Strangeness in compact stars

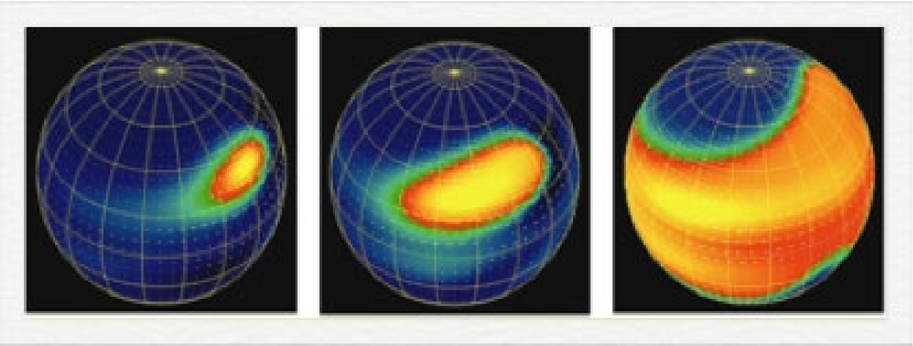
Alessandro Drago
University of Ferrara and INFN sez. Ferrara

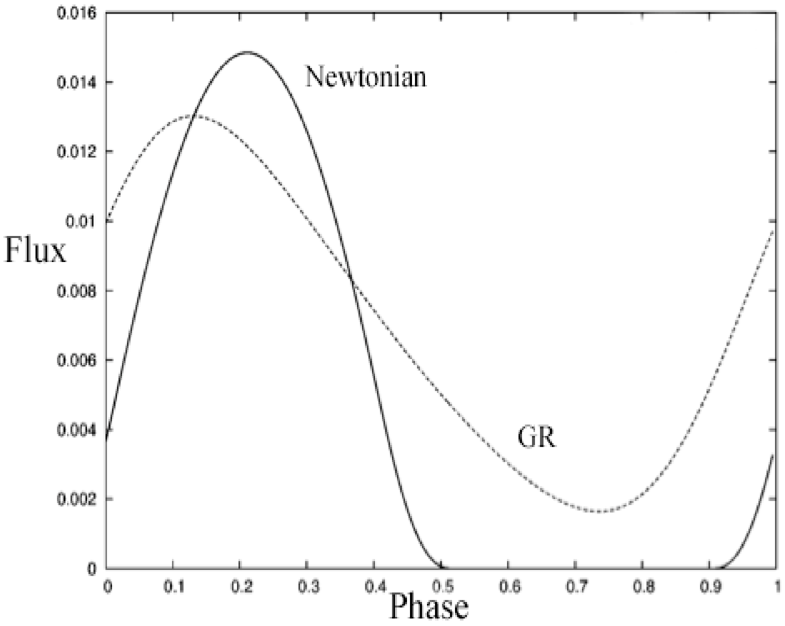
Outline of the talk

- The results from NICER and the limits from GW170817
- A «simple» model
  - The role of strangeness: hyperons and kaon condensation
- Other more controversial data
  - Small radii, very large masses, kilonova signals
- An alternative explanation, the two-families scenario: strange quark stars co-existing with neutron stars
  - The role of strangeness: hyperons (and kaons) as triggers of deconfinement to strange quark matter
- Conclusions and outlook

NICER (and eXTP)

A new way of measuring M and R
from rapidly spinning compact stars with a hot spot, based on GR corrections of the signal (M/R) and on Doppler effect (R)





Main results from NICER observations of PSR J0740+6620 and of PSR J0030+0451

PSR J0740+6620 $M=2.072\ (+0.067; -0.066)\ M_s$

Miller et al. $R = 13.7\ (+2.6; - 1.5)$ km arXiv:2105.06979

Riley et al. $R = 12.39\ (+1.30; -0.98)$ km arXiv:2105.06980

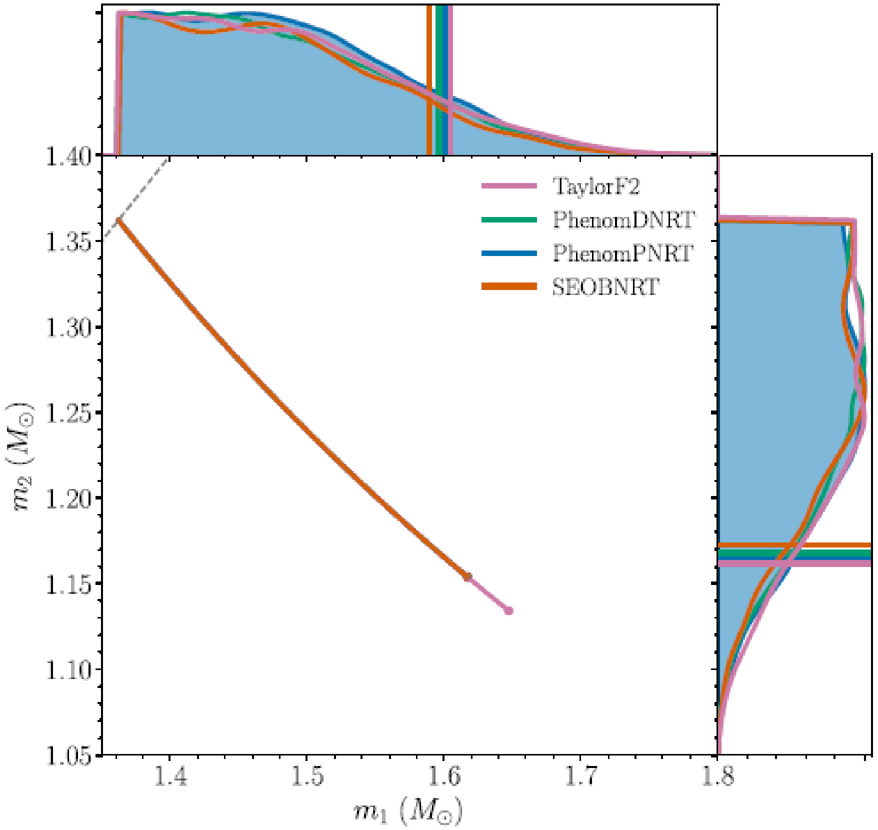
PSR J0030+0451 $M/R = 0.156\ (+0.008; - 0.010)$

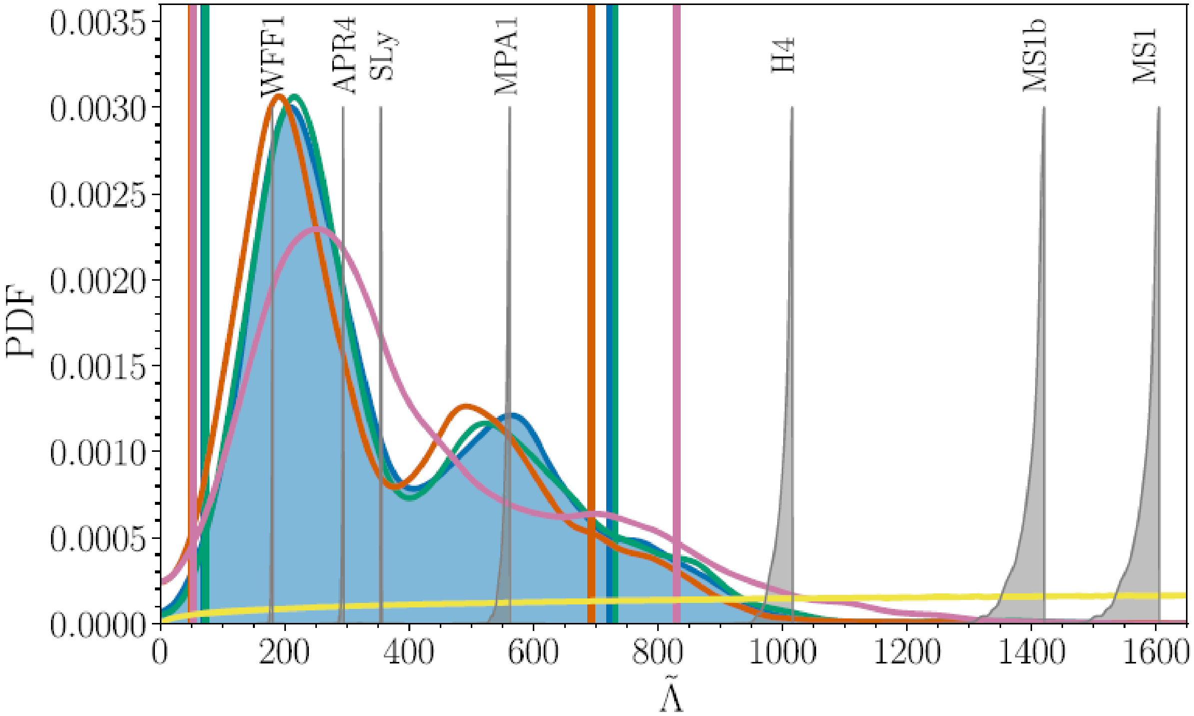
Miller et al. $R = 13.02\ (+1.24; -1.06)$ km $M = 1.44\ (+ 0.15; - 0.14)\ M_s$ ApJ 887 (2019)L24

Riley et al. $R = 12.71\ (+1.14; -1.19)$ km $M = 1.34\ (+ 0.15; - 0.16)\ M_s$ ApJ 887 (2019)L21

GW170817: the first NS-NS merger

masses estimated from chirp mass (combination of m_1 and m_2),
radius from tidal deformability

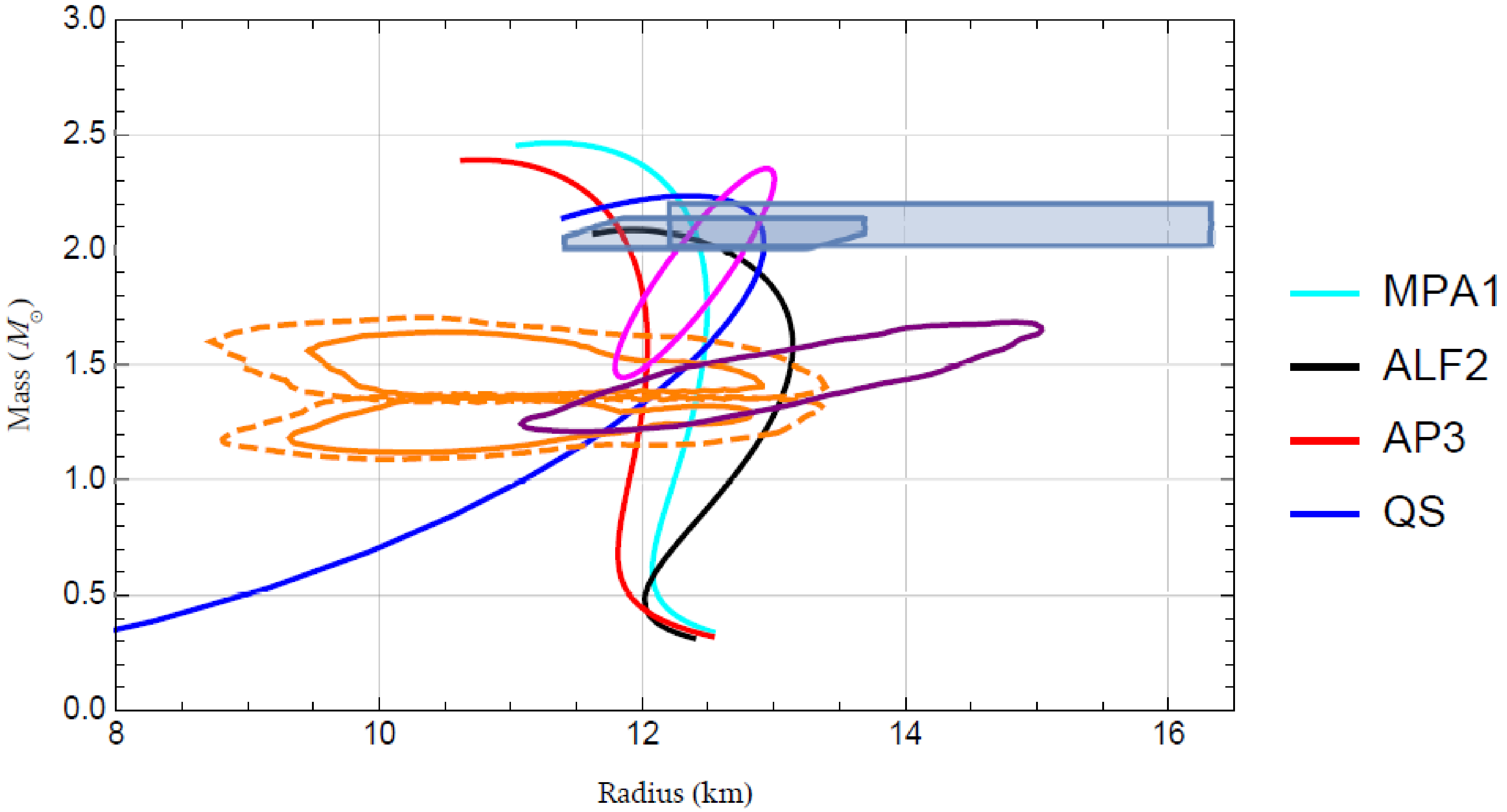




a 1.36 $M_\odot$ NS has a radius of 10.4 km (WFF1), 11.3 km (APR4), 11.7 km (SLy), 12.4 km (MPA1), 14.0 km (H4), 14.5 km (MS1b), and 14.9 km (MS1).

A combined analysis of few astrophysical data:

NICER PSR J0740+6620 and of PSR J0030+0451
GW170817 (from tidal deformability)
4U 1702-429 (Nattila et al.)



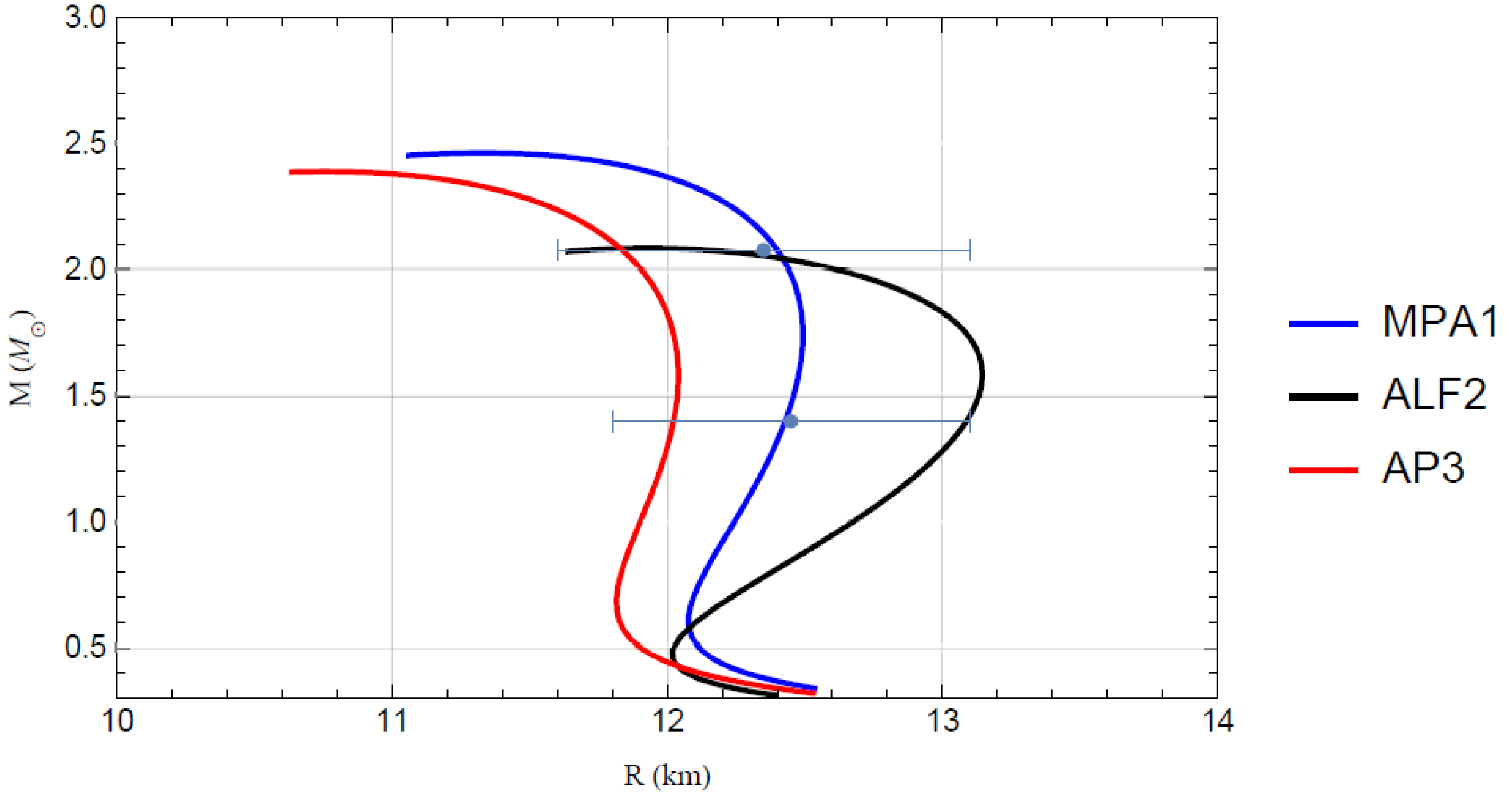
A “simple” model:

combined analysis of the two NICER results and of GW170817 assuming the NS has a crust as described by theory up to 0.5 ρ_0

Miller et al. :

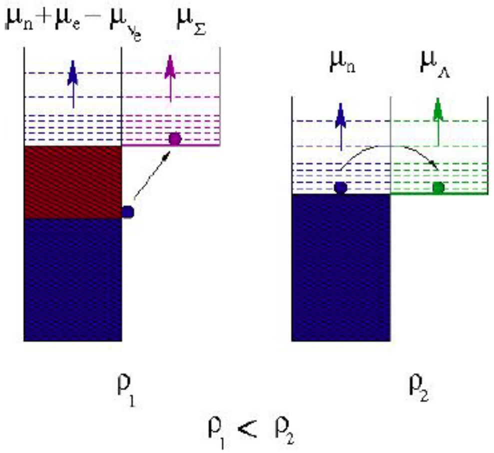
R = 12.45 +/- 0.65 km M = 1.4 M_s

R = 12.35 +/- 0.75 km M = 2.08 M_s



How to produce hyperons?
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.



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

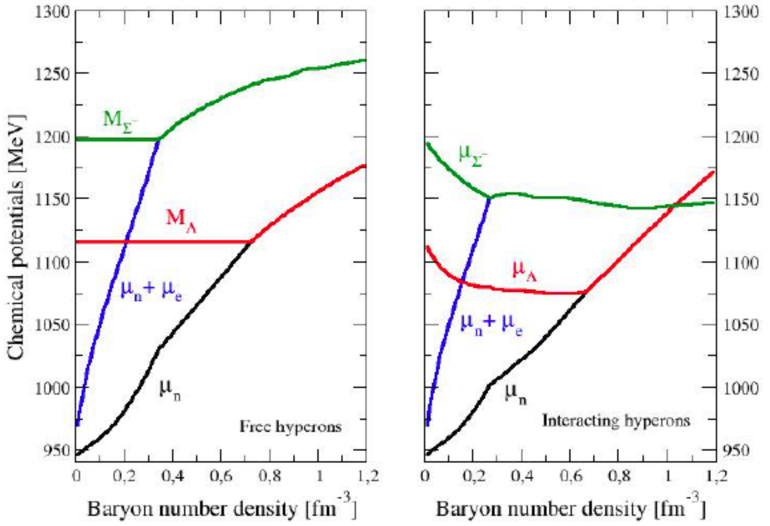
$$\mu_\Lambda = \mu_n$$

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

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

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

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

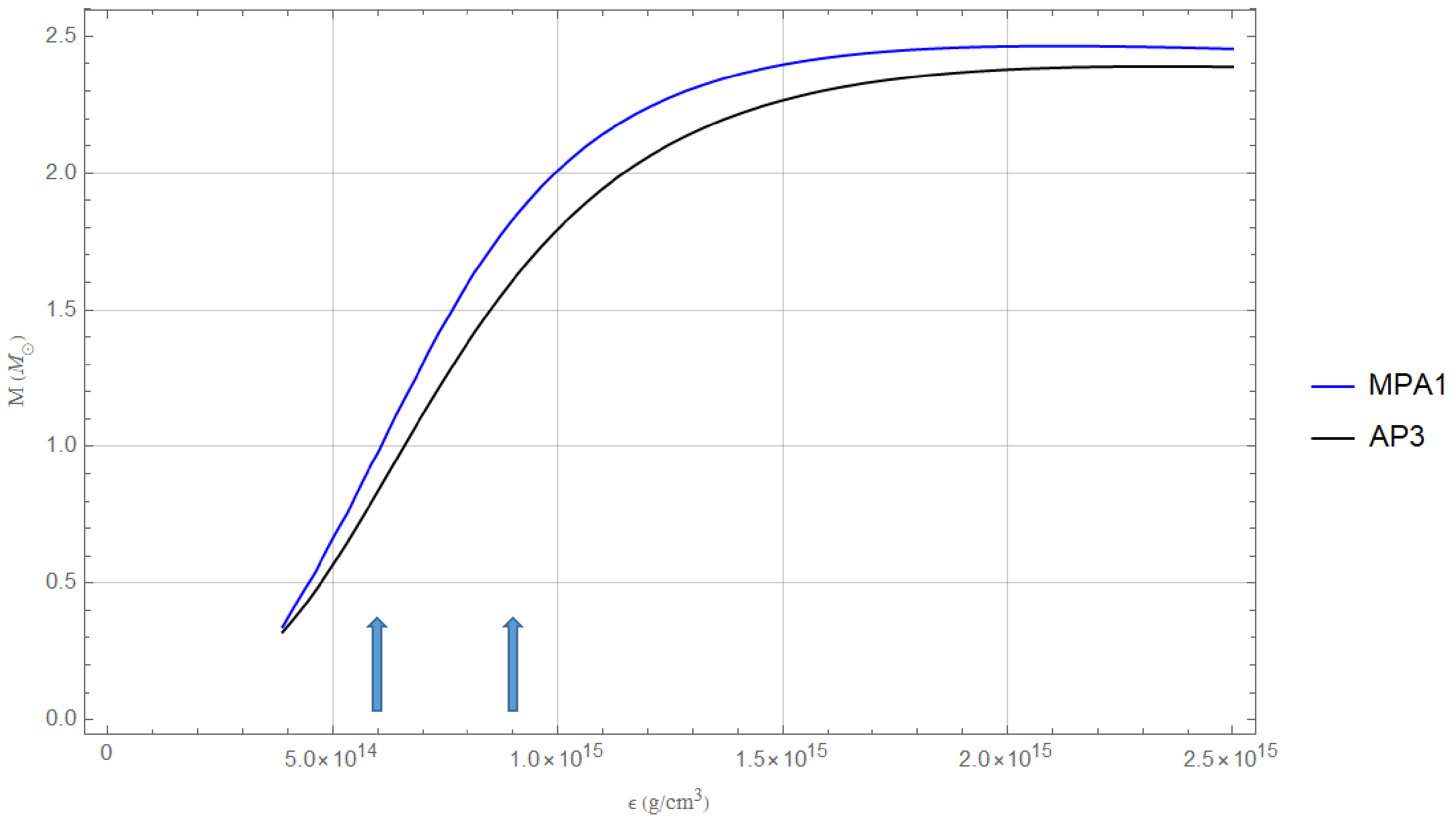


The production of strangeness

MPA1 and AP3 are purely nucleonic EoSs, but very large densities are reached at least for the most massive stars

The central densities exceed 2-3 ρ_0 at least for the most massive stars:

→ Hyperons should be produced

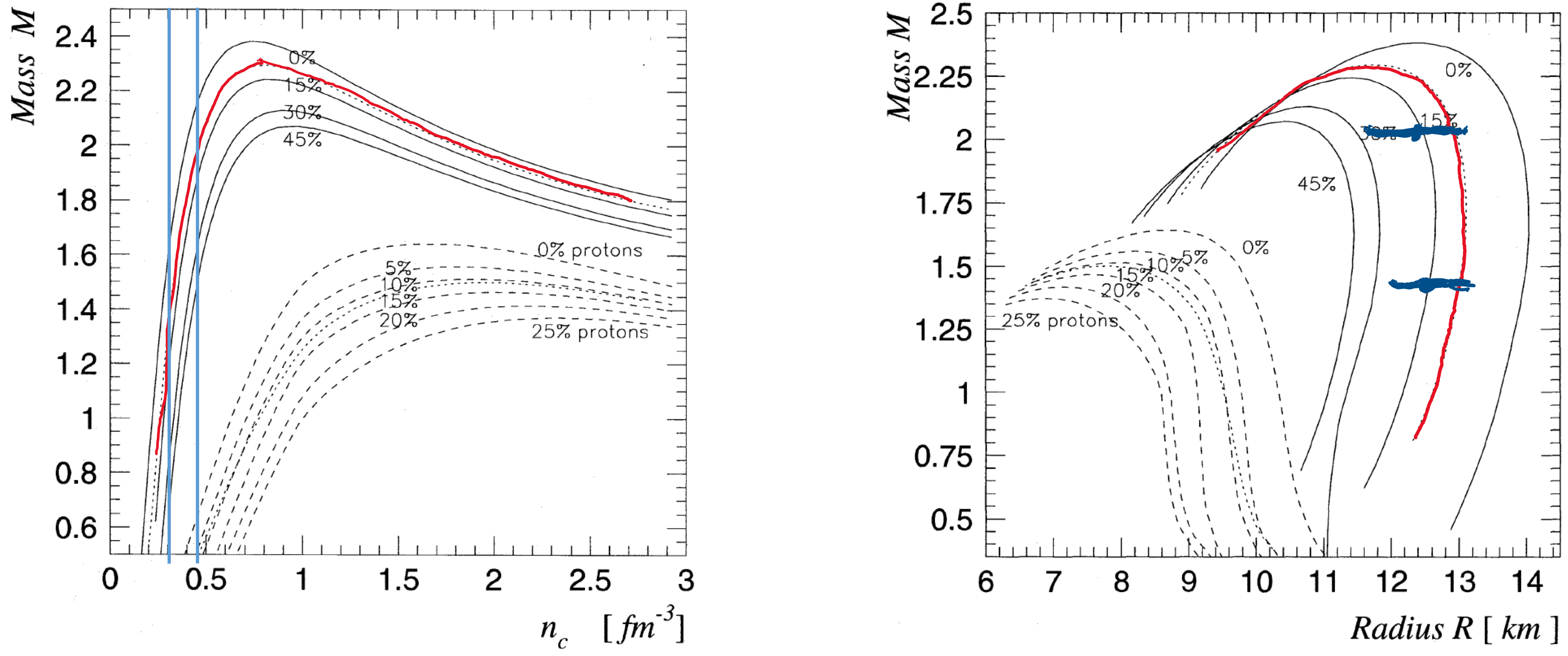


The production of strangeness

Another example close to the largest R indicated by the analysis of Miller et al. arXiv:2105.06979.

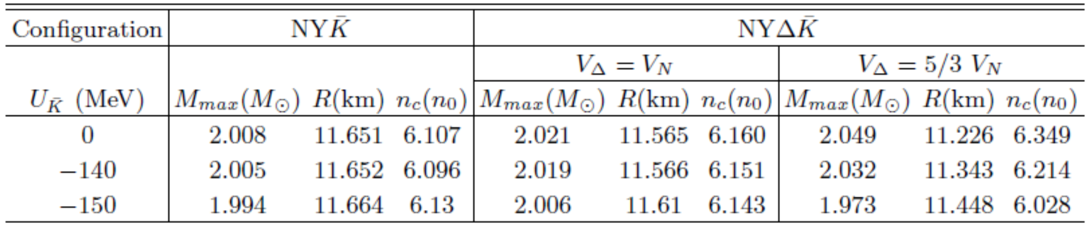
Also in this case hyperons should appear at least for the most massive stars.

Engvik et al. ApJ L469 (1996) 794



Example of an EoS satisfying the "simple" limits and including Δ resonances, hyperons and kaons

Thapa, Sinha, Li, Sedrakian, arXiv:2102.08787



Configuration	NY$\bar{K}$			NY$\Delta\bar{K}$					
				$V_\Delta = V_N$			$V_\Delta = 5/3\ V_N$		
$U_{\bar{K}}$ (MeV)	$M_{max}(M_\odot)$	R(km)	$n_c(n_0)$	$M_{max}(M_\odot)$	R(km)	$n_c(n_0)$	$M_{max}(M_\odot)$	R(km)	$n_c(n_0)$
0	2.008	11.651	6.107	2.021	11.565	6.160	2.049	11.226	6.349
−140	2.005	11.652	6.096	2.019	11.566	6.151	2.032	11.343	6.214
−150	1.994	11.664	6.13	2.006	11.61	6.143	1.973	11.448	6.028

Hyperons are produced at densities of 2-3 ρ_0. Kaon condensation can also take place if the (anti-)kaon attractive potential exceeds about 140 MeV.

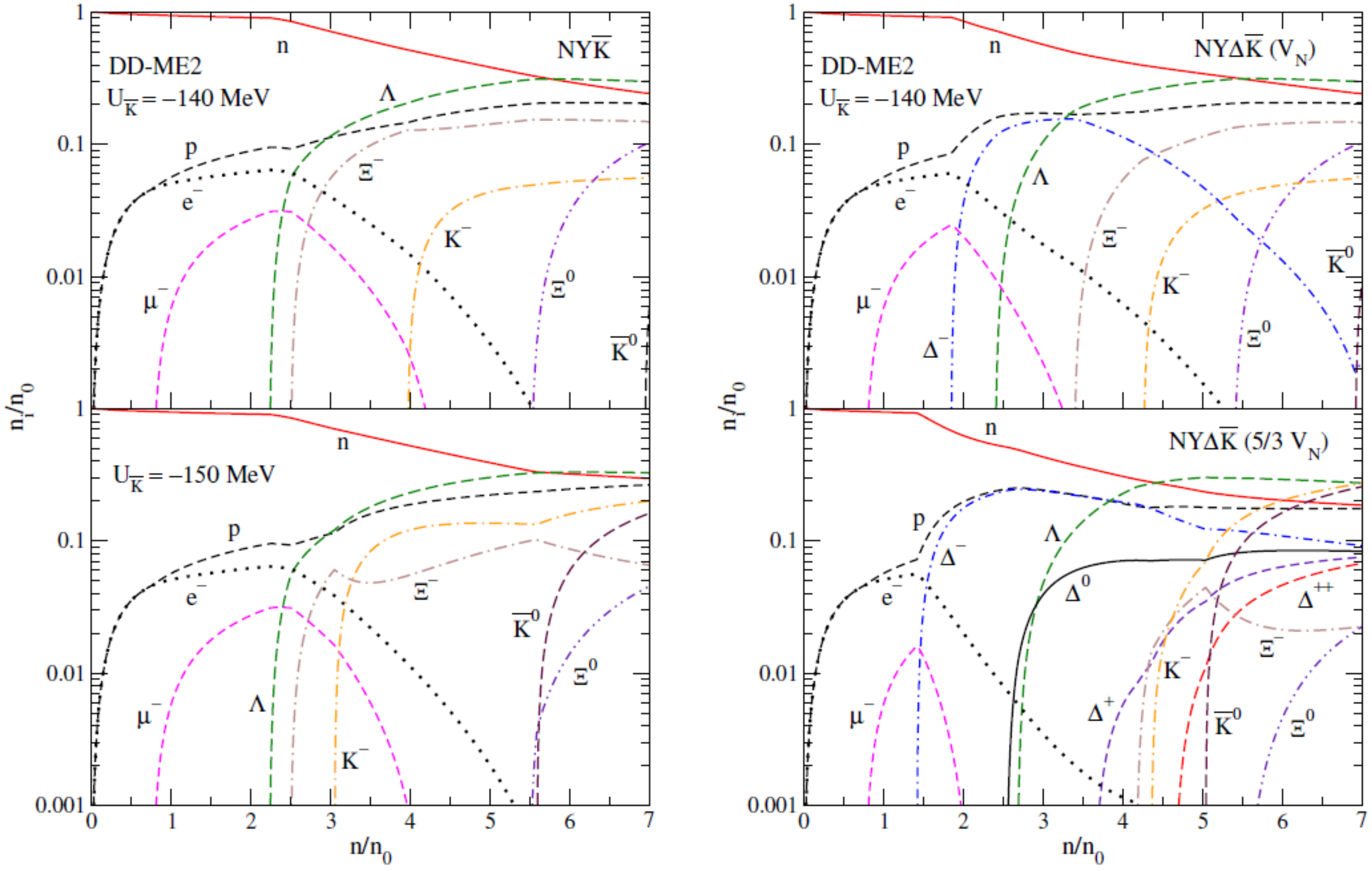
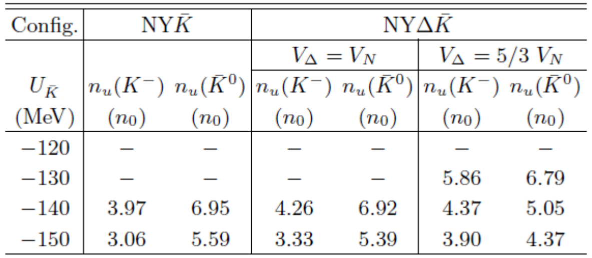


TABLE V. Threshold densities, n_u for (anti)kaon condensation in NY and NYΔ matter for different values of Δ-potentials and K^- optical potential depths $U_K(n_0)$.

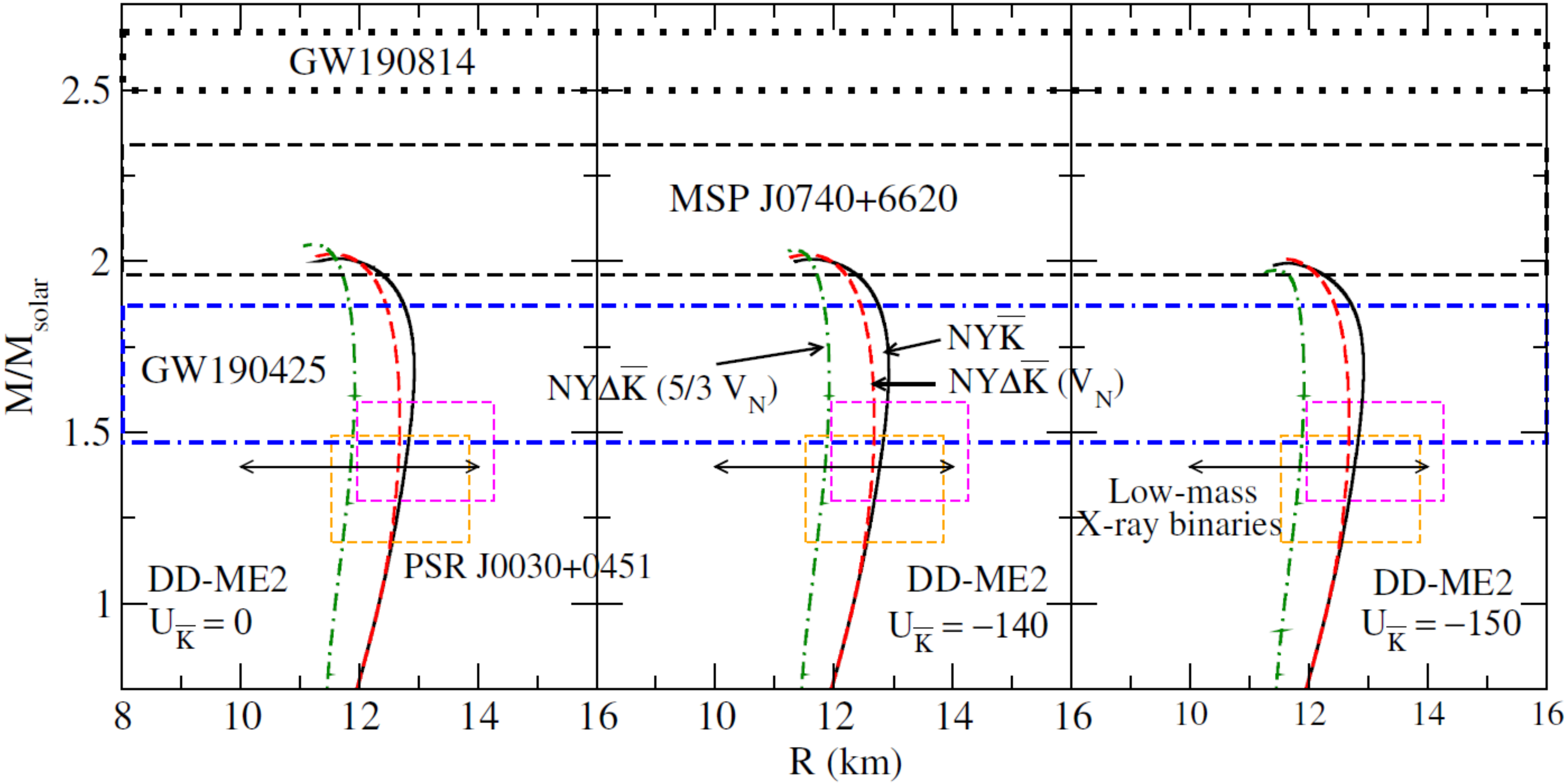


Config.	NY$\bar{K}$		NY$\Delta\bar{K}$			
			$V_\Delta = V_N$		$V_\Delta = 5/3\ V_N$	
$U_{\bar{K}}$ (MeV)	$n_u(K^-)$ (n_0)	$n_u(\bar{K}^0)$ (n_0)	$n_u(K^-)$ (n_0)	$n_u(\bar{K}^0)$ (n_0)	$n_u(K^-)$ (n_0)	$n_u(\bar{K}^0)$ (n_0)
−120	–	–	–	–	–	–
−130	–	–	–	–	5.86	6.79
−140	3.97	6.95	4.26	6.92	4.37	5.05
−150	3.06	5.59	3.33	5.39	3.90	4.37

Example of an EoS satisfying the “simple” limits and including Δ resonances, hyperons and kaons

Miller et al. limits are well satisfied.

Notice that **the maximum mass cannot significantly exceed about 2 M_s**



Properties of dense matter, such as viscosity, thermal and electrical conductivity strongly depend on the composition.

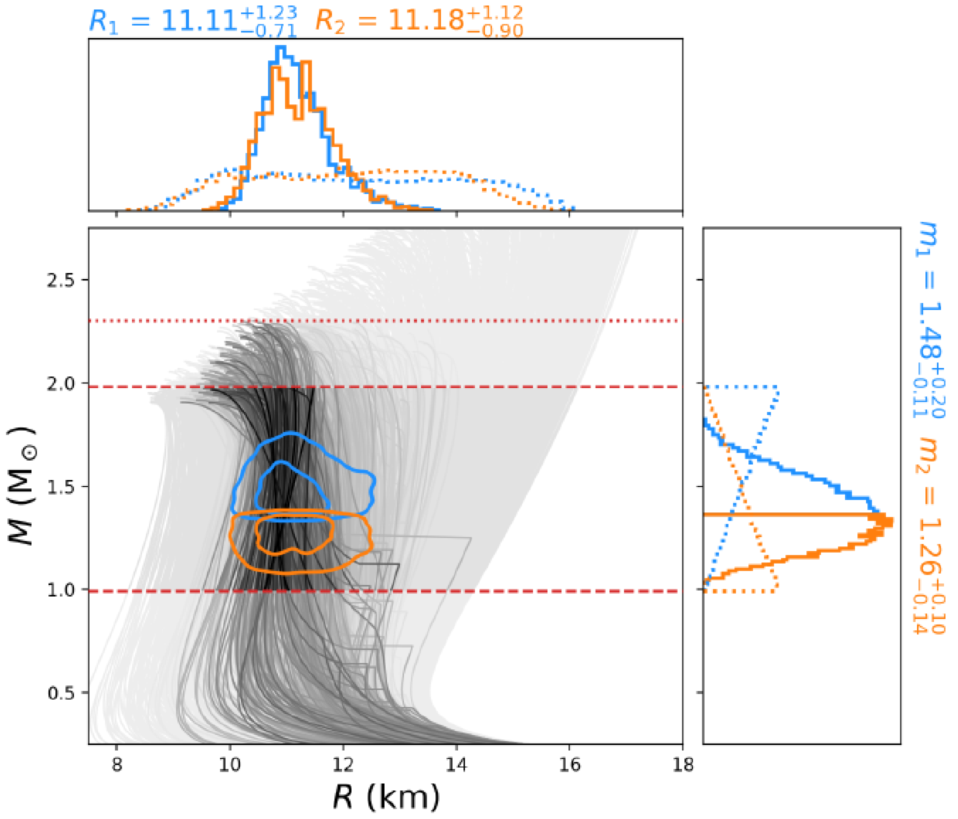
Connection with nuclear/hadronic physics

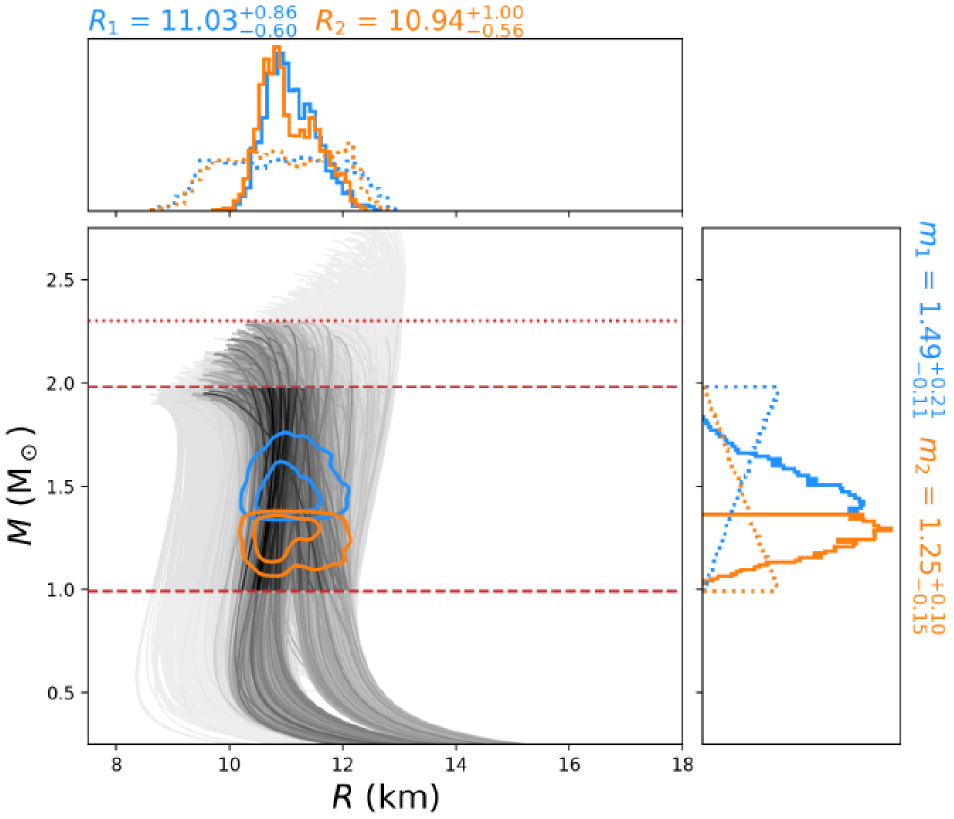
Crucial role played by:

- Symmetry energy at about 2 ρ_0
- Δ nuclear potential
- kaon optical potential
- Hyperons nuclear potential
- Hyperon-hyperon interaction
- σ^* meson

All clear then? A few controversial data: small radii from GW170817 if the maximum mass is limited to be less than 2.3 M_s and using theory up to 1-2 ρ_0

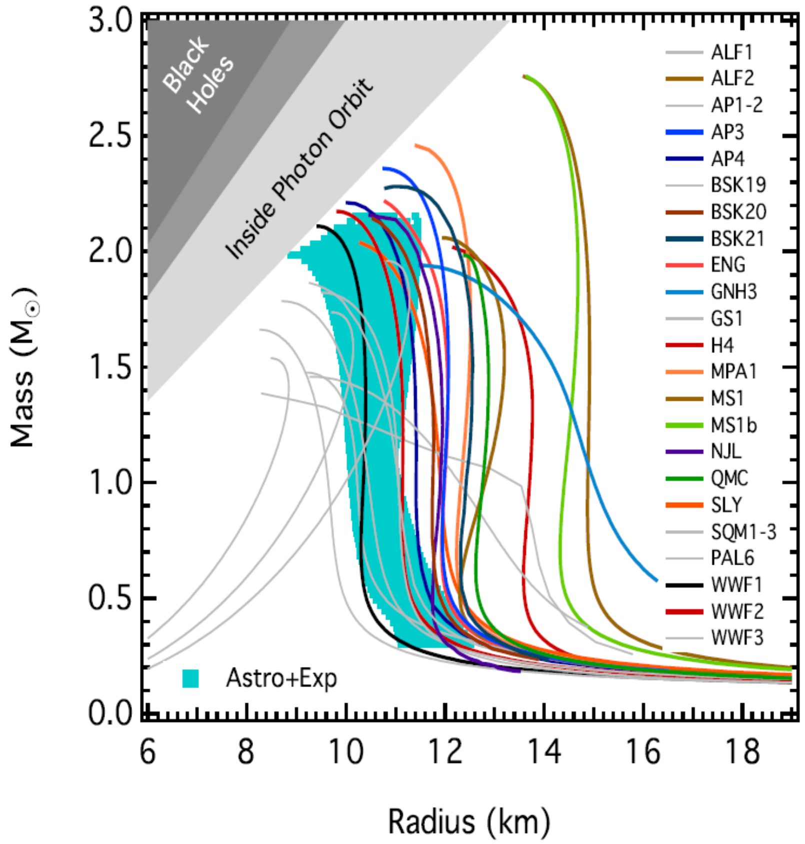
Capano et al. Nature Astronomy 4 (2020) 625





Small radii from x-ray spectra

Oezel and Freire,
Ann.Rev.Astron.Astrophys. 54 (2016) 401



Steiner et al. MNRAS 476 (2018) 412
«Our model with the largest evidence suggests that $R_{1.4}$ is less than 12 km to 95 percent of confidence»

d’Etivaux et al. ApJ 887 (2019) 48
“In our analysis, we have shown that without nuclear physics inputs, the constant-RNS approximation prefers radii around ~11.1 +/- 0.4 km “

Was GW190814 a black-hole neutron star system? Tension with nuclear physics and with small radii

The gravitational wave signal GW190814 has been generated by the merger of a binary system whose components are a 23M_s black hole and a (2.5-2.67)M_s compact object.

R. Abbott et al. (LIGO Scientific, Virgo), Astrophys. J.Lett.896, L44 (2020), 2006.12611

If we assume M_{max} = 2.5M_s, the causal limit is strictly violated for $R_{1.4}$ = 11.38 km, and if we assume M_{max}=2.6M_s, the causal limit is strictly violated for $R_{1.4}$ = 11.8 km.

Godzieba, Radice, Bernuzzi, Astrophys.J. 908 (2021) 122

EOSs which allow for the existence of such massive NSs are in tension with constraints obtained from heavy-ion collisions experiments and from the tidal deformability constraints derived from GW170817 which favor softer EOSs.

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

NS-BH kilonova signal

Strong kilonova expected if the radii are large, no signal detected up to now: the signal is suppressed if the radii are small

Di Clemente, Drago, Pagliara, in preparation

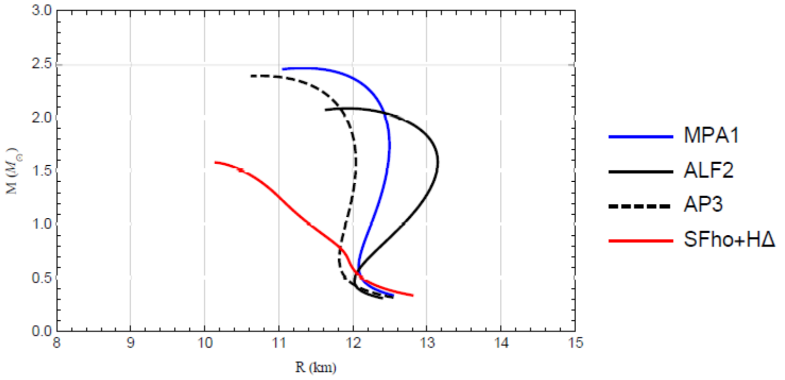
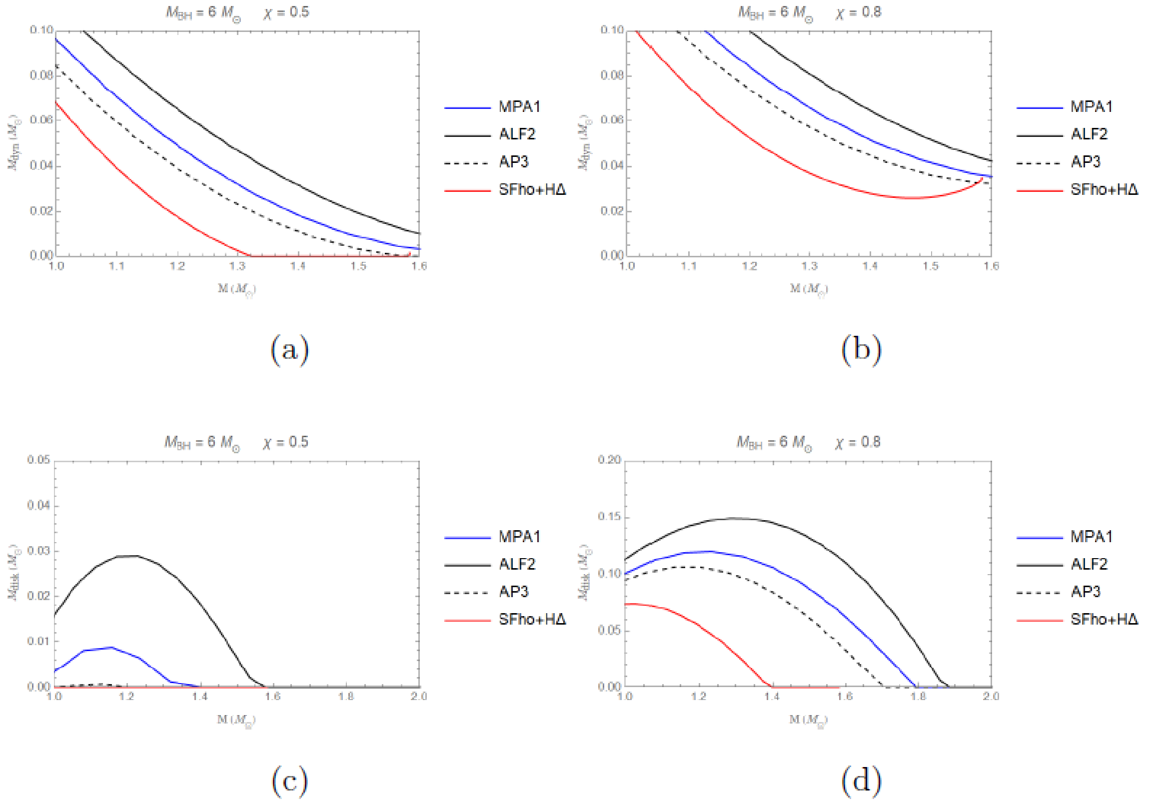


Figure 1: Mass-Radius diagram for four different EoS



(a) (b)

(c) (d)

Figure 7: Plots of dynamical ejected mass and of the mass of the disk as a function on NS masses, for a $6\,M_\odot$ BH for two values of BH spin, $\chi = 0.5$ and $\chi = 0.8$. (a), (b) are relative to the dynamical ejected mass and (c), (d) the mass of the disk

Deconfined quark matter in compact stars?

- A mixed phase of hadrons and quarks is soft
- A pure phase of quarks can be very stiff

Hybrid stars: compact stars containing pure or mixed quark matter in the interior

Strange quark stars: compact stars made almost entirely of quark matter (their existence is based on Witten’s hypothesis).

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

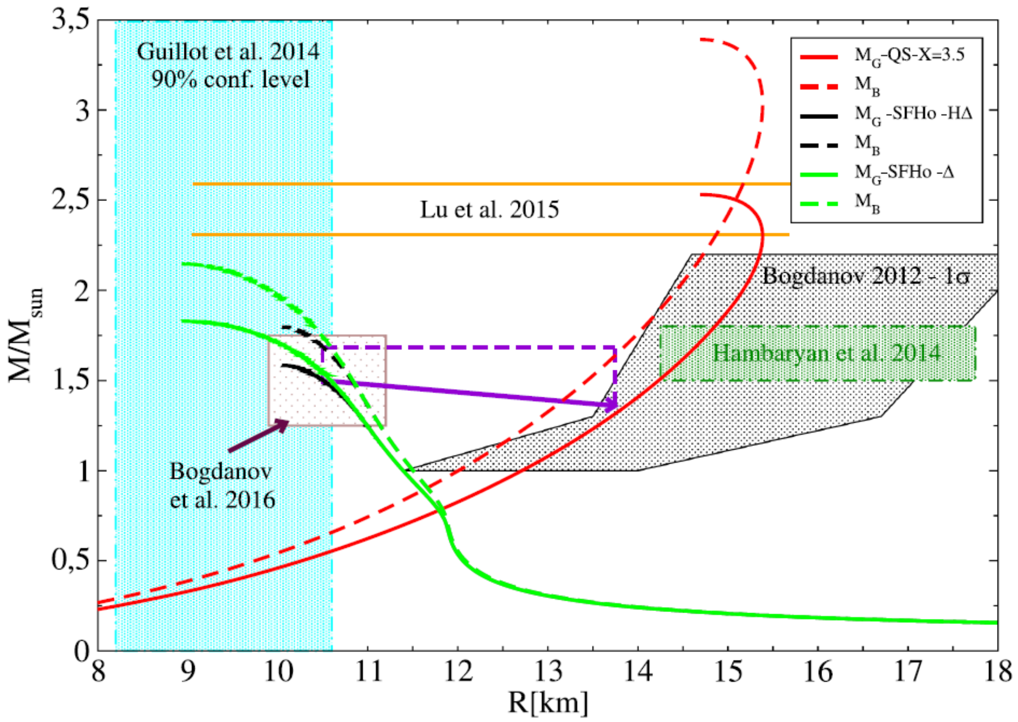
The Strange Matter hypothesis

Strange Stars

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

Models with a strong phase transition: two-families of compact stars
Stars made of hadrons co-exist with stars made of strange quark matter

A. Drago, A. Lavagno, G. Pagliara, Phys. Rev. D89 (2014) 043014
G. Wiktorowicz, A.Drago, G. Pagliara, S. Popov; Astrophys. J. 846 (2017) 163



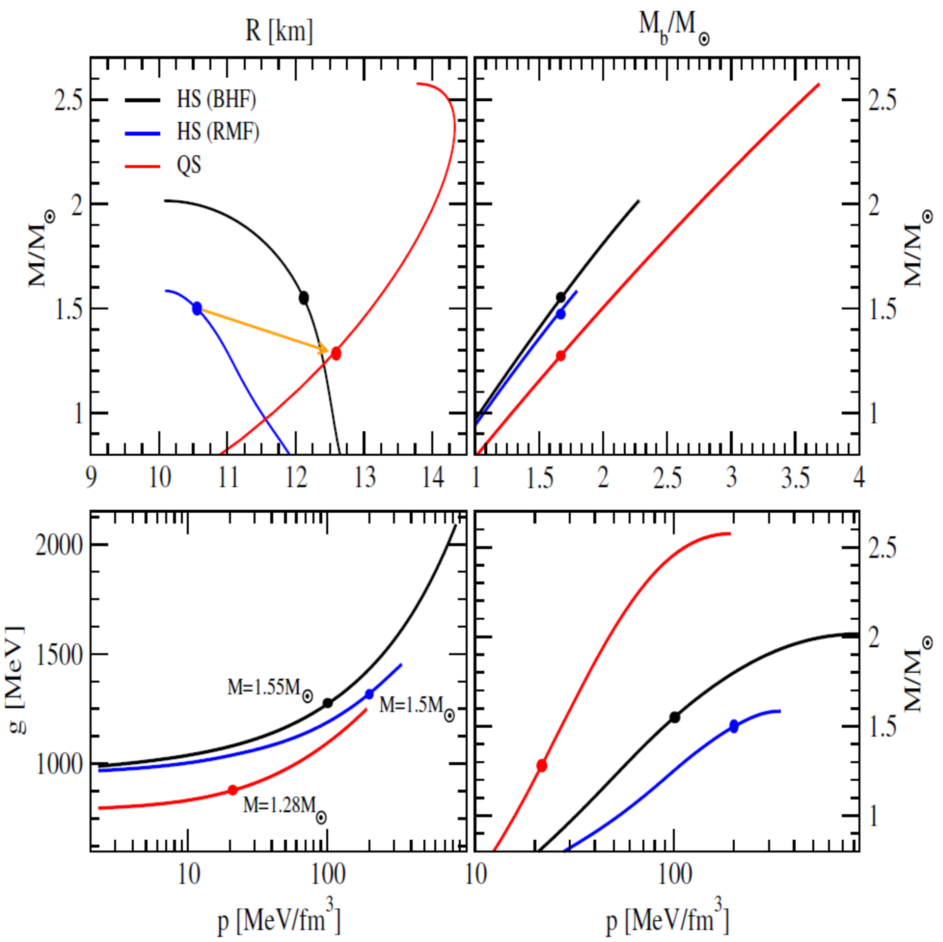
The existence of strange quark stars is based on the validity of the validity of the Witten's hypothesis, telling that the absolute ground state of matter is made of a mix of deconfined up, down and strange quarks.

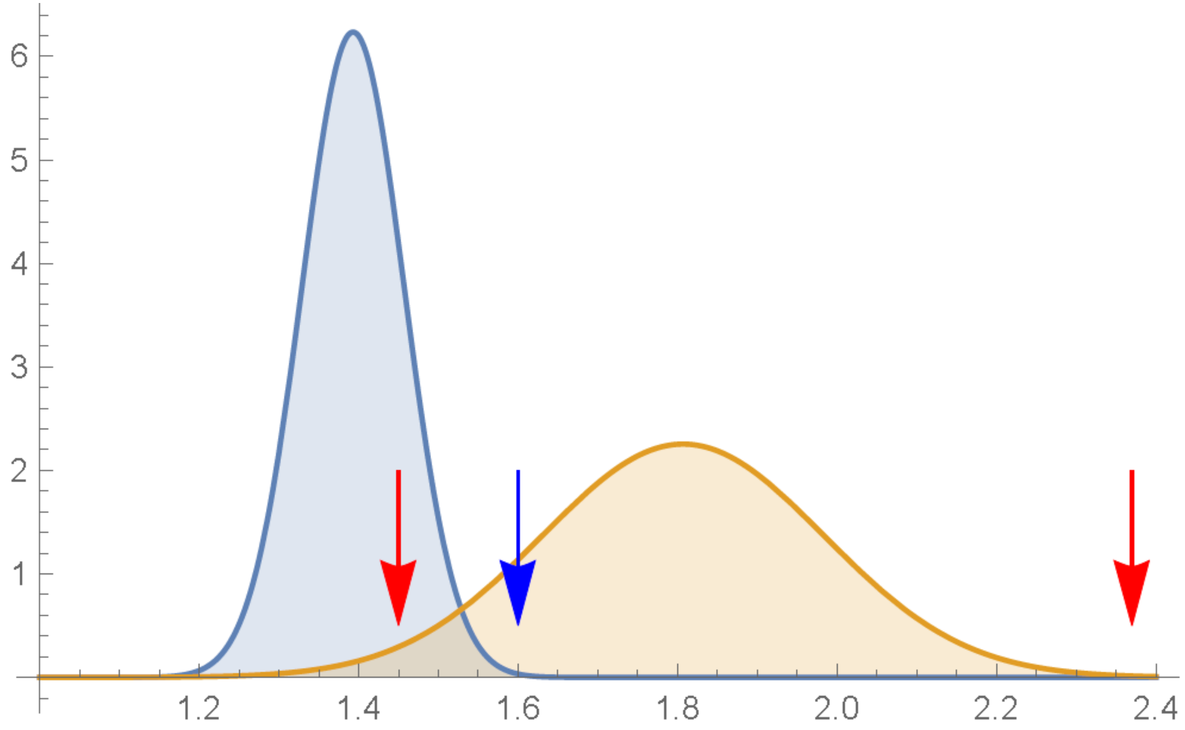
The velocity of sound in quark matter need not to be close to 1 in this scheme.

Massive stars have larger radii, at variance with models based on one family and with the twin stars scenario.

The process of quark deconfinement is triggered by the formation of a large hyperon content (or maybe by kaon condensation) at the center of the hadronic star.

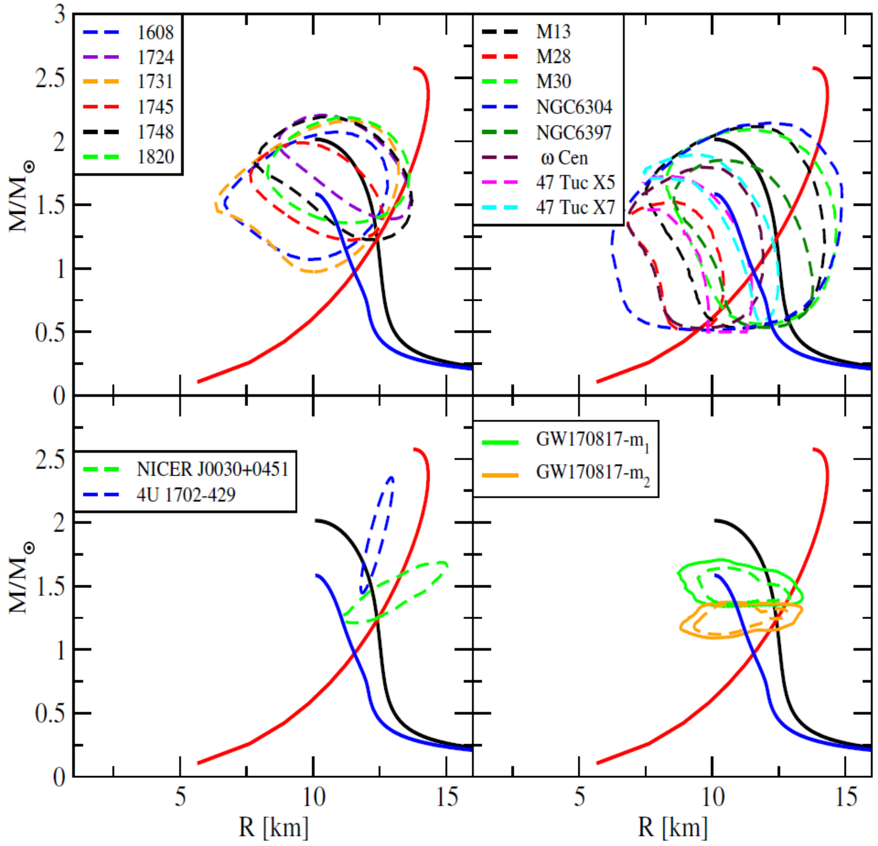
Evidence of bimodality in the mass distribution of MSPs with a WD companion (from Antoniadis et al. 2016 and Tauris et al. 2017) compared with the two-families scenario





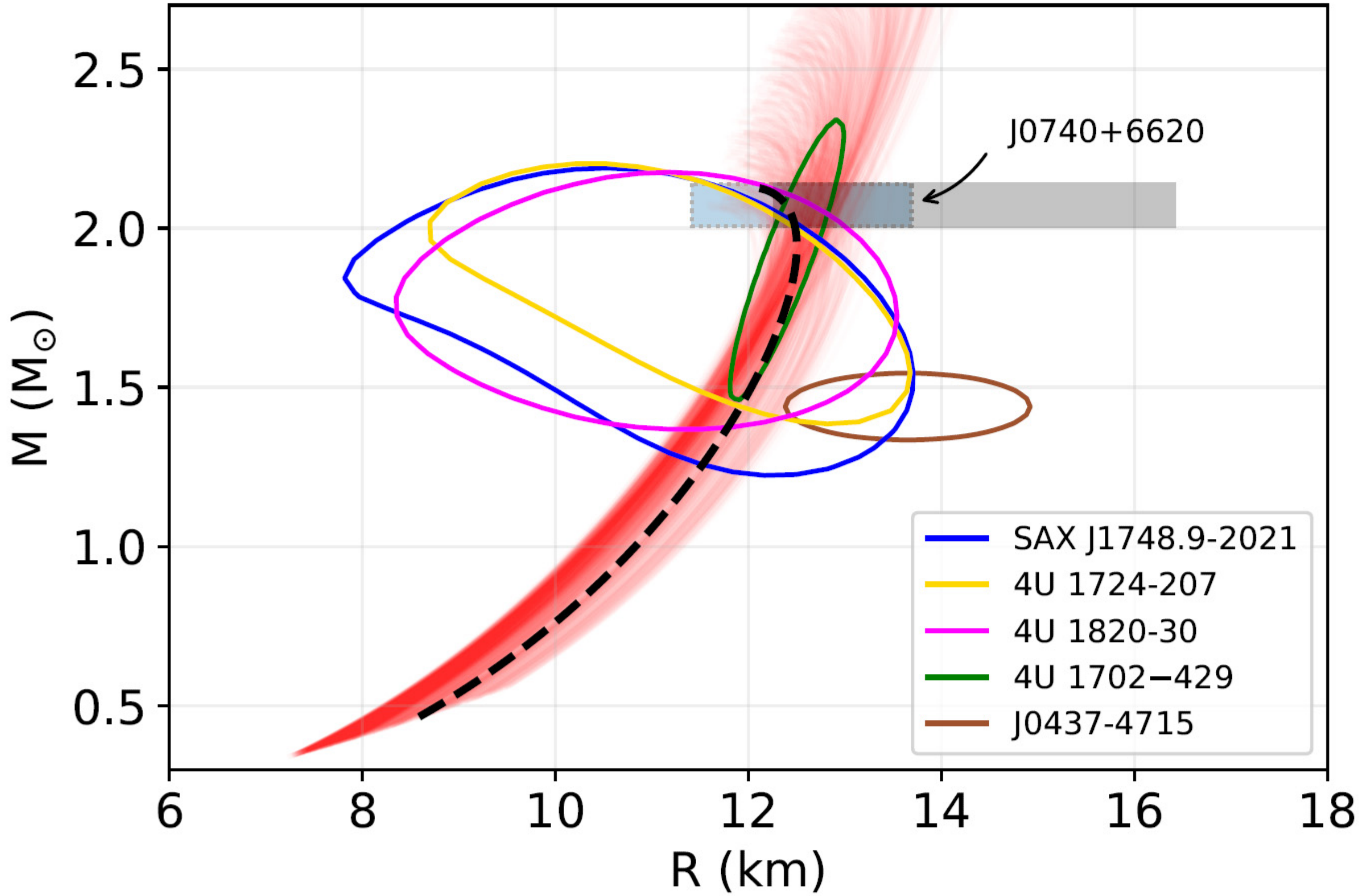
Was GW190814 a black-hole strange quark star system?

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



NICER analysis of J0740+6620 suggests a rather stiff EOS: a QS satisfies perfectly that request. Analysis NOT based onto J0740+6620, whose radius is predicted

Traversi, Char, Pagliara, Drago, in preparation



Conclusions and tests from masses, radii and moments of inertia and from GWs analysis

New measurements of masses and radii challenge nuclear physics:
tension between high mass and small radii. The new analysis from NICER increases this tension.
A 2.4 M_s candidate already exists and GW190814 could be a BH-'neutron-star' system.

New missions (NICER, eXTP), 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} >= 1.88 purely nucleonic stars ($\rho_{max} \leq 3\ \rho_0$)**
- **11.5 km < $R_{1.4}$ < 13 km or 1.55 <= I_{45} <= 1.88 hyperonic or hybrid stars**
- **$R_{1.4}$ << 11.5 km or I_{45} << 1.55 two families of compact stars**

Very strong predictions of the two-families scenario for mergers:

- **Possible direct collapse to a BH for masses smaller than GW170817**
- **«anomalous» KN for low mass HS-HS merger (large dynamical mass ejected)**
- **Strongly suppressed KN signal in NS-BH mergers**
- **Behaviour of tidal deformability as a function of m_{chirp} (different in 1-f vs 2-f vs twin-stars)**
- **Spectrum of GWs in the mergers (soft to hard transition in the post-merger EoS, implying a change from high to low frequencies)**

Open questions within the two-families scenario

- Can we really describe GW170817 as a NS-QS merger as suggested in ApJ L852 (2018) 32, ApJ 860 (2018) 139, ApJ 881(2019)122 ?
- What about the KN signal AT2017gfo?
- What about strangelets production?
- Can dark matter be composed of primordial quark nuggets?
- Are there precursory signals of deconfinement associated with strangeness?
    - Anomalous behaviour of kaonic systems
    - Anomalous behaviour of hyperons

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

  Two-families scenario

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Phys.Rev. C90 (2014) 065809

  Delta resonances and «delta-puzzle»

- A.D., G.Pagliara, Phys. Rev. C 92 (2015) 045801

  Combustion of hadronic stars into quark stars: the turbulent and the diffusive regime

- A.D., A.Lavagno, G.Pagliara, D.Pigato, Eur.Phys.J. A52 (2016) 40

  A.D., G.Pagliara, Eur.Phys.J. A52 (2016) 41

  Review papers on the two-families scenario

- A.D., A.Lavagno, B.Metzger, G.Pagliara, Phys. Rev. D93 (2016) 103001

  Quark deconfinement and duration of short GRBs

- A.G.Pili, N.Bucciantini, A.D., G.Pagliara, L. del Zanna, MNRAS 462 (2016) L26

  Quark deconfinement and late-time activity in long GRBs

- G.Wiktorowicz, A.D., G.Pagliara, S.Popov, Astrophys.J. 846 (2017) 163

  Strange quark stars in binaries: formation rates, mergers and explosive phenomena

- A.D., G.Pagliara, Astrophys.J. 852 (2018) L32

  Merger of two neutron stars: predictions from the two-families scenario

- A.D. et al., Universe 4 (2018) 50

  A short overview of GW170817/ GRB170817A/ AT2017gfo

- F.Burgio, A.D., G.Pagliara, H.-J. Schulze, J.B.Wei, Astrophys.J 860 (2018) 139

  Are small radii for hadronic stars compatible with GW170817/AT2017gfo?

- R.De Pietri, A.D., A.Feo, G.Pagliara, M.Pasquali, S.Traversi, G.Wiktorowicz, Astrophys.J. 881 (2019) 122

  Merger of compact stars in the two-families scenario

- N. Bucciantini, A.D., G.Pagliara, S. Traversi, 1908.02501

  Production and evaporation of strangelets

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

  Was GW190814 a black hole -- strange quark star system?