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SMR.1751 - 53

Fifth International Conference on
**PERSPECTIVES IN HADRONIC PHYSICS**
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

**22 - 26 May 2006**

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# The quark-deconfinement model of Gamma-Ray-Bursts

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# The quark-deconfinement model of Gamma-Ray-Bursts

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Andrea Lavagno (Torino)

Giuseppe Pagliara, Irene Parenti

# Two main questions

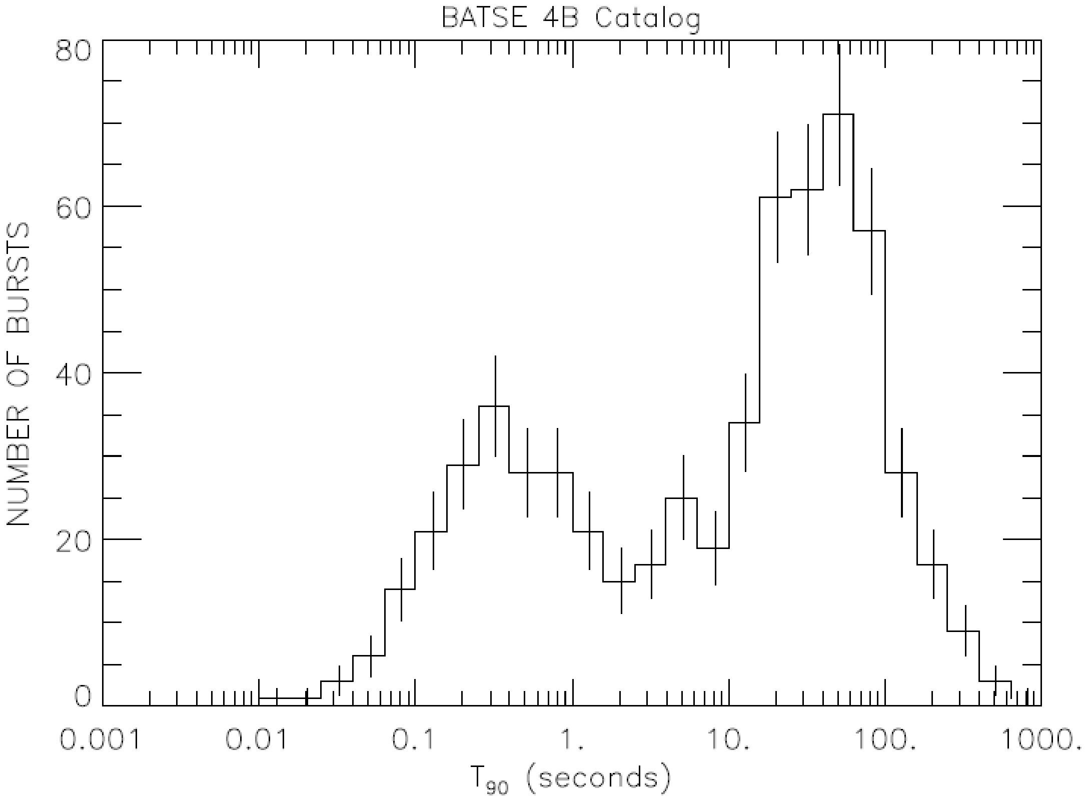
How the GRB develops from the underlying microphysics? (formation of a critical drop of Quark Matter,  expansion of the drop, transfer of the released energy to gamma rays, …)

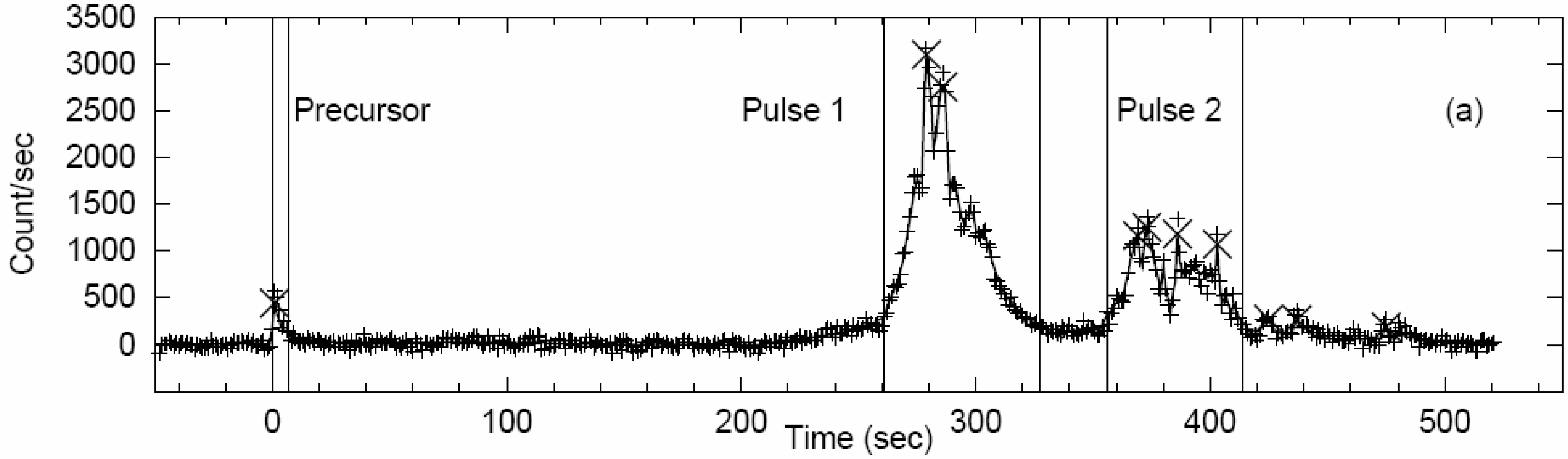
How the model compares with the observations? (time structure, energy released, expected number of the GRBs, …)

# A few features of GRBs

- Isotropic spatial distribution
- Cosmological distance
- Emitted energy: order of $10^{51}$ erg
  (taking beaming into account)
- Duration: two classes, below and above 2s

# Bimodal distribution of durations of BATSE GRBs




3500
3000
2500
2000
1500
1000
500
0
Count/sec
0
100
200
300
400
500
Time (sec)
Precursor
Pulse 1
Pulse 2
(a)

# Hypernova model (Collapsars)

Rotating massive stars, whose central region collapses to a black hole surrounded by an accretion disk.

Outflows are collimated by passing through the stellar mantle.

\+ Detailed numerical analysis of jet formation.

Fits naturally in a general scheme describing collapse of massive stars.

\- Large angular momentum needed, difficult to achieve.

SN – GRB time delay: less then 100 s.

# Hadronic Stars → Hybrid or Quark Stars

Z.Berezhiani, I.Bombaci, A.D., F.Frontera, A.Lavagno, ApJ586(2003)1250

Metastability due to delayed production of Quark Matter.
1) conversion to Quark Matter (it is NOT a detonation)
2) cooling (neutrino emission)
3) neutrino – antineutrino annihilation
4)(possible) beaming due to strong magnetic field and star rotation

\+ Fits naturally into a scheme describing QM production.
**Energy and duration of the GRB are OK.**

\- No calculation of beam formation, yet.

SN – GRB time delay: minutes → years
depending on mass accretion rate

# RMF EOS with hyperons and quarks
# B=(155 MeV)$^4$

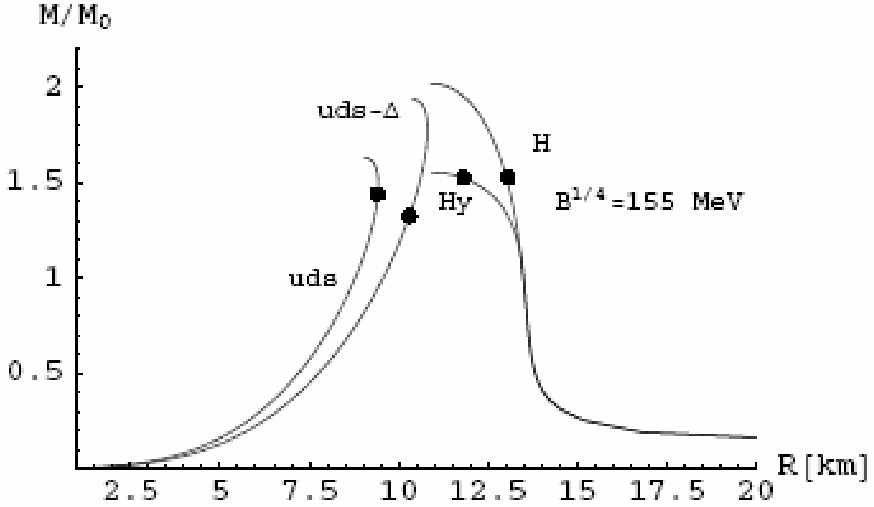


Fig. 7.— Mass-radius relations of nucleonic stars (H), hyperonic stars (Hy), quark stars made of unpaired quark matter (uds) and of color superconducting CFL phase (uds-Δ). The dots indicate stars whose baryonic mass is $M_B = 1.7\ M_\odot$. Here $B^{1/4} = 155$ MeV.

# RMF EOS with hyperons and quarks B=(165 MeV)$^4$

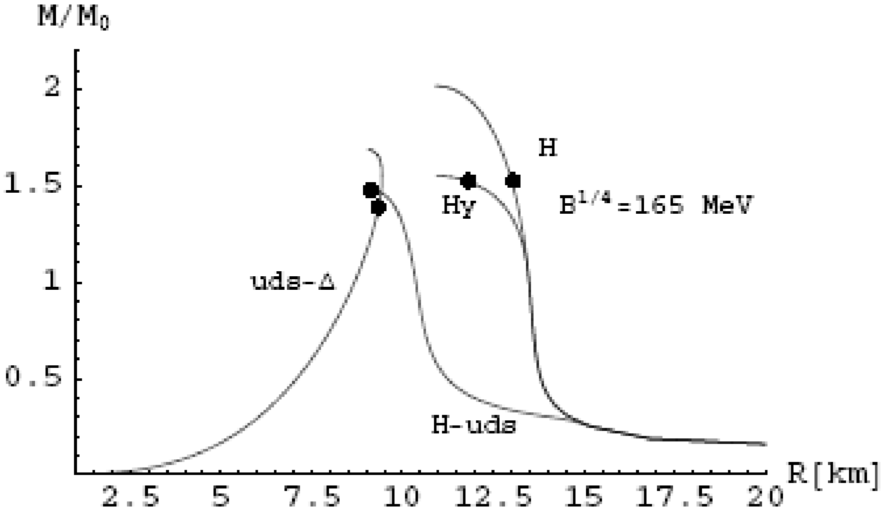


Fig. 8.— Mass-radius relations of nucleonic stars (H), hyperonic stars (Hy), hybrid stars made of hadrons and of unpaired quark matter (H-uds) and quark stars made of color superconducting CFL phase (uds-Δ). The dots indicate stars whose baryonic mass is $M_B$ = 1.7 $M_\odot$. Here $B^{1/4}$ = 165 MeV.

# QM formation after deleptonization and cooling

Pons et al. PRL 86 (2001) 5223

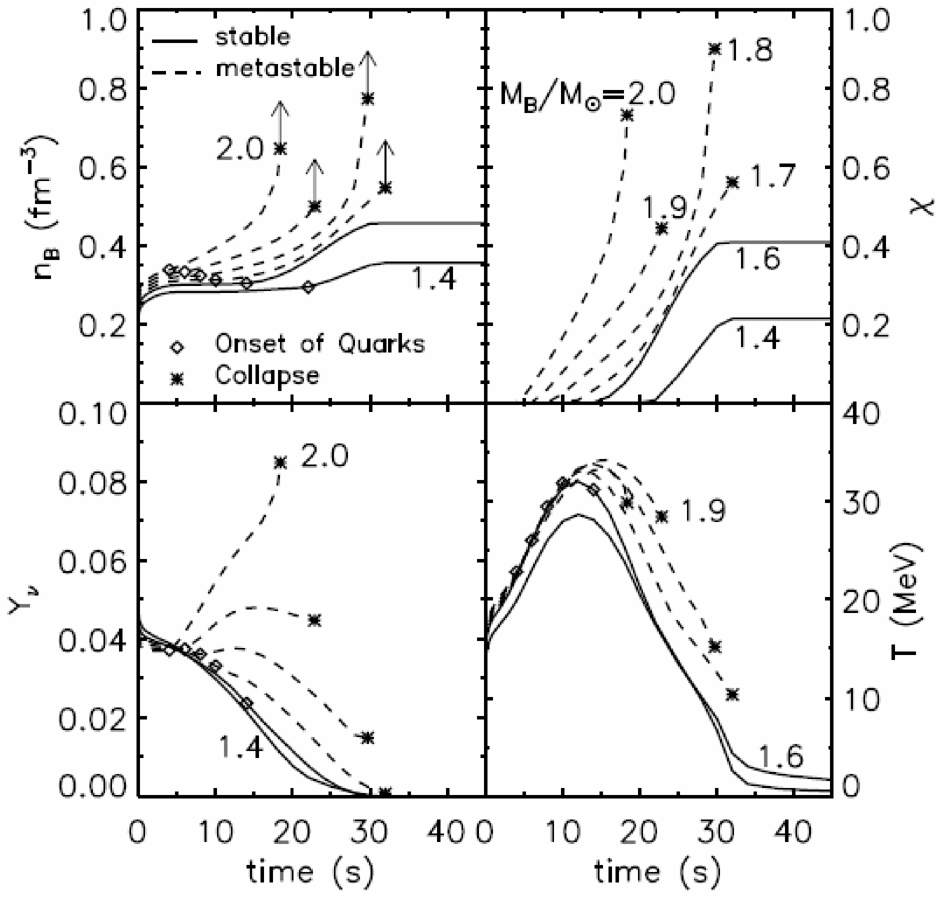


FIG. 1. Evolutions of the central baryon density $n_B$, $\nu$ concentration $Y_\nu$, quark volume fraction $\chi$ and temperature $T$ for different baryonic masses $M_B$. Solid lines correspond to stable stars; stars with larger masses are metastable (dashed lines). Diamonds indicate when quarks appear at the star's center, and asterisks denote when metastable stars become gravitationally unstable.

# Quantum nucleation

I.M. Lifshitz and Y. Kagan, Sov. Phys. JETP 35 (1972) 206
K. Iida and K. Sato, Phys. Rev. C58 (1998) 2538

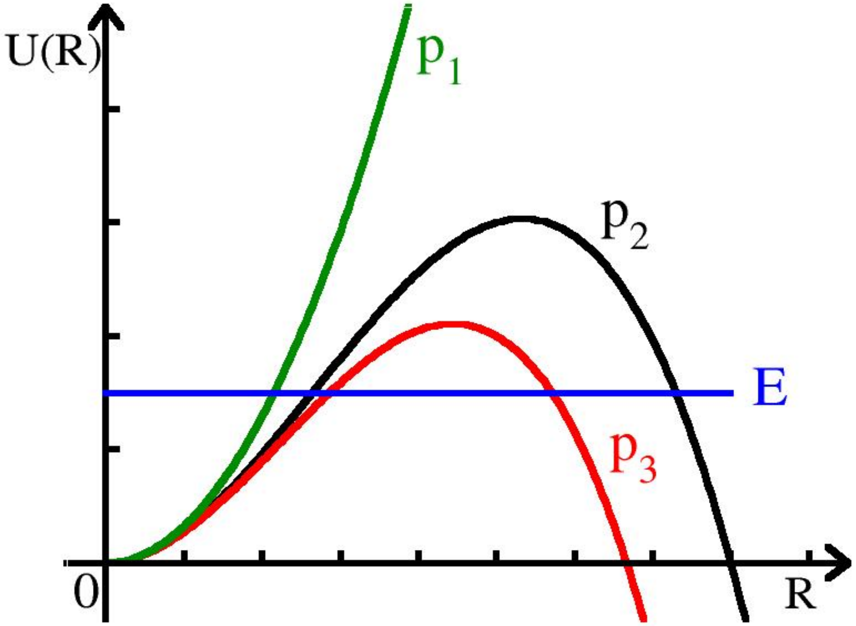
**Droplet potential energy:**

$$\mathbf{U}(\mathbf{R}) = \frac{4}{3}\pi \mathbf{n}_{\mathbf{Q}*}\left(\mu_{\mathbf{Q}*} - \mu_{\mathbf{H}}\right)\mathbf{R}^3 + 4\pi\sigma\mathbf{R}^2 = \mathbf{a}_{\mathbf{V}}\mathbf{R}^3 + \mathbf{a}_{\mathbf{s}}\mathbf{R}^2$$

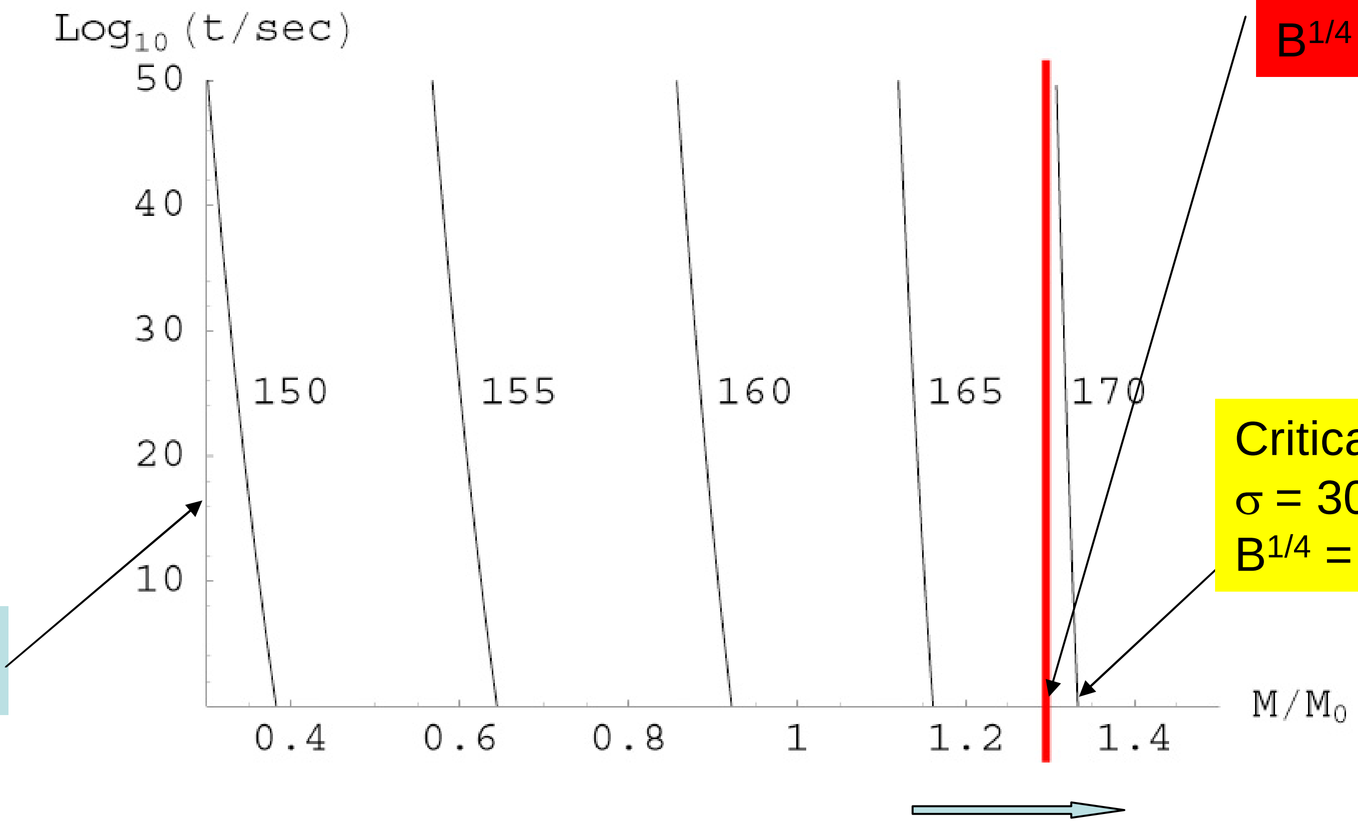
$n_{Q*}$ baryonic number density in the Q*-phase at a fixed pressure P.

$\mu_{Q*}, \mu_H$ chemical potentials at a fixed pressure P.

$\sigma$ surface tension (=10,30 MeV/fm$^2$)



# Quark droplet nucleation time
## “mass filtering”



Critical mass for
♦ ▣ ▭
$B^{1/4}$ = 170 MeV

Critical mass for
$\sigma$ = 30 MeV/fm$^2$
$B^{1/4}$ = 170 MeV

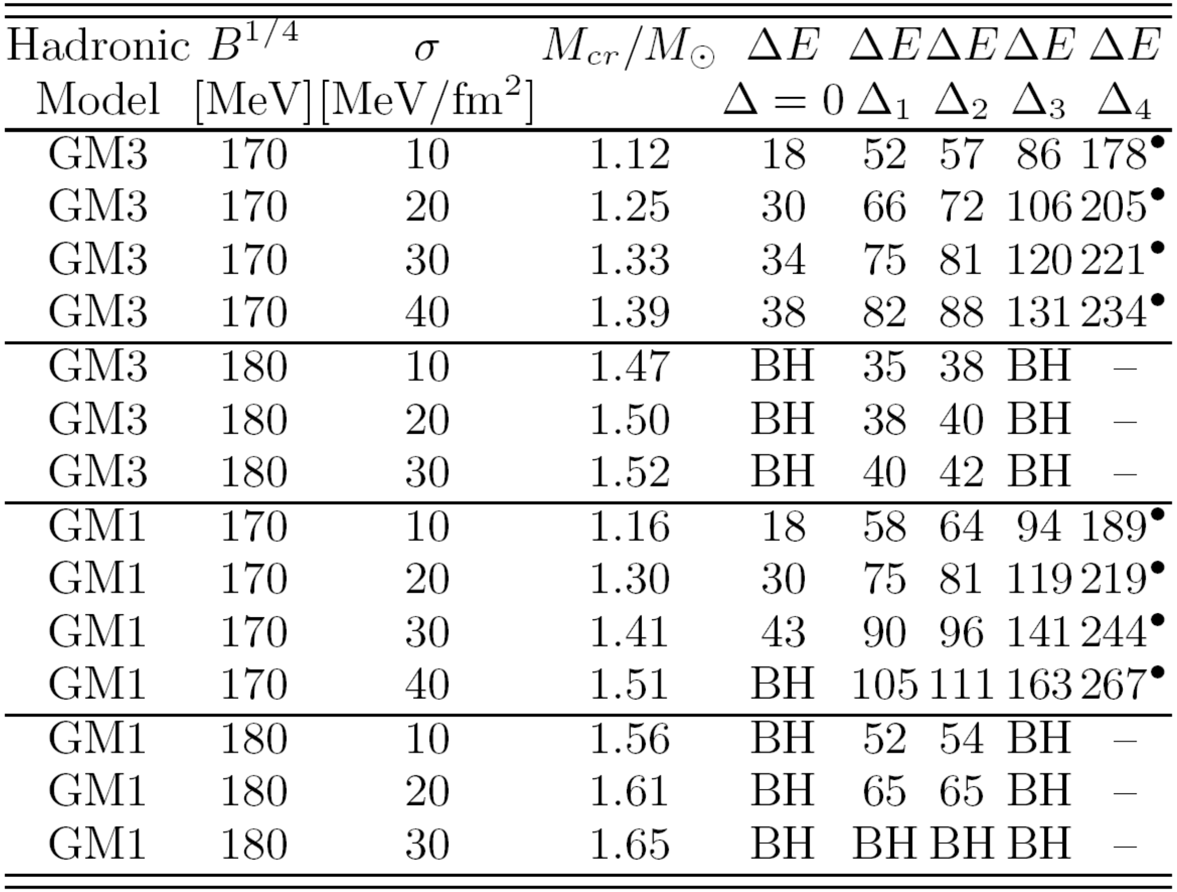
Age of the Universe!

Mass accretion

# Energy released in the HS→HyS(QS) convertion

A.D., A.Lavagno, G.Pagliara, PRD69(2004)057505

CFL gaps



| Hadronic Model | $B^{1/4}$ [MeV] | $\sigma$ [MeV/fm$^2$] | $M_{cr}/M_\odot$ | $\Delta E$ $\Delta = 0$ | $\Delta E$ $\Delta_1$ | $\Delta E$ $\Delta_2$ | $\Delta E$ $\Delta_3$ | $\Delta E$ $\Delta_4$ |
|---|---|---|---|---|---|---|---|---|
| GM3 | 170 | 10 | 1.12 | 18 | 52 | 57 | 86 | $178^\bullet$ |
| GM3 | 170 | 20 | 1.25 | 30 | 66 | 72 | 106 | $205^\bullet$ |
| GM3 | 170 | 30 | 1.33 | 34 | 75 | 81 | 120 | $221^\bullet$ |
| GM3 | 170 | 40 | 1.39 | 38 | 82 | 88 | 131 | $234^\bullet$ |
| GM3 | 180 | 10 | 1.47 | BH | 35 | 38 | BH | – |
| GM3 | 180 | 20 | 1.50 | BH | 38 | 40 | BH | – |
| GM3 | 180 | 30 | 1.52 | BH | 40 | 42 | BH | – |
| GM1 | 170 | 10 | 1.16 | 18 | 58 | 64 | 94 | $189^\bullet$ |
| GM1 | 170 | 20 | 1.30 | 30 | 75 | 81 | 119 | $219^\bullet$ |
| GM1 | 170 | 30 | 1.41 | 43 | 90 | 96 | 141 | $244^\bullet$ |
| GM1 | 170 | 40 | 1.51 | BH | 105 | 111 | 163 | $267^\bullet$ |
| GM1 | 180 | 10 | 1.56 | BH | 52 | 54 | BH | – |
| GM1 | 180 | 20 | 1.61 | BH | 65 | 65 | BH | – |
| GM1 | 180 | 30 | 1.65 | BH | BH | BH | BH | – |

Based on the “simple” scheme of Alford and Reddy PRD67(2003)074024

# How to generate GRBs

The energy released (in the **strong deflagration**) is carried out by neutrinos and antineutrinos.

The reaction that generates gamma-ray is:

$$\boxed{\nu + \bar{\nu} \rightarrow e^{+} + e^{-} \rightarrow 2\gamma}$$

The efficency of this reaction in a strong gravitational field is:

$$\boxed{\eta \approx 10\%}$$

[J. D. Salmonson and J. R. Wilson, ApJ 545 (1999) 859]

$$\boxed{E_{\gamma} = \eta\, E_{conv} \approx 10^{51} - 10^{52}\, erg}$$

# Detonation or deflagration?

Continuity eqs. through the front

Energy momentum tensor

$$\begin{aligned}(e_h + p_h) v_h \gamma_h^2 &= (e_q + p_q) v_q \gamma_q^2 \,, \\ (e_h + p_h) v_h^2 \gamma_h^2 + p_h &= (e_q + p_q) v_q^2 \gamma_q^2 + p_q\end{aligned}$$

Baryon flux

$$\rho_B^h v_h \gamma_h = \rho_B^q v_q \gamma_q$$

| | | |
|---|---|---|
| $v_h > v_{sh}$ | $v_q < v_{sq}$ | strong detonation |
| $v_h > v_{sh}$ | $v_q > v_{sq}$ | weak detonation |
| $v_h < v_{sh}$ | $v_q < v_{sq}$ | weak deflagration |
| $v_h < v_{sh}$ | $v_q > v_{sq}$ | strong deflagration |

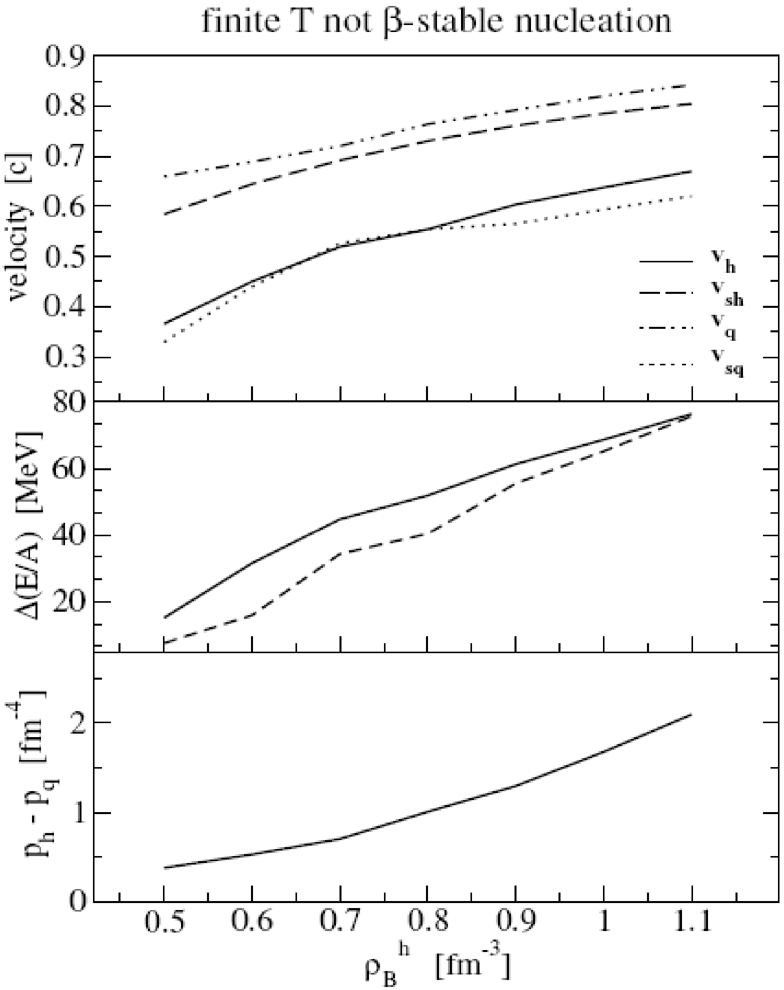


Fig. 16.— Upper panel: velocity of hadronic phase $v_h$, of the burned phase $v_q$ and corresponding sound velocities $v_{sh}$ and $v_{sq}$, all in units of the velocity of light and in the front frame. Center panel: energy difference between the two phases (in the hadron phase rest frame). The dashed and the solid lines correspond to the first and to the second iteration in the solution of Eqs. 1,2,3,19. Lower panel: pressure difference between the uncombusted and the combusted phase. Here the combusted phase is obtained using $B^{1/4} = 170$ MeV, temperatures from 5 to 40 MeV (as estimated from the solid line in the central panel) and it is not $\beta$-stable.

# Scheme for convection

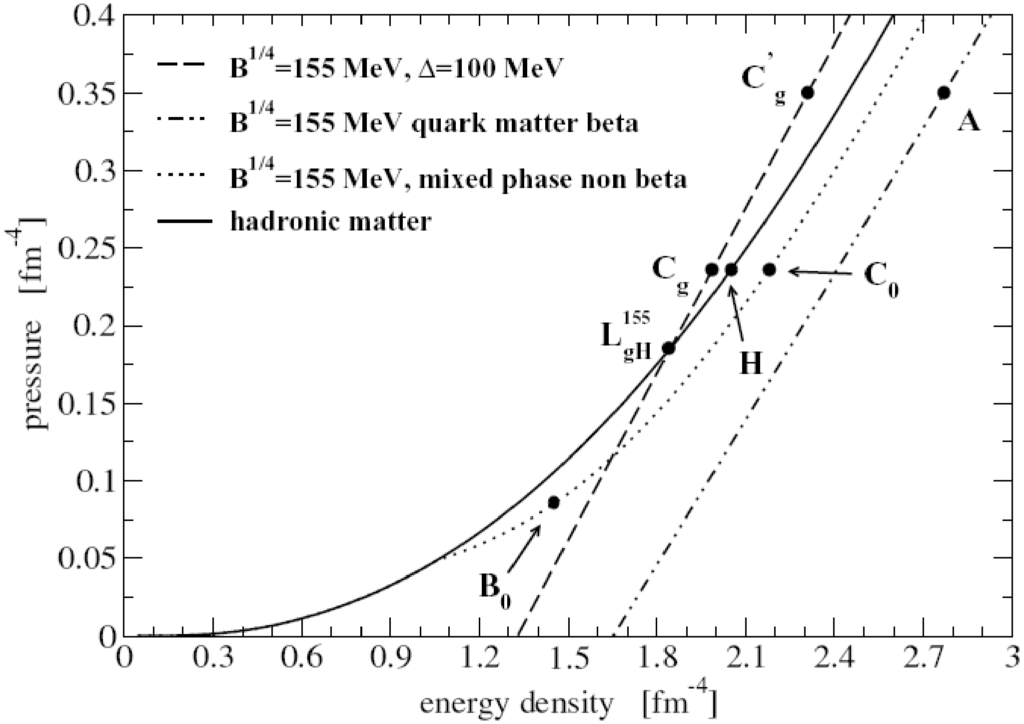


Fig. 19.— Scheme for convection: H represents the drop of hadronic matter just before deconfinement, $B_0$ represents the drop of newly formed QM, C stays for the drop of QM after pressure equilibration and L indicates the end point of the convective layer. Finally A represents a drop of ungapped quark matter before its transition to CFL phase. Here $B^{1/4} = 155$ MeV and hyperons are not included.

Main results:

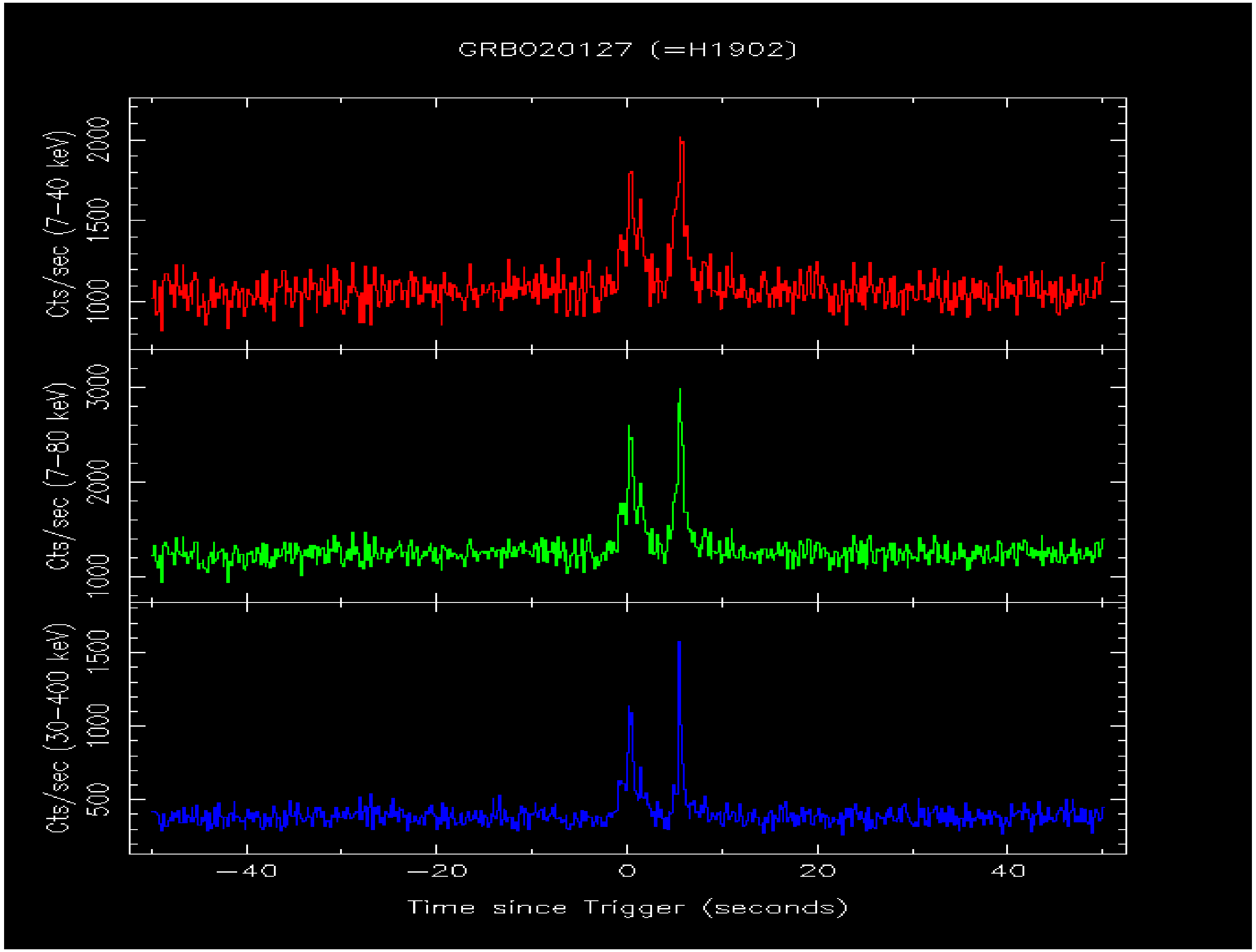
→ Never a detonation (no mechanical shock)

→ Always a deflagration with an unstable front

→ Convection can develop if hyperons are present in the hadronic phase or if diquark can condensate

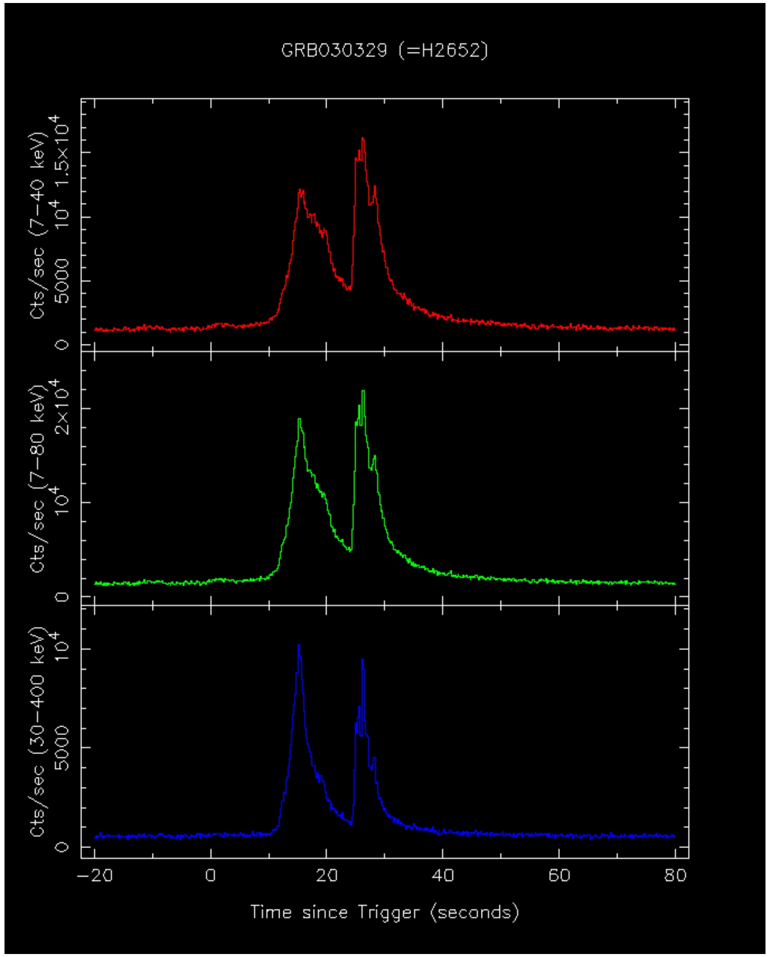
# Double bursts → Quiescent time

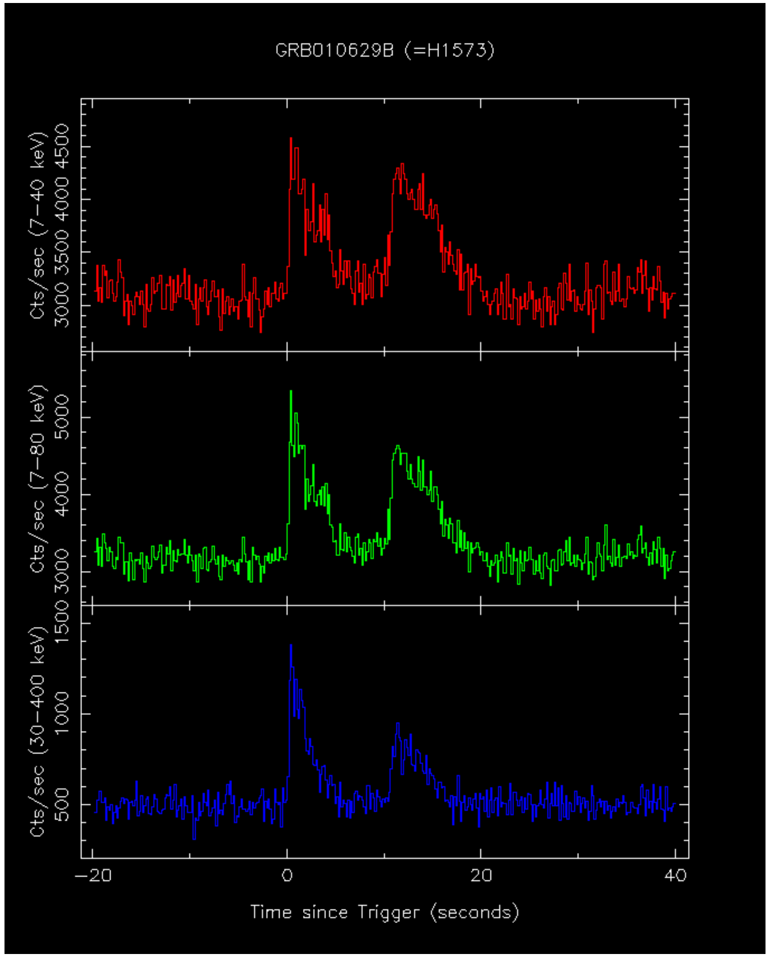
## HETE Catalog



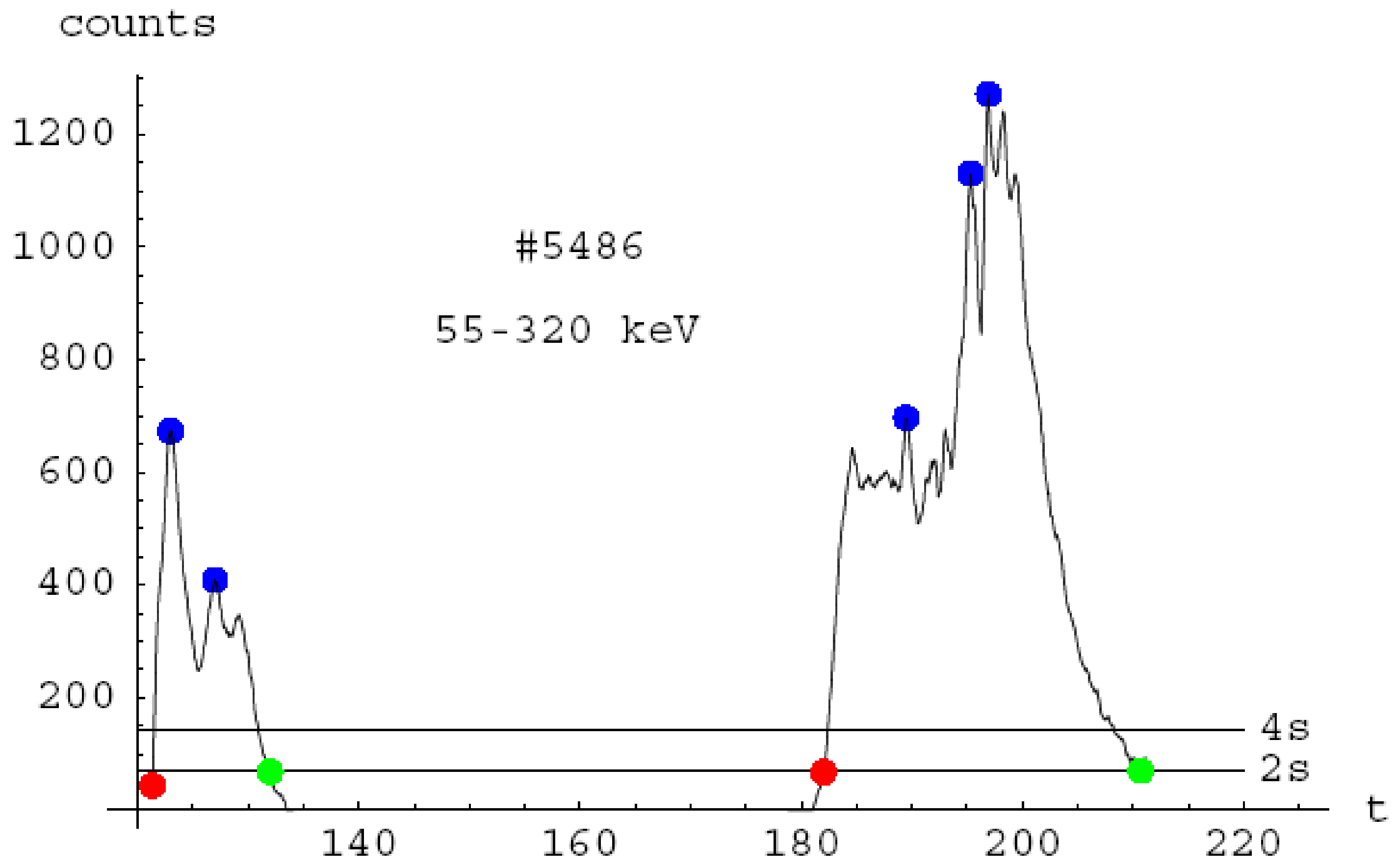
# Further examples of double bursts

## from HETE Catalog





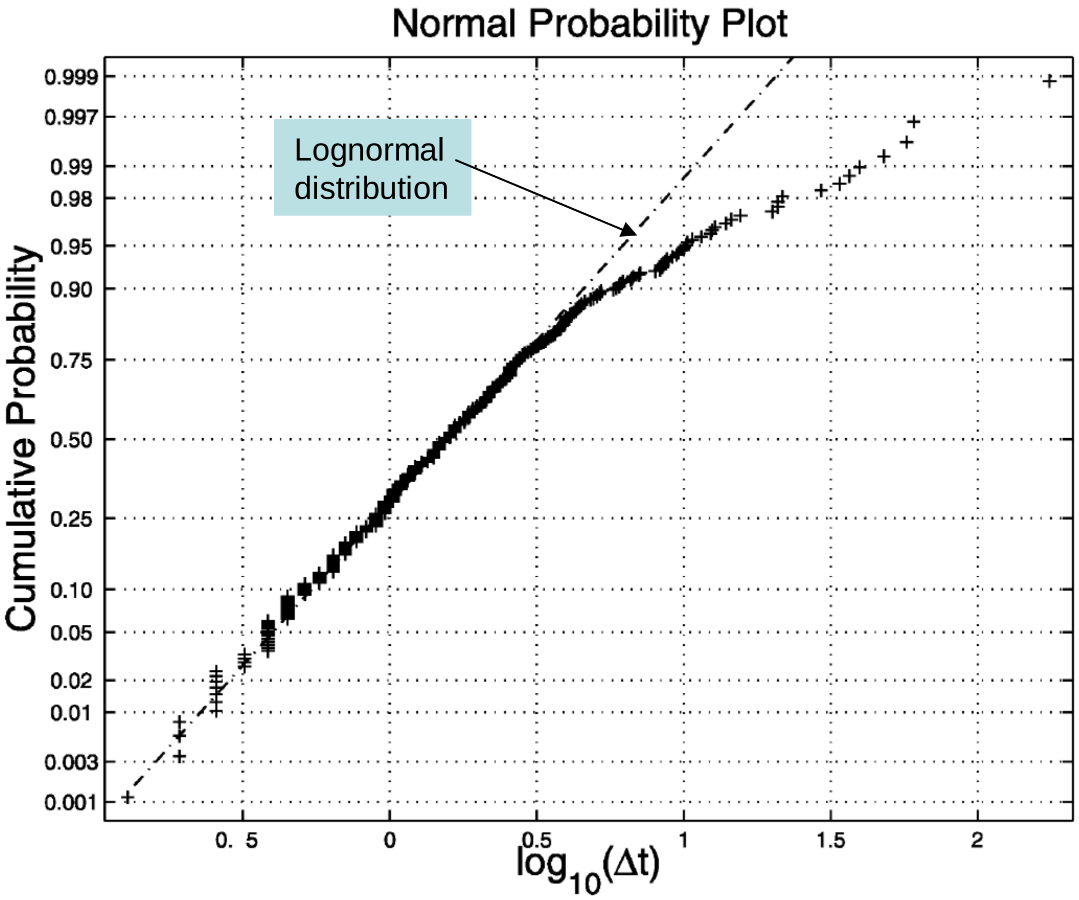
# Temporal structure of BATSE 5486



# Cumulative distribution of quiescent times

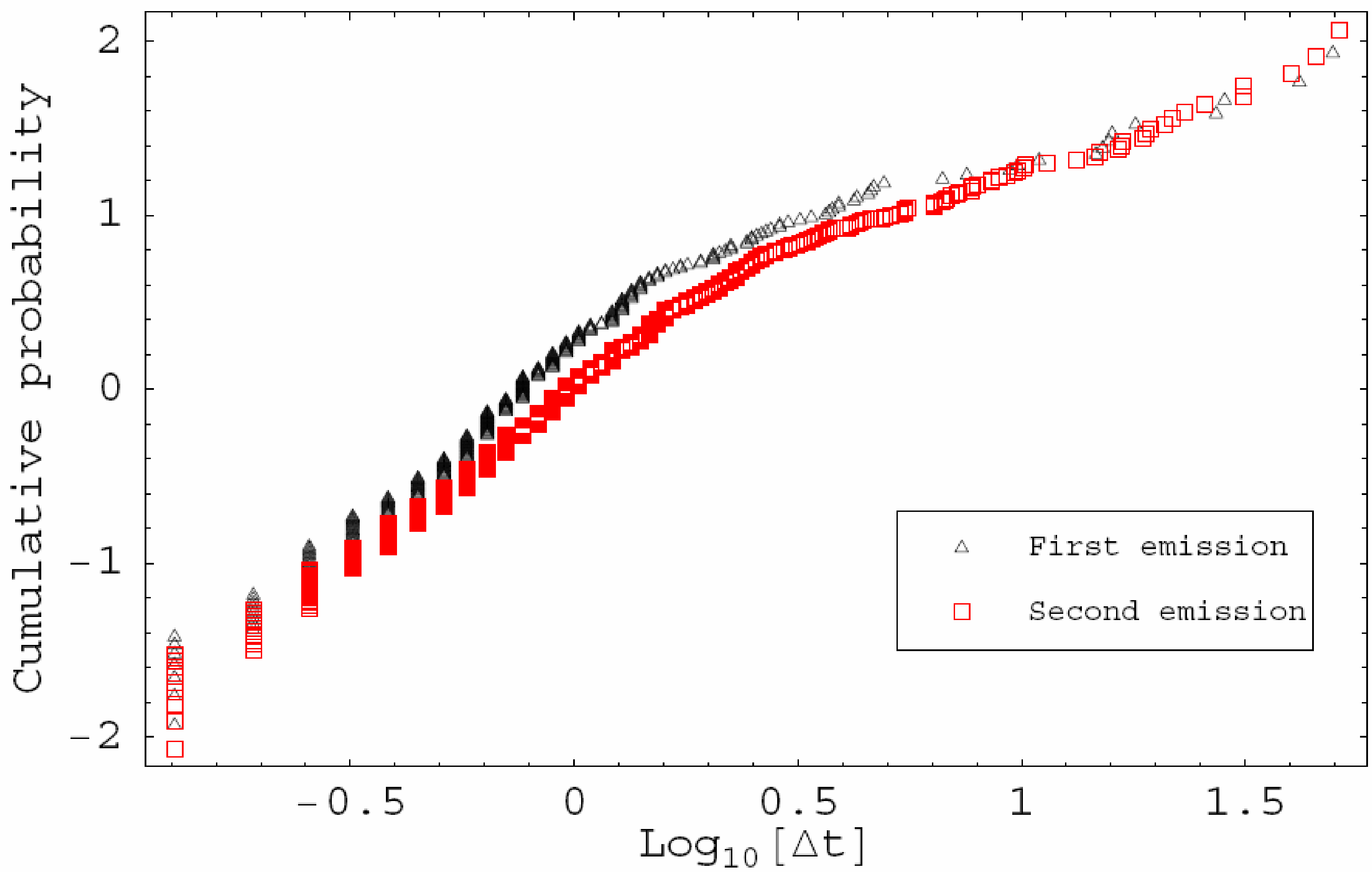
## E.Nakar and T.Piran, MNRAS 331 (2002) 40

## data from Batse catalog

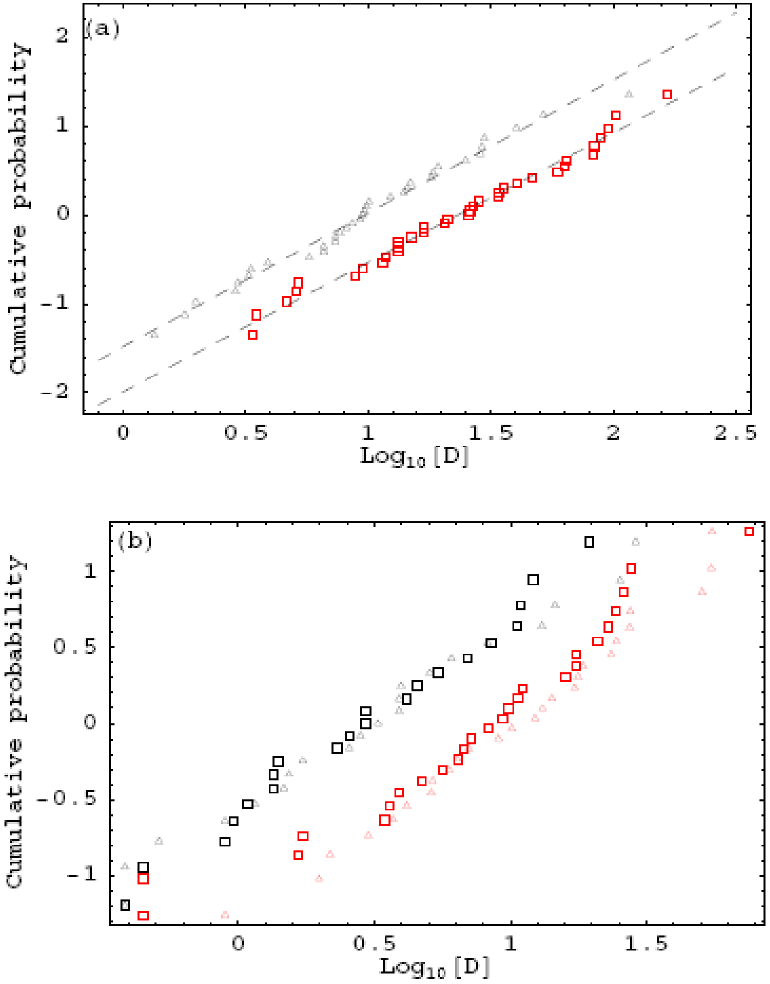


"… the quiescent times are made by a different mechanism then the rest of the intervals"
Nakar and Piran 2002

# Analysis of time intervals between peaks within each emission episod

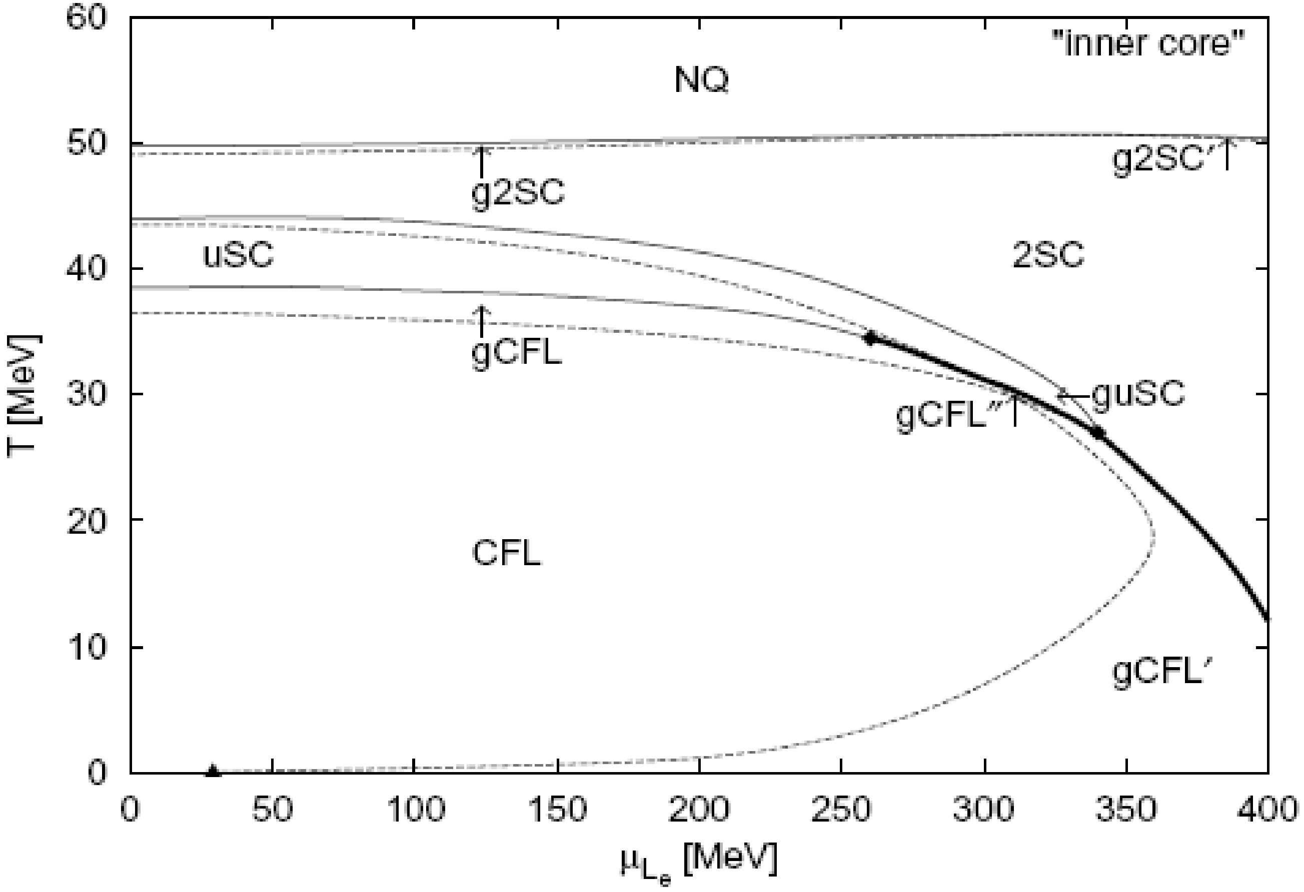


# Analysis of durations of the two emission episods a) and within each episode b)



# Phase diagram of neutral quark matter: effect of neutrino trapping

Ruster et al. PRD73 (2006) 034025

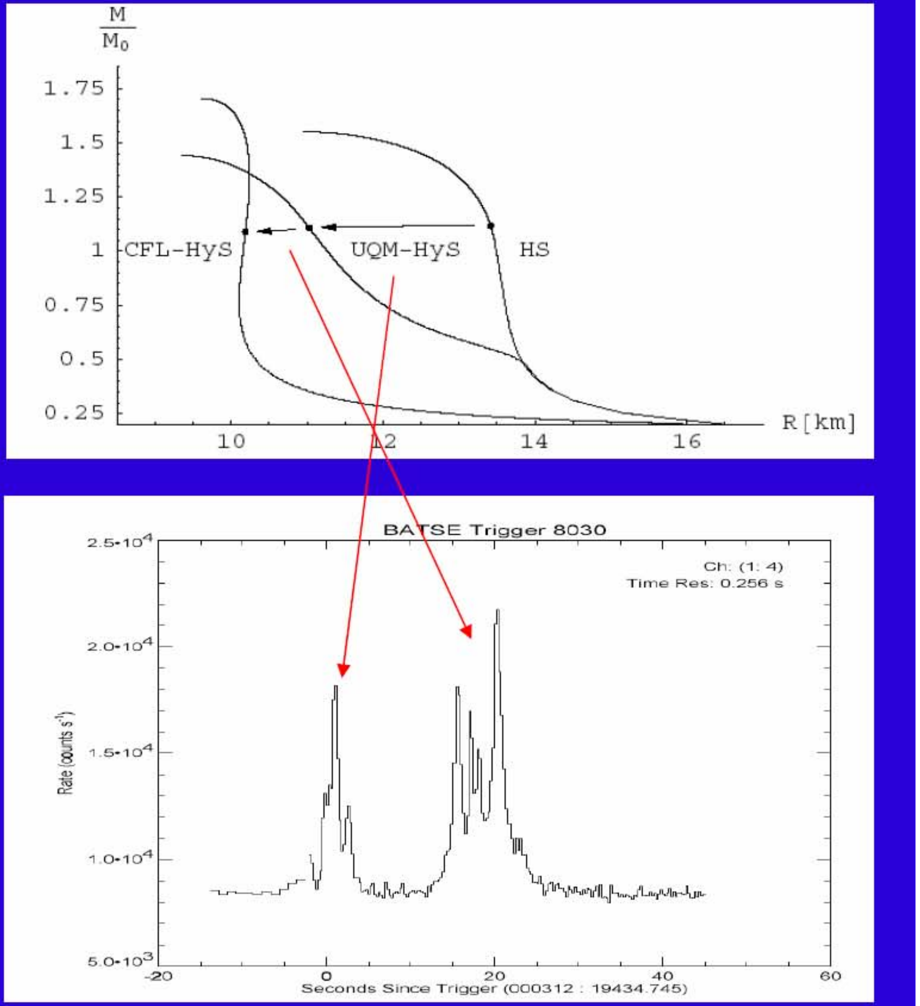


# *Double GRBs generated by double phase transitions*

Two steps:

1) transition from hadronic matter to unpaired or 2SC quark matter. “Mass filtering”

2) The mass of the star is now fixed. After strangeness production, transition from 2SC to CFL quark matter. Decay time scale τ few tens of second



# Conclusions

- The conversion of an hadronic star into a hybrid or quark star can be at the origine of (at least part of) the long GRBs.
- While in the collapsar model SN explosion and GRB need to be almost simultaneous, in the QM formation model a time delay between SN and GRB can exist, and its duration is regulated by mass accretion.
- The existence of two stars having similar masses but very different radii would constitute a very strong support to the QM formation model.
- The formation of diquark condensate can significantly increase the total energy released.
- “Evidence” of two active periods in long GRBs.

  The first transition, from hadronic matter to unpaired (or 2SC) quark matter acts as a “mass filter”. The second transition, producing (g)CFL quark matter can be described as a decay having a life-time of order tens of seconds
- Possible to test MP formation in the lab with scattering at intermediate energies