GW190814 and the possible existence of quark stars
(based on PRL,126 (2021) 162702)

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EMMI Workshop

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Department of Physics and Astronomy "A. Righi", University of Bologna, Italy
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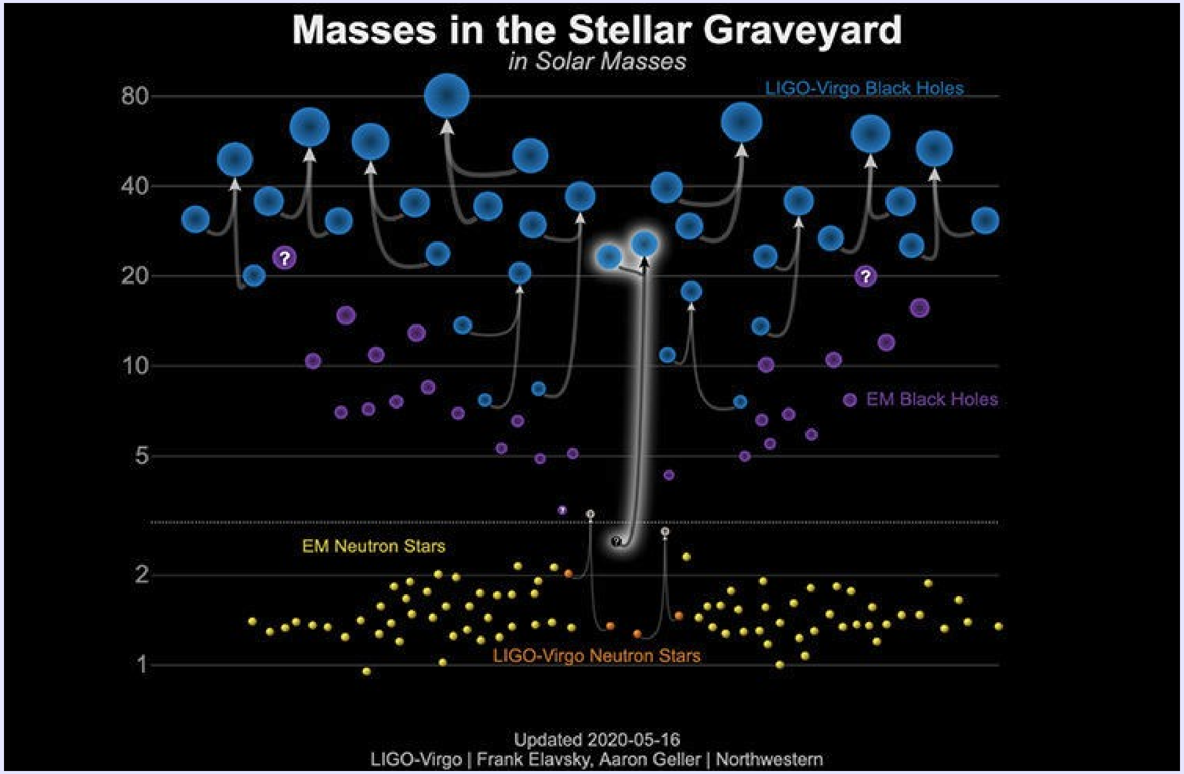
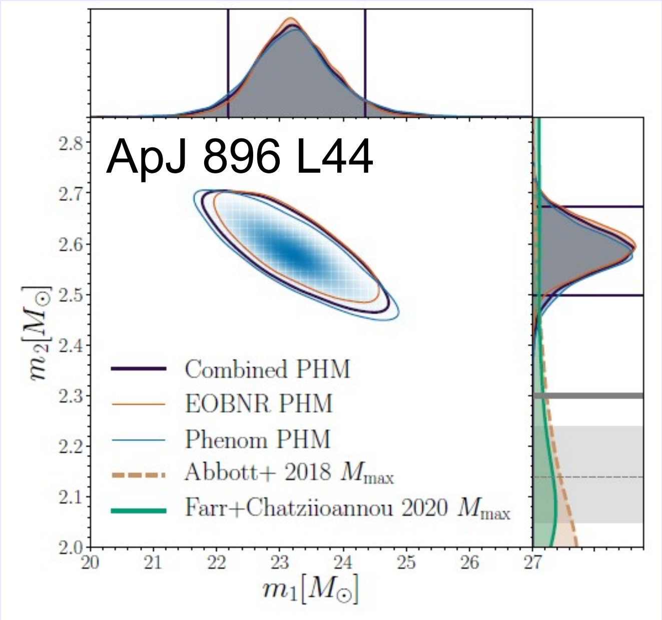
A 2.6M_{sun} compact object!



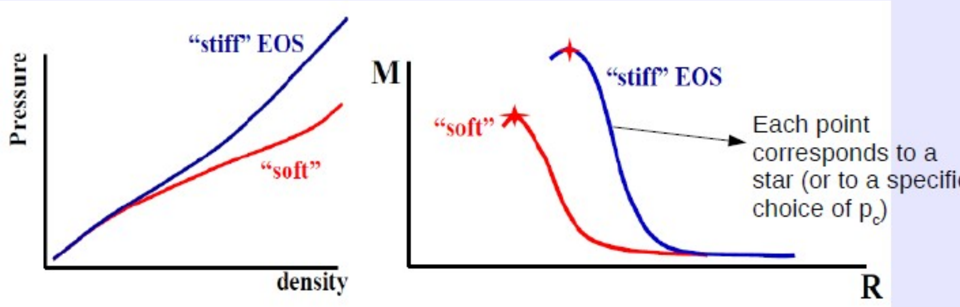


Big challenge for theory: how to explain the existence of such a light BH or such a massive neutron star?

BH interpretations:
- -) triple system (two NS merging)
- -) primordial BH
- -) accretion induced collapse of the neutron star due to the SN ejecta kept bound in the binary
- -) extended gravity
- -) …
- -) others, not in this talk

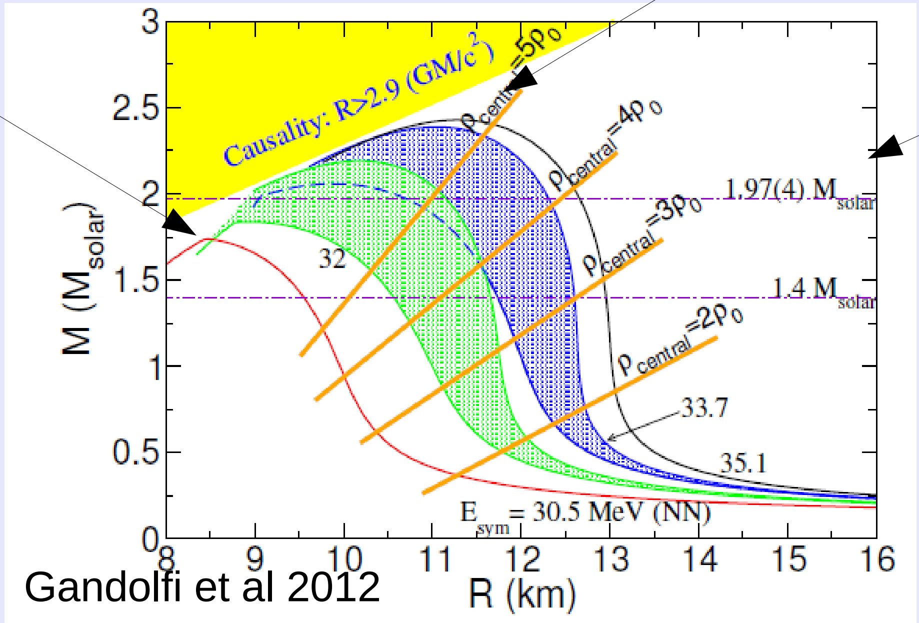
Neutron star interpretations

The (unknown) equation of state of dense matter: soft, stiff or “both”?

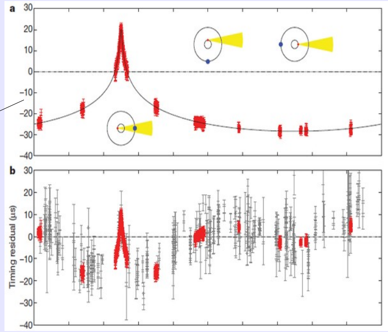


Stiff: high maximum mass – less compact configurations, small central densities, small central baryon chemical potential

Soft: small maximum mass – compact configurations, large central densities, large central baryon chemical potential (which could reach 1.5 GeV, hyperons and deltas resonances likely to appear)



Gandolfi et al 2012



Strongest and reliable constraint from **Shapiro delay: maximum mass of at least ~ $2M_{sun}$**

Neutron star interpretations

From GW170817 and several direct measurements: the maximum mass of a non-rotating star <2.2 M_{sun} (see e.g. ApJL 908 2, L28), equation of state not too stiff.

Bayesian analysis: nuclear physics within chiral effective field theory up to 1 or 2 n_{sat} and generic parametrization for higher densities.

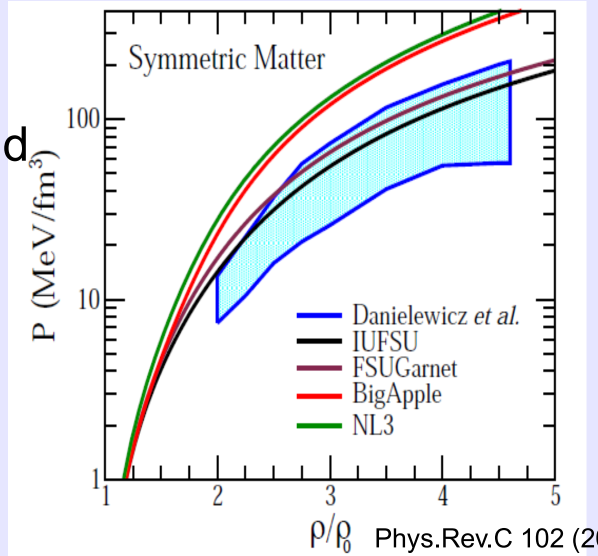
Data from multimessenger astrophysics (GW+KN for GW170817)

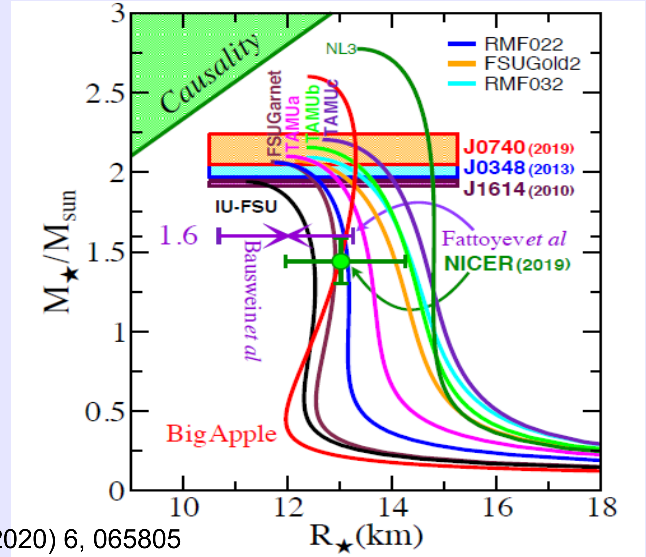
Observable	Analysis stage	n_{sat}	$2n_{sat}$
$R_{1.4}$[km]	Prior	12.1 ± 2.6	10.9 ± 1.4
	+GW	$10.5^{+1.8}_{-1.2}$	$10.5^{+1.3}_{-1.0}$
	+EM	$11.2^{+1.2}_{-0.8}$	$11.0^{+0.9}_{-0.6}$
$\tilde{\Lambda}$	Prior	330^{+1780}_{-300}	160^{+630}_{-130}
	+GW	180^{+340}_{-100}	190^{+210}_{-100}
	+EM	270^{+260}_{-100}	256^{+139}_{-75}
M_{max} [$M_\odot$]	Prior	$2.39^{+1.09}_{-0.48}$	$2.12^{+0.41}_{-0.21}$
	+GW	$2.01^{+0.33}_{-0.10}$	$2.01^{+0.34}_{-0.11}$
	+EM	$2.07^{+0.20}_{-0.14}$	$2.10^{+0.18}_{-0.17}$
P_{max}[MeV/fm^3]	Prior	517^{+512}_{-371}	644^{+437}_{-394}
	+GW	730^{+350}_{-380}	730^{+350}_{-440}
	+EM	600^{+380}_{-330}	570^{+320}_{-320}
$P_{4n_{sat}}$[MeV/fm^3]	Prior	170^{+182}_{-111}	158^{+142}_{-101}
	+GW	123^{+107}_{-70}	125^{+118}_{-68}
	+EM	154^{+58}_{-49}	161^{+58}_{-46}

Nature Astron. 4 (2020) 6, 625

GW190814: the star was, before the merger, rapidly rotating.
Problem: old object still rotating? Or collapsed supramassive star (do they form in SNe?)

Or: the equation of state is very stiff and allows for such massive neutron stars.
Problem: how to reconcile with low energy heavy ions collisions data?

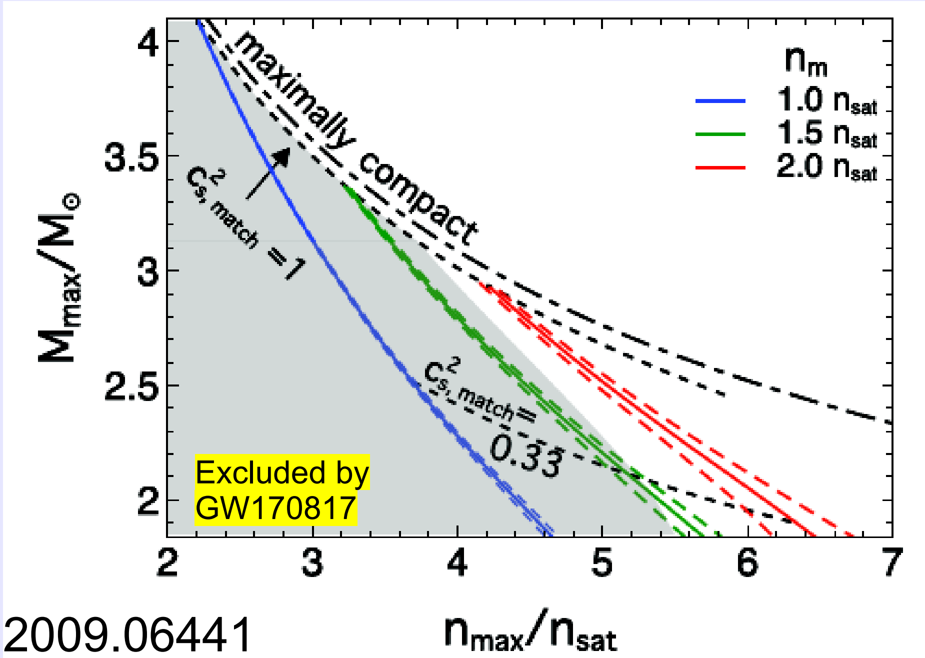




Phys.Rev.C 102 (2020) 6, 065805

Softening channels

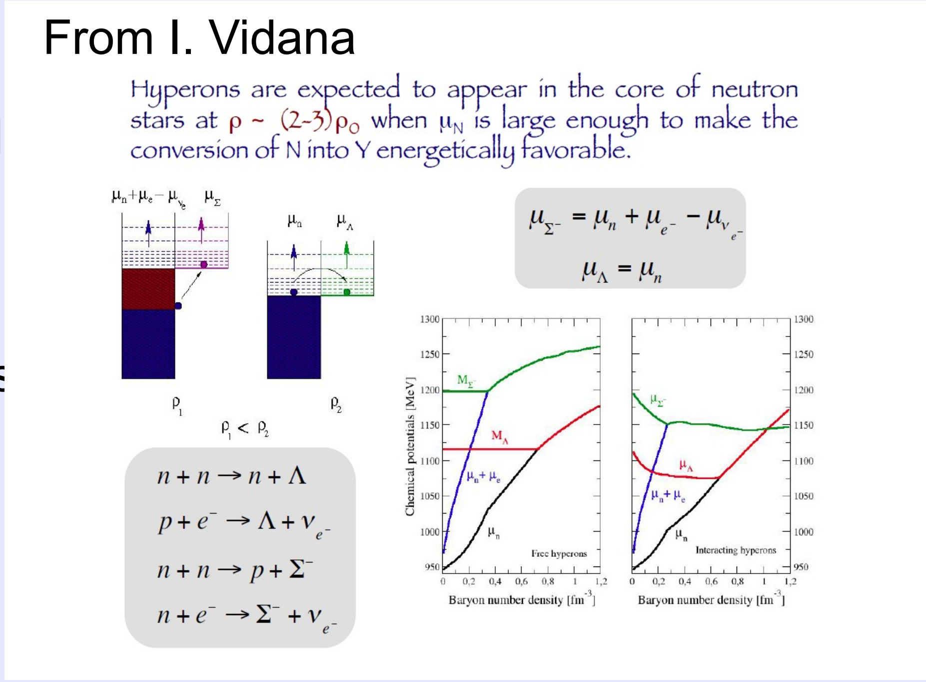
For a 2.6M$_{sun}$ star the central density is of the order of 5n$_{sat}$ or more. Is it conceivable that at those large densities hyperons/delta resonances are not produced?



Hyperons should be taken into account when computing the EoS. At the moment there are no calculations indicating that hyperonic stars could reach 2.6M$_{sun}$

Instead: they can significantly soften the equation of state and reduce the maximum mass to values even smaller than 2M$_{sun}$.

Unless ΛNN strongly repulsive and no hyperon puzzle anymore, see Gal's talk.



Masses and Radii

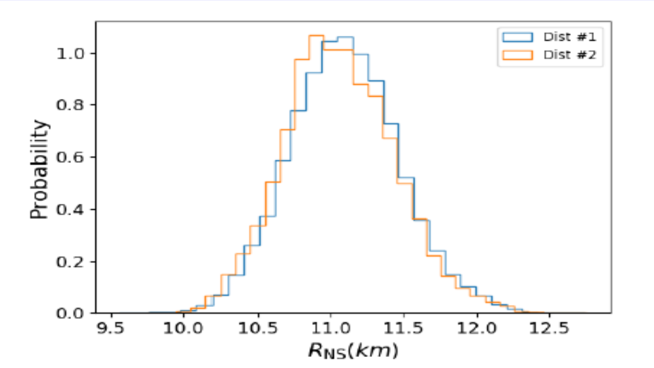
Evidence of massive stars: PSR J0952-0607, M=2.19 M_{sun} 1σ lower limit

Astrophys.J.Lett. 934 (2022) 2, L18

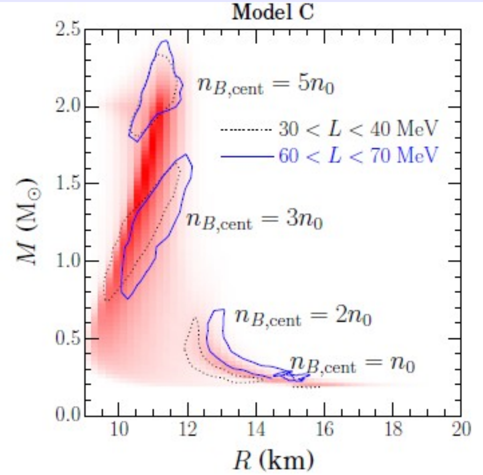
Stiff EoS!!

Possible small radii:

$R_{1.4}$<12km

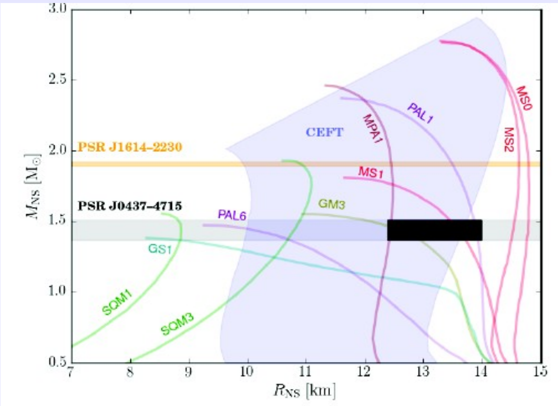


QLMXB, constant R model,
Guillot et al 1905.01081
(without priors on nuclear symmetry energy)
Soft EoS!!



Indication of strong phase transition
Steiner et al MNRAS 2018

Possible large radii:



Thermal emission of PSRJ0437-4715 1904.1211

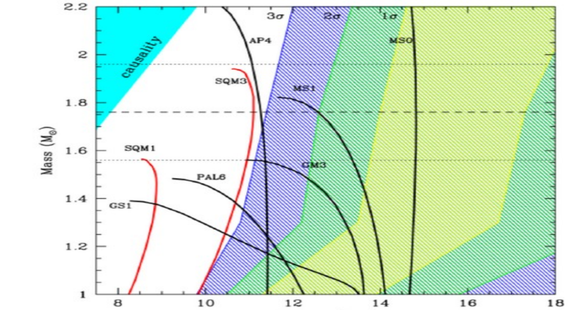


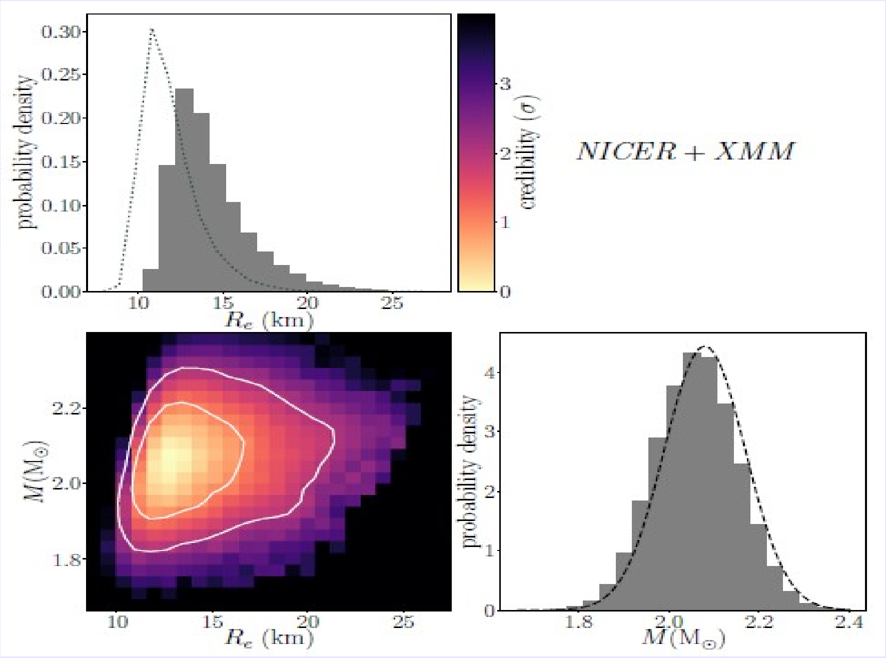
Figure 6. Mass–radius plane for neutron stars showing the 1σ, 2σ, and 3σ confidence contours (yellow, green, and blue hatched regions, respectively) for PSR J0437–4715. The solid lines are representative theoretical model tracks (from Lattimer & Prakash 2001). The horizontal lines show the pulsar mass measurement from radio timing (dashed line) and the associated 1σ uncertainties (dotted lines) from Verbiest et al. (2008).

ApJ 762 (2013) 96

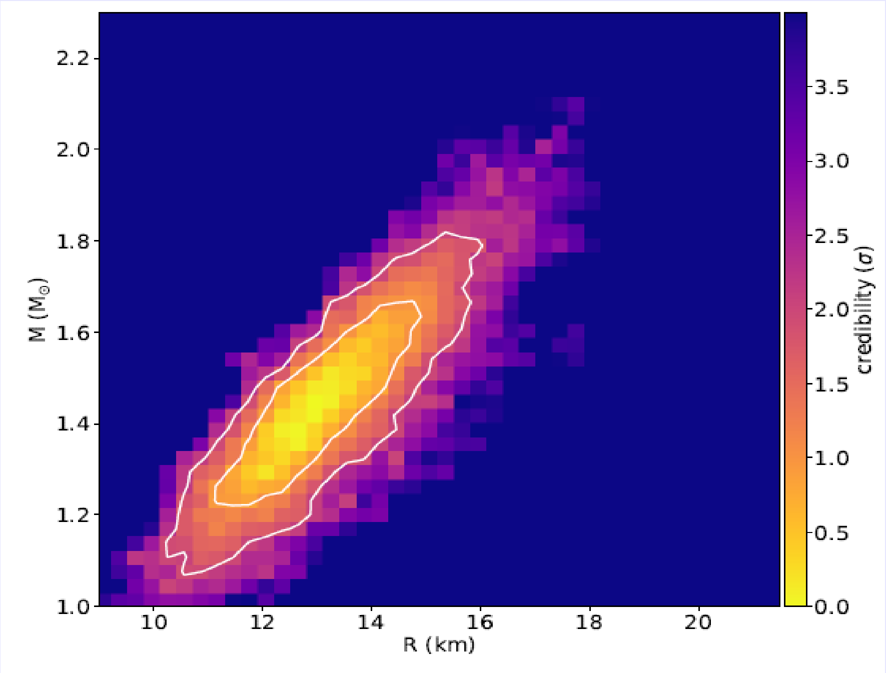
Stiff EoS!!

NICER results

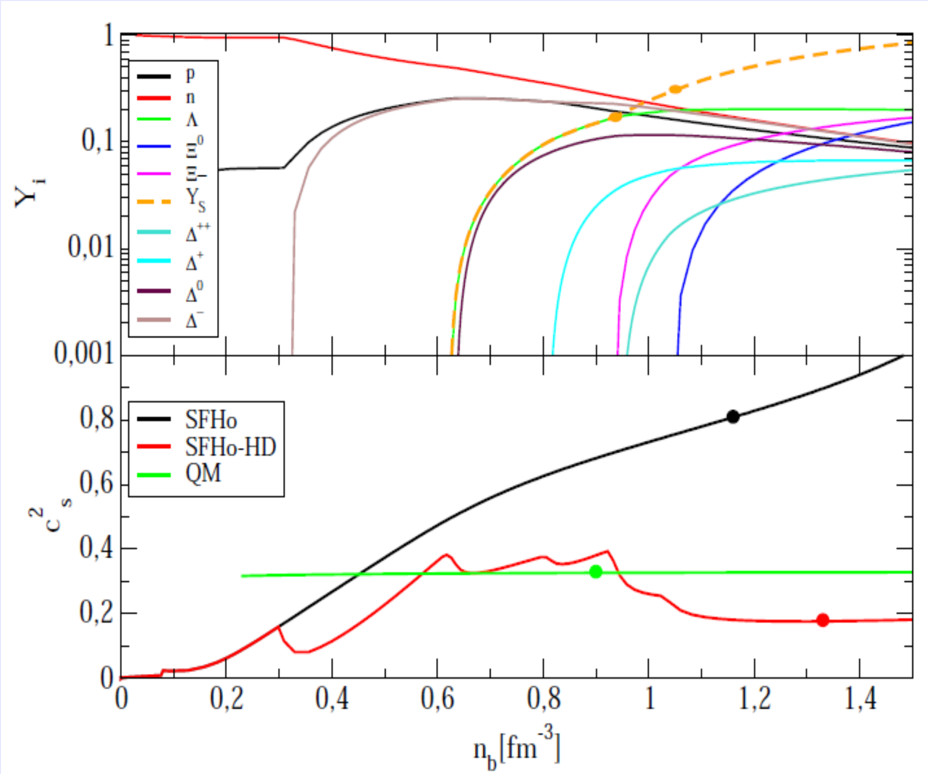
PSR J0740+6620: M=2.072 (+0.067; -0.066) M_s
Miller et al. R = 13.7 (+2.6; - 1.5) km
arXiv:2105.06979
Riley et al.   R = 12.39 (+1.30; -0.98) km
arXiv:2105.06980



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



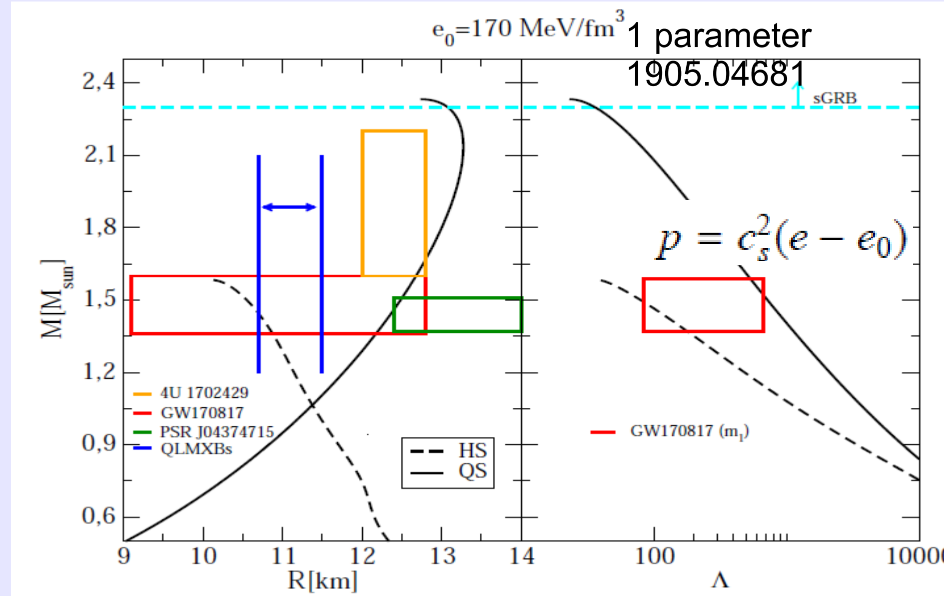
Two families of compact stars?



Hadronic matter: SFHo+hyperons+deltas
Quark matter: MIT bag model like or constant speed of sound EoS

1) Transition to quark matter only when enough hyperons are present in the core (masses larger than about $1.5M_{sun}$)

2) Speed of sound does not need to reach values close to the causal limit (as in all the one family scenario!!). The conformal limit of 1/3 is naturally obtained.



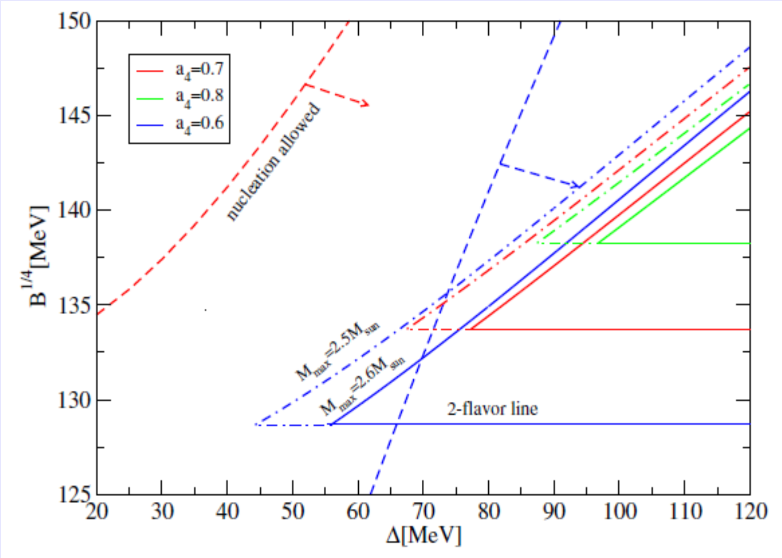
Hadronic stars would fulfill the small radii limits while strange stars would fulfill the large masses/radii limits.
Note: at fixed baryon mass, strange stars could be energetically convenient even if the radius is larger than the corresponding hadronic star configuration.

How to reach 2.6M_{sun}

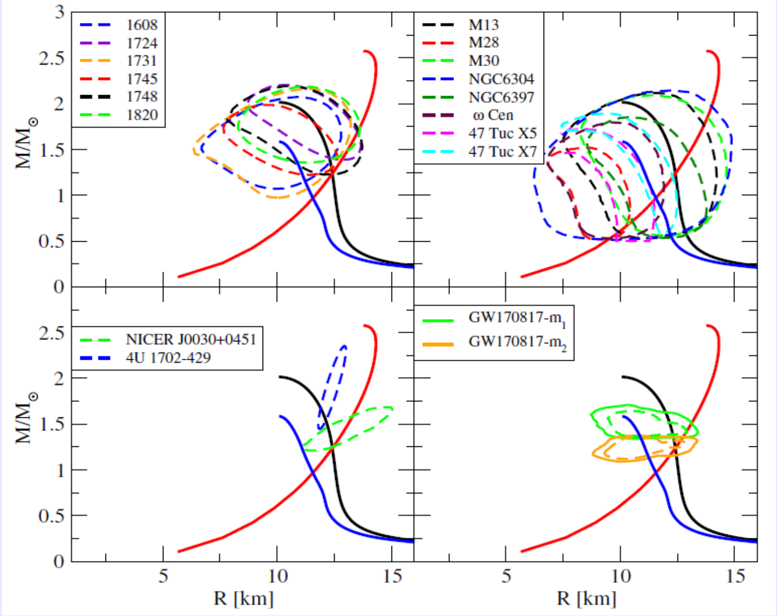
Color superconductivity, CFL case in our case, allows to stiffen the EoS if a sizable gap is assumed (100 MeV).

$$\Omega = -\frac{3}{4\pi^2} a_4 \mu^4 + \frac{3}{4\pi^2}\mu^2 (m_s^2 - 4\Delta^2) + B$$

see also: Weissenoborn et al.   Astrophys.J.Lett. 740 (2011) L14

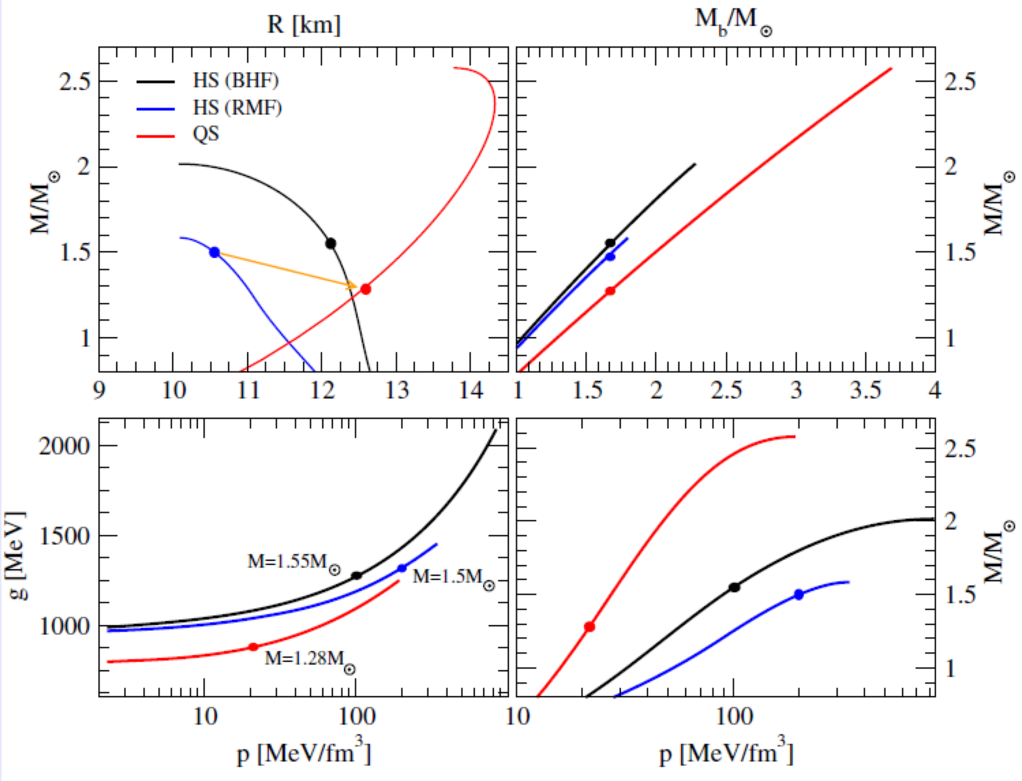


The maximum mass can reach values up to 2.6 M_{sun} or more. As a consequence: there should exist stars with masses 1.4M_{sun} and $R_{1.4}$ $\sim$ 13 km together with stars with $R_{1.4}$ $\sim$ 11 km. At 2M_{sun} the radius should reach values close to 14km. In agreement with the radius of PSR J0740+6620 as measured by NICER.



How can two-families coexist?

When enough hyperons are produced at the center of a hadronic star, nucleation of strange quark matter could start (its Gibbs potential smaller than the one of the hadronic phase). When a droplet of critical radius is produced (quantum or thermal nucleation) the conversion process will start. It is exothermic, mass defect ~ $0.1M_{sun}$.



This enormous amount of energy could provide signatures:

SN explosions, GRBs … a long list of works

See Bombaci&Datta ApJ 2000 Berezhiani et al APJ 2003, see also Drago,Pagliara, Eur.Phys.J. A52 (2016) 41 for a review

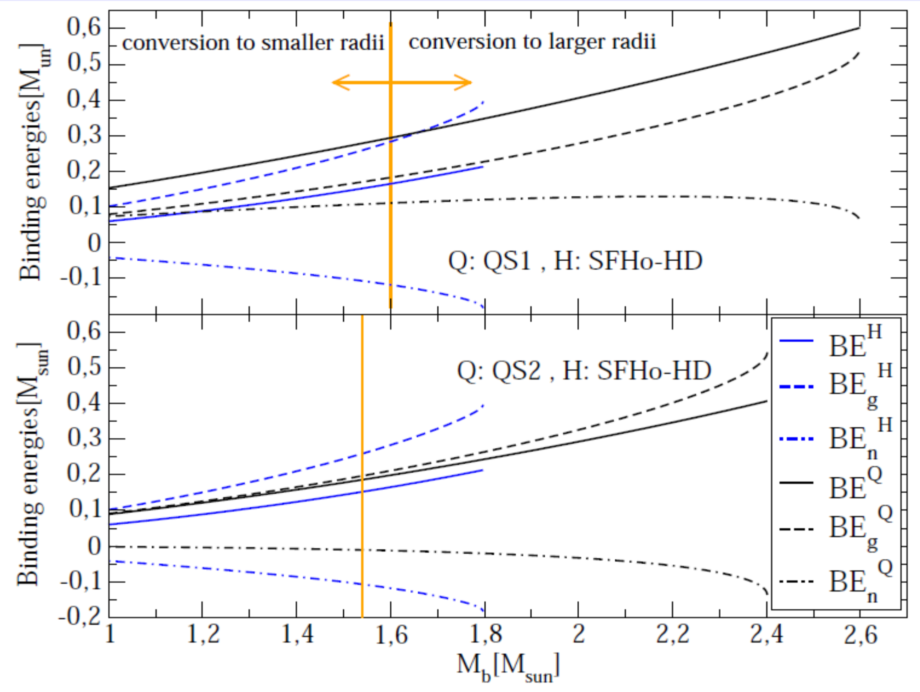
Exothermic process and radii

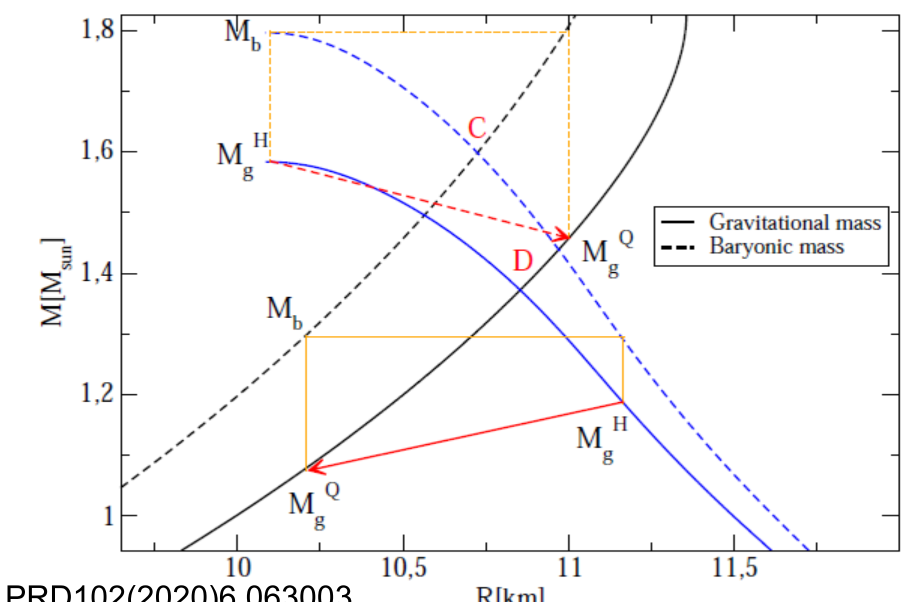
By defining the proper mass (see Bombaci&Datta ApJ2000):

$$M_p = \int_0^R \mathrm{d}r \; 4\pi r^2 \frac{e(r)}{\sqrt{1 - 2M_g(r)/r}}$$

The total binding energy can be divided into a nuclear binding energy and a gravitational binding energy $BE_n = M_b - M_p$ and $BE_g = M_p - M_g$. While BE_n is always negative (anti-binding) for hadronic stars, it is "often" positive for quark stars. The reduction of the gravitational binding due to a larger radius of the final quark star configuration is compensated by the gain in nuclear binding energy.

The conversion could lead to a smaller or larger quark star depending on the value of the baryonic mass. If $M_b > M_C$ ($M_b < M_C$) larger (smaller).





PRD102(2020)6,063003

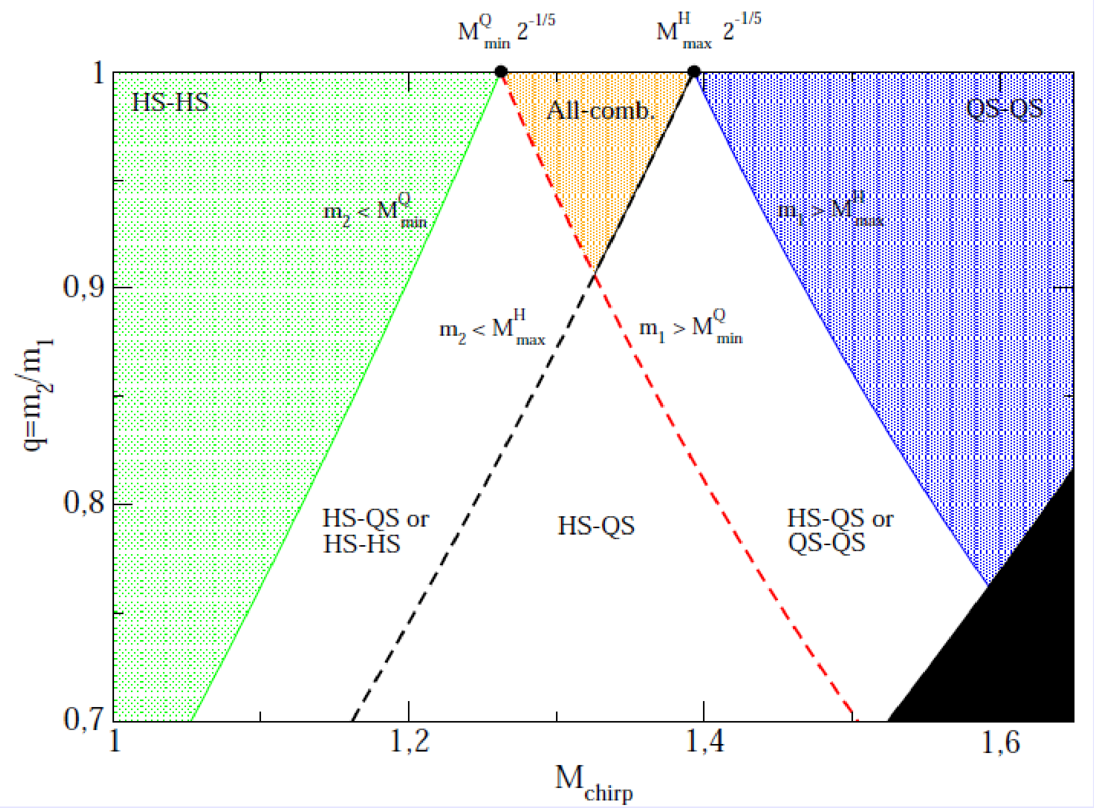
Testing the two-families scenario

Complicated (rich) merger phenomenology

Astrophys.J 881 (2019) 122

Three types of merger depending on the total mass and on the mass asymmetry:
1) HS-HS
2) HS-QS
3) QS-QS

These three cases have three different values for the threshold mass above which a prompt collapse is obtained. $M_{threshold}$ scales almost linearly with the compactness of the maximum mass configuration (see Bauswein MNRAS 2017).



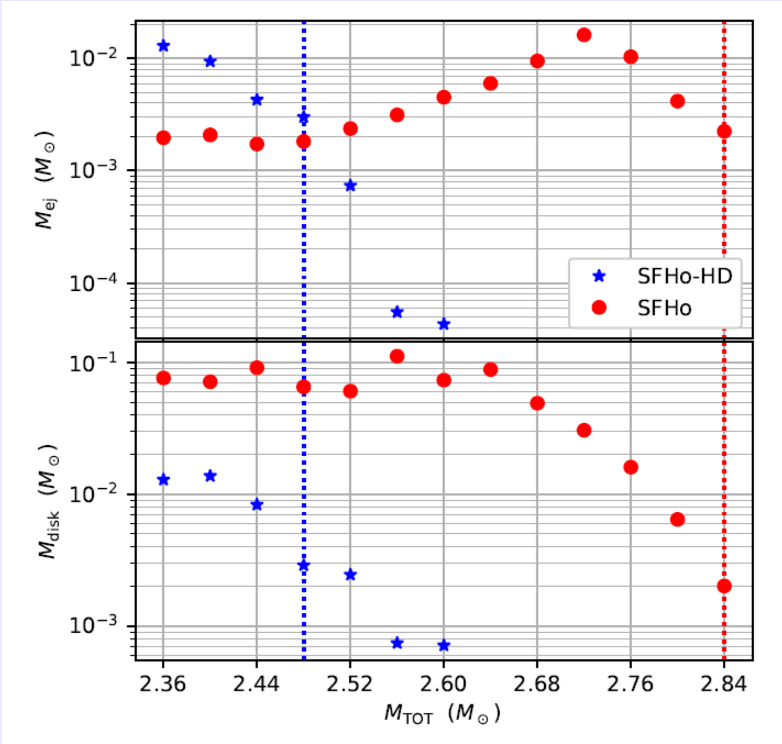
Population synthesis analysis:

	all mergers			GW170817-like					
				$0.7 < q < 1.0$			$0.7 < q < 0.85$		
Model	HS-HS	HS-QS	QS-QS	HS-HS	HS-QS	QS-QS	HS-HS	HS-QS	QS-QS
$M^H_{max} = 1.5 M_\odot$	9.1	3.1	0.2	6.4	0.4	0.01	0.03	0.2	–
$M^H_{max} = 1.6 M_\odot$	9.2	3.2	0.02	6.5	0.3	–	0.1	0.2	–
one-family	12.8	–	–	6.6	–	–	0.3	–	–

10^{-3}/year within D=100Mpc

1) QS-QS rare
2) GW170817 plausible as HS-QS

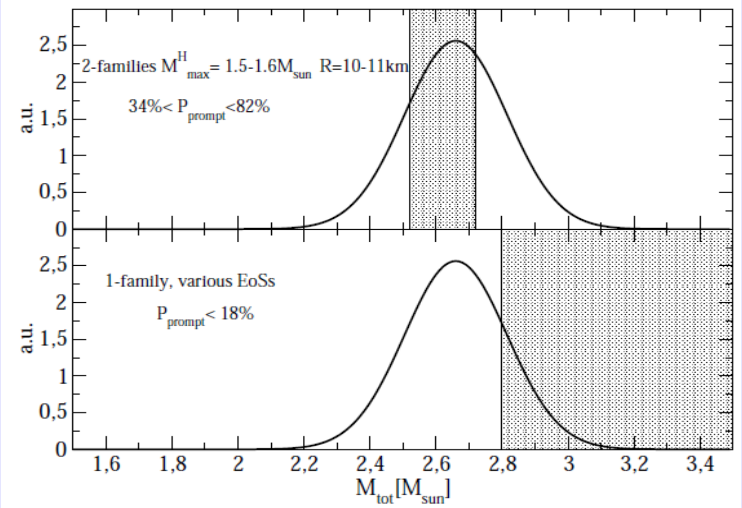
From numerical simulations:
Estimates of mass dynamically ejected and mass left in the disk.
Values up to 0.01 M_{sun} (SFHo and SFHo-HD)for the first and up to 0.1M_{sun} for the latter (for SFHo).
Non linear relation between the maximum of ejected mass and the total mass of the system.



Main prediction of the two families scenario:
Threshold mass for the prompt collapse of about 2.5M_{sun} for HS-HS systems thus smaller than the mass associated with GW170817 (2.73M_{sun}).

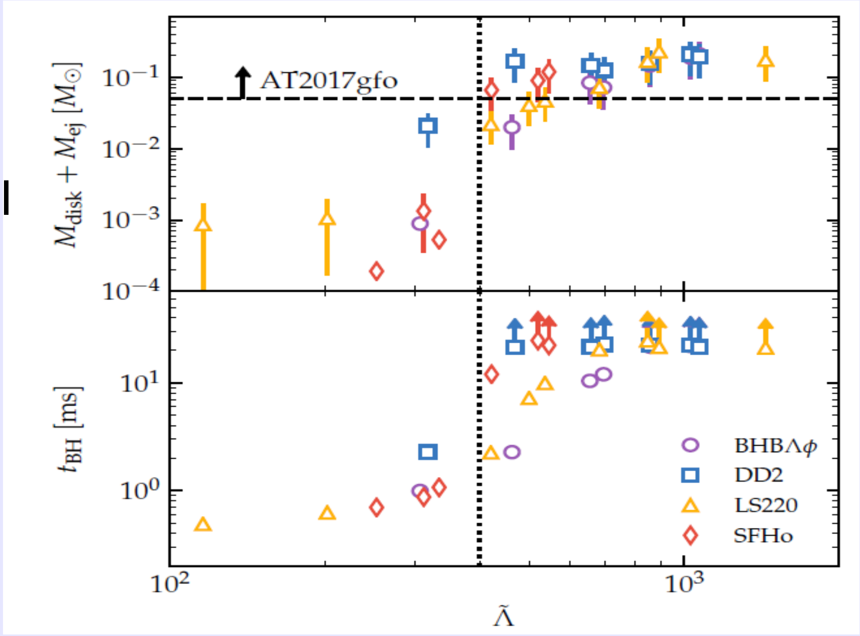
1) GW170817 is interpreted as a HS-QS system
2) **A single detection of a merger with total mass smaller than 2.73 M_{sun} but lacking the EM counterpart (no shortGRB + no or very faint KN) would be interpreted as due to a HS-HS merger**

How many cases of prompt collapses ?
Estimates using the mass distribution of DNS systems
ApJ852(2018)L32



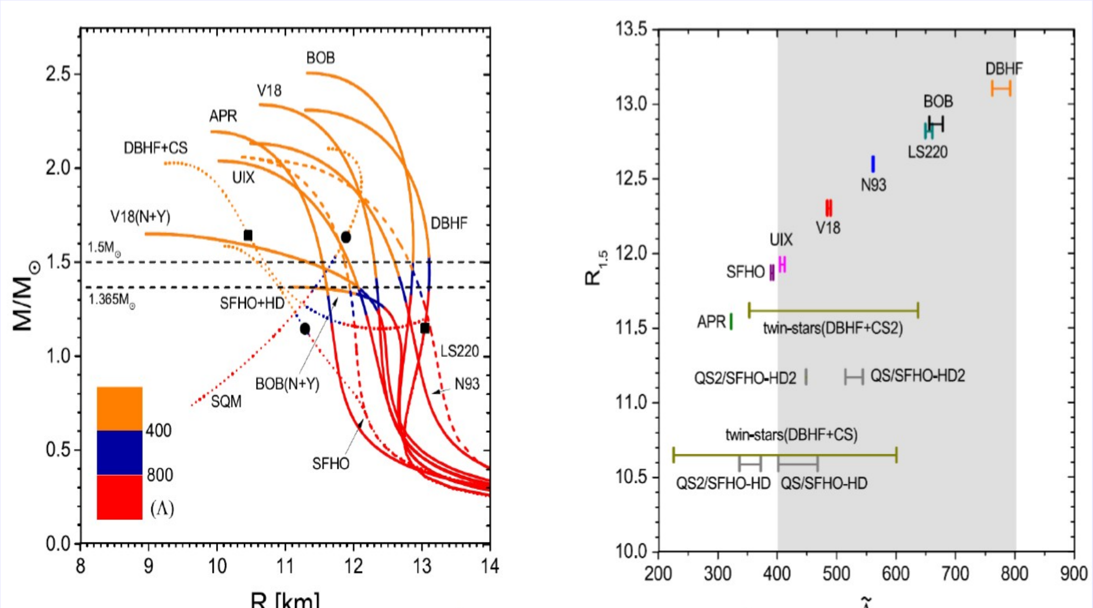
Relation between average tidal deformability and radii:

Estimates of lower limit on the average tidal deformability from the amount of KN ejecta: dynamical ejecta+mass of the disk as obtained from numerical simulations. It should be larger than about 400.



Radice et al APJL 852 (2017) 29

While for the standard one family scenario, a tidal deformability larger than 400 implies a radius larger than about 12km, within the two families scenario (and the twin stars scenario) it is possible to fulfill the constraints on the tidal deformability from GW170817 and to obtain at the same time radii smaller than about 11km (thus closer to some observational analyses on radii). This is due to the large difference in radii of the two components of the mixed binary system.



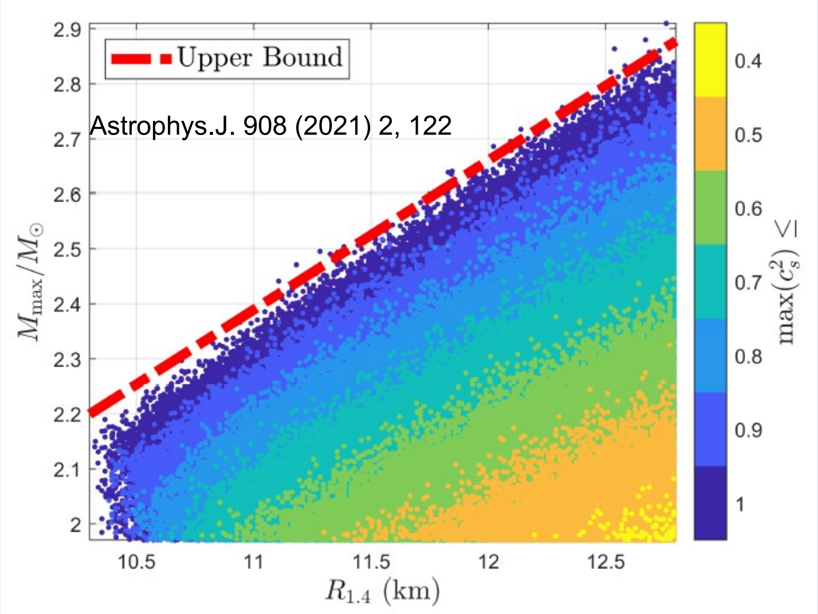
$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_A}{(M_A+M_B)^5} + (A \leftrightarrow B)\right]$$

(Burgio et al. ApJ 860 (2018) 139)

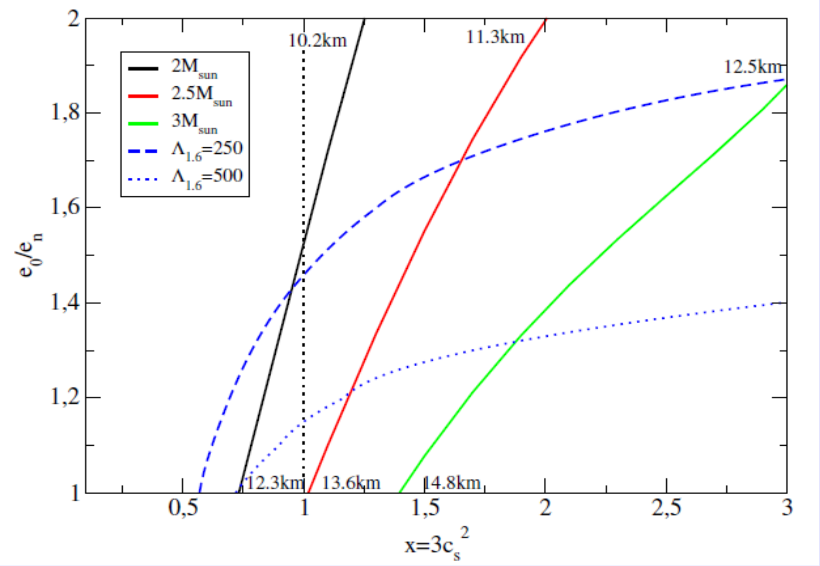
Speed of sound in dense matter

One family scenario, piecewise polytropes EoS

-) Within the conformal limit, $c_s^2 < 1/3$, M_{max} barely reaches $2M_{sun}$ and $R_{1.4}$ >13km
-) If M_{max} >2.6 M_{sun} the causal limit is violated if $R_{1.4}$ < 11.8 (thus in tension with GW170817 constraints)

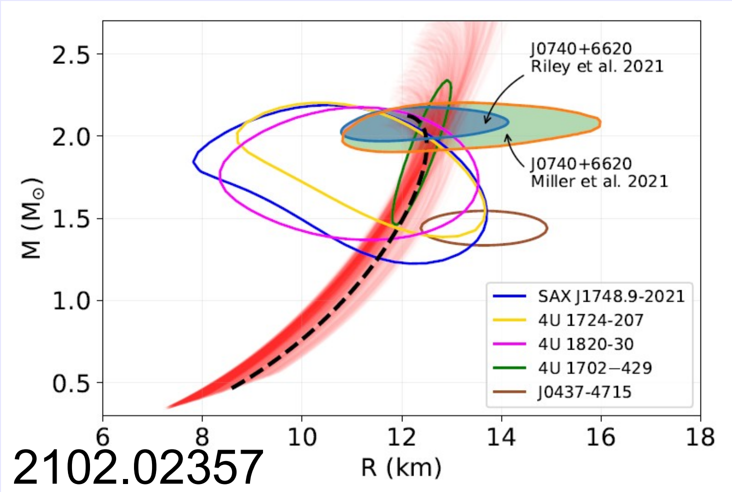


When considering quark stars, their self-boundness allows for large M_{max} even within the conformal limit.
Results with constant speed of sound model.
(Traversi et al. A&A2022)

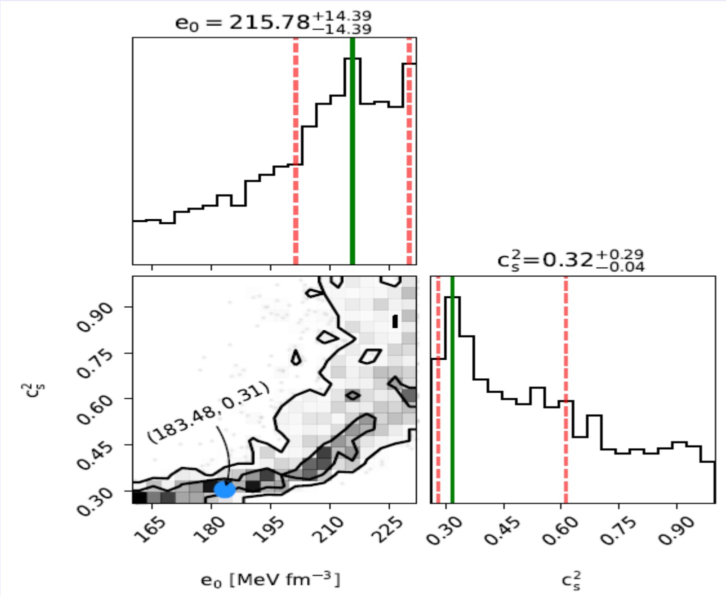


A bayesian analysis with quark stars

Within the two-families scenario one can (with a certain degree of uncertainty) select sources which are interpreted as quark stars (masses above $\sim 1.6 M_{sun}$ and radii larger than $\sim$ 13km) and perform a bayesian analysis with a constant speed of sound equation of state. GW190814 not included in this analysis.



Peak of the posterior distribution at c_s^2 =0.32 thus in agreement with the conformal limit (no need of values close to the causal limit)



The equation of state with the largest joint probability predicts a M-R curve with $M_{max} \sim 2.1\ M_{sun}$ and which falls nicely within the recent NICER limits for J0740+6620.

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.

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

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

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

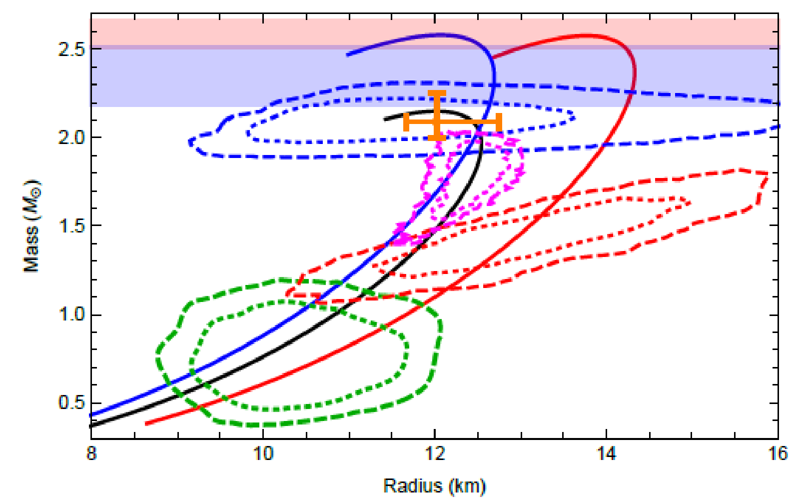


Figure Mass-radius relation of QSs from [6] (solid red), [11] (solid blue) and [12] (solid black) with observational constraints at 68% of confidence level (dotted) and at 90% (dashed). Blue: analysis of PSR J0740+6620 from NICER and XMM-Newton data from [14]. Magenta: analysis of 4U 1702-429 from [15]. 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].

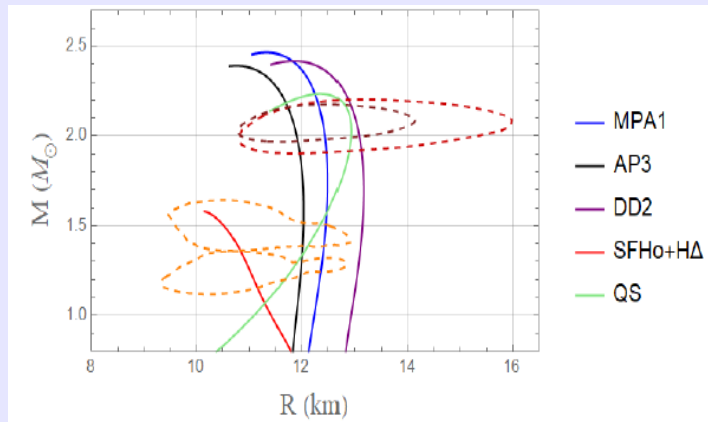
$M_b\,(M_\odot)$	$M_g^{NS}\,(M_\odot)$	$M_{g,A}^{QS}\,(M_\odot)$	$M_{g,B}^{QS}\,(M_\odot)$	$M_{g,C}^{QS}\,(M_\odot)$
1.28	1.17	0.99	1.00	0.95 – 1.05
1.32	1.20	1.01	1.03	0.98 – 1.08

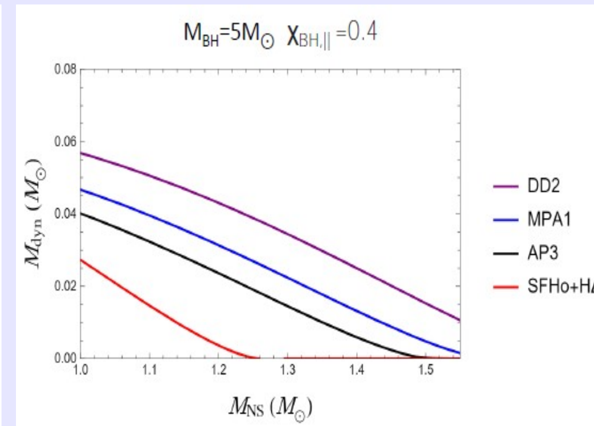
Table Minimum allowed mass for NSs and for QSs in three models. A refers to the EoS in [6] (solid red line in the Figure). B refers to a EoS derived in [11] (solid blue line). C refers to the most probable EoS having a constant speed of sound and is obtained from the bayesian analysis in [12] which does 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].

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.

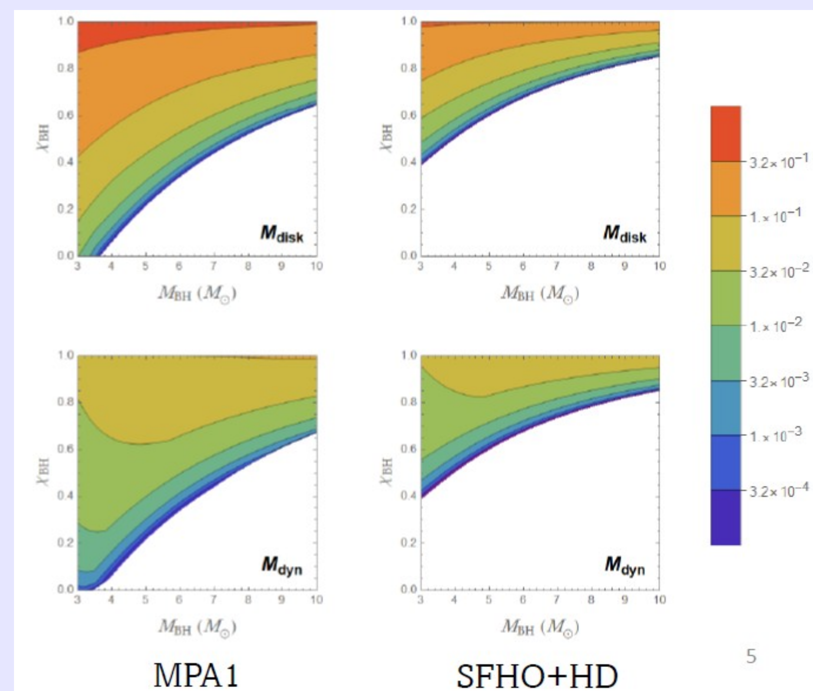




Annual number of detections

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.



Conclusions

-) The hypothesis of existence of two branches of compact stars allows to fulfill high masses and small radii constraints, even if M_{max} is above $2.6M_{sun}$.

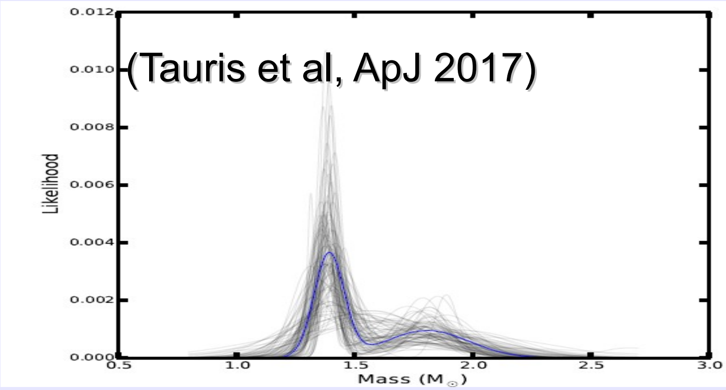
Testing the two-families scenario:
cases of prompt collapse for masses smaller than $2.73M_{sun}$, postmerger GW signal with frequencies higher than 1family stars (not discussed here)

$R_{1.4}$ smaller than about 11km (need to be confirmed)

R_2 ~ 13km (as NICER seems to indicate)

BH-NS merger: faint or no KN signal

Bimodal mass distribution of MSP (not discussed here)



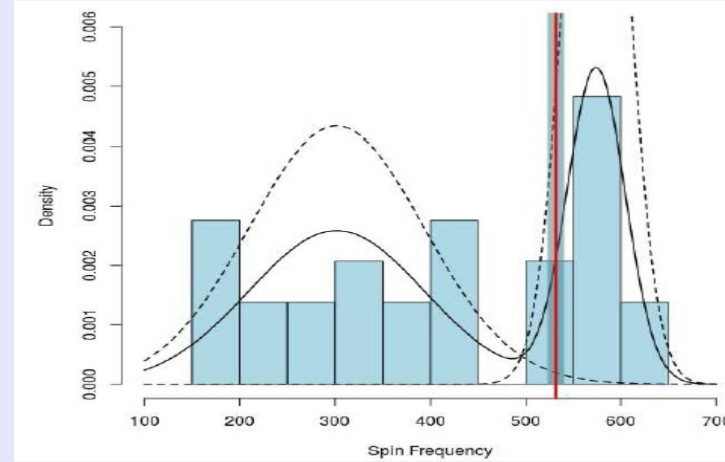
Theoretical constraints on c_s , no need of violating the conformal limit (if $M_{max} < 2.5M_{sun}$)

Explosive phenomena: long and short GRBs (not discussed here)

Appendix

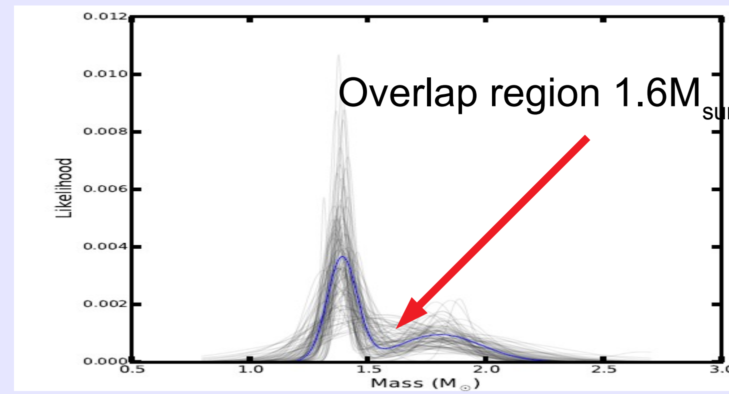
Other (possible) intriguing results

	Estimate	Confidence Interval (95%)
μ_1 (Hz)	302	255–348
σ_1 (Hz)	92	68–135
μ_2 (Hz)	574	555–593
σ_2 (Hz)	30	21–48
λ	0.6	0.4–0.8
Cut-point (Hz)	538	526–548

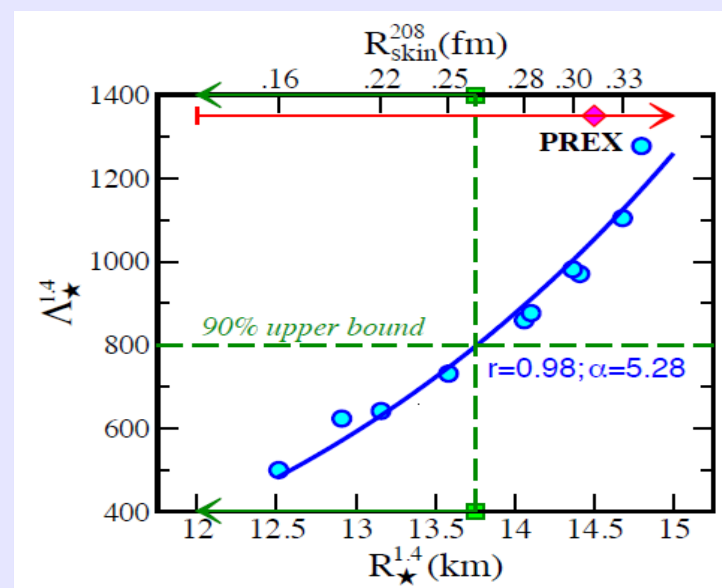


Bimodal spin distribution in LMXBs ? ApJ 850 (2017) 106

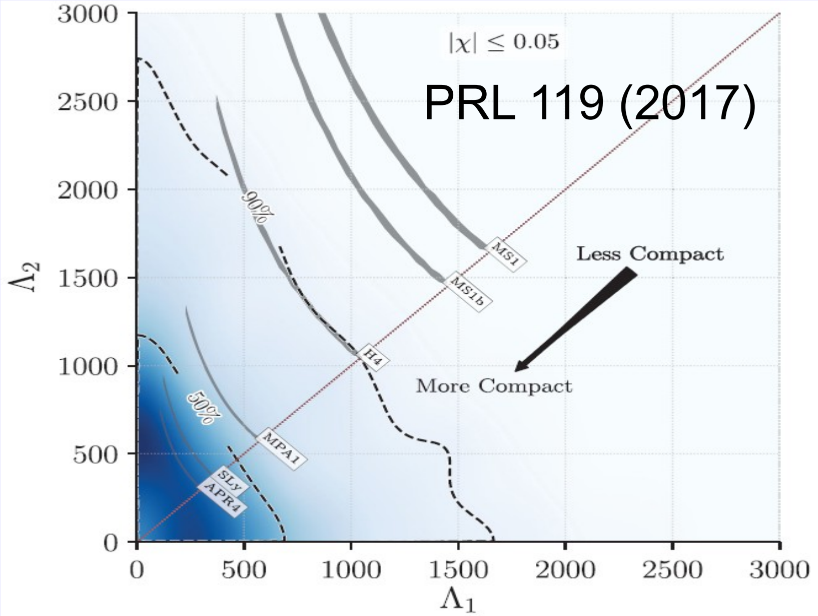
Bimodal mass distribution in millisecond pulsars? “...not a result of the recycling process, but rather reflects differences in the NS birth masses”
(Tauris et al, ApJ 2017)



Are massive compact stars formed by massive blue giant stars through quark deconfinement ?
(Fischer et al, nat.astron.2018)



Correlation between neutron skin thickness and radii / tidal deformability.
A (to be confirmed) tension between lab and astro measurements: stiff EoS in atomic nuclei, soft EoS implied by GW170817, PRL 120 (2018) 172702



Very stiff EoS disfavoured by GW170817.
Nucleonic EoSs (with $R_{1.4} \approx 12$km) such as Sly and APR4 seem to be fine !!
… but…considering for instance Sly (Douchin&Haensel 2001):

1) $1.4M_{sun}$ - $3\rho_0$ (central density)
2) $2M_{sun}$ - $9\rho_0$ (central density)

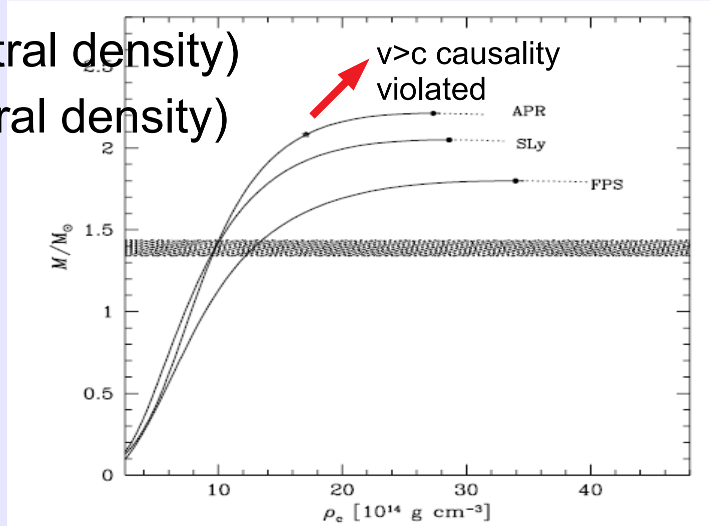


Fig. 4. Gravitational mass M versus central density ρ_c, for the SLy, FPS, and APR EOS of dense matter. Maximum on the mass-central density curves is indicated by a filled circle. On the APR curve, configurations to the right of the asterisk contain a central core with $v_{\rm sound} > c$. Configurations to the right of the maxima are unstable with respect to small radial perturbations, and are denoted by a dotted line. The shaded band corresponds to the range of precisely measured masses of binary radio pulsars.

Really just nucleons?
Hyperons puzzle, delta isobars puzzle…
Stiff ? Soft ? (huge literature)
A firm point: hypernuclei do exist (though unstable) !! Λ baryons are bound in nuclear matter.
Those particles must be taken into account in the calculations and not just artificially excluded.

Two viable solutions to the hyperon puzzle

1) Hyperons (and Delta) do take place but $R_{1.4}$ > 12 km (large nuclear matter skewness allows to reach large masses)

See Li & Sedrakian ApJ 2019

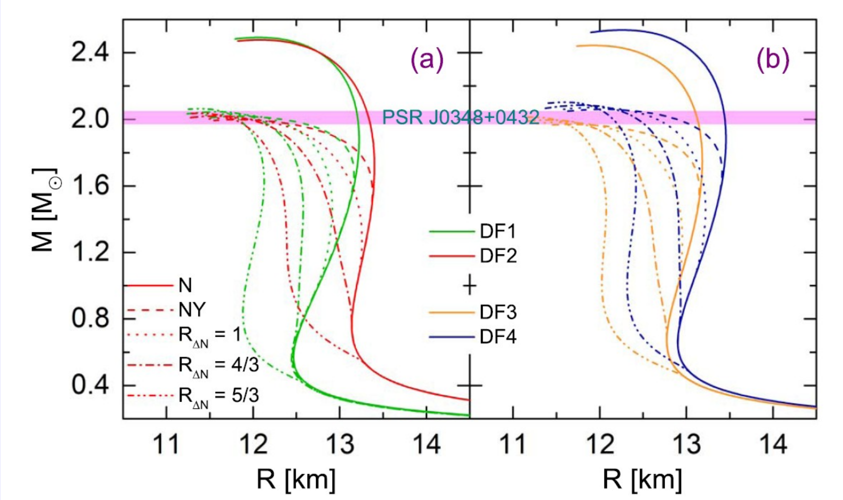
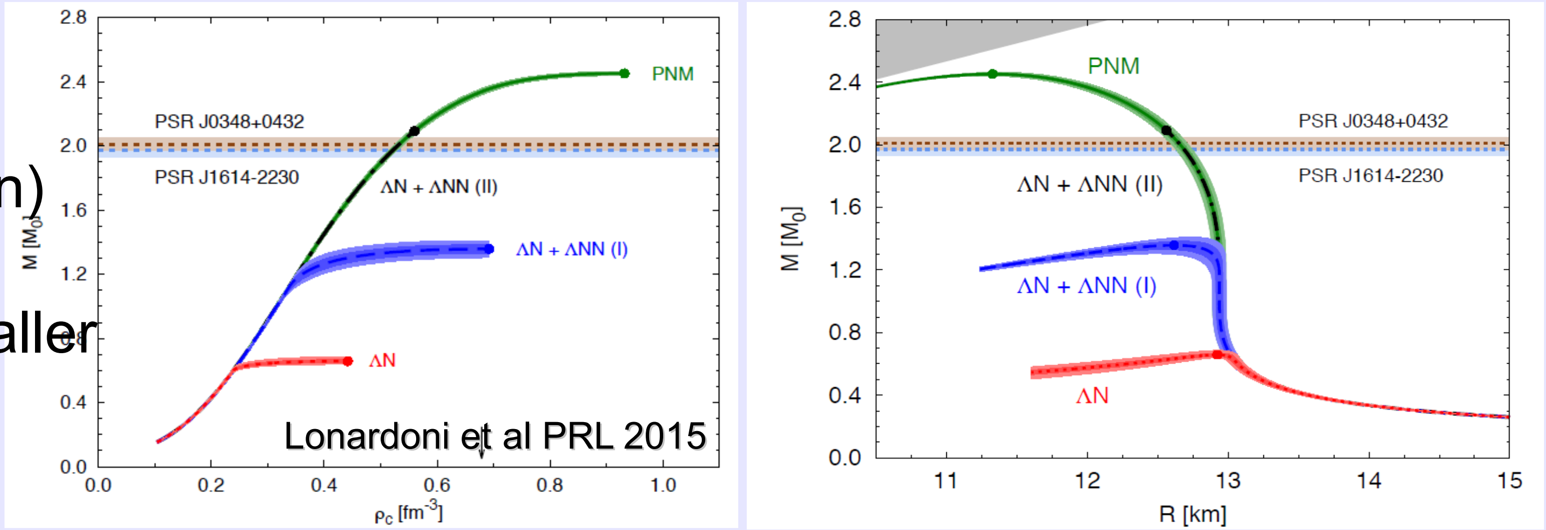


Figure 1. Mass–radius relation for a set of EoSs with varying $L_{\rm sym}$ (a) and $Q_{\rm sat}$ (b) and assuming purely nucleonic (N), hyperonic (NY), and hyperon-Δ admixed ($NY\Delta$) compositions of stellar matter. Three values of the Δ-potential have been used: $R_{\Delta N} = V_\Delta/V_N = 1$, $4/3$, and $5/3$, where V_N is the nucleon potential in isospin-symmetrical matter at saturation density.

2) Hyperons do not form (strong repulsion) but $R_{1.4}$ > 13 km

Central densities smaller than about $4n_0$

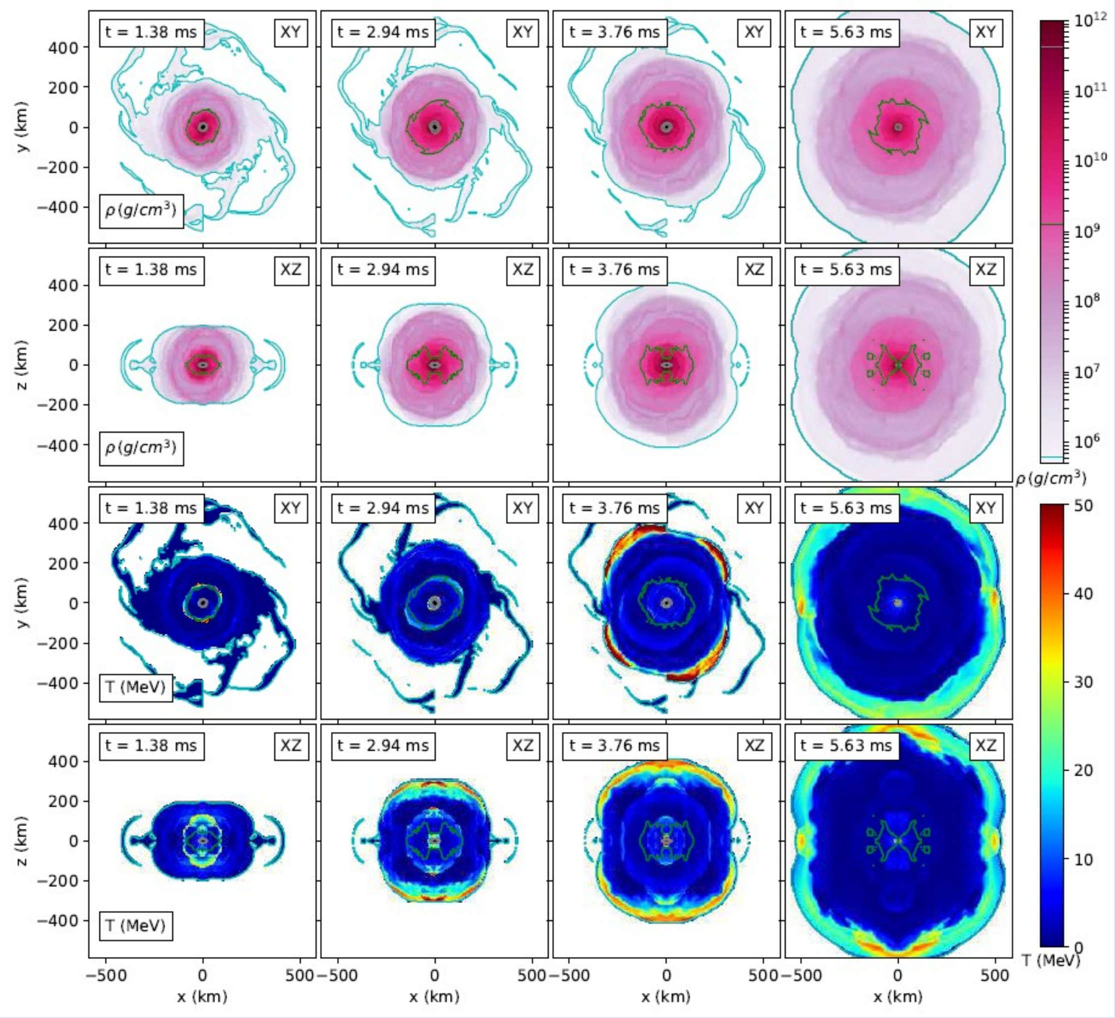


Lonardoni et al PRL 2015

HS-HS merger simulations

-Simulations by using the Einstein toolkit & Lorene
-Polytropic approximation for the EoS
-Thermal adiabatic index
- Two EoSs: SFHo and SFHo with the inclusion of hyperons and delta resonances
-) Symmetric systems with 7+13 total mass values

Model	M_{ej} ($mM_\odot$)	M_{disk} ($mM_\odot$)	E_{gw}^{POST} ($mM_\odot$)	f_2 (kHz)	t_{BH} (ms)
SFHo-HD 118vs118	12.993	12.92	25.42	3.71	3.82
SFHo-HD 120vs120	9.435	13.81	22.42	4.00	3.16
SFHo-HD 122vs122	4.290	8.34	6.06	—-	1.91
SFHo-HD 124vs124	3.011	2.89	0.66	—-	1.00
SFHo-HD 126vs126	0.737	2.45	0.20	—-	0.79
SFHo-HD 128vs128	0.055	0.74	0.04	—-	0.70
SFHo-HD 130vs130	0.043	0.71	0.01	—-	0.59
SFHo 118vs118	1.968	76.66	42.16	2.88	- - -
SFHo 120vs120	2.085	71.72	43.87	2.90	- - -
SFHo 122vs122	1.730	91.81	42.00	2.90	- - -
SFHo 124vs124	1.824	65.58	52.98	2.96	- - -
SFHo 126vs126	2.375	60.86	58.33	2.98	- - -
SFHo 128vs128	3.145	112.24	50.33	3.05	- - -
SFHo 130vs130	4.523	73.82	59.33	3.06	- - -
SFHo 132vs132	6.007	88.87	67.29	3.18	25.75
SFHo 134vs134	9.511	49.27	65.09	3.25	13.55
SFHo 136vs136	16.244	30.71	58.76	3.40	9.42
SFHo 138vs138	10.367	16.09	46.06	3.55	5.06
SFHo 140vs140	4.170	6.45	22.39	—-	2.13
SFHo 142vs142	2.247	2.01	2.02	—-	0.98



Model: 1.18 vs 1.18 SFHo-HD
Collapse time 4ms.

Key points of the two families scenario:

1) A merger would always produce at some stage a strange star (stable or unstable) but for the case of the prompt collapse
2) In the cases of prompt collapse, the remnant collapses within $t_c \sim \text{few ms}$ which is comparable with the time needed for the turbulent conversion of the hadronic star, t_{turb} (again few ms, Drago et al 2015)
3) In the cases of prompt collapse the relevant M_{max} is not the maximum mass of strange stars but the maximum mass of hadronic stars which is in our scenario of the order of 1.5 - 1.6 M_{sun}
We expect therefore to have a large number of cases in which the prompt collapse occurs.

Conversion of a cold, non-rotating hadronic star
(Pagliara et al 2013)

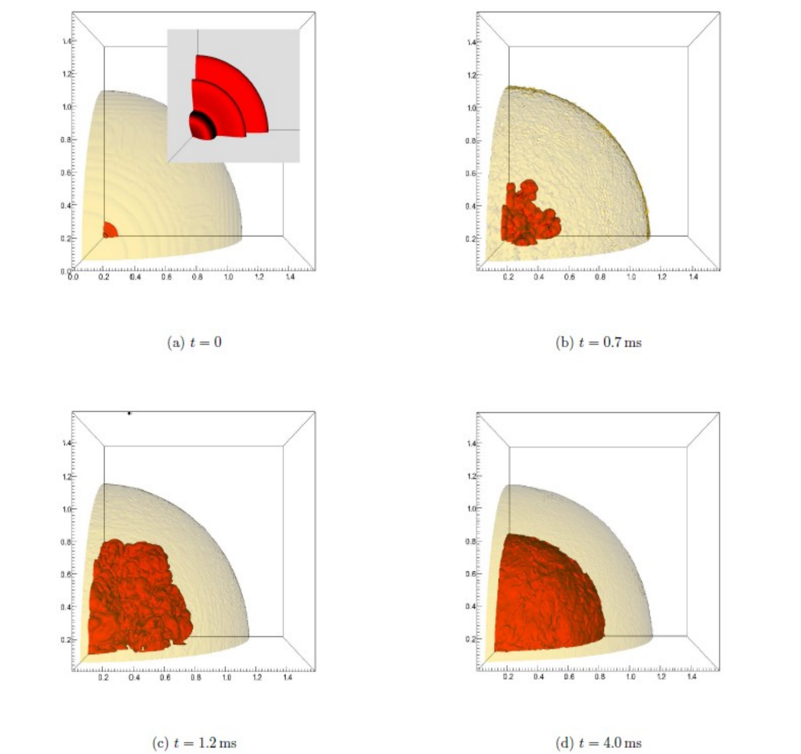
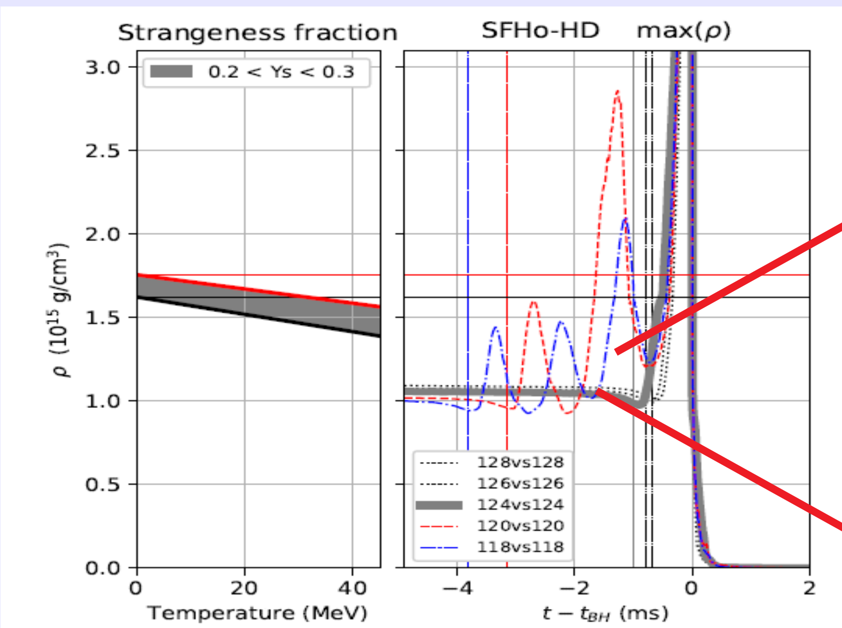


FIG. 8. (color online) Model B150_192: Conversion front (red) and surface of the neutron star (yellow) at different times t. In (a) a close-up of the central region is added. Spatial units 10^6 cm.

M_{tot} <   the threshold mass

When a prompt collapse is not realised, the remnant lives for a time scale larger than about a few ms, the formation of hyperons would trigger the conversion to quark matter which helps to stabilize the star and would result in a dramatic change of its structure.



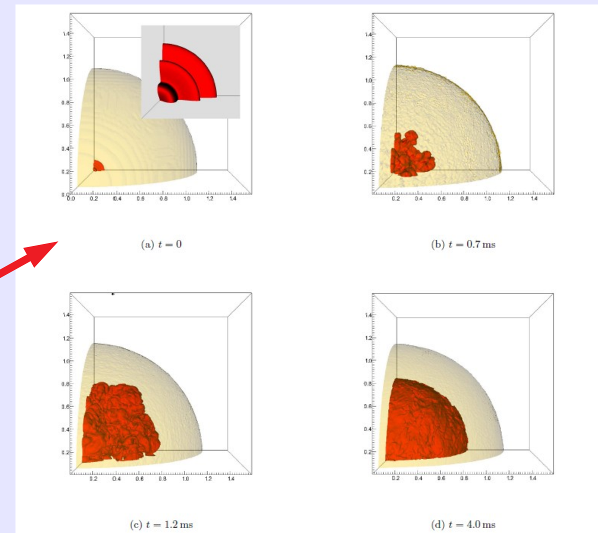
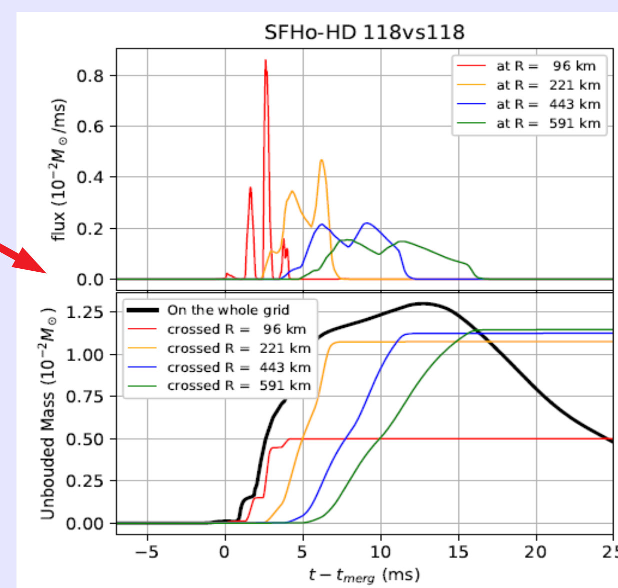


FIG. 8. (color online) Model B150_192: Conversion front (red) and surface of the neutron star (yellow) at different times t. In (a) a close-up of the central region is added. Spatial units 10^6 cm.

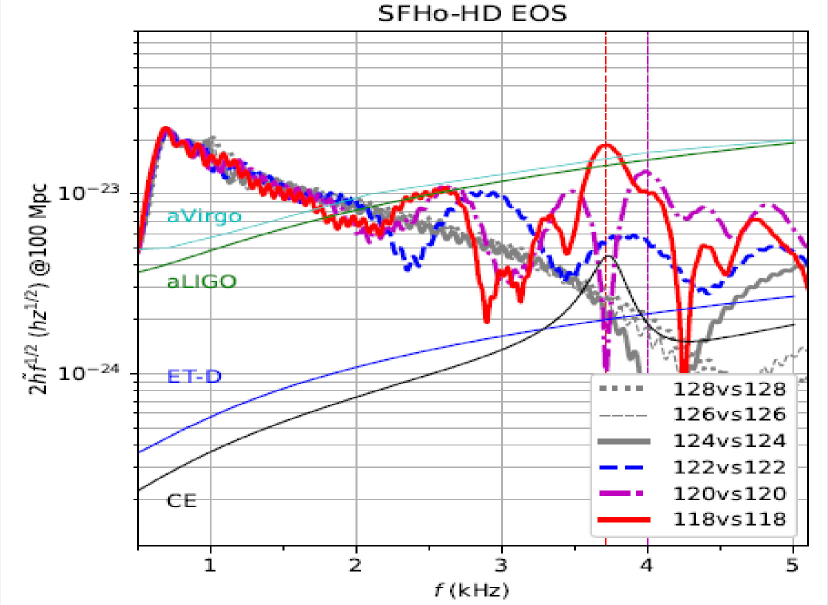
Turbulent conversion of the star (PRD87 (2013), 103007)

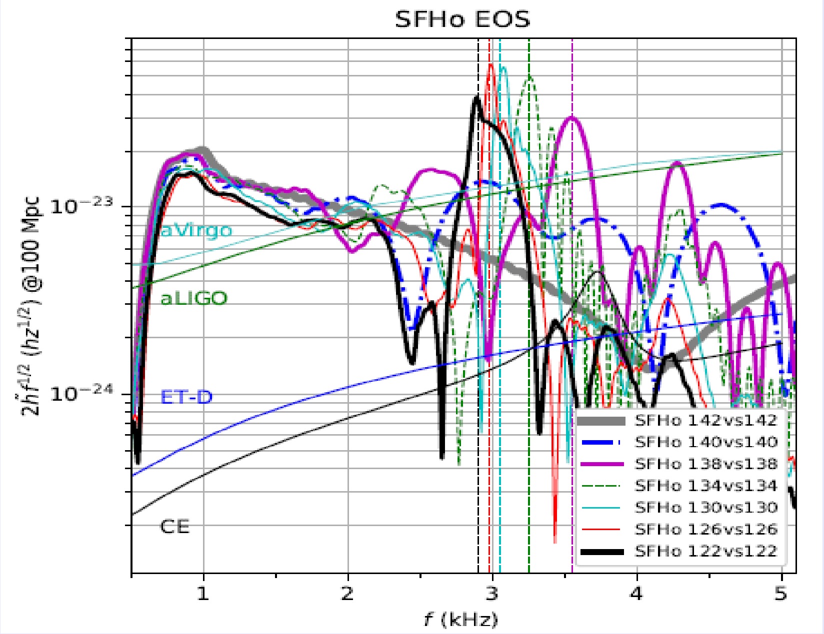


Oscillations of the remnant are associated with outward propagating shocks which drive matter ejection

Postmerger GWs

If the postmerger signal will be detected in the future:
For HS-HS systems the frequency of the f_2 mode is about 1kHz higher than the frequency of the same mode in the case of the one-family scenario (SFHo) and it should evolve towards smaller frequencies during the formation of the quark star.





Strangelets released by the merger

Bucciantini et al. 1908.02501

1)Condition to create a fragment: Weber number We larger than 1. We=$(\rho/\sigma)\, v^2_{turb}\, d$ (mass density, surface tension, turbulent velocity and drop size). By assuming v^2_{turb} to scale (Kolmogorov) with $v^2_0\ (d/d_0)^{5/3}$ where d_0 ~1km and v_0 ~0.1c , we obtain d ~1mm and thus A ~ 10^{39} very big fragments. Those fragments are part of the tidal ejecta (cold matter, order of 10^{-4} M_{sun}) , the corresponding flux is so small that it is very unlikely to directly detect strangelets or to allow for capture by MS stars.

2) Ejecta produced by the shock waves and evaporation of the accretion torus. Several processes: neutron evaporation and absorption, neutrino cooling and absorptpion, chemical unbalances w.r.t. the strangeness...

$$\frac{dA}{dt} = \Big[\frac{m_n T_s^2}{2\pi^2} e^{-\frac{I}{T_s}} - N_n \Big(\frac{T_s}{2\pi m_n}\Big)^{\frac{1}{2}}\Big](f_n + f_p)\sigma_0 A^{\frac{2}{3}}$$

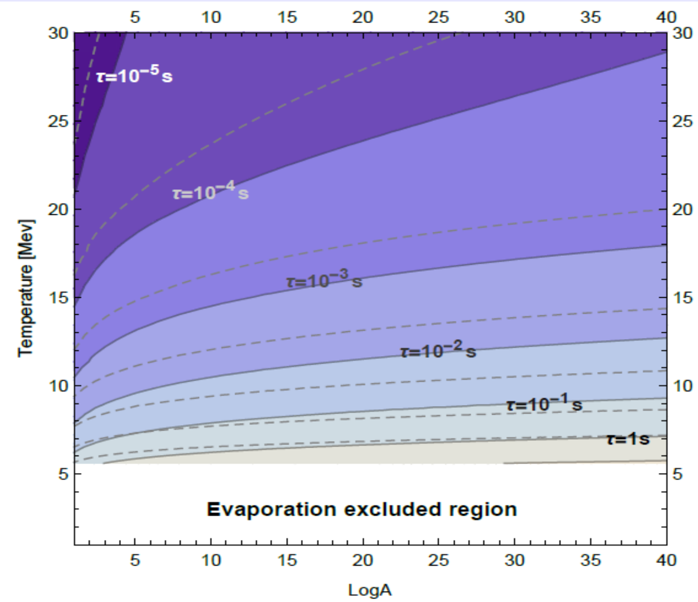


FIG. 3: Evaporation time-scale computed by assuming that neutrino absorption is the only re-heating mechanism and that the nucleon density is determined by the evaporated nucleons. Solid lines and color shading refer to $I = 50\,\mathrm{MeV}$, the dashed lines correspond to $I = 70\,\mathrm{MeV}$.

For T<5MeV neutron reabsorption dominates over evaporation.

T>5 MeV: efficient evaporation (time scales of ms) for the typical temperatures reached in shock heated material.

Parameters space of two-families

Drago et al, Astr.Nach. 2019

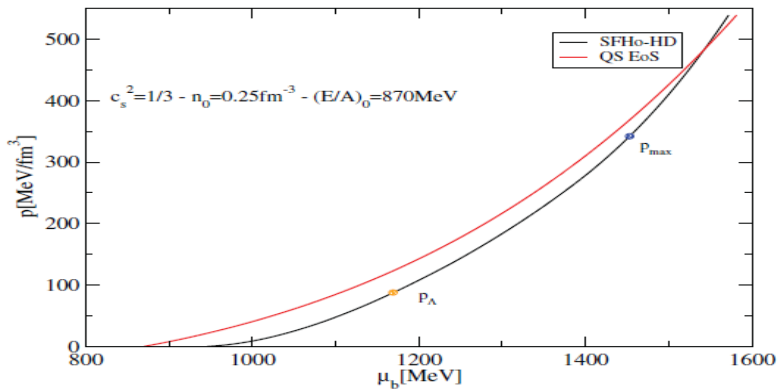


FIGURE 1 Comparison between the equation of state (EoS) of hadronic matter and of quark matter (with a specific choice of the free parameters of the model). The blue and the orange points on the hadronic EoS correspond to the central pressure of the maximum mass hadronic configuration and to the onset of formation of hyperons, respectively

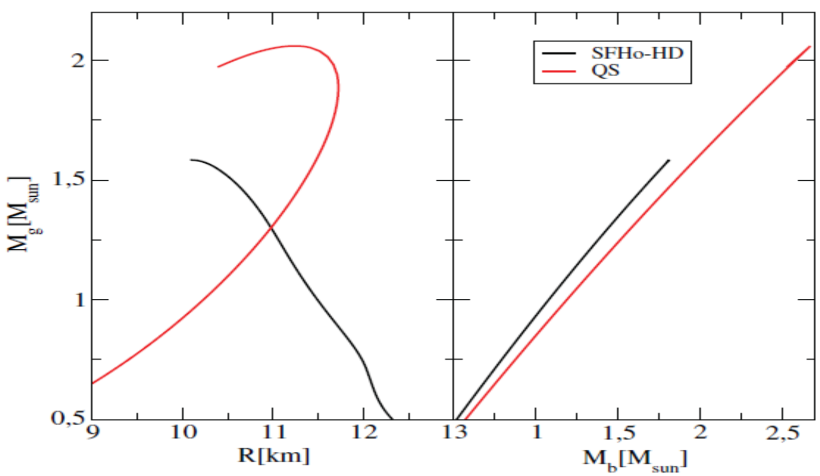


FIGURE 2 Left panel: mass radius curves of HSs and QSs (same parameters of Figure 1). Right panel: relations between gravitational mass and baryonic mass for HSs and QSs. While radii of QSs could be smaller or larger than the radii of HSs at fixed gravitational mass, at fixed baryonic mass QSs are always lighter than HSs and thus energetically favored

A simple study with constant speed of sound quark matter

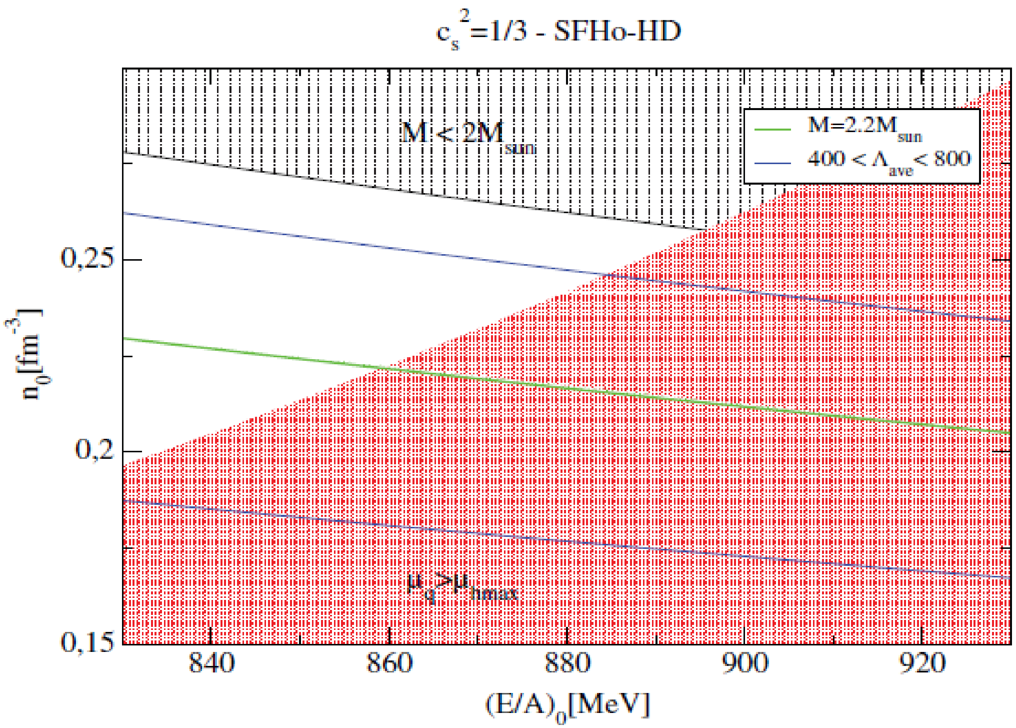


FIGURE 3 Parameter space of the two-families scenario with constant-speed-of-sound quark equation of state with $c_s^2 = 1/3$. The black and red areas are excluded (see text). The green line determines the parameters for which the maximum mass is $2.2M_\odot$ and the blue box encloses the values for which the two-families scenario is in agreement with the data on the average tidal deformability obtained from the analysis of GW170817

Constraints from the amount of matter ejected

Comparison between a soft and stiff equation of state (Shibata et al 2017)

TABLE I. Equations of state employed, the maximum mass for cold spherical neutron stars, $M_{\max}$, in units of the solar mass, the radius, R_M, and the dimensionless tidal deformability Λ_M of spherical neutron stars of gravitational mass $M = 1.20$, 1.30, 1.40, and $1.50 M_\odot$. R_M is listed in units of km. The last five data show the binary tidal deformability for $\eta = 0.250$, 0.248, 0.246, 0.244, and 0.242 with $\mathcal{M} = 1.19 M_\odot$.

EOS	$M_{\max}$	$R_{1.20}$	$R_{1.30}$	$R_{1.40}$	$R_{1.50}$	$\Lambda_{1.20}$	$\Lambda_{1.30}$	$\Lambda_{1.40}$	$\Lambda_{1.50}$	Λ
SFHo	2.06	11.96	11.93	11.88	11.83	864	533	332	208	388, 387, 387, 386, 385
DD2	2.42	13.14	13.18	13.21	13.24	1622	1053	696	467	797, 788, 780, 772, 764

TABLE II. Merger remnants and properties of dynamical ejecta for two finite-temperature neutron-star EOS, SFHo and DD2 and for the cases with different mass. The quantities for the remnants are determined at ≈ 30 ms after the onset of merger. HMNS, BH, and MNS denote hypermassive neutron star, black hole, and massive neutron star, respectively. The torus mass for the DD2 EOS is determined from the mass located outside the central region of MNS with density $\rho \le 10^{13}\,\mathrm{g/cm^3}$. The values of mass are shown in units of $M_\odot$. The BH spin means the dimensionless spin of the remnant black hole. Y_e and $\bar{v}_{\rm ej}$ are the average value of the electron fraction, Y_e, and average velocity of the dynamical ejecta, respectively. We note that Y_e is broadly distributed between ~ 0.05 and ~ 0.5, irrespective of the models (see Refs. [34, 35]).

EOS	m_1 & m_2	m_2/m_1	Remnant	BH mass	BH spin	Torus mass	$M_{\rm ej}$	Y_e	$\bar{v}_{\rm ej}/c$
SFHo	1.35, 1.35	1.00	HMNS $\to$ BH	2.59	0.69	0.05	0.011	0.31	0.22
SFHo	1.37, 1.33	0.97	HMNS $\to$ BH	2.59	0.70	0.06	0.008	0.30	0.21
SFHo	1.40, 1.30	0.93	HMNS $\to$ BH	2.58	0.67	0.09	0.006	0.27	0.20
SFHo	1.45, 1.25	0.86	HMNS $\to$ BH	2.58	0.69	0.12	0.011	0.18	0.24
SFHo	1.55, 1.25	0.81	HMNS $\to$ BH	2.69	0.76	0.07	0.016	0.13	0.25
SFHo	1.65, 1.25	0.76	BH	2.76	0.77	0.09	0.007	0.16	0.23
DD2	1.35, 1.35	1.00	MNS	—	—	0.23	0.002	0.30	0.16
DD2	1.40, 1.30	0.93	MNS	—	—	0.23	0.003	0.26	0.18
DD2	1.45, 1.25	0.86	MNS	—	—	0.30	0.005	0.20	0.19
DD2	1.40, 1.40	1.00	MNS	—	—	0.17	0.002	0.31	0.16

THE ELECTROMAGNETIC COUNTERPART OF THE BINARY NEUTRON STAR MERGER LIGO/VIRGO GW170817.
III. OPTICAL AND UV SPECTRA OF A BLUE KILONOVA FROM FAST POLAR EJECTA

M. Nicholl[1], E. Berger[1], D. Kasen[2,3], B. D. Metzger[4], J. Elias[5], C. Briceño[6], K. D. Alexander[1], P. K. Blanchard[1], R. Chornock[7], P. S. Cowperthwaite[1], T. Eftekhari[1], W. Fong[8], R. Margutti[8], V. A. Villar[1], P. K. G. Williams[1], W. Brown[1], J. Annis[9], A. Bahramian[10], D. Brout[11], D. A. Brown[12], H.-Y. Chen[13], J. C. Clemens[14], E. Dennihy[14], B. Dunlap[14], D. E. Holz[15,13,16,17], E. Marchesini[18,19,20,21,22], F. Massaro[20,21,23], N. Moskovitz[24], I. Pelisoli[25,26], A. Rest[27,28], F. Ricci[29,1], M. Sako[11], M. Soares-Santos[9,30], J. Strader[10]

Computations of mass ejected not yet completely under control: for instance the neutrino transport is modeled by simple leakage schemes.

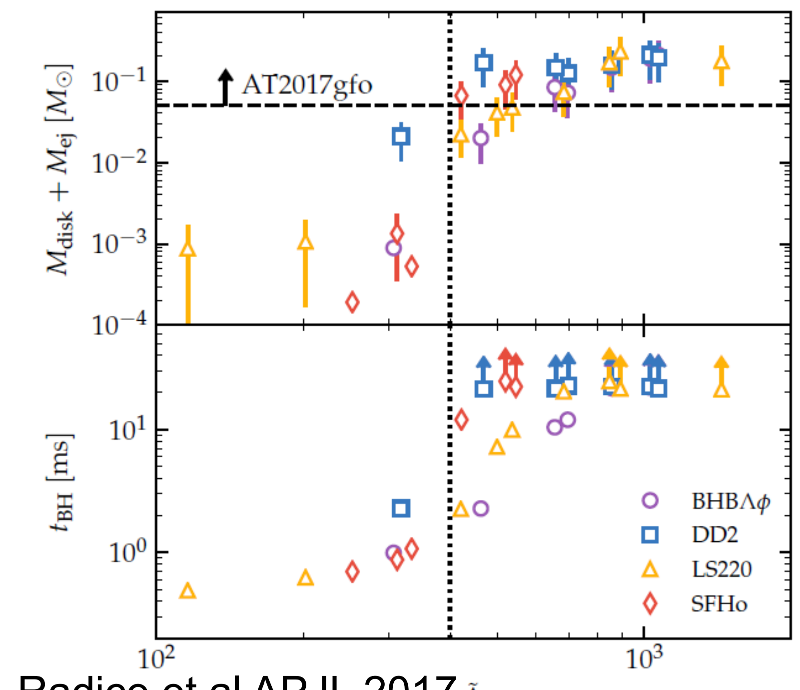
ABSTRACT

We present optical and ultraviolet spectra of the first electromagnetic counterpart to a gravitational wave (GW) source, the binary neutron star merger GW170817. Spectra were obtained nightly between 1.5 and 9.5 days post-merger, using the SOAR and Magellan telescopes; the UV spectrum was obtained with the *Hubble Space Telescope* at 5.5 days. Our data reveal a rapidly-fading blue component ($T \approx 5500$ K at 1.5 days) that quickly reddens; spectra later than $\gtrsim 4.5$ days peak beyond the optical regime. The spectra are mostly featureless, although we identify a possible weak emission line at ~ 7900 Å at $t \lesssim 4.5$ days. The colours, rapid evolution and featureless spectrum are consistent with a "blue" kilonova from polar ejecta comprised mainly of light r-process nuclei with atomic mass number $A \lesssim 140$. This indicates a sight-line within $\theta_{\rm obs} \lesssim 45°$ of the orbital axis. Comparison to models suggests $\sim 0.03\,\mathrm{M_\odot}$ of blue ejecta, with a velocity of $\sim 0.3c$. The required lanthanide fraction is $\sim 10^{-4}$, but this drops to $< 10^{-5}$ in the outermost ejecta. The large velocities point to a dynamical origin, rather than a disk wind, for this blue component, suggesting that both binary constituents are neutron stars (as opposed to a binary consisting of a neutron star and a black hole). For dynamical ejecta, the high mass favors a small neutron star radius of $\lesssim 12$ km. This mass also supports the idea that neutron star mergers are a major contributor to r-process nucleosynthesis.

Average tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_A}{(M_A + M_B)^5} + (A \leftrightarrow B)\right]$$

From numerical simulations: an empirical relation between the average tidal deformability and the sum of the mass ejected and the mass of the accreting disk.
Estimate of the lower limit on the average tidal deformability ~ 400



Radice et al APJL 2017

Use of chiral effective theory results for subsaturation densities and pQCD calculations at (very) high densities and interpolate between them with pieceweise polytropes

$2M_{sun}$ limit and constraints on the tidal deformability obtained with GW170817 : 400< Λ <800 for a 1.4 M_{sun} .

Its radius **12.2km<$R_{1.4}$ <13.4km**

(tension with small radii measurements)

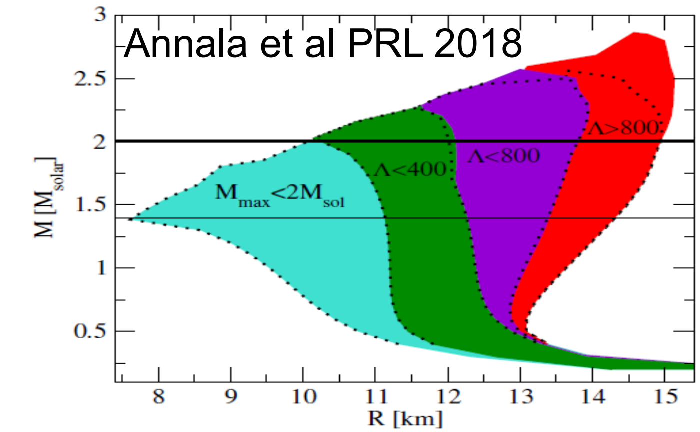
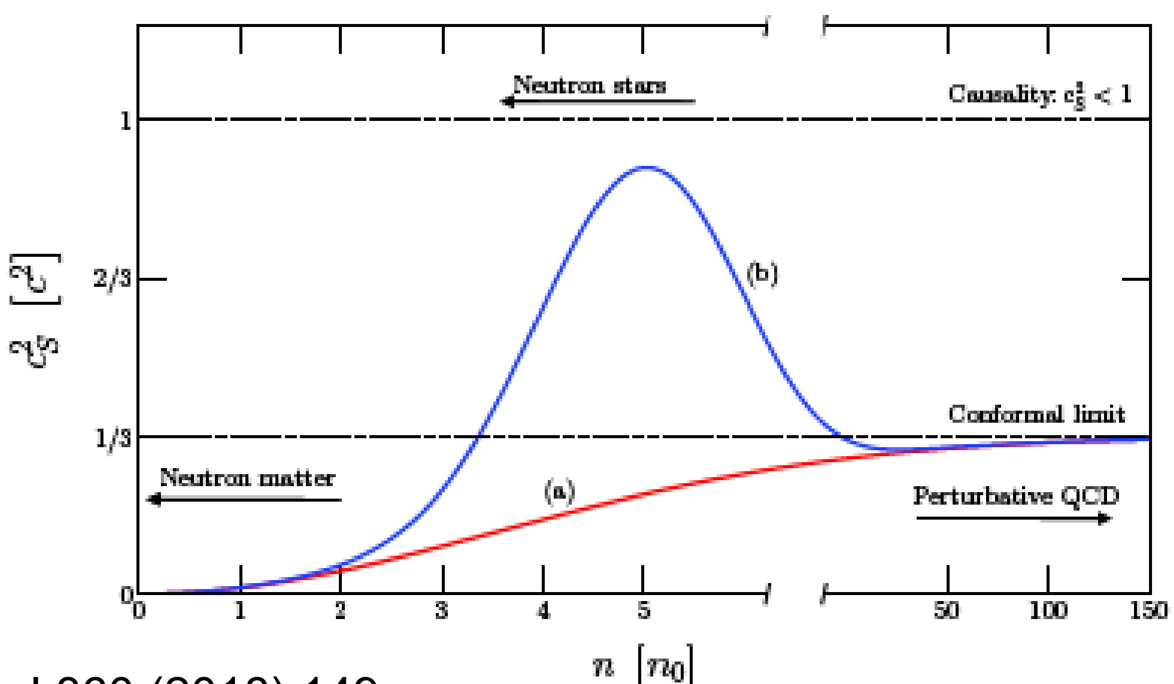


FIG. 1: The mass-radius clouds corresponding to our EoSs. The cyan area corresponds to EoSs that cannot support a $2M_\odot$ star, while the rest denote EoSs that fulfill this requirement and in addition have $\Lambda(1.4M_\odot) < 400$ (green), $400 < \Lambda(1.4M_\odot) < 800$ (violet), or $\Lambda(1.4M_\odot) > 800$ (red), so that the red region is excluded by the LIGO/Virgo measurement at 90% credence. This color coding is used in all of our figures. The dotted black lines denote the result that would have been obtained with bitropic interpolation only.

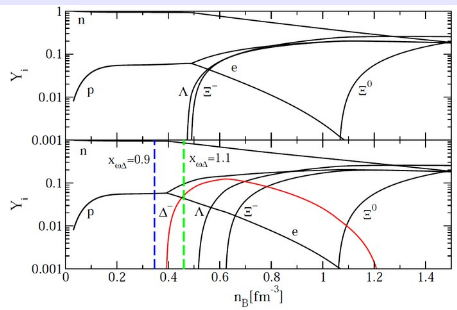
Speed of sound



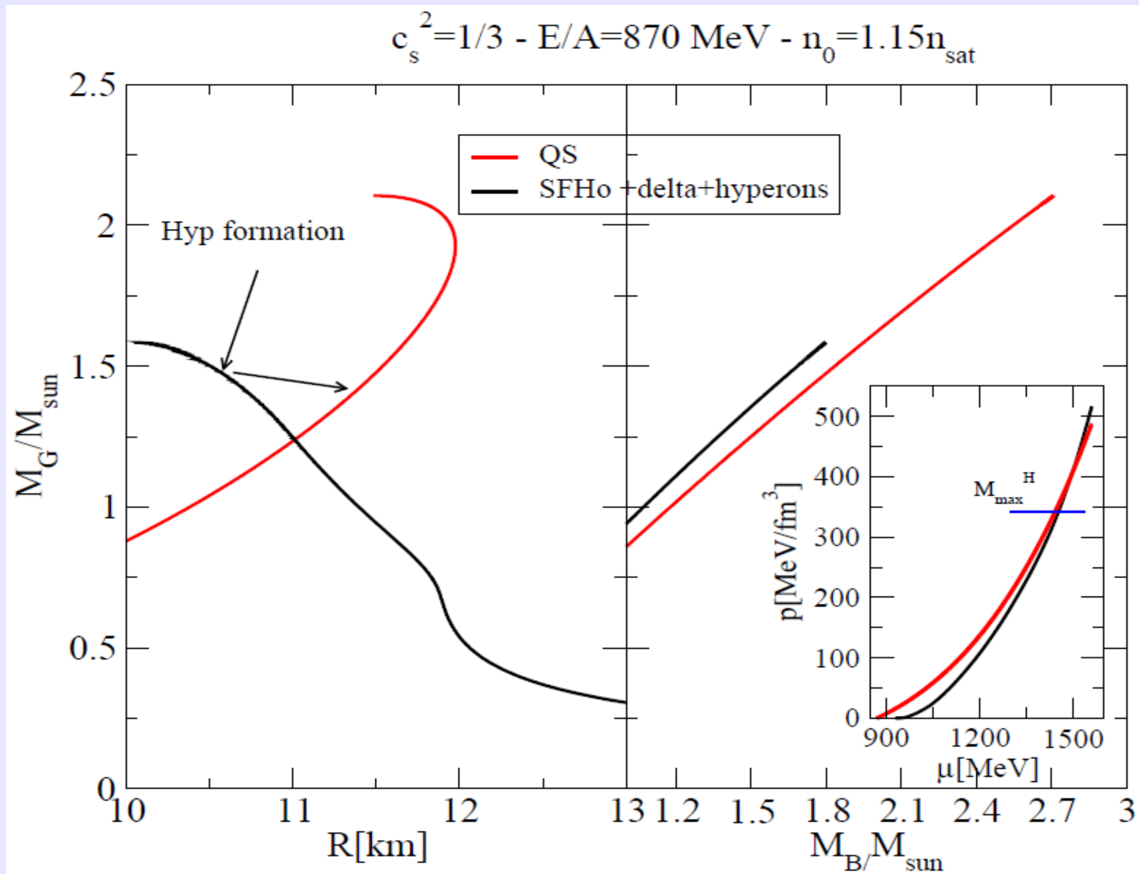
ApJ 860 (2018) 149

Two families of compact stars?

(exercise with constant speed of sound quark EoS, Dondi et al 2016)



RMF model for hadronic matter



Three parameters: Speed of sound, energy density and baryon density at pressure=0

$$p = c_s^2(e - e_0)$$

$$k = \frac{e_0 c_s^2}{1+c_s^2}$$

$$p = k((n/n_0)^{1+c_s^2} - 1)$$

Hadronic stars would fulfill the small radii limits while strange stars would fulfill the large masses limits. Note: at fixed baryon mass, strange stars could be energetically convenient even if the radius is larger than the corresponding hadronic star configuration.

... is this surprising?

Also at finite density the quark matter equation of state could be stiffer than the hadronic equation of state in which new particles are produced as the density increases

Heavy ions physics: **(Kolb & Heinz 2003)**

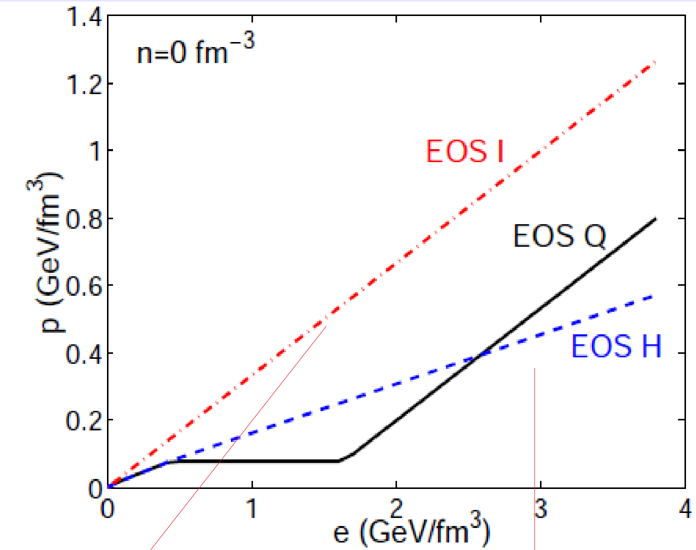


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

Hadron resonance gas p=e/6