Can very compact ***and*** very massive neutron stars both exist?

or

Deltas, hyperons, quarks and all those «exotica»

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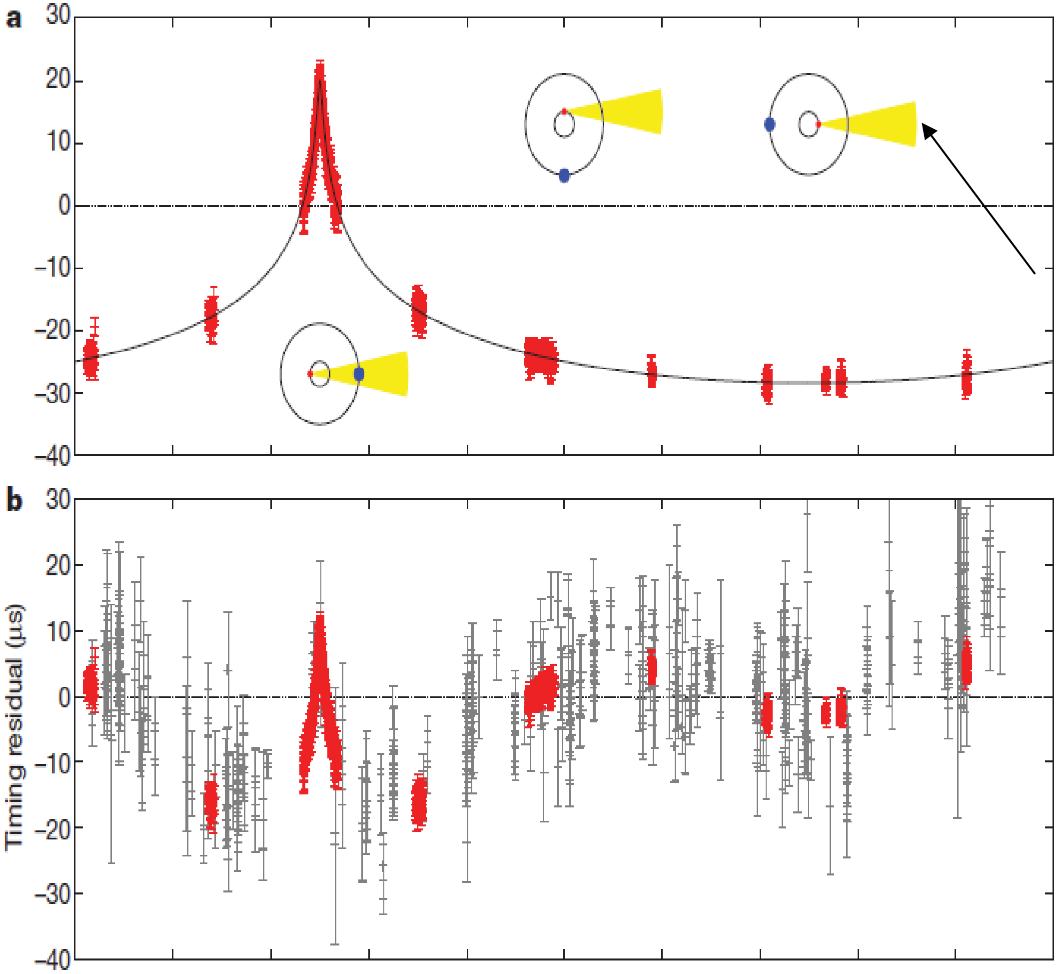
- Low density behaviour is now rather well under control
- At which densities «exotic» degrees of freedom need to appear?
- Hyperons: too much softening?
- What about Δ resonances?
- Are hybrid stars a realistic solution?
- Quark stars and the two-families solution
- The role of the radius in determining the composition.

A.D., A.Lavagno, G.Pagliara, Phys.Rev. D89 (2014) 043014

G.Pagliara, A.D., A.Lavagno, D.Pigato, arXiv: 1404.6070

A milestone for neutron stars physics: PSR J1614-2230, M = (1.97± 0.04) Msun

Demorest et al. Nature 2010

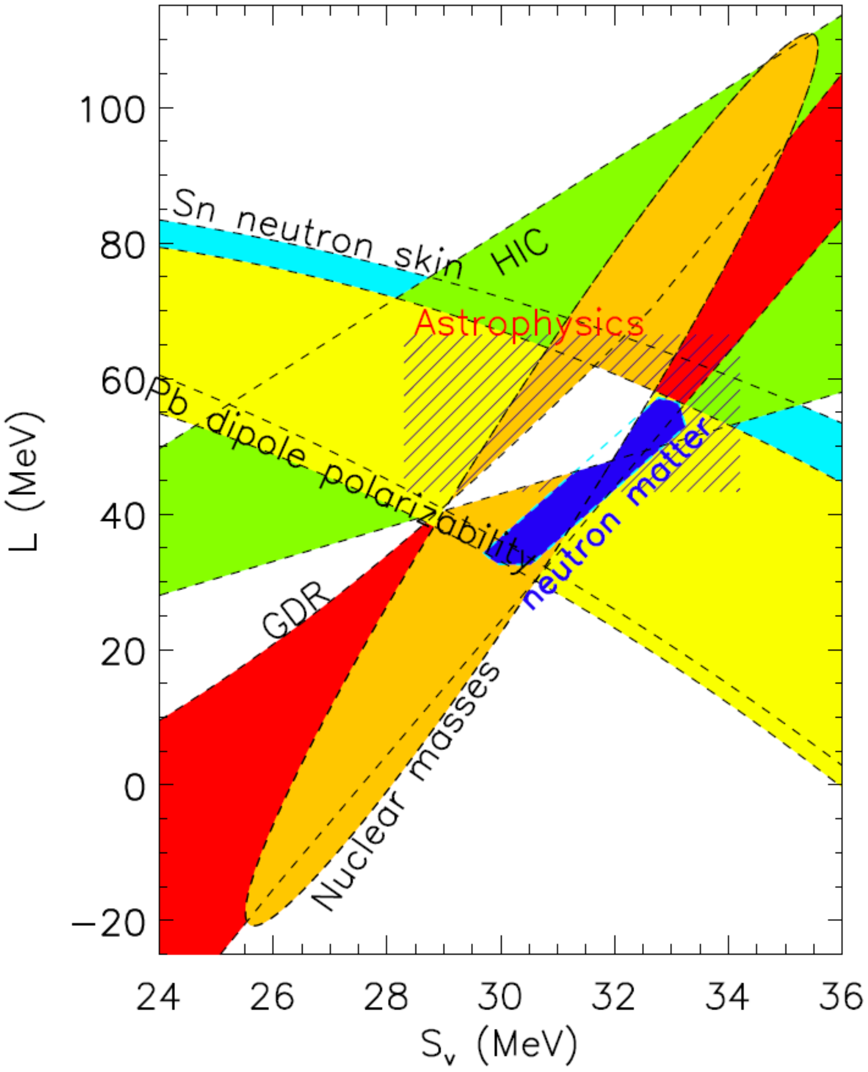


Nuclear and subnuclear densities: symmetry energy

Hebeler et al. 2013

$$S_v = \frac{1}{8}\frac{\partial^2 \epsilon(\bar{n},x)}{\partial x^2}\Big|_{\bar{n}=1,x=1/2}$$

$$L = \frac{3}{8}\frac{\partial^3 \epsilon(\bar{n},x)}{\partial \bar{n}\partial x^2}\Big|_{\bar{n}=1,x=1/2}$$



Stars with a normal crust: «possible» Equations of State

Hebeler et al. 2013

Γ_1 = 2.25 -- 2.5, ρ_1 = 1.1 ρ_0

a stiff EOS (maybe purely nucleonic)

$$\Gamma_1 = 4.5,\ \rho_{12} = 1.5\,\rho_0,\ \Gamma_2 = 5.5,\ \rho_{23} = 2.0\,\rho_0,\ \Gamma_3 = 3.0$$

$$\rho_{\max} = 3.3\,\rho_0$$

an intermediate EOS

(maybe hyperonic or hybrid)

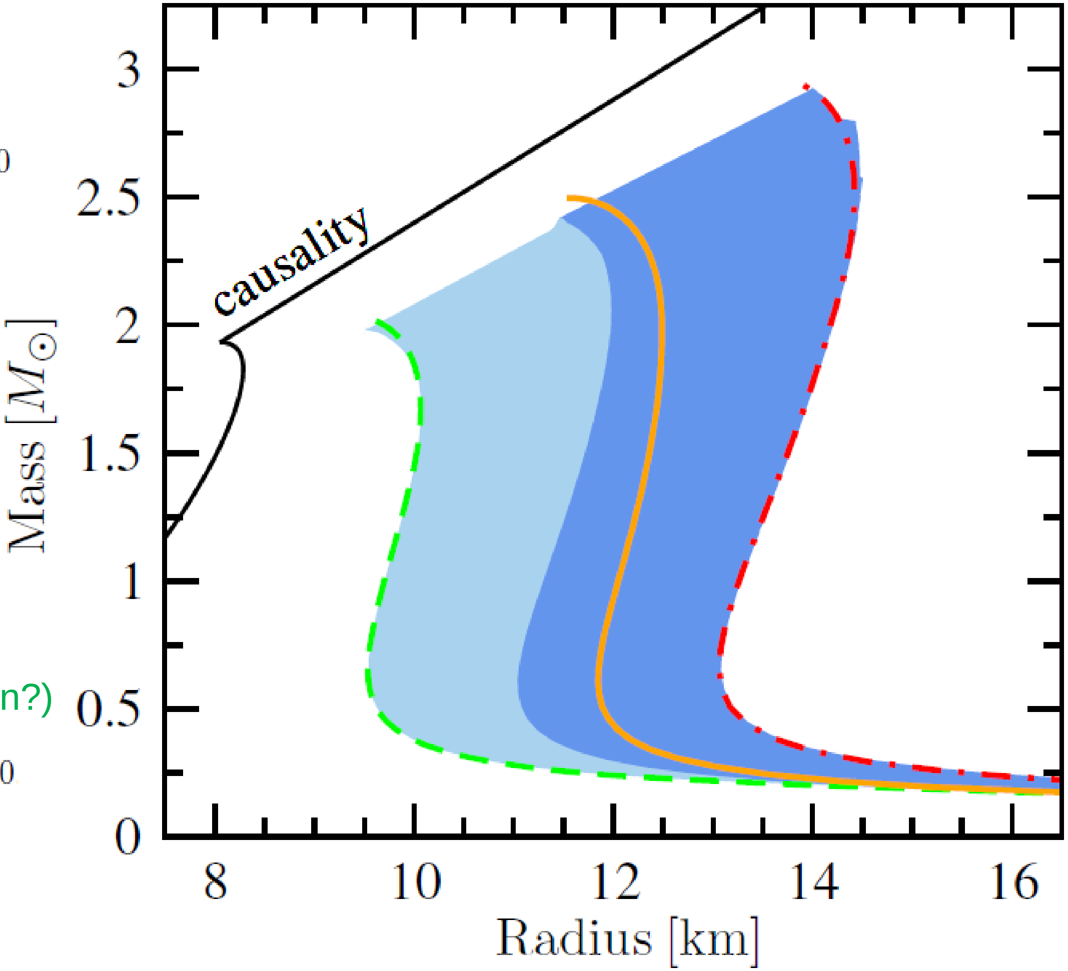
$$\Gamma_1 = 4.0,\ \rho_{12} = 3.0\,\rho_0,\ \Gamma_2 = 3.0,\ \rho_{23} = 4.5\,\rho_0,\ \Gamma_3 = 2.5$$

$$\rho_{\max} \approx 5.4\,\rho_0$$

a soft EOS (physical realizations? Early transition?)

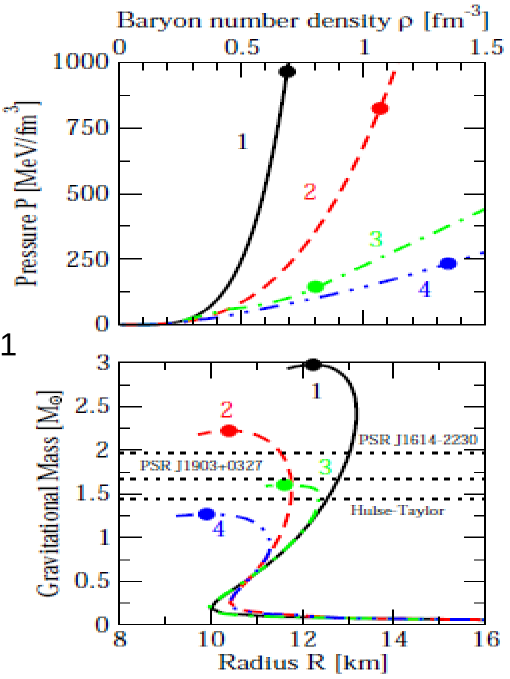
$$\Gamma_1 = 1.5,\ \rho_{12} = 2.5\,\rho_0,\ \Gamma_2 = 6.0,\ \rho_{23} = 4.0\,\rho_0,\ \Gamma_3 = 3.0$$

$$\rho_{\max} \approx 7.0\,\rho_0.$$



Hyperons in compact stars

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



Vidana et al 2011

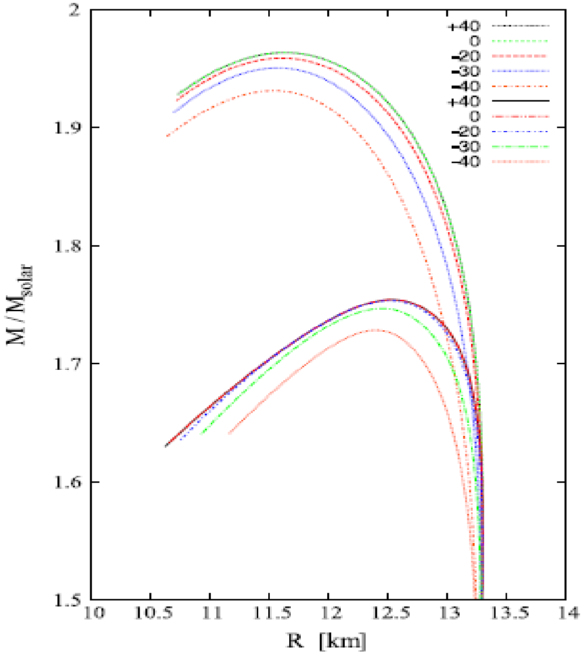
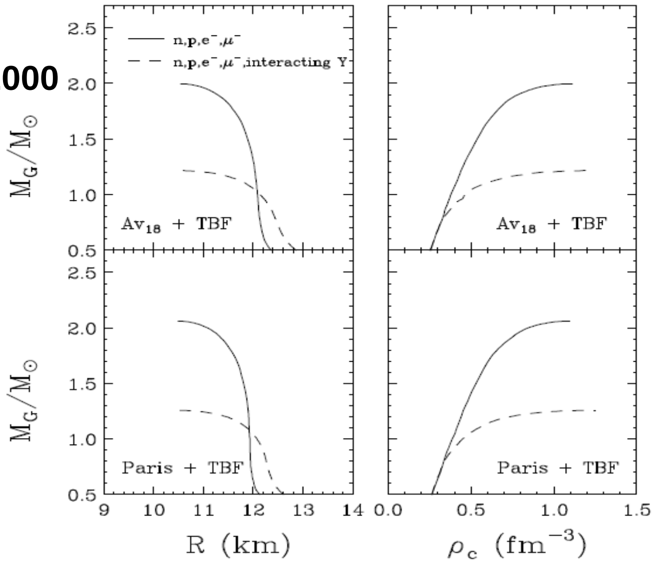


Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_\Sigma^{(N)}$ in "model $\sigma\omega\rho$" cannot account for the observed neutron star mass limit (lower branch), unless the ϕ meson is included in the model (upper branch).

Baldo et al 2000

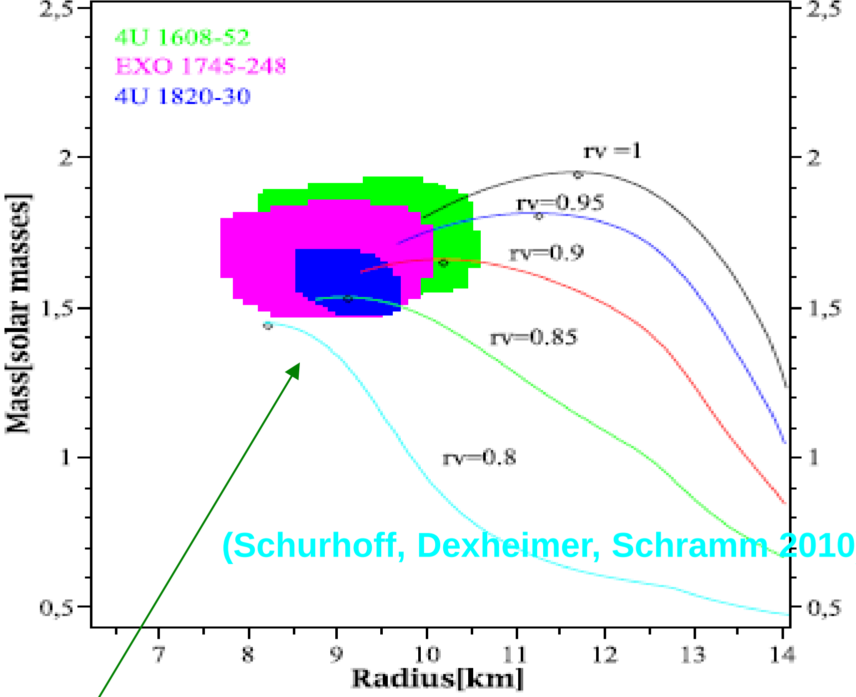


The 2Msun limit could be fulfilled within RMF models
but not in microscopic calculations

What about Δ's?

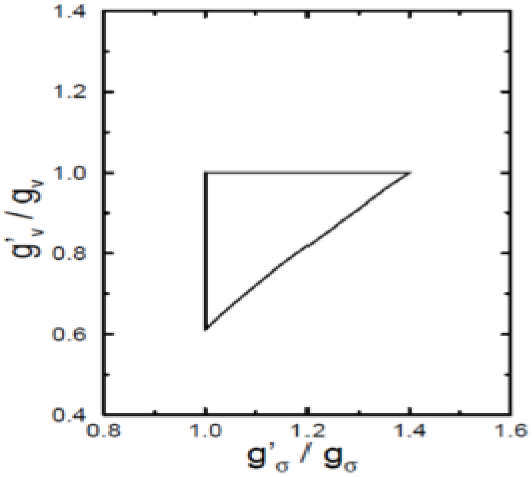
Similar effects:
softening of the equation of state.
Small changes of the
couplings with vector mesons
sizably decrease the
maximum mass and the radius

Here only Δ are included



(Schurhoff, Dexheimer, Schramm 2010)

Notice: very small radii



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

→

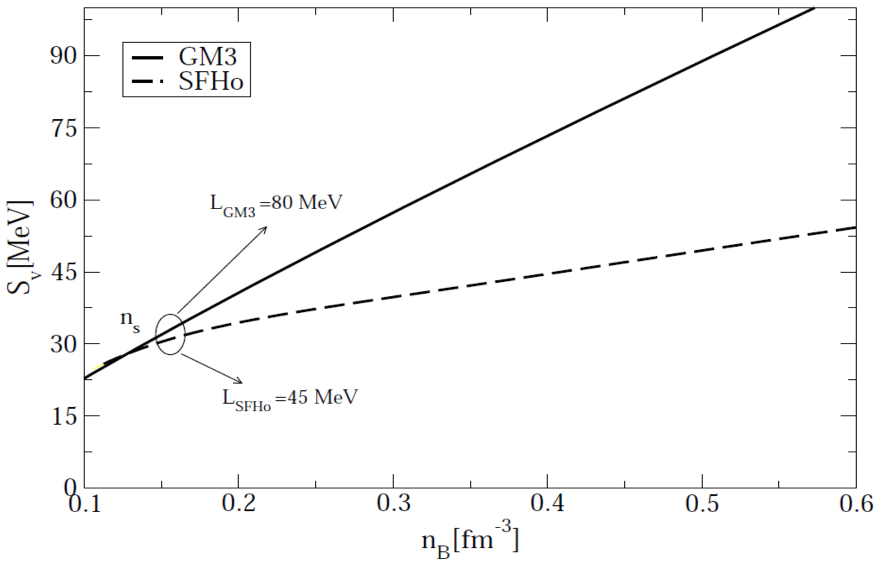
Some constraints on the couplings
with mesons from nuclear matter properties,
electron scattering on nuclei
and QCD sum rules

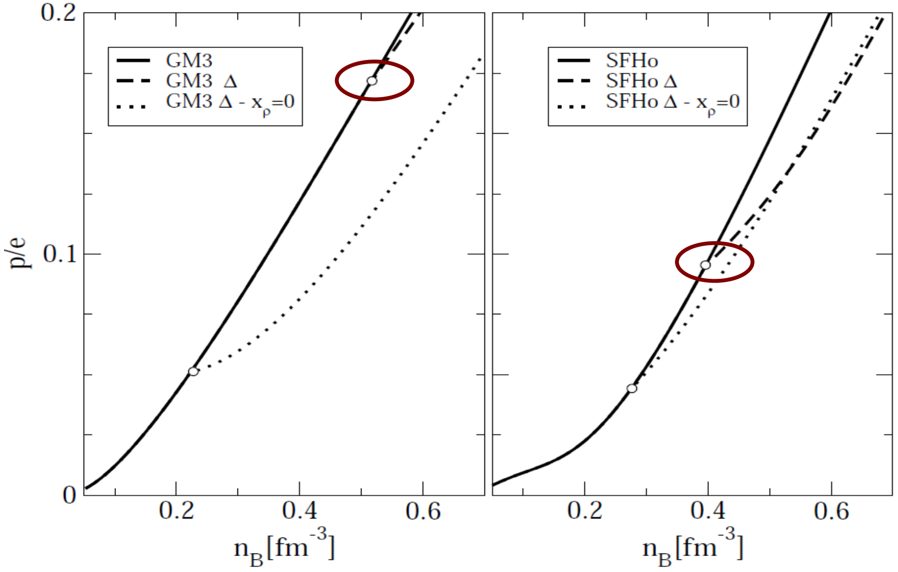
Why Δs have been neglected so far? (within RMF models)

In Glendenning-Moskowski models (large L) they appear after the hyperons and are therefore irrelevant (Δ^- is electric charge favored but isospin unfavoured).

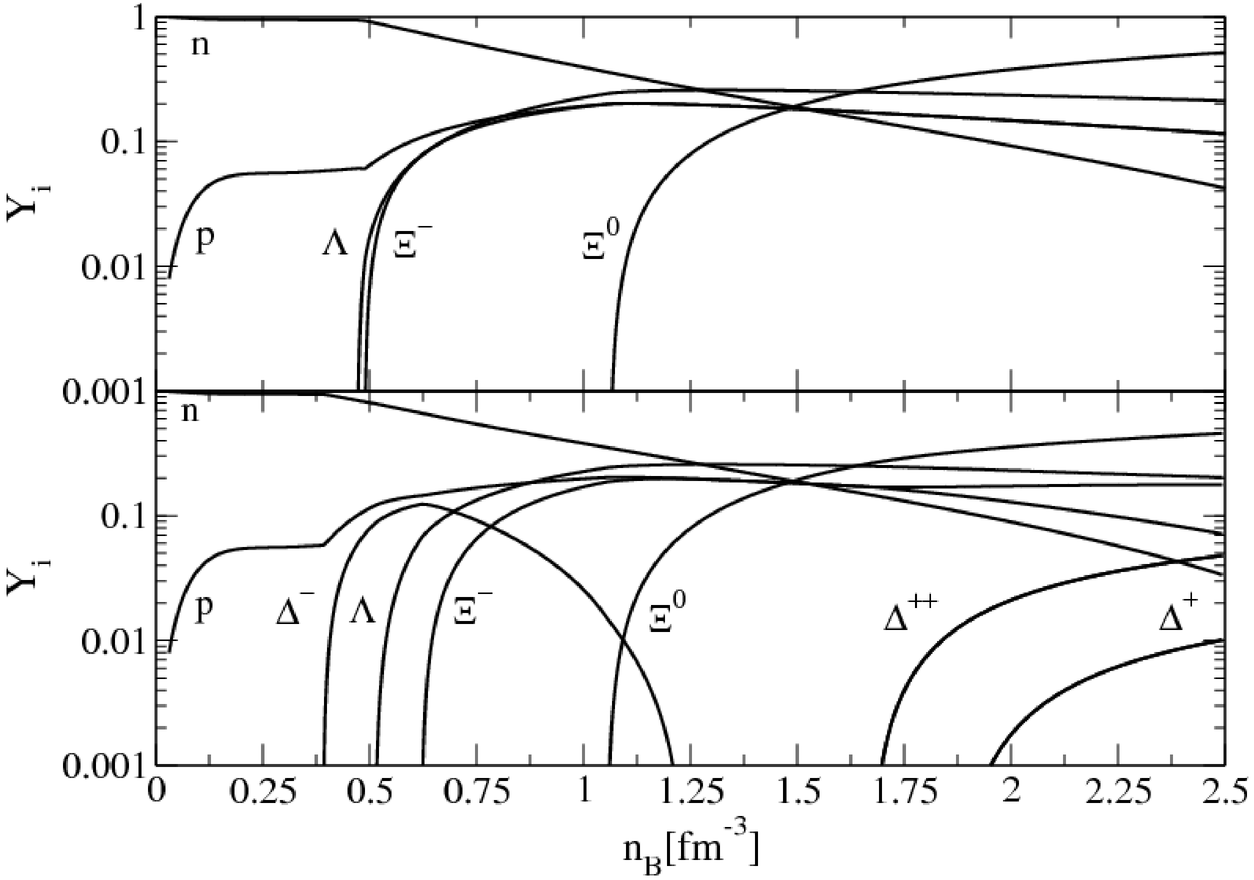
In more recent RMF parameterizations (with non-linear terms for the vector mesons), such as SFHo (Steiner, Fischer & Hempel 2013) where new constraints on the symmetry energy are implemented, Δs appears before hyperons.

The lower value of L implies a smaller effective coupling with the ρ meson.

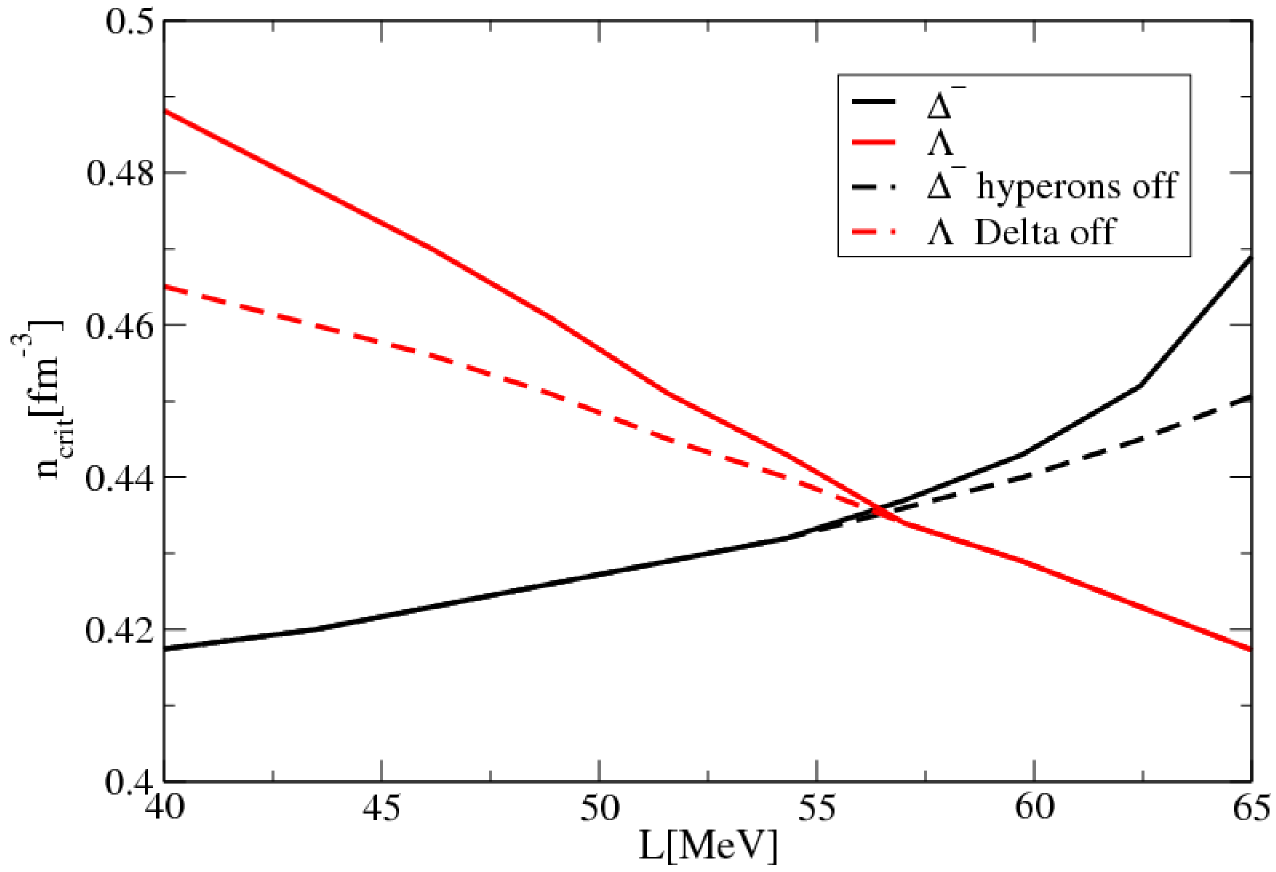




Populations with and without deltas

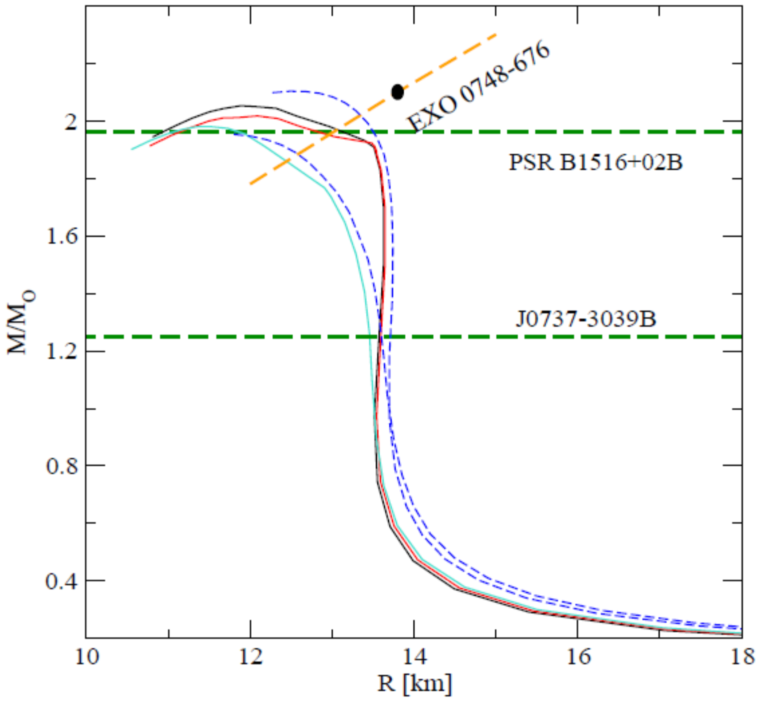


Threshold densities for production of Λ and of Δ^- as functions of symmetry energy parameter L

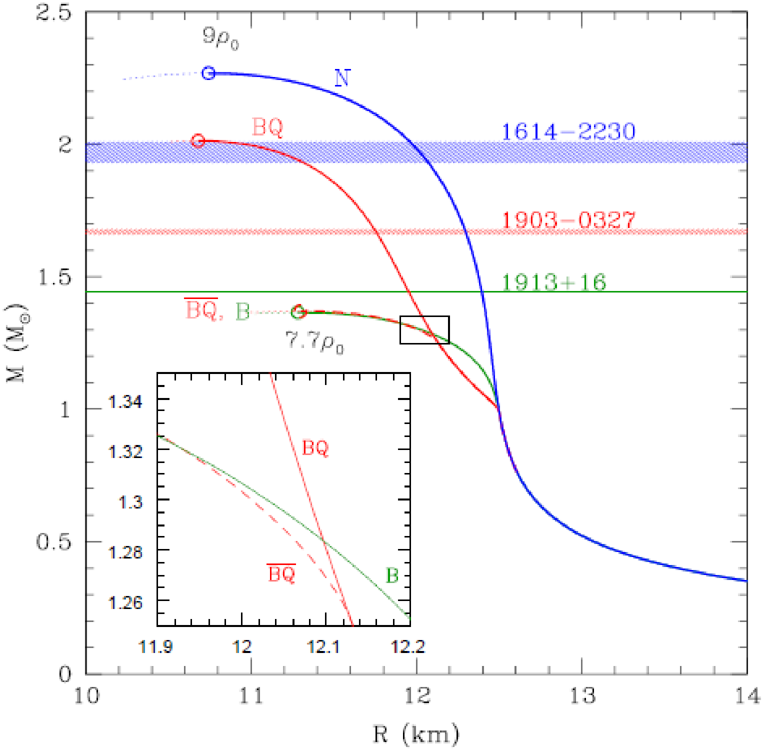


Struggling with hybrid stars

Ippolito et al. Phys.Rev. D77 (2008) 023004



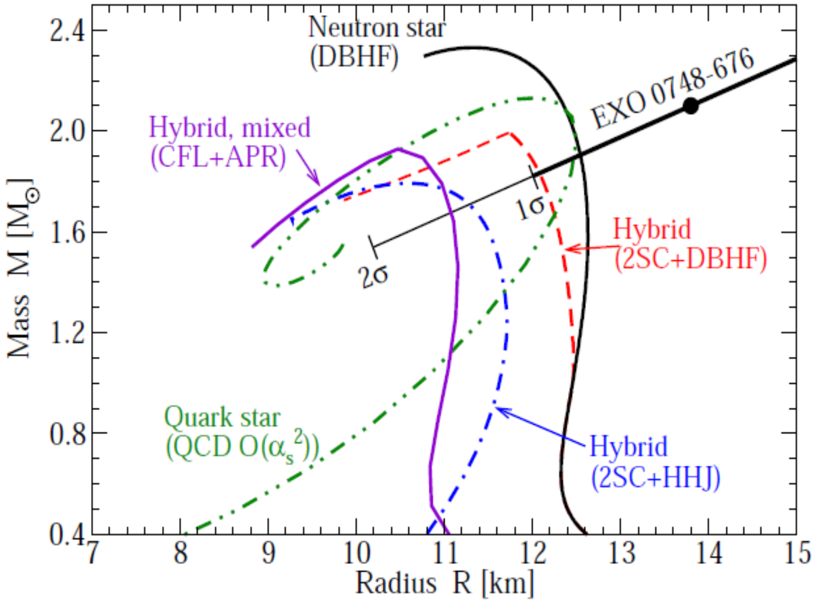
Zdunik and Haensel A&A, 551 (2013) A61

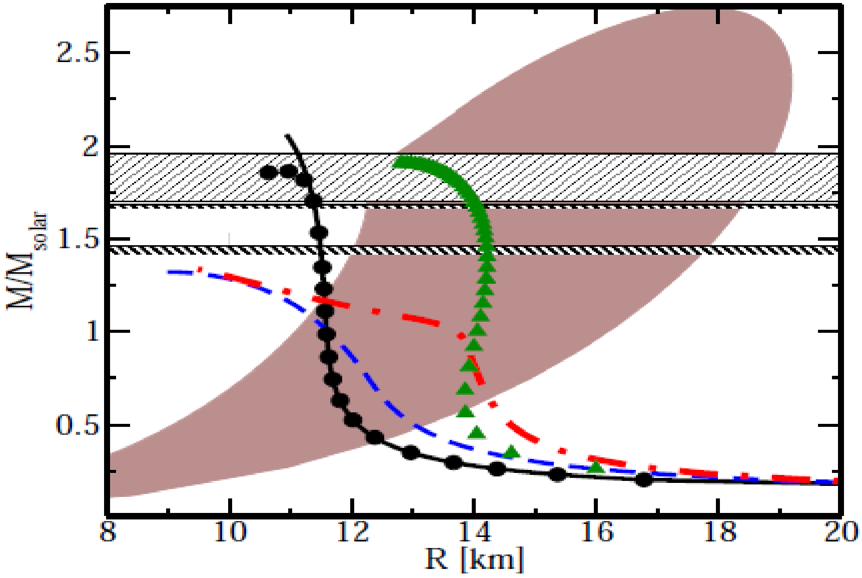


It is not impossible to satisfy the 2 M$_s$ limit with a hybrid star but special limits on the parameters' values have to be imposed

Radius of a 1.4 M$_s$ hybrid star 12-14 km

Hybrid stars or quark stars?





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 2Msun stars!!

… is this surprising?

Heavy ions physics:

(Kolb & Heinz 2003)

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

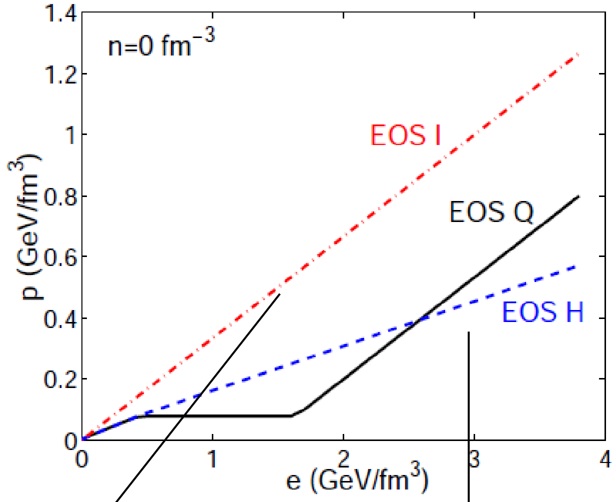
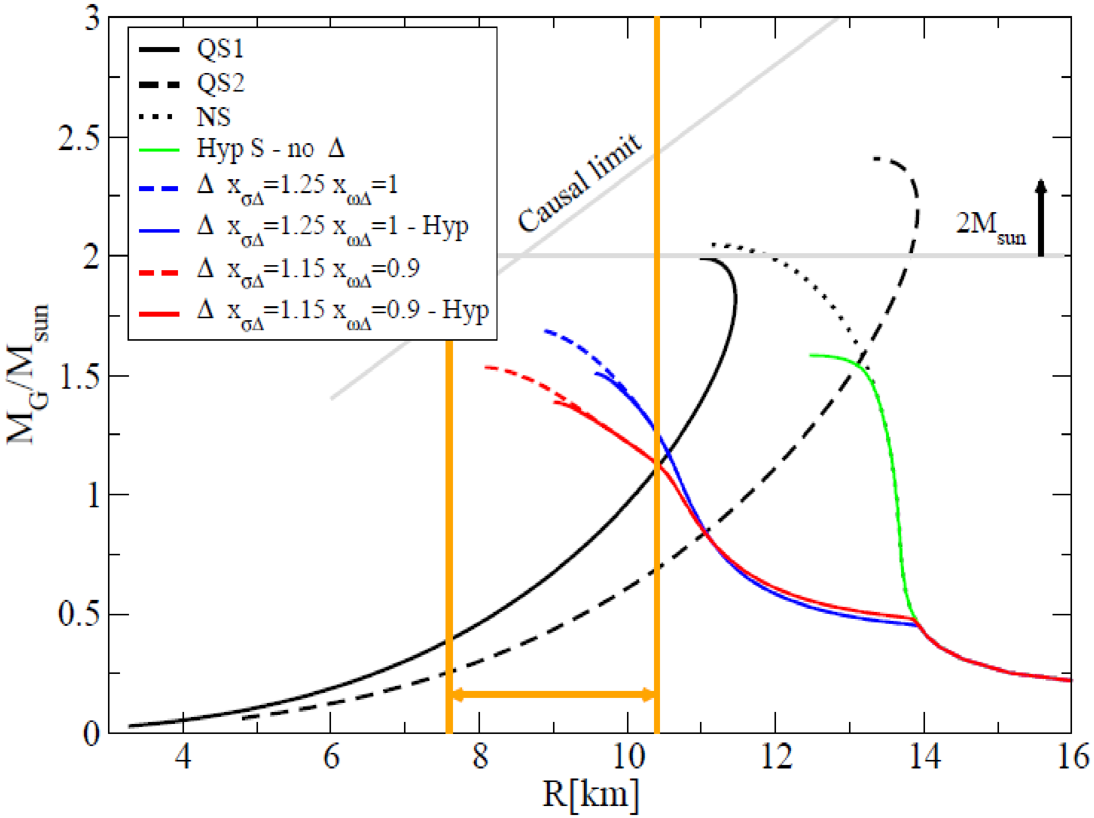


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

Hadron resonance gas p=e/6

A.D., A.Lavagno, G.Pagliara Phys.Rev. D89 (2014) 043014



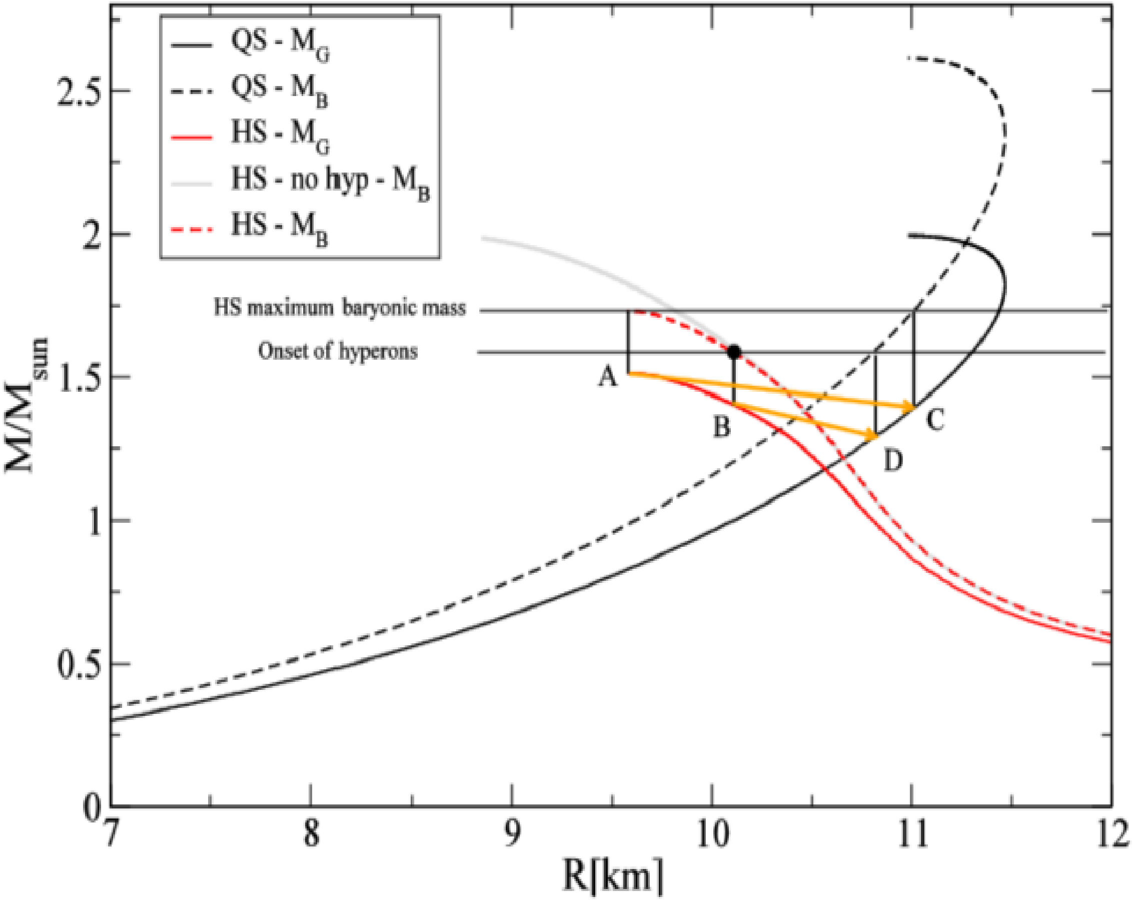
Two families of compact stars:

1) **low mass (up to ~1.5 Msun) and small radii (down to 9-10km) stars are hadronic stars**
2) **high mass and large radii stars are strange stars**

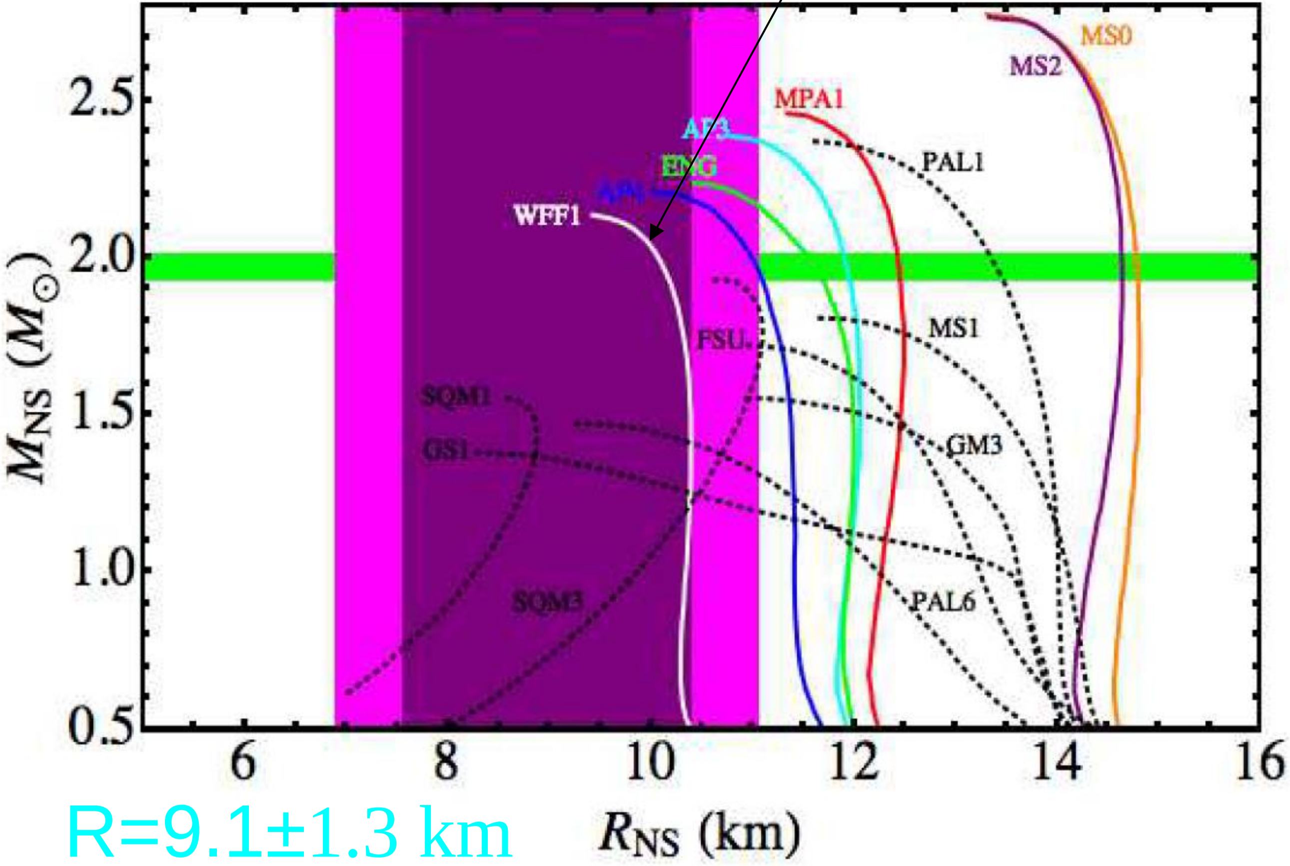
Why conversion should then occur?
Quark stars are more bound:
at a fixed total baryon number
they have a smaller gravitational
mass wrt hadronic stars.

The hadronic stars are stable
till when some strangeness
component (e.g. hyperons)
starts appearing in the core.
Only at that point quark matter
nucleation can start.

Finite size effects (surface tension)
can further delay the formation
of the first droplet of strange matter



Nice, but just nucleons,
And it violates causality!



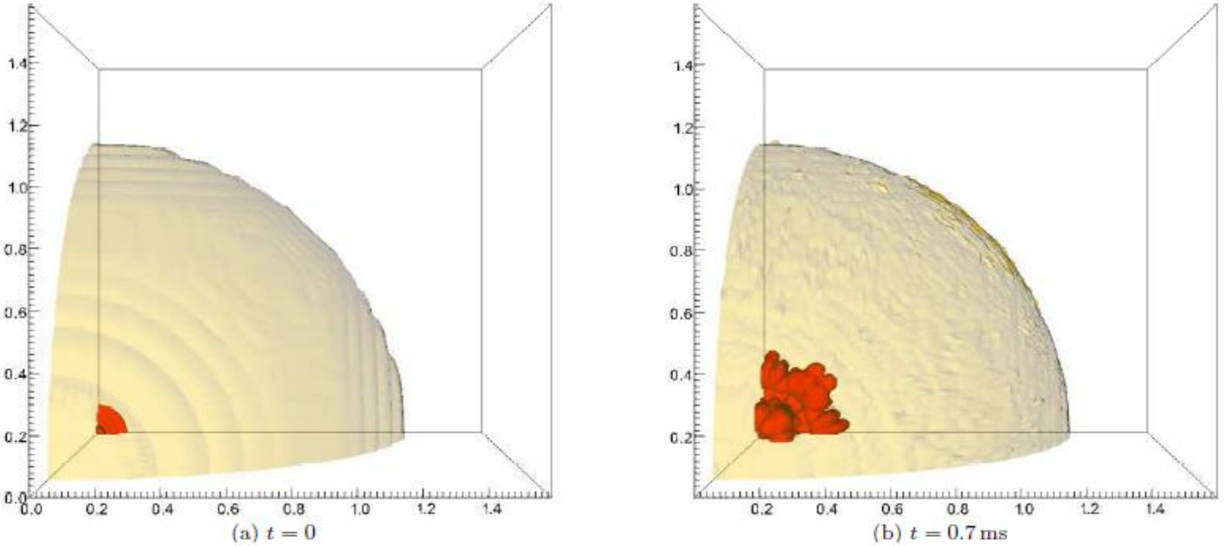
R=9.1±1.3 km

Guillot et al. ApJ772(2013)7
analysis of 5 QLMXBs

Conversion of a 1.4 Msun star

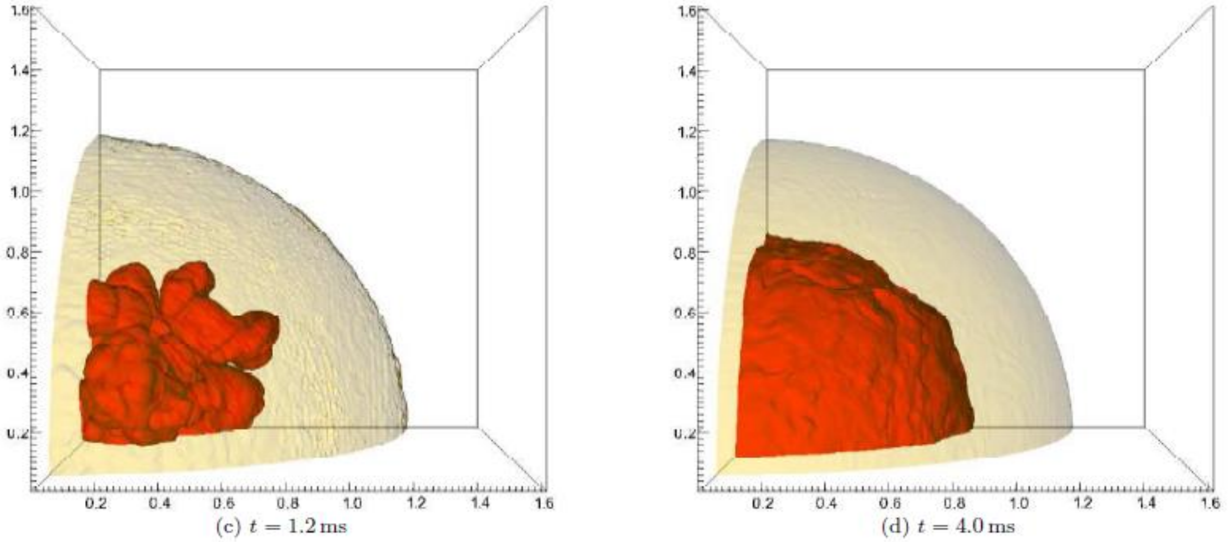
Rayleigh-Taylor instabilities develop and the conversion occurs on time scales of ms.

The burning stops before the whole hadronic matter has converted
(the process is no more exothermic,
about 0.5 Msun of unburned material)



(a) $t = 0$ (b) $t = 0.7\,\mathrm{ms}$

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

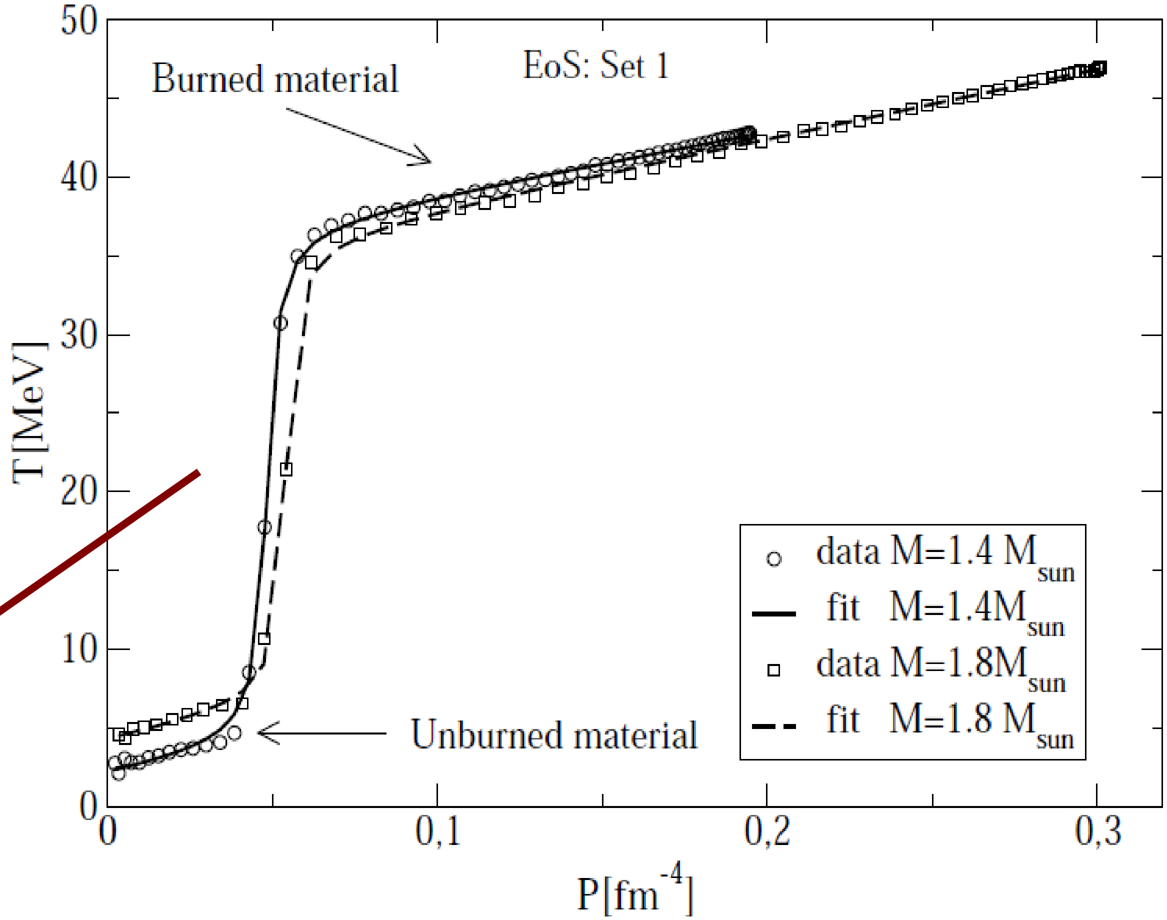


(c) $t = 1.2\,\mathrm{ms}$ (d) $t = 4.0\,\mathrm{ms}$

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

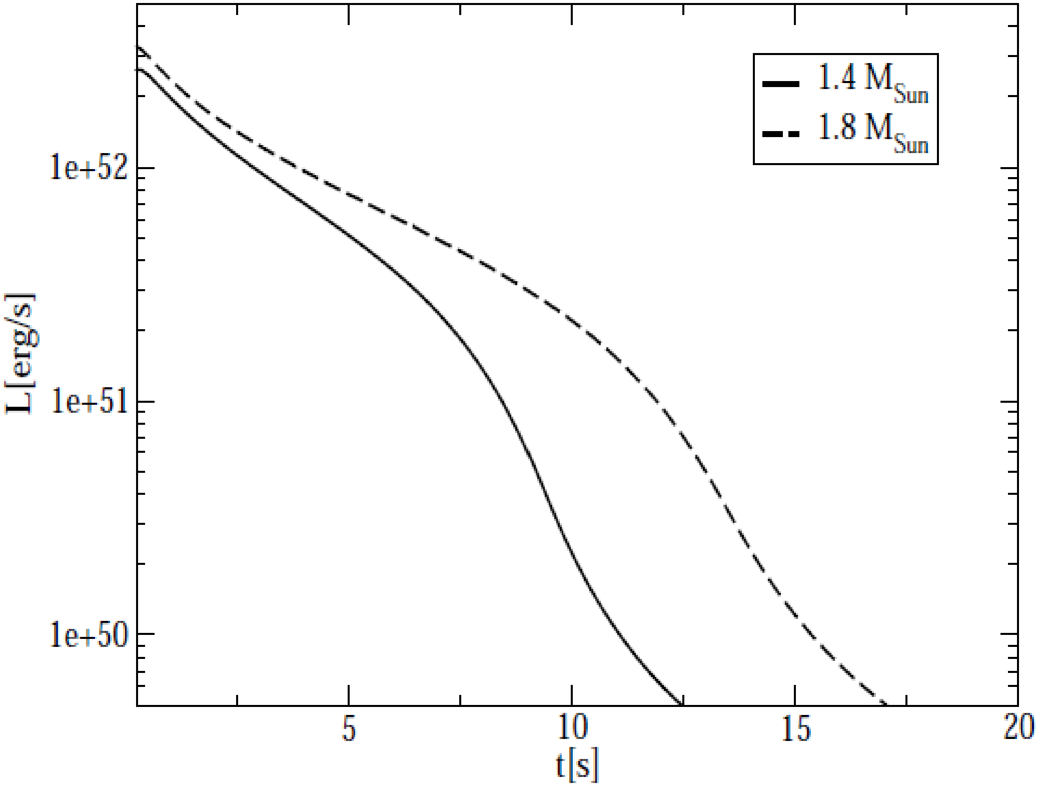
The huge energy released in the burning significantly heats the star, up to temperatures of a few tens of MeV in the center.



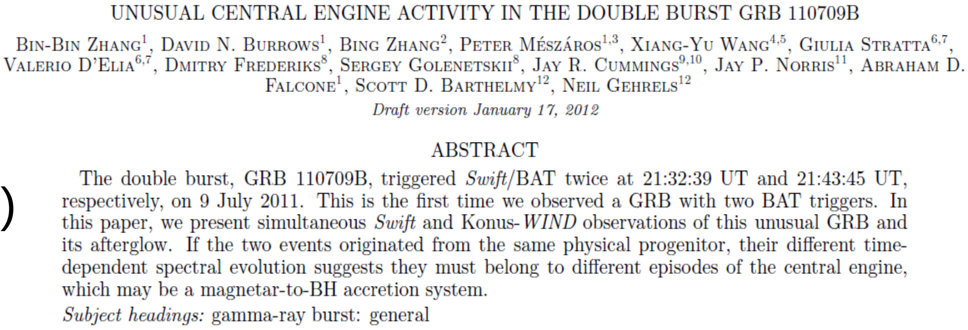
Steep gradient of the temperature

Luminosity curves similar to the protoneutron stars neutrino luminosities.

The (partial) burning
of the more external layers
can originate a prolongated
neutrino emission,
not included in this figure



Possible phenomenology:
GRBs with a double burst
(maybe within the protomagnetar
model of Bucciantini and Metzger)



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

Summary

- Delta resonances can appear before hyperons, shifting the hyperon threshold to larger densities.
- This does NOT solve the hyperonic puzzle, since also Δ resonances make the EOS soft,
  but it can help in having a physically consistent two-families solution:
  low mass – hadronic stars;   high mass – quark stars.
- The production of strangeness would be the trigger of the transition to deconfined quark matter
  and therefore to quark stars.
- Rich phenomenology, specially in relation to explosive phenomena.

New masses and radii measurements challenge nuclear physics:
tension between high mass and small radii. A 2.4 Msun candidate already exists.

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