# Death of neutron stars and birth of quark stars

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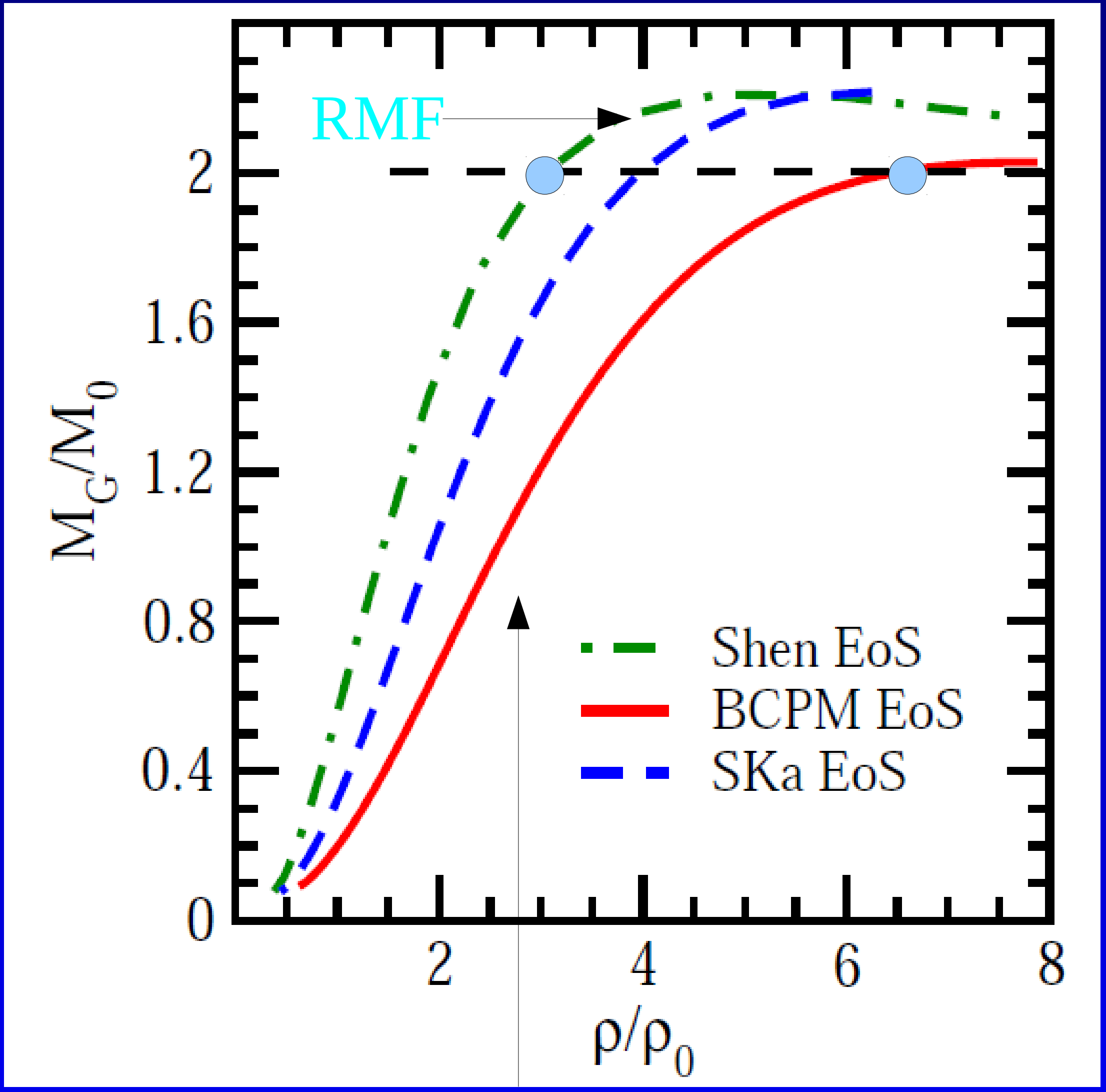
*Structure and signals of neutron stars: from birth to death, Florence 27/03/14*

# What does a 2$M_{sun}$ star mean?

"Standard" neutron stars, just nucleons and electrons.




Central baryon densities of a 2$M_{sun}$ star 3-7 times nuclear saturation density. Are there really just nucleons? Hyperons & Δ ?

Microscopic calculation: nucleon nucleon potential and three body forces (Baldo et al 2013)

# Hyperons in compact stars

**Few experimental data allow to fix some of the interactions parameters.**

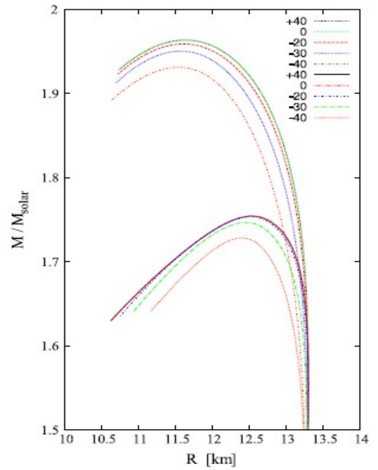
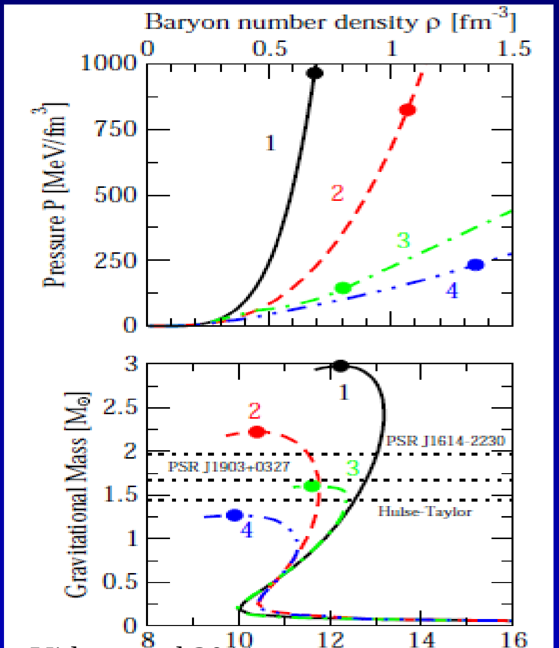
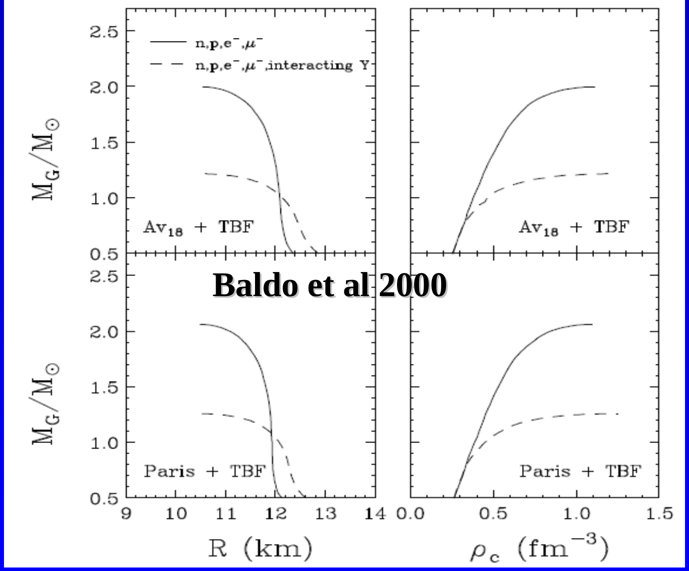



Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_{\Sigma}^{(N)}$ in "model $\sigma\omega\rho$" cannot account for the observed neutron star mass limit (lower branch), unless the $\phi$ meson is included in the model (upper branch).




Vidana et al 2011



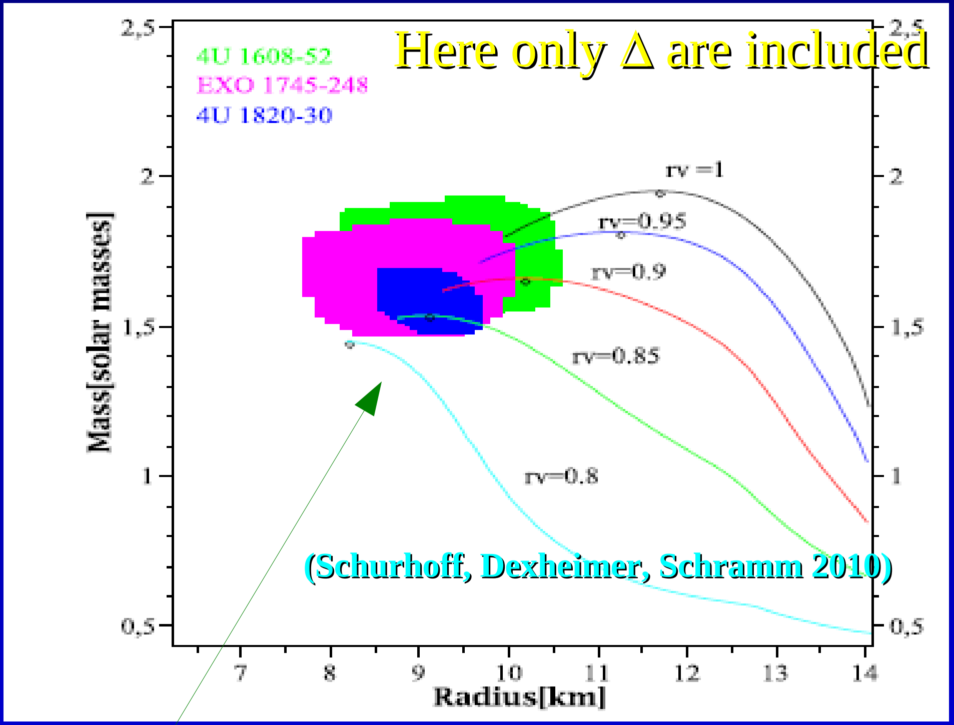

**Baldo et al 2000**

Within RMF see talk of J. Schaffner-Bielich, P. Haensel, Gulminelli, Mendez…
(see Weissenborn, Chatterjee, Schaffner-Bielich 2012)

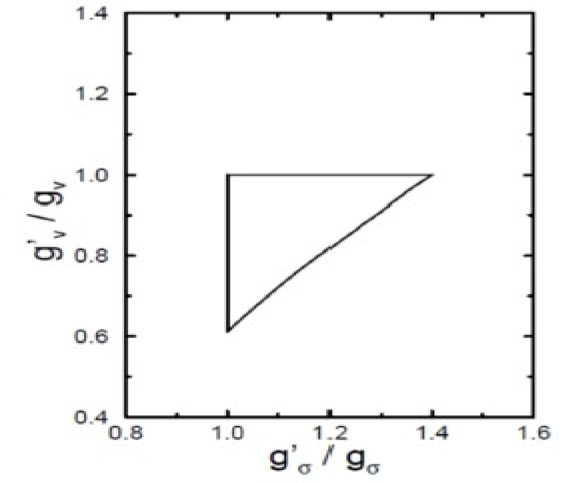
The 2M$_{sun}$ limit could be fulfilled within RMF models but not in microscopic calculations (see talk of Schulze)

# What about Δ (see talk of Schramm) ?

Similar effects: softening of the equation of state. Just small changes of the couplings with vector mesons sizably decrease the maximum mass



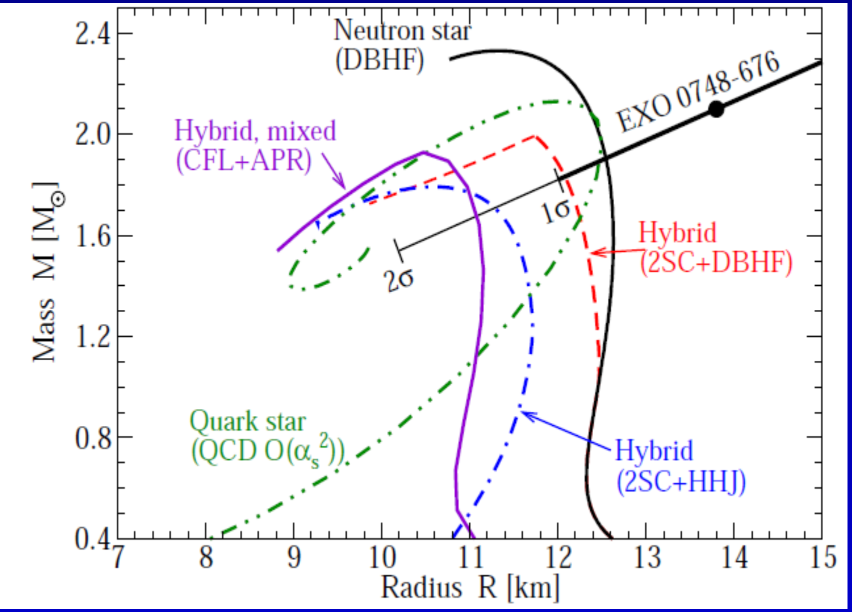

Notice: very small radii

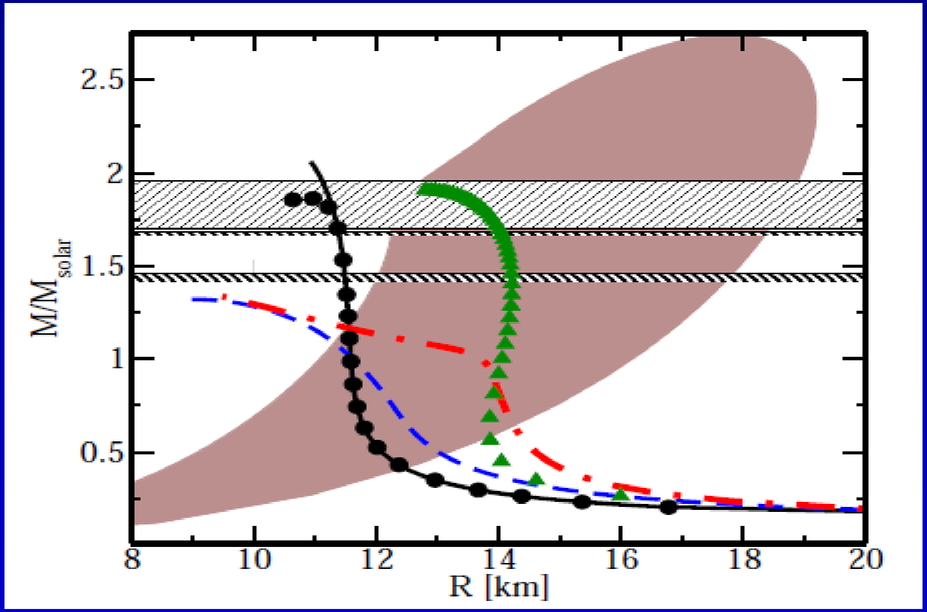



Kosov, Fuchs, Marmyanov, Faessler, PLB 421 (1998) 37

Some constraints on the couplings with mesons from nuclear matter properties and QCD sum rules

# Stars containing quark matter?




Alford et al Nature 2006

Kurkela et al 2010

pQCD calculations: “ … equations of state including quark matter lead to hybrid star masses up to 2Ms, in agreement with current observations. For strange stars, we find maximal masses of 2.75Ms and conclude that confirmed observations of compact stars with M > 2Ms would strongly favor the existence of stable strange quark matter”

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

# … is this surprising?

Also at finite density the quark matter equation of state should be stiffer than the hadronic equation of state in which new particles are produced as the density increases

**Heavy ions physics:** (Kolb & Heinz 2003)

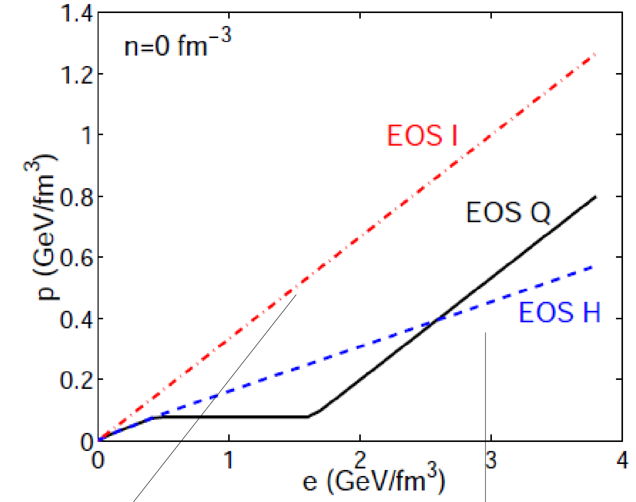
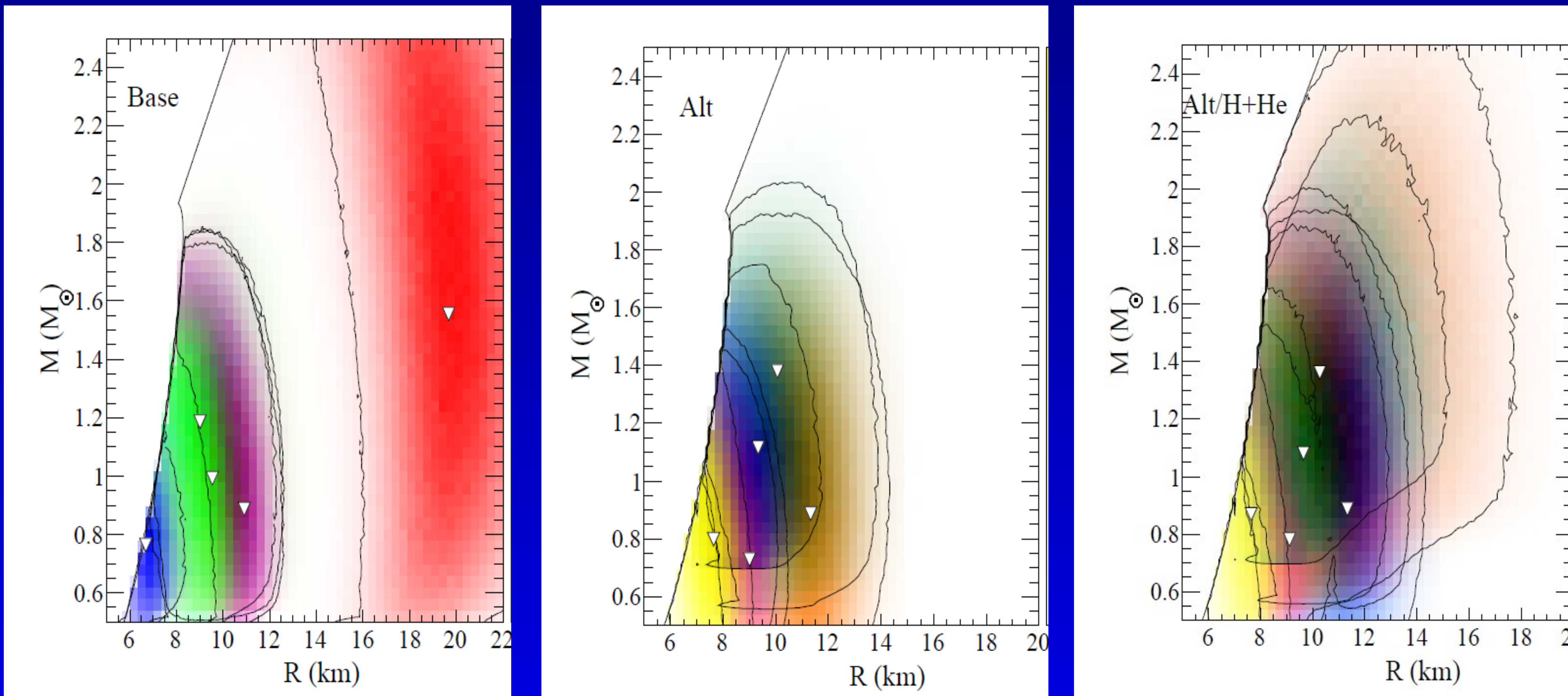



Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

**p=e/3 massless quarks**

**Hadron resonance gas p=e/6**

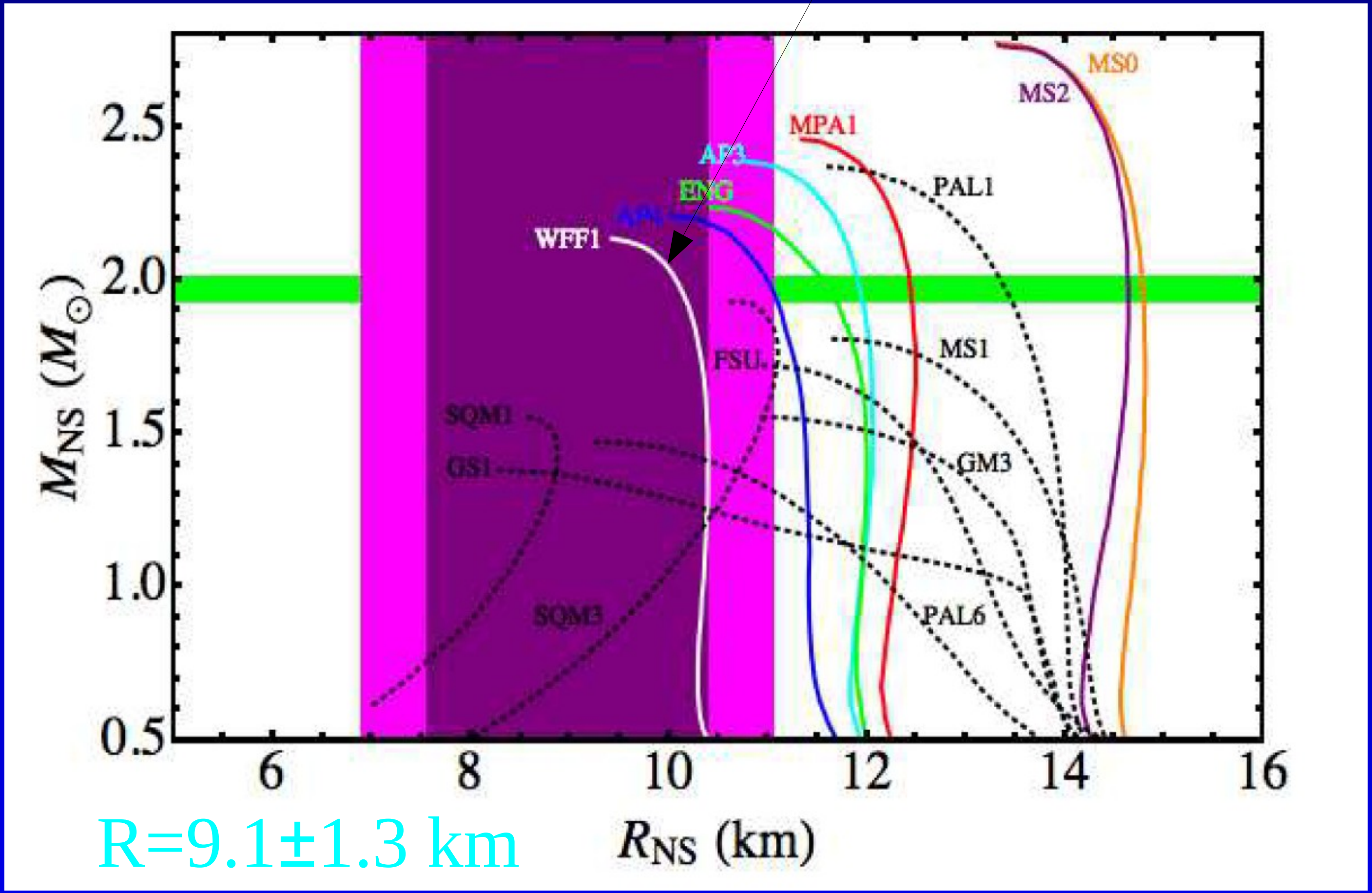
# Recent radii measurements




Guillot et al. ApJ772(2013)7

Lattimer and Steiner 1305.3242

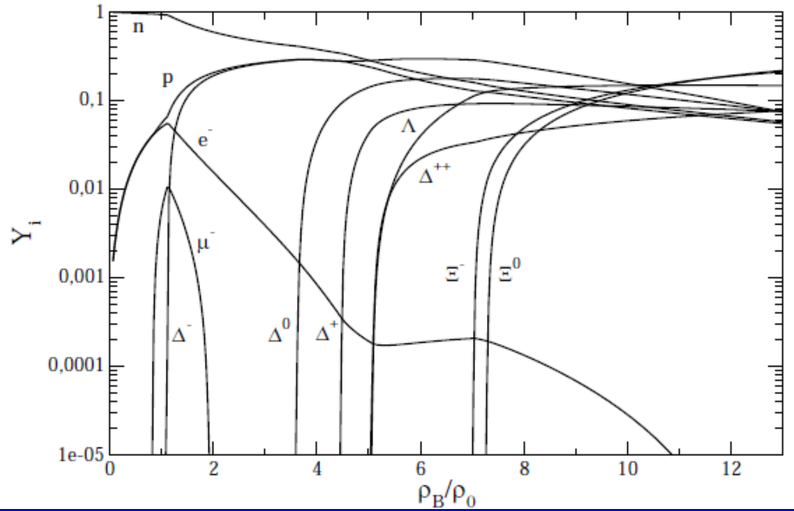
Nice, but just nucleons

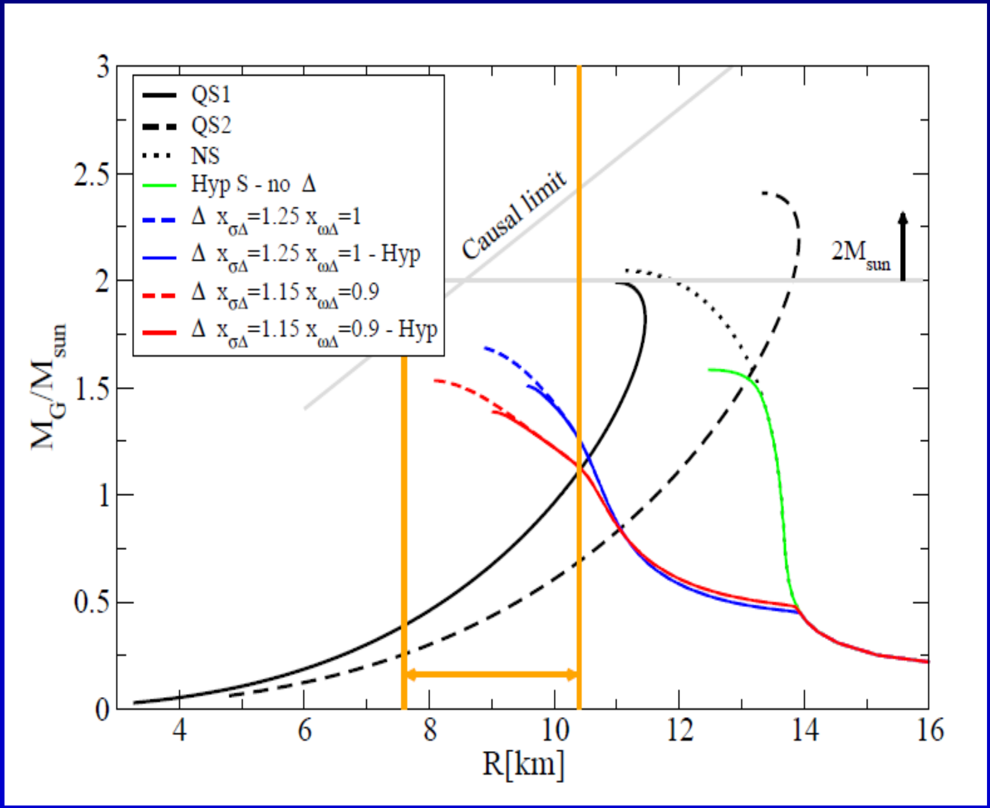



Two apparently contraddicting results: high mass → stiff equation of state
small radii → soft equation of state

# Drago, Lavagno, G.P. 2013

(results from RMF models for hadronic matter and simple parametrizations for quark mater)



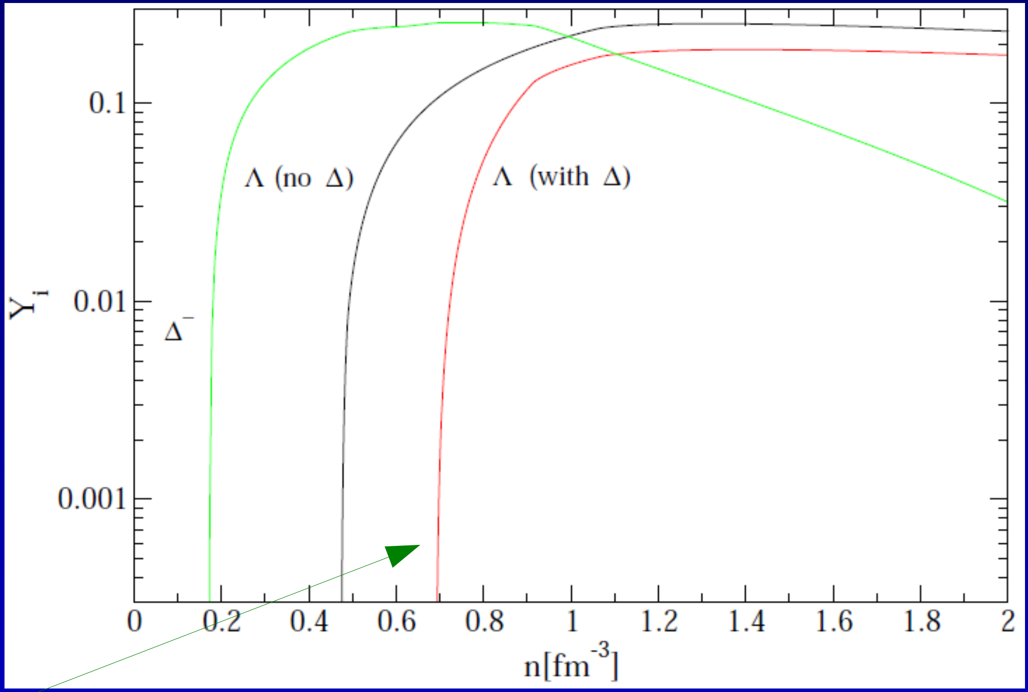




**Two families of compact stars:**

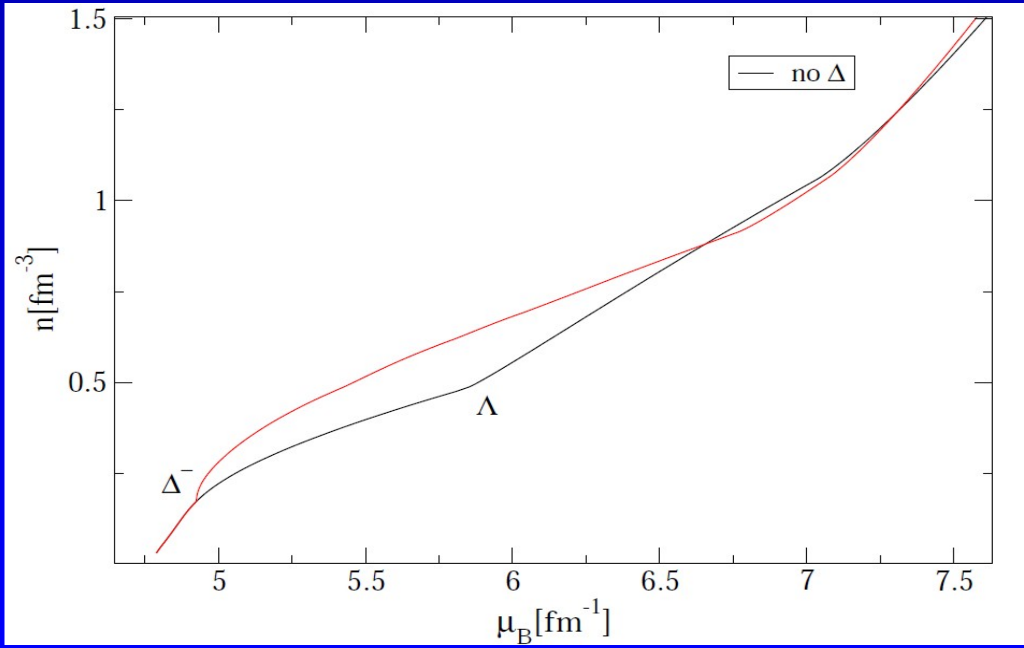
**1) low mass (up to ~1.5 Msun) and small radii (down to 9-10km) stars are hadronic stars (containing nucleons, Δ and hyperons) and they are metastable**

**2) high mass and large radii stars are strange stars (strange matter is absolutely stable (Bodmer-Witten hyp.))**

A star containing only nucleons and Δ cannot convert into a quark star because of the lack of strangeness (need for multipole simultaneous weak interactions). Only when hyperons start to form the conversion can take place.

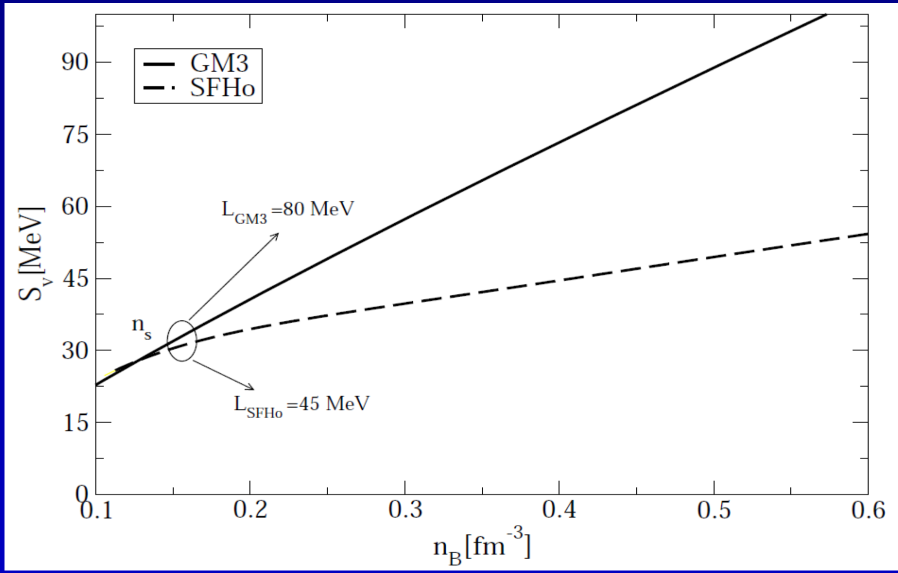


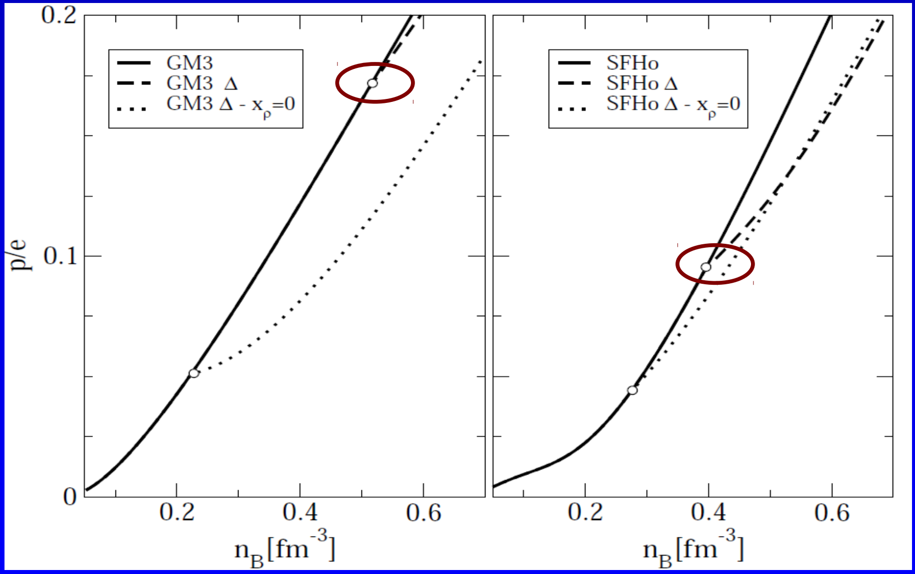

The appearance of Δ' s shifts the hyperon's thresholds to higher densities



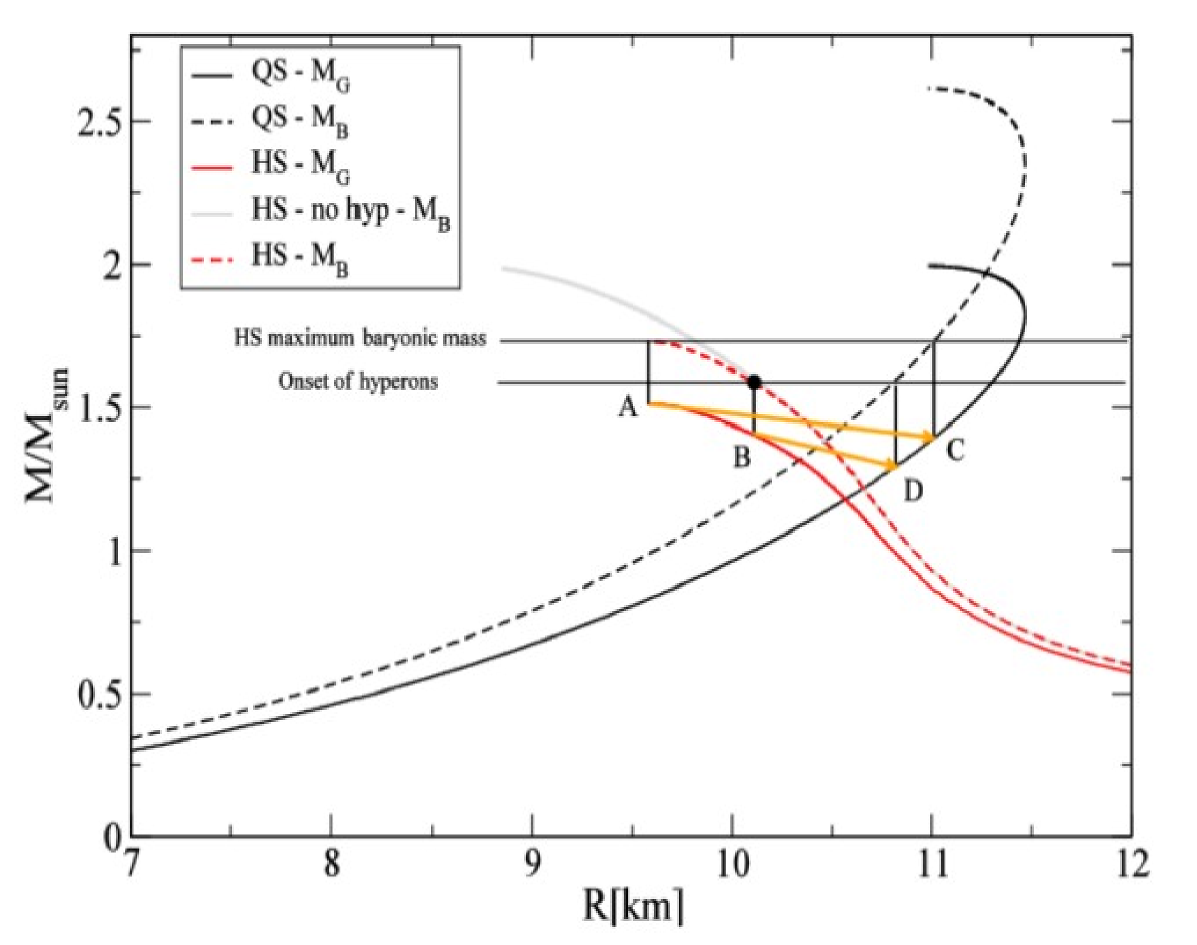
# Why have Δs been neglected so far? (within RMF models)

The couplings of Δ with mesons should be very close to the ones of nucleons (e-scattering). In Glendenning-Moskowski models they appear after the hyperons and are therefore irrelevant ($\Delta^-$ is electric charge favored but isospin unfavoured). In more recent RMF parameterizations (with non-linear terms for the vector mesons), such as SFHo (Steiner, Fischer & Hempel 2013) where new constraints on the symmetry energy are implemented, Δs appears before hyperons.
The lower value of L implies a smaller effective coupling with the ρ meson.



**Why conversion should then occur? Quark stars are more bound: at a fixed total baryon number they have a smaller gravitational mass wrt hadronic stars**



# Hydro simulations to study the conversion

(see talk of F. Roepke)

**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).**

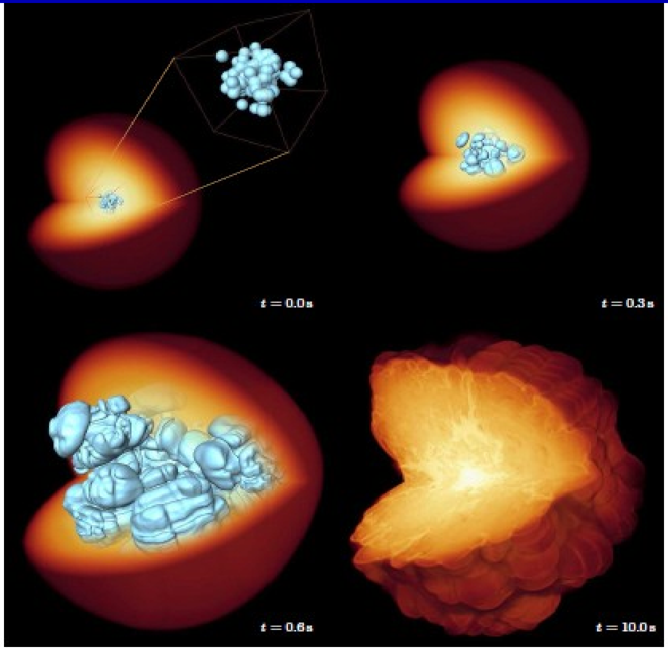



**FIGURE 1.** Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and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

**Condition for exothermic combustion**

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

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

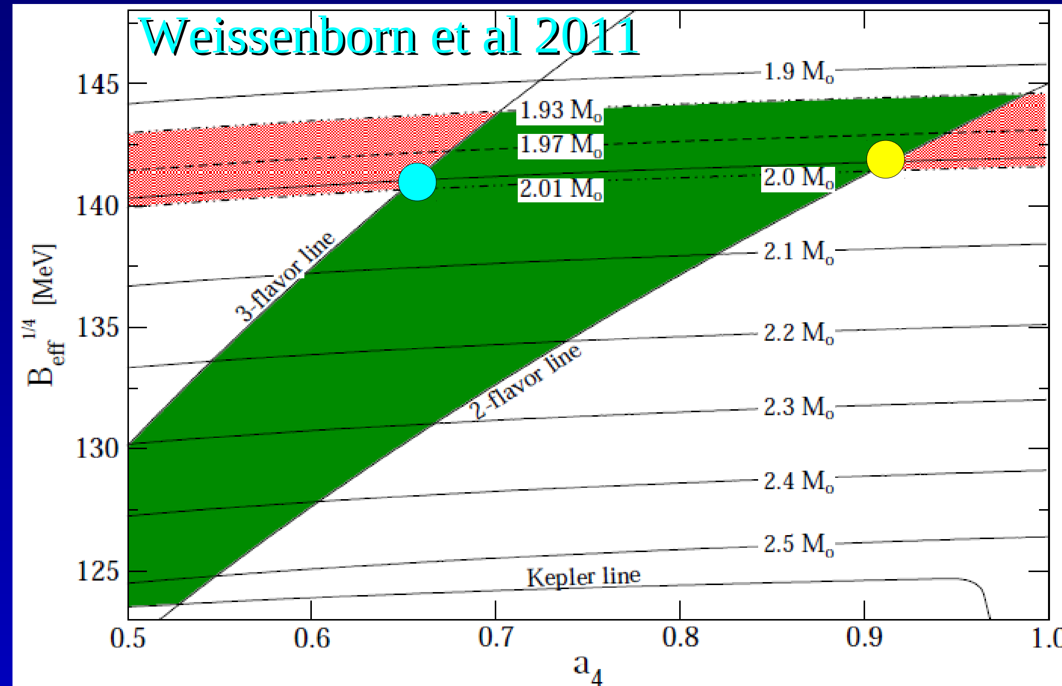
Within a simple parametrization:

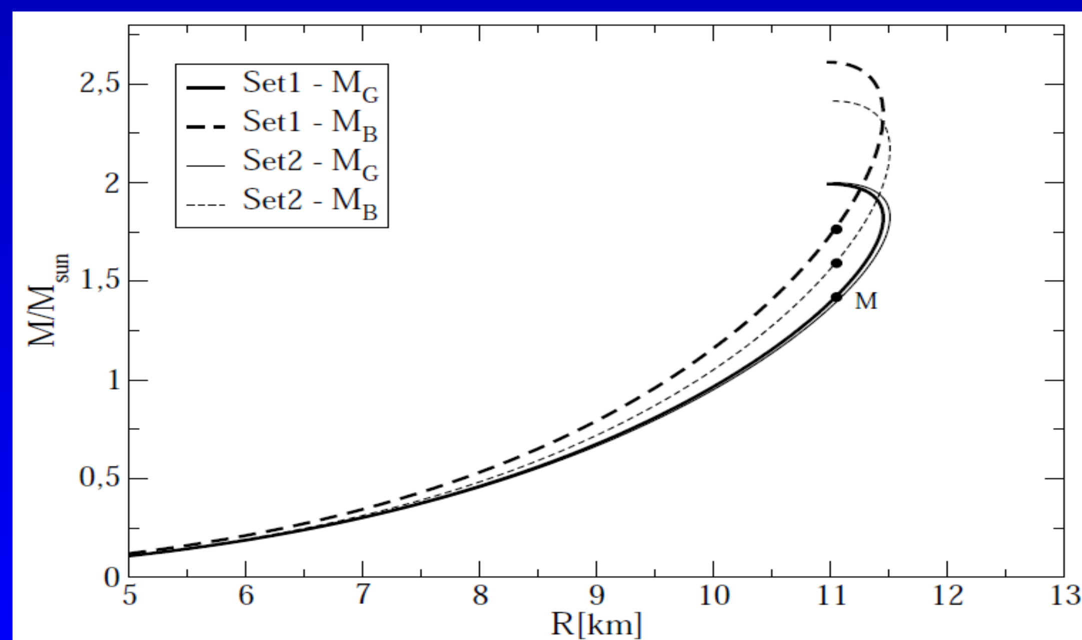
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1-a_4) + B_{eff}$$

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

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

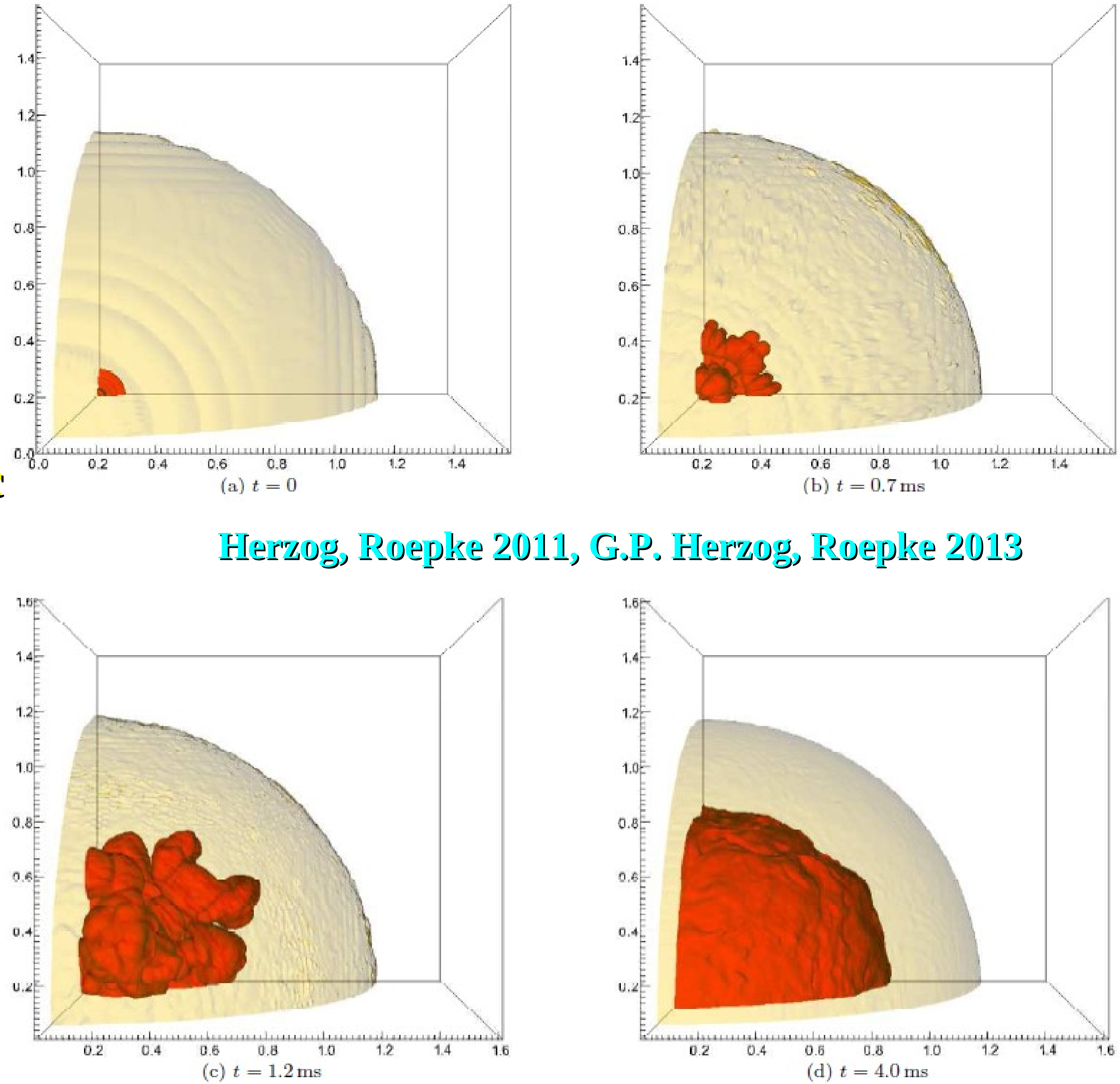
Different QSs binding energy $M_B$-$M_G$



# Conversion of a 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)

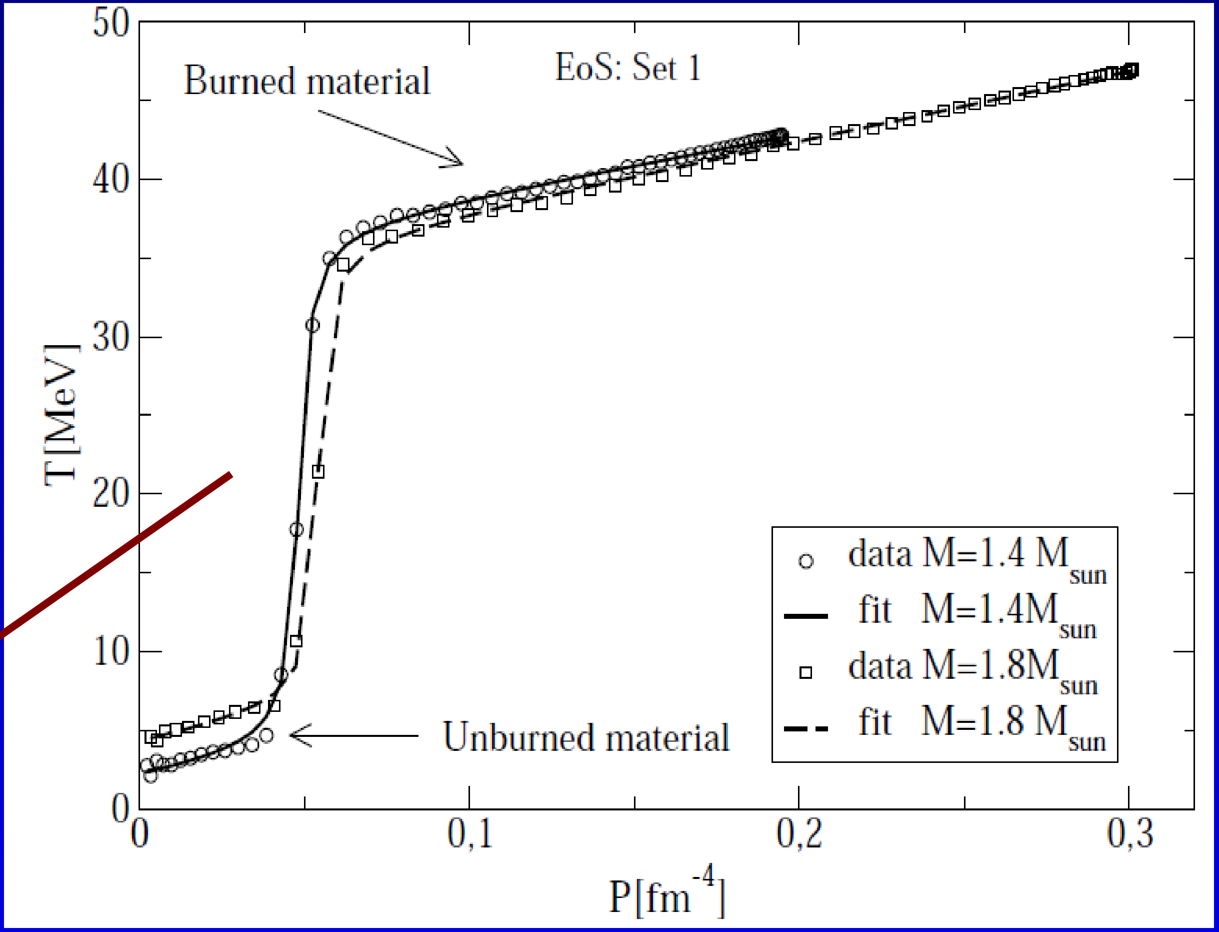



Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

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**

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

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

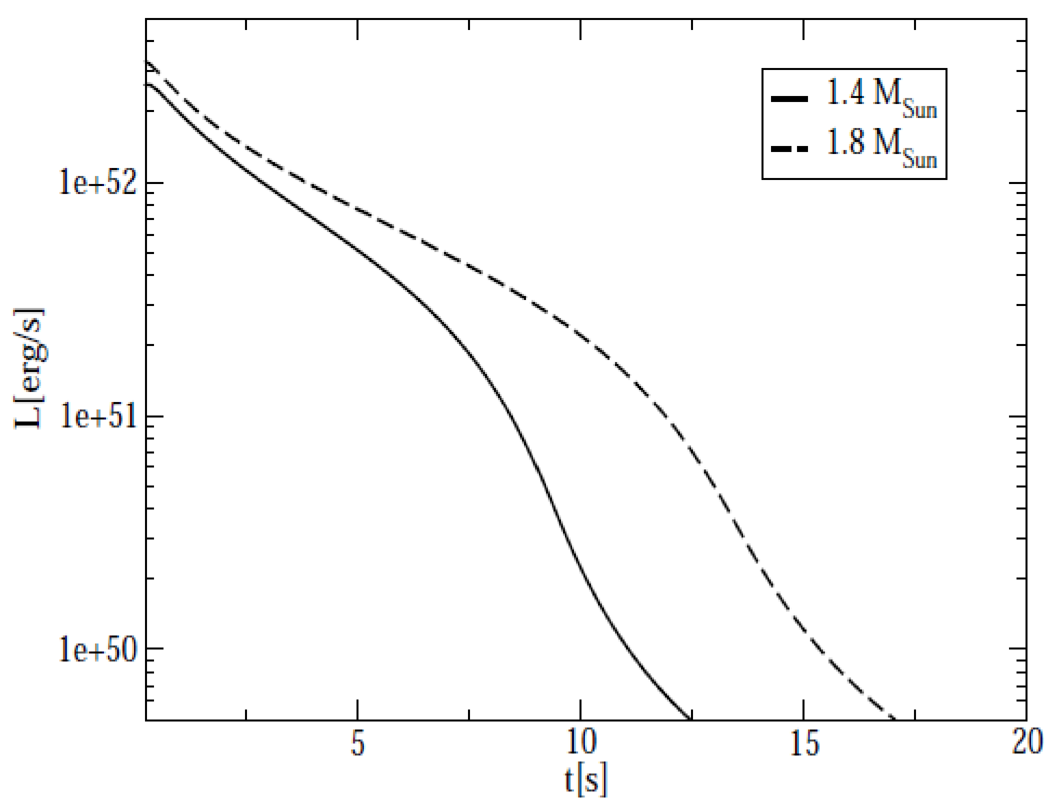
**Assumption: quark matter is formed already in beta equilibrium, no lepton number conservation imposed in the burning simulation, no lepton number diffusion**

**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

**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

# Conclusions

-) New masses and radii measurements challenge nuclear physics: tension between high mass and small radii. A 2.4 $M_{sun}$ candidate already exists.

-) New missions (LOFT?, NICER), with a precision of 1km in radii measurements, could possibly confirm the existence of very compact stars

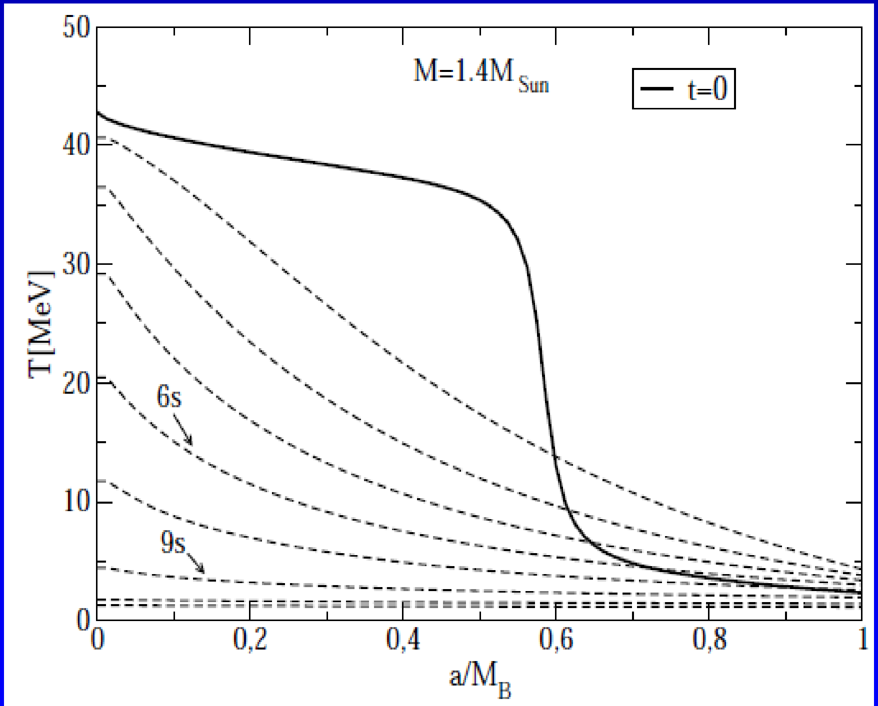
-) Possible existence of two families of compact stars (high mass – quark stars, low mass – hadronic stars). Rich phenomenolgy: cooling, frequency distributions, explosive events...

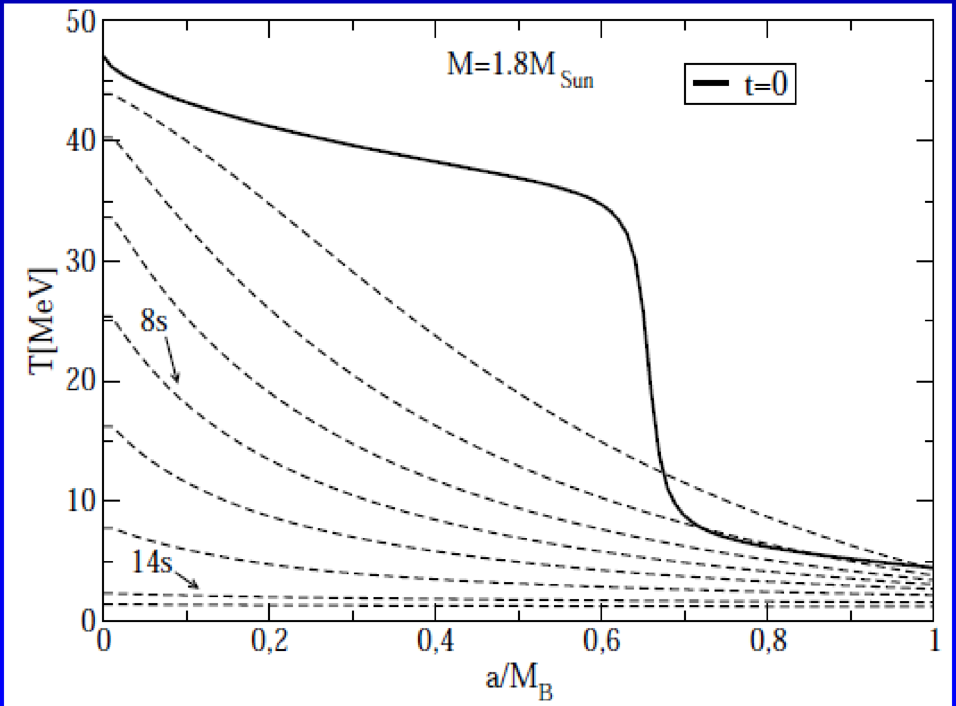
# Appendix

**Expected smaller cooling times with respect to hot neutron stars**

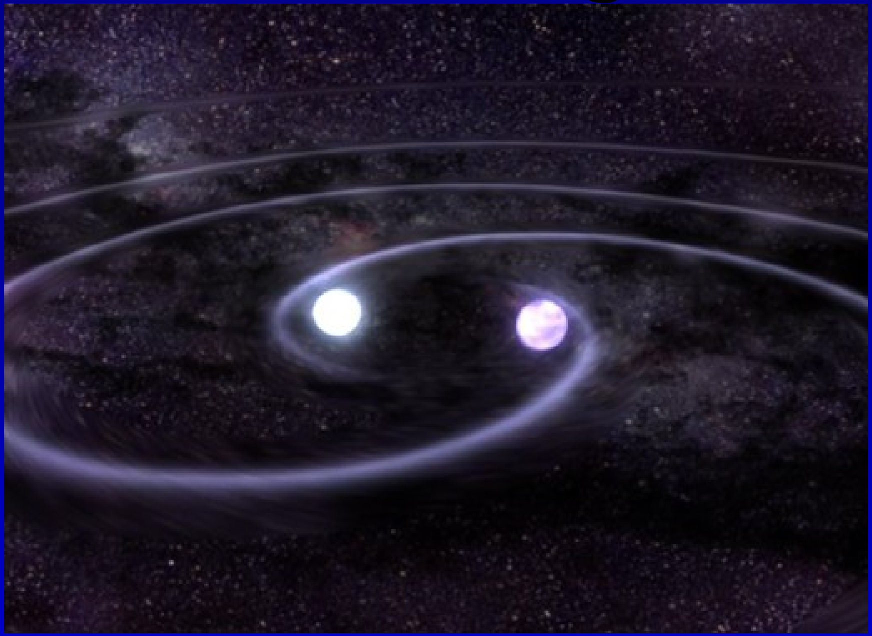
| phase | process | $\lambda$(T=5 MeV) | $\lambda$(T=30 MeV) |
|---|---|---|---|
| Nuclear Matter | $\nu n \to \nu n$ | 200 m | 1 cm |
| | $\nu_e n \to e^- p$ | 2 m | 4 cm |
| Unpaired Quarks | $\nu q \to \nu q$ | 350 m | 1.6 m |
| | $\nu d \to e^- u$ | 120 m | 4 m |
| CFL | $\lambda_{3B}$ | 100 m |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

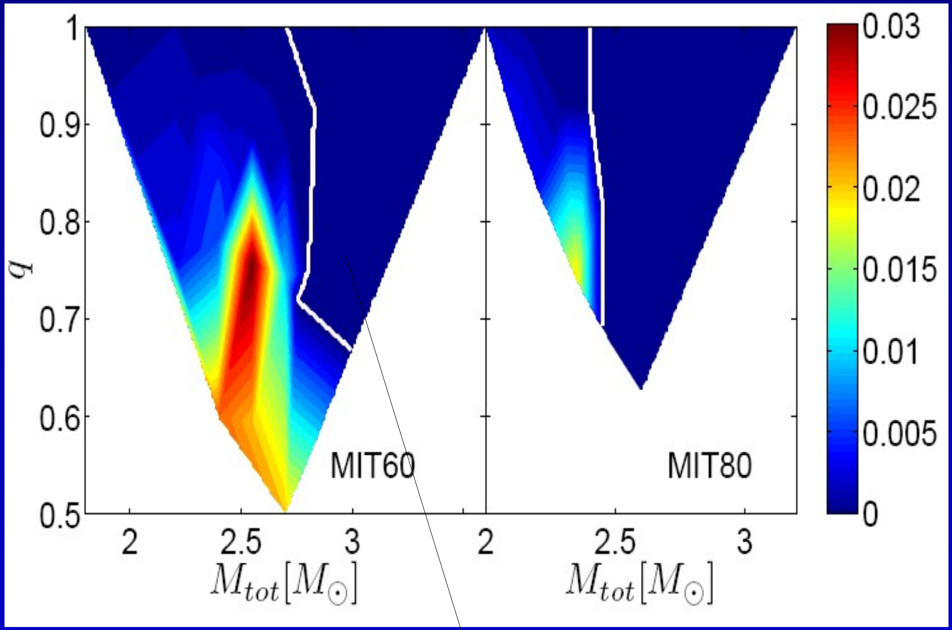
**Reddy et al 2003**



# Are all compact stars strange?: Merger of strange stars






MIT60: 8 $10^{-5}$ Msun, 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)

**Prompt collapse: in our scenario quark stars have masses larger than ~ 1.5 $M_{sun}$, no strangelets emitted.**

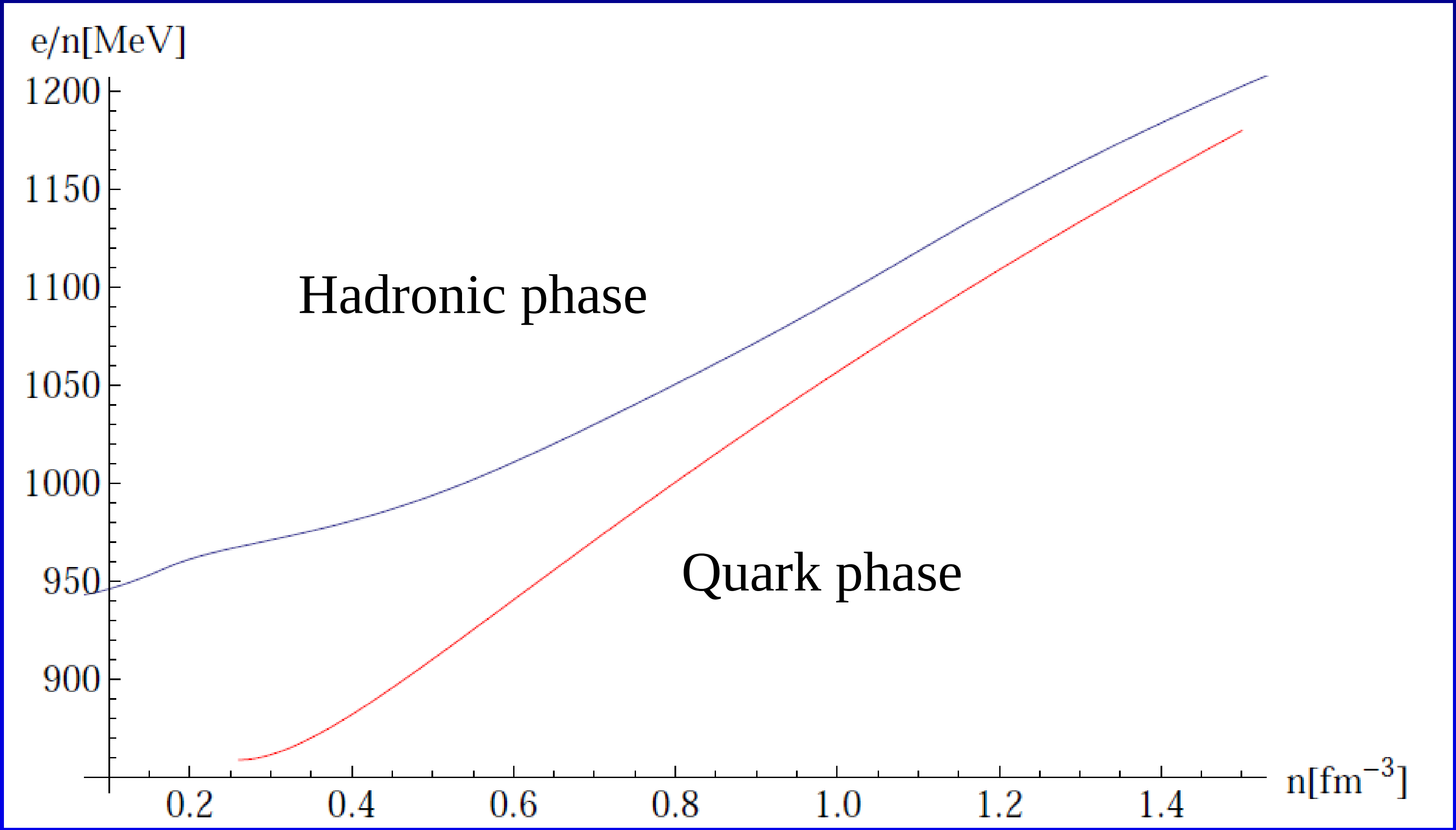
# Appendix2

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

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

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

Drago et al 2007



e/n[MeV]
1200
1150
1100
1050
1000
950
900
Hadronic phase
Quark phase
0.2
0.4
0.6
0.8
1.0
1.2
1.4
n[fm$^{-3}$]