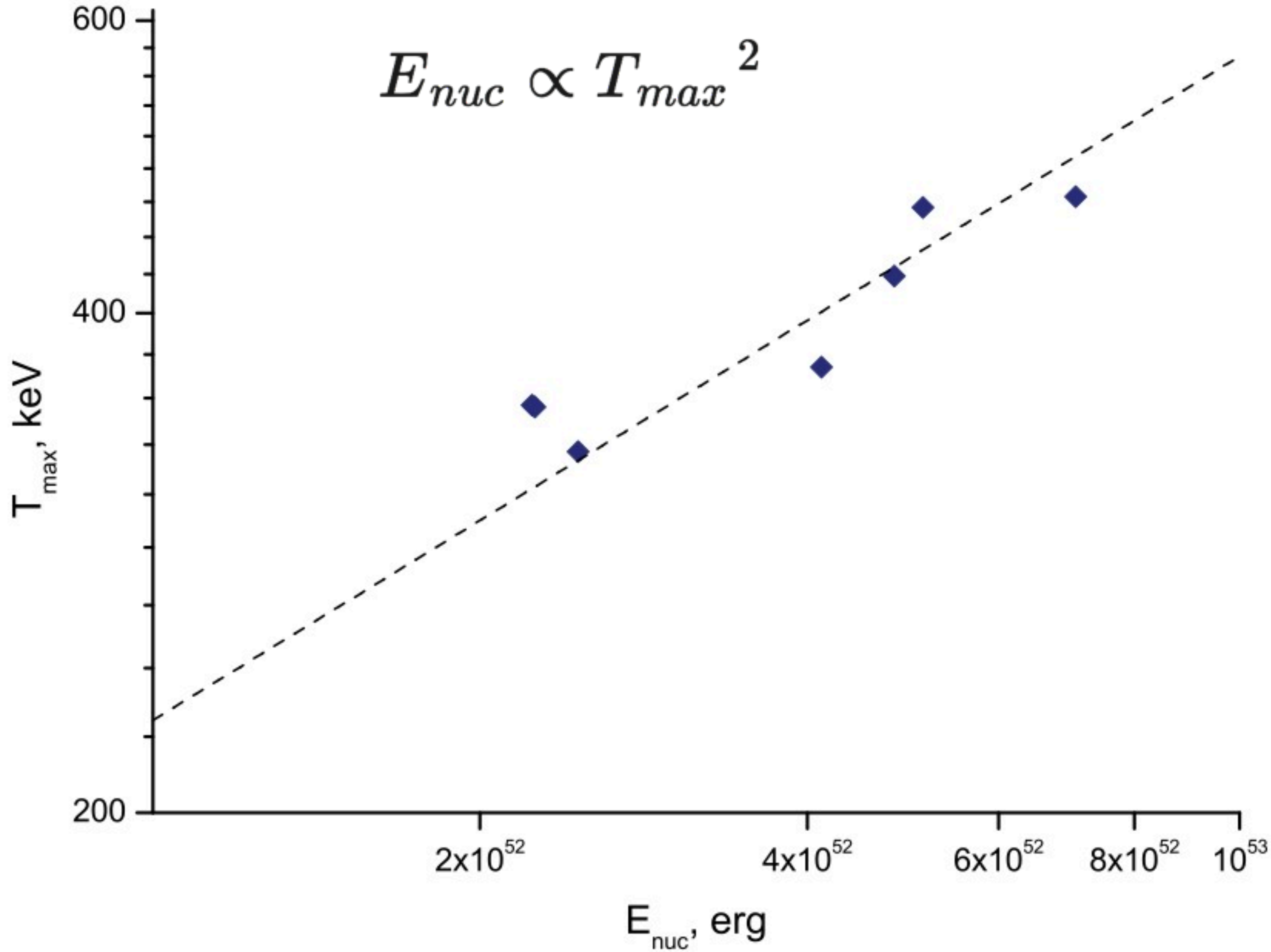


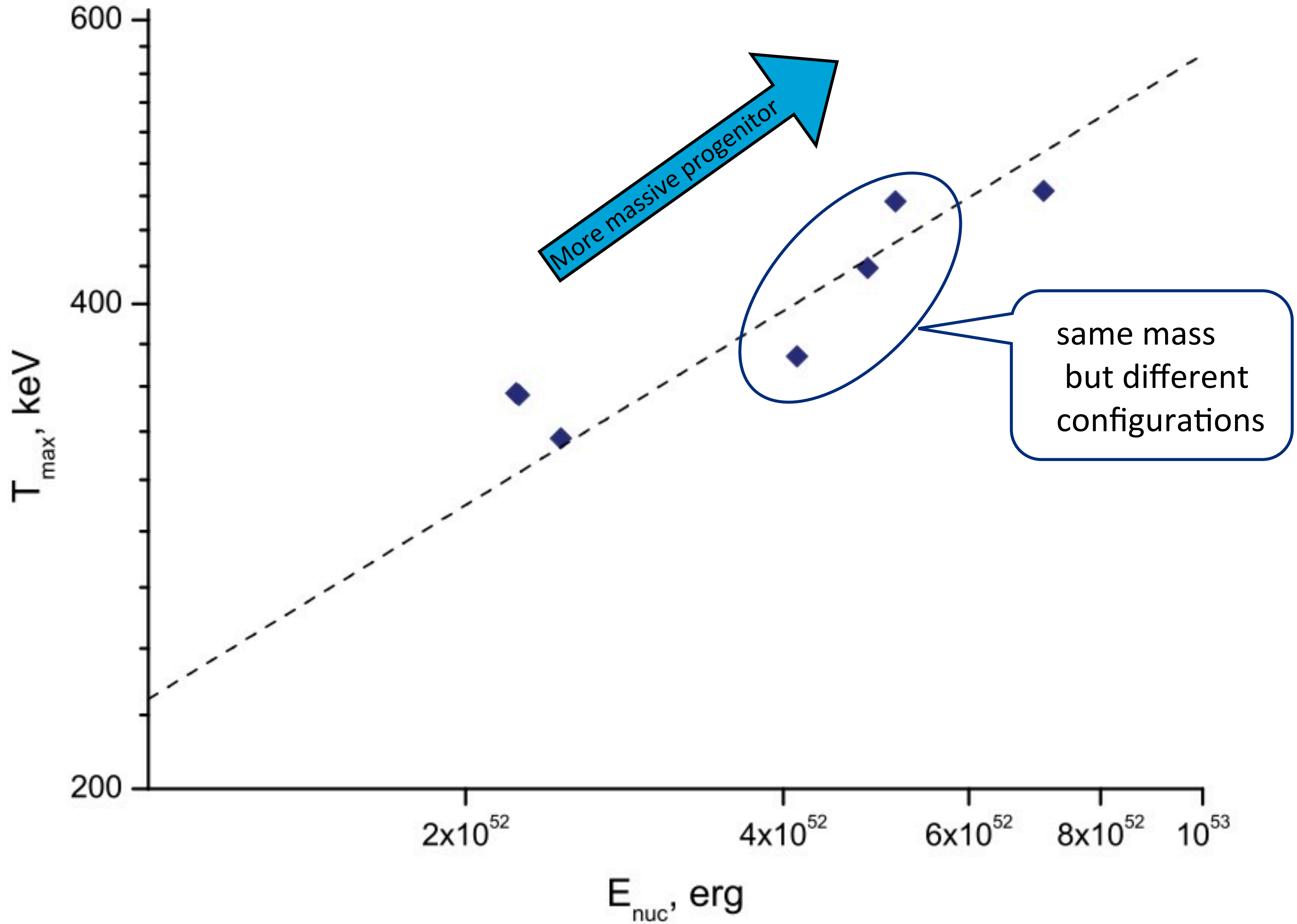
# Results: timescale

Nuclear burning energy

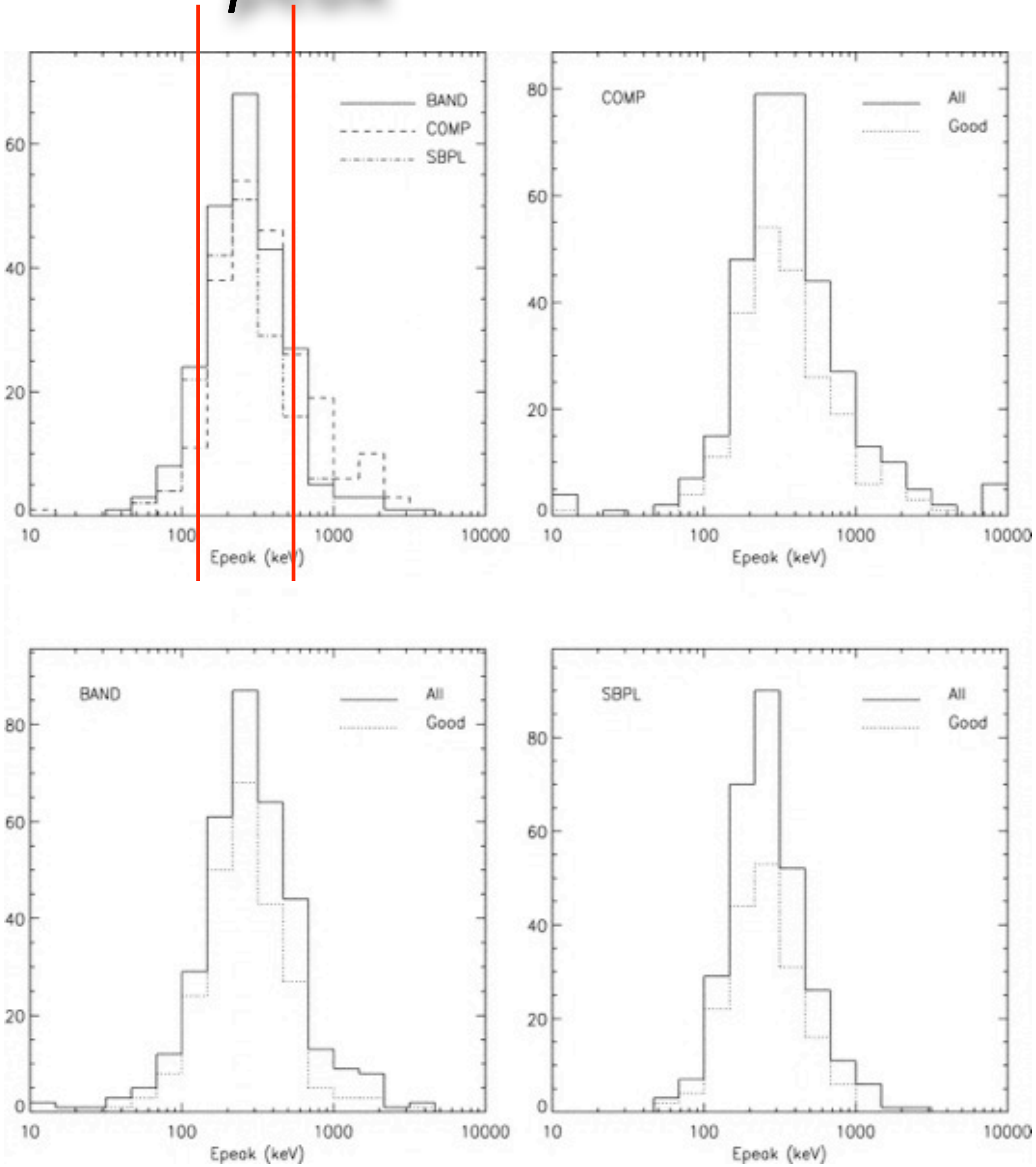


| $M/M_\odot$ | $\rho_c, 10^5 g/cc$ | $T_{max}, keV$ | $E_{nucl}, 10^{52}$ ergs | fate |
|---|---|---|---|---|
| **60** | 0.87 | 352 | 2.23 | explosion |
| **60** | 1.15 | 351 | 2.25 | explosion |
| **78** | 0.60 | — | — | collapse |
| **78** | 2.00 | — | — | collapse |
| **78** | 3.00 | 330 | 2.46 | 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 |


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


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

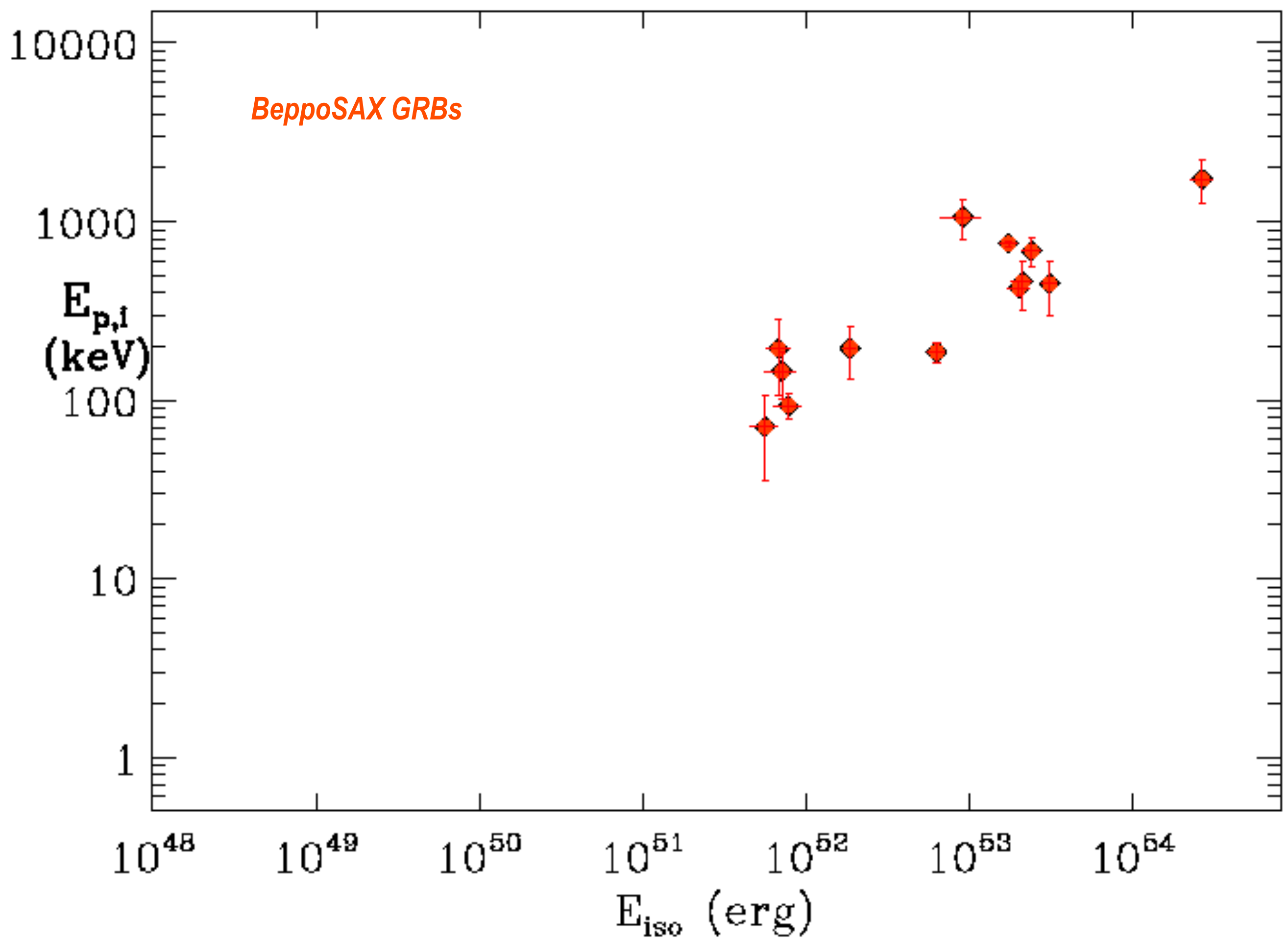
# $E_{peak}$ in GRBs




Kaneko et al., The Complete Spectral Catalog of Bright BATSE Gamma-Ray Bursts, 2006

Amati et al. (A&A 2002)

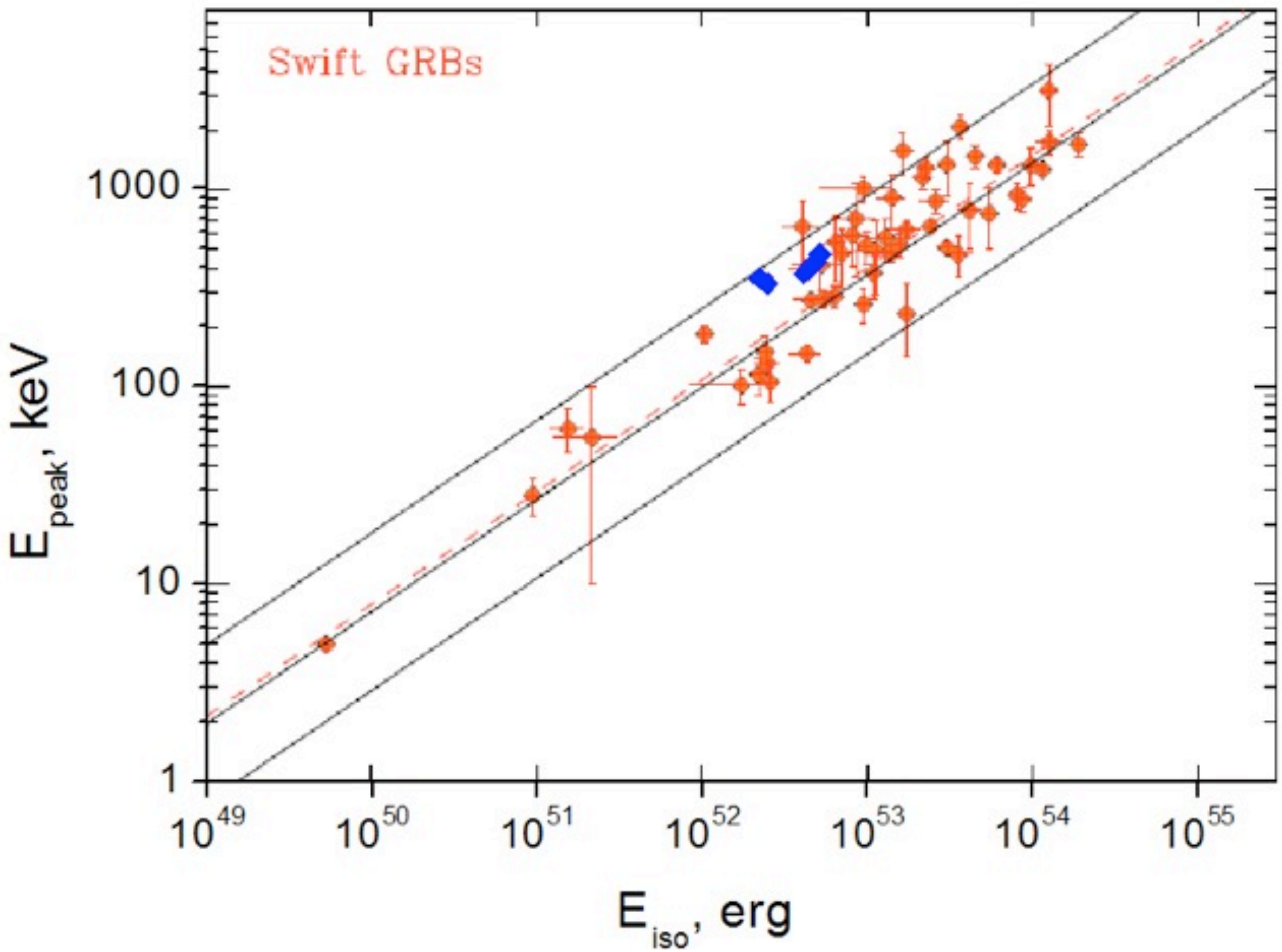
$T_{max}$ ⇒




⇑

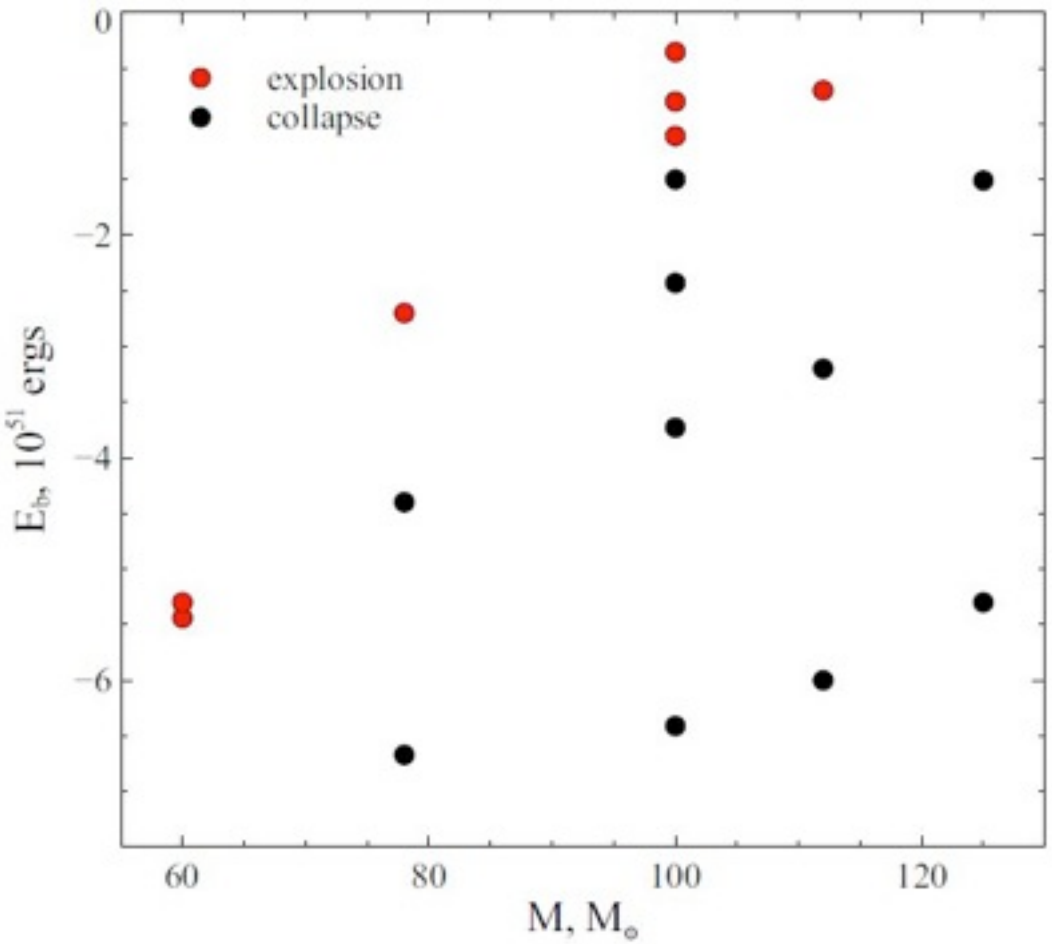
$E_{nuc}$

# Amati Relation: $E_{nucl} \propto T_c{}^2$



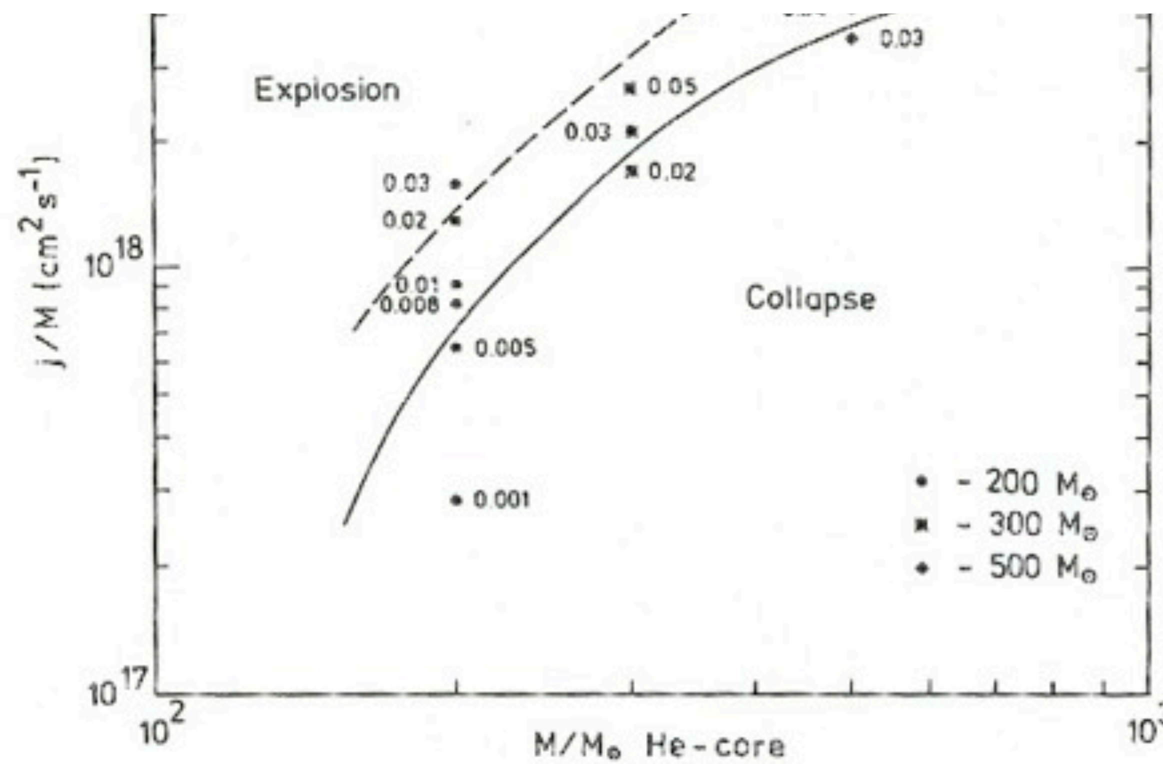

Amati relation from [L. Amati, F. Frontera and C. Guidorzi, 2009]

# Binding energy




$$E_b = \int_a^b \left(\frac{-Gm}{r} + E\right) dm$$

# Importance of rotation (Woosley/ Glatzel)




Higher values of mass and
also on Enuc or Eiso

## A1: In the framework of PISNe explosion, the mass of the progenitor is a key parameter to understand GRBs physics

Consequence : if GRBs are a subset of PISNe then we can compute the ratio of GRBs to SN type Ibc using Salpeter function

$$R_{GRB/SN} \propto \left(\frac{M_{GRB}}{M_{SN}}\right)^{-2.35} \sim 4.10^{-3}$$

But new questions...

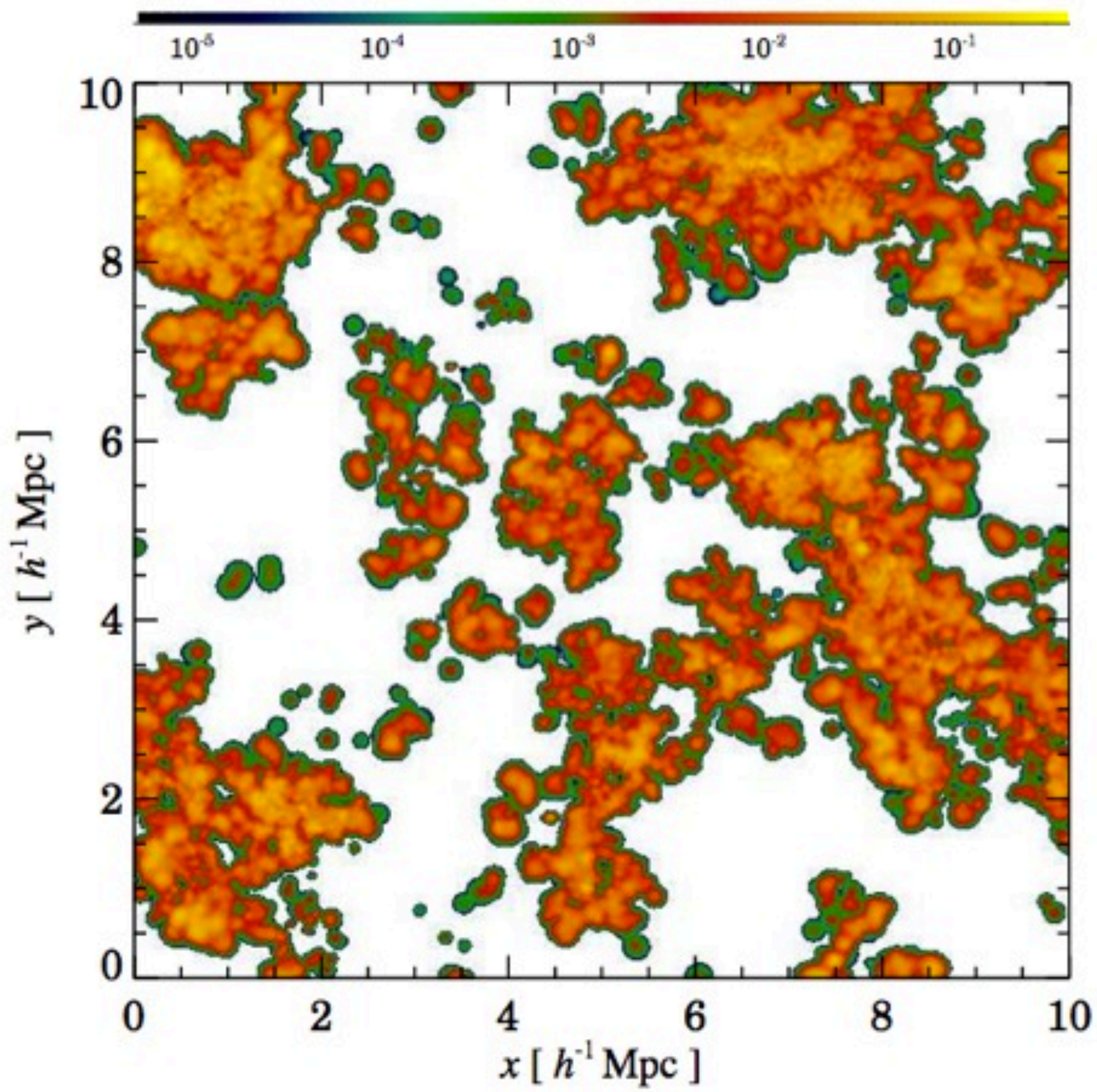
Q2: Are all PISNe doing GRBs explosion ?

A2 : Presumably not all - We need more investigation.
Certainly related to core-envelope understanding
How the star expel the envelope:
oscillations / violent eruptions

# Q3: Are PISNe too massive to be observed in our local Universe ?

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

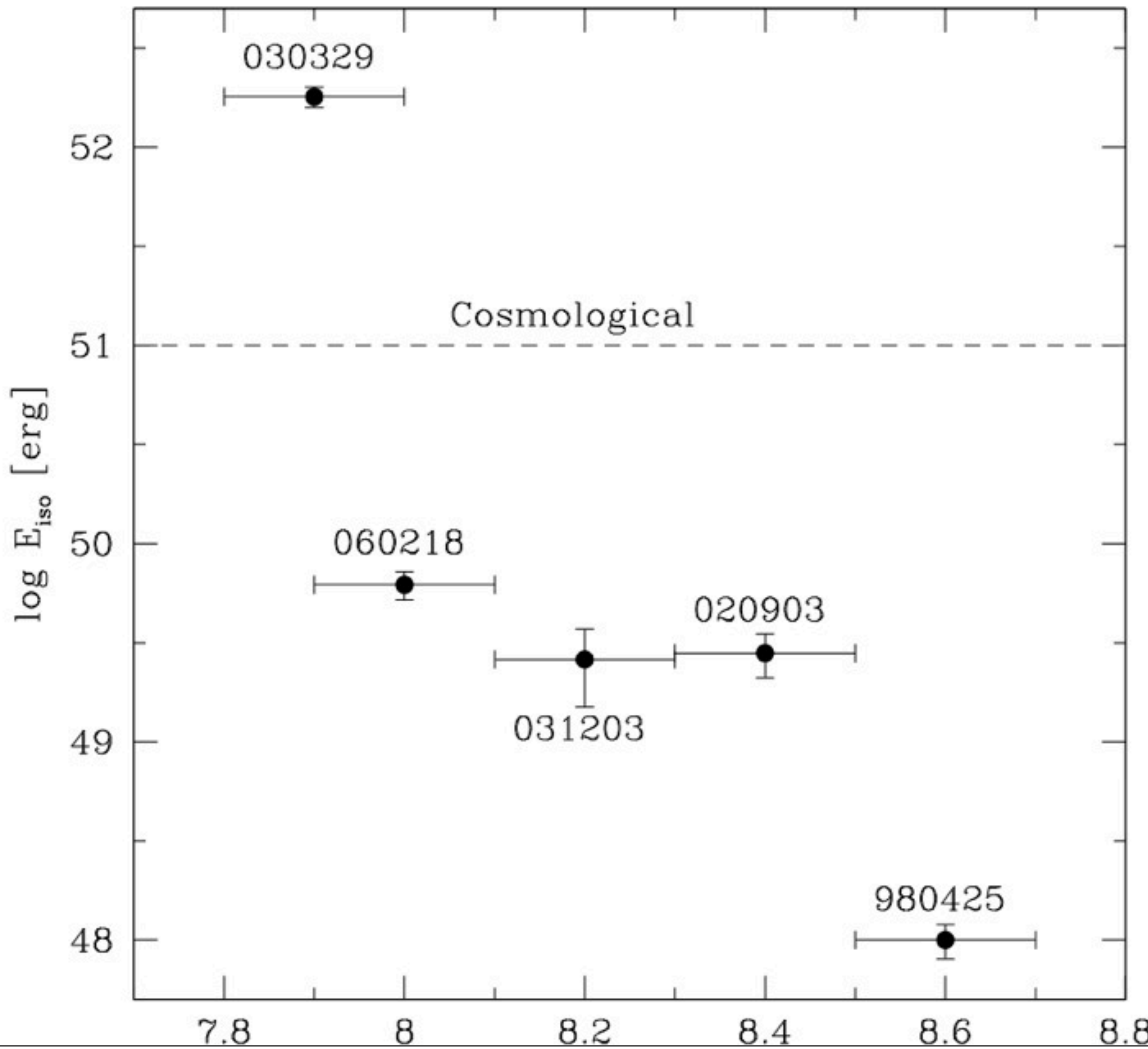
Population III stars: hidden or disappeared




A3: Pockets of almost pristine gas (Z<Zcr) continue to exist

**Protecting Life in the Milky Way: Metals Keep the GRBs Away**
**Stanek et al. 2006**

?



# Q4: How to explain the time variability of the prompt emission ?

This is fundamental question that could be solved only with more accurate computations

It is related to the fragmentation of the core during the explosion

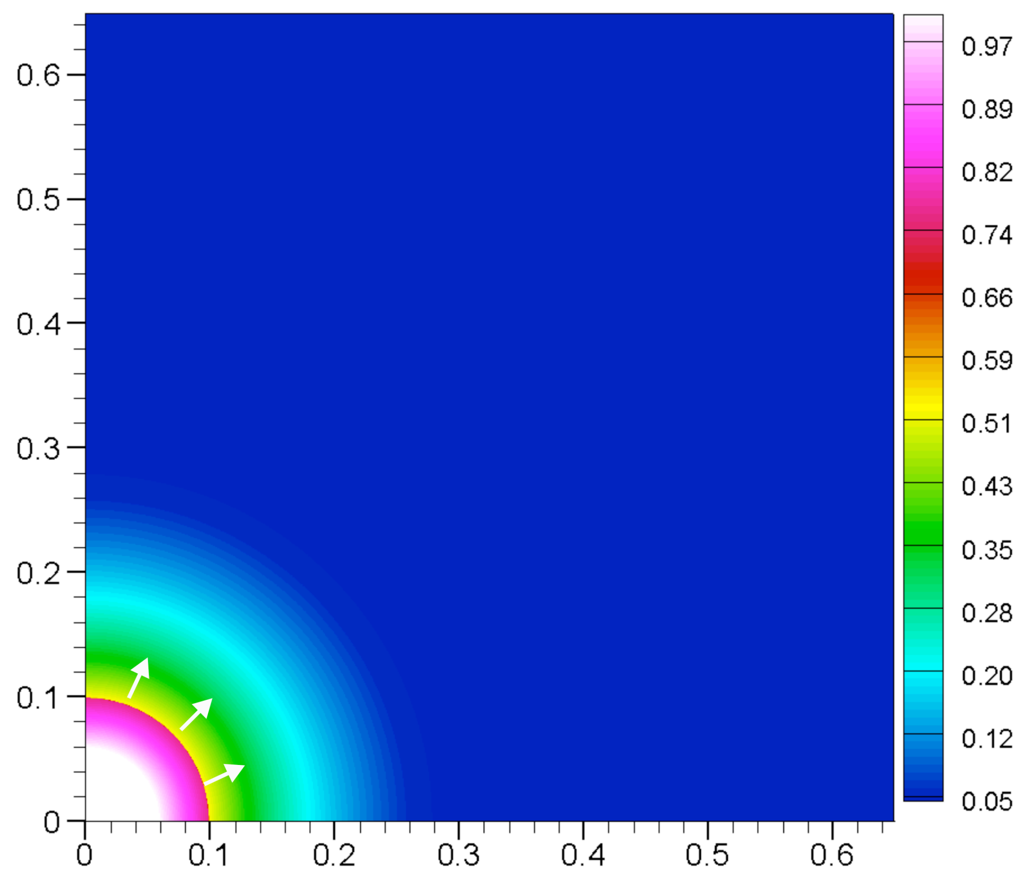
We have proposed a toy model in order to test this idea

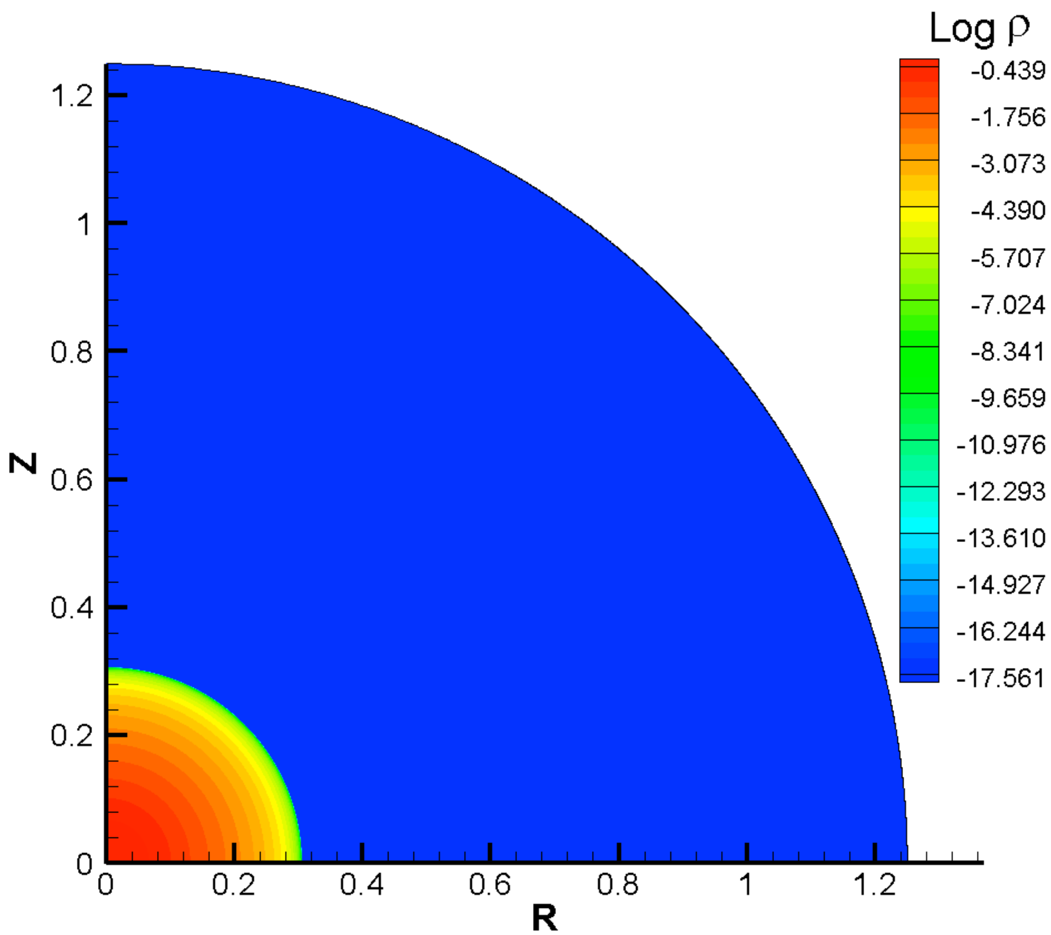
# Multidimensional approach

- 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 : $Tc \sim 2 \times 10^9 K$

PPML algorithm described in Ustyugov et al. (2009)

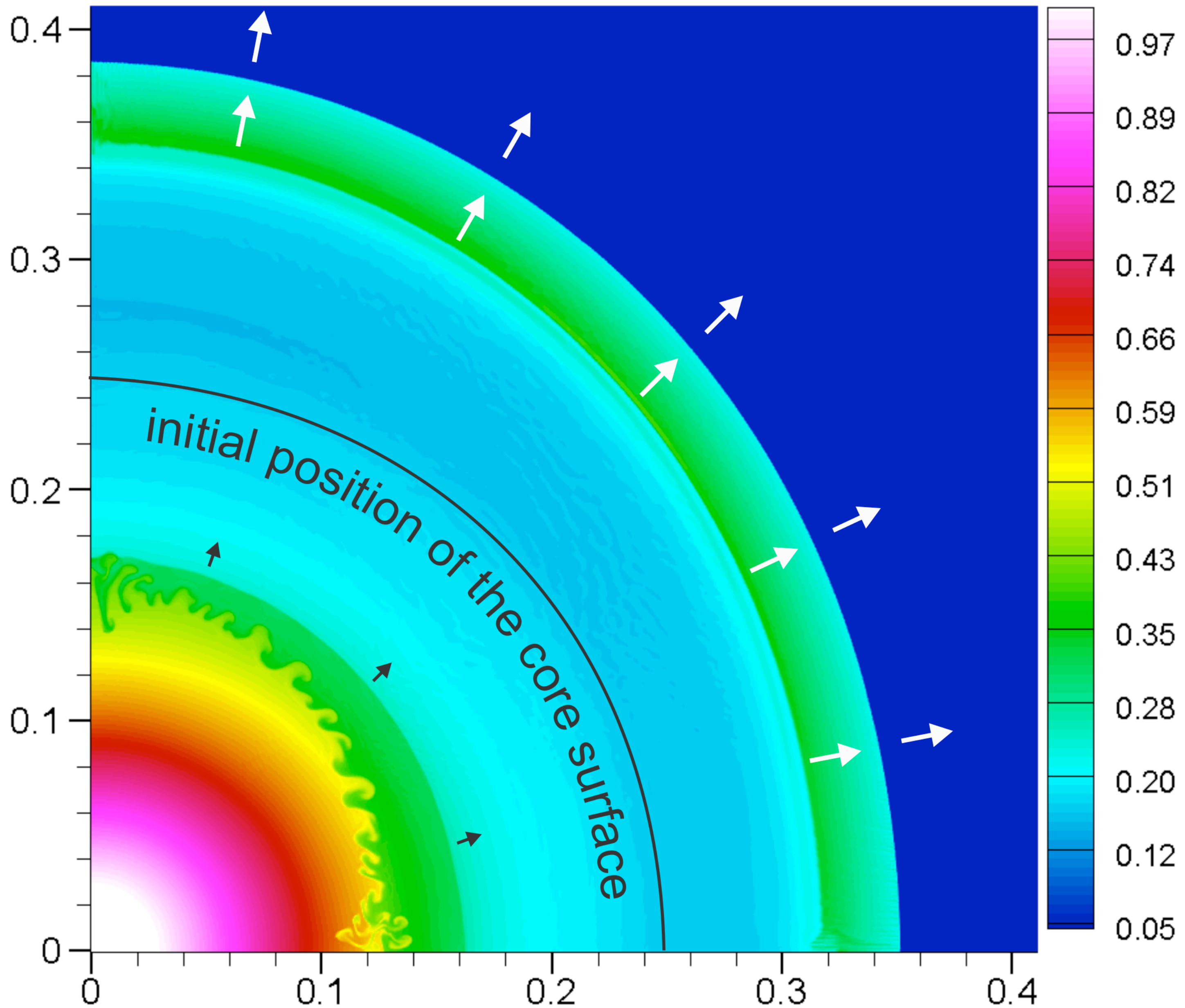
# Initial conditions



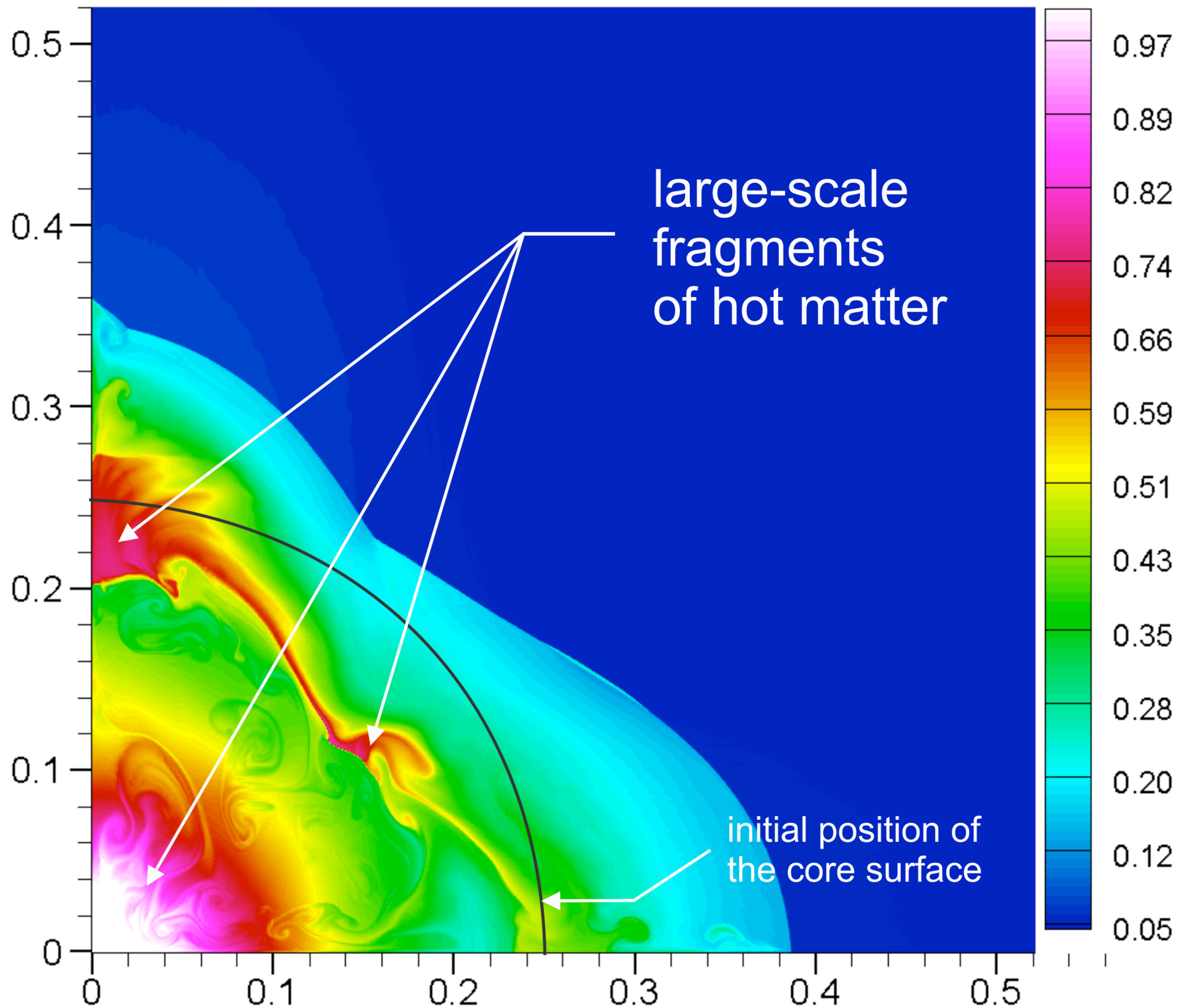




The energy 5. 10^52 ergs was deposited in the central region . This region contains 60 solar mass.

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




at t=25 s, Richtmyer-Meshkov is created

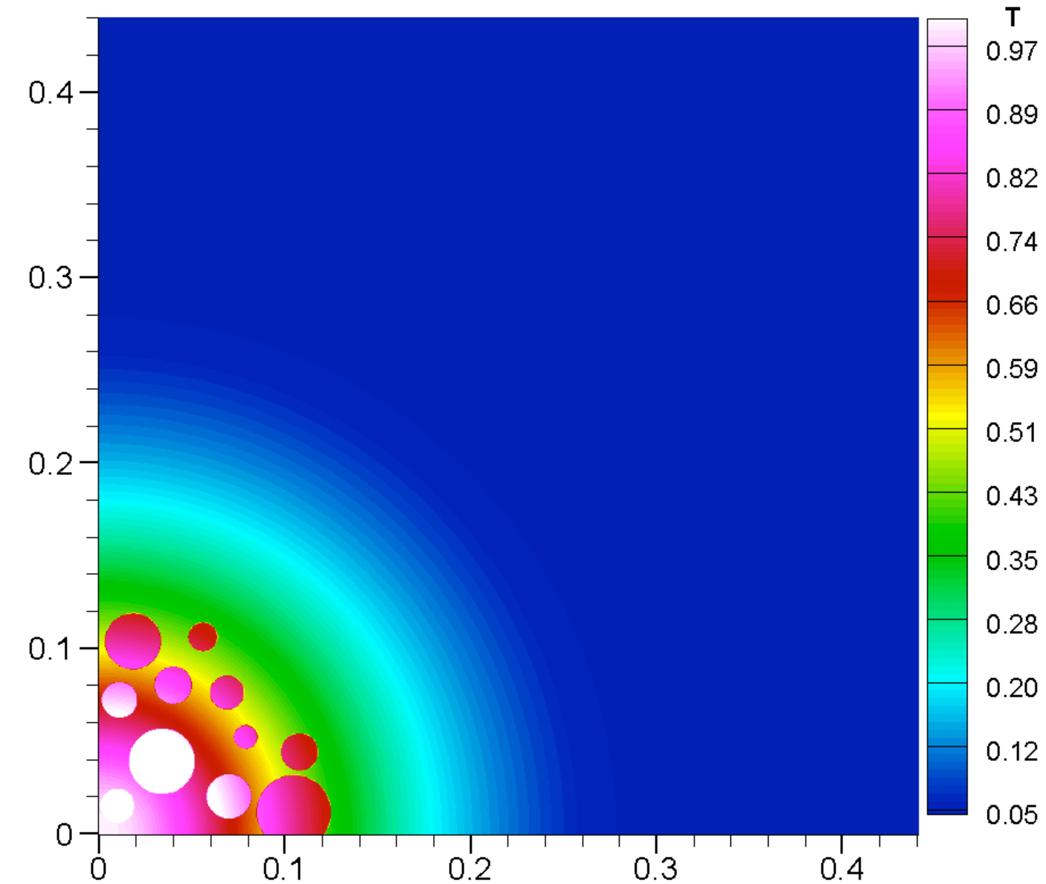

large-scale
fragments
of hot matter
initial position of
the core surface
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05

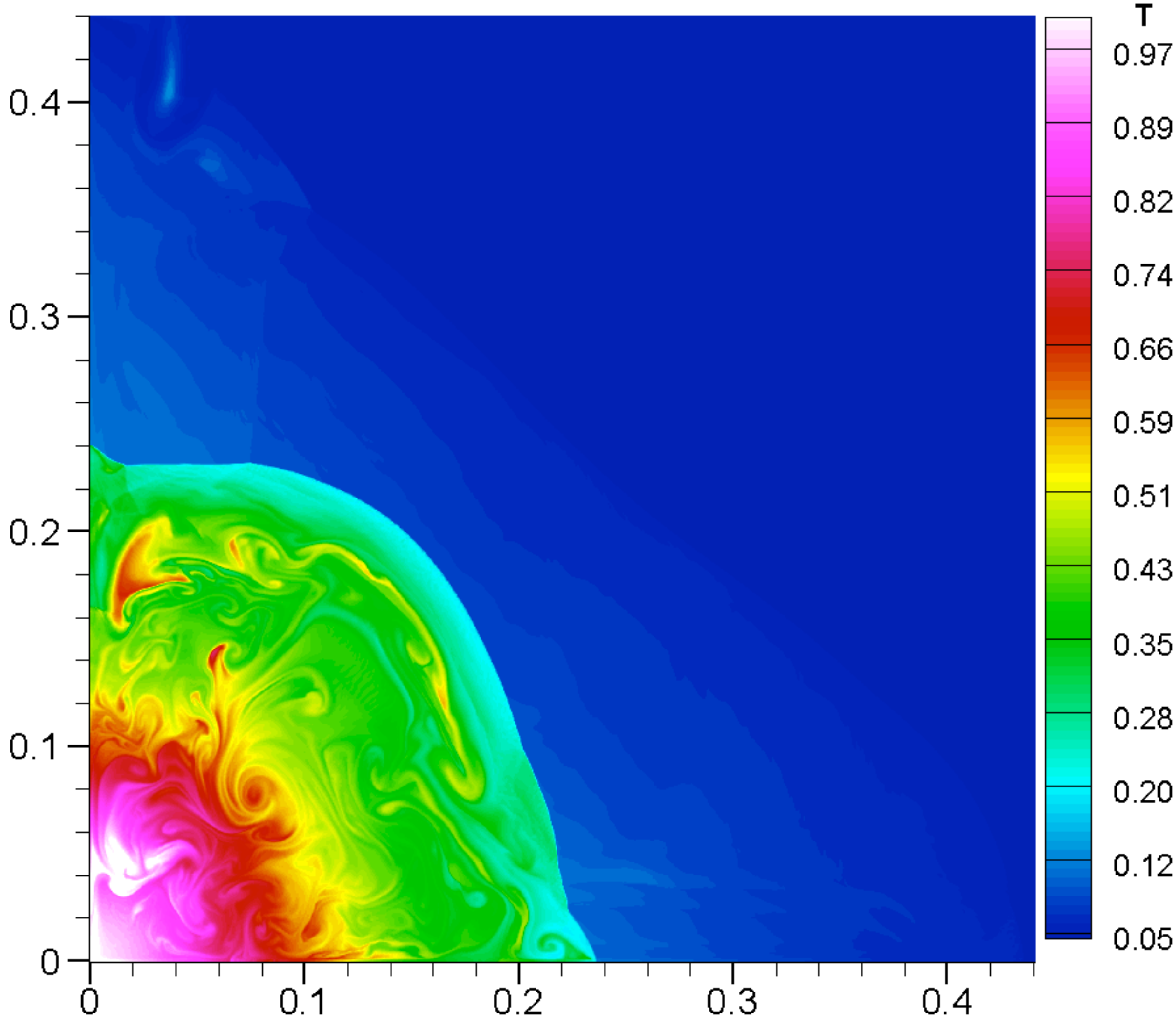
# Multi-explosion core

- 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




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

# Always new questions...

Q5 : GRB spectrum,
Evidence of thermal component + power law

Q6 : Cosmology with GRBs,
Rather specific since PISNe will predict an enhancement of GRBs at high z

Q7 : Association GRBs with SN Ibc
related to question 2

# Conclusions

- The Amati Relation is a fundamental property of the engine and could be explained in first approximation by the mass of the progenitor
- Multidimensional code could explain the prompt emission during the fragmentation of the core
- More energetic GRBs expected at high z
- GRB/SN rate using Salpeter function
- Better understanding of PISNe related to GRBs: key role of how the envelope is expelled