Segnali di stranezza e/o deconfinamento nelle stelle compatte

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Collaborazione con gruppi di gravità numerica (Roma, Parma) e con INAF

Collaborazione con gruppi sperimentali di fisica adronica (LNF, Torino)

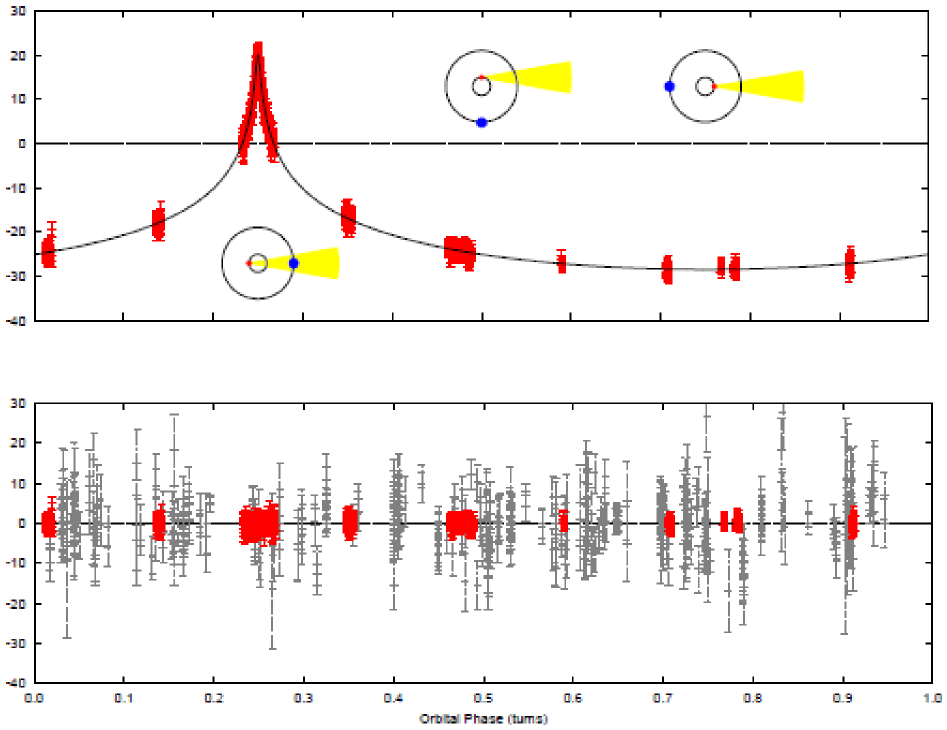
Network europeo (New)-Compstar

- Principali dati osservativi dalle stelle (e dal laboratorio)
    - Massa massima di una stella compatta
    - Energia di simmetria
- Cosa ci si aspetta dalle future osservazioni?
    - Misure del raggio di una stella compatta
    - Misure del momento d’inerzia
- Che implicazioni avranno sulla composizione della materia?
    - Relazione fra compattezza della stella e composizione
    - Raggio minimo di una stella neutronica, iperonica e ibrida (quark e adroni)
    - L’ipotesi di Witten sulla stabilità assoluta della materia a quark strana è testabile tramite le osservazioni?
- Che cosa si potrà imparare dalle osservazioni delle onde gravitazionali prodotte nel merger di due stelle di neutroni?

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

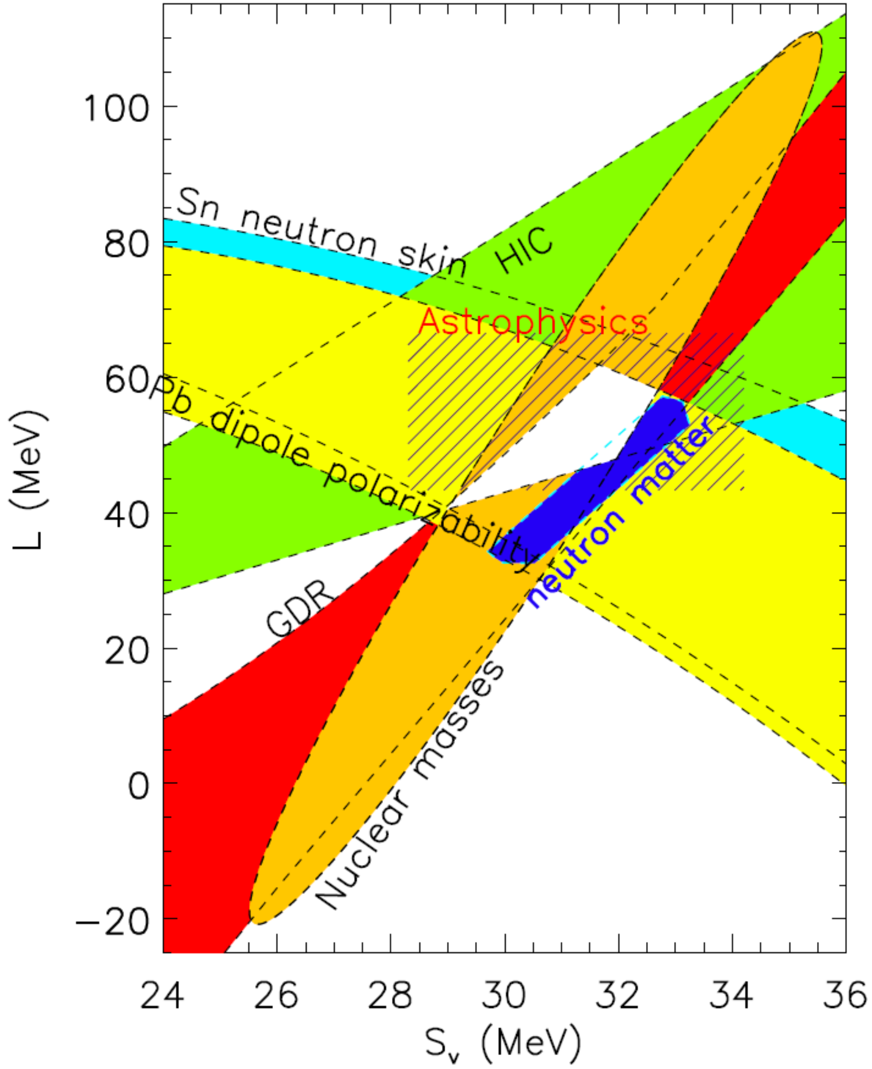


Nuclear and subnuclear densities: symmetry energy

Hebeler et al. ApJ 773 (2013) 11

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

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



What about Δ?

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

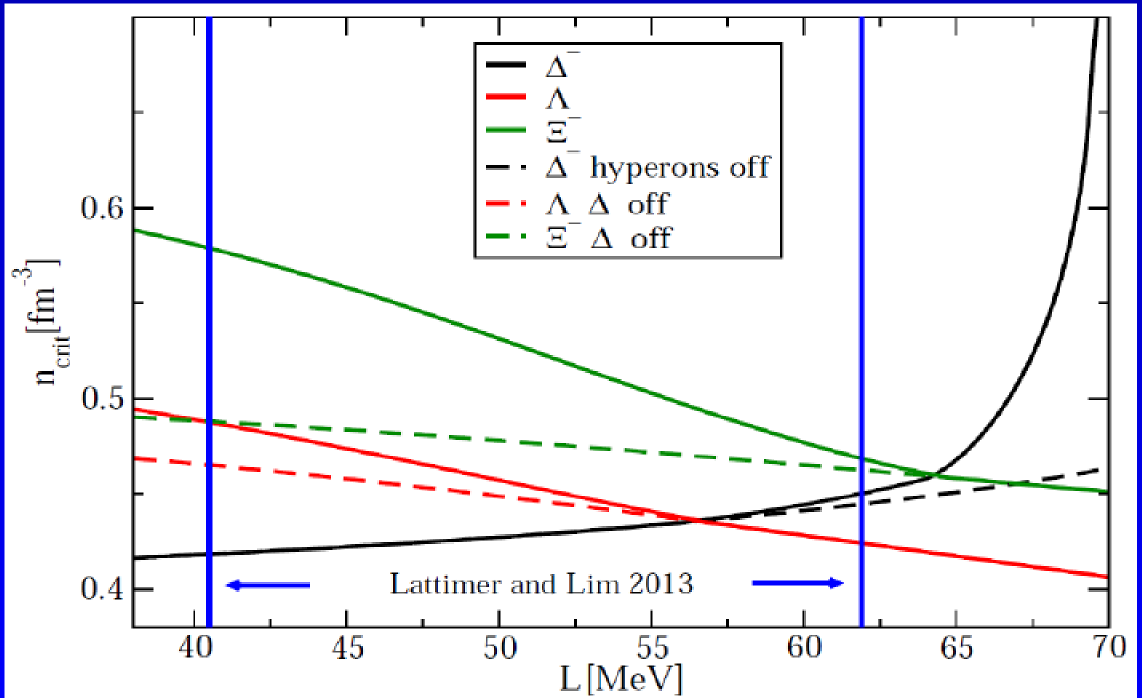
$$\mu_i = \mu_B + c_i\,\mu_C$$

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)

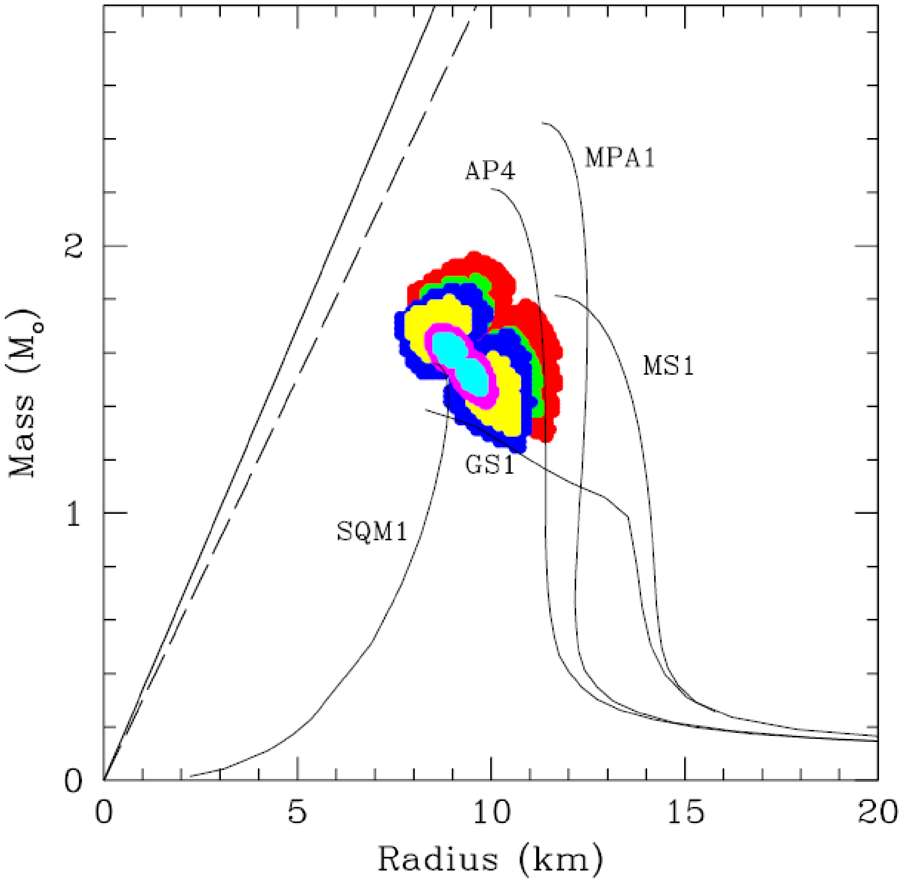


Glendenning's results

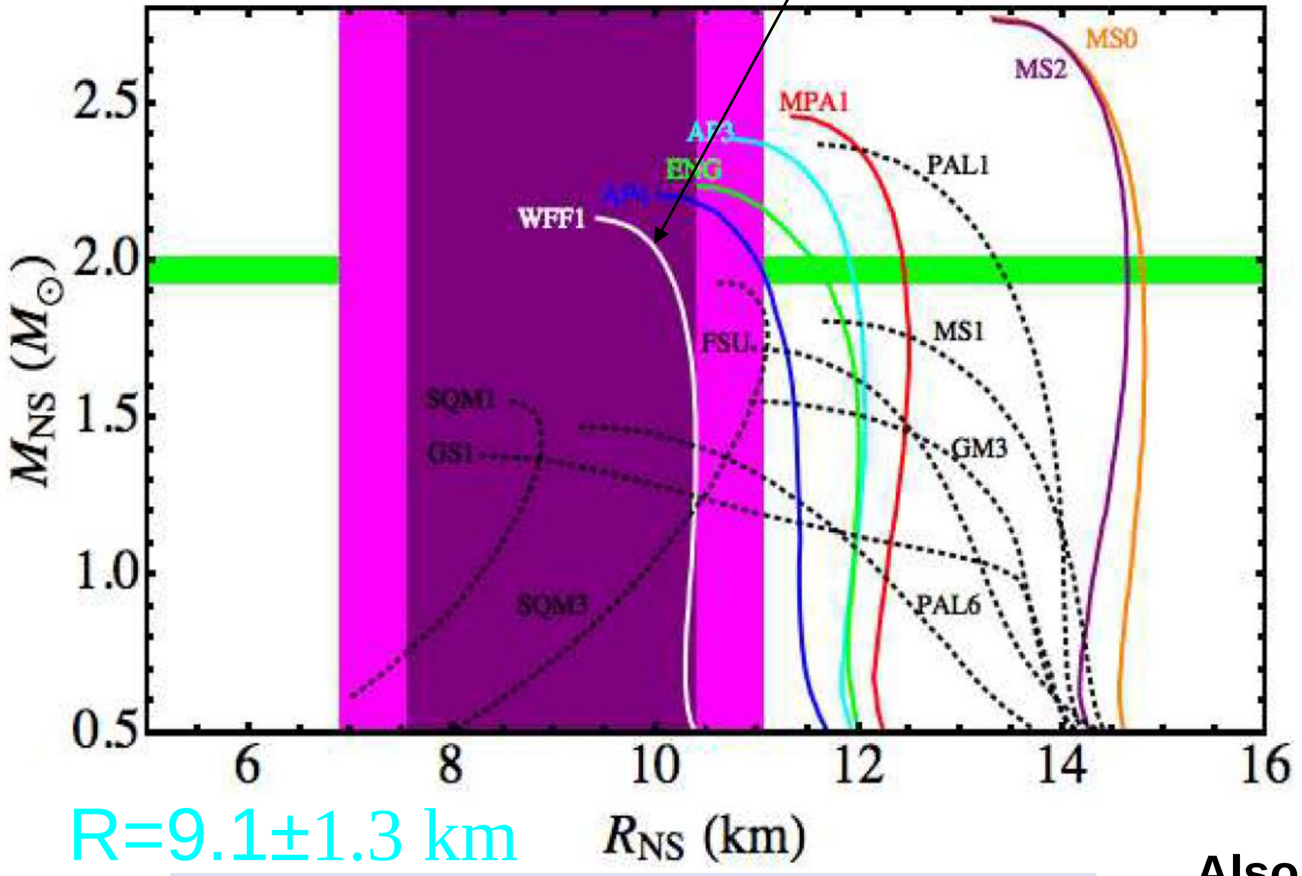
Misura del raggio di una stella compatta tramite rivelatori satellitari di raggi-X (LOFT, NICER)

Indications for SMALL radii: a VERY controversial result

Oezel, Baym, Guever PRD82 (2010) 101301



Nice, but just nucleons,
And it violates causality!

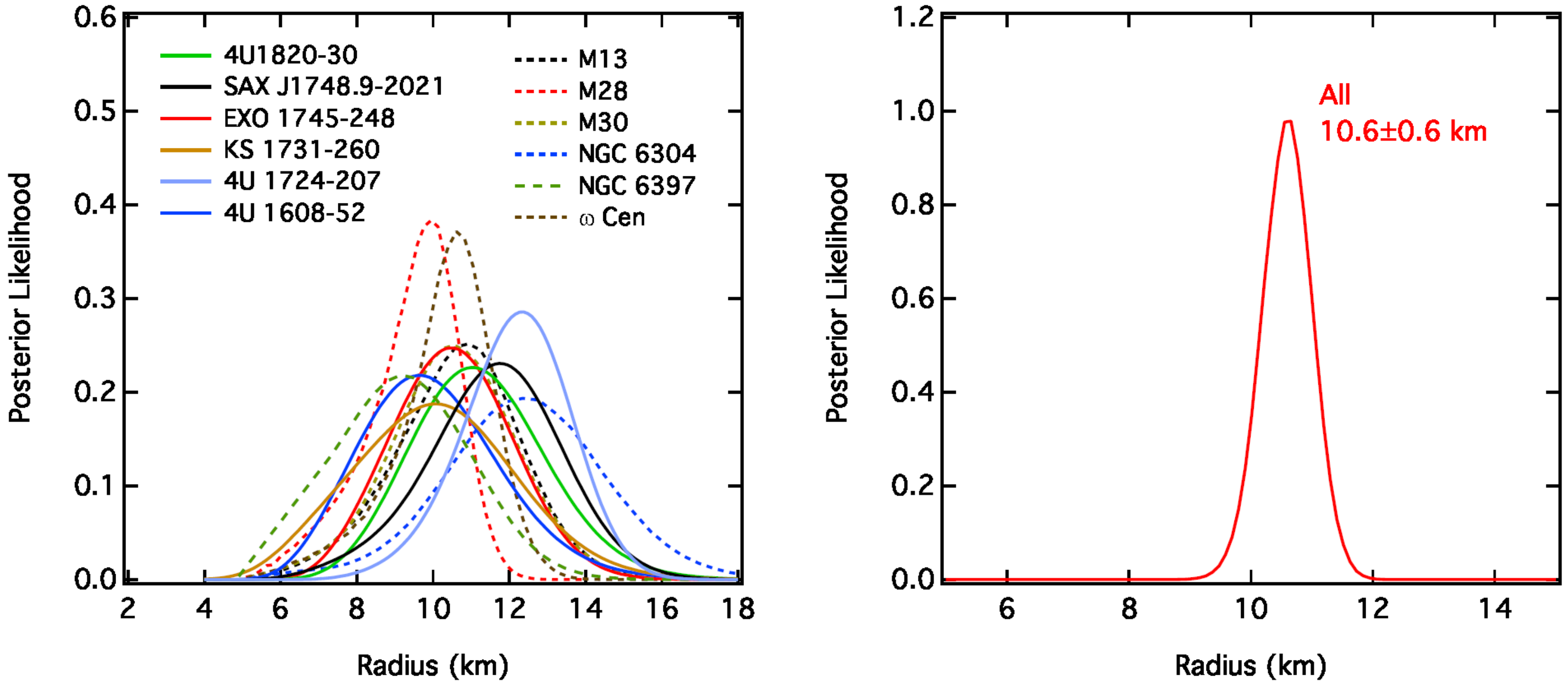


R=9.1±1.3 km

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

Also Guillot and Rutledge 1409.4306
R=(9.4 ± 1.2)km

Oezel, Psaltis, Guever, Baym, Heinke, Guillot, ApJ 820(2016)28



Bogdanov, Heinke, Ozel, Guver, arXiv:1603.01630
R ~ (9.9—11.2) km for a 1.5 M s star

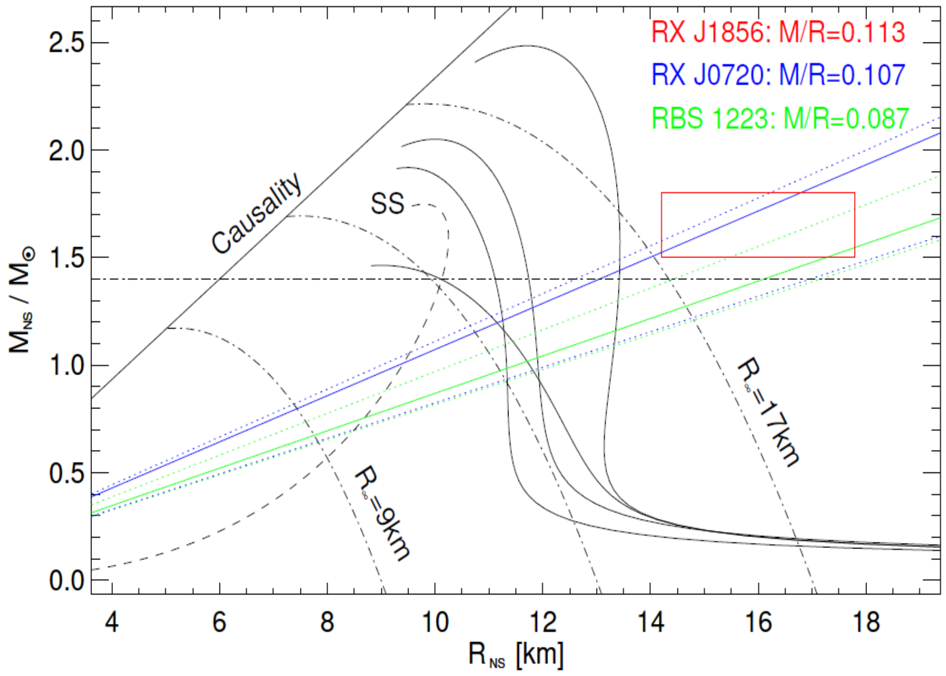
Indications for LARGE radii

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%).

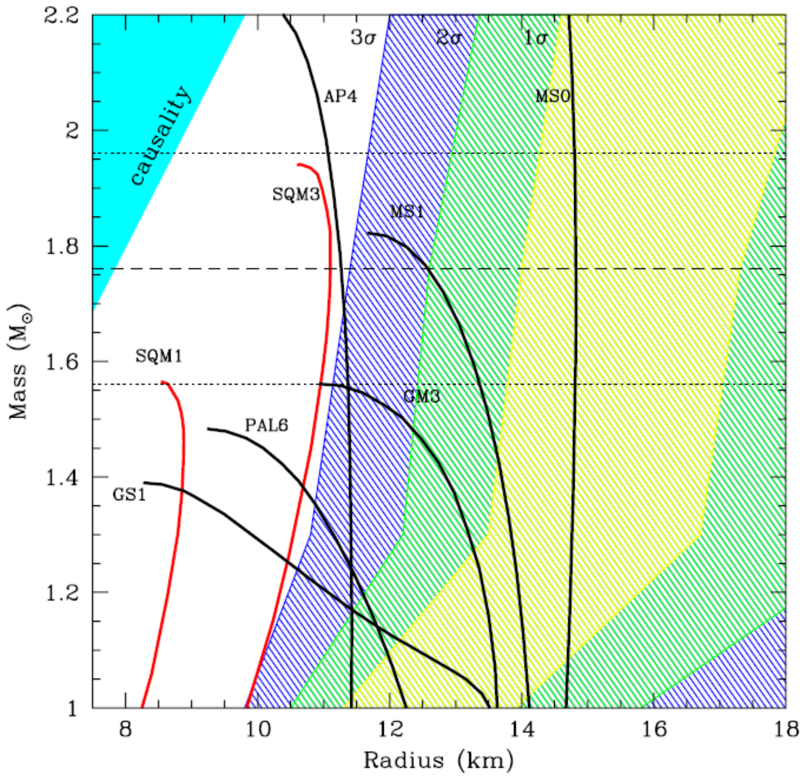


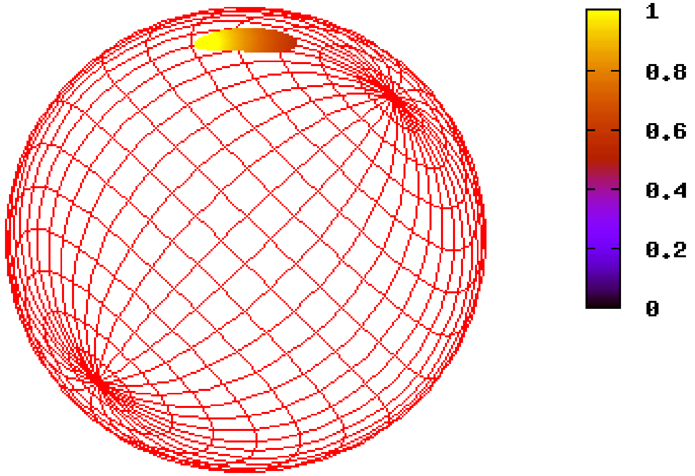
Bogdanov 2013

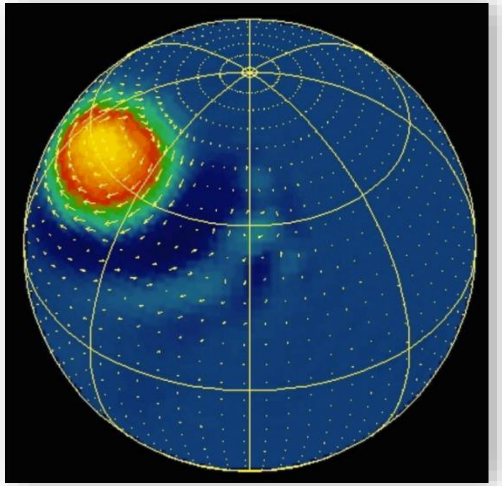
PSR J0437–4715, *XMM-Newton*

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

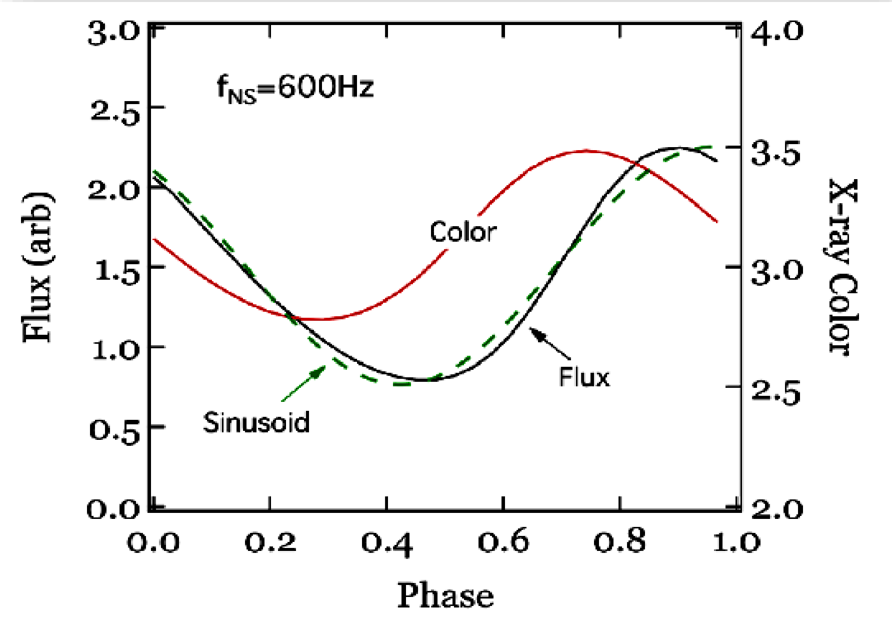
The coolest component, on the other hand, appears to cover a significant portion of the stellar surface







Spitkovsky et al. 2002

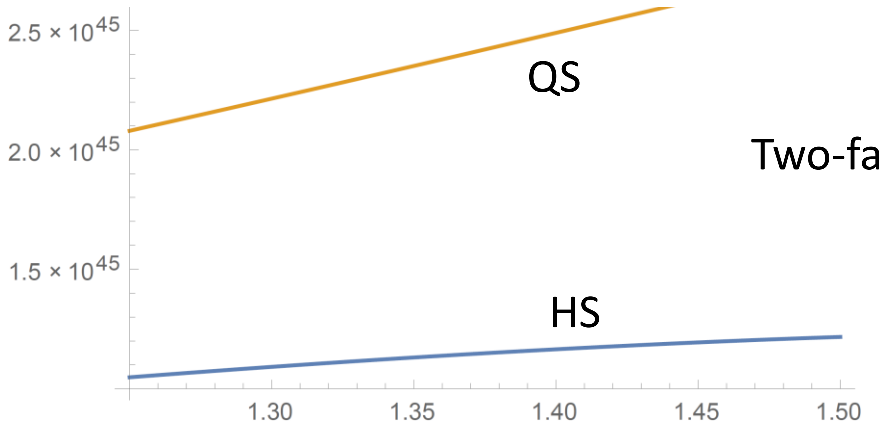


Hotspots on accreting neutron stars generate pulsations whose properties depend on M and R.

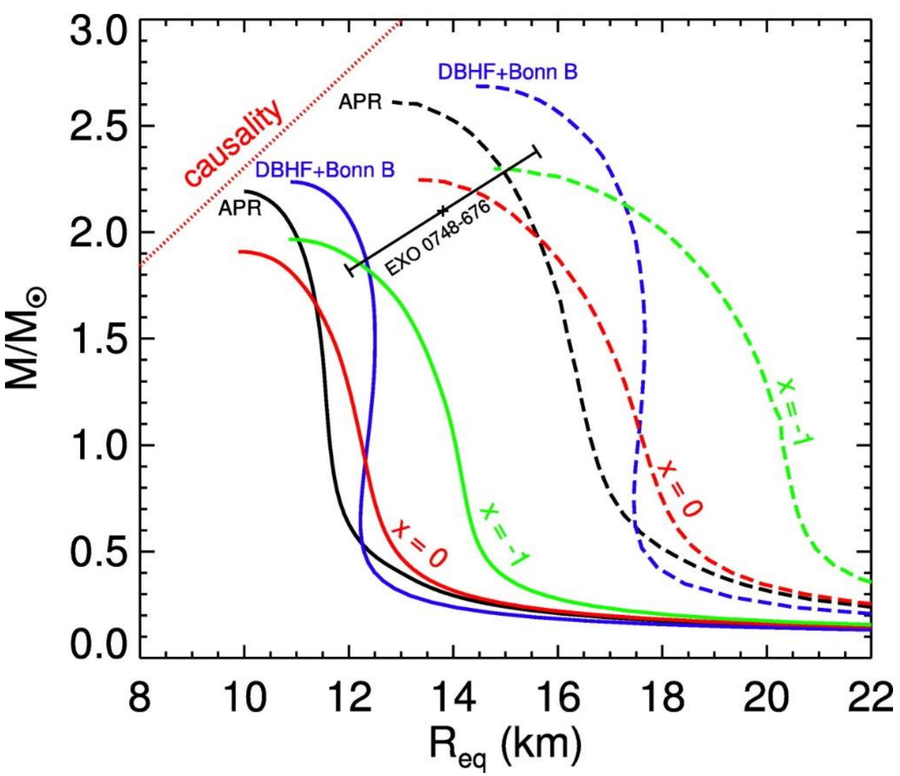
LOFT CAN RECOVER M AND R SIMULTANEOUSLY BY FITTING THE PHOTON ENERGY-DEPENDENT PULSE PROFILE.

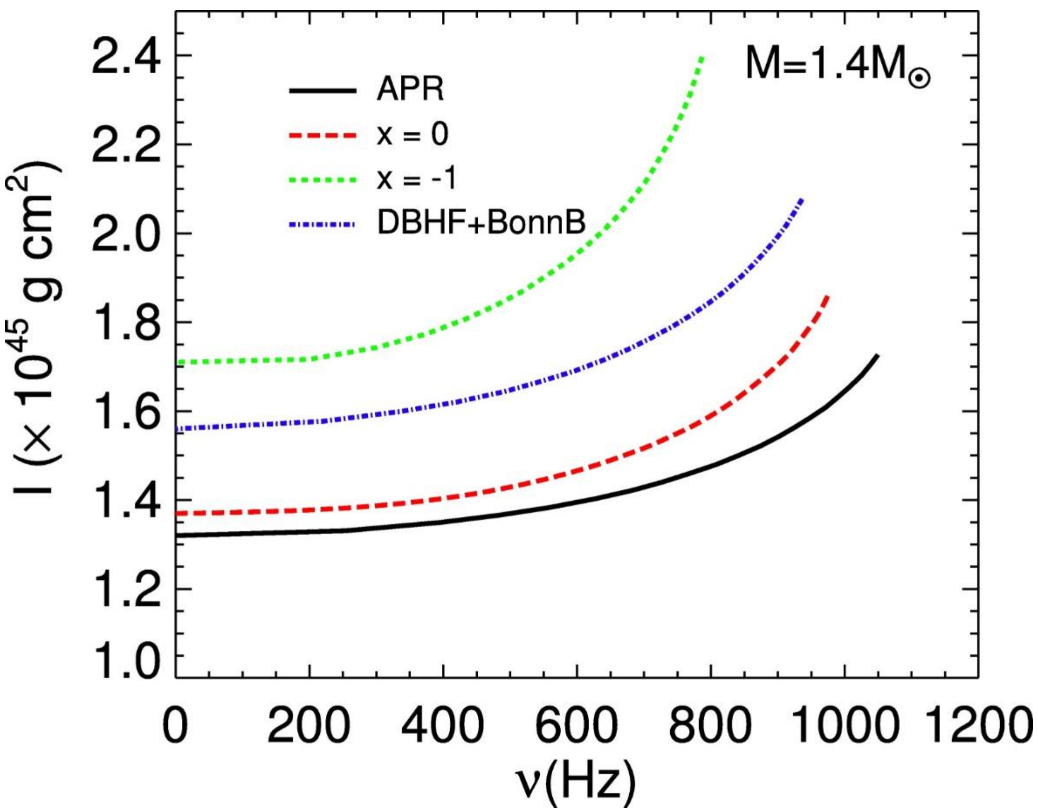
Misura del momento d’inerzia di una stella compatta tramite radiotelescopi (SKA)

Moments of inertia for various EoSs, slow rotating stars.



Two-families scenario

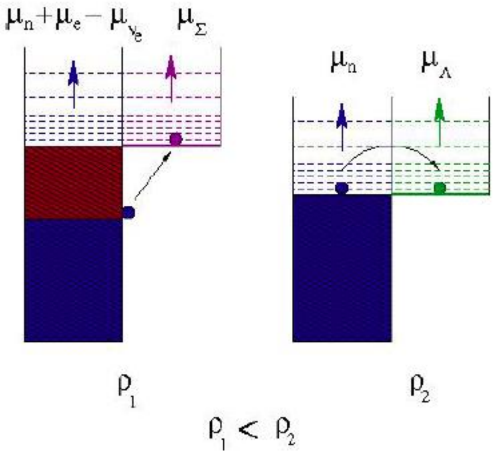




Iperoni (e risonanze delta)
nelle stelle compatte

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.



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

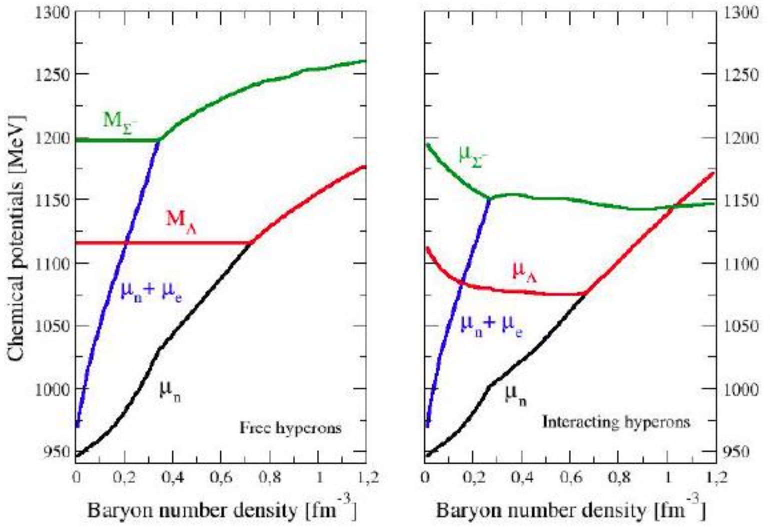
$$\mu_\Lambda = \mu_n$$

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

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

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

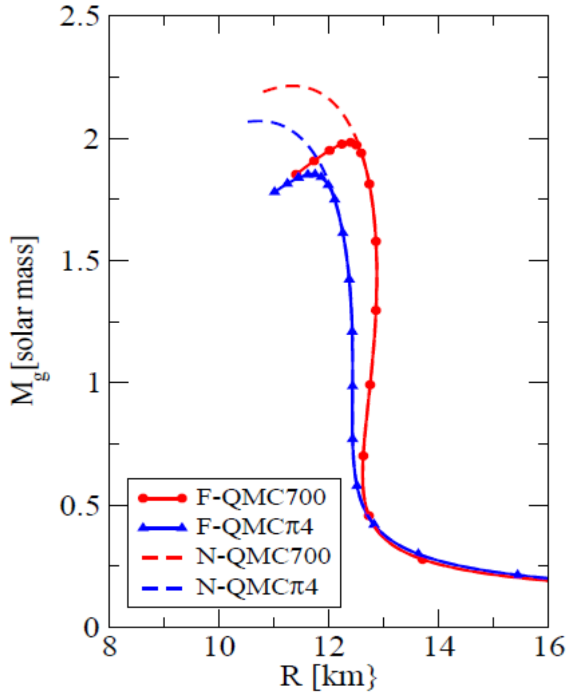
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$



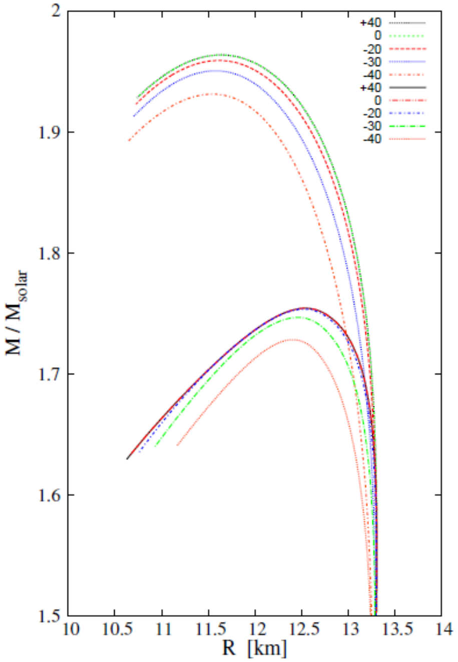
Hyperons in compact stars

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

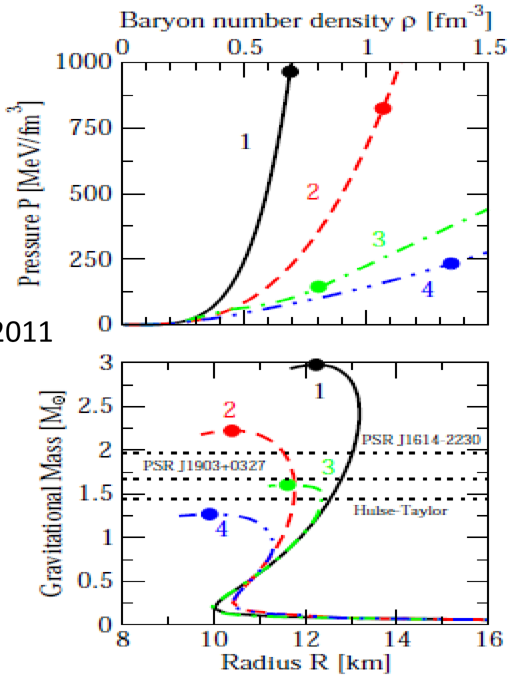
Stone et al. NPA 792(2007)341



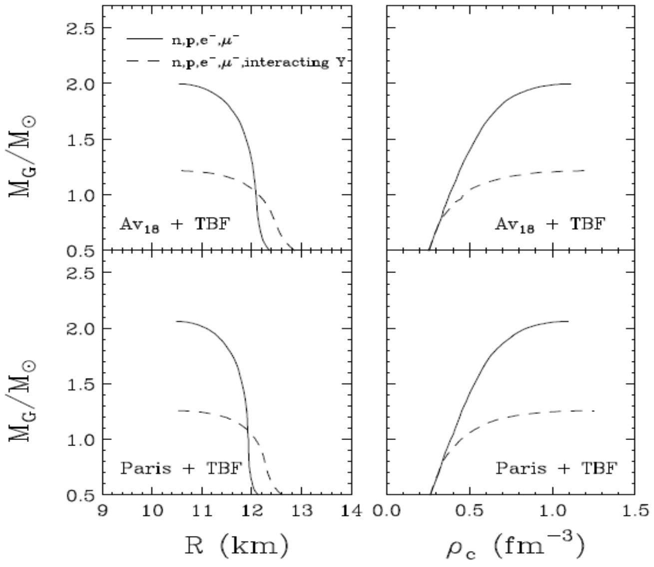
Weissenborn et al.
NPA 881(2011)62



Vidana et al 2011



Baldo et al 2000

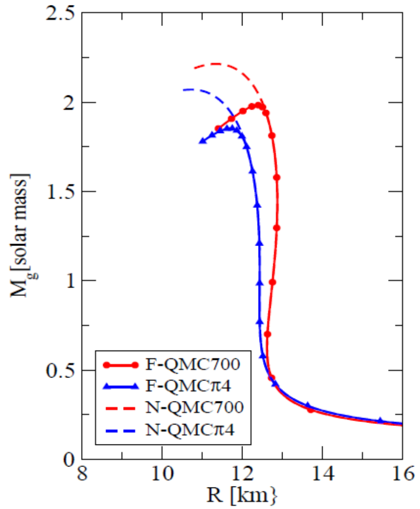


The 2Msun limit can be fulfilled within RMF models.

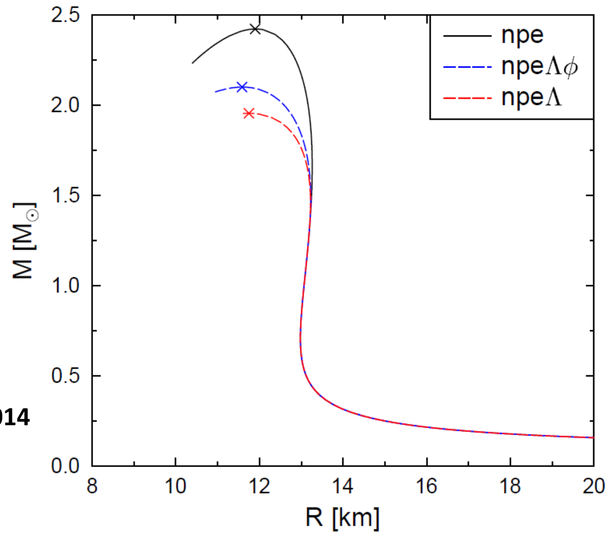
In microscopic non-relativisitc calculations it is fulfilled only if very strong and repulsive 3-body forces YNN are present (Pederiva et al. 2014).

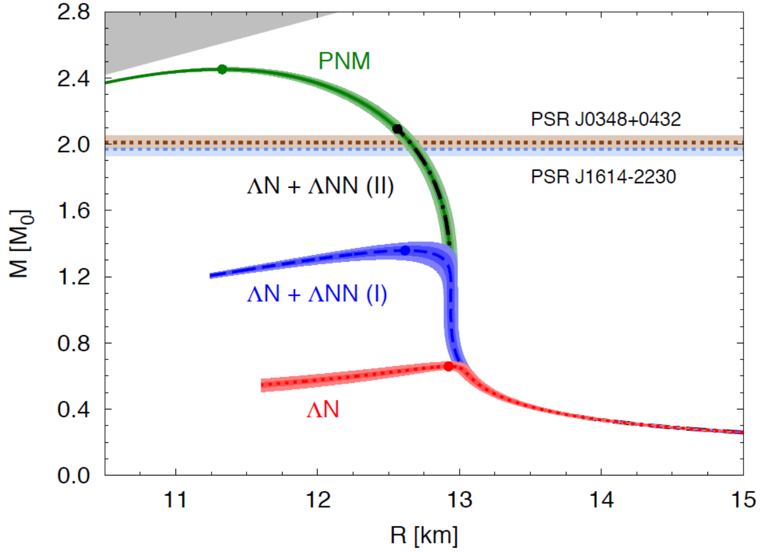
Minimum radius for a 1.4 M_s star: hadronic stars

Stone et al 2006



Banik et al. 2014

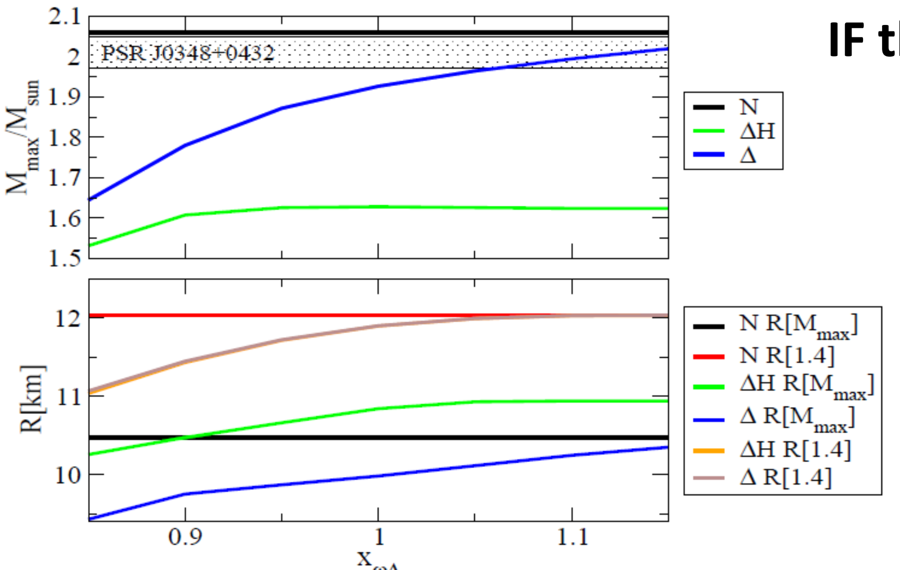




Lonardoni et al 2015

Hyperonic stars: $R_{1.4}$ > 12 km

IF the 2 M s constraint needs to be imposed



Delta – resonance stars

$R_{1.4}$ order of (10-11) km,

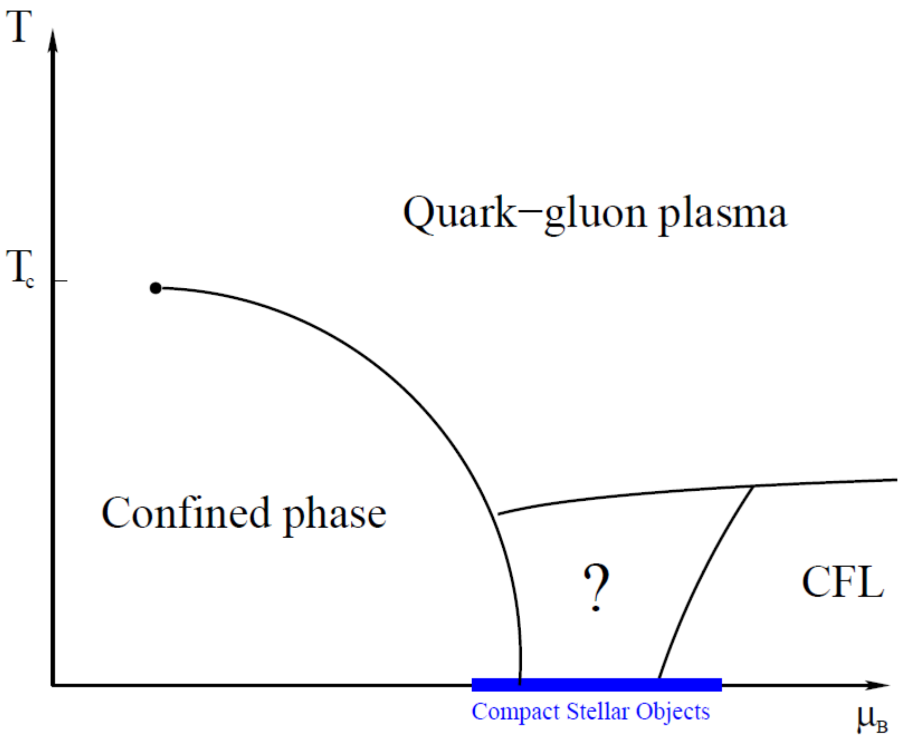
BUT the maximum mass

is smaller than 2 M_s

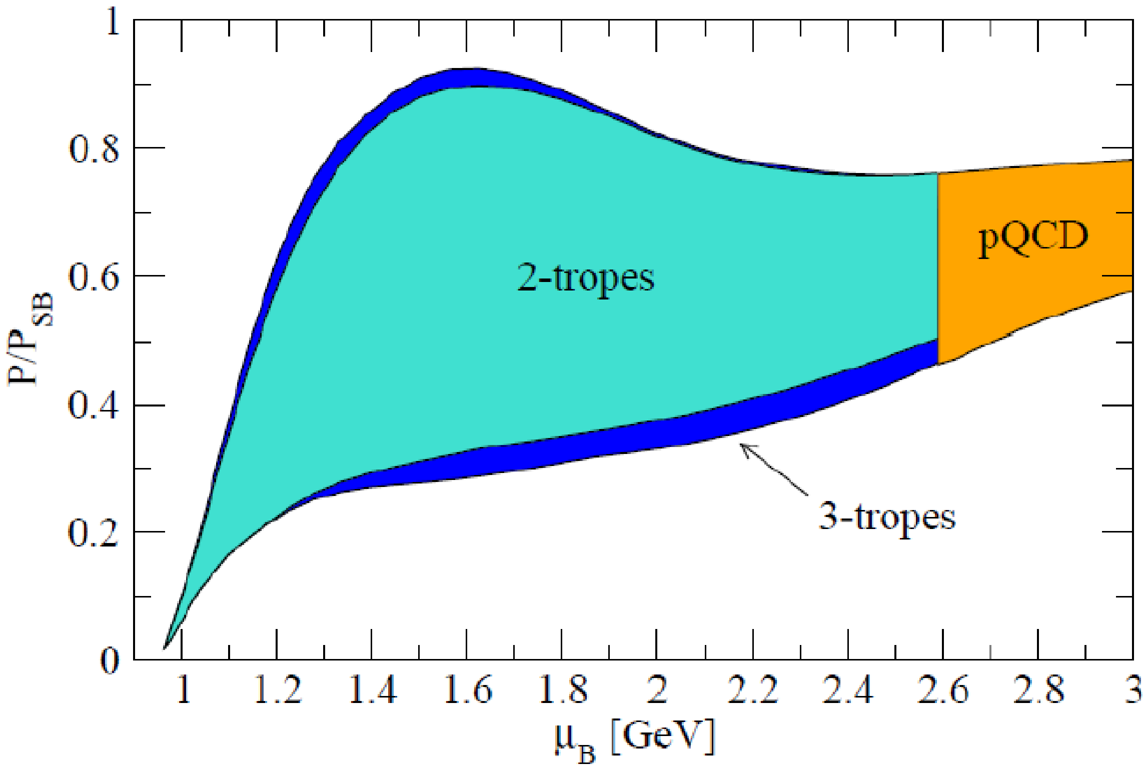
Quark deconfinati e stelle ibride
(adroni nella parte esterna del core e quark in quella interna)

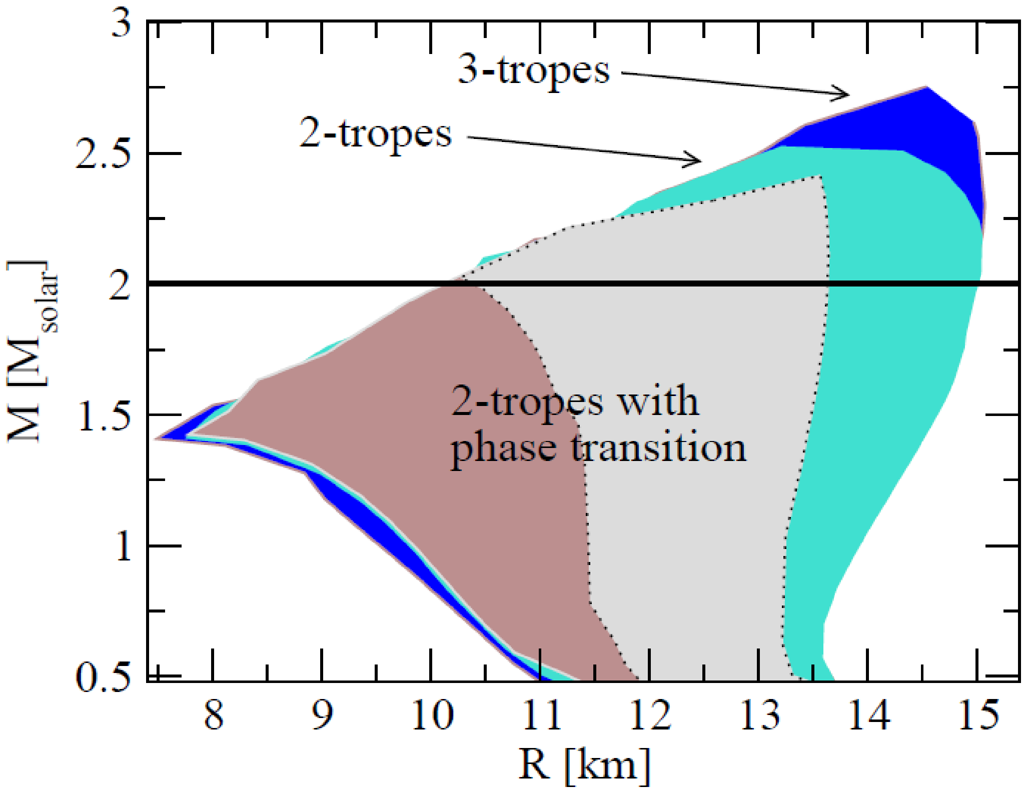
Deconfined quarks can appear at large densities

At which densities and following which dynamics is still unknown, but conditions for their existence can be derived based only on general properties of hadronic and of quark matter.
Ideas concerning which phases can exist at densities relevant for compact stars are discussed e.g. in Anglani, Casalbuoni, Ciminale, Gatto, Ippolito, Mannarelli, Ruggieri, Rev.Mod.Phys. 86 (2014) 509



Kurkela et al. 2014
Hybrid stars: $R_{1.4} > 11.5$ km





From Alford, Burgio, Han, Taranto, Zappalà, **Phys.Rev. D92 (2015) 083002**

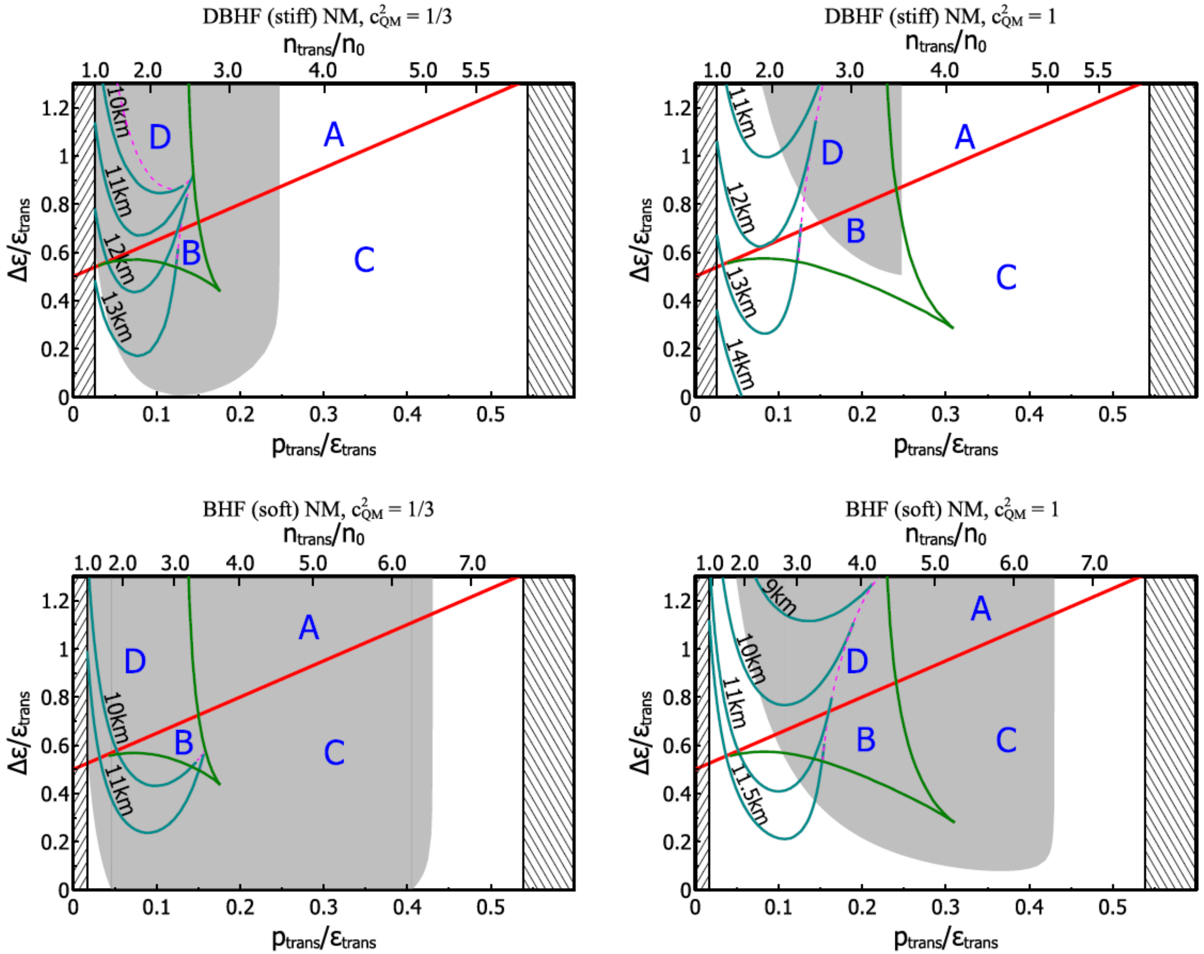


FIG. 4: (Color online). Contour plots similar to Fig. 3 showing the radius of a hybrid star of mass $M = 1.4\,M_\odot$ as a function of the CSS parameters. Such stars only exist in a limited region of the space of EoSs [delimited by dashed (magenta) lines]. The grey shaded region is excluded by the observational constraint $M_{max} > 2\,M_\odot$. For a magnified version of the low-transition-pressure region for $c^2_{QM} = 1/3$, see Fig. 5.

Radii smaller than about 11 km for stars of $M = 1.4\ M_s$ are possible ONLY if c^2 is close to 1. Not very realistic.

Stelle strane (anche dette stelle di quark): interamente costituite da quark deconfinati

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**

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

From I. Bombaci

The Strange Matter hypothesis

⇓

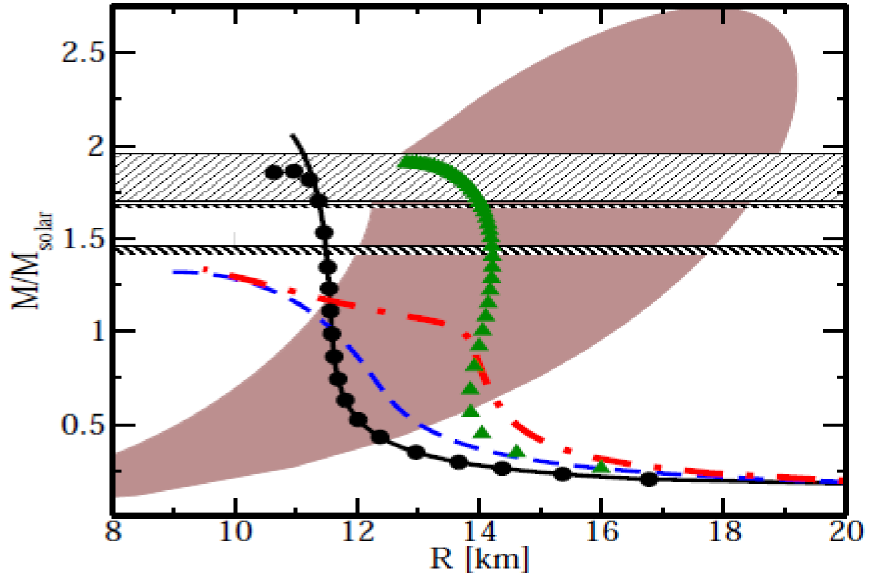
Strange Stars

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

Can Bodmer-Witten hypothesis on the absolute stability of strange quark matter be realized by using various models of quark dynamics?

- MIT bag model: YES Farhi and Jaffe, 1984
  - Parameters are not well constrained in the model, no chiral dymanics, but there is confinement
- Chiral models without confinement: NO Klaehn and Fischer 2015
  - The low density behaviour forces masses to be too large to satisfy BW
- Chiral models with a «confining» B: maybe Zacchi, Stiele, Schaffner-Bielich 2015
  - IF there is a parameters' space for BW it corresponds to too low densities or it falls back into a MIT-bag scenario in which chiral symmetry plays no role.
- Schwinger-Dyson model with a «confining» B: YES Chen, Wei, Schulze 2016
- Chiral models with confinement (Color Dielectric model): YES Dondi, Drago, Pagliara in preparation

Hybrid stars or quark stars?



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!!

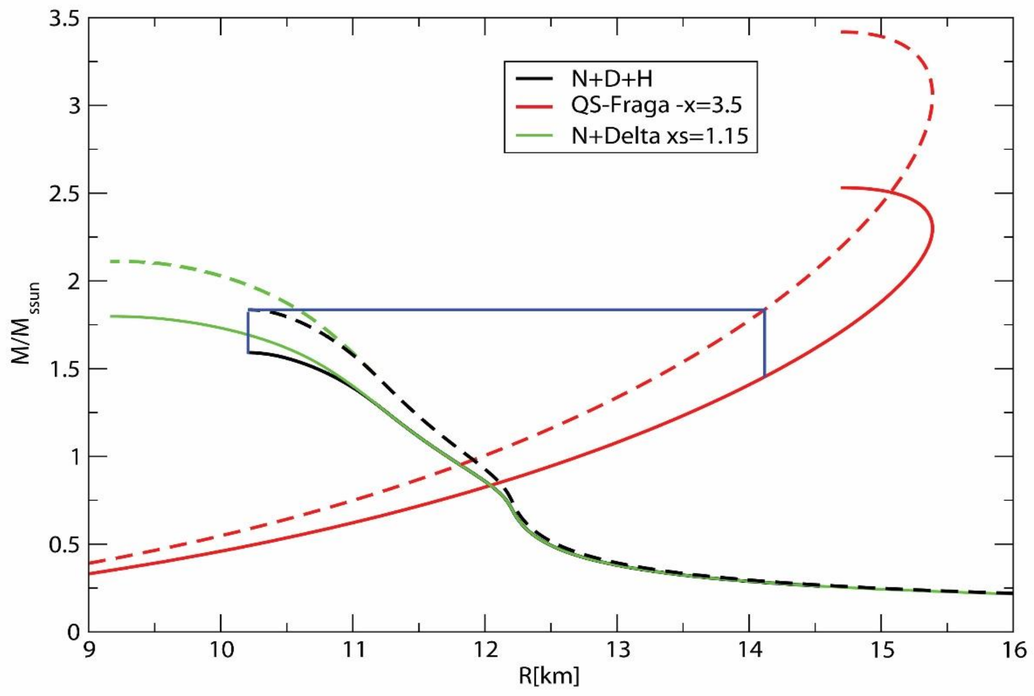
The two-families scenario

Stars having very small radii are made of neutrons, protons, hyperons…

Stars having very large masses are strange quark stars

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

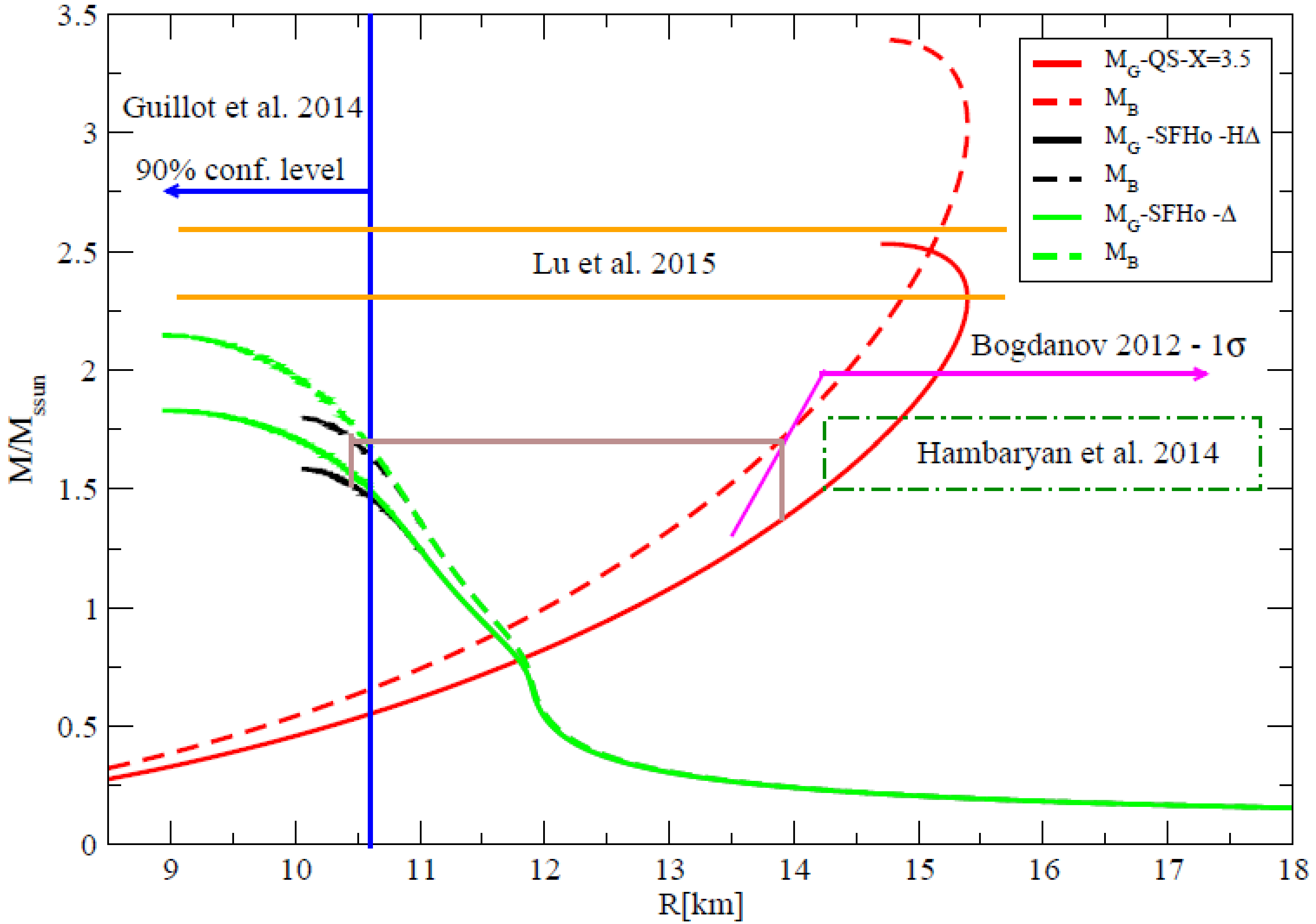
The hadronic stars are stable till when some strangeness component (e.g. hyperons) starts appearing in the core. Only at that point quark matter nucleation can start.



The maximum mass of a quark star can be as large as
2.75 $M_s \geq 2 \times (1.3 \div 1.4)\ M_s$.(Dynamically stable up to almost 1.3+1.3)
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.

Previsions and tests of the two-families scenario

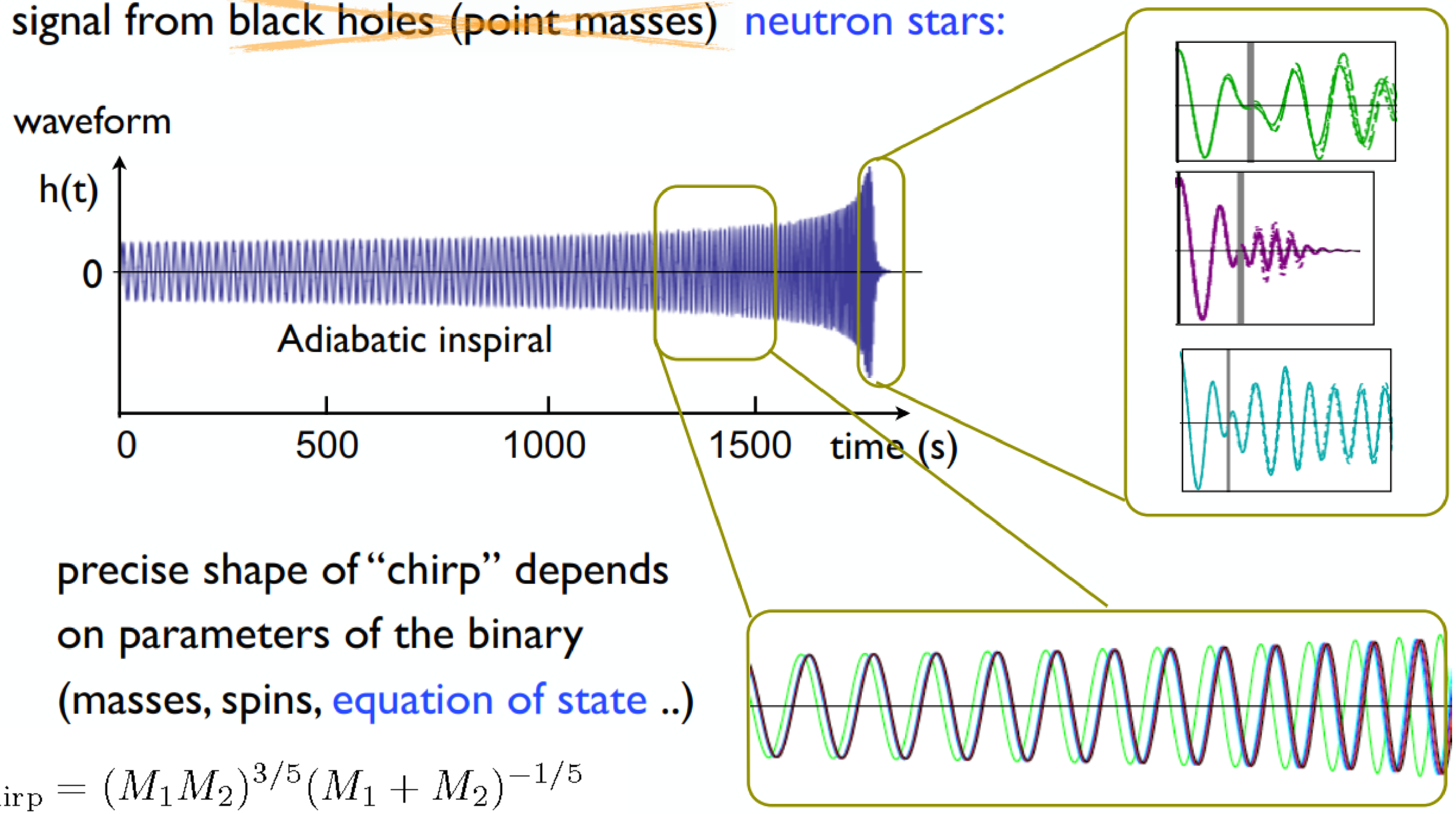
- Radii (NICER, LOFT)
- Anomalous mass distribution (SKA)
- Moment of inertia (SKA)
- GW signal in NS-NS merger (LIGO & VIRGO)
- Implications for long and short Gamma Ray Bursts (**see poster of A. Pili et al.**)



Cosa impariamo dal segnale in onde gravitazionali generato dalla coalescenza di due stelle di neutroni?

Gravitational wave signal from coalescing binaries

- expect to observe ~ tens of NS binary inspirals per year [0.4-400]
- signal from ~~black holes (point masses)~~ neutron stars:

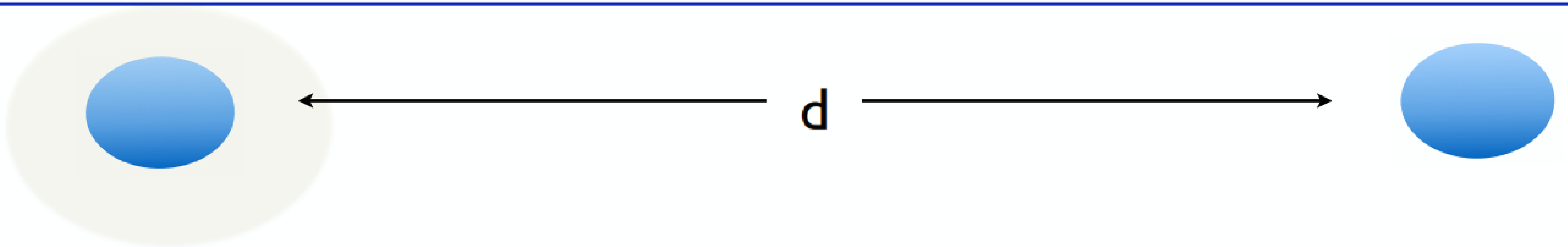


precise shape of "chirp" depends on parameters of the binary (masses, spins, equation of state ..)

$$M_{\rm chirp} = (M_1 M_2)^{3/5}(M_1+M_2)^{-1/5}$$

From T. Hinderer

NS in a binary



- companion's tidal field $\mathcal{E}$
- leading order linear response:

induced quadrupole

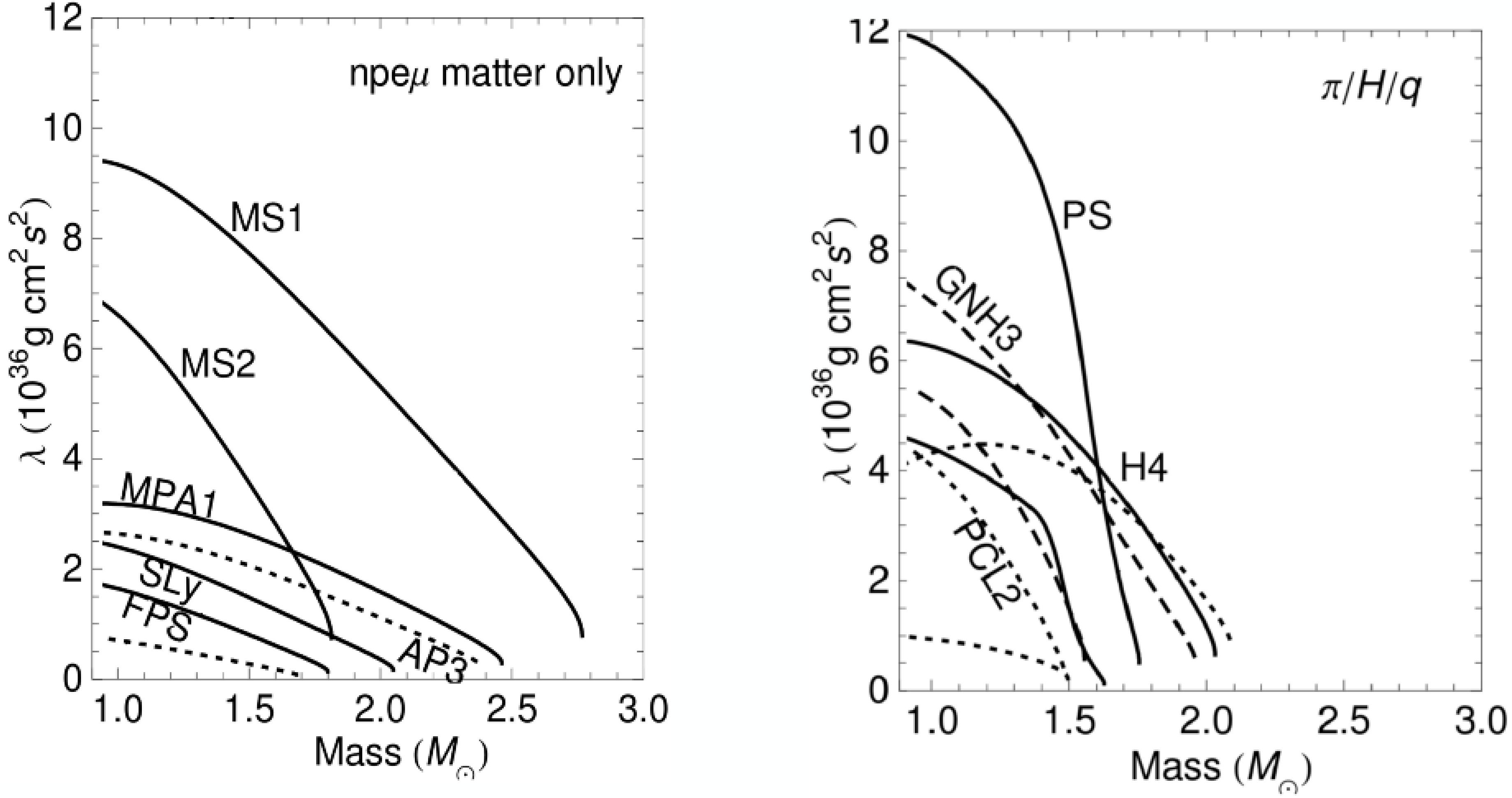
$$\mathcal{Q} = -\lambda\,\mathcal{E}$$

definition of tidal deformability λ

- quantities defined by the asymptotic gravitational potential:

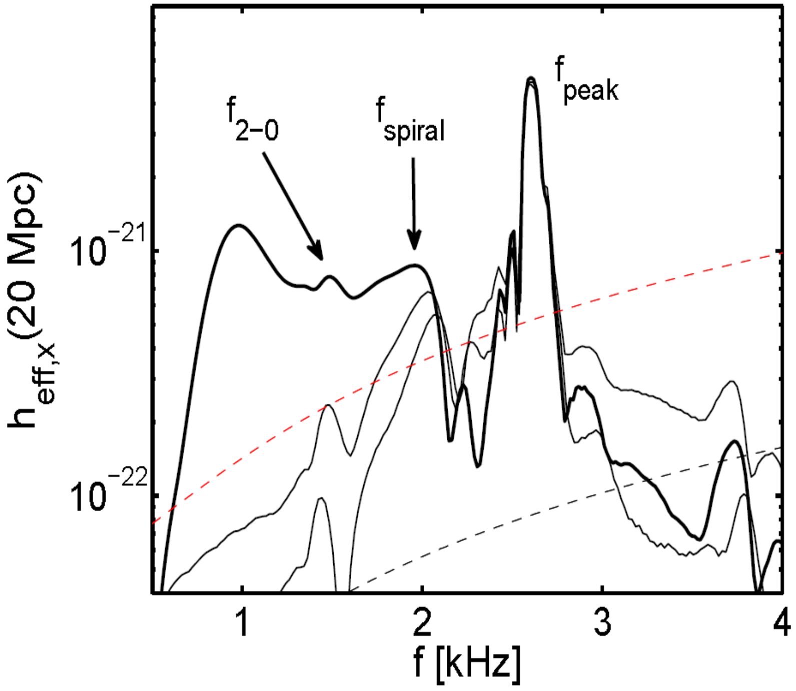
$$\frac{(1+g_{tt})}{2} = -\frac{\mathrm{m}}{r} - \frac{3\,\mathcal{Q}\,Y_{20}(\theta,\phi)}{2\,r^3} + \ldots + \frac{1}{2}\,\mathcal{E}\,r^2\,Y_{20}(\theta,\phi) + \ldots$$

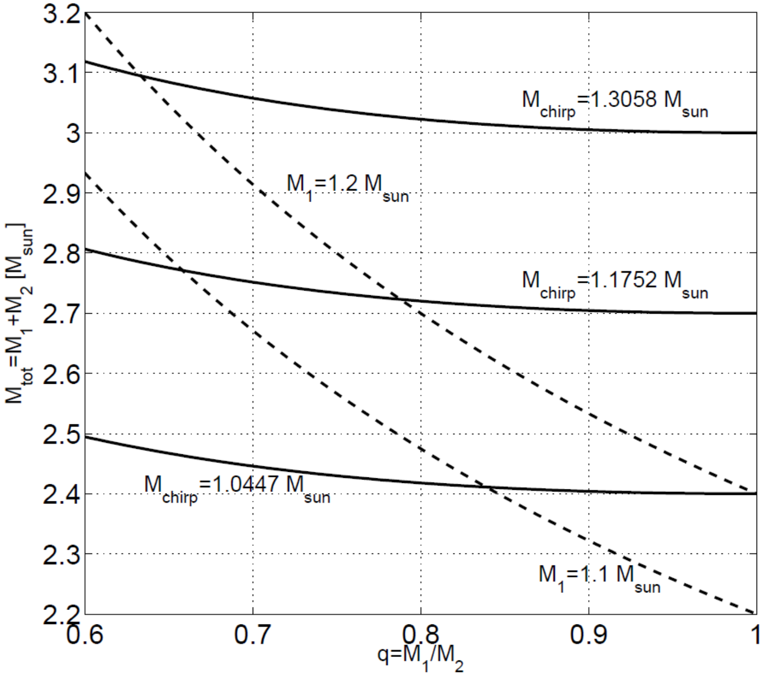
λ vs. mass for various EoS

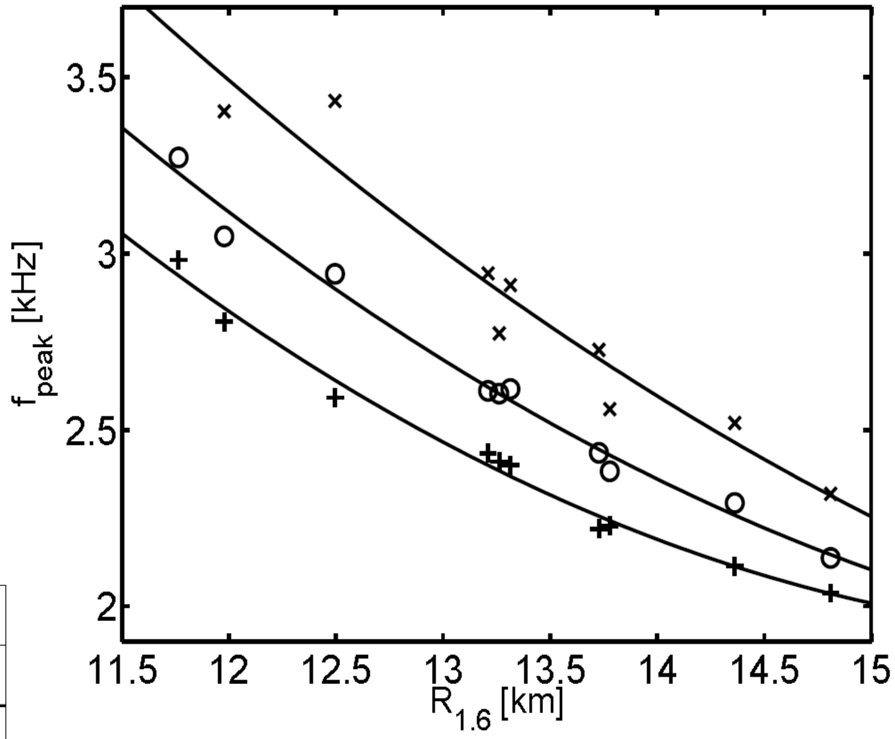


Hinderer, Lackey, Lang & Read 2009

Radii from post-merger analysis
Bauswein, Stergioulas, Janka 2015







Conclusioni

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 (NICER, LOFT), reaching a precision of ~ 1km in the measure of radii , can clarify the composition of compact stars, similarly a measure of the moment of inertia with a precision of about 20-30 percent (SKA):

- **$R_{1.4} >= 13$ km or $I_{45} >= 1.6$ purely nucleonic stars ($\rho_{max} \leq 3\ \rho_0$)**
- **11.5 km $< R_{1.4} <$ 13 km or $1.3 <= I_{45} <= 1.6$ hyperonic or hybrid stars (ρ_{max} as large as 5 ρ_0)**
- **$R_{1.4} <<$ 11.5 km or $I_{45} << 1.3$ two families of compact stars**

Witten's hyphotesis verified!

Decisive data expected from x-ray satellites, radiotelescopes and GW detectors

Possible search of precursor signals in hypernuclei with S = -2 ?