Electromagnetic and gravitational wave probe of high-density matter

Alessandro Drago – University of Ferrara

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Plan of lectures

- Theory of «neutron» star structure
  - TOV equation
  - β-stable and charge neutral matter
  - The microphysics: nucleons, hyperons, (deltas), quarks
  - Quark stars?
- Data on masses and radii from radio and X-ray observations
- What happens when two NSs merge?
  - Gravitational wave signal
  - Short GRBs

Einstein equations

$$\boxed{R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} \overline{R} = \frac{8\pi G}{c^4} T^{\mu\nu}}$$

$R^{\mu\nu}$ = Ricci tensor, $\overline{R} = g_{\mu\nu} R^{\mu\nu}$ = scalar curvature

for the present **static, spherical symmetric** case the Einstein's field equations take the form called the **Tolman – Oppenheimer – Volkov equations (TOV)**

$$\frac{dP}{dr} = -G \frac{m(r)\rho(r)}{r^2} \left(1 + \frac{P(r)}{c^2 \rho(r)}\right) \left(1 + 4\pi \frac{r^3 P(r)}{m(r)\; c^2}\right) \left[1 - \frac{2Gm(r)}{c^2 \; r}\right]^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{d\Phi}{dr} = -\frac{1}{\rho(r)c^2} \frac{dP}{dr} \left(1 + \frac{P(r)}{\rho(r)c^2}\right)^{-1}$$

In the limit: $P << \rho c^2, \quad P r^3 << mc^2, \quad \frac{2Gm}{c^2} << r$

Newtonian case

$$\boxed{\begin{aligned} \frac{dP}{dr} &= -G \frac{m(r)\rho(r)}{r^2} \\ \frac{dm}{dr} &= 4\pi r^2 \rho(r) \\ c^2 \frac{d\Phi}{dr} &= \frac{Gm}{r^2} \end{aligned}}$$

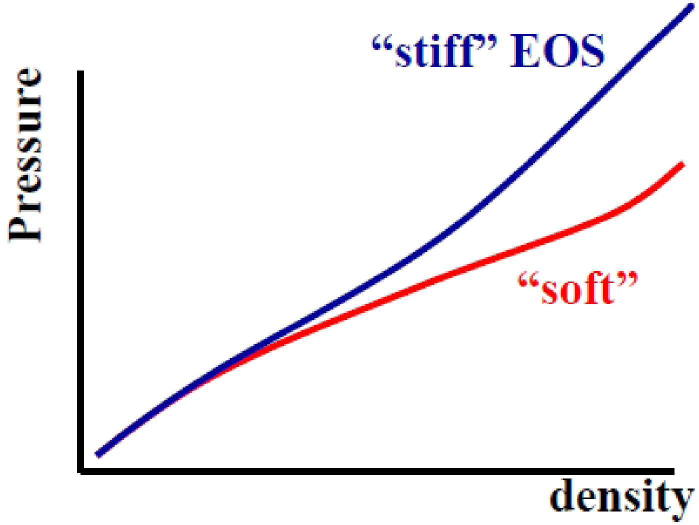
$$U(r) = c^2 \Phi(r) = -\frac{Gm}{r}$$

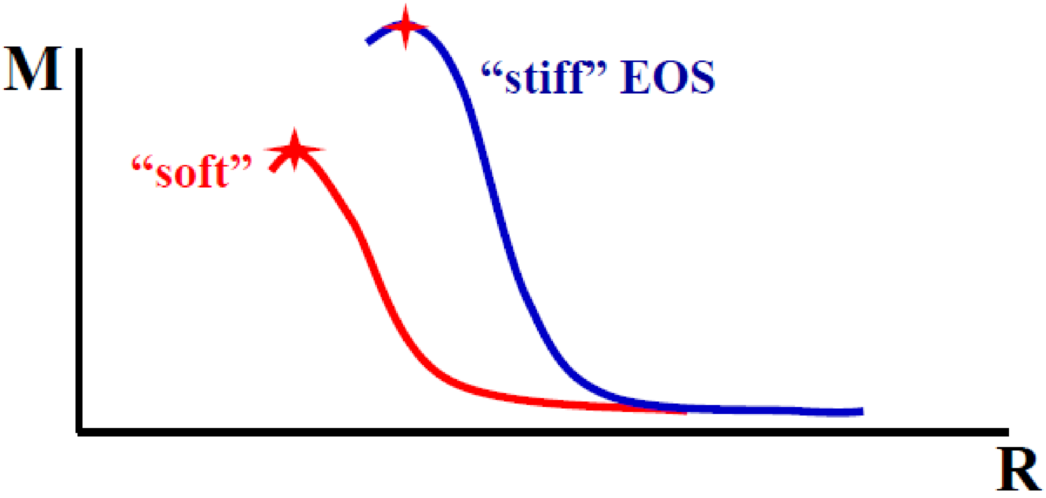
The Oppenheimer-Volkoff maximum mass

There is a maximum value for the gravitational mass of a Neutron Star that a given EOS can support. This mass is called the Oppenheimer-Volkoff mass

$$M_{max} = (1.4 - 2.5)\ M_\odot$$

EOS dependent





The OV mass represent the key physical quantity to separate (and distinguish) Neutrons Stars from Black Holes.

The first calculation of the Neutron Stars structure

- Neutron ideal relativistic Fermi gas

  (Oppenheimer, Volkoff, 1939).

$M_{max} = 0.71\ M_\odot$, $R = 9.5$ km, $n_c/n_0 = 13.75$

$$M_{max} < M_{PSR1913+16} = 1.4408 \pm 0.0003\ M_\odot$$

Too soft EOS : needs repulsions from nn strong interaction !

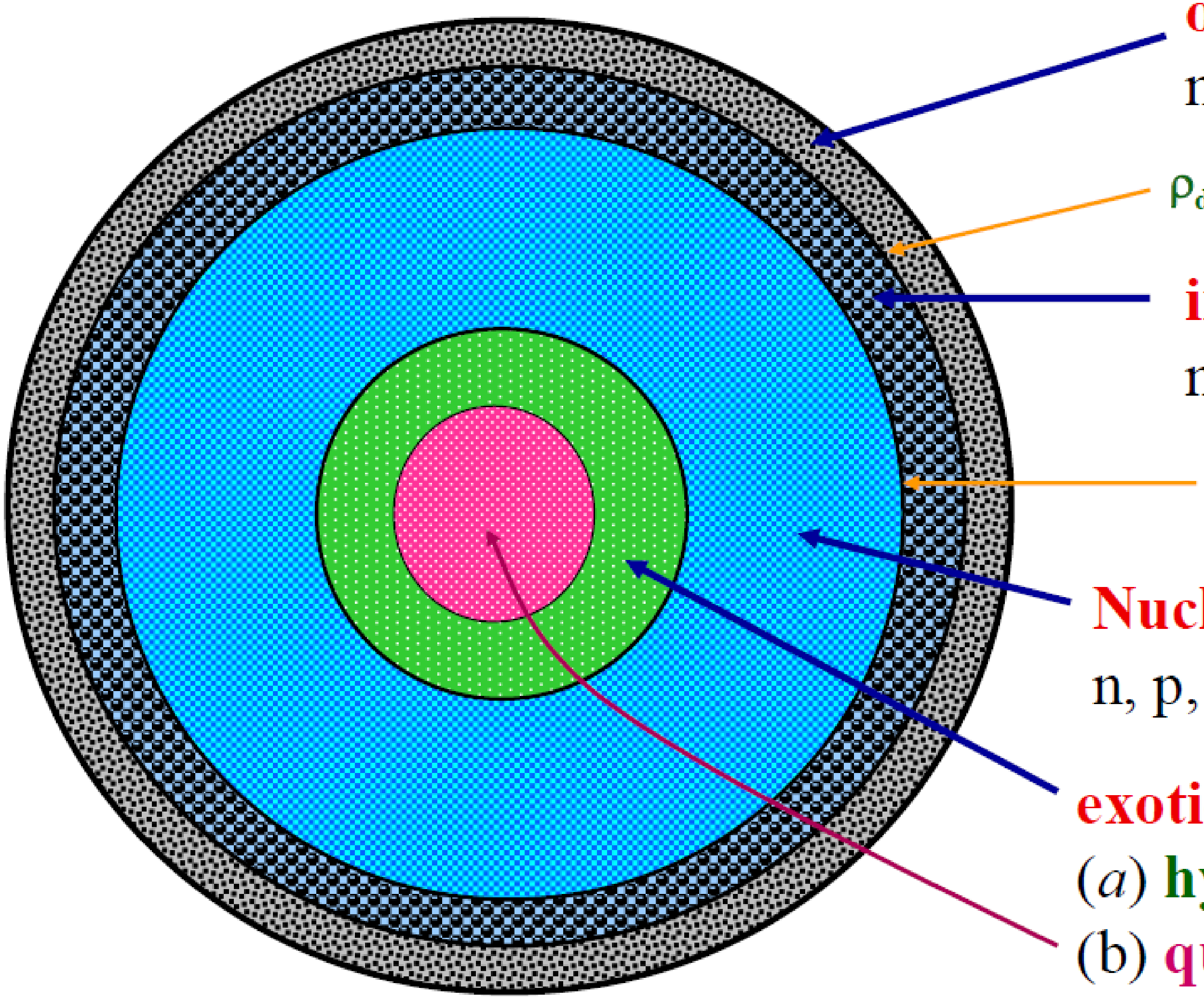
- Role of the weak interaction

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Some protons must be present in dense matter to balance this reaction.

The core of a Neutron Star can not be made of pure neutron matter

Schematic cross section of a Neutron Star



outer crust

nuclei, e^-

$\rho_{drip} = 4.3 \times 10^{11}$ g/cm^3

inner crust

nuclei, n, e^-

~1.5 ×10^{14} g/cm^3

Nuclear matter layer

n, p, e^-, μ^-

exotic core

(*a*) **hyperonic matter**

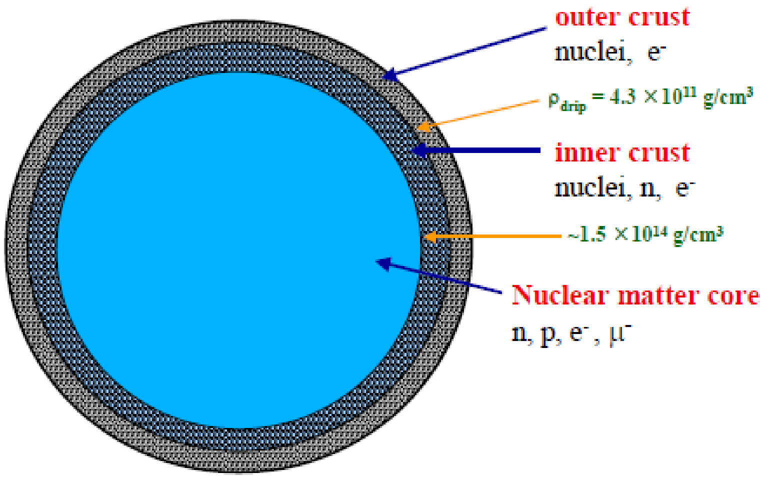
(b) **quark matter**

$M \sim 1.4\ M_\odot$ **R ~ 10 km**

Neutron Stars with a nuclear matter core

As we have already seen due to the weak interaction, the core of a Neutron Star can not be made of pure neutron matter.

Core constituents: n, p, e^-, μ^-



outer crust
nuclei, e^-

$\rho_{drip} = 4.3 \times 10^{11}$ g/cm^3

inner crust
nuclei, n, e^-

~1.5×10^{14} g/cm^3

Nuclear matter core
n, p, e^-, μ^-

β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$
$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$\text{if} \quad \mu_e \geq m_\mu = 105.6\,MeV$$
$$e^- \leftrightarrow \mu^- + \nu_e + \bar{\nu}_\mu$$
$$p + \mu^- \leftrightarrow n + \nu_\mu$$

$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

neutrino-free matter

☐ **Equilibrium with respect to the weak interaction processes**

$$\mu_n - \mu_p = \mu_e$$
$$\mu_\mu = \mu_e$$

☐ **Charge neutrality**

$$n_p = n_e + n_\mu$$

To be solved for any given value of the total baryon number density n_B

Proton fraction in β-stable nuclear matter and role of the nuclear symmetry energy

$$\boxed{\hat{\mu} \equiv \mu_n - \mu_p = -\frac{\partial(E/A)}{\partial x} = 2\frac{\partial(E/A)}{\partial \beta}}$$

$$\boxed{E_{sym}(n) \equiv \frac{1}{2}\frac{\partial^2(E/A)}{\partial \beta^2}\bigg|_{\beta=0}}$$

$$\begin{cases} \beta = (n_n - n_p)/n = 1 - 2x \\ n = n_n + n_p \end{cases}$$

$\beta = (n_n - n_p)/n = 1 - 2x$ asymmetry paramter

$x = n_p/n$ proton fraction

$n = n_n + n_p$ total baryon density

Energy per nucleon for asymmetric nuclear matter(*)

$$E(n,\beta)/A = E(n,\beta=0)/A + E_{sym}(n)\,\beta^2$$

$\beta = 0$ **symm nucl matter**

$\beta = 1$ **pure neutron matter**

$$E_{sym}(n) = E(n,\beta=1)/A - E(n,\beta=0)/A$$

⇒

$$\boxed{\hat{\mu} = 4\ E_{sym}(n)\ [1 - 2x]}$$

Chemical equil. + charge neutrality (no muons)

$$\boxed{3\pi^2(\hbar c)^3\, n\, x(n) - \left[4\, E_{sym}(n)\, \big(1 - 2\, x(n)\big)\right]^3 = 0}$$

The composition of β-stable nuclear matter is strongly dependent on the nuclear symmetry energy.

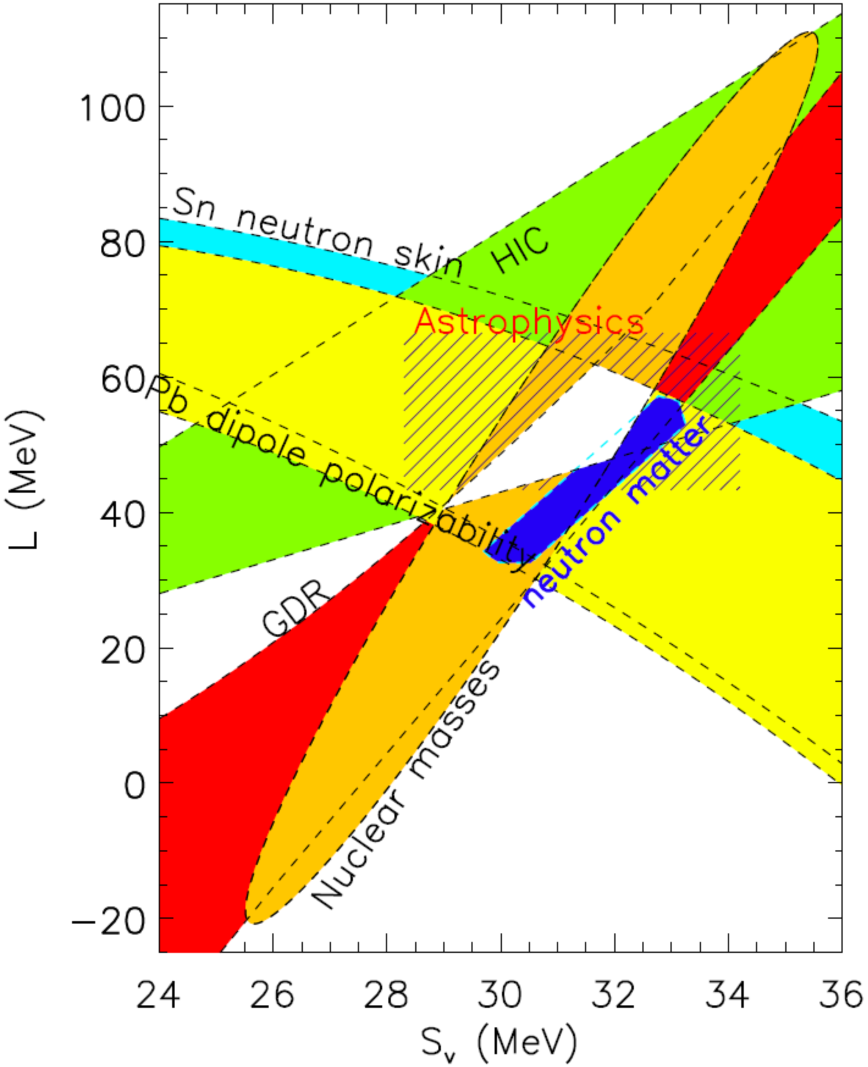
(*) Bombaci, Lombardo, Phys. Rev: C44 (1991)

Nuclear and subnuclear densities: symmetry energy

Hebeler et al. ApJ 773 (2013) 11

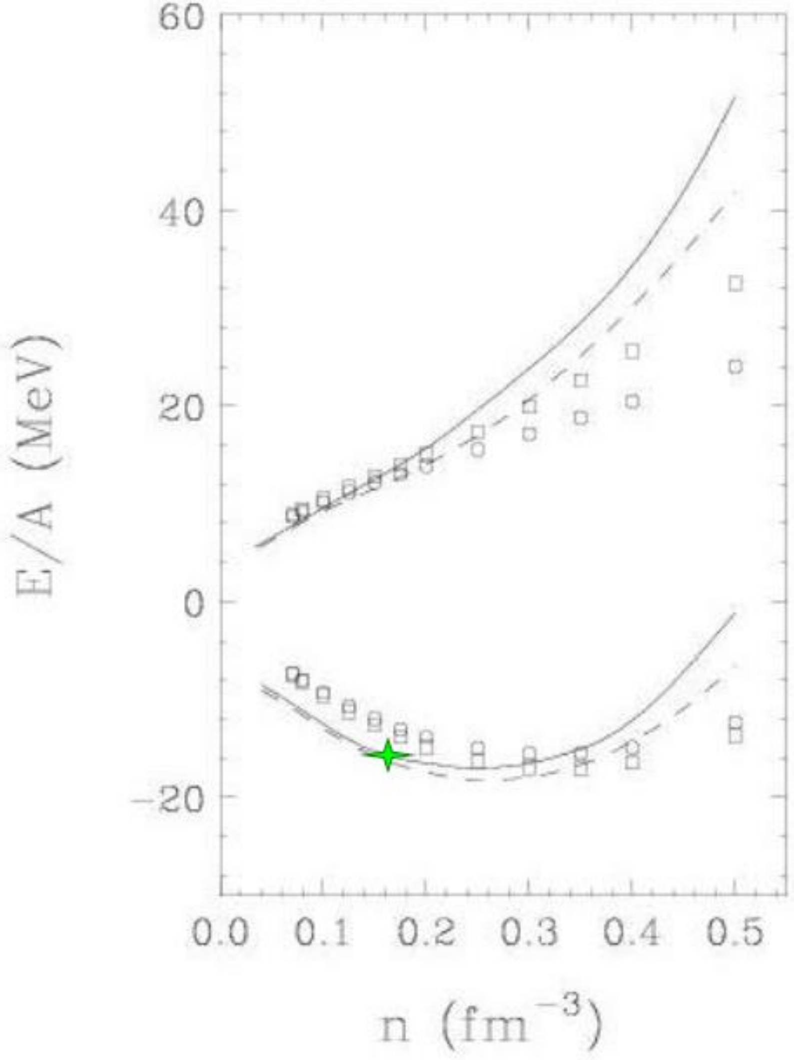
$$S_v = \frac{1}{8}\frac{\partial^2 \epsilon(\bar{n},x)}{\partial x^2}\bigg|_{\bar{n}=1,x=1/2}$$

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



Energy per baryon

(two body forces only)



Three Body Forces (TBF) **are necessary to get the** **correct saturation point** **of nuclear matter in non-relativistic many-body calculations**

Empirical saturation point ✦

BHF with A14 - - - - - - - - -

BHF with Paris ———————

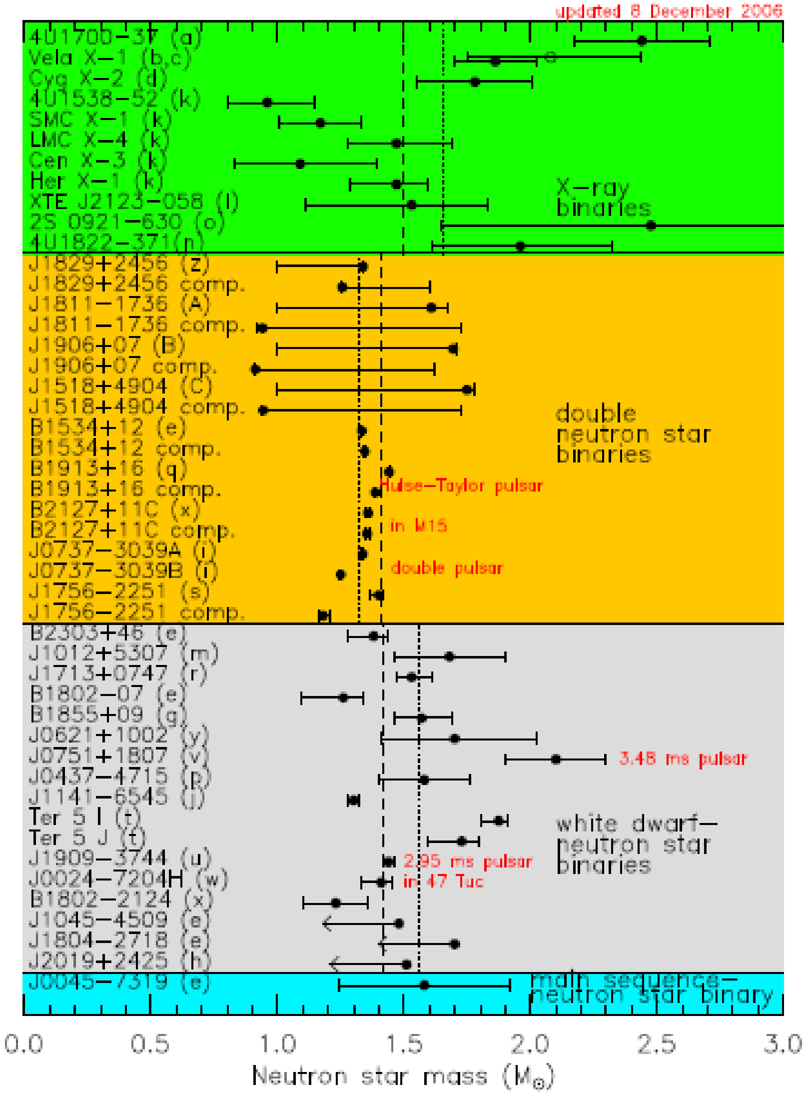
WFF: CBF with U14 □□□□□□□□□□

WFF: CBF with A14 ○○○○○○○○○○

Baldo, Bombaci, Burgio, Astr. & Astrophys. 328, (1997)

Masses

Lattimer and Prakash 2007



B1516+02B
M=1.96 (+0.09-0.12)
Freire 2008

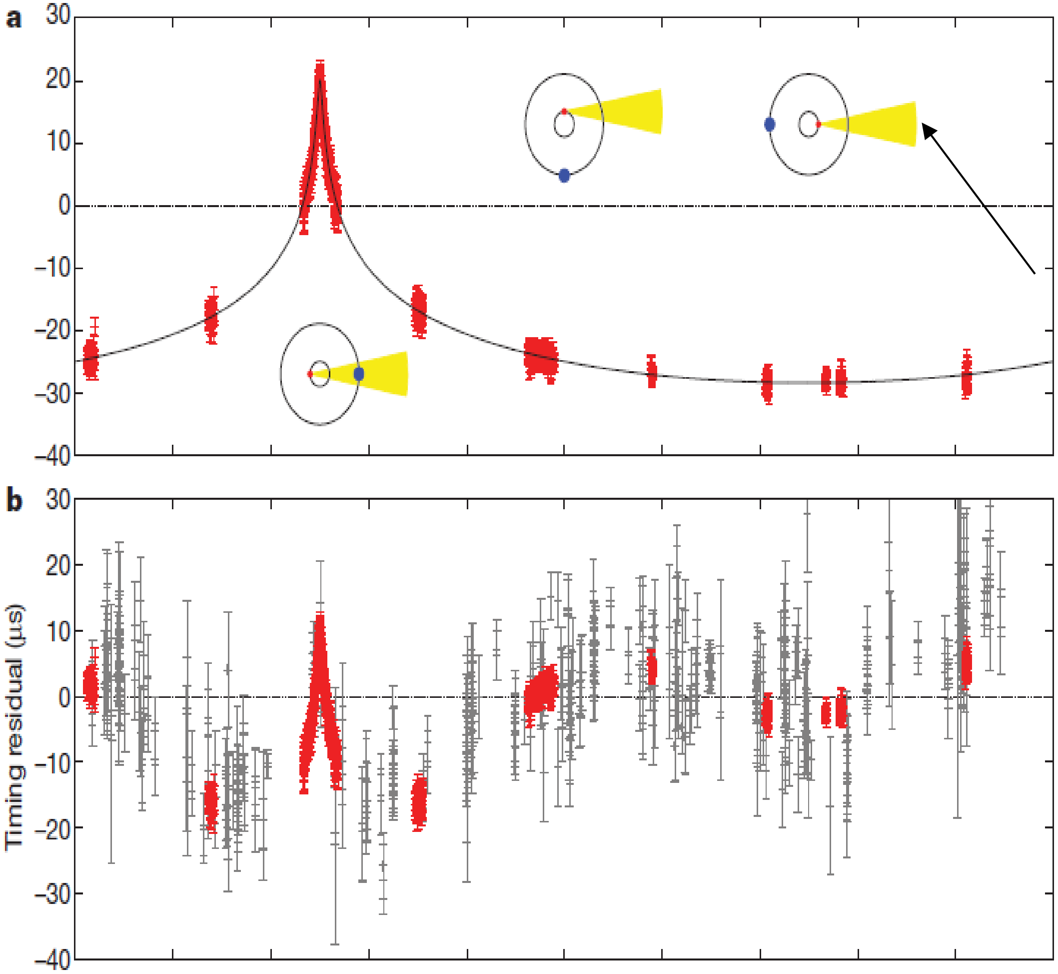
A milestone for neutron stars physics: PSR J1614-2230, M = (1.97± 0.04) $M_\odot$

Demorest et al. Nature 2010

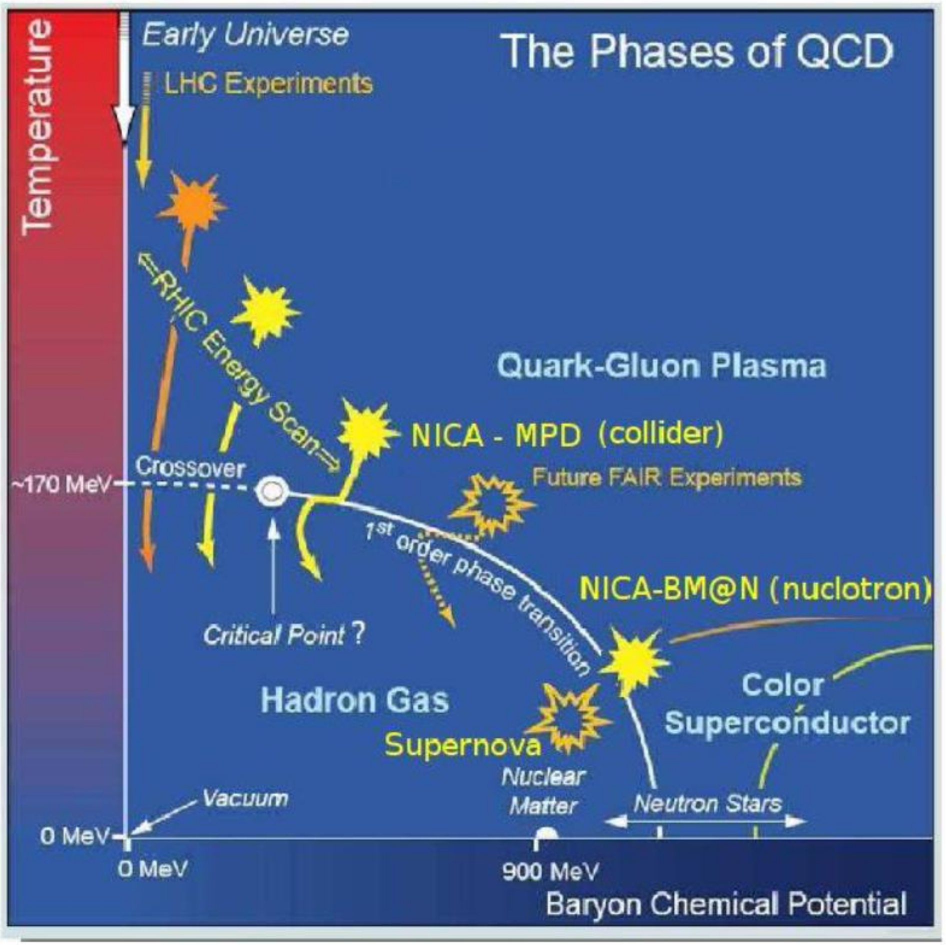
More recently, a second star: PSR J0348+0432, M= 2.01±0.04 $M_\odot$

Antoniadis et al. 2013

Shapiro delay



Testing matter in the lab and in the stars



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%

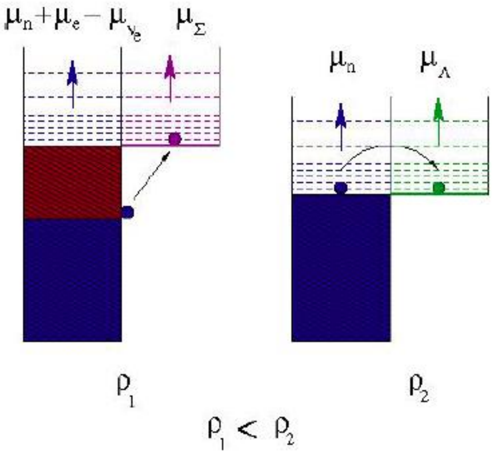
- In a compact star strangeness is mainly produced by weak interaction. Hyperons «normally» start appearing at densities above (2.5 – 3) ρ_0

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

  2 M_s compact star with hyperons? Yes, but…

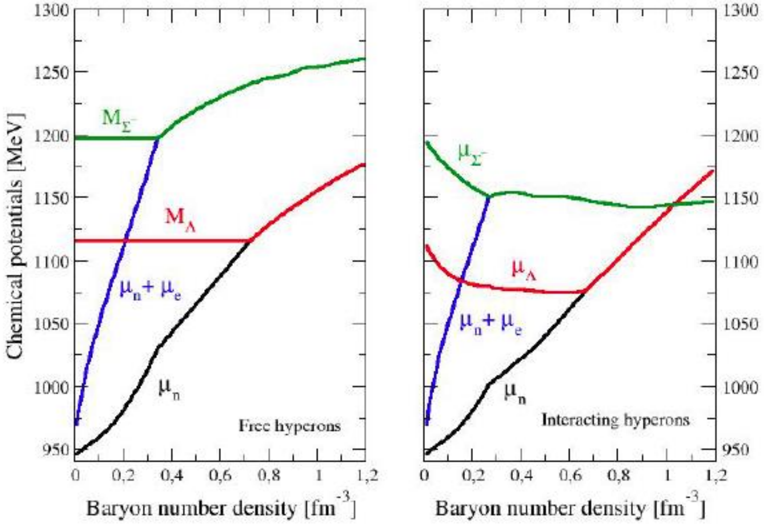
Borrowed from I. Vidana

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

$$\mu_\Lambda = \mu_n$$



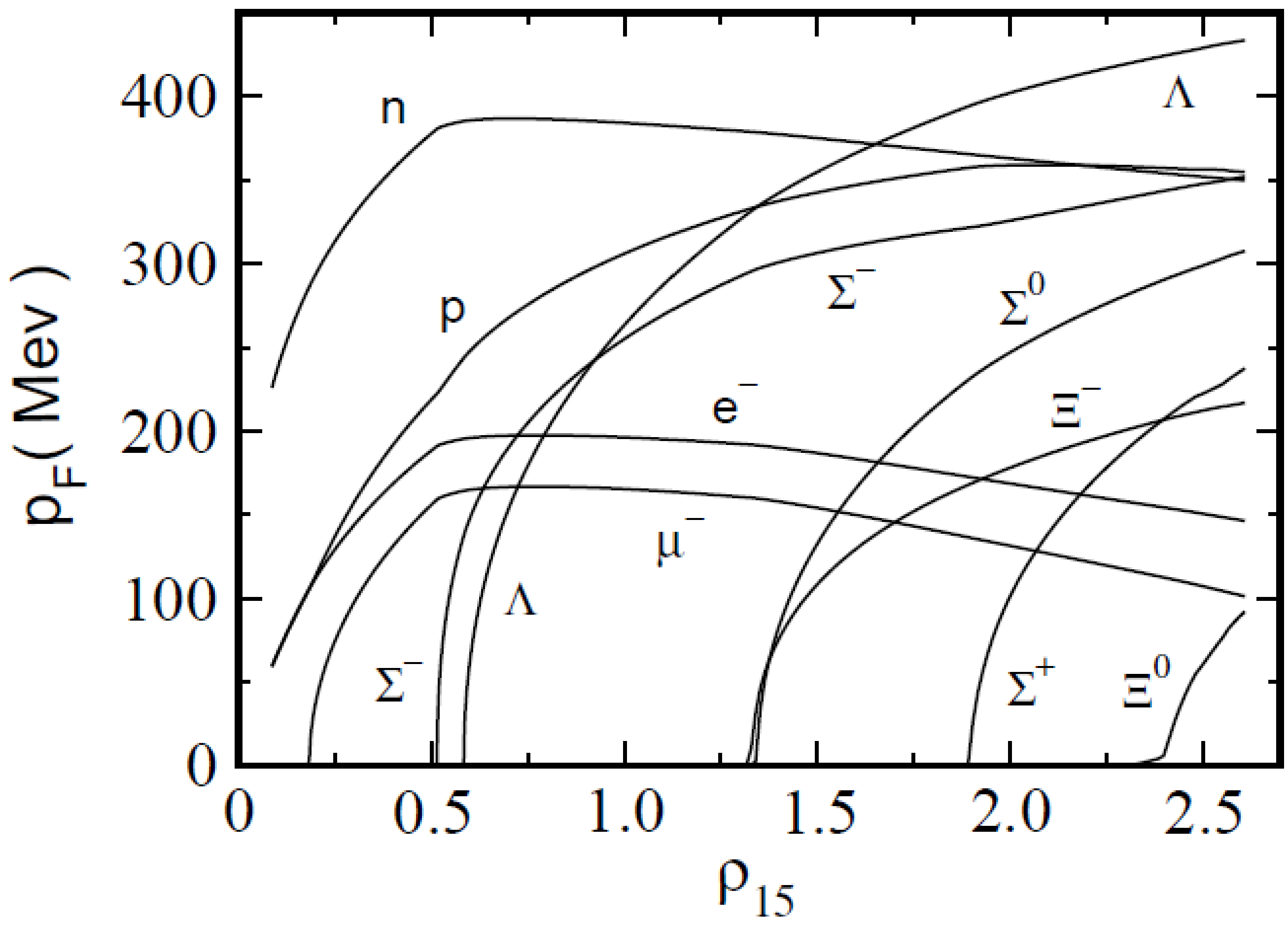
$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Hyperons in β-stable matter



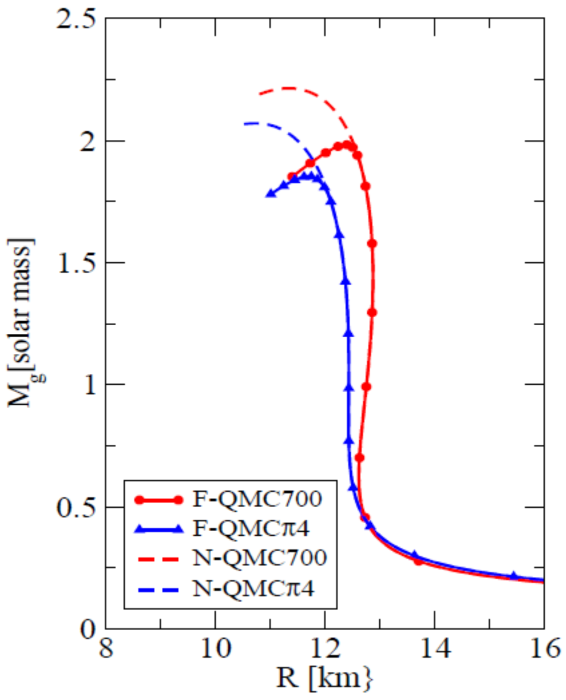
Stone, Guichon and Thomas 1012.2919, in connection with the discovery by Demorest et al. of a 2 M_s star:

"…Rather than being a surprise to find hyperons it would stretch our understanding of fundamental strong and weak interaction processes to breaking point if they were not to appear. It is certainly inconceivable that a nucleon-only EoS could be realistic at such large densities."

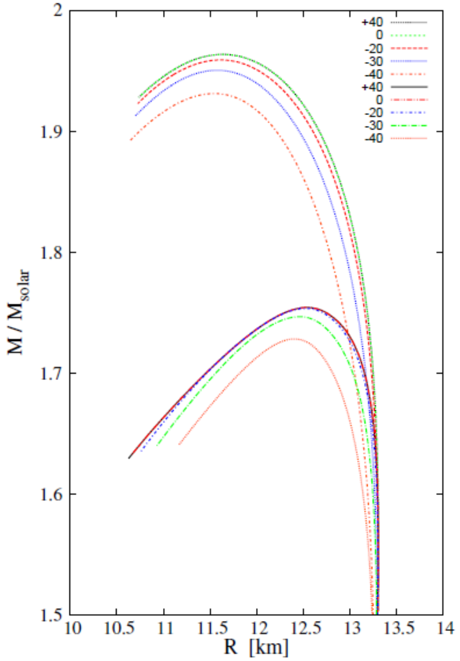
Hyperons in compact stars

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

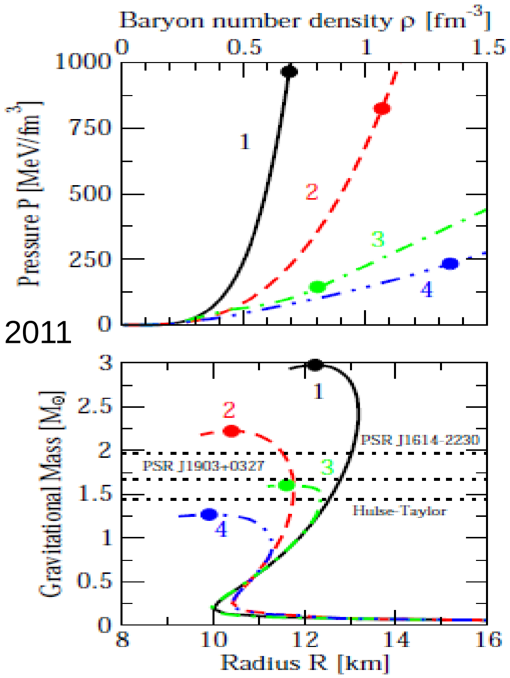
Stone et al. NPA 792(2007)341



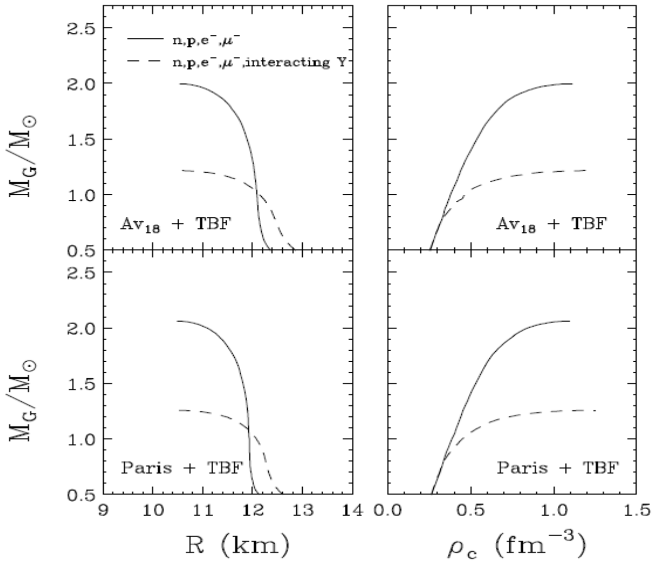
Weissenborn et al.
NPA 881(2011)62



Vidana et al 2011



Baldo et al 2000



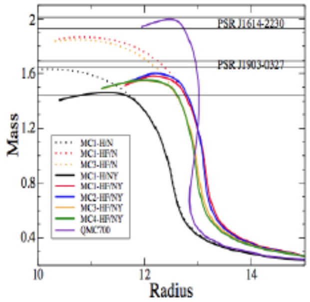
The 2Msun limit can be fulfilled within RMF models.

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

Borrowed from I. Vidana

Situation not much clear with phenomenological approaches

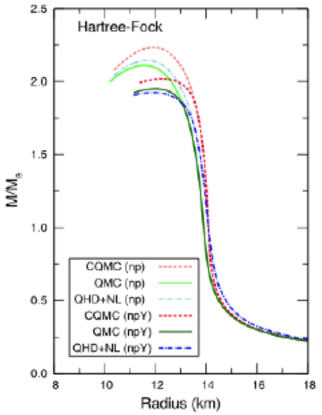
(Massot et al. 2012)



- ✓ χ-LM & QMC
- ✓ Hartree-Fock

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

(Miyatsu et al. 2012)



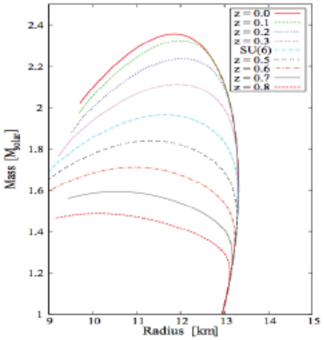
- ✓ RHF & QMC
- ✓ π & f_{vB}

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

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

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

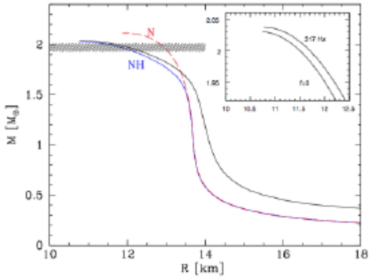
(Weissenborn et al. 2012)



(Bednarek et al. 2012)

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

$M_{\max} > 2 M_{\odot}$

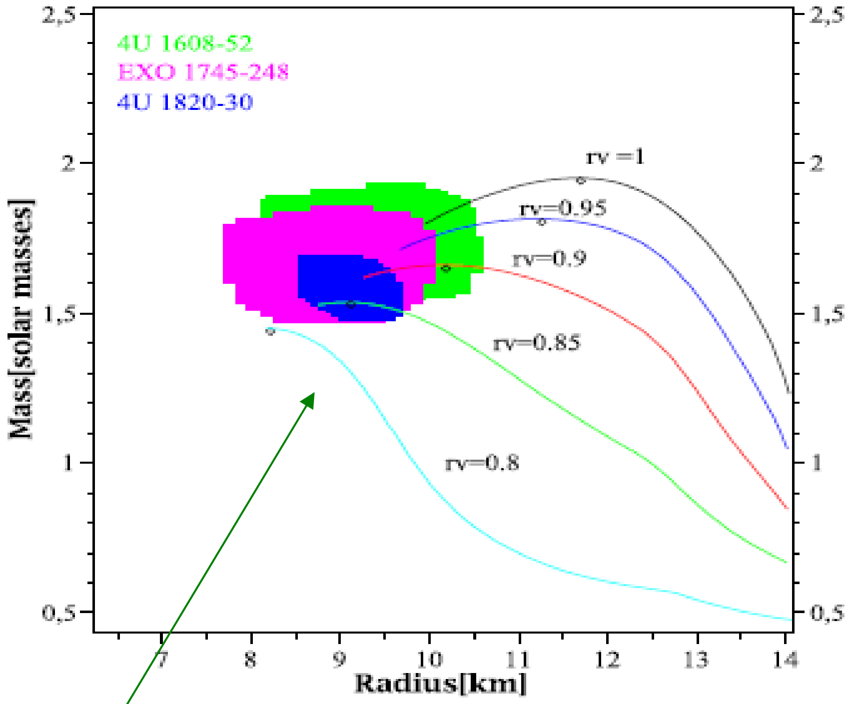


What about Δ’s?

Schurhoff, Schramm, Dexheimer ApJ 724(2010) L74

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:

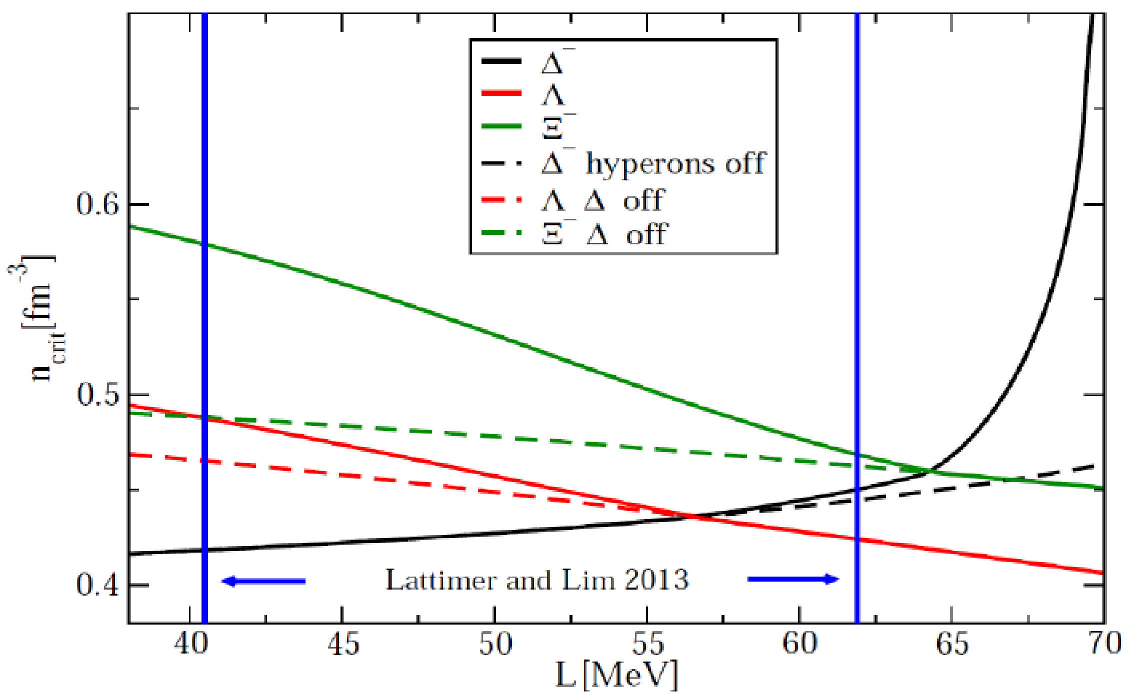
$$\mu_i = \mu_B + c_i\,\mu_C$$

But, it is isospin unfavored:

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

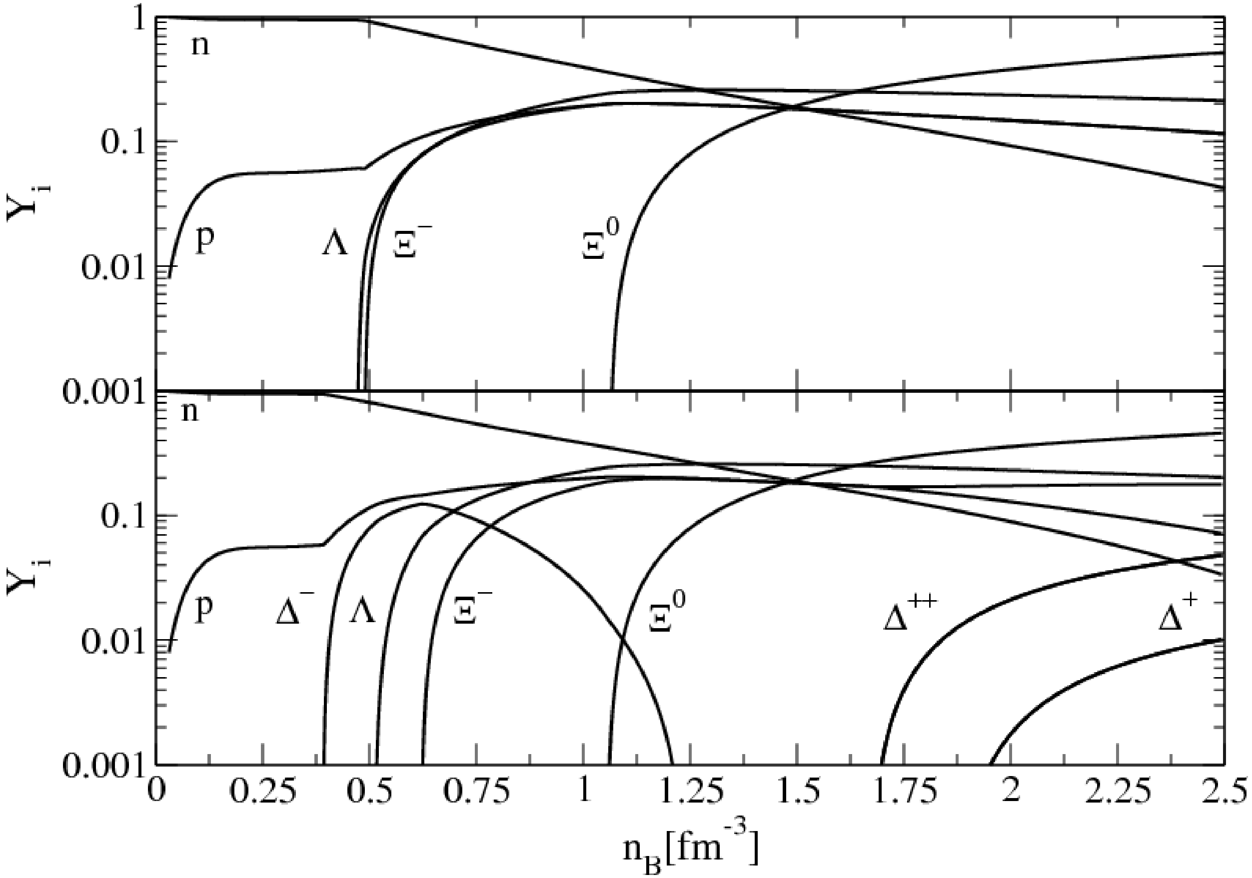
Indeed, in old calculations (see e.g. Glendenning 1985), no deltas are formed in neutron star matter. This is due to the large value of the symmetry energy at densities above saturation.

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

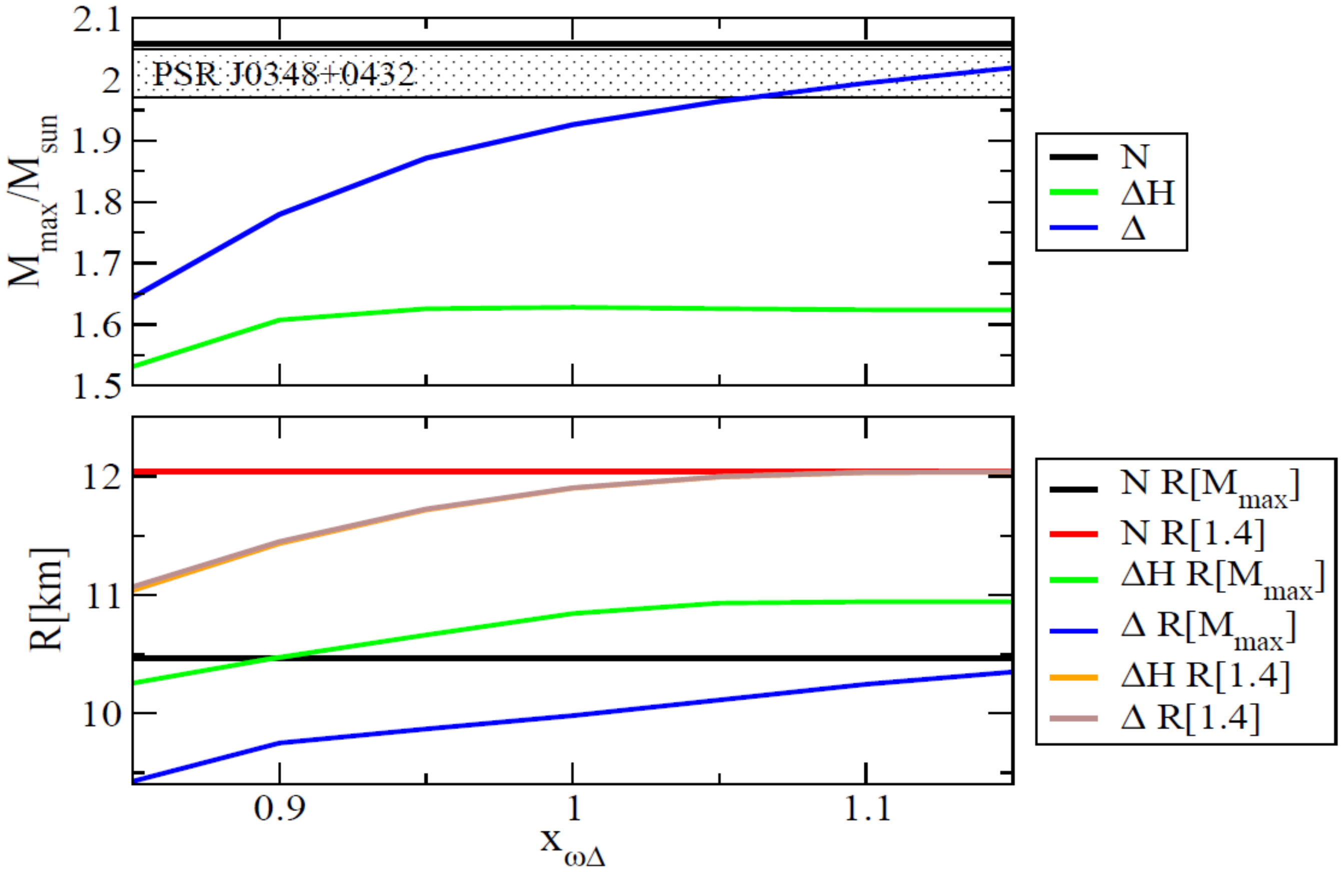
Pion scattering:

$\Sigma_\Delta = -30$ 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

Masses and radii with Deltas and Hyperons



Is there a Delta-resonance puzzle, similar to the hyperon 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

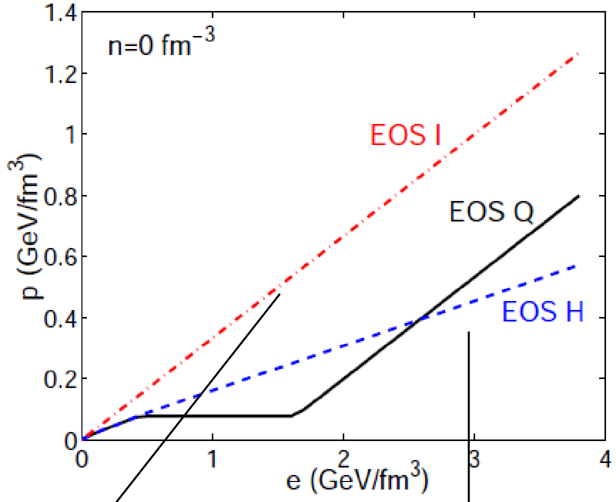


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

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

The EOS for Hybrid Stars

∗ Hadronic phase :

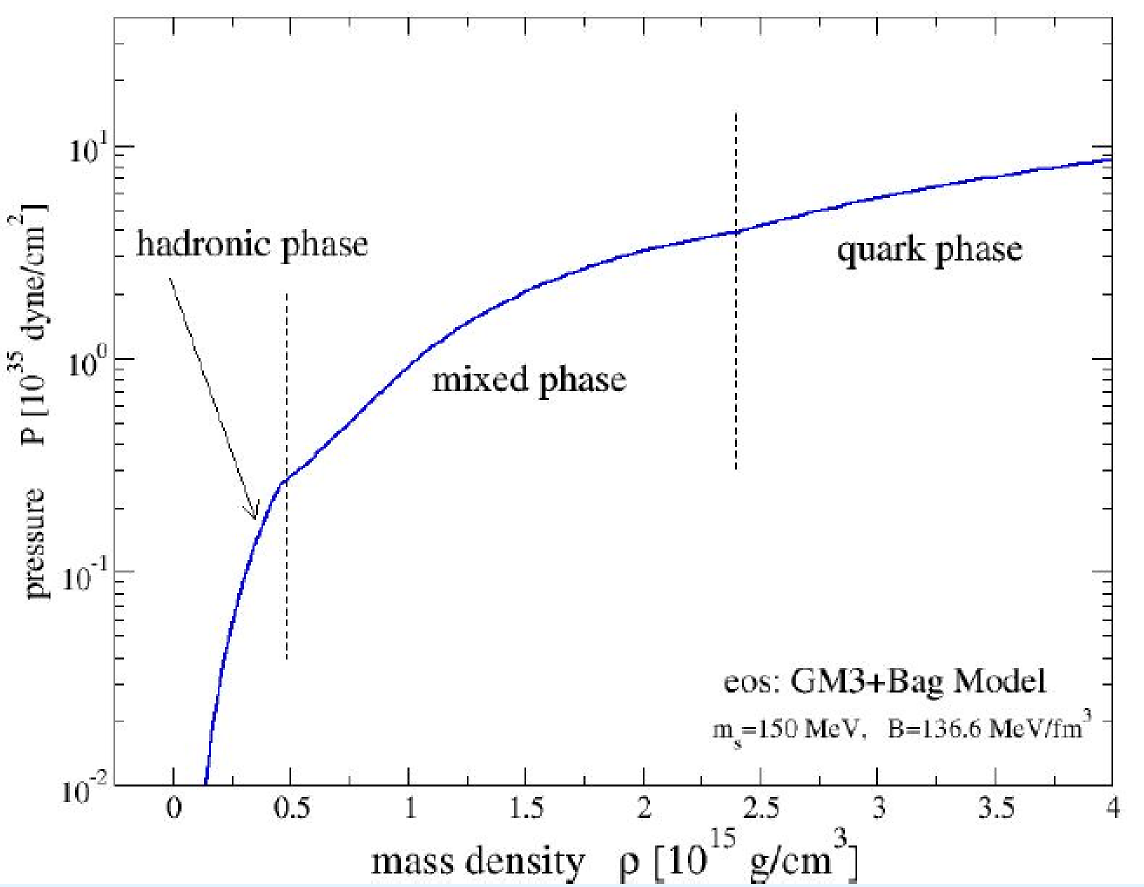
Relativistic Mean Field Theory of hadrons interacting via meson exch. [e.g. Glendenning, Moszkowsky, PRL 67(1991)]

∗ Quark phase :

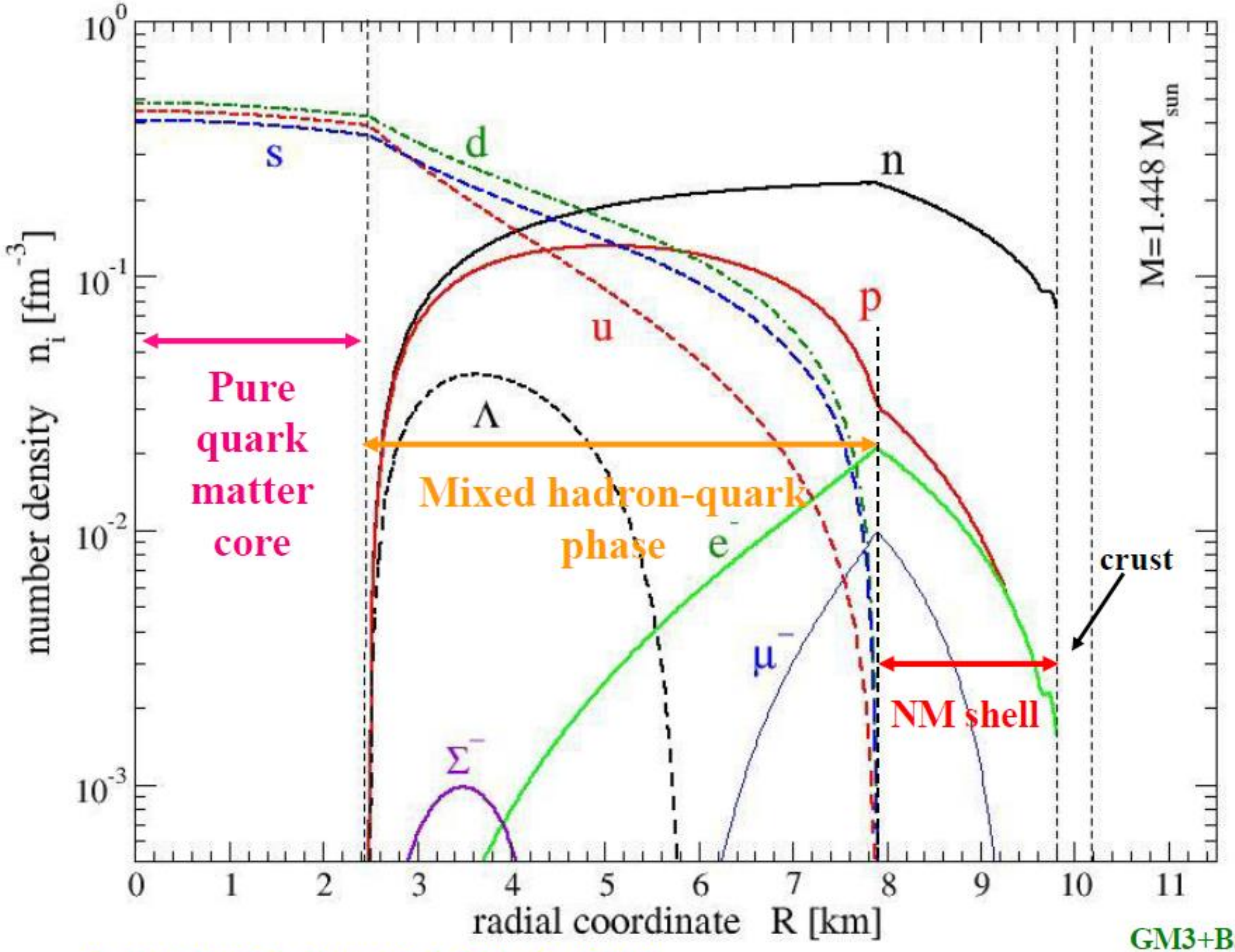
EOS based on the MIT bag model for hadrons. [Farhi, Jaffe, Phys. Rev. D46(1992)]

∗ Mixed phase :

Gibbs construction for a multicomponent system with two conserved “charges”. [Glendenning, Phys. Rev. D46 (1992)]



Hybrid Star

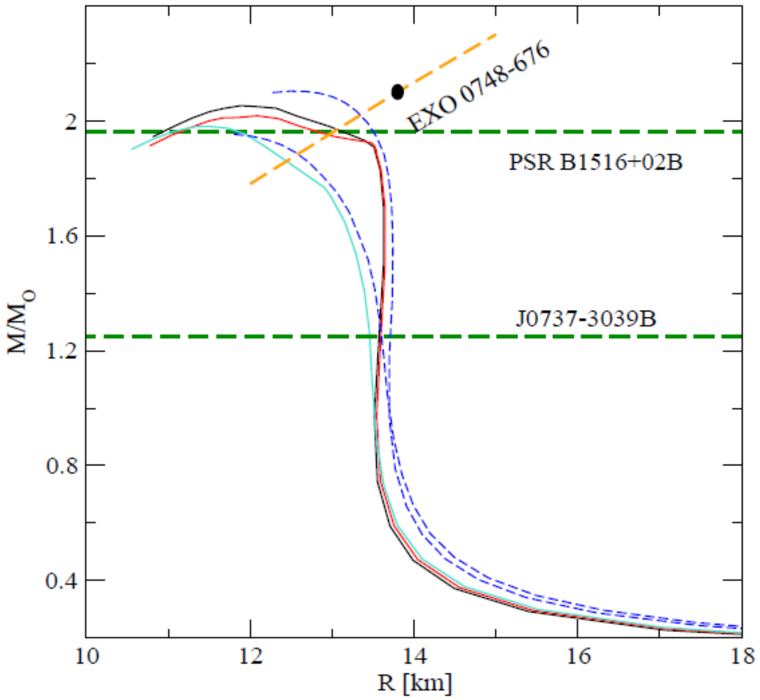


I. Bombaci, I. Parenti, I. Vidaña (2004)

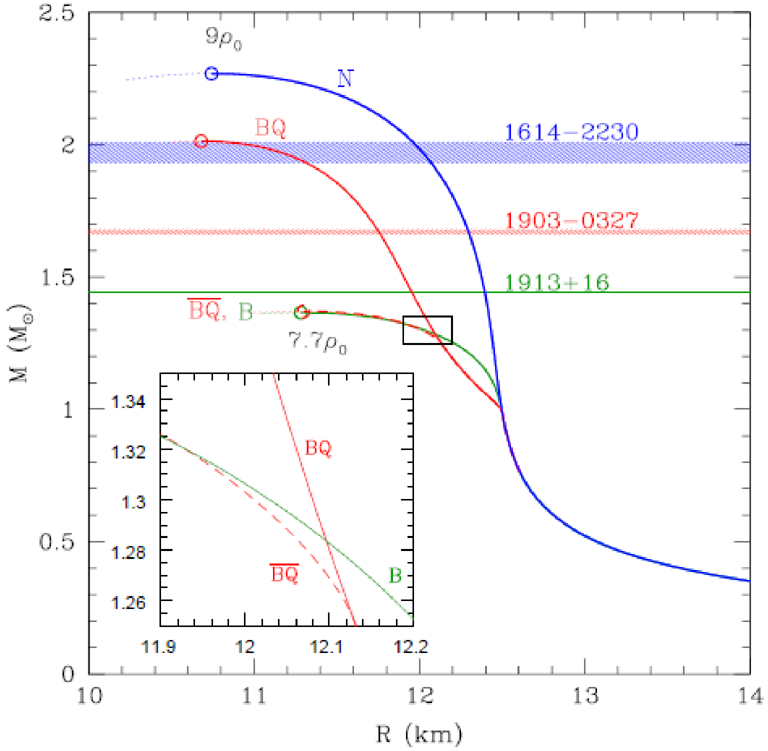
GM3+Bag model
m_s=150 MeV, B=13.6.6Mev/fm^3

Hybrid stars: their radii

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



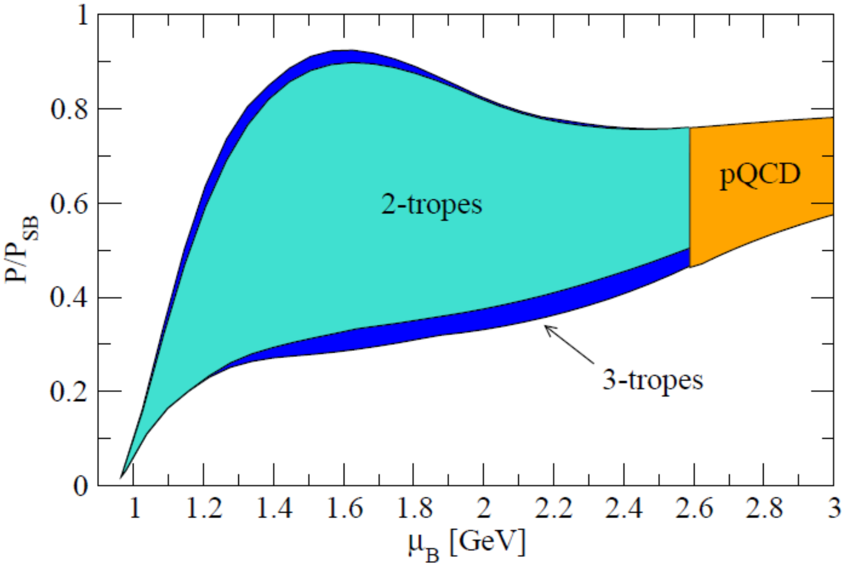
Zdunik and Haensel A&A, 551 (2013) A61

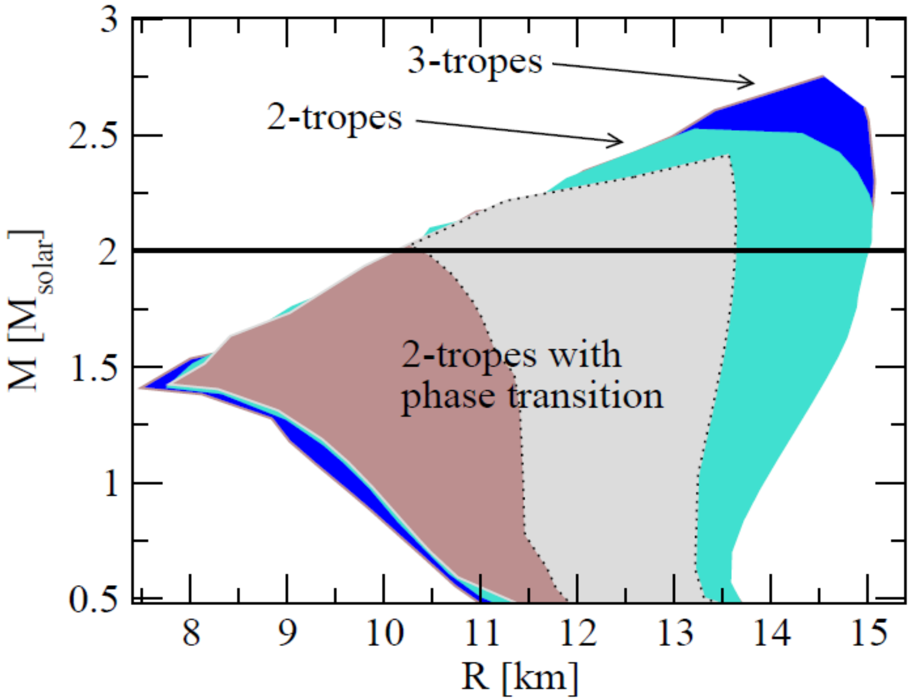


It is possible to satisfy the 2 M_s limit with a hybrid star, but the radius of a 1.4 M_s hybrid star is about 11.5 -- 14 km

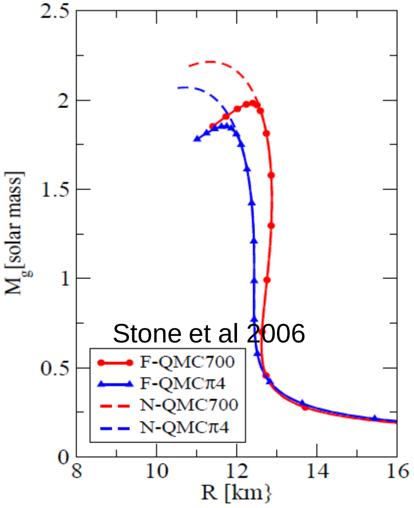
Connecting low densities to very high densities

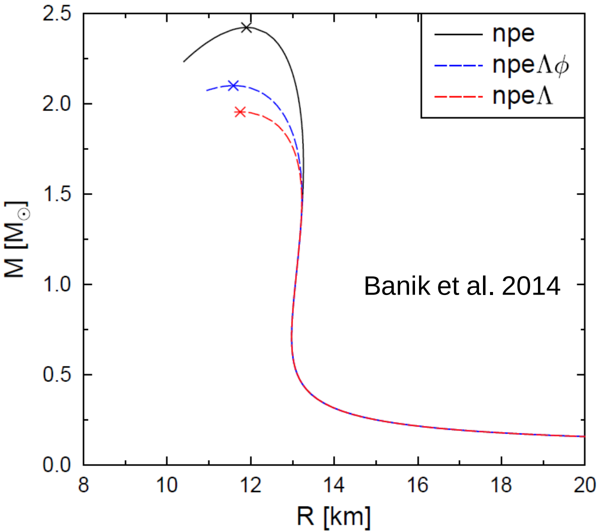
Kurkela, Fraga, Schaffner-Bielich, Vuorinen ApJ 789 (2014) 127



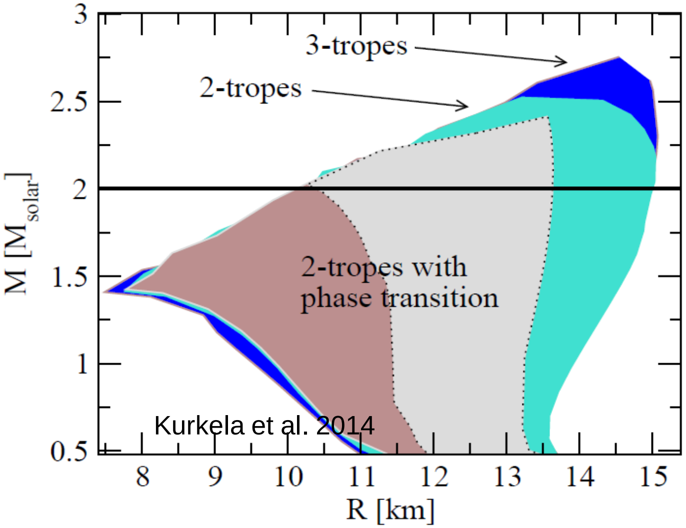


Minimum radius for a 1.4 M_s star

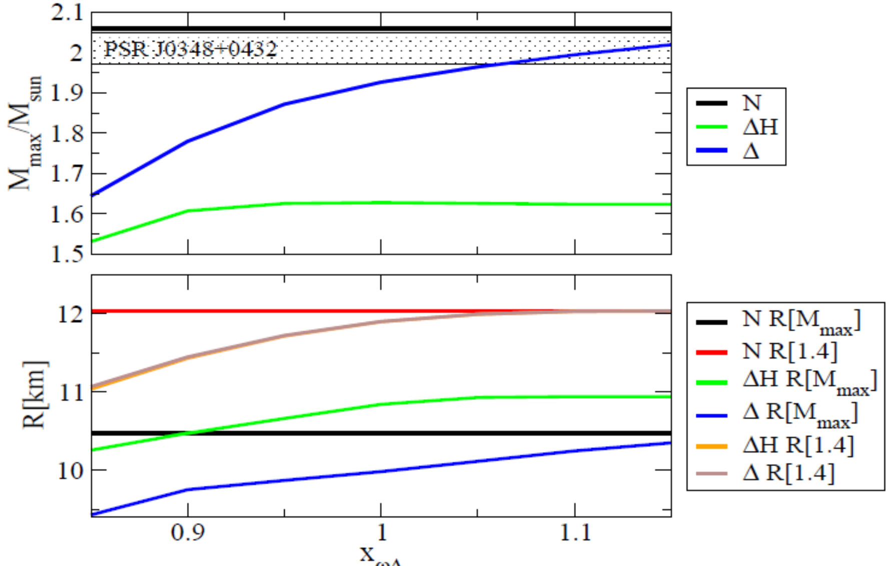




Hyperonic stars $R_{1.4}$ > (12.5 – 13) km



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

The Strange Matter hypothesis

Strange Stars

new family of compact stars made of
strange quark matter (*u*,*d*,*s* quark matter)

The Strange Matter hypothesis

Bodmer (1971), Terazawa (1979), Witten (1984): BTW hypothesis

Three-flavor *u,d,s* quark matter, in equilibrium with respect to the weak interactions, could be the true ground state of strongly interacting matter, rather than ^{56}Fe

$$E/A|_{SQM} \leq E(^{56}Fe)/56 \sim 930.4 \text{ MeV}$$

Stability of Nuclei with respect to u,d quark matter

The success of traditional nuclear physics provides a clear indication that **quarks in the atomic Nucleus are confined within protons and neutrons**

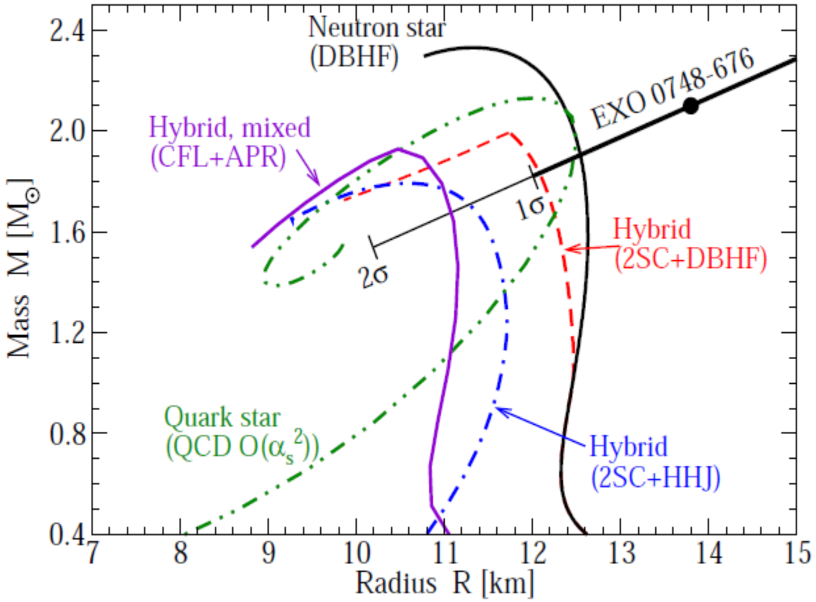
$$E/A|_{ud} \geq E(^{56}Fe)/56$$

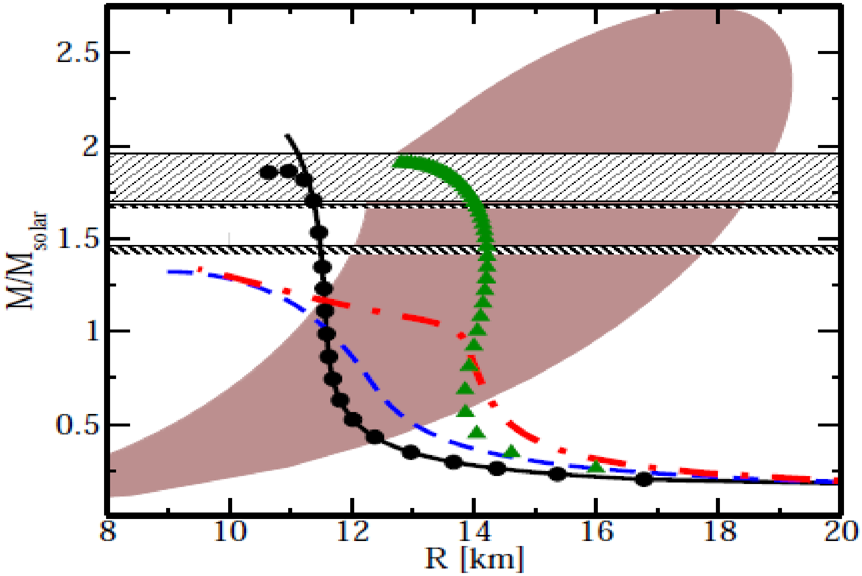
Stability of atomic nuclei against decay to SQM droplets

- If the SQM hypothesis is true, why nuclei do not decay into SQM droplets (strangelets) ?
- One should explain the existence of atomic nuclei in Nature.

Multiple simultaneus β-decays would be needed, making the life-time of Fe much longer than the age of Universe!

Hybrid stars or quark stars?





Alford et al Nature 2006

Kurkela et al PRD81(2010)105021

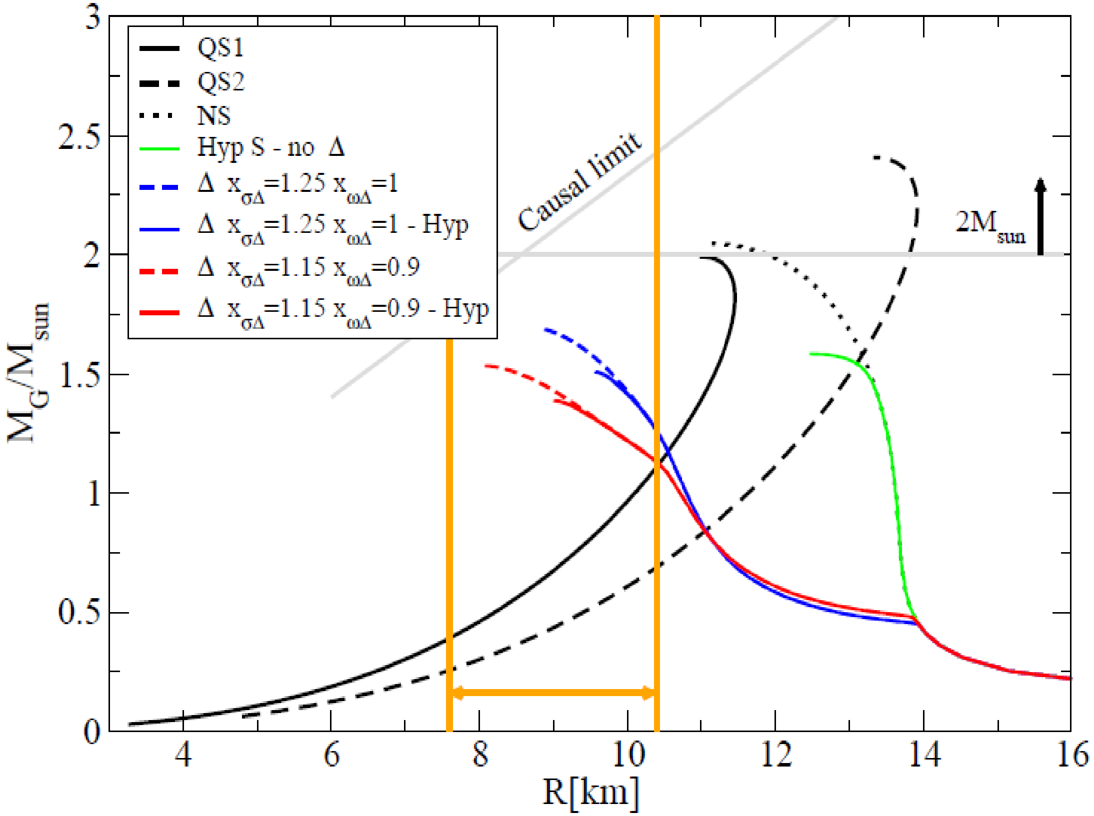
pQCD calculations: “ … equations of state including quark matter lead to hybrid star masses up to 2Ms, in agreement with current observations.

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!!

Two families of compact stars

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



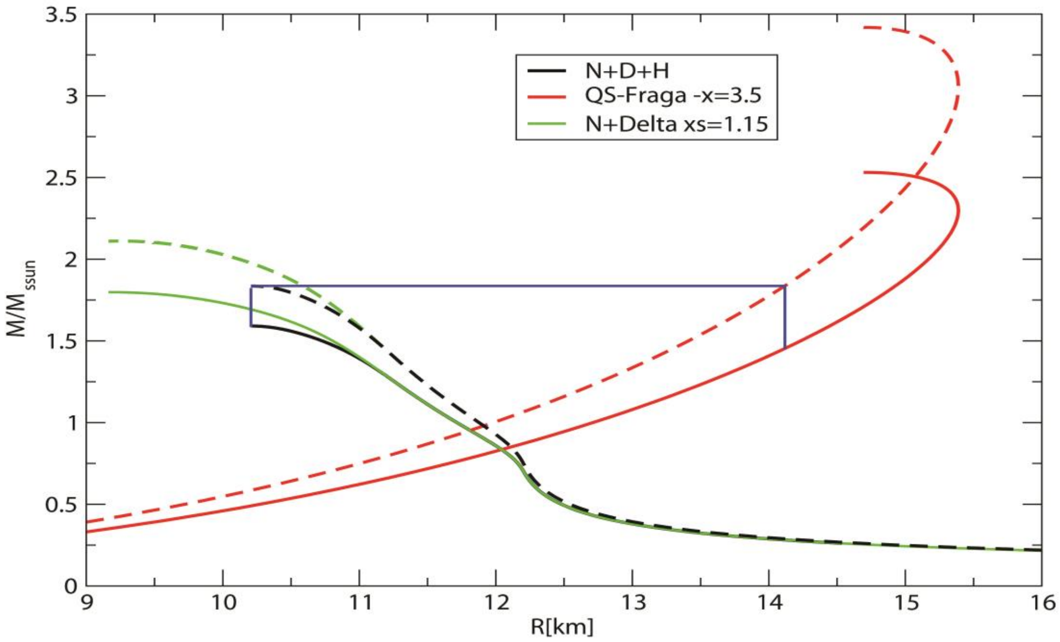
Two families of compact stars:

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.

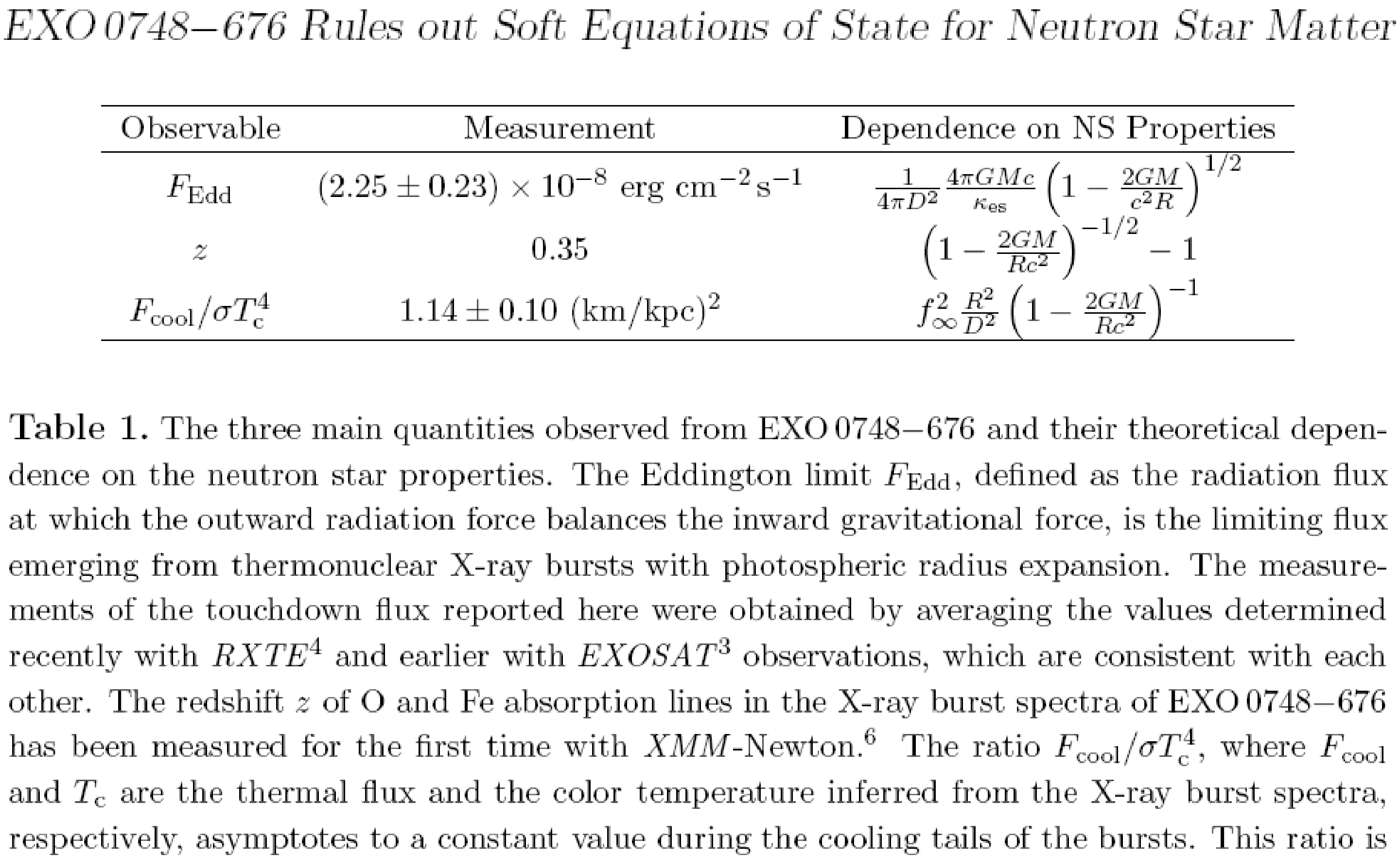
Finite size effects (surface tension)
can further delay the formation
of the first droplet of strange matter



The maximum mass of a quark star can be as large as
2.75 $M_s \geq 2 \times (1.3 \div 1.4) M_s$
Therefore it is possible to have a ultra-massive quark star produced
by the merging of two normal-mass neutron stars.
The post-merging e.m. signal of the associated short GRB could show a
quasi-plateau emission, similar to the one observed in many long GRBs.

How to measure the radius of a compact star?

Ozel Nature 441 (2006) 1115



EXO 0748−676 Rules out Soft Equations of State for Neutron Star Matter

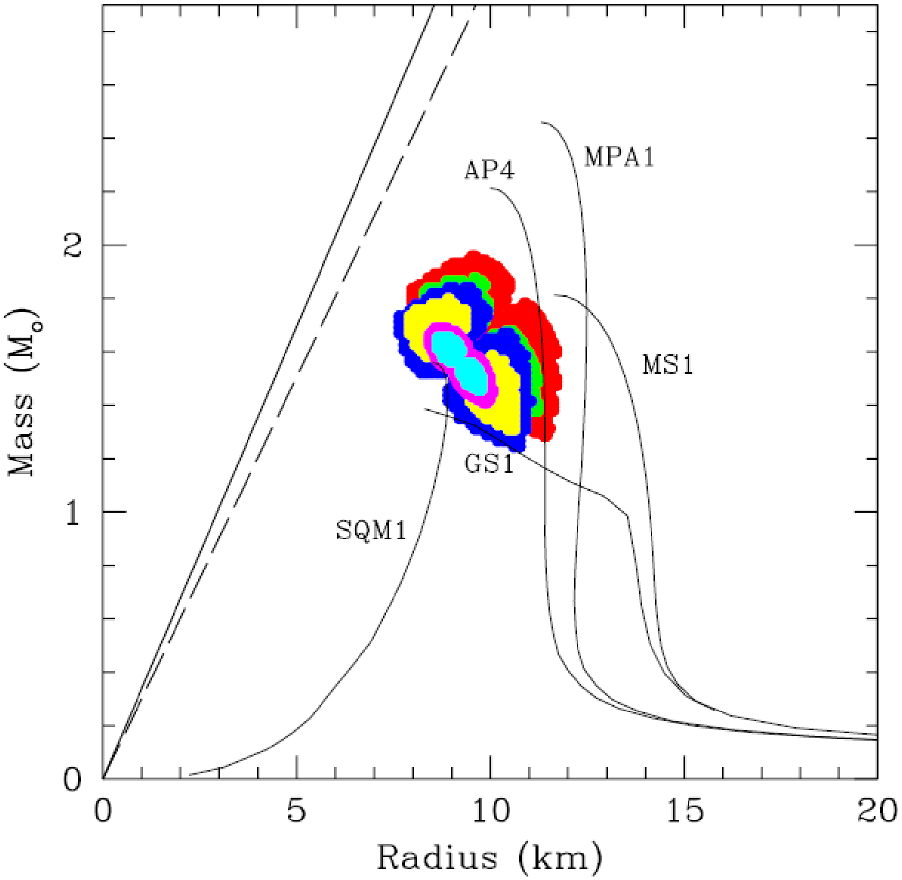
Observable	Measurement	Dependence on NS Properties
$F_{\rm Edd}$	$(2.25 \pm 0.23) \times 10^{-8}$ erg cm^{-2}s^{-1}	$\frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa_{\rm es}}\left(1-\frac{2GM}{c^2R}\right)^{1/2}$
z	0.35	$\left(1-\frac{2GM}{Rc^2}\right)^{-1/2}-1$
$F_{\rm cool}/\sigma T_{\rm c}^4$	1.14 ± 0.10 (km/kpc)^2	$f_\infty^2 \frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}$

Table 1. The three main quantities observed from EXO 0748−676 and their theoretical dependence on the neutron star properties. The Eddington limit $F_{\rm Edd}$, defined as the radiation flux at which the outward radiation force balances the inward gravitational force, is the limiting flux emerging from thermonuclear X-ray bursts with photospheric radius expansion. The measurements of the touchdown flux reported here were obtained by averaging the values determined recently with *RXTE*[4] and earlier with *EXOSAT*[3] observations, which are consistent with each other. The redshift z of O and Fe absorption lines in the X-ray burst spectra of EXO 0748−676 has been measured for the first time with *XMM*-Newton.[6] The ratio $F_{\rm cool}/\sigma T_{\rm c}^4$, where $F_{\rm cool}$ and $T_{\rm c}$ are the thermal flux and the color temperature inferred from the X-ray burst spectra, respectively, asymptotes to a constant value during the cooling tails of the bursts. This ratio is

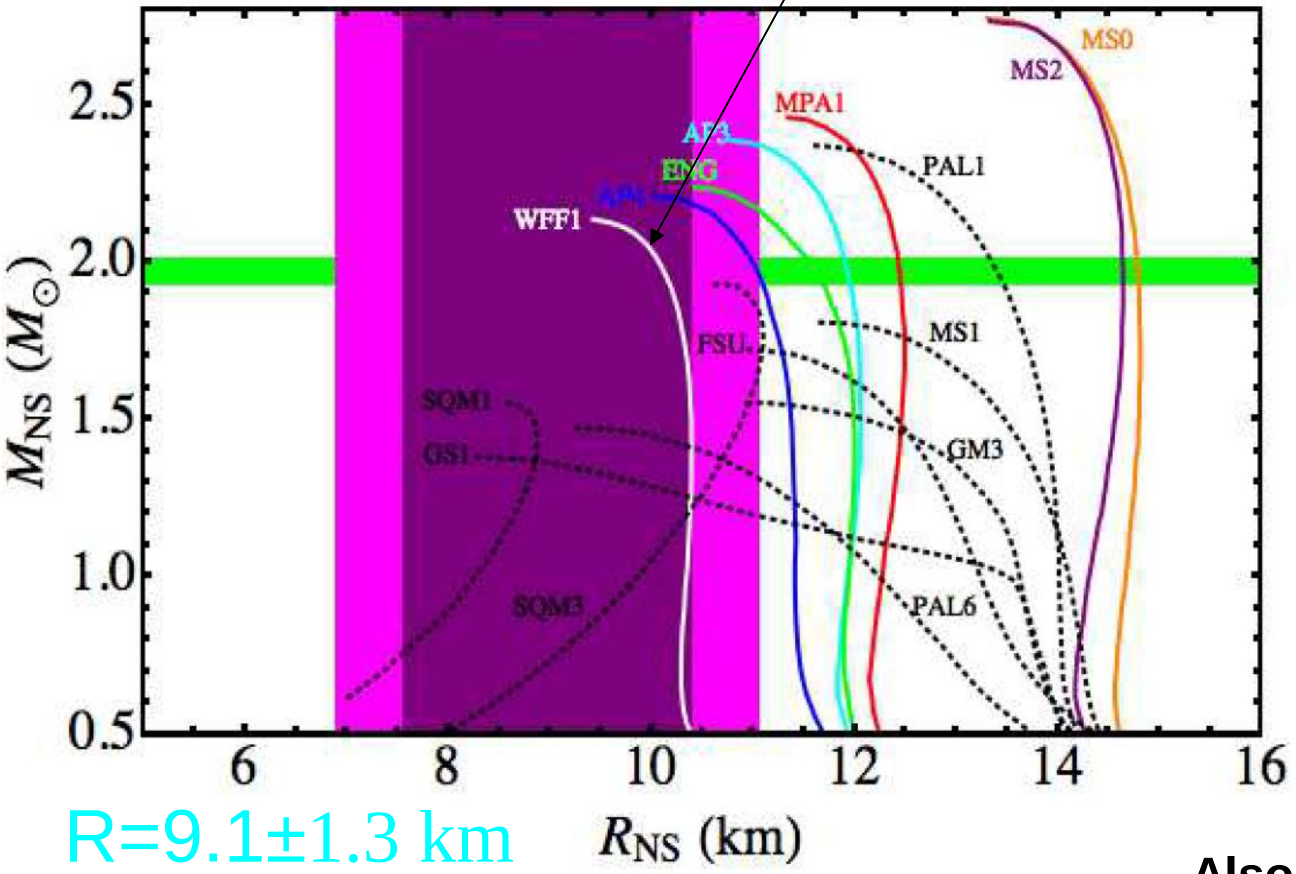
The apparent surface area remains constant in time and is highly reproducible in multiple events from the same source, indicating that the entire neutron star surface, rather than a variable area on the surface, participates in the burst emission.

A VERY controversial result

Oezel, Baym, Guever PRD82 (2010) 101301



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 R=(9.4 ± 1.2)km

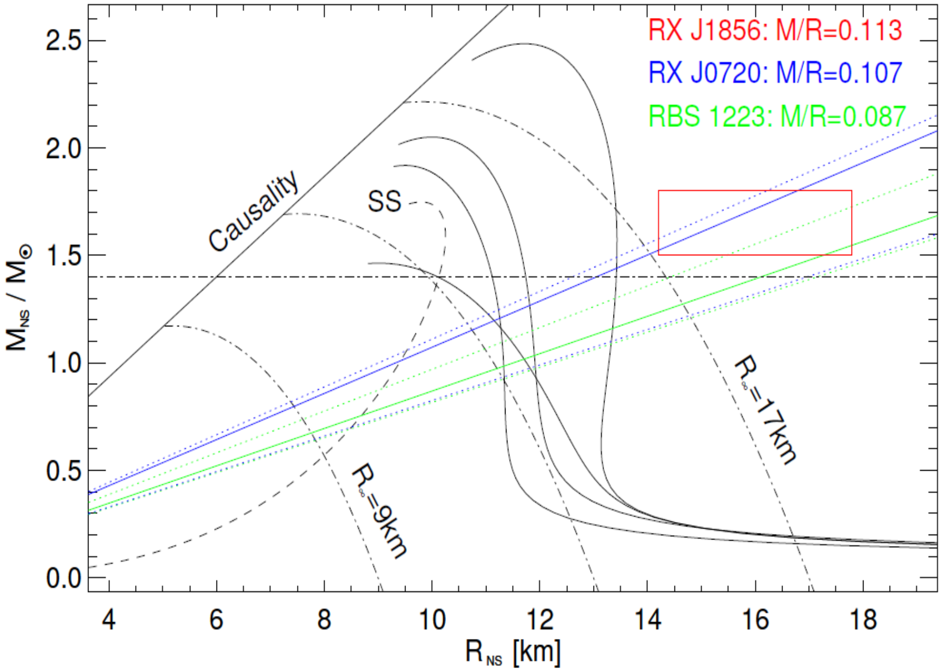
Indications for LARGE radii

Hambaryan et al 2014

RXJ1856.5-3754

Is the nearest INS and the distance (d = 123+11-15 pc) is known with relatively good accuracy.

The X-ray spectrum does not show any signicant absorption feature and the pulsed fraction is quite low (1.5%).

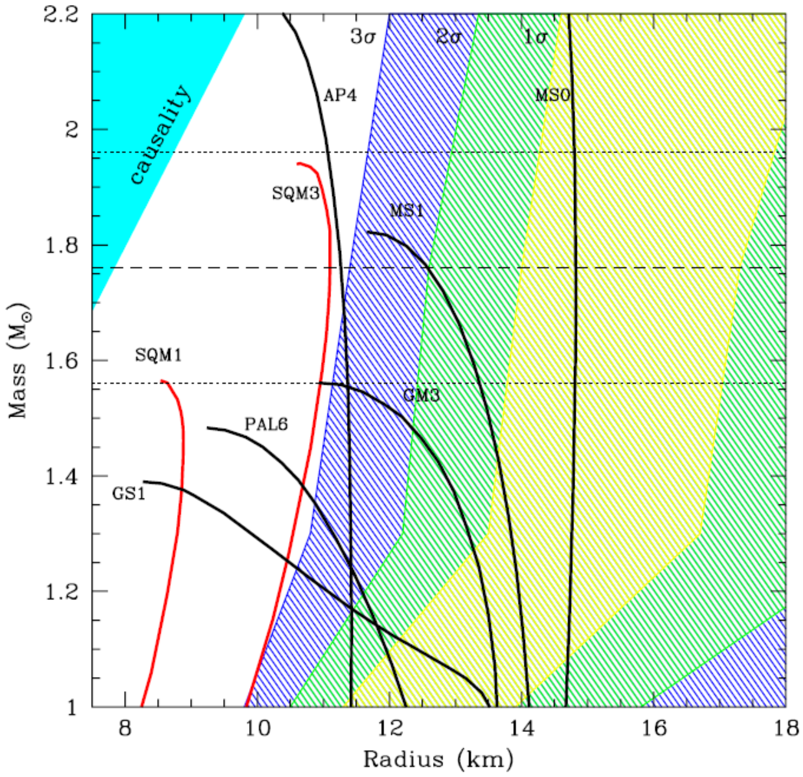


Bogdanov 2013

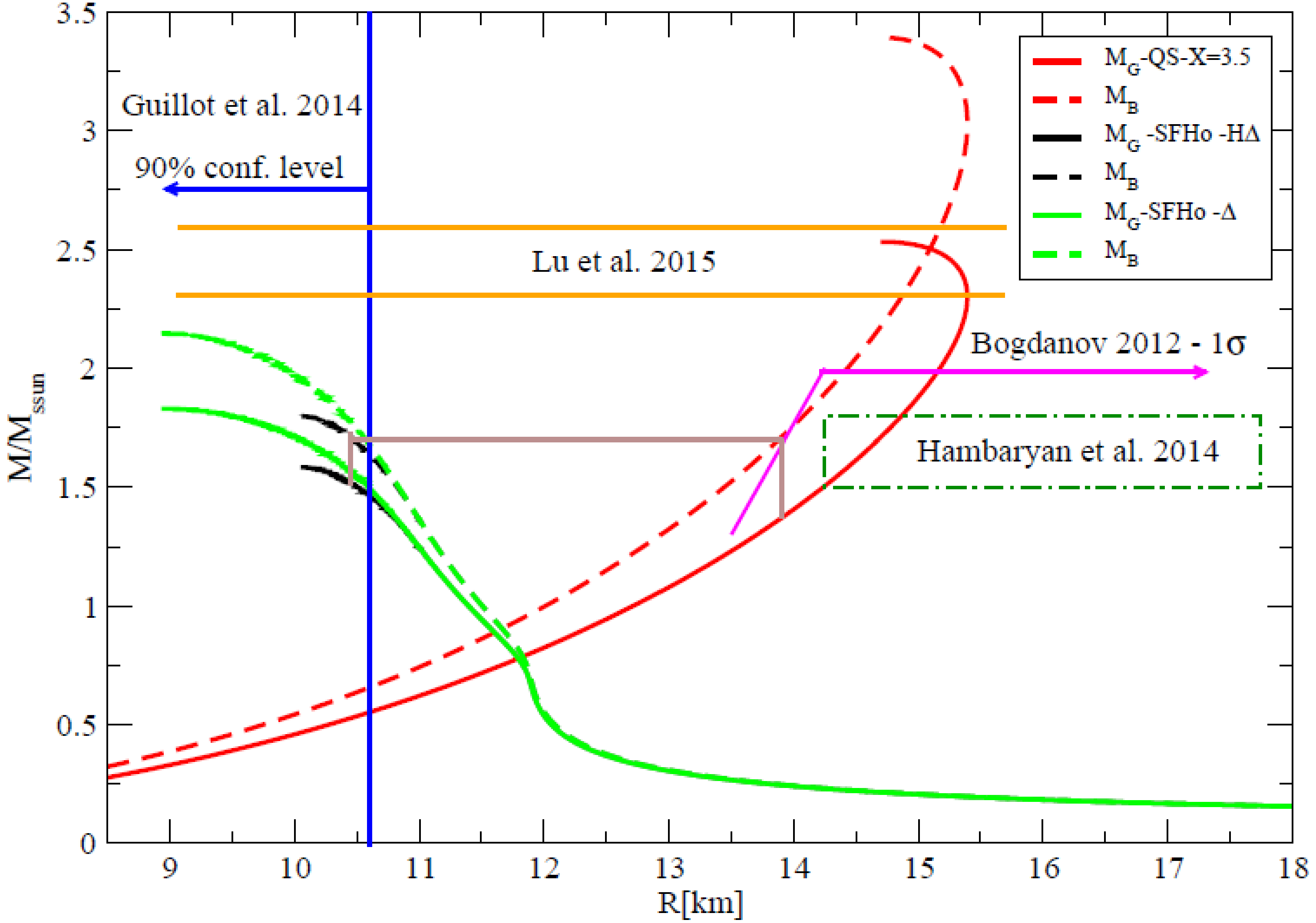
PSR J0437–4715, *XMM-Newton*

The thermal radiation exhibits at least three components, with the hottest two having total effective areas consistent with the expected polar cap size.

The coolest component, on the other hand, appears to cover a significant portion of the stellar surface



Small and large radii
within the two-families scenario



Conclusions concerning EOS vs M-R

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

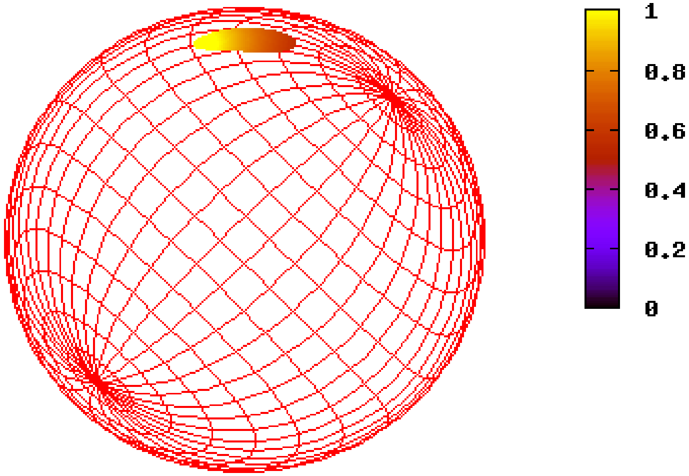
New missions (LOFT), reaching a precision of ~ 1km in the measure of radii , can clarify the composition of compact stars:

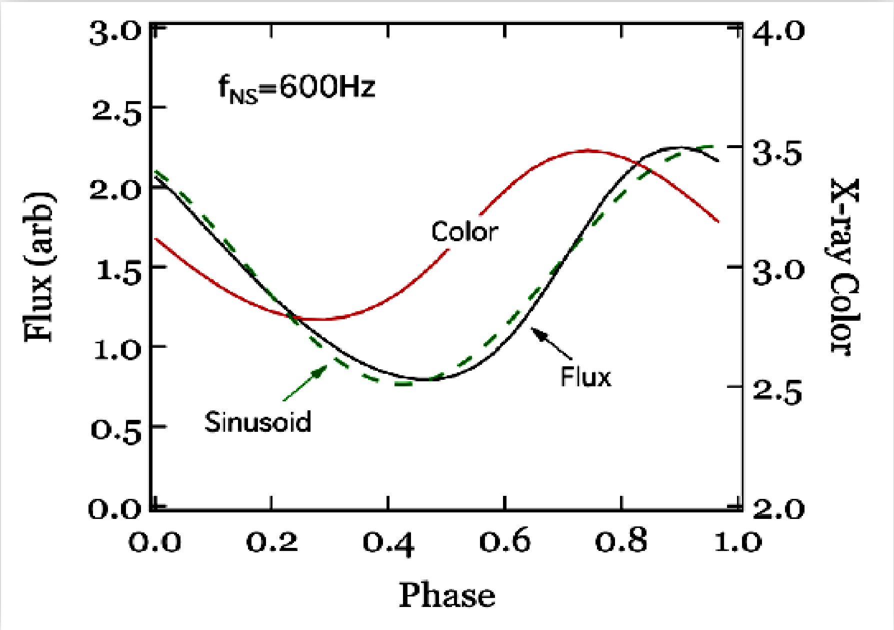
- **$R_{1.4}$ >= 13 km purely nucleonic stars ($\rho_{max} \leq 3\, \rho_0$)**
- **11.5 km < $R_{1.4}$ < 13 km hyperonic or hybrid stars (ρ_{max} as large as 5 ρ_0)**
- **$R_{1.4}$ << 11.5 km two families of compact stars** → **Witten's hypothesis verified!**

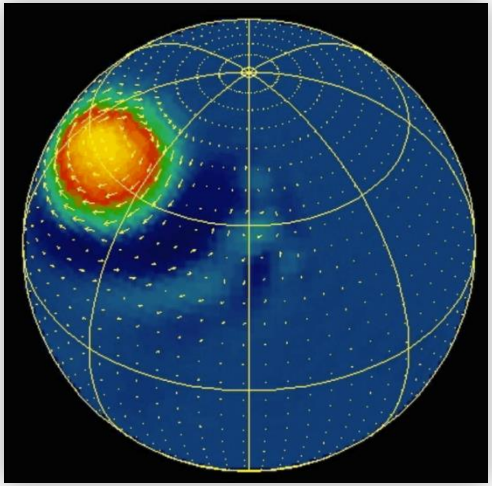
Witten's hypothesis has extremely far reaching consequences:

- *the proof of its validity would be comparable to the discovery of nuclear fusion.*
- It would open the possibility that dark matter is made, at least in part, of nuggets of strange quark matter.

PULSE PROFILE MODELLING (1)







Spitkovsky et al. 2002

Hotspots on accreting neutron stars generate pulsations whose properties depend on M and R.

LOFT CAN RECOVER M AND R SIMULTANEOUSLY BY FITTING THE PHOTON ENERGY-DEPENDENT PULSE PROFILE.