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

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Outline

- What do we learn from the existence of stars of 2 M_s ?
    - Are hyperons excluded?
    - Are hybrid quark-hadron stars excluded?
    - Are quark stars excluded?
- Are radii smaller than about 10 km excluded by theory?

  A. D., A. Lavagno and G. Pagliara; arXiv:1309.7263

- What will we learn from the measurement of the radius with an error-bar of about 1 km, as possible with LOFT?

What do we learn from the existence of stars of 2 M_s ?

Strangeness production

- In heavy ion experiments strangeness can be produced only by strong-interaction and therefore via associated production (weak interaction does not have time to take place).

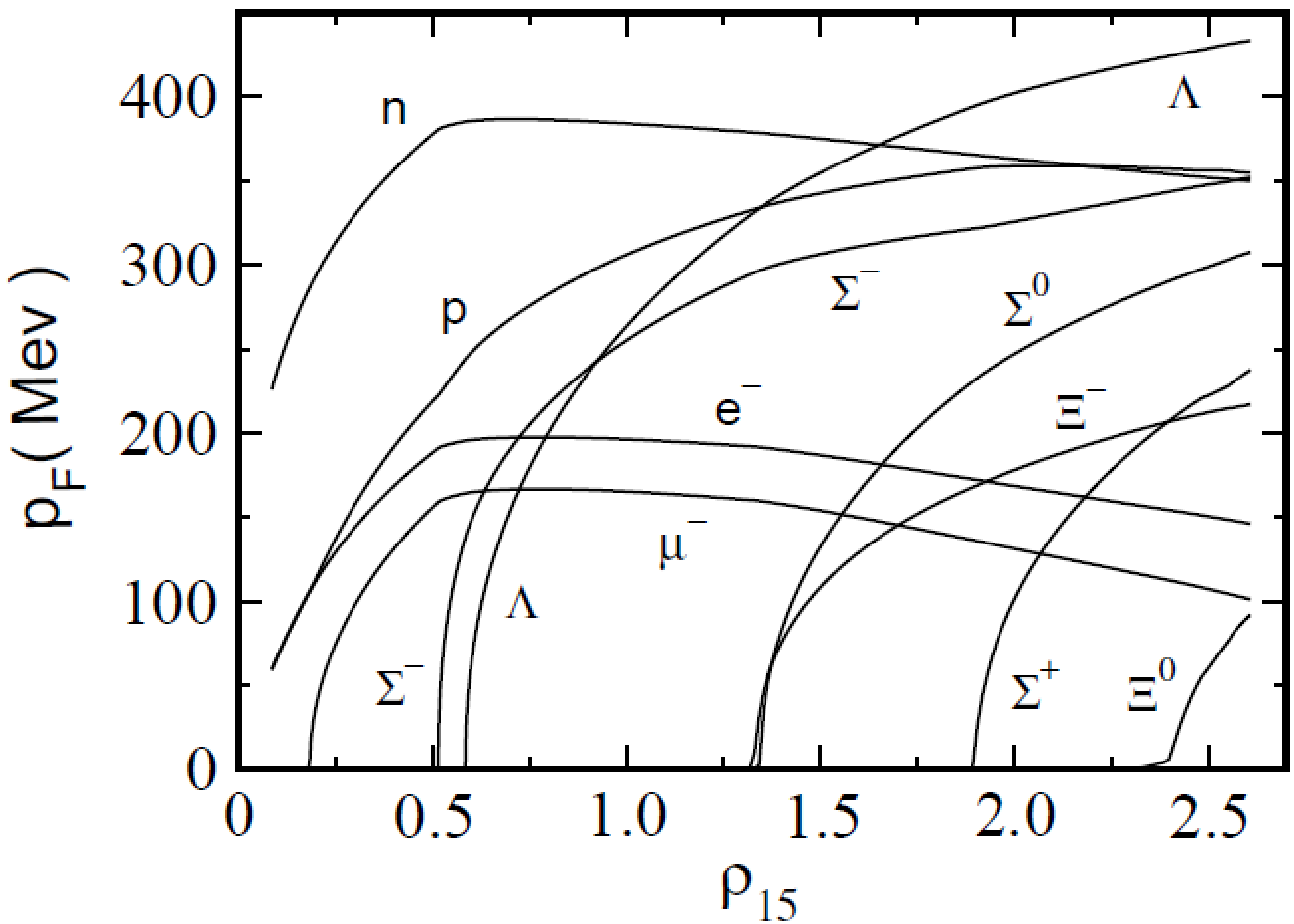
  The typical fraction of strangeness is less than 10%

- In a compact star strangeness is mainly produced by weak interaction. Hyperons «normally» start appearing at densities above (2.5 – 3) ρ_0

- Hyperons can significantly soften the EoS: is it possible to have a

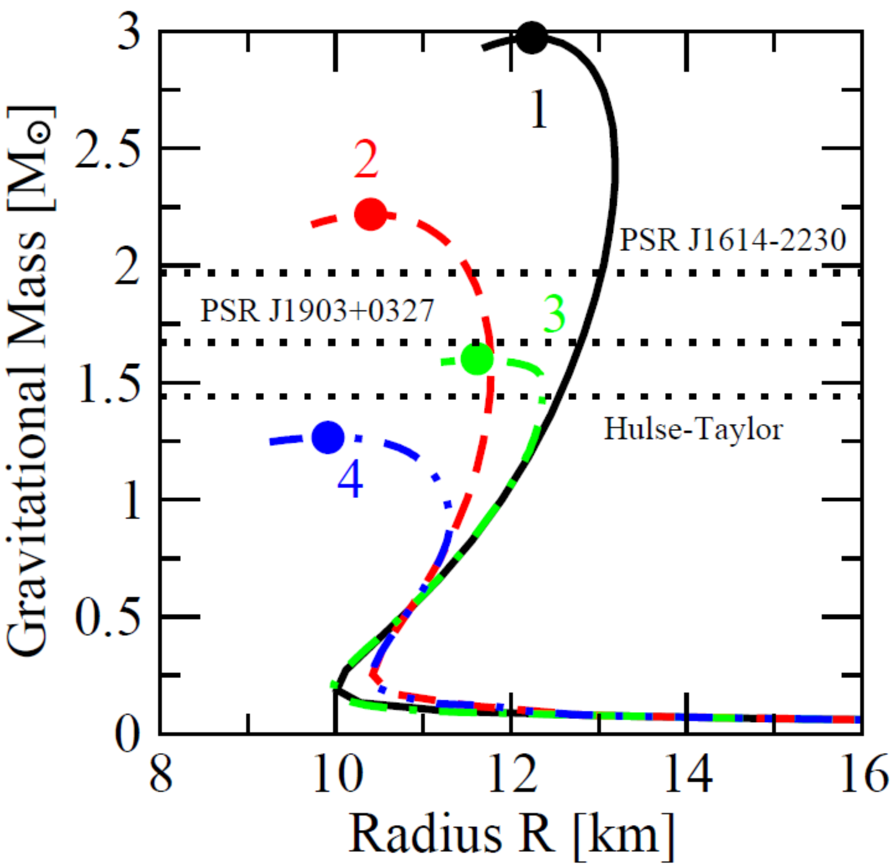
  2 M_s compact star with hyperons? Yes, but…

Hyperons in β-stable matter



Hyperonic stars in a non-relativistic BHF with parametrised 3-body forces between hyperons

Vidana et al. Europhys.Lett. 94 (2011) 11002



Radius of a purely nucleonic star about 12 km

stiffer and softer pure nucleonic EoS (curves 1 and 2)
stiffer and softer hyperonic stars (curves 3 and 4)

3-body forces are not sufficent to reach two solar masses

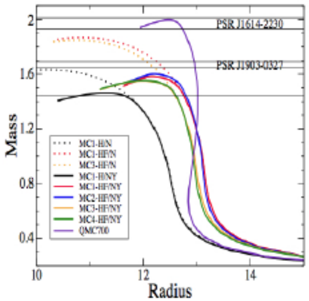
The central density is very large, 5 – 9 ρ_0

A relativistic approach could be needed

Borrowed from I. Vidana

Situation not much clear with phenomenological approaches

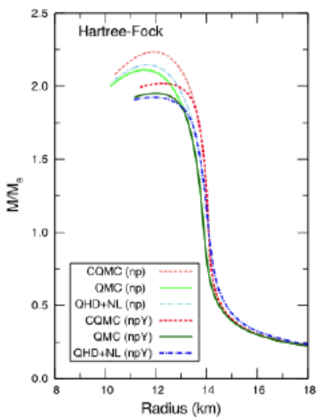
(Massot et al. 2012)



- ✓ χ-LM & QMC
- ✓ Hartree-Fock

$M_{max} = 1.6 - 1.66 M_\odot$

(Miyatsu et al. 2012)



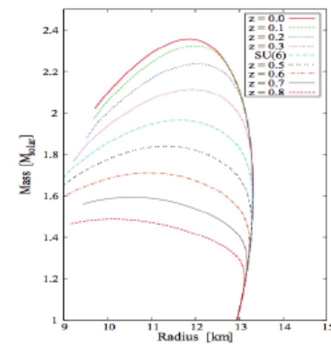
- ✓ RHF & QMC
- ✓ π & f_{vB}

M_{max} compatible with $1.97 M_\odot$

(Weissenborn et al. 2012)

- ✓ RMF
- ✓ SU(6) → SU(3)
- ✓ Vary $z = g_8/g_1$, α_v
- ✓ φ mesons

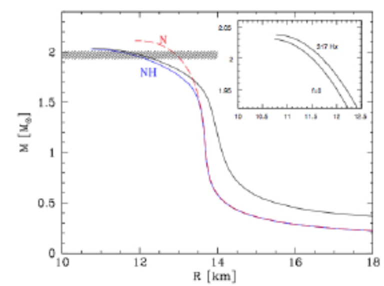
M_{max} compatible with $1.97 M_\odot$



(Bednarek et al. 2012)

- ✓ RMF
- ✓ σ^4 terms
- ✓ σ^*, φ mesons

$M_{max} > 2 M_\odot$



Radii for a 1.4 M_s star are about 12-14 km

Basic questions

Threshold for Λ:

$\mu_n = \mu_\Lambda$

Possibilities:

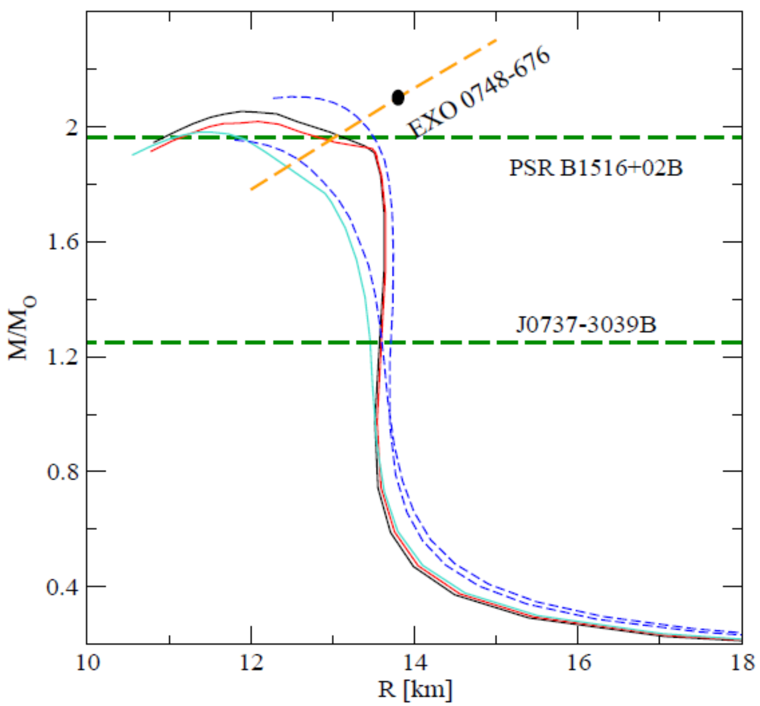
- to reduce the mass of the nucleon, since $\mu_n = (m_n^{*2} + K_f^2)^{1/2} + \ldots$
- to increase the chemical potential of the Λ

1. How much can the mass of the nucleon be reduced?
2. How strongly repulsive can be the YNN, YYN, YYY three-body forces?

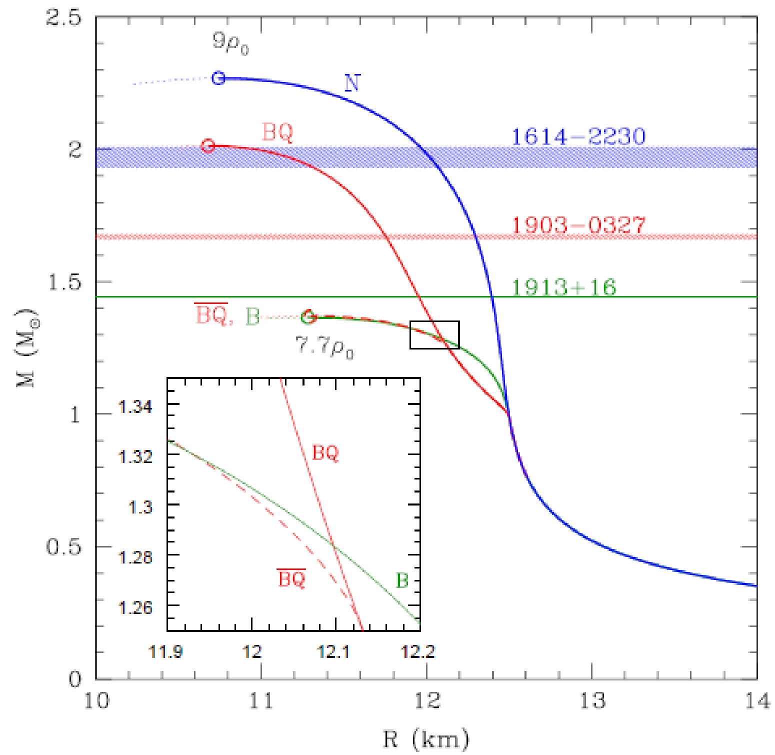
   Can it be much more repulsive than NNN three-body force at high density?

Struggling with hybrid stars

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



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

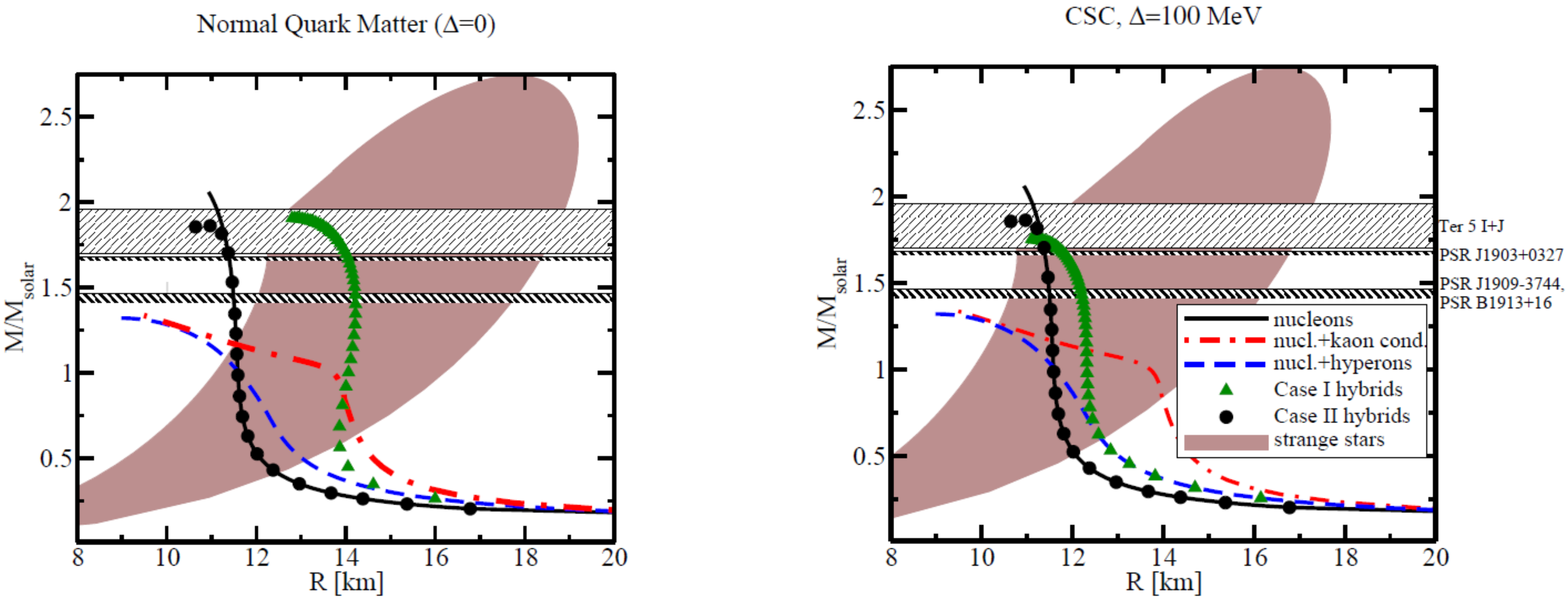


It is not impossible to satisfy the 2 M_s limit with a hybrid star but special limits on the parameters' values have to be imposed

Radius of a 1.4 M_s hybrid star 12-14 km

Cold quark matter:
a perturbative QCD approach

Kurkela, Romatschke, Vuorinen; Phys.Rev. D81 (2010) 105021



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

Passing the test with quark stars

Weissenborn et al.; Astrophys.J. 740 (2011) L14

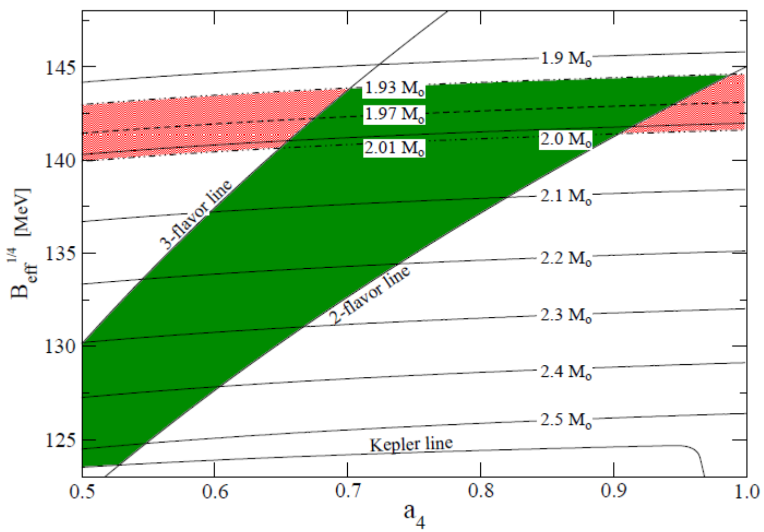


FIG. 1.— Maximum masses of unpaired strange quark stars as a function of B_{eff} and a_4. The green shaded area marks the allowed parameter region according to the constraints of the existence of nuclei (2-flavor line), absolute stability of strange quark matter (3-flavor line), stability of fast rotating stars (Kepler line), and the mass of PSR J1614-2230 including its 1σ error.

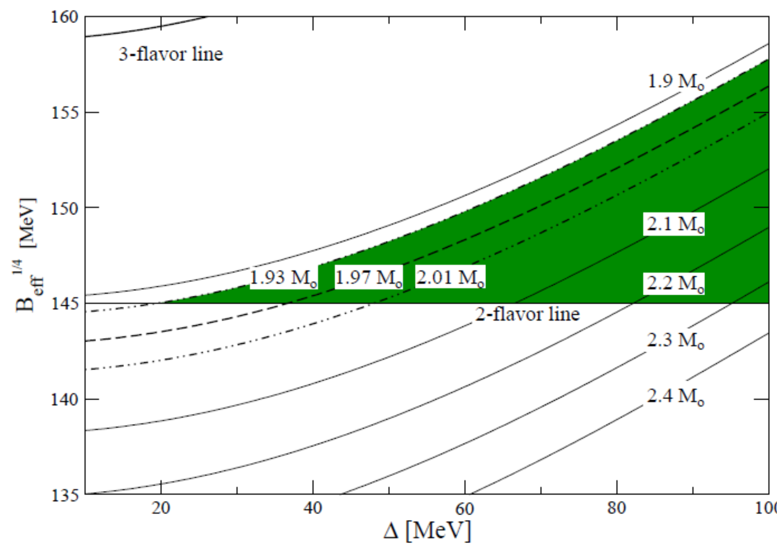
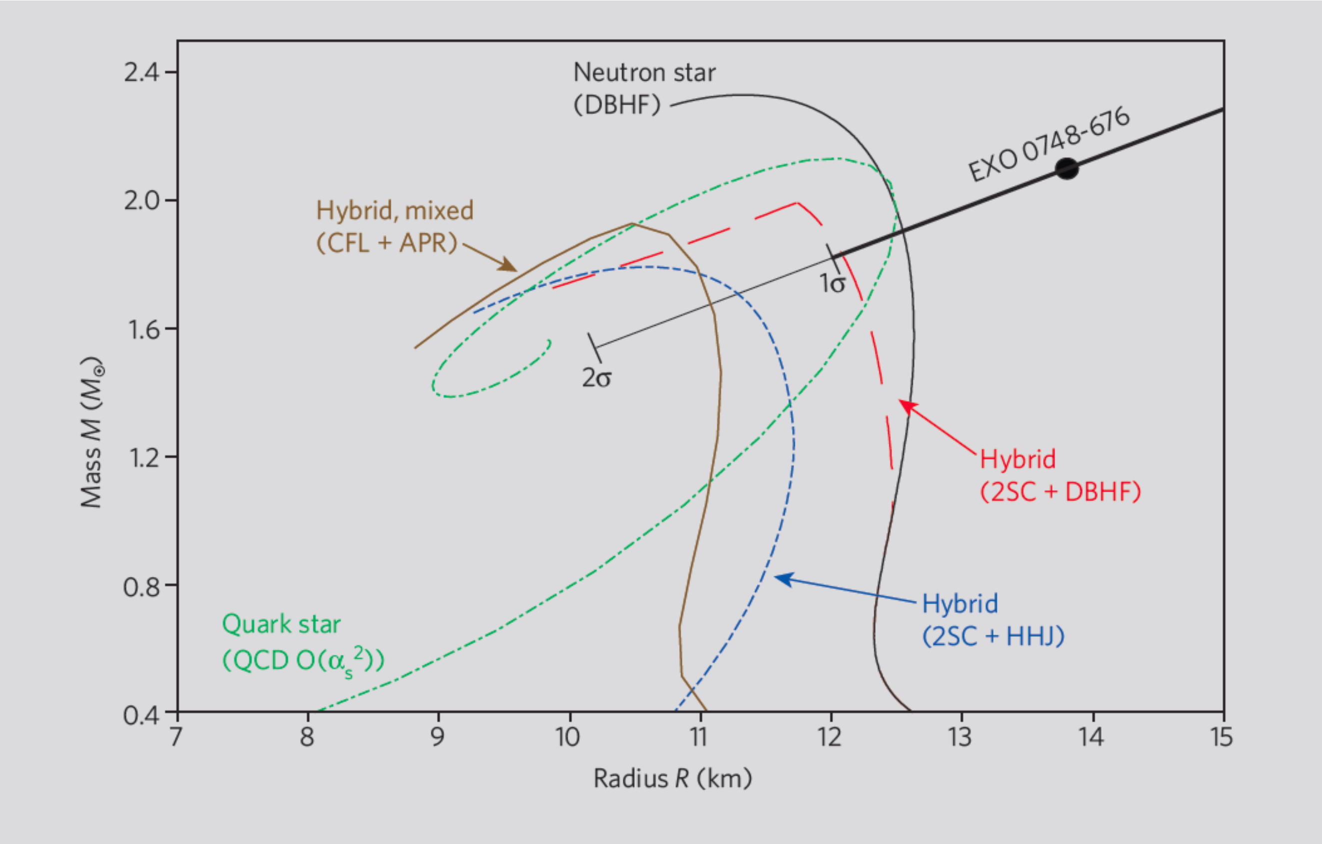


FIG. 2.— Same as in Fig. 1, but this time for color-superconducting strange quark matter with the pairing gap Δ and fixed $a_4 = 1.0$.

It is not particularly difficult to reach masses larger than 2 M_s in the case of quark stars. In principle even larger masses can be obtained.

A remark concerning «history»

M.Alford, D.Blaschke, A.Drago, T.Klaehn, G.Pagliara, J.Schaffner-Bielich
Nature, 445 (2007) E7

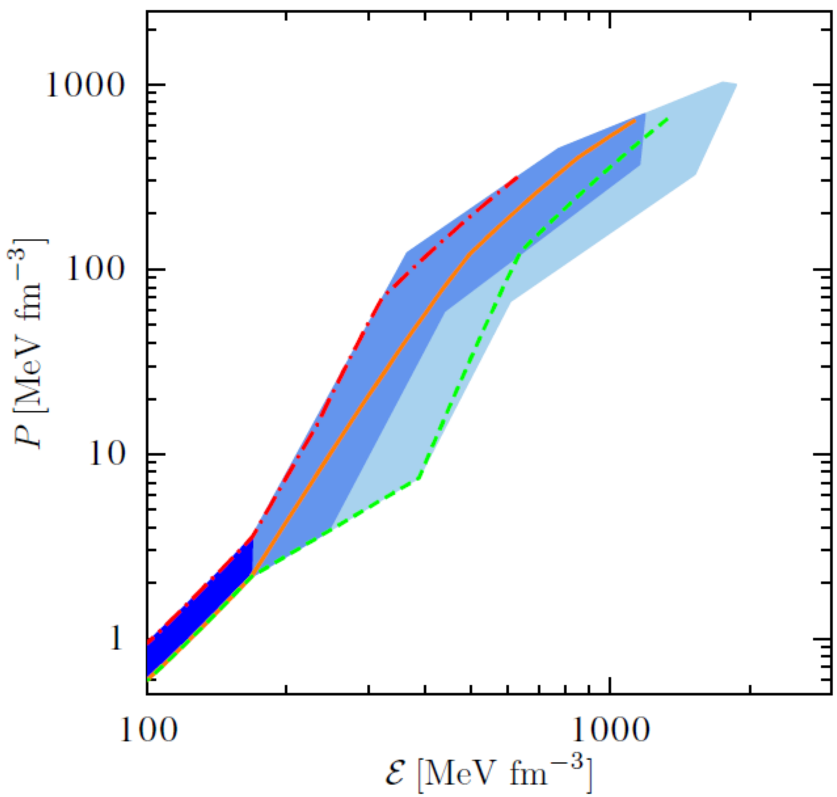


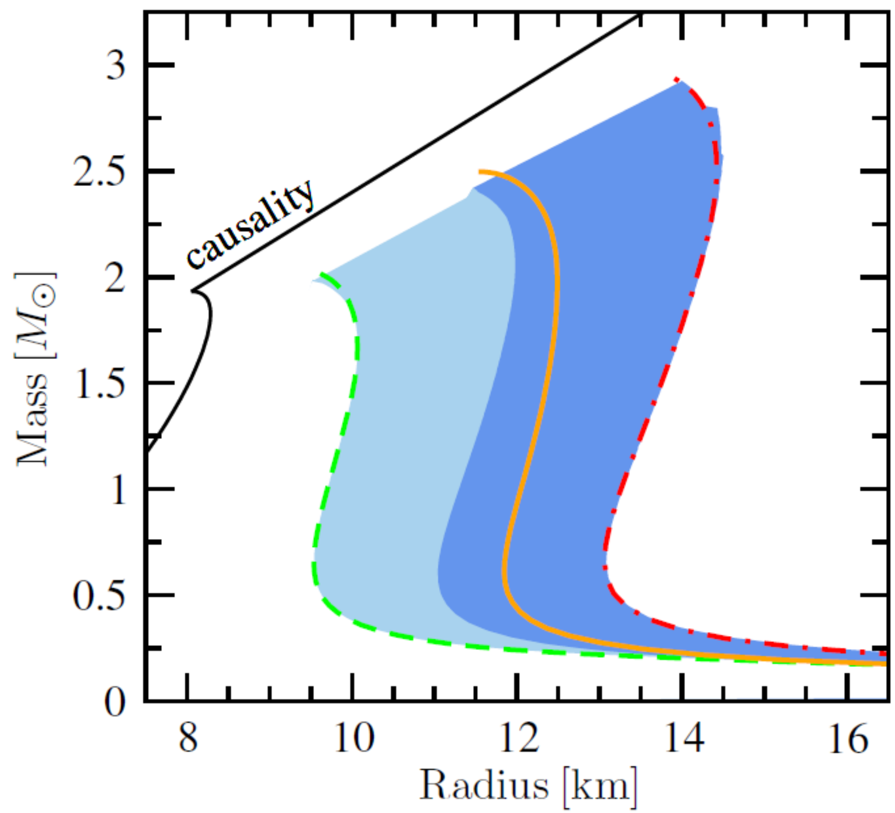
Radii for a 1.4 M_s star larger than 11 km

Based on papers published **before** 2006

2. Alford, M., Braby, M., Paris, M. & Reddy, S. *Astrophys. J.* **629**, 969–978 (2005).
3. Fraga, E. S., Pisarski, R. D. & Schaffner-Bielich, J. *Phys. Rev. D* **63**, 121702 (2001).
4. Rüster, S. B. & Rischke, D. H. *Phys. Rev. D* **69**, 045011 (2004).

Hebeler, Lattimer, Pethick, Schwenk ApJ773(2013)11





Analysis based on politropic expansion: $R_{1.4}$ > 10 km
Explicit model calculations indicate a even slightly larger limit
If a 2.4 M s star will be discovered than $R_{1.4}$ > 12 km !

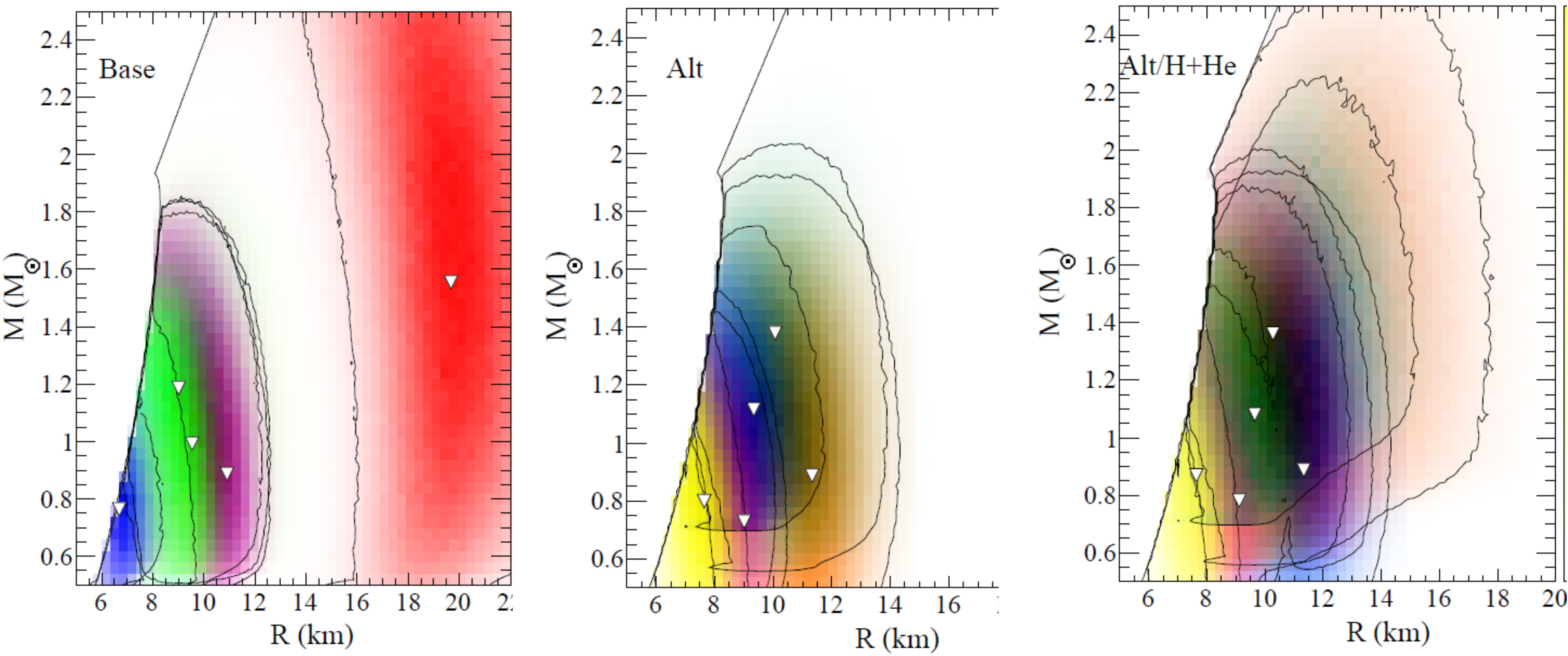
First «conclusion»

- It is possible to reach two solar masses with hyperonic and with hybrid stars, although tight limits on the parameters' space have to be imposed.
- The two solar mass constraint can be satisfied more easily with quark stars (but it is unlikely that ALL compact stars are quark stars).
- The radii of a 1.4 M_s star are larger than about (10 — 10.5) km

Are radii smaller than 10 km ruled out by microphysics?

(and what if a 2.4 M_s will be discovered?)

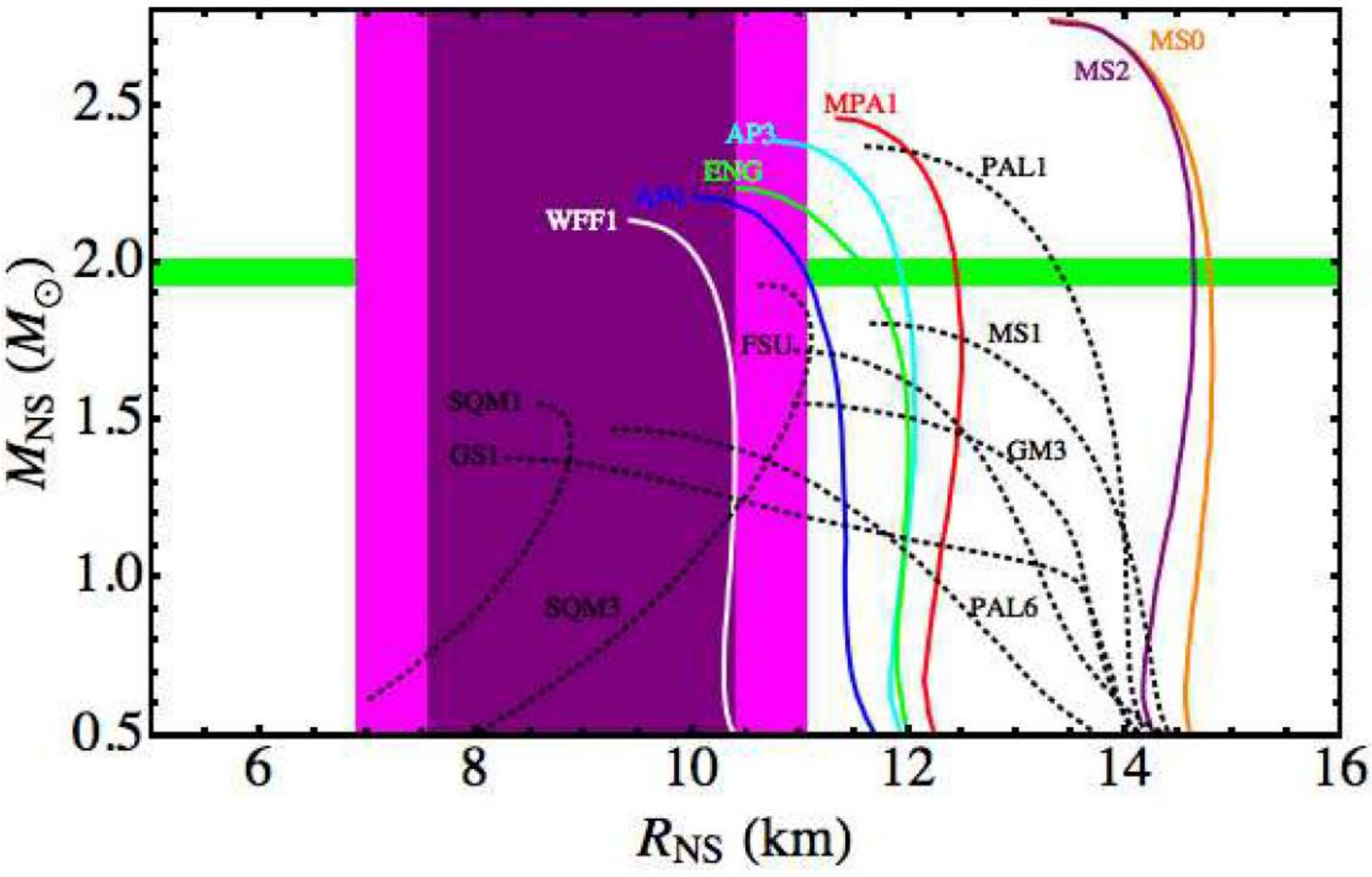
Analysis of 5 QLMXBs



Guillot et al. ApJ772(2013)7

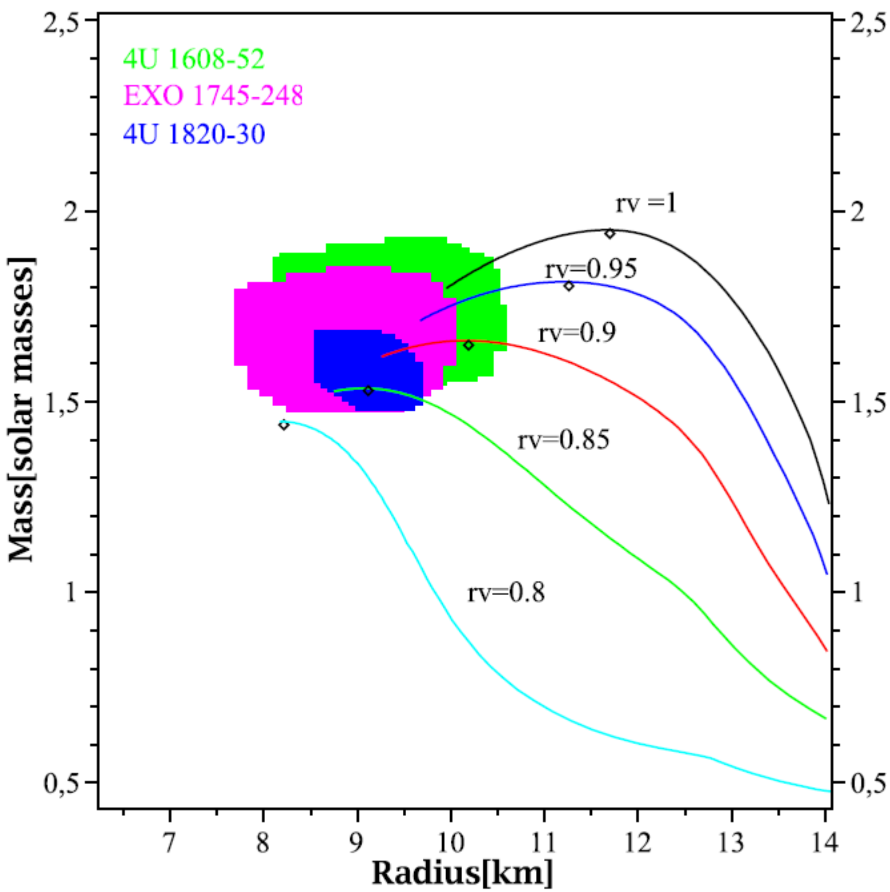
Lattimer and Steiner 1305.3242

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



The role of delta resonances

Schurhoff, Schramm, Dexheimer ApJ 724 (2010) L74



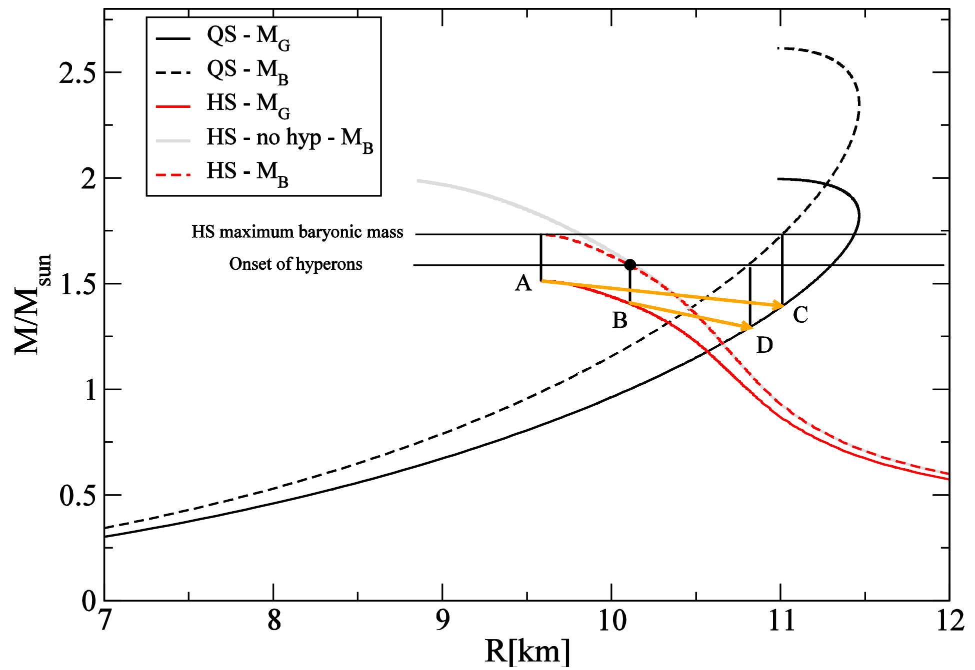
The delta-nucleon mass splitting **at nuclear matter saturation** can be tested via electron-nucleus scattering and therefore cannot be increased almost arbitrary as for the Lambda-nucleon mass splitting.

It could therefore be difficult to eliminate delta resonances (and the associate softening) from compact stars!

How to have small radii and large masses with two types of compact stars

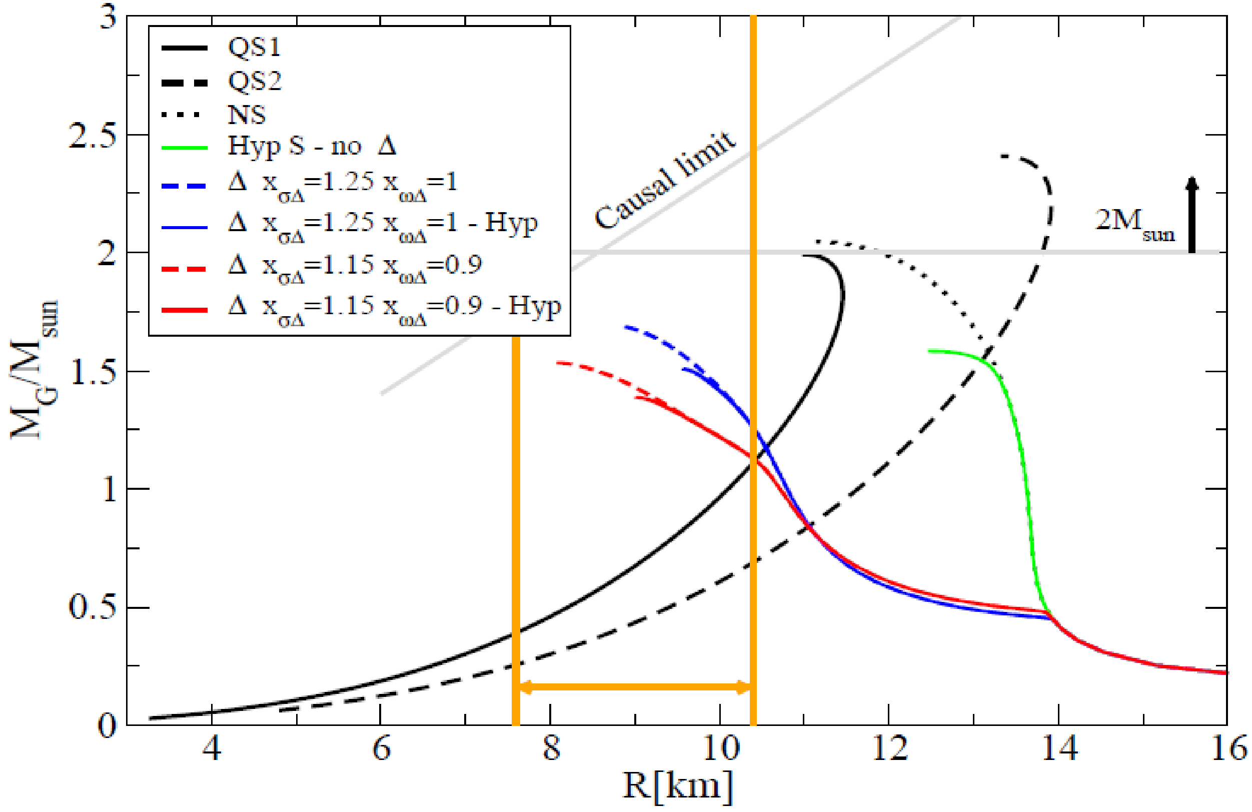
A.D., A. Lavagno, G. Pagliara arXiv:1309.7263

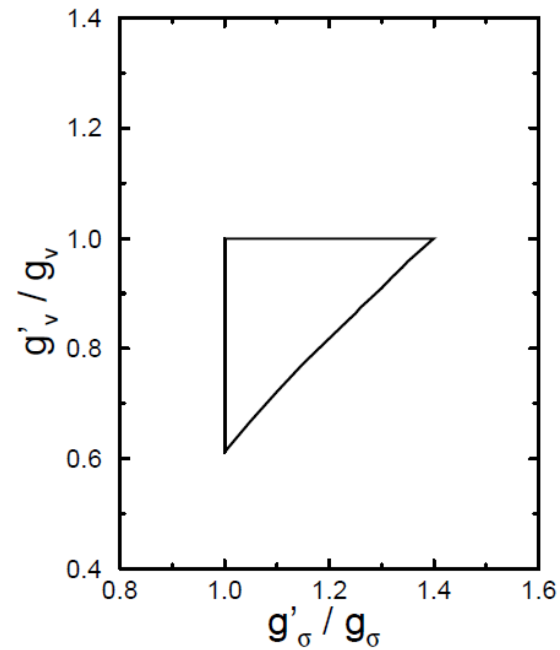
The hadronic star will not transform into a quark star till the moment in which hyperons start appearing, or slightly later. In this way stars with radii of the order of 10 km or smaller are possible and those stars are mainly made of nucleons and Δ-resonances. The most heavy stars would instead be quark stars.



Stars with a mass smaller than about 1.5 M_s would be composed of nucleons and of Δ resonances. Their properties concerning e.g. stability under rapid rotation would be similar to purely nucleonic stars. They would also have a crust. Most of the features of supermassive stars would instead differ from those of normal neutron stars.

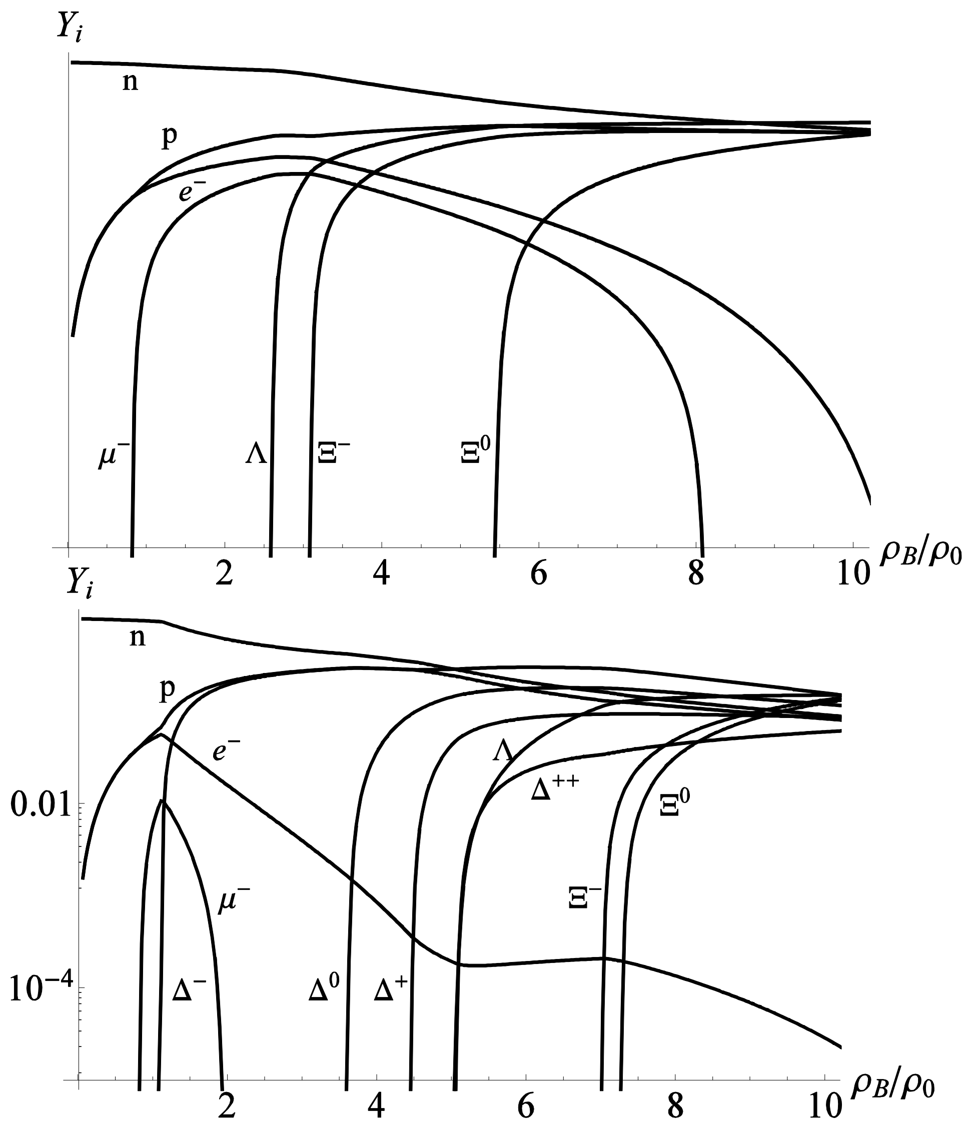
M-R relations and parameters' value





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

Composition of matter without and with Δ-resonances



Δ-resonances can take the place of hyperons, pushing the hyperons' threshold to larger densities

Signatures of a two family scenario

- The energy released in the conversion from hadrons to quarks is typically of the order of 10^{53} erg, large enough to produce a neutrino flux able to revitalize a failed SN explosion.
- A few GRBs could be associated with the conversion from hadrons to quarks. In particular GRBs not associated with a SN can exist.
- The radius of the most massive stars is expected to be large instead of relatively small.
- The most massive stars should be anomalous concerning e.g.:
  - «crust» vibration
  - Cooling
  - Caracteristic of an outburst associated with mass accretion
  - …
- A few (rare) stars with small masses and small radii can exist
- Stars with a mass significantly larger than 2 M_s can exist

Conclusions

- If all measured radii will be of the order of about 12 km we will be able to exclude certain solutions (e.g. the ones based on very stiff phenomenological EOSs at low-moderate densities).
  - «Exotica» will likely be present in at least the more heavy stars.
  - There will be no need to speculate about the existence of quark stars.

- If instead at least a few stars will be found to have radii of the order of 10 km or smaller, than most likely there are two families of compact stars
  - The most heavy objects will be quark stars.
  - Stars of normal mass will not contain significant amount of hyperons or strange quarks. They will behave similarly to nucleonic stars.
- LOFT should be able to distinguish between these two possibilities

Bauswein et al. PRL 103 (2009) 011101