1942-17

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Formation of Quark Phases in compact stars.

A. Drago
Ferrara
Italy

G. Pagliara
Frankfurt
Germany

G. Pagliaroli
National Laboratory Gran Sasso
Italy

F. Vissani
National Laboratory Gran Sasso
Italy

F. Villante
L'Aquila
Italy

Formation of quark phases in compact stars

Alessandro Drago (Ferrara)
Giuseppe Pagliara (Frankfurt)
Giulia Pagliaroli (Lab. Naz. Gran Sasso)
Francesco Villante (L'Aquila)
Francesco Vissani (Lab. Naz. Gran Sasso)

Outline

- When and how to deconfine?
- The role of convection in deconfinement
- The astrophysical scenario, the role of rotation
- Still puzzled by SN 1987a
- SNe and GRBs

What we would like to learn:

- how is the neutrino signal modified?
- can quark deconfinement influence SN explosions (and GRBs) ?

When to deconfine?

1) During the process of core collapse **before** deleptonization

- Softening at low density, mechanical effect
- “universal”, influences all SNe

- Migdal A B, Cherenoutsan A I and Mishustin I N 1979 *Phys. Lett.* B **83** 158
- Gentile N A, Aufderheide M B, Mathews G J, Swesty F D and Fuller G M 1993 *Astrophys. J.* **414** 701
- Cooperstein J 1993 *Nucl. Phys.* A **556** 237
- Drago A and Tambini U 1999 *J. Phys.* G **25** 971

2) During (or after) the deleptonization of the protoneutron star

- Influences the observable neutrino emission
- Temporal separation between core collapse and deconfinement (rotation)

- Pons J A, Steiner A W, Prakash M, Lattimer J M 2001 *Phys. Rev. Lett.* **86** 5223
- Aguilera D N, Blaschke D, Grigorian H 2004 *Astron.& Astrophys.* **416** 991
- Berezhiani Z, Bombaci I, Drago A, Frontera F, Lavagno A 2003 *Astrophys.J.***586** 1250

How to deconfine?

- **Assuming quark deconfinement is a smooth transition (Pons et al.)**
  No metastability, deconfinement timescale driven by deleptonization
  Gradual process, the total thermal energy emitted in neutrino increases, the luminosity of the thermal neutrino emission smoothly increases
  (*no extra neutrino burst*)

- **Assuming quark deconfinement is a first order transition**
  The star can enter a (short?) metastable phase
  The conversion proceeds as a deflagration with an unstable front
  The conversion timescale and the neutrino emission are driven by hydrodynamical instabilities and by convection
  The total energy emitted increases
  The neutrino emission can have a new burst

(anti)-neutrino count rates without and with quark deconfinemnt

Pons et al. PRL 86 (2001) 5223

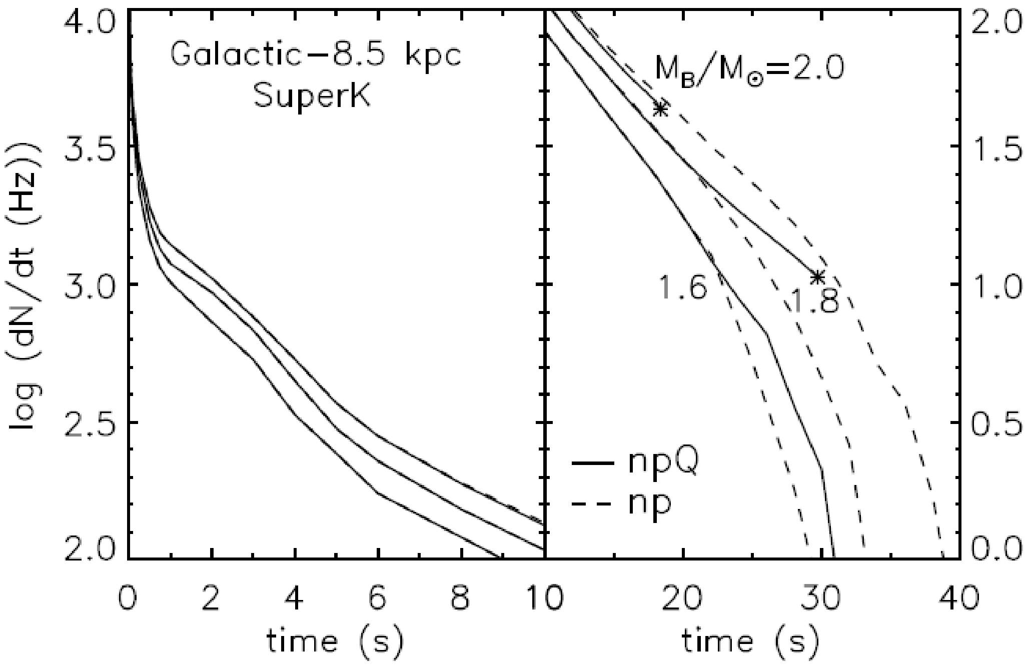


FIG. 2. A comparison of $\bar{\nu}_e$ count rates expected in SuperK from a PNS containing either *np* or *npQ* matter. The left panel shows times less than 10 s, while the right panel shows times greater than 10 s.

Theoretical frame

In the following I will study quark deconfinement under the hypothesis that:

1. It takes place after (at least partial) deleptonization
2. It corresponds to a first order phase transition

Main points concerning metastability of compact stars

- **The energy released** in the transition from a metastable hadronic star into a hybrid or a quark star **is of the order of a few hundred Bethe**, i.e. a few 10^{53} erg
  (many papers by Bombaci, A.D., Lavagno, Lugones, Pagliara, Panda, Providencia, Vidana et al.)

- In the following I will concentrate on the transition to hybrid stars.
  If quark stars are not ruled out, they can provide a even more efficent way to extract energy from a compact star

Anyway:

the conversion to a hybrid star is ***sufficent*** to satisfy both the energy requests and the observed time scales
(can produce a large neutrino luminosity)

Detonation or deflagration?

A.D., A.Lavagno, I.Parenti, ApJ 659 (2007) 1519

Continuity eqs. through the front

Energy momentum tensor flux

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

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

Deflagration: velocity of a laminar front

Olinto 1987 computed the velocity of slow combustion (laminar front) taking into account the production and diffusion of strangeness. The velocity depends on:

- Temperature of the system
- $a_0 = (\rho_d - \rho_s)/2\rho_b$ where ρ_s is the minimum amount of strangeness needed to have stable quark matter.

  We can re-interprete a_0 as the minimum amount of strangeness for which the process is exothermic.

For T=0.1 MeV: $v_{sc} \rightarrow$ a few km/s

v_{sc} scales as 1/T

Hydrodynamical instabilities and effective velocity

Horvath and Benvenuto 1988 showed that the front is always unstable in the presence of gravity (Rayleigh-Taylor instability).

The increase of the conversion velocity can be estimated using a fractal scheme

$$v_{eff} = v_{sc}(l_{max}/l_{min})^{D-2}$$

D is the fractal dimension and

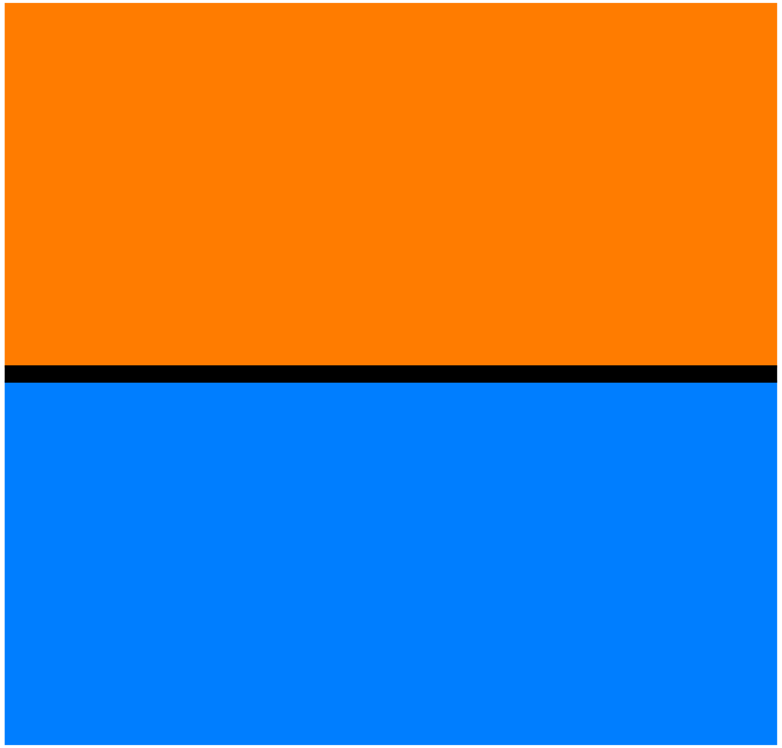
$$D = 2+D_0\,\gamma^2$$

where $\gamma = 1-e_2/e_1$ and $D_0=0.6$.

Typical values for γ are 0.4 or smaller (for not β-stable) and 0.7 or smaller for β-stable quark matter.

The conversion velocity can increase by up to 2 orders of magnitude, but in general the process remains a deflagration.

Quasi-Ledoux convection

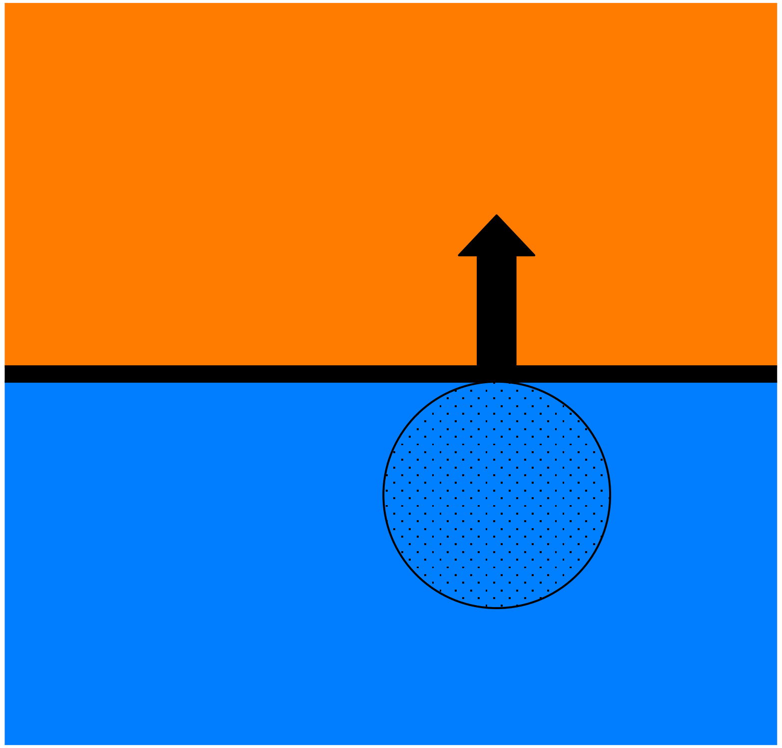


Hadronic phase

Quark phase

Quasi-Ledoux convection

Hadronic phase

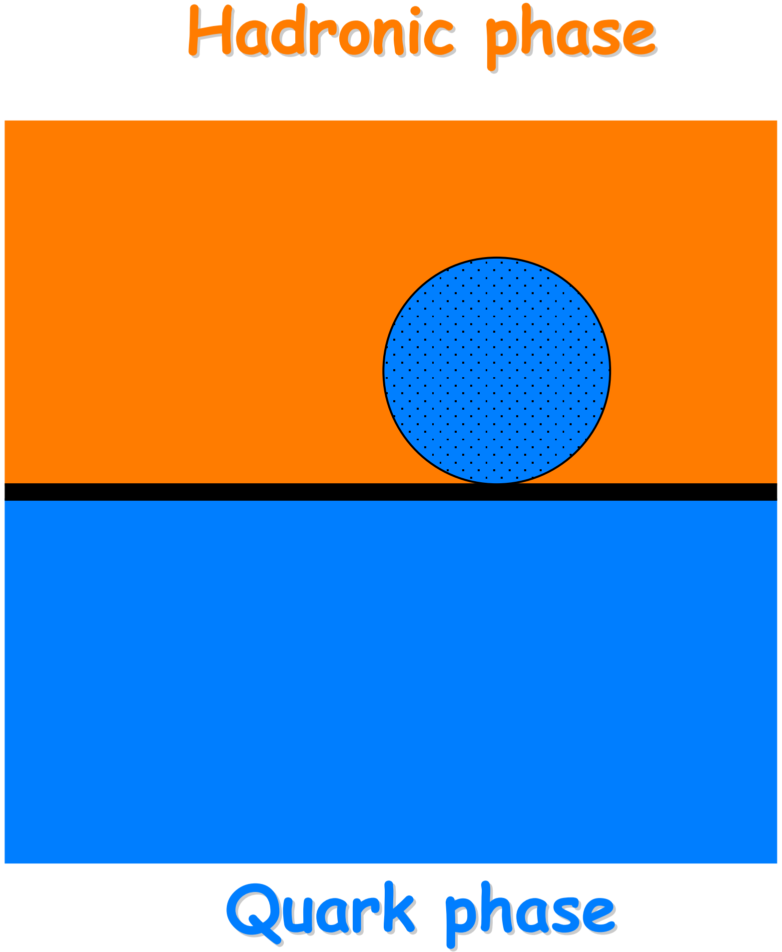


Quark phase

$\rho_Q < \rho_H$

$P_Q < P_H$

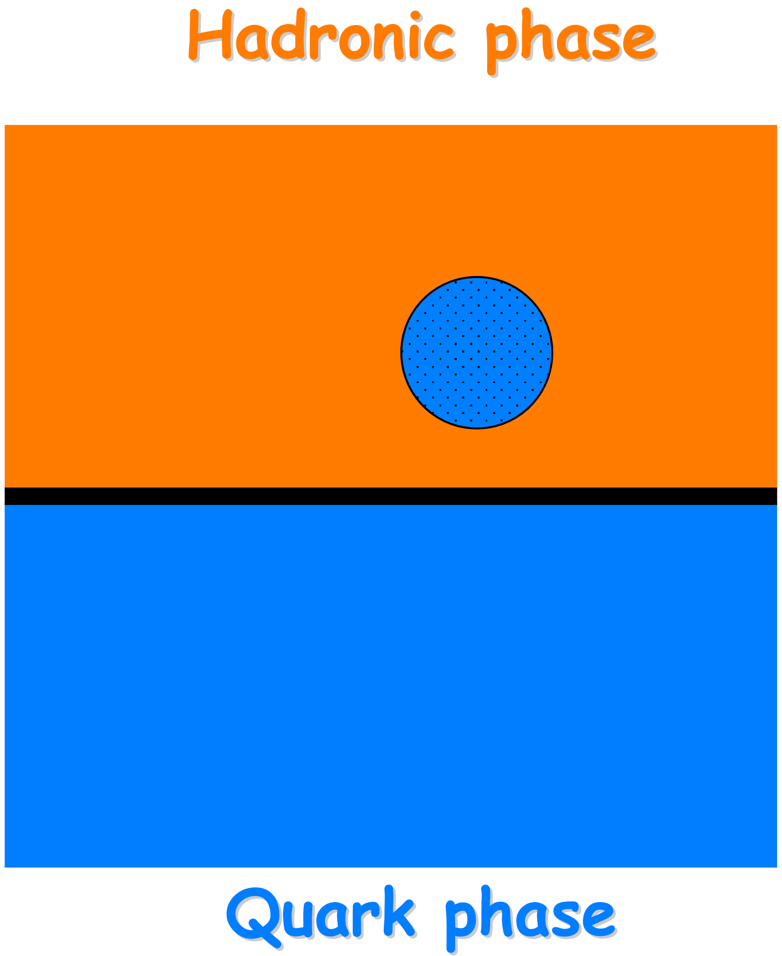
Quasi-Ledoux convection



$\rho_Q < \rho_H$

$P_Q < P_H$

Quasi-Ledoux convection

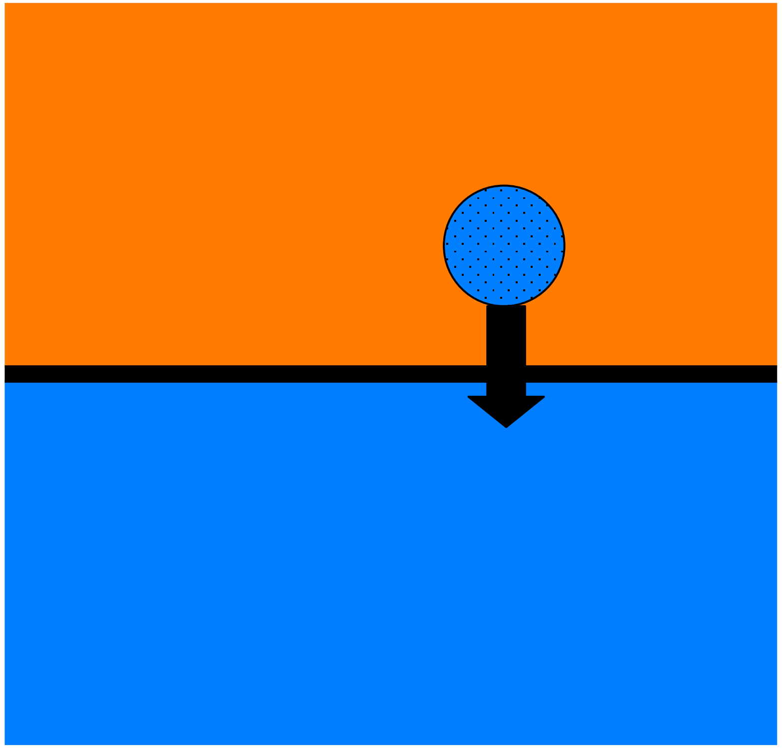


$\rho_Q \;?\; \rho_H$

$P_Q = P_H$

Quasi-Ledoux convection

Hadronic phase



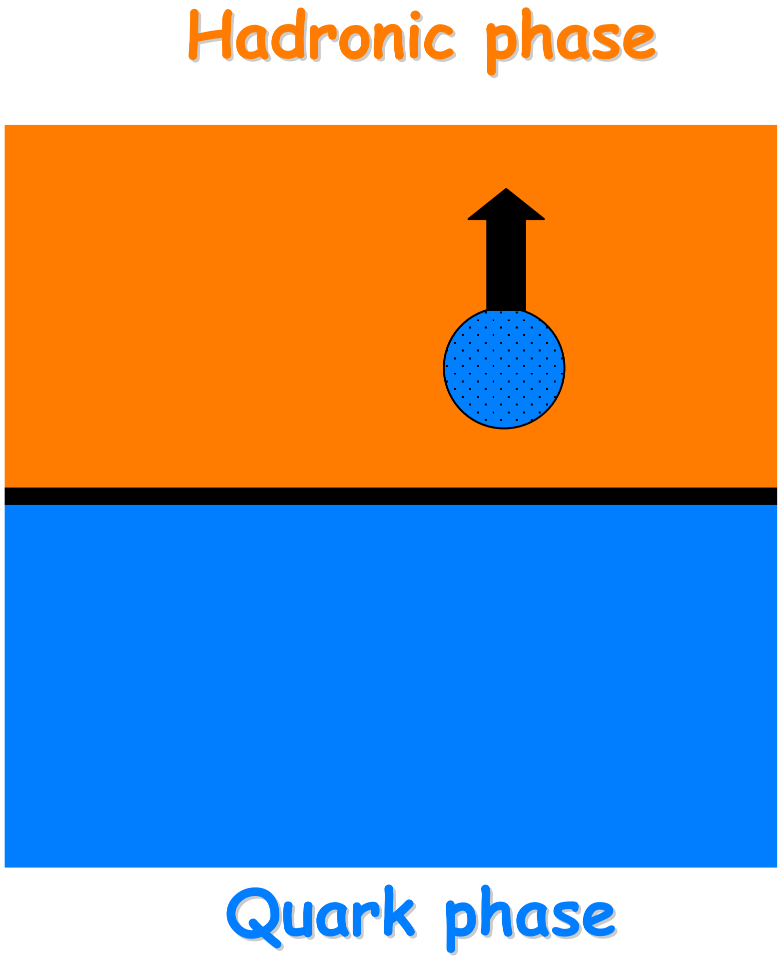
Quark phase

1

$\rho_Q > \rho_H$

$P_Q = P_H$

Quasi-Ledoux convection



Hadronic phase

Quark phase

2

$\rho_Q < \rho_H$

$P_Q = P_H$

Scheme for convection

A.D., A.Lavagno, I.Parenti, ApJ 659 (2007) 1519

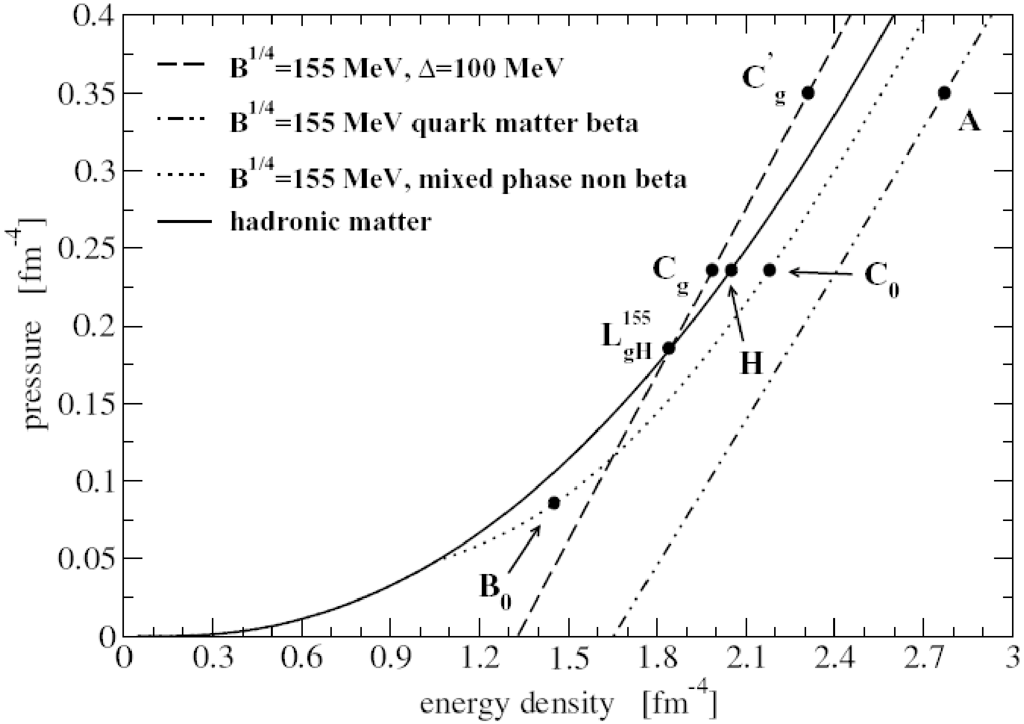


Fig. 19.— Scheme for convection: H represents the drop of hadronic matter just before deconfinement, B_0 represents the drop of newly formed QM, C stays for the drop of QM after pressure equilibration and L indicates the end point of the convective layer. Finally A represents a drop of ungapped quark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

Quark bubble convection

Quark bubble formation – Reasonable numbers:

Temperature of the bubble - T_b = 30-40 MeV
Linear dimension of the bubble - R_b = 0.1-1.0 cm
Estension of the convective layer - D_{conv} = 5-10 Km
Velocity of the bubble - V_b = 10^{4-5} km s^{-1}

Extended convective layer, large velocities → large overshooting → **Convection brings "hot" bubbles close to the surface**.

Note that:

$R_b \ll \lambda_\nu$ → neutrinos are not trapped in the bubbles

Drift time: $t_d \sim R / v_b = 10^{-3} - 10^{-4}$ s → Adiabatic expansion → $(T_b)_{external} = 10$ MeV

Convection: simple estimates

- Convection more efficient than bubble neutrino cooling:

$\varepsilon_\nu\, t_d \;<\; e_b \sim (E_{released} \,/\, V_{tot})$ → $\boxed{\varepsilon_\nu < 10^{37.5\text{ - }38.5}\ \text{erg cm}^{-3}\ \text{s}^{-1}}$

where:

ε_ν = neutrino emissivity
t_d = Drift time = 10^{-3} - 10^{-4} s
e_b = energy stored in the bubble (per unit volume)
E_{tot} = total energy released in the transition to QM ~ 3 10^{53} erg
V_{tot} = total volume of the star ~ 10^{19} cm^{-3}

- Neutrino luminosity due to bubble close to the surface:

$L_\nu = \gamma\, V_{tot}\, \varepsilon_\nu$ → $L_\nu = 10^{53}$ erg s^{-1} corresponds to:

$\boxed{\varepsilon_\nu = (10^{34} / \gamma)\ \text{erg cm}^{-3}\ \text{s}^{-1}}$

where

γ = fraction of the volume occupied by hot radiating bubbles

Main results about convection

- Convection can develop if hyperons are present in the hadronic phase or if diquark can condensate
- It is a very efficient way to transport heat to the surface of the star
- The drift time is very short (much shorter than a second)
- In order to get a large luminosity, only a small fraction of matter need to be involved in convection (order of percent or smaller).

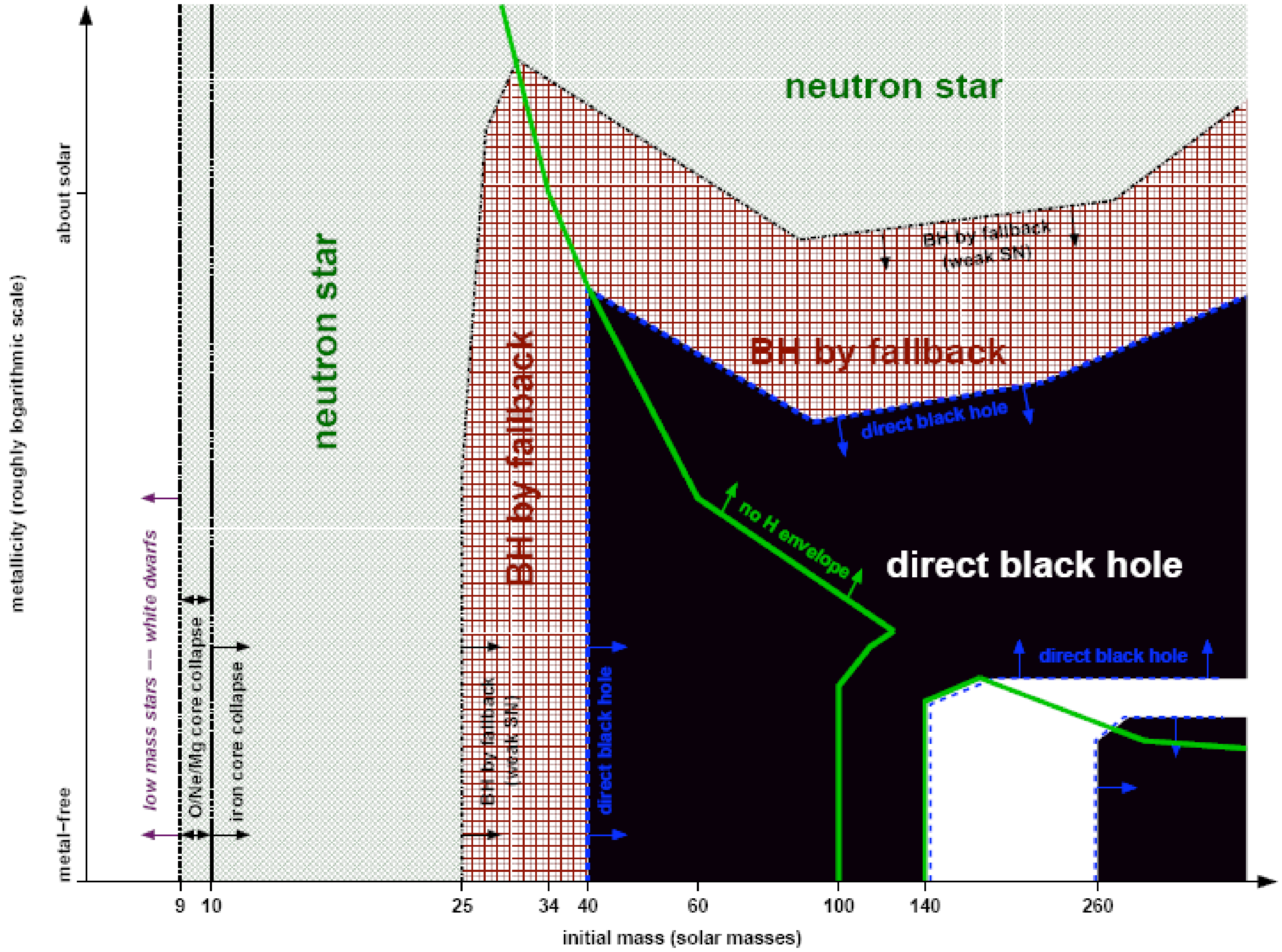
Therefore:

convection can be at the origin of a strong neutrino burst

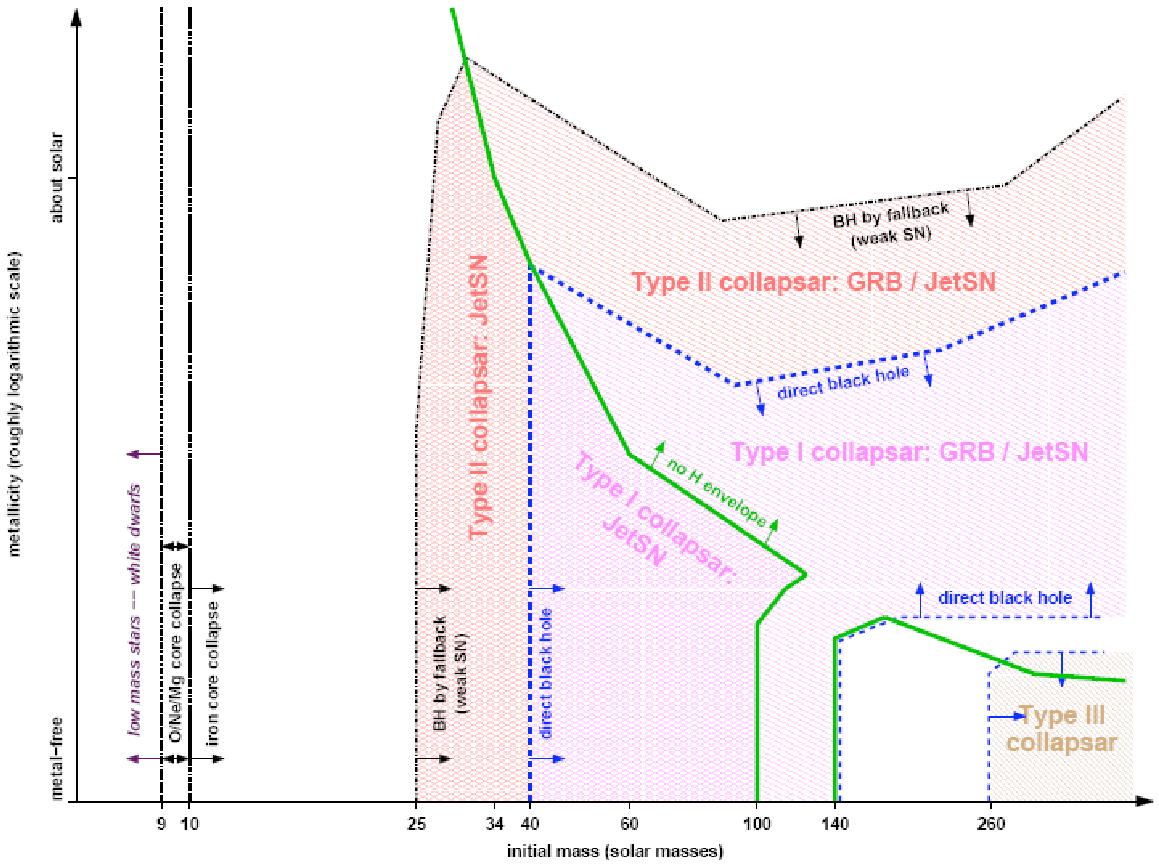
The astrophysical scenario

How does the quark-deconfinement scenario merge with the “standard” scenario of supernova explosions?

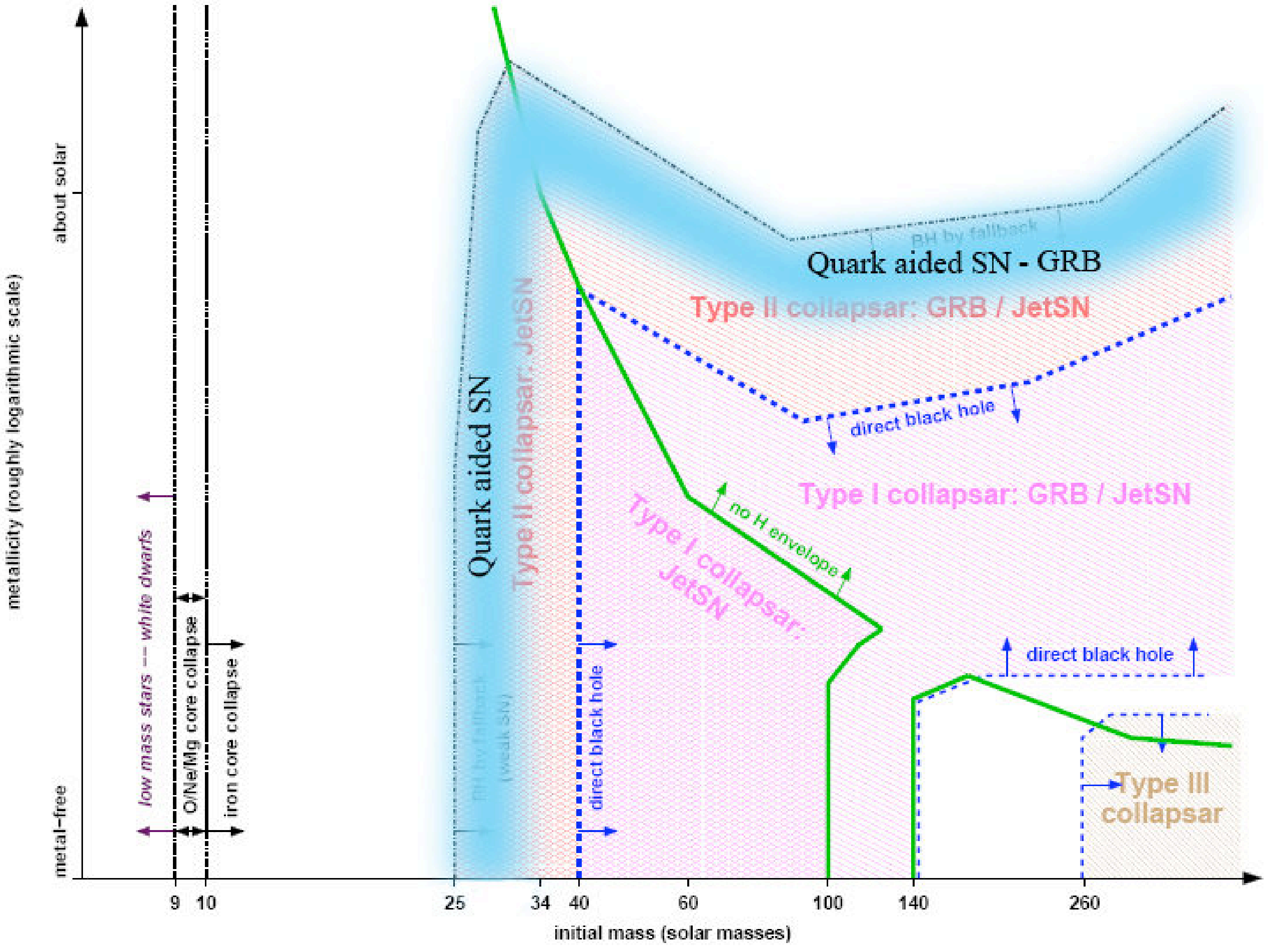
From: ”How massive single stars end their life”
Heger, Fryer, Woosley and Langer 2003



From: ”How massive single stars end their life”
Heger, Fryer, Woosley and Langer 2003



Adapted from: ”How massive single stars end their life” Heger, Fryer, Woosley and Langer 2003

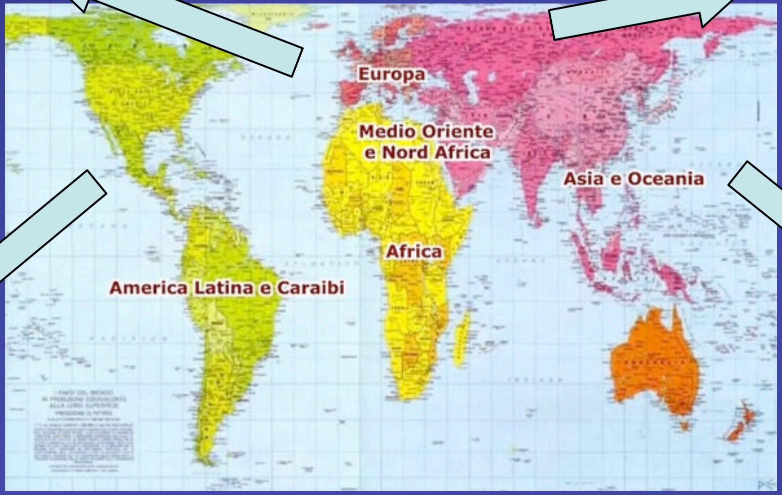


The SN1987A

February 23,1987

LSD
Scintillator
UT = 2:52:37
5 events

BAKSAN
Scintillator
UT = 7:36:12
5 events



IMB
Water
Cherenkov
UT = 7:35:41
8 events

KII
Water
Cherenkov
UT = 7:35:35
12 events

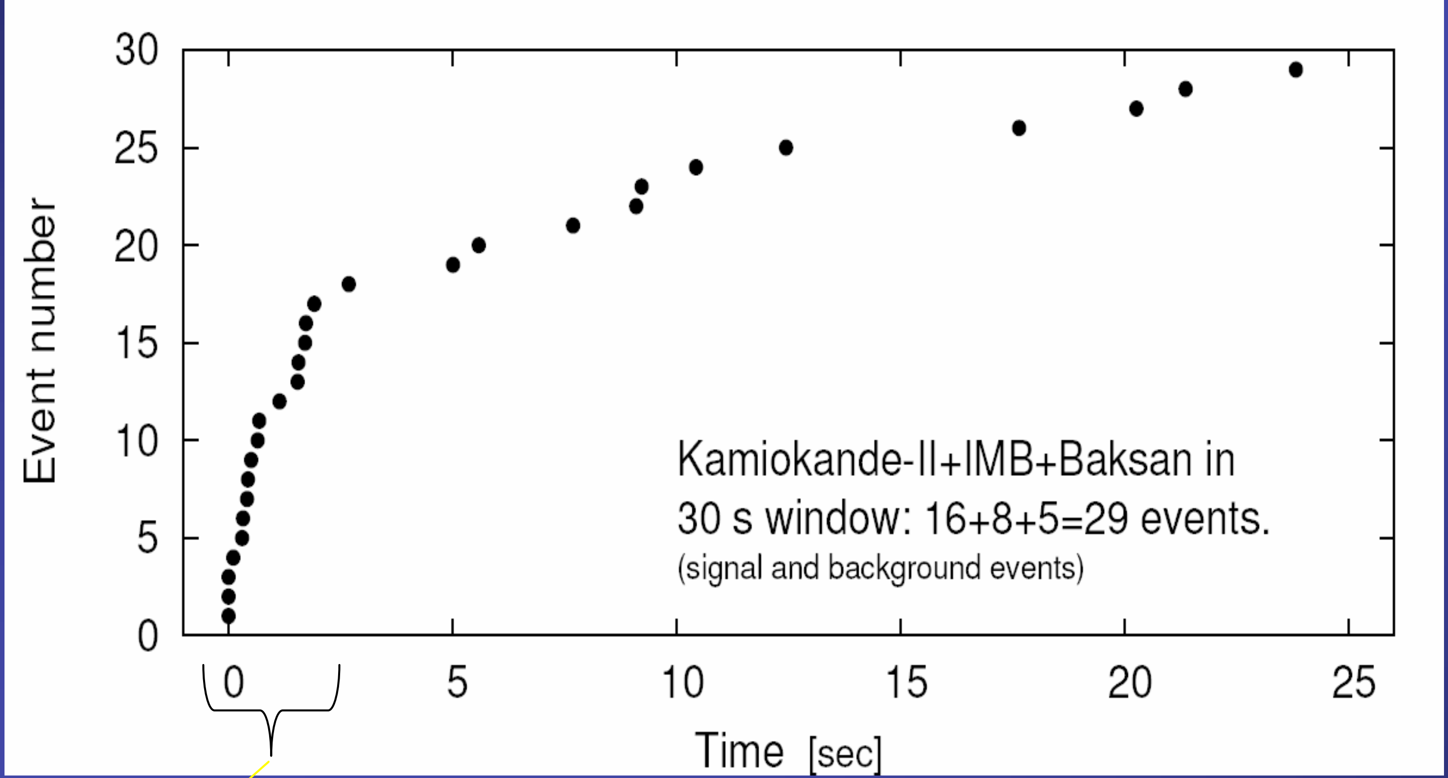
Detector Interactions

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\nu_e + {}^{56}_{26}Fe \rightarrow {}^{56}_{27}Co^* + e^-$$

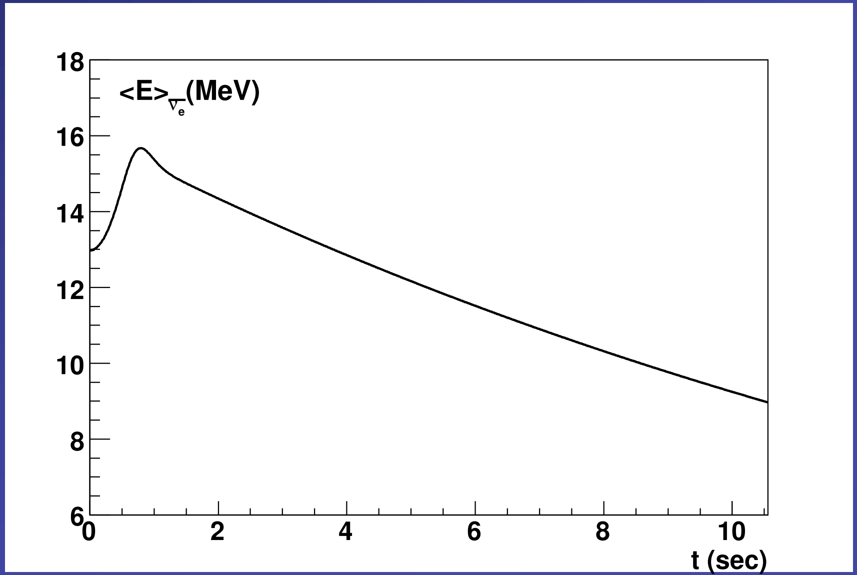
KII	IMB	BAK	LSD
2.14Kt	6.8Kt	0.2Kt	0.09Kt
0	0	0.16Kt	0.2Kt

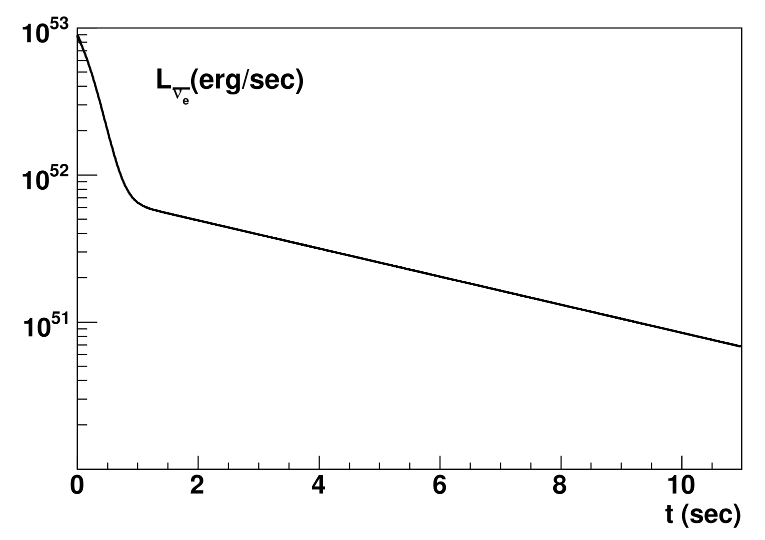
TIME SERIES OF KII+IMB+BAKSAN DATA (NO LSD)


Kamiokande-II+IMB+Baksan in 30 s window: 16+8+5=29 events.
(signal and background events)

THIS SUGGESTS HIGH INITIAL NEUTRINO LUMINOSITY

RESULTS OF A STATISTICAL ANALYSIS BASED ON CONVENTIONAL VIEW





The initial luminous phase is consistent with the delayed explosion scenario

The estimated emitted energy is $\boxed{E_\nu \cong (1-4)\cdot 10^{53}\, erg}$

IMSHENNIK-RYAZHSKAYA SCENARIO
(2003)

- Fast rotating core emits copiously ν_e of roughly 40 MeV as in a prolonged neutronization phase

  LSD sees $\nu_e + {}^{56}_{26}Fe \rightarrow {}^{56}_{27}Co^{*} + e^{-}$

- A subcritical fragment (0.1 M_s) explodes .
  The main fragment undergoes a “standard collapse”:
  KII+IMB+BAKSAN see $\overline{\nu}_e + p \rightarrow e^{+} + n$

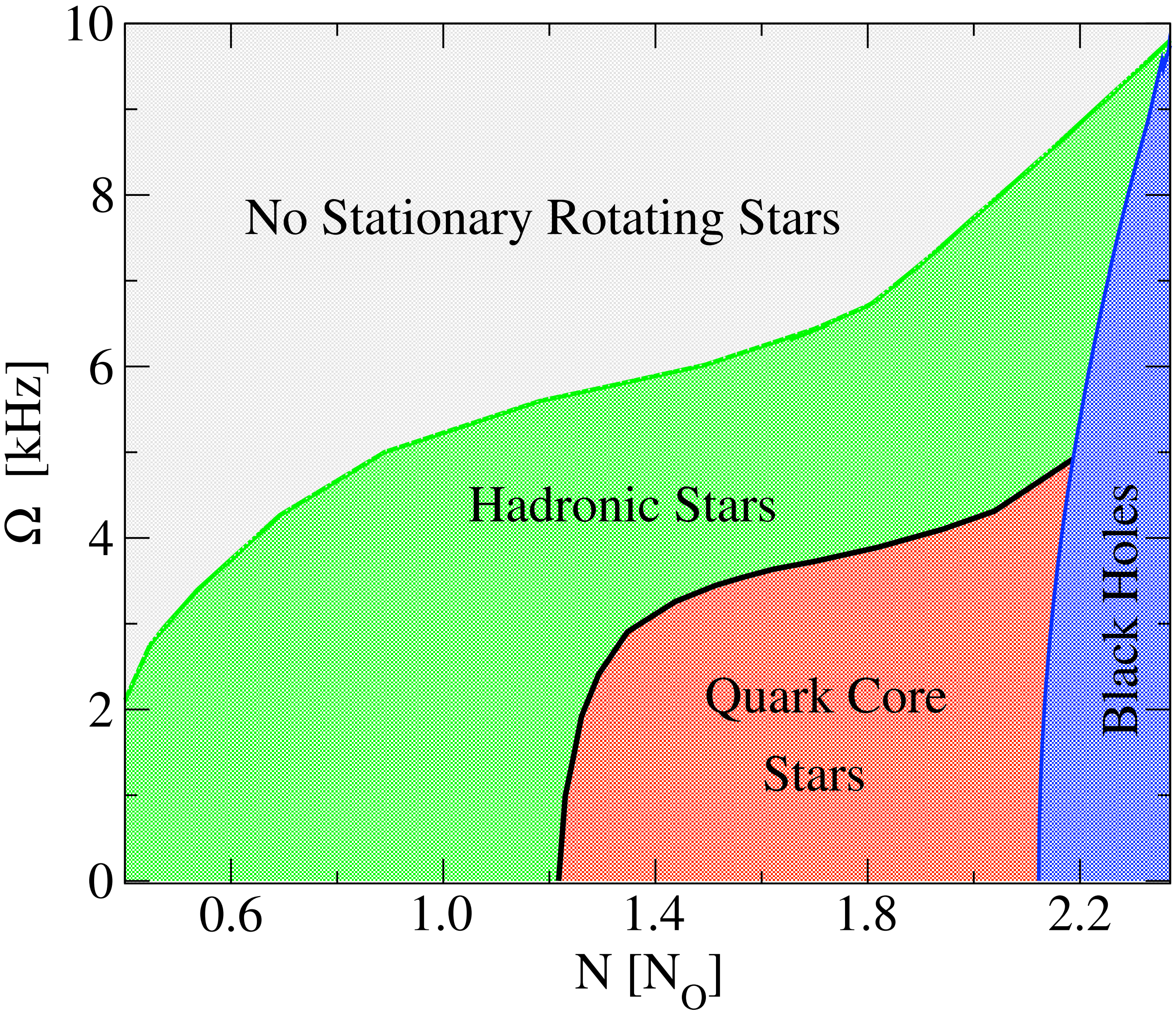
The ν_e emission can help to explain LSD events, but the rest of observations becomes less easy to understand

A new model for all neutrinos of SN 1987a

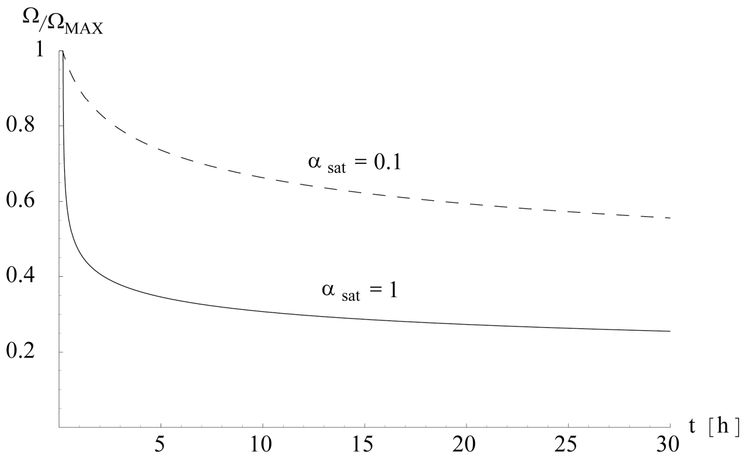
1. Electron neutrino signal at LSD as in the Imshennik-Ryazhskaya scenario

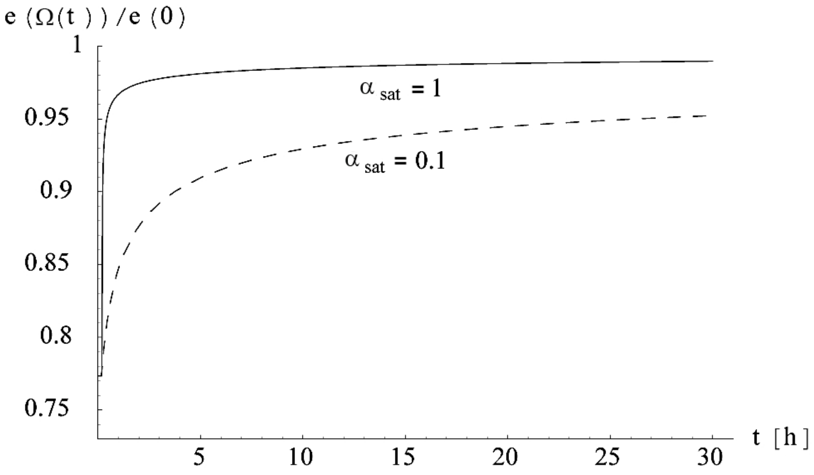
2. The Kamiokande-Baksan-IMB signals are generated by a delayed quark deconfinement transition

Effect of rotation on a compact star structure
From Blaschke, Grigorian, Poghosyan 2002



Frequency and density evolution due to r-mode instabilities: *an example*





In a few hours the central density can increase enough to make the compact star unstable respect to the formation of deconfined quarks

SNe and GRBs

GRBs are assumed to be associated with the gravitational collapse of massive stars, which have lost the hydrogen and helium shells (Wolf-Rayet stars)

In the collapsar-hypernova model GRBs are associated with a **failed** SN

Rapid rotation plays a role in the collapsar-hypernova model, since it delays the fallback and it allows collimation with the formation of a jet

SN1987a was probably an example of a SN with many features of a GRB

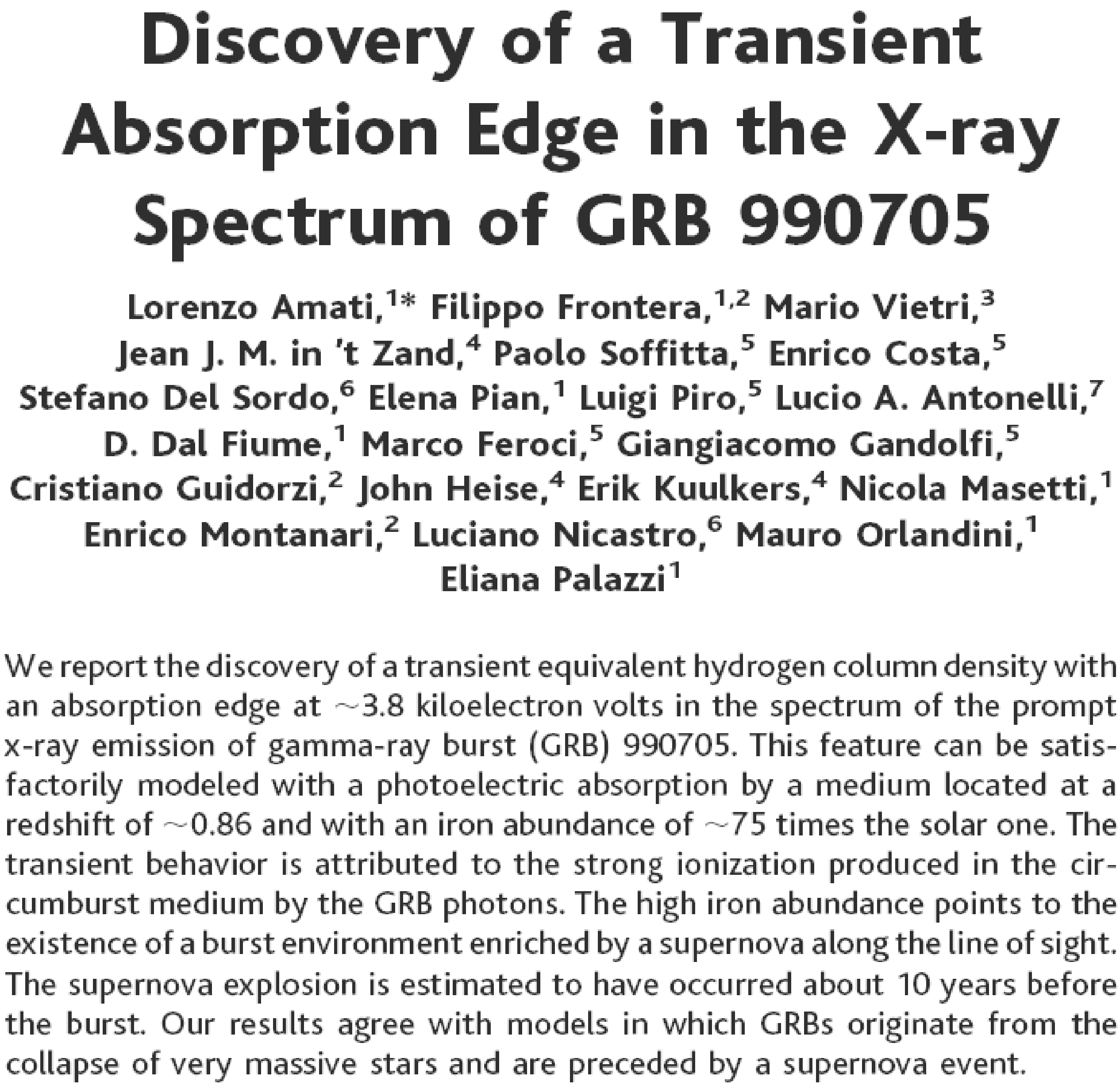
- Large mass (maybe 25 M_s)
- Rapidly rotating

Temporal delays in SNe and in GRBs

- SN1987a displays a delay of more than 4 hours between:
  1) collapse (MontBlanc signal, neutronization) and
  2) final detonation (Kamiokande, Baksan and IMB, quark deconfinement)

- Is there any evidence of a similar delay in GRBs?
  We are looking for:
  1) a partially failed SN explosion, (neutronization) preceding
  2) the main event of the GRB (quark deconfinement)…

The first example!



Discovery of a Transient Absorption Edge in the X-ray Spectrum of GRB 990705

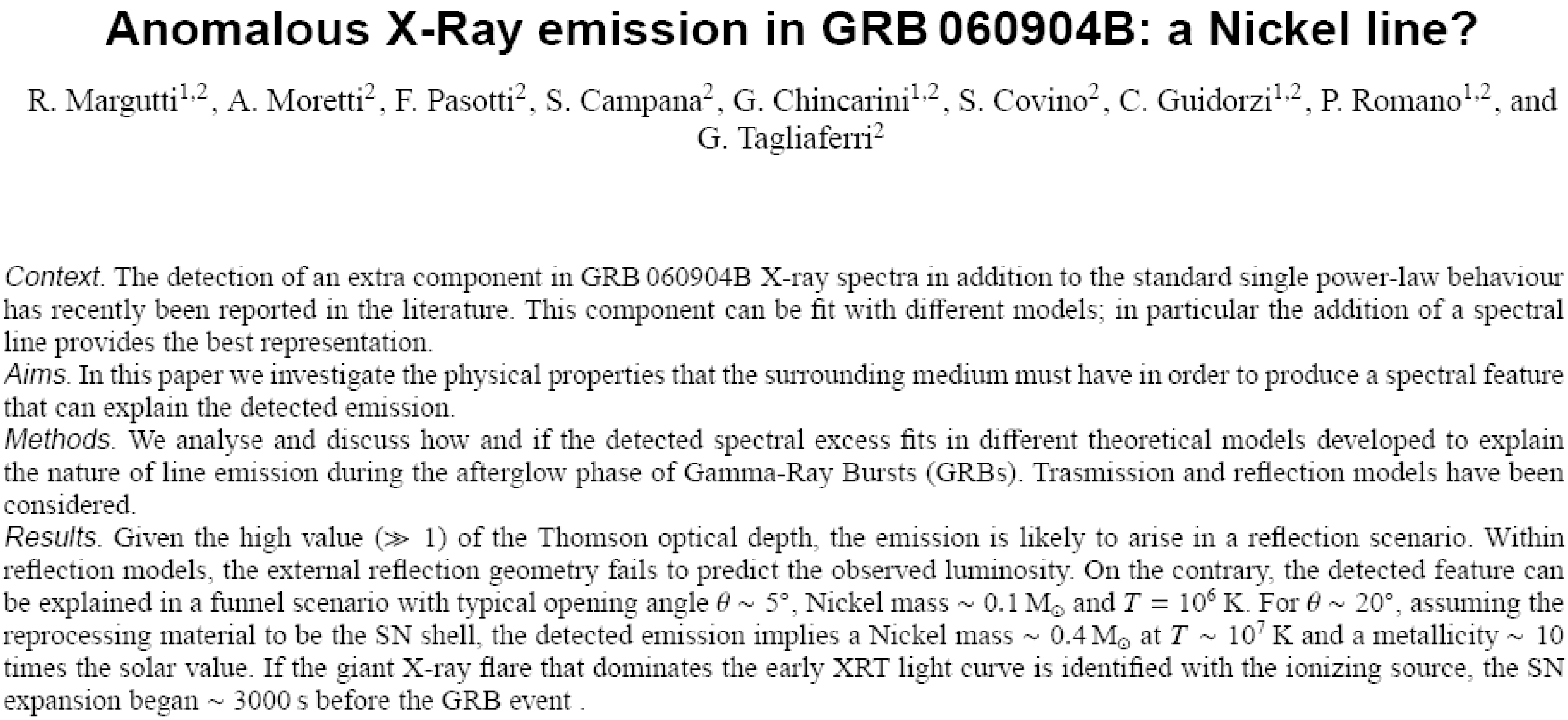
Lorenzo Amati,[1*] Filippo Frontera,[1,2] Mario Vietri,[3]
Jean J. M. in 't Zand,[4] Paolo Soffitta,[5] Enrico Costa,[5]
Stefano Del Sordo,[6] Elena Pian,[1] Luigi Piro,[5] Lucio A. Antonelli,[7]
D. Dal Fiume,[1] Marco Feroci,[5] Giangiacomo Gandolfi,[5]
Cristiano Guidorzi,[2] John Heise,[4] Erik Kuulkers,[4] Nicola Masetti,[1]
Enrico Montanari,[2] Luciano Nicastro,[6] Mauro Orlandini,[1]
Eliana Palazzi[1]

We report the discovery of a transient equivalent hydrogen column density with an absorption edge at $\sim$3.8 kiloelectron volts in the spectrum of the prompt x-ray emission of gamma-ray burst (GRB) 990705. This feature can be satisfactorily modeled with a photoelectric absorption by a medium located at a redshift of $\sim$0.86 and with an iron abundance of $\sim$75 times the solar one. The transient behavior is attributed to the strong ionization produced in the circumburst medium by the GRB photons. The high iron abundance 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. Our results agree with models in which GRBs originate from the collapse of very massive stars and are preceded by a supernova event.

Science 290 (2000) 953

A more recent example

Eprint 0712.1412



Anomalous X-Ray emission in GRB 060904B: a Nickel line?

R. Margutti[1,2], A. Moretti[2], F. Pasotti[2], S. Campana[2], G. Chincarini[1,2], S. Covino[2], C. Guidorzi[1,2], P. Romano[1,2], and G. Tagliaferri[2]

Context. The detection of an extra component in GRB 060904B X-ray spectra in addition to the standard single power-law behaviour has recently been reported in the literature. This component can be fit with different models; in particular the addition of a spectral line provides the best representation.
Aims. In this paper we investigate the physical properties that the surrounding medium must have in order to produce a spectral feature that can explain the detected emission.
Methods. We analyse and discuss how and if the detected spectral excess fits in different theoretical models developed to explain the nature of line emission during the afterglow phase of Gamma-Ray Bursts (GRBs). Trasmission and reflection models have been considered.
Results. Given the high value ($\gg 1$) of the Thomson optical depth, the emission is likely to arise in a reflection scenario. Within reflection models, the external reflection geometry fails to predict the observed luminosity. On the contrary, the detected feature can be explained in a funnel scenario with typical opening angle $\theta \sim 5°$, Nickel mass $\sim 0.1\,M_{\odot}$ and $T = 10^6$ K. For $\theta \sim 20°$, assuming the reprocessing material to be the SN shell, the detected emission implies a Nickel mass $\sim 0.4\,M_{\odot}$ at $T \sim 10^7$ K and a metallicity ~ 10 times the solar value. If the giant X-ray flare that dominates the early XRT light curve is identified with the ionizing source, the SN expansion began ~ 3000 s before the GRB event .

Conclusions

- A first order deconfinement transition generates a rather clear signature through a “new” neutrino burst.
- The standard scenario of SN explosions and GRBs can be supplemented by a quark aided mechanism, which in particular helps massive stars to explode.
- Rotation plays an important role, allowing a temporal separation between gravitational collapse and deconfinement.
- Signatures of “double explosions”, one associated with the collapse and one with quark deconfinement are maybe already present. Continous monitoring of GRBs (and future neutrino signals!) can provide a clear indication of this mechanism.