Gamma-Ray-Bursts in Nuclear Astrophysics

Giuseppe Pagliara

Università di Ferrara

Scuola di Fisica Nucleare "Raimondo Anni" Otranto 2006

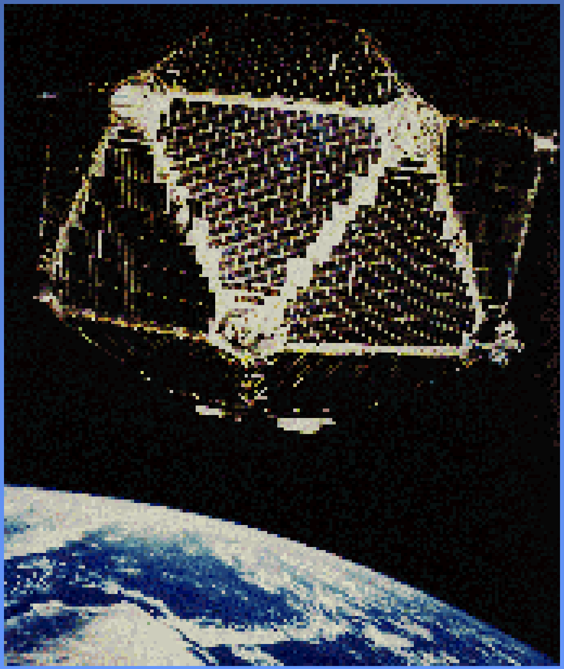
Overview

- *GRBs phenomenology*

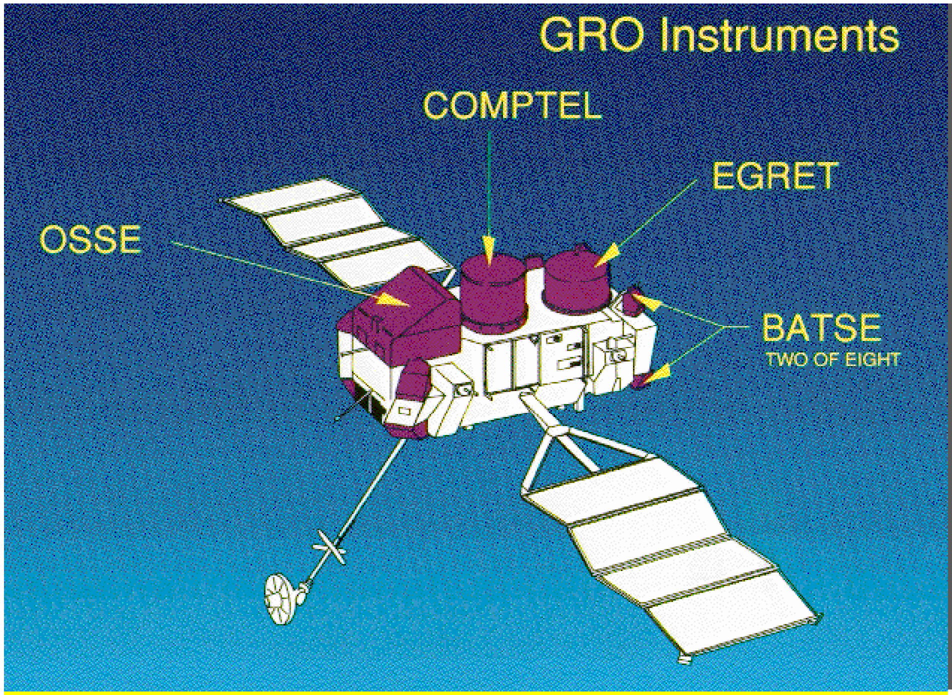
- *Theoretical models of the "inner engine" : Collapsar Model vs Quark deconfinement model*

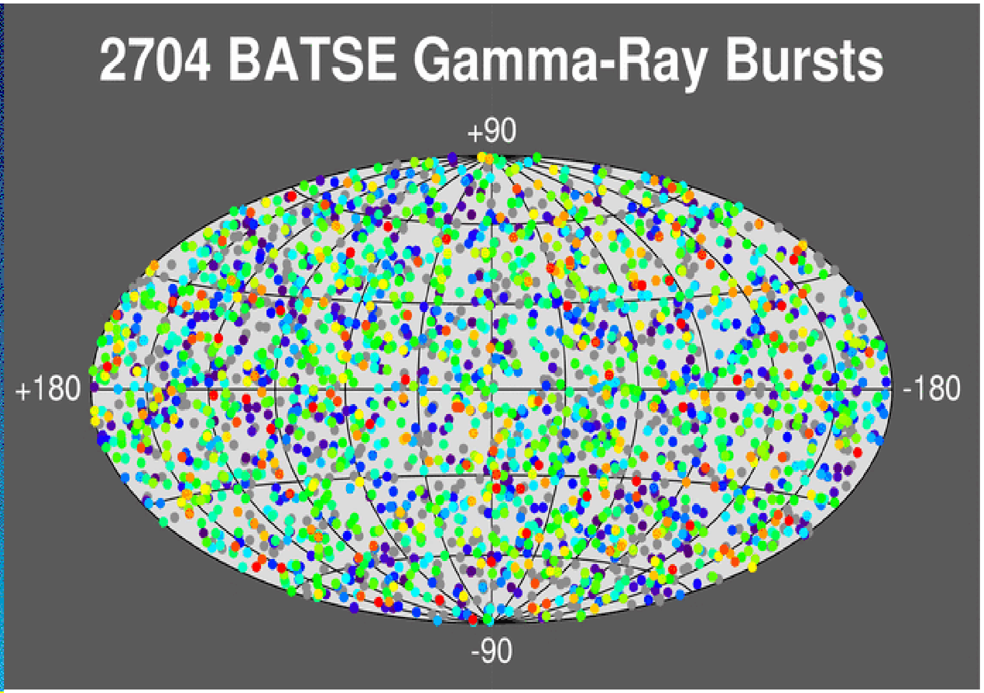
THE DISCOVERY

Gamma-Ray Bursts (GRBs) Short (few seconds) bursts of 100keV- few MeV were discovered accidentally by Klebesadal Strong and Olson in 1967 using the Vela satellites (defense satellites sent to monitor the outer space treaty). The discovery was reported for the first time only in 1973.



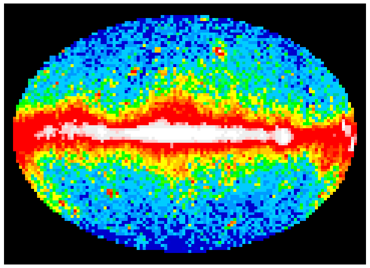
- There was an “invite prediction”. S. Colgate was asked to predict GRBs as a scientific excuse for the launch of the Vela Satellites

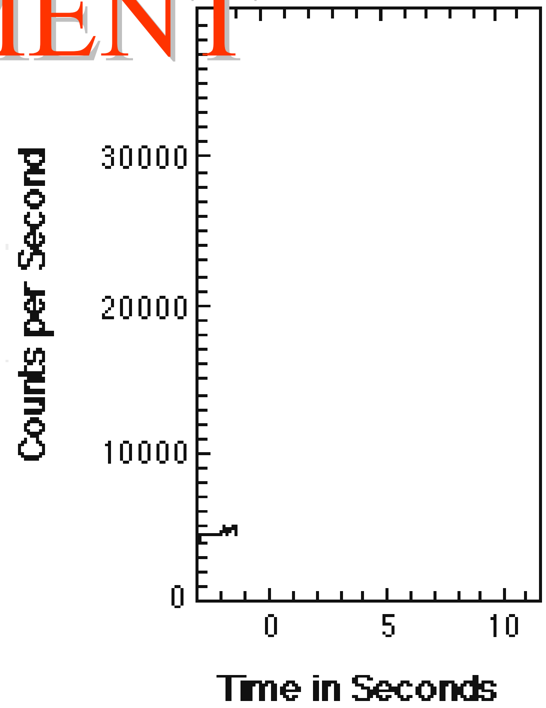




BATSE EXPERIMENT

- *Duration 0.01-100s*
- *~ 1 burst per day*
- *Isotropic distribution - rate of ~2 Gpc^{-3} yr^{-1}*
- *~100keV photons*
- *Cosmological Origin (supposed)*
- *The brightness of a GRB, E~10^{52}ergs, is comparable to the brightness of the rest of the Universe combined.*



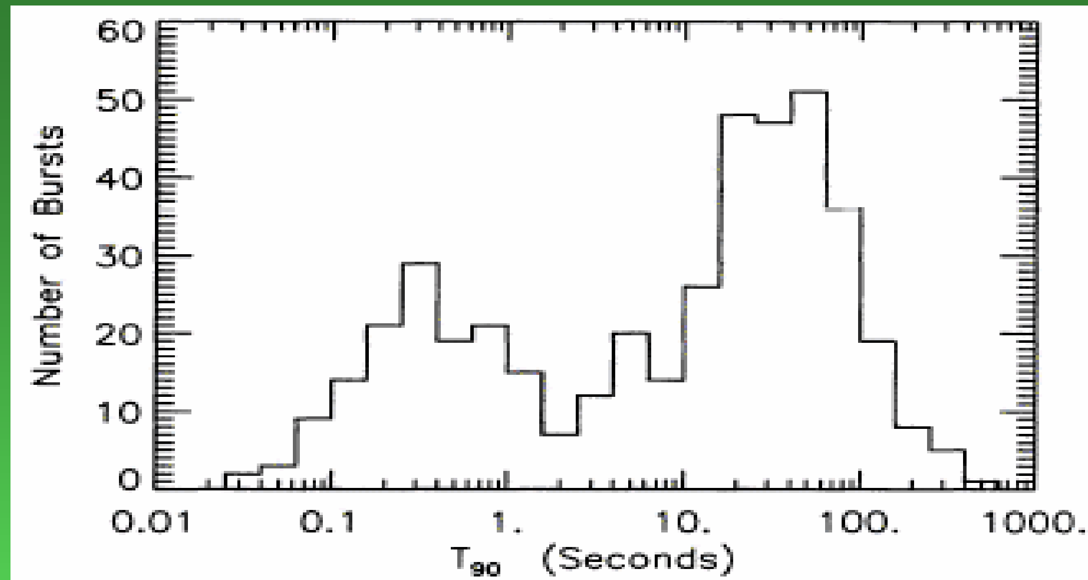


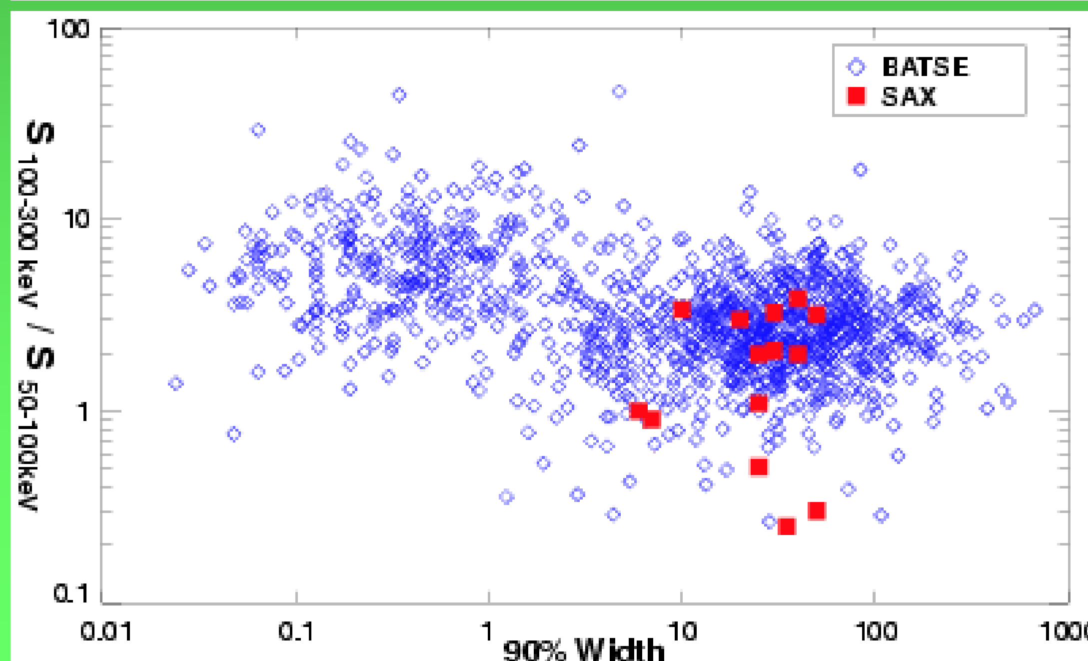
Durations

- Two classes:

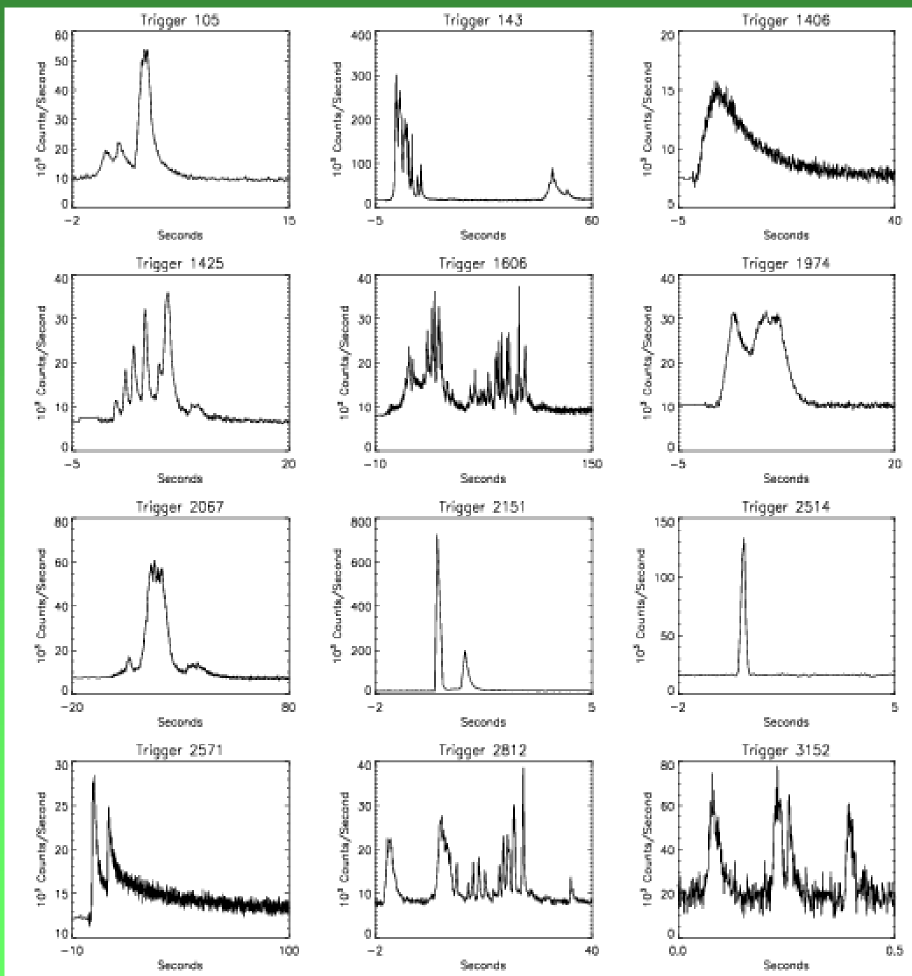
    1. Short: $T_{90} < 2$ s, harder

    2. Long: $T_{90} > 2$ s, softer





Temporal structure



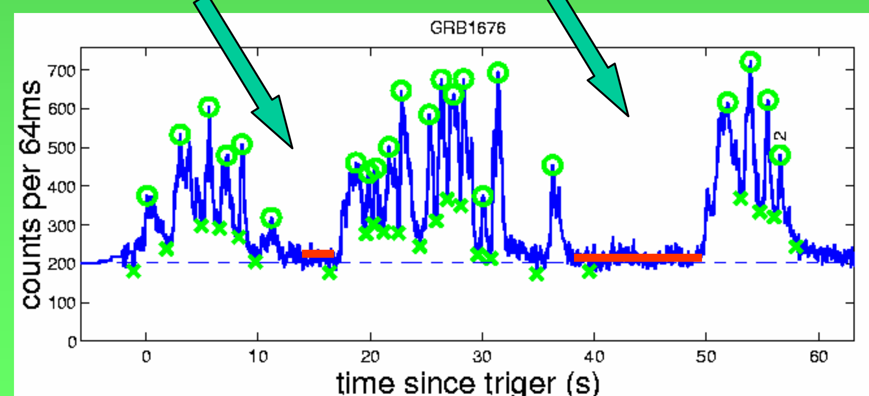
Three time scales:

Peaks intervals: $\delta T \leq .1$ sec

Total durations: T = few tens of s

Quiescent times: QT = tens of s

(see second part)

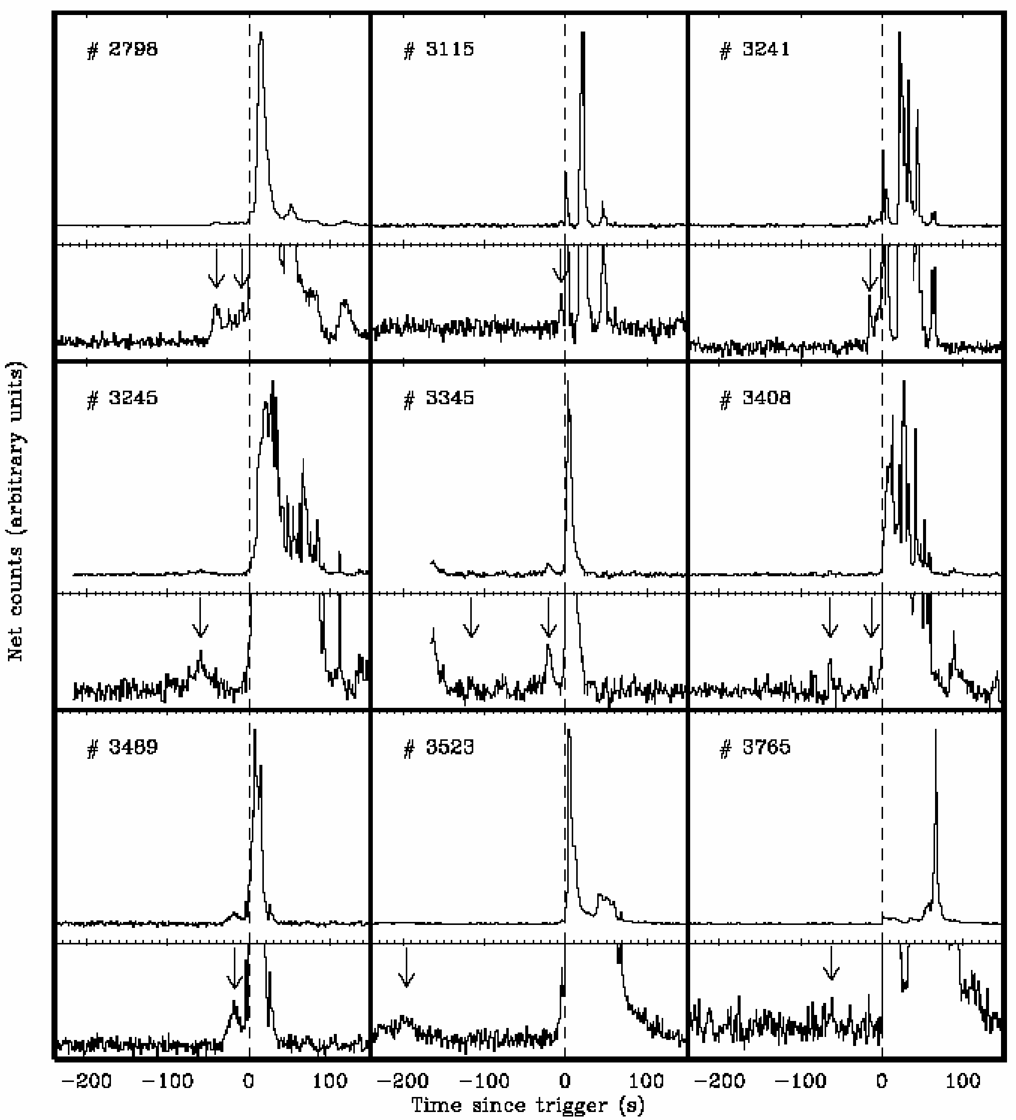


Single peak :FRED

Precursors

- In 20% there is evidence of emission above the background coming from the same direction of the GRB. This emission is characterised by a softer spectrum with respect to the main one and contains a small fraction (0.1 – 1%) of the total event counts.

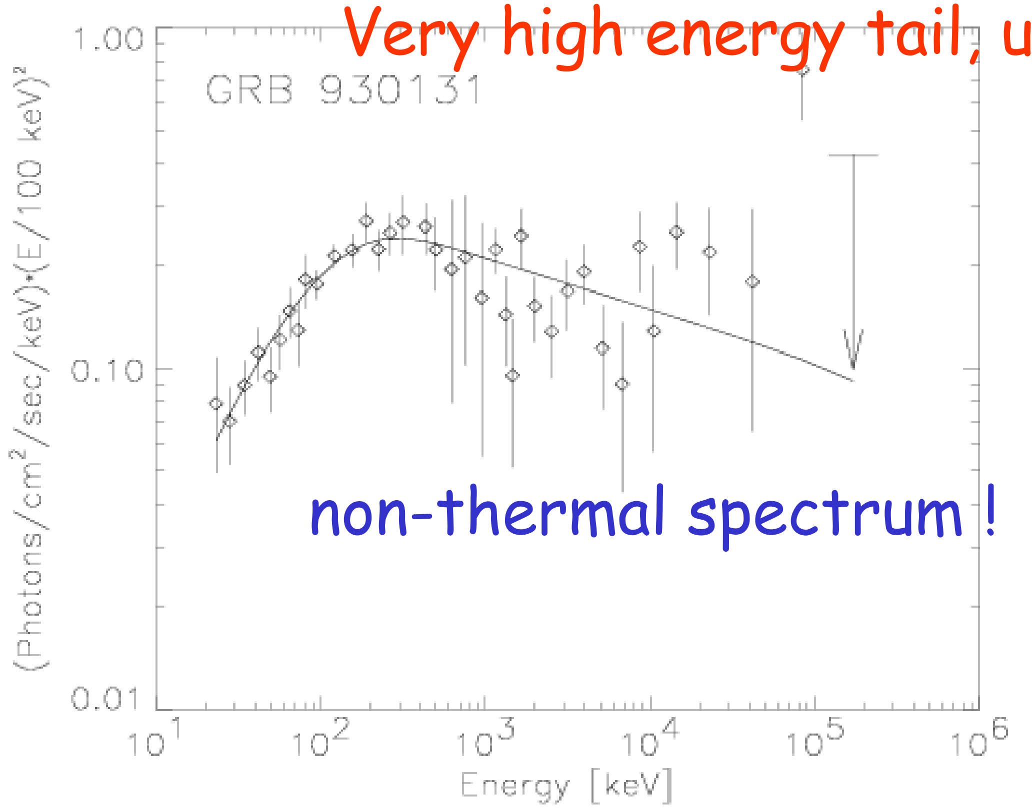
- typical delays of several tens of seconds extending (in few cases) up to 200 seconds. Their spectra are typically non-thermal power-law. Such long delays and the non-thermal origin of their spectra are hard to reconcile with any model for the progenitor.



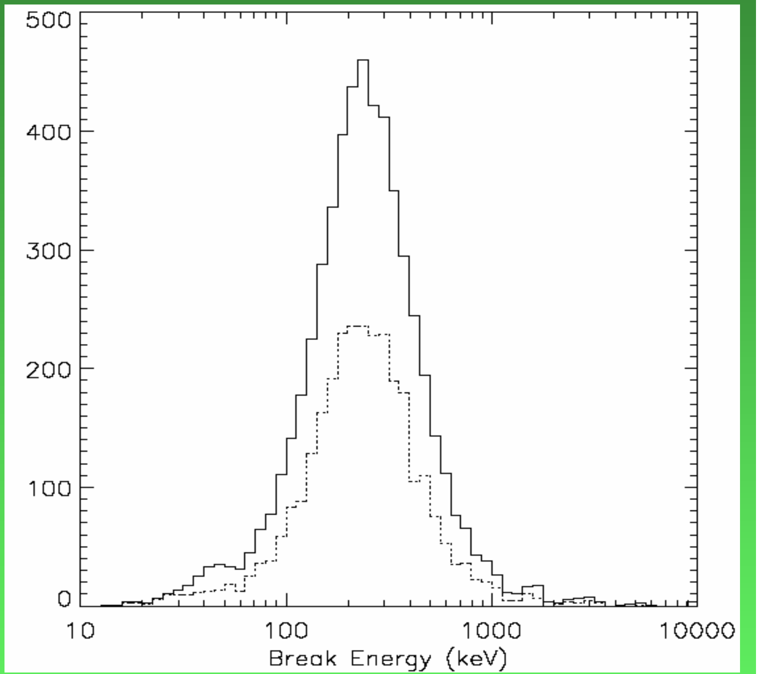
(Lazzati 2005)

Spectrum

Very high energy tail, up to GeV !



non-thermal spectrum !

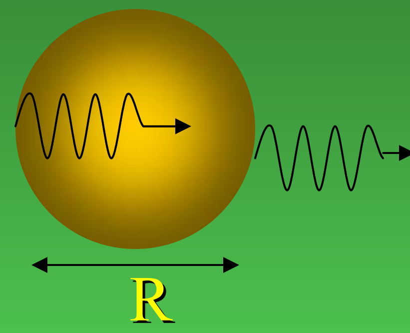


Band function

$$N(\nu) = N_0 \begin{cases} (h\nu)^{\tilde{\alpha}} \exp(-\frac{h\nu}{E_0}) & \text{for } h\nu < (\tilde{\alpha} - \tilde{\beta})E_0 \\ [(\tilde{\alpha} - \tilde{\beta})E_0]^{(\tilde{\alpha}-\tilde{\beta})} (h\nu)^{\tilde{\beta}} \exp(\tilde{\beta} - \tilde{\alpha}), & \text{for } h\nu > (\tilde{\alpha} - \tilde{\beta})E_0 \end{cases}$$

Compactness problem

- $\delta T \leq .1$ sec $\Rightarrow$ maximum size of the source $R \leq c\delta T = 3\ 10^9$ cm.
- $E \cong 10^{51}$ergs.



Due to the large photon density and energy $\gamma\gamma \rightarrow e^+e^-$

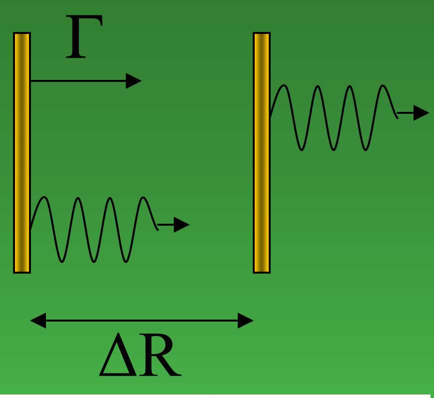
$\tau_{\gamma\gamma} = n_\gamma \sigma_T R \geq 10^{15}$ Very large optical depth !

□$\sigma_T \sim 10^{-25} cm^2$

Expected thermal spectrum and no high energy photons

??

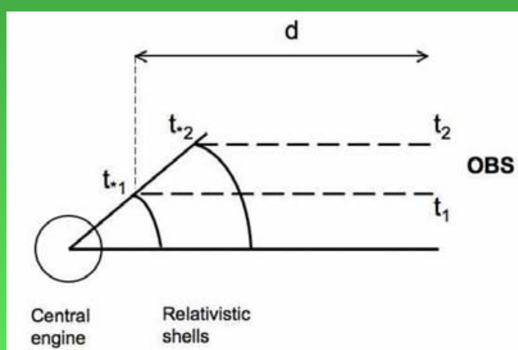
Need of relativistic motion



$\Longrightarrow$ $\delta T = \Delta R/v - \Delta R/c$

$\Downarrow$

$\Delta R \leq 2c\,\Gamma^2 \delta T$



blue shift: E_{ph} (obs) = $\Gamma\, E_{ph}$ (emitted)

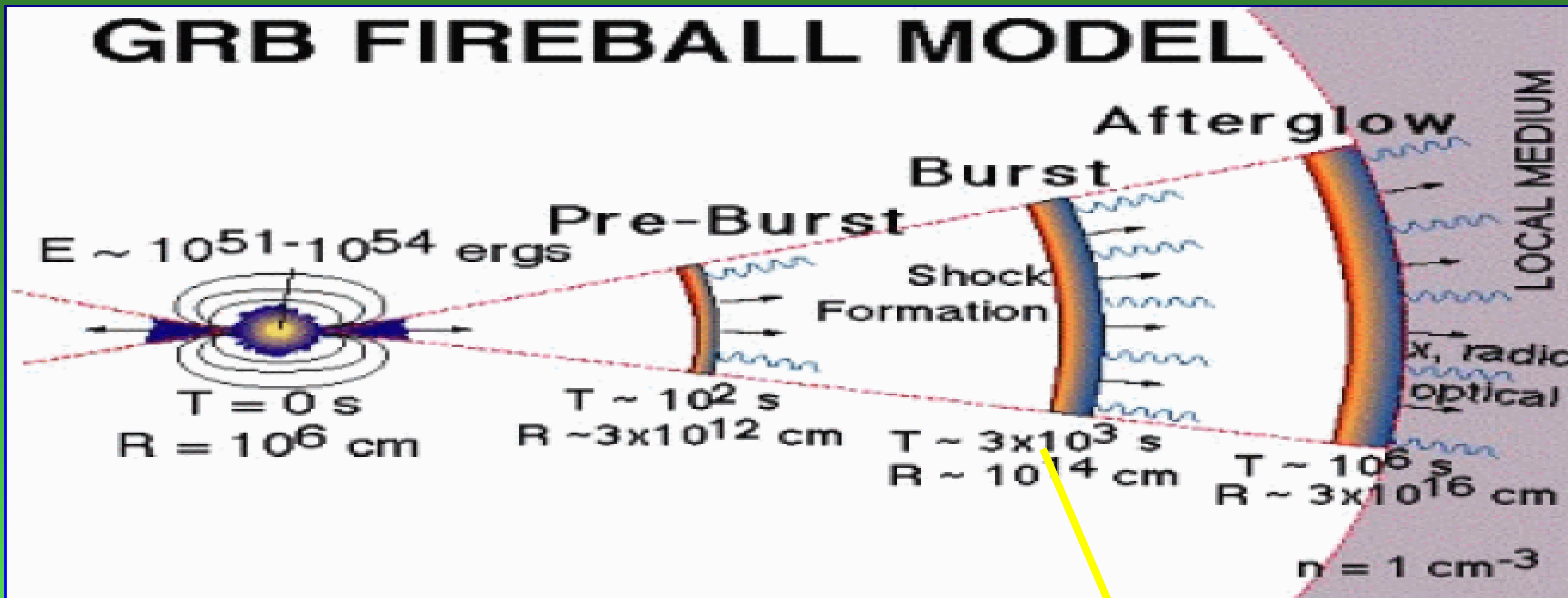
$N(E)dE = E^{-\alpha}dE$ $\Longrightarrow$ correction $\Gamma^{-2\alpha+2}$

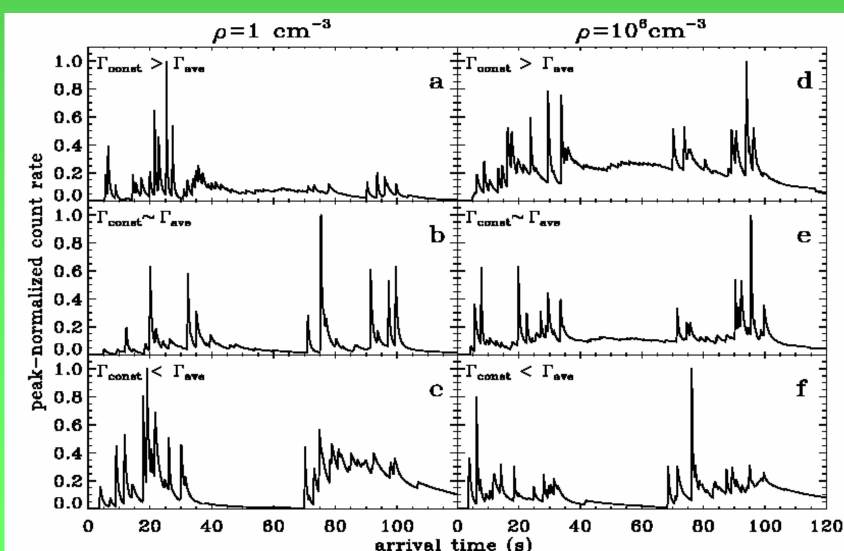
$$\tau_{\gamma\gamma} = \Gamma^{-(2+2\alpha)} \quad n_\gamma \sigma_T \Delta R \quad \geq 10^{15}/\,\Gamma^{(2+2\alpha)}$$

To have $\tau_{\gamma\gamma} < 1$ $\Longrightarrow$ $\Gamma \geq 100$ ($\alpha \cong 2$)

GRBs are the most relativistic objects known today

The Internal-External Fireball Model





Internal shocks can convert only a fraction of the kinetic energy to radiation

It should be followed by additional emission.

Internal shocks between shell with different Γ

Emission mechanism

Prompt emission: Synctrotron – Inverse Compton … ?

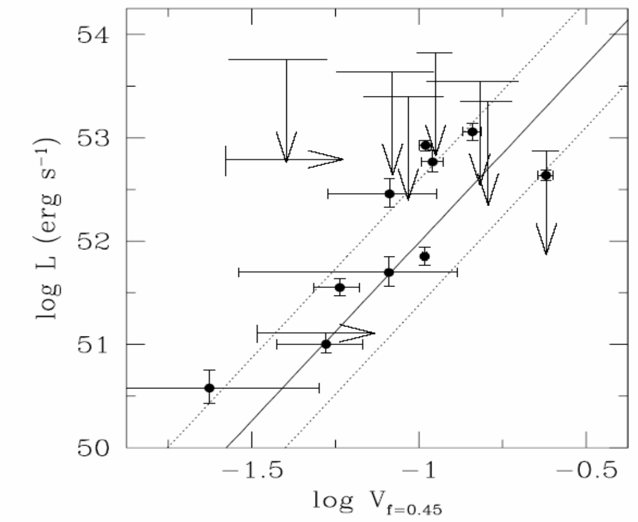
$$(h\nu_{syn})_{obs} = \frac{\hbar q_e B}{m_e c}\gamma_e^2\Gamma$$

synctrotron

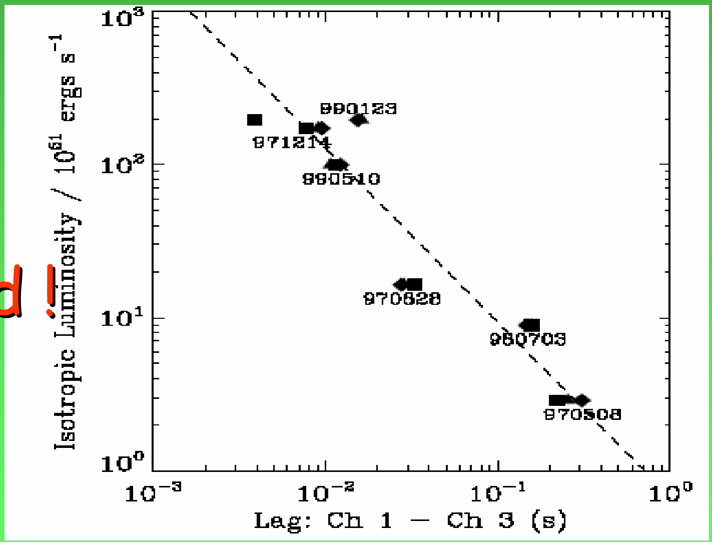
$$(h\nu_{IC})_{obs} = \frac{\hbar q_e B}{m_e c}\gamma_e^4\Gamma$$

High energy photons

Some interesting correlations



Still unexplained !



isotropic-equivalent peak luminosities L of these bursts positively correlate with a rigorously-constructed measure of the variability of their light curves

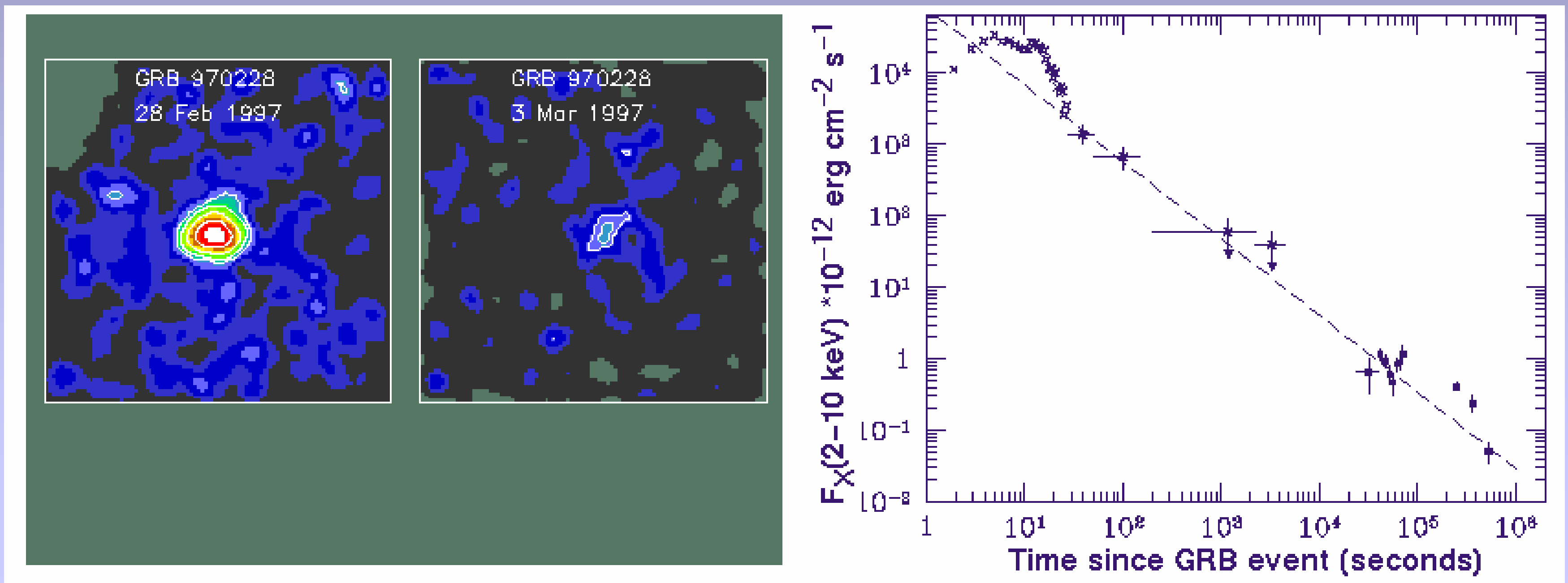
(Reichart et al 2001)

The spectral evolution timescale of pulse structures is anticorrelated with peak luminosity

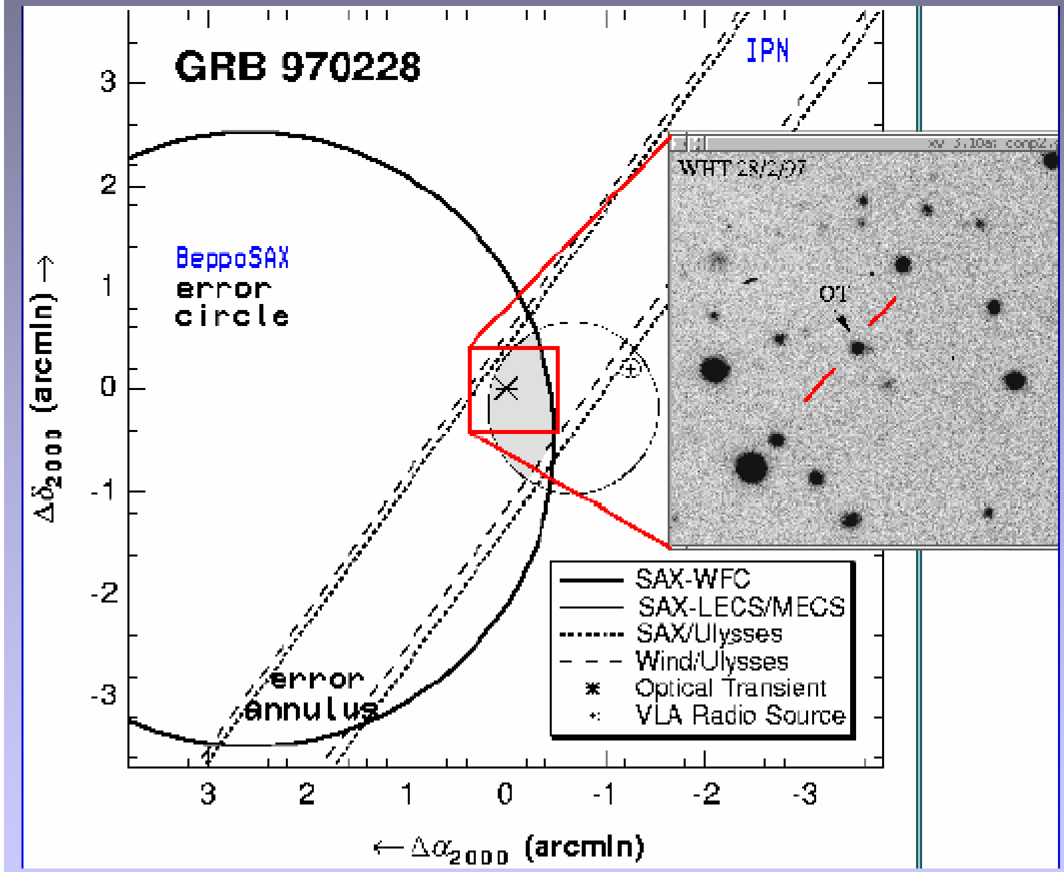
(Norris et al 2000)

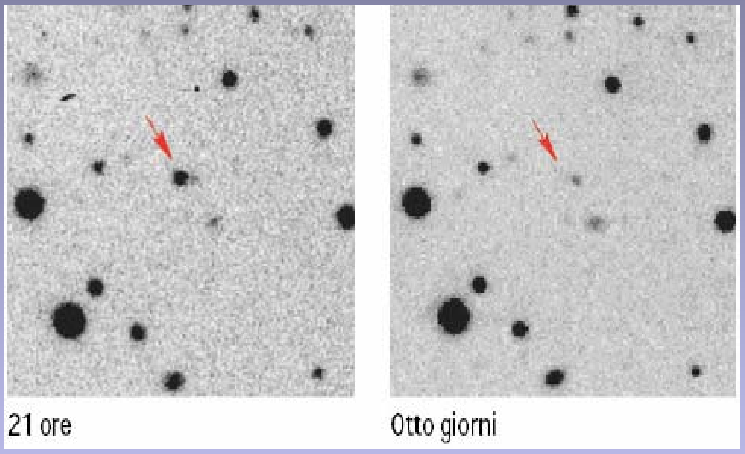
SAX EXPERIMENT

- The Italian/Dutch satellite BeppoSAX discovered x-ray afterglow on 28 February 1997 (Costa et. al. 97).

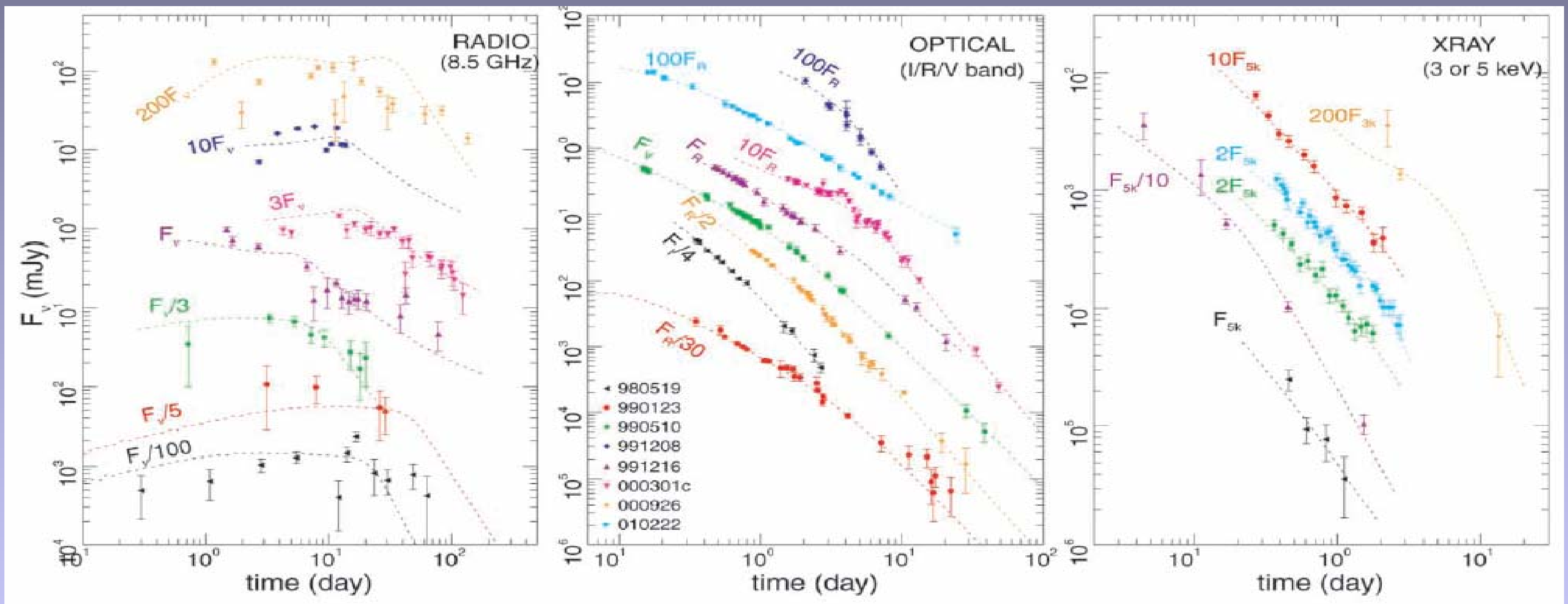


▪Immediate discovery of Optical afterglow (van Paradijs et. al 97).



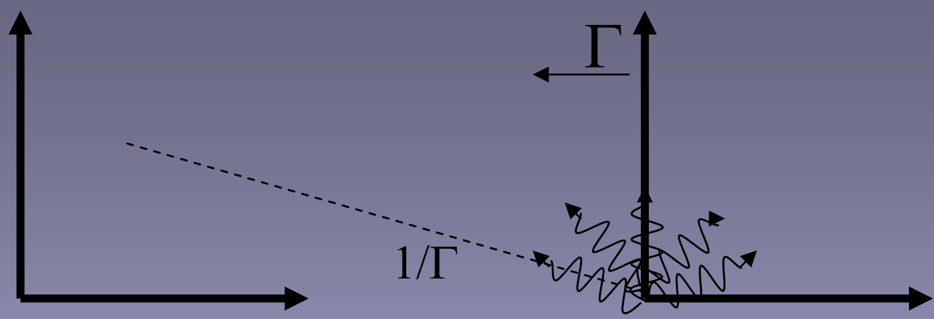


Afterglow: slowing down of relativistic flow and synchrotron emission fit the data to a large extent



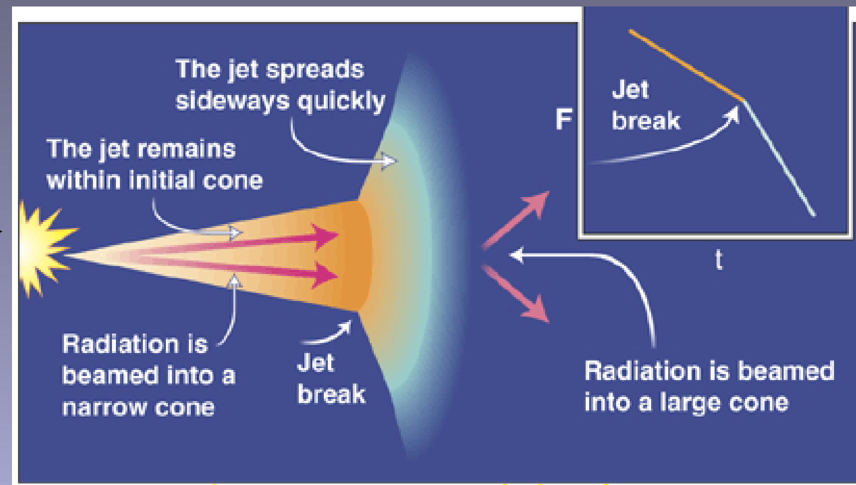
Panaitescu et al APJ 2001

Beaming of GRB

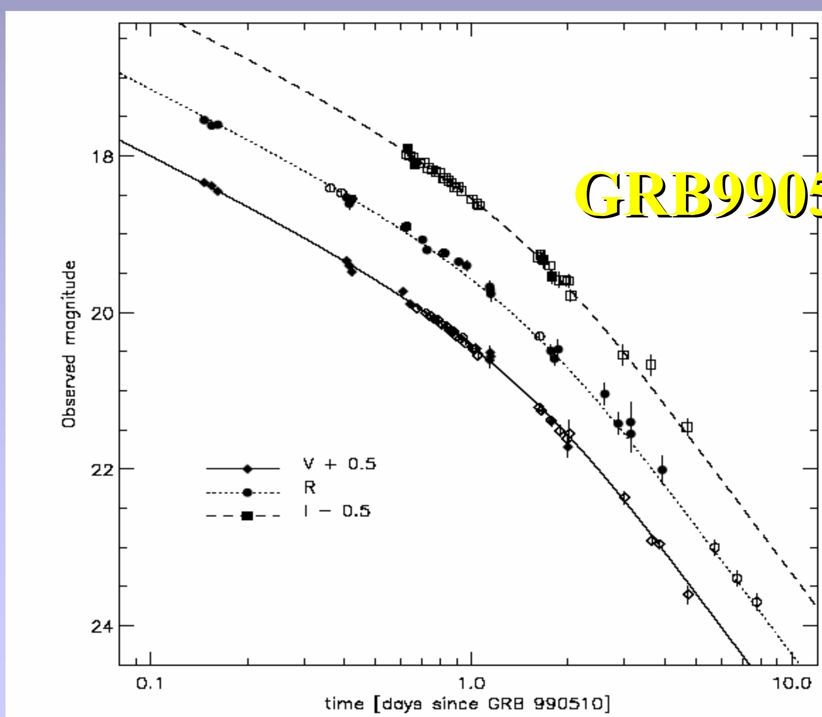


Relativistic beaming effect

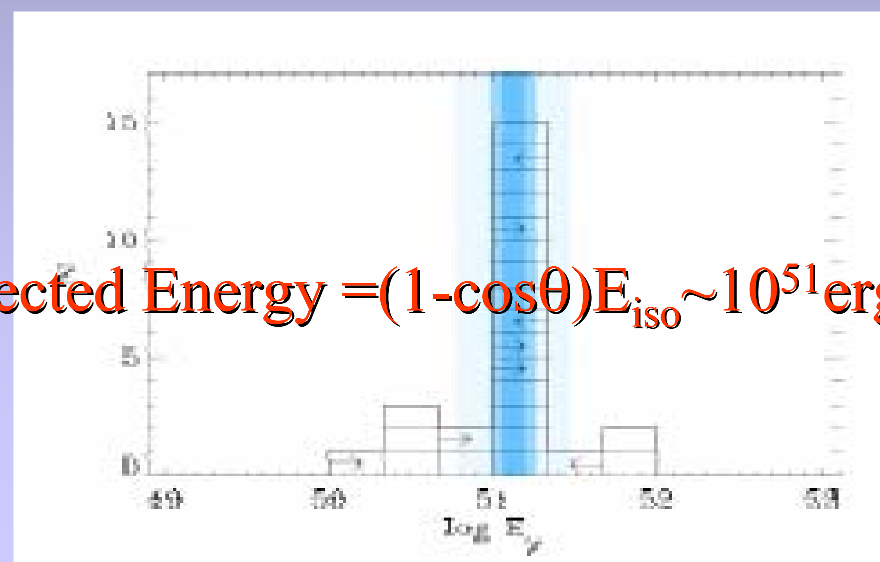
If the GRB is collimated θ



Γ decreases with time

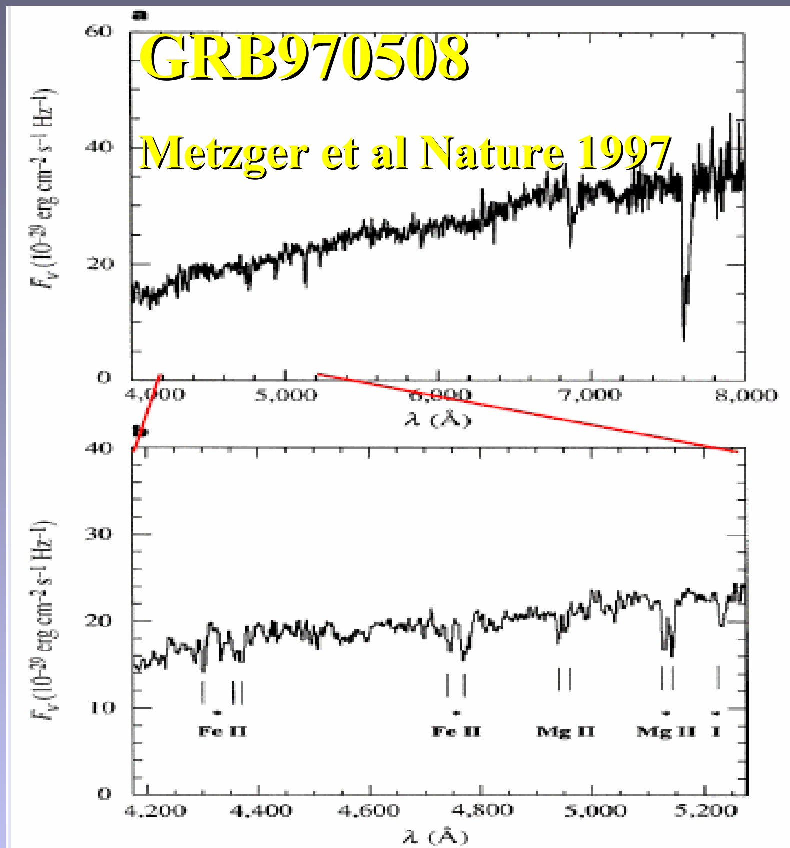


GRB990510



Corrected Energy =(1-cosθ)E_{iso}~10^{51}ergs

Redshift from the afterglow



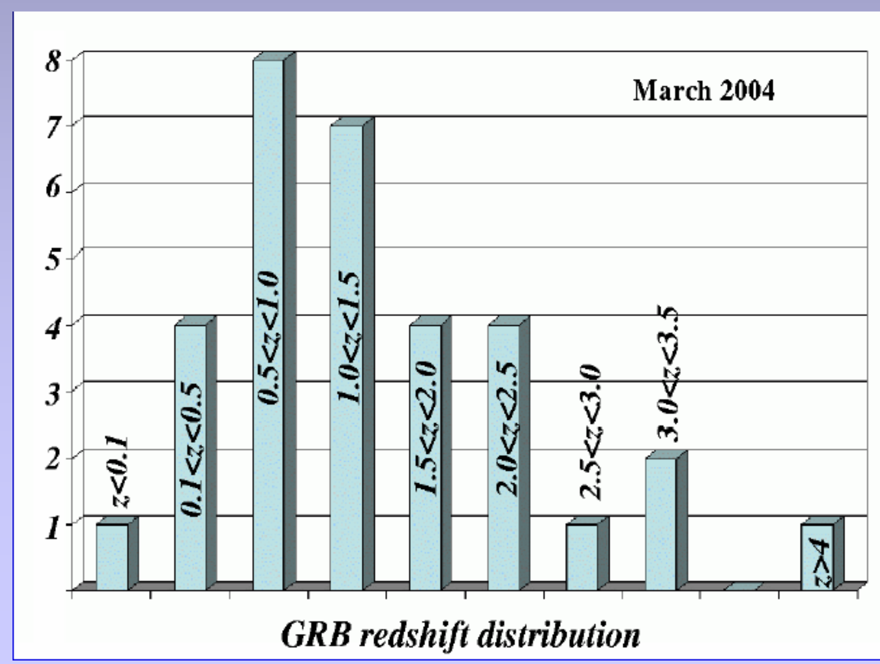
Optical counternpart- absorption lines

$1+z= \lambda_{obs}/ \lambda_{emit}$

$z=0.83$

Confirm the cosmological origin and the large amount of energy, galaxies star forming regions

$d \propto z \cong 10^9$ light years

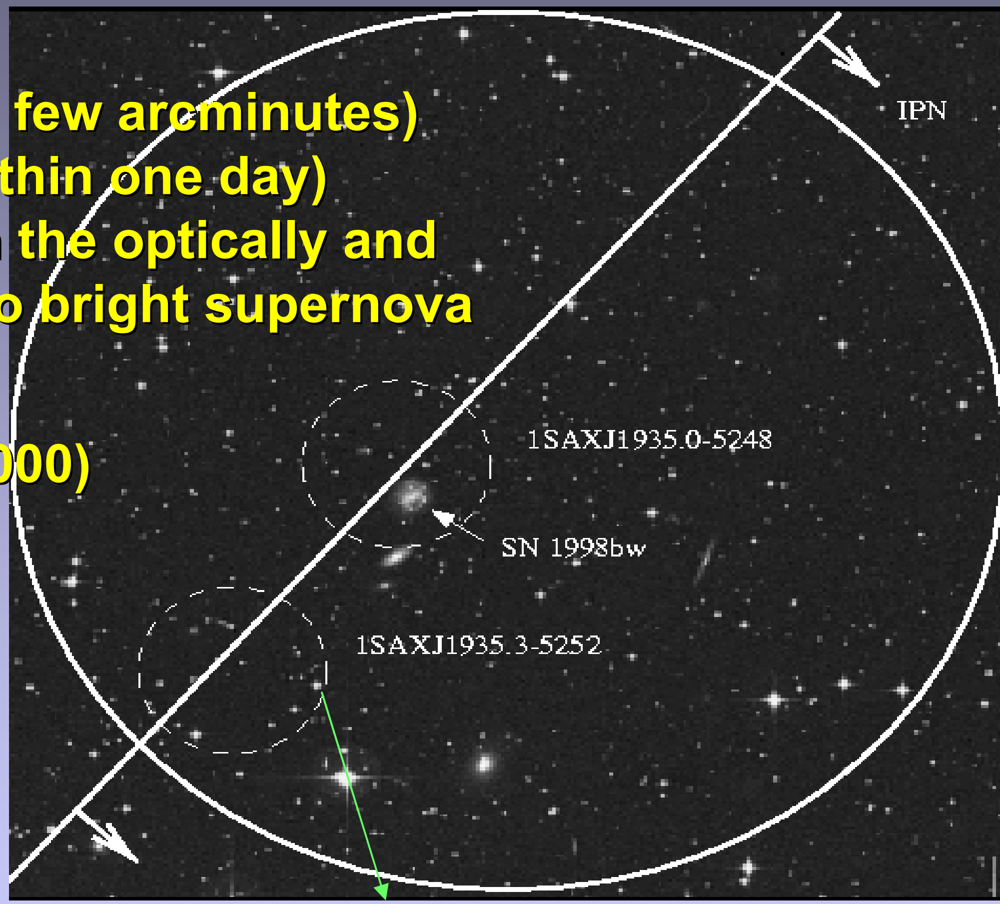


SN-GRB connection

SN 1998bw/GRB 980425

"spatial (within a few arcminutes) and temporal (within one day) consistency with the optically and exceedingly radio bright supernova 1998bw"

(Pian et al ApJ 2000)



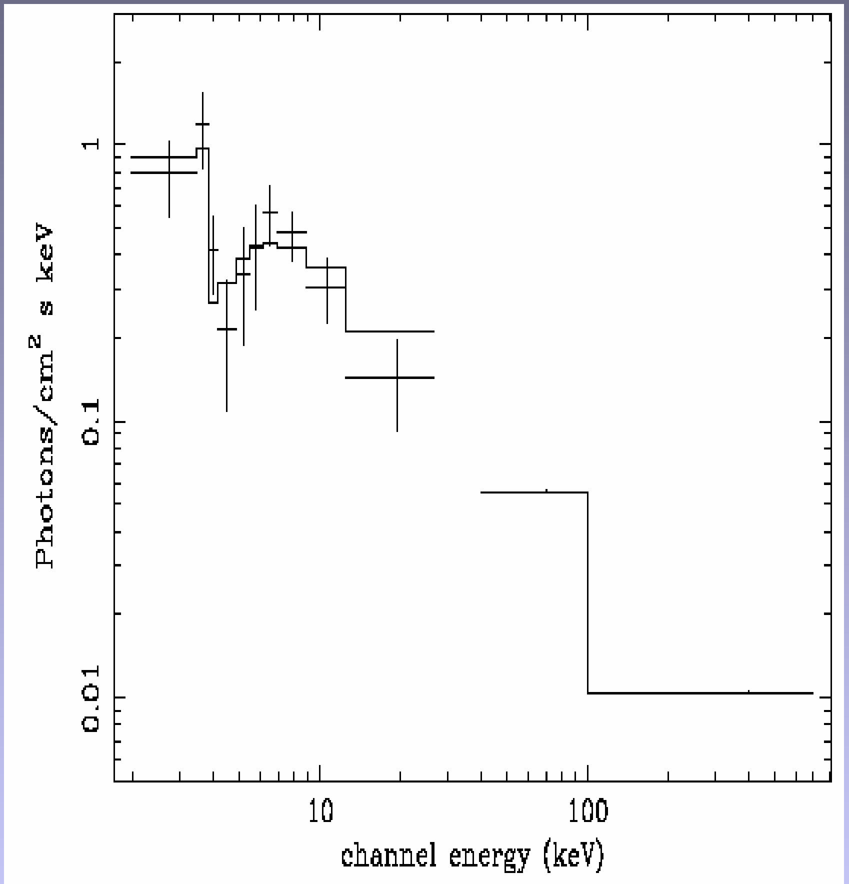
a group of small faint sources

Spectroscopic "evidences"

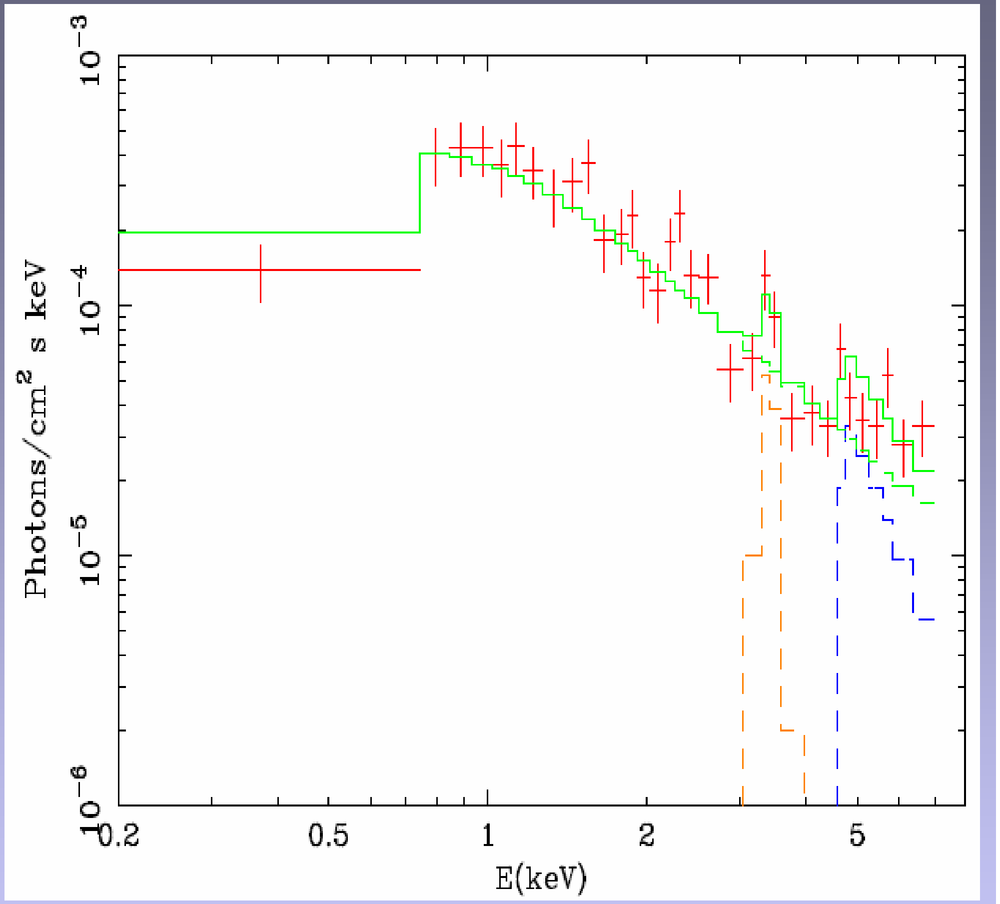
"Absorption x–ray emission of GRB 990705. This feature can be modeled by a medium located at a redshift of 0.86 and with an iron abundance of 75 times the solar one. The high iron abundance found points to the existence of a burst environment enriched by a supernova along the line of sight"…

"The supernova explosion is estimated to have occurred about 10 years before the burst "

(Amati et al, Science 2000)



"We report on the discovery of two emission features observed in the X-ray spectrum of the afterglow of the gamma-ray burst (GRB) of 16 Dec. 1999 by the Chandra X-Ray Observatory… ions of iron at a redshift z = 1.00±0.02, providing an unambiguous measurement of the distance of a GRB. Line width and intensity imply that the progenitor of the GRB was a massive star system that ejected, before the GRB event, $0.01M_{sun}$ of iron at 0.1c"

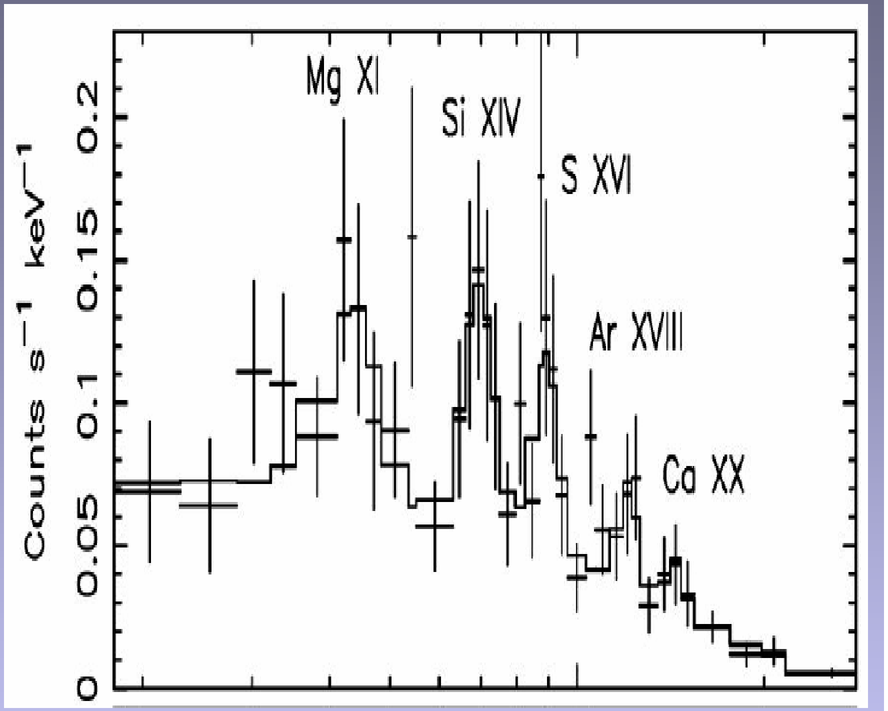


…the simplest explanation of our results is a mass ejection by the progenitor with the same velocity implied by the observed line width. The ejection should have then occurred R/v = (i.e., a few months) before the GRB.

GRB991216, Piro et al Nature 2001

"The X-ray spectrum reveals evidence for emission lines of Magnesium, Silicon, Sulphur, Argon, Calcium, and possibly Nickel, arising in enriched material with an outflow velocity of order 0.1c. …

The observations strongly favour models where a supernova explosion from a massive stellar progenitor precedes the burst event and is responsible for the outflowing matter…. delay between an initial supernova and the onset of the gamma ray burst is required, of the order several months".

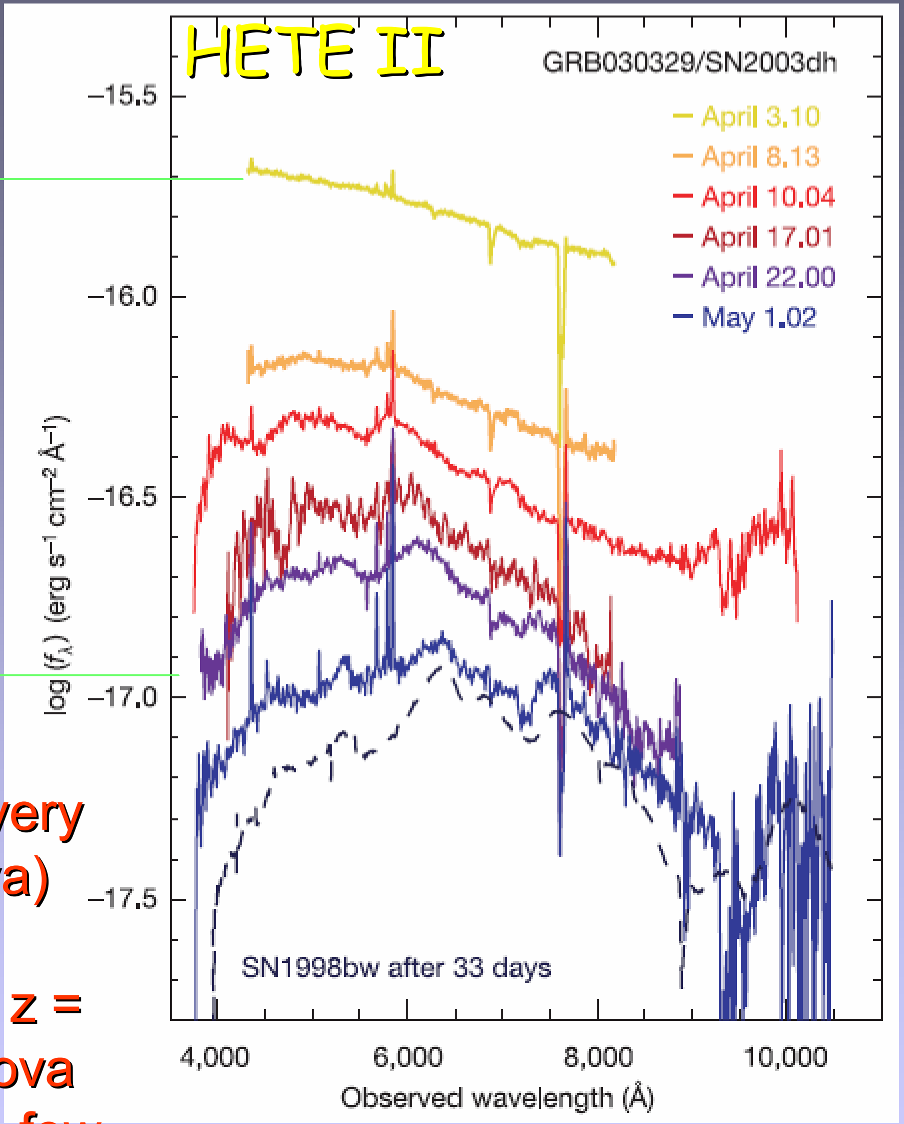


(Reeves et al., Nature 2001)

Still debated !

Typical afterglow power-low spectrum

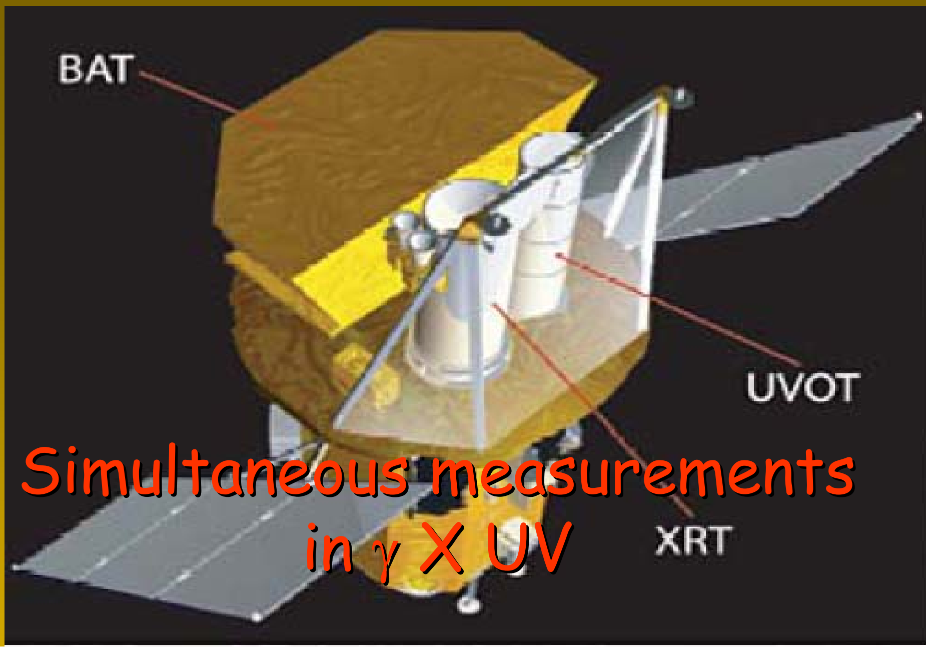
SN spectrum

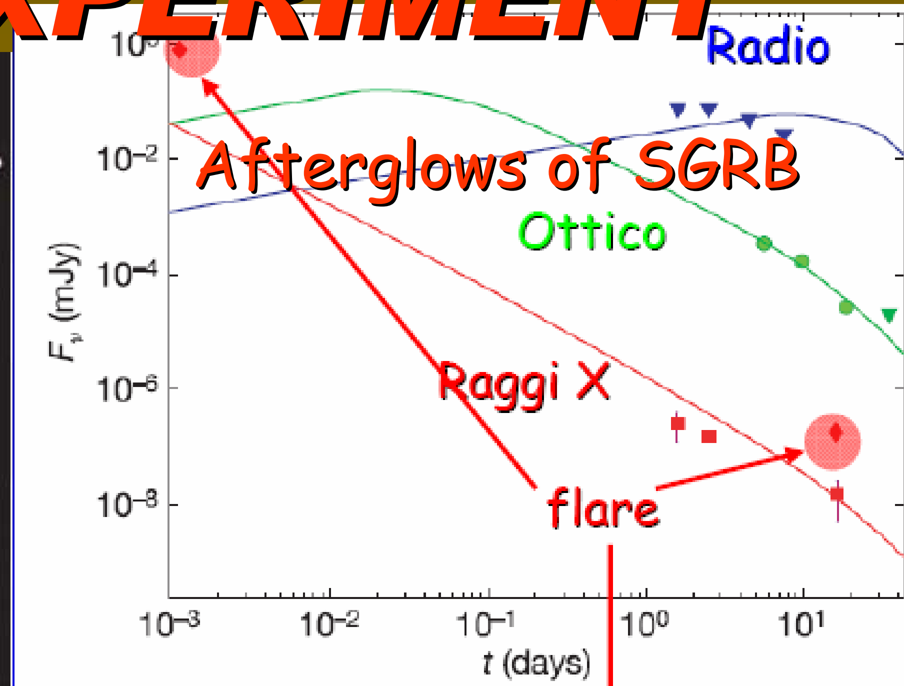


Hjorth et al Nature 2003

"Here we report evidence that a very energetic supernova (a hypernova) was temporally and spatially coincident with a GRB at redshift z = 0.1685. The timing of the supernova indicates that it exploded within a few days of the GRB"

SWIFT EXPERIMENT

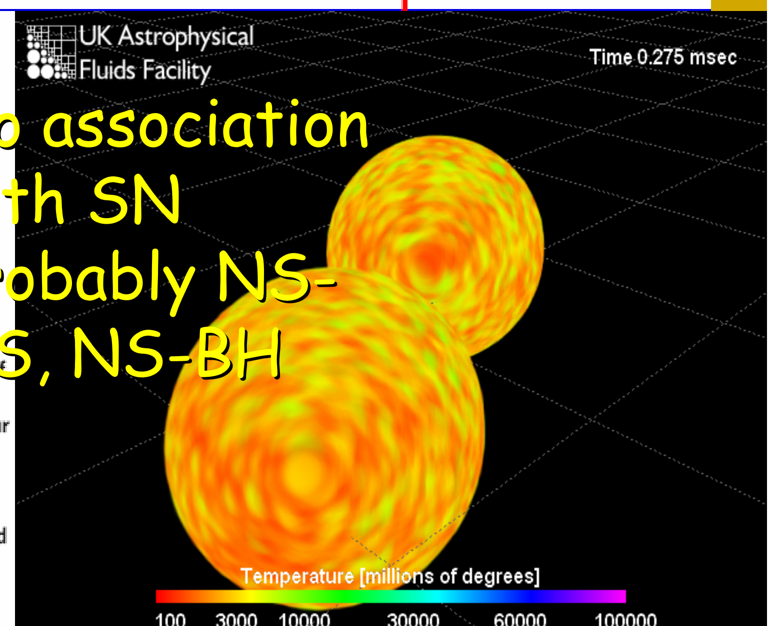




The afterglow of GRB 050709 and the nature of the short-hard γ-ray bursts

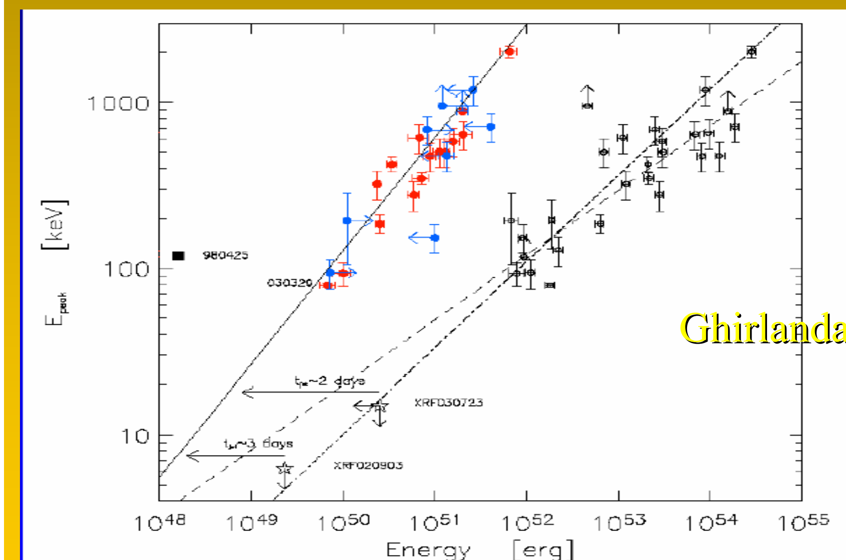
D. B. Fox[1,2], D. A. Frail[3], P. A. Price[4], S. R. Kulkarni[1], E. Berger[5], T. Piran[1,6], A. M. Soderberg[1], S. B. Cenko[1], P. B. Cameron[1], A. Gal-Yam[1], M. M. Kasliwal[1], D.-S. Moon[1], F. A. Harrison[1], E. Nakar[1], B. P. Schmidt[7], B. Penprase[8], R. A. Chevalier[9], P. Kumar[10], K. Roth[11], D. Watson[12], B. L. Lee[13], S. Shectman[5], M. M. Phillips[5], M. Roth[5], P. J. McCarthy[5], M. Rauch[5], L. Cowie[4], B. A. Peterson[7], J. Rich[7], N. Kawai[14], K. Aoki[15], G. Kosugi[15], T. Totani[16], H.-S. Park[17], A. MacFadyen[18] & K. C. Hurley[19]

The final chapter in the long-standing mystery of the γ-ray bursts (GRBs) centres on the origin of the short-hard class of bursts, which are suspected on theoretical grounds to result from the coalescence of neutron-star or black-hole binary systems. Numerous searches for the afterglows of short-hard bursts have been made, galvanized by the revolution in our understanding of long-duration GRBs that followed the discovery in 1997 of their broadband (X-ray, optical and radio) afterglow emission. Here we present the discovery of the X-ray afterglow of a short-hard burst, GRB 050709, whose accurate position allows us to associate it unambiguously with a star-forming galaxy at redshift $z = 0.160$, and whose optical lightcurve definitively excludes a supernova association. Together with results from three other recent short-hard bursts, this suggests that short-hard bursts release much less energy than the long-duration GRBs. Models requiring young stellar populations, such as magnetars and collapsars, are ruled out, while coalescing degenerate binaries remain the most promising progenitor candidates.

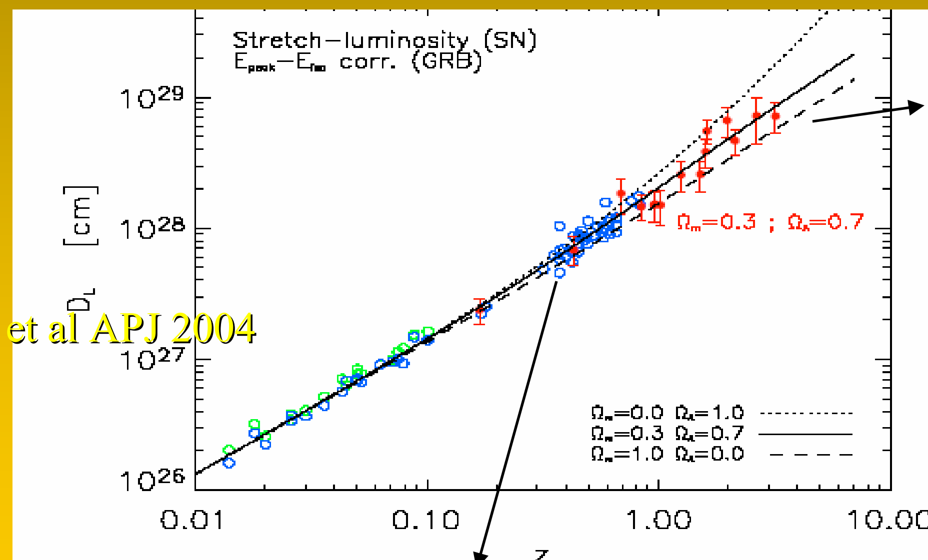


GRB 050904 at redshift 6.3: observations of the oldest cosmic explosion after the Big Bang*

correlation between the peak of the –ray spectrum Epeak and the collimation corrected energy emitted in –rays. The latter is related to the isotropically equivalent energy E,iso by the value of the jet aperture angle. The correlation itself can be used for a reliable estimate of E,iso, making GRBs distance indicators



Ghirlanda et al APJ 2004



GRB

supernovae

GRBs as standard candles to study Cosmology

Conclusions

- Afterglow:good understanding (external shocks), collimation. Orphan afterglow?
- Prompt emission: good "description" of temporal structure (internal shocks), still not completely understood the mechanism. High energy photons, neutrinos?
- High redshift and SN-GRB connection
- What about the inner engine? See next lecture

INNER ENGINE OF GRBs

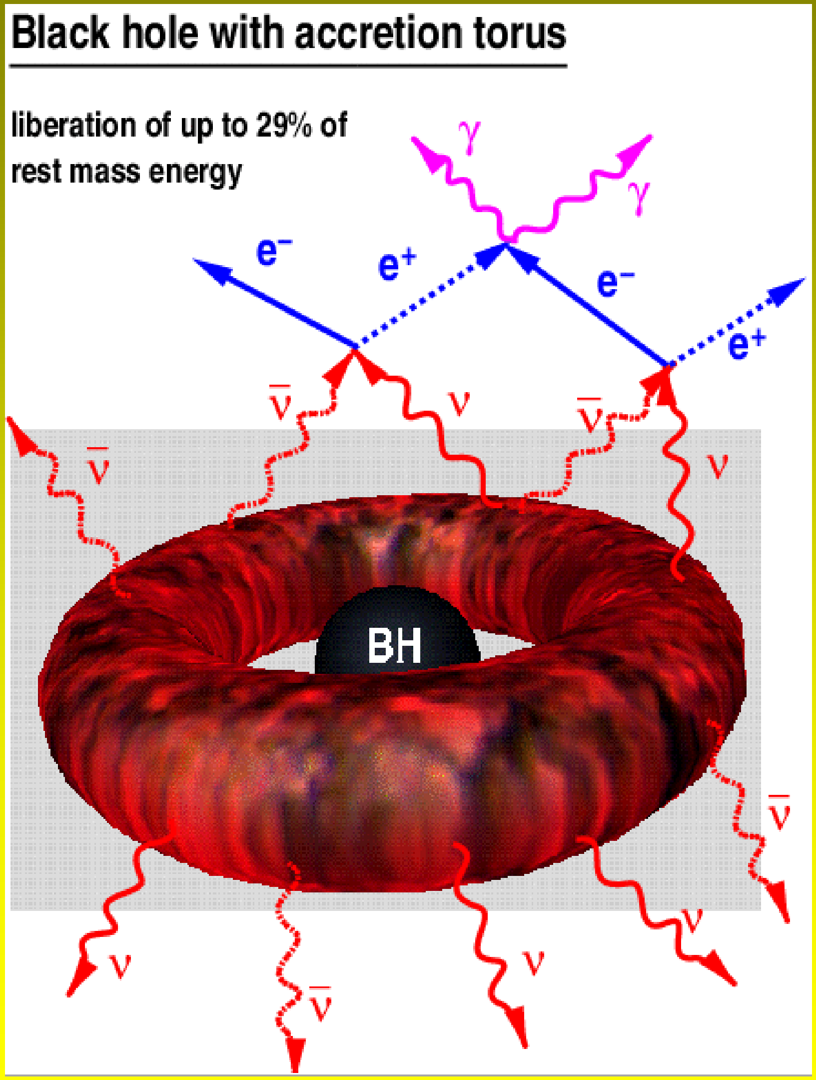
REQUIREMENTS:

- *Huge energy: E~10^{52}ergs (10^{51} beaming)*
- *Provide adequate energy at high Lorentz factor*
- *Time scales: total duration few tens of second, variability <0.1s, quiescent times*
- *SN(core collapse)-GRB connection*

The Collapsar model

Collapsars (Woosley 1993)

- Collapse of a massive (WR) rotating star that does not form a successful SN to a BH ($M_{BH} \sim 3M_{sol}$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.
- The viscous accretion onto the BH strong heating thermal $\nu\tilde{\nu}$ annihilating preferentially around the axis .



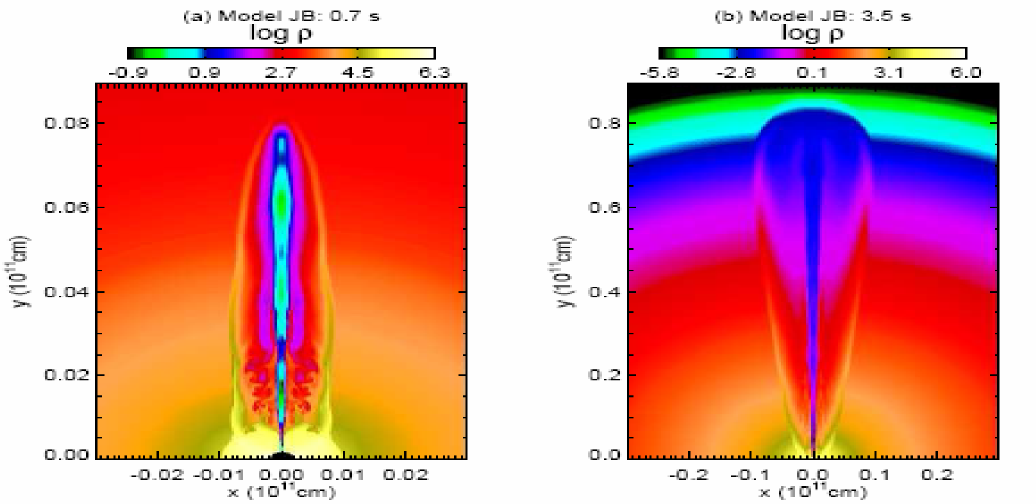
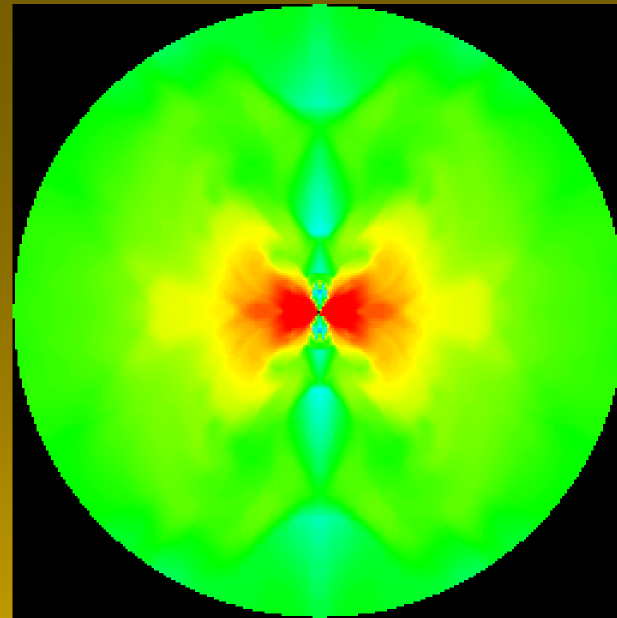
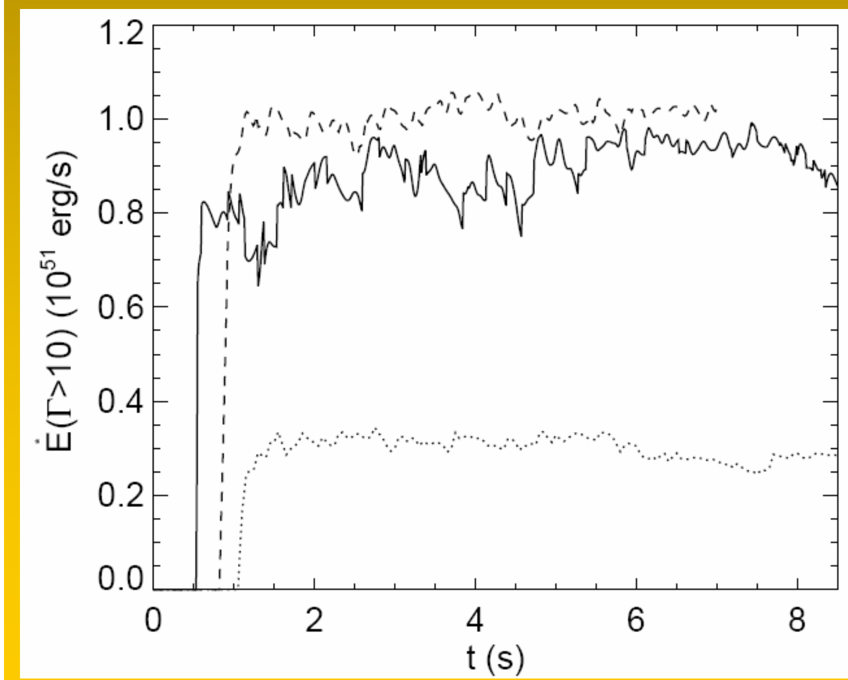


Fig. 2.— Density structure in the local rest frame for Model JB at (a) $t = 0.7$ s (*left*) and (b) 3.5 s (*right*). In (a), only the central region of the star is shown. Note the much higher degree of collimation than in Model JA.





Outflows are collimated by passing through the stellar mantle.

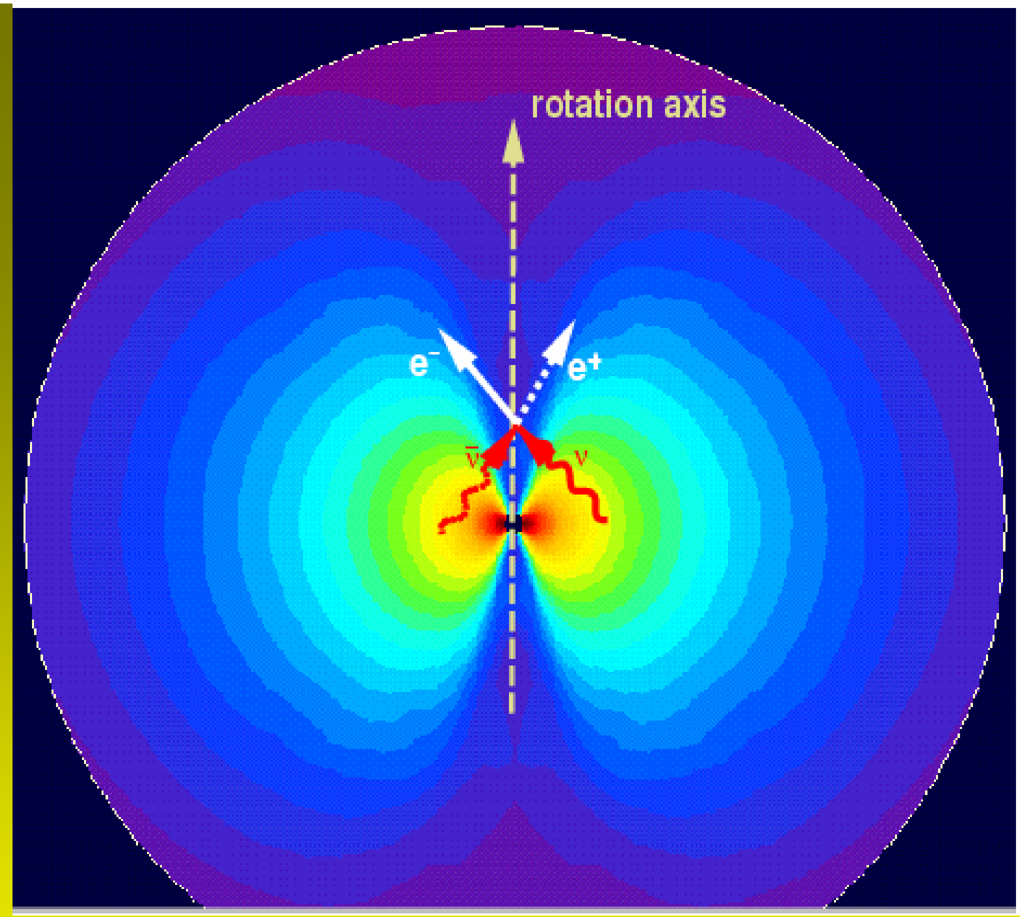
		Conservative			Optimistic		
$\dot{M}$	a	L_ν	$L_{\nu\bar{\nu}}$	efficiency	L_ν	$L_{\nu\bar{\nu}}$	efficiency
$M_\odot\ s^{-1}$		10^{51} erg s^{-1}	10^{51} erg s^{-1}	%	10^{51} erg s^{-1}	10^{51} erg s^{-1}	%
0.05	0.50	1.2	0.00023	0.019	1.6	0.0012	0.075
0.05	0.75	2.2	0.0012	0.055	3.6	0.016	0.44
0.05	0.89	4.3	0.017	0.41	8.6	0.18	2.1
0.05	0.95	7.6	0.061	0.81	18	1.3	7.4
0.0631	0.95	23	1.9	8.2	35	3.7	10
0.0794	0.95	35	1.9	5.3	39	2.1	5.3
0.1	0.50	6.1	0.0083	0.14	7.8	0.027	0.34
0.1	0.75	13	0.071	0.56	18	0.27	1.6
0.1	0.89	33	1.2	3.6	36	1.2	3.5
0.1	0.95	41	1.3	3.2	46	1.7	3.6

+ Detailed numerical analysis of jet formation.

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

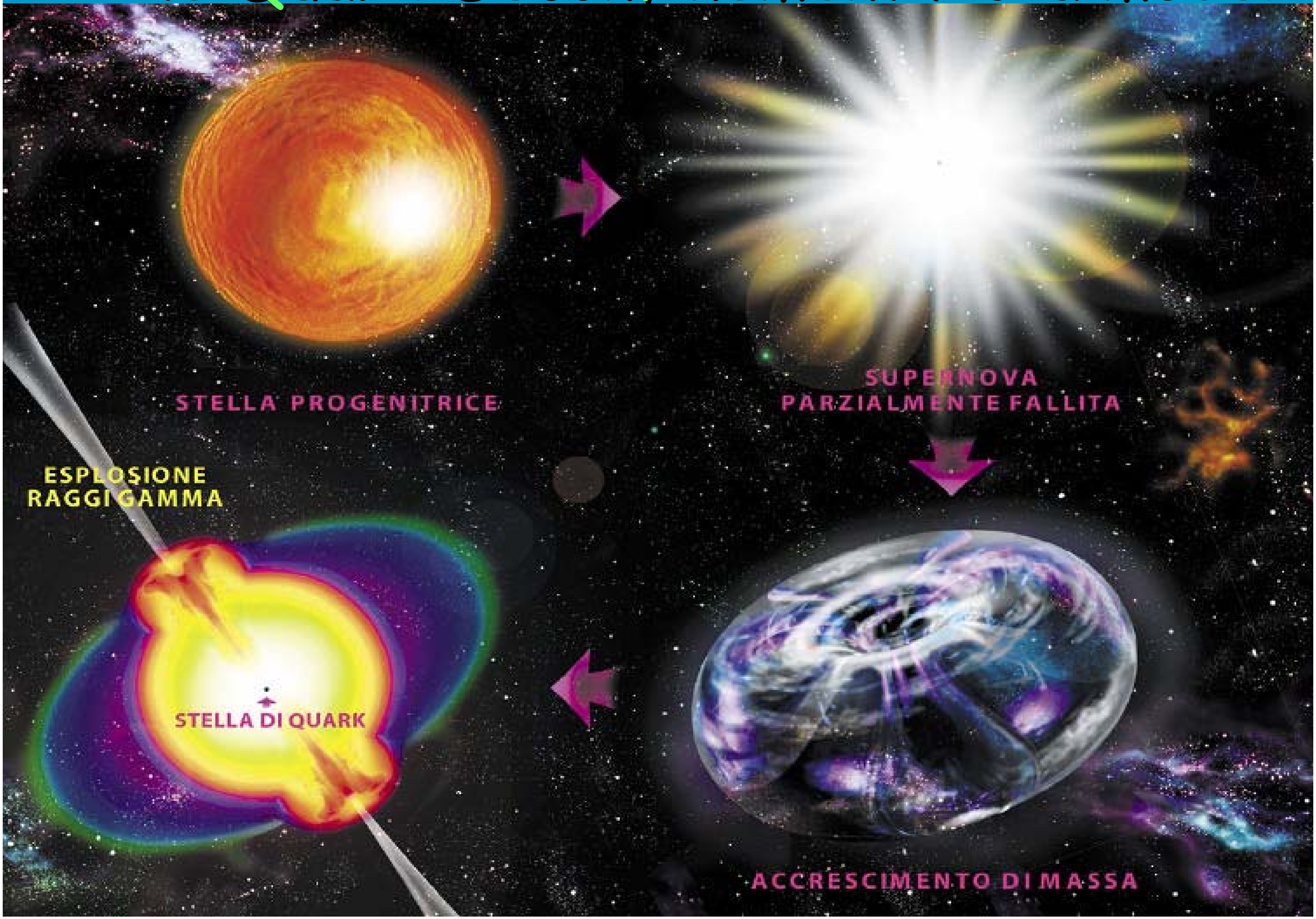
-

$j_{16} = j/(10^{16}\ cm^2\ s^{-1})$, $j_{16} < 3$, material falls into the black hole almost uninhibited. No outflows are expected. For $j_{16} > 20$, the infalling matter is halted by centrifugal force outside 1000 km where neutrino losses are negligible. For $3 < j_{16} < 20$, however, a reasonable value for such stars, a compact disk forms at a radius where the gravitational binding energy can be efficiently radiated as neutrinos.



SN – GRB time delay: less then 100 s.

The Quark-Deconfinement Nova model



Delayed formation of quark matter in Compact Stars

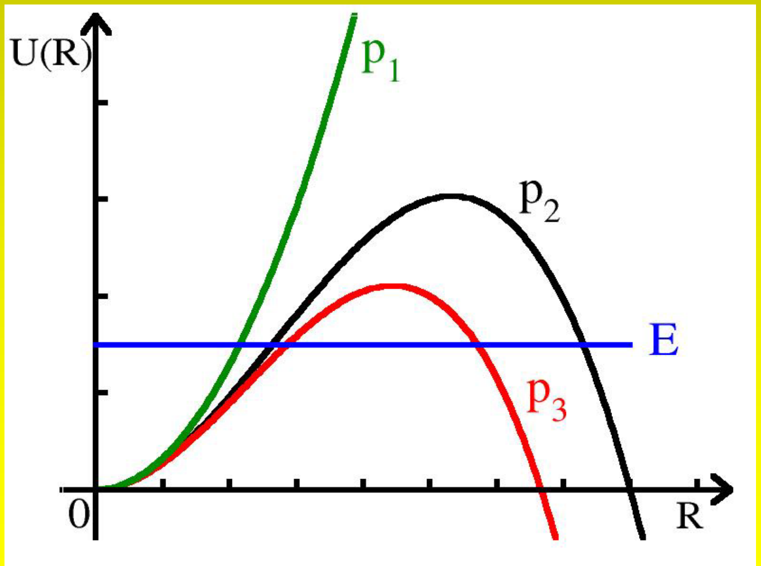
Quark matter cannot appear before the PNS has deleptonized (Pons et al 2001)

Quantum nucleation theory

Droplet potential energy:

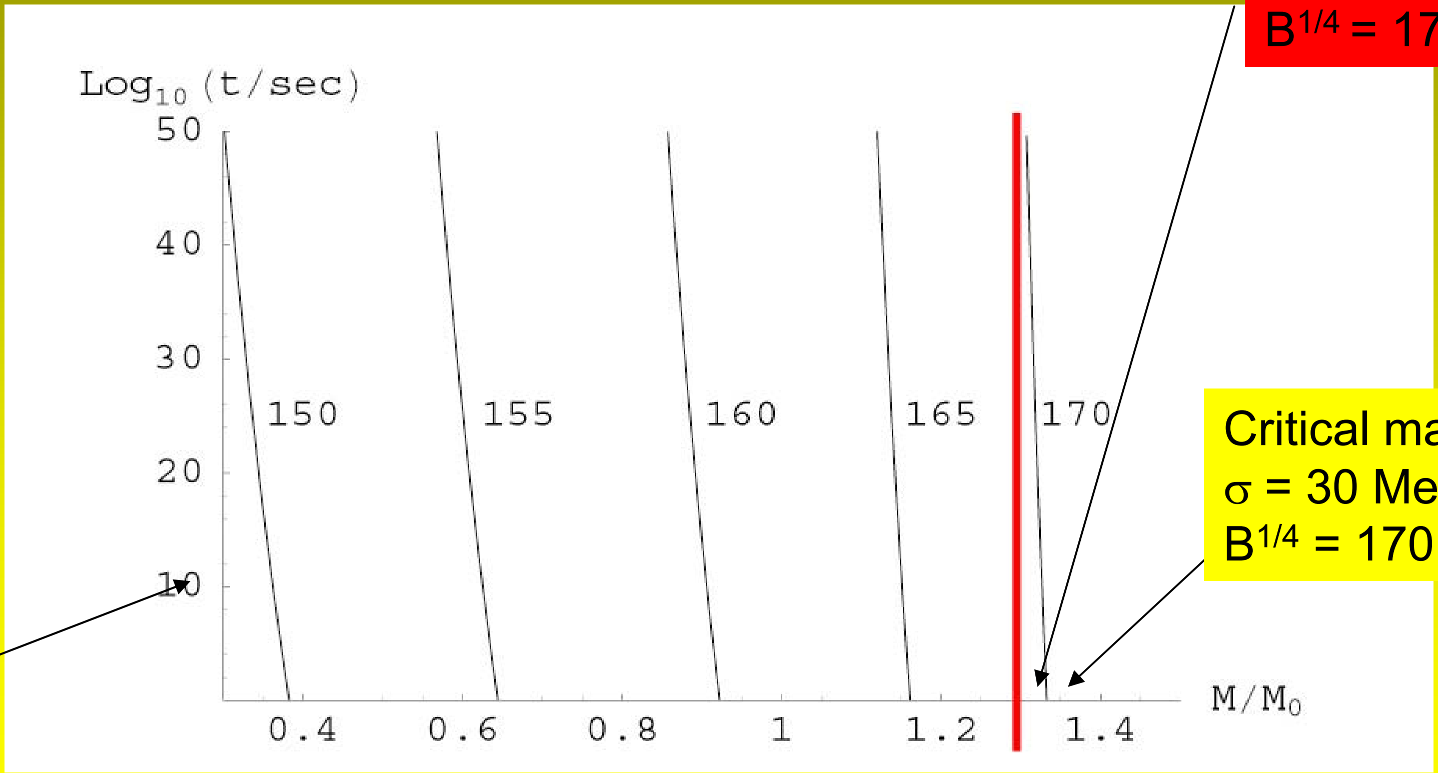
$$U(R) = \frac{4}{3}\pi n_{Q^*}\left(\mu_{Q^*} - \mu_H\right) R^3 + 4\pi\sigma R^2 = a_V R^3 + a_s R^2$$

- n_{Q^*} baryonic number density in the Q*-phase at a fixed pressure P.
- μ_{Q^*}, μ_H chemical potentials at a fixed pressure P.
- σ surface tension (=10,30 MeV/fm^2)



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

Quark droplet nucleation time
"mass filtering"

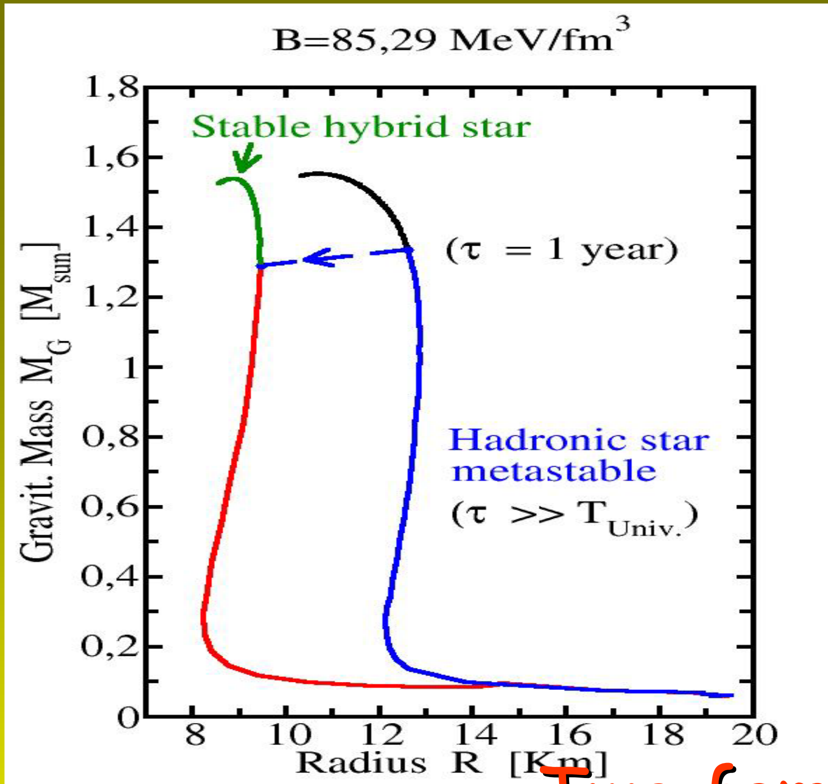


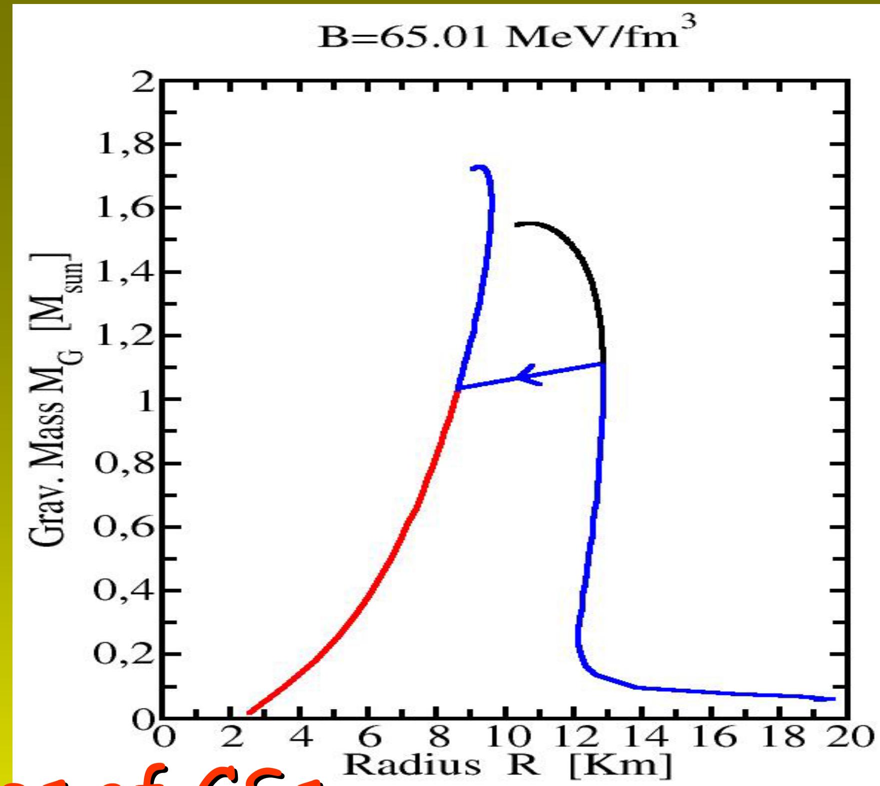
Critical mass for
$\sigma = 0$
$B^{1/4}$ = 170 MeV

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

Age of the Universe!

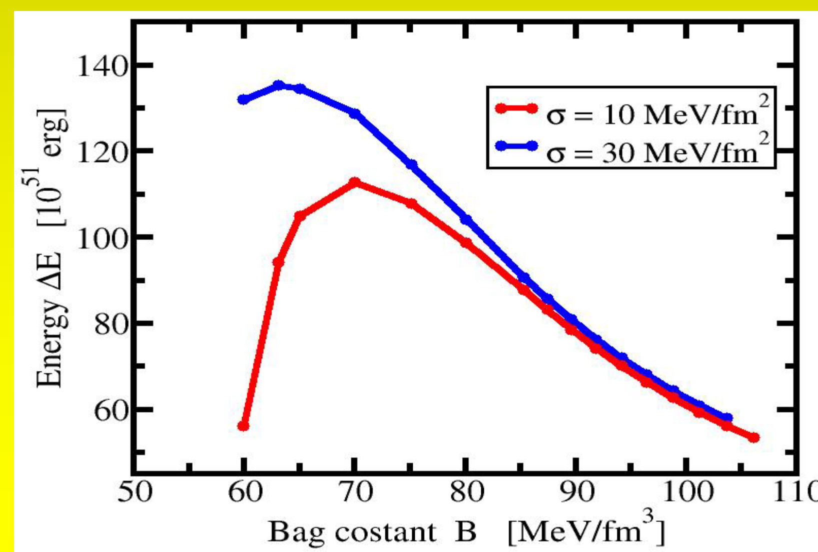
Mass accretion





Two families of CSs

Conversion from HS to HyS (QS) with the same M_B



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:

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

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

$$\eta \approx 10\%$$

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

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

Hadronic Stars → Hybrid or Quark Stars

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

Drago, Lavagno Pagliara 2004, Bombaci Parenti Vidana 2004…

Metastability due to delayed production of Quark Matter .

1) conversion to Quark Matter (it is NOT a detonation (see Parenti))

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.

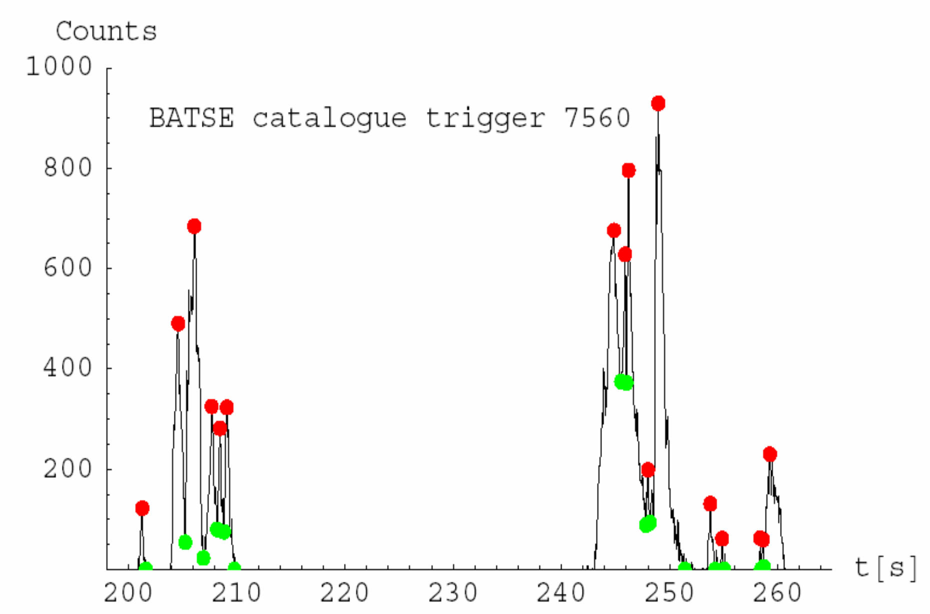
- *No calculation of beam formation, yet.*

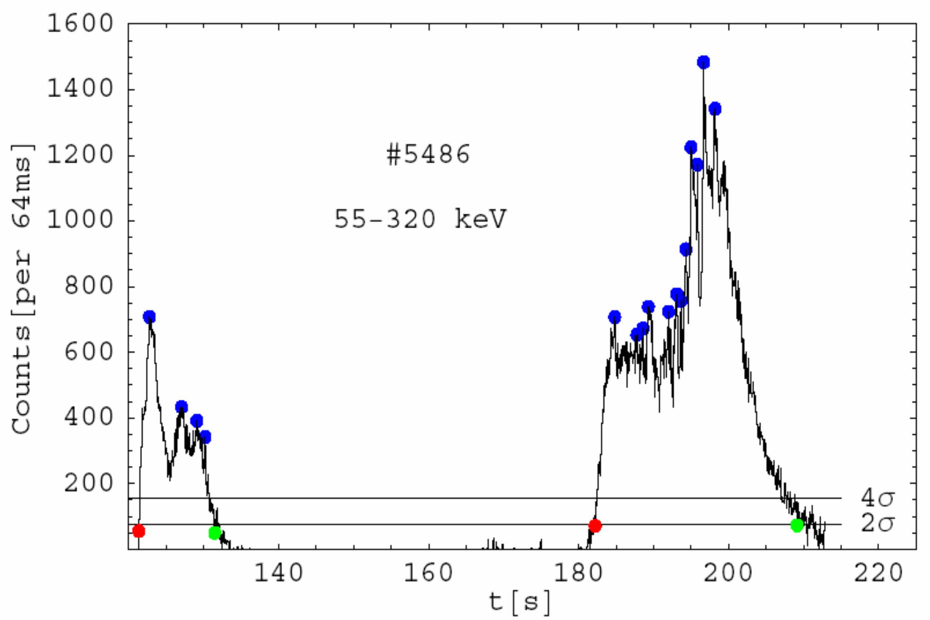
SN – GRB time delay: minutes → years

depending on mass accretion rate

... back to the data

Temporal structure of GRBs



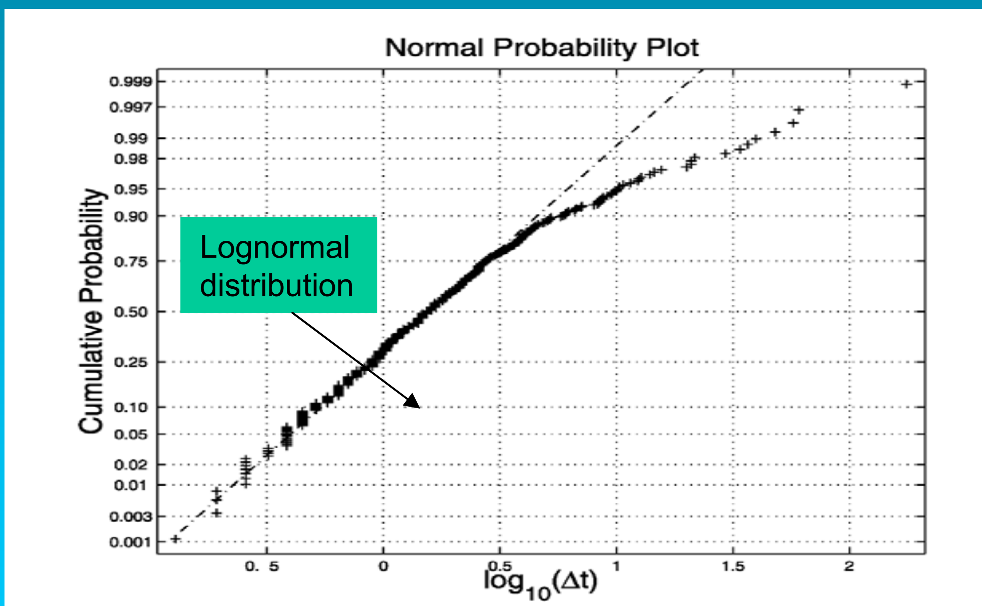


ANALYSIS of the distribution of peaks intervals

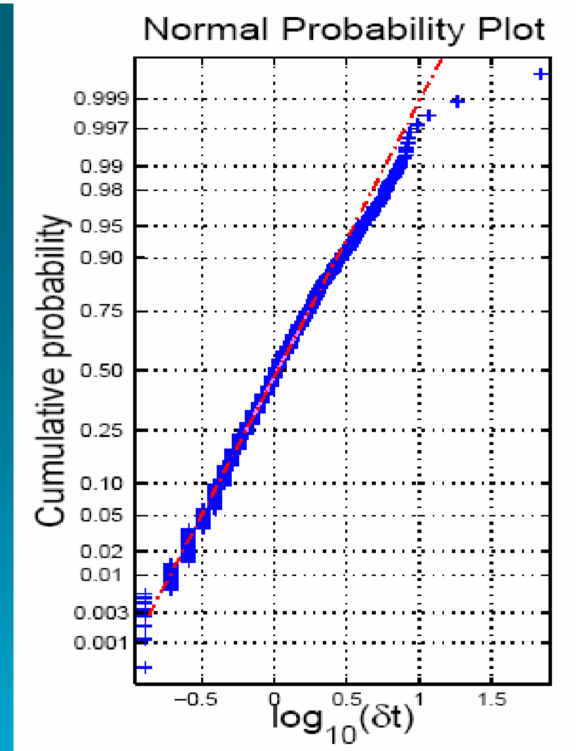
Lognormal distribution

$$f(x)dx = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\log x - \mu)^2}{2\sigma^2}\right] d\log x, & \text{if} \quad x > 0 \\ 0, & \text{if} \quad x \le 0 \end{cases}$$

Central limit theorem

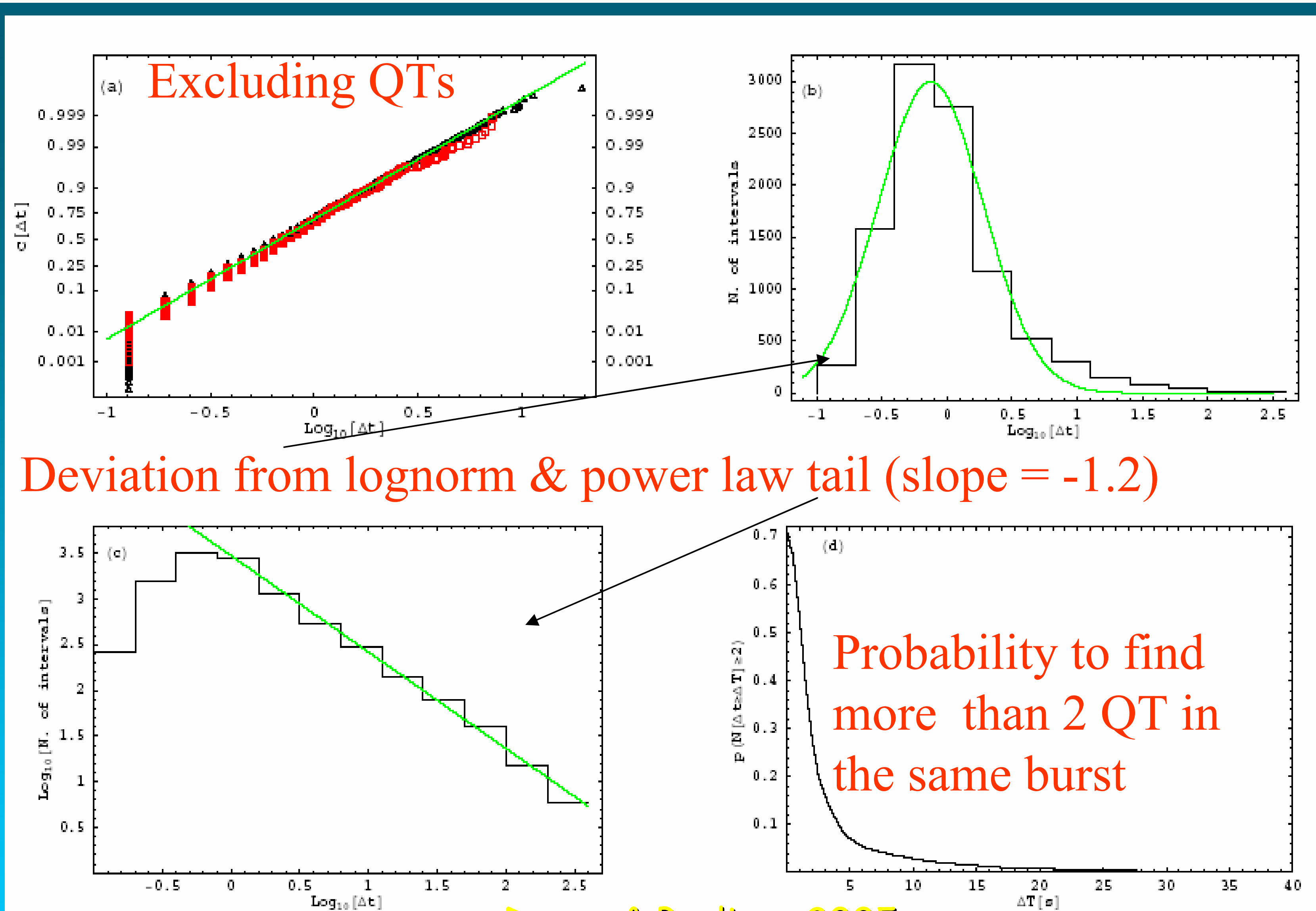


$\Delta t \simeq (L/c)(1+z)$



$\delta t \simeq (L/c)(\gamma_s^2/\gamma_m^2)(1+z)$

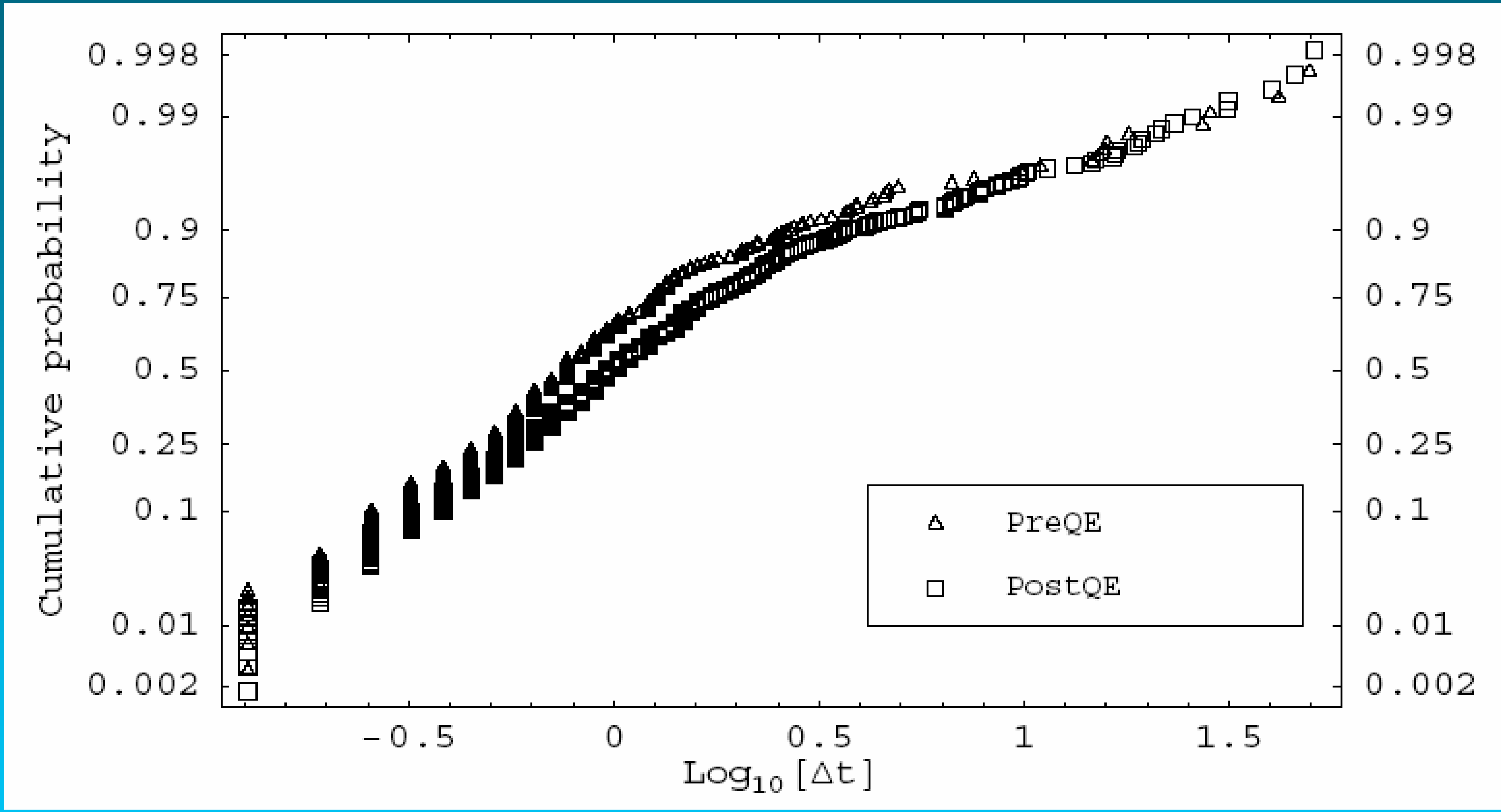
"… the quiescent
times are made by a different
mechanism
then the rest of the intervals"
Nakar and Piran 2002



Drago & Pagliara 2005

Analysis on 36 bursts having long QT (red dots): the subsample is not anomalous

Analysis of PreQE and PostQE



Same "variability": the same emission mechanism, internal shocks

Same dispersions but different average duration

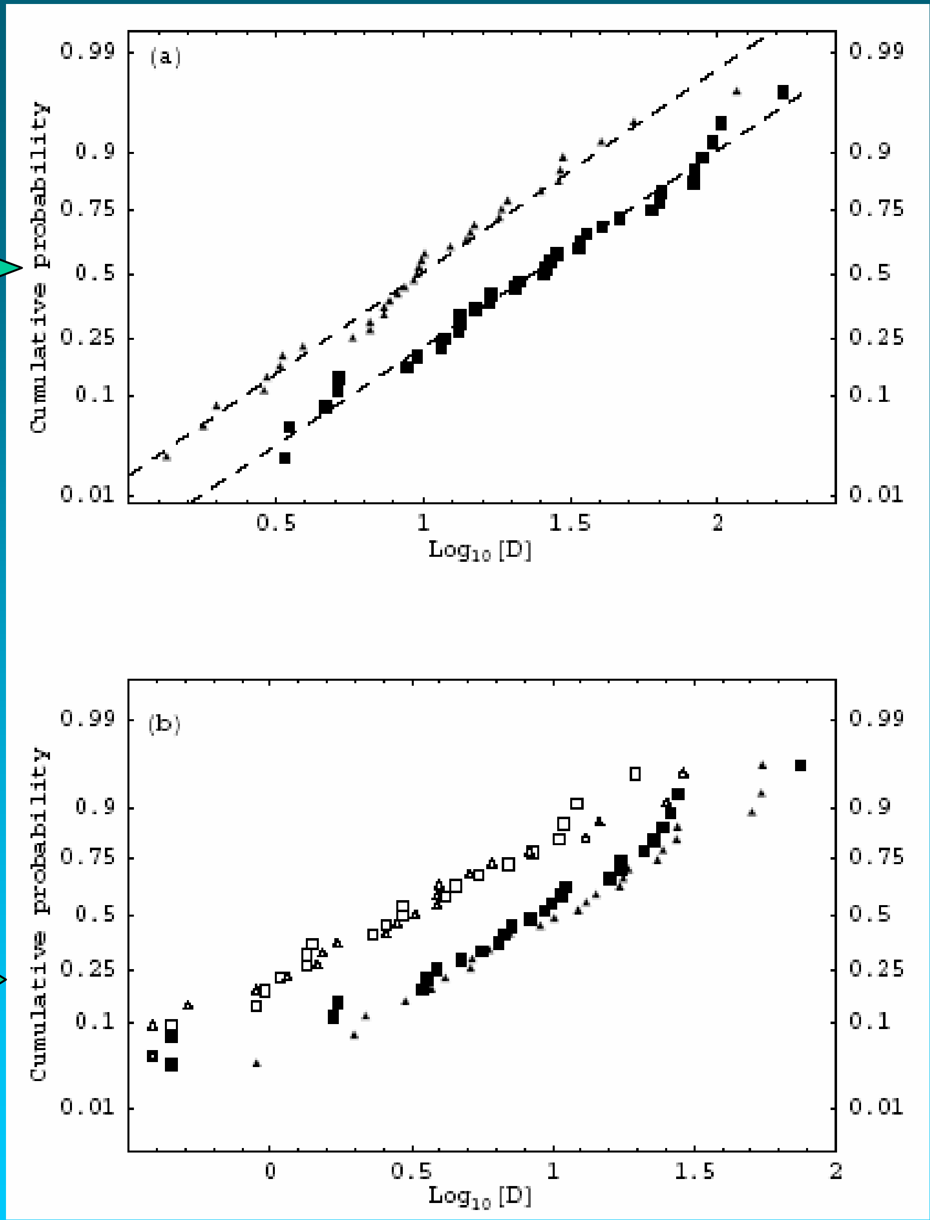
PreQE: ~10s

PostQE:~20s

QTs:~ 50s

Three characterisitc time scales

No evidence of a continuous time dilation



Interpretation:

1) Wind modulation model: during QTs no collisions between the emitted shells

Huge energy requirements

No explanation for the different time scales

It is likely for short QT

2) Dormant inner engine during the long QTs

Reduced energy emission

Possible explanation of the different time scales in the Quark deconfinement model

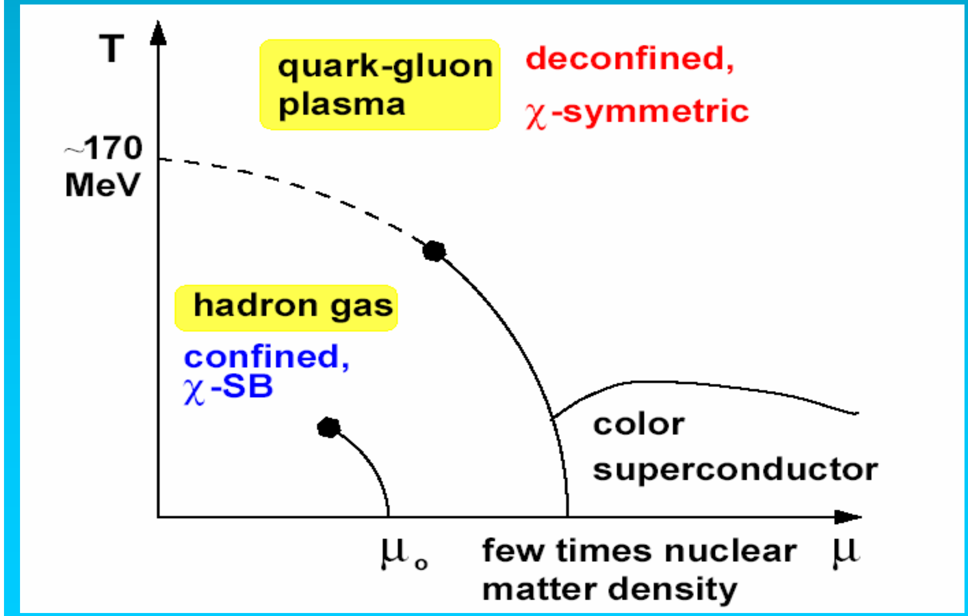
It is likely for long QT

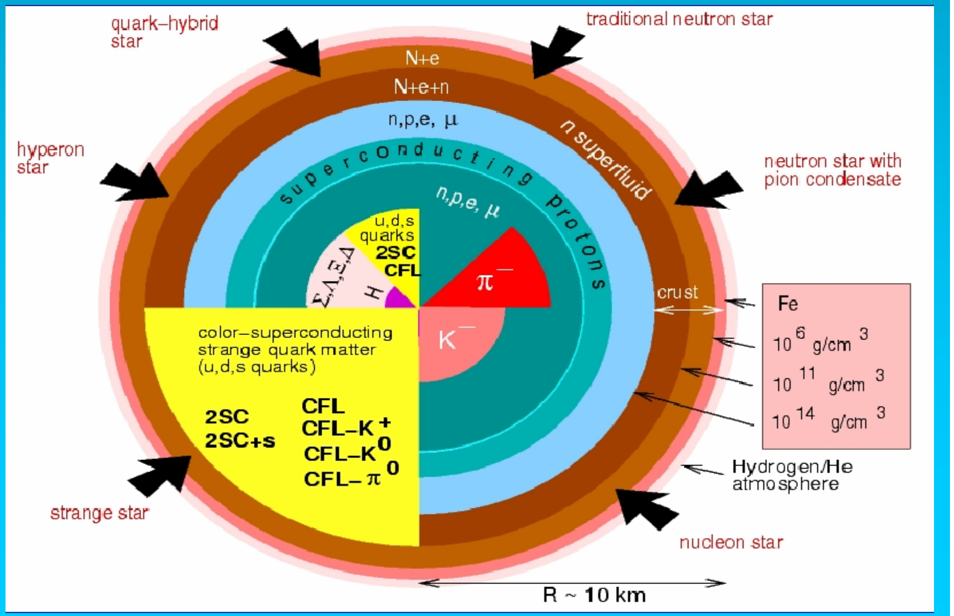
... back to the theory

In the first version of the Quark deconfinement model only the MIT bag EOS was considered

...but

in the last 8 years, the study of the QCD phase diagram revealed the possible existence of Color Superconductivity at "small" temperature and large density





High density: Color flavor locking

From perturbative QCD at high density: attractive interaction among u,d,s Cooper pairs having binding energies ~ 100 MeV

At low densitity,NJL-type Quark model

(Alford Rajagopal Wilczek 1998)

$$H = \int d^3x\, \bar{\psi}(x)(\nabla\!\!\!/ - \mu\gamma_0)\psi(x) + H_I,$$

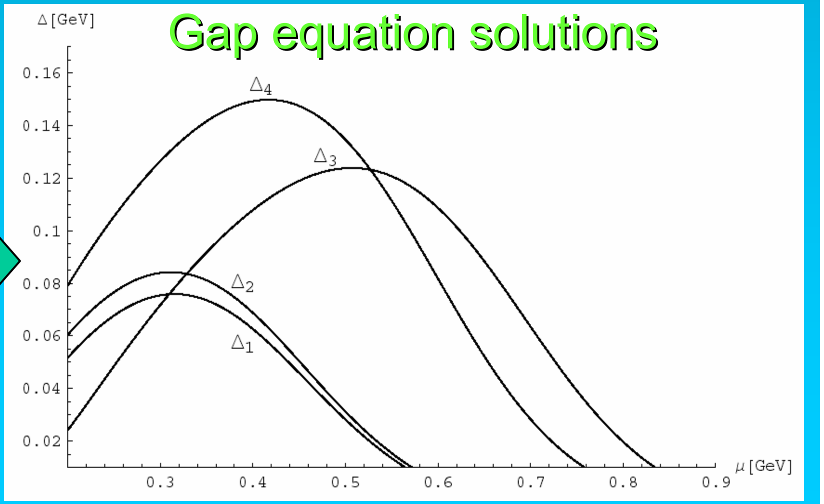
$$H_I = K \sum_{\mu,A} \int d^3x\, \mathfrak{F}\, \bar{\psi}(x)\gamma_\mu T^A \psi(x)\, \bar{\psi}(x)\gamma^\mu T^A \psi(x)$$

$$\langle\psi|\psi^{\dagger i}{}_{\alpha\dot{a}}\psi^{\dagger j}{}_{\gamma\dot{c}}\epsilon^{\dot{a}\dot{c}}|\psi\rangle \sim \kappa_1\delta_i^\alpha\delta_j^\beta + \kappa_2\delta_j^\alpha\delta_i^\beta$$

CFL pairing pattern

BCS theory of Superconductivity

$$G(\Delta) = -\frac{1}{2}\sum_{\mathbf{k}}\left\{\frac{F(k)^2\Delta}{\sqrt{(k-\mu)^2+F(k)^4\Delta^2}} + \frac{F(k)^2\Delta}{\sqrt{(k+\mu)^2+F(k)^4\Delta^2}}\right\}$$



Vanishing mass for s !

Modified MIT bag model for quarks

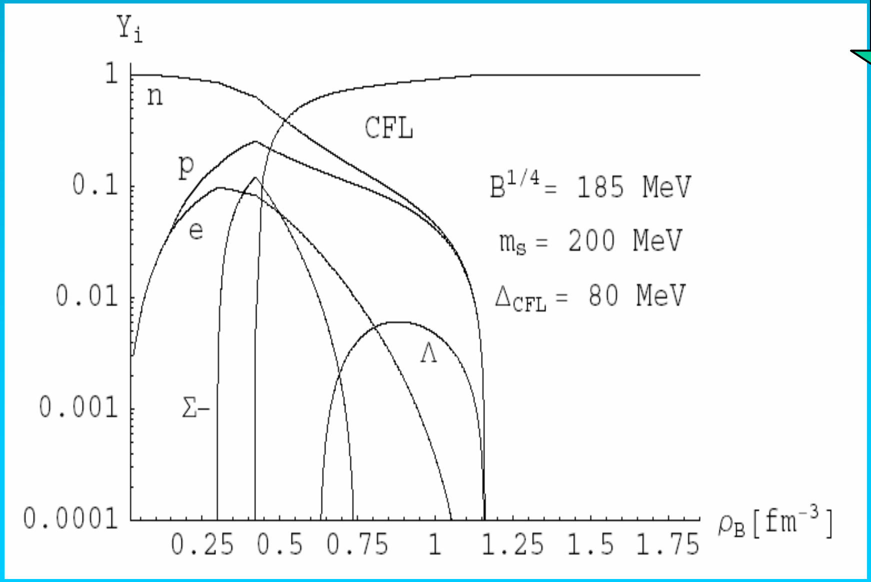
For small value of m_s it is still convenient to have equal Fermi momenta for all quarks (Rajagopal Wilczek 2001)

$$\frac{M_s^2}{\mu} < 4\Delta_{CFL}$$

$$\Omega_{CFL}(\mu) = \frac{6}{\pi^2}\int_0^{\nu} k^2(k-\mu)\,\mathrm{d}k + \frac{3}{\pi^2}\int_0^{\nu} k^2(\sqrt{k^2+m_s^2}-\mu)\,\mathrm{d}k - \frac{3\Delta^2\mu^2}{\pi^2}$$

Binding energy density of quarks near Fermi surface ~ $\Delta VN \sim \mu^2 \Delta^2$

Hadron-Quark first order phase transition and Mixed Phase



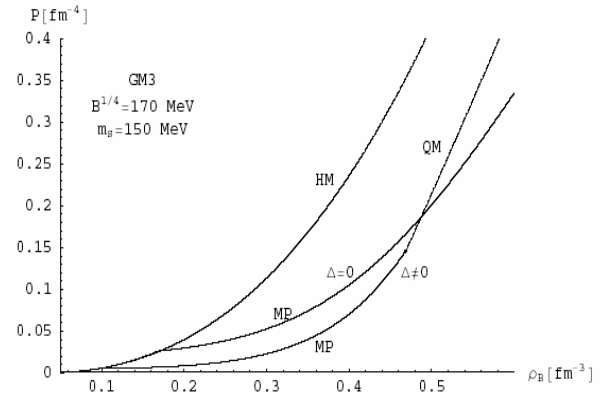
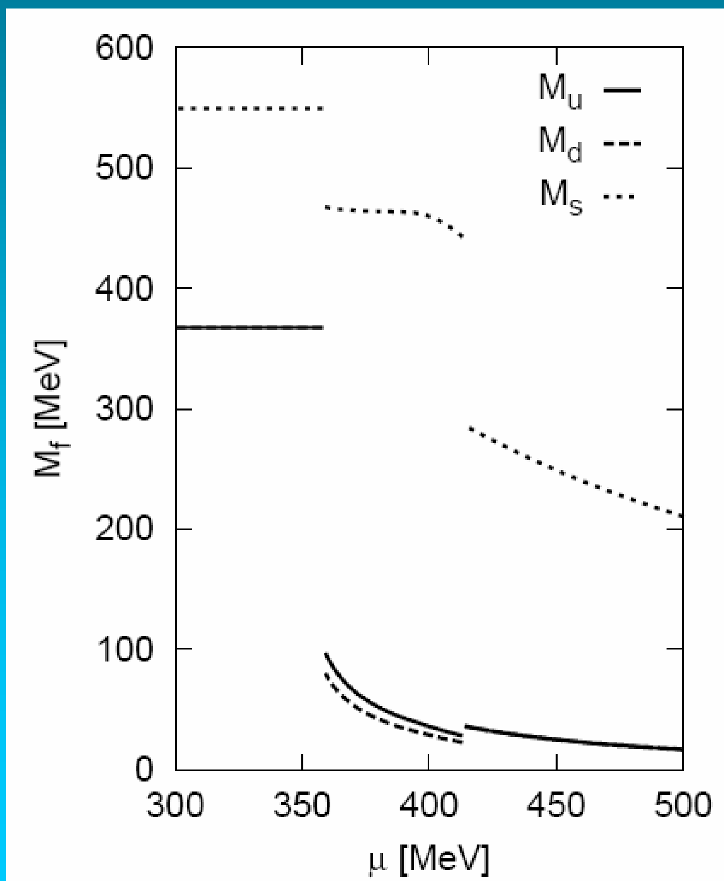
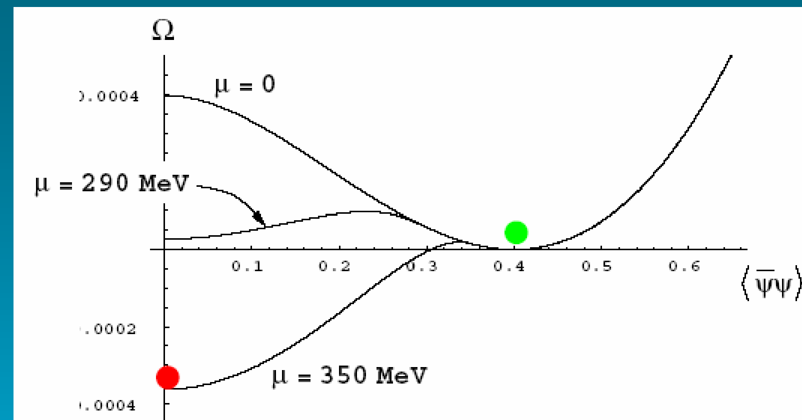


Fig. 2. Pressure versus baryonic density. HM indicates a purely hadronic EOS, MP a mixed-phase of hadrons and quarks and QM pure quark matter. The effect of a non-vanishing superconducting gap is displayed.

Intermediate density

Chiral symmetry breaking at low density



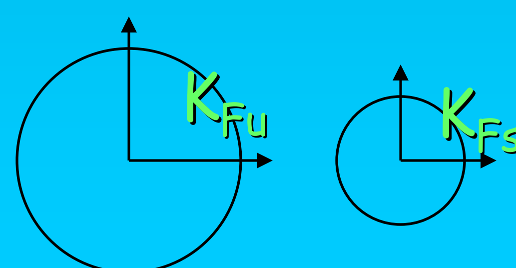


M_s increases too much and

$$\frac{M_s^2}{\mu} < 4\Delta_{CFL}$$

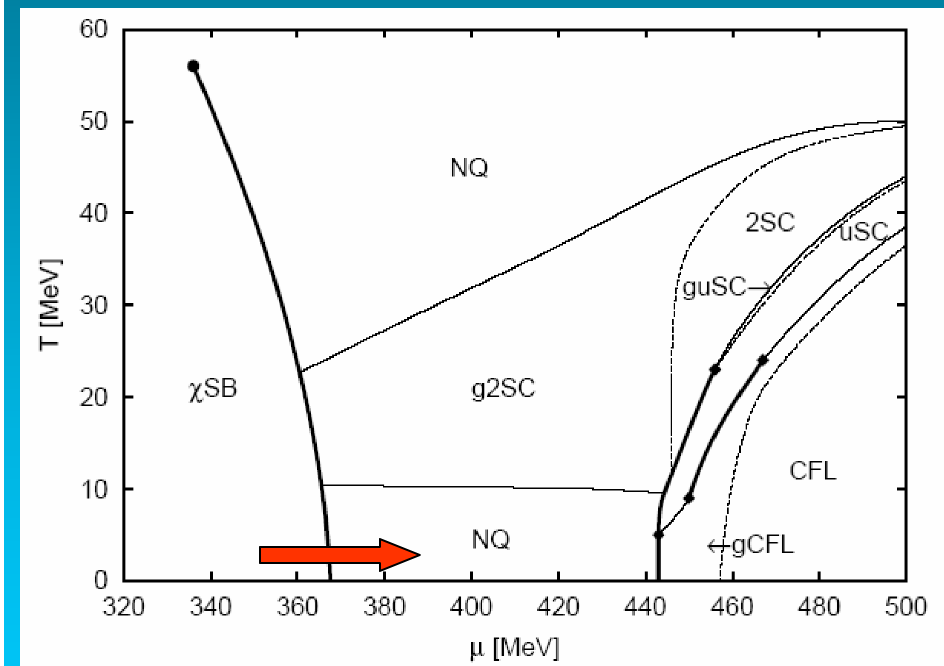
is not respected

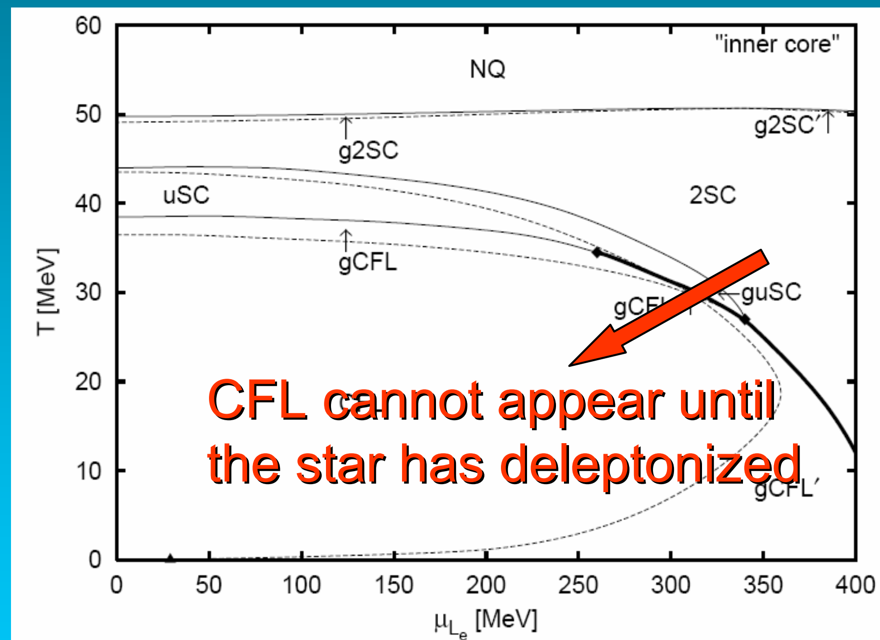
No more CFL pairing !



More refined calculations

$$\mathcal{L} = \bar\psi\,(i\partial\!\!\!/ - \hat m\,)\psi + G_S\sum_{a=0}^{8}\left[(\bar\psi\lambda_a\psi)^2 + (\bar\psi i\gamma_5\lambda_a\psi)^2\right]$$
$$+\, G_D\sum_{\gamma,c}\left[\bar\psi^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta\right]\left[(\bar\psi_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^s_\sigma\right]$$





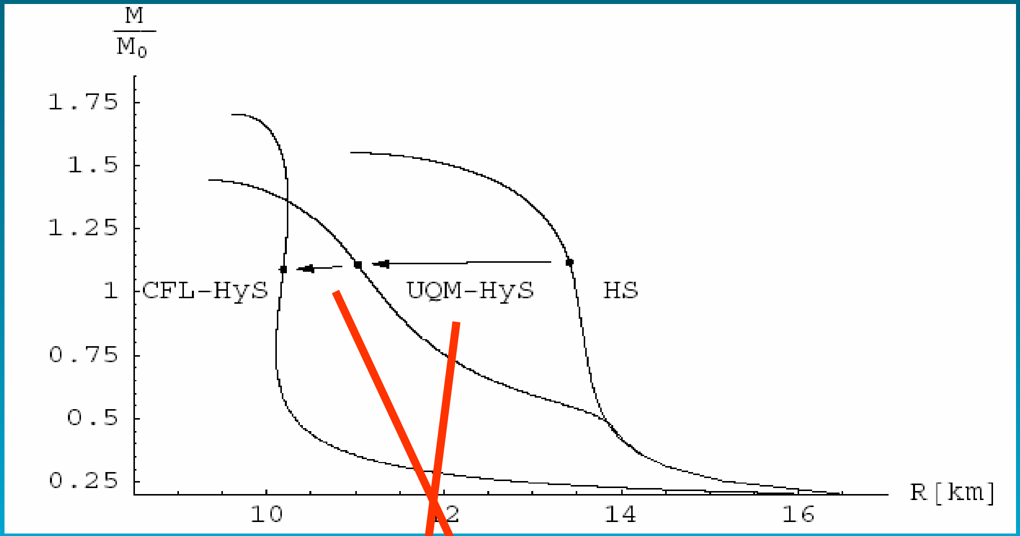
Ruster et al hep-ph/0509073

Two first order phase transitions:

Hadronic matter ⇨ Unpaired Quark Matter(2SC) ⇨ CFL

Double GRBs generated by double phase transitions

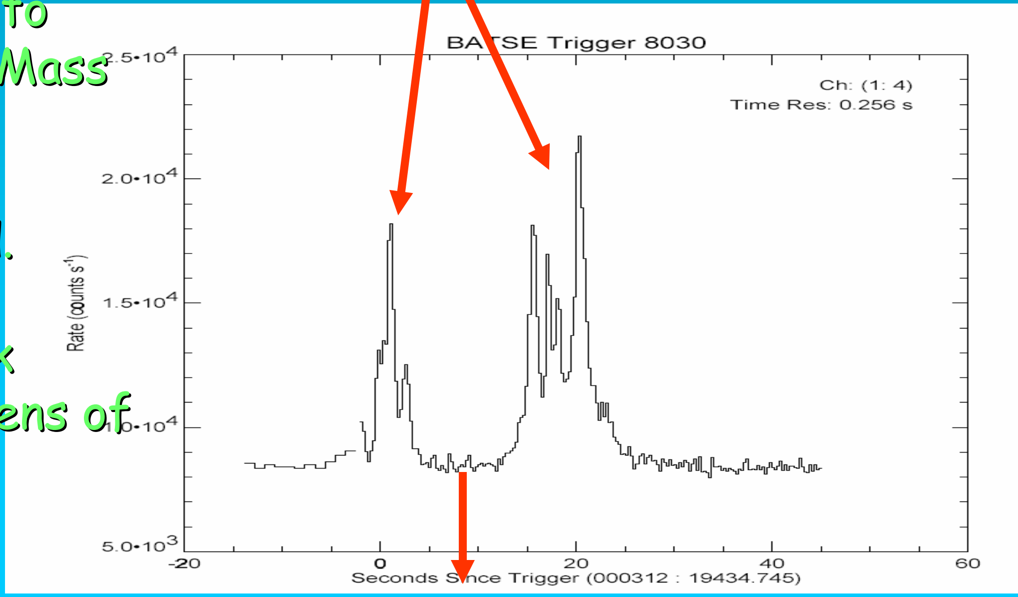
$$M_B = m_n \int_0^R dr \frac{4\pi r^2}{(1-2m(r)/r)^{1/2}} \rho_B(r)$$



Two steps (same barionic mass):

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



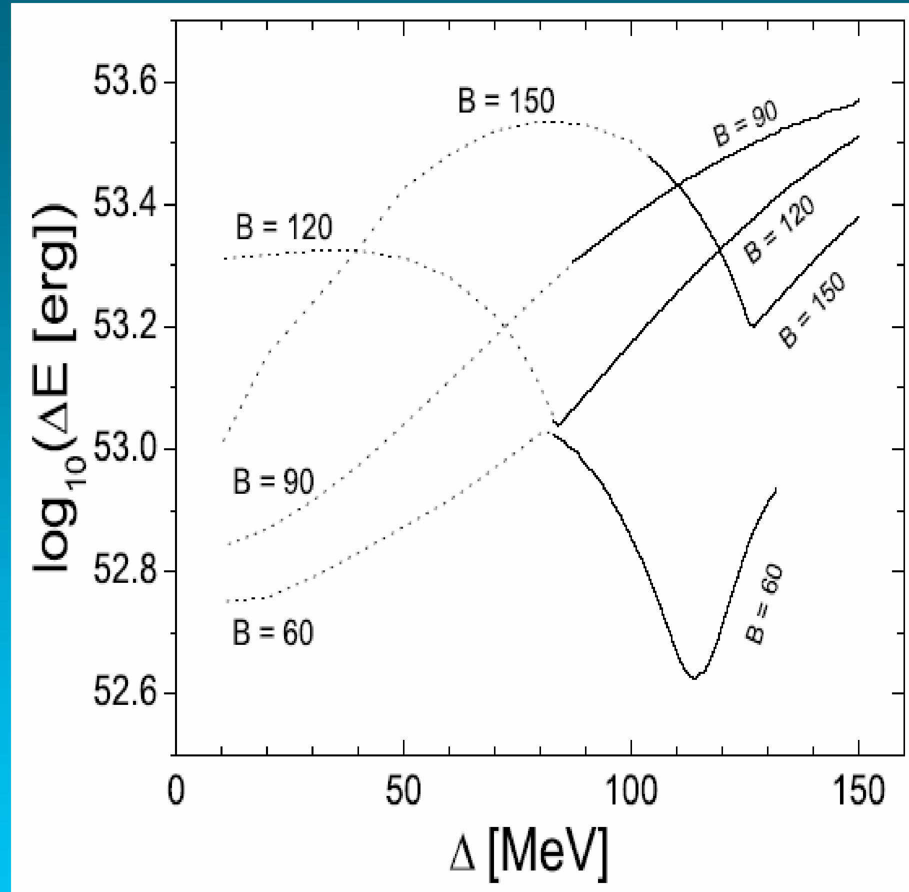
Nucleation time of CFL phase

Energy released

Hadronic Model	$B^{1/4}$ [MeV]	σ [MeV/fm^2]	$M_{cr}/M_\odot$	ΔE $\Delta = 0$	ΔE Δ_1	ΔE Δ_2	ΔE Δ_3	ΔE Δ_4
GM3	170	10	1.12	18	52	57	86	178•
GM3	170	20	1.25	30	66	72	106	205•
GM3	170	30	1.33	34	75	81	120	221•
GM3	170	40	1.39	38	82	88	131	234•
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•
GM1	170	20	1.30	30	75	81	119	219•
GM1	170	30	1.41	43	90	96	141	244•
GM1	170	40	1.51	BH	105	111	163	267•
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	–

TABLE II: Energy released ΔE in the conversion to hybrid or quark star, for various sets of model parameters, assuming the hadronic star mean life-time $\tau = 1$ yr (see text). M_{cr} is the gravitational mass of the hadronic star at which the transition takes place, for fixed values of the surface tension σ and of the mean life-time τ. Notations as in Tab. 1

Drago, Lavagno, Pagliara 2004



Bombaci, Lugones, Vidana 2006

Energy of the second transition larger than the first transition due to the large CFL gap (100 MeV)

... a very recent M-R analysis

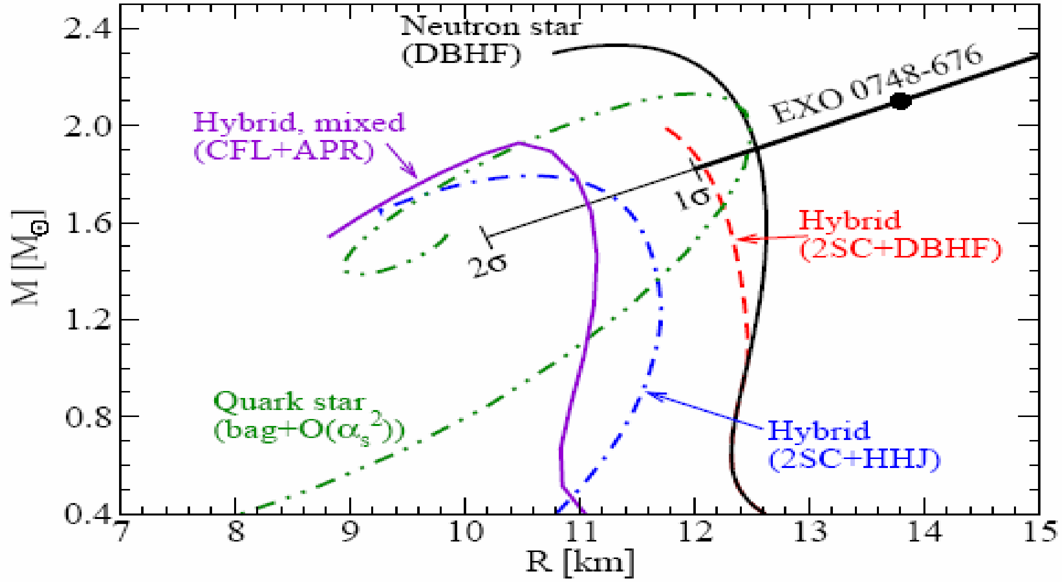


Figure 1: The constraint on M and R from Özel's analysis of EXO 0748-676 [1] (We show one and two sigma error bars), and the calculated results for results for various quark matter and nuclear matter equations of state. Pure nuclear matter (DBHF) [3](?); hybrid star with 2SC quark matter core and HHJ nuclear mantle [3], hybrid star with 2SC quark matter core and APR nuclear mantle [3], hybrid star with mixed phase of APR nuclear matter and CFL quark matter [2], and a pure quark matter star using a bag model EoS that includes a parameterization of $\mathcal{O}(\alpha_s^2)$ QCD corrections [5]. It is clear that quark matter is not excluded.

Color superconductivity (and other effects) must be included in the quark EOSs !!

Other possible signatures

Origin of power law:

SOLAR FLARES

For a single Poisson process

$$P(\Delta t) = \lambda \exp(-\lambda \Delta t)$$

Variable rates

$$P(\Delta t) = \frac{1}{\lambda_0} \int_0^\infty f(\lambda) \lambda^2 e^{-\lambda \Delta t} \, d\lambda$$

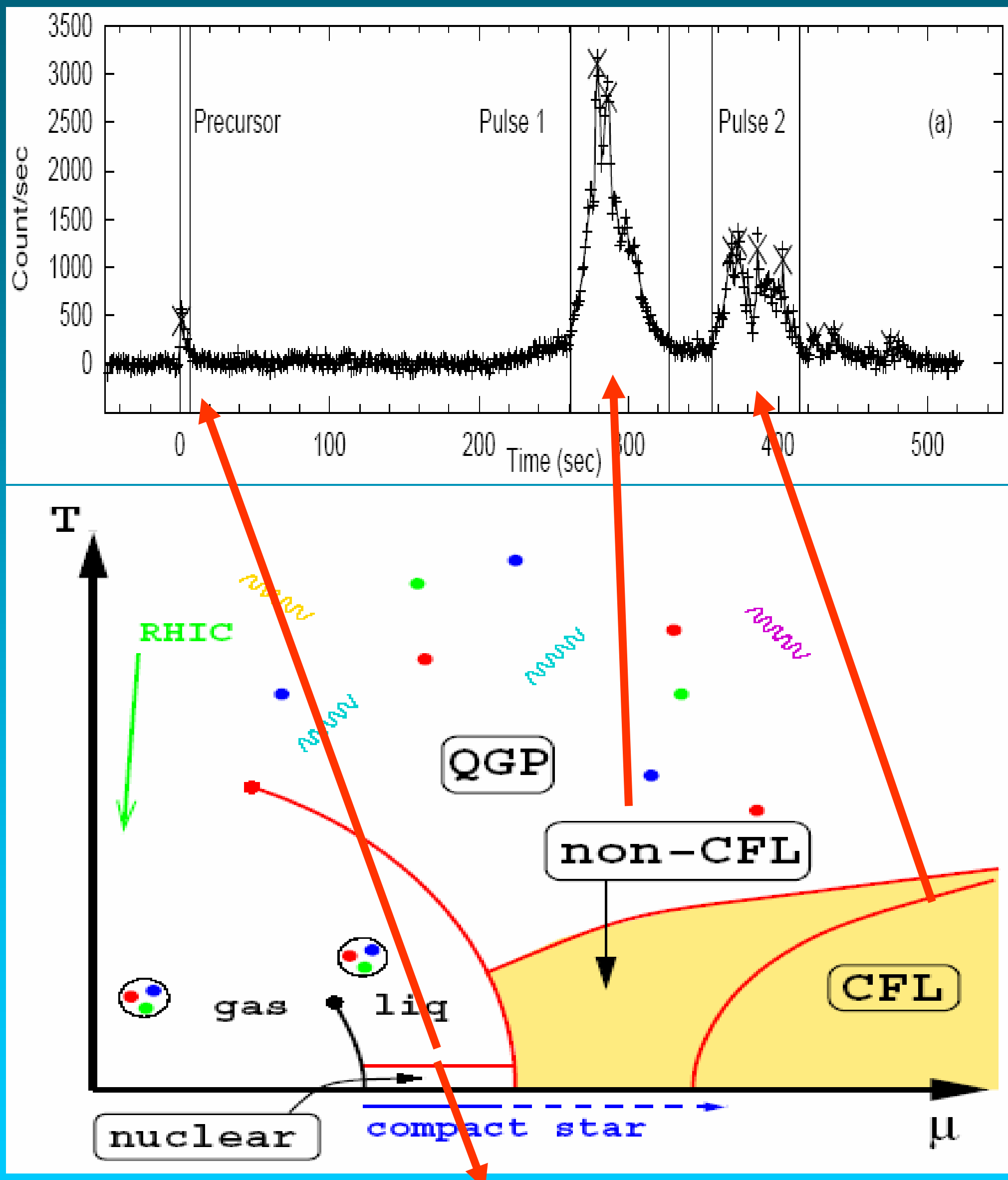
$$f(\lambda) = \lambda_0^{-1} \exp(-\lambda/\lambda_0)$$

$$P(\Delta t) = \frac{2\lambda_0}{(1 + \lambda_0 \Delta t)^3}$$

Power law distribution for Solar flares waiting times (Wheatland APJ 2000)

The initial masses of the compact stars are distributed near M_{crit}, different central desity and nucleation times τ of the CFL phase $f(\tau(M))$

Could explain the power law tail of long QTs ?



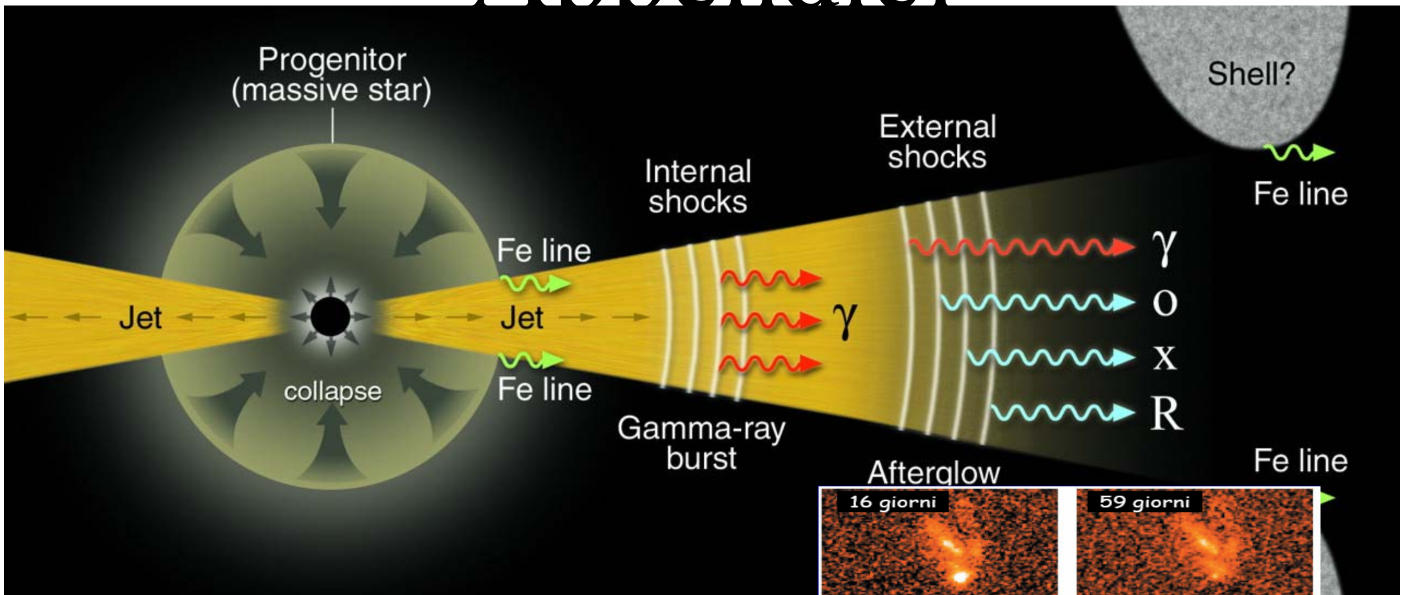
Are LGRBs signals of the successive reassesments of Compact stars?

Low density: Hyperons - Kaon condensates...

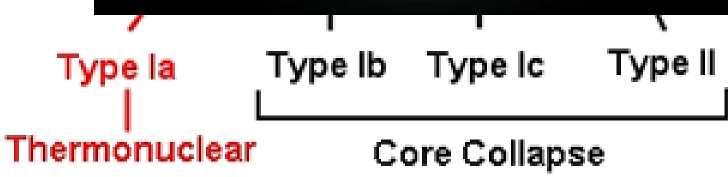
Conclusions

- A "standard model" the Collapsar model
- One of the alternative model: the quark deconfinement model
- Possibility to connect GRBs and the properties of strongly interacting matter!

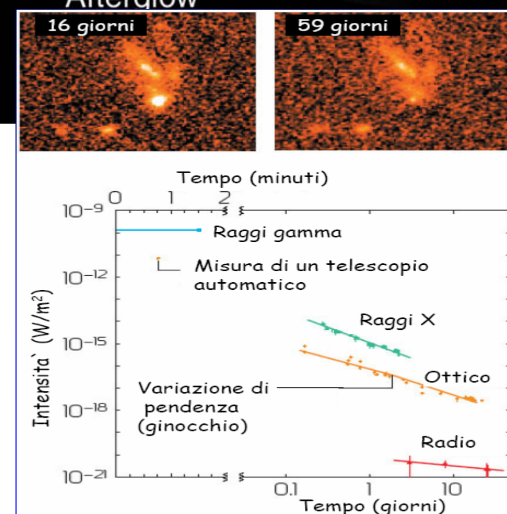
Appendici



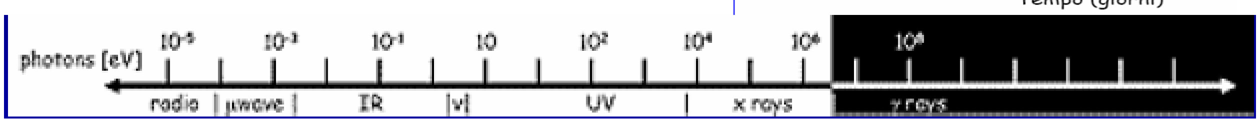
Progenitor
(massive star)
Shell?
External
shocks
Internal
shocks
Fe line
Jet
Jet
Fe line
collapse
Fe line
γ
γ
o
x
R
Gamma-ray
burst
Afterglow
Fe line



Type Ia
Thermonuclear
Type Ib
Type Ic
Type II
Core Collapse



16 giorni
59 giorni
Tempo (minuti)
0
1
2
Raggi gamma
Misura di un telescopio
automatico
Raggi X
Ottico
Variazione di
pendenza
(ginocchio)
Radio
Intensita` (W/m²)
10⁻⁹
10⁻¹²
10⁻¹⁵
10⁻¹⁸
10⁻²¹
0.1
1
10
Tempo (giorni)



photons [eV]
10
radio
μwave
IR
v
UV
x rays
γ rays

Oscillation frequency of the virtual drop inside the potential well

$$\nu_0 = (dI/dE)^{-1} \quad \text{for } E = E_0$$

$$I(E_0) = \frac{2}{3}\pi \hbar$$

$$I(E) = 2\int_0^{R_-} dR\,\sqrt{2M(R)[E - U(R)]}$$

Action of the zero point oscillations

Penetrability of the potential barrier (WKB appox.)

$$p_0 = \exp\left[-\frac{A(E_0)}{\hbar}\right]$$

$$A(E) = 2\int_{R_-}^{R_+} dR\,\sqrt{2M(R)[U(R) - E]}$$

Nucleation time

$$\tau = (\nu_0 p_0 N_c)^{-1}$$

$N_c \sim 10^{48}$
numb. of nucleation centers in the star core