Delta-resonance production in compact stars

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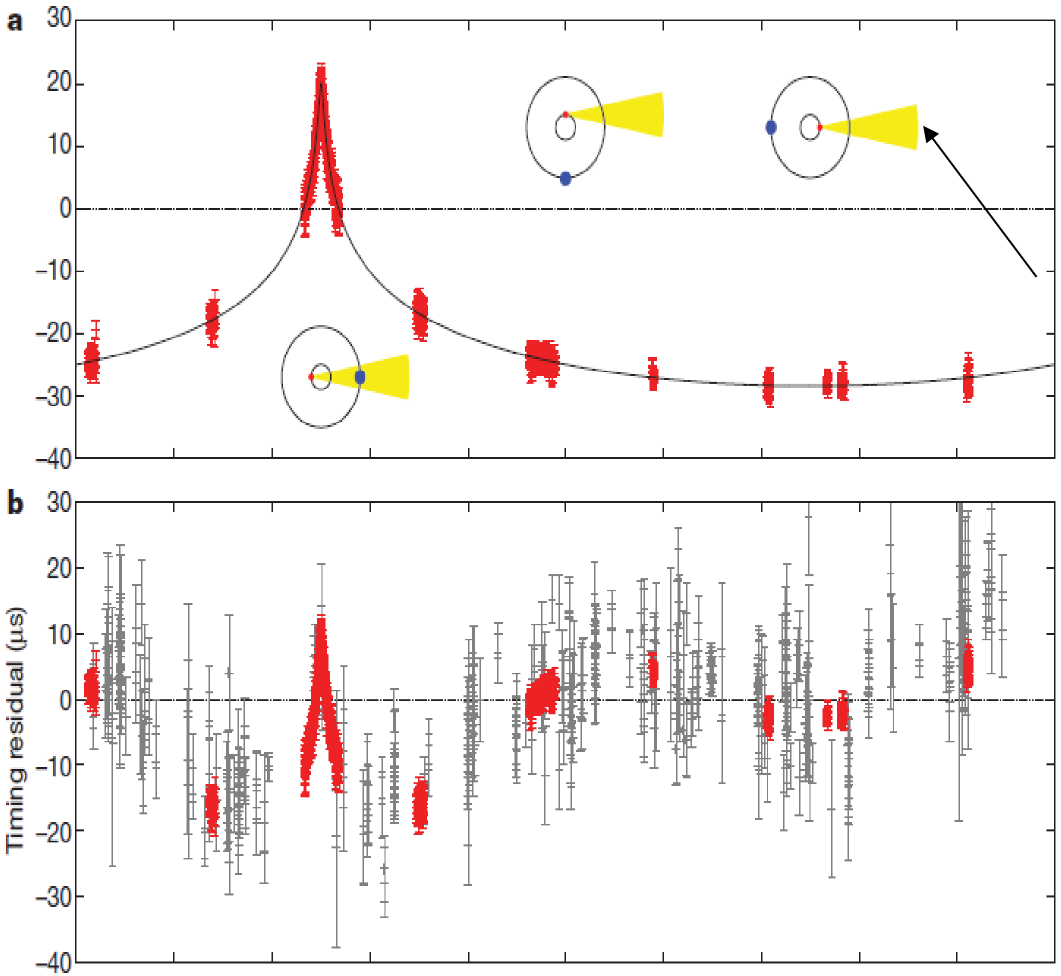
- «Low density» behaviour of matter is now rather well under control.
- The hyperon puzzle: too much softening?
- What about Δ resonances?
- Are hybrid stars a solution?
- Quark stars and the two-families solution.
- The role of the radius in determining the composition.

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

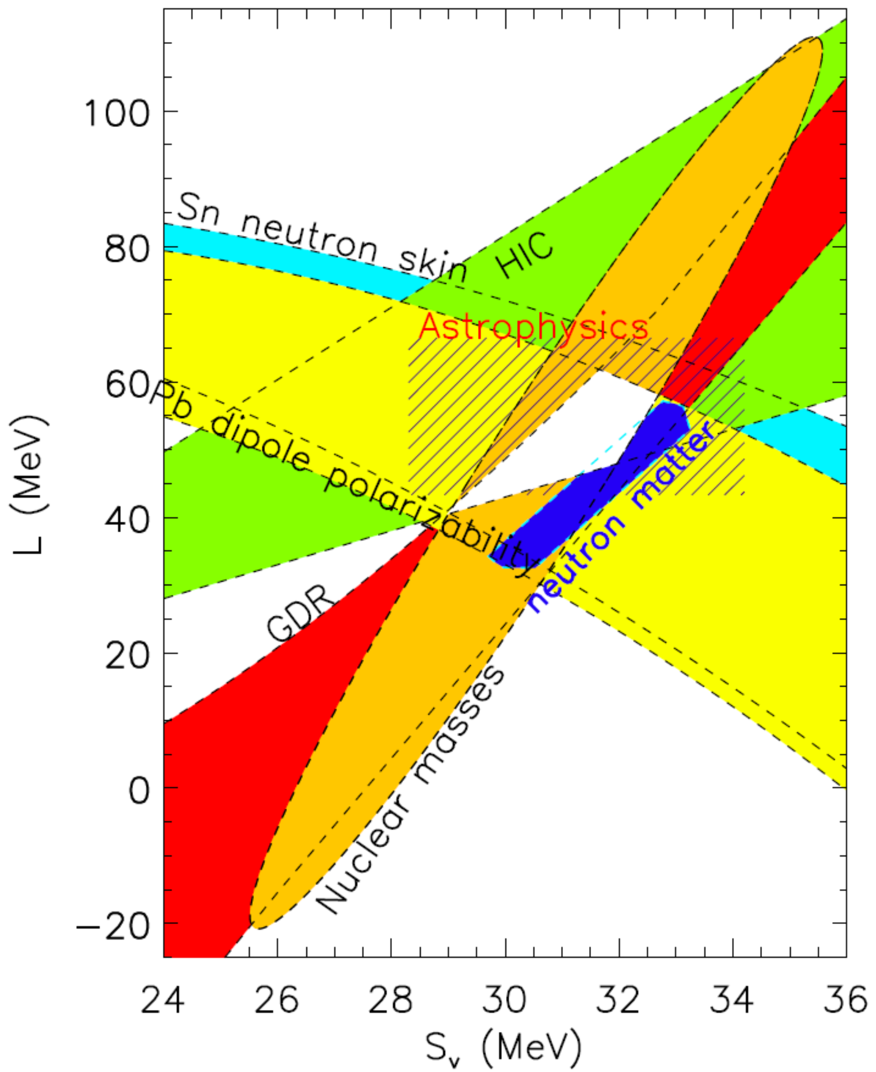
Demorest et al. Nature 2010



Nuclear and subnuclear densities: symmetry energy
Hebeler et al. 2013

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

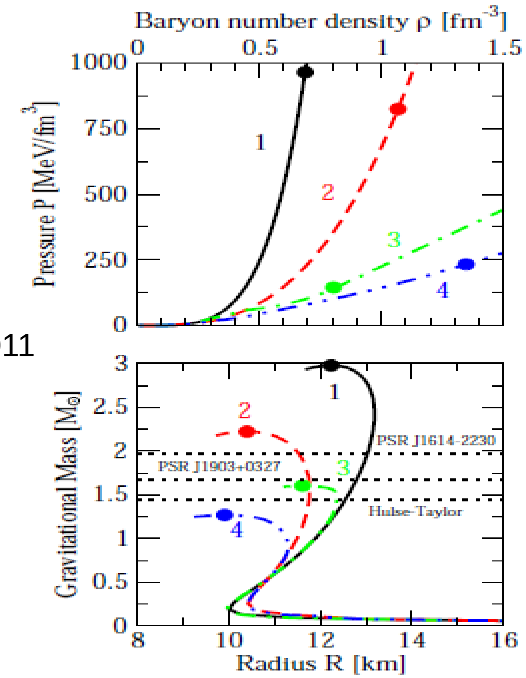
$$L = \frac{3}{8}\frac{\partial^3 \epsilon(\bar{n},x)}{\partial \bar{n}\partial x^2}\bigg|_{\bar{n}=1,x=1/2}$$



Hyperons in compact stars

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

Vidana et al 2011



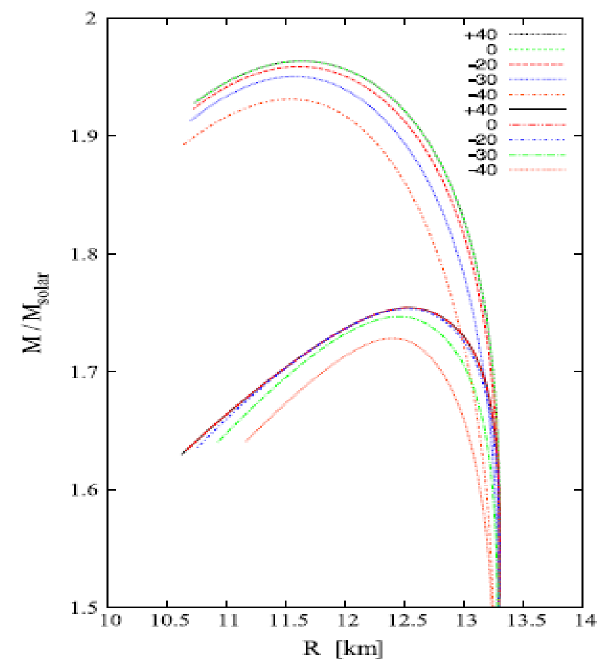
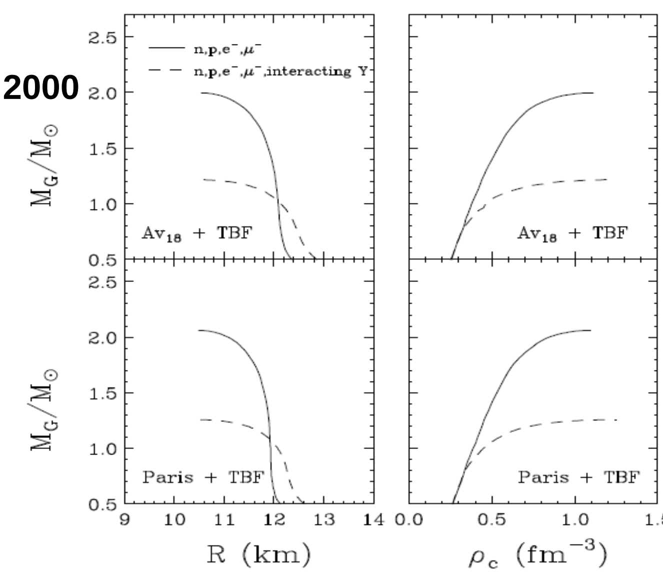


Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_\Sigma^{(N)}$ in "model σωρ" cannot account for the observed neutron star mass limit (lower branch), unless the φ meson is included in the model (upper branch).

Baldo et al 2000

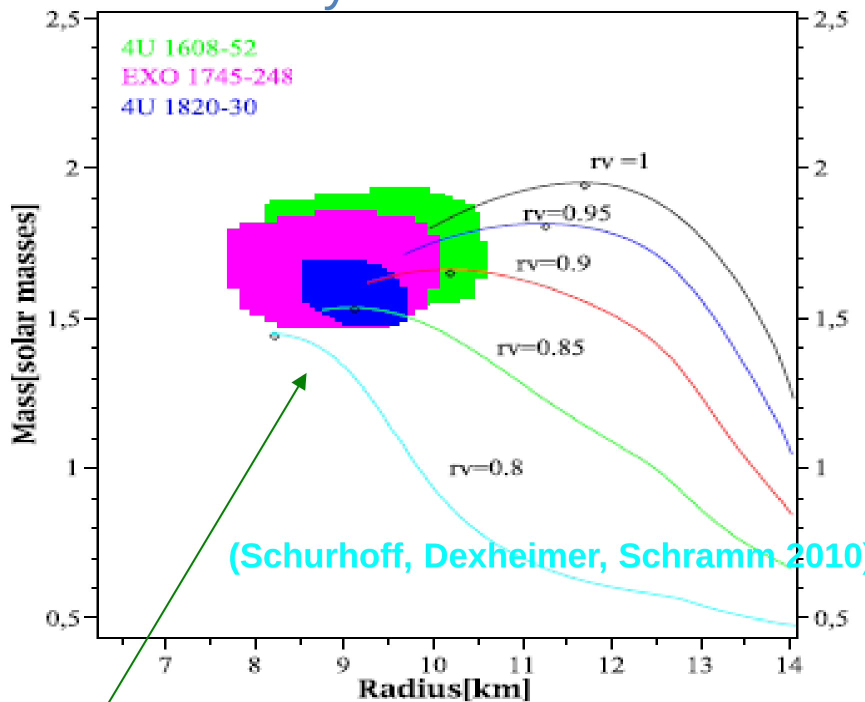


The 2Msun limit can be fulfilled within RMF models.

In microscopic not-relativisitc calculations it is fulfilled only if very strong and repulsive 3-body forces YNN are present.

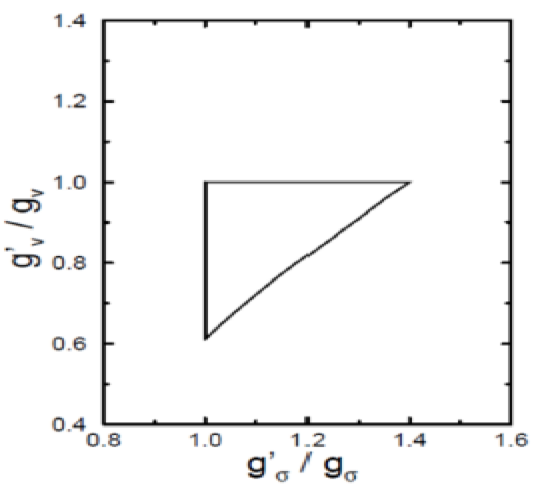
What about Δ's?

Here only Δ are included



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

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

What about Δ?

Among the four isobars, the Δ^- is likely to appear first in beta-stable matter because it is charge-favored:

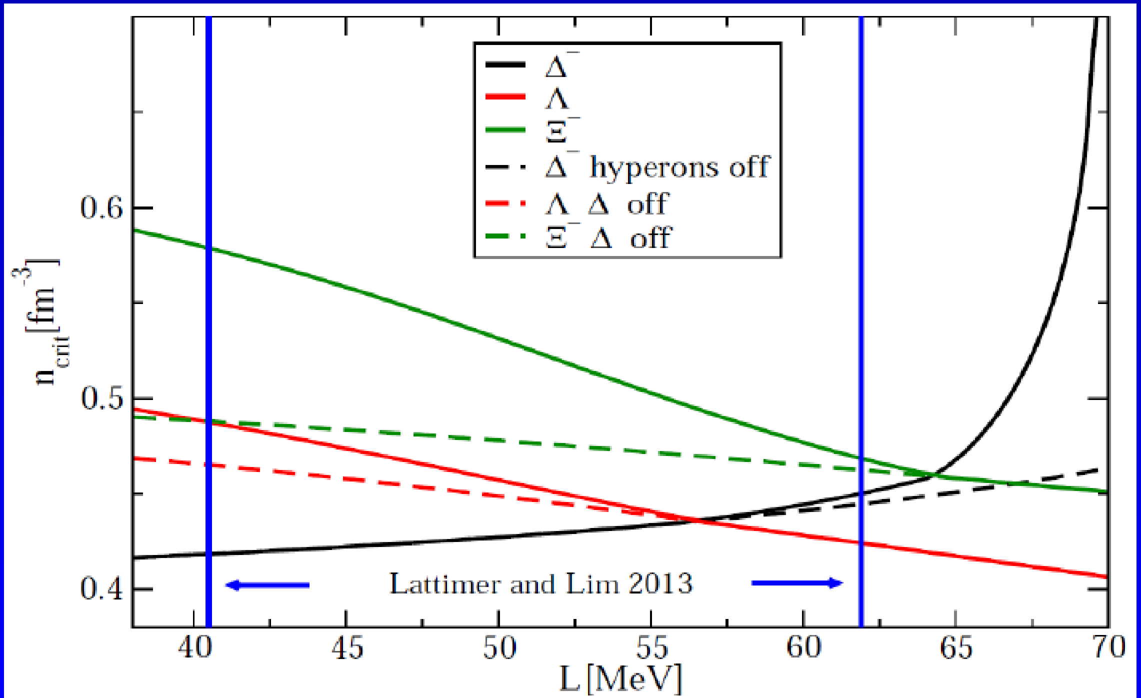
$$\mu_i = \mu_B + c_i\,\mu_C$$

But, it is isospin unfavored:

$$\mu_i \geq m_i - g_{\sigma i}\sigma + g_{\omega i}\omega + t_{3i} g_{\rho i}\rho$$

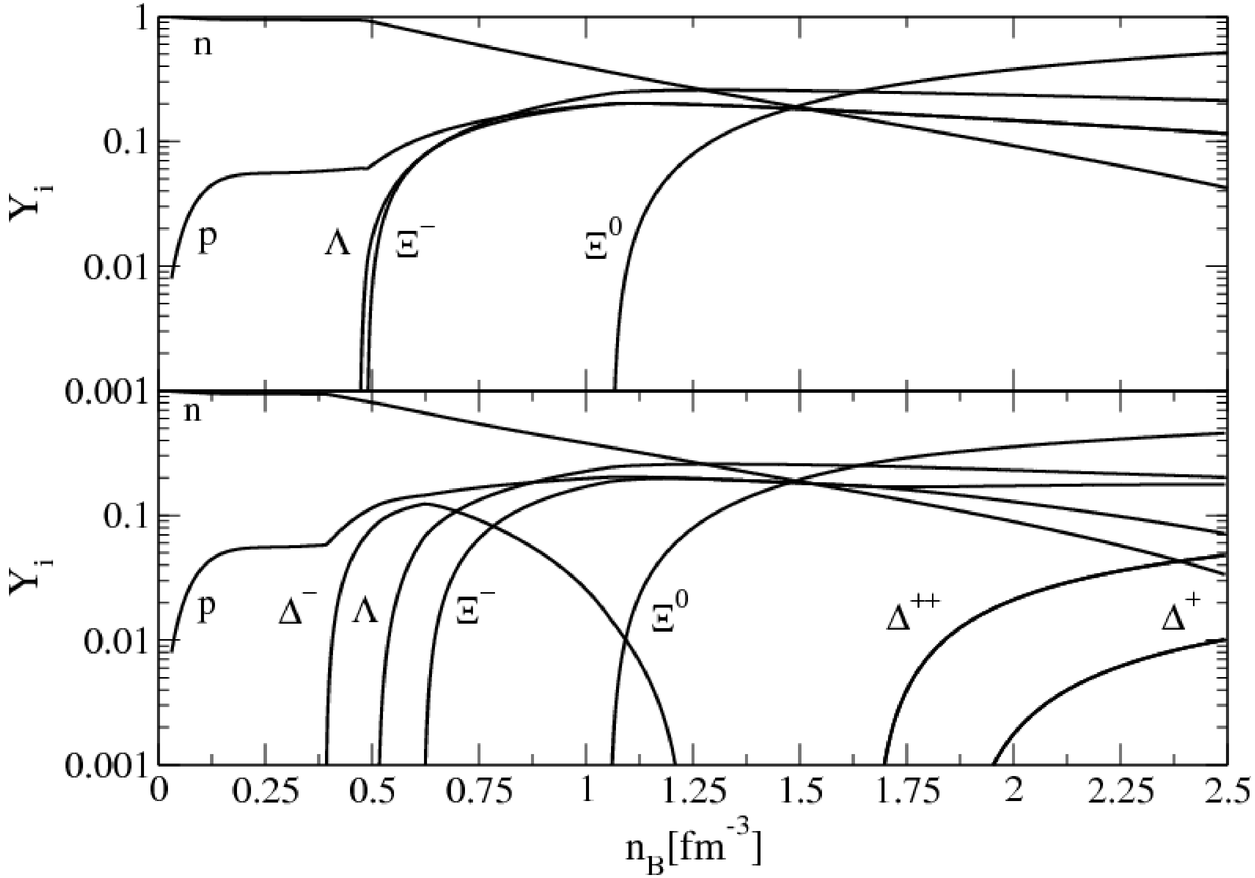
Indeed, in old calculations (see e.g. Glendenning 1985), no deltas are formed in neutron star matter. This is due to the large value of the symmetry energy at densities above saturation.

Investigating the role of the symmetry energy on the formation of the deltas by use of the density derivative of the symmetry energy L, within RMF models (Drago, Lavagno, G.P., Pigato 2014)



Glendenning's results

Populations with and without deltas



Electron or pion scattering on nuclei (O'Connel et al 1990, Wehrberger et al1989). Indications of a delta potential in the nuclear medium deeper than the nucleon potential. Several phenomenological and theoretical analyses lead to similar conclusions.

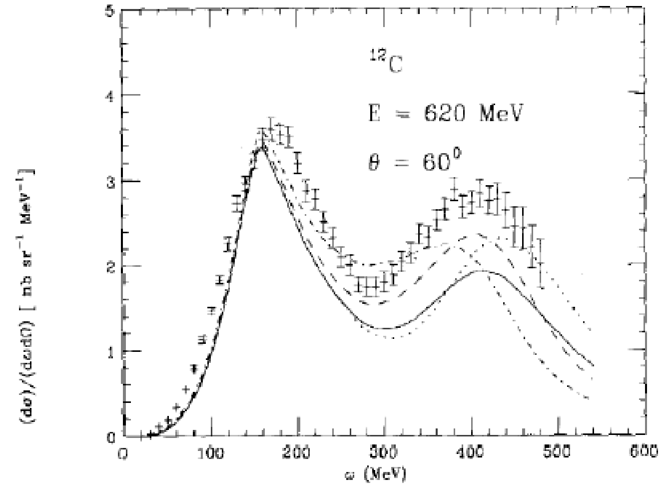
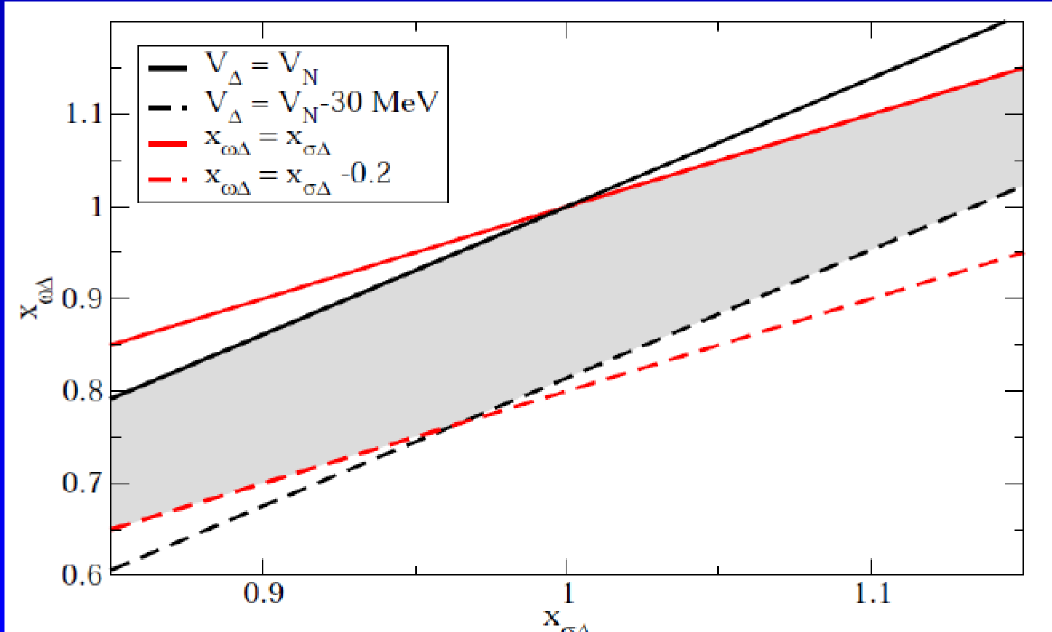
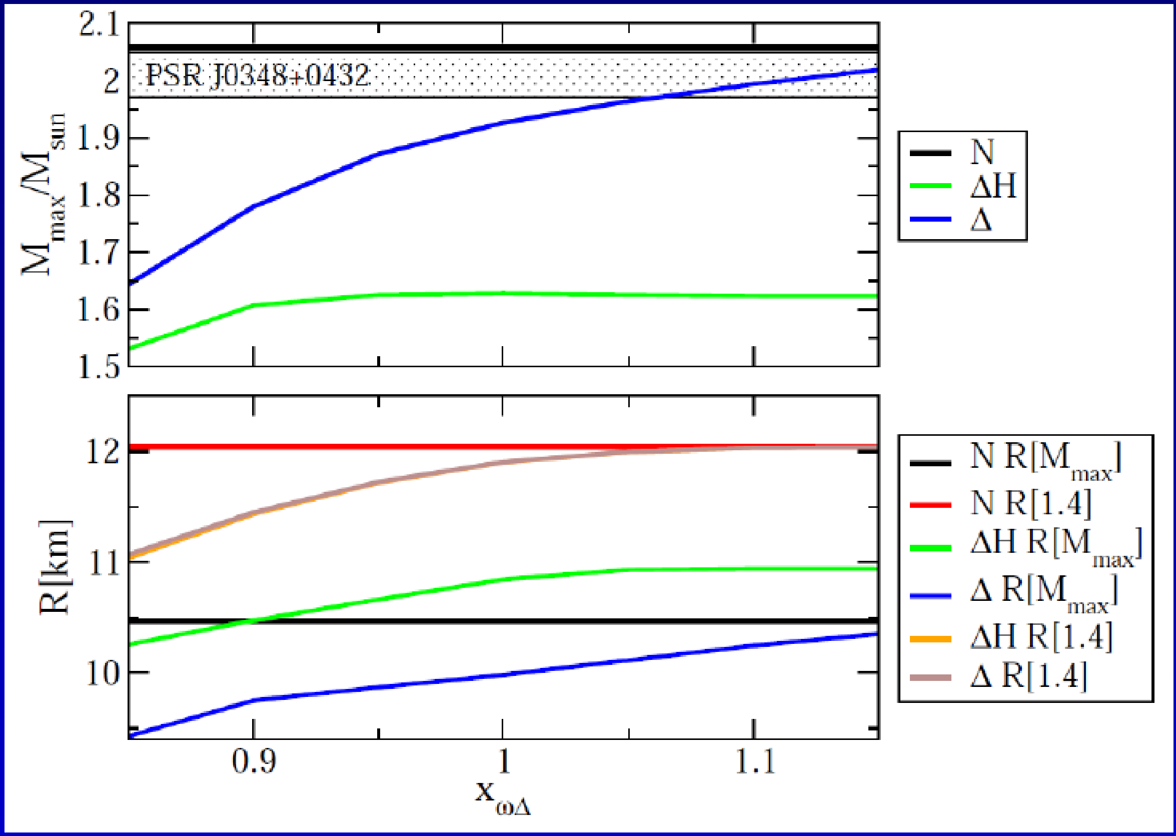


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and Δ-excitation. The dotted line shows the cross section for free Δ's, and the dashed and dot-dashed lines for no coupling to the vector field and a ratio $r_s = 0.15$ and 0.30 of the scalar coupling of the Δ to the scalar coupling of the nucleon. The solid line is obtained for universal coupling. The data are from ref. [16]).

This allows to constrain the free parameters within the RMF model. Notice: coupling with ω mesons suppressed.



Maximum mass and radii: the maximum mass is significantly smaller than the measured ones. Also, very compact stellar configurations are possible.



Punchline/?: beside the "hyperon puzzle" is there also a "delta isobars puzzle"?

Strong softening… 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

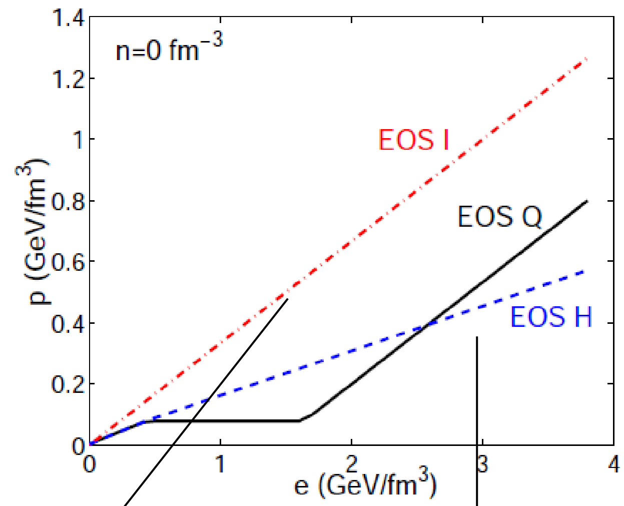
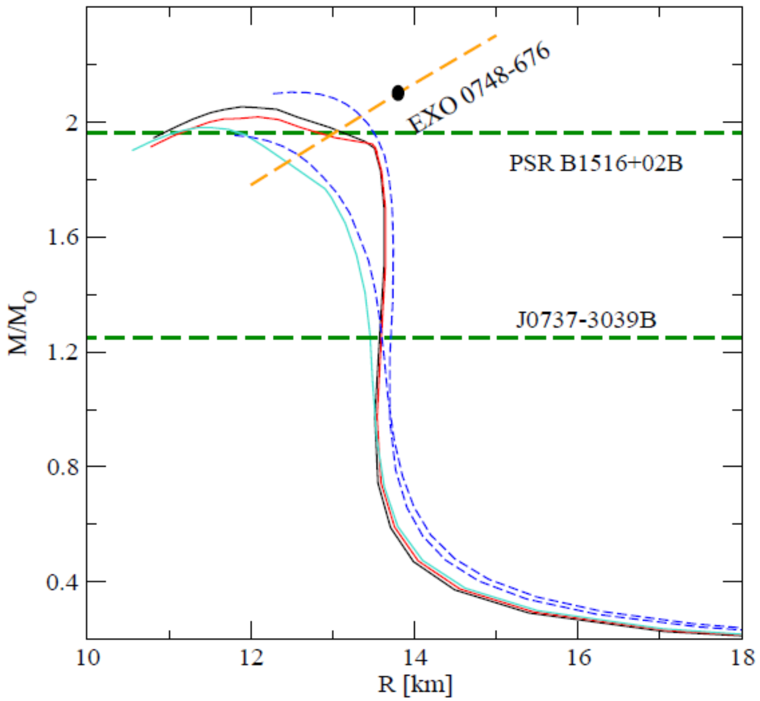


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

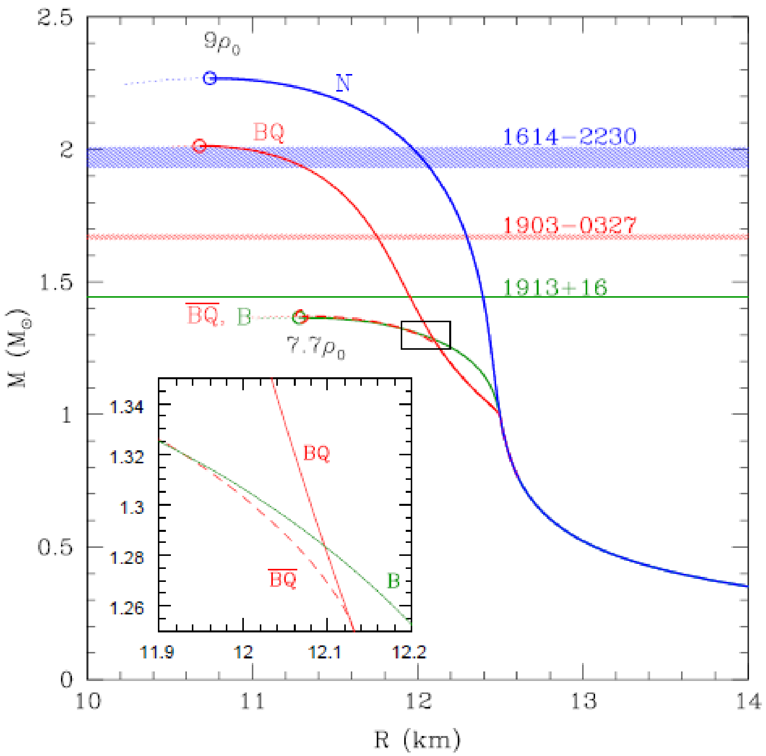
p=e/3 massless quarks **Hadron resonance gas p=e/6**

Hybrid stars: their radii

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

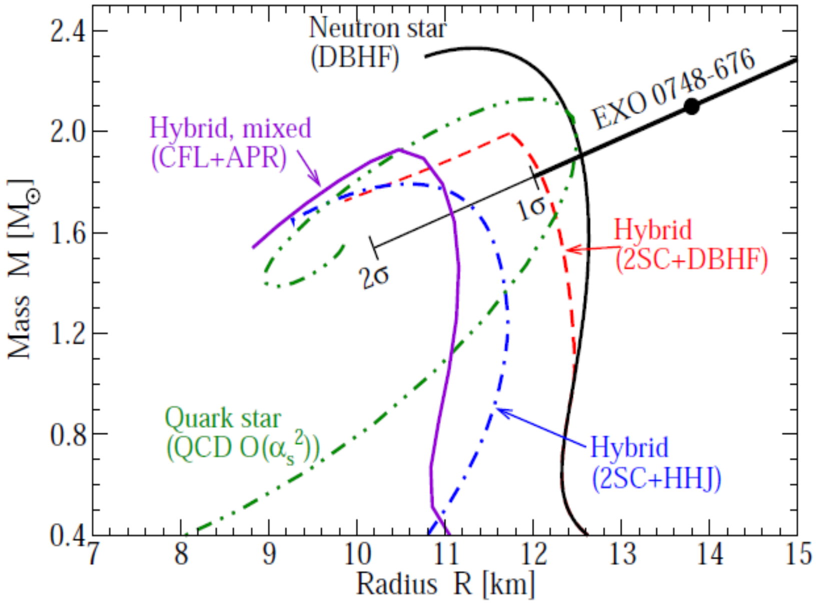


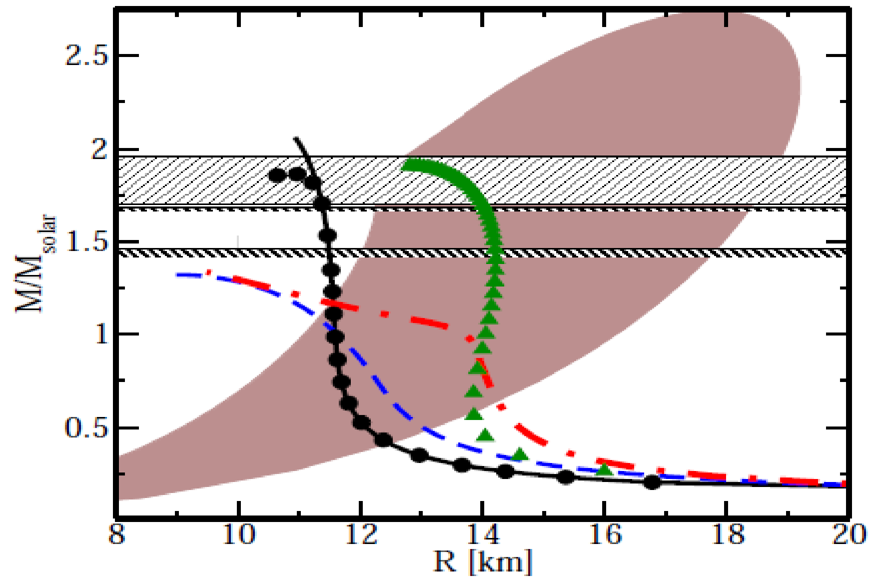
Zdunik and Haensel A&A, 551 (2013) A61



It is possible to satisfy the 2 M_s limit with a hybrid star, but the radius of a 1.4 M_s hybrid star is about 11.5 -- 14 km (see also the talk of Fraga and Kurkela et al. 2014).

Hybrid stars or quark stars?





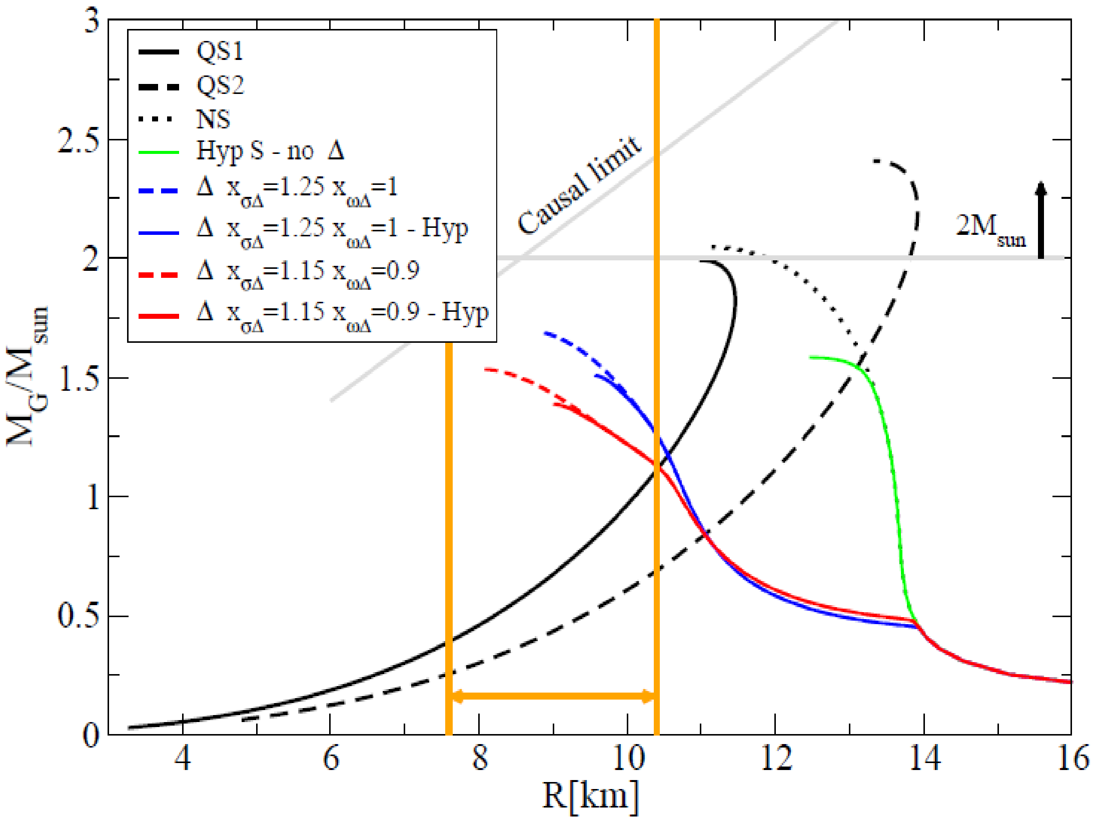
Alford et al Nature 2006

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!!

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



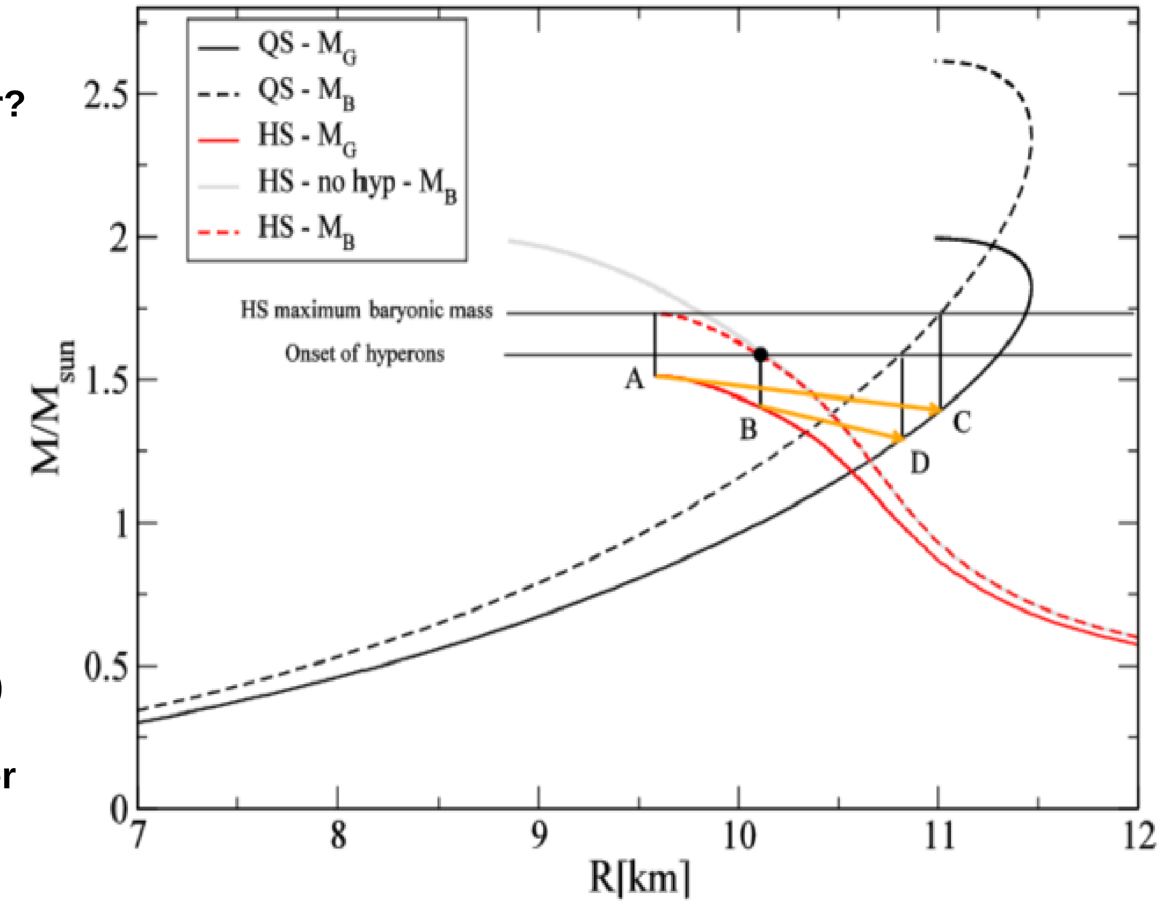
Two families of compact stars:

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**

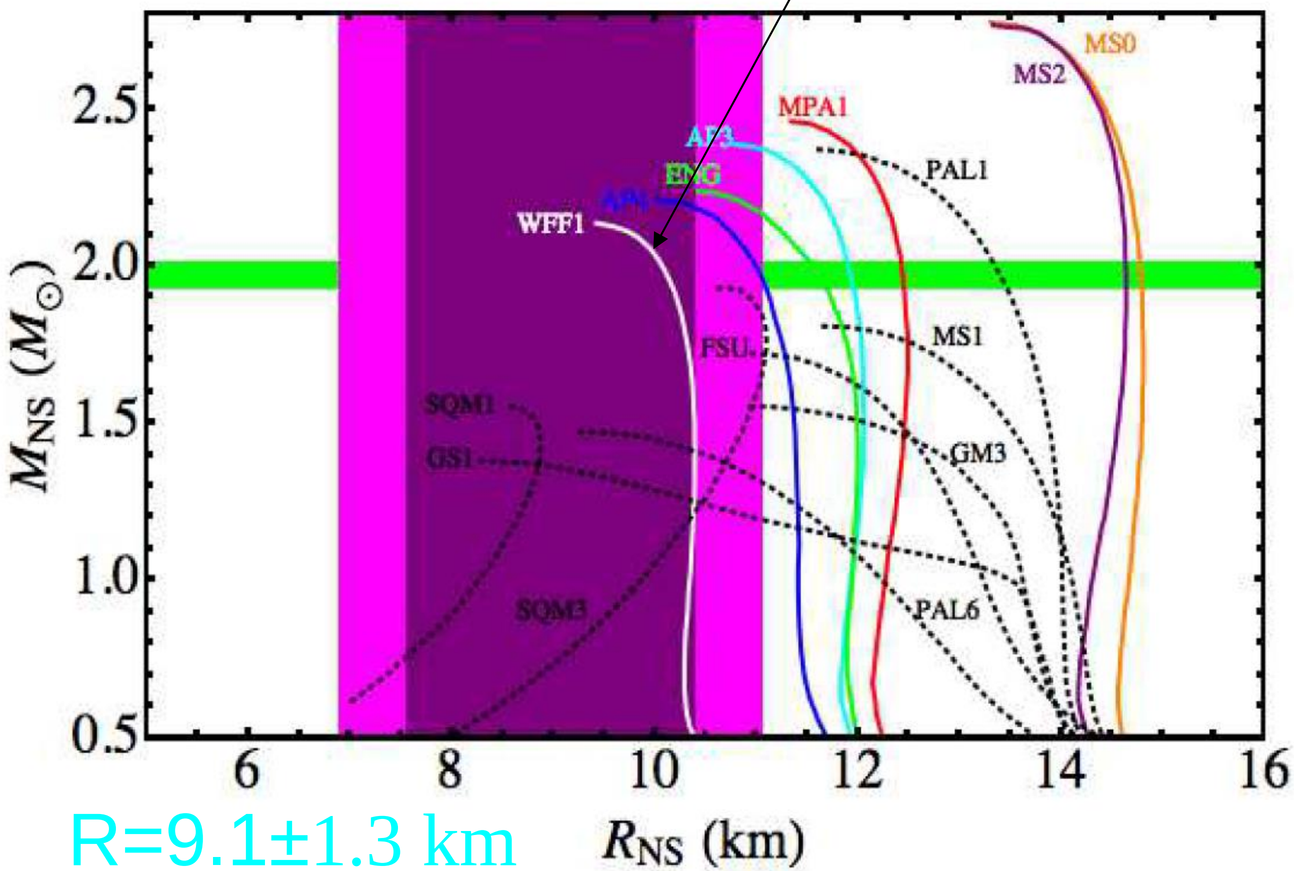
Why conversion should then occur?
Quark stars are more bound:
at a fixed total baryon number
they have a smaller gravitational
mass wrt hadronic stars.

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

Summary

- **Delta resonances 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.