

Merger of two compact stars within the two-families scenario

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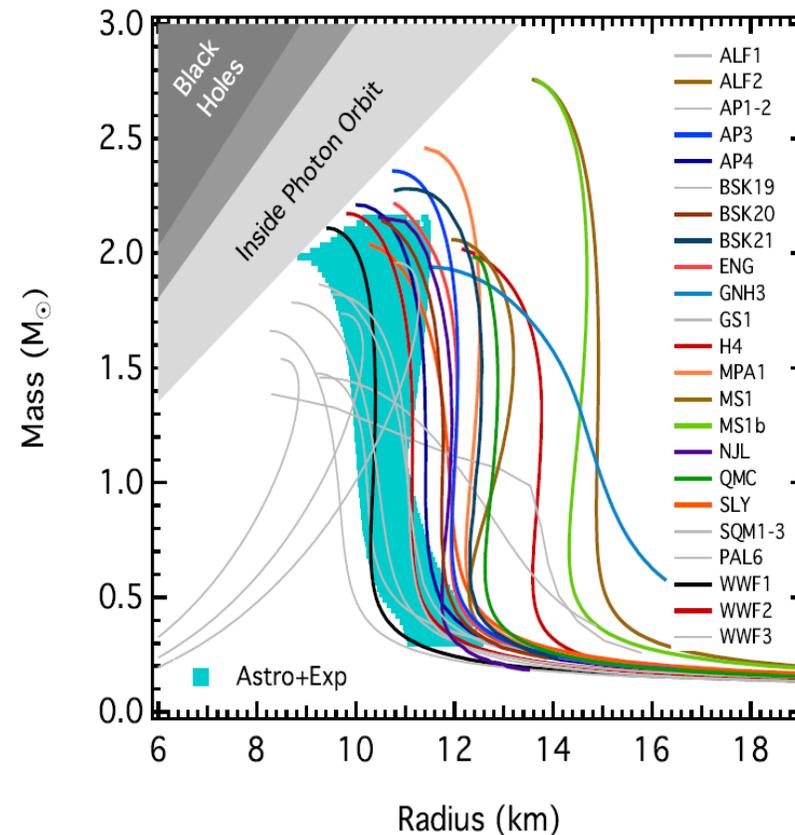
Outline

- What is the two-families scenario?
- Comparison with the twin-stars scenario
- What did we learn from GW170817/AT2017gfo/GRB170817a?
 - Why was it a hadronic-star quark-star merger?
- Classification of mergers within the two-families scenario
- Clear cut prediction → HS-HS undergoes a prompt collapse to BH for a total mass smaller than the one of GW170817
- First results from merger simulations: large amount of mass ejected by shock wave in case of HS-HS merger
- Predictions for NICER and SKA

- 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
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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?

Radii from x-ray spectra

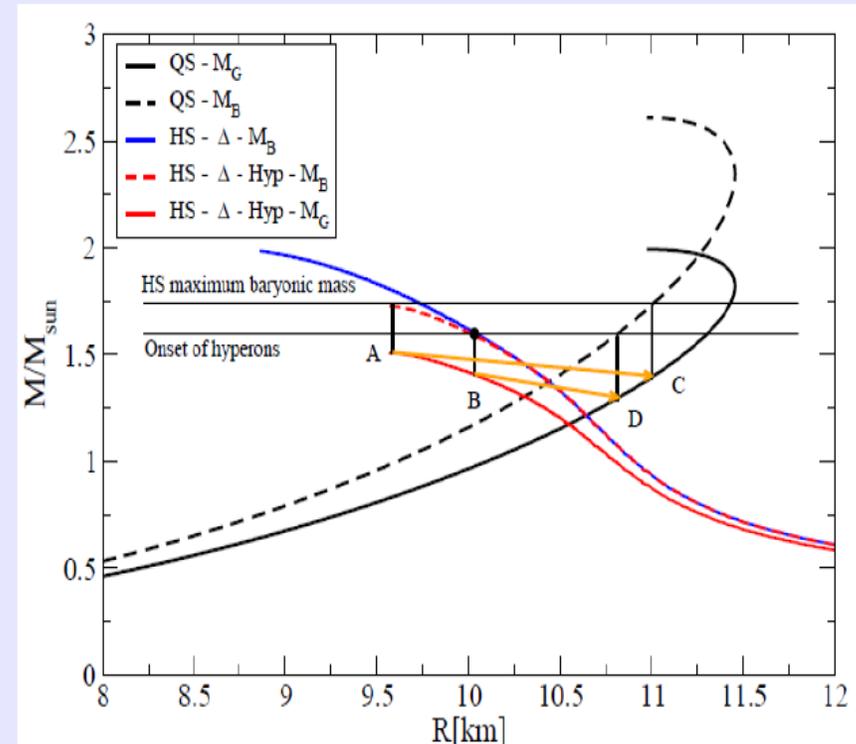
Oezel and Freire, Ann.Rev.Astron.Astrophys. 54 (2016) 401



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»

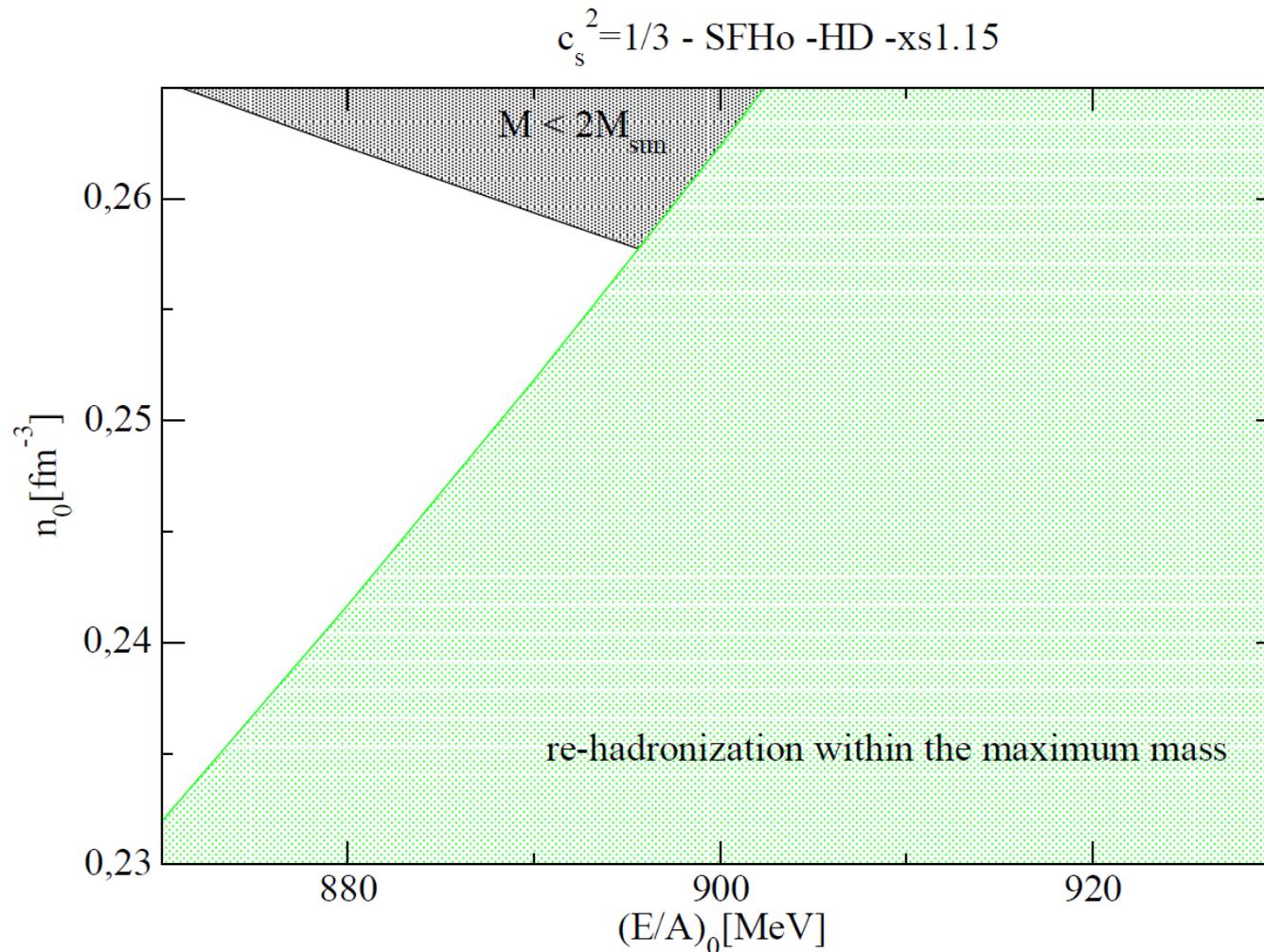
Very small radii, $R_{1.4} < (11.5 - 12)$ km: two-families of compact stars?

Main hypothesis: the ground state of nuclear matter is strange quark matter.
Hadronic stars are metastable and, under some specific conditions, convert into strange quark stars (at fixed baryonic mass the gravitational mass of strange quark stars is smaller).
Hadronic stars and strange quark stars would populate two separated branches.
Heavy stars ($2M_{\text{sun}}$) are strange quark stars.



Observations will tell the maximum mass of the strange quark star family.
GW170817/AT2017gfo/GRB170817a suggests a value of about $(2.1-2.2) M_s$

Parameters fixing in the two-families: an example using constant speed of sound in the quark phase



The condition for quantum nucleation of quark matter droplets inside hadronic matter (to be used at $T < \text{a few tens MeV}$) is:

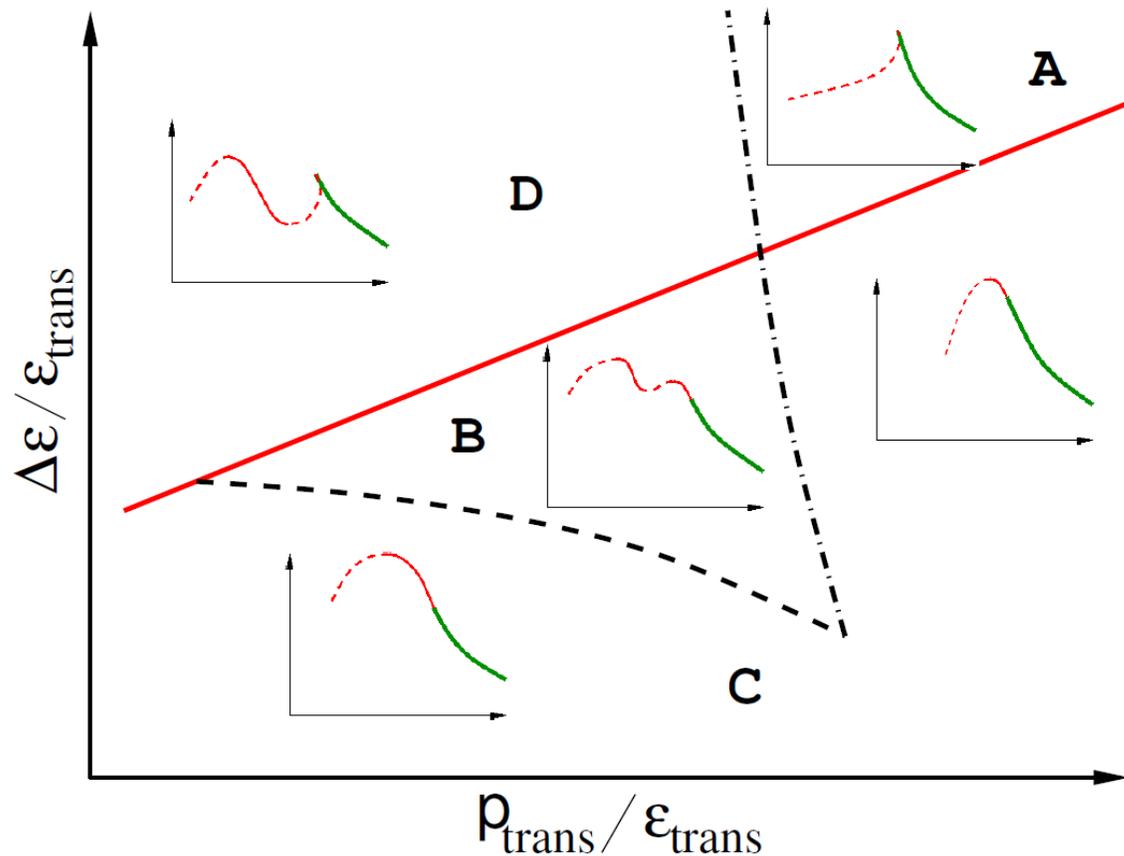
$$\mu_Q < \mu_H \quad \text{at a same pressure } P$$

If this condition is not satisfied nucleation would go in the opposite direction: one would get re-hadronization

One needs also to check that the strangeness fraction in the hadronic phase is large enough to allow quantum nucleation of quark droplets

Comparing with the twin-stars scenario: classification of all possible hybrid stars

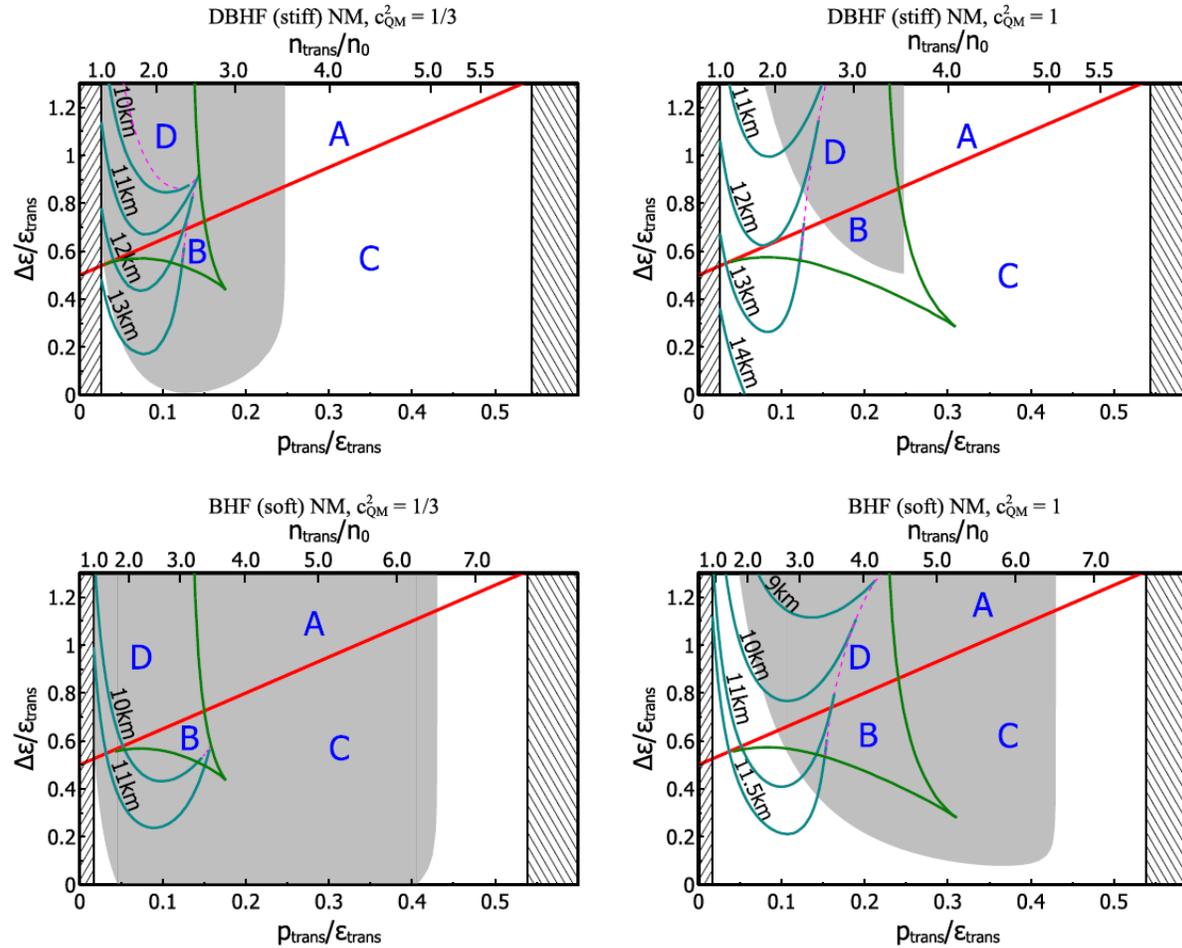
From Alford, Han, Prakash, Phys.Rev. D88 (2013) 083013



Note that in B and D the formation of quarks triggers the instability, i.e. quarks are at the origin of the instability producing the formation of the second configuration. At variance, in the two-families scenario the first family becomes unstable while quark are not yet present. The quark matter phase stabilizes the system.

Small radii are possible only for «twin stars» configurations

Alford, Burgio, Han, Taranto, Zappalà, PRD92 (2015) 083002

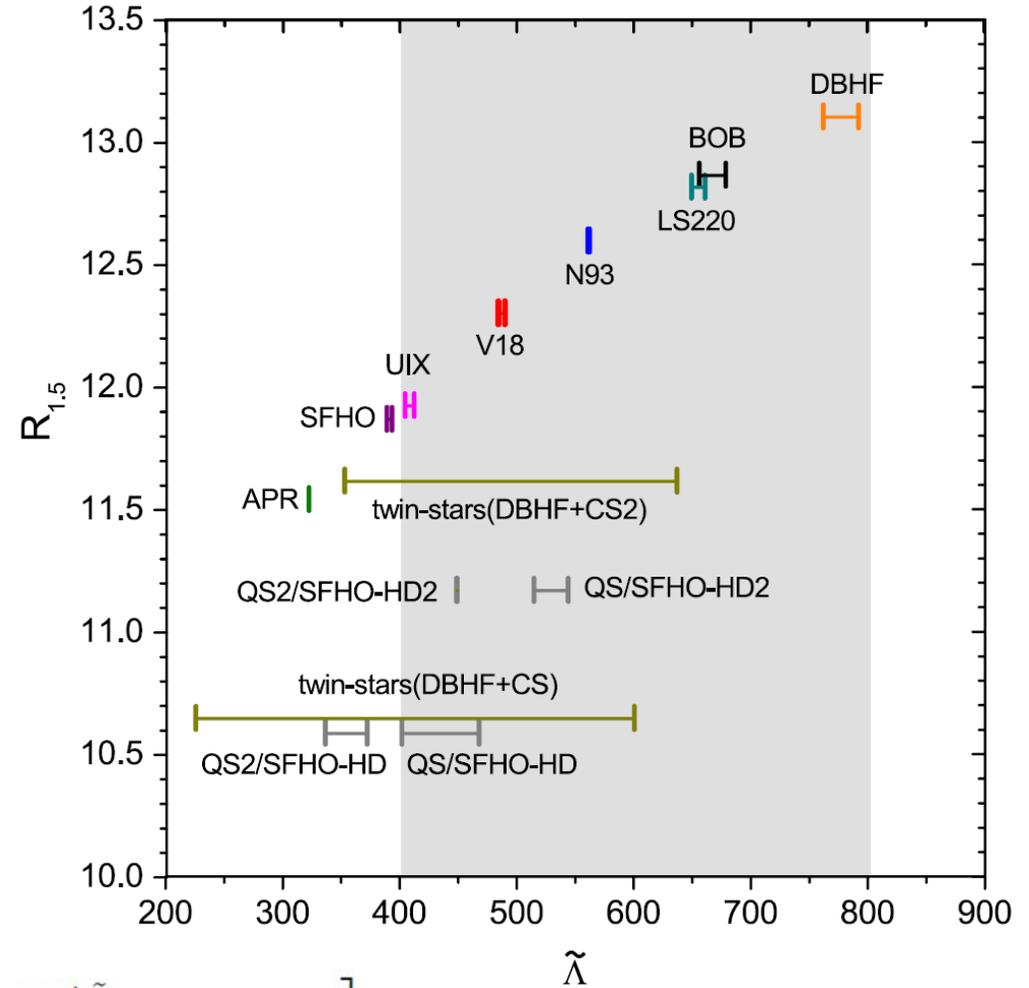
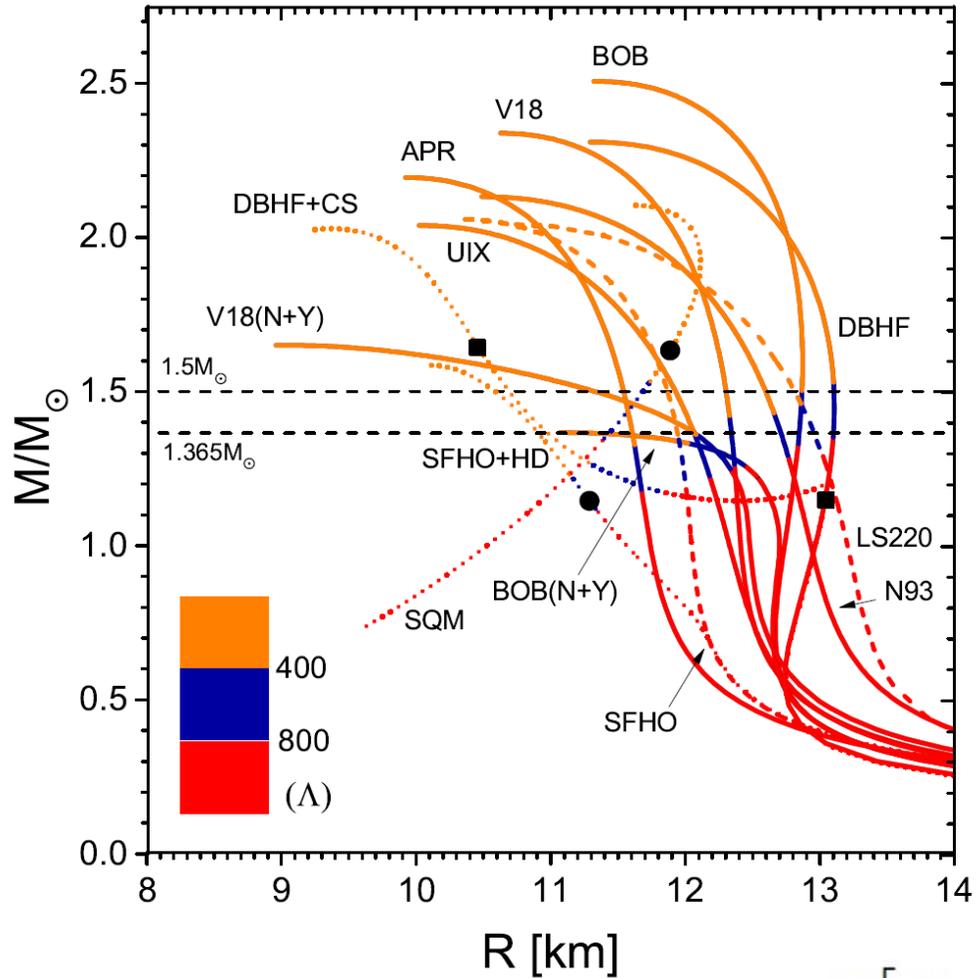


Radii smaller than about 11.5 km for stars of $M = 1.4 M_{\odot}$ are possible ONLY if c^2 is close to 1.

FIG. 4: (Color online). Contour plots similar to Fig. 3 showing the radius of a hybrid star of mass $M = 1.4 M_{\odot}$ as a function of the CSS parameters. Such stars only exist in a limited region of the space of EoSs [delimited by dashed (magenta) lines]. The grey shaded region is excluded by the observational constraint $M_{\max} > 2 M_{\odot}$. For a magnified version of the low-transition-pressure region for $c_{\text{QM}}^2 = 1/3$, see Fig. 5.

Average tidal deformability and radii

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



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

Total mass of the merger and possible outcomes. Crucial input parameters: M^H_{TOV} and M^Q_{TOV}

From those two numbers (and the corresponding EoSs) one can derive the maximum mass for the supramassive configuration and the threshold mass (above which there is a direct collapse to a BH)

An example:

$$\begin{array}{lll} M^H_{\text{TOV}} = 1.6 M_{\odot} & M^H_{\text{supra}} = 1.6 M_{\odot} \times 1.2 = 1.92 M_{\odot} & M^H_{\text{threshold}} = 2.48 M_{\odot} \text{ (from simulations)} \\ M^Q_{\text{TOV}} = 2.1 M_{\odot} & M^Q_{\text{supra}} = 2.1 M_{\odot} \times 1.44 = 3.024 M_{\odot} & M^Q_{\text{threshold}} \text{ only slightly larger than } M^Q_{\text{supra}} \\ M^{\text{Hyb}}_{\text{TOV}} = M^Q_{\text{TOV}} = 2.1 M_{\odot} & M^{\text{Hyb}}_{\text{supra}} = 2.6 M_{\odot} & M^{\text{Hyb}}_{\text{threshold}} \text{ not known} \end{array}$$

The «hybrid» configuration corresponds to the mechanically stable – chemically unstable configuration that forms after the few ms needed to burn the central region of the star. After that rapid burning the process of combustion of hadrons into quarks is much slower (order of seconds).

Possible types of mergers in the two-families scenario

- HS-HS

- For $M_{\text{tot}} > M_{\text{th}} \sim 2.48 M_s$ there is direct collapse to a BH
- For $M_{\text{tot}} < M_{\text{th}} \sim 2.48 M_s$ sGRB via the protomagnetar scheme
 - Possibility of extended emission and quasi-plateau
 - Large value of mass ejected by the shock, not very massive disk

- HS-QS

- For $M_{\text{tot}} > M_{\text{th}} \sim 3.1 M_s$ there is direct collapse to a BH
- For $2.6 M_s < M_{\text{tot}} < M_{\text{th}} \sim 3.1 M_s$ sGRB via BH and torus
 - No extended emission and no quasi plateau
 - Smaller value of mass ejected by the shock, massive disk
- For $M_{\text{tot}} < 2.6 M_s$ sGRB via the protomagnetar scheme
 - Possibility of extended emission and quasi-plateau
 - Smaller value of mass ejected by the shock, massive disk

- QS-QS

- For $M_{\text{tot}} > M_{\text{th}} \sim 3.1 M_s$ there is direct collapse to a BH
- For $M_{\text{tot}} < M_{\text{th}} \sim 3.1 M_s$ sGRB à la Haensel, Paczinski, Amsterdamski

A very strong prediction of the two-families scenario

if $M_g \geq M_{\text{threshold}}^{\text{H}} = 2.48 M_{\odot}$

→ HS-HS direct collapses to a BH without any significant electromagnetic emission.

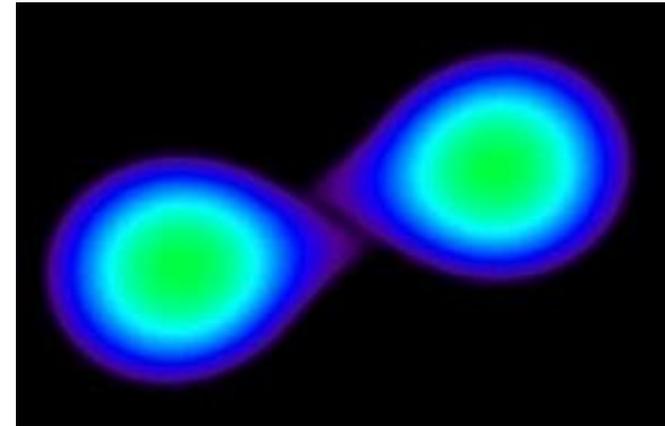
There is no equivalent in the twin-stars scenario, because the process of quark combustion is there assumed to proceed without any delay.

- In the two-families scenario quark matter production stabilizes the hadronic star configuration.
- In the twin-stars scenario quark matter production destabilizes the hadronic configuration and produces the transition to the “third family”, i.e. to the second configuration.

EJECTION MECHANISMS

➤ Dynamical ejection:

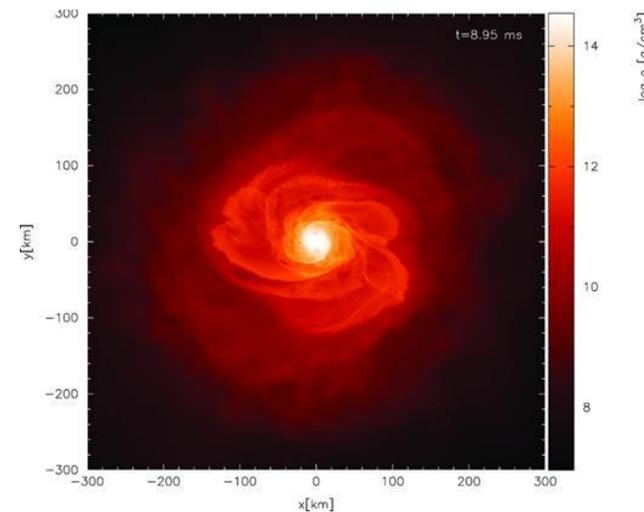
❖ Tidal deformation: equatorial plane



❖ Shock at NSs interface and radial oscillations

➤ Disk: $10^{-3} M_{\odot} < M_{disk} < 0.03 M_{\odot}$

❖ Viscous or neutrino heating



Preliminary results

R. De Pietri, A.D., A. Feo, M. Maione, G. Pagliara, S. Traversi

❖ Dynamical ejecta: SFHo $\sim 10^{-3} M_{\odot}$, H2F $\sim 5 \cdot 10^{-3} M_{\odot}$

- For softer EOS the **shock component** is more relevant
- For configurations near the threshold mass, strong **radial oscillations** can eject matter

❖ Disk: SFHo $\sim 10^{-1} M_{\odot}$, H2F $\sim 10^{-2} M_{\odot}$

- For stiff EOS the **tidal deformability** is bigger

Future observations

- New missions (NICER, LOFT), reaching a precision of ~ 1 km 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):
- $R_{1.4} \geq 13$ km or $I_{45} \geq 1.6$ purely nucleonic stars ($\rho_{\max} \leq 3 \rho_0$)
- 11.5 km $< R_{1.4} < 13$ km or $1.3 \leq I_{45} \leq 1.6$ hyperonic or hybrid stars (ρ_{\max} as large as $5 \rho_0$)
- $R_{1.4} \ll 11.5$ km or $I_{45} \ll 1.3$ two-families or twin stars
- Predictions for HS-HS mergers are completely different in the two-families scenario and in the twin-stars scenario \rightarrow possibility of distinguishing between these two schemes.