High density matter in compact stars

Alessandro Drago (Ferrara)

Andrea Lavagno (Torino Politecnico)
Giuseppe Pagliara (Ferrara)
Daniele Pigato (Torino Politecnico)

- «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

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

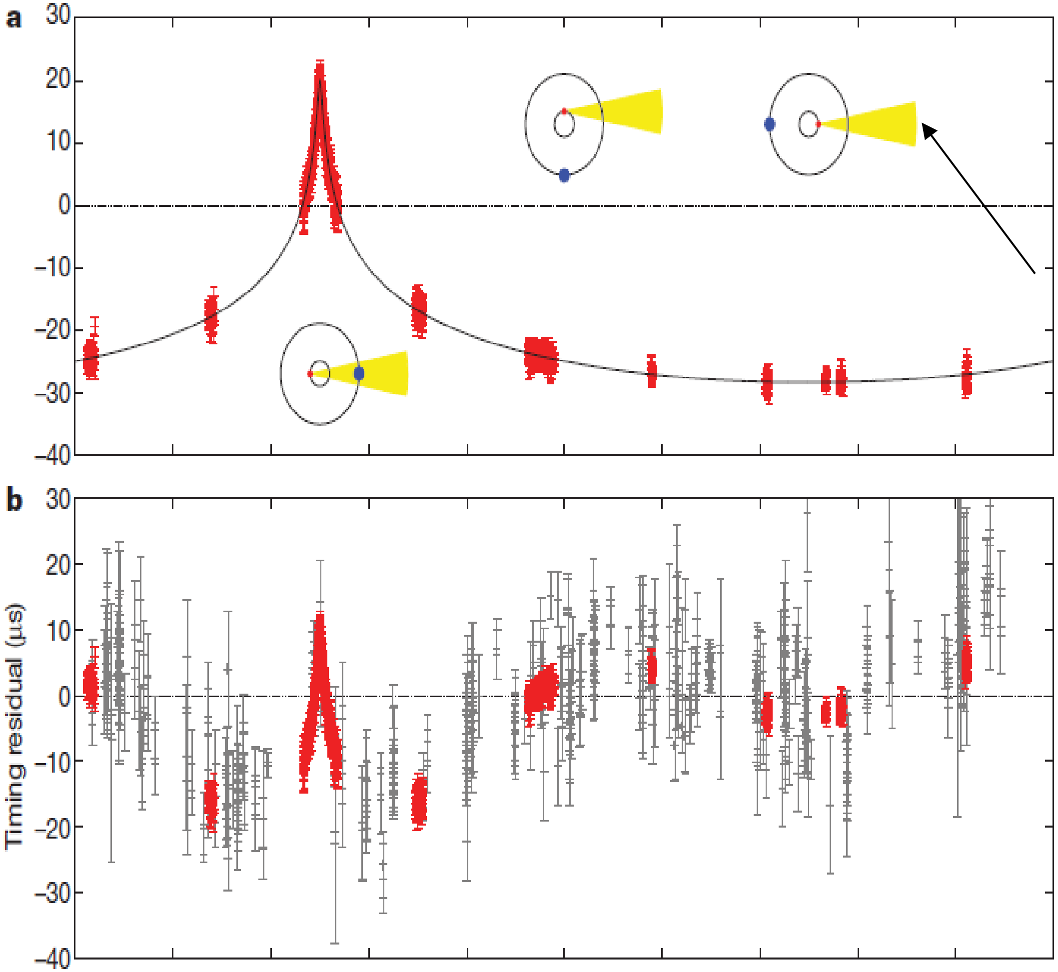
A milestone for neutron stars physics: PSR J1614-2230, M = (1.97± 0.04) Msun

Demorest et al. Nature 2010

More recently, a second star: M= 2.01±0.04 $M_\odot$

Antoniadis et al. 2013

Shapiro delay

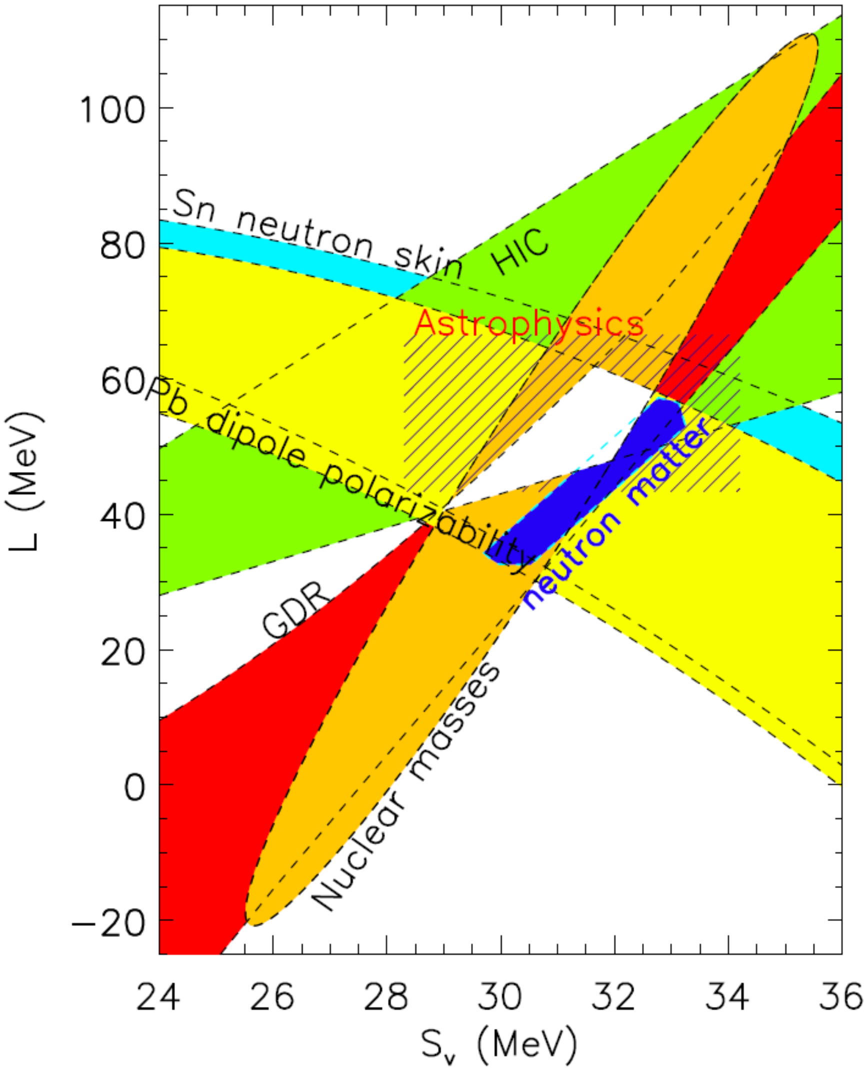


Nuclear and subnuclear densities: symmetry energy

Hebeler et al. 2013

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

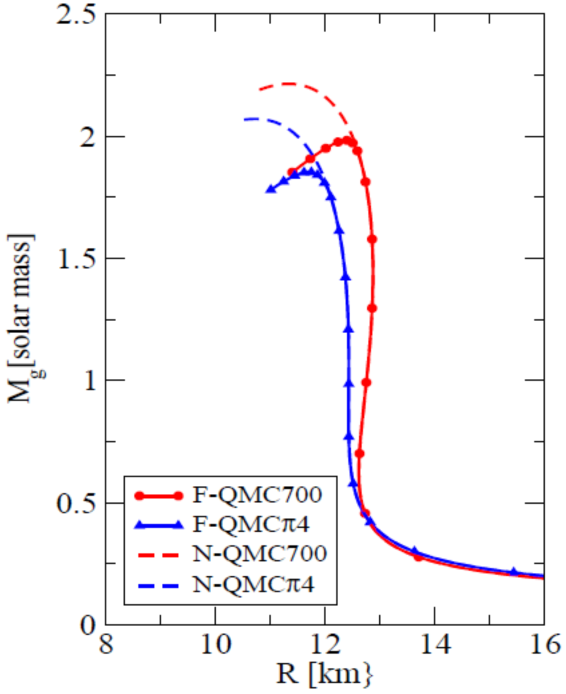
$$L = \frac{3}{8}\frac{\partial^3 \epsilon(\bar{n},x)}{\partial \bar{n}\partial x^2}\Big|_{\bar{n}=1,x=1/2}$$



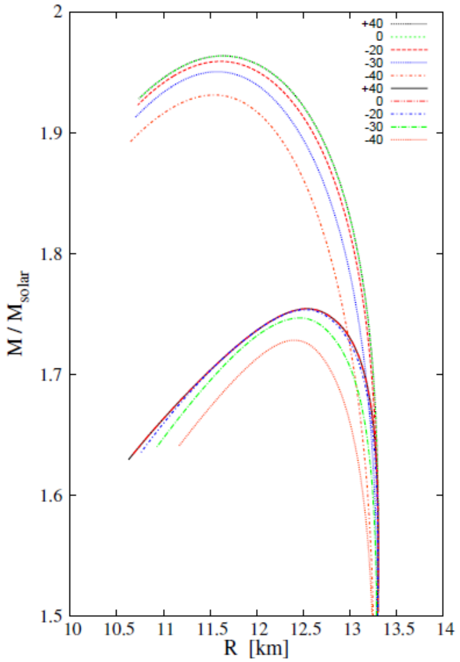
Hyperons in compact stars

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

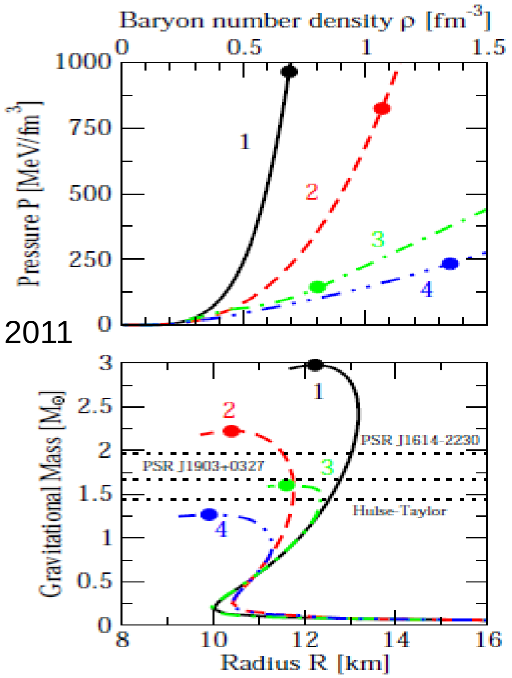
Stone et al. 2006



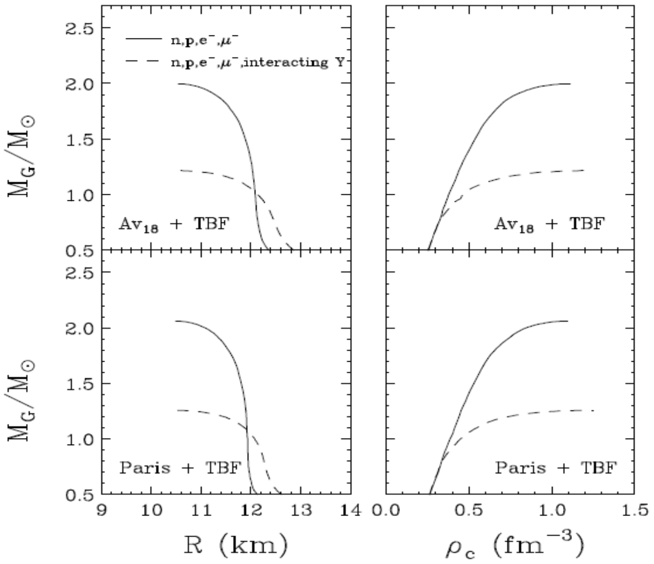
Weissenborn et al. 2011



Vidana et al 2011



Baldo et al 2000



The 2Msun limit can be fulfilled within RMF models.

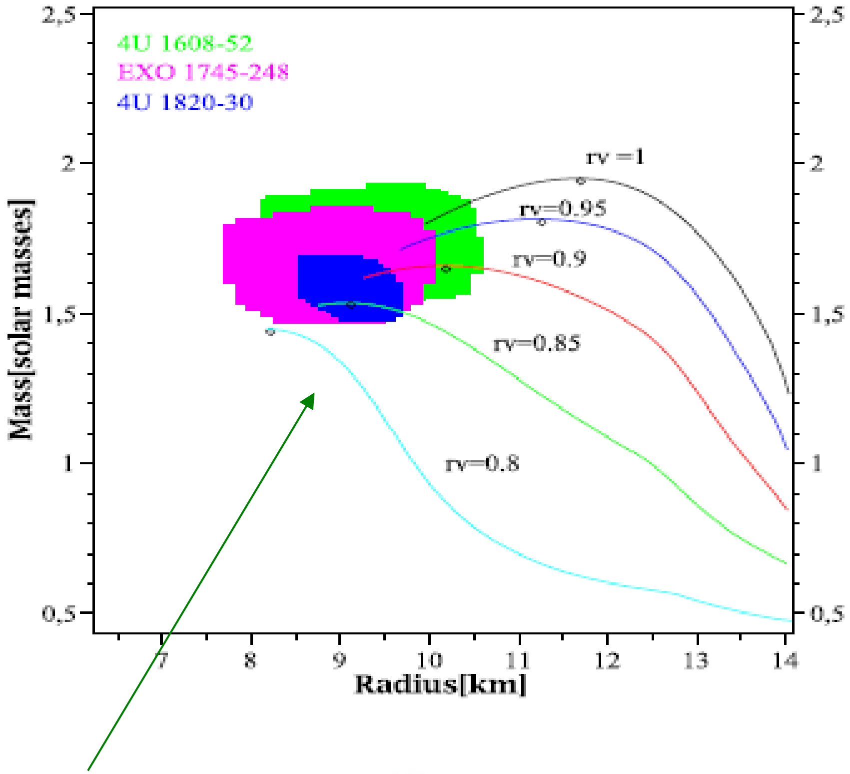
In microscopic not-relativisitc calculations it is fulfilled only if very strong and repulsive 3-body forces YNN are present (Pederiva et al. 2014).

What about Δ's?

(Schurhoff, Dexheimer, Schramm 2010)

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

What about Δ?

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

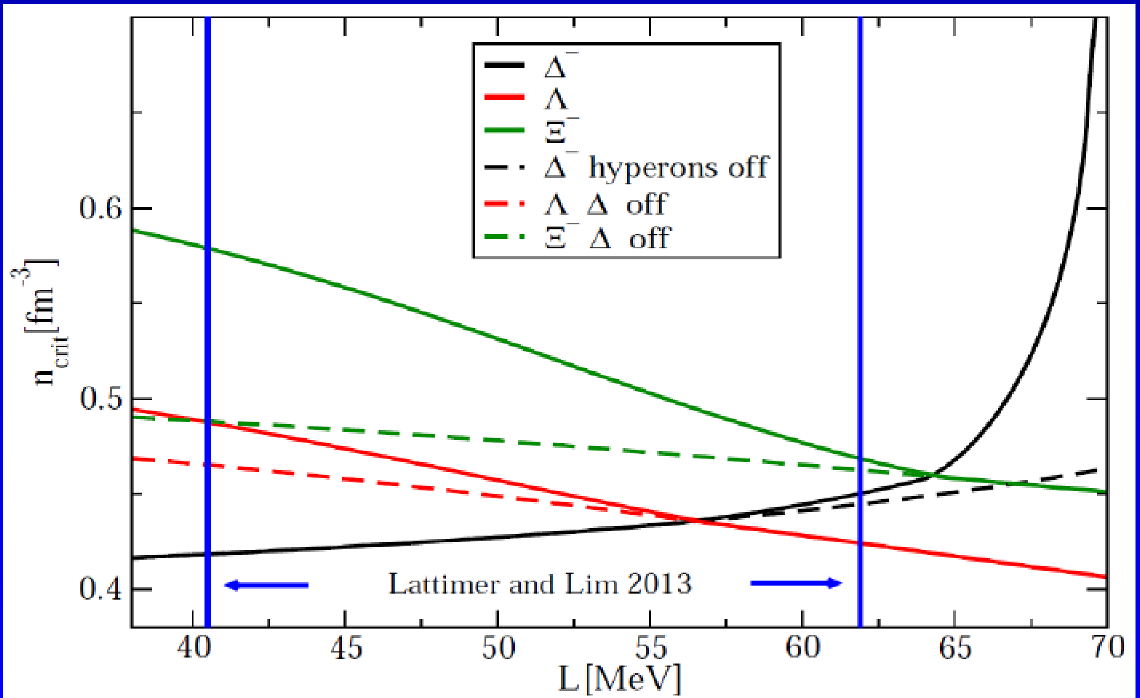
$$\mu_i = \mu_B + c_i\,\mu_C$$

But, it is isospin unfavored:

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

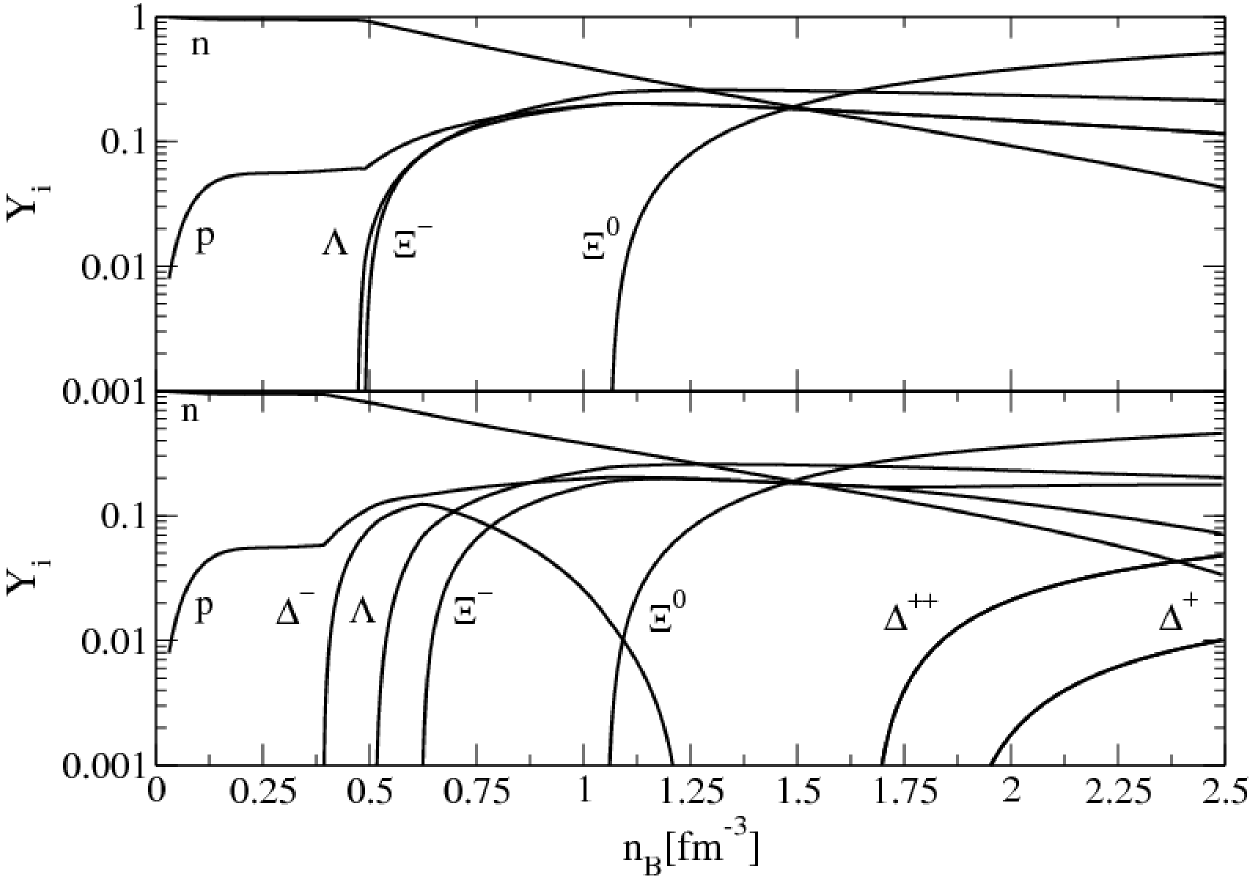
Indeed, in old calculations (see e.g. Glendenning 1985), no deltas are formed in neutron star matter. This is due to the large value of the symmetry energy at densities above saturation.

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



Theoretical and experimental information on Delta – meson couplings

Theoretical analysis:

QCD sum rules $x_\omega << 1$	PRC 51 (1995) 2260
$\Sigma_\Delta = \Sigma_N$ – 30 MeV at 0.75 ρ_0	NPA 468 (1987) 631

$X_\sigma = g_{\sigma\Delta} / g_{\sigma N}$
$X_\omega = g_{\omega\Delta} / g_{\omega N}$

Electron scattering:

$\Sigma_\Delta = -75\ \rho/\rho_0$ MeV	NPA 435 (1985) 765
$0 < x_\sigma - x_\omega < 0.2$	PRC 42(1990) 2290

Pion scattering:

$\Sigma_\Delta = -30$ MeV at $\rho_{surface}$	NPA 345 (1980) 386
$\Sigma_\Delta = \Sigma_N$	PRC 81(2010) 035502

Photo-absorption:

$\Sigma_\Delta = -80$ MeV	PLB 321 (1994) 177

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.

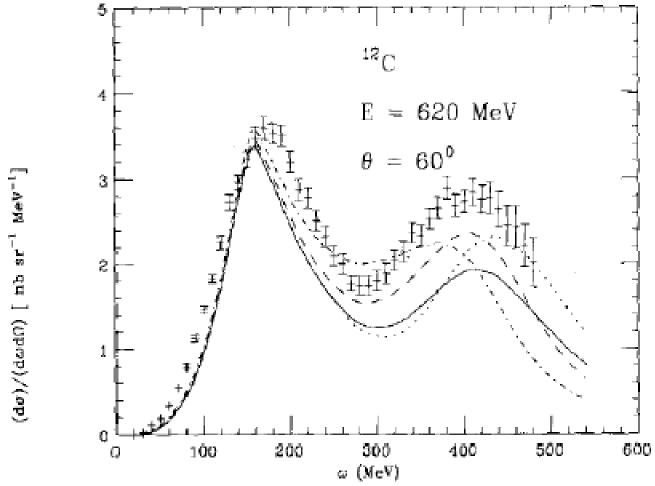
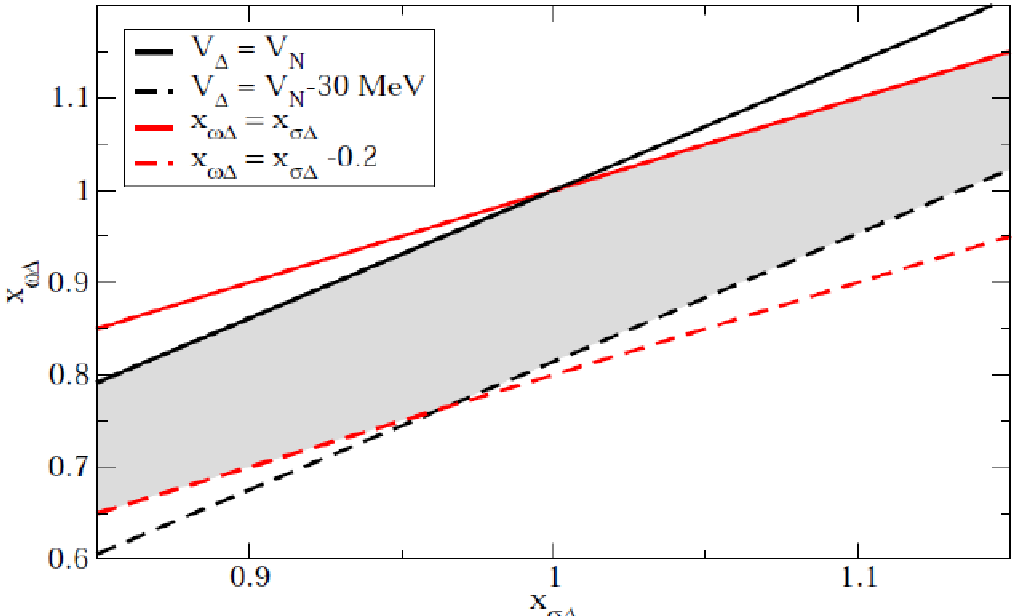
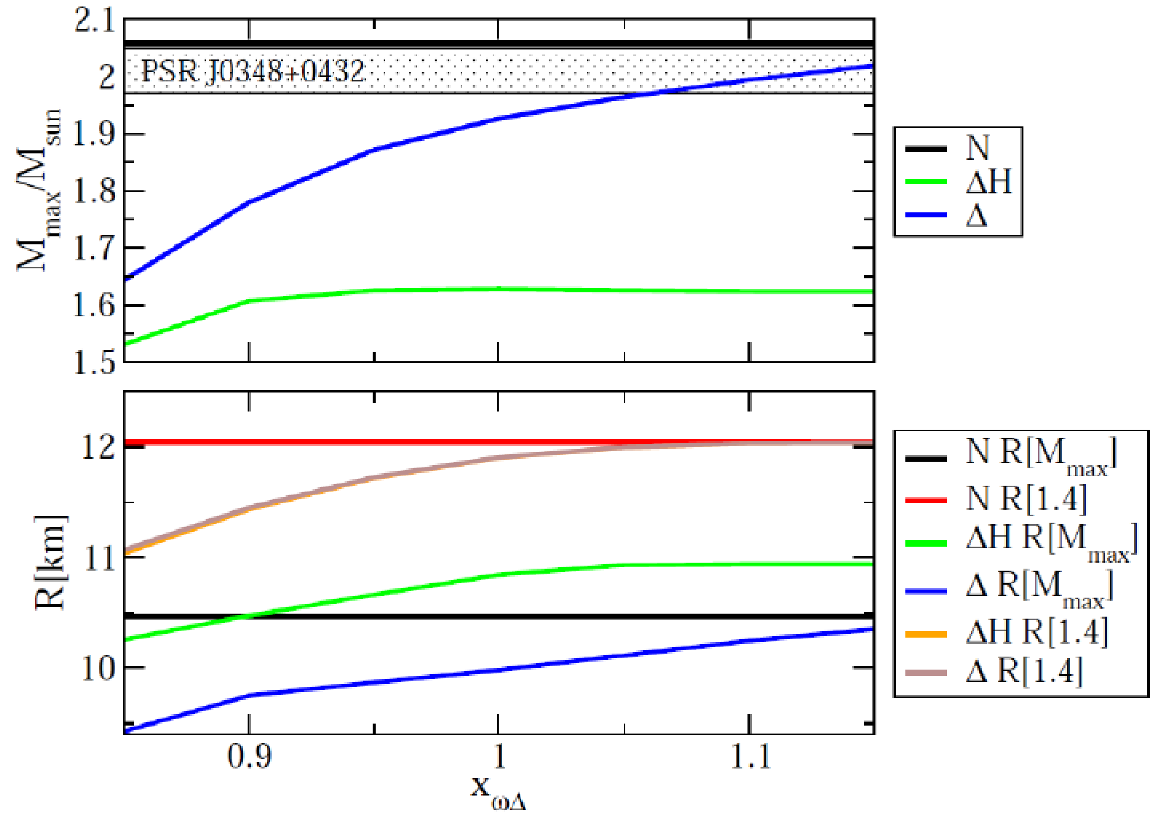


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and 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

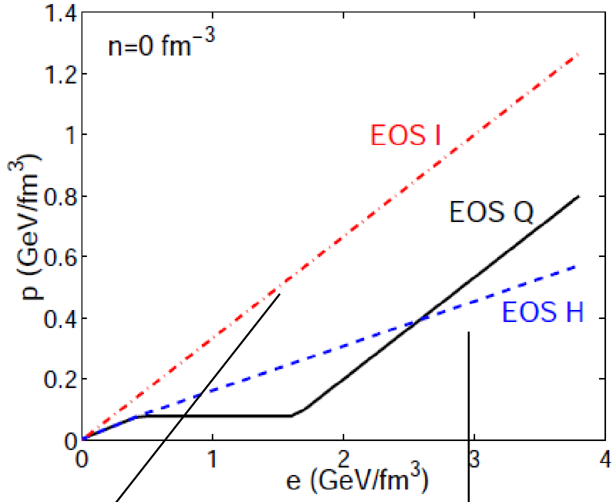
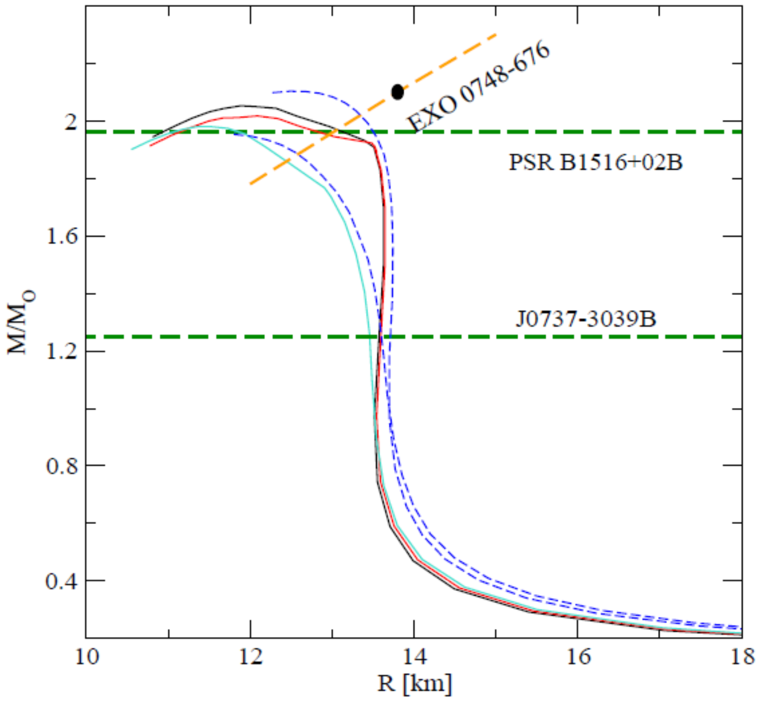


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

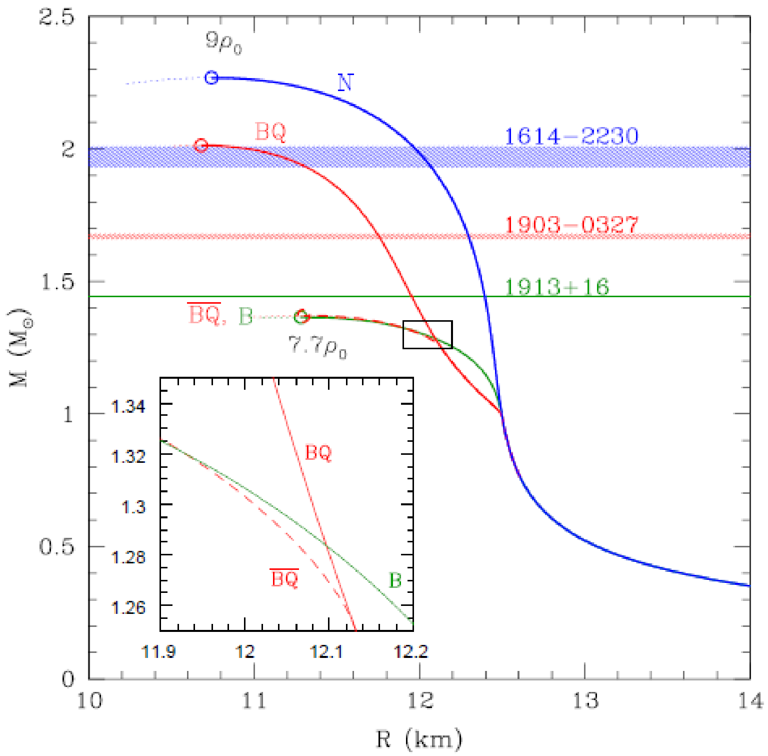
p=e/3 massless quarks **Hadron resonance gas p=e/6**

Hybrid stars: their radii

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



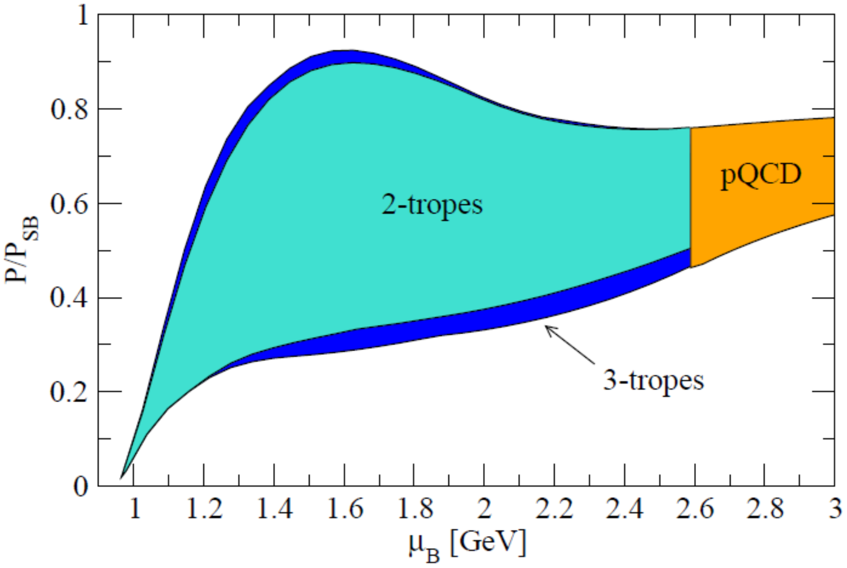
Zdunik and Haensel A&A, 551 (2013) A61

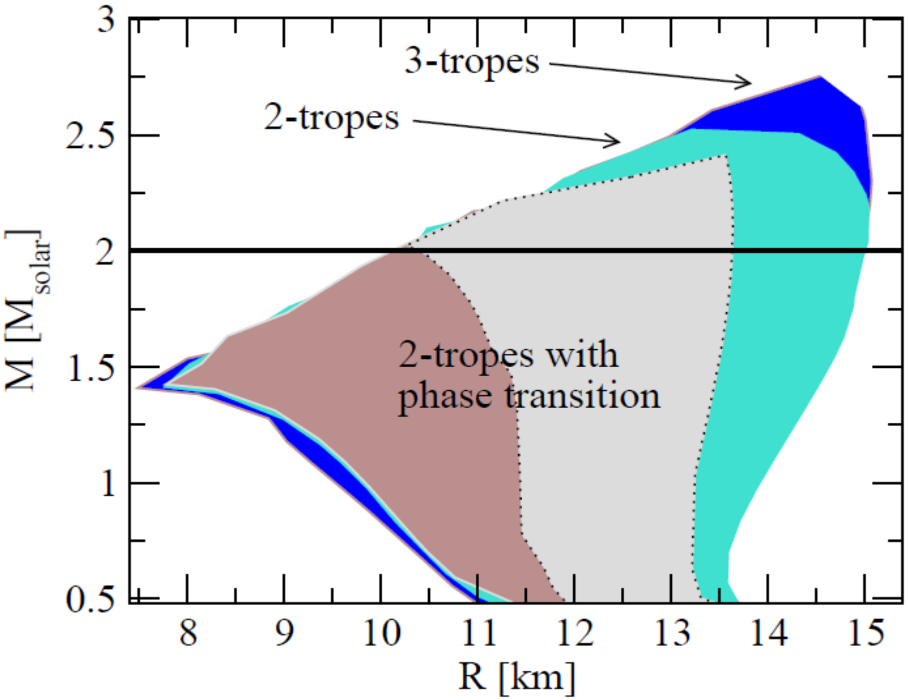


It is possible to satisfy the 2 M_s limit with a hybrid star, but the radius of a 1.4 M_s hybrid star is about 11.5 -- 14 km

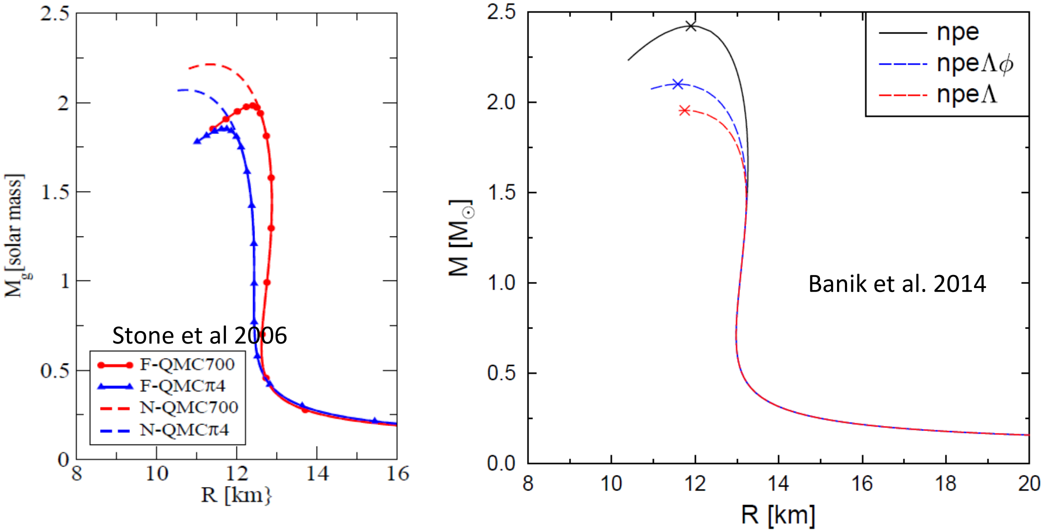
Connecting low densities to very high densities

Kurkela, Fraga, Schaffner-Bielich, Vuorinen 1402.6618

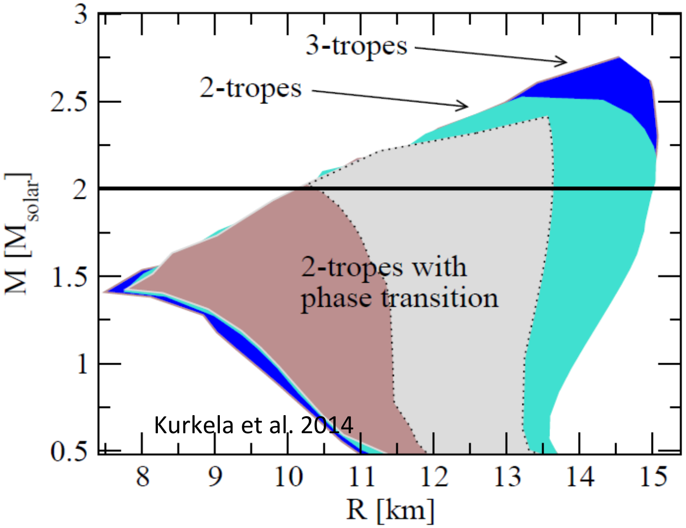




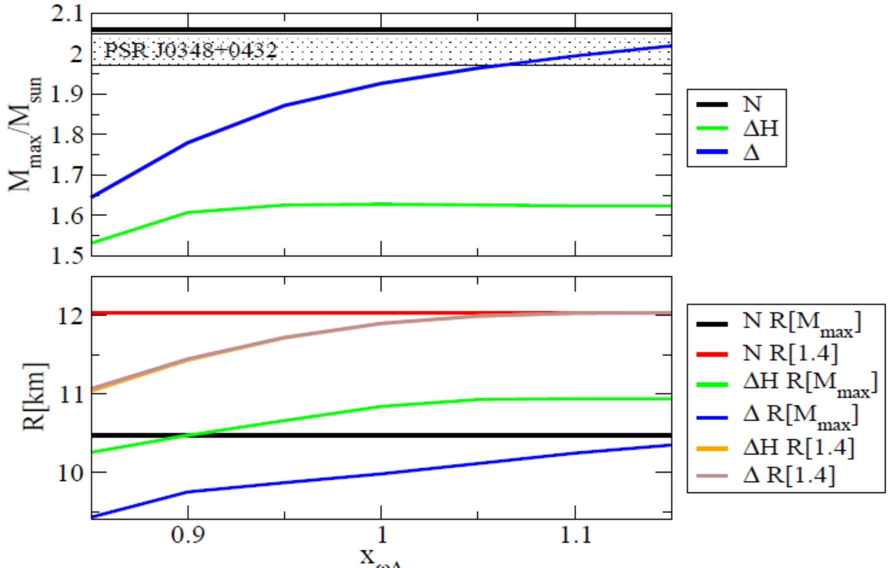
Minimum radius for a 1.4 M_s star



Hyperonic stars $R_{1.4}$ > (12.5 – 13) km

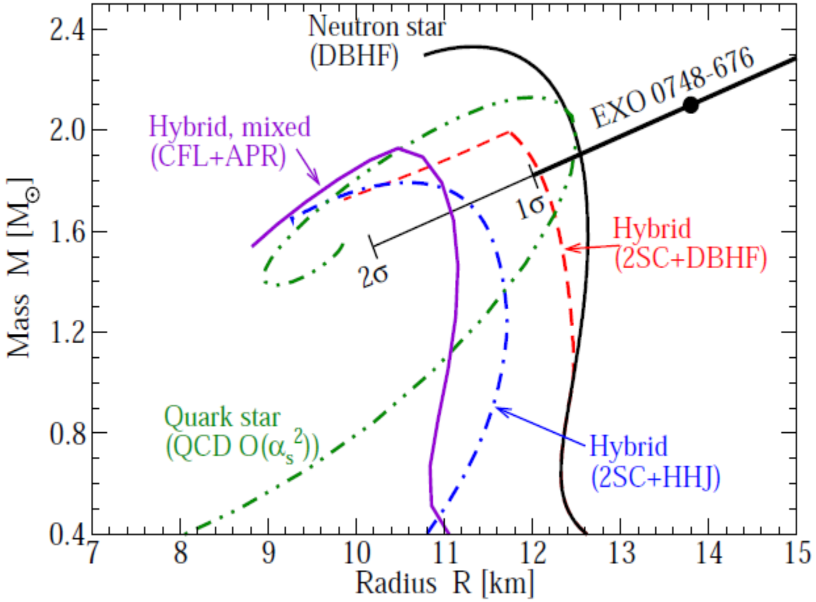


Hybrid stars $R_{1.4}$ > 11.5 km

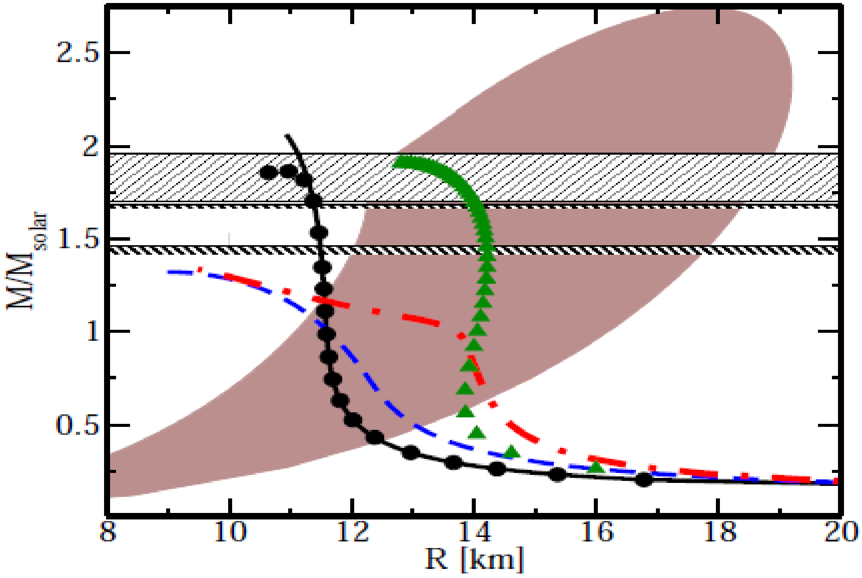


Delta – resonance stars $R_{1.4}$ order of (10-11) km, BUT the maximum mass is smaller than 2 M_s

Hybrid stars or quark stars?



Alford et al Nature 2006

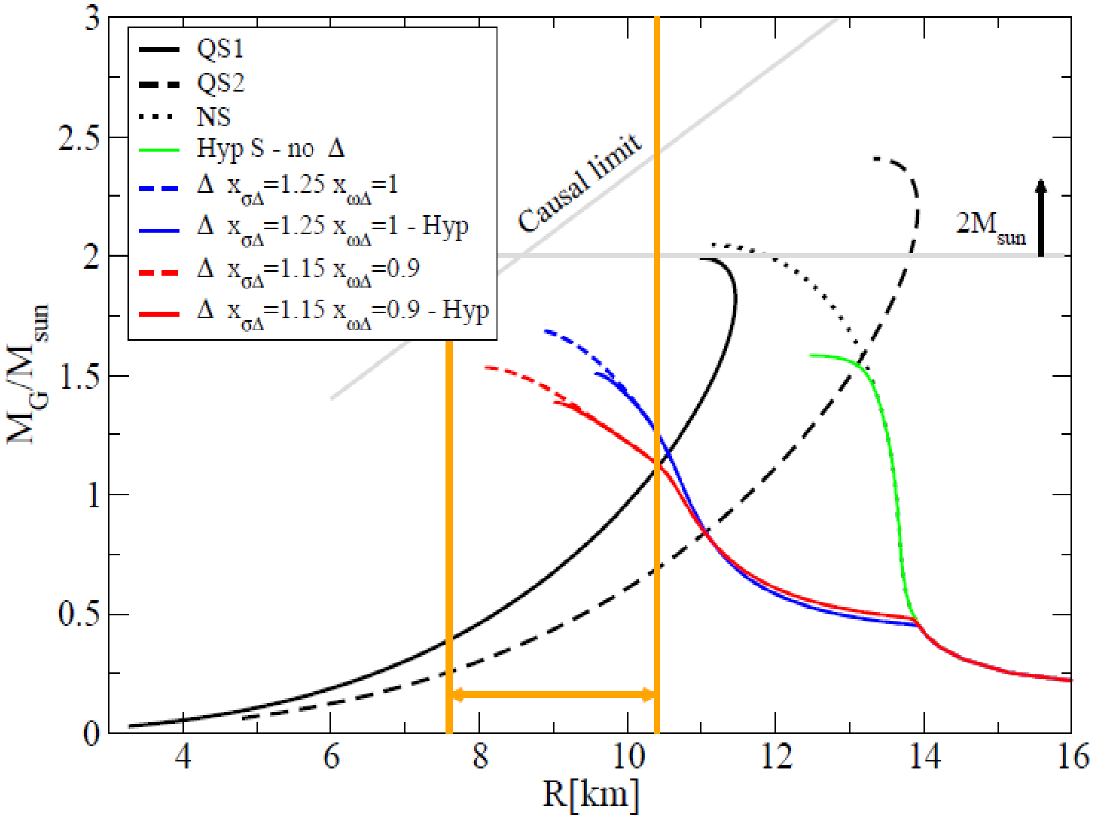


Kurkela et al 2010

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 > $2M_s$ would strongly favor the existence of stable strange quark matter"

Before the discoveries of the $2M_s$ stars!!

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



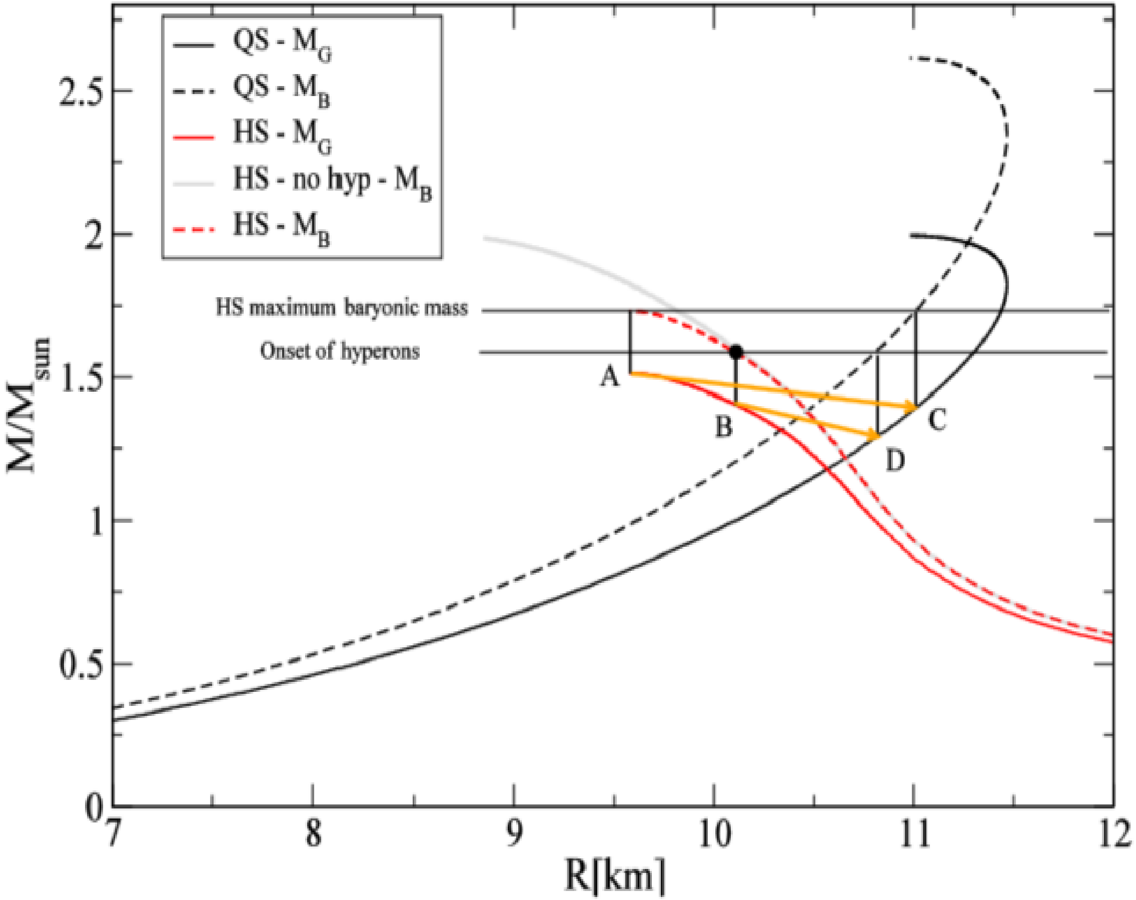
Two families of compact stars:

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.

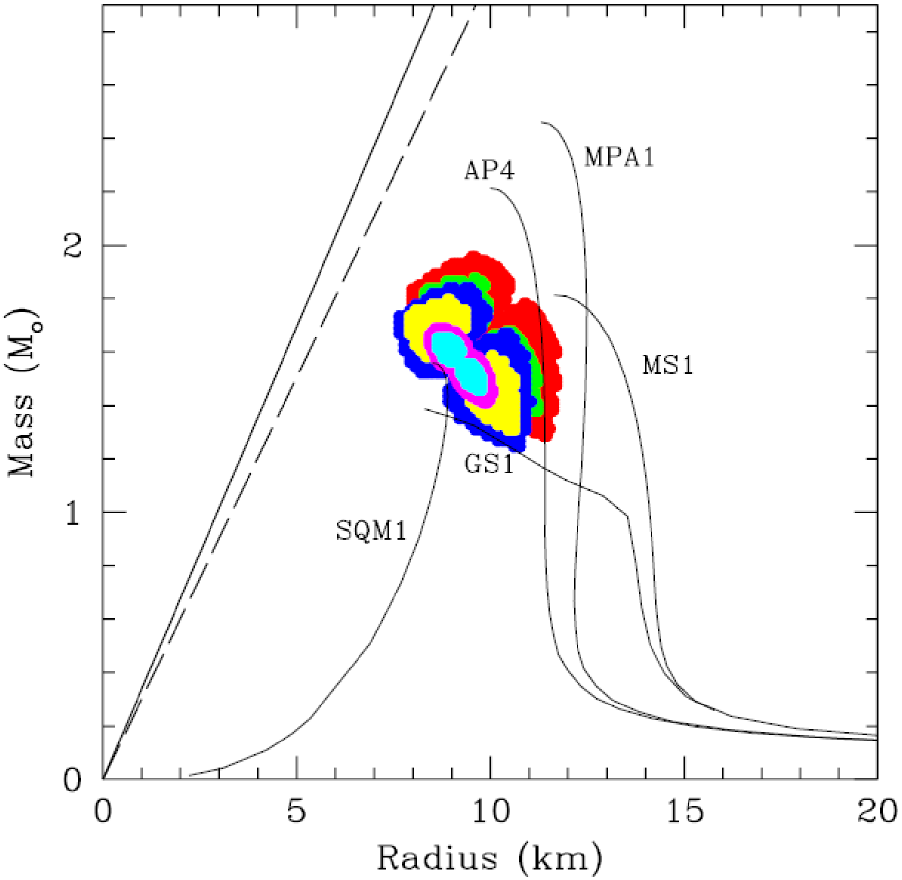
The hadronic stars are stable
till when some strangeness
component (e.g. hyperons)
starts appearing in the core.
Only at that point quark matter
nucleation can start.

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

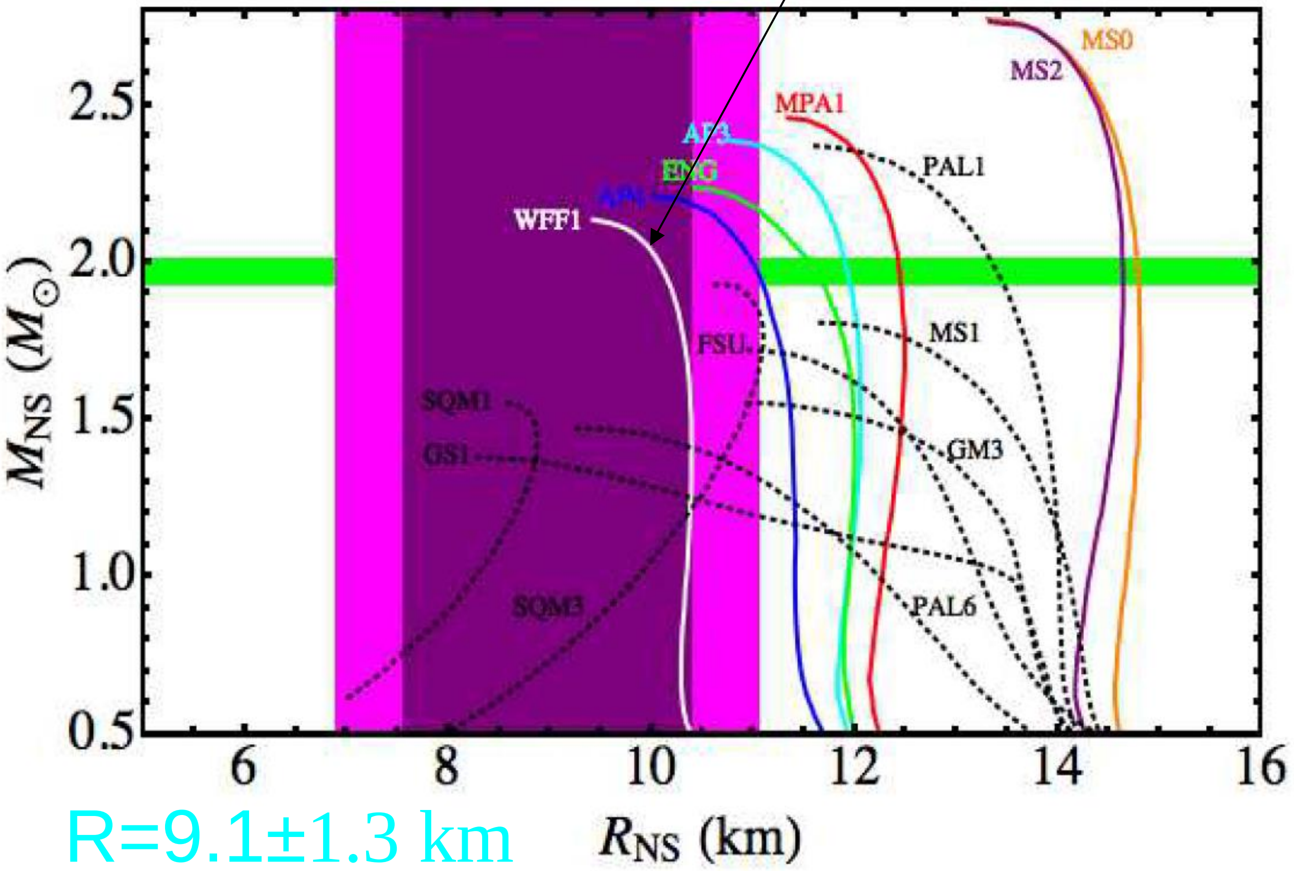


Is there any indication of small radii?
Yes, but they are VERY controversial

Oezel, Baym, Guever 2010



Nice, but just nucleons,
And it violates causality!



R=9.1±1.3 km

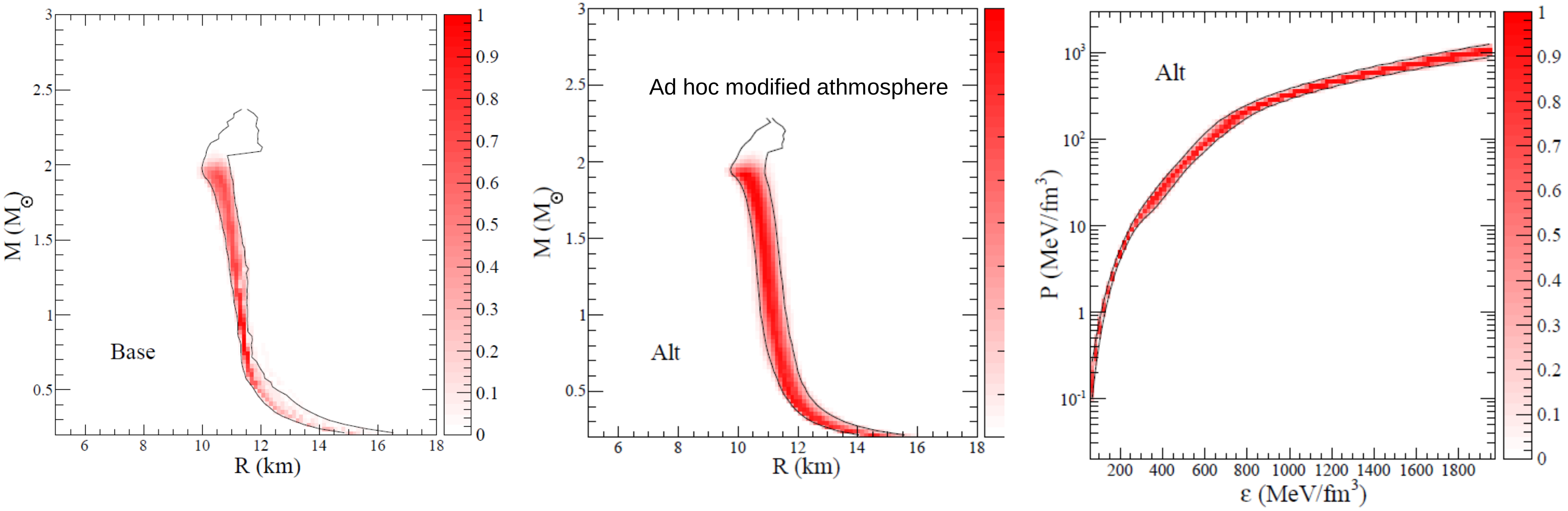
Guillot et al. ApJ772(2013)7
analysis of 5 QLMXBs

Also Guillot and Rutledge 1409.4306

Is bayesian analysis really useful?

From Lattimer & Steiner 2013, same data as Guillot et al 2013

Assuming a single family of compact stars



The hypothesis of the existence of only one family imposes STRONG biases on the data

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,
can clarify the composition of compact stars:

- **$R_{1.4}$ >= 13 km purely nucleonic stars**
- **11.5 km < $R_{1.4}$ < 13 km hyperonic or hybrid stars**
- **$R_{1.4}$ << 11.5 km two families of compact stars**