On the quark content of neutron star cores

Rana Nandi

SHIV NADAR
INSTITUTION OF EMINENCE DEEMED TO BE
UNIVERSITY
DELHI NCR

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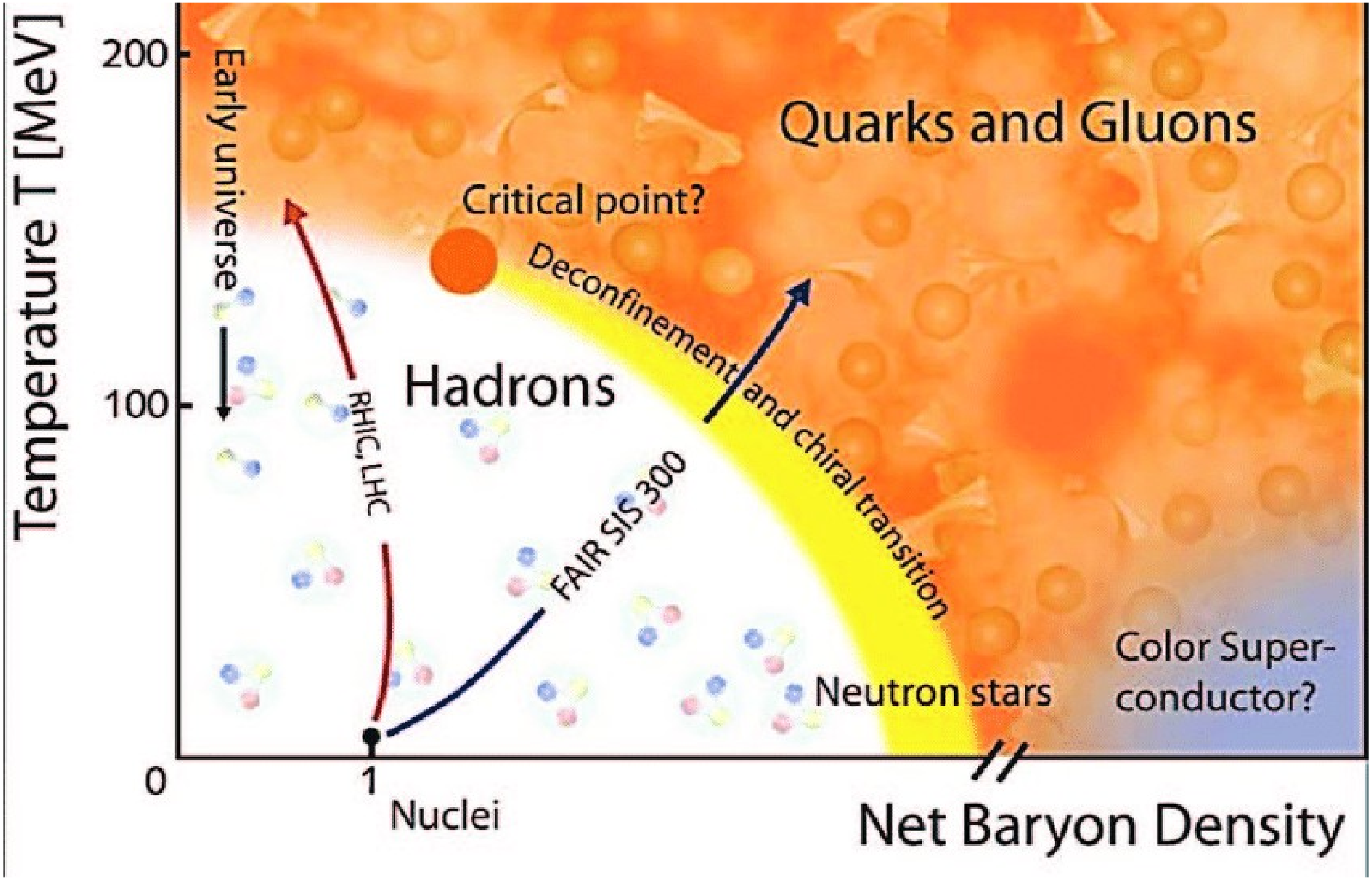
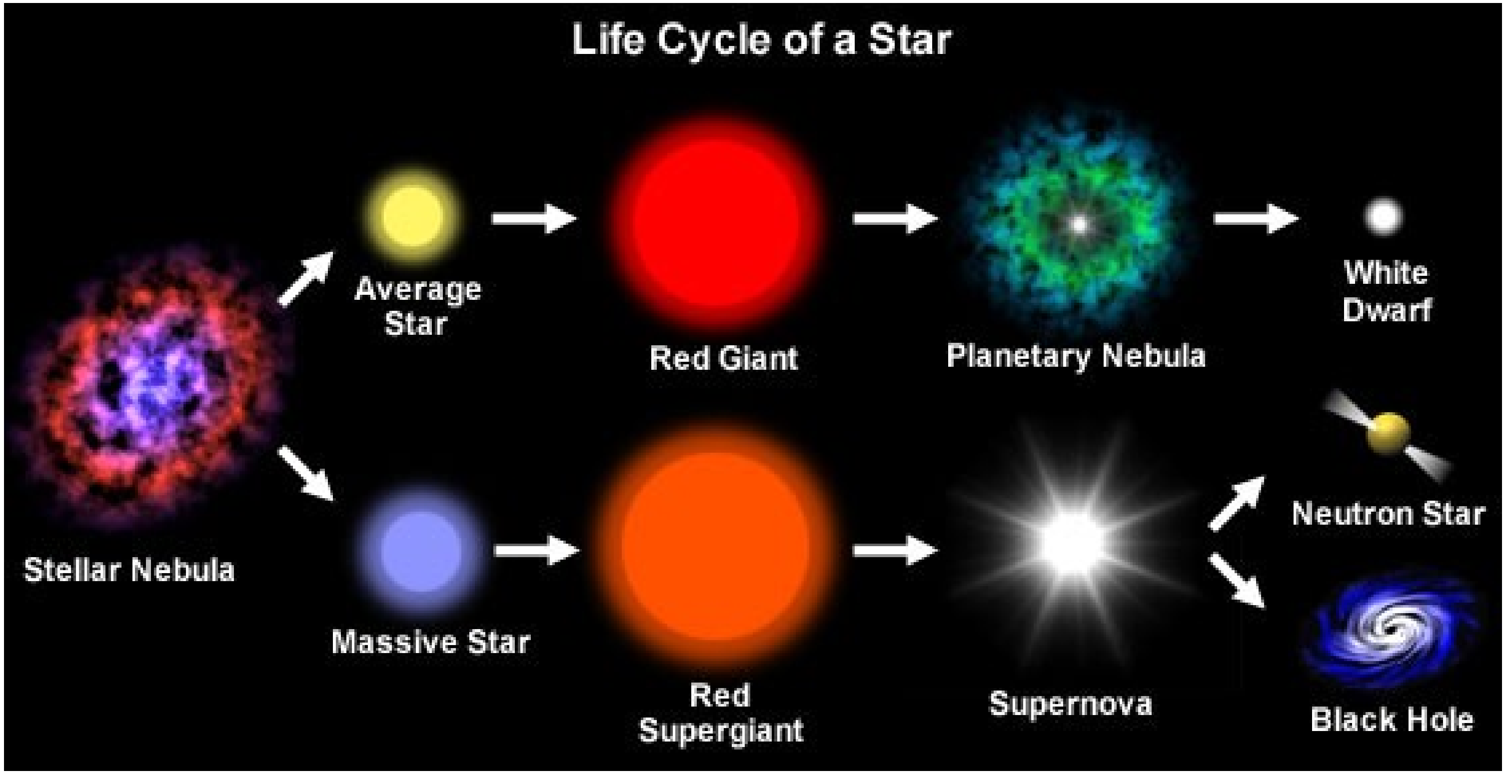
Introduction



- QCD predicts hadrons to quarks and gluons deconfinement transition at high density and/or temperature.
- The deconfinement transition at high temperature has been observed in heavy-ion collisions.
- But the presence of quarks at high density remains unsolved.
- One of the naturally occurring laboratories of the dense matter is the cores of neutron stars.
- However, the cores are not directly visible, and to have any information, we have to model NSs from the core to the surface and then match them with observations.

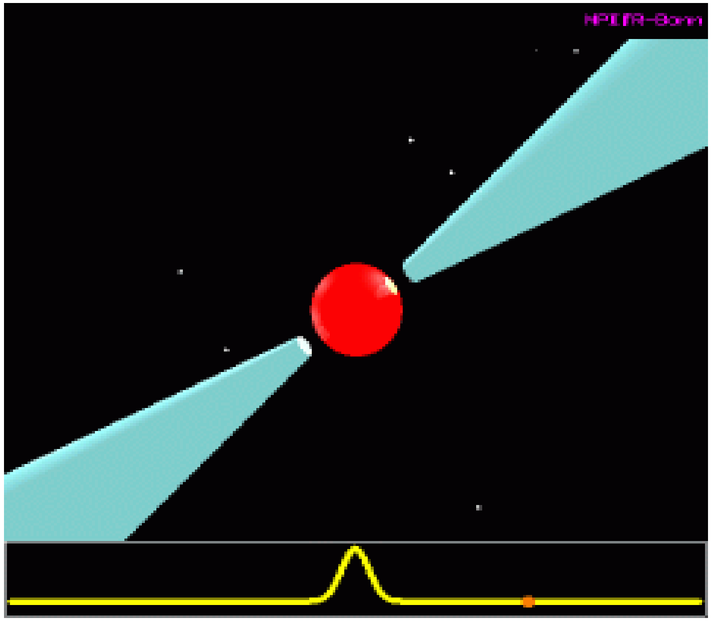
Introduction to NS

Neutron stars are dead stars, produced via the gravitational collapse of massive stars ($8M_\odot < M < 25M_\odot$) via supernova.



Properties of NS

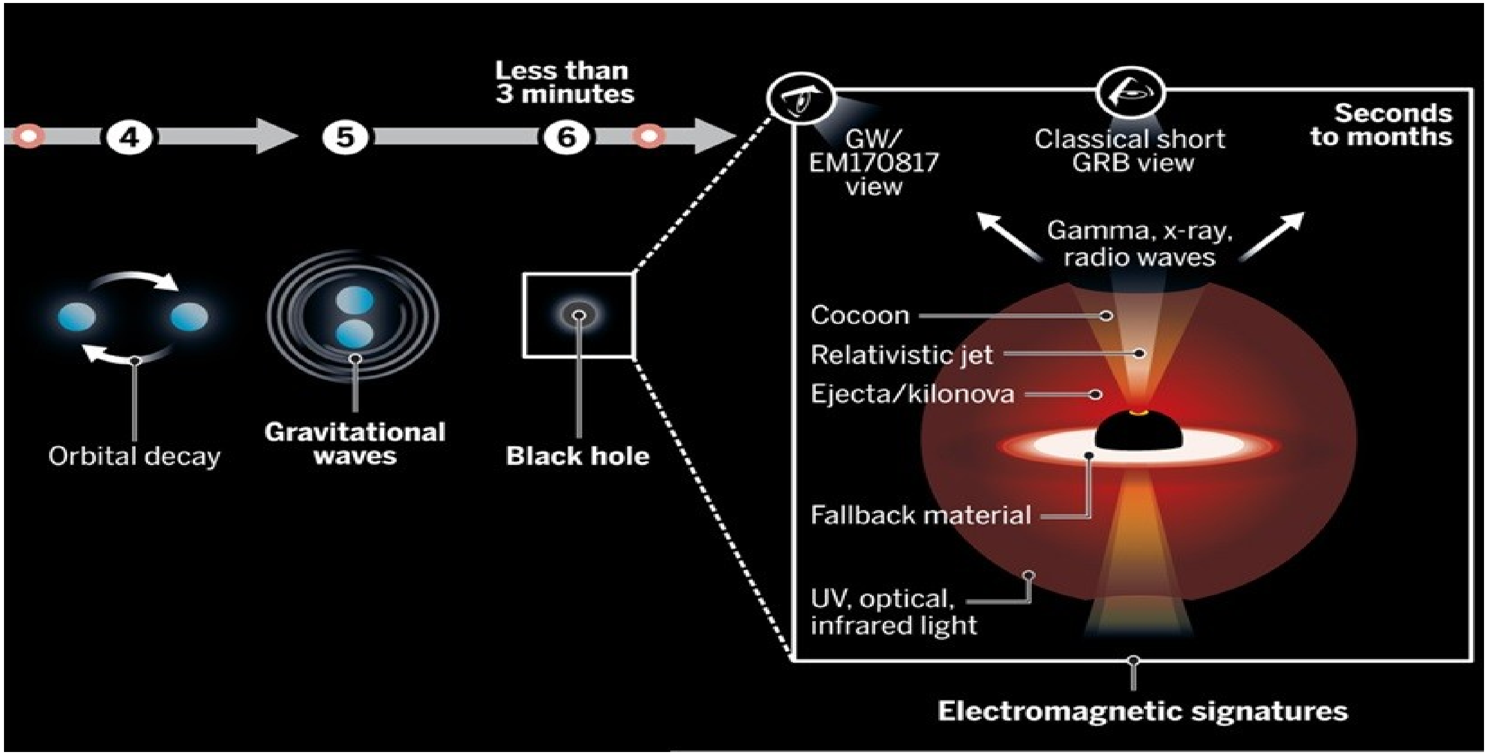
- Mass $\sim 1-3M_{\odot}$
- Radius $\sim 10-15$ km
- Density $\sim 10^{15}$ g/cc
- Period $\sim 1\,\mathrm{ms}-10\,\mathrm{s}$
- Mag. field $\sim 10^{8}-10^{15}$G



- Mostly observed as radio pulsars.
- Jocelyn Bell and Anthony Hewish (Nobel prize, 1974) discovered the first radio pulsar in 1967.
- Soon identified as a highly-magnetized rotating NS.
- More than 2500 pulsars are discovered so far.
- Also observed in x-rays, gammy-rays and optical.

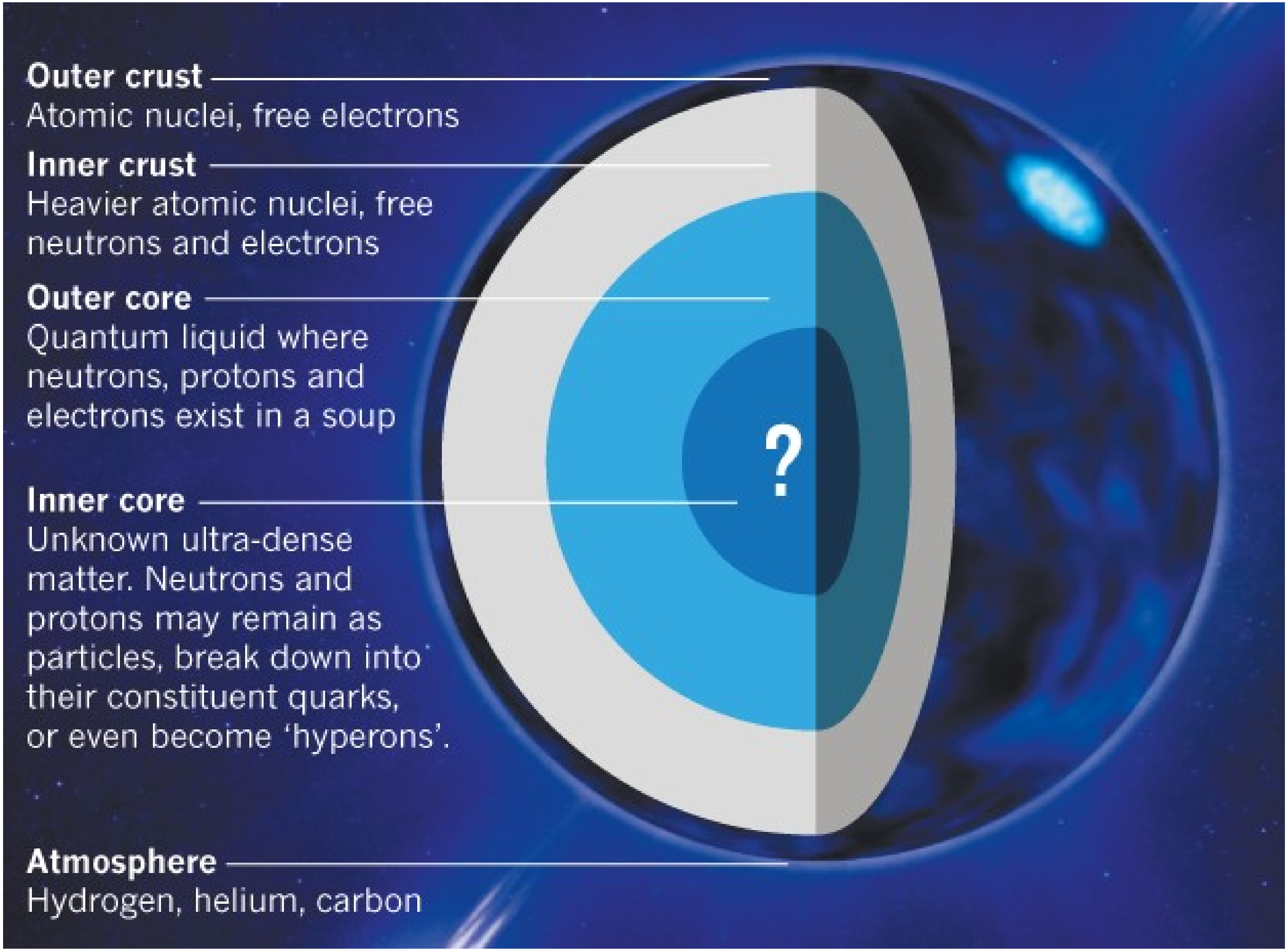
GW: A new window

- On August 2017, LIGO-Virgo collaboration detected first ever GW from a binary neutron star merger event: GW170817.
- Subsequent electromagnetic counterparts were detected by ~70 observatories.



- Marks the beginning of multi-messenger era of astronomy.

Neutron Star Interior



Outer crust
Atomic nuclei, free electrons

Inner crust
Heavier atomic nuclei, free neutrons and electrons

Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup

Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become ‘hyperons’.

Atmosphere
Hydrogen, helium, carbon

Building a NS

- The structure of a static (i.e., non-rotating) star with spherical symmetry in General Relativity is described by the Tolman-Oppenheimer-Volkoff (TOV) eqns:

$$\frac{dp}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{P(r)}{c^2\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)m(r)}{c^2}\right)\left(1-\frac{2Gm(r)}{c^2 r}\right)^{-1}$$

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

P = pressure , *ε*(*r*) = energy density

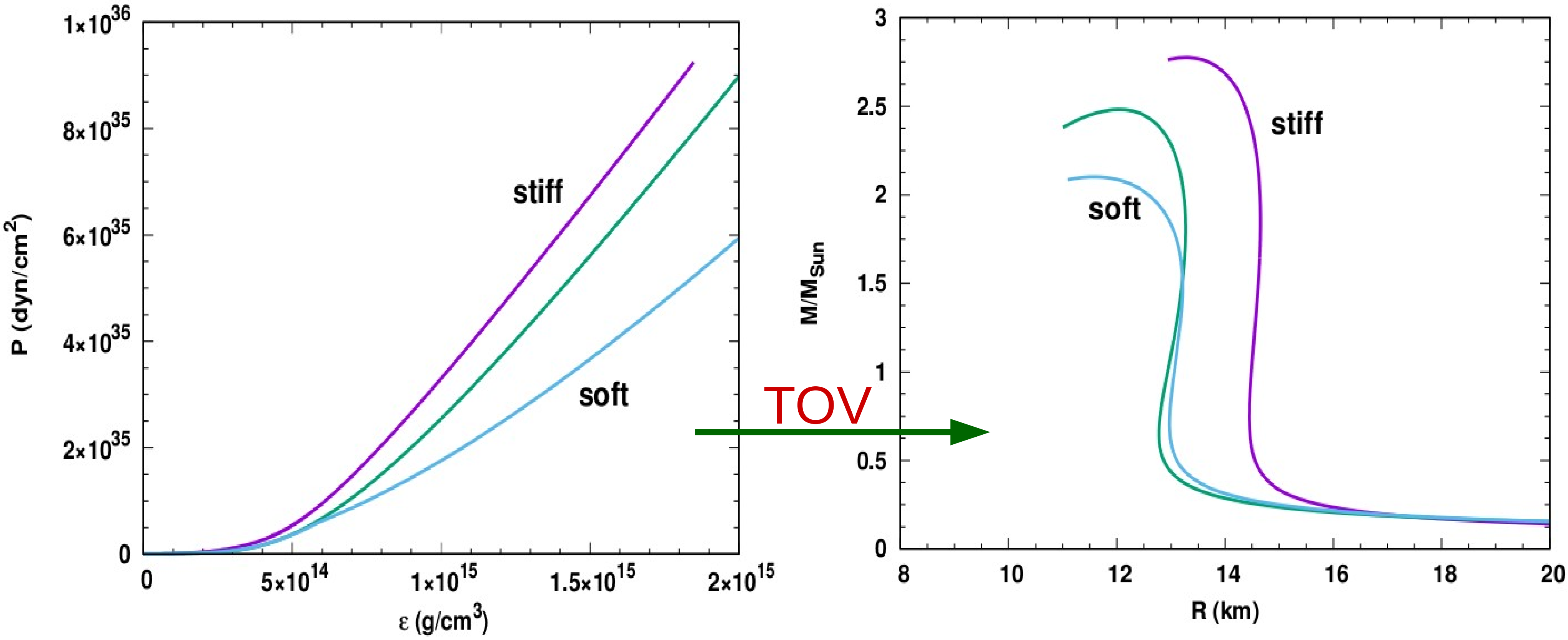
- Boundary Conditions:

$$P(r=0) = P_c, \quad m(r=0) = 0$$
$$P(r=R) = 0, \quad m(r=R) = M$$

Equation of State

- Essential ingredient to solve TOV

$$p = p(\varepsilon) \qquad \text{or} \qquad \varepsilon = \varepsilon(p)$$



- Each EOS corresponds to a maximum mass
- Stiffer EOS gives larger maximum mass and radius

EOS is highly uncertain

- Constituents are not known.
- Interaction between constituents are not fully known.
- Uncertainties in the many-body description.

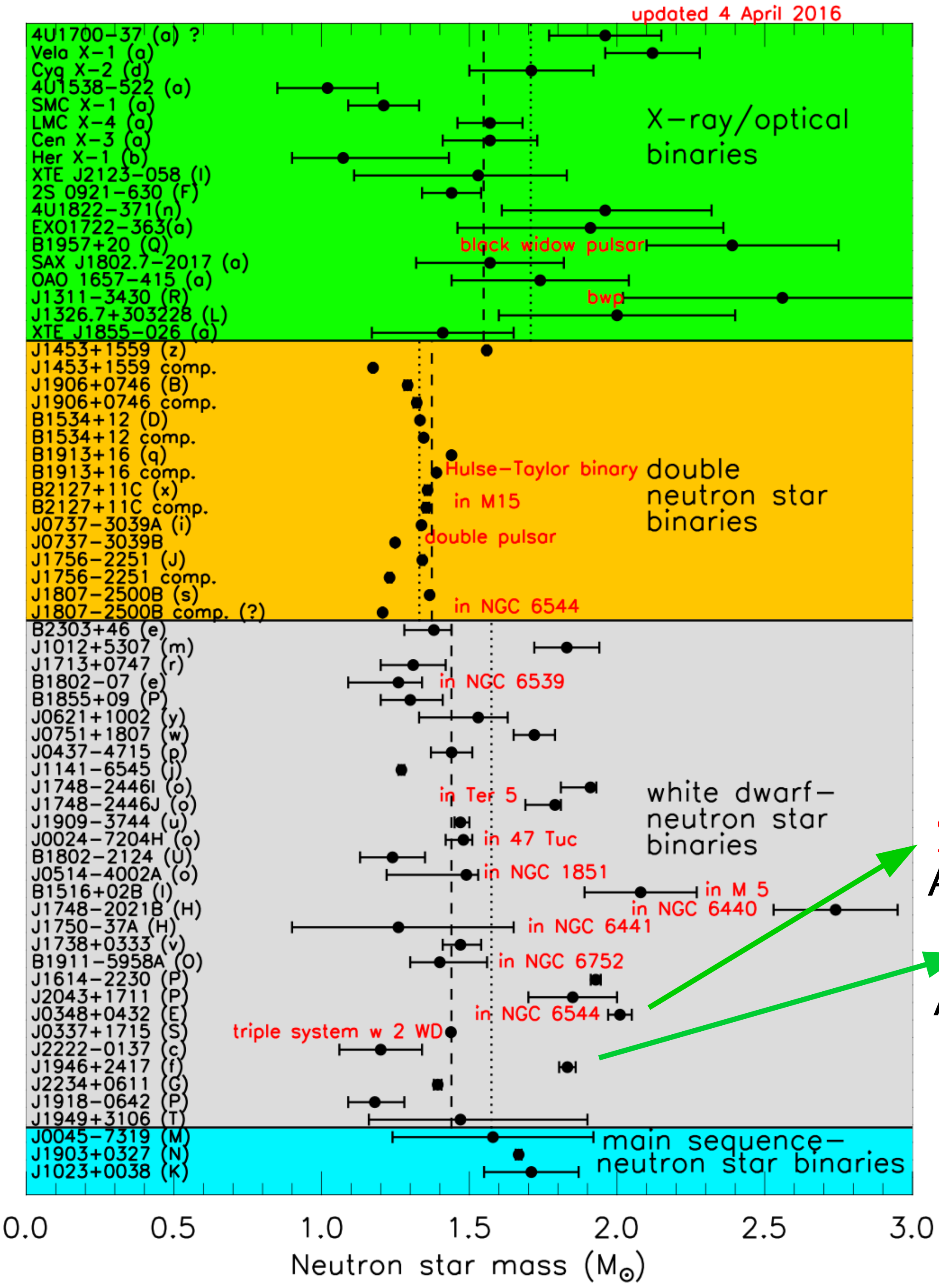
- However, the EOS at two extreme density limits at zero temperature, are known with a certain degree of accuracy.
- Up to nuclear saturation density, the matter is in the hadronic phase, and the modern nuclear theory (like chiral effective field theory) is quite accurate.
- In the very high-density limit perturbative-QCD (pQCD) techniques with quarks and gluons as their degrees of freedom become reliable.
- This indicates that there is a deconfinement phase transition from hadrons to quarks happening at densities between these two limits.

- The cores of neutron stars at their heart bears these intermediate densities where phase transition can occur.

EOS is highly model dependent

↓

Need to rely on astrophysical observations



➢ First breakthrough

Precise mass
Measurement of
massive NS

Excluded soft EOSs

$2.01 \pm 0.04 M_\odot$

Antoniadis et al *Science* 340 448(2013)

$1.908 \pm 0.016 M_\odot$

Arzoumanian et al *ApJS* 235 37(2018)

$2.08 \pm 0.07 M_\odot$

Fonseca et al *ApJL* 915 L12(2021)

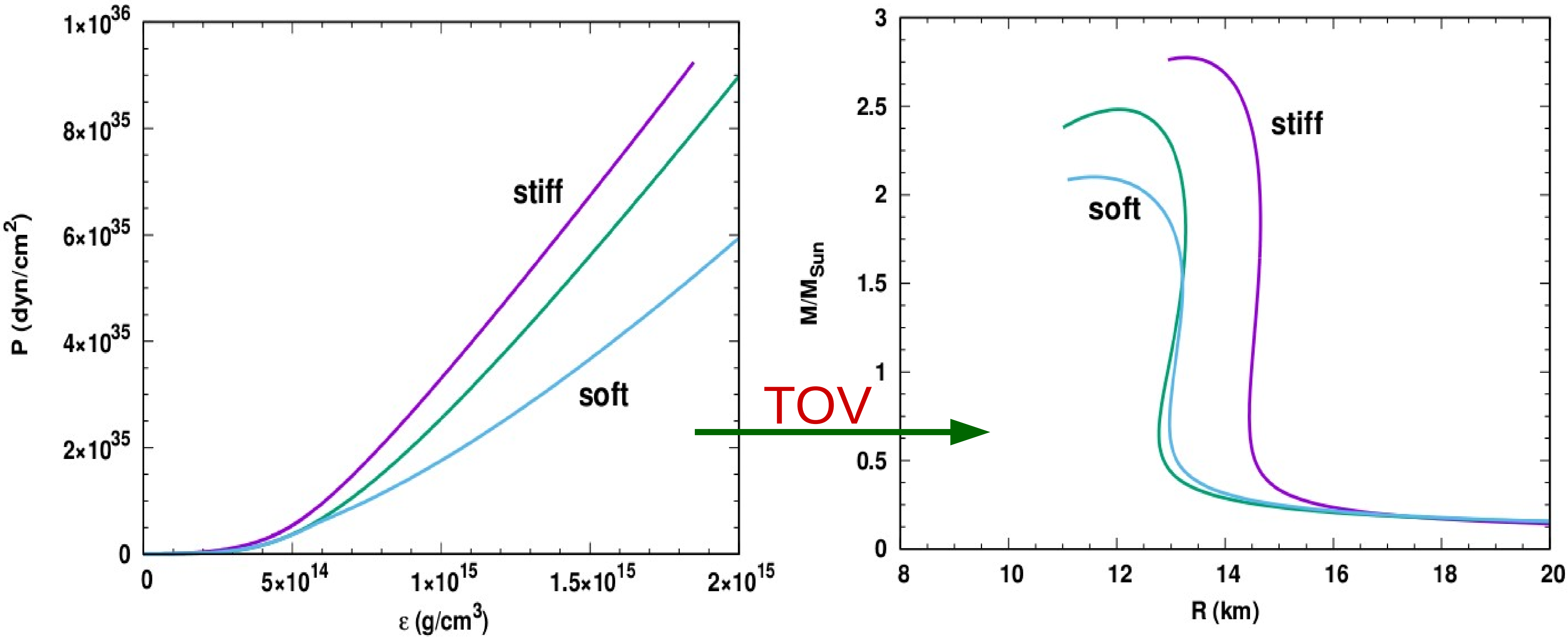
$2.35 \pm 0.17 M_\odot$

Romani et al *ApJL* 934 L17(2022)

Equation of State

- Essential ingredient to solve TOV

$$p = p(\varepsilon) \qquad \text{or} \qquad \varepsilon = \varepsilon(p)$$



We need precise and simultaneous mass-radius measurements → NICER mission started on 2017.

Tidal deformability

- Another significant constraint came from GW170817 with the measurement of tidal deformability (Λ), an EOS-sensitive quantity:

$\Lambda_{1.4} \leq 800$ LVC, PRL 119, 161101 (2017)

$\Lambda_{1.4} \leq 580$ LVC, PRL 121, 161101 (2018)

$$\Lambda = \lambda / M^5, \quad \lambda = \frac{2}{3} k_2 R^5, \quad k_2 = \text{love number}$$

- In 2019, NICER provided the First simutaneous measurement of mass-radius for PSR **J0030+0451:**

$$M = 1.34^{+0.15}_{-0.16} M_\odot, \quad R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$$

Riley et al, *ApJL* 887, L21 (2019)

$$M = 1.44^{+0.15}_{-0.14} M_\odot, \quad R = 13.02^{+1.24}_{-1.06}\,\mathrm{km}$$

Miller et al, *ApJL* 887, L24 (2019).

- In 2021, another measurement was reported by analysing NICER + XMM Newton data of **PSR J0740+6620**:

$$R = 13.7^{+2.6}_{-1.5}\,\mathrm{km}$$

Miller et al, *ApJL* 918, L28 (2019).

Quark matter

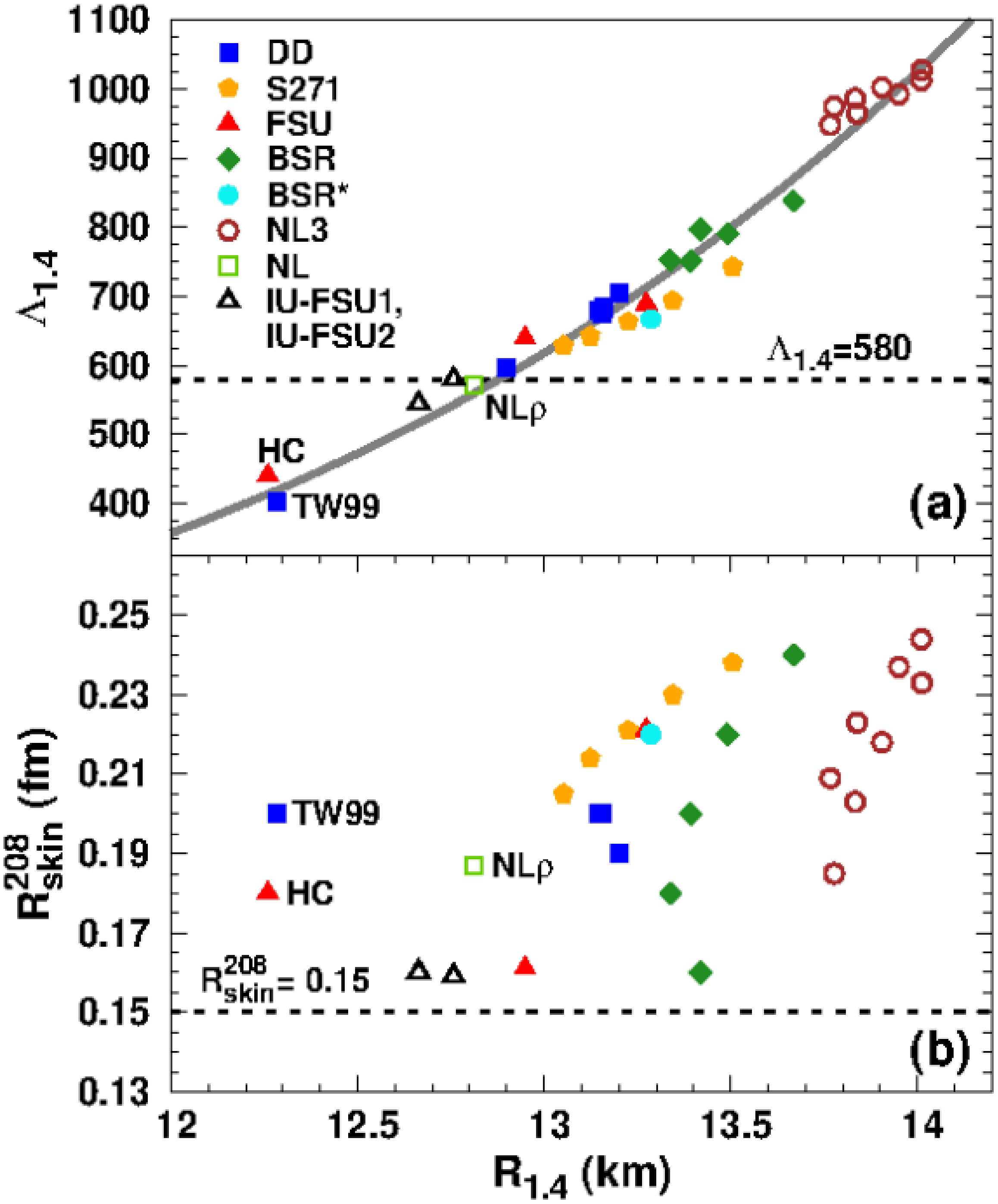
- Still we can’t say whether an NS core can shelter quark matter or not.
- In a recent study we explored the possibilty of distinguishing between neutron stars and neutron stars with a quark core (**Hybrid stars**).

R Mallick, D Kuzur and R Nandi
EpJC 82 512 (2022)

EOS considered

- We considered several Relativistic Mean Field (RMF) EOS to describe the hadronic part.

$$M \geq 1.97 M_\odot$$

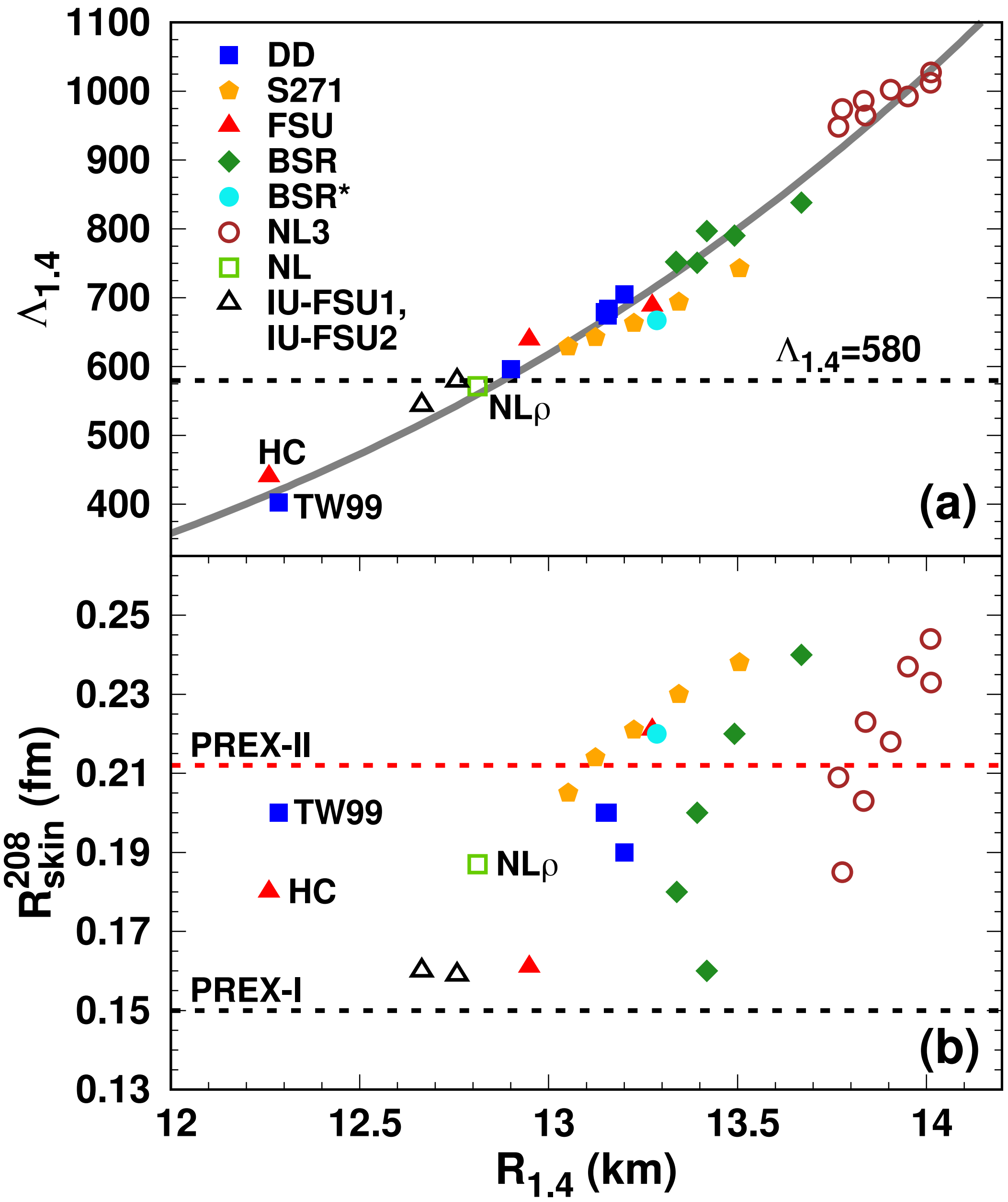


$$R_{\rm skin}^{208} \quad \lesssim \quad 0.20\,{\rm fm}$$

$$R_{\rm skin} \quad = \quad < r_n > - < r_p >$$

$$R_{\rm skin}^{208} \quad = \quad 0.33^{+0.16}_{-0.18}\,{\rm fm}$$

PREX-I, PRL108, 112502 (2012)



$$R^{208}_{\mathrm{skin}} \lesssim 0.20\,\mathrm{fm}$$

$$R_{\mathrm{skin}} = <r_n> - <r_p>$$

$$R^{208}_{\mathrm{skin}} = 0.33^{+0.16}_{-0.18}\,\mathrm{fm}$$

PREX-I, PRL108, 112502 (2012)

PREX-II:

$$R^{208}_{\mathrm{skin}} = 0.29 \pm 0.07\,\mathrm{fm}$$

PRL126, 172502 (2021).

EOS considered

- We considered several Relativistic Mean Field (RMF) EOS to describe the hadronic part.
- For the quark part we adopt the MIT Bag model

Quark EOS

- **MIT Bag model:**

$$\Omega = \sum_i \Omega_i^0 + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{\rm eff}, \quad i = u, d, s, e$$

$$P = -\Omega$$

$$\varepsilon = -P + \sum_i \mu_i n_i$$

$\Omega_i^0 \rightarrow$ Grand potentials of non-interacting Fermi gas

$\mu \rightarrow$ Baryon chemical potential of quarks

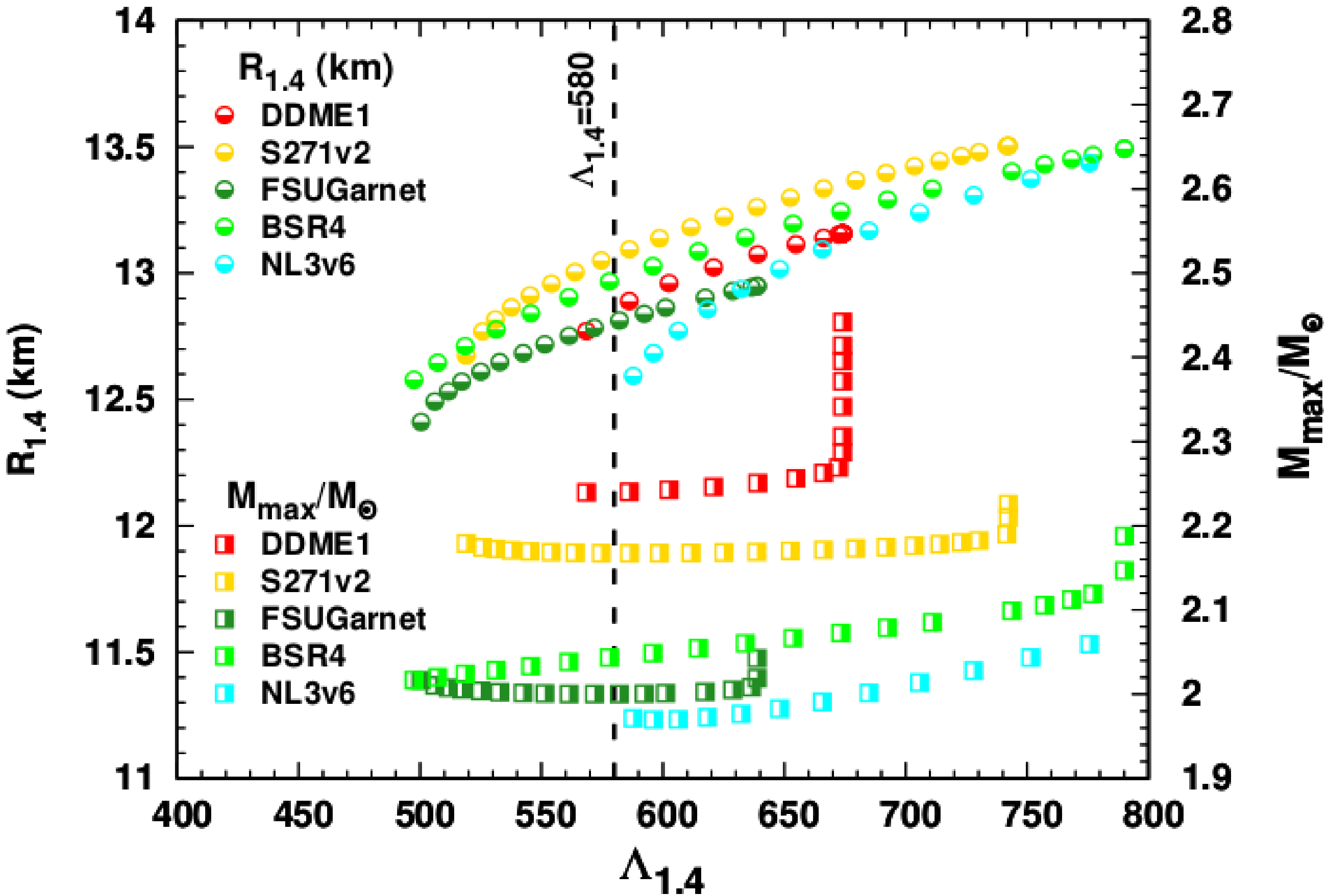
$B_{\rm eff} \rightarrow$ Bag constant

$a_4 \rightarrow$ Interaction parameter

$n_i \rightarrow$ Number density of *i*-th particle

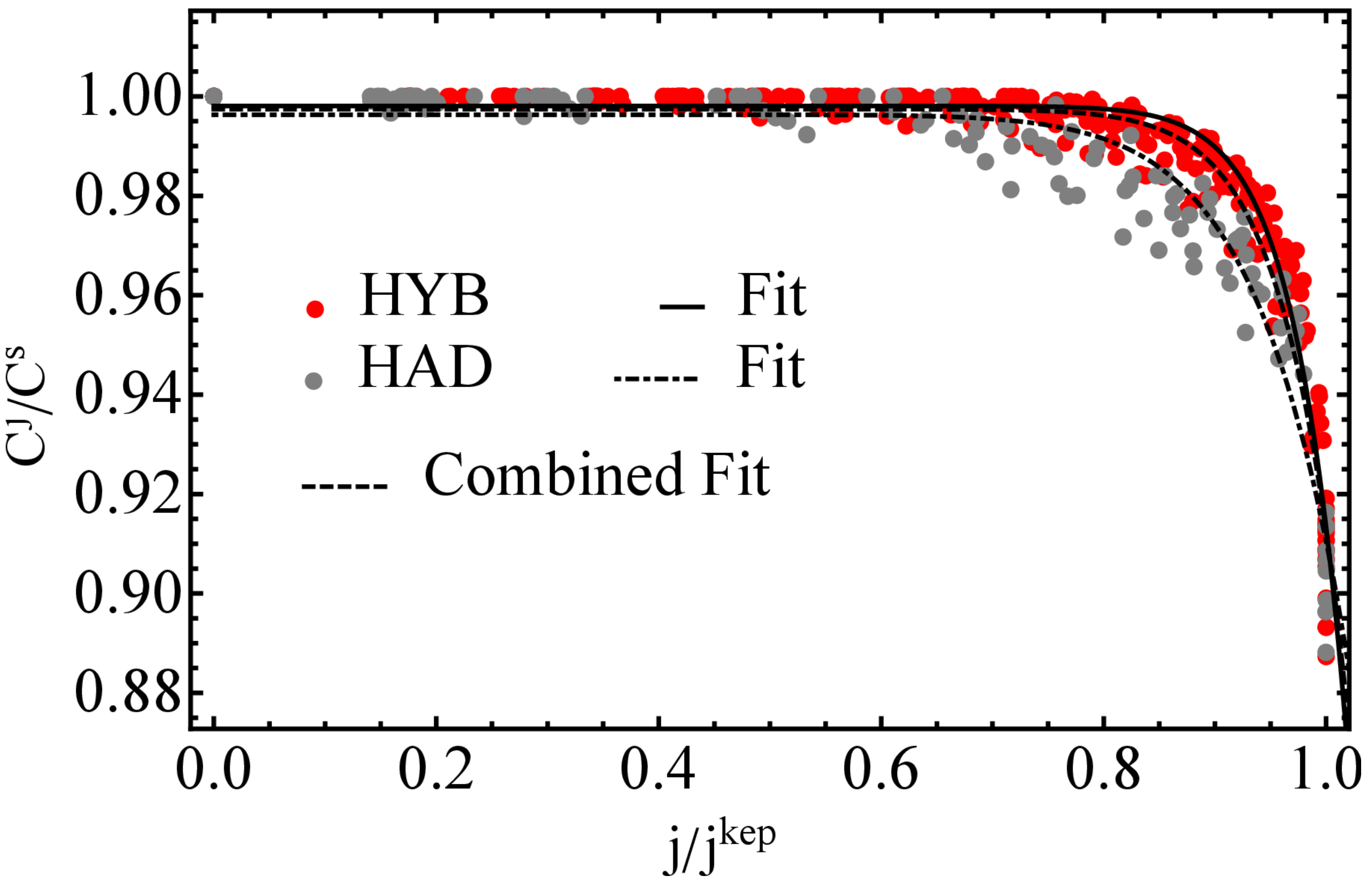
EOS considered

- We considered several Relativistic Mean Field (RMF) EOS to describe the hadronic part.
- For the quark part we adopt the MIT Bag model.
- A hybrid star contains hadronic matter at low densities, pure quark phase at high densities and hadron-quark mixed phase at intermediate densities.
- The transition density and the extent of the mixed phase depend on the hadroic EOS and the parameters of the quark matter EOS.

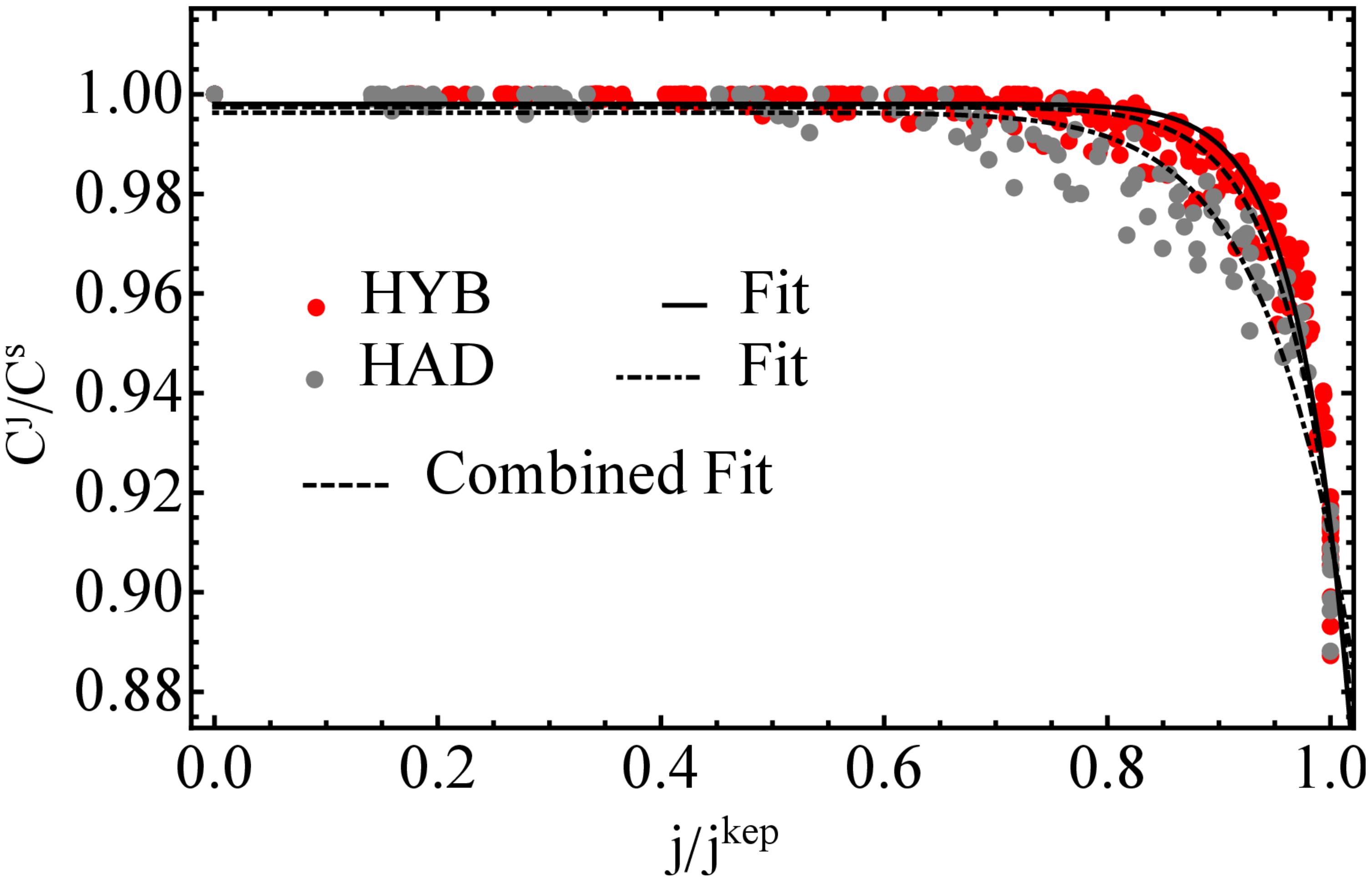


$\longrightarrow B_{\mathrm{eff}}^{1/4}$

➡ **Presence of quarks inside NS core is favored within RMF models**

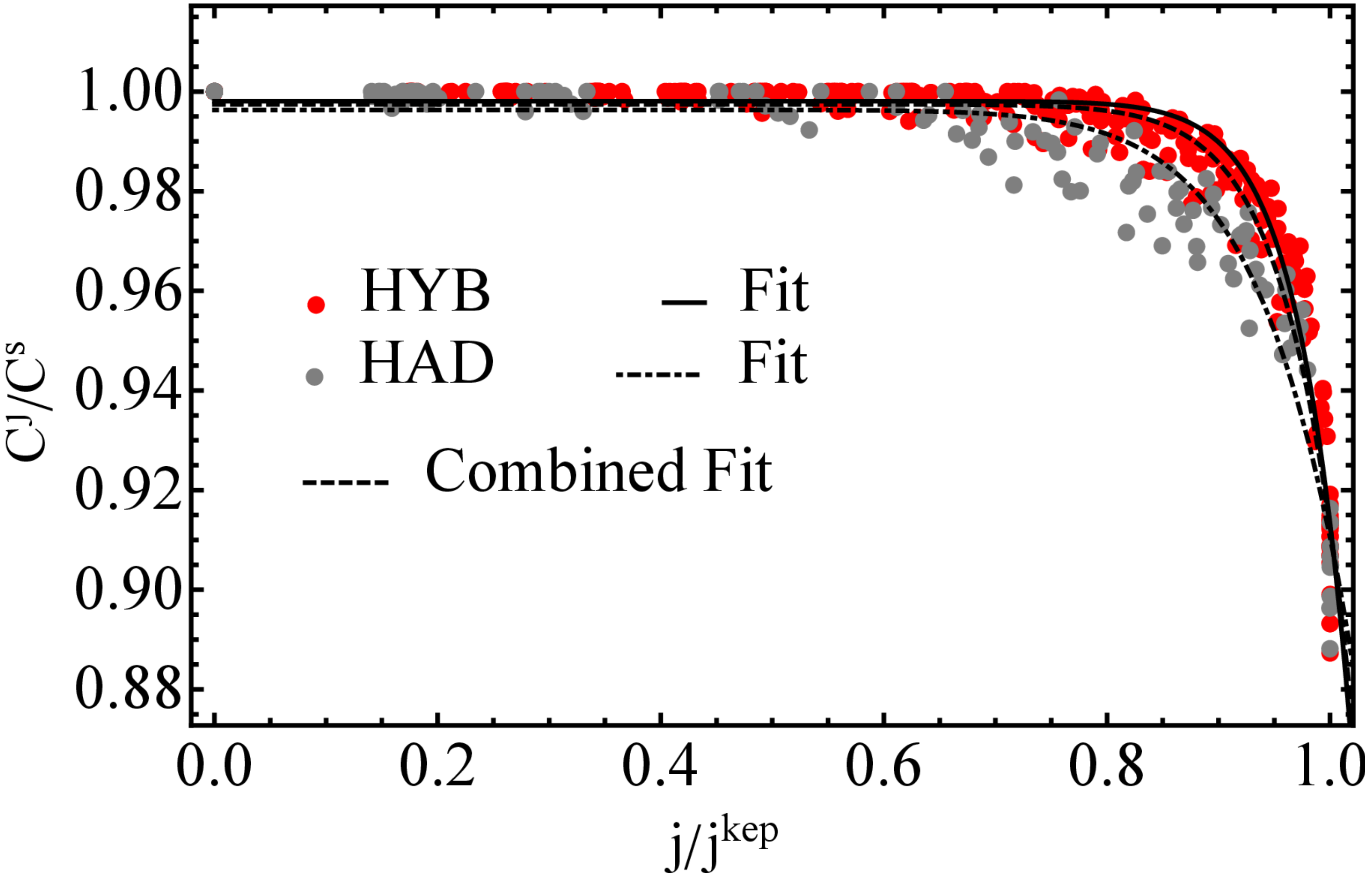


$C = M/R$ $\qquad$ $j = J/(M^j_{\max})^2$

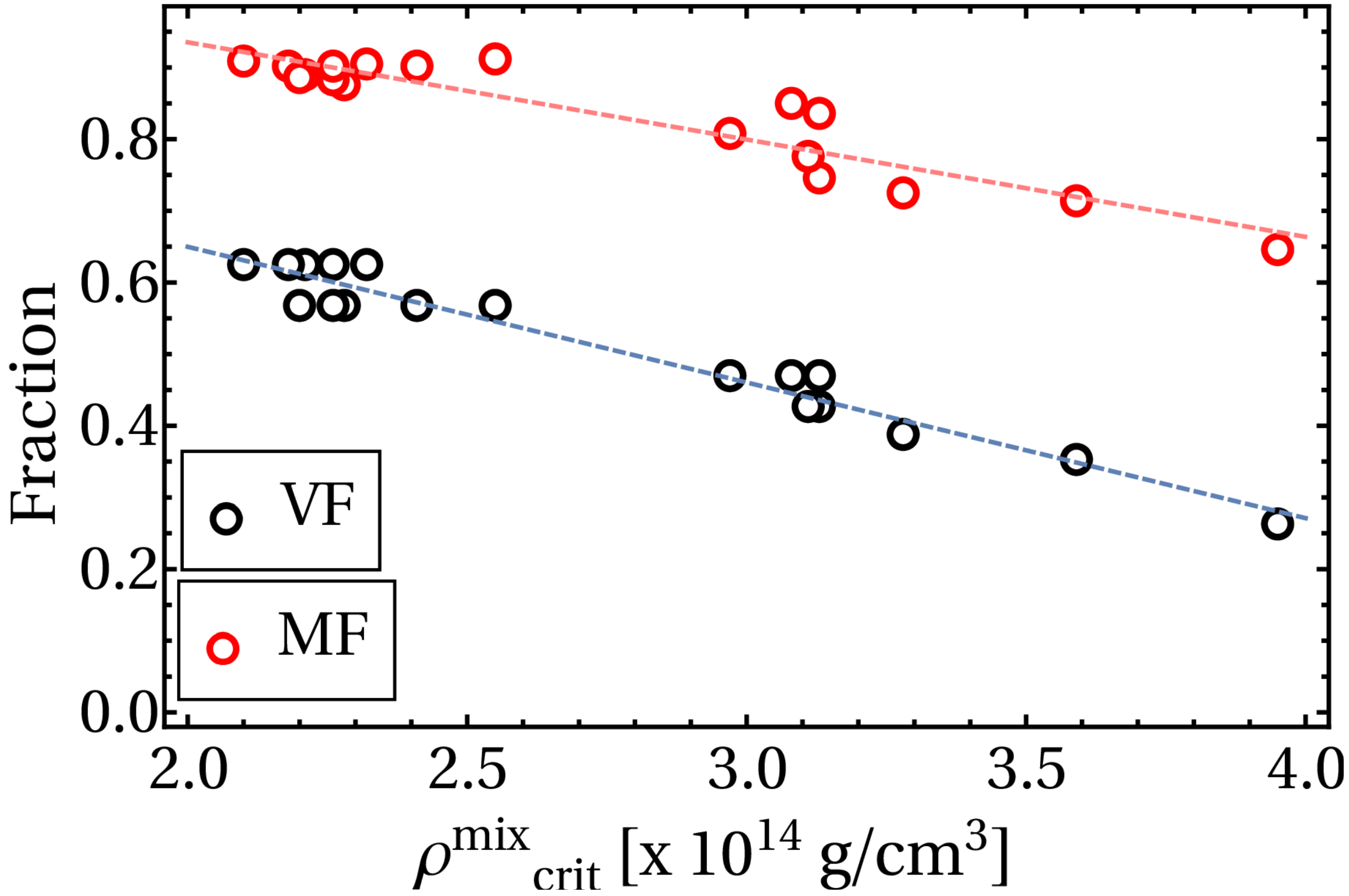


$$C = M/R \qquad j = J/(M^j_{\max})^2$$

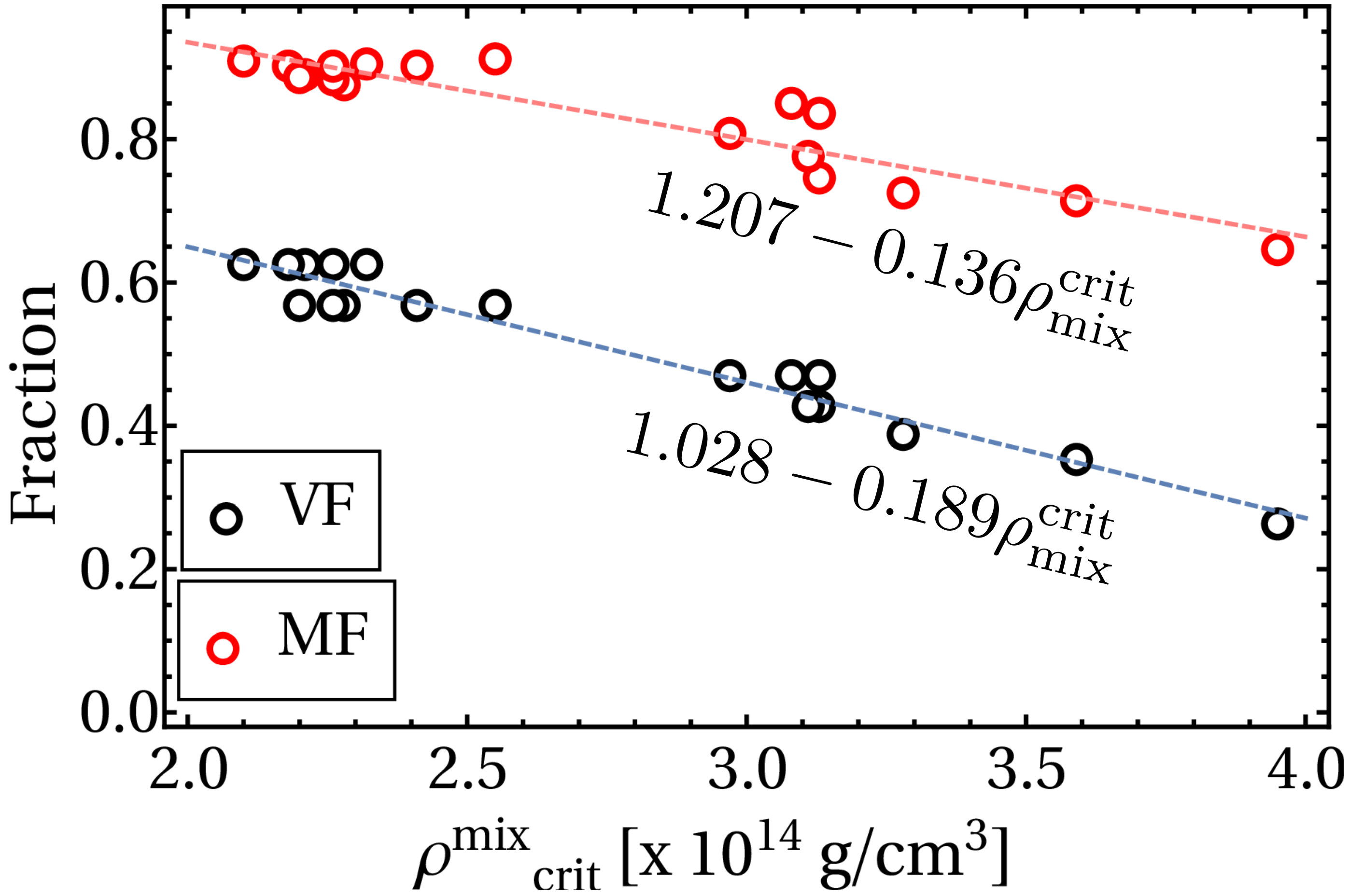
$$\frac{C^j}{C^s} = a + b\left(\frac{j}{j^k}\right)^c$$



C^j/C^s does not depend on whether a neutron star contains quarks or not.



Volume fraction (VF) and mass fraction (MF) of quark cores as a function of starting density of mixed phase



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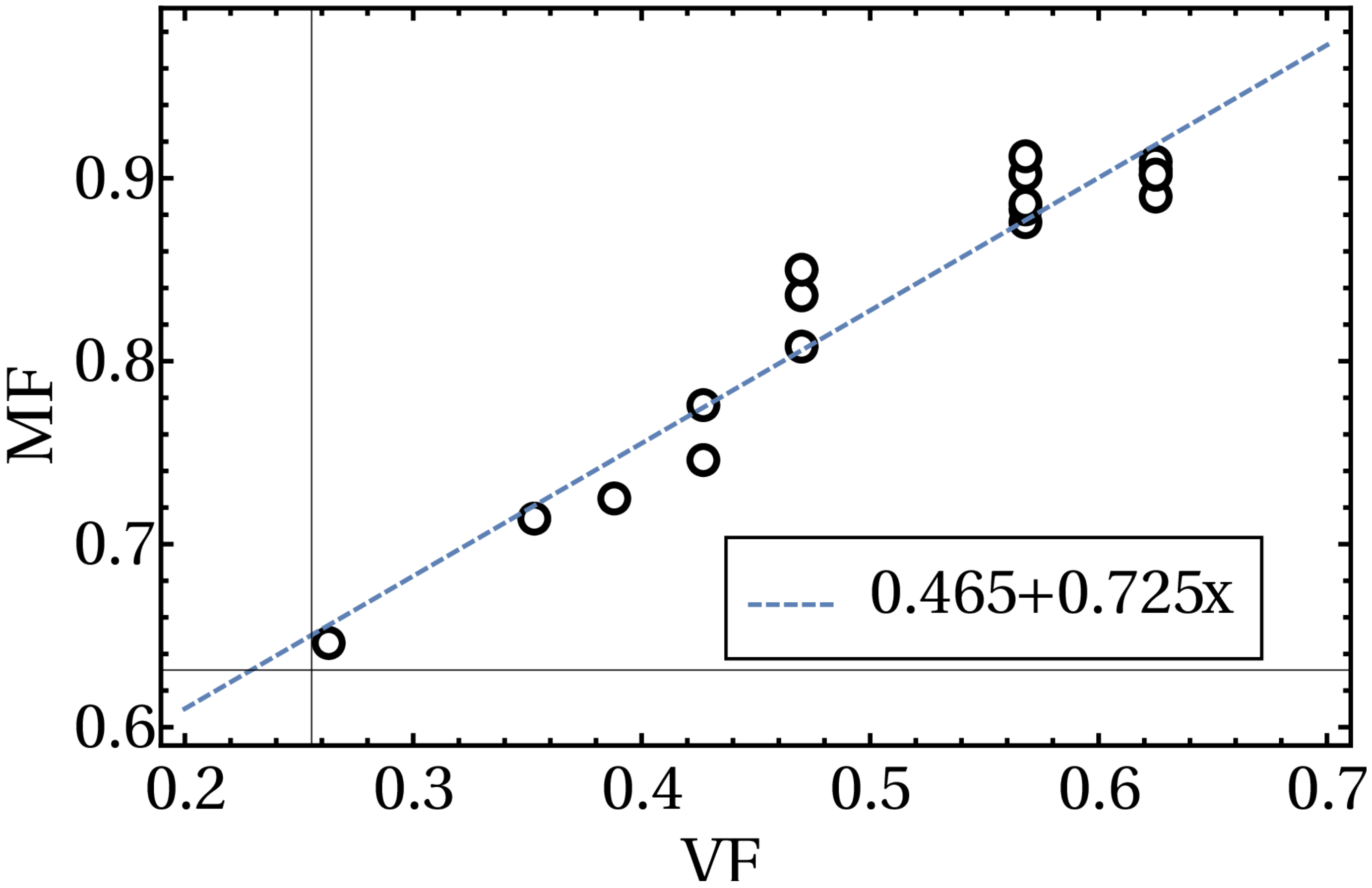
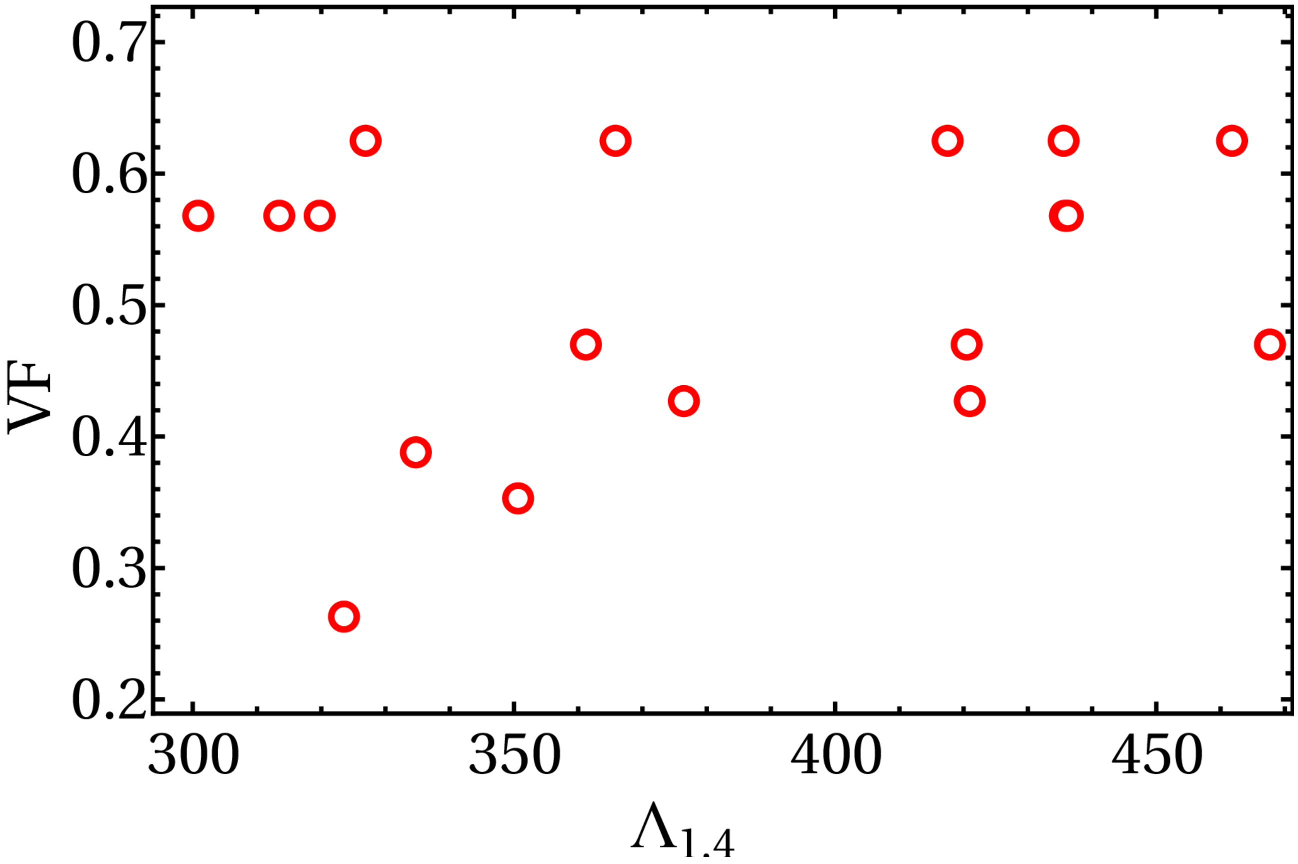
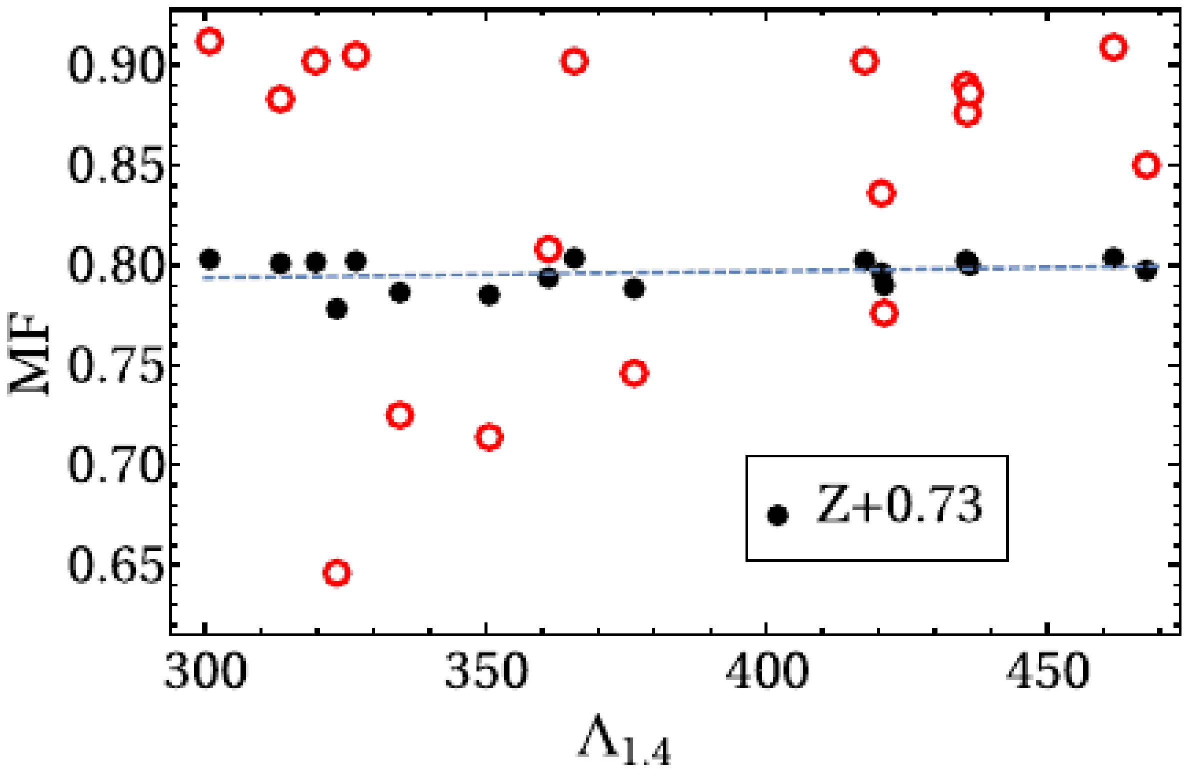


A linear relationship between the VF and MF exists.



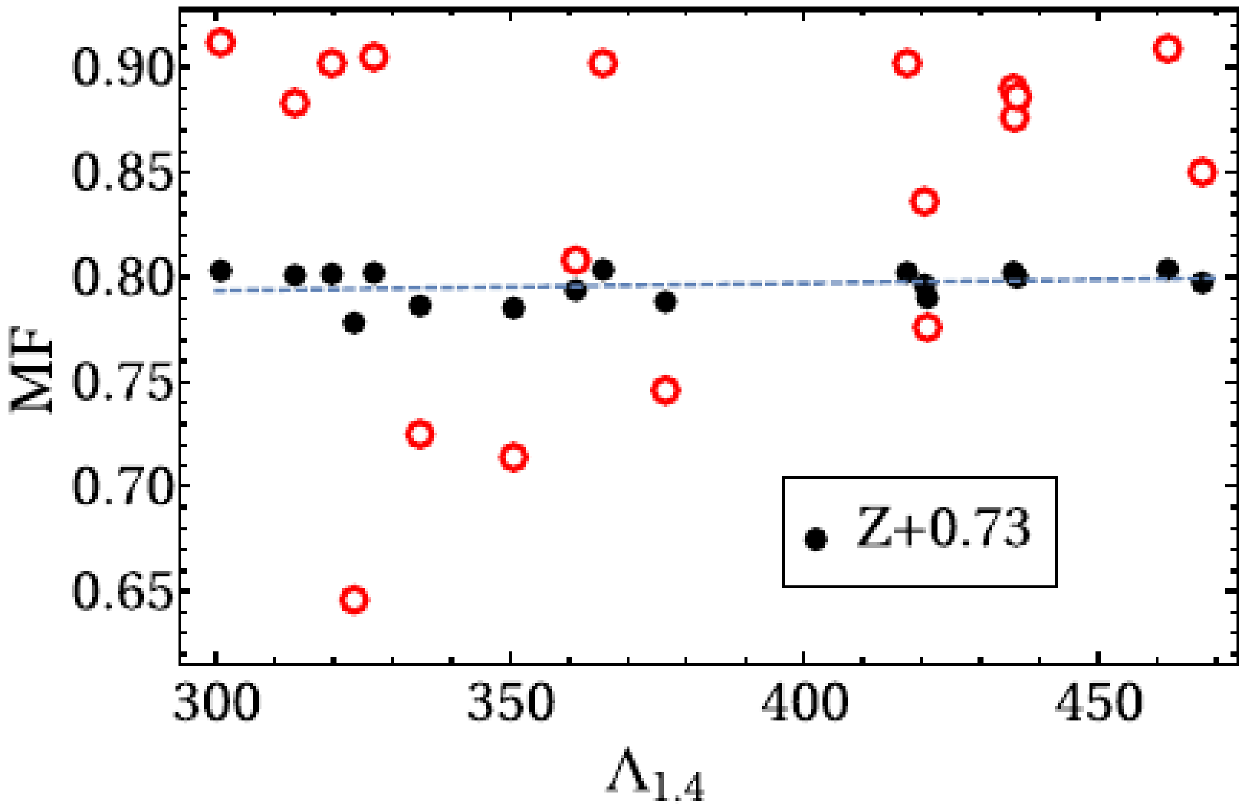
Volume fraction (VF) of quark cores as a function of tidal deformability of 1.4-solar mass stars.

No correaltion found



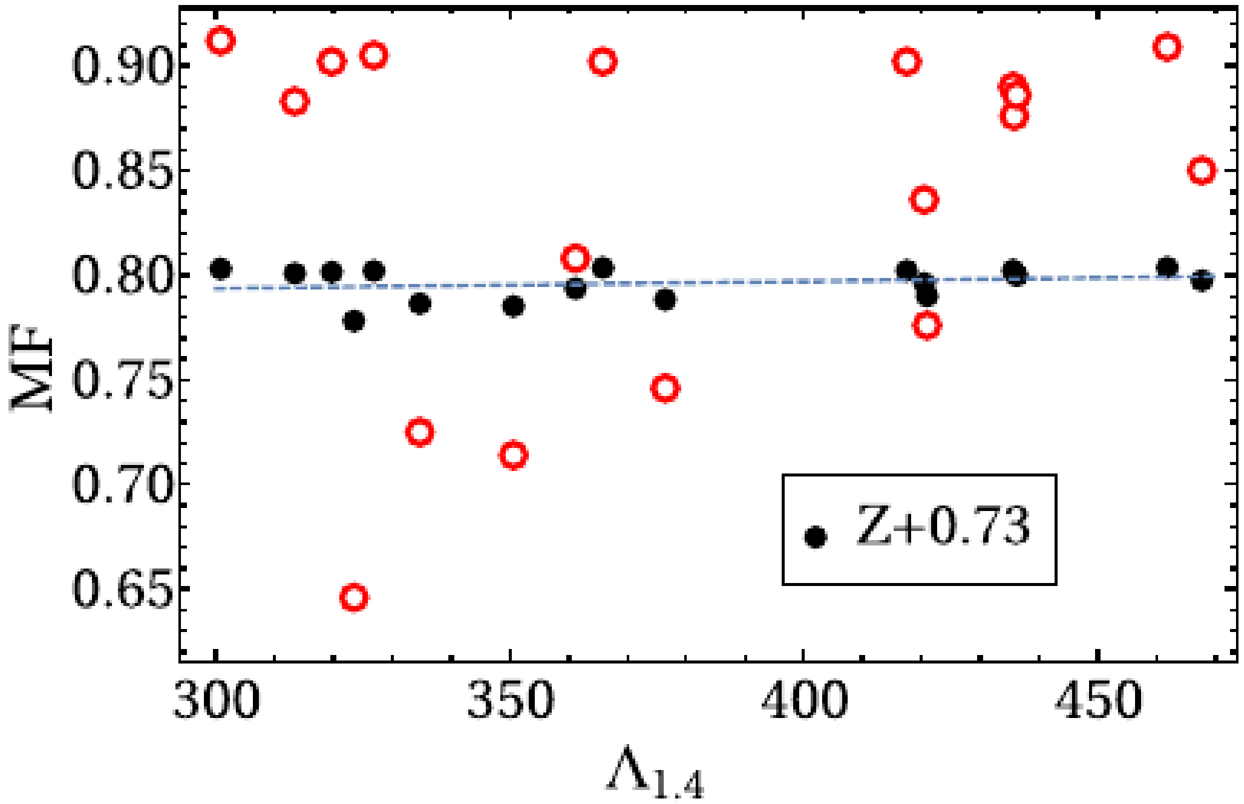
Mass fraction (MF) of quark cores as a function of tidal deformability of 1.4-solar mass stars.

No correaltion found



Mass fraction (MF) of quark cores as a function of tidal deformability of 1.4-solar mass stars.

$$Z \equiv \left(MF \times \frac{M}{R^k} \right)_{1.4}$$

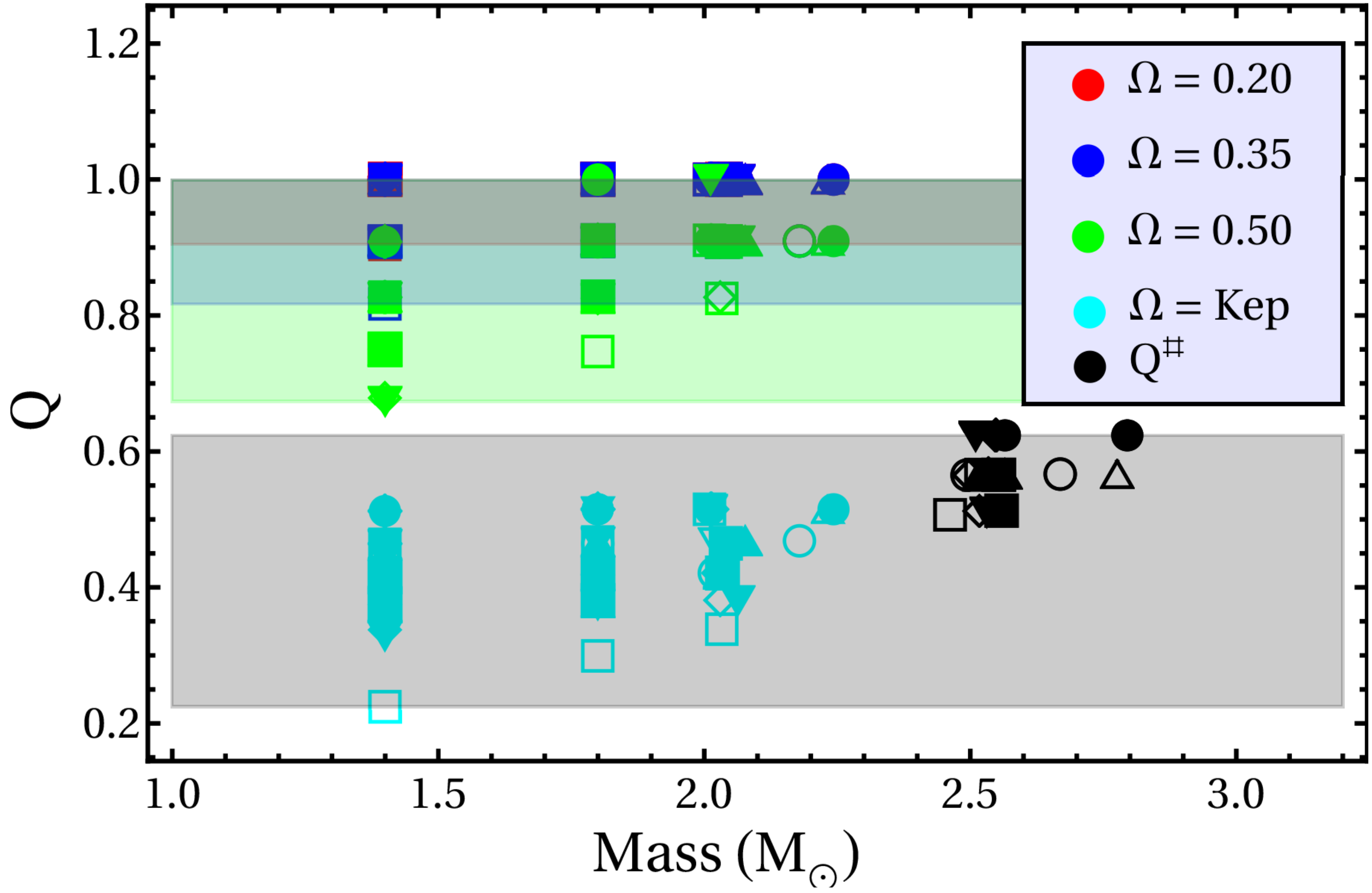


Mass fraction (MF) of quark cores as a function of tidal deformability of 1.4-solar mass stars.

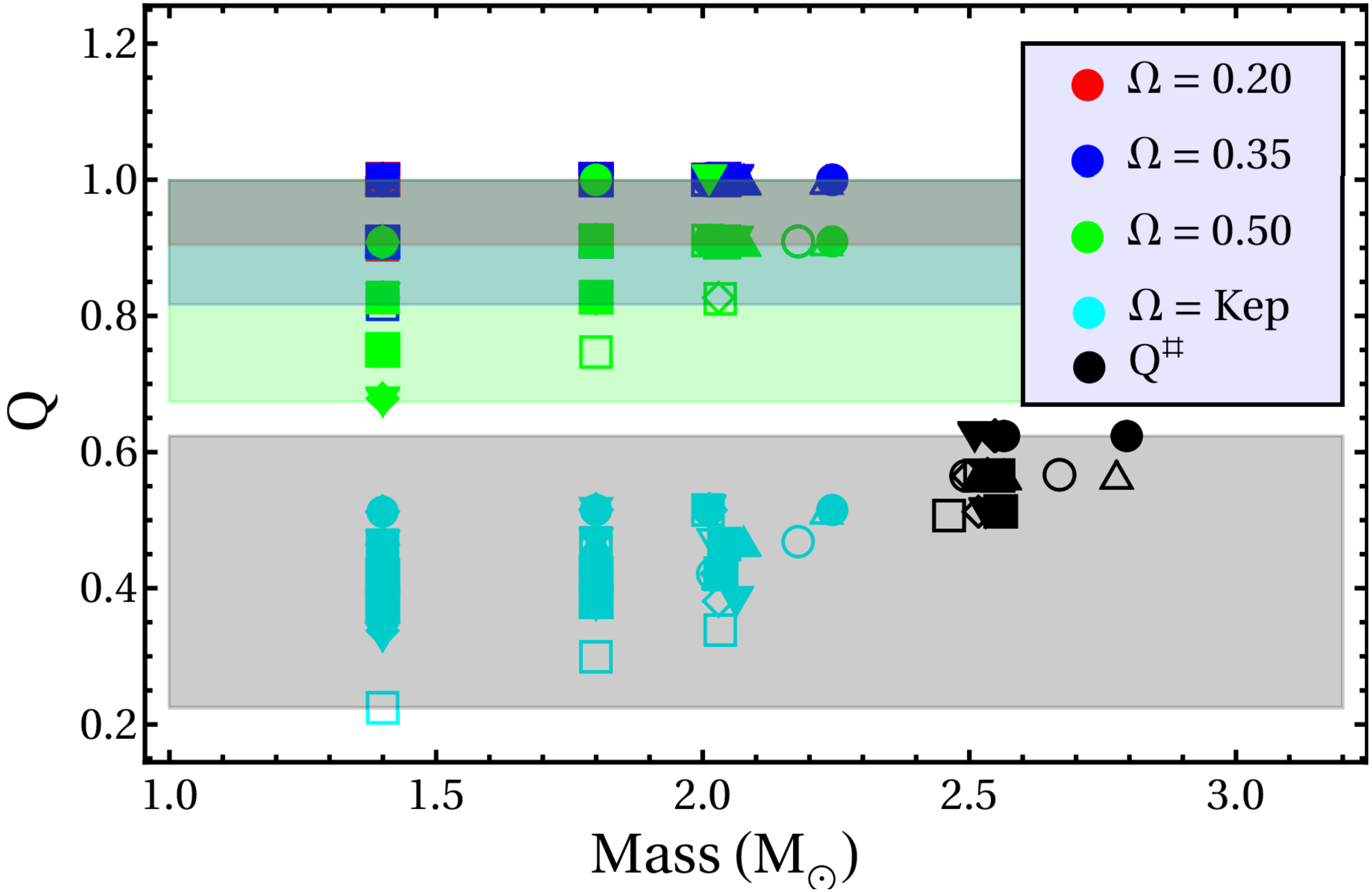
$$Z \equiv \left(MF \times \frac{M}{R^k} \right)_{1.4}$$

Z does not change with $\Lambda_{1.4}$.

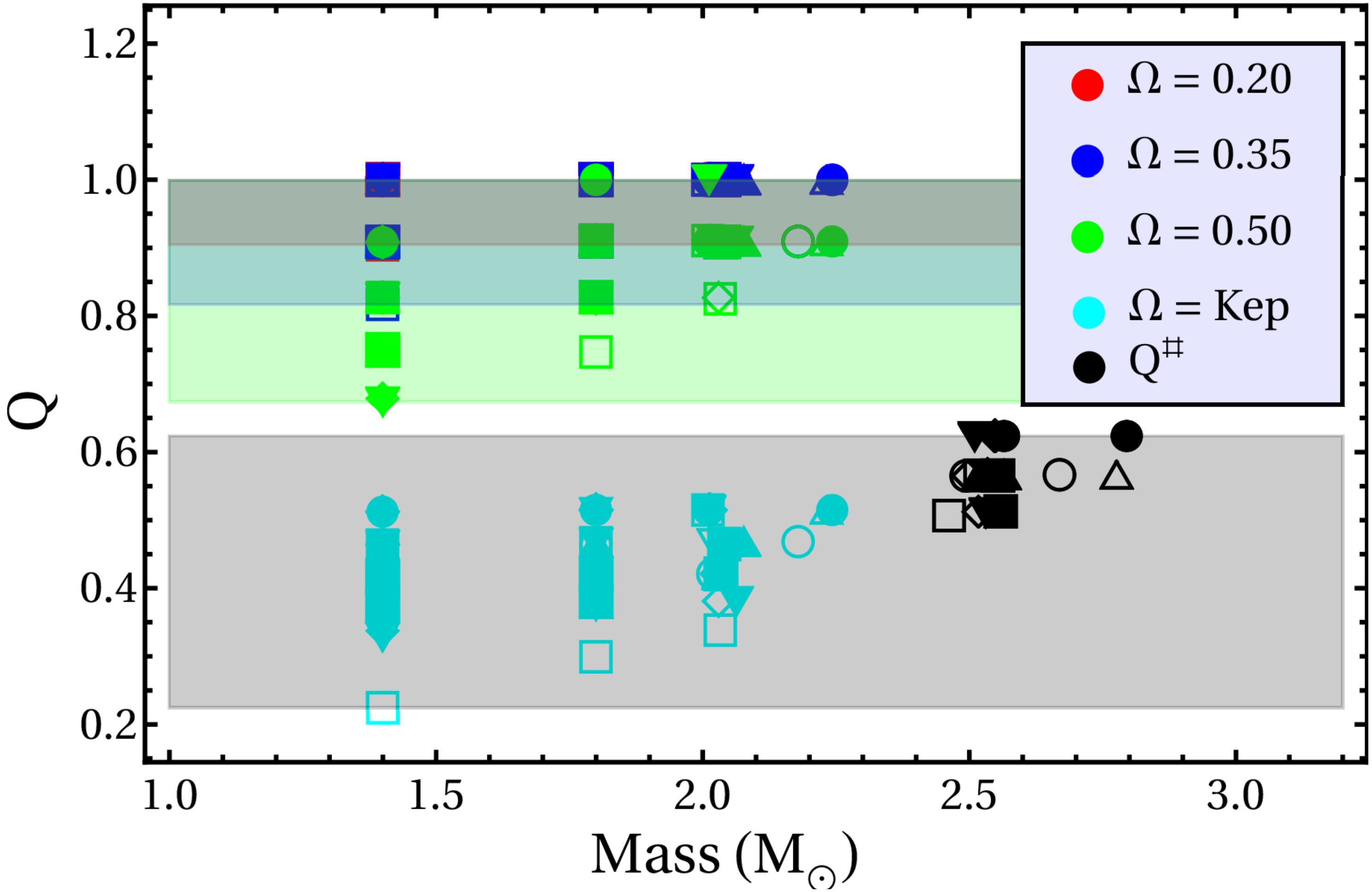
$$Z = 0.783 - 0.00003\Lambda_{1.4}\ (\chi^2_{\text{red}} = 5.850 \times 10^{-5})$$



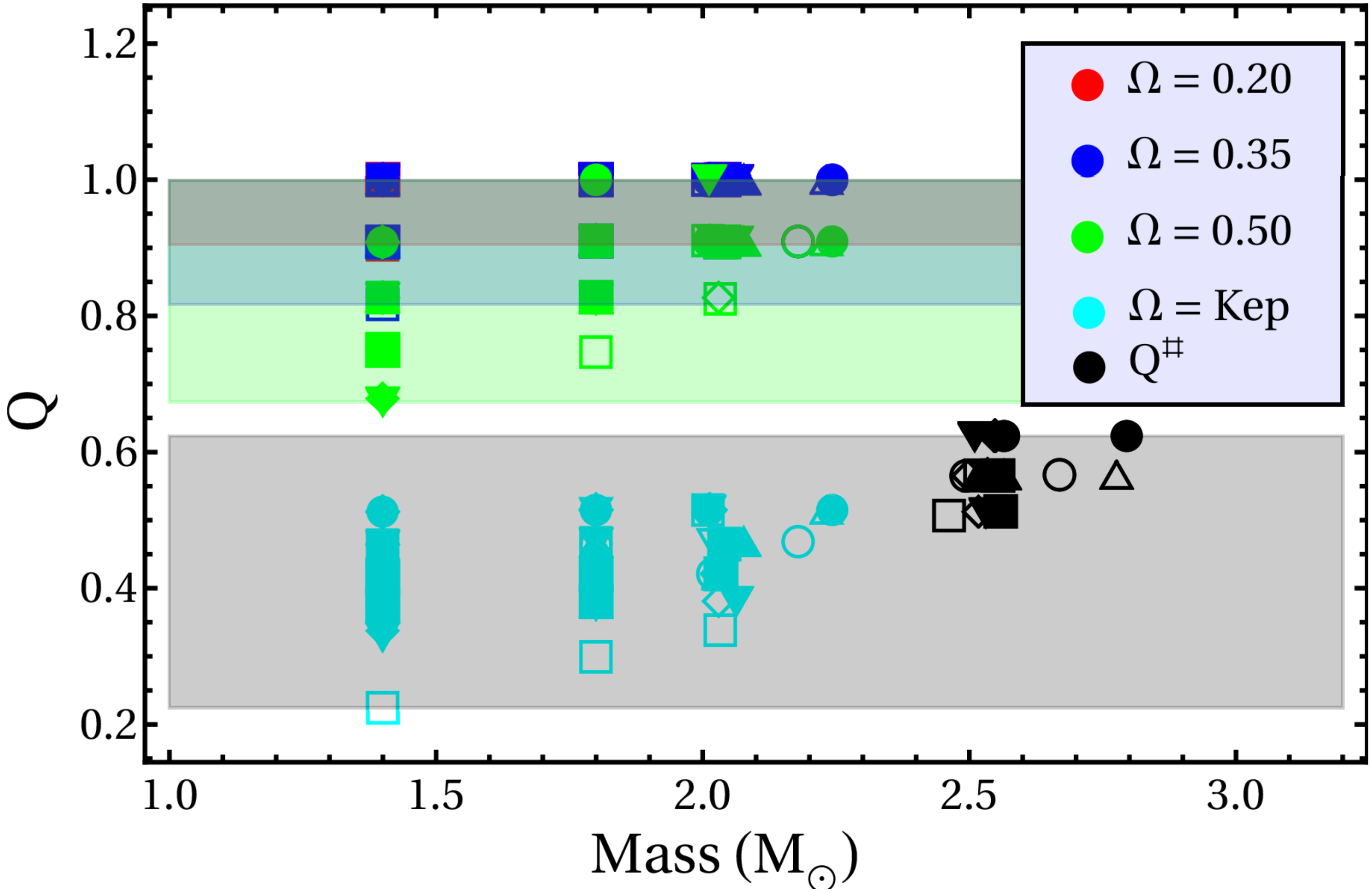
$$Q \equiv \left(\frac{V F^{\Omega}}{V F^{s}} \right)_M$$



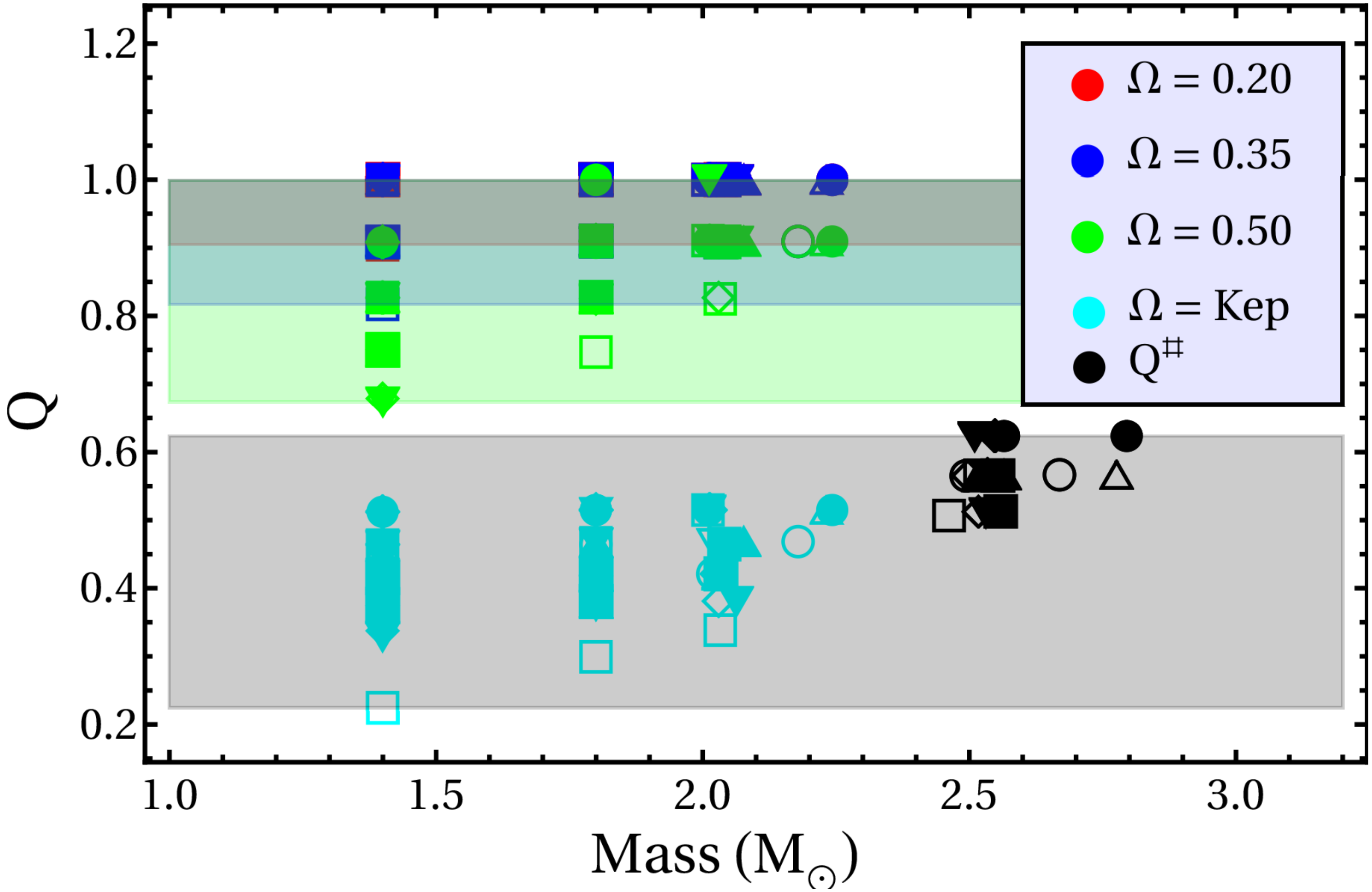
- The Q measures the loss of quark content by a rotating star compared to a static star of the same mass.
- As the rotational velocity increases, its quark content reduces.
- For a specific rotational value, it lies in a range.
- The range increases with the increase in rotational velocity.



- For a star rotating with Keplerian velocity, the quark content is minimum, and the Q value lies in a patch having the bound of **$0.224 \leq Q \leq 0.514$**.
- A hybrid star with a quark core must lie within the Q bound to be stable and not start shedding mass or collapse into a black hole.



$$Q^{\sharp} \equiv \left(\frac{VF^{k}}{VF^{s}}\right)_{M=M_{\max}}$$



$$Q^\sharp \equiv \left(\frac{VF^k}{VF^s}\right)_{M=M_{\max}}$$

- Interestingly Q$^\#$ lies in a narrow range between ∼ **0.506–0.623** universally across the EoS

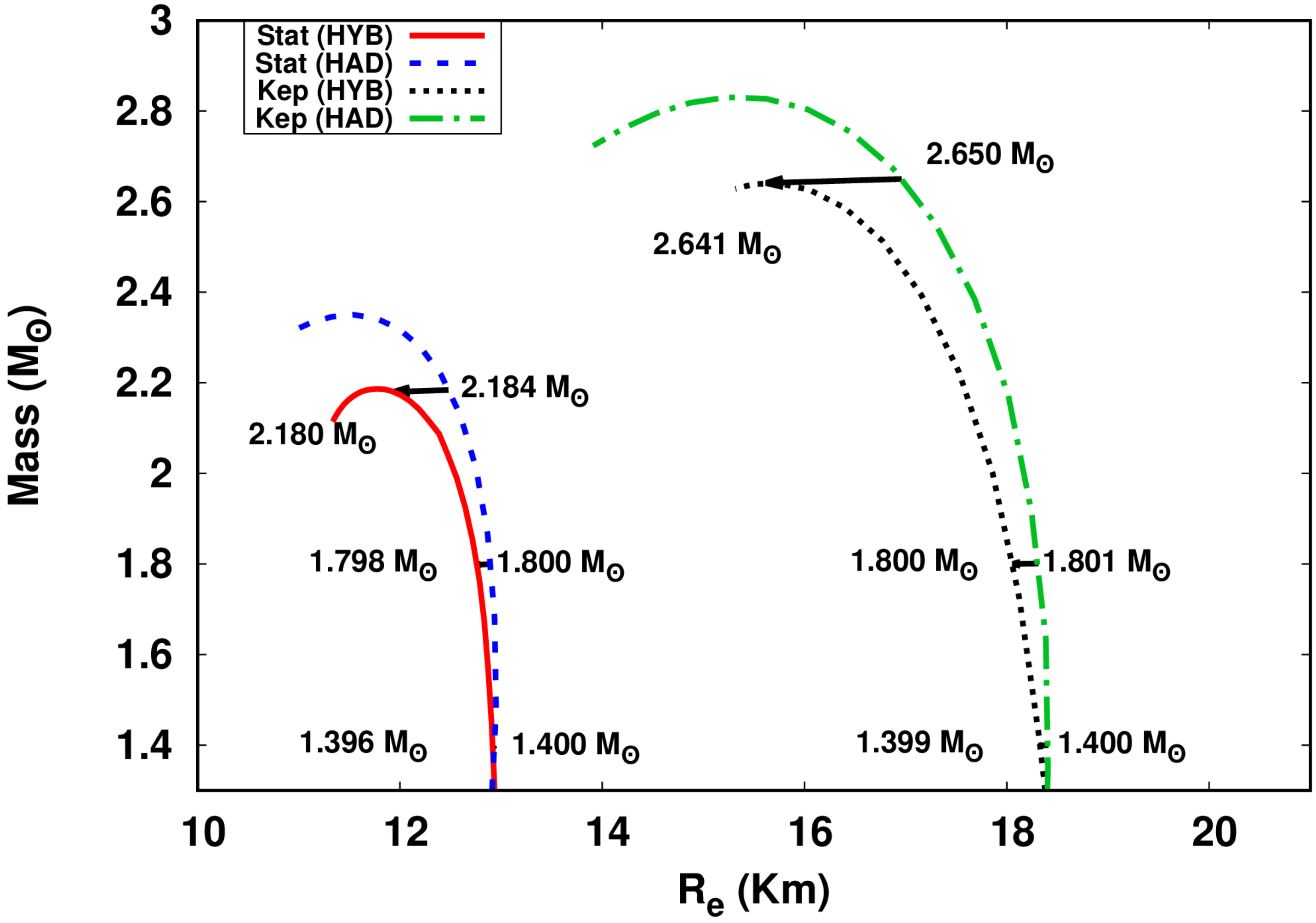
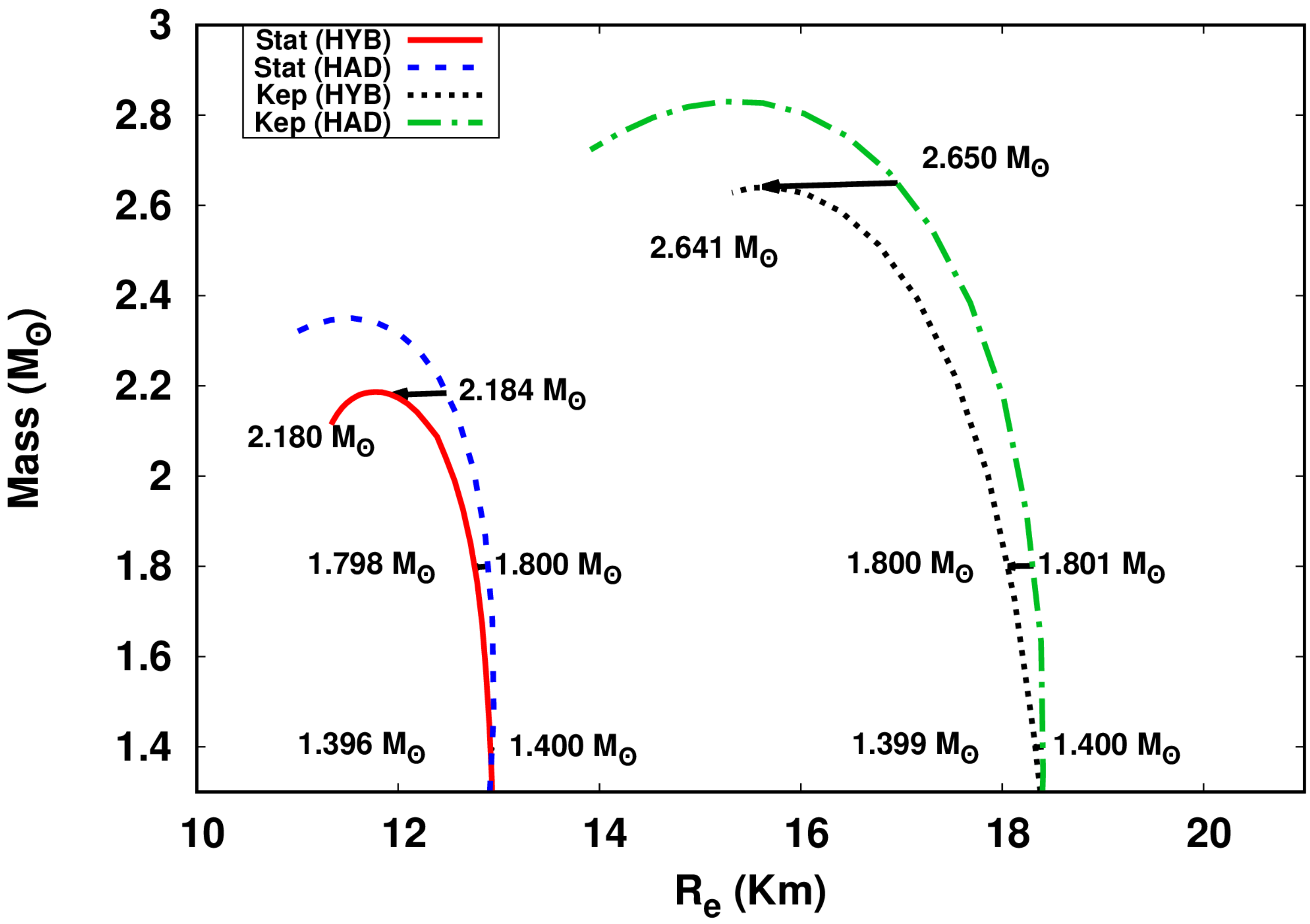
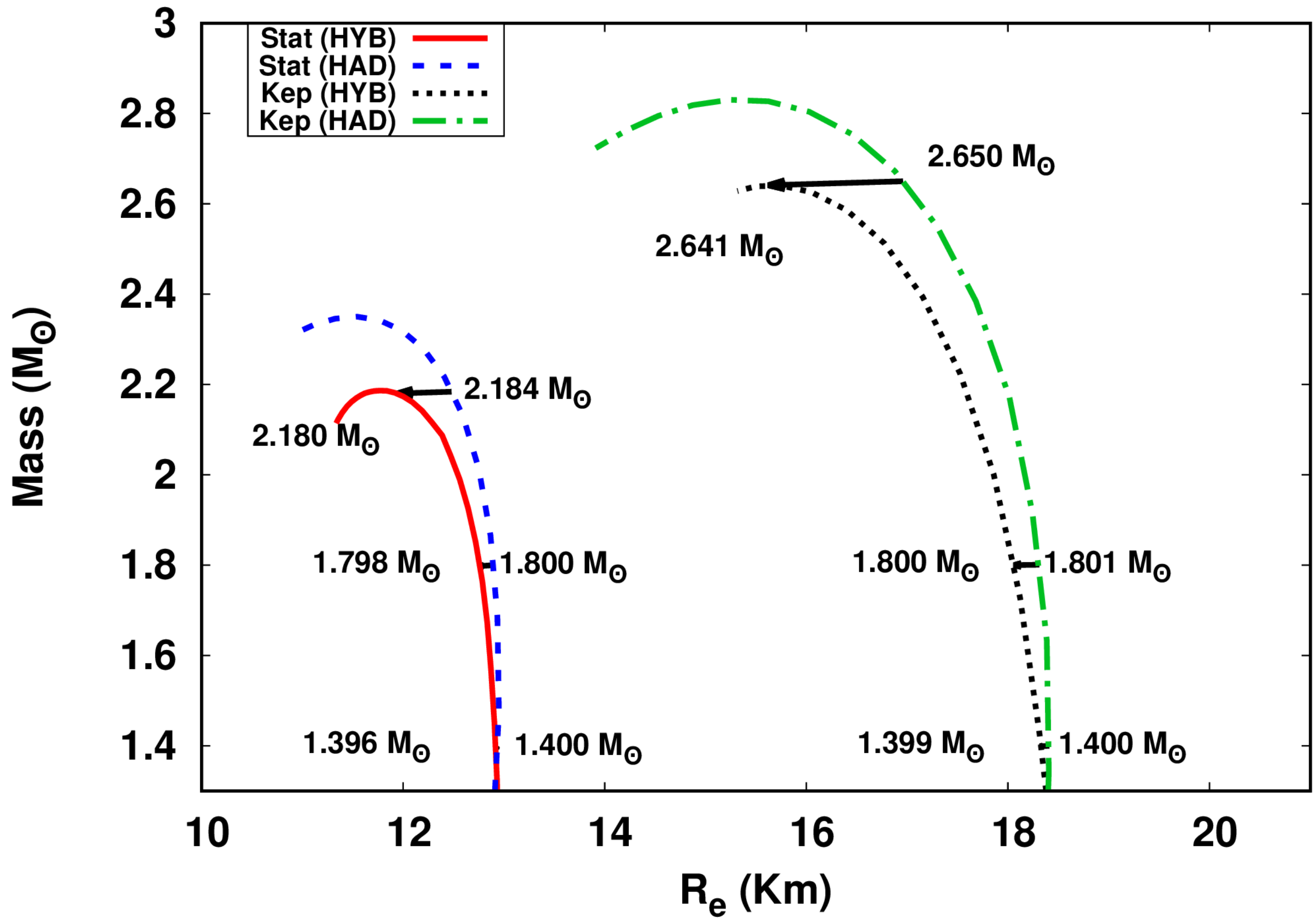


Figure shows how the gravitational mass and radius of a star changes if a hybrid star is formed via phase transition from a NS.

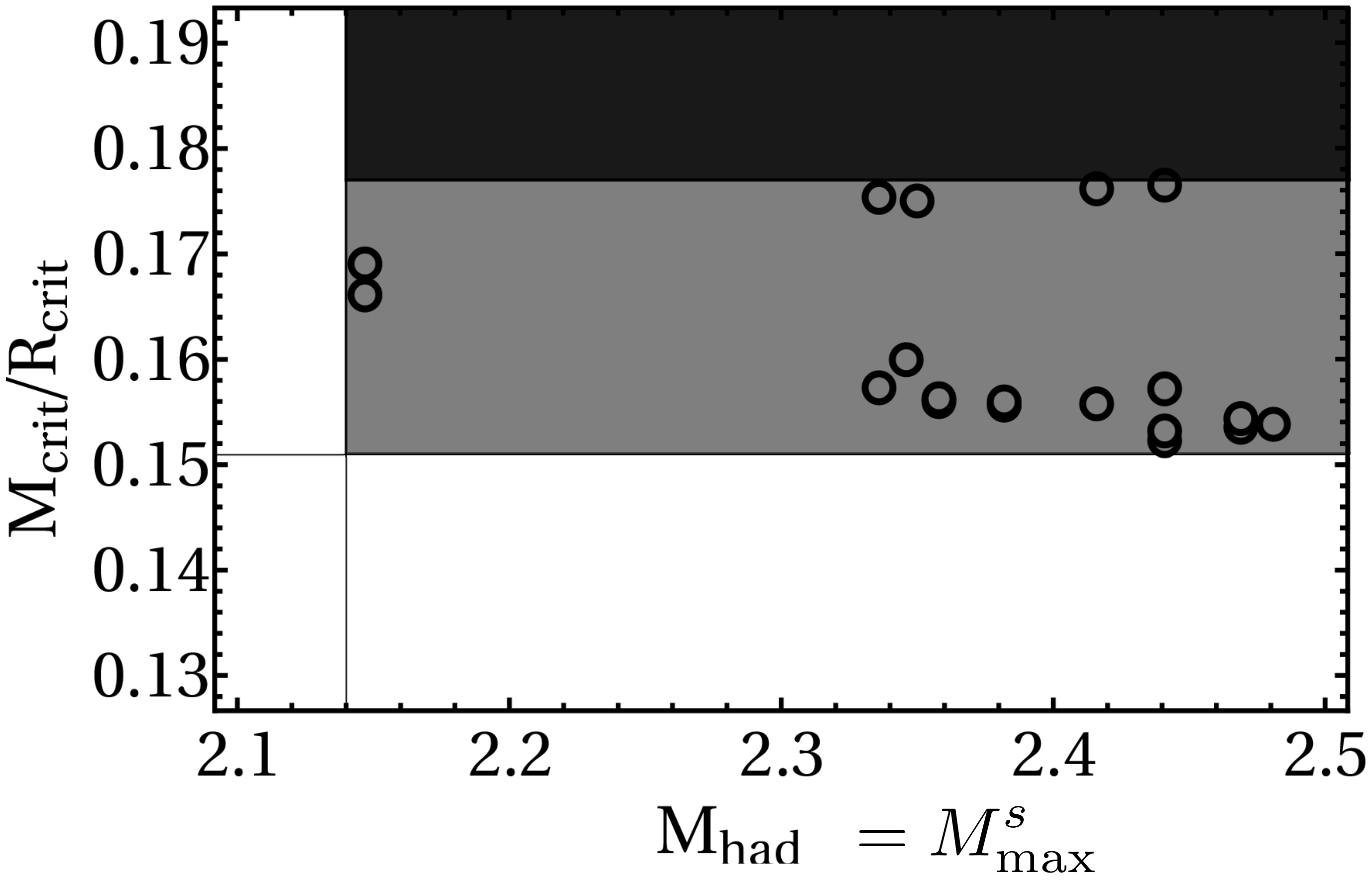


- Although the change in the gravitational mass is relatively small, the radius shrinks considerably.

- Therefore, as phase transition occurs and a quark core is formed inside a star, the star becomes more compact.

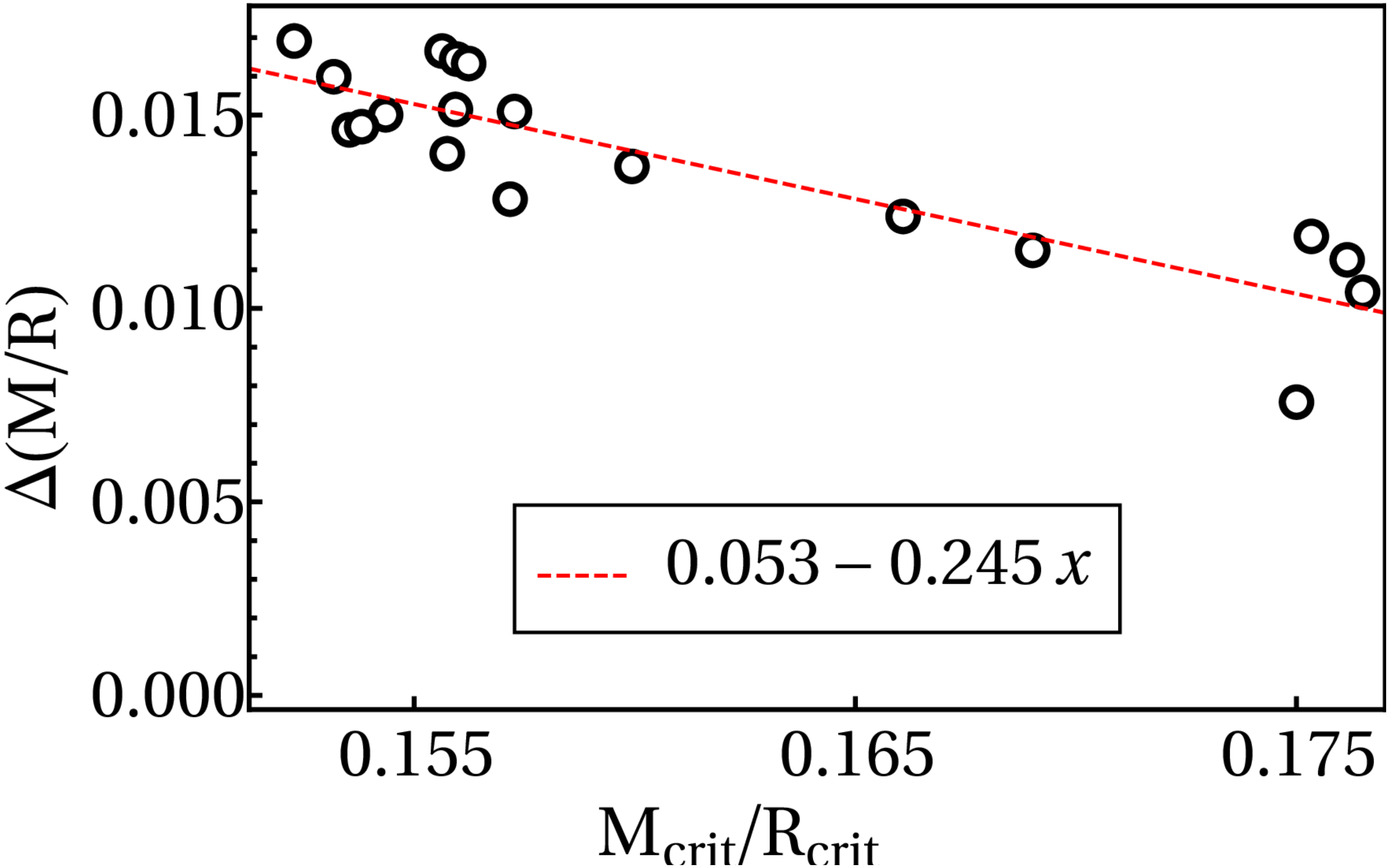


- A massive NS after phase transition can become unstable and probably collapses to a Black Hole.
- For a given EOS one can find the upper bound on mass and radius M_{crit} and R_{crit}, beyond which it is not possible to produce a stable hybrid star.



$$\boldsymbol{M_{\rm crit}/R_{\rm crit} \lesssim 0.18}$$

If a neutron star undergoing phase transition is more compact it will collapse to a black hole



Change in the compactness of stars due to phase transition.

The change in compactness (and thereby the mass) can be used to estimate the energy released during the phase transition.

Summary

- The presence of quarks inside NS core is still debatable.
- It would be very useful to find a EOS indpendent quantity that can distinguish between NS and hybrid stars.
- We found that the ratio C_j /C_s shows different behavior for fast rotating NSs compared to fast-rotating HSs and is independent of EoS.
- However, it would require unnaturally precise measurement to infer the occurrence of a quark core at the center ofthe star.
- We showed that if there are quarks in NS core, it is possible to obtain some semi-universal relations between quantities that quantify the content of quarks.