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Whas GW190814 a Black Hole – Strange Quark Star system?

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GW190814

In August 2019, the LIGO-Virgo gravitational-wave network observed a GW signal produced by the merger of a **23 $M_\odot$ black hole** and a **compact star with mass $M_2 = (2.50 – 2.67)\ M_\odot$** .

GW190814's secondary mass lies in the hypothesized lower **mass gap of 2.5–5 $M_\odot$ between known NSs and BHs.**

GW190814's secondary could be the **heaviest neutron star** or the **lightest black hole** ever observed.

R. Abbott et al., Astrophys. J. Lett. 896 (2020) L44

or could GW190814's secondary be a **Strange Quark Star?**

I. Bombaci, A. Drago, D. Logoteta, G. Pagliara, I. Vidaña, Phys. Rev. Lett. 126 (2021) 162702

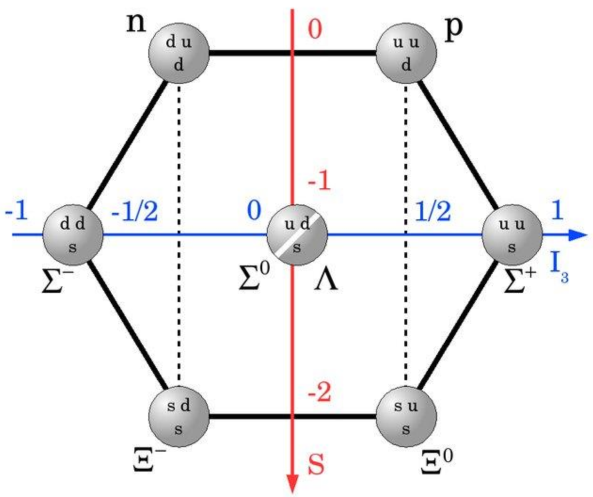
Neutron Stars

Due to the large values of the central stellar density, various **particle species** and **phases of dense matter** are expected in NS interiors.

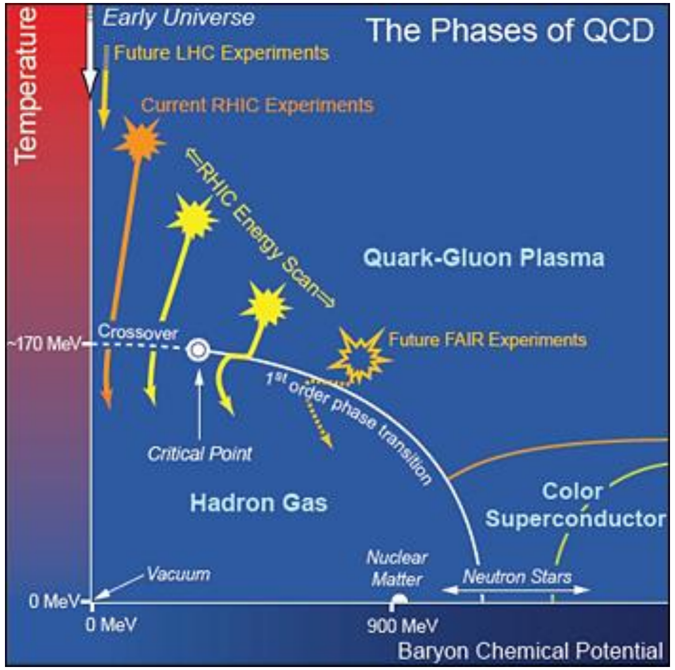
Mass	$\mathbf{M \sim 1.1 - 2.1\ M_\odot}$
Radius	$\mathbf{R \sim 10 - 15\ km}$
Centr. Density	$\mathbf{\rho_c = (4 - 8)\ \rho_0}$
Baryon number	$\mathbf{A \sim 10^{57}}$
Binding energy	$\mathbf{B \sim 10^{53}\ erg}$
B/A ~ 100 MeV,	$\mathbf{B/(Mc^2) \sim 10\%}$

nuclear saturation density

$\mathbf{\rho_0 = 2.7 \times 10^{14}\ g/cm^3}$ $\mathbf{(n_0 \sim 0.16\ fm^{-3})}$

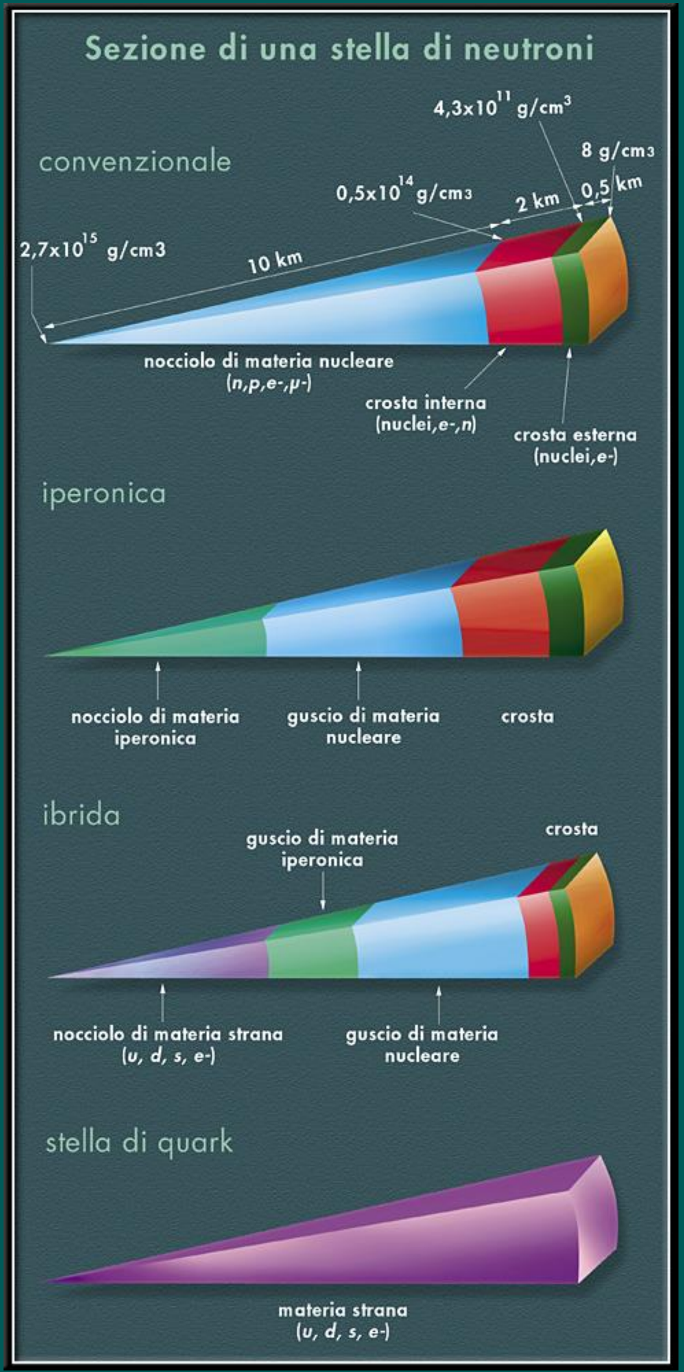


the baryon octet : $J^\pi = (1/2)^+$



The core of the most massive Neutron Stars is one of the best candidates in the Universe where a quark-deconfined phase of matter (Quark Matter) can be found

"Neutron Stars"



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

Nucleon Stars

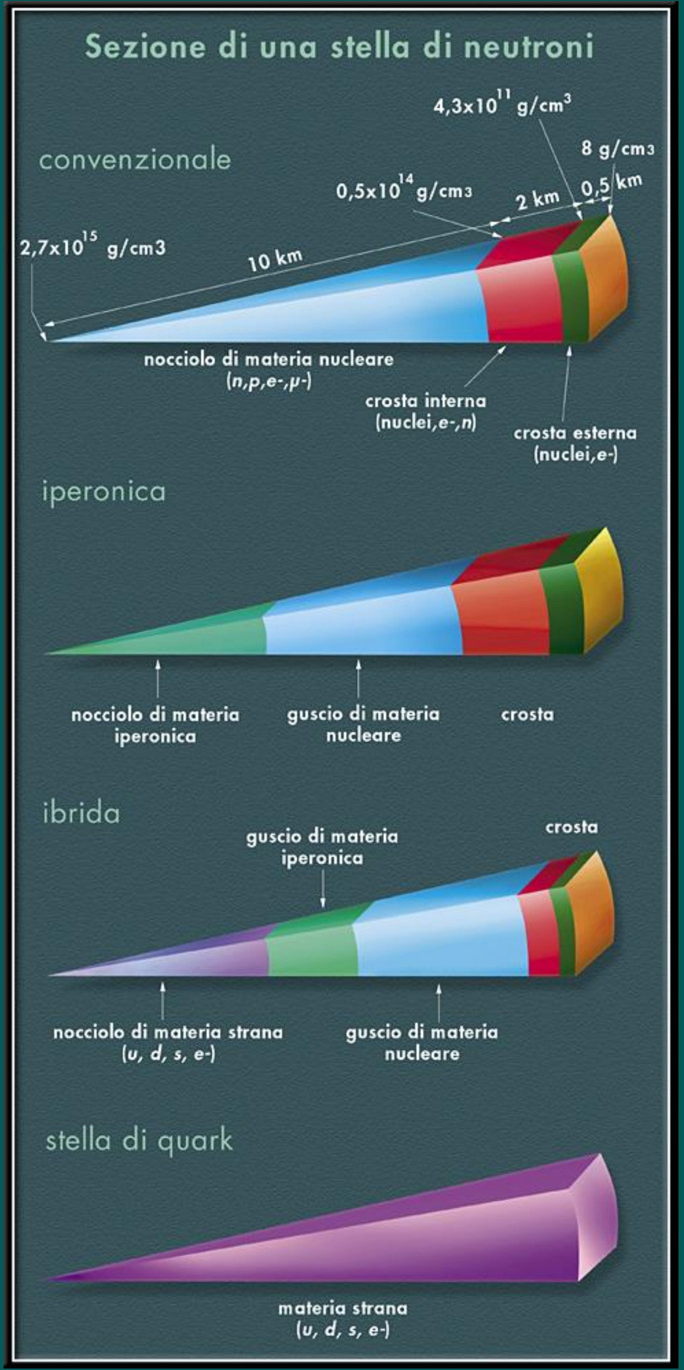
Hyperon Stars

} **Hadronic Stars**

Hybrid Stars

Strange Stars

} **Quark Stars**



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

"Neutron Stars"

Nucleon Stars

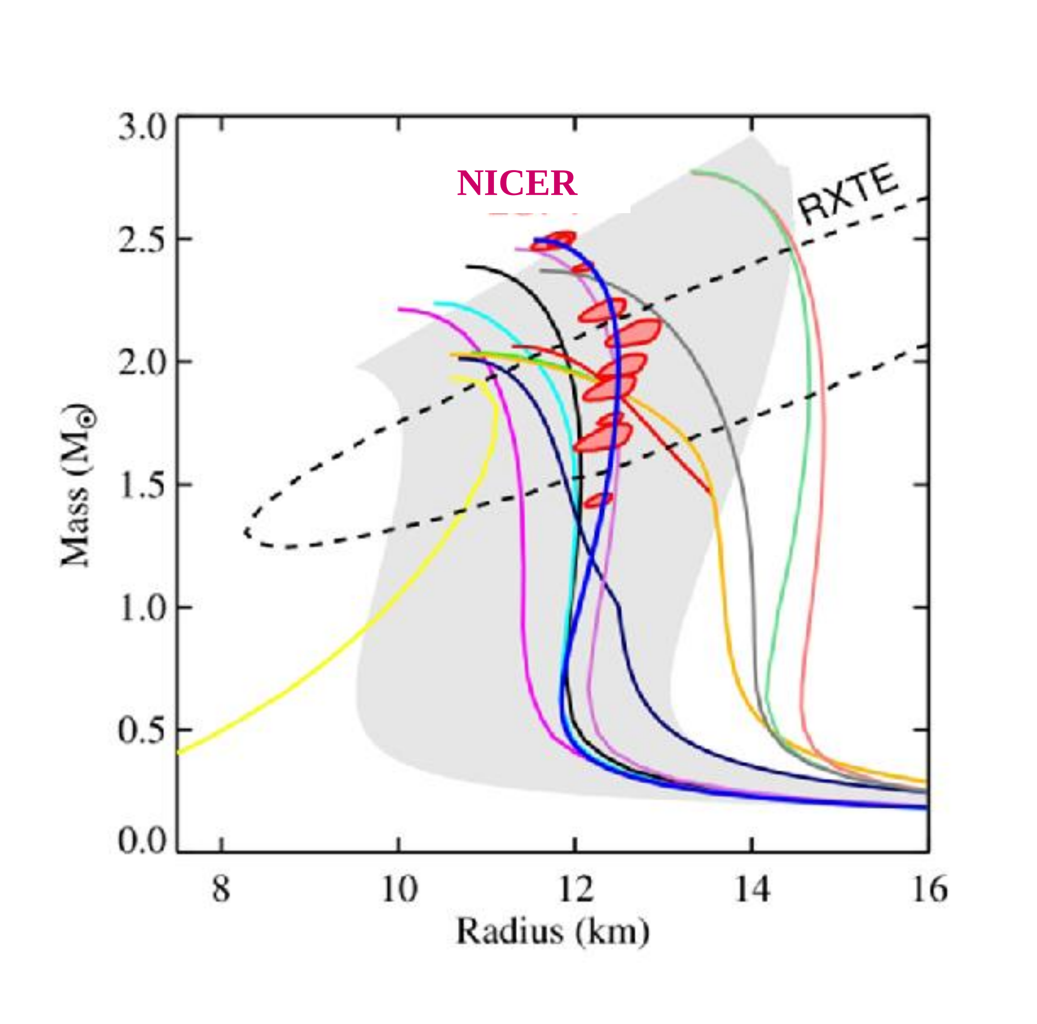
Hadronic Stars

What type(s) of Neutron Stars does Nature produce?

Quark Stars

Strange Stars

The current accepted paradigm:
one family of “Neutron Stars”



“Measuring” the EOS

accurate measurements of the mass and radius of several neutron stars

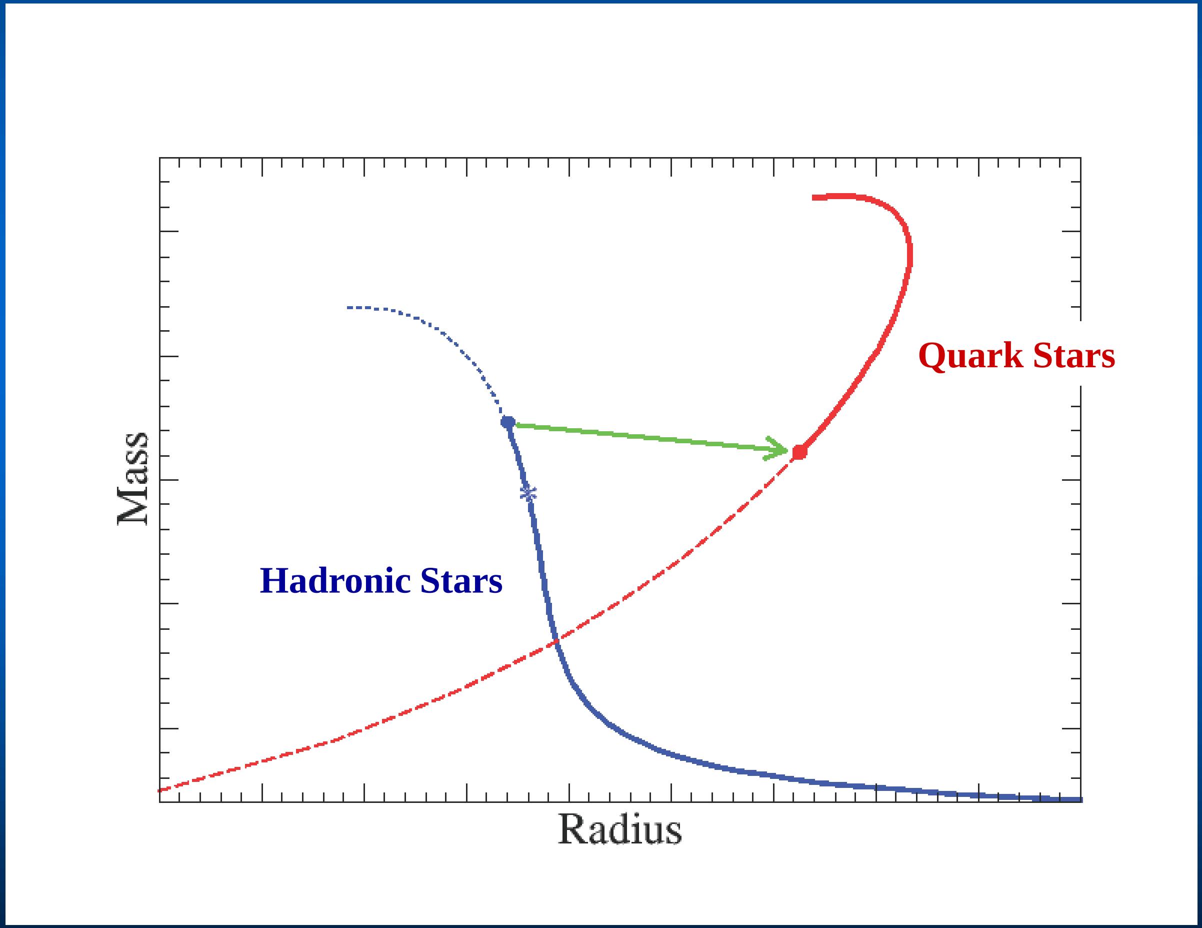
↓

Determination of the cold (T=0) dense matter EOS

$$P = P(\rho)$$

Relativistic inverse stellar structure problem:
L. Lindblom, ApJ 398 (1992) 569
T. E. Riley et al., MNRAS 478 (2018) 1093

The new paradigm:
Two coexisting families of "Neutron Stars"



ApJ 586 (2003)

The Astrophysical Journal, 586:1250–1253, 2003 April 1

GAMMA-RAY BURSTS FROM DELAYED COLLAPSE OF NEUTRON STARS TO QUARK MATTER STARS

Z. Berezhiani,[1] I. Bombaci,[2] A. Drago,[3] F. Frontera,[3,4] and A. Lavagno[5]
Received 2002 September 12; accepted 2002 December 2

ABSTRACT

We propose a model to explain how a gamma-ray burst can take place days or years after a supernova explosion. Our model is based on the conversion of a pure hadronic star (neutron star) into a star made at least in part of deconfined quark matter. The conversion process can be delayed if the surface tension at the

ApJ 614 (2004)

The Astrophysical Journal, 614:314–325, 2004 October 10

QUARK DECONFINEMENT AND IMPLICATIONS FOR THE RADIUS AND THE LIMITING MASS OF COMPACT STARS

Ignazio Bombaci,[1] Irene Parenti,[1] and Isaac Vidaña[1]
Received 2003 August 4; accepted 2004 June 22

ABSTRACT

We study the consequences of the hadron-quark deconfinement phase transition in stellar compact objects when finite-size effects between the deconfined quark phase and the hadronic phase are taken into account. We show that above a threshold value of the central pressure (gravitational mass) a neutron star is metastable to the decay (conversion) to a hybrid neutron star or to a strange star. The mean lifetime of the metastable configuration dramatically depends on the value of the stellar central pressure. We explore the consequences of the metastability of "massive" neutron stars and of the existence of stable compact quark stars (hybrid neutron stars or strange stars) on the concept of the limiting mass of compact stars. We discuss the implications of our scenario for the interpretation of the stellar mass and radius extracted from the spectra of several X-ray compact sources.

The new paradigm:
Two coexisting families of "Neutron Stars"

A **1st order quark-deconfinement phase transition** occurs in the core of sufficiently massive **Neutron Stars**

The order of a phase transition: Eherenfest classification

By a phase is meant a physically homogeneous part of a system differing in physical properties from other parts of the system and separated from them by a well defined boundary (interface)

The order of a phase-transition is the order of the lowest derivative of the free energy that is discontinuous at the transition

First-order phase-transition: discontinuity in the first order derivarive of the free energy (e.g. **liquid-vapor phase transition** in water)

Second-order phase-transition: discontinuity in the second order derivarive of the free energy (e.g. **ferromagnetic phase transition**: discontinuity in the magnetic susceptibility)

1st **order phase transitions** are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**

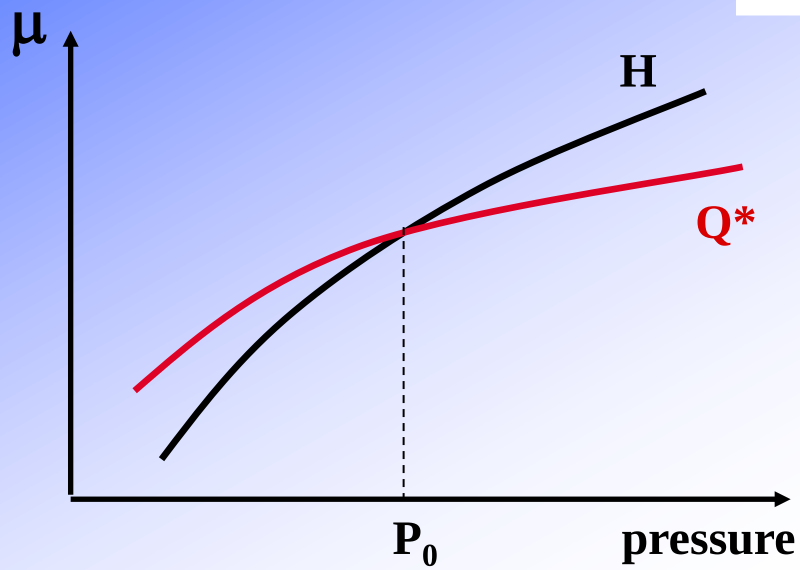
Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

A common event in nature, e.g.:

- **fog or dew formation in supersaturated vapor**
- **ice formation in supercooled water**

Pure and distilled water at standard pressure (100 kPa) can be supercooled down to a temperature of -48.3 ^{o}C. In the tempearture range (-48.3 — 0) ^{o}C, water is in a metastable phase and ice cristals will form via a nucleation process.

Gibbs' criterion for phase equilibrium



$$\mu_H = \mu_Q \equiv \mu_0$$

$$T_H = T_Q \equiv T$$

$$P(\mu_H) = P(\mu_Q) \equiv P(\mu_0) \equiv P_0$$

μ_j = **Gibbs' energy per baryon**
(j-phase average chemical pot.) j = H, Q

$$\mu_H = \frac{\varepsilon_H + P_H - s_H T}{n_{b,H}}$$

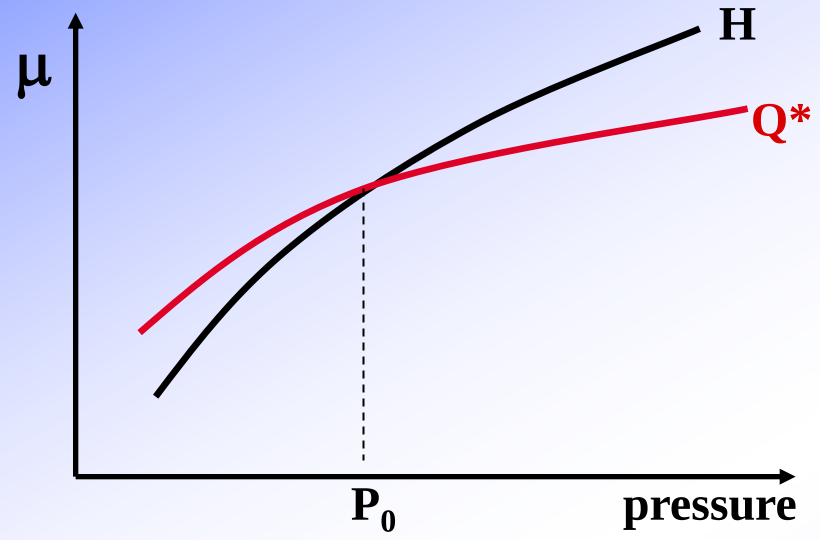
$$\mu_Q = \frac{\varepsilon_Q + P_Q - s_Q T}{n_{b,Q}}$$

In **NS cores** when **P_{centr} = P(r=0) > P_0**

Hadronic matter phase is metastable

The **stable Quark matter phase** is formed by a **nucleation process**

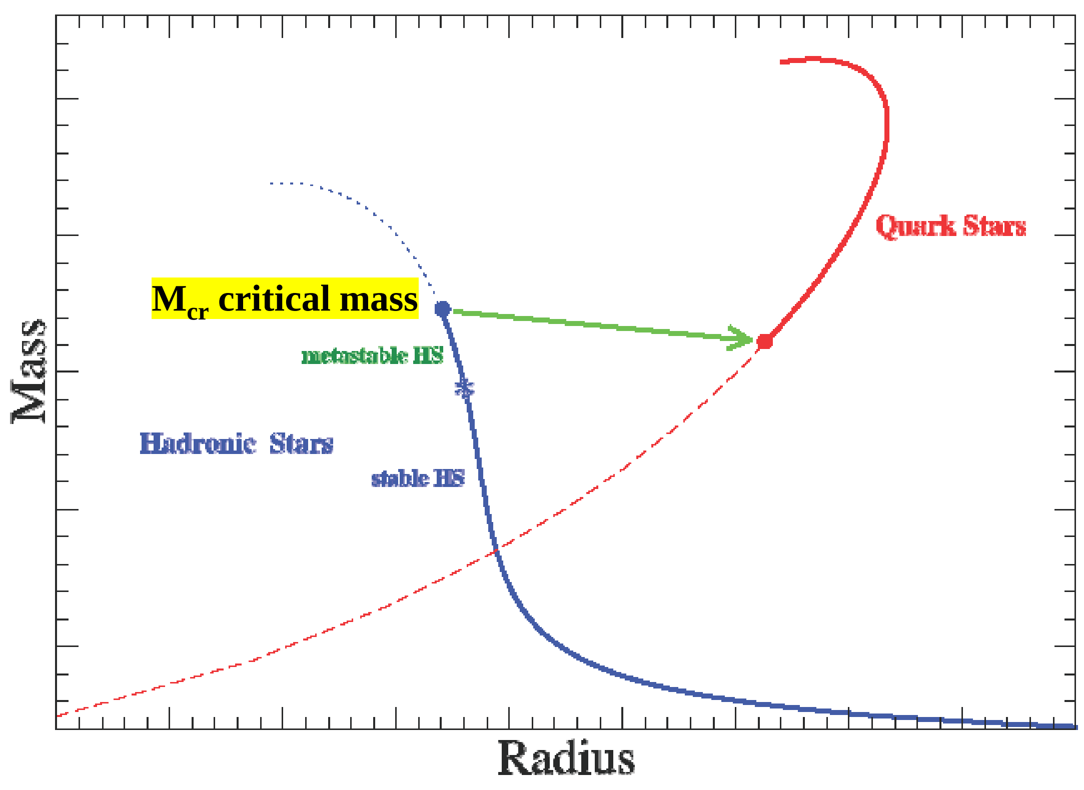
First drop of Q*-matter → **stellar conversion process HS→QS**



Hadronic Stars with $P_{centr} > P_0$ are **metastable** to the **conversion** **to Quark Stars**

The **mean lifetime** of the **metastable Hadronic Star configuration** is related to **nucleation time (τ)** of the first drop of **Q*-phase**

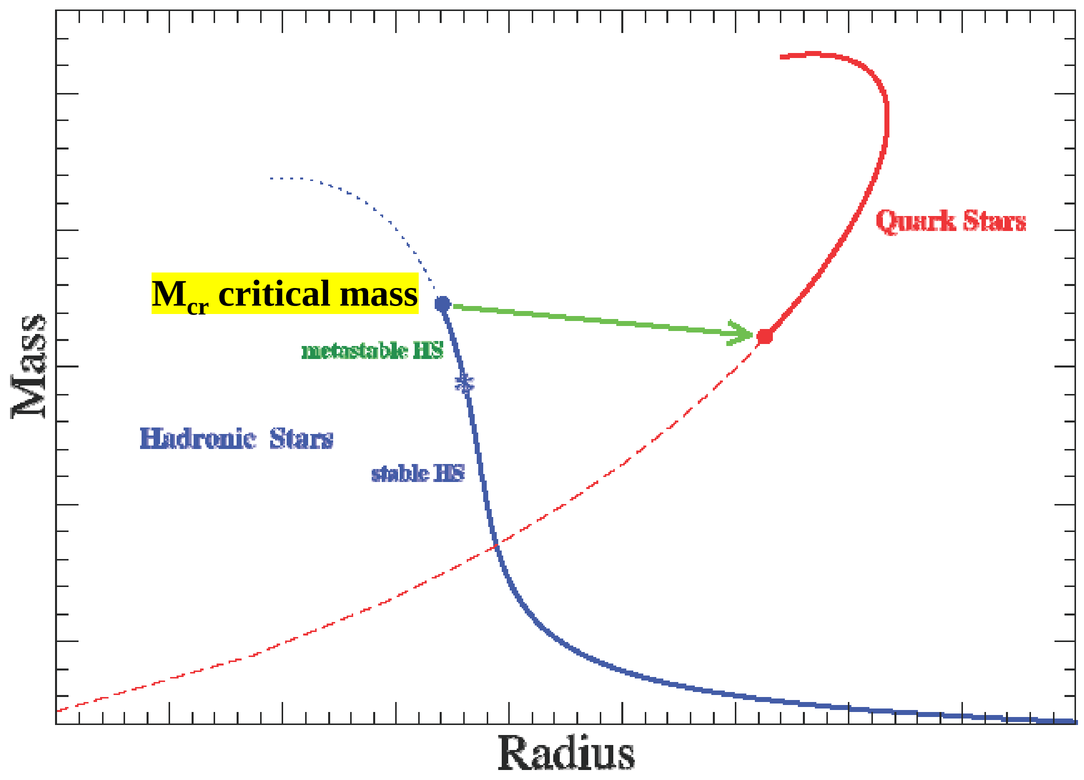
Metastability of Hadronic Stars



Hadronic Stars above a threshold value of their gravitational mass are **metastable** to the **conversion** to **Quark Stars (QS)**

Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys. 528 (2011) A71
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago, G. Pagliara, EPJA 52 (2016) 41

Metastability of Hadronic Stars



- M_{cr} , critical mass of hadronic stars.
- Two coexisting families of compact stars
- stellar conversion HS→QS

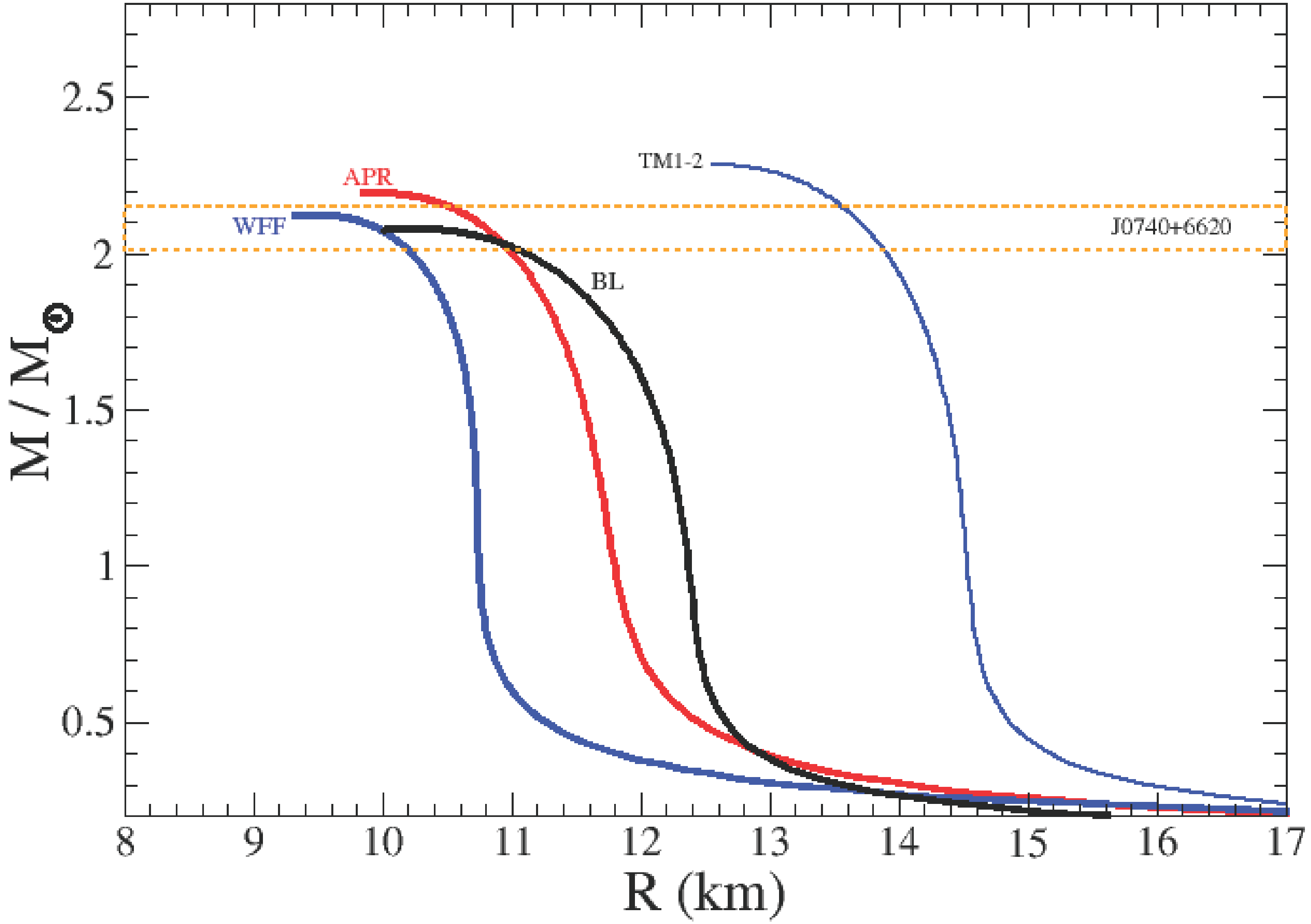
$E_{conv} \sim 10^{53}$ erg

Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys. 528 (2011) A71
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago, G. Pagliara, EPJA 52 (2016) 41

The neutron stars’ mass–radius relation from microphysical EOS
and
the contraints from astrophysical observations

Nucleon Stars

(n,p,e^-,μ^-)



WFF
R.B. Wiringa, V. Ficks and A. Fabrocini, Phys. Rev. C 38 (1988) 1010.

APR
A. Akmal, V.R. Pandharipande and D.G. Ravenhall, Phys. Rev. C 58 (1998) 1804.

BL
I. Bombaci, D. Logoteta. Astron. & Astrophys. 609 (2018) A128

TM1-2
C. Providencia, A. Rabhi, Phys. Rev. C, 87 (2013) 055801

$R_{1.4}$ = (10.5 — 14.5) km

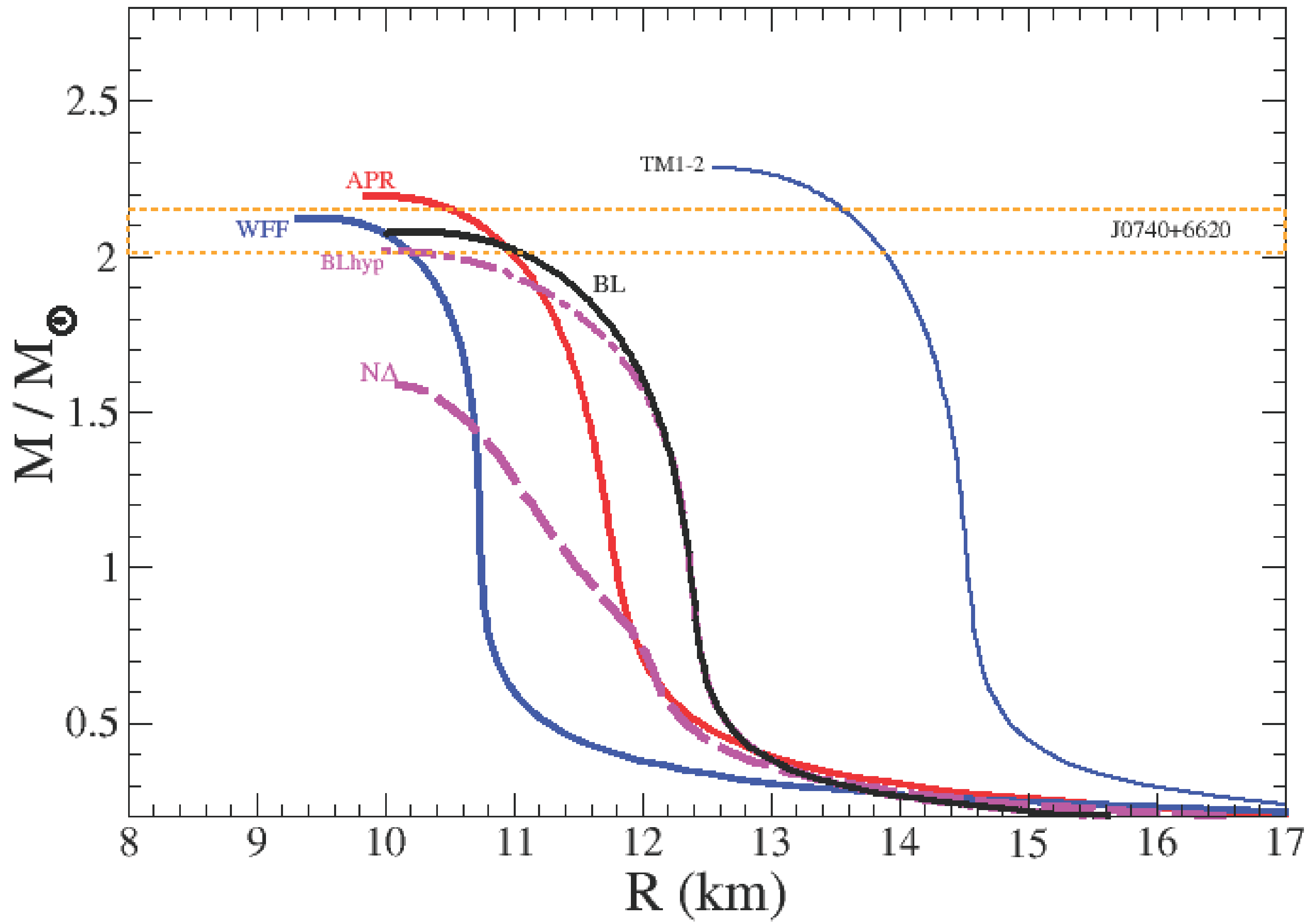
PRS J0740+6620

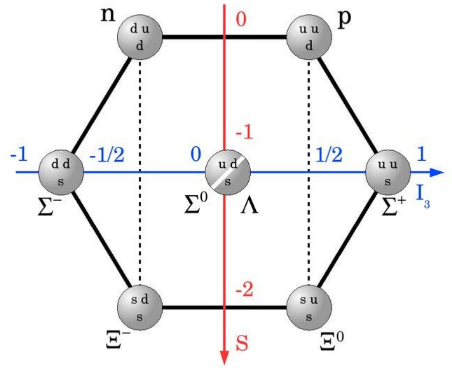
$M = (2.08 \pm 0.07)\ M_\odot$

Fonseca et al. arXiv:2104:00880 (2021) ApJL in press

Hyperon Stars

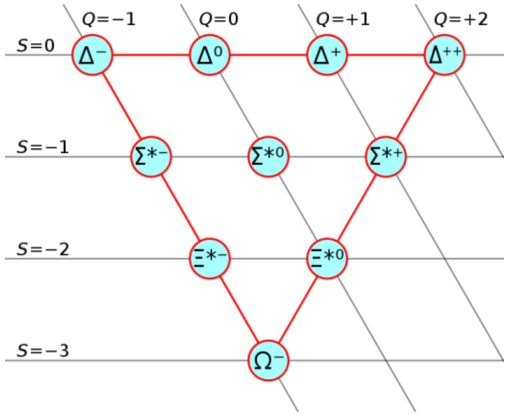
($n,p,\Lambda, \Sigma^-,\ldots,e^-,\mu^-$)



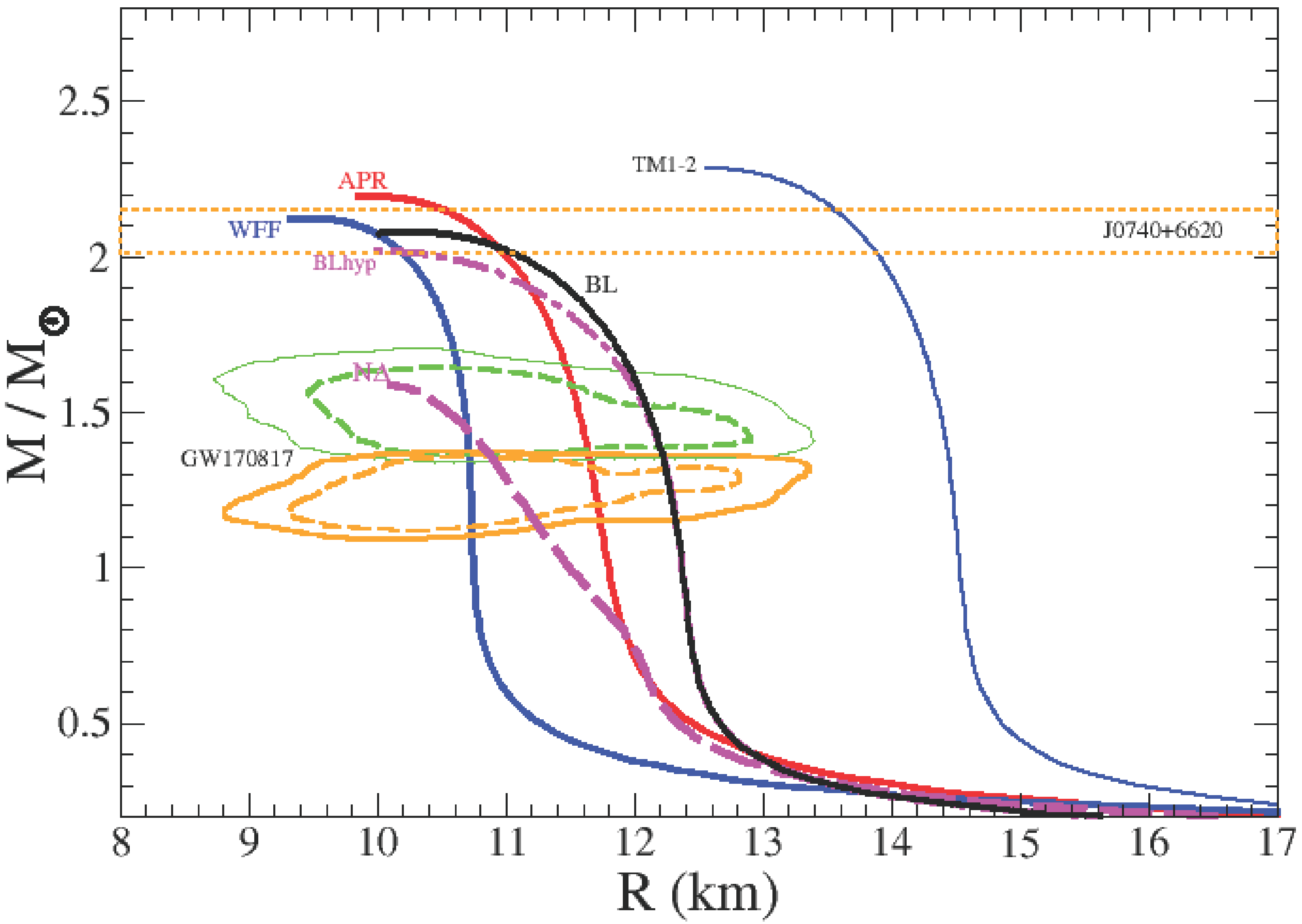


BLhyp
D. Logoteta. I. Vidana, I Bombaci, Eur. Phys. J. A 55 (2019) 207

+ Δs



NΔ
A. Drago, A. Lavagno, G. Pagliara, D. Pigato, Phys. Rev. C 90 (2014) 065809



Constraints from astrophysical observations

GW170817

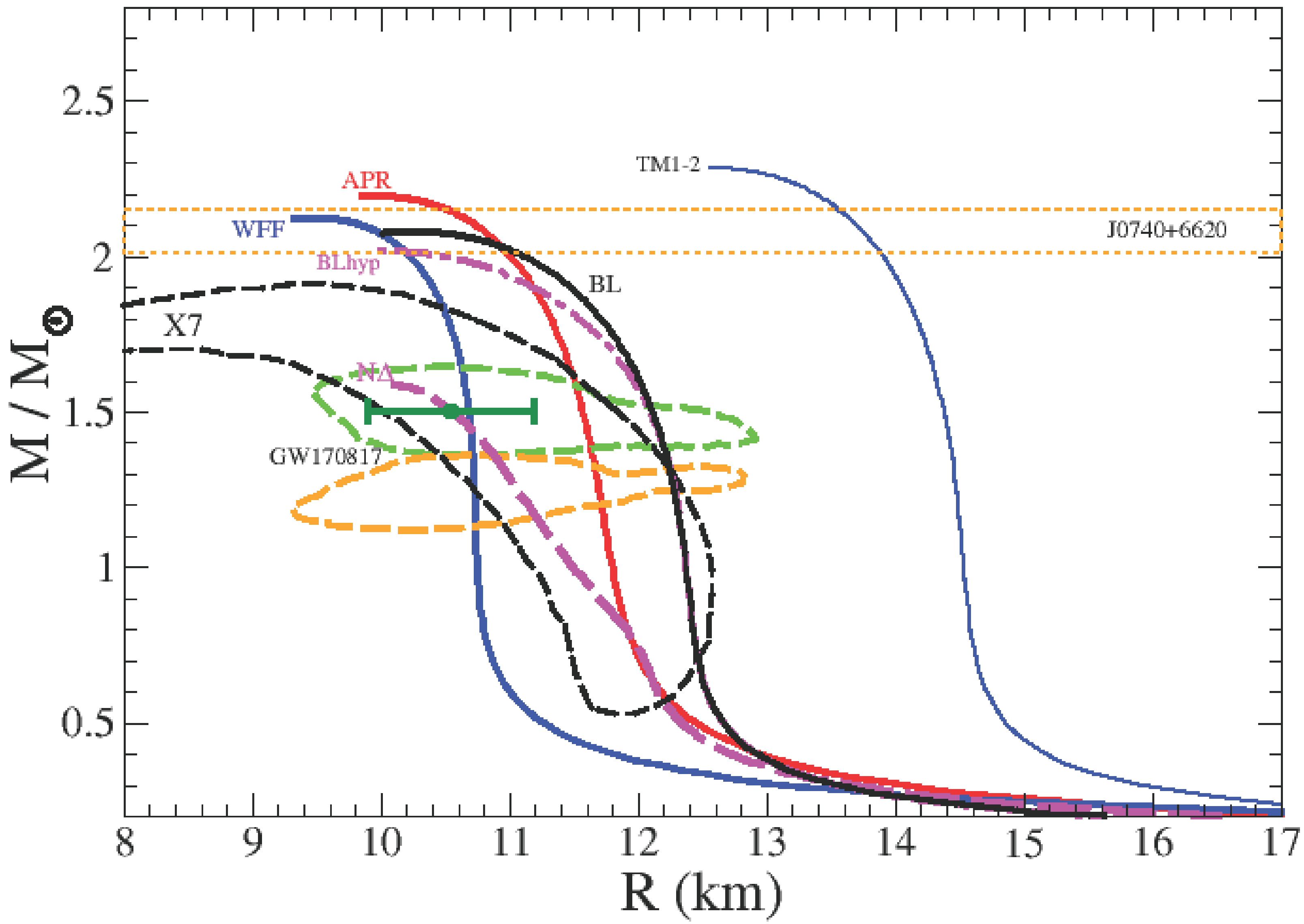
$R = (9 - 13)$ km (90% CL)

$70 < \Lambda_{1.4} < 580$

P.B. Abbott et al., Phys. Rev. Lett. 121 (2018) 161101

$\Lambda_{1.4}$ (BL) = 385

Constraints from astrophysical observations



qLMXBs

(quiescent Low-Mass X-ray Binaries)

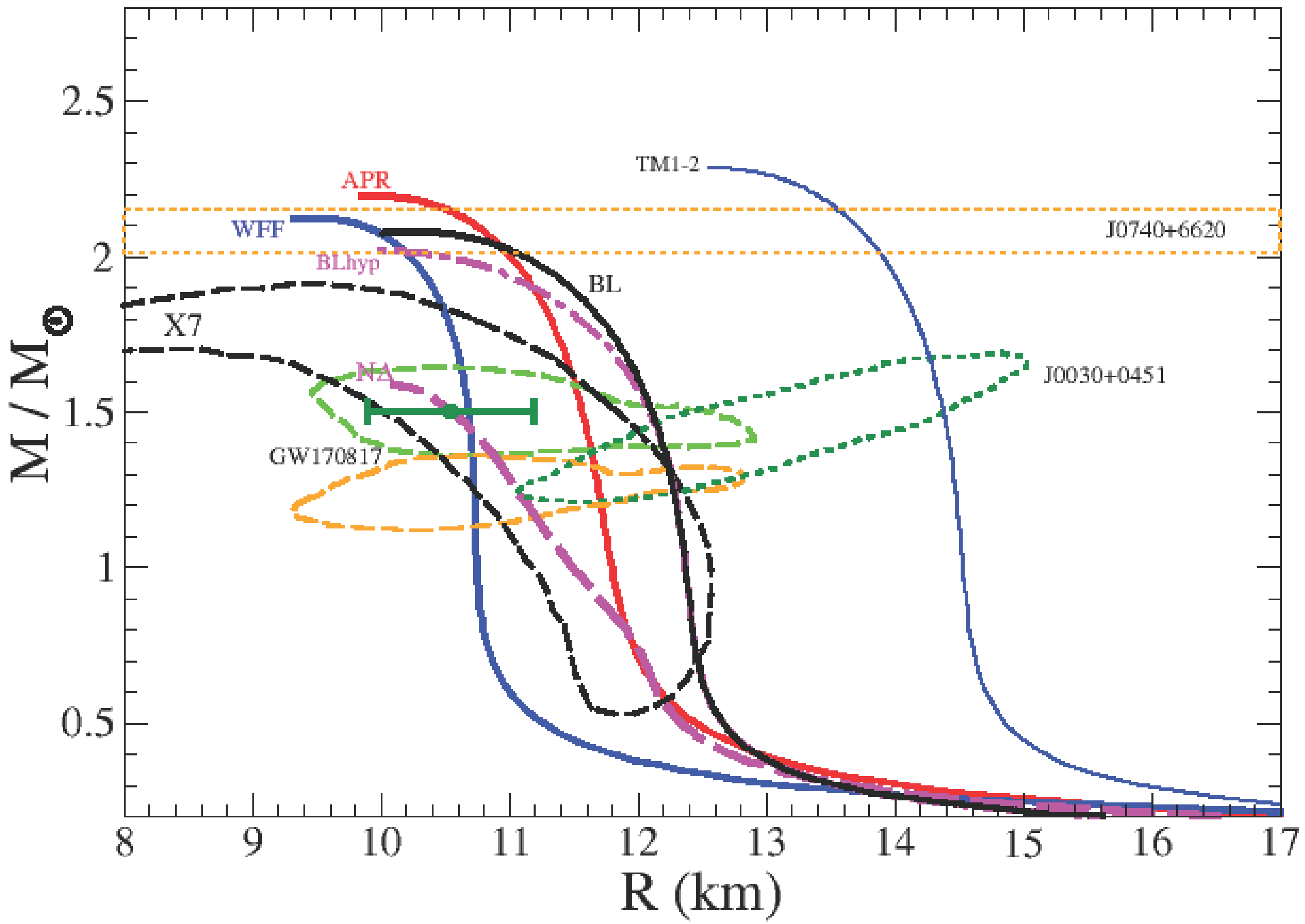
X7 in globular cluster 47 Tuc

16 qLMXBs sources

$$R_{1.5} = (9.9 — 11.2) \text{ km}$$

S. Bogdanov et al., Astrophys. Jour. 831 (2016) 184

Authors'words: «These measurements strongly point out to a dense matter EOS that is somewhat softer than the nucleonic one that are consistent with laboratory experiments al low density » «and may point to new degrees of freedom appearing at around 2 ρ_{sat}»



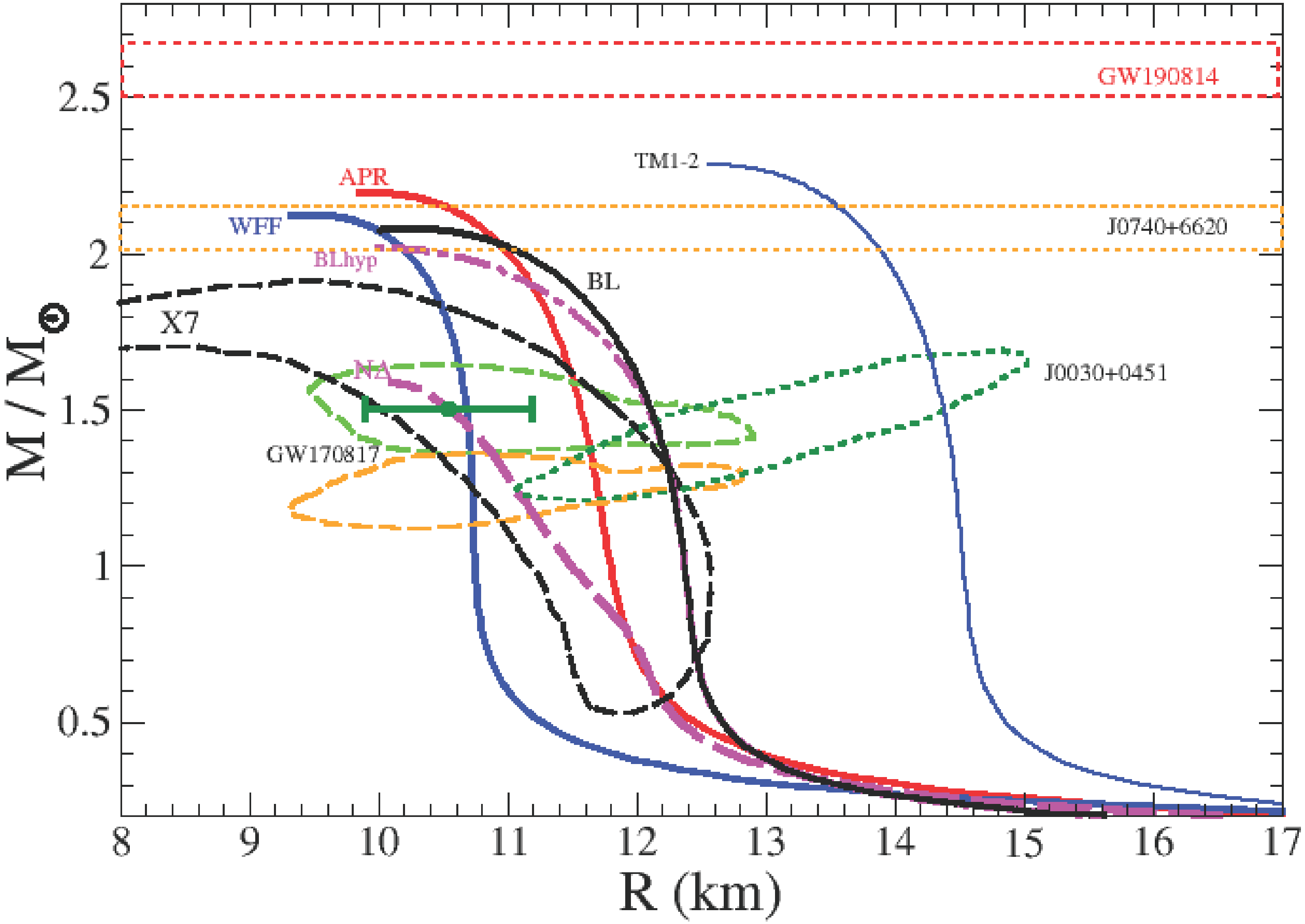
Constraints from astrophysical observations

PSR J0030+0451

NICER data

T.E. Riley et al., Astrophys. J. Lett. 887 (2019) L21

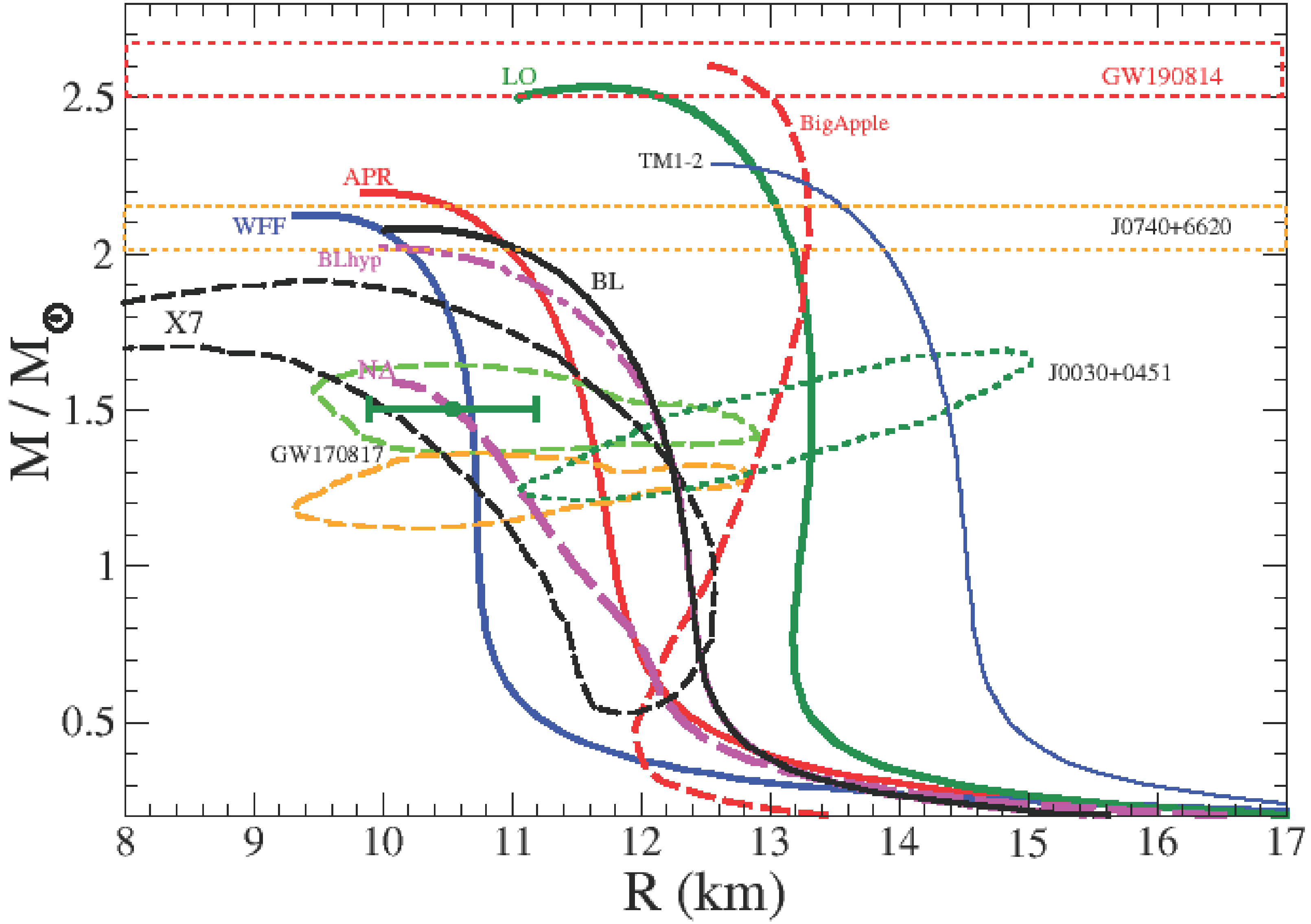
Signal of a tension with the results from qLMXBs



GW190814

$M_2 = (2.50 - 2.67)\ M_\odot$

R. Abbott et al., Astrophys. J. Lett. 896 (2020) L44



GW190814

M_2 as a Neutron Star

EOS:

BigApple

F. Fattoyev, C. Horowitz, J.Piekarewicz, B. Reed, Phys. Rev. C 102 (2020) 065805

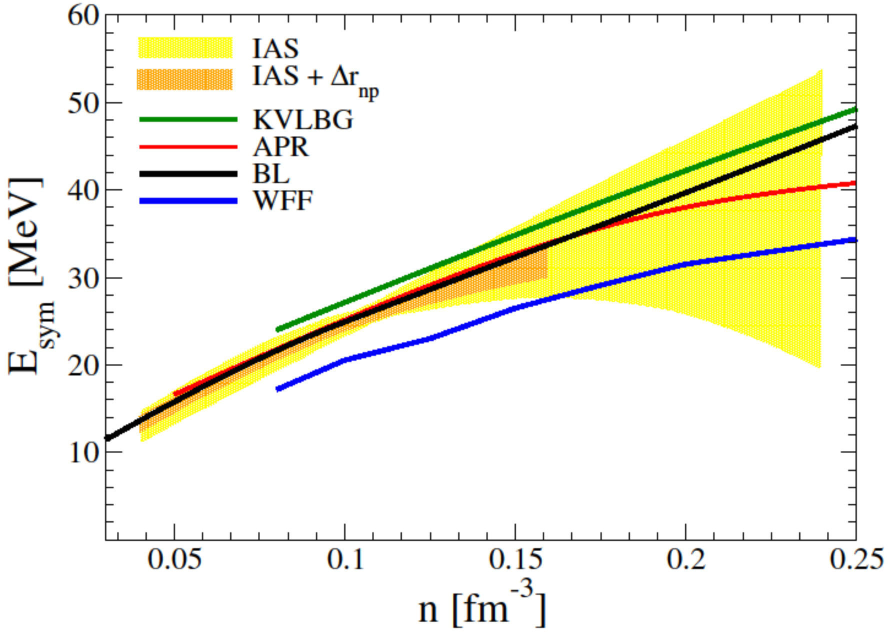
$\Lambda_{1.4}$ = 717 **inconsistent** with GW170817 $70 < \Lambda_{1.4} < 580$; **inconsistent** with constraints **from Heavy-Ion Collision exp.s**

LO

A. Kievsky, M. Viviani, D. Logoteta, I. Bombaci, L. Girlanda, Phys. Rev. Lett. 121 (2018) 072701

$\Lambda_{1.4}$ = 714 **inconsistent** with GW170817 $70 < \Lambda_{1.4} < 580$; **inconsistent** with constraints **from Heavy-Ion Collision exp.s**

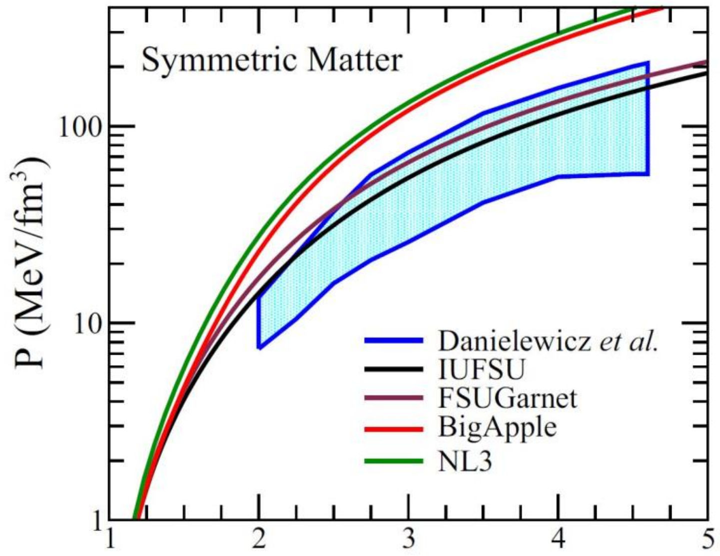
Symmetry energy



IAS = constraint from Isobaric Analog States in nuclei
(P. Danielewicz, J. Lee, Nucl. Phys. A922 (2014) 1)

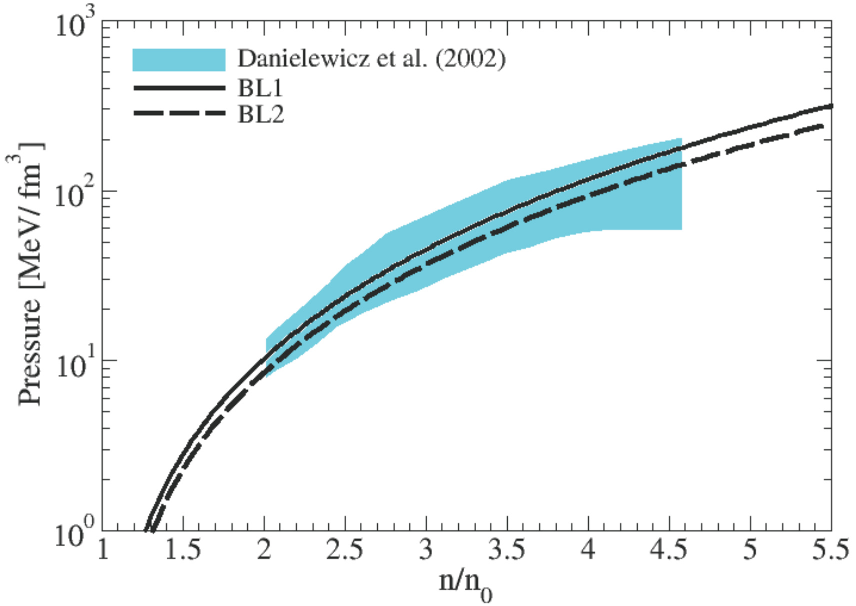
Δr_{np} = neutron skin thickness of heavy nuclei
(X. Roca-Maza et al., Phys. Rev. C 87 (2013) 034301)

Pressure in symmetric NM



F. Fattoyev, et al., Phys. Rev. C 102 (2020) 065805

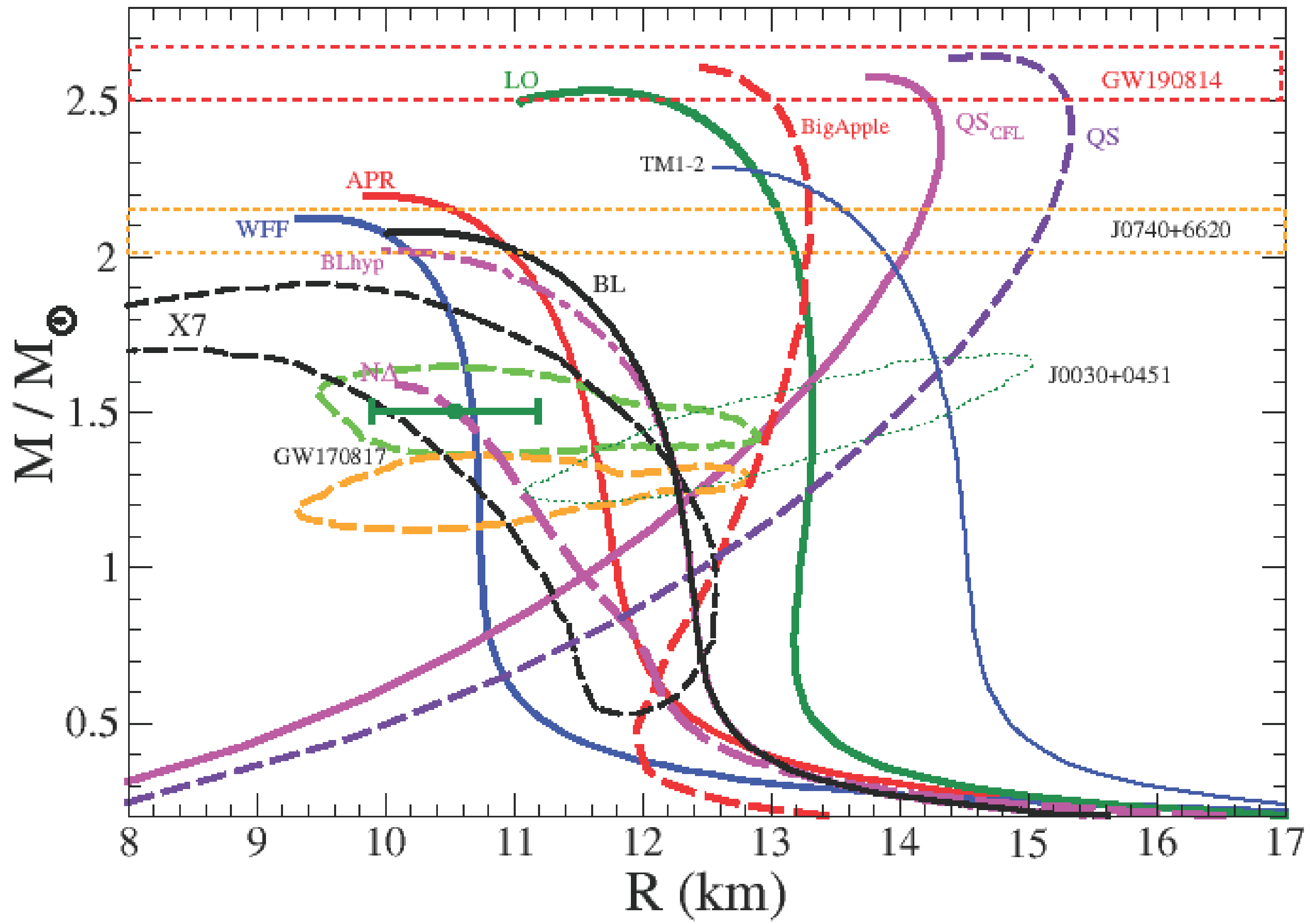
The **cyan hatched area** represents the region in the pressure–density plane for **SNM** which is consistent with the measured **elliptic flow of matter in collision experiments between heavy atomic nuclei** (Danielewicz et al. 2002).



I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

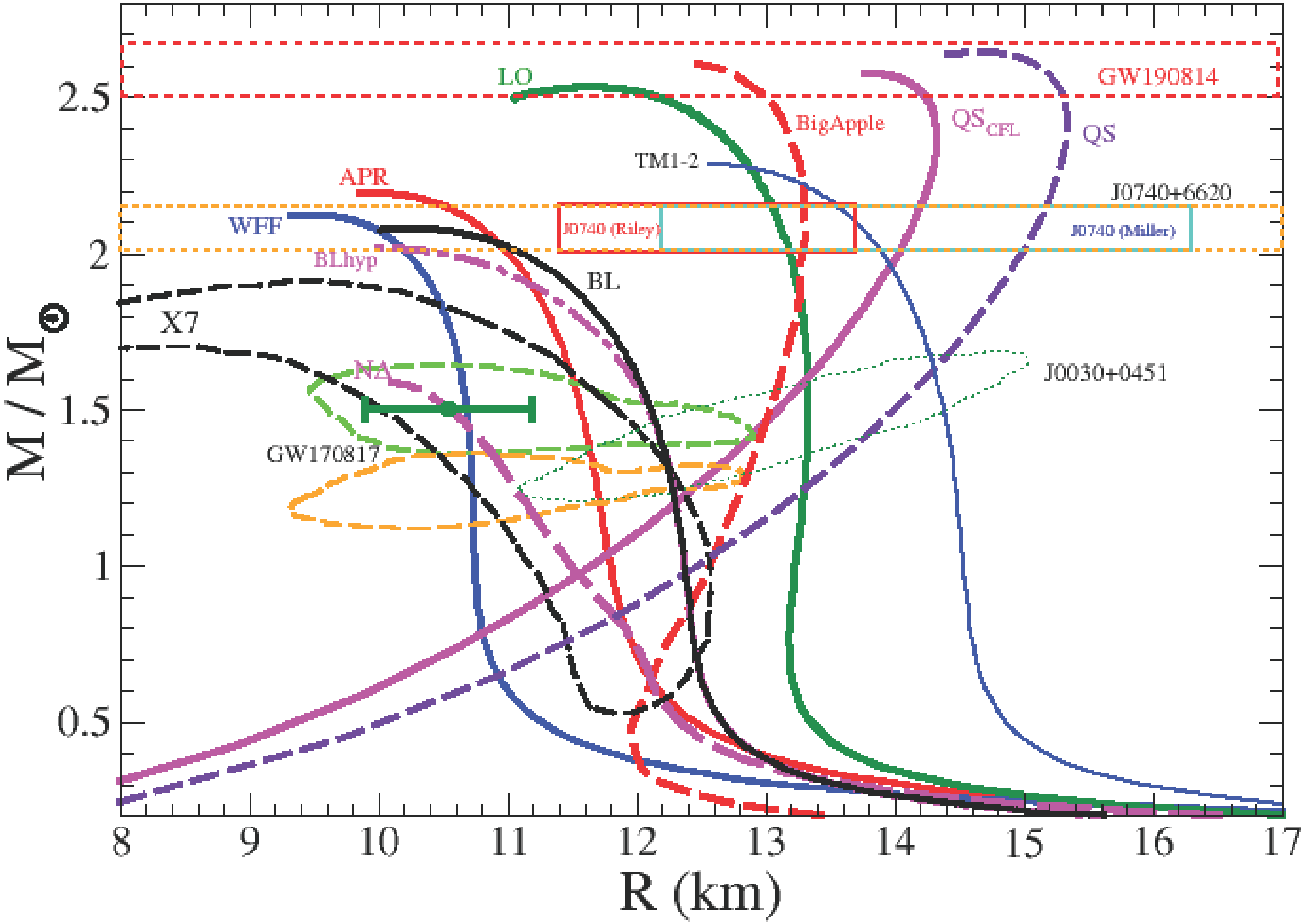
GW190814

M_2 as a **Strange Quark Star**



EOS for SQM

E. Fraga, R.D. Pisarki, J. Schaffner-Bielich, Phys. Rev. D 63 (2001) 12172(R)
M. Alford, M. Braby, M. Paris, S. Reddy, ApJ 629 (2005) 969
S. Weissenborn, I. Sagert, G. Pagliara, M. Hempel, J. Schaffner-Bielich, ApJ 740 (2011) L14



Constraints from astrophysical observations

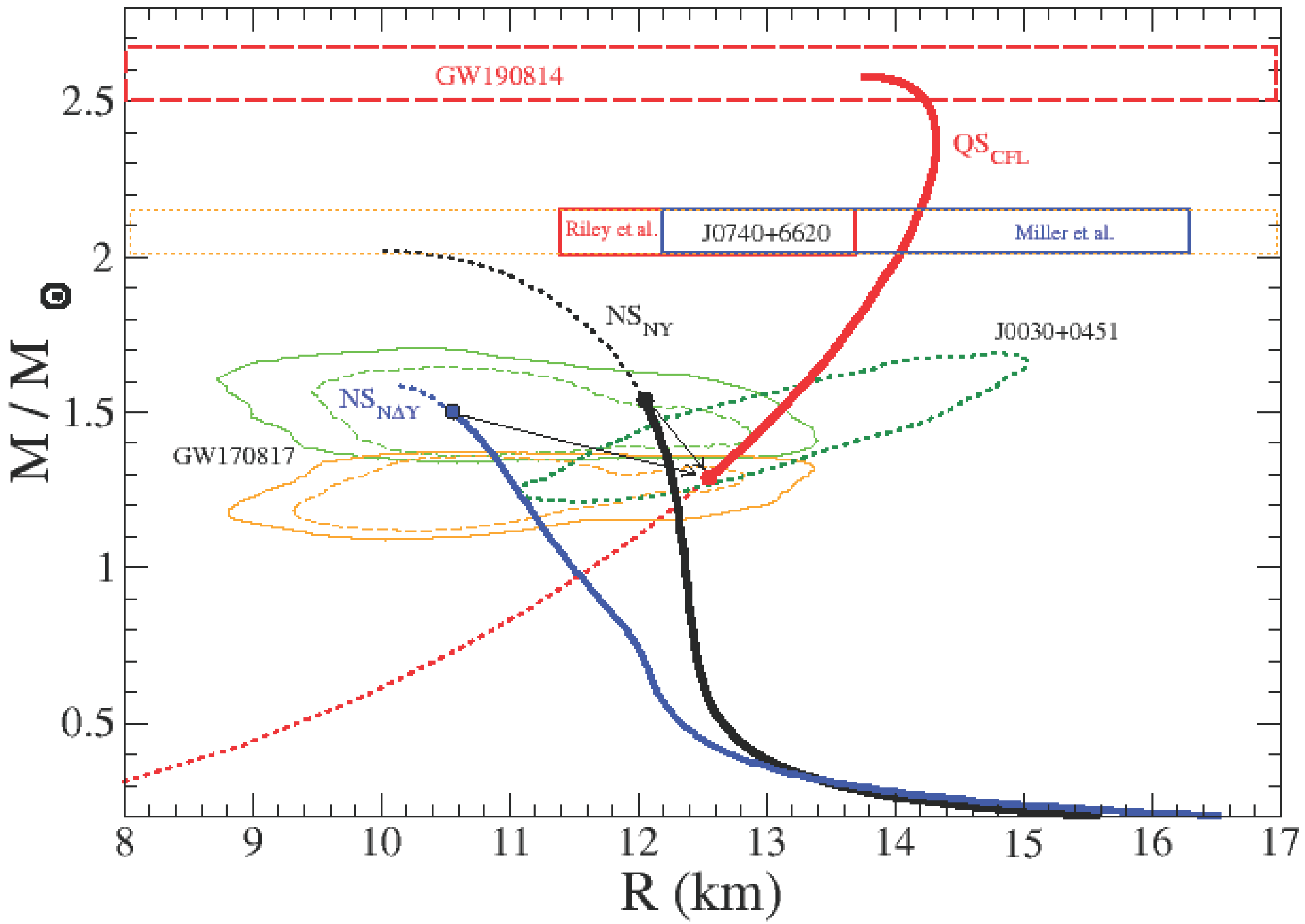
PSR J0740+6620

NICER data

T.E. Riley et al. (2021) arXiv:2105:06980

M.C. Miller et al. (2021) arXiv:2105:06979

Two coexisting families of Compact Stars



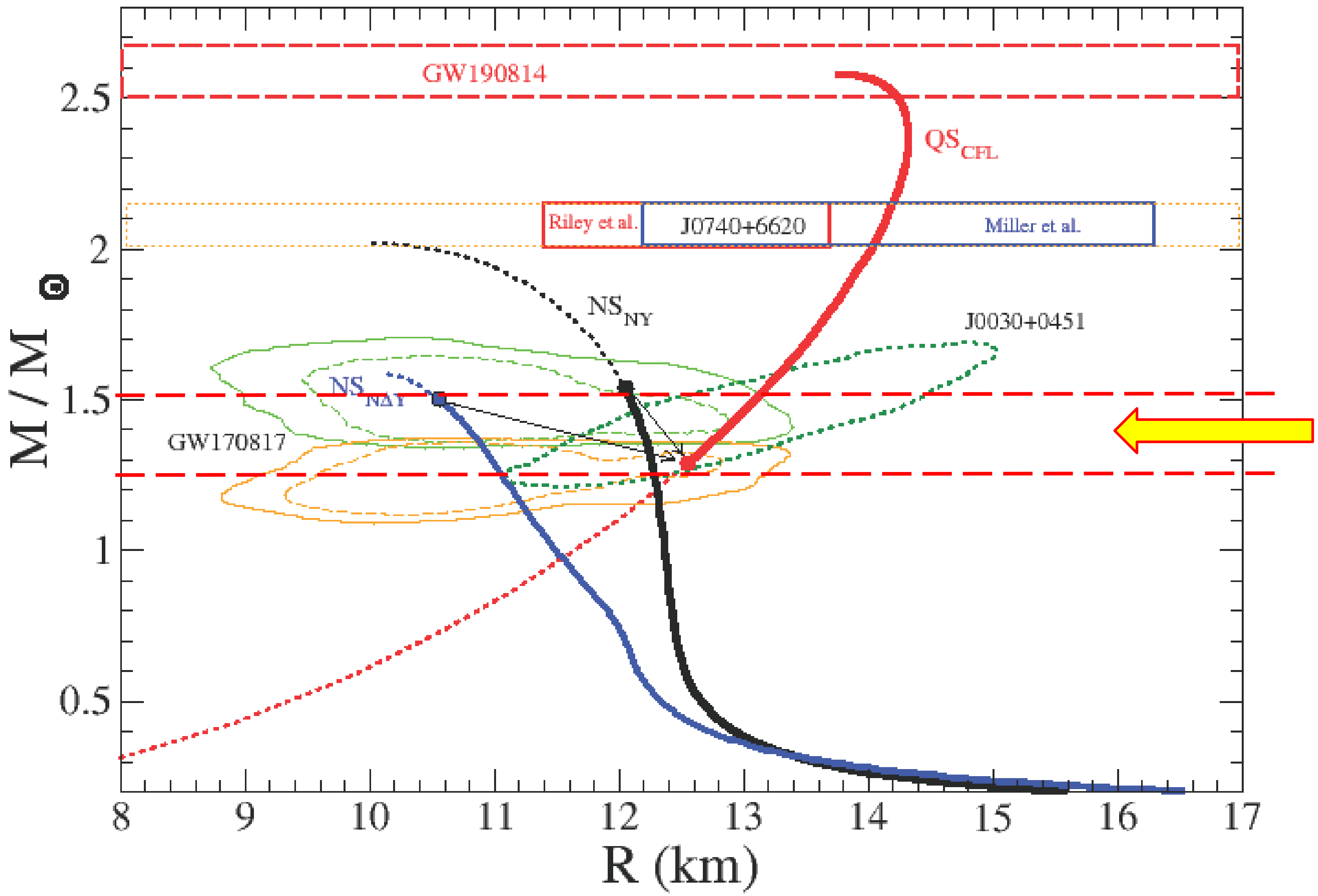
consistent with the interpretation of the secondary component of GW190814 as a strange quark star

and

relieve the tension between some measurements of NS radii

(stars with «small» radii are Hadroic Stars and stars with «large» radii are Strange Quark Stars)

Two coexisting families of Compact Stars

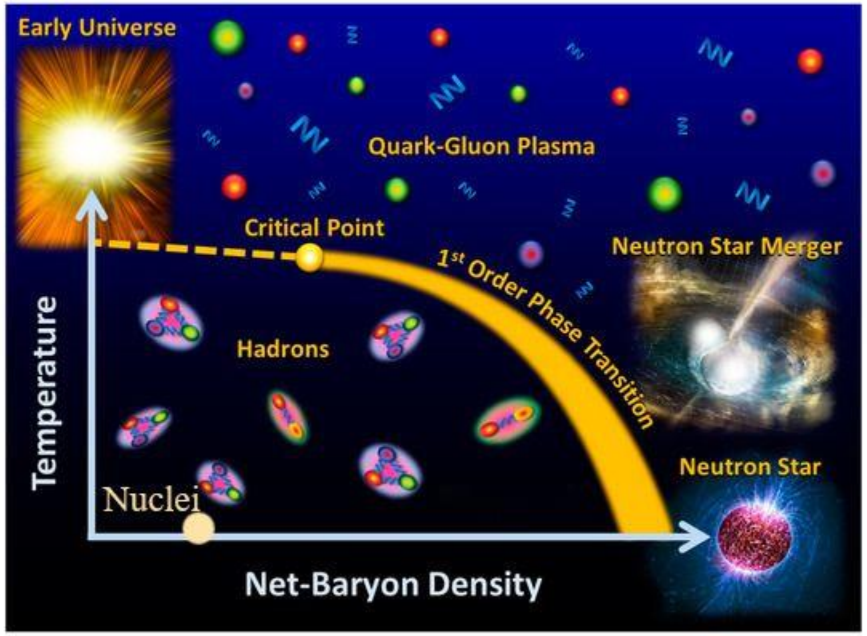


An observationally testable prediction of the two-family scenario:
existence in nature of compact star having the same mass but different radii.

This observation would falsify the scenario with a single family of compac stars (hadronic stars).

Probing dense QCD matter in the laboratory

Whether the **quark-deconfinement phase transition** is of the **first-order with a critical endpoint**, or whether it proceedes smothly by a **crossover** is still an open question.



Adapted from P. Senger, and N. Herrmann, Nuclear Physics News, Vol. 28, No 2 (2018) 23.

New dedicated experiments are under construction at future facilities

Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (**FAIR**) in **Darmstadt**,

J-PARC Heavy-Ion-project at the Japan Proton Accelerator Research Complex (**J-PARC**) in **Tōkai**,

Heavy-Ion-program at the Nuclotron-based Ion Collider fAcility (**NICA**) at the Joint Institute for Nuclear Research in **Dubna**.

The prospects in the quest to uncover the correct EoS which describes Neutron Stars look thus very bright.

Thank you very much for your attention

and special thanks to my collaborators

Alessandro Drago

Domenico Logoteta

Giuseppe Pagliara

Isaac Vidaña

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S. Bhattacharyya, I. Bombaci, D. Logoteta, A.V. Thampan, ApJ 848 (2017) 65
R. De Pietri et al, Astrophys. Jour. 881 (2019) 122
A. Drago, G. Pagliara, Phys. Rev. D 102 (2020) 063003
I. Bombaci, A. Drago, D. Logoteta, G. Pagliara, I. Vidaña, Phys. Rev. Lett. 126 (2021) 162702