COST Action CA16214

Constraints from the GW170817 merger event on the nuclear matter EoS

Fiorella Burgio
INFN Sezione di Catania

CRIS18, Portopalo di Capo Passero, June 18-22, 2018

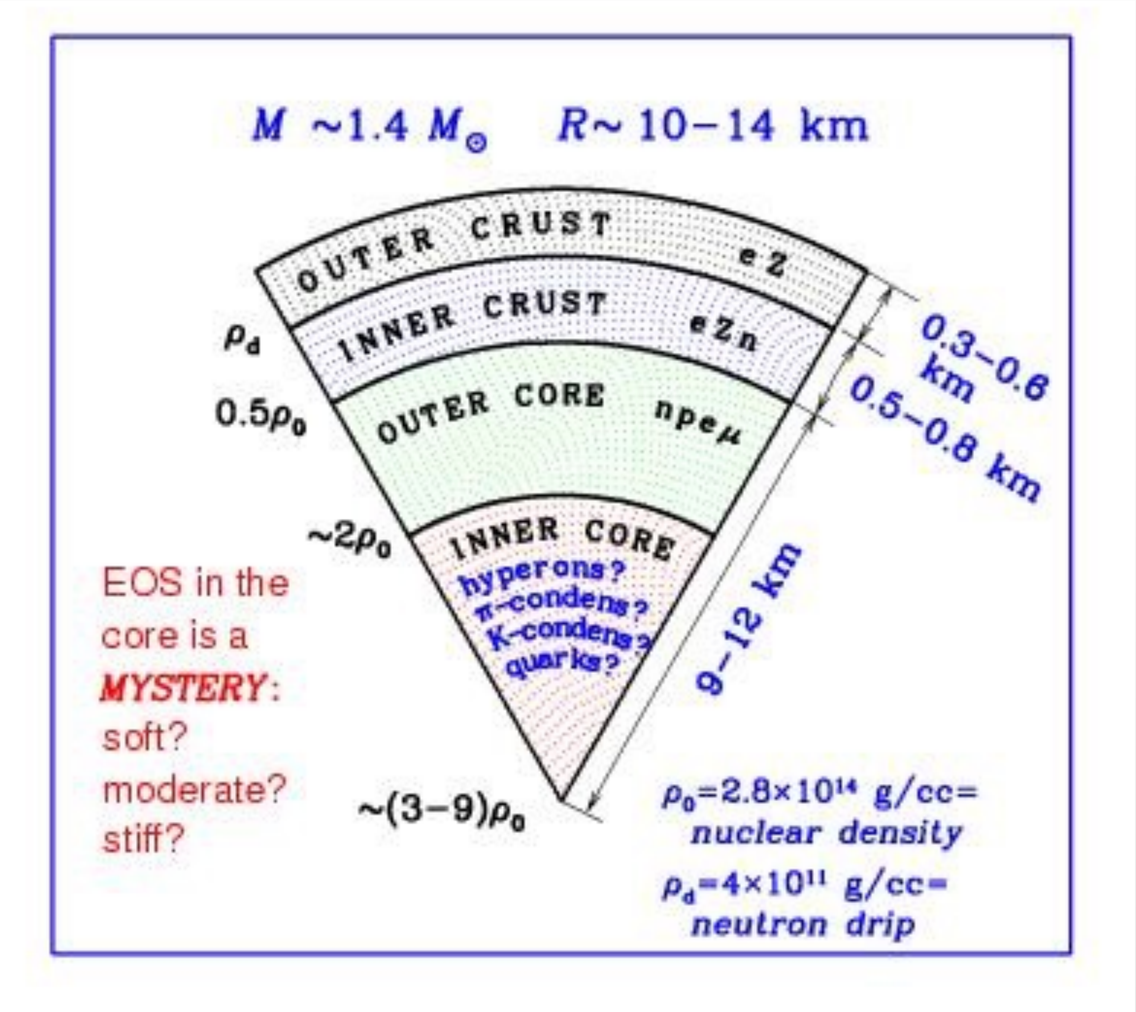
Schematic view of a neutron star

Outer crust. Neutron-rich nuclei immersed in e- gas up to the neutron drip point, $\rho = 4 \times 10^{11} g/cm^3$.

Inner crust. Gas of free neutrons, free electrons and nuclear clusters.

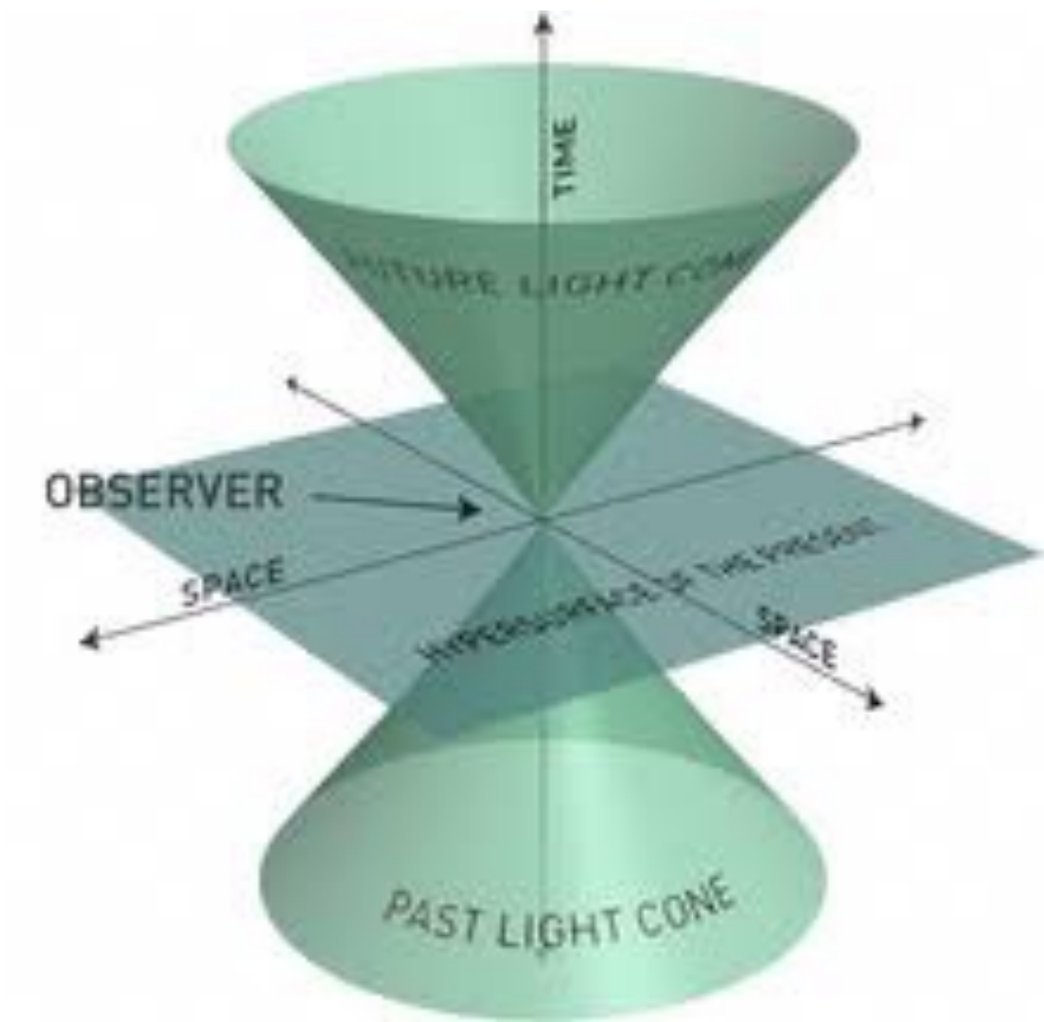
Outer core. Asymmetric nuclear matter composed by neutrons, protons, electrons and muons. Its exact composition depends on the nuclear matter Equation of State (EoS).

Inner core. The most unknown region. "Exotic matter" . Hyperons ? Kaons ? Quarks ?



☞ **EoS in the crust is known reasonably well.**
☞ **EoS in the outer core is not very certain.**
☞ **EoS in the inner core is a mystery.**

Neutron Star Structure Equations



$$\boxed{R_{ik} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^4} T_{ik}}$$ **Einstein Equations**

R_{ik} = Ricci curvature tensor; $R = R_i^i$ = scalar curvature

$T_{ik} = (P+E)\, u_i u_k - P\, g_{ik}$ = energy-momentum tensor

($E = \rho c^2$, u^i = 4-velocity, g_{ik} = metric tensor)

Einstein Equations for a Star

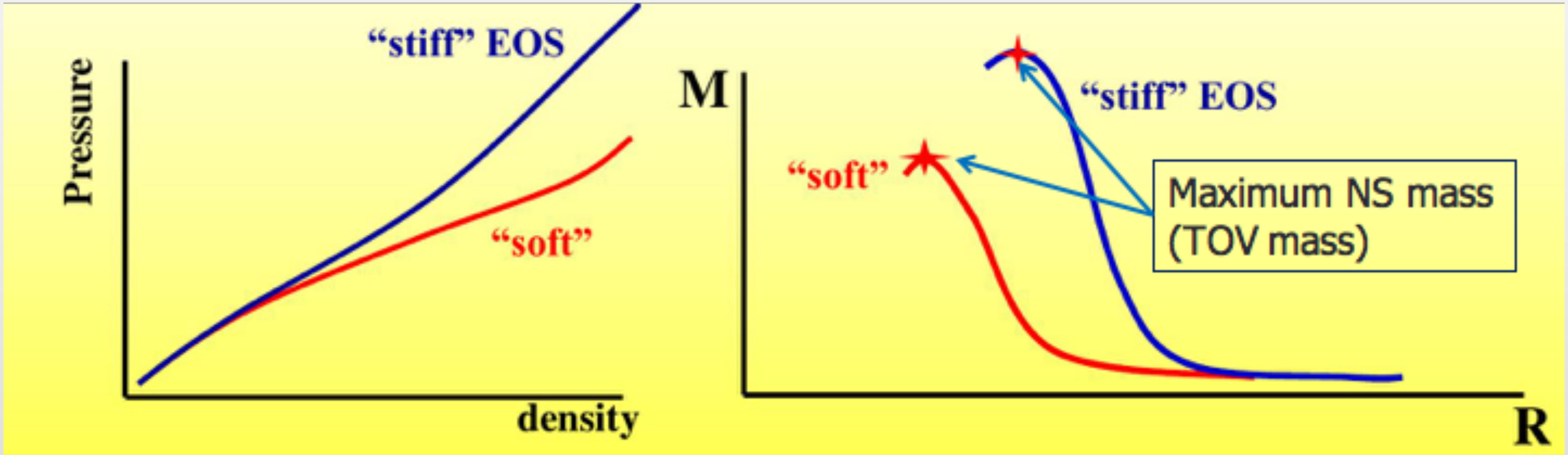
$$\begin{cases} (1)\quad \dfrac{dP}{dr} = -\dfrac{G\rho m}{r^2}\left(1+\dfrac{P}{\rho c^2}\right)\left(1+\dfrac{4\pi r^3 P}{mc^2}\right)\left(1-\dfrac{2Gm}{rc^2}\right)^{-1} \\ (2)\quad \dfrac{dm}{dr} = 4\pi r^2 \rho \\ (3)\quad \dfrac{d\Phi}{dr} = -\dfrac{1}{\rho c^2}\dfrac{dP}{dr}\left(1+\dfrac{P}{\rho c^2}\right)^{-1} \end{cases}$$

Tolman-Oppenheimer-Volkoff (1939)

Imposing boundary conditions : $\begin{matrix} \rho(0) = \rho_c \\ m(0) = 0 \end{matrix} \Rightarrow \begin{matrix} R,\ p(R) = 0 \\ M = m(R) \end{matrix}$

Need an Equation of State
$P = P(\rho)$

Given an EoS, compute sequence of equilibrium models:
the Mass-Radius relation



The construction of the EoS : two possible philosophies

Phenomenological approaches

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

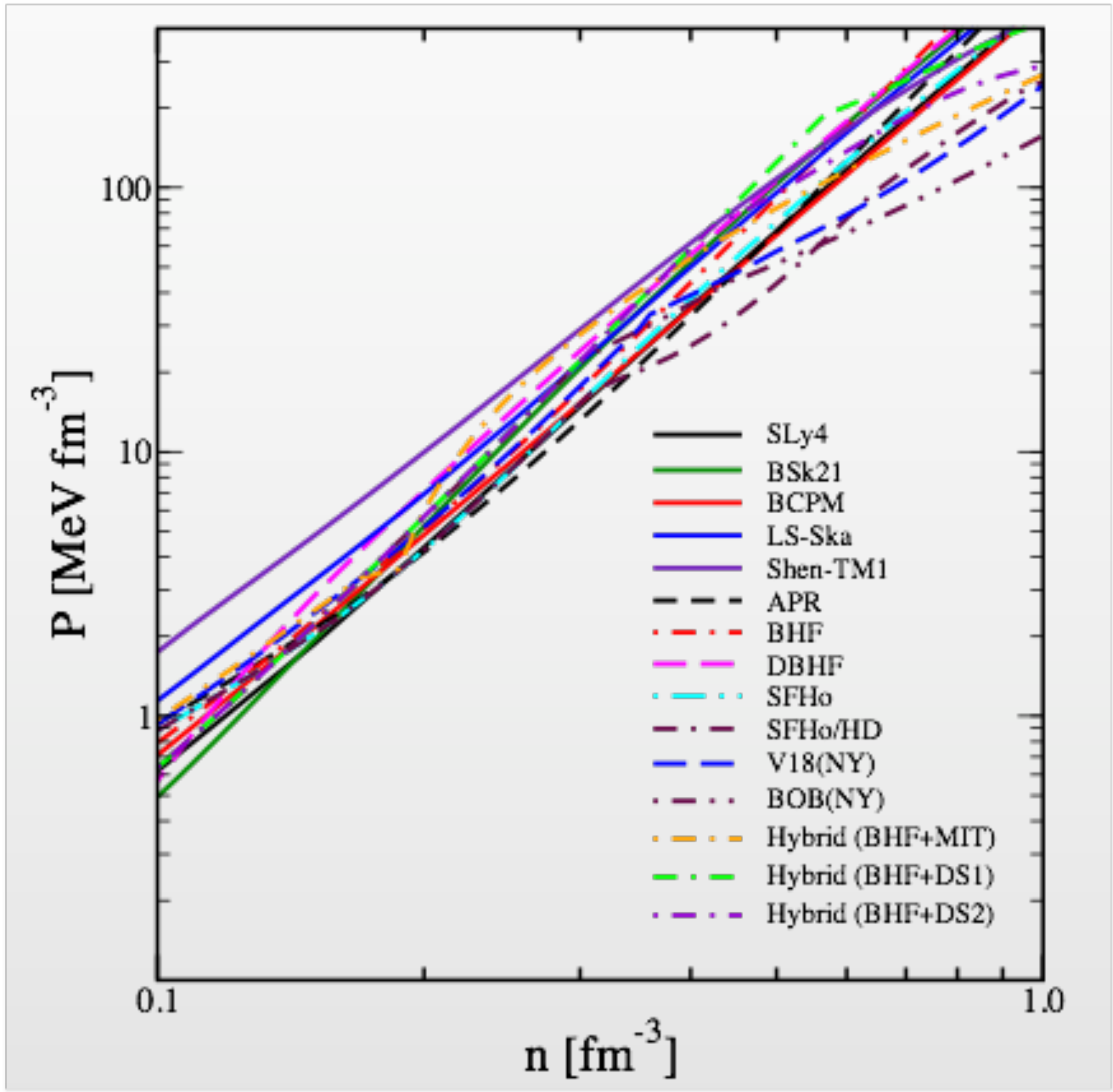
- Liquid Drop models
  - BPS Baym et al, ApJ **170**, 299 (1971)
  - BBP Baym et al., NPA **175**, 225 (1971)
  - LS Lattimer&Swesty, NPA **535**, 331 (1991)
  - DH Douchin&Haensel, A&A **380**, 151 (2001)
- TF + RMF
  - Shen et al., NPA **637**, 435 (1998)
- ETFSI + Eff. Skyrme force
  - BSk Goriely 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)

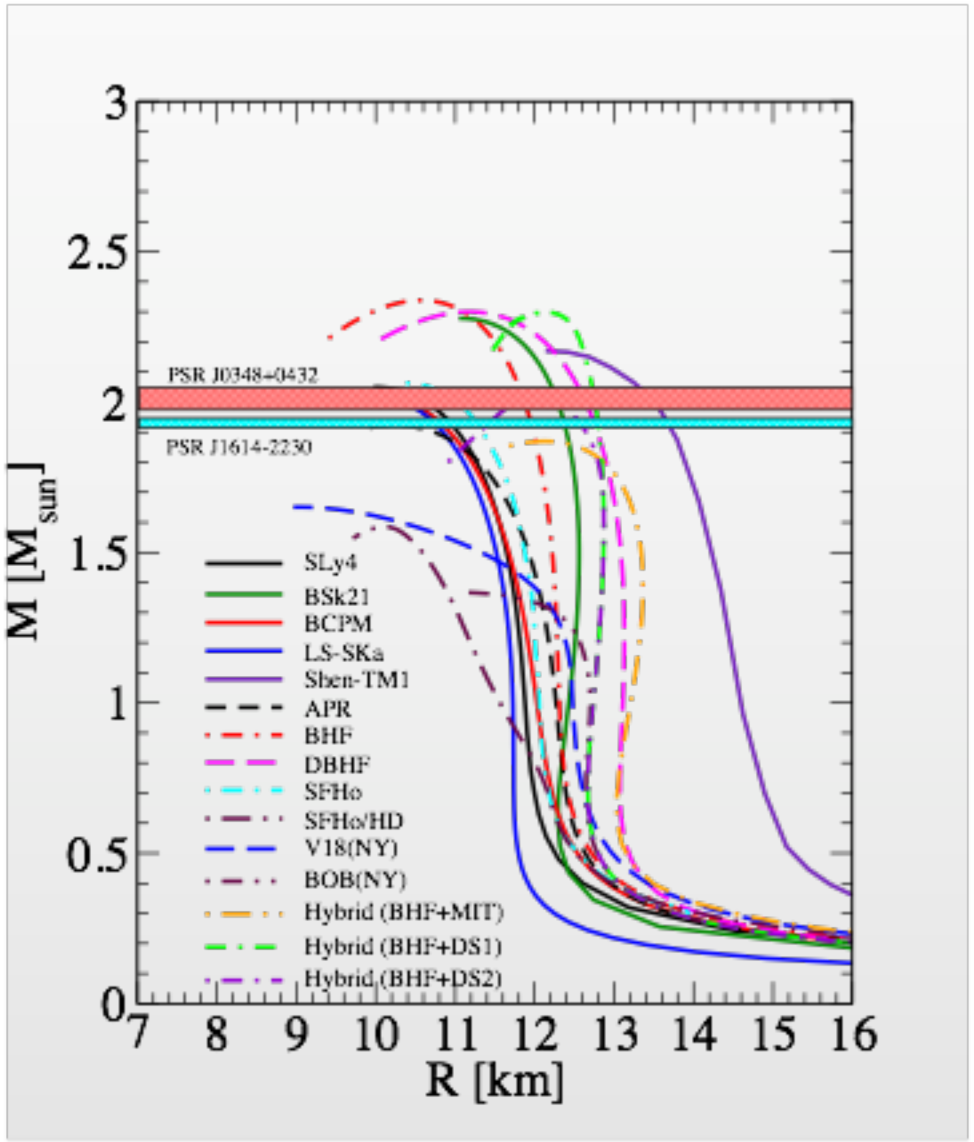
Ab initio approaches

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)

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





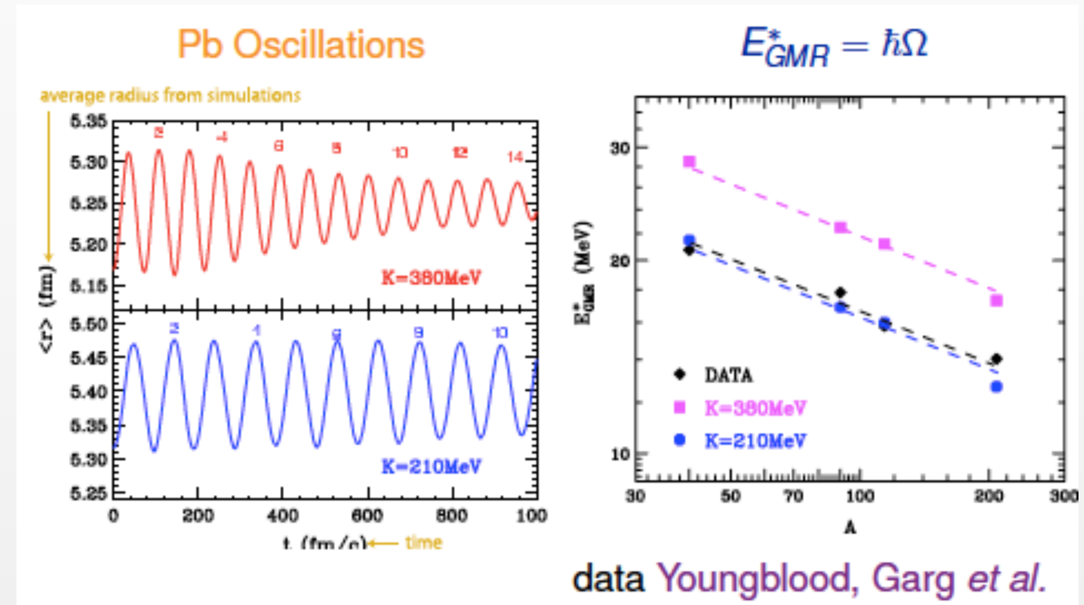
F. B. and A. Fantina,
"Nuclear Equation of state for Compact Stars and Supernovae",
White Book of the NewCompstar COST Action,
arXiv:1804.03020

The EoS : where do we stand ?

Close to saturation density $\rho_0 = 2\times10^{14}\,\mathrm{g/cm^3}$

☞ Structure properties of about 3339 nuclides.

☞ Compressibility from Giant Monopole Resonance.

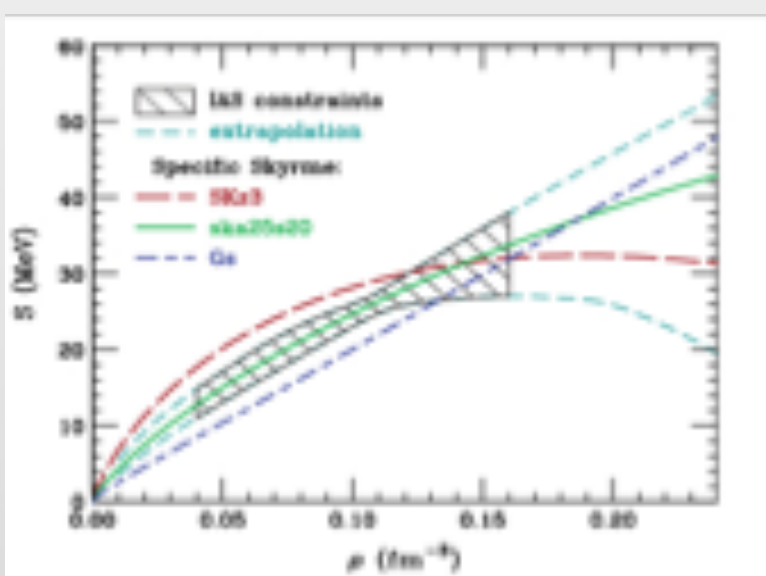


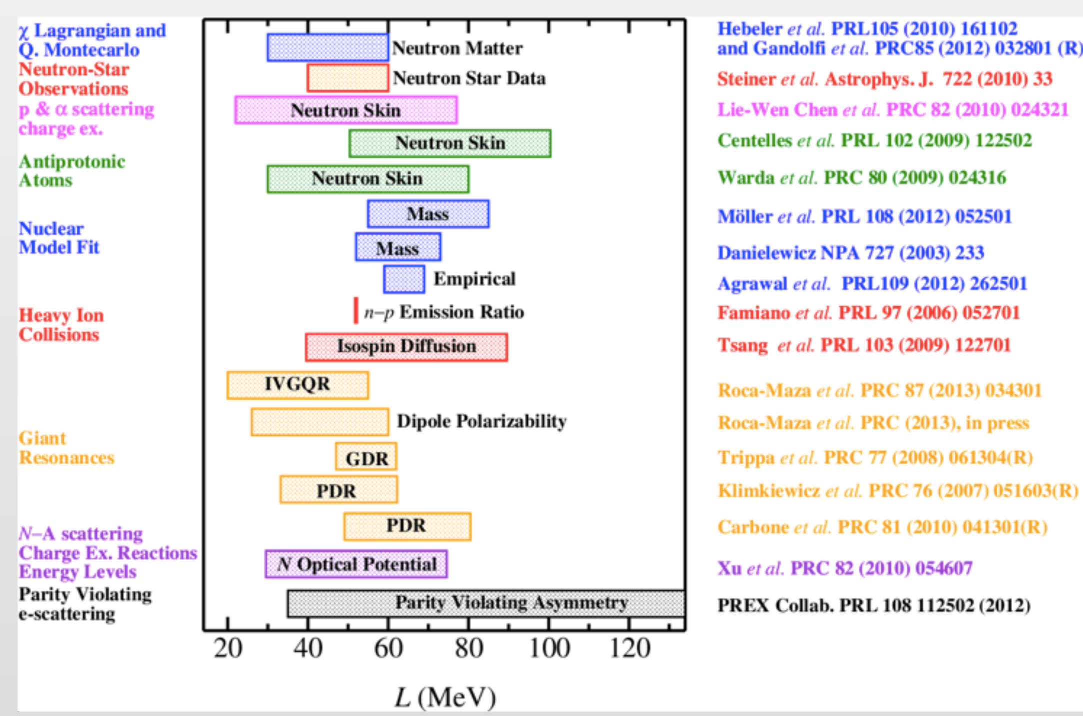
J.P. Blaizot, (1980), $K_\infty = 210 \pm 30\,\mathrm{MeV}$

G. Colo'et al., (2004), $K_\infty = 240 \pm 10\,\mathrm{MeV}$

J. Piekarewicz, (2004), $K_\infty = 248 \pm 8\,\mathrm{MeV}$

☞ Symmetry energy S_0 and its slope L.



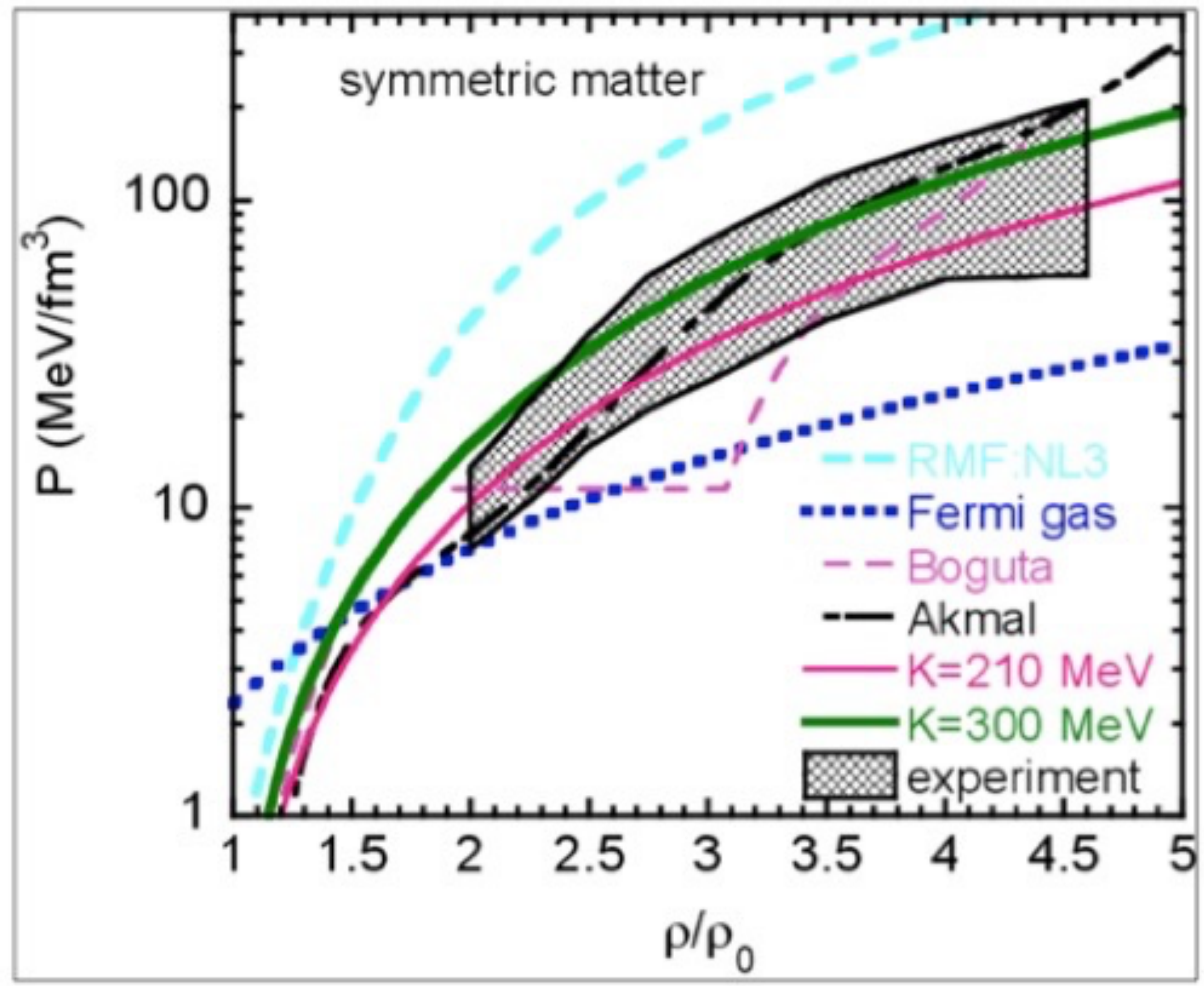


The EoS above saturation density : Constraints from heavy-ion reactions

- Transverse flow measurements in Au + Au collisions at E/A=0.5 to 10 GeV

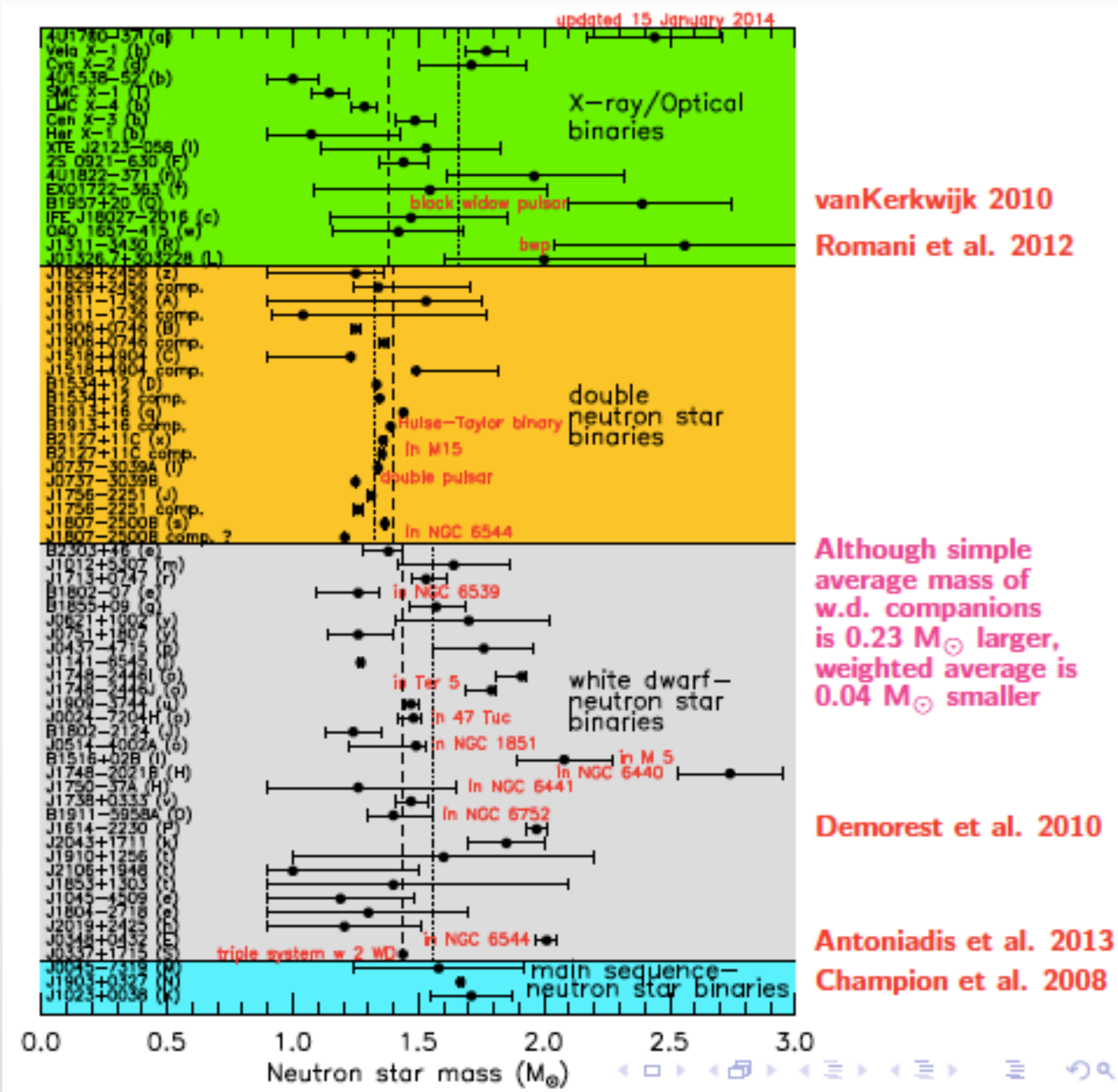
- Pressure determined from simulations based on the Boltzmann-Uehling Uhlenbeck transport theory

- Flow data exclude very repulsive and very soft equations of state



P. Danielewicz, Science 298, 1592 (2002)

The EoS above saturation density : NS masses observations

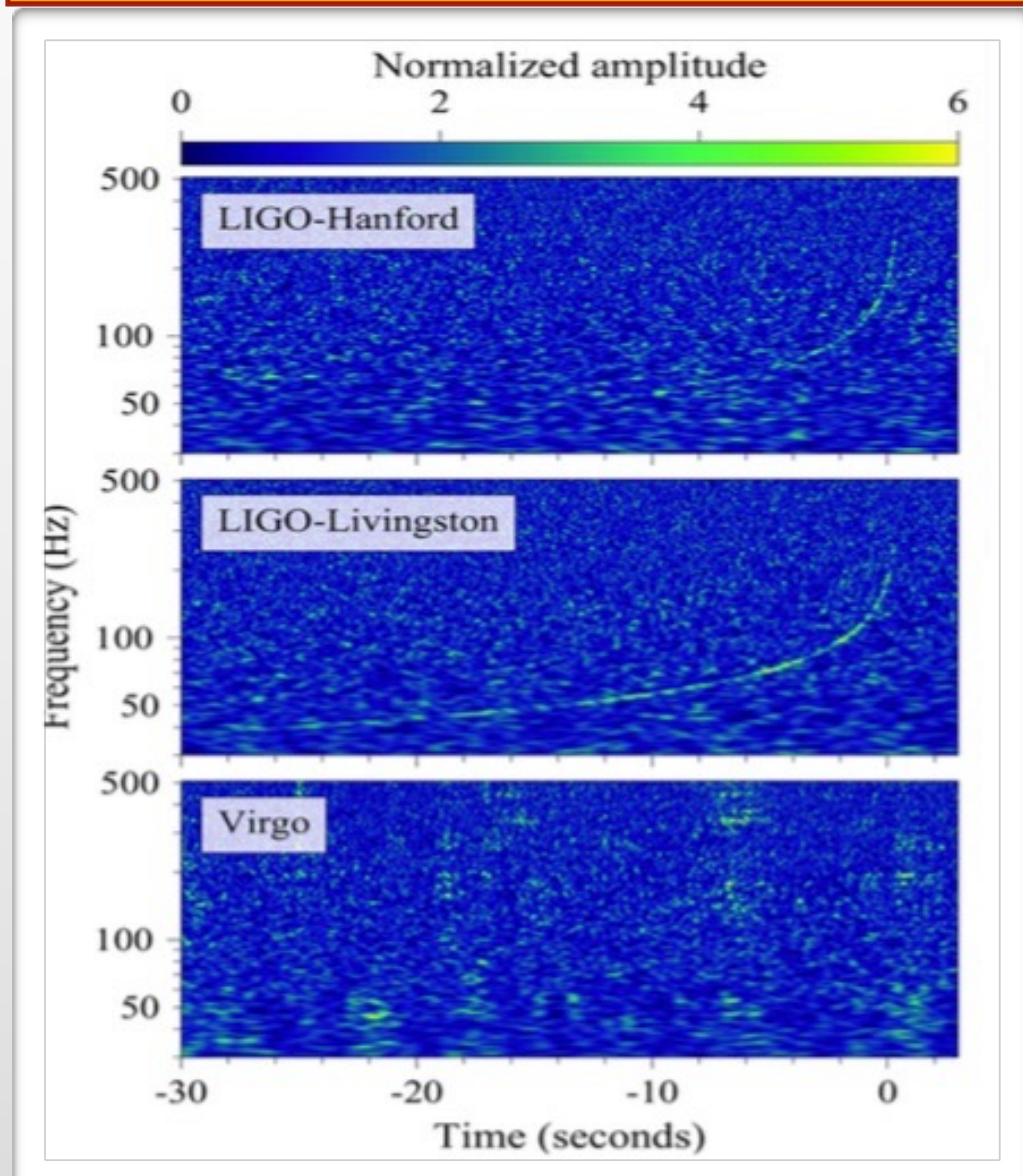


Compilation by J. Lattimer

* Several soft EOS are excluded !

The dawn of multi-messenger astronomy

On August 17, 2017, the LIGO-VIRGO detector network
observed a gravitational-wave signal from the inspiral of
two low-mass compact objects consistent with a binary neutron star (BNS) merger.



Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

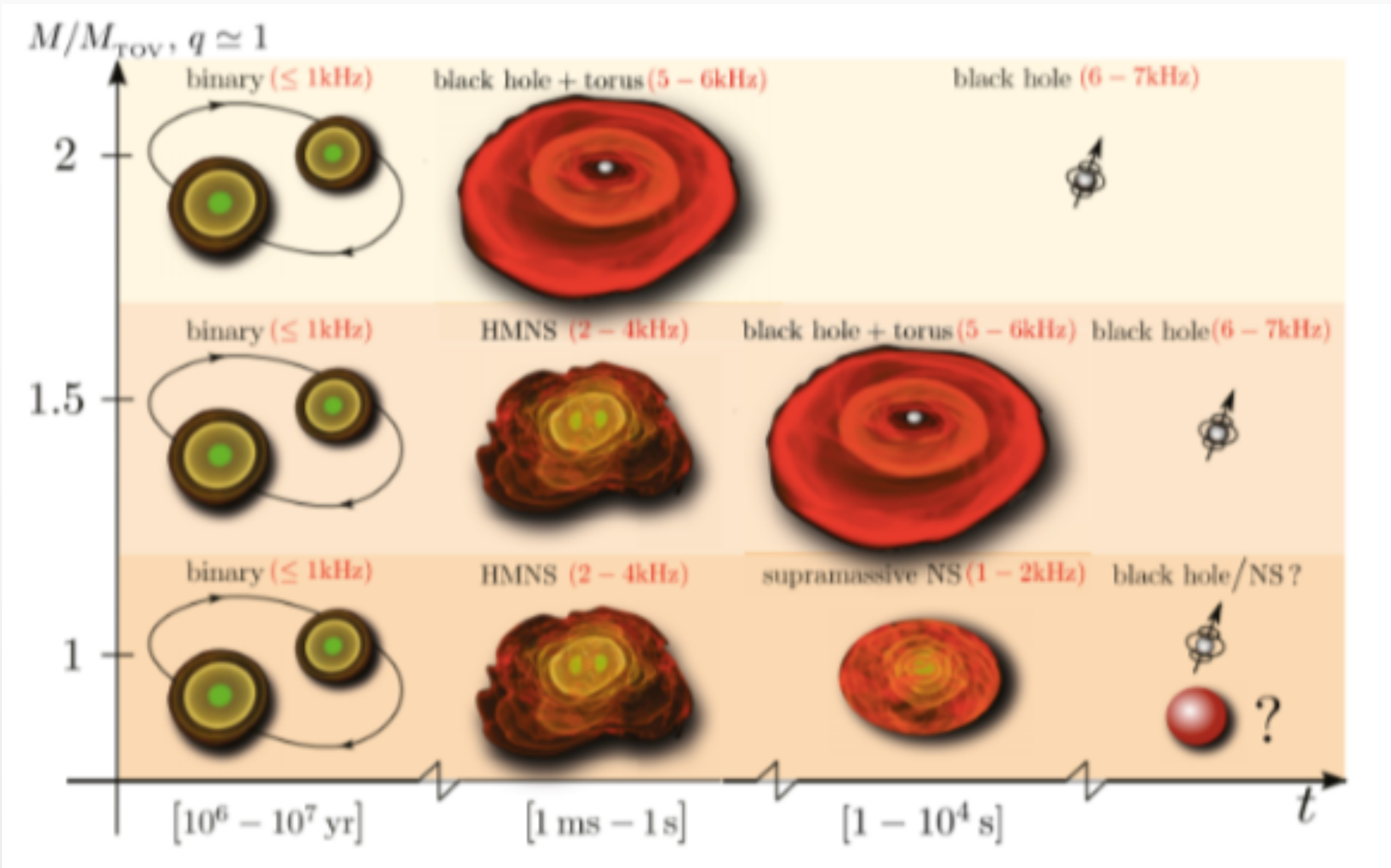
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

About 60 groups/collaborations participated to the investigations of GW170817, GRB170817A, AT2017fgo

Role of the EoS during NS-NS merger



- **Inspiral** decay of the orbital separation with progressive reduction of the orbit. GW emission. Strong tidal forces depending on the compactness M/R, i.e. EoS.
- **Merger** Duration and fate depend on EoS and total mass. Stiffer EoS —-> larger supported mass —-> collapse to BH delayed or avoided.
- **Post-merger** Remnant size and frequency of the dominant oscillation mode dependent on the EoS.

☞ NS mergers as valuable probe for testing the EoS !!!!

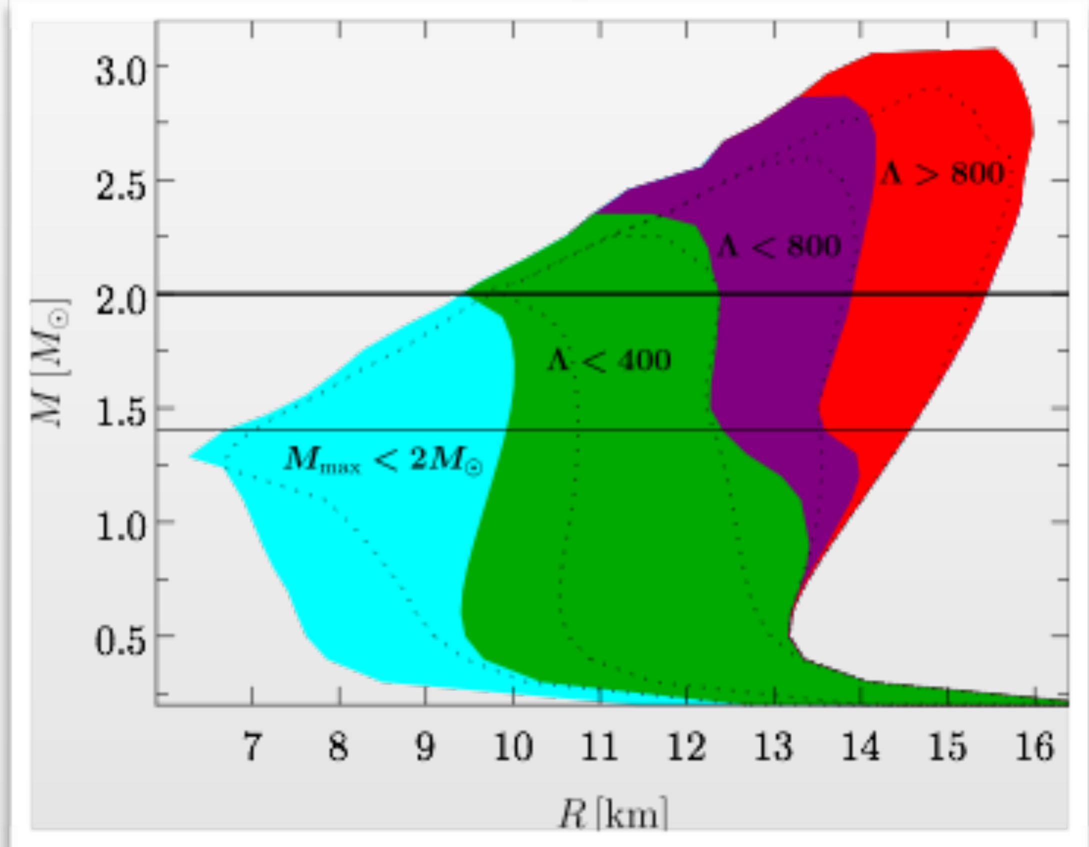
L. Baiotti and L. Rezzolla, Rep. Prog. Phys. (2017), arXiv:1607.03540

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

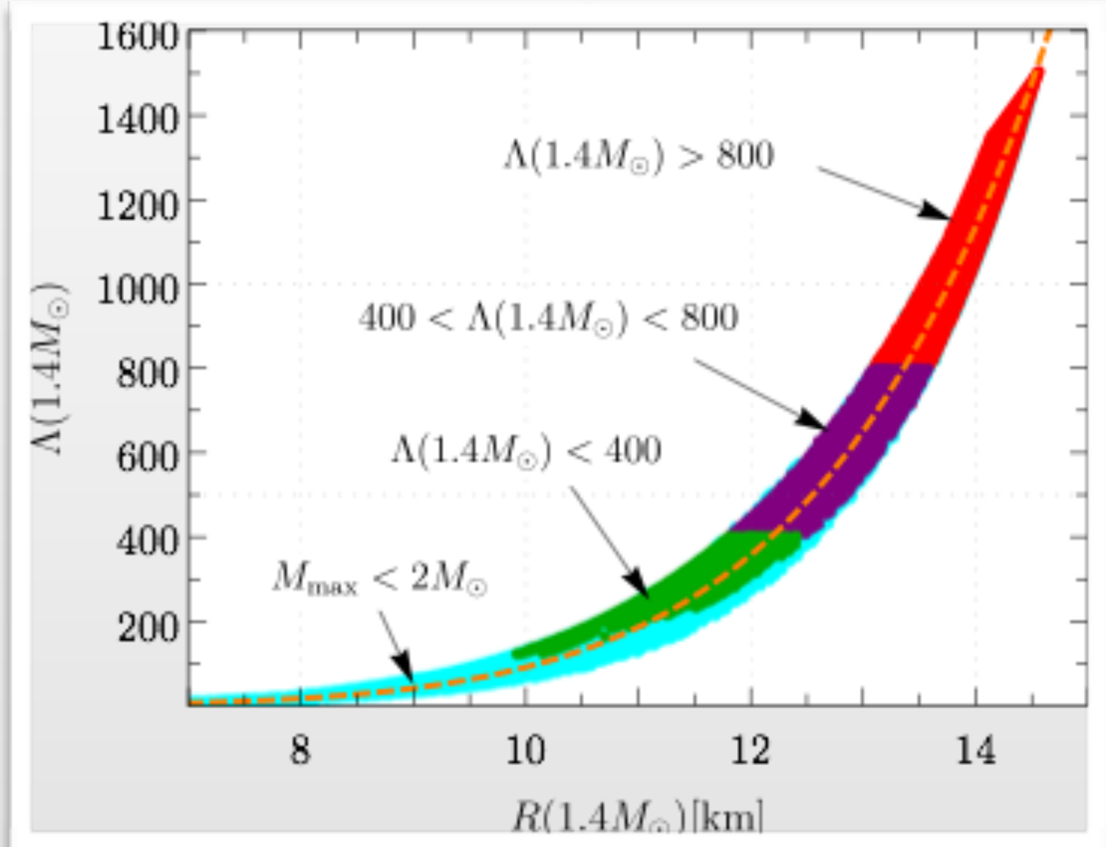
Constraints from GW170817: the tidal deformability Λ

$\Lambda_{1.4} < 800$ at 90% confidence level

This excludes very stiff EoS, which lead to large radii and hence to large values of Λ.



This translates into a limit for the radius $R_{1.4} < 13.6$ km.



Annala et al., PRL 120, 172703 (2018)

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

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

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

What about the radius ? Any lower limit ?

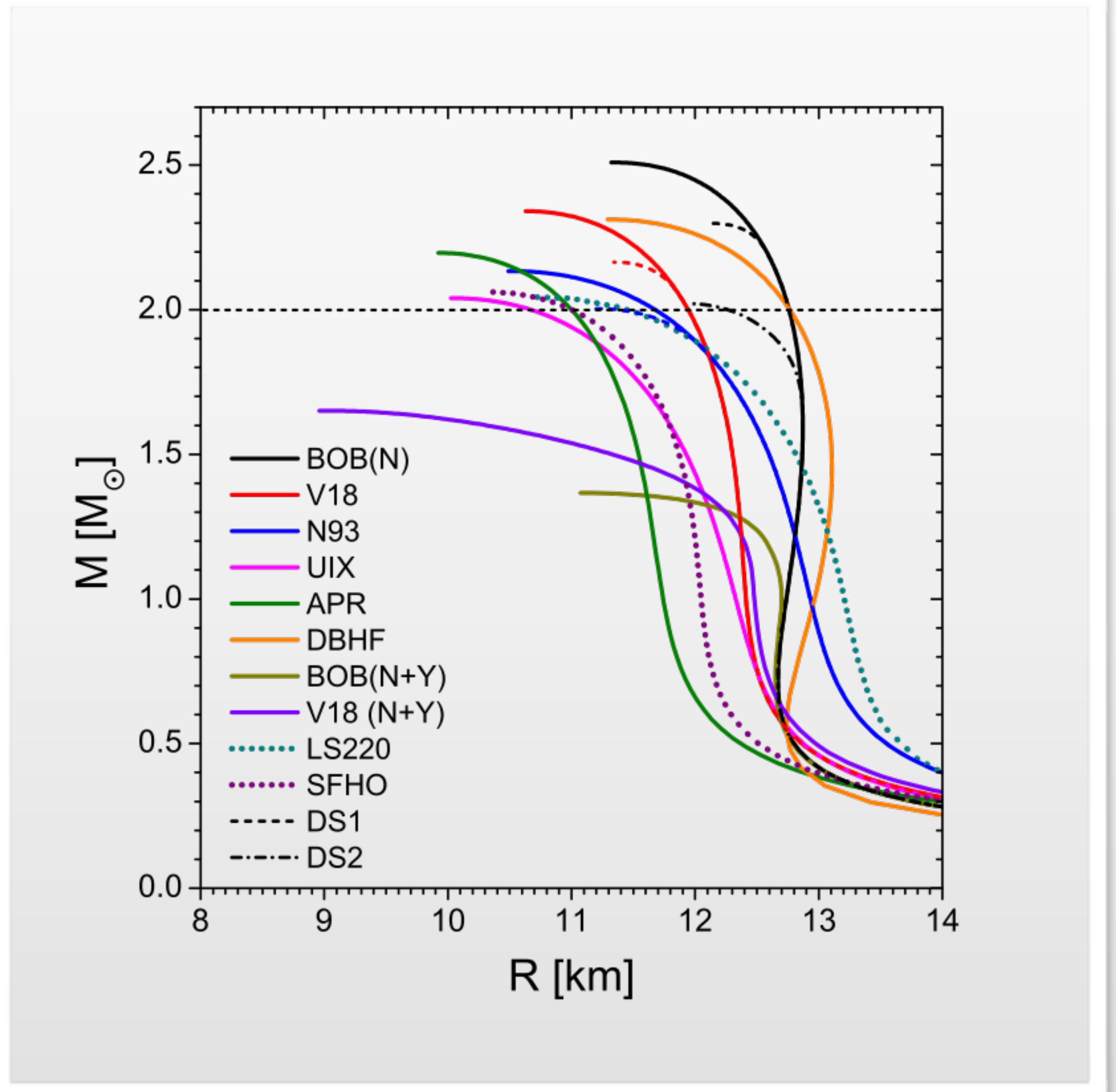
Annala et al., PRL 120, 172703 (2018) — $R_{1.4} > 12$ km

Most et al., arXiv:1803.00549
Lim et al., arXiv:1803.02803 — $R_{1.4} > (11.5\text{-}12)$ km

Fattoyev, PREX experiment (neutron skin), PRL 108, 112502 (2012) — $R_{1.4} > 12.55$ km

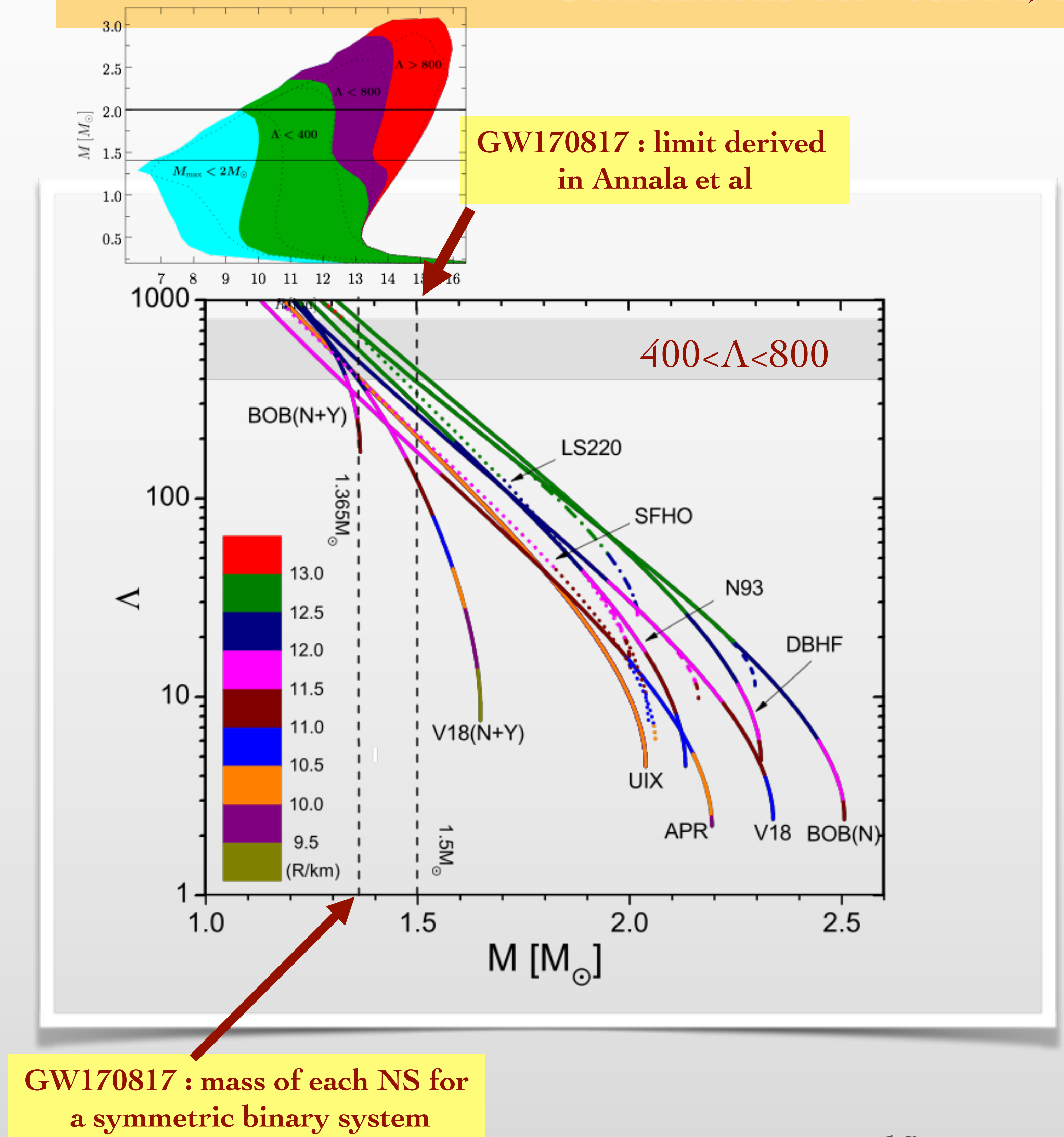
Constraint on the Mass-Radius relations

- 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
- Hybrid EoS : BHF with Bonn B and Dyson-Schwinger EoS for QM. DS1 and DS2.
- *All give maximum masses above 2M0 except the ones with hyperons.*



Constraining the EoS

Correlations between M, R and Λ



- Fixed chirp mass

$$\mathcal{M}_c = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} = 1.188\, M_\odot$$

$$q = \frac{M_2}{M_1} = 0.7 - 1$$

- The conditions $M_1 = M_2 = 1.365\ M_0$ and $400 < \Lambda < 800$ imply **12<R<13 km**

- Compatible EoS : V18(N+Y), UIX, V18,N93, BOB(N), DBHF, LS220, DS1, DS2.

- Not compatible : APR, BOB(N+Y), and SFHO (marginally).

Selection of the EoS !

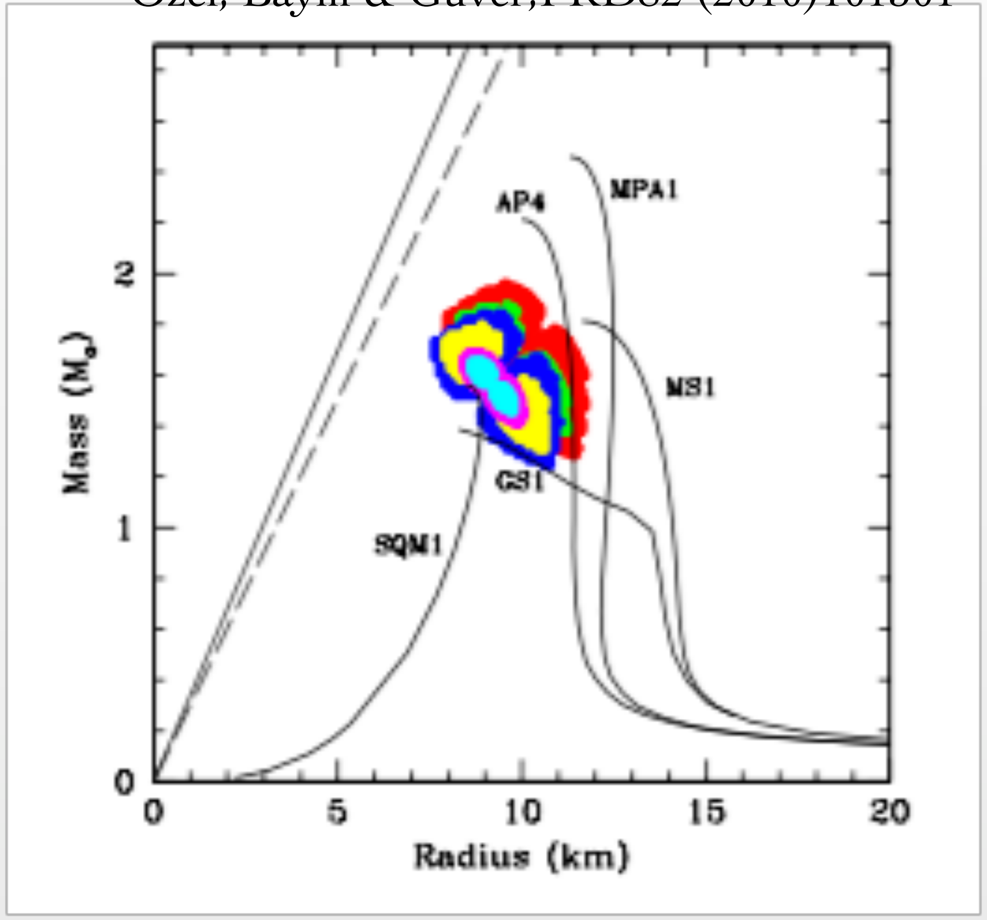
More about the radius….

Ozel&Freire, Ann.Rev. Astron.Astroph. 54 (2016)401

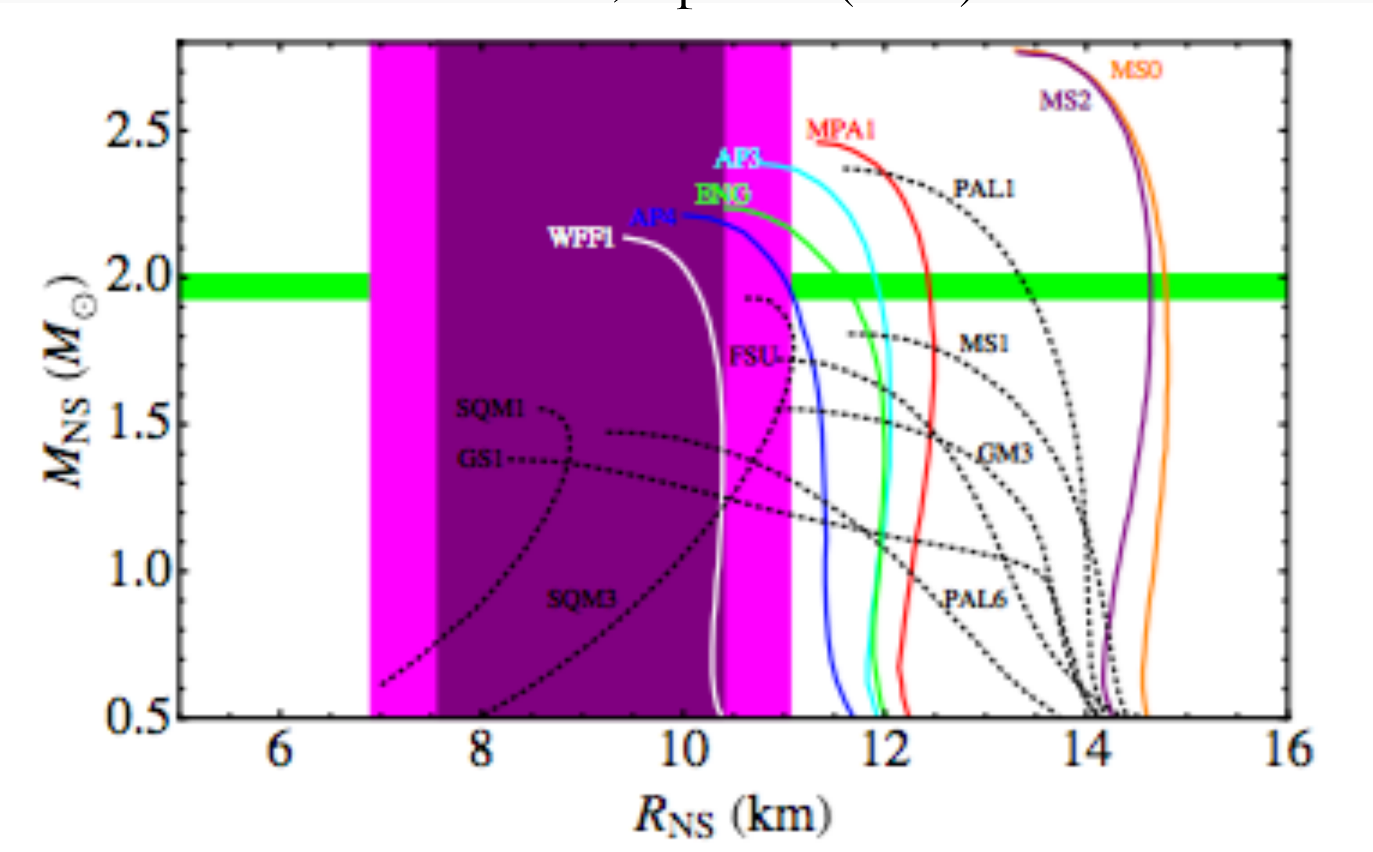
Is there any indication of small radii ? Very controversial ….

Also Guillot&Rutledge arXiv:1409.4306, R=(9.4±1.2)km

Ozel, Baym & Guver,PRD82 (2010)101301



Guillot et al., ApJ772 (2013)7



R=9.1±1.3 km

Analysis of 5 QLMXBs

Thermal emission of isolated NSs

Dependence of the fit on many parameters :

☞ chemical composition of the atmosphere,
☞ magnetic field,
☞ distance to the source,
☞ interstellar absorption.

Future X-ray telescopes (NICER, Athena+) : M-R constraints with a precision of 5%.

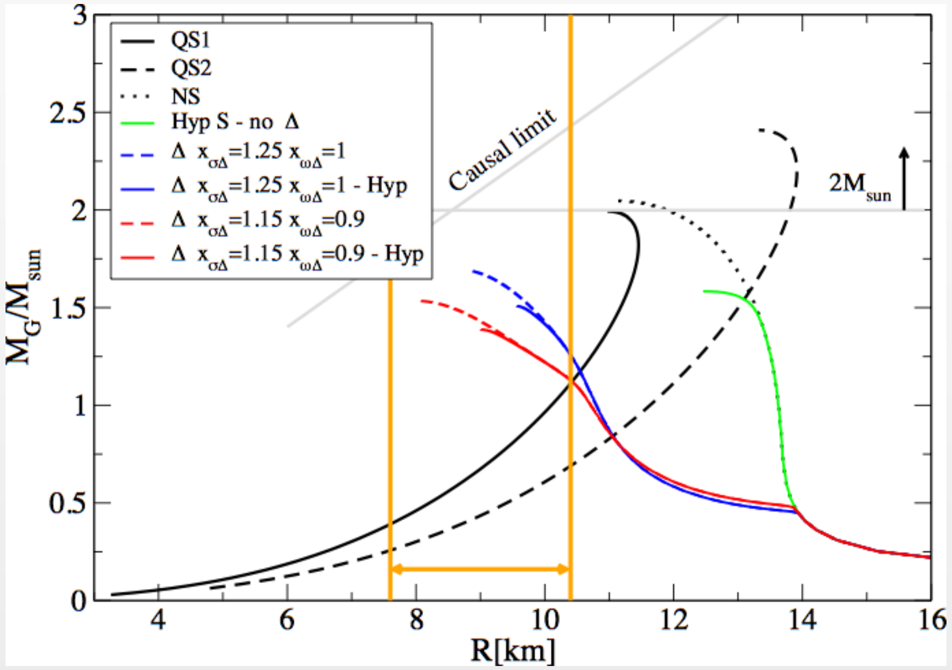
Question :

Under which conditions R < 12 km is consistent with GW170817/AT2017gfo limits on Λ?

F.B., A. Drago, G. Pagliara, H.-J. Schulze, J. Wei
arXiv:1803.09696
Astrophysical Journal, in press

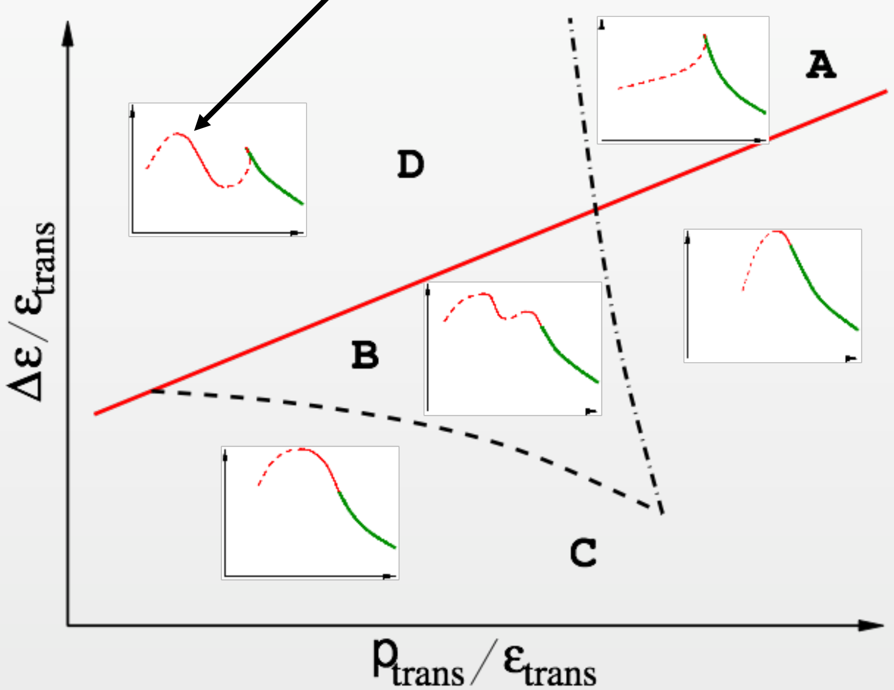
A possible scenario : phase transition to quark matter

Two-families of compact stars: hadronic and quark stars



- Hadronic stars are stable until strangeness onset (e.g. hyperons) in the core. Conversion to strange quark matter.
- **Low mass (up to ~ 1.5 M0) and small radii (down to 9-10km) stars are HS.**
- **High mass and large radii stars are QS.**

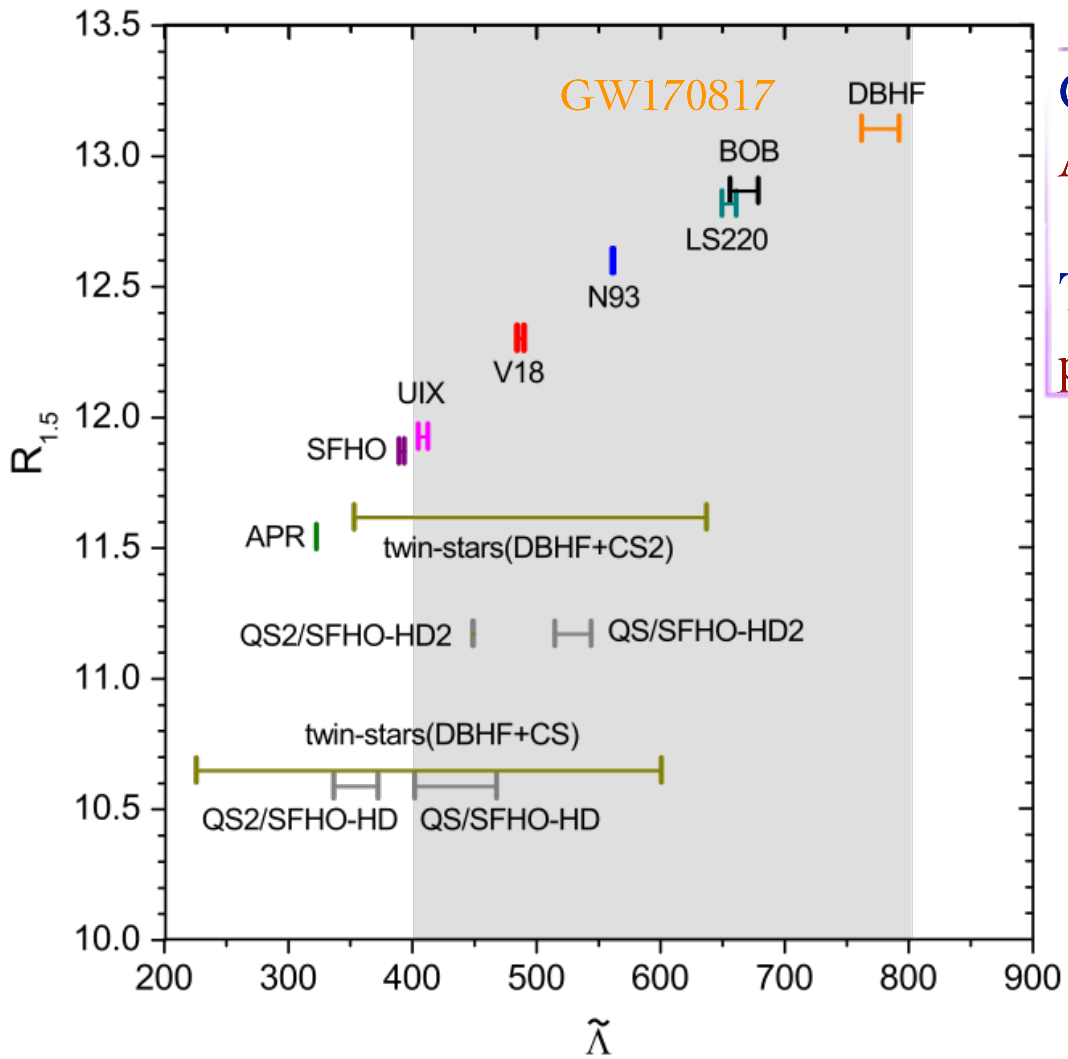
Twin stars : a strong first-order PT to quark matter



- QM branch separated from the HM branch by unstable configurations.
- *Twin-masses.* **Two equal mass stars in HM and QM branches, but different R and composition.**
- **Hybrid CS composed of hadronic mantle and quark core.**

Correlations between $\tilde{\Lambda}$ and $R_{1.5}$

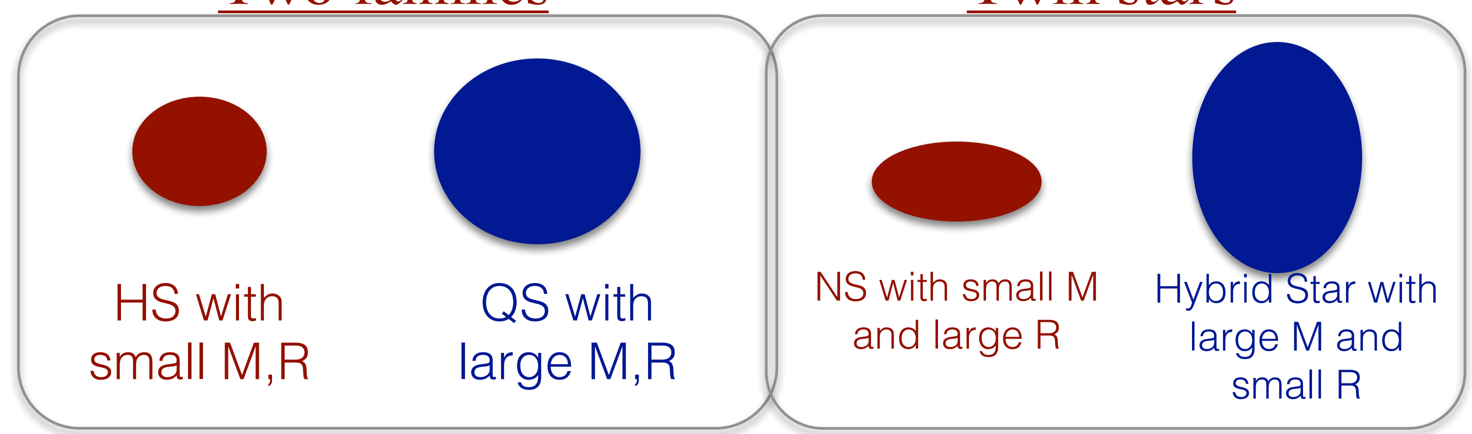
$R_{1.5}$ indicates the radius of the most compact star.



One-family-scenario : monotonic correlation between $R_{1.5}$ and $\tilde{\Lambda}$. All EoS with $\tilde{\Lambda}>400$ have $R_{1.5}>11.8$ km, except APR and SFHO.

Two-families and twin-stars scenarios : $R_{1.5} < 11.8$ km are possible with $\tilde{\Lambda}>400$.

Two-families | Twin stars



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

The differences in their M vs.R relation and composition should be visible in GW and kilonova signal !

Conclusions

- Several constraints on the EoS from nuclear structure, heavy-ions, maximum observed mass but still not enough constraining ….

GW170817 event has added one more constraint :
the tidal deformability $400<\Lambda<800$ and the radius $12<R<13$ km.

- Lower limit on the tidal deformability compatible with radii smaller than 12 km, if a two-family scenario is assumed.

The source of GW170817 is a mixed binary system: a hadronic star and a quark/hybrid star.

- Tighter constraints from NICER and SKA telescopes.