Signals of Quark-Gluon Plasma Formation in Astrophysical Environments

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A Fundamental Problem

At present we still do not know the composition of matter at densities as high as those expected at the interior of the usually called “neutron stars”.

$$\rho \geq 10^{14}\, g\ cm^{-3}$$

Posible compositions:

- **Normal Matter: Protons, neutrons and electrons**
- **Hyperonic Matter: Protons, neutrons, electrons and hyperons**
- **Quark Matter: up, down, strange (u, d, s)**

For example:

a protón   is made up of quarks u u d,

a neutron is u d d

a lambda is u d s

Non strange quark matter is unstable

Strange quark matter may be stable

$$P = (\rho - 4B)/3$$

Some properties of elementary partícles

Particle Properties[a]

Particle	I	J^P	Mass (MeV)	Mean Life (s)
Leptons				
e		$\frac{1}{2}$	0.511003	Stable
μ		$\frac{1}{2}$	105.6594	2.19714×10^{-6}
τ		$\frac{1}{2}$	1784	5×10^{-13}
Nonstrange Baryons				
p	$\frac{1}{2}$	$\frac{1}{2}^+$	938.280	Stable
n	$\frac{1}{2}$	$\frac{1}{2}^+$	939.573	925
Δ	$\frac{3}{2}$	$\frac{3}{2}^+$	1232	6×10^{-24}
Strangeness −1 Baryons				
Λ	0	$\frac{1}{2}^+$	1115.60	2.63×10^{-10}
Σ^+	1	$\frac{1}{2}^+$	1189.36	8.00×10^{-11}
Σ^0	1	$\frac{1}{2}^+$	1192.46	6×10^{-20}
Σ^-	1	$\frac{1}{2}^+$	1197.34	1.48×10^{-10}
Strangeness −2 Baryons				
Ξ^0	$\frac{1}{2}$	$\frac{1}{2}^+$	1314.9	2.9×10^{-10}
Ξ^-	$\frac{1}{2}$	$\frac{1}{2}^+$	1321.3	1.64×10^{-10}
Strangeness −3 Baryon				
Ω^-	0	$\frac{3}{2}^+$	1672.5	8.2×10^{-11}
Nonstrange Charmed Baryon				
Λ_c^+	0	$\frac{1}{2}^+$	2282	1×10^{-13}
Nonstrange Mesons				
π^+	1	0^-	139.567	2.603×10^{-8}
π^0	1	0^-	134.963	8.3×10^{-17}
η	0	0^-	548.8	8×10^{-19}
ρ	1	1^-	769	4.3×10^{-24}
ω	0	1^-	782.6	6.6×10^{-23}
η'	0	0^-	957.6	2.4×10^{-21}
ϕ	0	1^-	1019.6	1.6×10^{-22}
J/Ψ	0	1^-	3096.9	1.0×10^{-20}
Υ		1^-	9456	1.6×10^{-20}

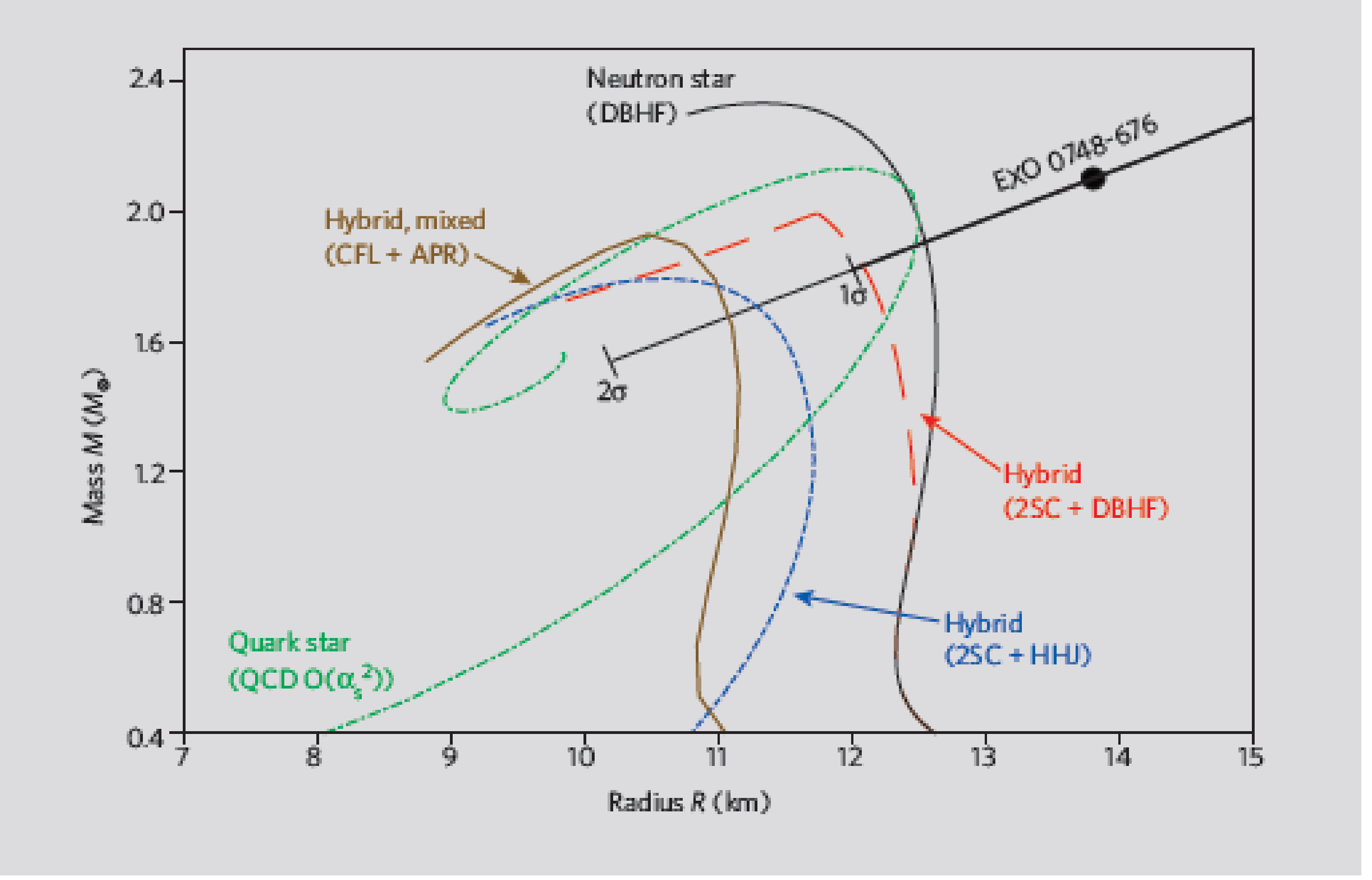
Tabulated lifetimes correspond to terrestrial laboratory conditions.

Barions and leptons are fermions. So, at the neutron star interiors those decays are inhibited because of the Pauli's Exclusion Principle.

At these conditions these particles do not decay.

Some ways proposed to differentiate quark stars from neutron stars

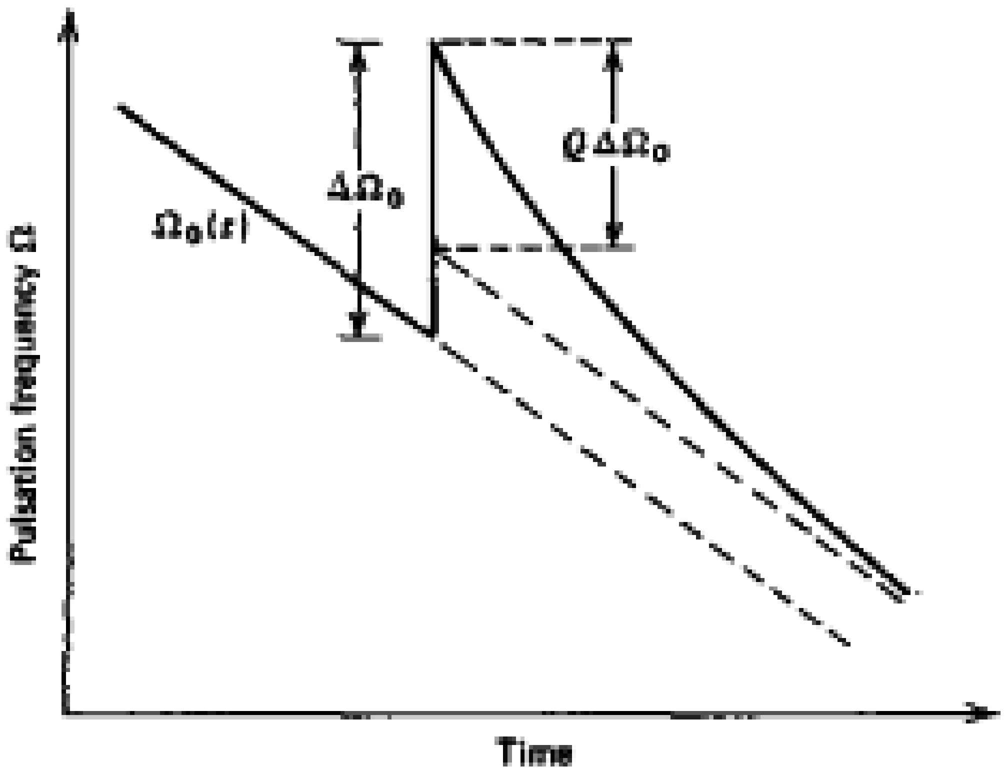
- Nuclear matter is expected to have an equation of state (EOS) very different from the EOS corresponding to self-bound quark matter. Thus, the mass-radius relations for these objects should be very different.



Neutron star
(DBHF)
EXO 0748-676
Hybrid, mixed
(CFL + APR)
1σ
2σ
Hybrid
(2SC + DBHF)
Hybrid
(2SC + HHJ)
Quark star
(QCD O(α_s^2))
Mass M ($M_\odot$)
Radius R (km)
2.4
2.0
1.6
1.2
0.8
0.4
7
8
9
10
11
12
13
14
15

- If the transition from nuclear matter to quark matter occurs, it will change the moment of inertia of the star
- If so, in a rotating pulsar, this process should be detected as a *giant glitch*.

A sudden change in the rotation rate of the neutron star: “Glitch”



Difficulties related with these methods:

1.- related with the employment of the mass radius relation, it is very difficult to measure the radius of a neutron star: Do we measure an effective magnetospheric radius or the radius of the underlying compact object?

2.- For the occurrence of a giant glitch, the density of the neutron star should be extremely close to the transition conditions. These are fine tuned conditions.

Proposal:

The most likely moment to detect the transition from nuclear matter to quark matter is during the hot stage called “proto neutron star”. The ideal way is by observing the neutrino emission of the next nearby core collapse supernova.

This main aim of this work is to predict the neutrino signal of a core collapse supernova including the occurrence of quark matter formation.

At present this work is in progress

The equations of relativistic stellar evolution with neutrino transport

Pons J. A., Reddy S., Prakash M., Lattimer J. M., Miralles J. A., 1999, ApJ, 513, 780

- We use the metrics ($c = 1$, $G = 1$, $\hbar = 1$)

$$ds^2 = -e^{2\phi}dt^2 + e^{2\Lambda}dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\Phi^2 \qquad (1)$$

The neutrino mean free path is very short compared with the size of the star: diffusive regime

- The flux of lepton number

$$H_\nu = -\frac{T^2 e^{-\Lambda-\phi}}{6\pi^2}\left[D_2 \frac{\partial(Te^{-\phi})}{\partial r} + (Te^{-\phi}) D_3 \frac{\partial}{\partial r}\left(\frac{\mu}{T}\right)\right] \qquad (2)$$

- The flux of energy

$$F_\nu = -\frac{T^3 e^{-\Lambda-\phi}}{6\pi^2}\left[D_3 \frac{\partial(Te^{-\phi})}{\partial r} + (Te^{-\phi}) D_4 \frac{\partial}{\partial r}\left(\frac{\mu}{T}\right)\right] \qquad (3)$$

- Diffusion coeficientes (equivalent to the well know "Rosseland mean" but for neutrino transport.):

Consider electron, muon and tau neutrinos. Muon and tau neutrinos are due to pair creation: $\mu_{\nu_e} \neq 0$, $\mu_{\nu_\mu} = 0$, $\mu_{\nu_\tau} = 0$. Then

$$D_2 = D_2^{\nu_e} + D_2^{\bar{\nu}_e} \qquad (4)$$

$$D_3 = D_3^{\nu_e} - D_3^{\bar{\nu}_e} \qquad (5)$$

$$D_4 = D_4^{\nu_e} + D_4^{\bar{\nu}_e} + 4D_4^{\nu_\mu} \qquad (6)$$

where

$$D_n^j = \int_0^\infty dx\, x^n D^j(E_1) f(E_1)\left(1 - f(E_1)\right), \quad j = \nu_e, \bar{\nu}_e, \nu_\mu \qquad (7)$$

• Equation of lepton number conservation

$$\frac{\partial Y_L}{\partial t} + e^{-\phi}\frac{\partial}{\partial a}(4\pi r^2 e^{\phi} F_\nu) = 0 \tag{8}$$

• Equation of energy number conservation

$$e^{\phi} T \frac{\partial s}{\partial t} + e^{\phi}\mu_\nu \frac{\partial Y_L}{\partial t} + e^{-\phi}\frac{\partial}{\partial a}(4\pi r^2 e^{2\phi} H_\nu) = 0 \tag{9}$$

• Equation of hydrostatic equilibrium (Tolman, Oppenheimer, Volkoff)

$$\frac{\partial P}{\partial a} = -\frac{e^{\Lambda}}{4\pi r^4 n_B}(\rho + P)(m + 4\pi r^3 P) \tag{10}$$

• Equation of the gravitational mass

$$\frac{\partial m}{\partial a} = \frac{\rho}{n_B e^{\Lambda}} \tag{11}$$

• Equation for the radius

$$\frac{\partial r}{\partial a} = \frac{1}{4\pi r^2 e^{\Lambda} n_B} \tag{12}$$

• Equation for the metrics

$$\frac{\partial \phi}{\partial a} = \frac{e^{\Lambda}}{4\pi r^4 n_B}(m + 4\pi r^3 P) \tag{13}$$

• Boundary conditions:

∘ At the center

$$r(a=0) = 0; \quad m(a=0) = 0; \quad H_\nu(a=0) = 0; \quad F_\nu(a=0) = 0 \tag{14}$$

∘ At the surface

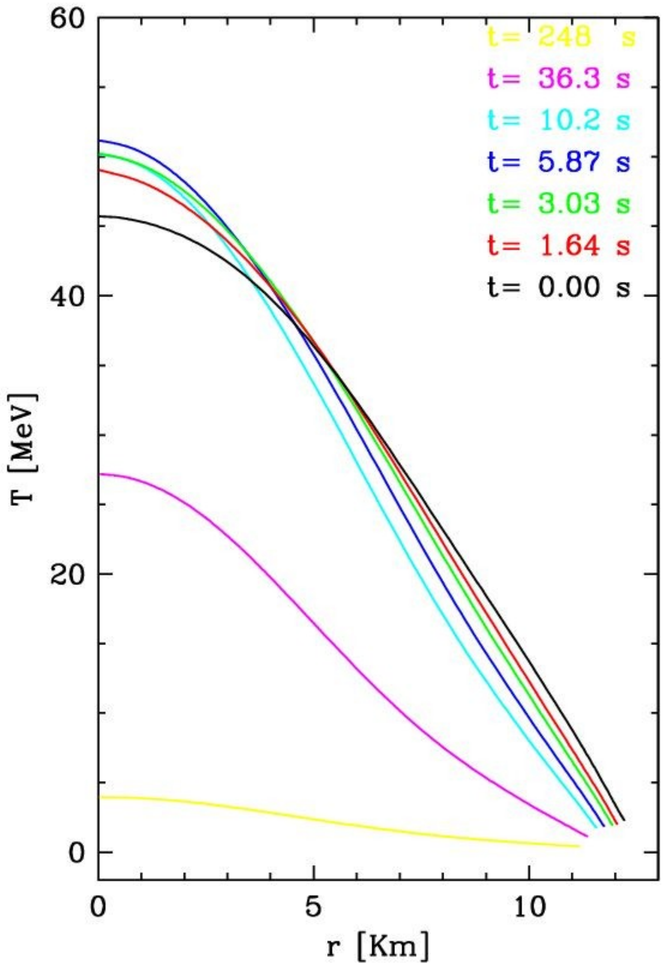
$$\phi(a = a_s) = \frac{1}{2}\log\left[\frac{2m(a=a_s)}{r(a=a_s)}\right]; \qquad P(a = a_s) = P_s \tag{15}$$

• The neutrino luminosity is:

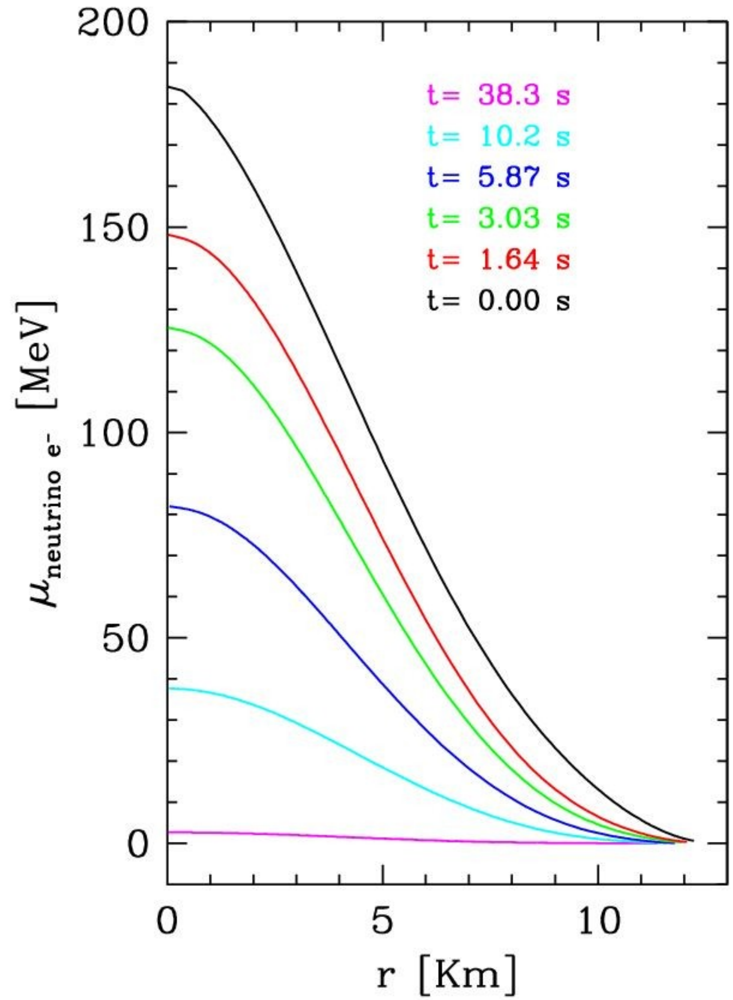
$$L_\nu = e^{2\phi} 4\pi r^2 H_\nu \tag{16}$$

It is solver by means of two coupled Henyey schemes: one for the structure and the other for the transport.

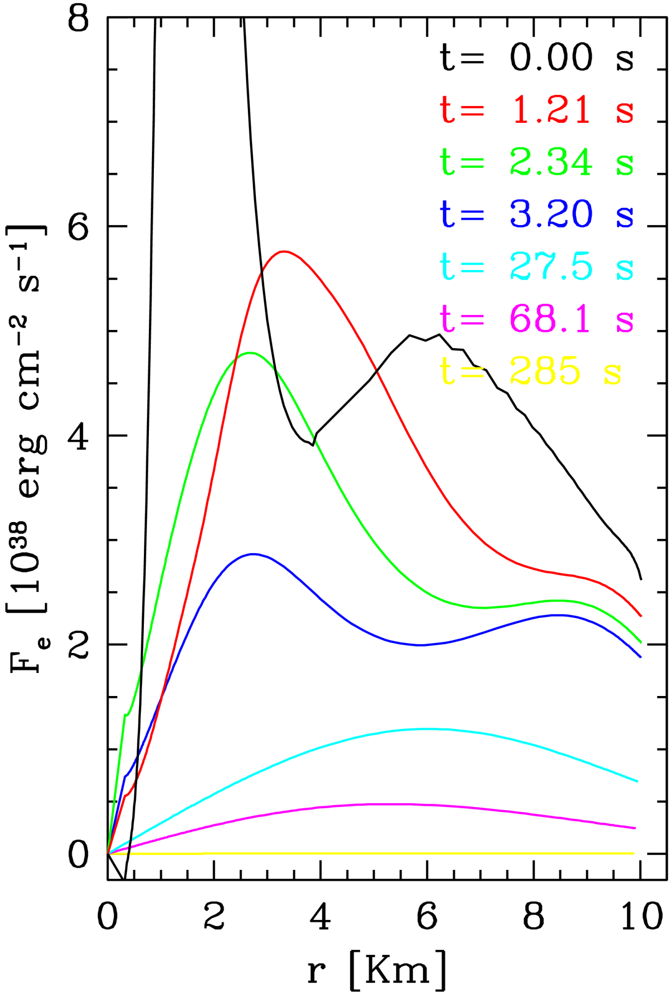
Evolution of the temperature profile



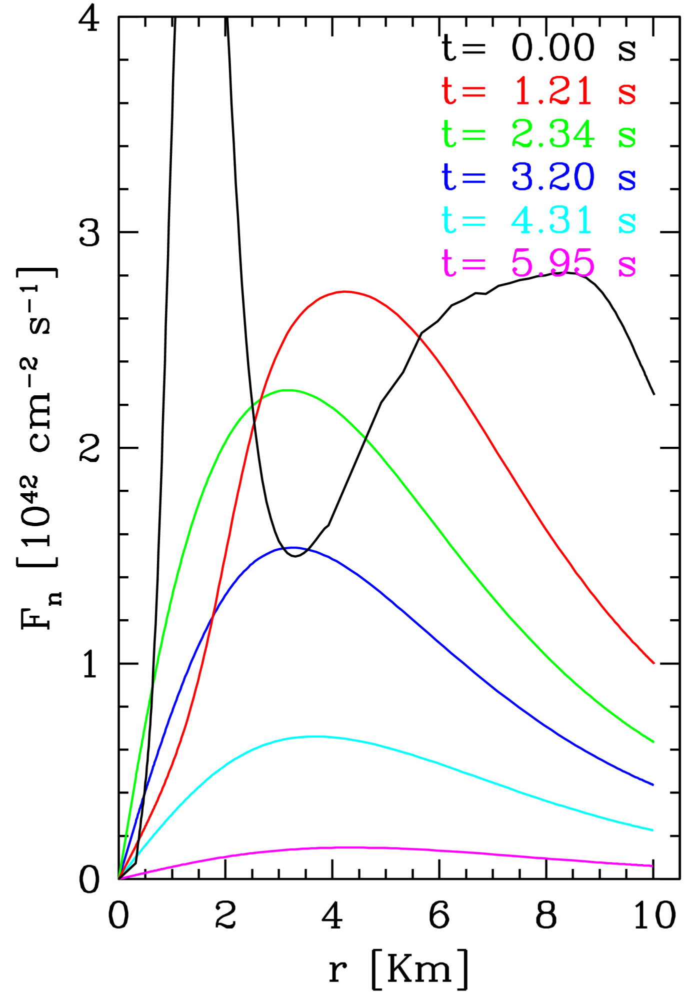
Evolution of the profile of chemical potential of electron neutrinos



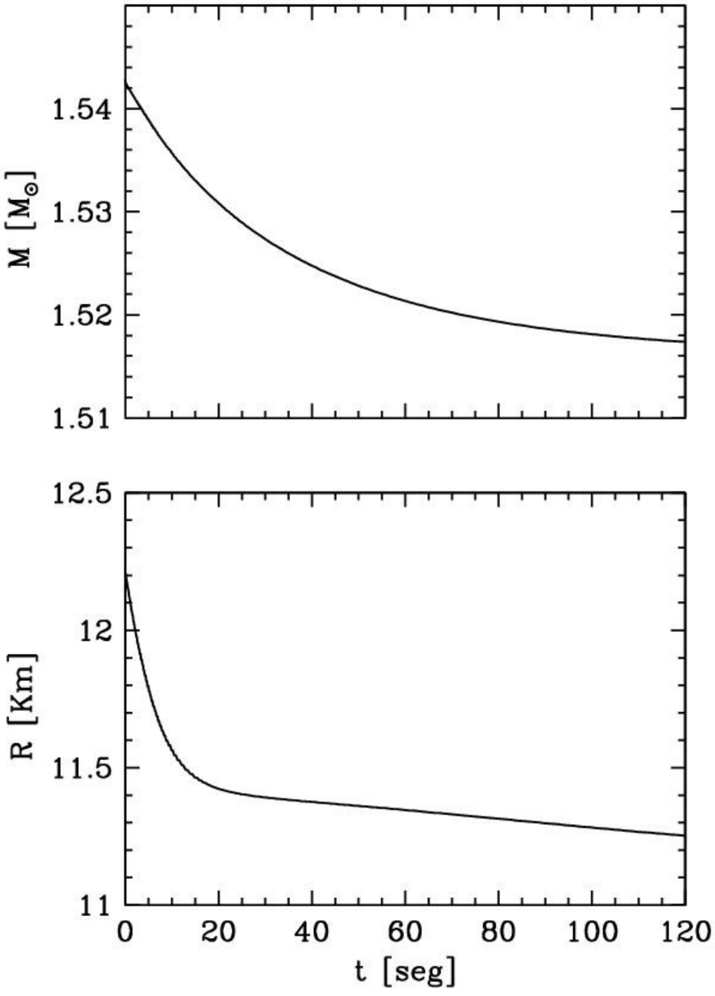
Energy flux



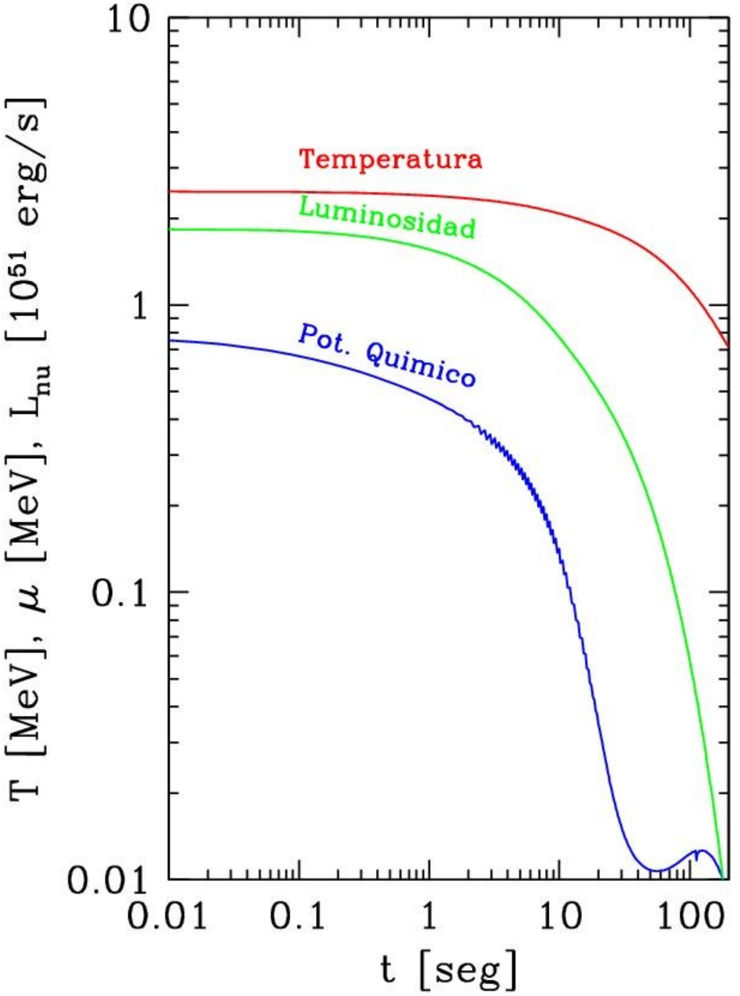
Lepton number flux



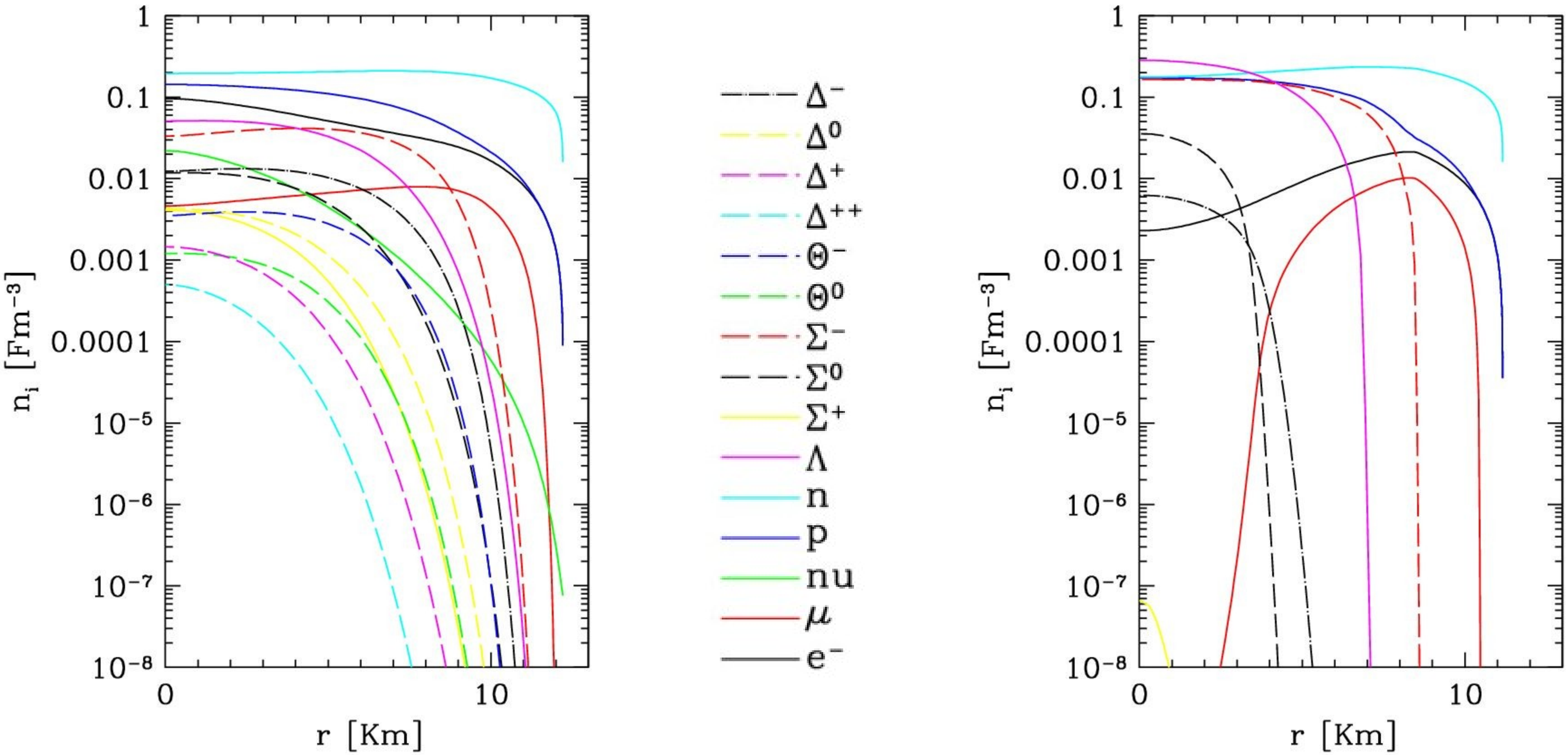
Evolution of the mass and radius of the star



Thermodynamics of the neutrinosphere



Particle composition of the stellar inteior at different moments of evolution



Initial Model
(full of neutrinos)

Last Model
(without neutrinos)

The neutrino release *favours* the occurrence of the transition to a quark matter phase

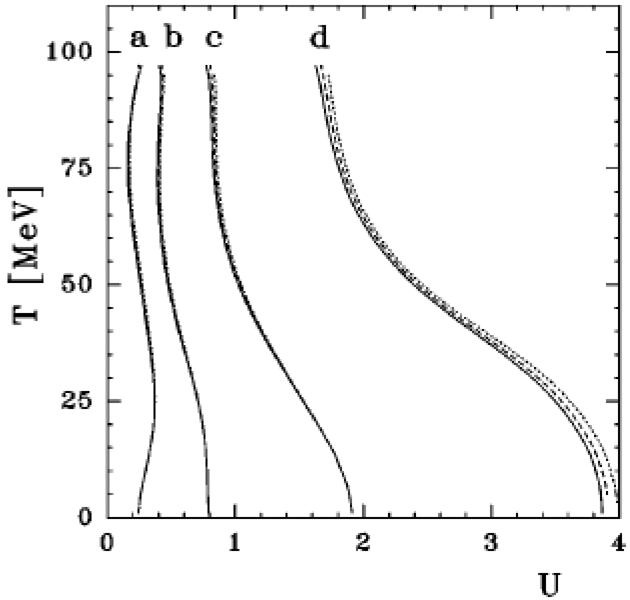


FIG. 2. The hadron matter mass-energy density of deconfinement phase transition versus the temperature T as given by the full calculation of Sec. III B. Density is given in units of the nuclear saturation density: $U=\rho_h/\rho_0$ being $\rho_0=2.7\times10^{14}$ g cm^{-3}. The bag constant is assumed to be $B=60$ MeV fm^{-3}. Full lines correspond to a value of the strange quark mass of $m_s=100$ MeV, dashed lines to $m_s=150$ MeV, and dotted lines to $m_s=200$ MeV. The labels a, b, c, and d correspond to different values of the chemical potential of the electron neutrinos in hadron matter: 0, 100, 200, and 300 MeV respectively.

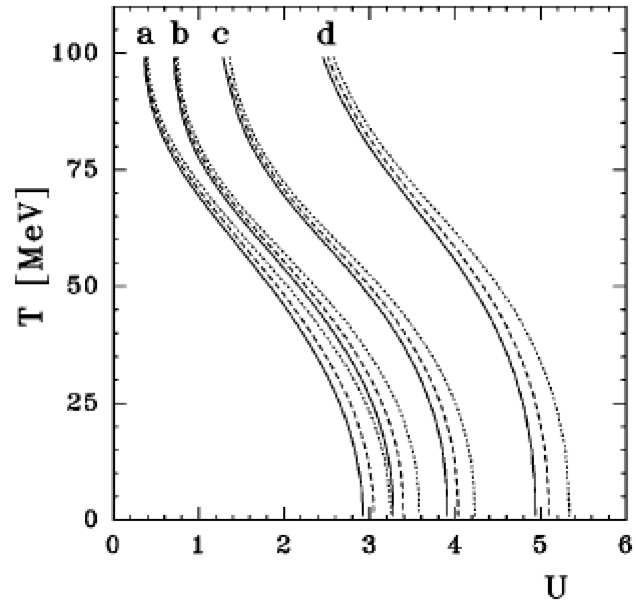


FIG. 4. The same as Fig. 2 but for $B=100$ MeV fm^{-3}.

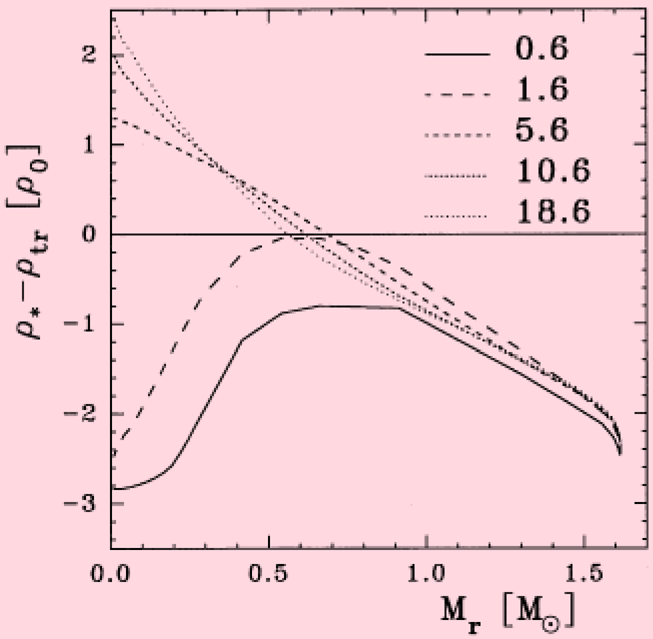


Figure 3. As Fig. 2, but for $B = 80\,\mathrm{MeV\,fm^{-3}}$. The transition conditions are reached off-centre, soon after 1.6 s after core bounce.

Benvenuto O.~G., Lugones G., 1999, MNRAS, 304, L25
Lugones G., Benvenuto O.~G., 1998, PhRvD, 58, 083001

- The composition of the hot *proto neutron star* is in local thermodynamic equilibrium with its neutrino content
- As the star releases its neutrino content its composition shifts towards heavy hyperons
- The material gets closer to transition conditions
- We expect that the neutrino emission due to quark matter transition to be delayed a neutrino diffusion timescale (~seconds)
- Is it related to the last neutrinos detected by Kamiokande in the SN 1987A explosion?

Observation of neutrinos from SN 1987 A at Kamiokande

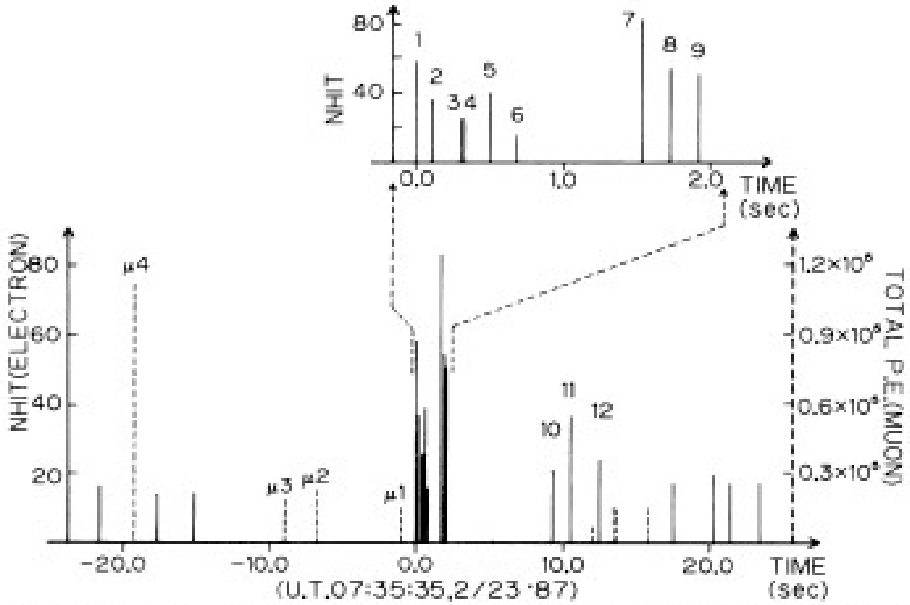


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu1-\mu4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

Hirata K., et al., 1987, Phys. Rev. Lett., 58, 1490

- Unfortunately we cannot be sure: Detected neutrinos are too few to answer this question.
- We have to wait for another nearby supernova.

Conclusions

- Within the present uncertainties we may expect a phase transition from nuclear matter to quark matter during the first few seconds after the birth of a neutron star in core collapse supernovae
- For quark matter formation we need beta decays to occur (~10 ns)
- But heavy ion collisions are far shorter
- Neutron stars are plenty of time !

Conclusions

- If this transition really takes place in Nature its signals should be found among the neutrinos to be detected by Superkamiokande in the next nearby supernova
- Other kind of observations seem hardly useful for this purpose

Thank you very much !!!