Astrophysical tests of 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 can undergo 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 for small values of M_{tot}
- 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

  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

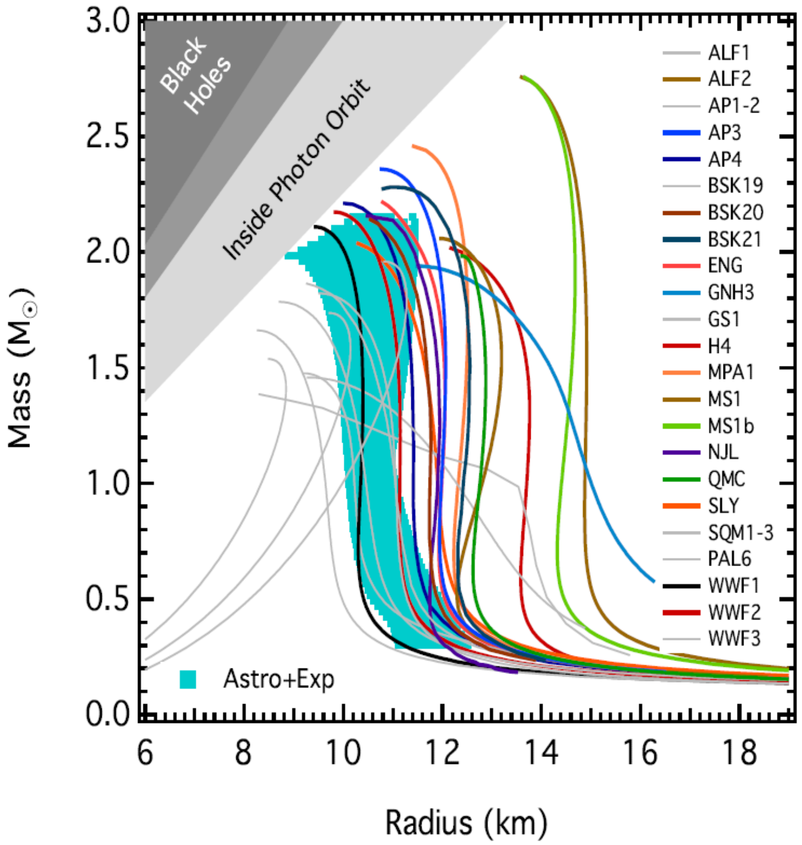
  Merger of two neutron stars: predictions from the two-families scenario
- A.D. et al., Universe 4 (2018) 50

  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, in preparation

  Merger of compact stars in the two-families scenario

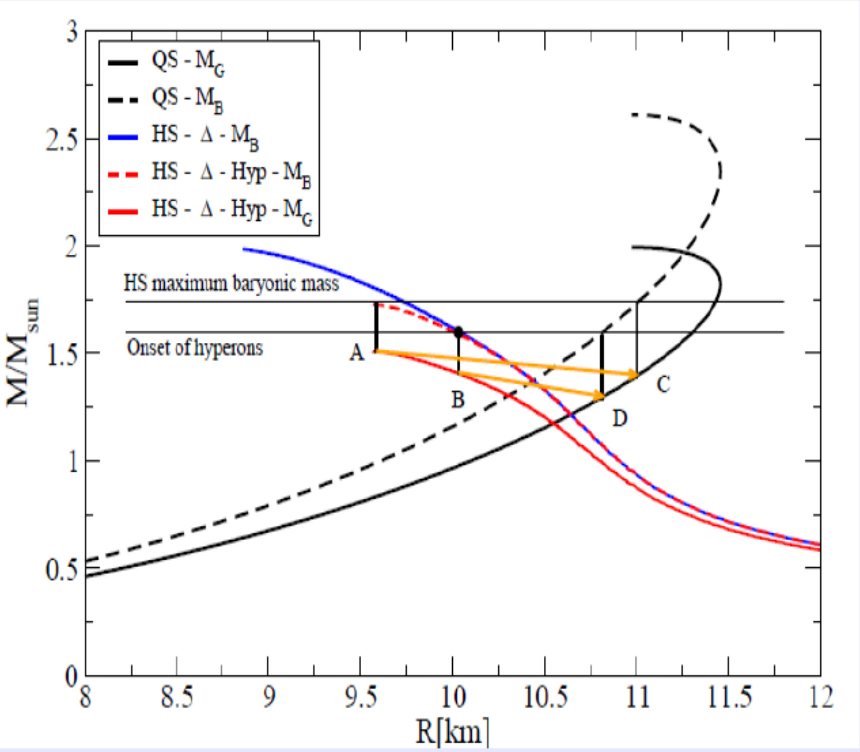
Radii from x-ray spectra
Oezel and Freire, Ann.Rev.Astron.Astrophys. 54 (2016) 401



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»

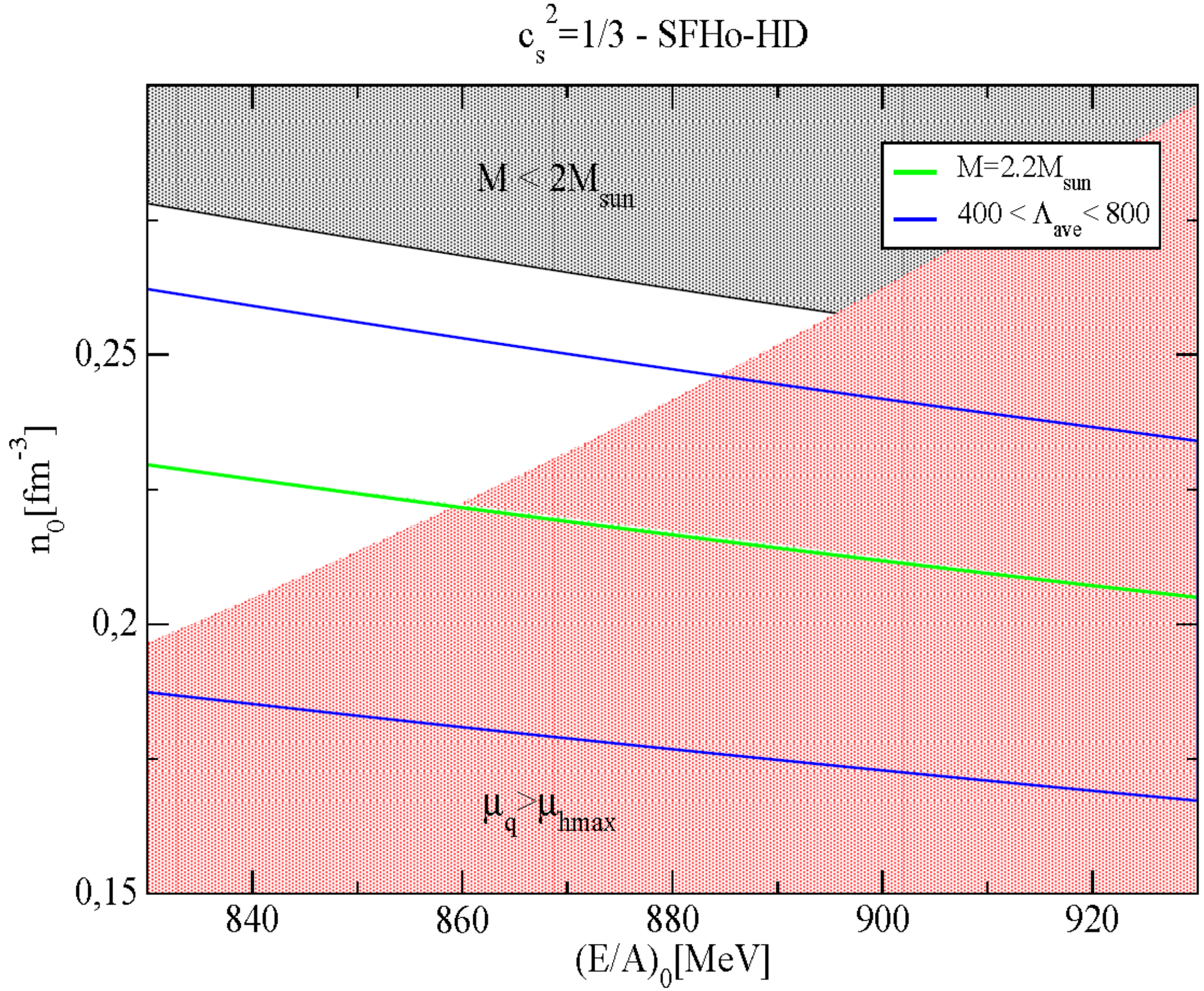
Very small radii, $R_{1.4} < (11.5 – 12)$ km: two-families of compact stars?

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 ($2M_{sun}$) are strange quark stars.



Observations will tell the maximum mass of the strange quark star family.
GW170817/AT2017gfo/GRB170817a suggests a value of about (2.2 ± 0.2) 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 < a few tens MeV) is:

$\mu_Q < \mu_H$ at a same pressure P

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

Also**, strangeness fraction in the hadronic phase must be large enough** to allow quantum nucleation of quark droplets

The merger of two NSs can produce a strange quark star

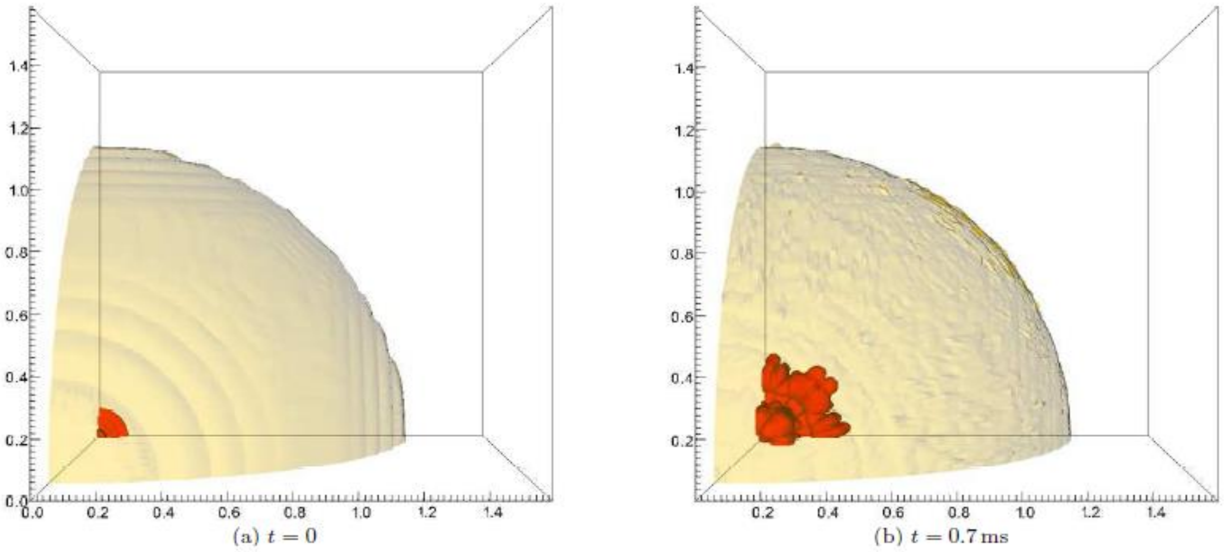
Rayleigh-Taylor instabilities develop and **the conversion of the core occurs on the time scale of ms.**

The rapid burning stops before the whole hadronic matter has converted
(the process is no more exothermic
as a hydrodynamical process,
about 0.5 Msun of unburned material)

The configuration obtained after the rapid burning is mechanically stable
although not yet in chemical equilibrium

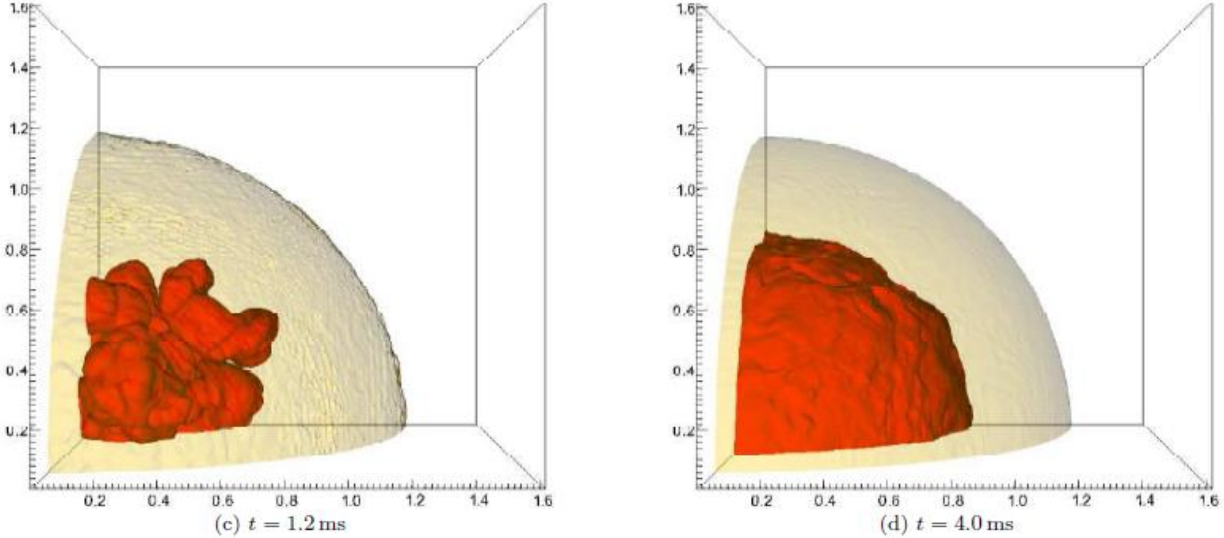
After the rapid burning the conversion proceeds via strangeness production and diffusion.

The burning reaches the surface of the star after about 10s.



(a) $t = 0$ (b) $t = 0.7\,\mathrm{ms}$

Herzog, Roepke 2011, Pagliara, Herzog, Roepke 2013

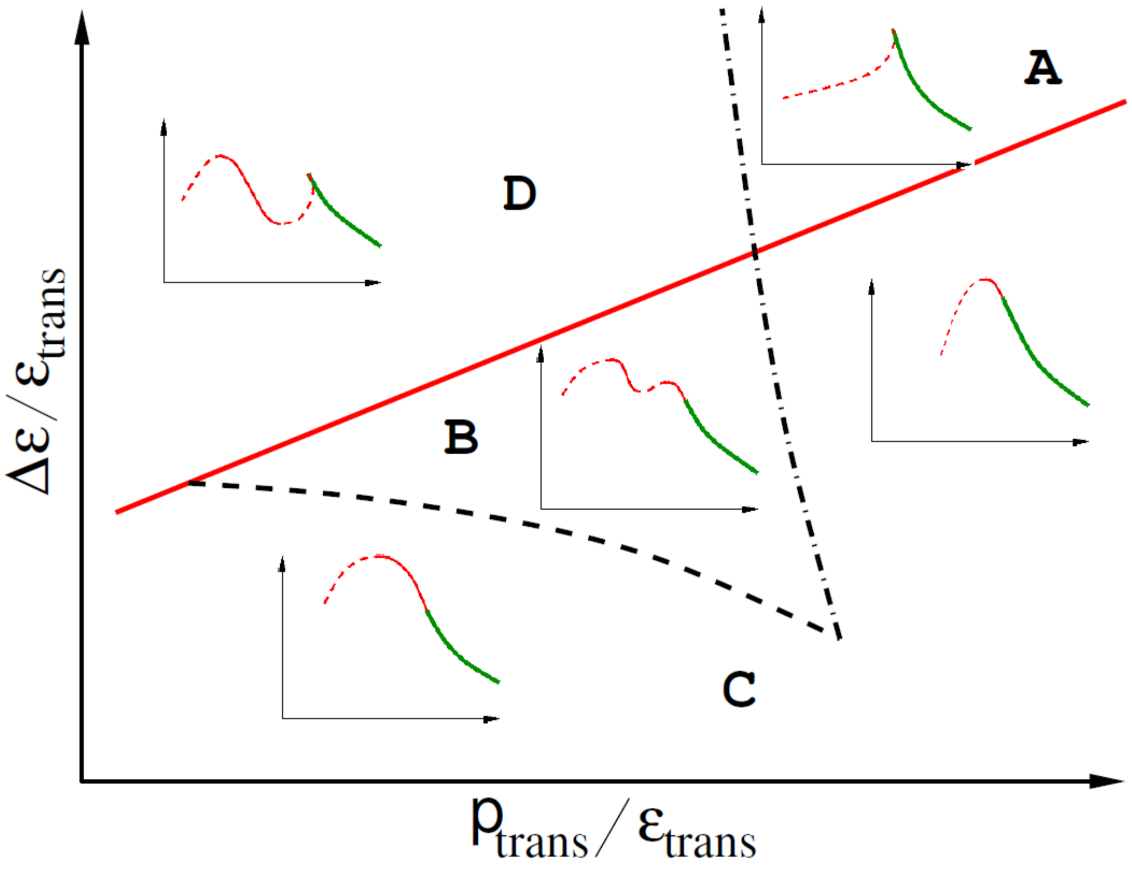


(c) $t = 1.2\,\mathrm{ms}$ (d) $t = 4.0\,\mathrm{ms}$

FIG. 1: (color online) Model: Set 1, $M = 1.4 M_\odot$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

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 stabilizies the system.

Small radii are possible for «twin stars» configurations

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

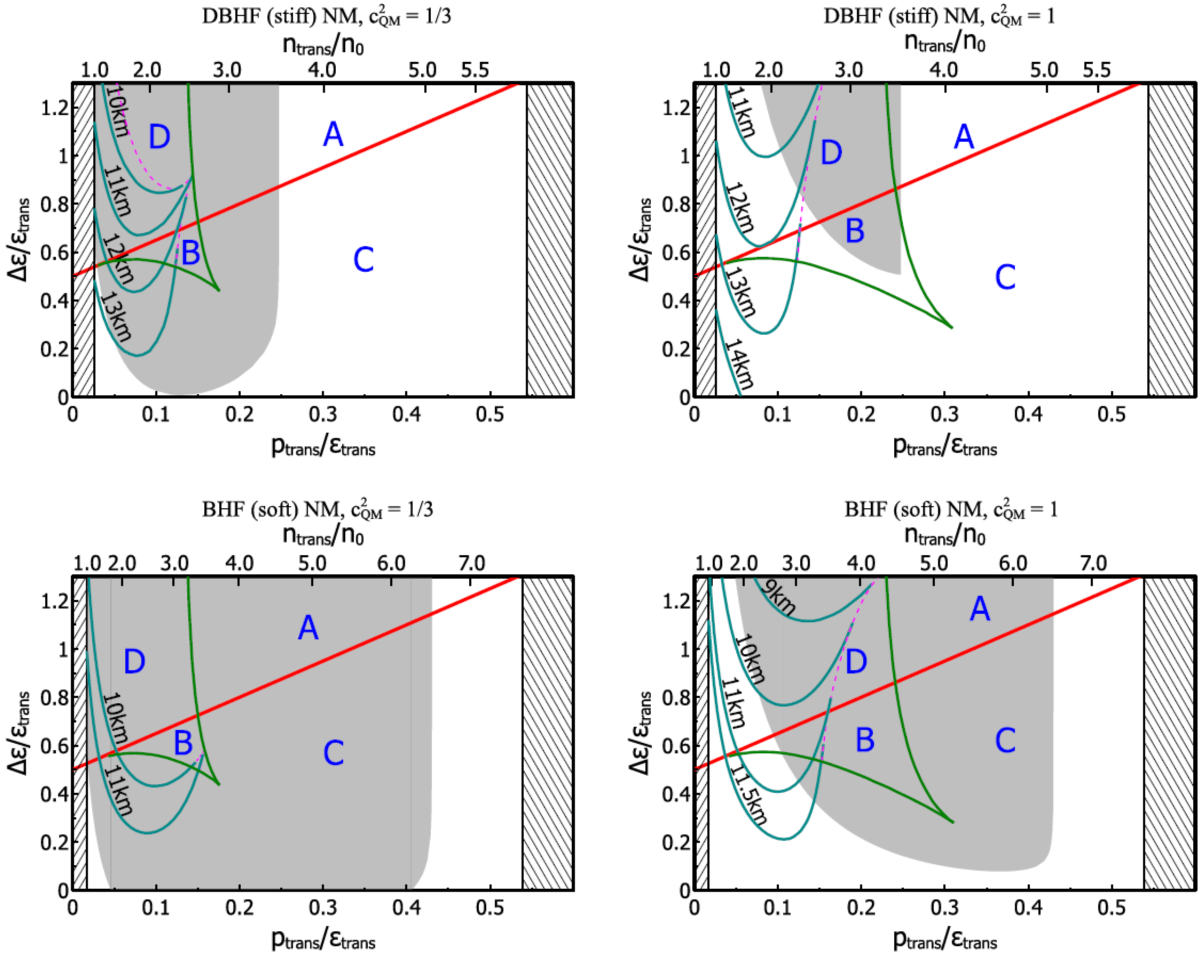


FIG. 4: (Color online). Contour plots similar to Fig. 3 showing the radius of a hybrid star of mass $M = 1.4\,M_\odot$ as a function of the CSS parameters. Such stars only exist in a limited region of the space of EoSs [delimited by dashed (magenta) lines]. The grey shaded region is excluded by the observational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

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

See also 1811.10929 by Montana et al. with compatible results

Why strange quark stars can reach large masses while keeping $c_s^2 \leq 1/3$? Because the adiabatic index diverges at the surface of the star.

Haensel, Zdunik, Schaeffer, A&A 160 (1986) 121

$$\Gamma = \frac{\varrho + P/c^2}{P} \frac{dP}{d\varrho} .$$

The condition for stability
in post-newtonian approx. is:

$$\Gamma > \frac{4}{3} + \kappa \frac{2GM}{Rc^2}$$

The divergence of Γ is due to
the vanishing of the pressure at
a finite density ρ_s

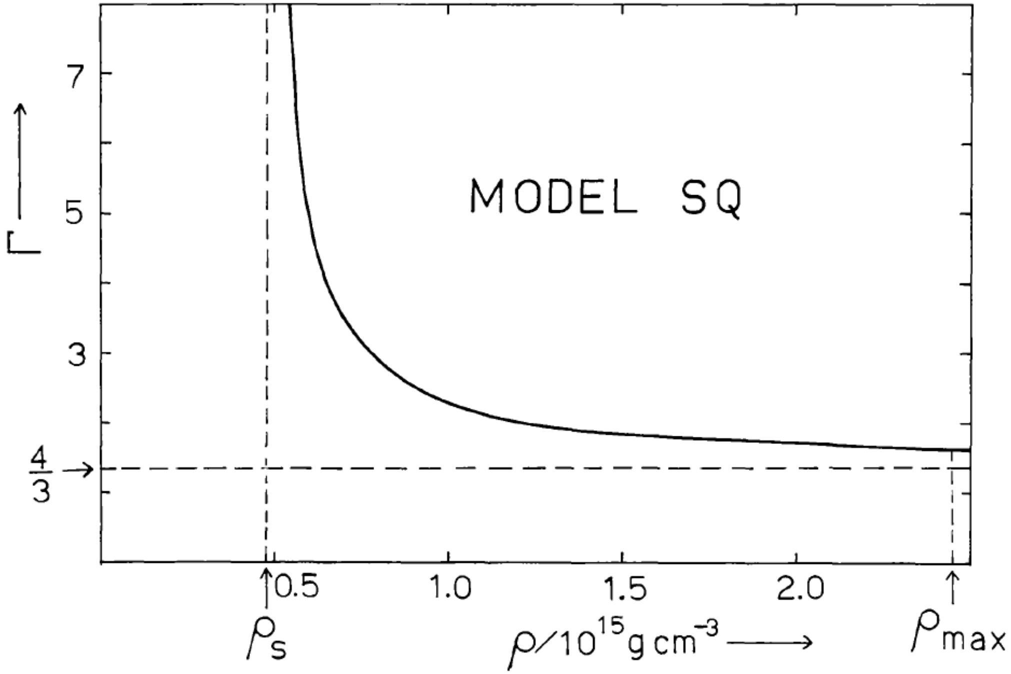


Fig. 5. Relativistic adiabatic index of quark matter, Γ, versus mass density, ϱ, for the strange quark matter model *SQ*

Confining quark models and gluon condensate

A contribution associated with the gluon condensate appears both in the MIT bag model and in Color-Dielectric model:

$$P_{MIT} = P_Q - B$$

$$P_{CDM} = P_Q - ½ M^2 \chi^2$$

The gluon condensate term is responsible for confinement in both models. Models without gluon condensate are in general models without confinement. The same contribution is responsible for the vanishing of the pressure at finite density.
A lattice QCD calculation shows that the gluon condensate contributes significantly to the totale mass of the proton, roughly as estimated within the MIT bag model and the CDM model.
Yi-Bo Yang et al., PRL 121 (2018) 2122001

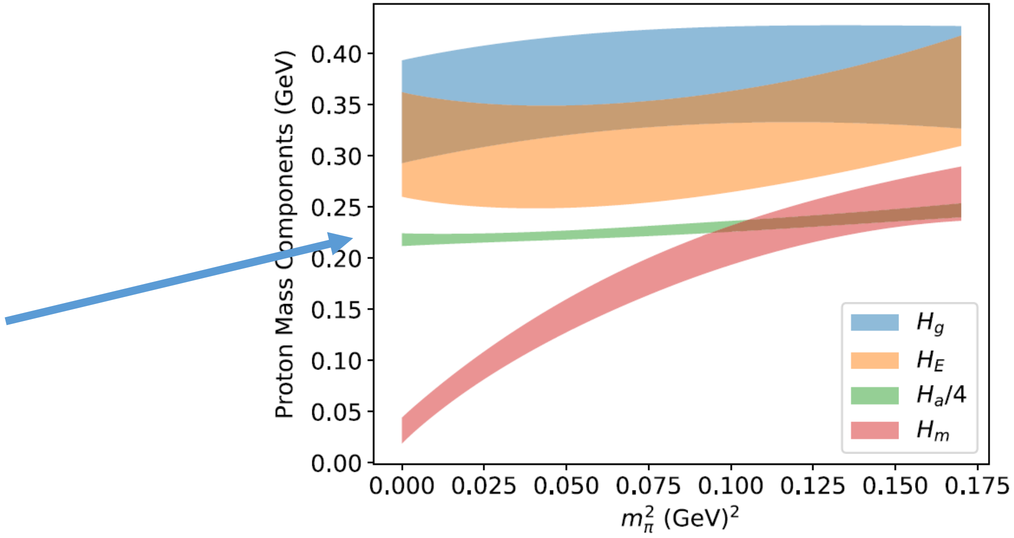
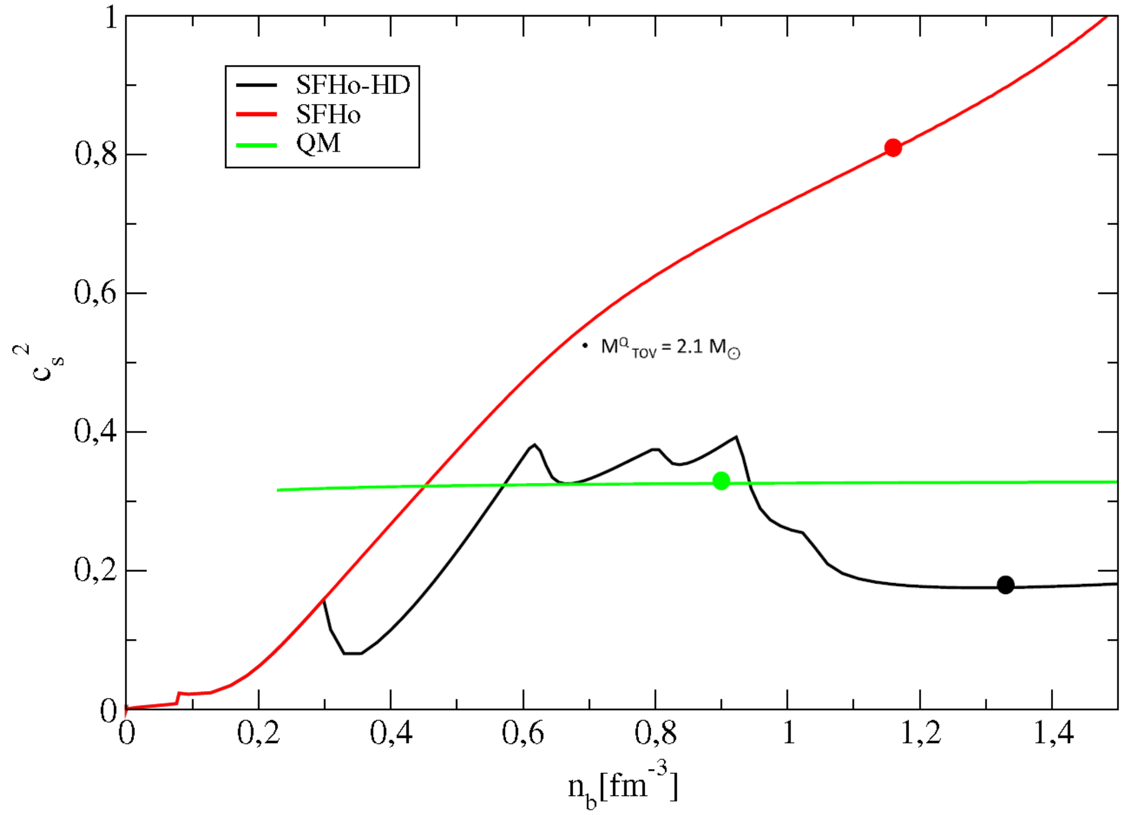


FIG. 3. The valence pion mass dependence of the proton mass decomposition in terms of the quark condensate $\langle H_m \rangle$, quark energy $\langle H_E \rangle$, glue field energy $\langle H_g \rangle$, and trace anomaly $\langle H_a \rangle/4$.

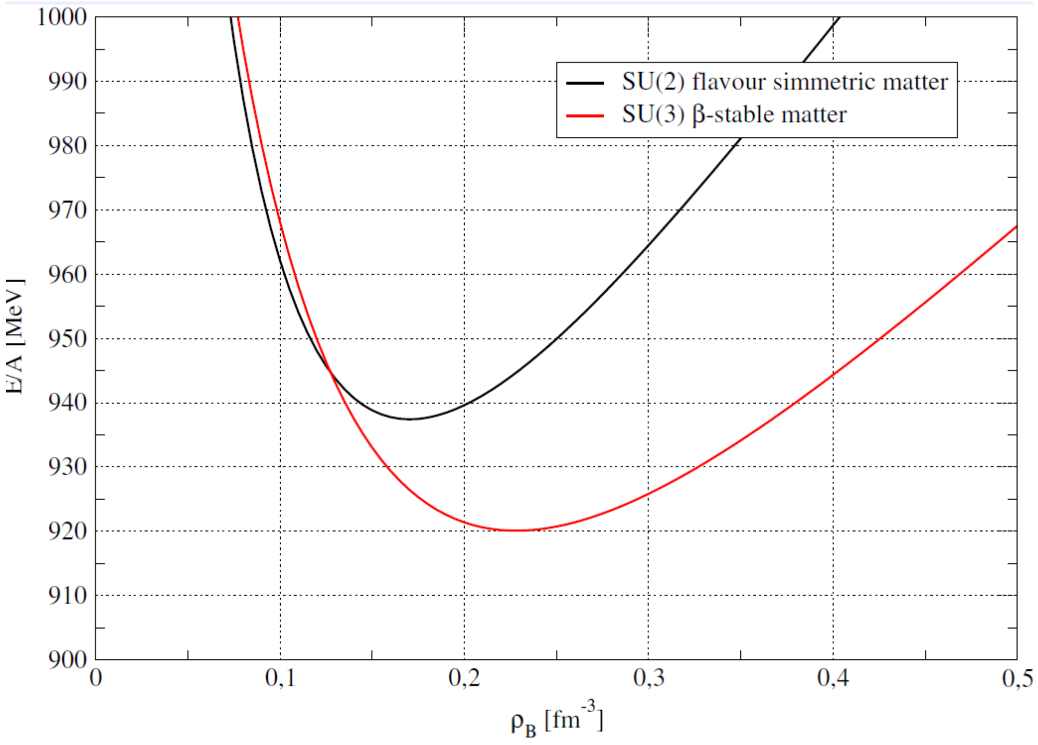
In the two-families scenario sound velocity never needs to be large



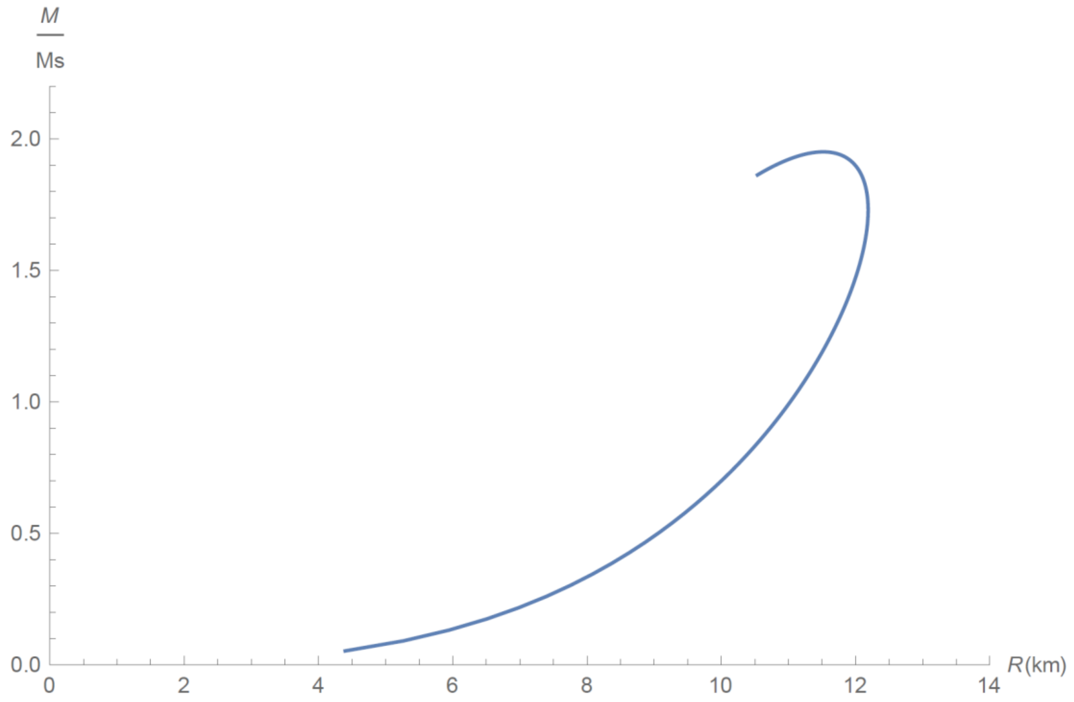
Strange quark stars within the Chiral CDM

A.D., N.A.Dondi, G.Pagliara, EPJ Web Conf. 137 (2017) 09004

$$\mathcal{L}_\chi = \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}M_\chi^2\chi^2 \qquad \mathcal{L}_{int} = -\frac{\sqrt{2}\,g_\sigma}{\chi}(\bar{q}Sq)$$



The minimum of E/A always contains strange quarks



The EOS has been computed using the RMFA, including the Hartree but not the Fock term. The inclusion of the Fock term will increase the mass and the radius by about 10-15 percent, allowing to get M_{max}~ 2.2-2.3 Ms with radii of about 13-14 km

Three possible types of mergers in the two-families scenario

Chirp mass of GW170817 is 1.188 $M_\odot$
Could be HS-HS or HS-QS, but HS-HS would correspond to a direct BH formation

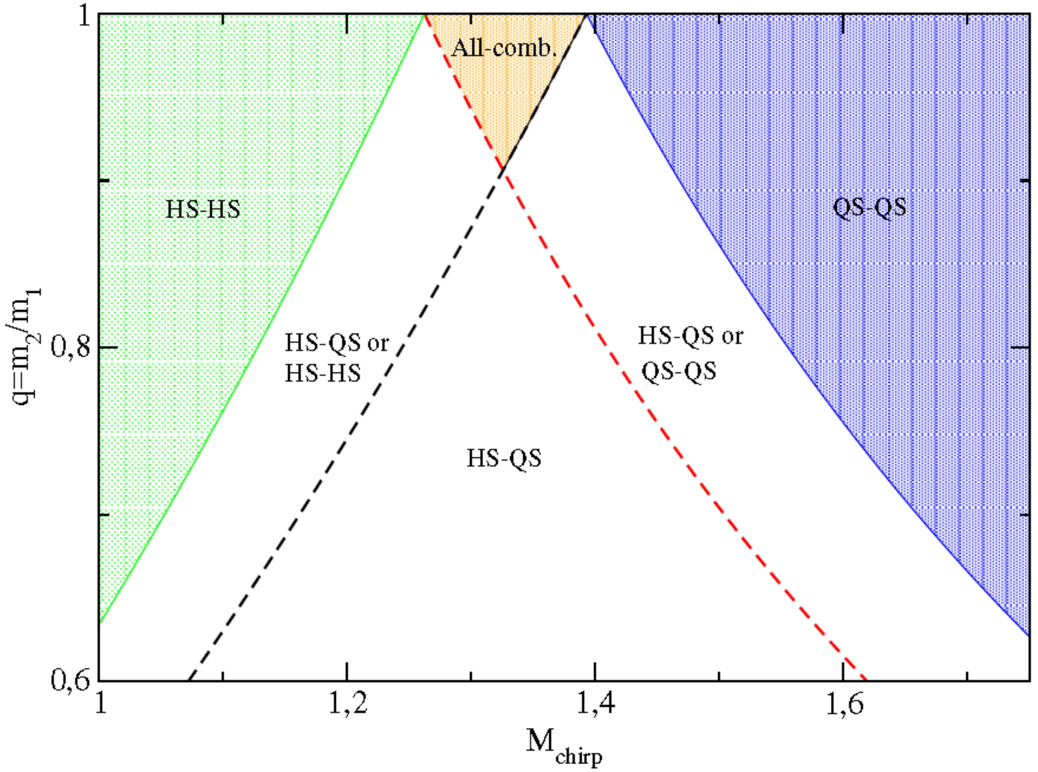
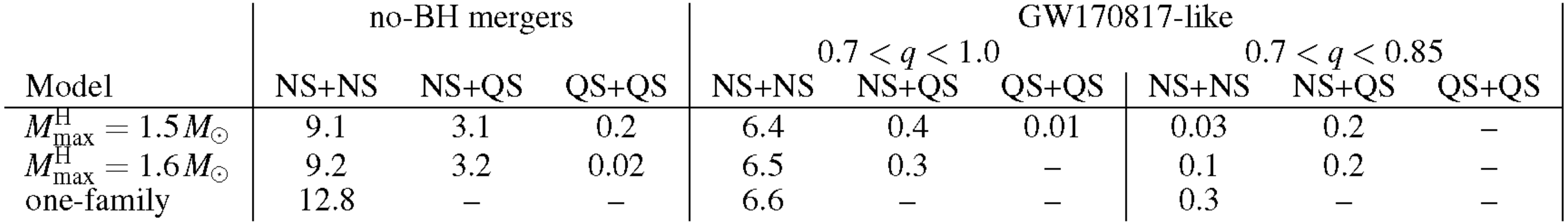


FIG. 3.— Different possible merger processes within the two families scenario depending on the chirp mass and the mass asymmetry of the binary. Parameters: $M^H_{\rm TOV} = 1.6 M_\odot$, $M^Q_{\rm TOV} = 2.1 M_\odot$ and the minimum masses of HSs and QSs are set respectively to $1 M_\odot$ and $1.45 M_\odot$.

Population synthesis estimates of mergers

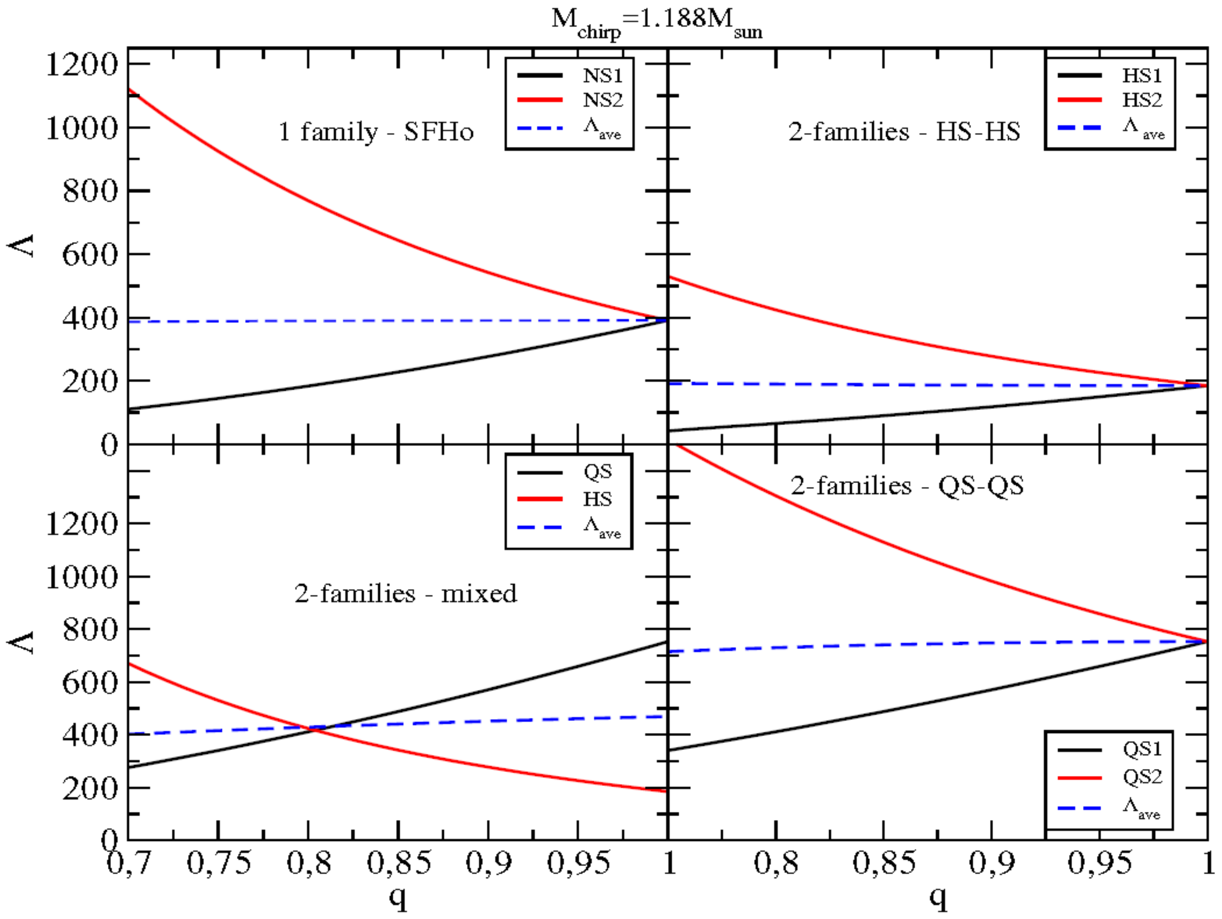
Startrack code of Belczynski et al., modified by Wiktoriwicz



	no-BH mergers			GW170817-like					
				$0.7 < q < 1.0$			$0.7 < q < 0.85$		
Model	NS+NS	NS+QS	QS+QS	NS+NS	NS+QS	QS+QS	NS+NS	NS+QS	QS+QS
$M^{\mathrm{H}}_{\mathrm{max}} = 1.5 M_{\odot}$	9.1	3.1	0.2	6.4	0.4	0.01	0.03	0.2	–
$M^{\mathrm{H}}_{\mathrm{max}} = 1.6 M_{\odot}$	9.2	3.2	0.02	6.5	0.3	–	0.1	0.2	–
one-family	12.8	–	–	6.6	–	–	0.3	–	–

HS-QS mergers are rather rare respect to HS-HS, but they become dominant for q ≤ 0.85

Average tidal deformability 1 vs 2 families



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:

$M^H_{TOV} = 1.6\,M_\odot$ $M^H_{supra} = 1.6\,M_\odot \times 1.2 = 1.92\,M_\odot$ $M^H_{threshold} = 2.48\,M_\odot$ (from simulations)

$M^Q_{TOV} = 2.1\,M_\odot$ $M^Q_{supra} = 2.1\,M_\odot \times 1.44 = 3.024\,M_\odot$ $M^Q_{threshold}$ only slightly larger than M^Q_{supra}

$M^{Hyb}_{TOV} = M^Q_{TOV} = 2.1\,M_\odot$ $M^{Hyb}_{supra} = 2.6\,M_\odot$ $M^{Hyb}_{threshold}$ not known

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).

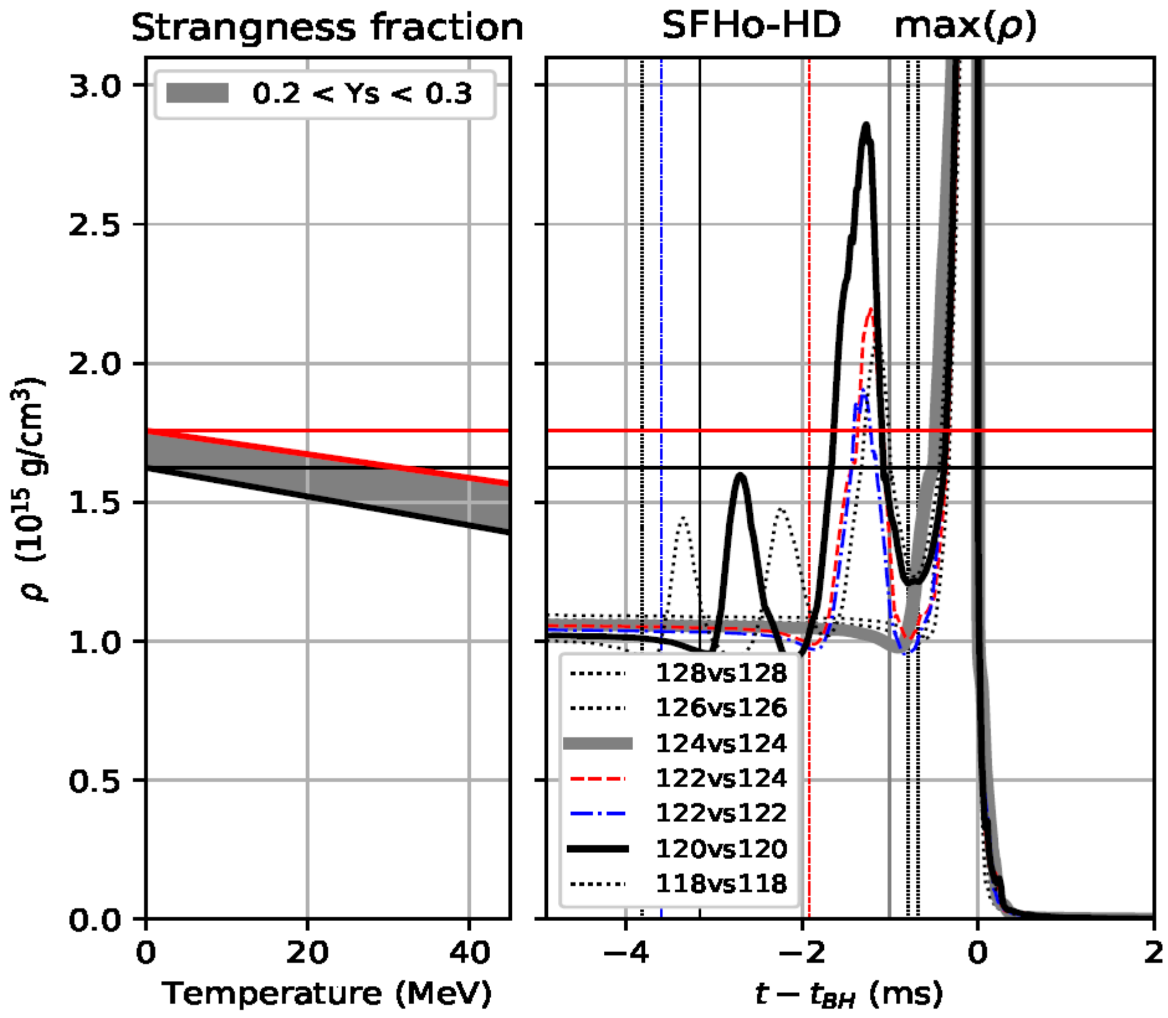
M^Q_{TOV} is not well determined, could be as large as $2.4\,M_\odot$

Possible types of mergers in the two-families scenario (to be concrete here we assume $M^Q{}_{TOV} = 2.1\,M_\odot$)

- HS-HS
  - For $M_{tot} > M_{th} \sim 2.48\,M_s$ there is direct collapse to a BH
  - For $M_{tot} < M_{th} \sim 2.48\,M_s$ sGRB via the protomagnetar scheme (supramassive)
    - Possibility of extended emission and quasi-plateau
    - Large value of mass ejected by the shock, not very massive disk
- HS-QS
  - For $M_{tot} > M_{th} \sim 3.1\,M_s$ there is direct collapse to a BH
  - For $2.6\,M_s < M_{tot} < M_{th} \sim 3.1\,M_s$ sGRB via BH and torus (hypermassive)
    - No extended emission and no quasi plateau
    - Smaller value of mass ejected by the shock, massive disk
  - For $M_{tot} < 2.6\,M_s$ sGRB via the protomagnetar scheme (supramassive)
    - Possibility of extended emission and quasi-plateau
    - Smaller value of mass ejected by the shock, massive disk
- QS-QS
  - For $M_{tot} > M_{th} \sim 3.1\,M_s$ there is direct collapse to a BH
  - For $M_{tot} < M_{th} \sim 3.1\,M_s$ sGRB à la Haensel, Paczinski, Amsterdamski (supramassive)

Condition for quark deconfinement in HS-HS merger

De Pietri, Drago, Feo, Pagliara, Pasquali, Traversi, Wiktorowicz, in preparation



A very strong prediction of the two-families scenario

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

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

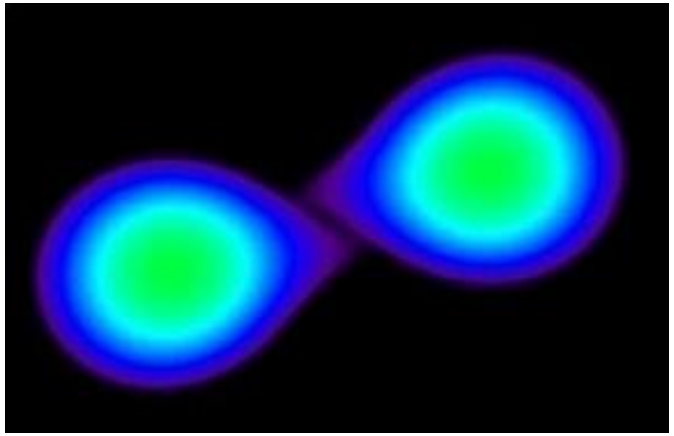
There is no equivalent in the twin-stars scenario, because the process of quark combustion is there assumed to proceed without any delay.

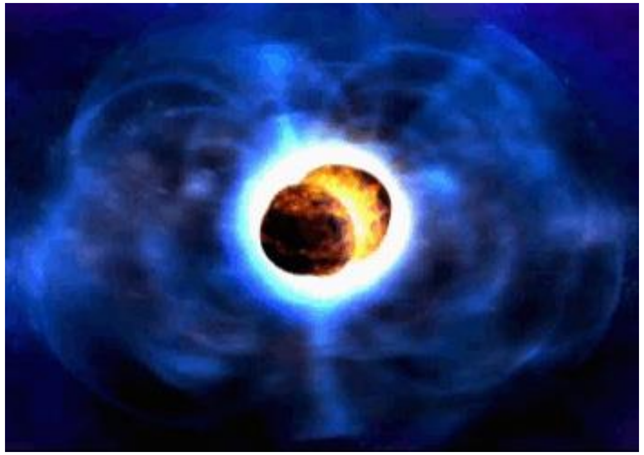
- In the two-families scenario quark matter production stabilizes the hadronic star configuration.
- In the twin-stars scenario quark matter production destabilizes the hadronic configuration and produces the transition to the "third family", i.e. to the second configuration.

MASS EJECTION MECHANISMS

- **Dynamical ejection:**

- Tidal deformation: equatorial plane

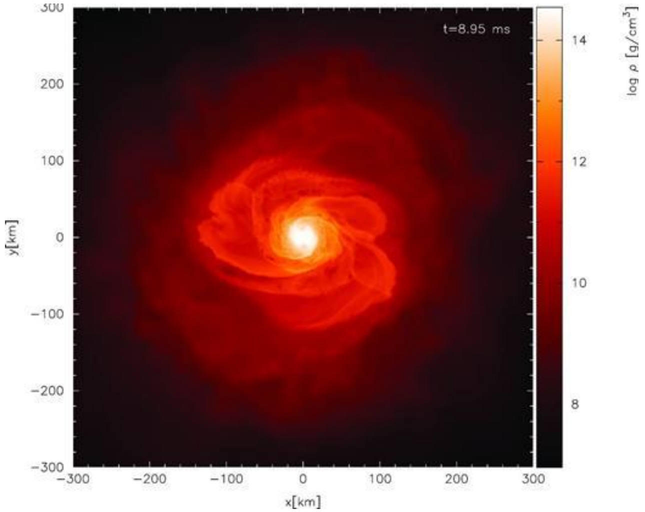




- Shock at NSs interface and radial oscillations

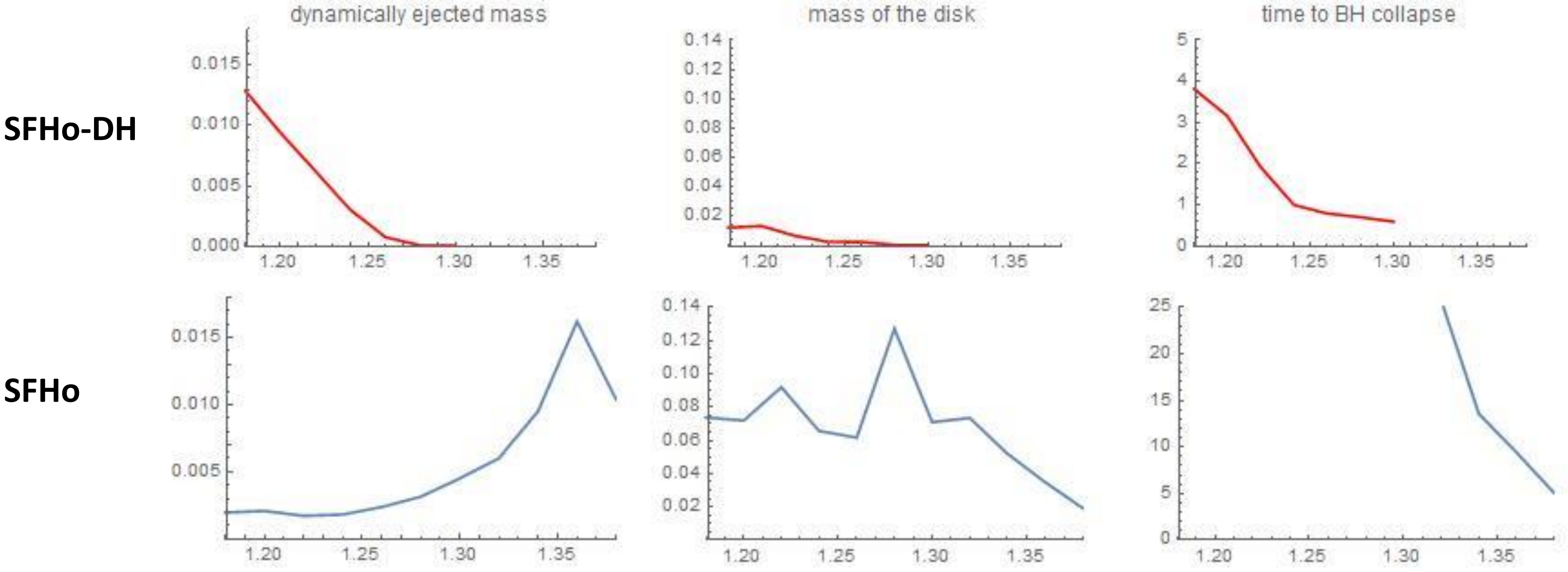
- **Disk:** $10^{-3}\, M_{\odot} < M_{disk} < 0.03 M_{\odot}$

- Viscous or neutrino heating



Mass ejected: 1 vs 2-families (SHFo vs SFHo-DH)

De Pietri, Drago, Feo, Pagliara, Pasquali, Traversi, Wiktorowicz, in preparation



Future observations

- New missions (NICER, LOFT), 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} >= 1.6 purely nucleonic stars ($\rho_{max} \lesssim 3\ \rho_0$)

- 11.5 km < $R_{1.4}$ < 13 km or 1.3 <= I_{45} <= 1.6 hyperonic or hybrid stars (ρ_{max} as large as 5 ρ_0)

- $R_{1.4}$ << 11.5 km or I_{45} << 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 → possibility of distinguishing between these two schemes.