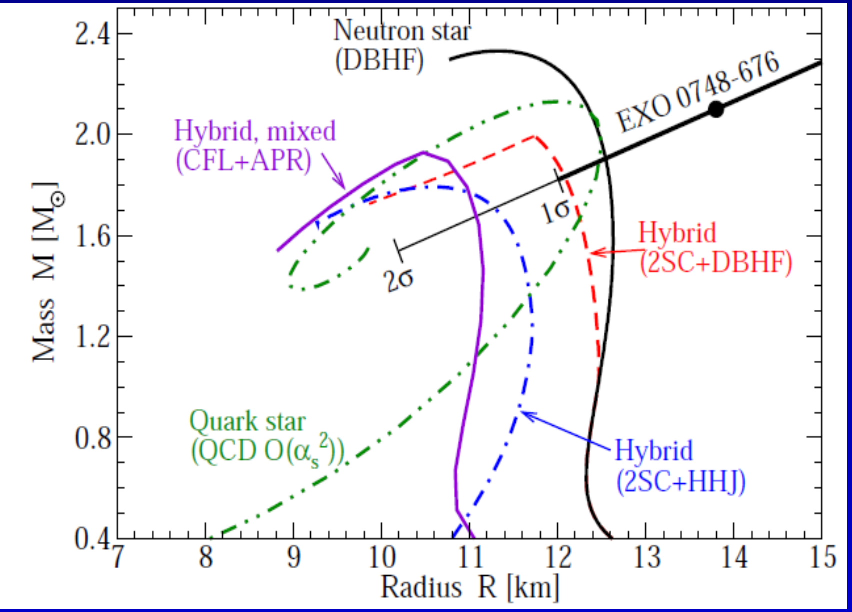
Birth of quark stars

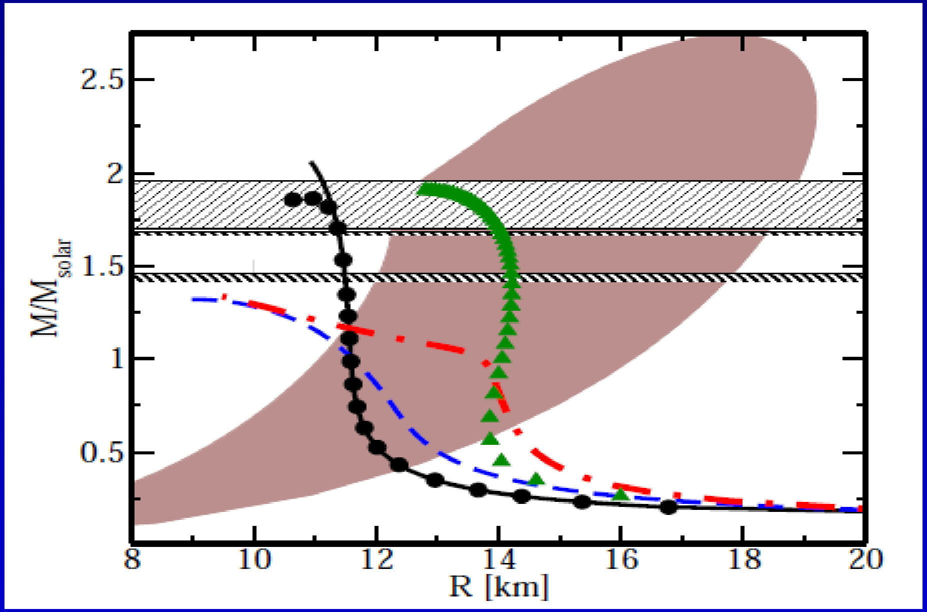
Giuseppe Pagliara

Dipartimento di Fisica e Scienze della Terra, Universita' di Ferrara & INFN Ferrara, Italy

Emmi rapid reaction task force: Quark Matter in Compact Stars, 7-10/10/13 FIAS, Frankfurt am Main

Are quark stars massive enough?





Alford et al Nature 2006

Kurkela et al 2010

Before the discoveries of the two $2M_{sun}$ stars!!

Within a simple parametrization:

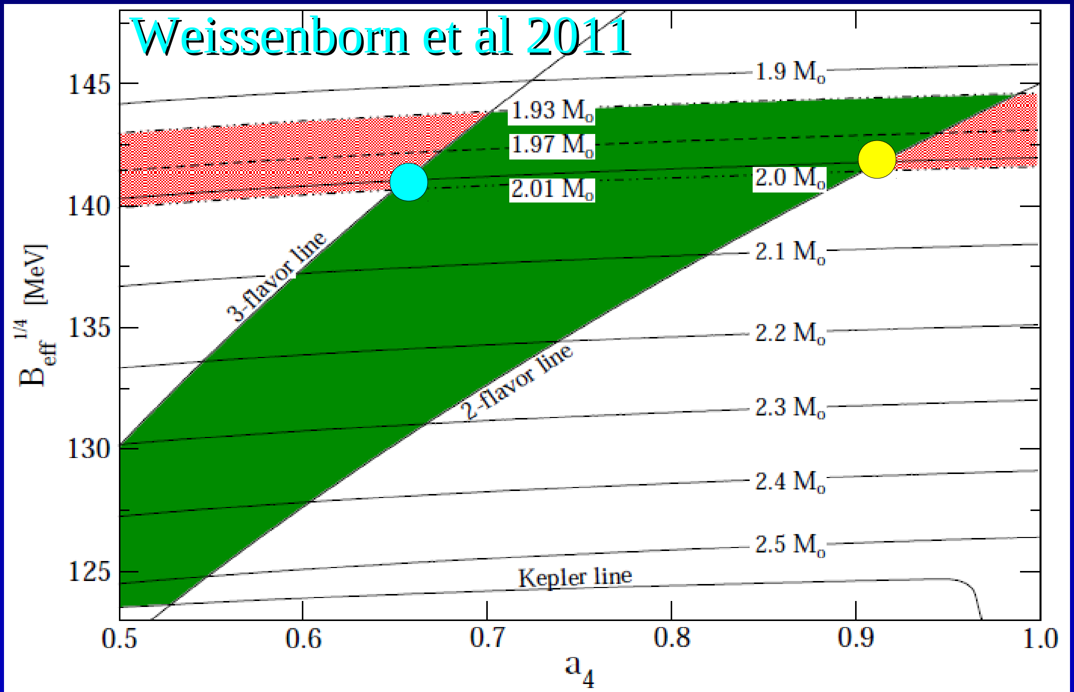
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{eff}$$

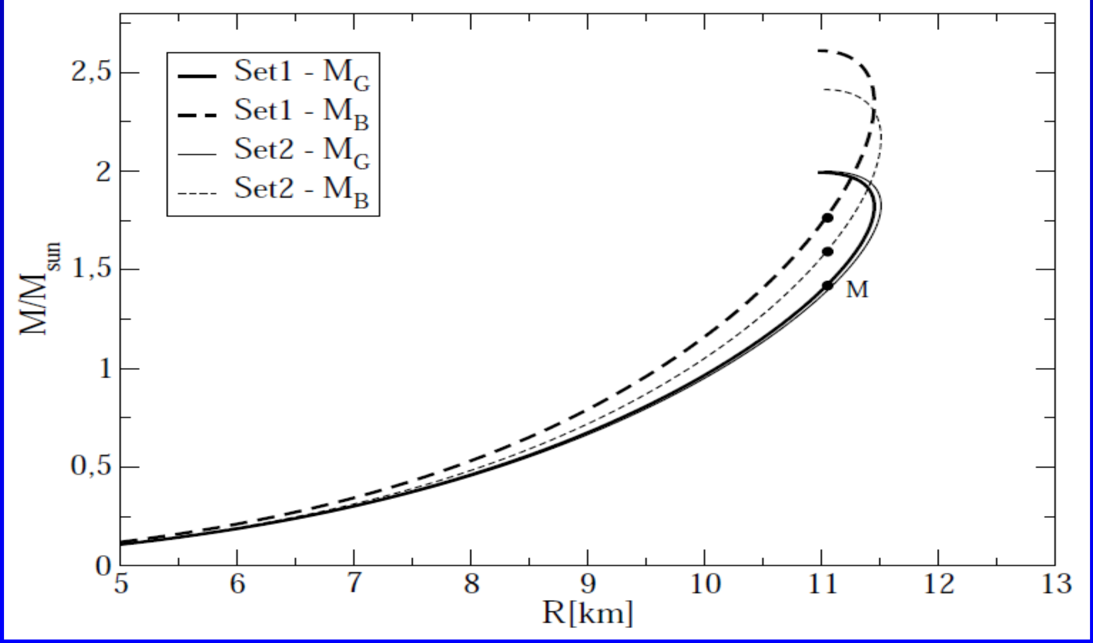
Two EoSs which provide a maximum mass of $2M_{sun}$

- E/A=860 MeV(set1)
- E/A=930 MeV(set2)

↓

Different QSs binding energy M_B-M_G





Conversion of a neutron star into a quark star

Importance of turbulence & hydrodynamical instabilities

-) Horvath et al 1988

-) Lugones et al 1994, Cho et al 1994

-) Tokareva et al 2006

-) Drago et al 2007

The process is similar to the thermonuclear burning inside a white dwarf during a Type Ia supernova, need for multidimensional numerical simulations

Herzog, Roepke 2011, use of the 3+1D hydrocode for SNIa to simulate the conversion of a neutron star and study the different possible combustion modes

Hydro simulations

Input from microphysics:

1) **EoS of hadronic matter & quark matter at finite temperature: at the moment both beta-stable, lepton number not conserved :-(**

2) **Detonation or deflagration & laminar burning velocity: at the moment only deflagration has been tested based on the results of Drago et al 2007 where a strong deflagration has been found in all the cases.**

3+1D code developped by Hillebrandt and collaborators for the study of SNIa adapted, by use of an effective relativistic potential, for handling the large compactness of NSs, (see Roepke et al A&A2005) Grid spacing 10m.

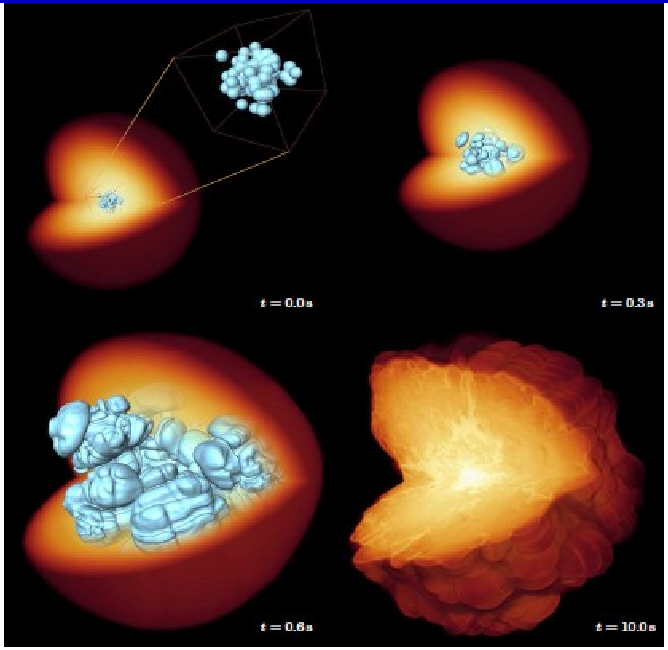


FIGURE 1. Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and is not on scale with the earlier snapshots.

Condition for exothermic combustion

$$e_h(P,X) > e_q(P,X)$$

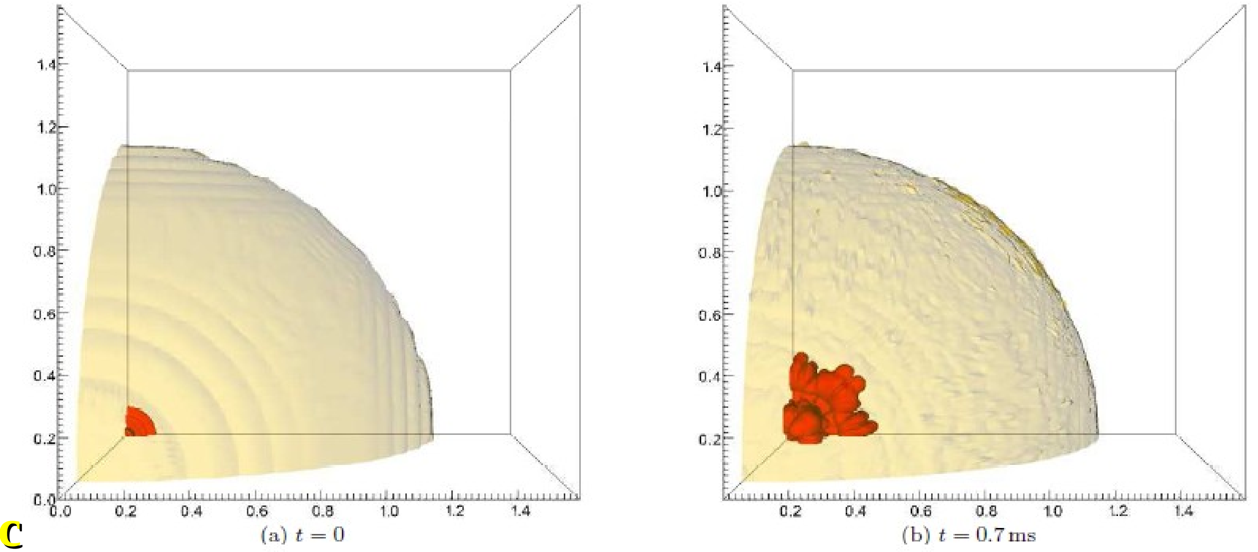
$$X = (e+P)/n_B^2$$

Conversion of a 1.4 M_{sun} star

-) Rayleigh-Taylor instabilities develop and the conversion occurs on time scales of ms.

-) The burning stops before the whole hadronic matter has converted (the process is no more exothermic, about 0.5 M_{sun} of unburned material)

-) A succesfull conversion need a small E/A, no conversion is possible with set2 (the one with a larger E/A=smaller binding energy)



Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

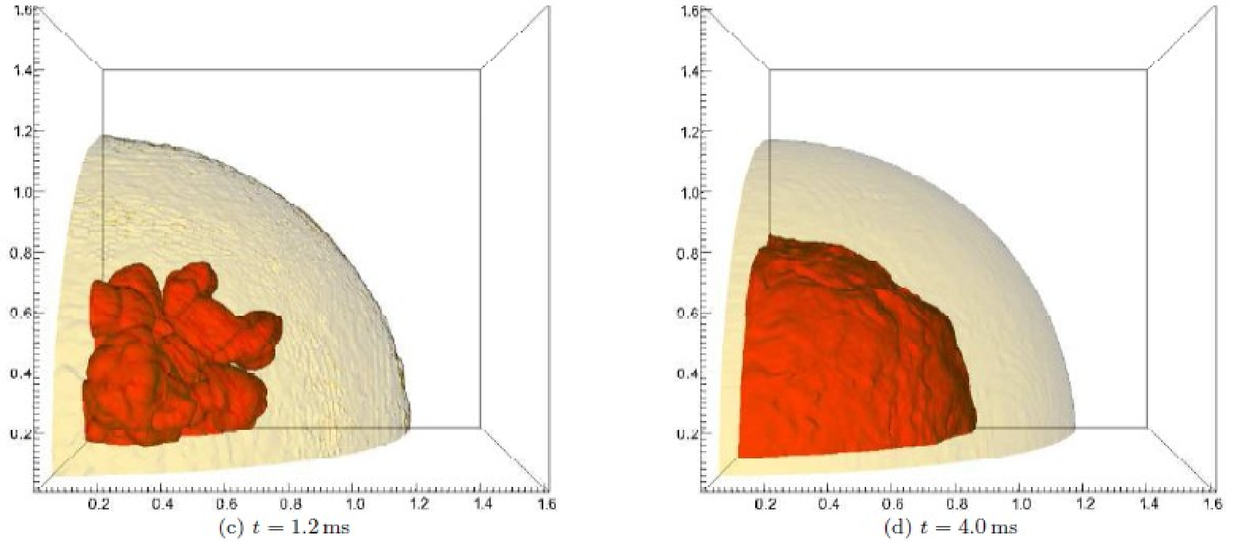
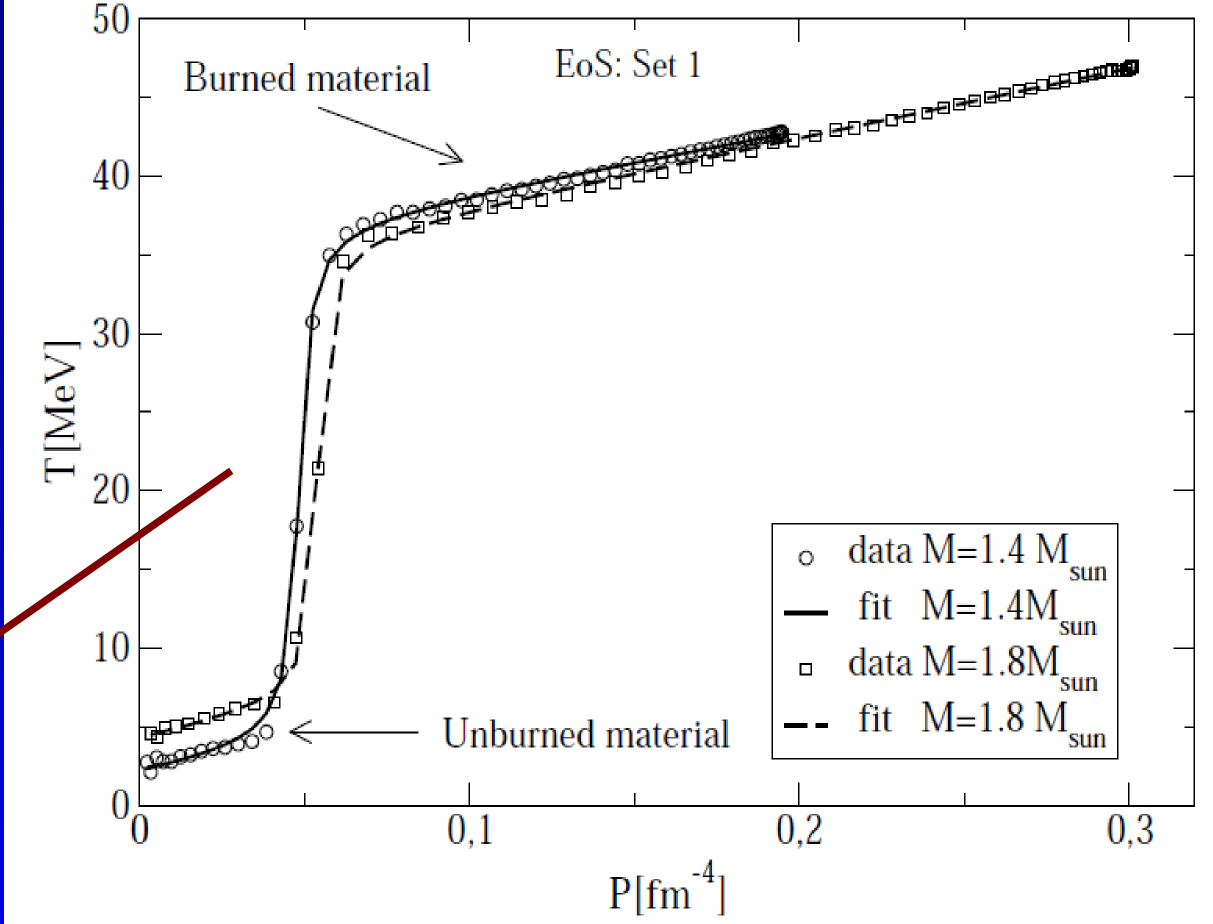


FIG. 1: (color online) Model: Set 1, $M = 1.4 M_{\odot}$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

Temperature profiles after the combustion

The huge energy released in the burning leads to a significant heating of the star, few tens of MeV in the center.



Steep gradient of the temperature

Since the burning occurs on time scales of the order of ms, it is decoupled from the cooling (typical time scales of the order of seconds)

Temperature profiles as initial conditions for the cooling diffusion equation

Heat transport equation due to neutrino diffusion

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{dt}}\frac{\epsilon_{tot}}{n_b} + P\frac{\mathrm{d}}{\mathrm{dt}}\frac{1}{n_b} &= -\frac{\Gamma}{n_b r^2 \mathrm{e}^{\Phi}}\frac{\partial}{\partial r}\left(\mathrm{e}^{2\Phi} r^2 \left(F_{\epsilon,\nu_e}\right.\right. \\
&\quad + \left.\left. F_{\epsilon,\nu_\mu}\right)\right) \\
\frac{dP}{dr} &= -(P+\epsilon_{tot})\frac{m+4\pi r^3 P}{r^2-2mr} \\
\frac{dm}{dr} &= 4\pi r^2 \epsilon_{tot} \\
\frac{da}{dr} &= \frac{4\pi r^2 n_b}{\sqrt{1-2m/r}} \\
\frac{d\Phi}{dr} &= \frac{m+4\pi r^3 P}{r^2-2mr}
\end{aligned}
$$

$$
\begin{aligned}
F_{\epsilon,\nu_e} &= -\frac{\lambda_{\epsilon,\nu_e}}{3}\frac{\partial \epsilon_{\nu_e}}{\partial r} \\
F_{\epsilon,\nu_\mu} &= -\frac{\lambda_{\epsilon,\nu_\mu}}{3}\frac{\partial \epsilon_{\nu_\mu}}{\partial r}
\end{aligned}
$$

Assumption: quark matter is formed already in beta equilibrium, no lepton number conservation imposed in the burning simulation, no lepton number diffusion

↓

Diffusion is dominated by scattering of non-degenenerate neutrinos off degenerate quarks

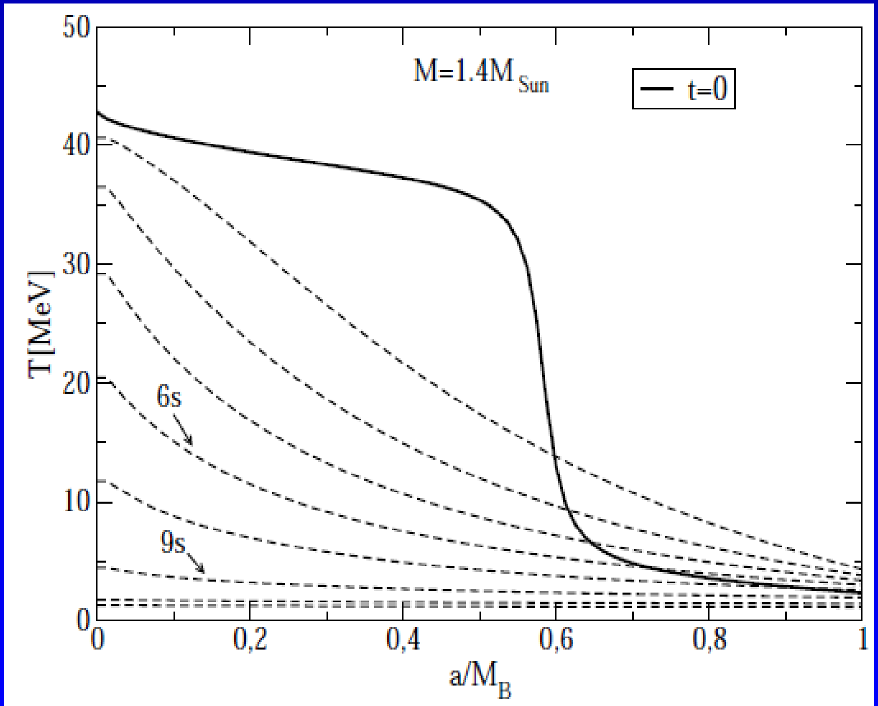
$$\frac{\sigma_S}{V} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$$

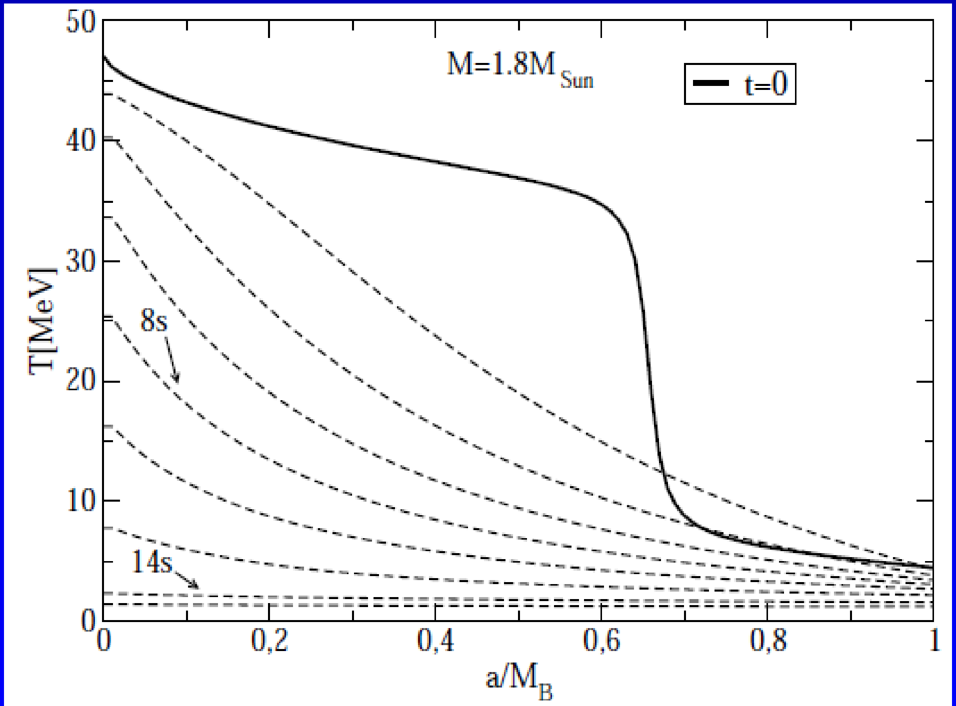
Steiner et al 2001

Expected smaller cooling times with respect to hot neutron stars

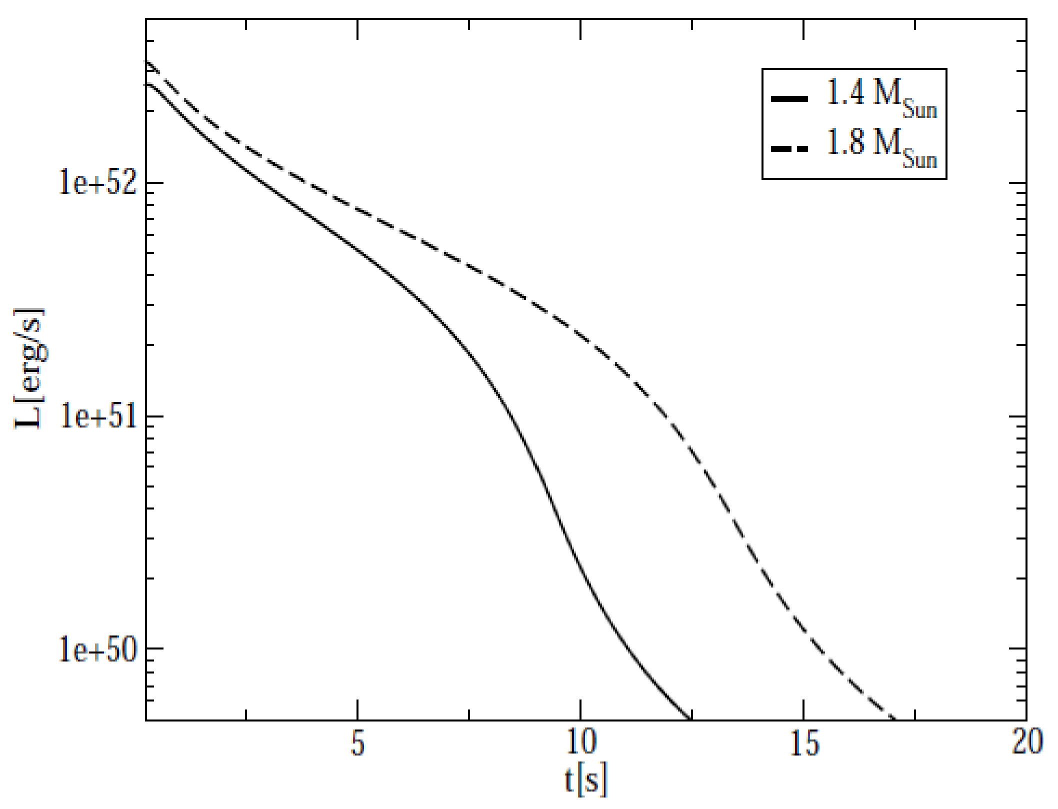
phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear Matter	$\nu n \to \nu n$	200 m	1 cm
	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired Quarks	$\nu q \to \nu q$	350 m	1.6 m
	$\nu d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu\phi \to \nu\phi$	>10 km	4 m

Reddy et al 2003





Luminosity curves similar to the protoneutron stars neutrino luminosities. Possible corrections due to lepton number conservation...



Phenomenology II: connection with double GRBs within the protomagnetar model

Phenomenology I: such a neutrino signal could be detected for events occurring in our galaxy (possible strong neutrino signal lacking the optical counterpart if the conversion is delayed wrt the SN)

UNUSUAL CENTRAL ENGINE ACTIVITY IN THE DOUBLE BURST GRB 110709B

Bin-Bin Zhang[1], David N. Burrows[1], Bing Zhang[2], Peter Mészáros[1,3], Xiang-Yu Wang[4,5], Giulia Stratta[6,7], Valerio D'Elia[6,7], Dmitry Frederiks[8], Sergey Golenetskii[8], Jay R. Cummings[9,10], Jay P. Norris[11], Abraham D. Falcone[1], Scott D. Barthelmy[12], Neil Gehrels[12]

Draft version January 17, 2012

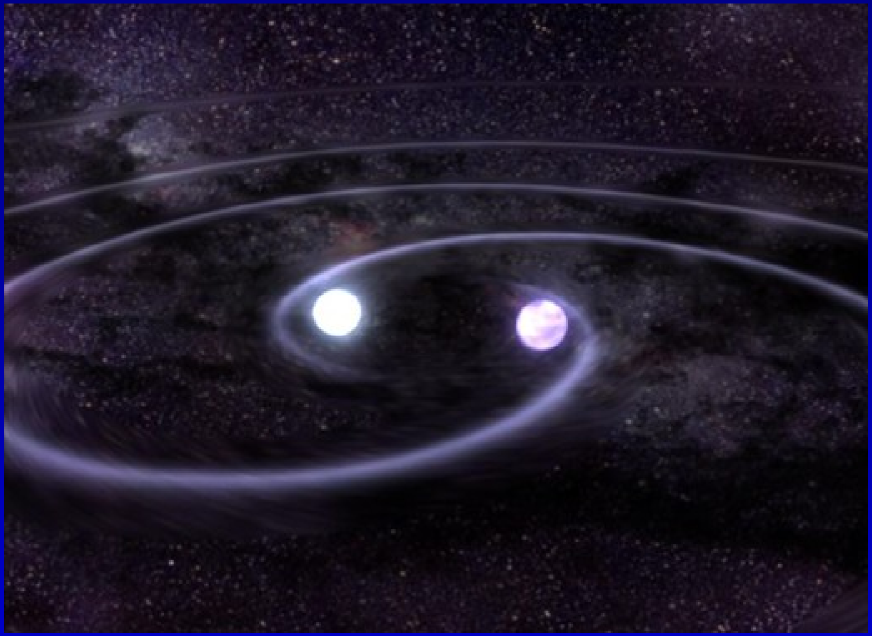
ABSTRACT

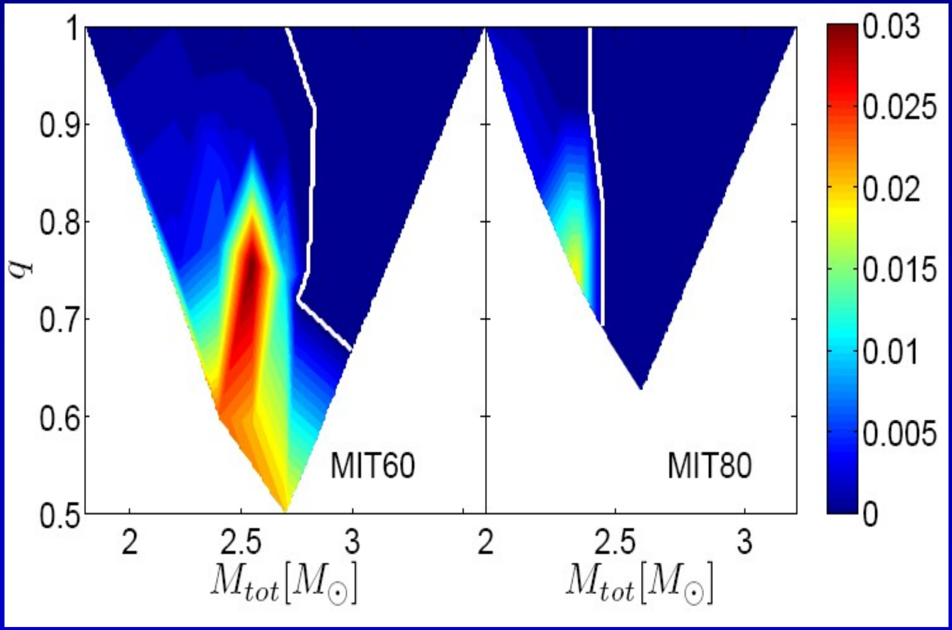
The double burst, GRB 110709B, triggered *Swift*/BAT twice at 21:32:39 UT and 21:43:45 UT, respectively, on 9 July 2011. This is the first time we observed a GRB with two BAT triggers. In this paper, we present simultaneous *Swift* and Konus-*WIND* observations of this unusual GRB and its afterglow. If the two events originated from the same physical progenitor, their different time-dependent spectral evolution suggests they must belong to different episodes of the central engine, which may be a magnetar-to-BH accretion system.

Subject headings: gamma-ray burst: general

Open questions: Seeding of quark matter

Are all CSs QSs ?: Merger of strange stars





MIT60: 8 $\times$ 10^{-5} M_{sun}, MIT80 no ejecta. By assuming a galactic merger rate of $10^{-4(-5)}$ /year, mass ejected: $10^{-8(-9)}$ M_{sun}/year. Constraints on the strangelets flux (for AMS02)

A. Bauswein et al PRL (2009)

Nucleation

(many papers!! done by many people of this workshop!!)

Hot stars: thermal nucleation

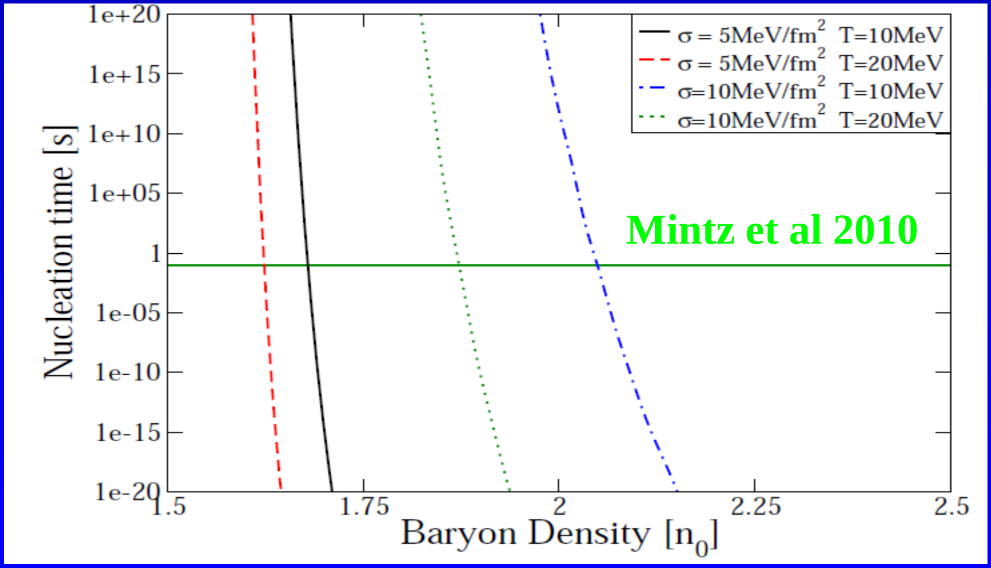
$$\Gamma = T^4 \exp\left[-\frac{16\pi}{3}\frac{\sigma^3}{(\Delta p)^2 T}\right]$$

Cold stars: quantum nucleation, WKB appr.

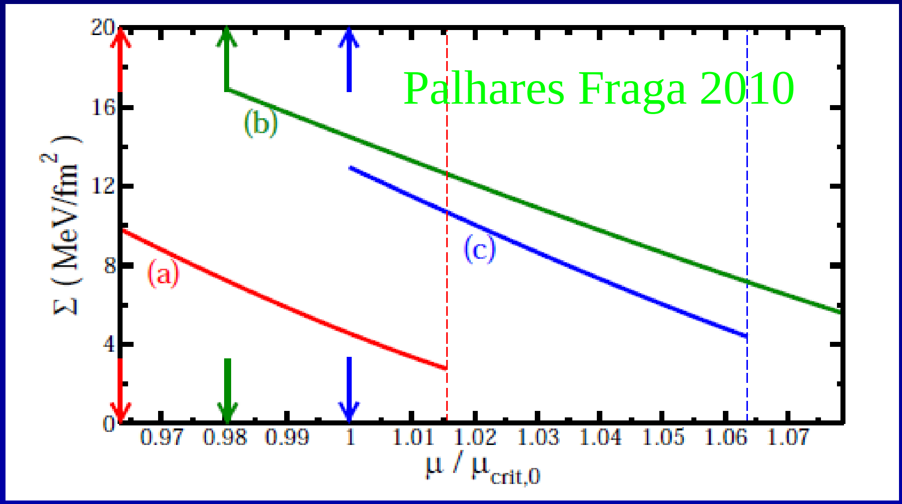
$$U(R) = \frac{4}{3}\pi R^3 n_q(\mu_q - \mu_h) + 4\pi\sigma R^2$$

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

As expected: strong dependence on surface tension and overpressure



Recent estimates of σ ~ 5–15 MeV/fm^2 in 2 and 3 flavor quark meson models (Palhares et al 2010, Mintz et al 2013), nucleation is likely to occur. Values of 100 MeV/fm^2 of Lugones (see previous discussions)



Frozen flavor composition?

Q*

$$\begin{pmatrix} x_u \\ x_d \\ x_s \end{pmatrix} = \begin{pmatrix} 2 & 1 & 1 & 2 & 1 & 0 & 1 & 0 \\ 1 & 2 & 1 & 0 & 1 & 2 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 2 & 2 \end{pmatrix} \begin{pmatrix} x_p \\ x_n \\ x_\Lambda \\ x_{\Sigma^+} \\ x_{\Sigma^0} \\ x_{\Sigma^-} \\ x_{\Xi^0} \\ x_{\Xi^-} \end{pmatrix}$$

Tiny amount of hyperons already allows nucleation (statistical fluctuations of the density for a drop of 2-3 fm allow to form beta-stable quark matter)

It shifts the nucleation threshold to considerably higher densities

Open questions related to the burning

1) Deflagration or detonation (in the numerical simulations of burning this is an input)

2) Full GR

3) Lepton number conservation

4) Effect of magnetic field (Lugones et al 2002) asymmetric combustion

… and of course EoS!!!

Deflagration to detonation transition in QSs?

Lugones et al 1994 –
Niebergal et al 2010

Also in SNIa this is still an open question: detonations do occur in these systems but in the simulations one forces the DDT to take place at an arbitrary chosen instant and location

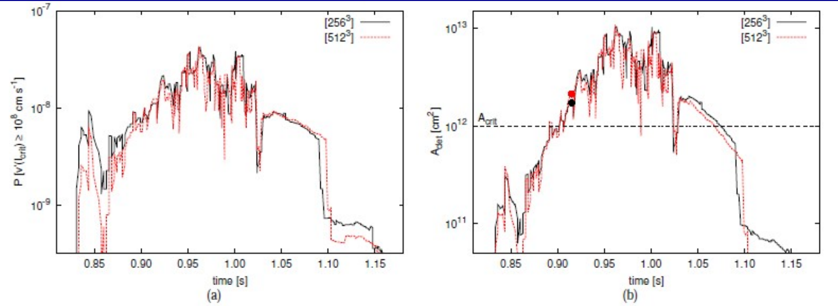
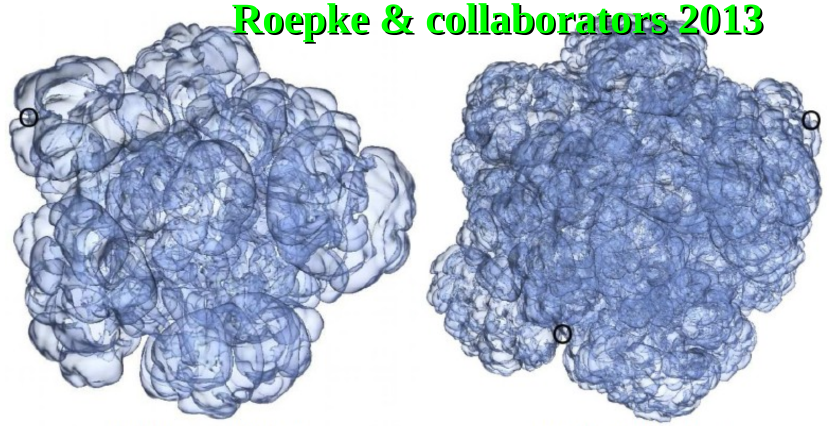


Fig. 3. (a) The probability $P[v'(\ell_{crit}) \geq 10^8\,\mathrm{cm\,s^{-1}}](t)$ of finding velocity fluctuations higher than $10^8\,\mathrm{cm\,s^{-1}}$ and (b) the size of the potential detonation area $A_{det}(t)$. For most of the time between $t = 0.90$ s and $t = 1.07$ s, $A_{det}(t) > A_{crit}$ holds. The DDT criterion is met for the first time at $t \approx 0.92$ s in both simulations (see dots at the curve of $A_{det}(t)$).

Roepke & collaborators 2013



(a) Simulation with 256^3 grid cells

(b) Simulation with 512^3 grid cells

Fig. 4. Shown is the deflagration flame (transparent iso-surface) at the time of the first DDT for both simulations. The DDT spots are encircled.

If it works, Quark nova model of Ouyed and collaborators →

- Double humped SN
- r-processes
-...

Appendix

$$(e_h + p_h) v_h \gamma_h^2 = (e_q + p_q) v_q \gamma_q^2 \,,$$

$$(e_h + p_h) v_h^2 \gamma_h^2 + p_h = (e_q + p_q) v_q^2 \gamma_q^2 + p_q \,,$$

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

$$\Delta \left(\frac{E}{A} \right) (T, \rho_B^h) \equiv \frac{e_h(u_h, \rho_B^h, T_h)}{\rho_B^h(u_h)} - \frac{e_q(u_q, \rho_B^q, T)}{\rho_B^q(u_q)} = c_V^q (T - T_h)$$

Drago et al 2007