Constraining the nuclear matter EoS from the GW170817 merger event

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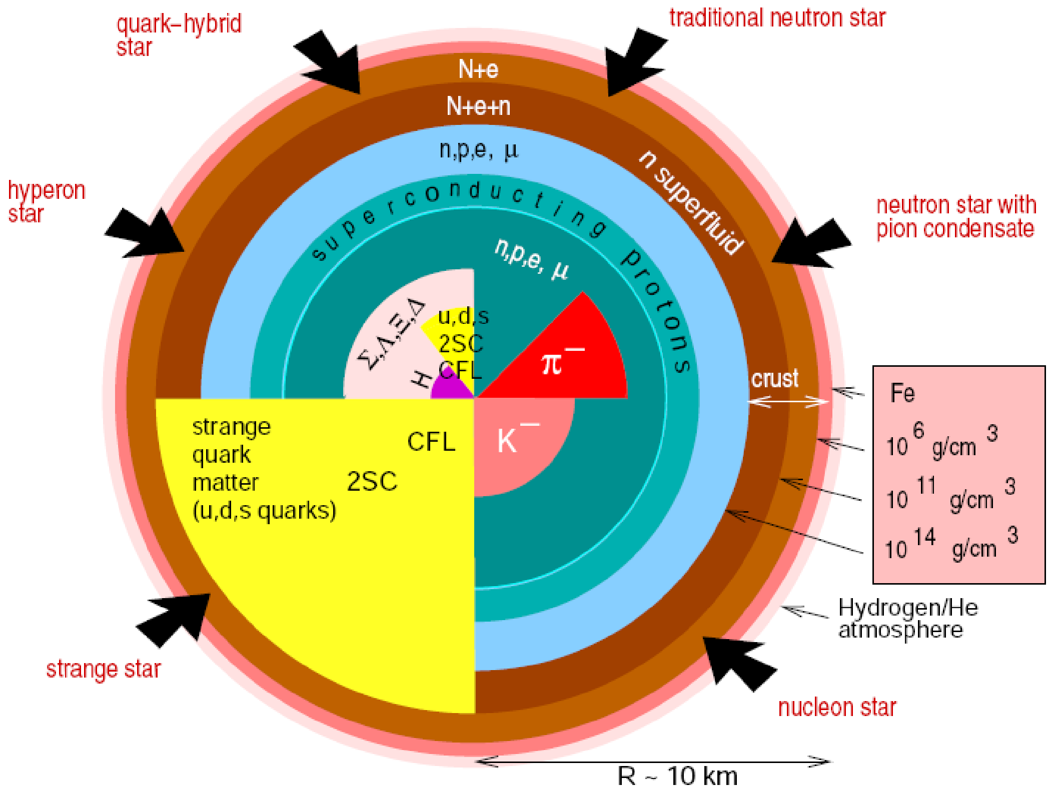
Coimbra, September 26th, 2018

Outline

- Neutron star
- EOS
- constraints from NS observations
- Results
- Conclusion

❖ Structure of Neutron stars



Highly relativistic objects

Typical mass:

$1 - 2\ M_\odot$

Radius:

10 -14 km

Average density:

$\approx 3\ \times 10^{14}\ g/cm^3$

Spin period：

≈ (0.2-2) s

EOS

Neutron stars

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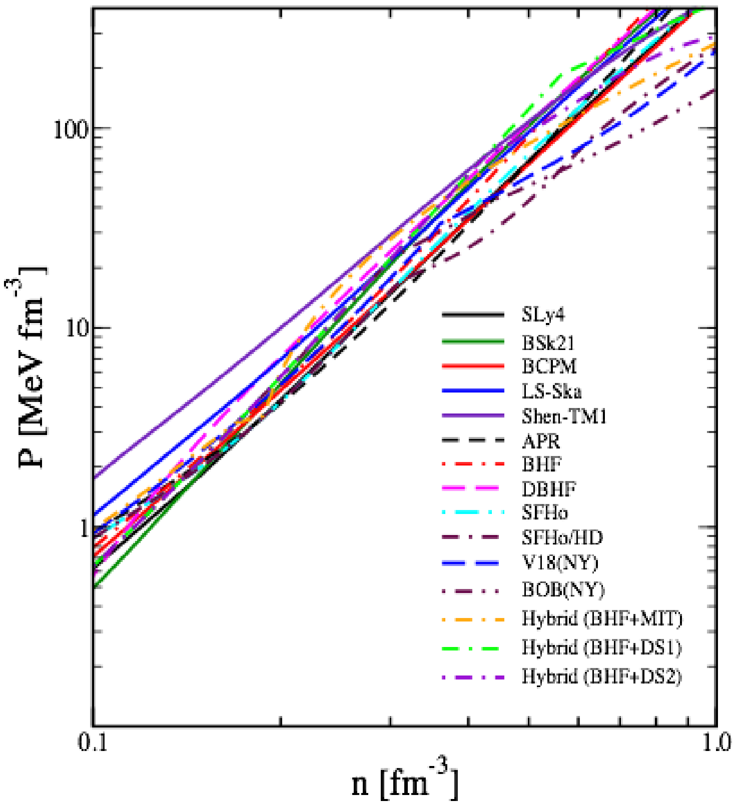
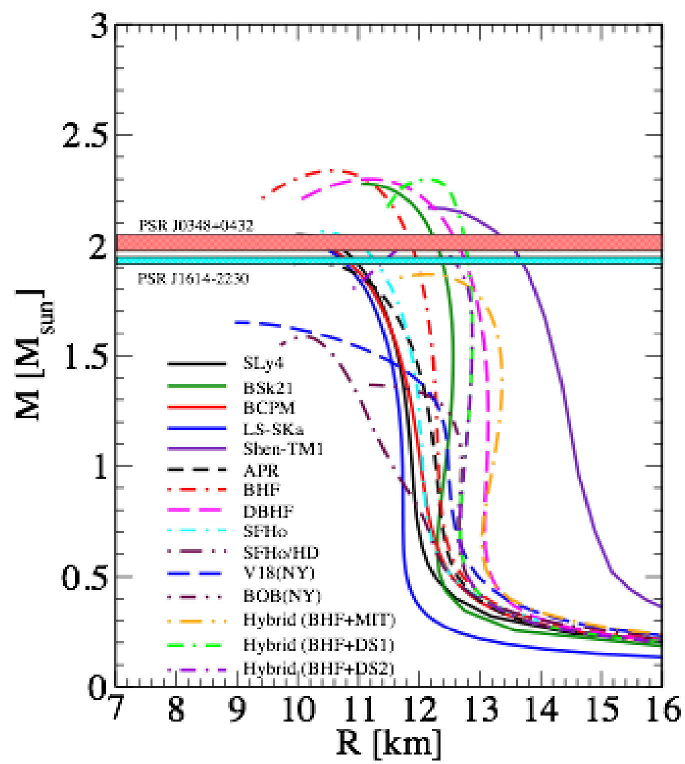
A large set of possible EoS (nucleons, hyperons, quark matter, etc….)





F. B. and A. Fantina, arXiv:1804.03020

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The construction of the EoS :two possible philosophies

Phenomenological approaches

Based on effective density-dependent NN force with parameters fitted on nuclei properties.

- Liquid Drop models
  - ✧ BPS Baym et al, *ApJ* ***170***, *299 (1971)*
  - ✧ BBP Baym et al., *NPA* ***175***, *225 (1971)*
  - ✧ LS Lattimer&Swesty, *NPA* ***535***, *331 (1991)*
  - ✧ DH Douchin&Haensel, *A&A* ***380***, *151 (2001)*
- TF + RMF
  - ✧ Shen et al., *NPA* ***637***, *435 (1998)*
- ETFSI + Eff. Skyrme force
  - ✧ BSk Goriely et al., *PRC* ***82***, *035804 (2010)*
- Hartree-Fock
  - ✧ NV Negele&Vautherin, *NPA* ***207***, *298 (1973)*
  - ✧ RMF Serot&Walecka, *Adv. NP 16, 1 (1986)*
  - ✧ RHF Boussy et al., *PRL* ***55***, *1731 (1985)*
  - ✧ QMC Guichon et al., *NPA* ***814***, *66 (2008)*
- Statistical models
  - ✧ NSE Raduta&Gulminelli. *PRC* ***82***, *065801 (2010)*
  - ✧ HS Hempel&Schaffner-Bielich, *NPA* ***837***, *210 (2010)*

Ab initio approaches

The nuclear problem is solved starting from the two- and three-body realistic nucleon interaction.

- Diagrammatic
  - ✧ BBG Day, *RMP****39***, *719 (1967)*
  - ✧ SCGF Kadanoff&Baym, Quantum Statistical Mechanics (1962)
  - ✧ DBHF Ter Haar&Malfiet, *Phys, Rep.* ***149***, *207 (1987);*
- Variational
  - ✧ APR Akmal et al., *PRC* ***58***, *1804 (1998)*
  - ✧ FHNC Fantoni&Rosati, *Nuovo Cimento A****20***, *179 (1974)*
  - ✧ CBF Fabrocini&Fantoni, *PLB* ***298***, *263(1993)*
  - ✧ LOCV Owen et al., *NPA* ***277***, *45 (1978)*
- Monte Carlo
  - ✧ VMC Wiringa, *PRC****43***, *1585 (1991)*
  - ✧ GFMC Carlson, *PRC****68***, *025802 (2003)*
  - ✧ AFDMC Schmidt&Fantoni, *PLB****446***, *99 (1999)*
- Renormalization Group method
  - ✧ V_{low-k} Bogner et al., *PR 286, 1 (2003)*

GW170817/AT2017gfo

❖ GW170817

Abbott et al., PRL 119, 161101 (2017)

- chirp mass : Mc = 1.188M⊙
  – mass ratio : m2/m1 = 0.7-1.0
  primary mass m1 = 1.36-1.6M⊙
  secondary mass m2 = 1.17-1.36M⊙

- tidal deformability :

$$\Lambda_{1.4} < 800$$

- effective tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12\,M_2)\,M_1^4}{(M_1 + M_2)^5}\Lambda_1 + (1 \leftrightarrow 2) \lesssim 800$$

arXiv:1805.11579: $70 < \tilde{\Lambda} < 720$

GW170817/AT2017gfo

❖ AT2017gfo

Couperthwaite et al., ApJ 848, L17 (2017)
E. Pian et al., Nature 551, 67 (2017)
Radice et al., ApJ 852, L29 (2018)

Constraints from GW170817: the kilonova signal AT2017gfo

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12\,M_2)\,M_1^4}{(M_1 + M_2)^5}\Lambda_1 + (1 \leftrightarrow 2)$$

$$\tilde{\Lambda} > 400$$

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Formalism

- Tidal deformability

$$\Lambda = 2\beta^5/3k_2$$

- Love number k2

β=M/R being the compactness

$$\frac{dy}{dr} = -\frac{y^2}{r} - \frac{y-6}{r-2Gm/c^2} - rQ,$$

$$Q = \frac{4\pi G}{c^4}\frac{(5-y)\epsilon + (9+y)p + (\epsilon+p)/c_s^2}{1-2Gm/c^2 r} - \left[\frac{2G(m+4\pi p r^3/c^2)}{r(rc^2-2Gm)}\right]^2,$$

$$k_2 = \frac{8}{5}\beta^5(1-2\beta)^2\left[2-y_R+2\beta(y_R-1)\right]/\mathcal{R}$$

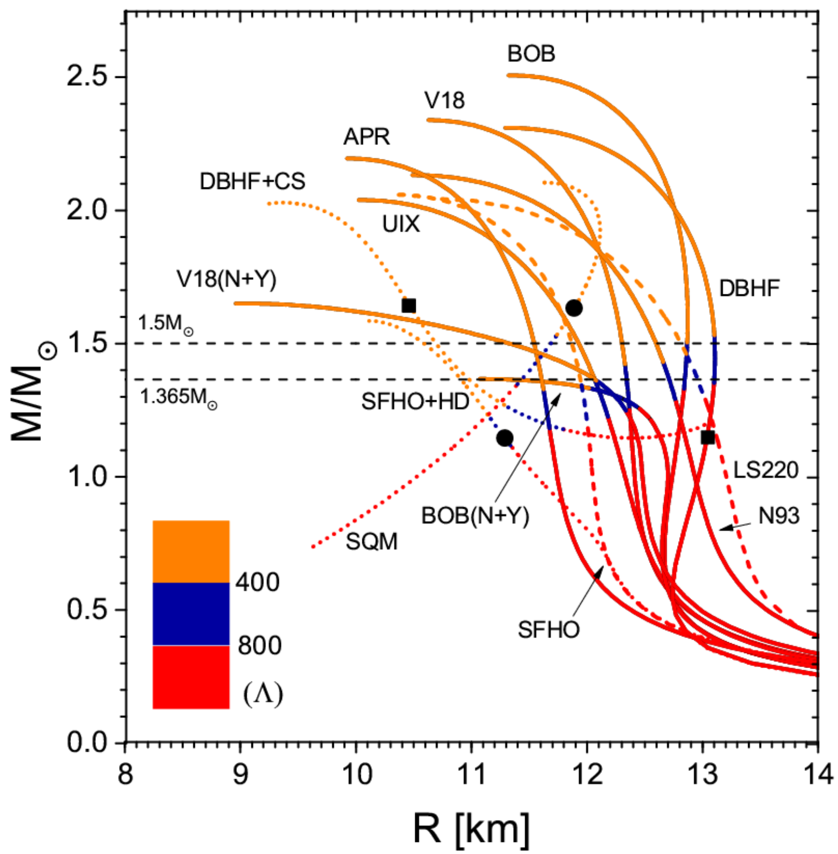
$$\mathcal{R} = 6\beta(2-y_R+\beta(5y_R-8)) + 4\beta^3\left[13-11y_R+\beta(3y_R-2)+2\beta^2(1+y_R)\right] + 3(1-2\beta)^2\left[2-y_R+2\beta(y_R-1)\right]\ln(1-2\beta),$$

Boundary condition:

$$(p, m, \omega, y)(r=0) = (p_c, 0, 0, 2) \quad \omega_R = \omega(R), y_R = y(R).$$

The tidal deformability depends on the compactness, hence on the EOS

R-M relation



- Microscopic non-relativistic EoS : BHF with Bonn B, V18, N93, UIX
- Variational : APR
- Microscopic relativistic EoS : DBHF
- Microscopic EoS with hyperons: BOB(N+Y), V18(N+Y)
- Phenomenological EoS : LS220, SFHO
- All give maximum masses above 2M⊙ except the ones with hyperons.

$400 < \Lambda_{1.365} < 800$ → $12\,\mathrm{km} \lesssim R_{1.5} \lesssim 13\,\mathrm{km}$

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Are small radii ruled out by GW170817/AT2017gfo?

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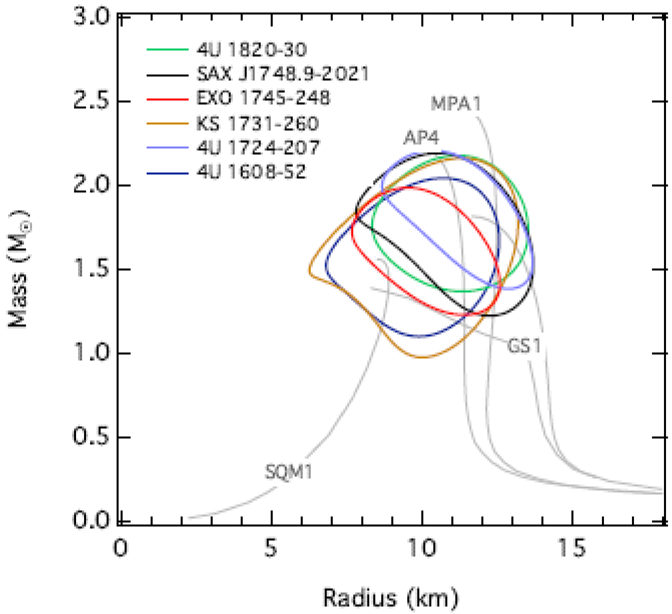
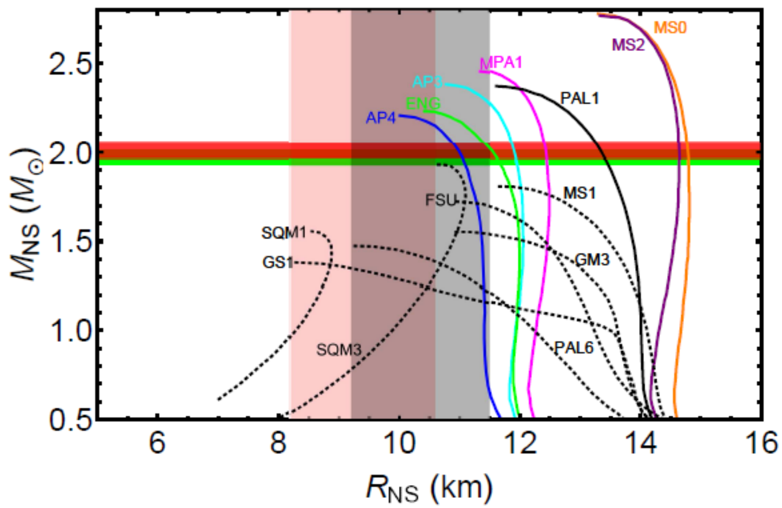
Also Ozel&Freire, Ann.Rev. Astron.Astroph. 54 (2016)401 R=(9.9-11.2)km



Thermonuclear bursts

S. Guillot, Mem. S. A. It. 87, 521 (2016).
R=(9.2-11.5) km



Analysis of 5 QLMXBs

If small-radius NS exist, how do they fulfill the constraint of GW170817/AT2017gfo?

Binary system

Neutron stars

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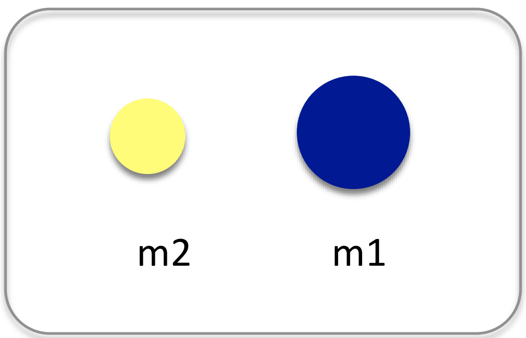
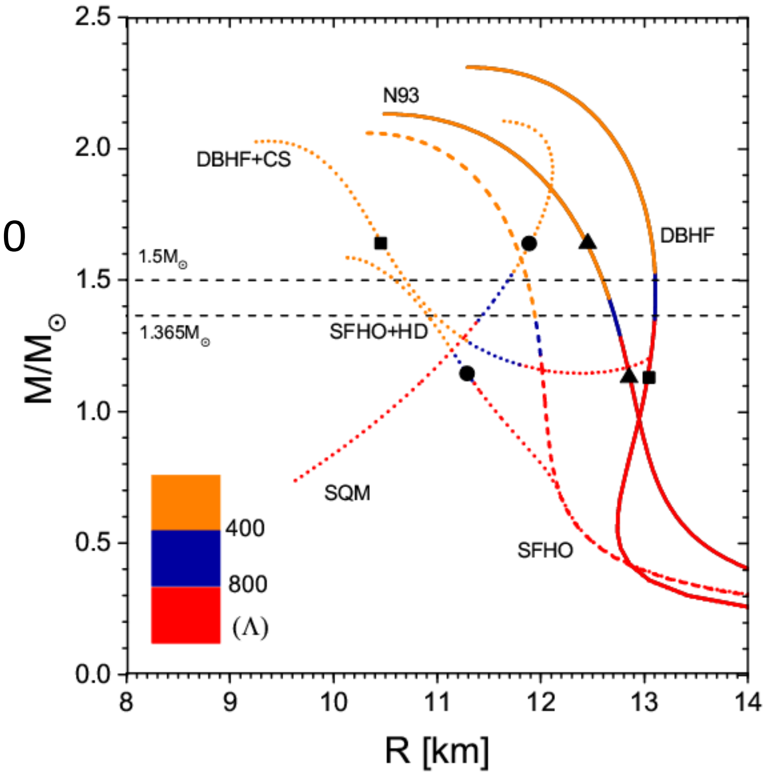
❖ Three scenarios

– chirp mass : Mc = 1.188M⊙
– mass ratio q : m2/m1 = 0.7-1.0





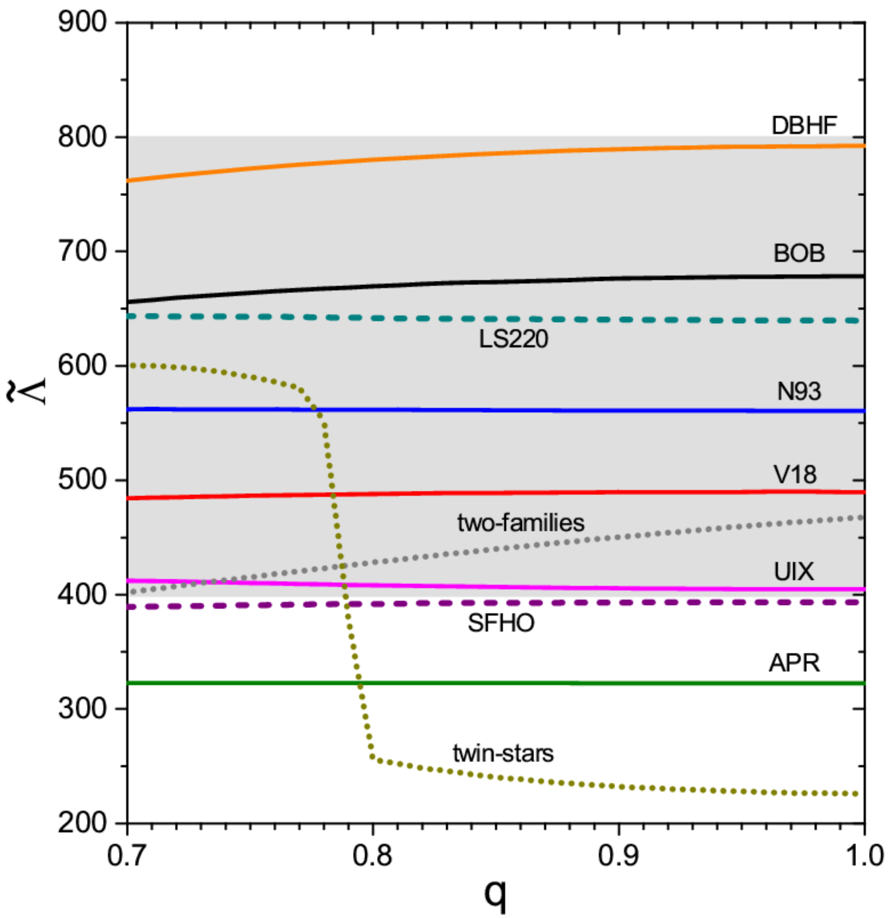
	m1	m2
One-family	Hadronic star(N93…)	Hadronic star(N93…)
Two-family	Quark star(QSM)	Hadronic star(SFHO+HD)
Twin-stars	Hybrid star(DBHF+CS)	Hadronic star(DBHF)

Binary system

One-family scenario : $\tilde{\Lambda}$ almost independent on q

Two-families and twin-stars scenario : non negligible dependence on q

Twin-stars : large difference in the radii of the two components $(R_1, R_2) = (10.7, 13.0)$ km



Correlations between Λ and $R_{1.5}$

Neutron stars

EOS

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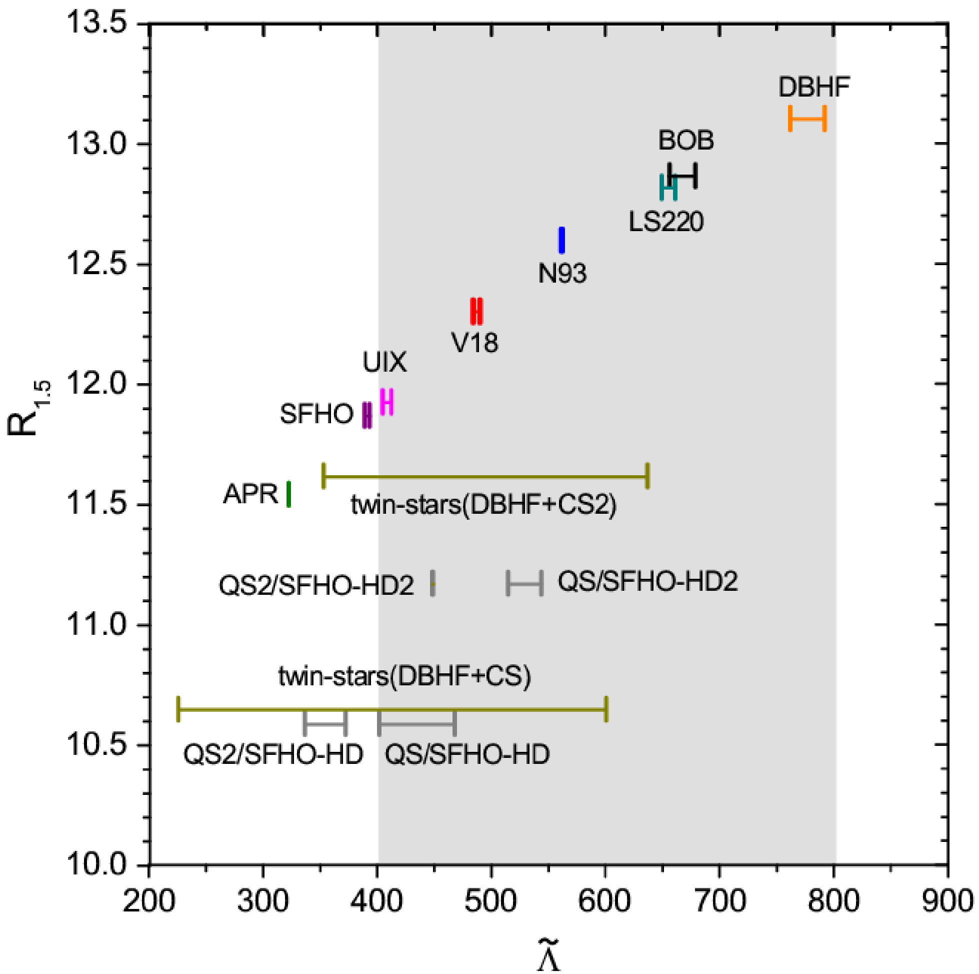

One-family-scenario : monotonic correlation between R1.5 and $\tilde{\Lambda}$. All EoS with $\tilde{\Lambda}$>400 have R1.5>11.8 km, except APR and SFHO.

Two-families and twin-stars scenarios : R1.5 < 11.8 km are possible with $\tilde{\Lambda}$>400.

GW170817 has to be interpreted as a "mixed case" : one of the objects is made only of hadrons and the other contains deconfined quarks.

Conclusion

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GW170817 event has added more constraints.

- GW170817 in the one-family scenario is compatible with the merging of two nucleonic neutron stars w ith a microscopic EoS, $M>2M_0$ and 12<R<13 km.

- The lower limit on the tidal deformability is compatible with radii of compact stars smaller than 12 km, if one assumes a population of compact stars not made by one-family only.

Conclusion

Thank you!