Wrap-up Friday

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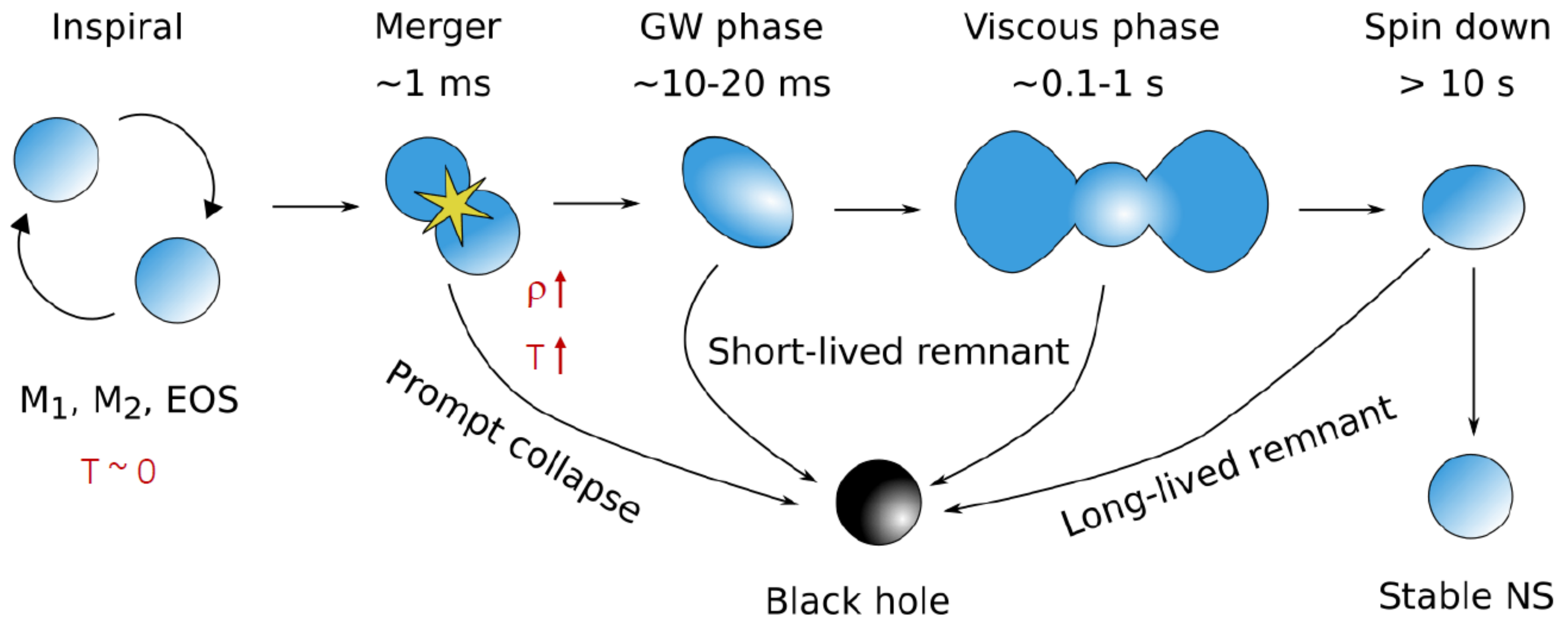
Which are the main research lines?

- Works aiming at clarifying what can be done by using standard “minimal” ingredients, i.e. nucleons, hyperons, deltas
  - Microscopic purely nucleonic EOSs, extension to finite temperature, neutrino-trapped matter
  - Hyperonic matter, both microscopic (three-body forces) and RMF, also at finite temperature
- Works suggesting the existence of deconfined quark matter, but only in the “central” region of compact stars
  - Description of the mixed phase of hadrons and quarks, also at finite temperature (mergers, Supernovae)
  - Relation between transition density, sound velocity in QM and masses and radii of compact stars
- Works suggesting the co-existence of strange quark stars and of hadronic stars
  - Conditions for the possible coexistence
  - Signatures of the existence of strange quark stars

“Minimal model”

Nucleons, hyperons, deltas

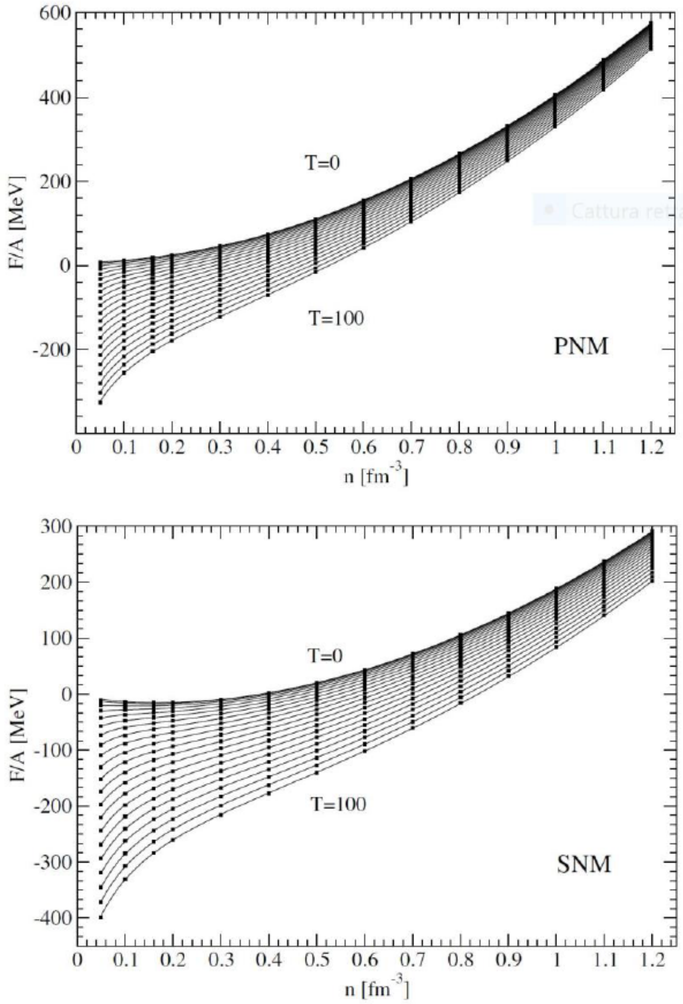
Phases of merging



Radice et al. ARNPS, 2020

The EOS of Nuclear Matter at finite temperature

Extension of the BHF approximation a T ≠ 0



Free energy per particle F/A

D. Logoteta, A. Perego, I. Bombaci, Astron. & Astrophys. 646 (2021)

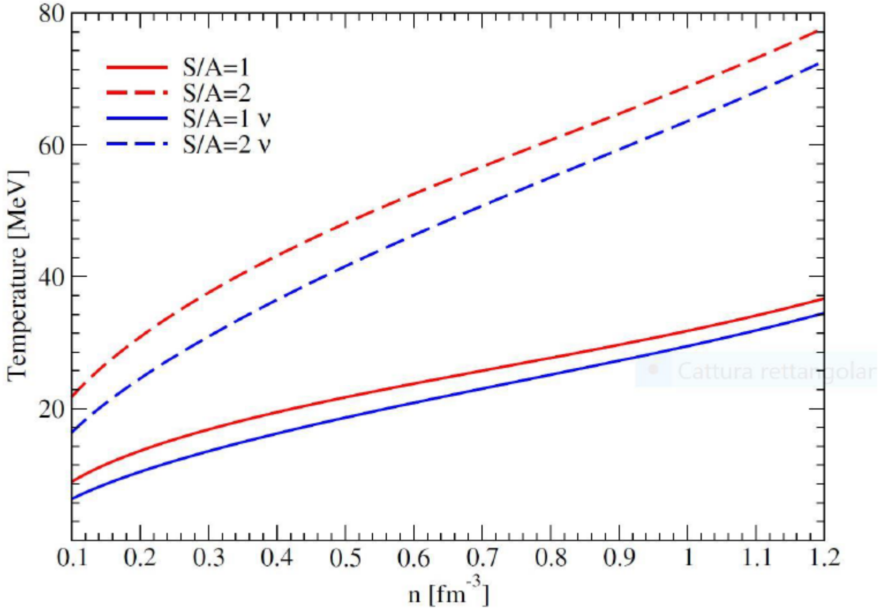


Fig. 5. Temperature profiles as a function of nuclear density n for isoentropic ($S/A = \text{const}$) β-stable EOSs in the case of neutrino-free (red lines) and neutrino trapped (blue lines) matter.

$$T_S = \chi(\beta)\,\frac{S}{A}\,n^{2/3},$$

where

$$\chi(\beta) = \frac{\hbar^2}{m}\left(\frac{3}{\pi}\right)^{2/3}\left[\left(\frac{1+\beta}{2}\right)^{1/3} + \left(\frac{1-\beta}{2}\right)^{1/3}\right]^{-1}.$$

I. Bombaci, T.T.S. Kuo, U. Lombardo, Phys. Rep. 242 ((1994)

From Bombaci

Hyperonic three-body interactions as a possible solution of the hyperon puzzle

As mentioned before, **three-nucleon interactions** are a necessary ingredient for an accurate description of nuclei and nuclear matter within non-relativistic approaches.

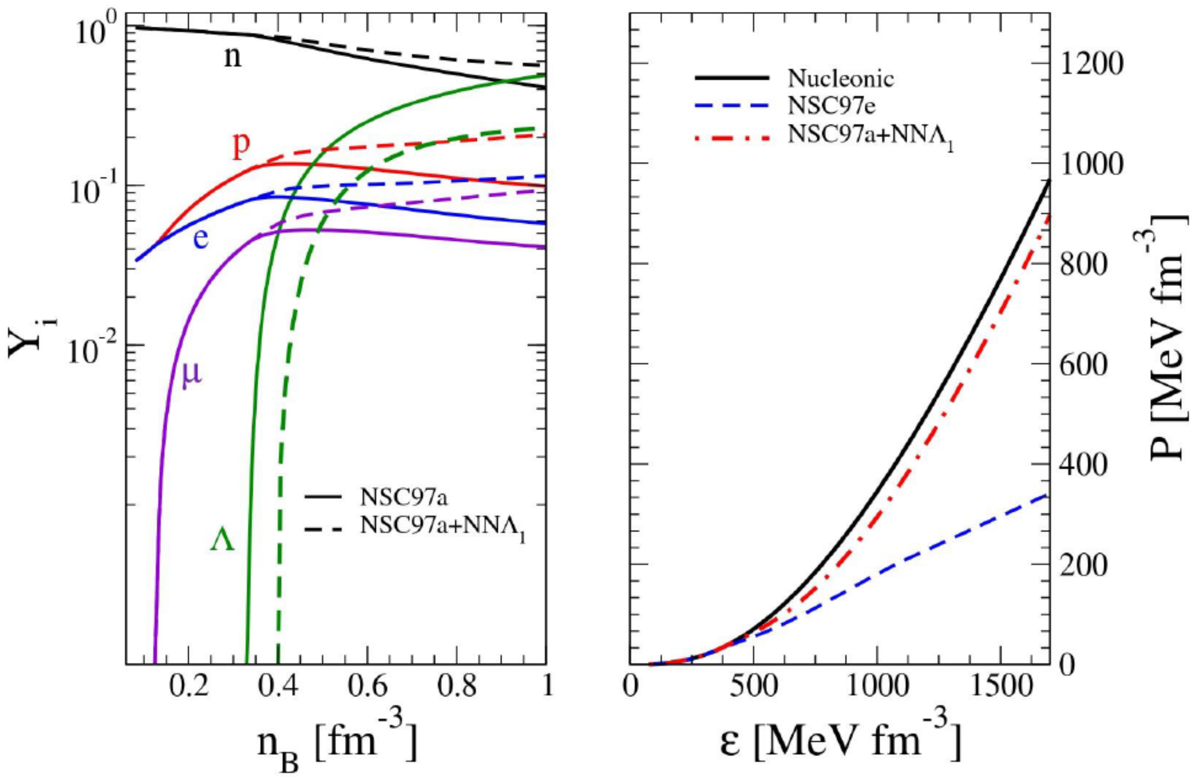
Thus, it is rather obvious to suppose the existence of **hyperonic three-body interactions** (of the type **NNY, NYY, YYY**).

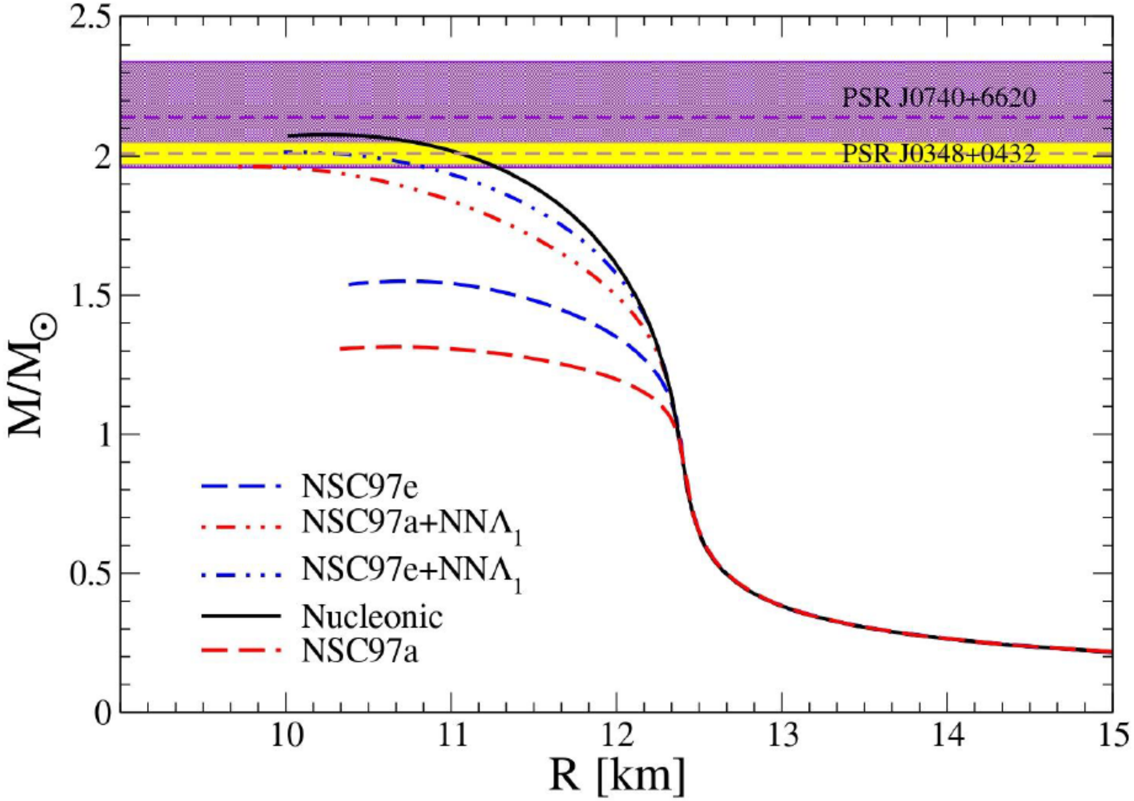
The **NNΛ interaction** was in fact first hypothesized at the end of the 1950s (*), *i.e.* during the early days of hypernuclear physics, as an important ingredient to calculate the **binding energy of hypernuclei**.

It is thus reasonable to expect that **hyperonic three-body interactions** can influence dense-matter EoS and represent a **likely candidate to solve the hyperon puzzle**.

(*) R. Spitzer, Phys. Rev., 110 (1958) 1190.
G. G. Bach, Nuovo Cimento XI (1959) 73.
R. H. Dalitz, 9th Int. Ann. Conf. on High-Energy Physics, Academy of Sciences, USSR, Vol I (1960) 587.

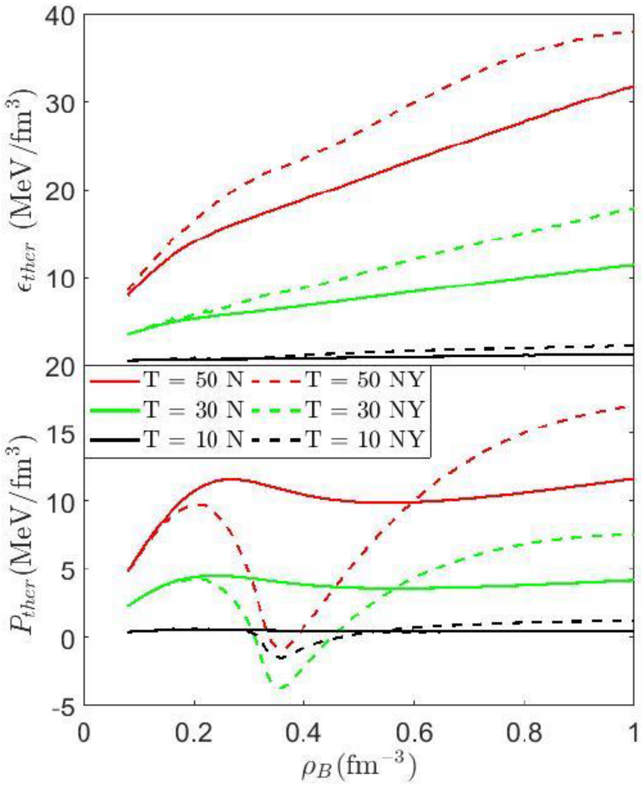
Hyperonic three-body interactions could represent a likely solution of the hyperon puzzle in Neutron Stars



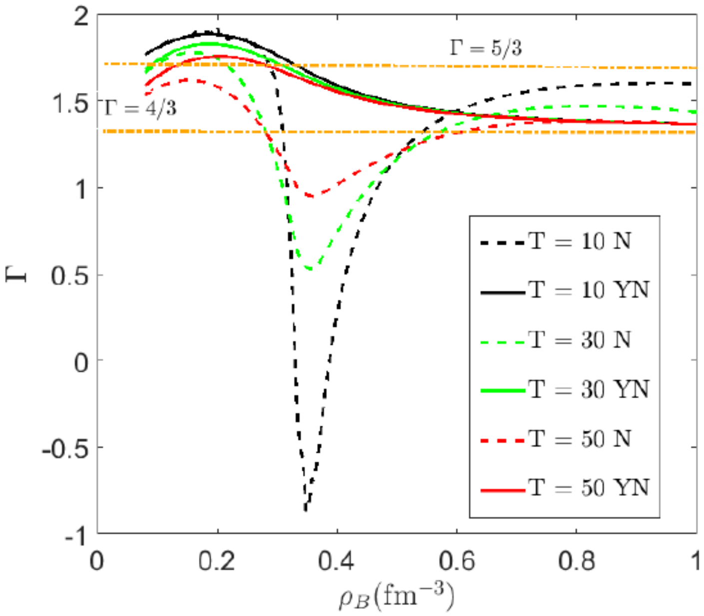


D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207

Thermal index – β- stable ν free matter in FSU2H*



- Thermal effect are more emphasized when hyperons are included.
- Significant effect on the thermal pressure – **can be lower than 0!**
- Induces a drop in the thermal index



Kochankovski et al, 2022, MNRAS

Deconfined quark matter in compact star center

Hybrid stars

Quark matter in supernova explosions

- $2M_\odot$ stars formation? (accretion is too slow)
- Supernovae with progenitor mass $\sim 50\ M_\odot$
- Quark-hadron transition stabilizes collapse

T. Fischer et al., Nature Astronomy 2, 980–986 (2018)

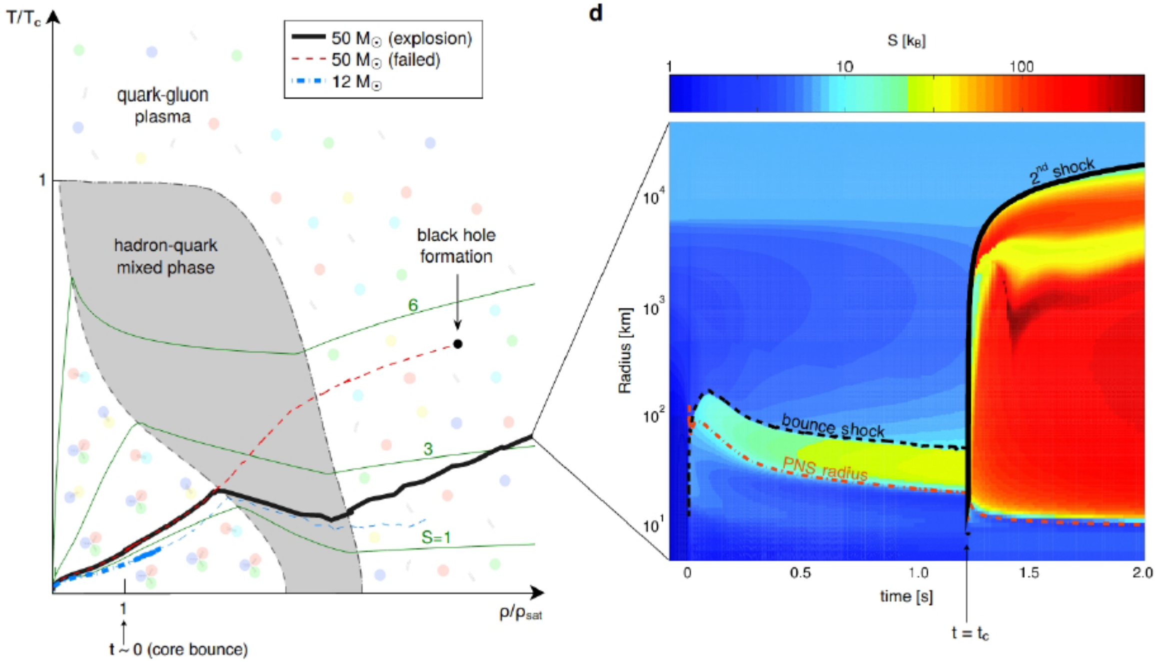
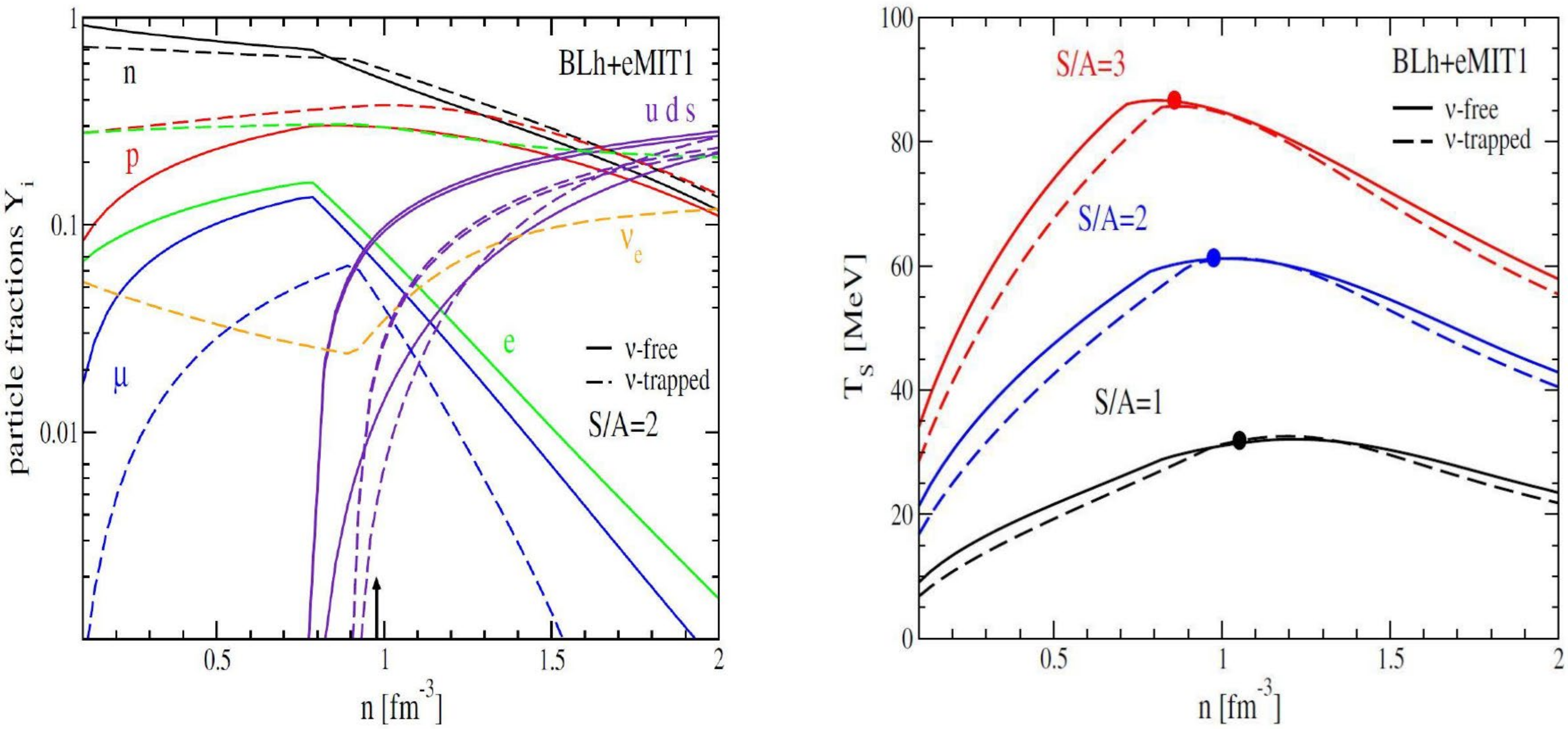


Table 1 | Summary of the supernova simulation results with hadron–quark phase transition

M_{ZAMS} ($M_\odot$)	t_{onset} (s)	$t_{collapse}$ (s)	$\rho\vert_{collapse}$ (ρ_{sat})	$T\vert_{collapse}$ (MeV)	$M_{PNS,collapse}$[a] ($M_\odot$)	t_{final} (s)	$\rho\vert_{final}$ (ρ_{sat})	$T\vert_{final}$ (MeV)	$M_{PNS,final}$[a] ($M_\odot$)	E^*_{expl} (10^{51} erg)
12[12]	3.251	3.489	2.49	28	1.727	3.598	5.5	17	1.732	0.1
18[12]	1.465	1.518	2.53	27	1.958	1.575	5.9	18	1.964	1.6
25[12]	0.905	0.976	2.40	31	2.163	0.983	9.6	19	2.171[b]	-
50[13]	1.110	1.215	2.37	32	2.105	1.224	5.8	31	2.092	2.3

Deconfinement is a supernova engine for massive blue giants

Isoentropic β-stable hybrid matter



D. Logoteta, I. Bombaci, A. Perego, Eur. Phys. J. A 58 (2022)

Comparison to NJL model

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \underbrace{(m + \Sigma_{MF})}_{\textbf{effective mass } \mathbf{m^*}})q + G_S(\overline{q}q)^2 + G_{PS}\left(\overline{q}i\vec{\tau}\gamma_5 q\right)^2 + \cdots + \mathcal{L}_V + \mathcal{L}_D$$

- **Similarities:**
  - current-current interaction
  - (pseudo)scalar, vector, diquark, ... channels
- **Differences:**
  - high m^* at low T, $\mu \Rightarrow$ **"confinement"**

$$\langle\overline{q}q\rangle = \langle\overline{q}q\rangle_0 \;\Rightarrow\; m^* = m - \frac{2G_0}{3\alpha^{2/3}\langle\overline{q}q\rangle_0^{1/3}}$$

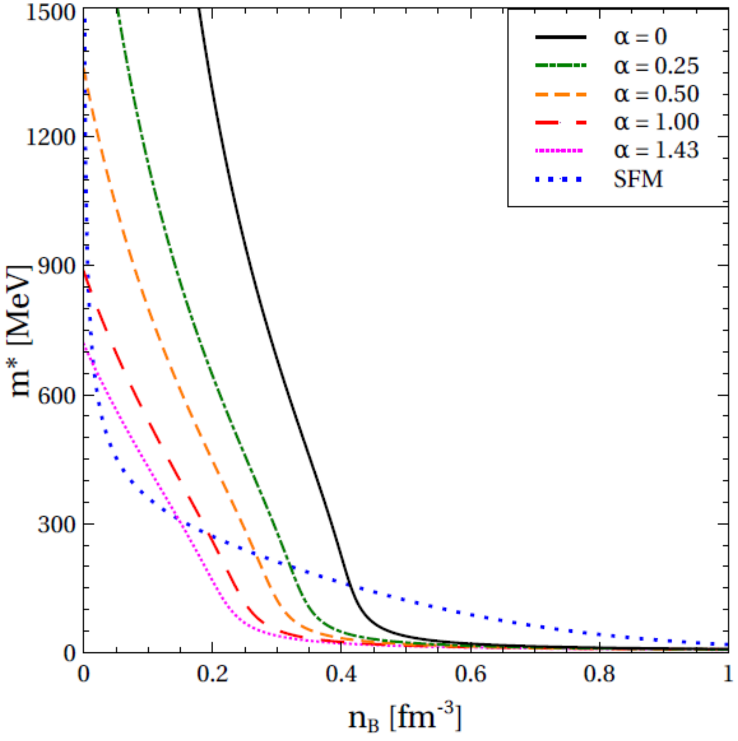
$$\Downarrow$$

$$m^* \to \infty \textbf{ at } \alpha \to 0$$

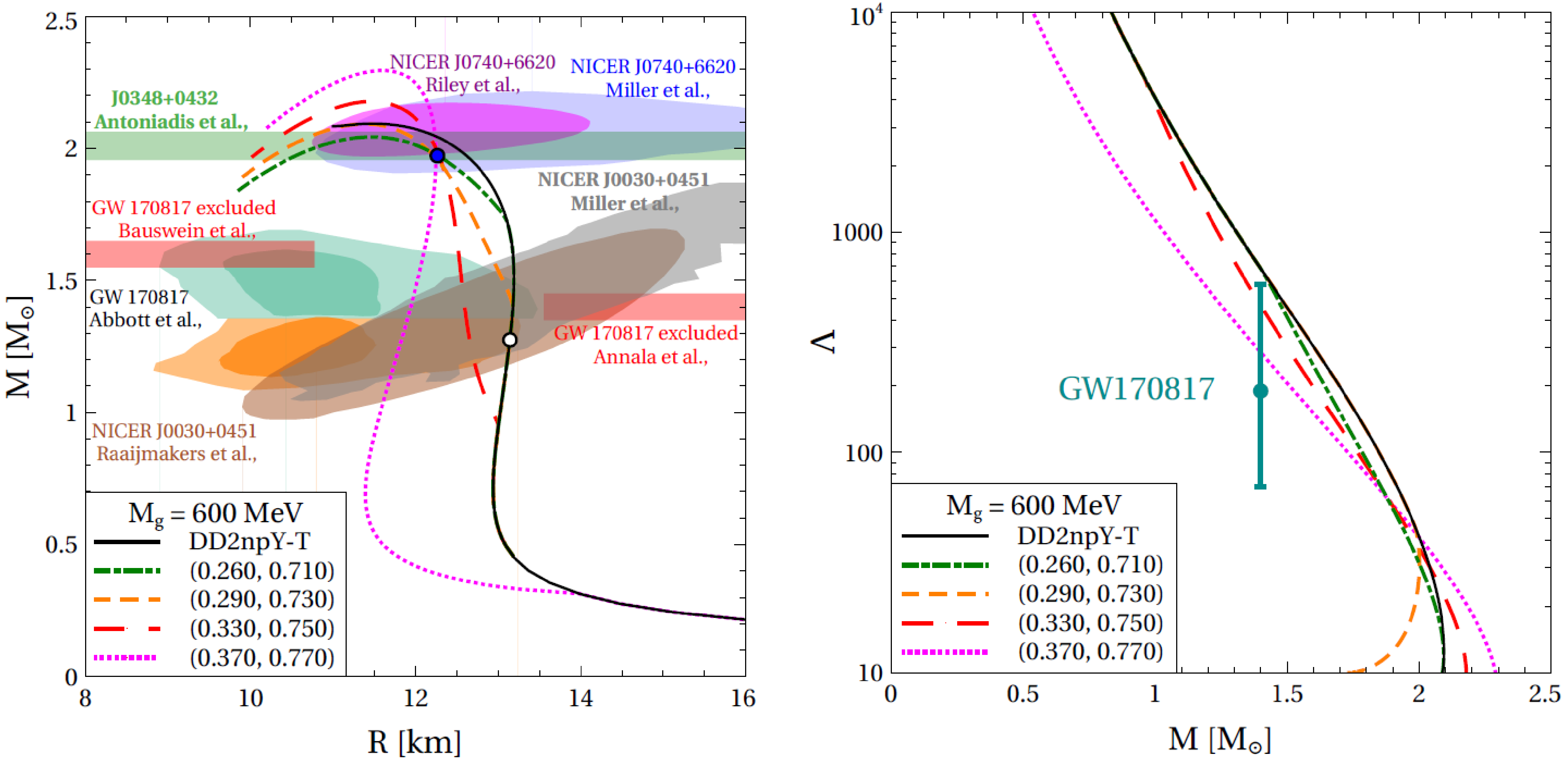
  - medium dependent couplings:

low T, μ, $\Rightarrow$ $G_S \neq G_{PS}$ $\Rightarrow$ χ-broken
high T, μ, $\Rightarrow$ $G_S = G_{PS}$ $\Rightarrow$ χ-symmetric

T = 0



Compact stars with asymptotically conformal EoS

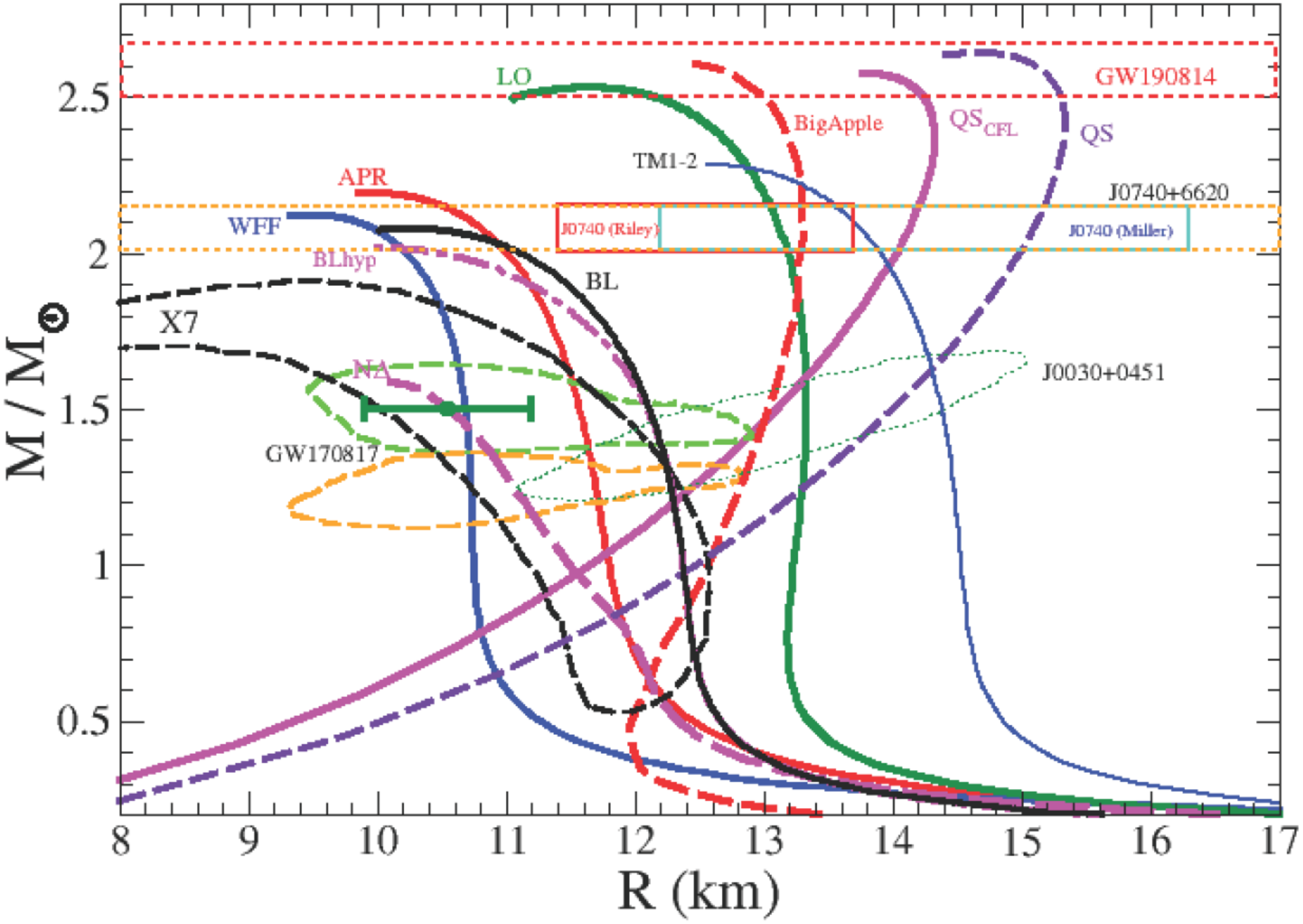


O. Ivanytskyi and D. Blaschke, arXiv:2209.02050

Strange quark stars co-existing with hadronic stars

Two-families scenario

From the talk of Bombaci



Constraints from astrophysical observations

PSR J0740+6620

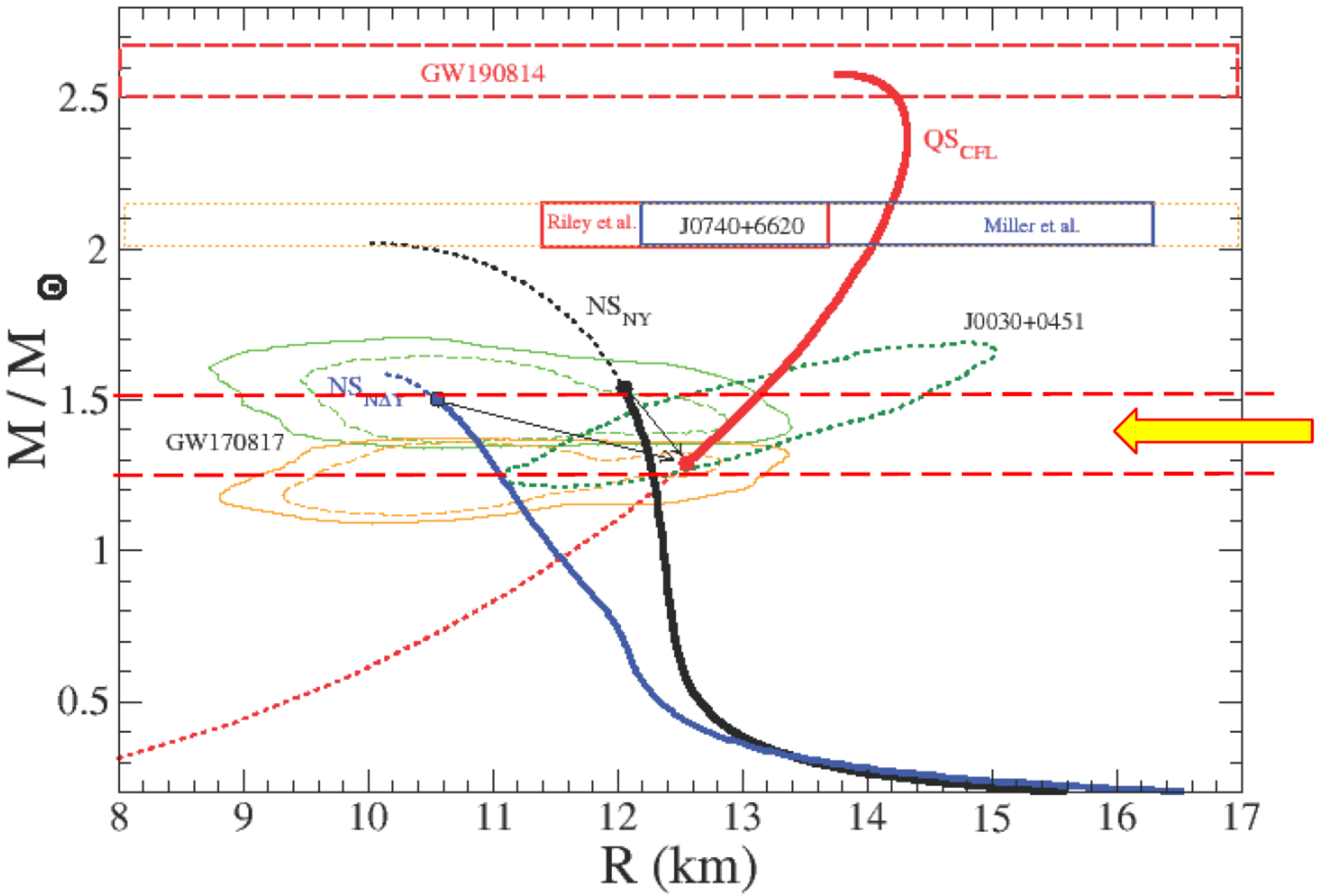
NICER data

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

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

Two coexisting families of Compact Stars

From Bombaci



An observationally testable prediction of the two-family scenario:

existence in nature of compact stars having the same mass but different radii.

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

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

Very recent:small masses?

Di Clemente et al. 2022

A better estimate of the distance of the compact object associated with the remnant of a known SN (HESS J1731-347) allows to to infer small mass and small radius.

Is the compact object associated with HESS J1731-347 a strange quark star?

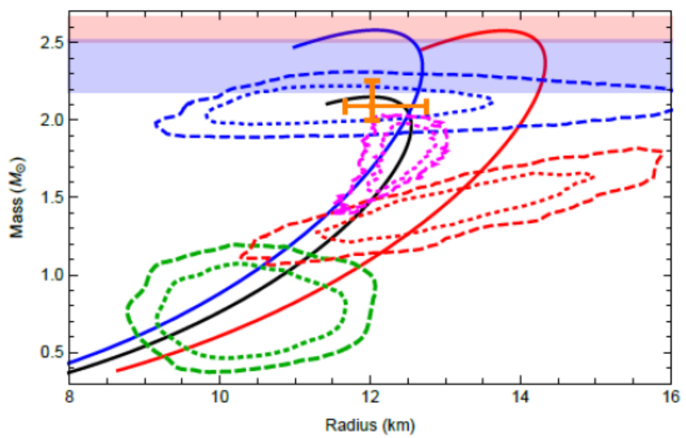


Figure Mass-radius relation of QSs from [6] (solid red), [11] (solid blue) and [12] (solid black) with observational constraints at 68% of confidence level (dotted) and at 90% (dashed). Blue: analysis of PSR J0740+6620 from NICER and XMM-Newton data from [14]. Magenta: analysis of 4U 1702-429 from [15]. Red: analysis of PSR J0030+0451 from [16]. Green: latest analysis of HESS J1731-347 from [1]. Orange error bars: analysis of 3XMM J185246.6+003317 from [17].

How are those light object formed? From SN theory we know that $M_b > 1.28 M_{sun}$

$M_b\,(M_\odot)$	$M_g^{NS}\,(M_\odot)$	$M_{g,A}^{QS}\,(M_\odot)$	$M_{g,B}^{QS}\,(M_\odot)$	$M_{g,C}^{QS}\,(M_\odot)$
1.28	1.17	0.99	1.00	0.95 – 1.05
1.32	1.20	1.01	1.03	0.98 – 1.08

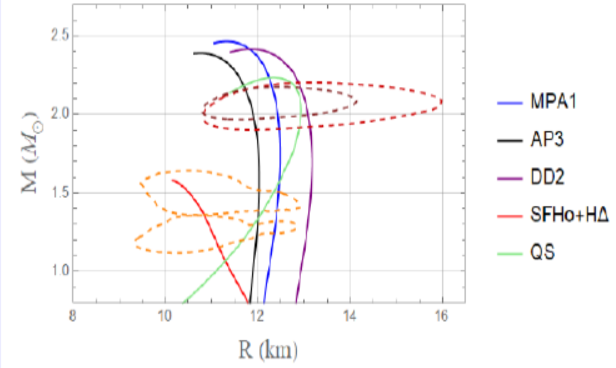
Table Minimum allowed mass for NSs and for QSs in three models. *A* refers to the EoS in [6] (solid red line in the Figure). *B* refers to a EoS derived in [11] (solid blue line). *C* refers to the most probable EoS having a constant speed of sound and is obtained from the bayesian analysis in [12] which does not include the most recent data on massive stars (solid black line). In the latter case a range of values is indicated, since the BE is not fixed by the bayesian analysis. The chosen values correspond to an energy per baryon of strange quark matter at zero pressure of $(E/A)_{p=0} = (765 - 850)$MeV, in agreement with the discussion in [13].

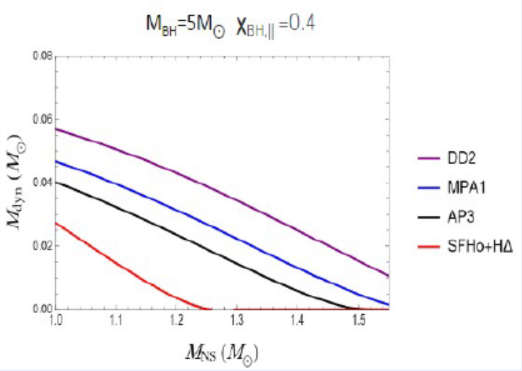
Again: the large binding energy of quark stars could help in explaining such small masses.

Merger of a Neutron Star with a Black Hole: one-family versus two-families scenario

Francesco Di Clemente, Alessandro Drago, Giuseppe Pagliara, 2022, *The Astrophysical Journal*, **929** 44

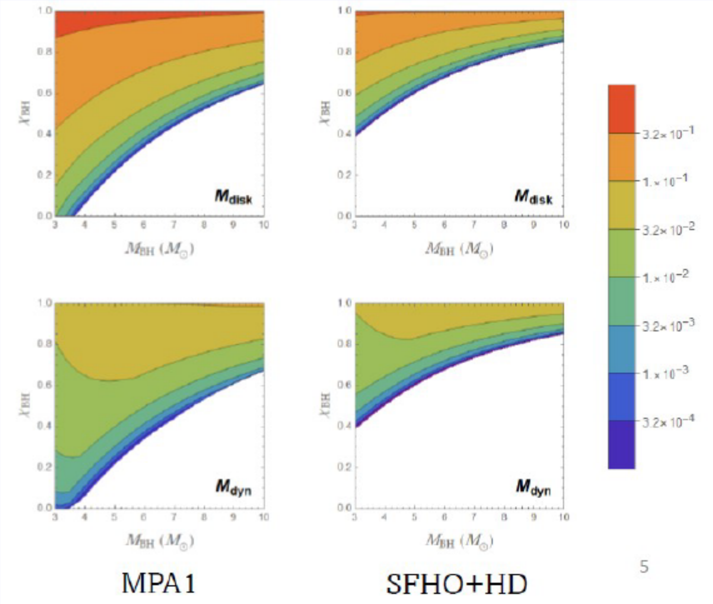
To date, 2 BH-NS mergers with no EM counterpart, but the expected upcoming events will represent an alternative way to test the EoS. The mass dynamically ejected in such a system depends on the spin and the mass of the BH and the simulation results are rather stable (it is “simpler” wrt to the double NS). As a general rule the smaller the radius the smaller the mass dynamically ejected, the fainter the kilonova signal.





Annual number of detections

O3 13^{+15}_{-9} O4 72^{+75}_{-38}.



Possible signature: a closeby merger (say 200Mpc) with no kilonova would be compatible with the two-families scenario.

- Astrophysical data are still too uncertain to drive to any conclusion: while a few data can be interpreted by using the “minimal” model, other data suggest possibilities inconsistent with that scheme.

  → better data will come soon from GWs, X-rays, radio-telescopes

- It is important to proceed both to:
  - clarify as much as possible the possibilities and the limits of the “minimal” model
  - propose clear signatures of “non-minimal” components and suggest interpretative schemes of observations which, if confirmed, are not compatible with the “minimal” model
- We are entering a very exciting era: data from labs (hypernuclei, hadron and nuclear production at colliders), data from astrophysics (properties of compact stars and explosive phenomena), data from cosmology (nature of dark matter, evolution of early galaxies), lattice QCD results and QCD inspired models of quark dynamics, all these data and analyses will contribute to provide a coherent description of matter under extreme conditions.