What are Gamma-ray Bursts ?

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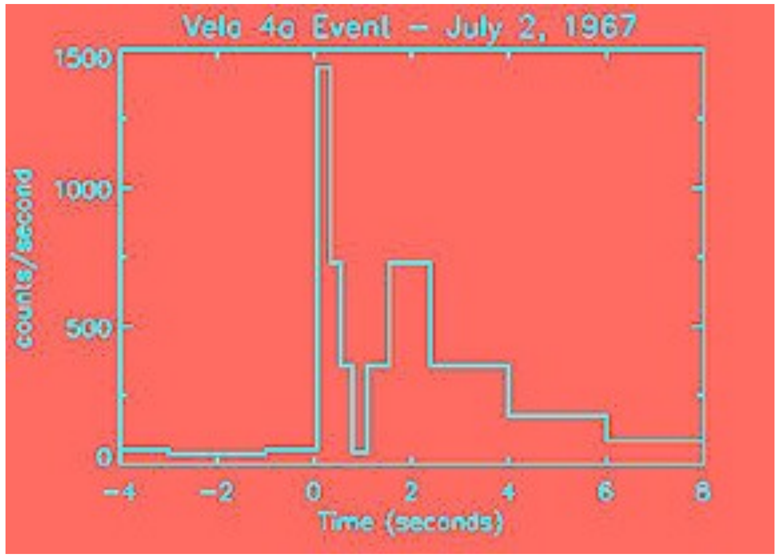
Overview

- Part I: overview of GRBs (Gamma-Ray Bursts)
- Part II : my personal point of view
- conclusions and outlook

What are GRBS

In the observational sense, «what are gamma-ray bursts?» has a straightforward answer:



GRBs are unannounced flashes of X and gamma-rays detected from random places in the Universe.

In few seconds, GRBs emit as much energy as our Sun will release in its entire 10 billions years lifetime.

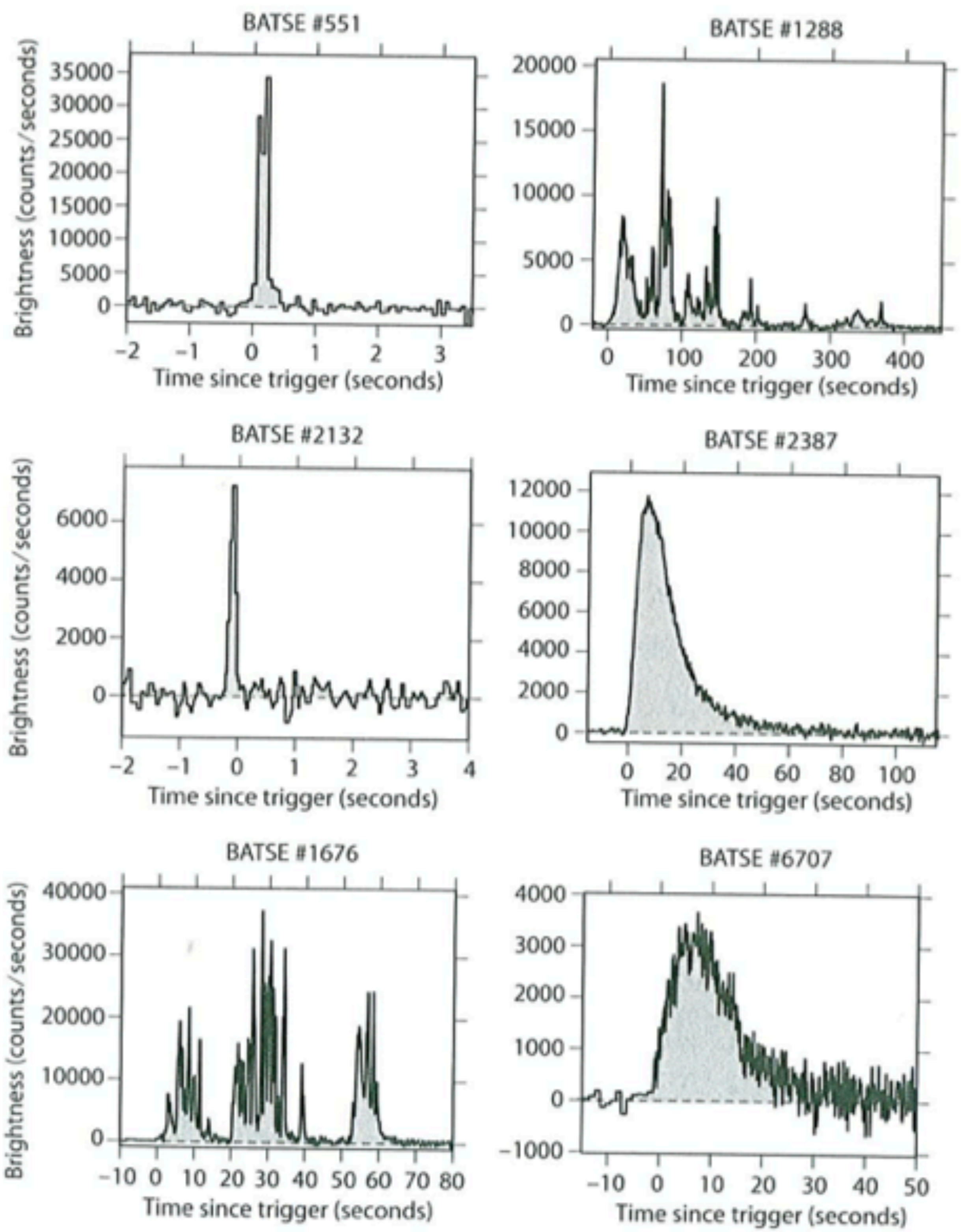
But «what are gamma-ray bursts?» means :

What are the astrophysical origin of gamma-ray bursts ?

What are the uses of gamma-ray bursts for cosmology ?

How they help us to understand the Universe

Light curves



The shape are different as the timescales which can vary from **ms** to few **100 s.**

The time profiles may present multiple peaks or they can be simple without fine structure.

The shortest structures identified in the light curves of GRBs last only few ms.

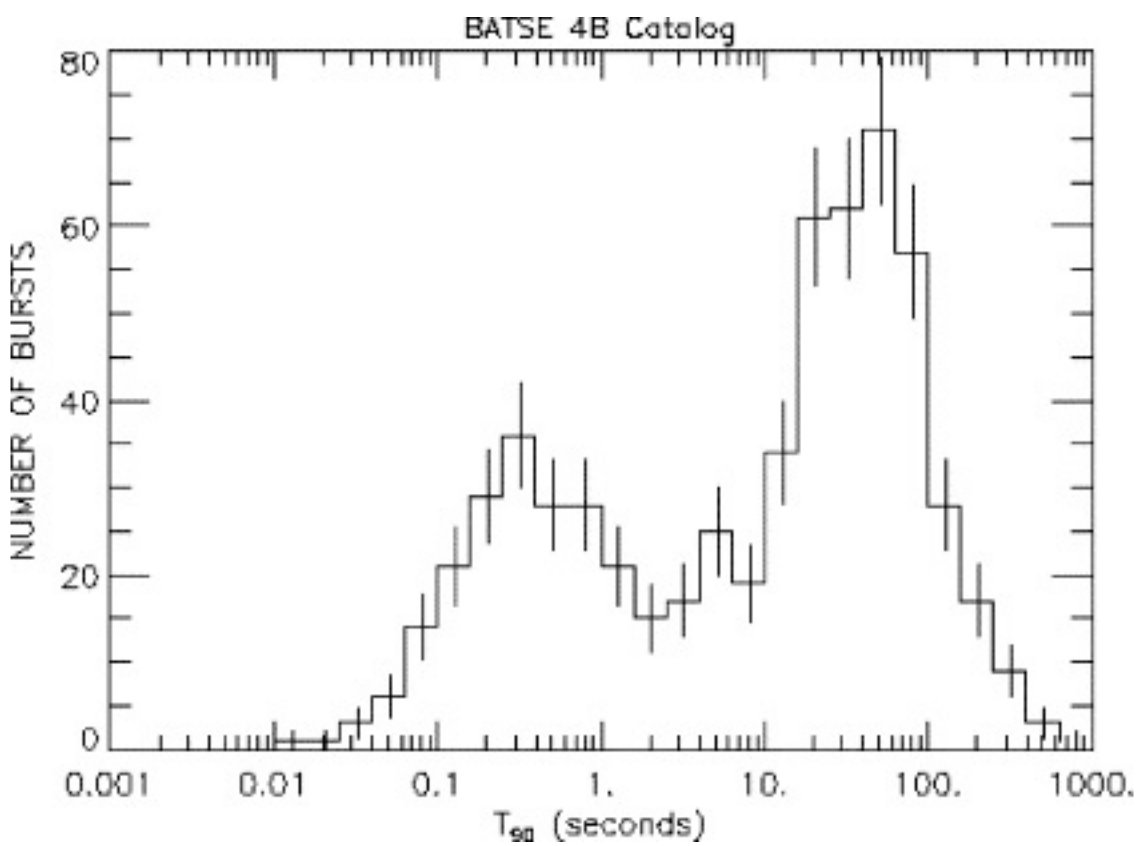
No GRB appears to have strong evidence for periodicity.

Light curves

Panoply of GRBs: GRBs light curves are like fingerprints: no two are alike but they share common properties:

duration : few 10s

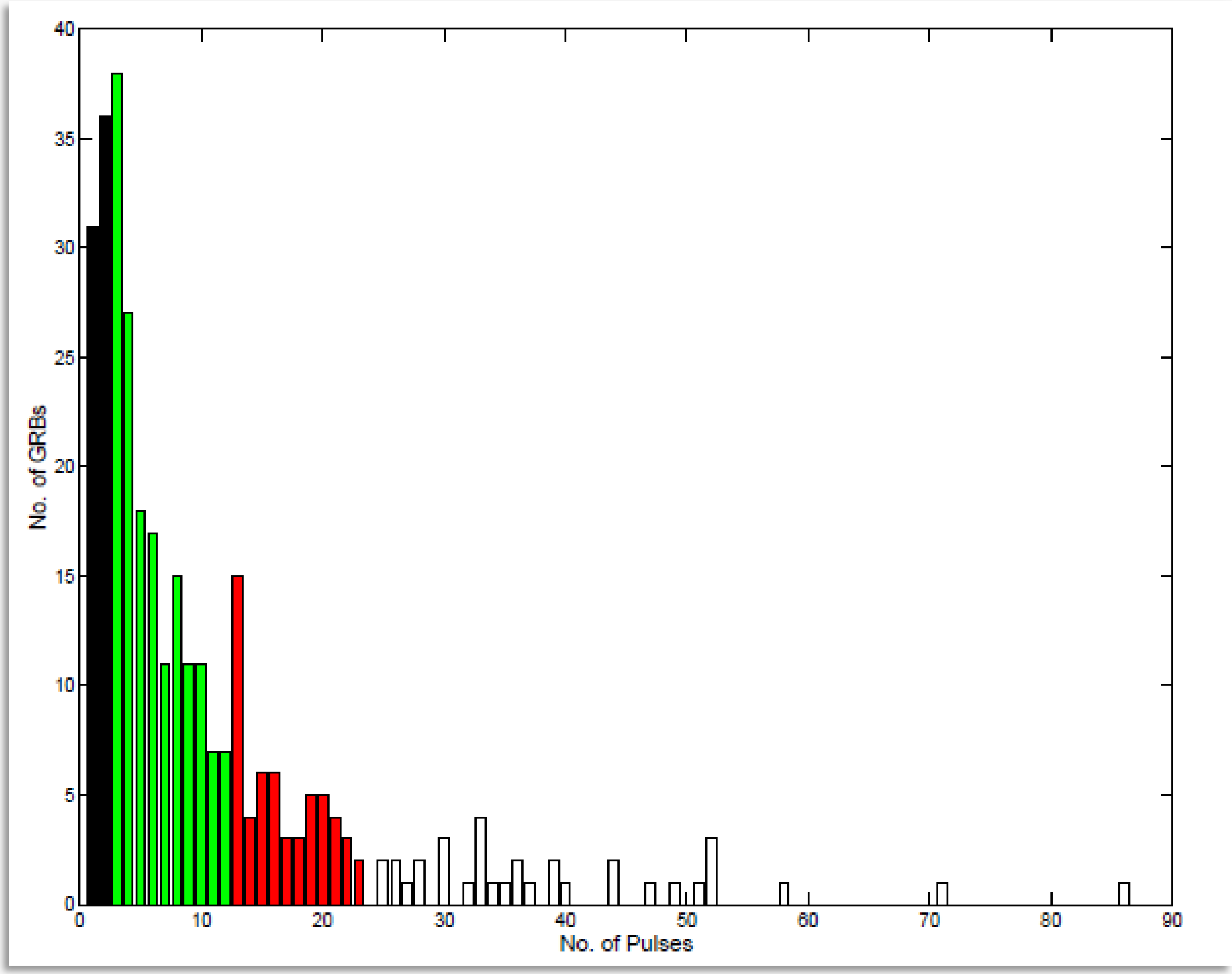
variability : subsecond



The analysis of GRB duration has shown a bimodal distribution with two broad peaks: 0.3 and 10-20 s

another common property: BAND spectrum

Temporal properties of GRBs



[F. Quilligan et al. (2002)]

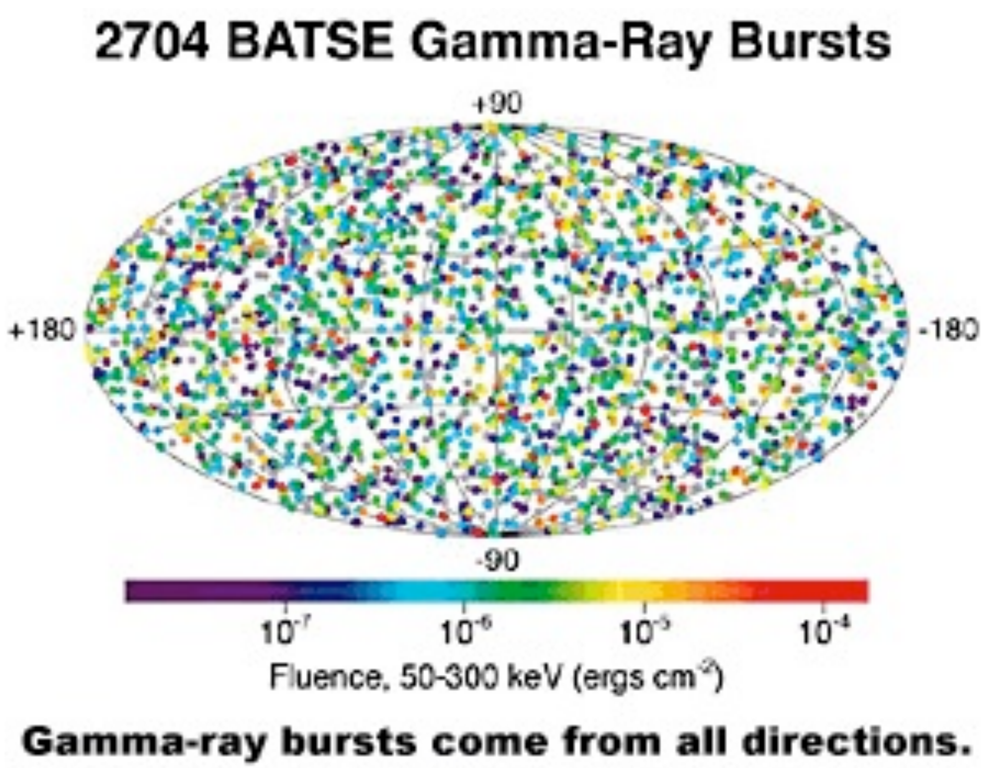
Morphology and temporal properties
the light curves of GRBs are quite variable from one GRB to another

No consistent physical model for GRB light curve that explain all the properties of all GRBs

At high energy GRB light curve appears sharper with short duration

Angular distribution and NS paradigm

In 1986, Pacynski pointed out that GRBs could be at cosmological distance, but



during the 15 years which preceded the launch of CGRB, GRBs sources are believed as isolated NS with strong magnetic field:

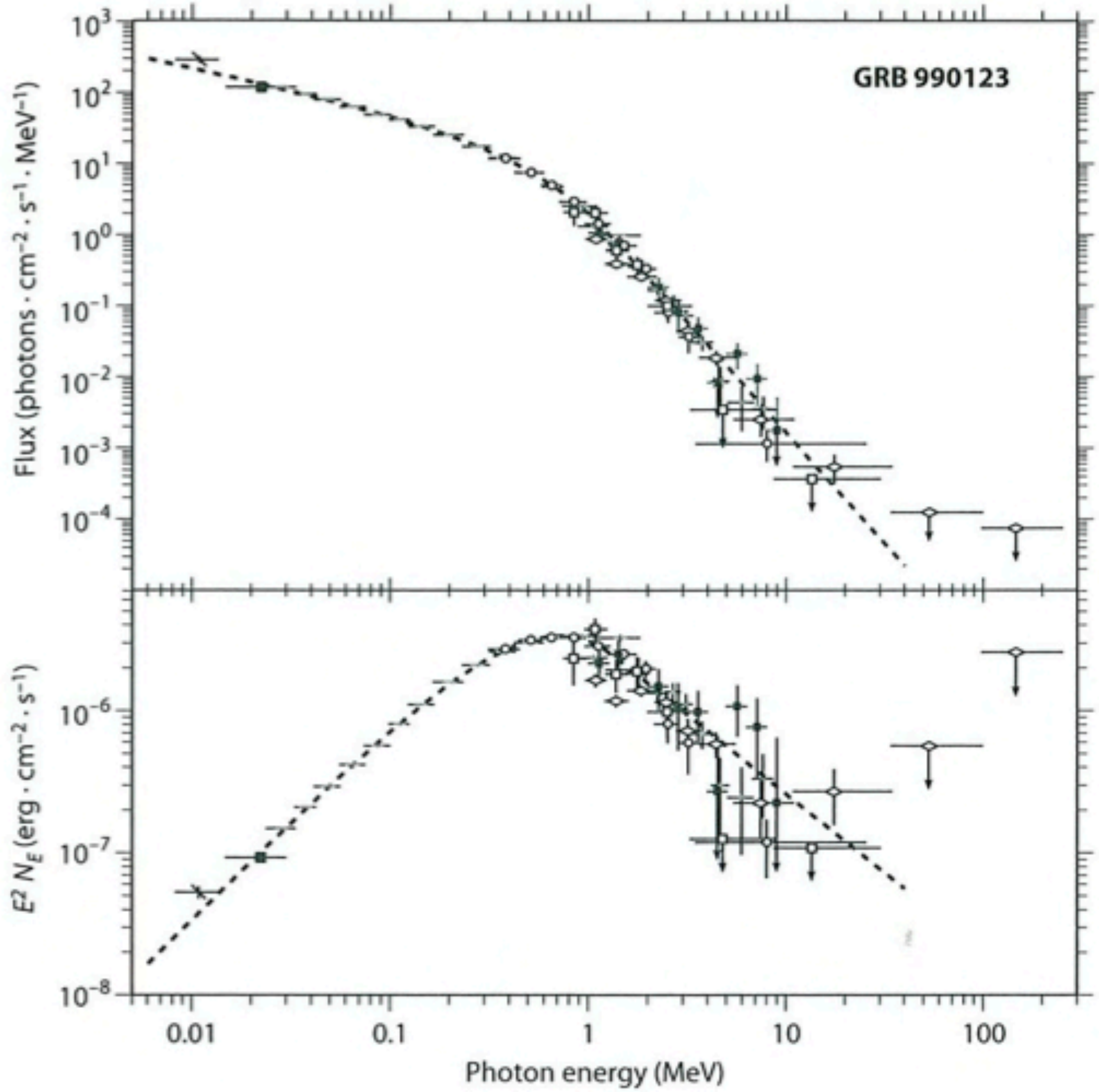
-light curves quite variable and spiky

-non thermal spectrum (Apollo XVI, Konus, Venera probes)

-absence of counterparts

-the energy budget was also an argument against cosmological origin

Spectra



The spectra of GRBs also exhibit differences between events but unlike light curves, the vast majority of spectra measured so far appear to be **well fitted by a simple empirical model**

Spectra

The BAND spectrum:

$$N(E) = A \times E^{\alpha} \times exp(-\frac{E}{E_0})$$

for low energy

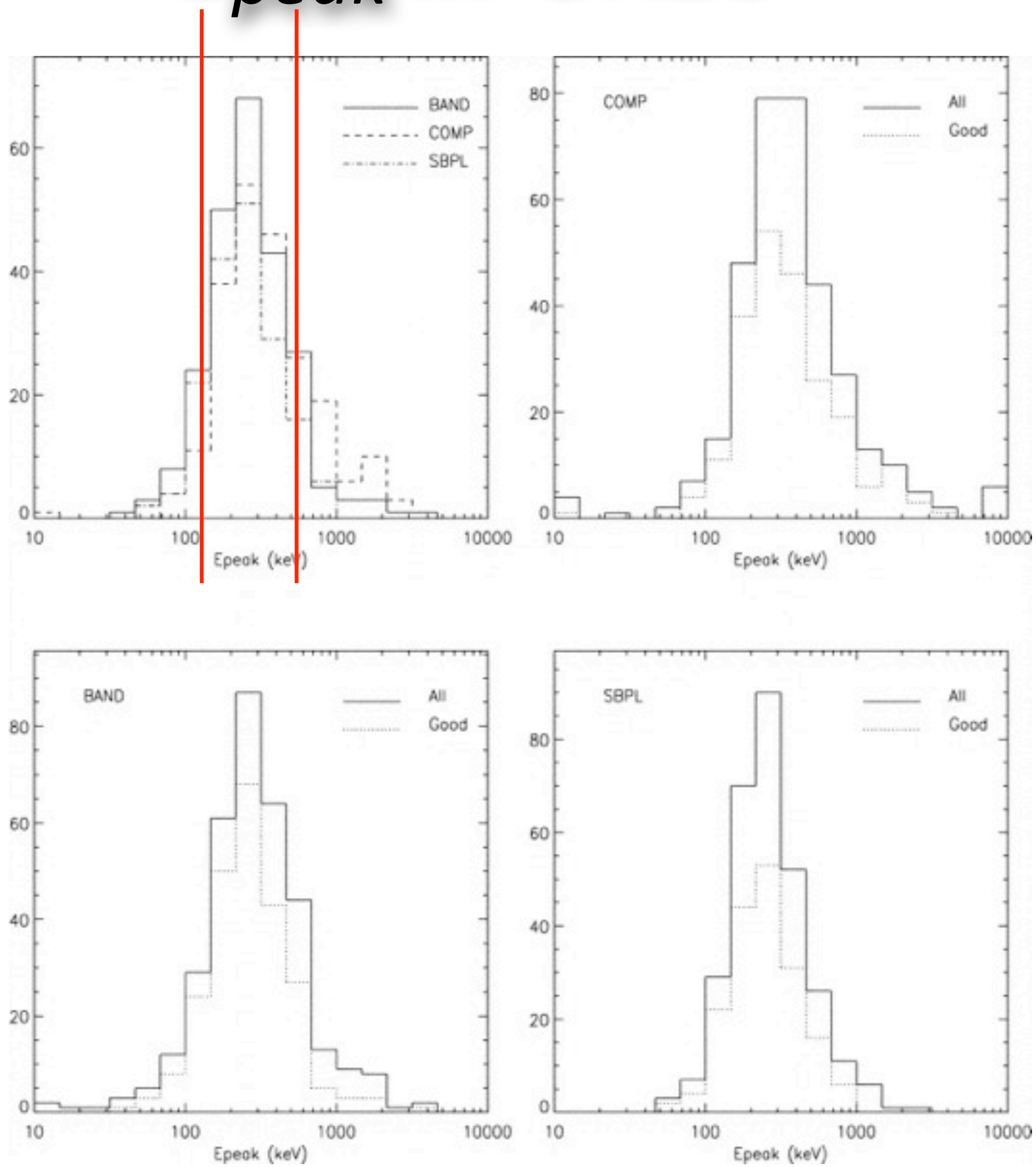
$$N(E) = B \times E^{\beta}$$

for high energy

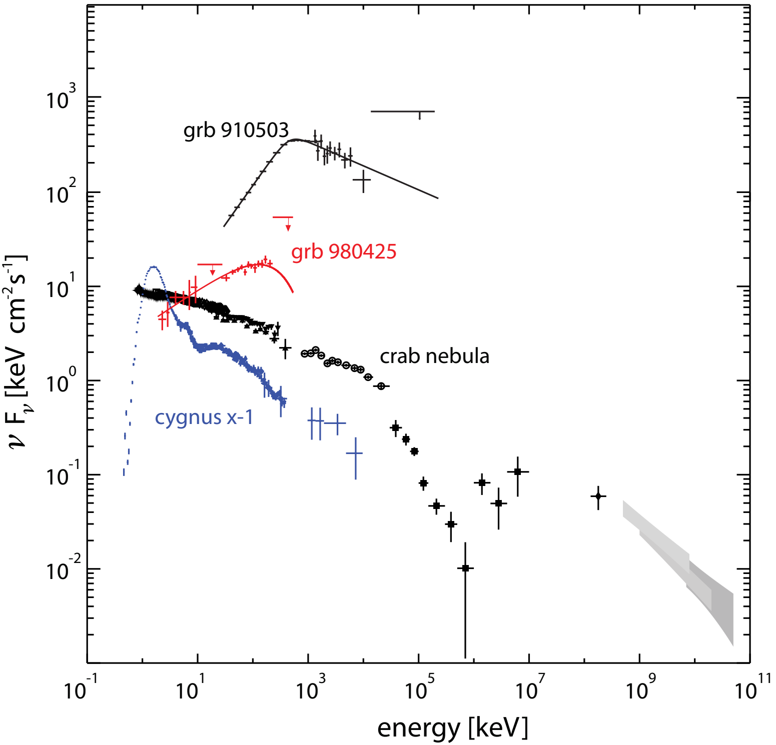
Typical numbers:

$$\alpha = -1 \quad \beta = -2, -3 \quad E_0 \sim 150\, keV$$

E_{peak} in GRBs



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


grb 910503
grb 980425
crab nebula
cygnus x-1
νF_ν [keV cm^{-2}s^{-1}]
energy [keV]
10^{-2}
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10^{0}
10^{1}
10^{2}
10^{3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}

more on Spectra

VELA not equiped to do spectroscopy

140 GRBs spectra with Konus and Venera Probes: well fitted by a thermal bremsstrahlung of a hot thin plasma

$$\frac{dN}{dE} \propto E^{-1} \times exp(-\frac{E}{T})$$

$$T \sim 10^9 \ K$$

1982: Fenimore proposed to explain spectrum by comptonization on BB (Tbb= 2 keV and Te = 150 keV)

1987 : synchrotron model for GRBs

Among 3000 bursts detected by BATSE, only 16 above 30 MeV and 5 with GeV photons

The Astrophysical Journal Letters, 727:L33 (5pp), 2011 February 1 doi:10.1088/2041-8205/727/2/L33

DETECTION OF A THERMAL SPECTRAL COMPONENT IN THE PROMPT EMISSION OF GRB 100724B

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Received 2010 October 20; accepted 2010 November 23; published 2011 January 10

ABSTRACT

Observations of GRB 100724B with the *Fermi* Gamma-Ray Burst Monitor find that the spectrum is dominated by the typical Band functional form, which is usually taken to represent a non-thermal emission component, but also includes a statistically highly significant thermal spectral contribution. The simultaneous observation of the thermal and non-thermal components allows us to confidently identify the two emission components. The fact that these seem to vary independently favors the idea that the thermal component is of photospheric origin while the dominant non-thermal emission occurs at larger radii. Our results imply either a very high efficiency for the non-thermal process or a very small size of the region at the base of the flow, both quite challenging for the standard fireball model. These problems are resolved if the jet is initially highly magnetized and has a substantial Poynting flux.

Key words: acceleration of particles – gamma-ray burst: individual (GRB 1000724B) – gamma rays: stars – radiation mechanisms: non-thermal – radiation mechanisms: thermal

1. INTRODUCTION

The prompt emission detected from gamma-ray bursts (GRBs) is believed to originate at large distances from the central engine, from within an ultrarelativistic outflow (Piran 2004). This ultrarelativistic motion is necessary to avoid strong $\gamma\gamma$ annihilation, a signature that is not observed (see, e.g., Piran 1999). Thermal emission is naturally expected in such a scenario. Indeed, since the densities at the base of the relativistic flow are very large, the medium is optically thick to radiation owing to Thomson scattering by entrained electrons. The optical depth decreases during the relativistic expansion and the outflow eventually becomes transparent for its own radiation, at the photospheric radius. Any internal energy that is still carried out by the flow can be radiated at the photosphere and will be observed as a thermal component in the prompt spectrum. This expected photospheric emission in GRB spectra was early suggested on such theoretical grounds by Goodman (1986), Mészáros (2002), and Rees & Mészáros (2005), among others. The non-thermal component observed in the spectrum has to be produced by another mechanism in the optically thin region, i.e., well above the photosphere. Due to the ultrarelativistic motion, this difference in the radius of the emission implies a delay between the observation of the two components that is usually small compared to the typical duration of a long GRB and is also small compared to the typical duration of time intervals used for time-dependent spectroscopic analysis. The thermal and non-thermal components should then appear superimposed for the observer (e.g., Mészáros & Rees 2000). Daigne & Mochkovitch (2002) pointed out that in the standard fireball model, the photospheric component can easily be dominant in the spectrum if the efficiency f_{NT} of the mechanism responsible for the non-thermal emission is only moderate ($f_{NT} \lesssim 40\%$).

Observationally, Ghirlanda et al. (2003), Ryde (2004, 2005), and Ryde et al. (2010) argued that a photospheric component is present in CGRO BATSE data. The limited energy range provided by BATSE (20–2000 keV), however, hampered the possibility of unambiguously identifying the emission process. Since the launch of *Fermi* in 2008, the combination of the Gamma-Ray Burst Monitor (GBM) and the Large Area Telescope (LAT) provides an unprecedented energy range for GRB spectroscopy, and the identification of the emission processes responsible for the gamma-ray prompt emission may become a reality. GBM alone covers a wider energy range than its predecessor BATSE,

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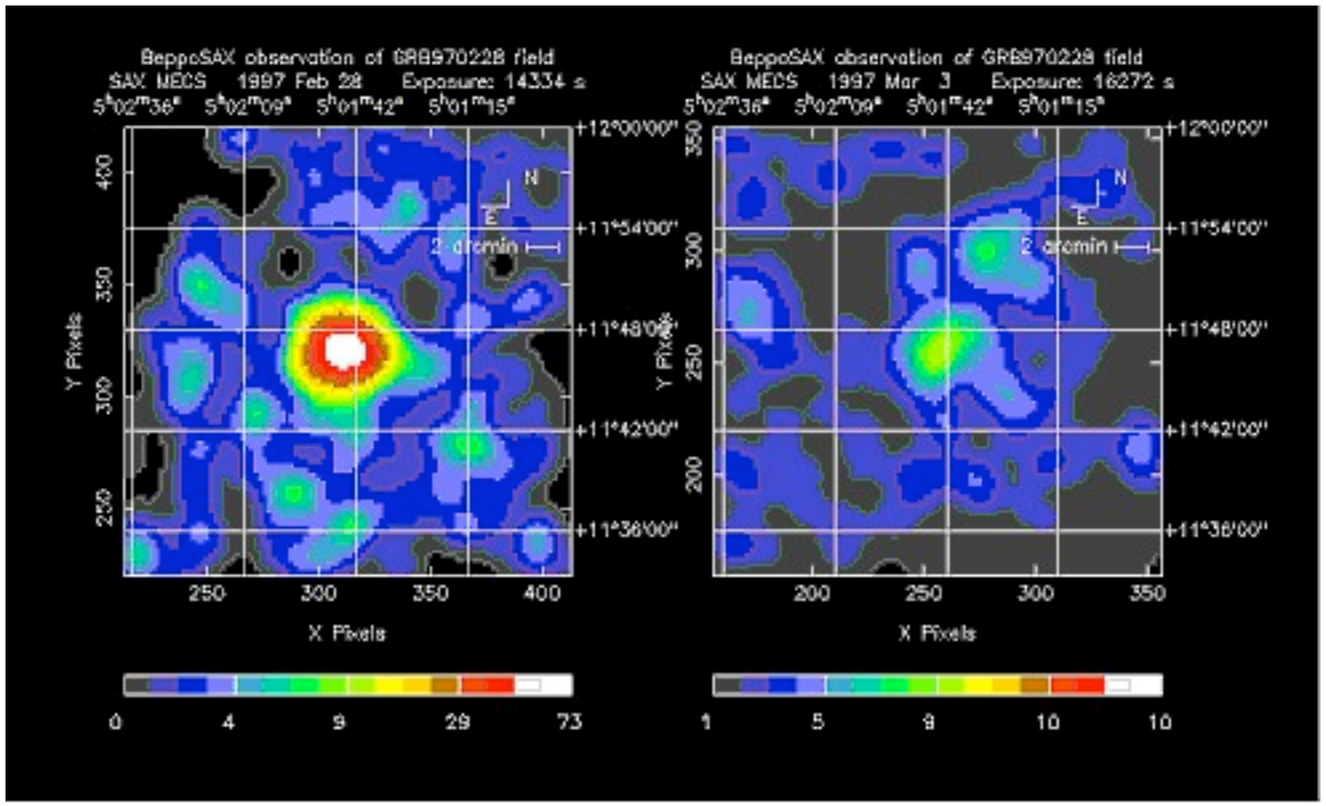
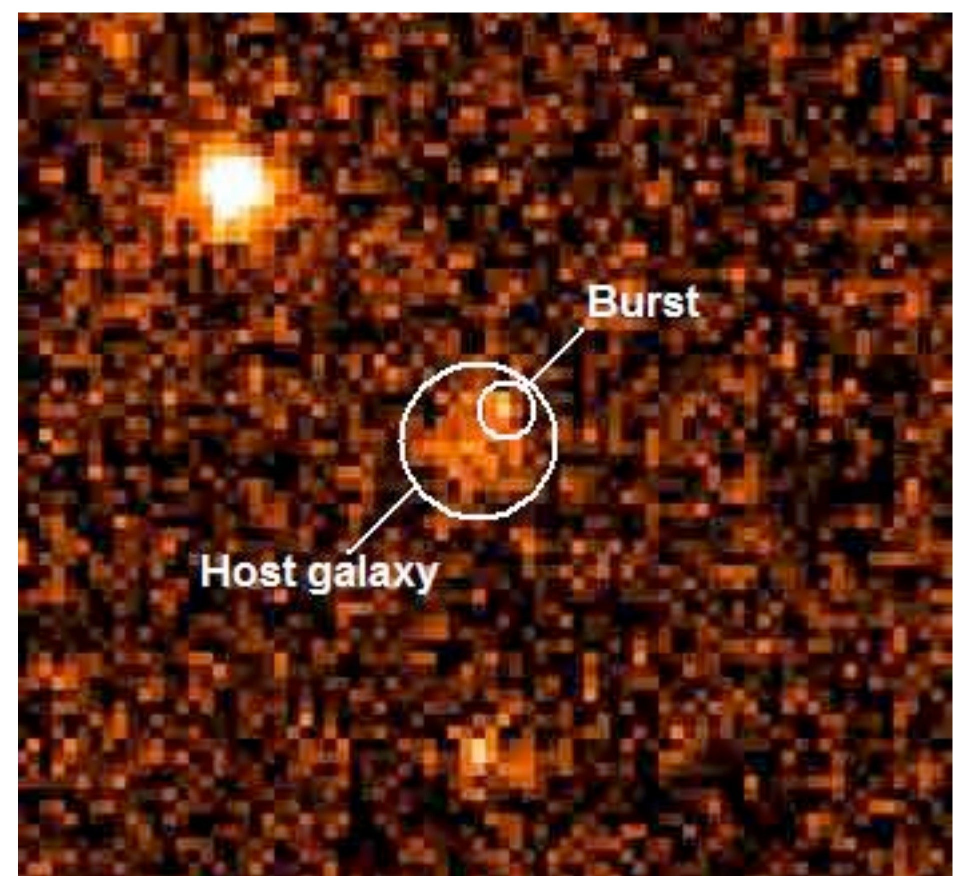
The Afterglow era and BeppoSAX

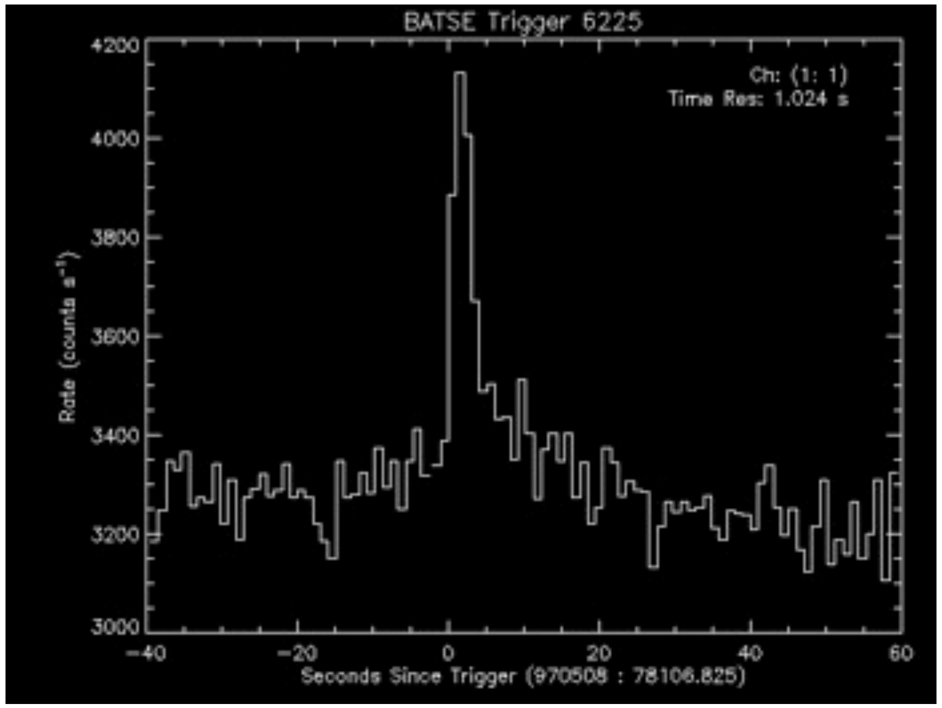


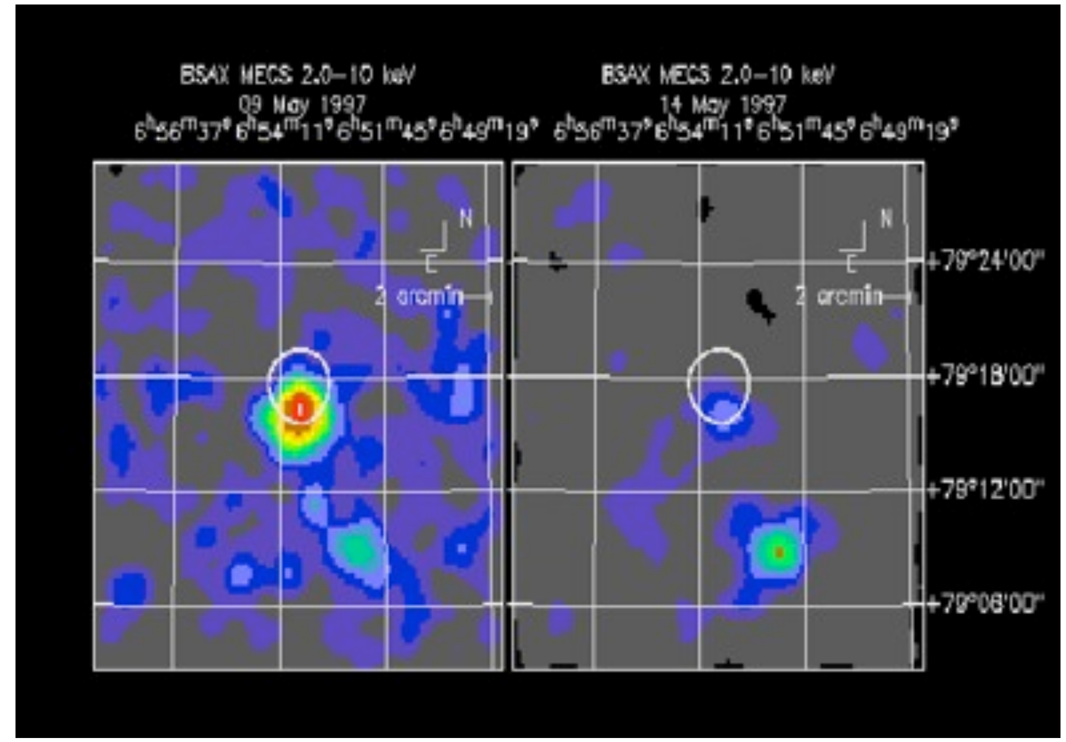
970228: the first X-ray afterglow at 8 hours and 3 days after GRB detection...

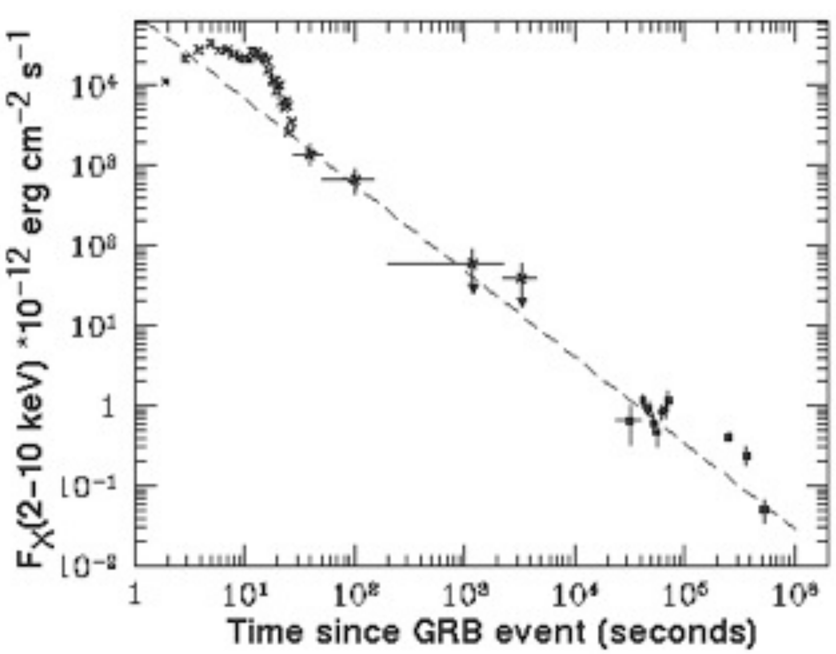
and the first optical counterpart detected

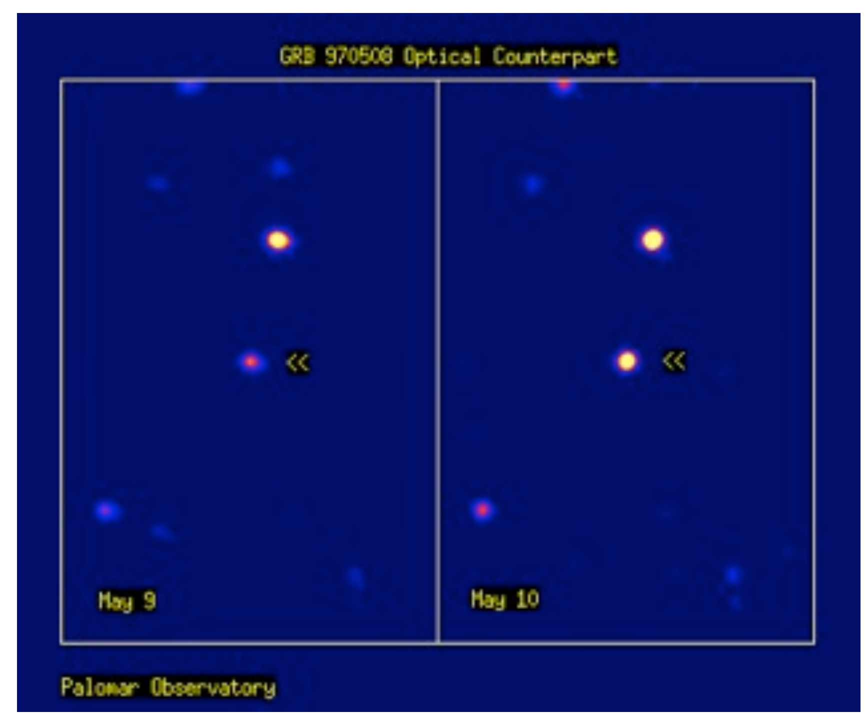


GRB 970508









Multi-wavelength spectrum from X-rays to radio

GRBs are at cosmological distance

- GRB970508 z=0.835
- GRB971214 z=3.42 the Universe was only 2 billions years old
- Huge luminosity:

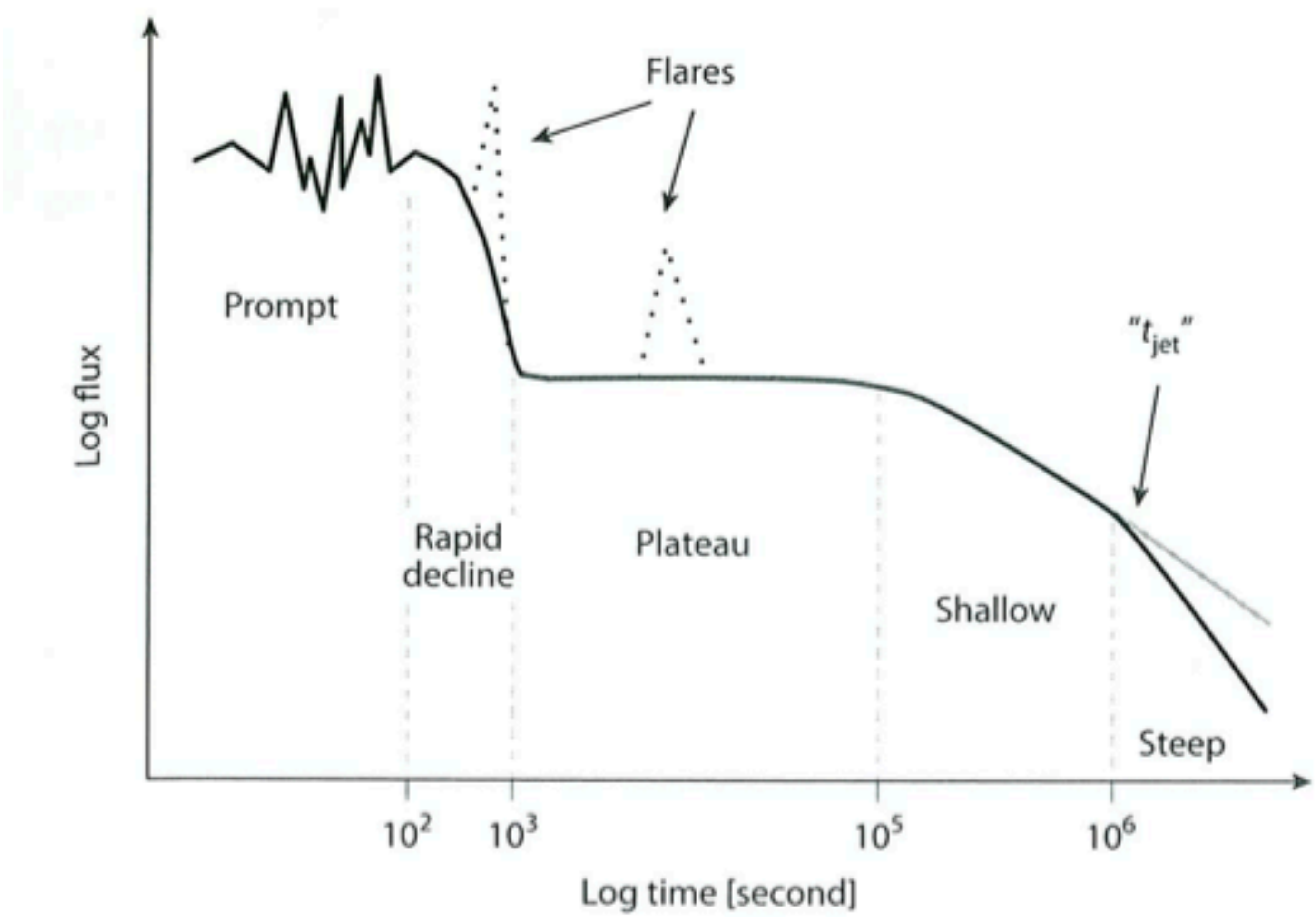
$$L_\gamma \simeq 3 \times 10^{53} \ erg.s^{-1}$$

- same order of energy released by NS coalescence but this luminosity is in X and gamma rays.

From the 1995 debate at the Baird Auditorium of the Smithsonian museum of Natural History in Washinghton

- **Bodhan Paczynski**: "At this time, the cosmological distance is strongly favored over the Galactic one, but it is not proven. ….At this time we have no clue as to their nature, even though well over a hundred suggestions were published in the scientific journals."
- **Don Lamb**: "We do not know the distance scale to GRBs. First I describe the recent discovery that many NS have high enough velocities to escape from the Milky Way. These high-velocity NS form a distant, previously unknown Galactic 'corona'. This corona is isotropic when viewed from the Earth, and consequently, the population of NS in it can easily explain the angular and brightness distribution of the BATSE bursts."

The canonical Afterglow



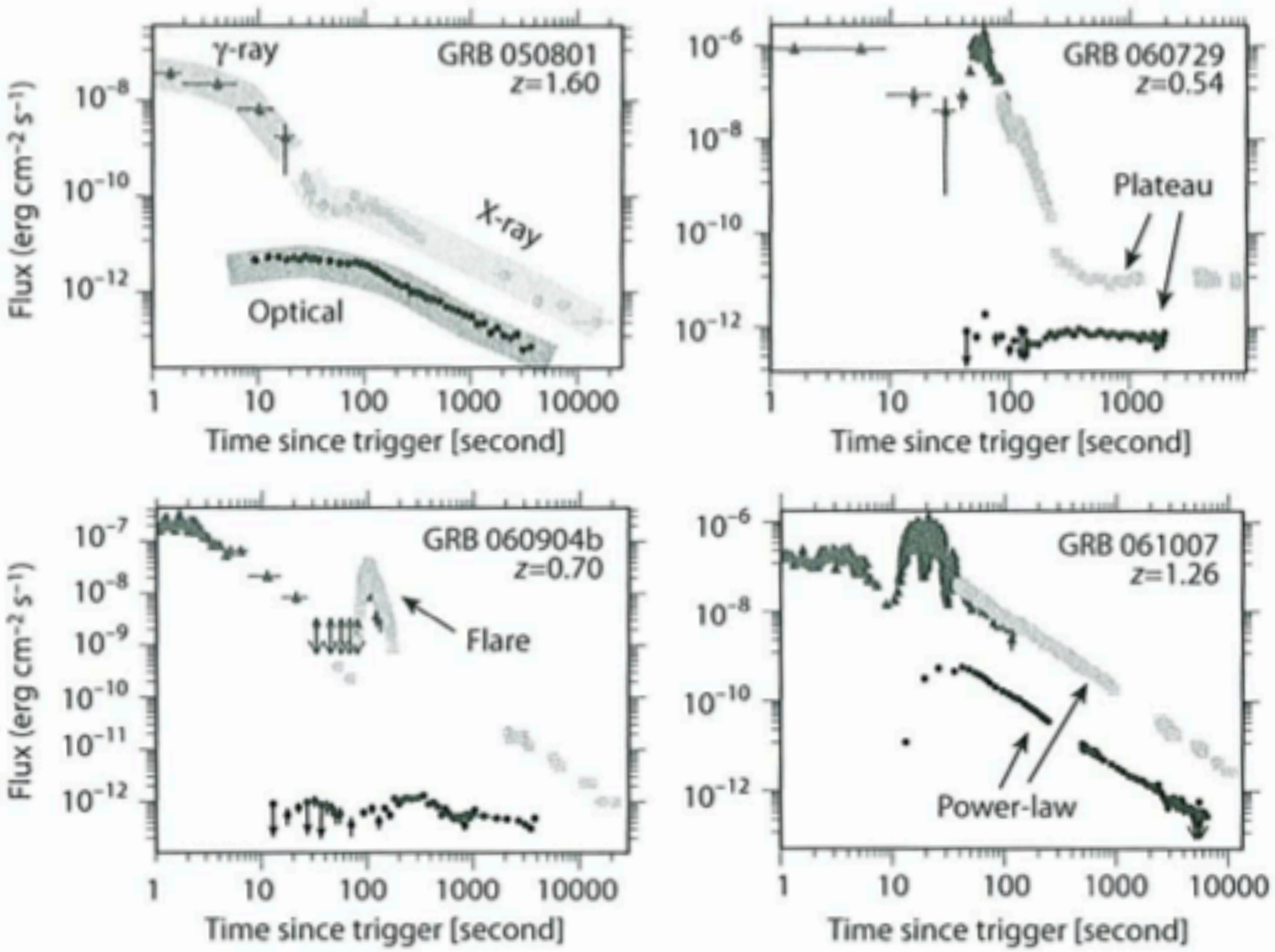
After the observations of X-rays afterglow by Swift a «canonical» light curve appeared

- 3 power law:

initial decay, very shallow decay and intermediate decay

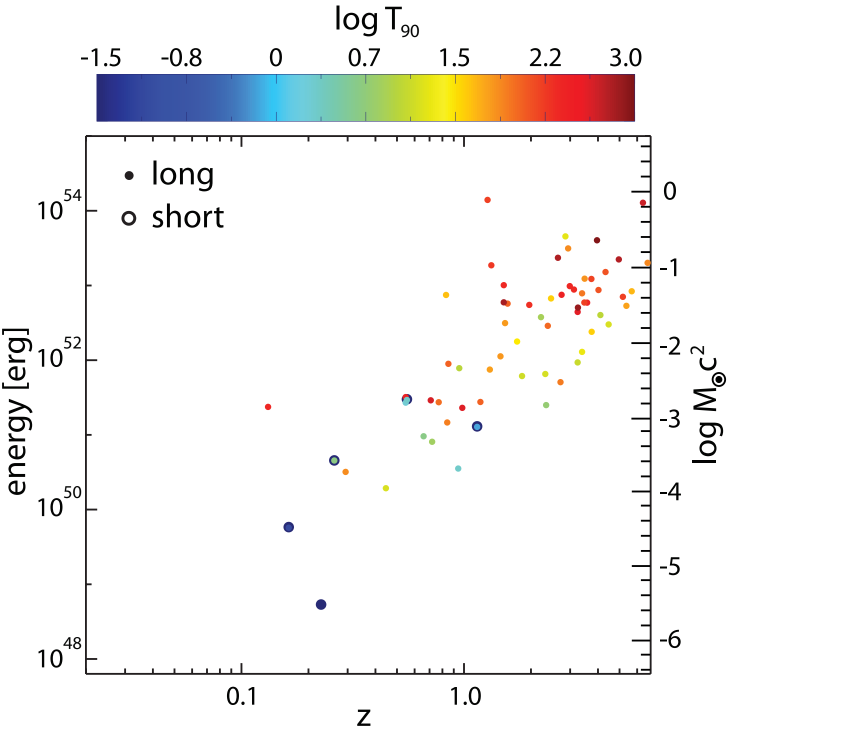
- but not seen in all GRBs

Afterglow (diversity)



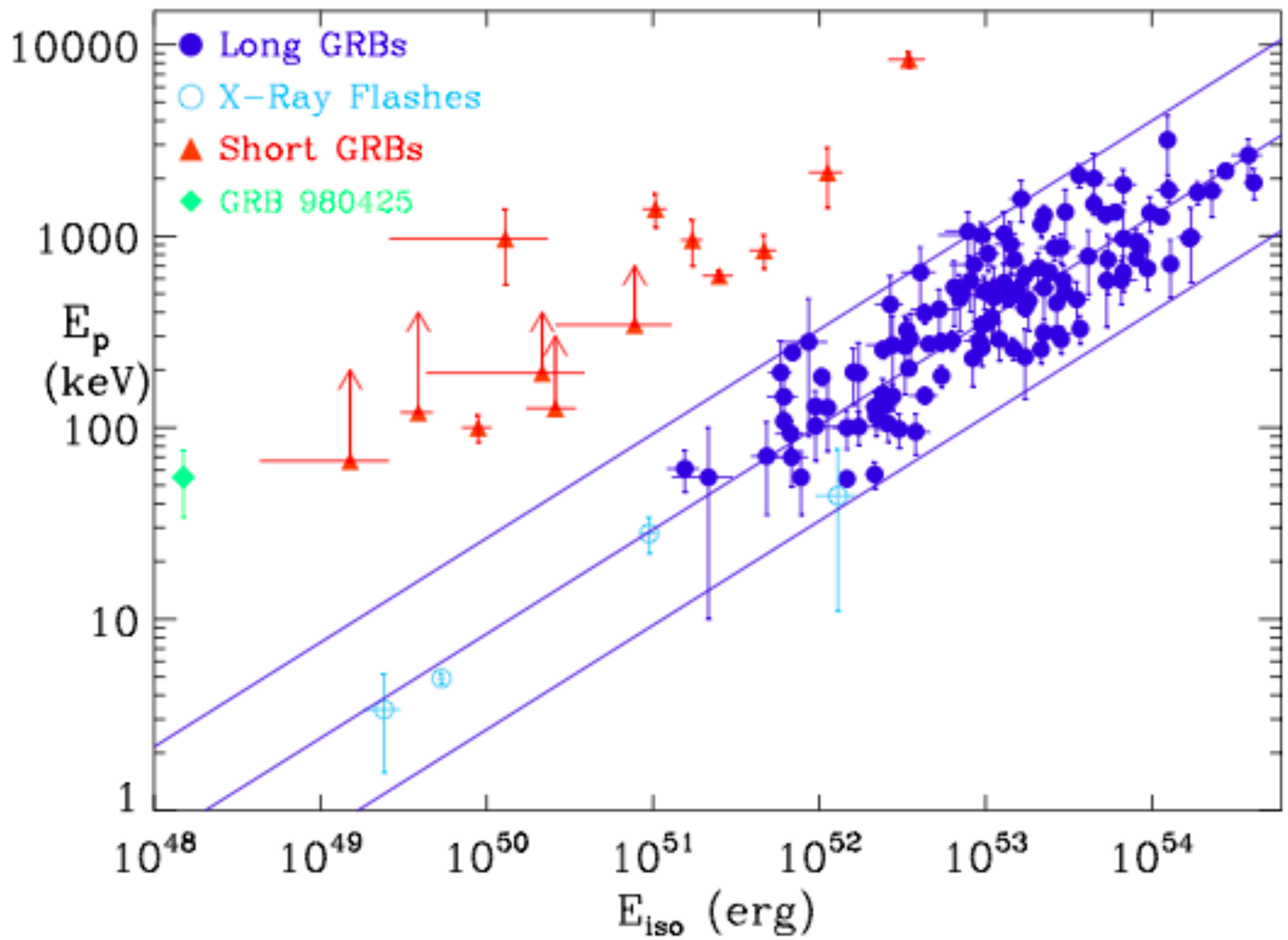
In the fireball scenario, the dominant emission mechanism is thought to be synchrotron radiation

But this theory fails to anticipate and explain the rich phenomenology of afterglows. This theory is an evolving one having been refined and added as the data have demanded



log T_{90}
-1.5
-0.8
0
0.7
1.5
2.2
3.0
long
short
energy [erg]
10^{54}
10^{52}
10^{50}
10^{48}
0.1
1.0
z
0
-1
-2
-3
-4
-5
-6
log $M_{\odot}c^2$

The Amati Relation



Intrinsic spectral properties and energetics (after correction for cosmological redshift)

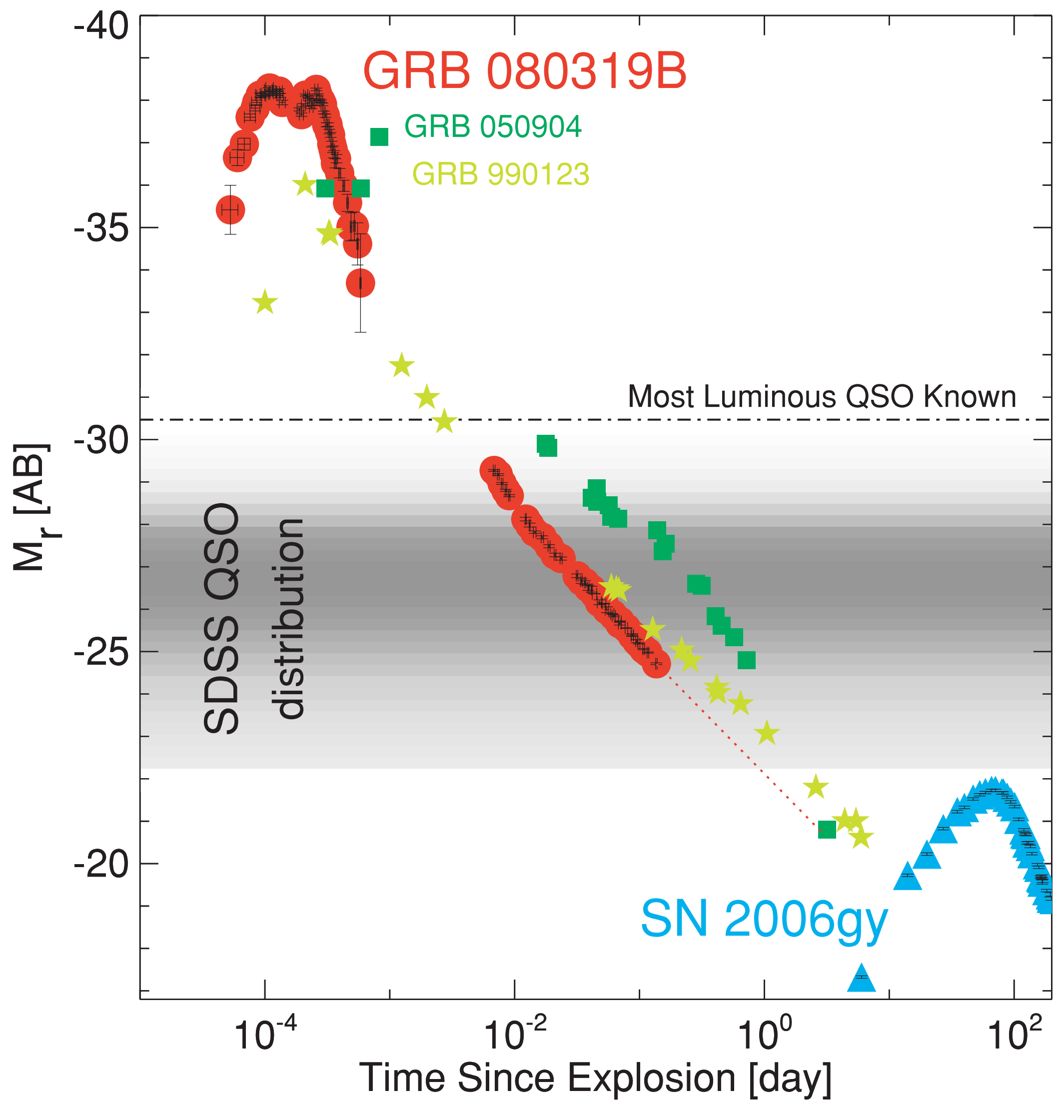
- small dispersion around the best fit
- quality of the correlation

The interpretation of the Amati relation is not straightforward because it is a reminiscent of a temperature-luminosity relation while GRB spectra are not thermal

GRBs as probes of the Universe

Metallicity can be inferred using absorption lines of different atomic species. Metallicity is a very important parameter of the content of the Universe. GRBs afterglow measurements use absorption diagnostics giving access to the enrichment history of the interstellar medium of GRB host galaxies in the Universe

History of star formation is another important aspect where GRBs will be useful
Traditionally: emission lines in optical give access to star formation rate (SFR). But if dust, undercounted SFR.
So idea: GRB in X and gamma penetrate dust and since we believe that long duration GRBs mark the birthplace of massive stars we can localize the SF irrespective of dust.
But difficult: 1) GRB progenitor prefer low metallicity -> bias
2) difficult to detect optical afterglow for redshift measurement



Measuring reonization and the first objects in the Universe is also a goal of what can be done with GRBs.

idea: QSO and galaxy appears to be decreasing at high z. On the other hand GRB are 100 or 1000000 more luminous than QSO or SN and there is no evidence that GRB should decrease at high z

Also: neutrinos, gravitational waves and cosmic rays

Compactness problem

Non thermal spectrum → optically thin region

$\tau \sim 1$

Variability → size of the source → optically thick region

$\sim c\,\delta t$

$\tau \gg 1$

such source cannot emit
non thermal photons

→ **ultra relativistic motion**

Opacity

$$\tau = R\, n_\gamma\, \sigma_T$$

density of photons (high energy):

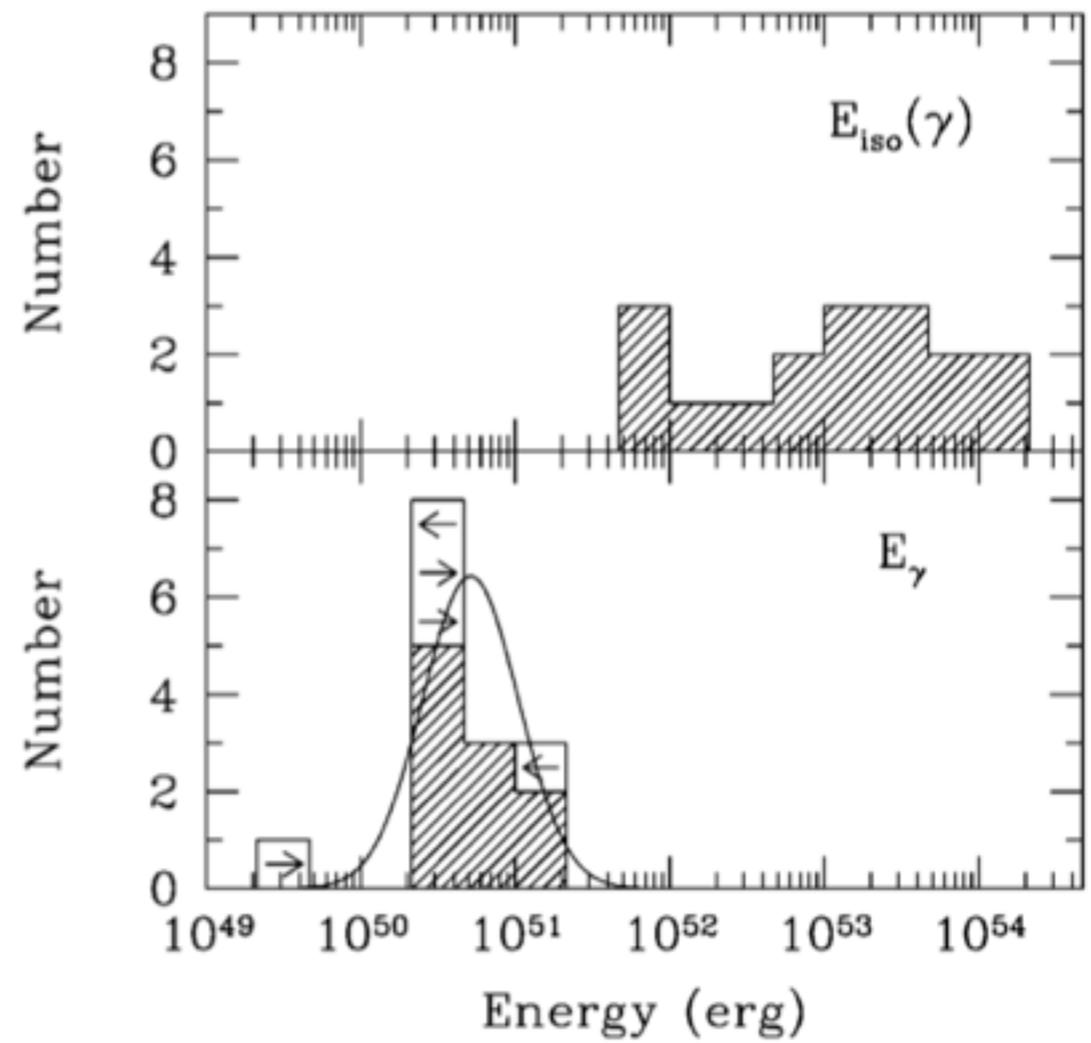
$$N_\gamma \simeq \frac{E_{pulse}}{mc^2} \qquad\qquad n_\gamma = \frac{N_\gamma}{4/3\pi R^3}$$

Fluence of the GRB: $$S = \frac{E_{pulse}}{4\,\pi\, D^2}$$

$$\tau \simeq \left(\frac{3\,\sigma_T\, D^2}{R^2\, mc^2}\right) S \qquad \sim 10^{10}$$

Jet and collimation

- Photons emitted isotropically with a Lorentz factor appear beamed in the observer frame
- There is no way to distinguish between isotropic emission or beamed emission
- but with time we can see jet breaks ($\theta \sim few\, degrees$)



Existence of a standard energy reservoir (Frail 2001)

$$E_\gamma = f_b \times E_{iso}$$

$$\langle E_\gamma \rangle \sim 5 \times 10^{50}\, erg$$

The «true» energy is computed with the efficiency of the fireball to convert kinetic energy to radiation

$$E_\gamma = \eta\, E_{true} \qquad \eta \sim 0.1$$

Consequence: this will modify the rate of GRB

$$R_{obs} = 0.5\, Gpc^{-3}.\, yr^{-1}$$

$$R_{true} \simeq 250\, Gpc^{-3}.\, yr^{-1}$$

$$R_{NS-NS} \simeq 80\, Gpc^{-3}.\, yr^{-1}$$

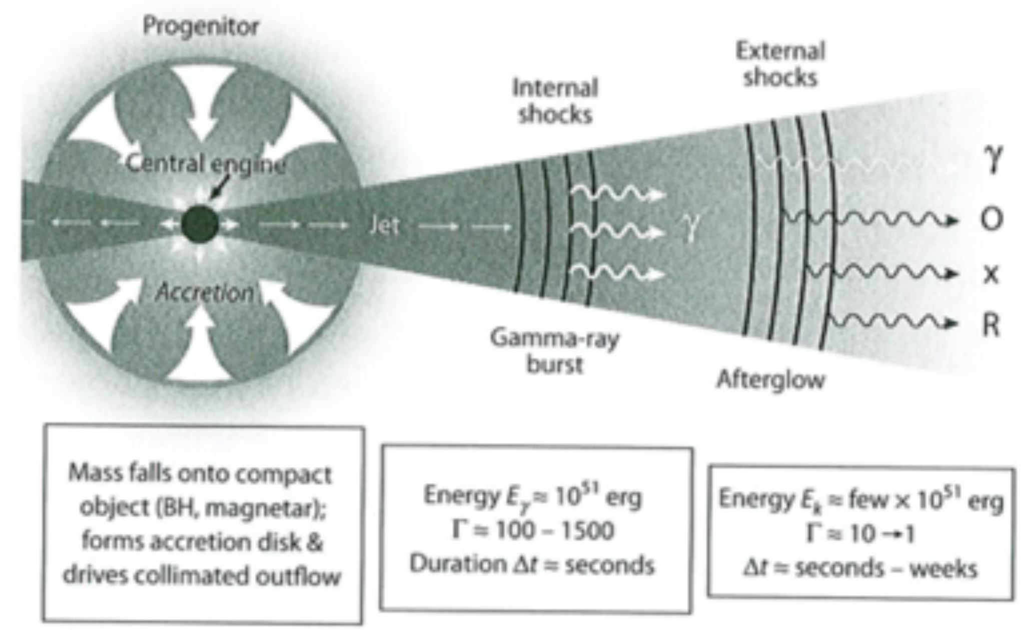
$$R_{SNIbc} \simeq 6 \times 10^4\, Gpc^{-3}.\, yr^{-1}$$

Fireball and internal shocks

Before the light of a GRB escapes, the outflowing material needs to accelerate to relativistic speeds

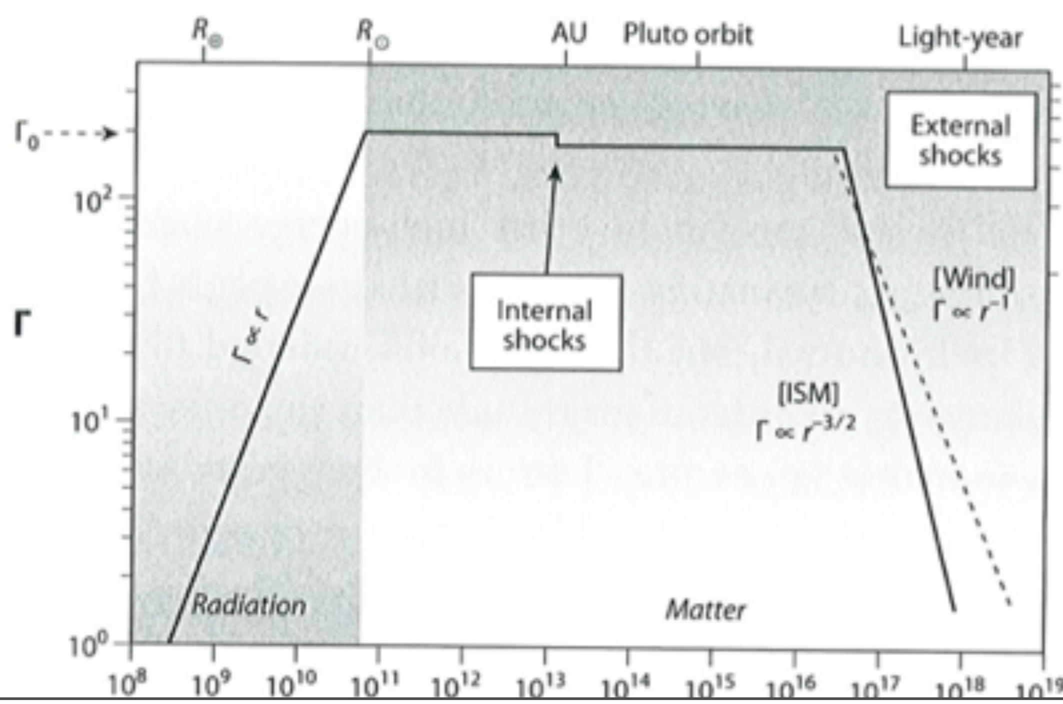
A significant amount of energy (at least what it is equal in gamma-rays) is deposited in a small region

The source is compact and the energy density is high. This soup of particle and light is opaque and only few photons escape



Therefore the energy is trapped and since there is nothing to confine the fireball, it expands.

The internal energy is converted into bulk outward flow



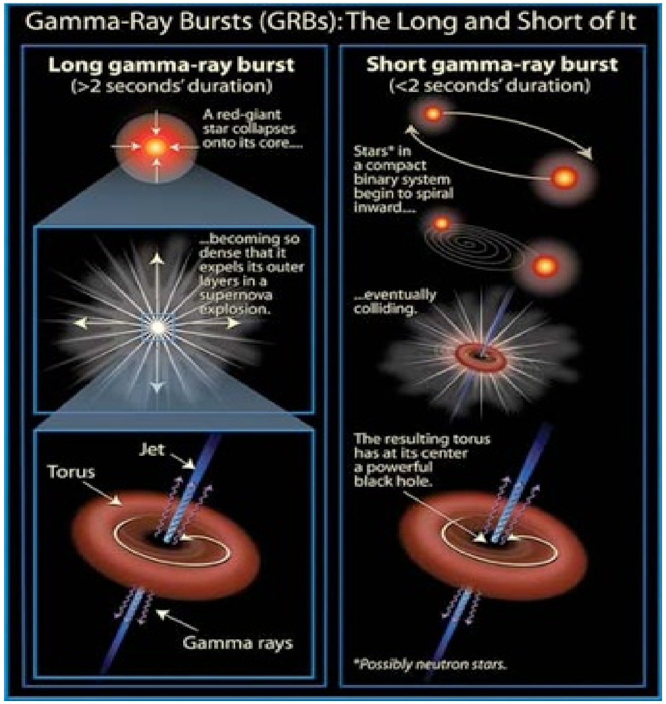
Relativistic collisionless shocks are the place where kinetic energy is transfered to radiation in two different ways: internal shocks of external shocks

The GRB possible progenitors

From energetics, variability time scales and GRB duration :

→ classification in short and long GRBs

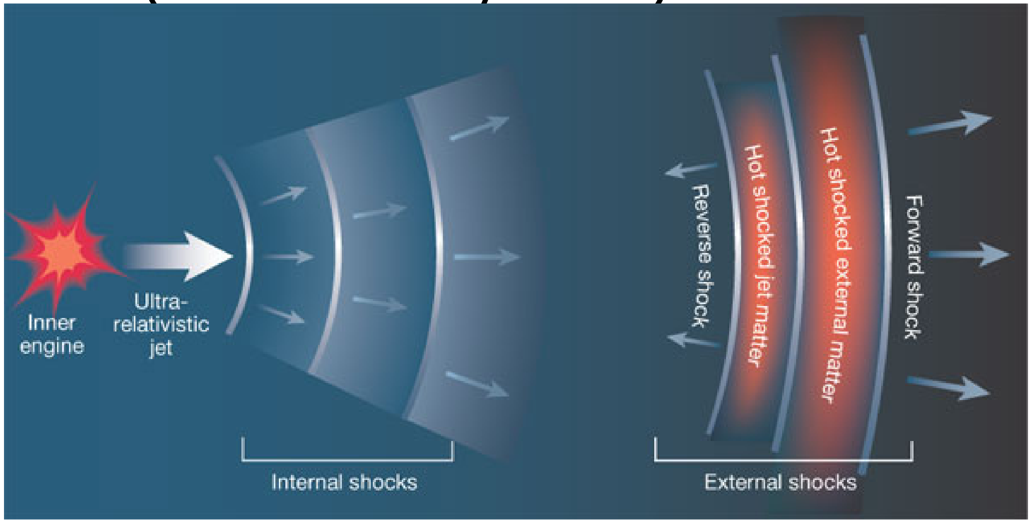
- Many models proposed:
  - Failed SNe (Woosley93);
  - collapsar (Paczynski98);
  - Binary NS or NS-BH merger (Narayan+92);
  - WD-NS merger
  - Fireshell Model (Ruffini+01)
  - Supranova model (Vietri+98)



- **Energetics**.
  - From the similar kinetic energy of outflowing shells, a small conversion efficiency (e.g., Daigne+98).

➡ Internal shocks can hardly produce the observed radiation.

- **Energy distribution between prompt and afterglow**
  - External shocks should be more efficient;
  - Instead we found more energy released during the prompt emission (confirmed by Swift).



GRBs are very rare phenomena (compared to SN explosions)

GRB/SNe-I$_{(b)}$c: 3%-0.01%
Ibc/CC ~ 0.25
GRB/CC-SN < 1% or << 1%

What causes some small fraction of CC-SNe to produce observable GRBs, while the majority do not?

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 ?

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

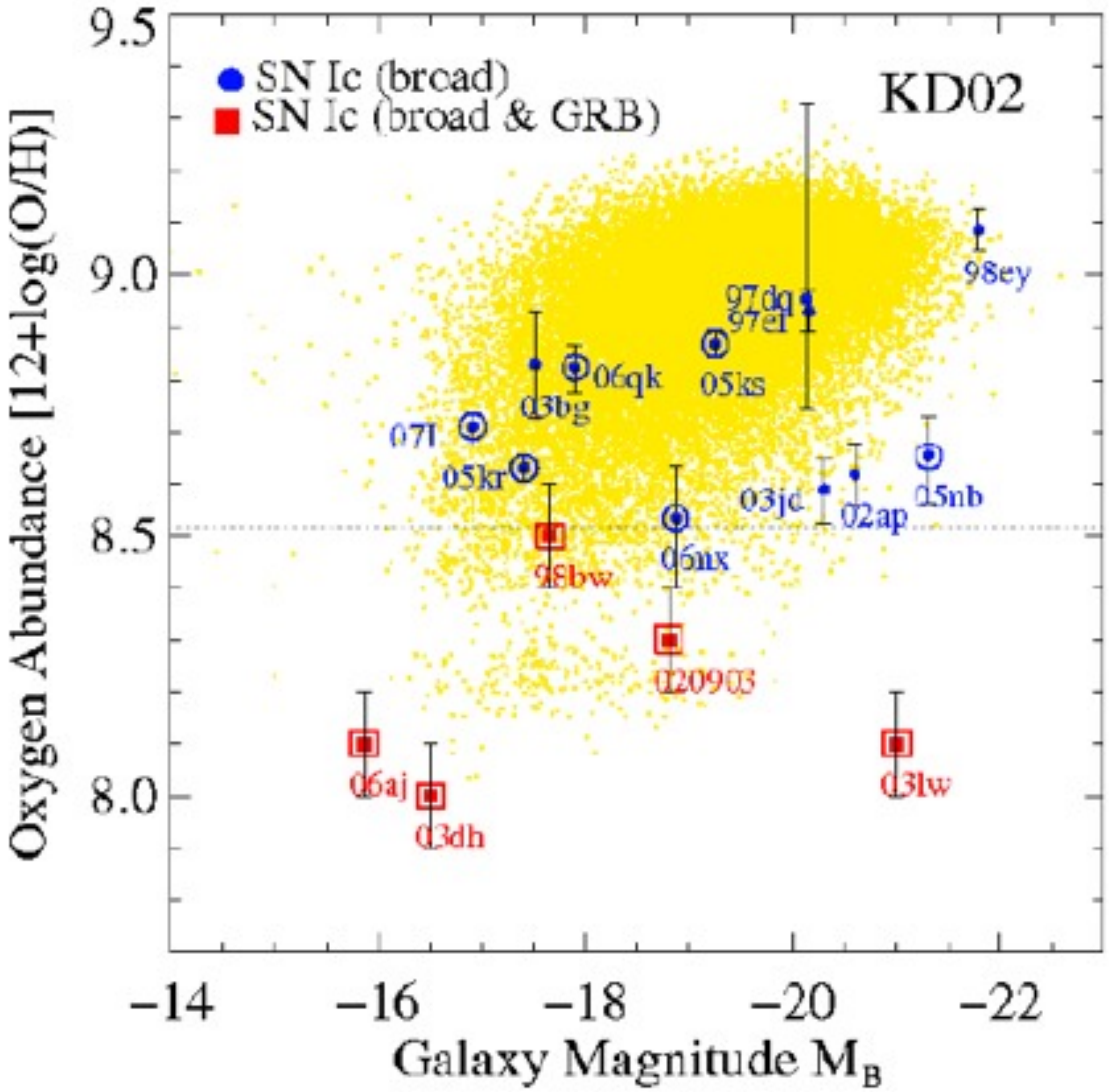
Environment

- 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)



PISNe as possible candidate

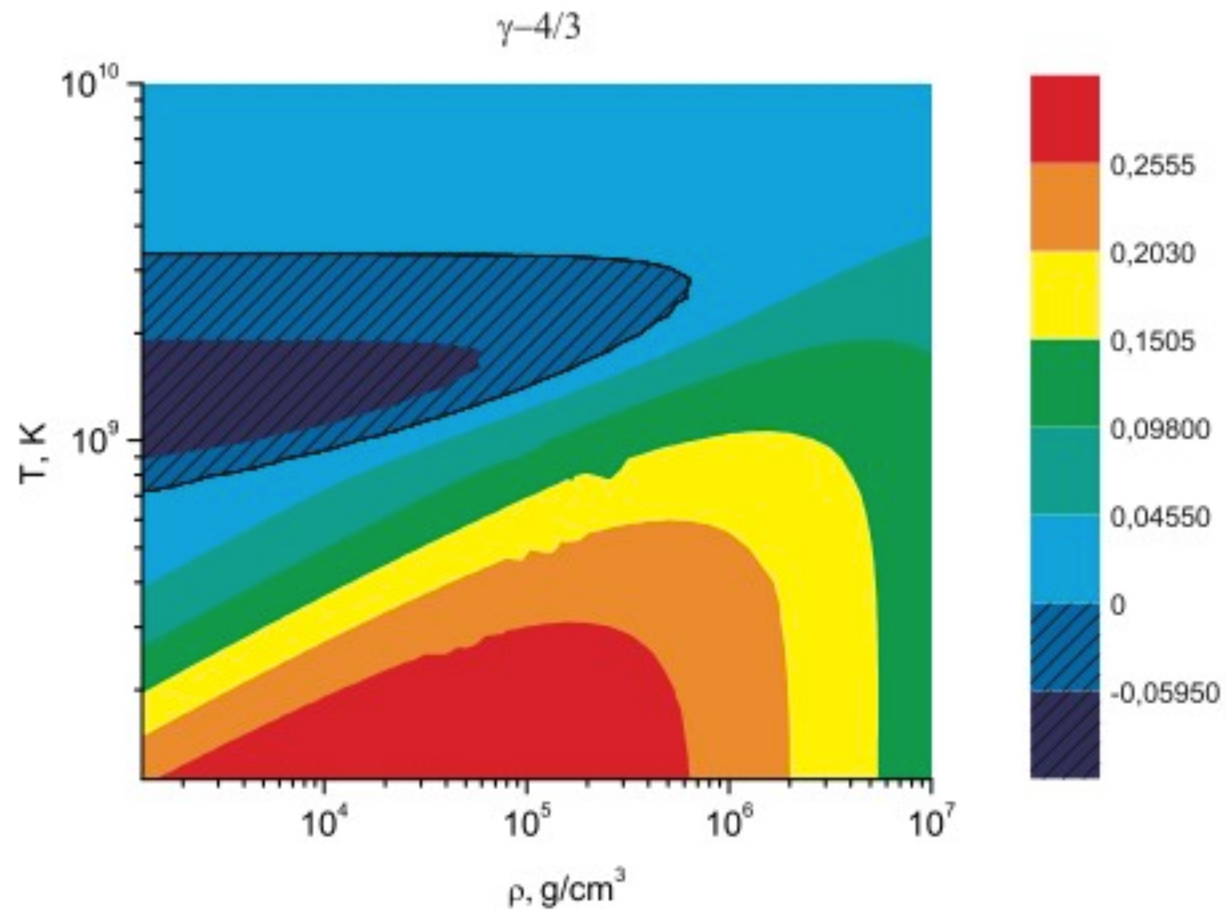
- Explosive process different form the CC SN
- Low metallicity
- High Energy budget

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

P. Chardonnet, V. Chechetkin and L. Titarchuk

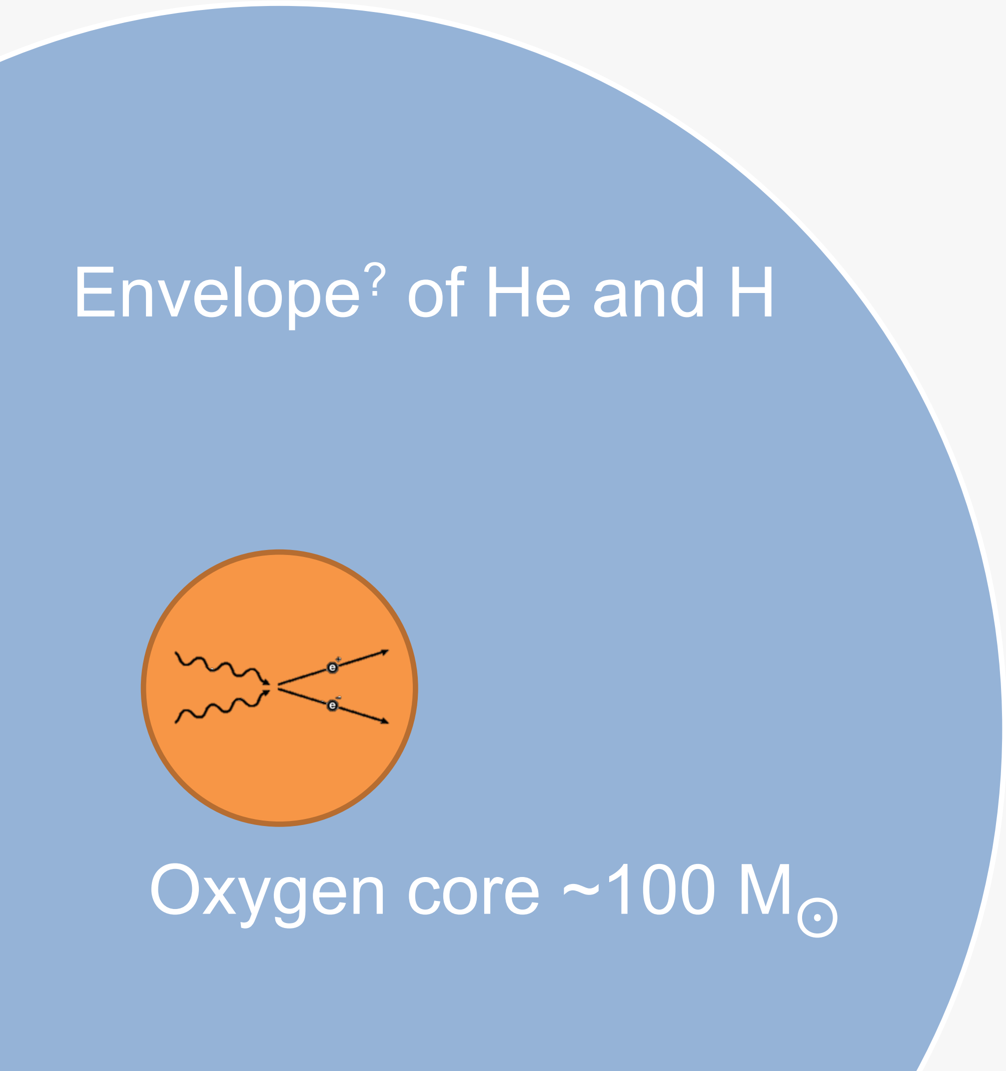
Astrophys.Space Sci.325:153-161,2010.

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



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

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

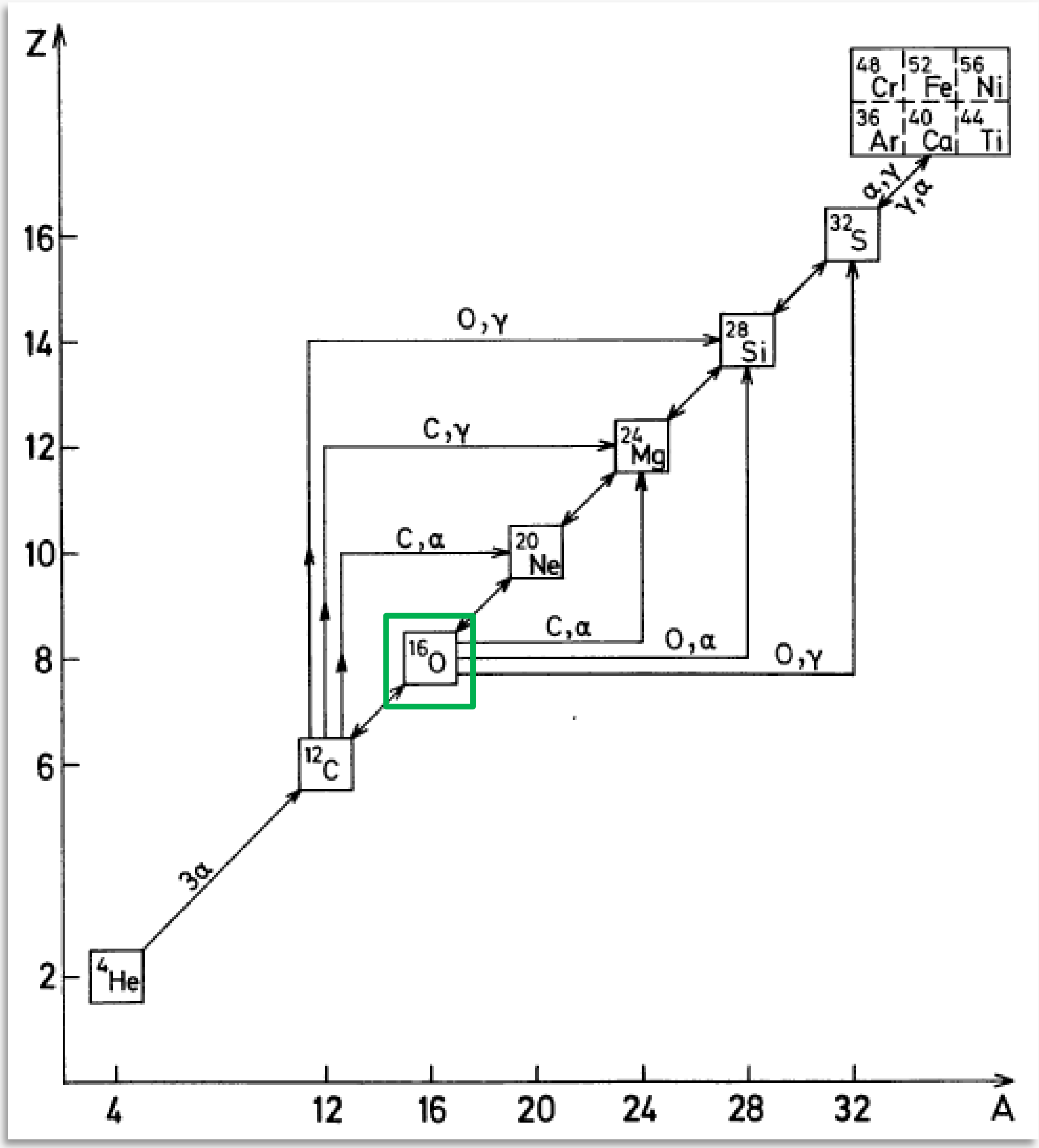
Numerical simulations

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

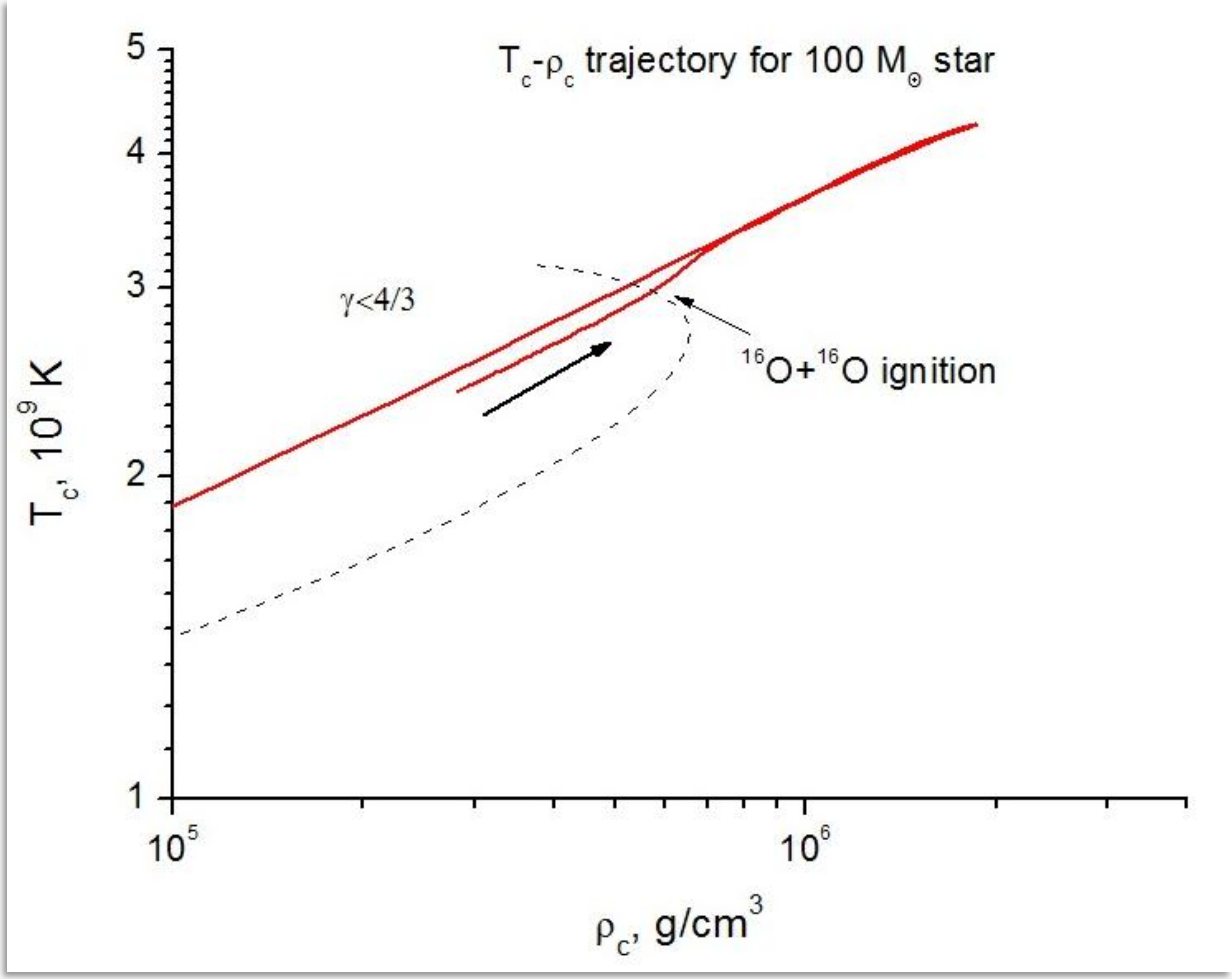
Nuclear burning

Neutrino losses

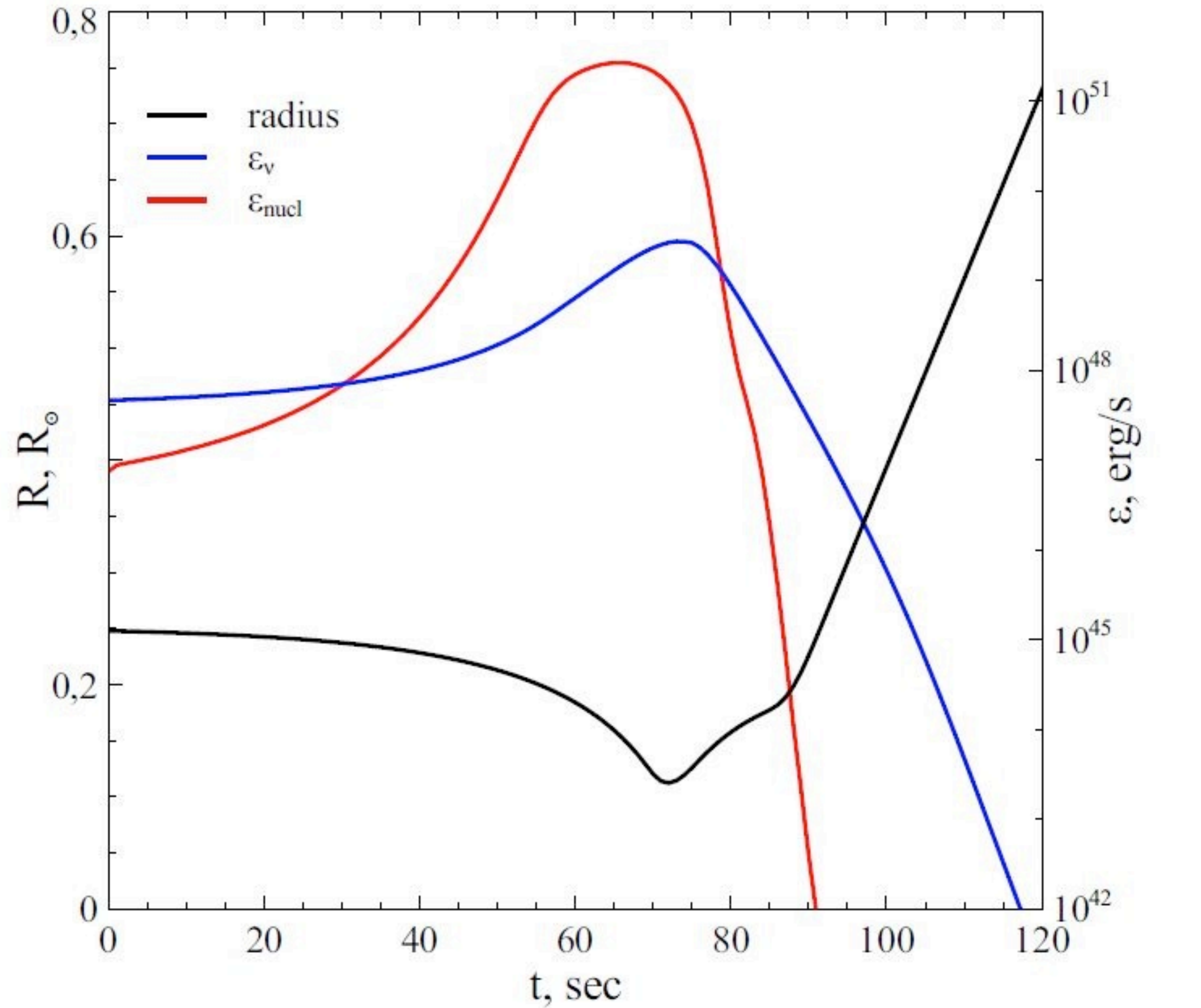
Nuclear reactions



Results

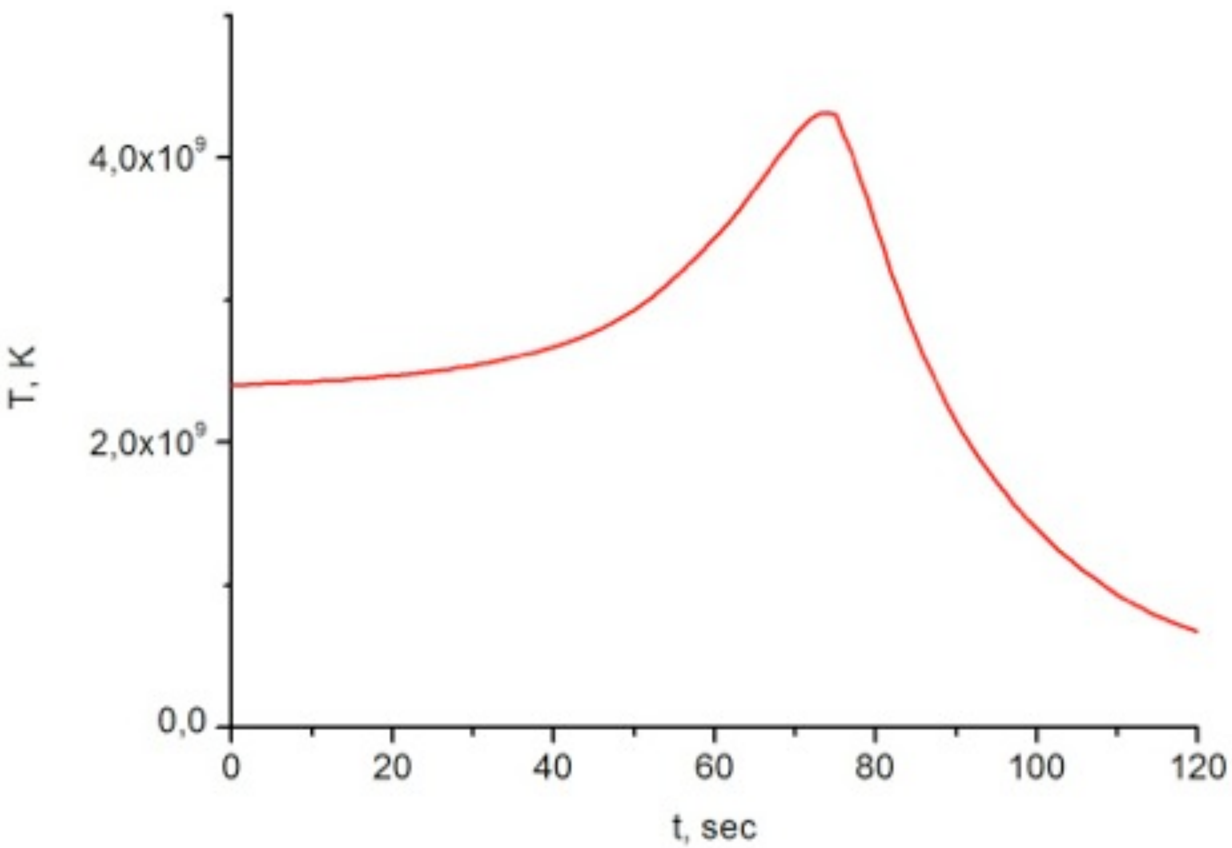


Tc-ρc trajectory for 100 M⊙ star
γ<4/3
16O+16O ignition
Tc, 10^9 K
ρc, g/cm3
5
4
3
2
1
10^5
10^6

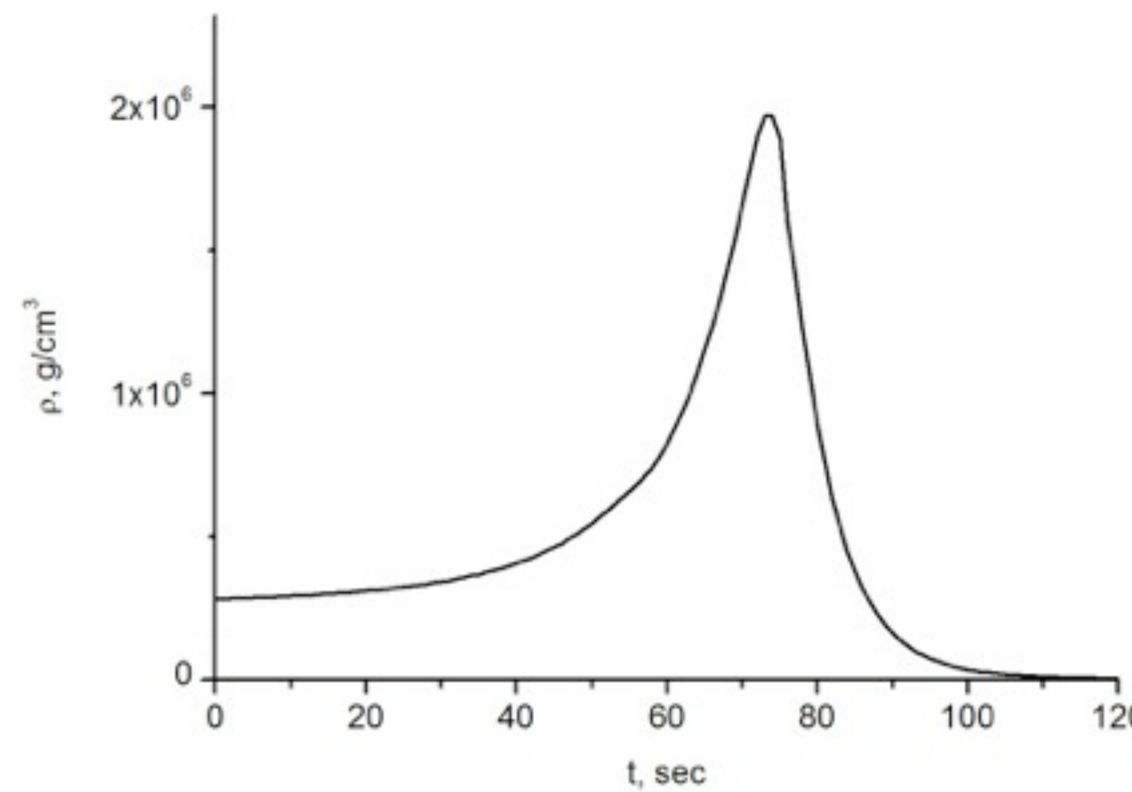

0,8
0,6
0,2
0
R, R⊙
radius
εν
εnucl
10^{51}
10^{48}
10^{45}
10^{42}
ε, erg/s
0
20
40
60
80
100
120
t, sec

Results: density – temperature

Central temperature

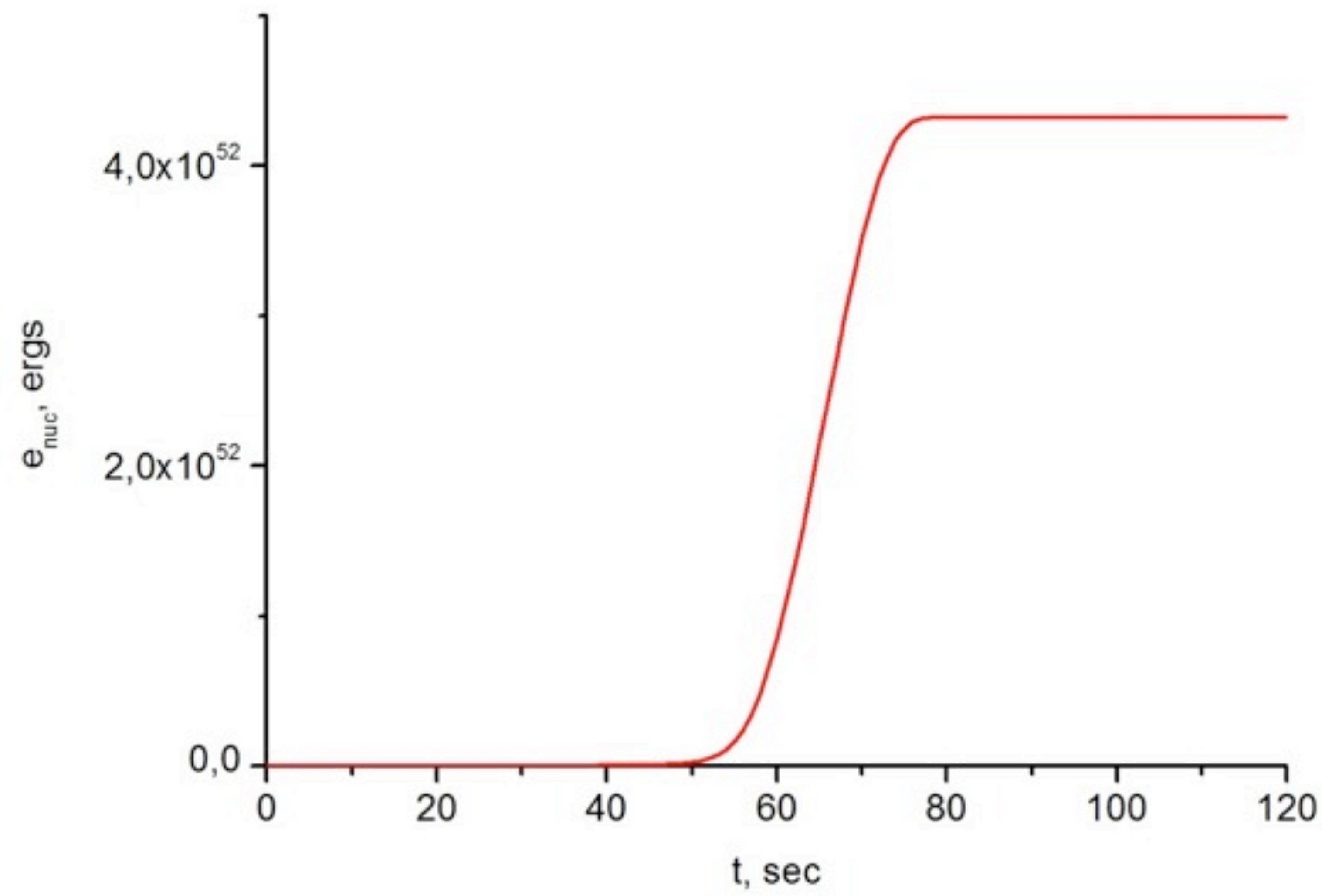


Central density

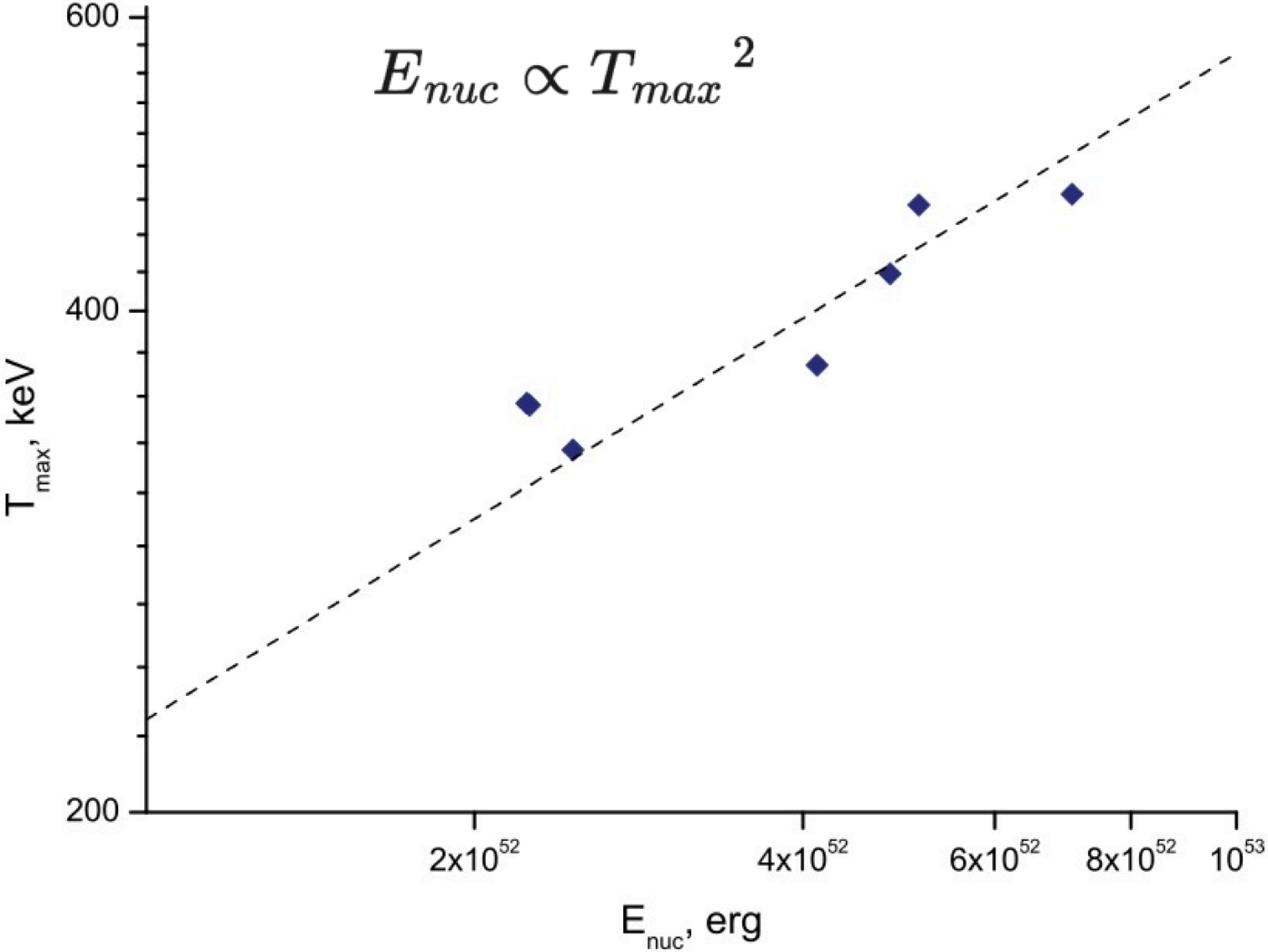


Results: timescale

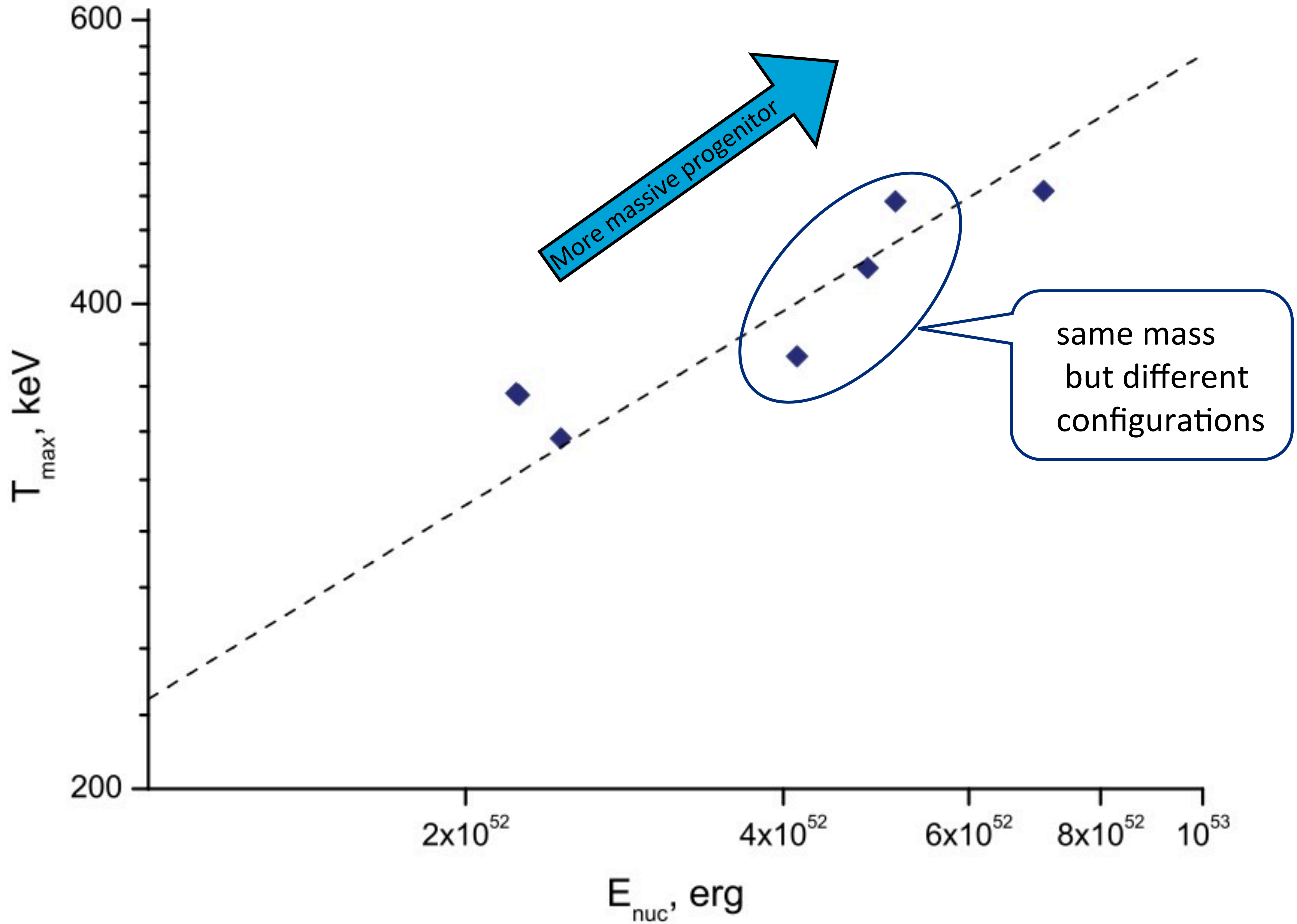
Nuclear burning energy



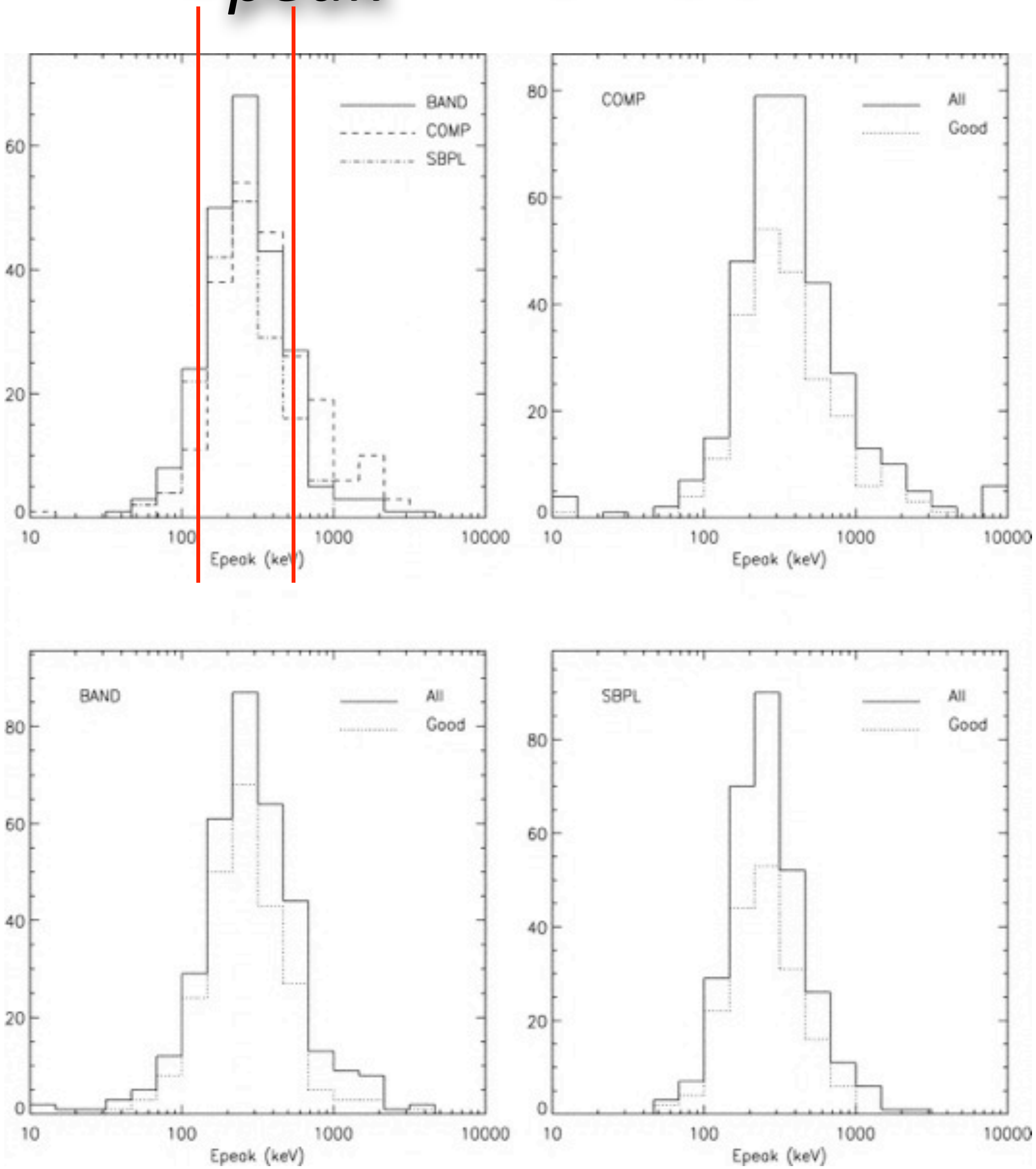
$M/M_\odot$	$\rho_c, 10^5 g/cc$	T_{max}, keV	$E_{nucl}, 10^{52}$ ergs	fate
60	0.87	352	2.23	explosion
60	1.15	351	2.25	explosion
78	0.60	—	—	collapse
78	2.00	—	—	collapse
78	3.00	330	2.46	explosion
100	1.00	—	—	collapse
100	1.65	—	—	collapse
100	2.00	—	—	collapse
100	2.25	—	—	collapse
100	2.40	463	5.11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


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

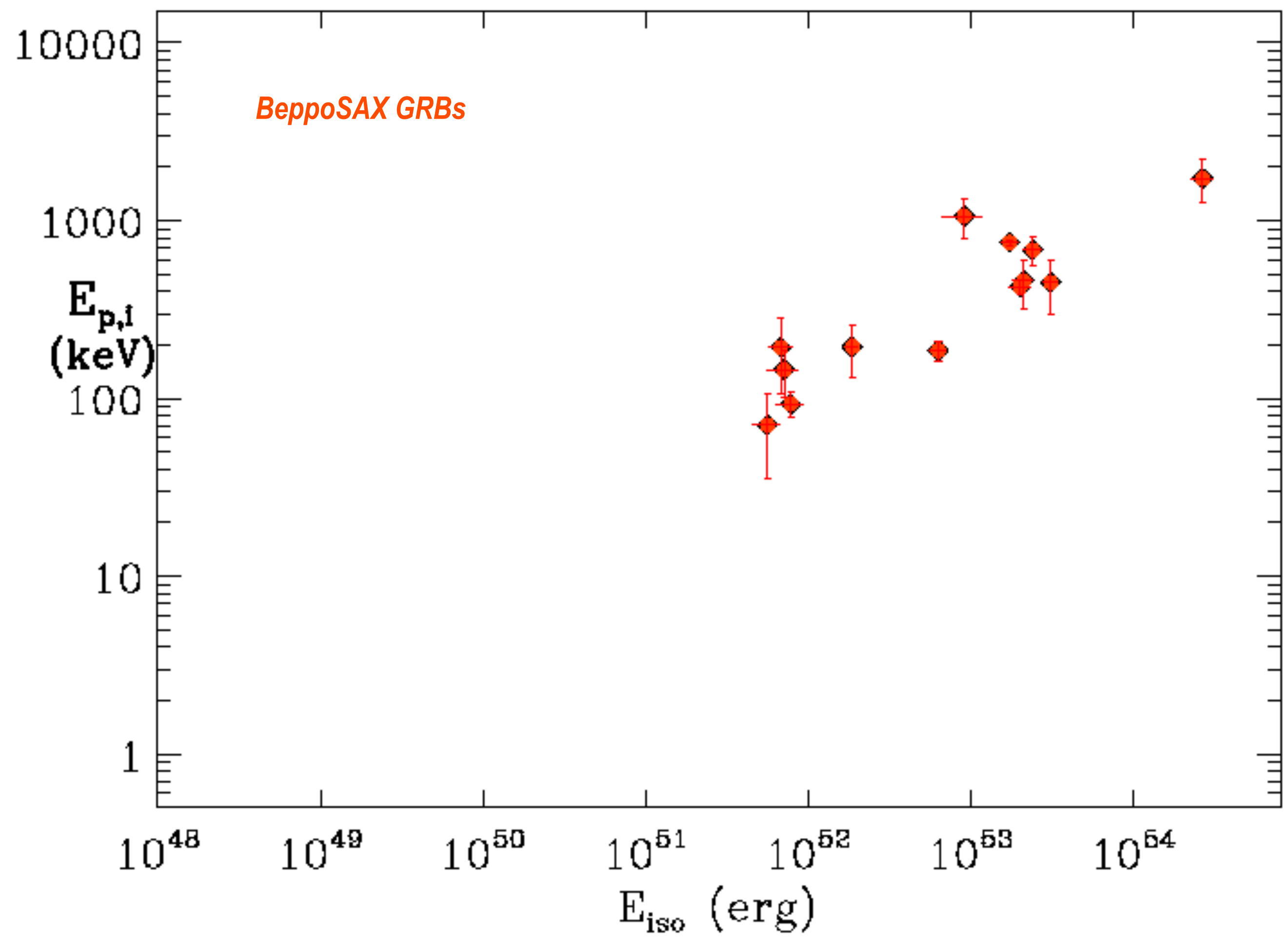
E_{peak} in GRBs



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

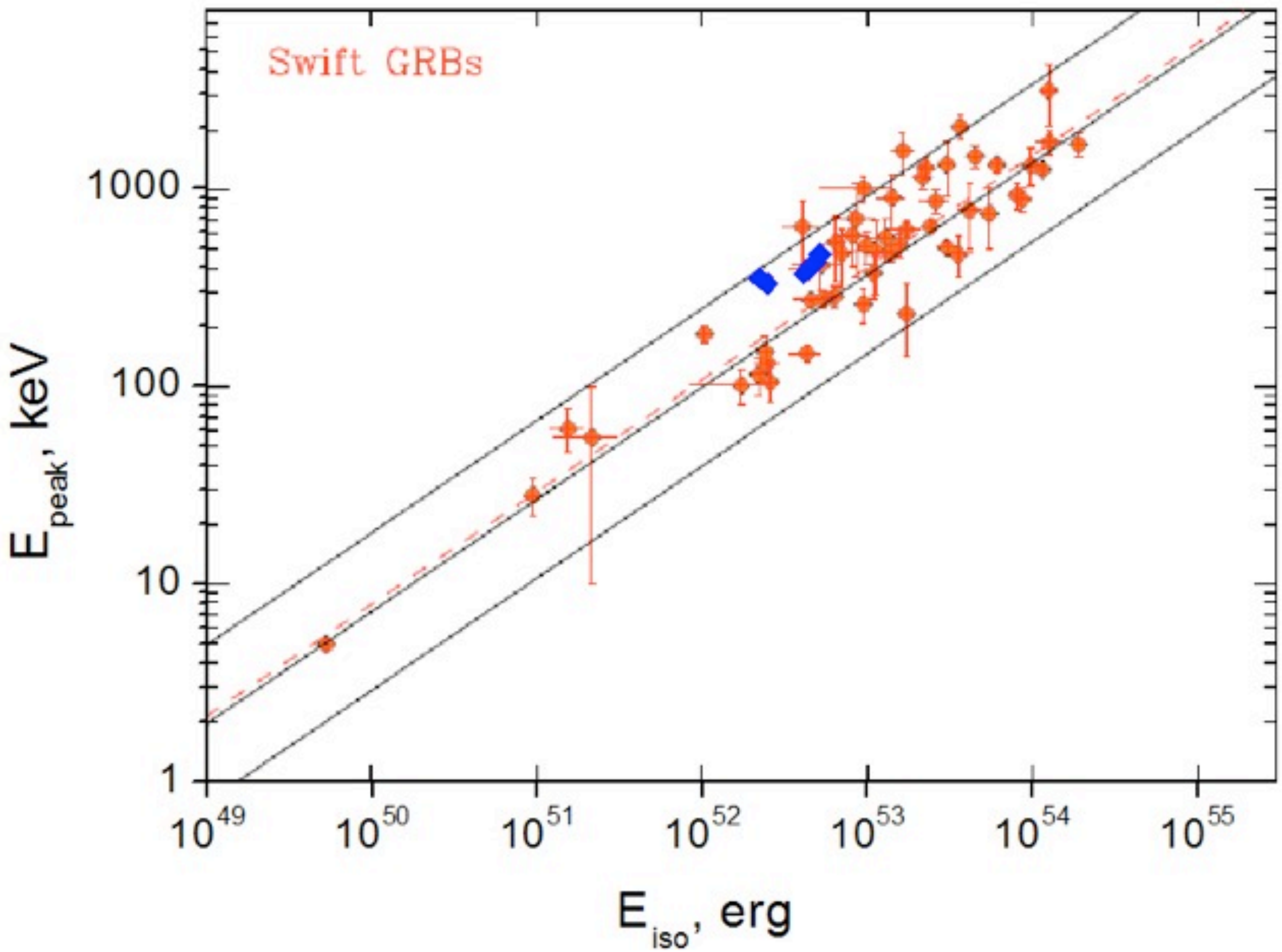
Amati et al. (A&A 2002)

$$T_{max}$$



$$E_{nuc}$$

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



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

On a physical interpretation of the Amati Relation

Since source of energy is nuclear burning

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

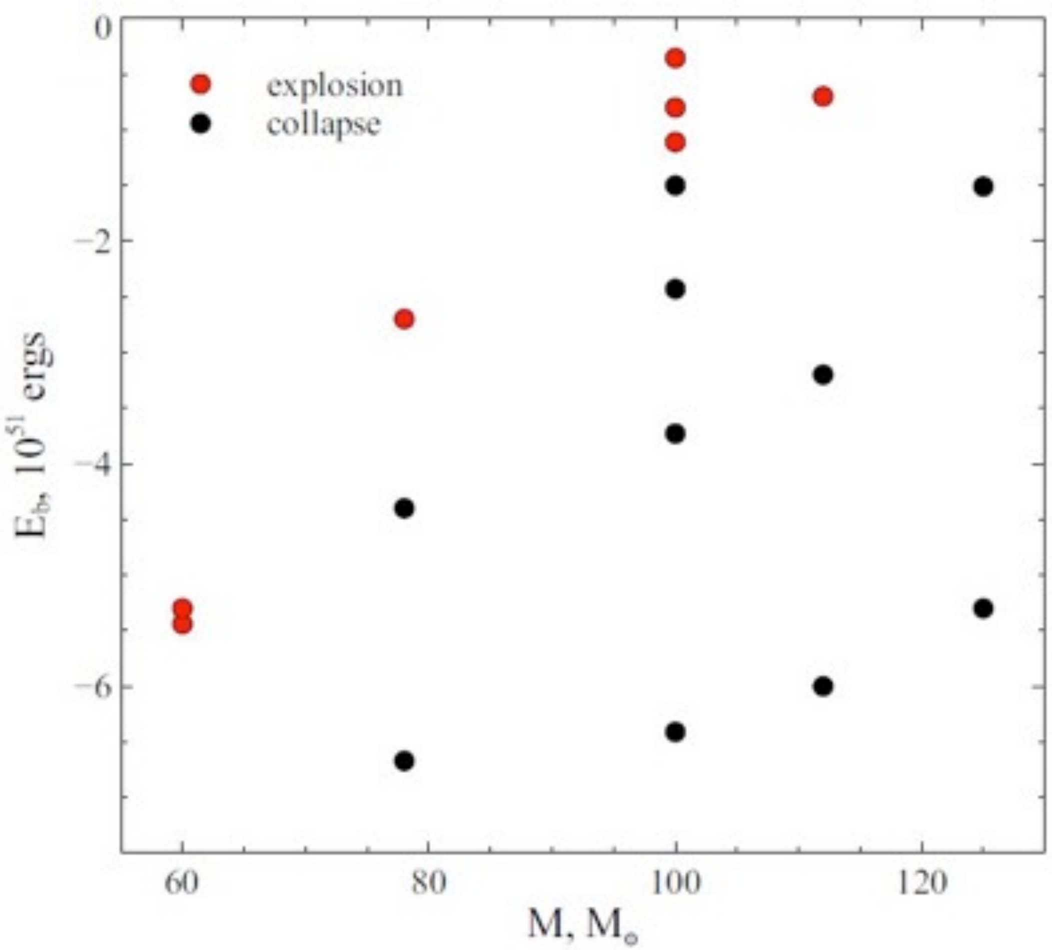
$$\frac{dT}{dR} = \frac{3\kappa\rho L}{16\pi a c T^3 R^2}$$

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

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

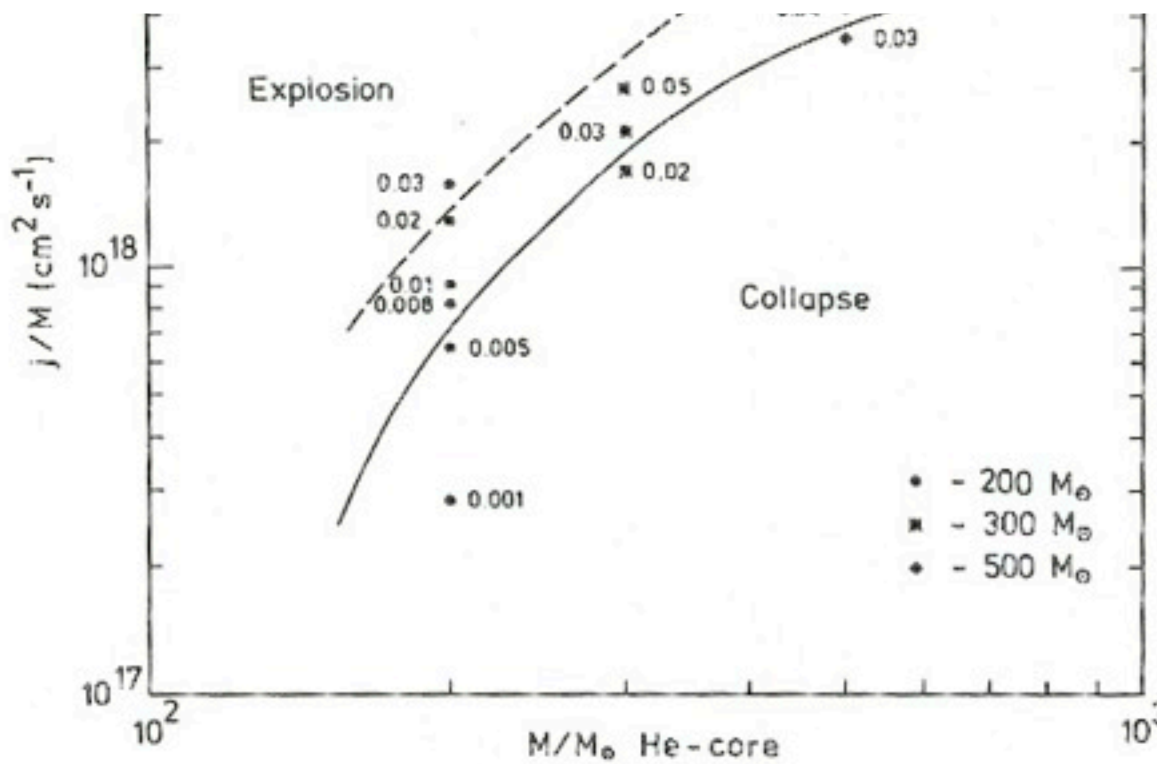
$$\boxed{T^2 \sim E_{Nucl}}$$

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

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

But new questions...

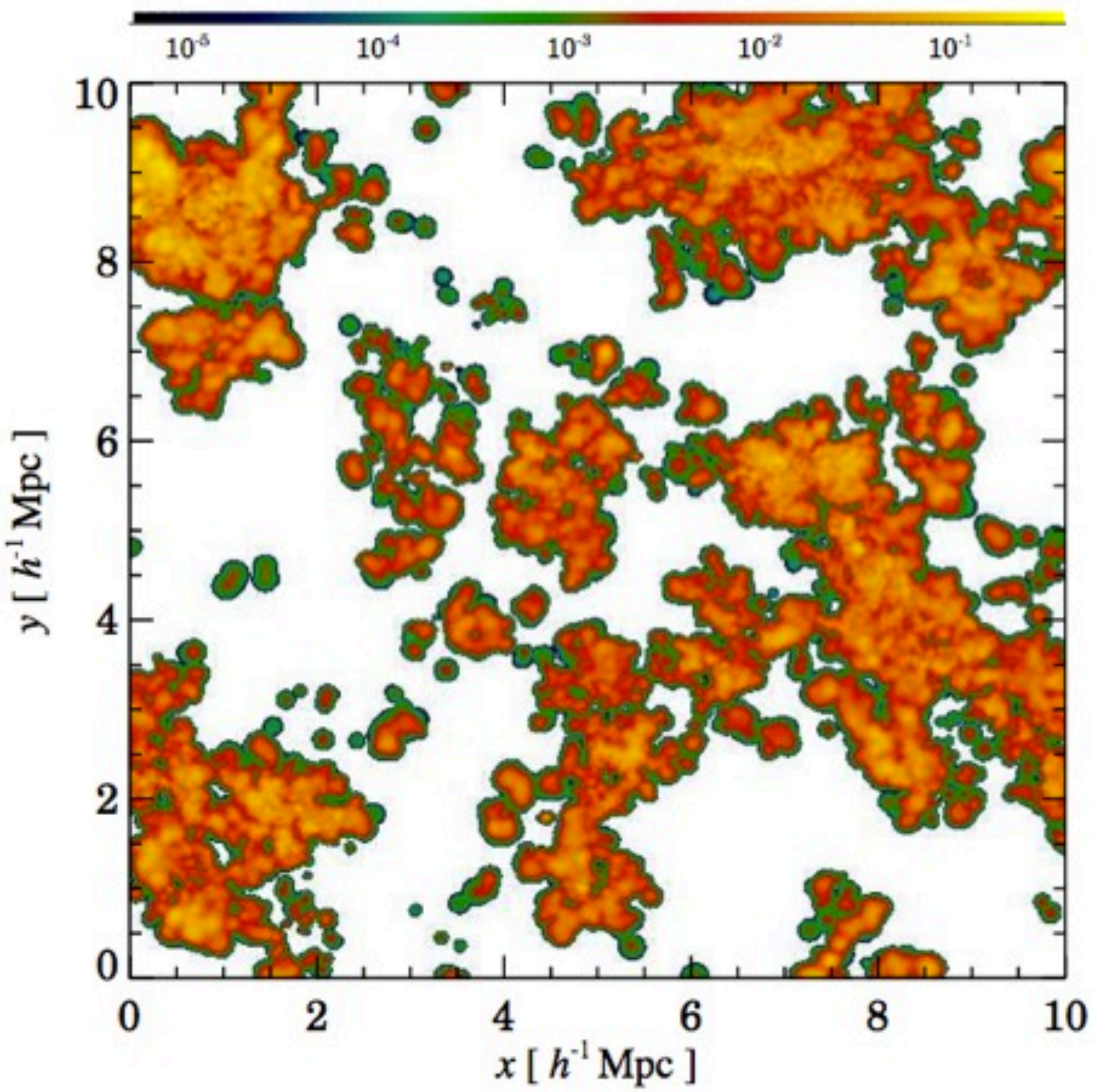
Q2: Are all PISNe doing GRBs explosion ?

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

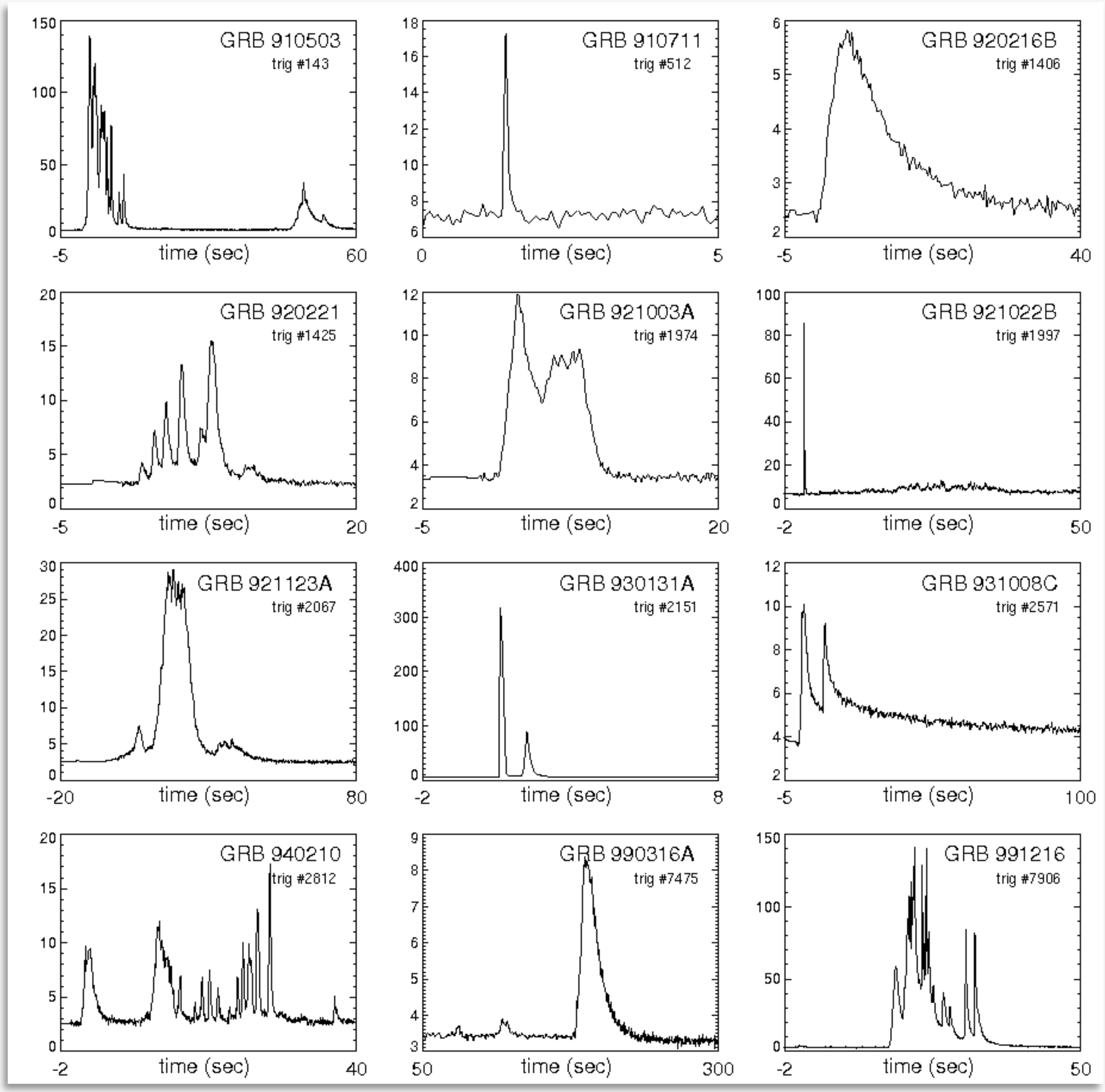
Q4: How to explain the time variability of the prompt emission ?

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

Temporal properties of GRBs

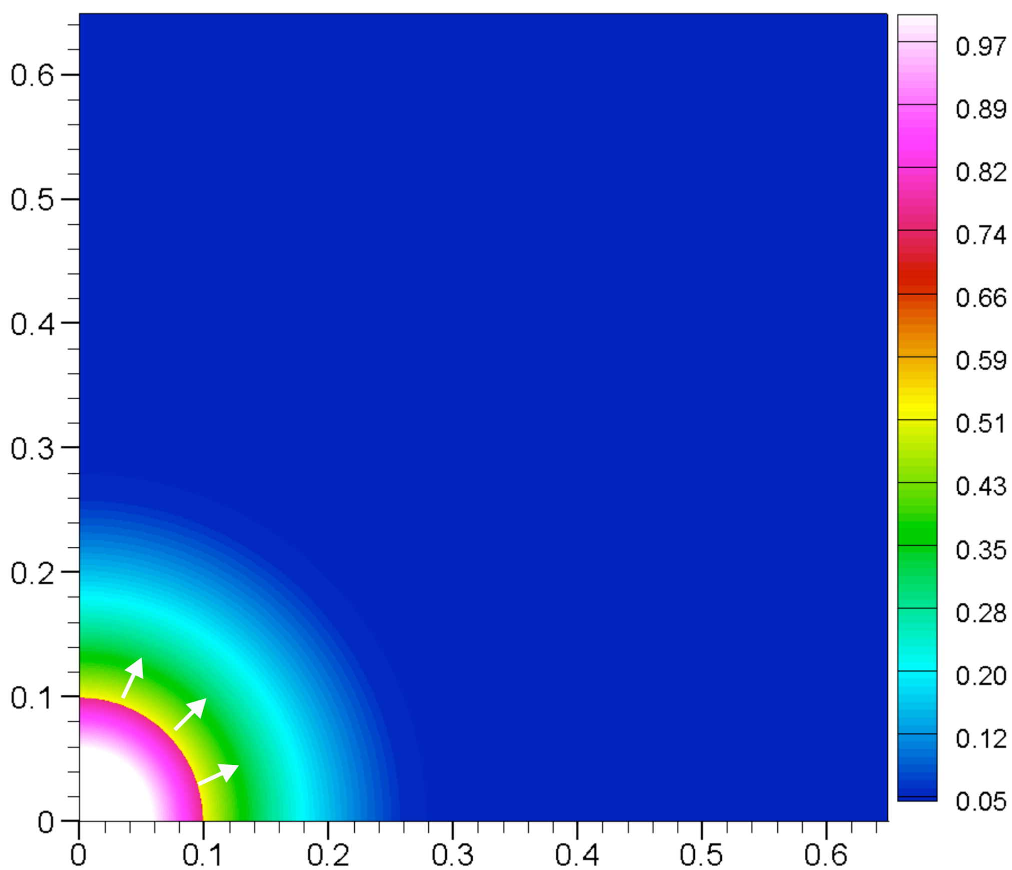


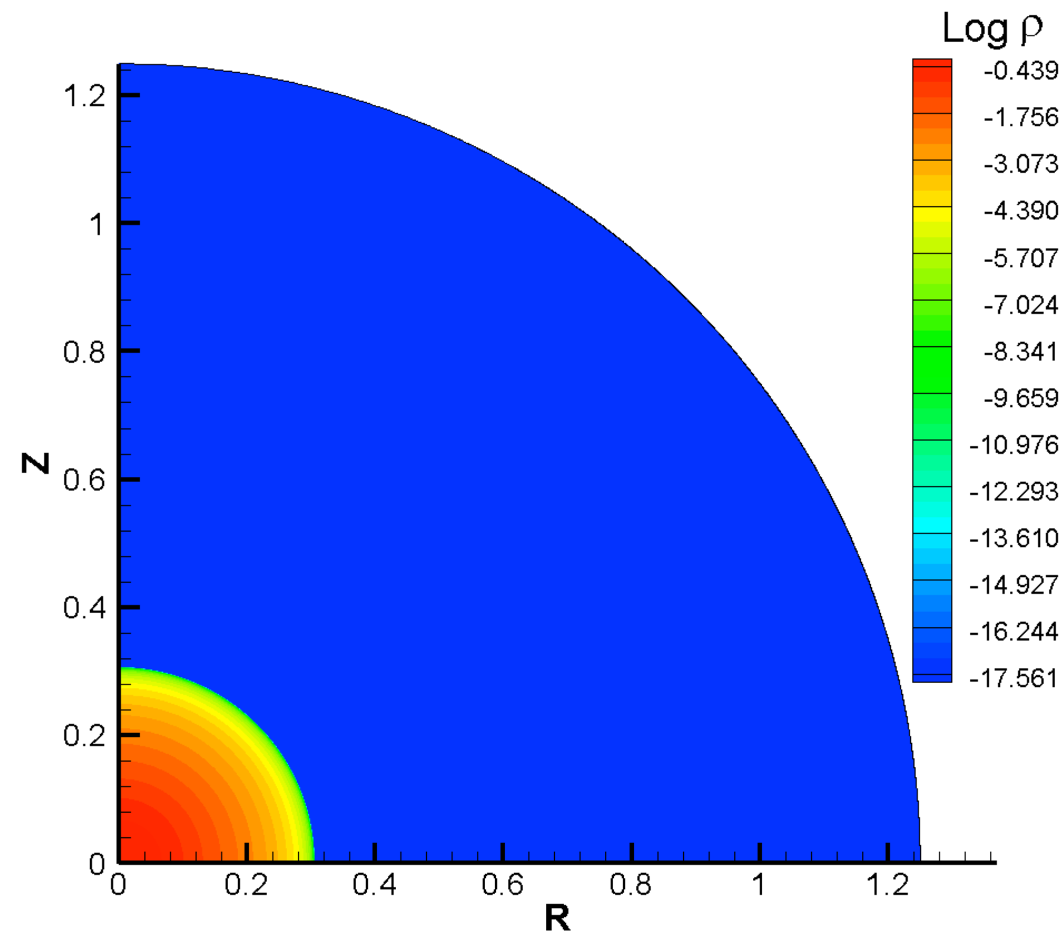
Multidimensional approach

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

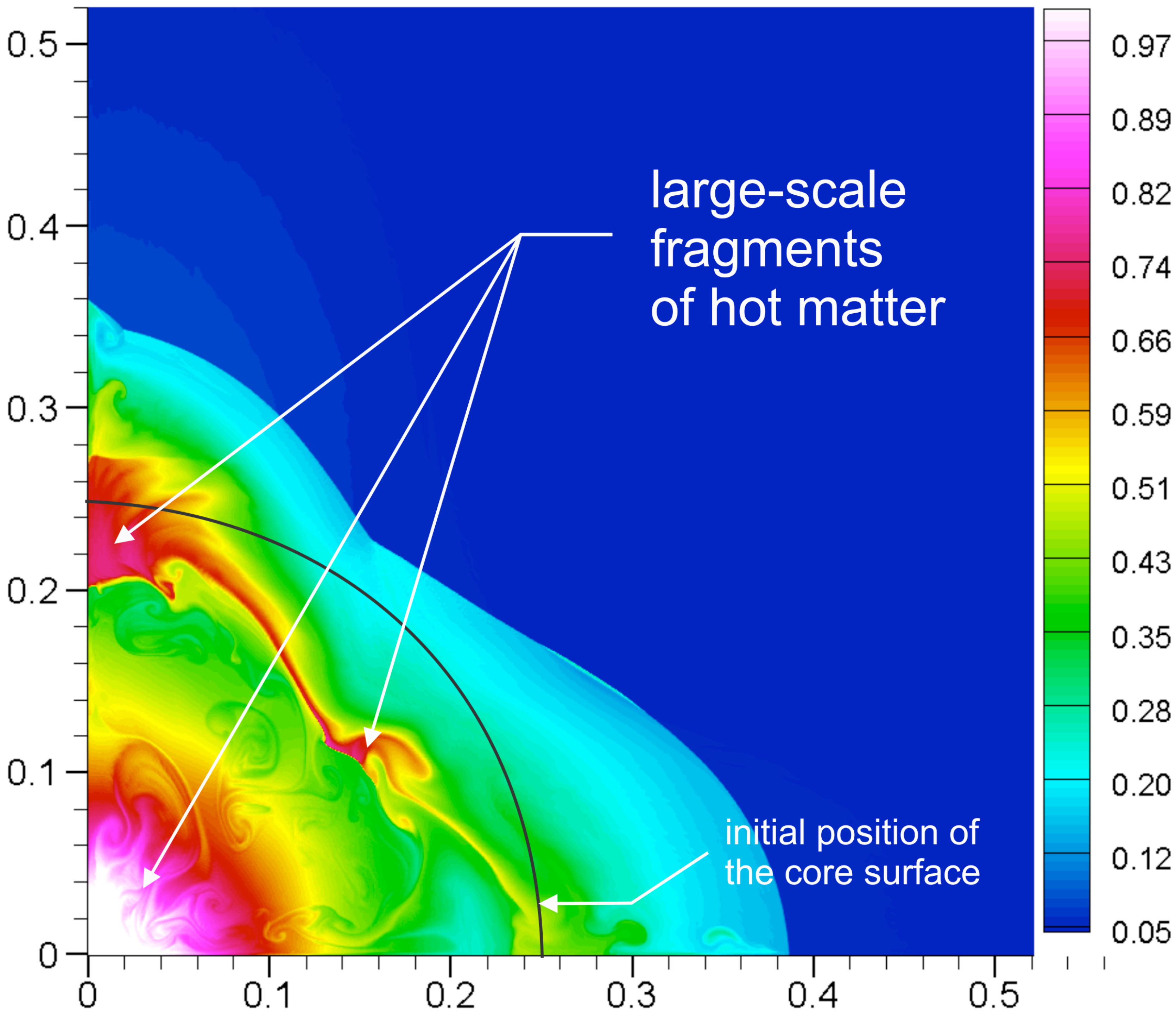
PPML algorithm described in Ustyugov et al. (2009)

Initial conditions





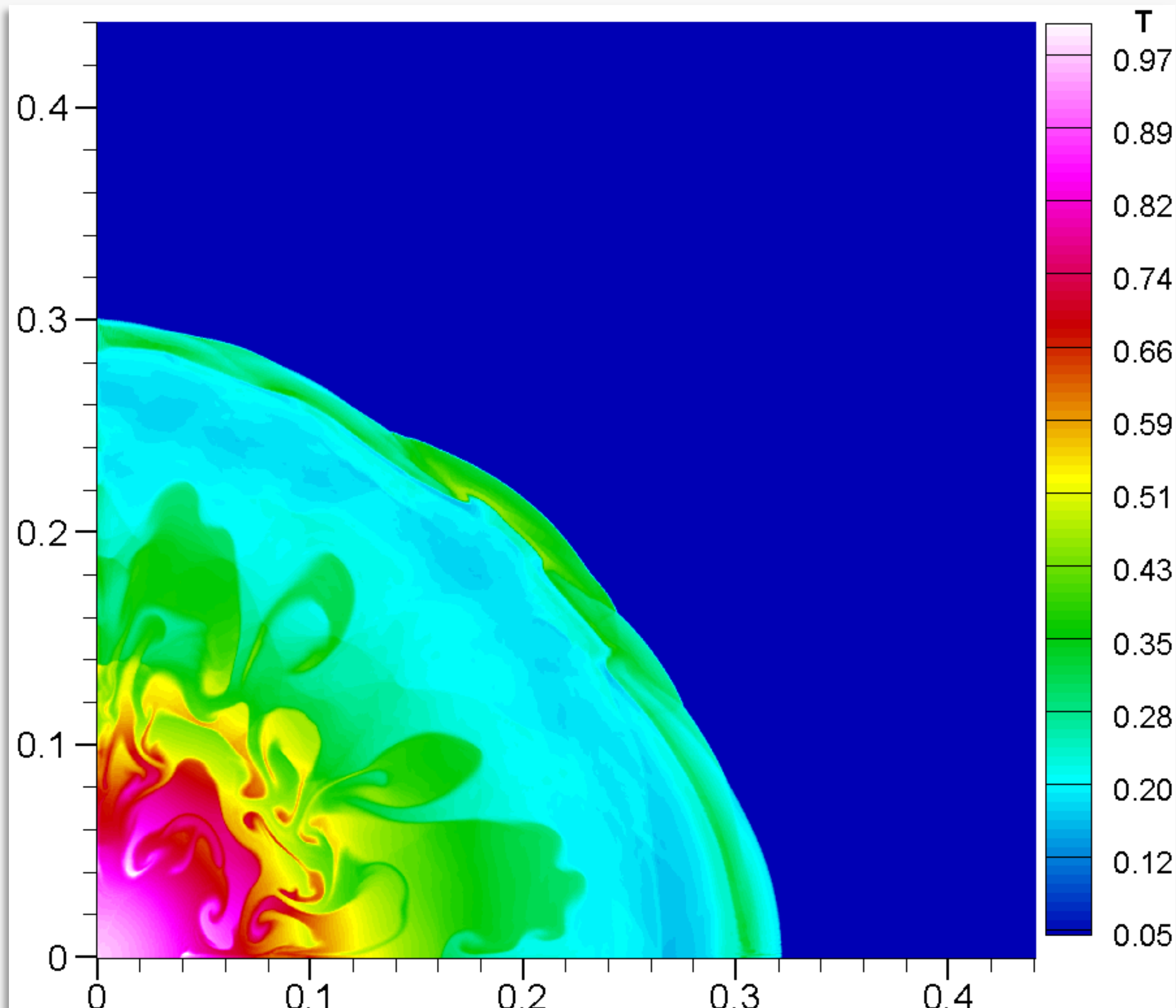
The energy 5. 10^52 ergs was deposited in the central region . This region contains 60 solar mass.
The pictures were obtained with 2D PPML code in cylindrical geometry (r,z) on 1600 1600 grid.



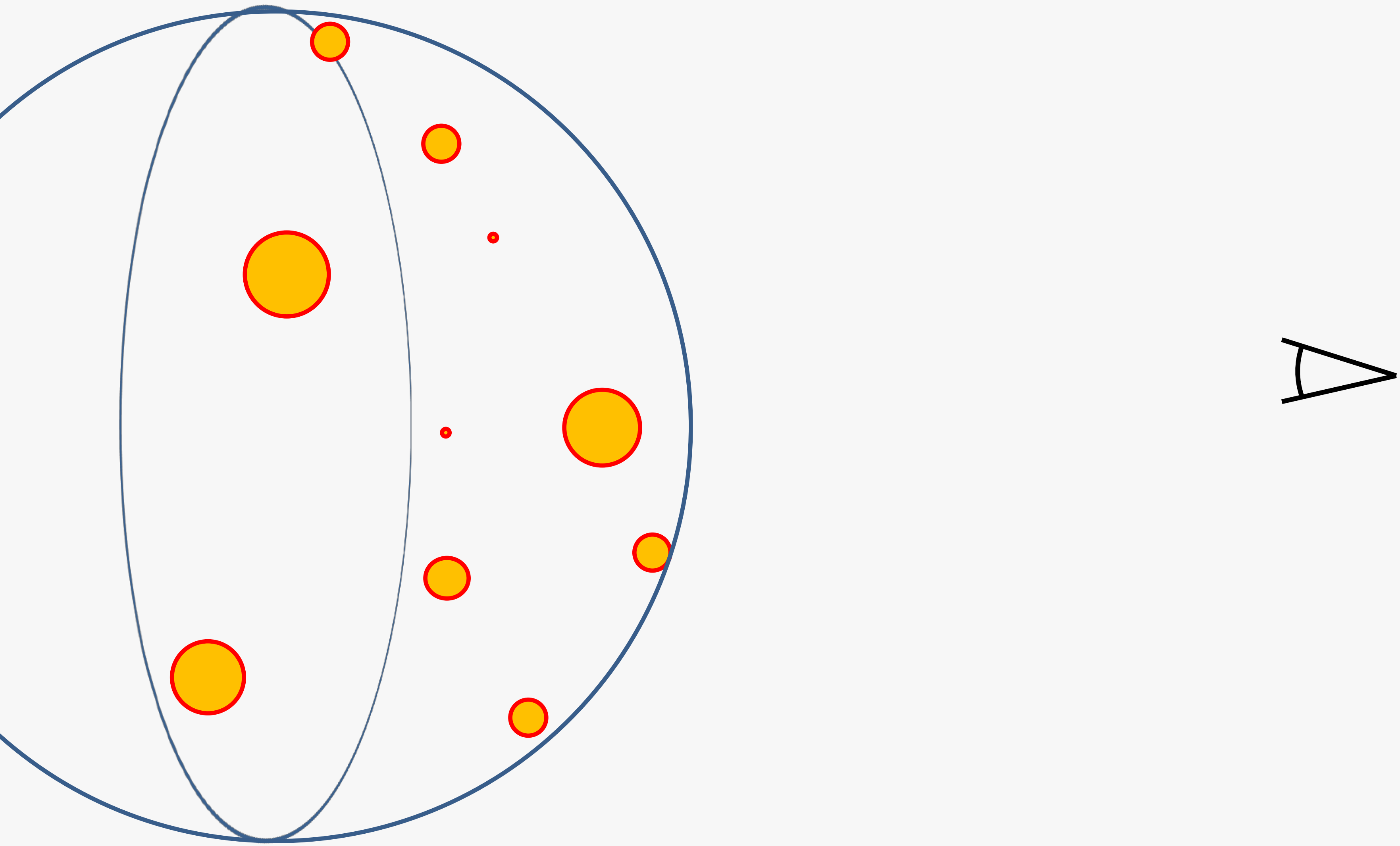
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
large-scale fragments of hot matter
initial position of the core surface
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05

Possible explanation of variability

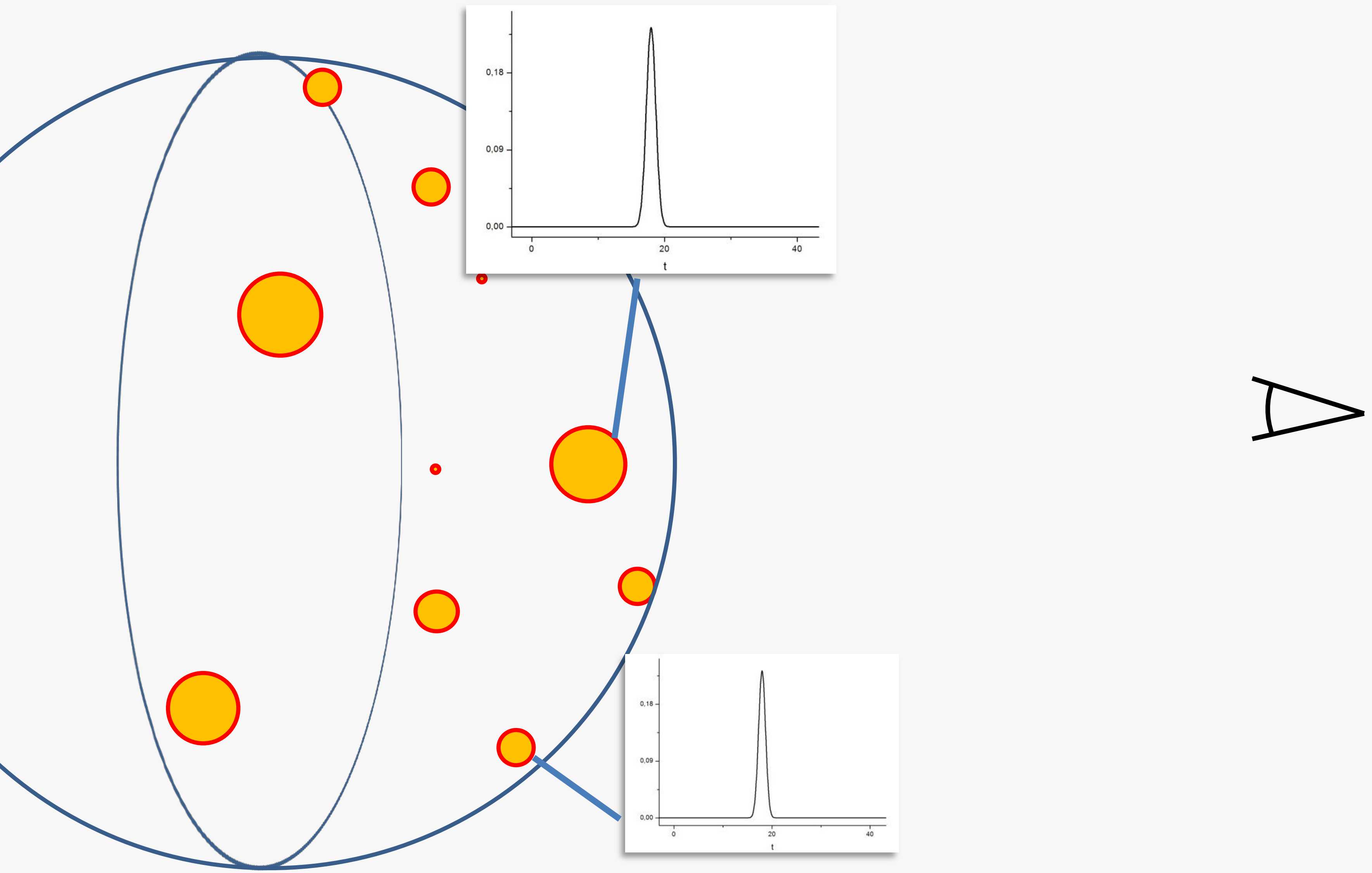
Example of simulation in 2D



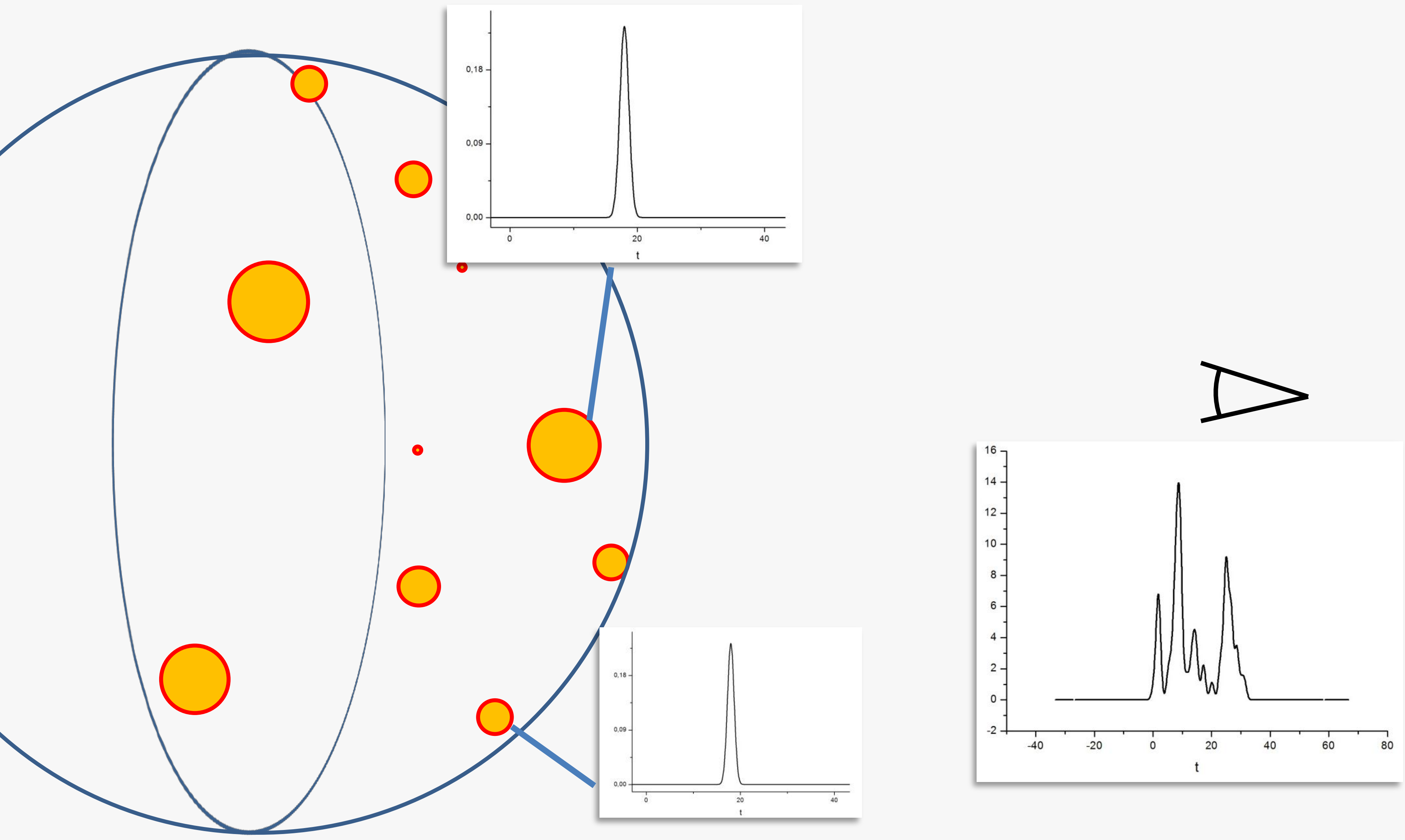
Simulated lightcurves



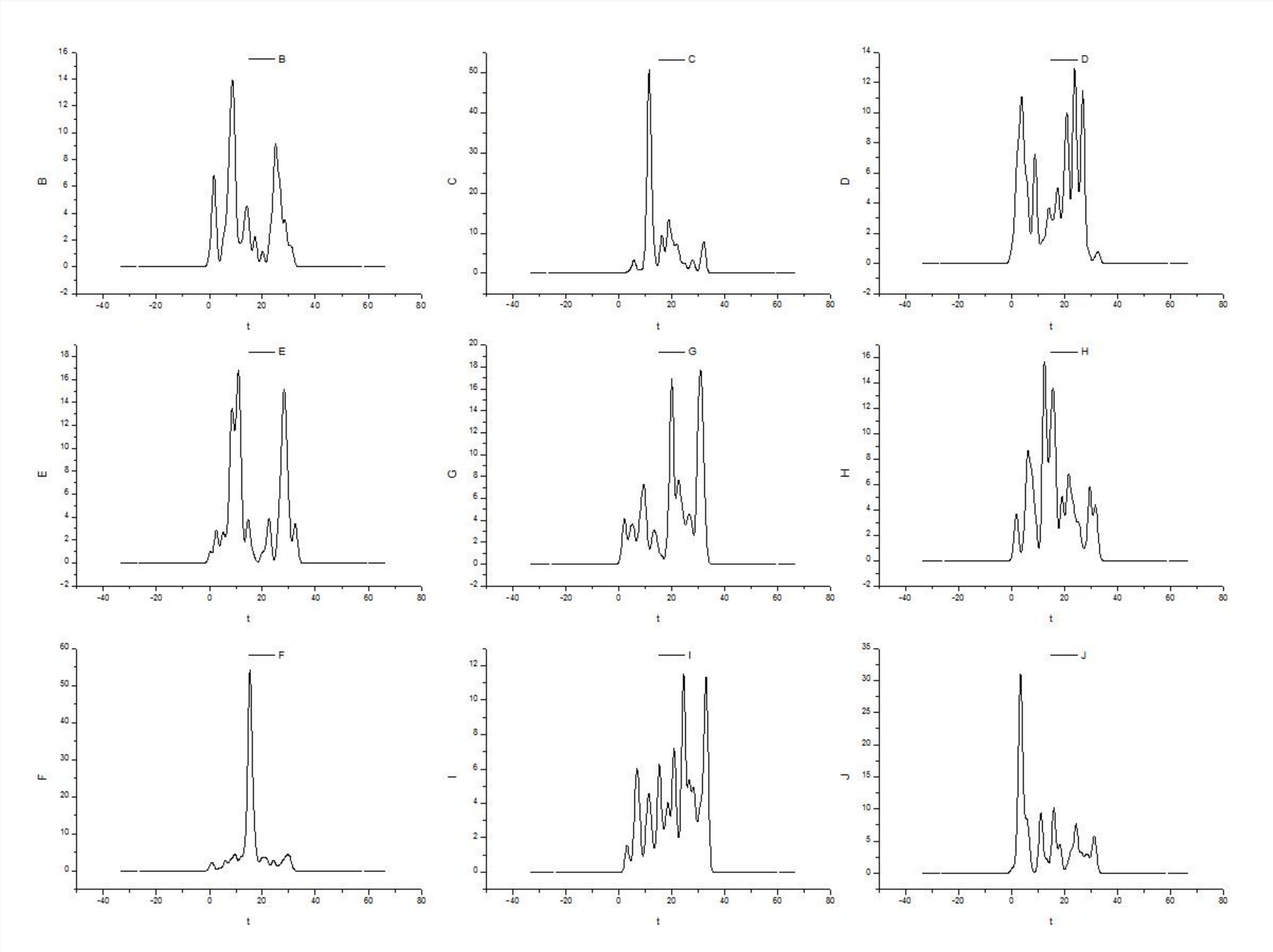
Simulated lightcurves



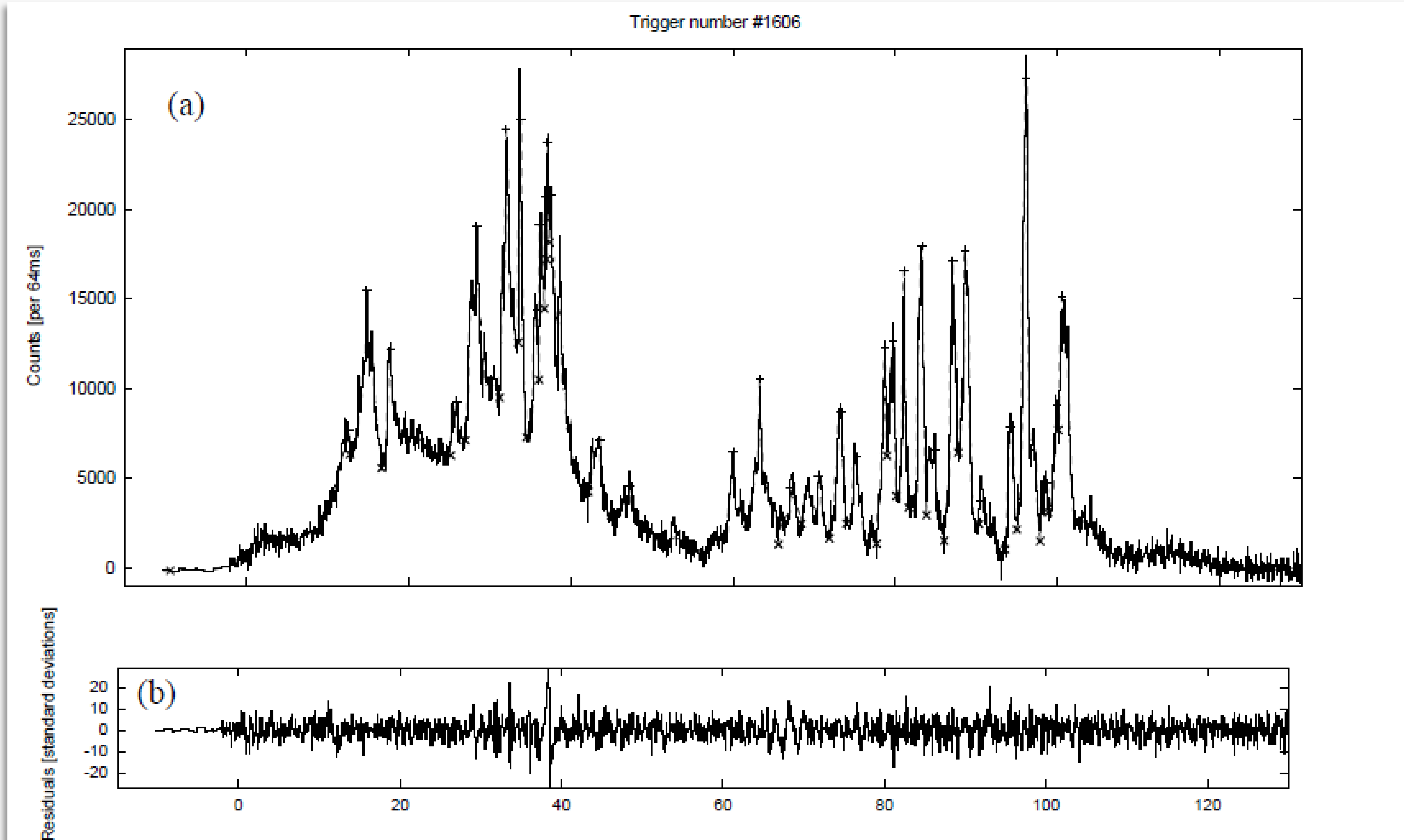
Simulated lightcurves



Simulated lightcurves



Temporal properties of GRBs



[F. Quilligan et al. (2002)]

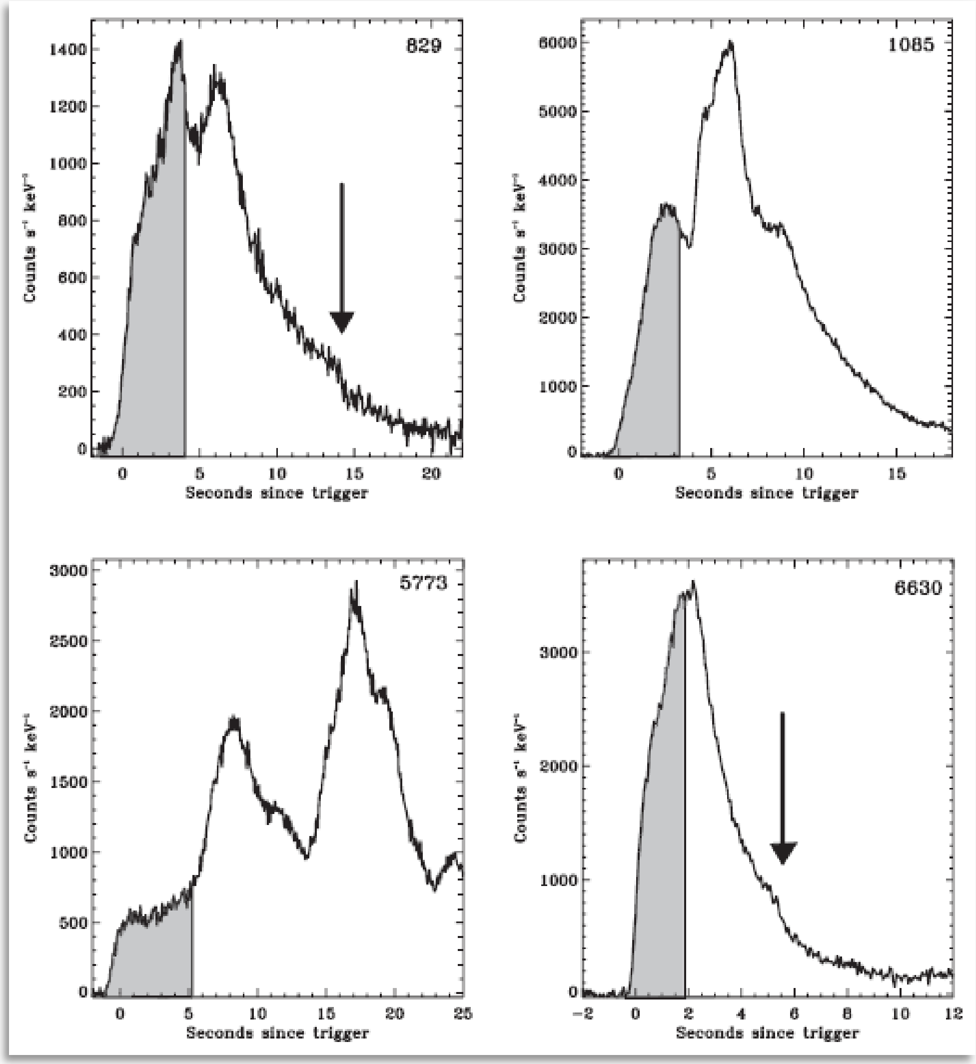
Always new questions...

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

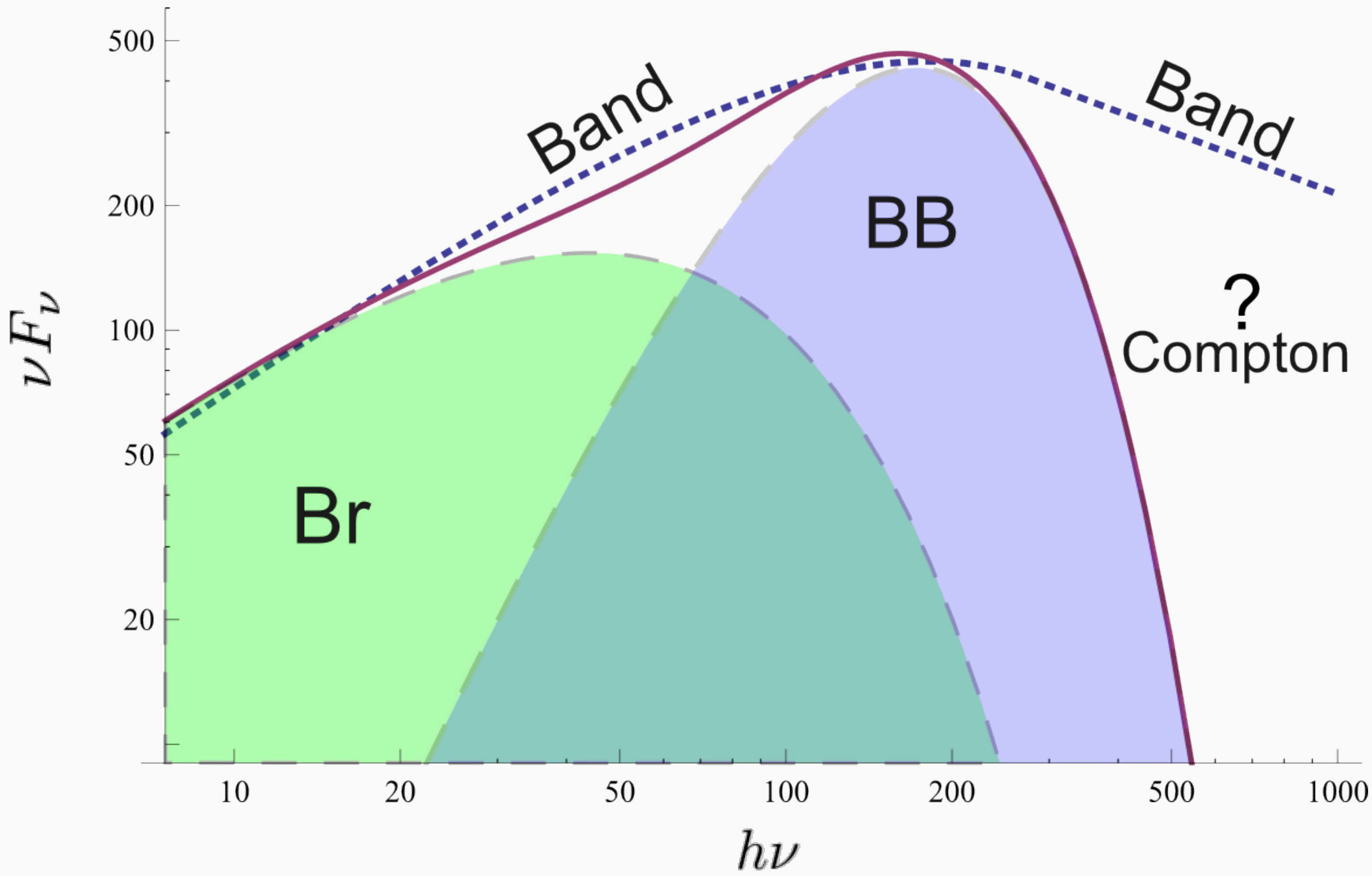
Q7 : Association GRBs with SN Ibc
related to question 2

A1: Spectrum
Black body component



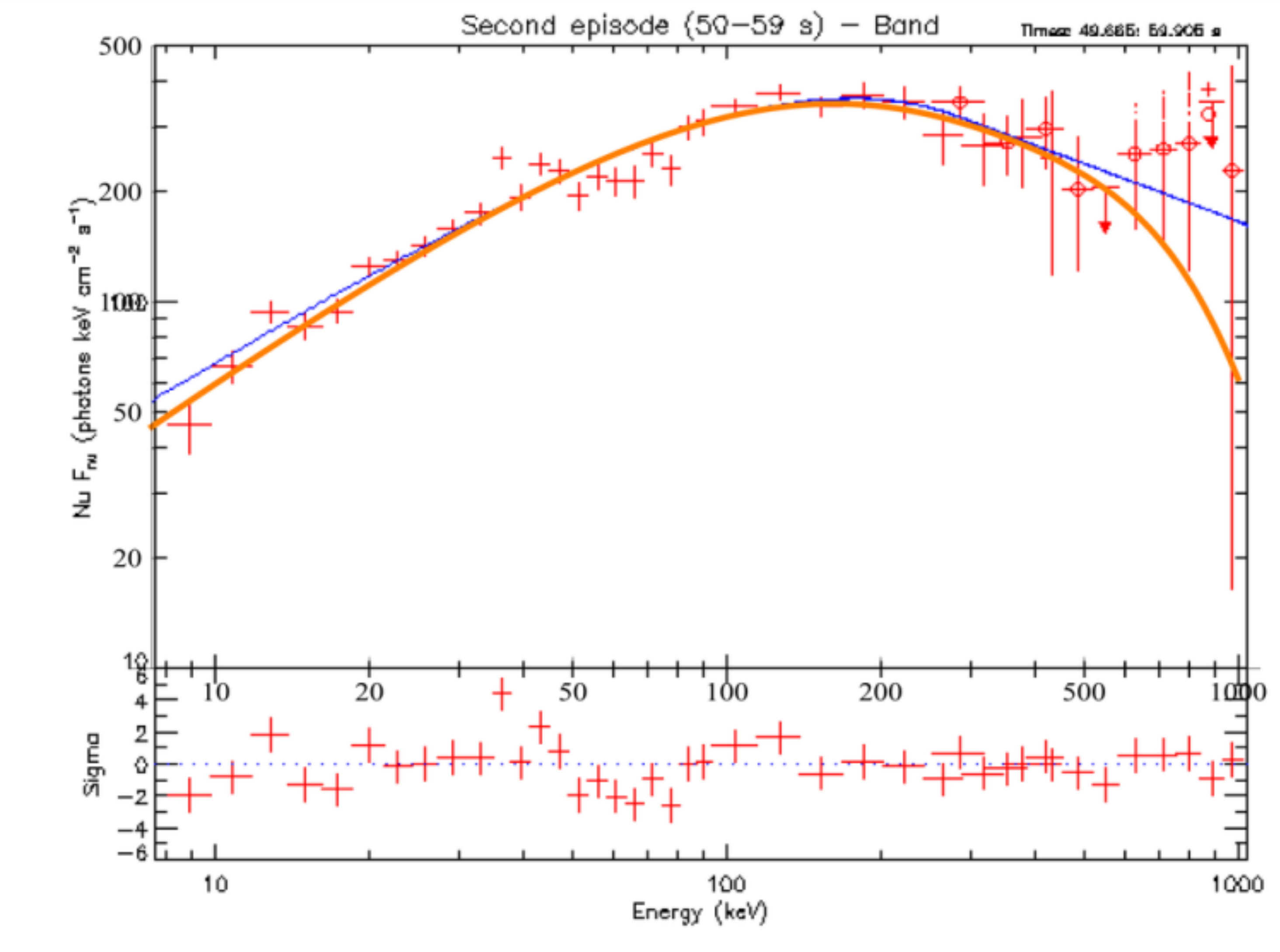
[F. Ryde (2004)]

Spectrum
Possible fit



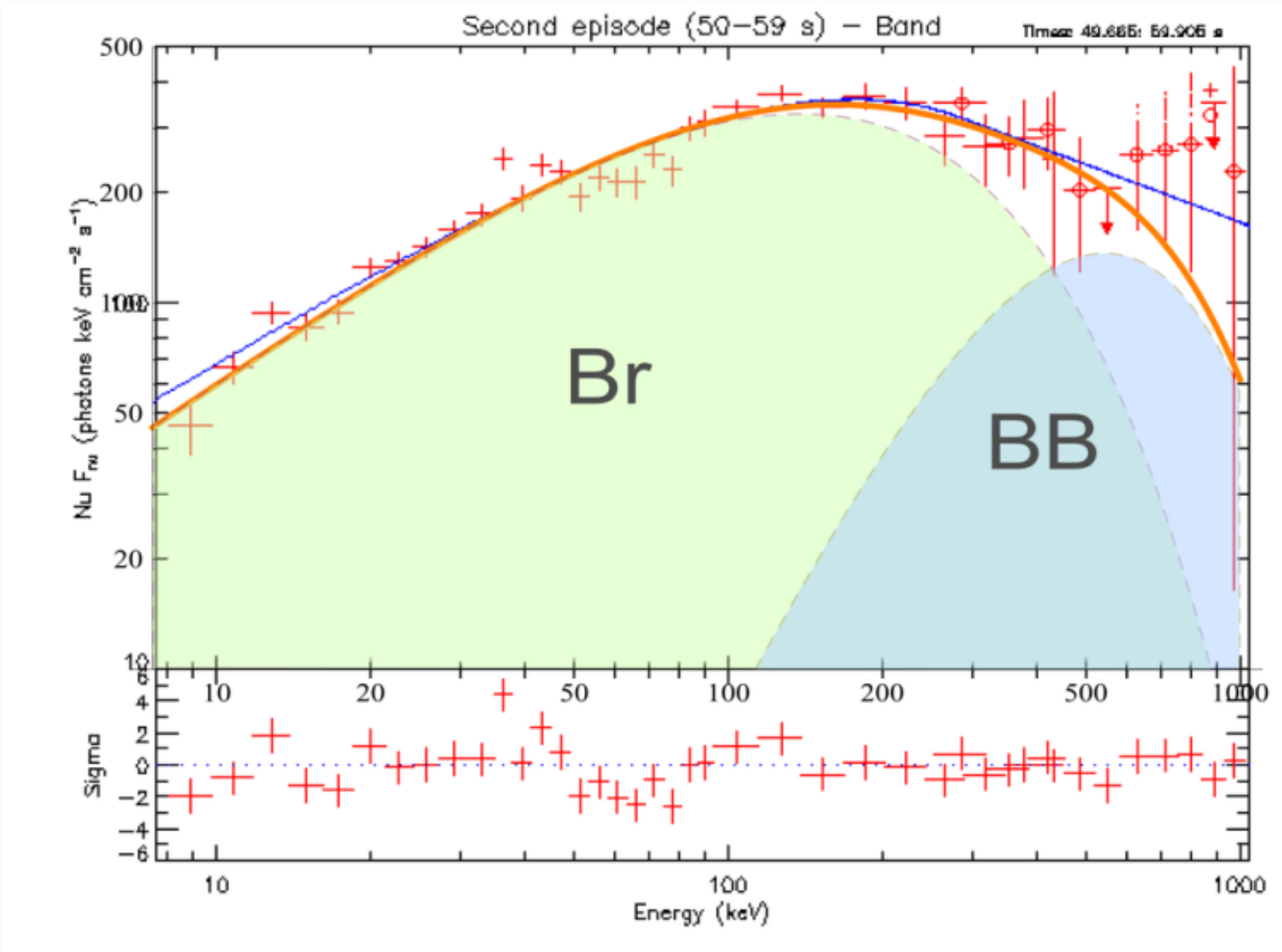
Spectrum

GRB 090618



Spectrum

GRB 090618



Conclusions (for part II)

- 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

Epilogue

Physical origin of GRBs remains a focal point of research and debate more than 40 years since they were first detected by VELA satellite in charge of monitoring the respect of BAN test treaty. When it was discovered that they were not atomic bomb, the world heaved a sigh of relief: it was not bomb but astrophysical objects.

But nobody take care, with the most important fact discovered by BeppoSAX in 1997 that they are the most extreme luminous objects in the Universe.

What will happen to our Earth is one GRBs exploded in our Galaxy ?