2009-2013 (ESF),
2013-2017 (COST)

2018-2021 (COST)

COST is supported by the EU Framework Programme Horizon 2020

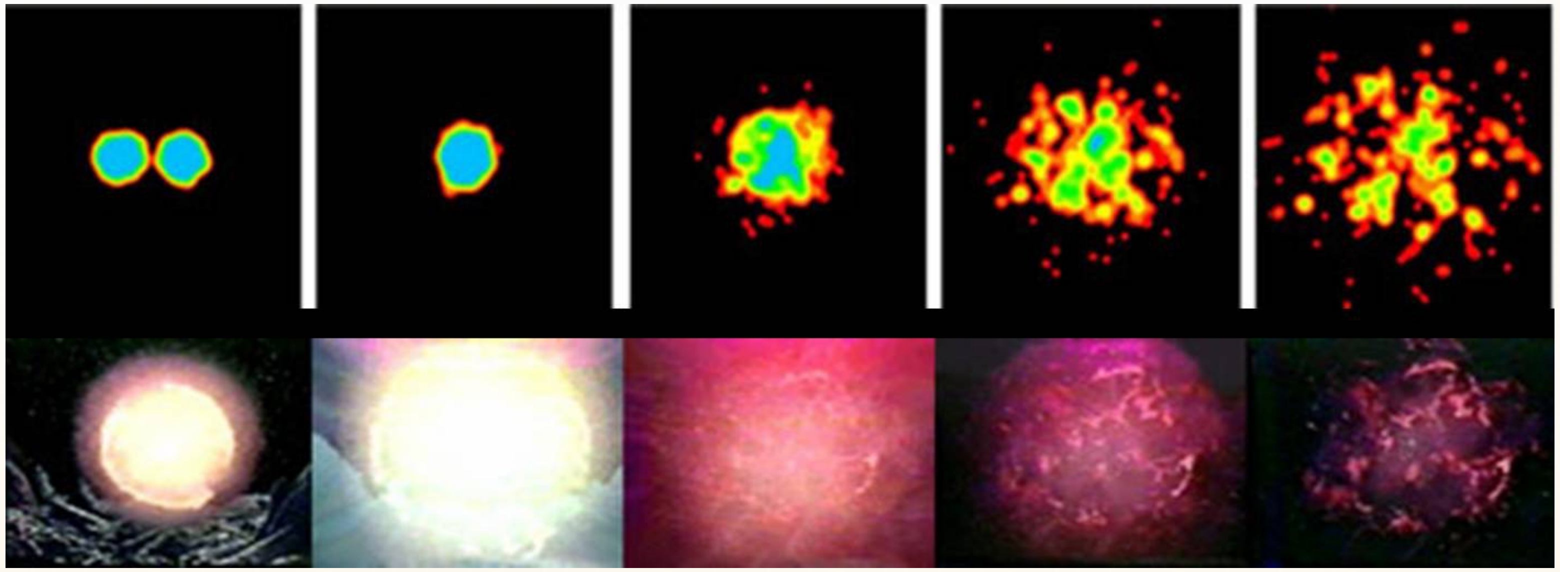
Combined constraints on the dense matter EoS from HIC and NS observations

Fiorella Burgio
INFN Sezione di Catania

ECT*, Trento, May 2019

The Nuclear EoS and its relevance

The Nuclear EoS of hot and dense matter is the fundamental input to describe static and dynamic properties of NS, core-collapse supernovae and binary compact-star mergers.



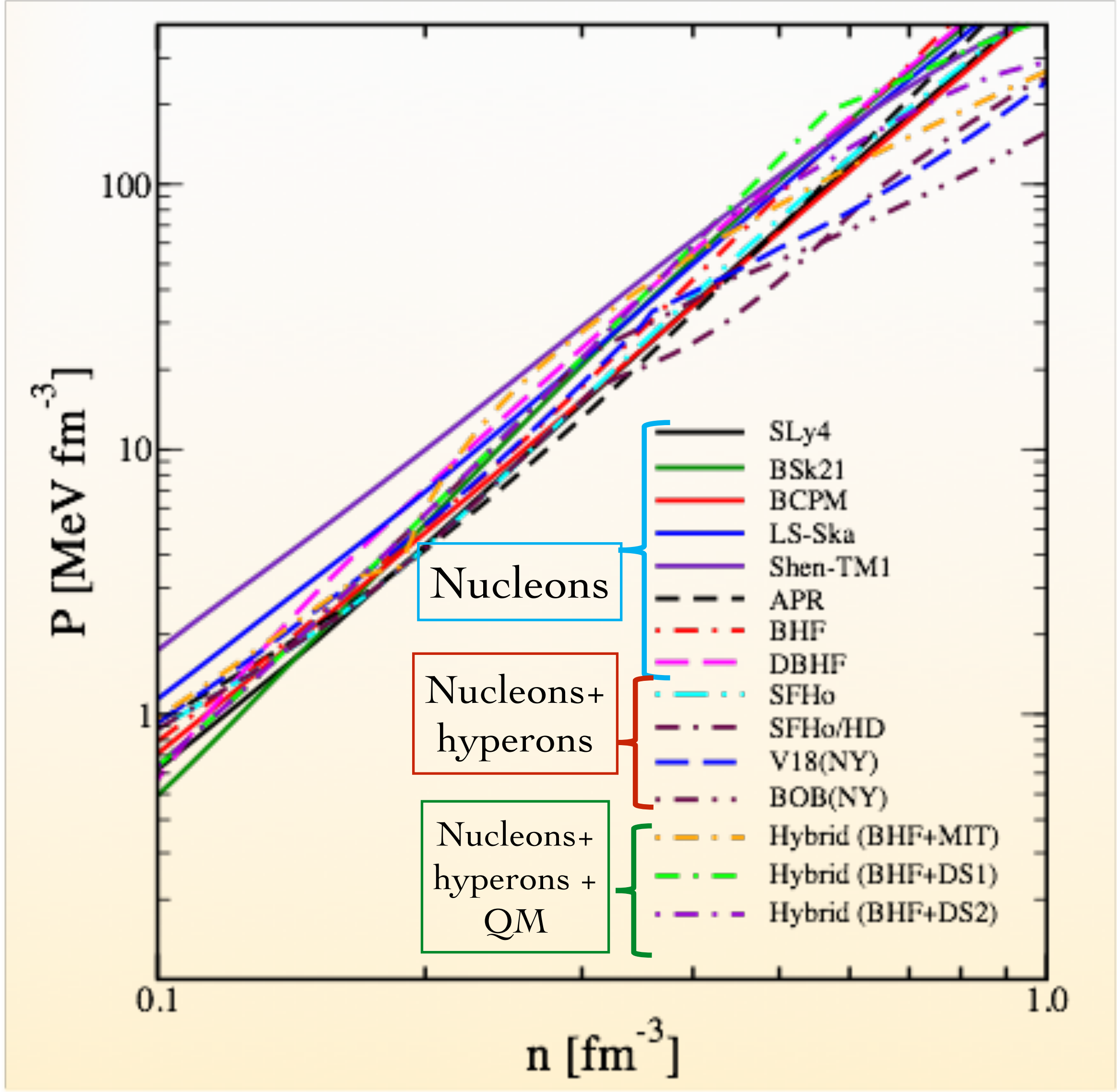
1. Heavy ion collisions (small N/Z, high T)
2. Supernovae and Neutron Stars (high N/Z, high (small) T in SN (NS))
3. Binary NS merger and GW emission (high density, high N/Z and T)

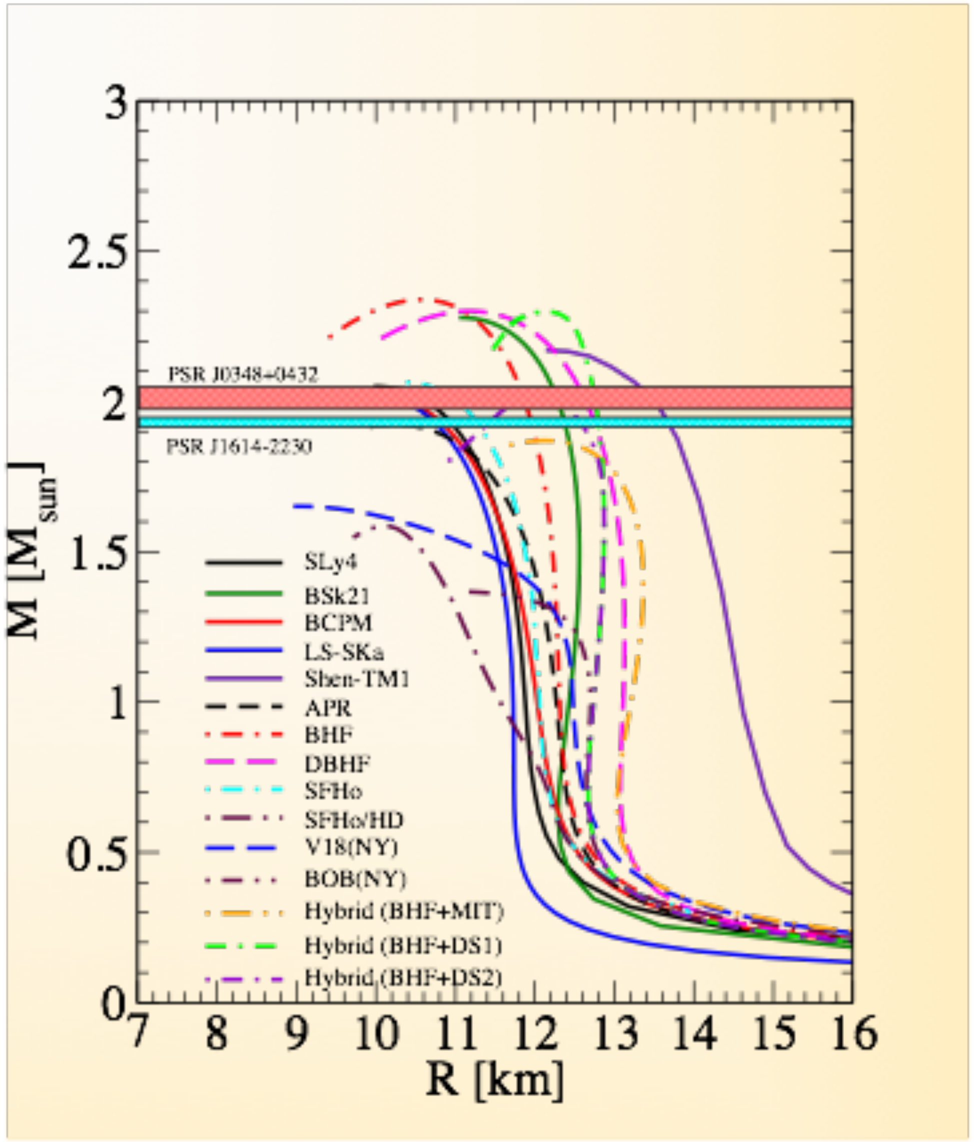
Quite different physical conditions in each case !

A nuclear matter theory must be able to treat all these physical situations.

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

☞ A large variety of mass-radius relations !





F. B. and A. Fantina,
"Nuclear Equation of state for Compact Stars and Supernovae",
Chap.6 of "The Physics and Astrophysics of Neutron Stars",
Springer, Berlin 2018. arXiv:1804.03020

Main difficulties come from :

- Solving the nuclear many-body problem : a very hard task !
- Lack of precise knowledge of the in-medium NN interaction.

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)

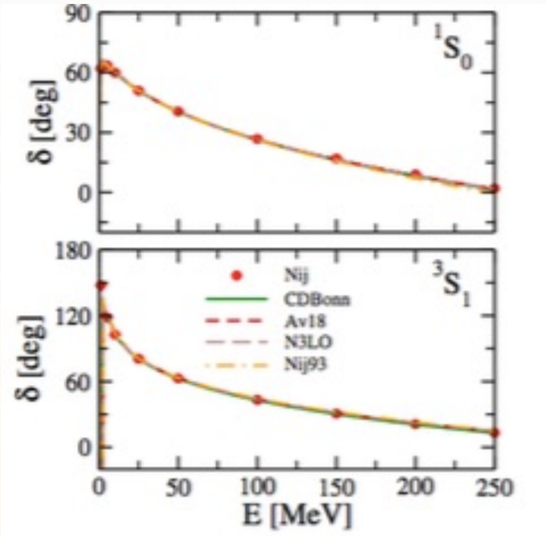
Ab initio approaches

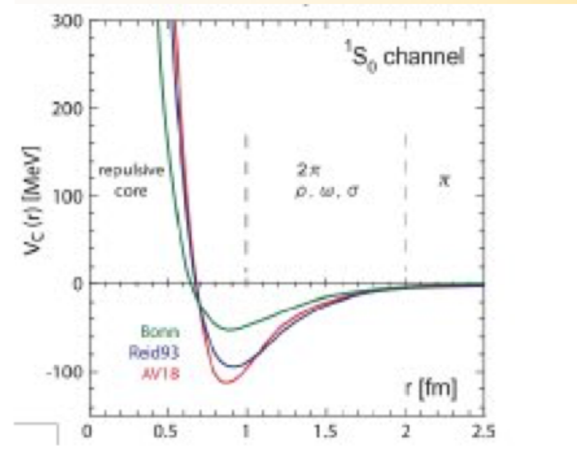
The nuclear problem is solved starting from the two- and three-body realistic nucleon interaction.

- 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)

The hard life with *ab-initio* approaches

- Several nucleon-nucleon potentials available in literature *(meson exchange models (Bonn, Njimegen), potential models (Urbana, Argonne))* **BUT** they are all phase-shift equivalent.

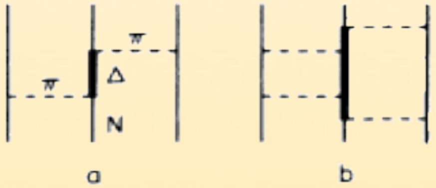


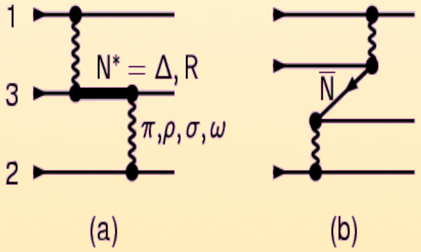


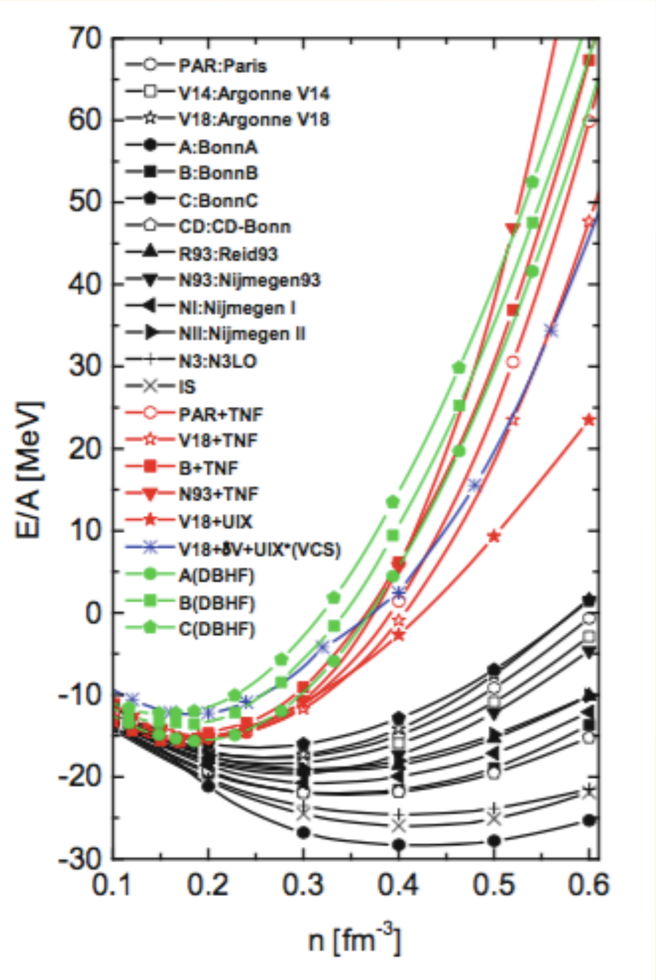
- **Strong short range repulsion**. It makes any perturbation theory in terms of V *meaningless*. Different ways of treating the SRC.

- Very complicated channel and operatorial form (central, tensor, spin-orbit, spin-spin, spin-isospin, etc…)

- **Three-body forces.**
  - Reproduce the spectra of light nuclei
  - Saturate properly in non-relativistic many-body calculations.
  - No ab-initio theory exists yet.
  - Phenomenological vs. microscopic approaches :



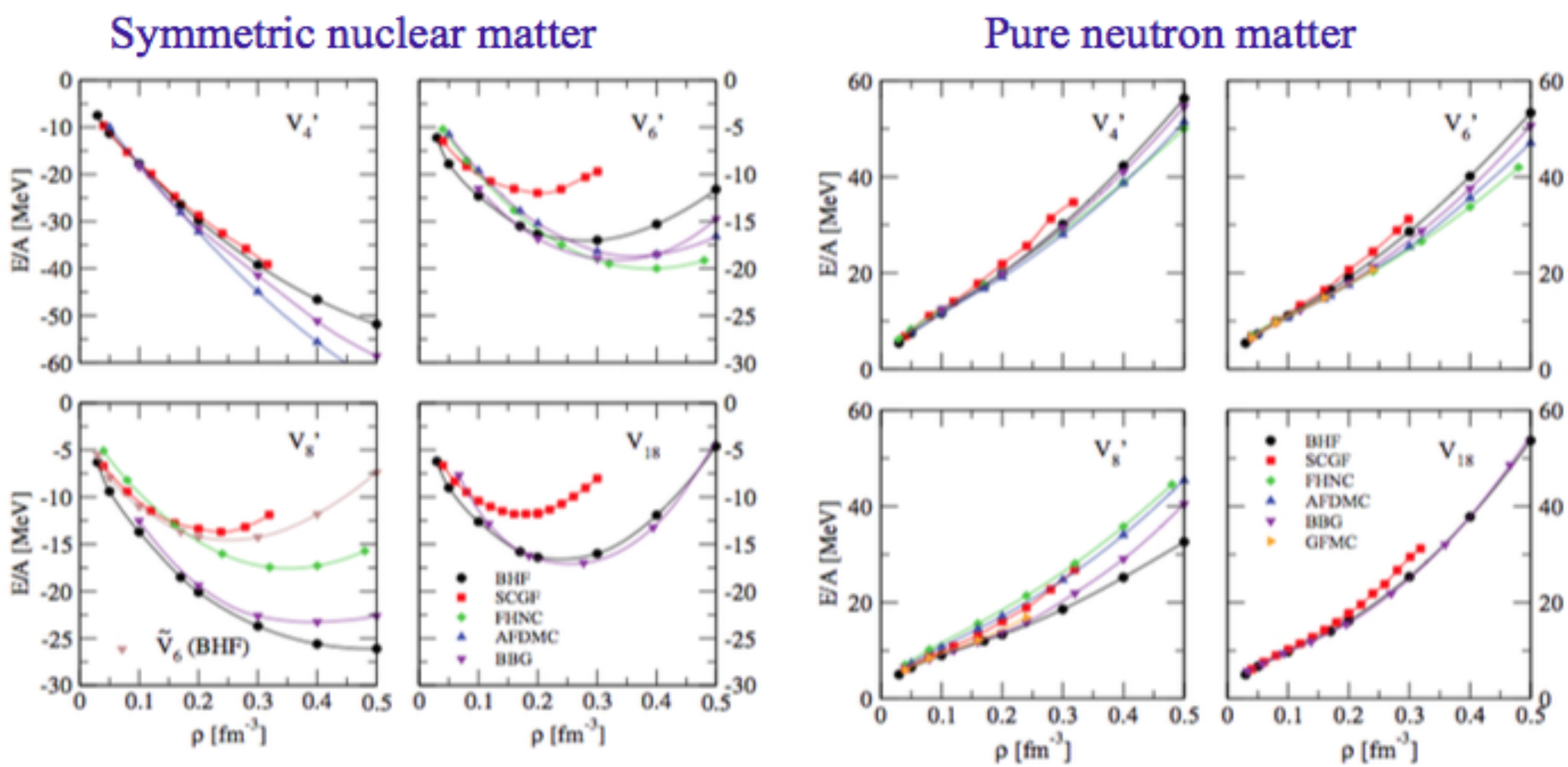




  - Large differences in the EoS at large density.

Comparing some ab-initio approaches

Compare different many-body techniques using the same NN interaction (Argonne family) to find the sources of discrepancies.



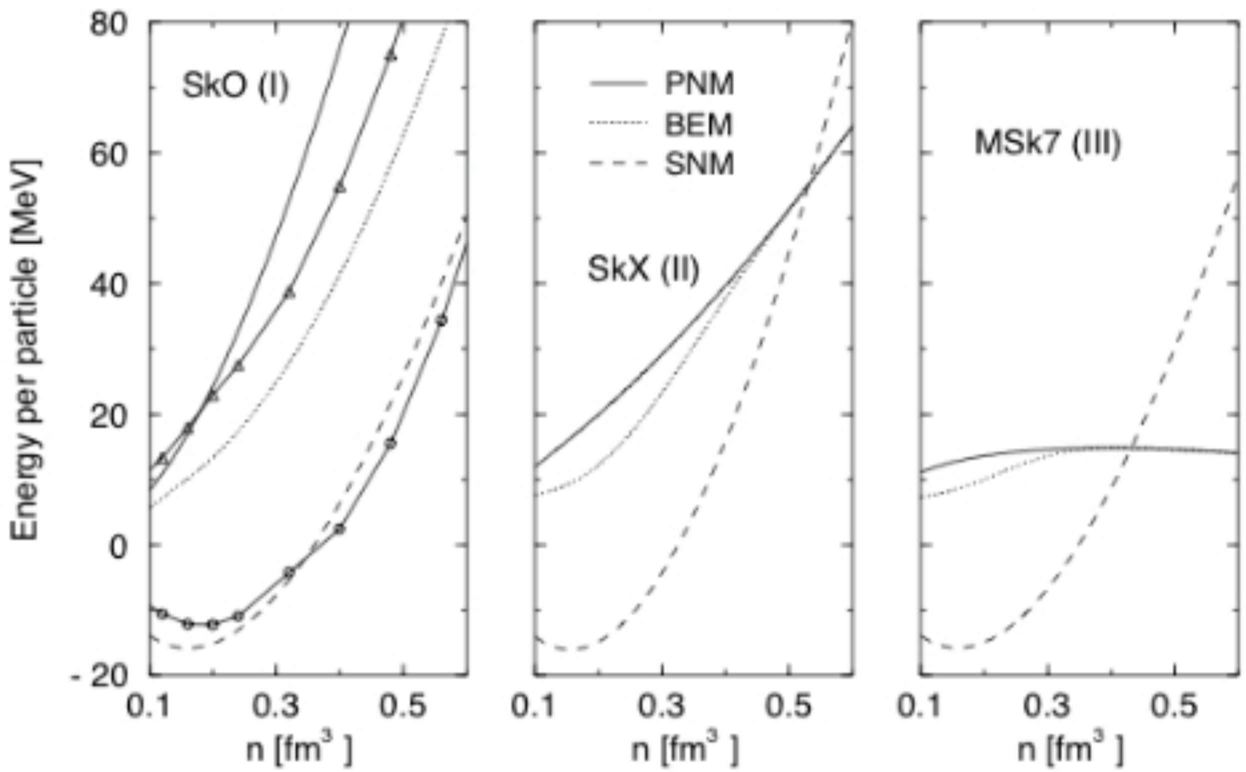
Tensor & spin-orbit and their in-medium treatment are at the heart of most of the observed discrepancies

M. Baldo, A. Polls, A. Rios, H.-J. Schulze & I.Vidaña, PRC 86, 064001 (2012)

Comparing some phenomenological models

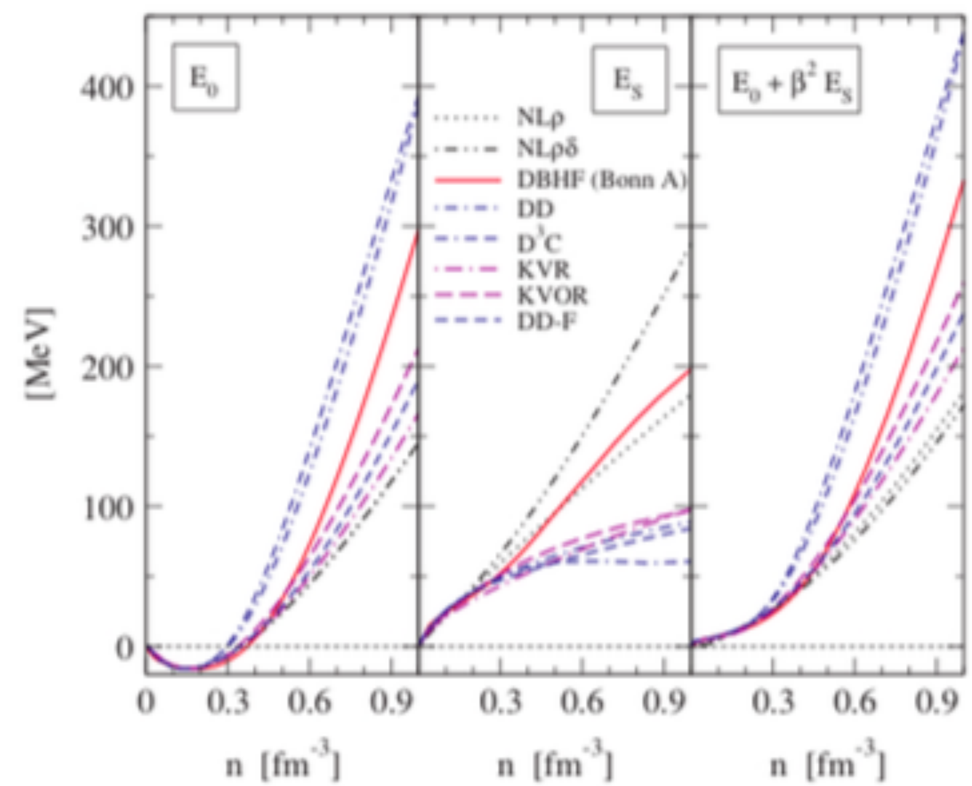
Plenty of many phenomenological models predicting different SNM&PNM EoS.

Skyrme forces



J. R. Stone et al., PRC 68, 034324 (2003)

RMF models



T. Klahn et al., PRC 74, 035802 (2006)

- Analysis of a set of 240 Skyrme forces, checking their ability to fulfill correctly saturation of nuclear matter, compressibility, symmetry energy and its derivative, data from heavy ions and NS observations. Only 5 passed all tests !

- The same analysis was performed on a set of 263 parameterizations of 7 different kinds of RMF models. Only 7 passed the tests !

A set of microscopic and phenomenological EoS

- Microscopic non-relativistic EoS
  Brueckner-Hartree-Fock-type calculations. NN scattering G-matrix with two (Bonn B, V18, N93, UIX) and three body forces (microscopic and Urbana model).

  FSS2CC & FSS2GC : BHF calculations with NN potential based on quark-gluon degrees of freedom.

- Microscopic relativistic EoS : Dirac-BHF

- Variational : APR (Akmal-Pandharipande-Ravenhall)
  Minimization of the nuclear Hamiltonian with two and three body forces (Argonne v18 + Urbana model)

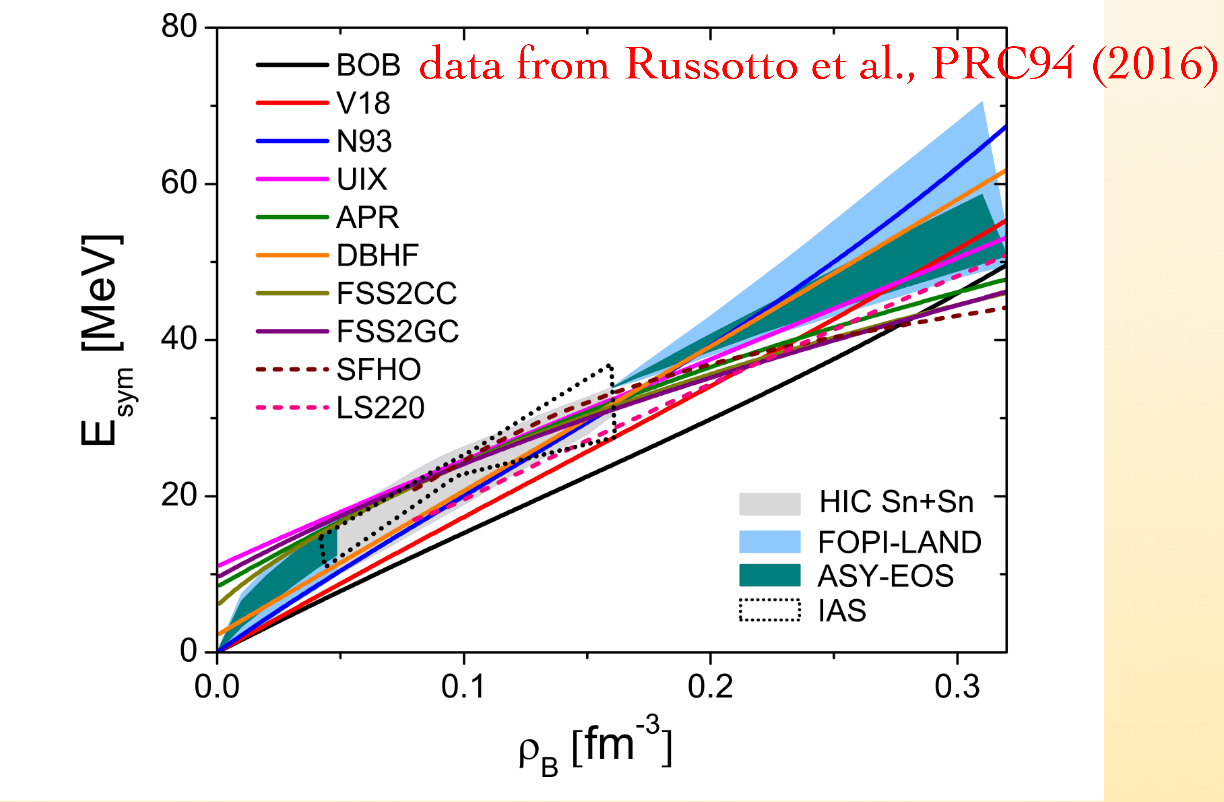
- Phenomenological EoS.

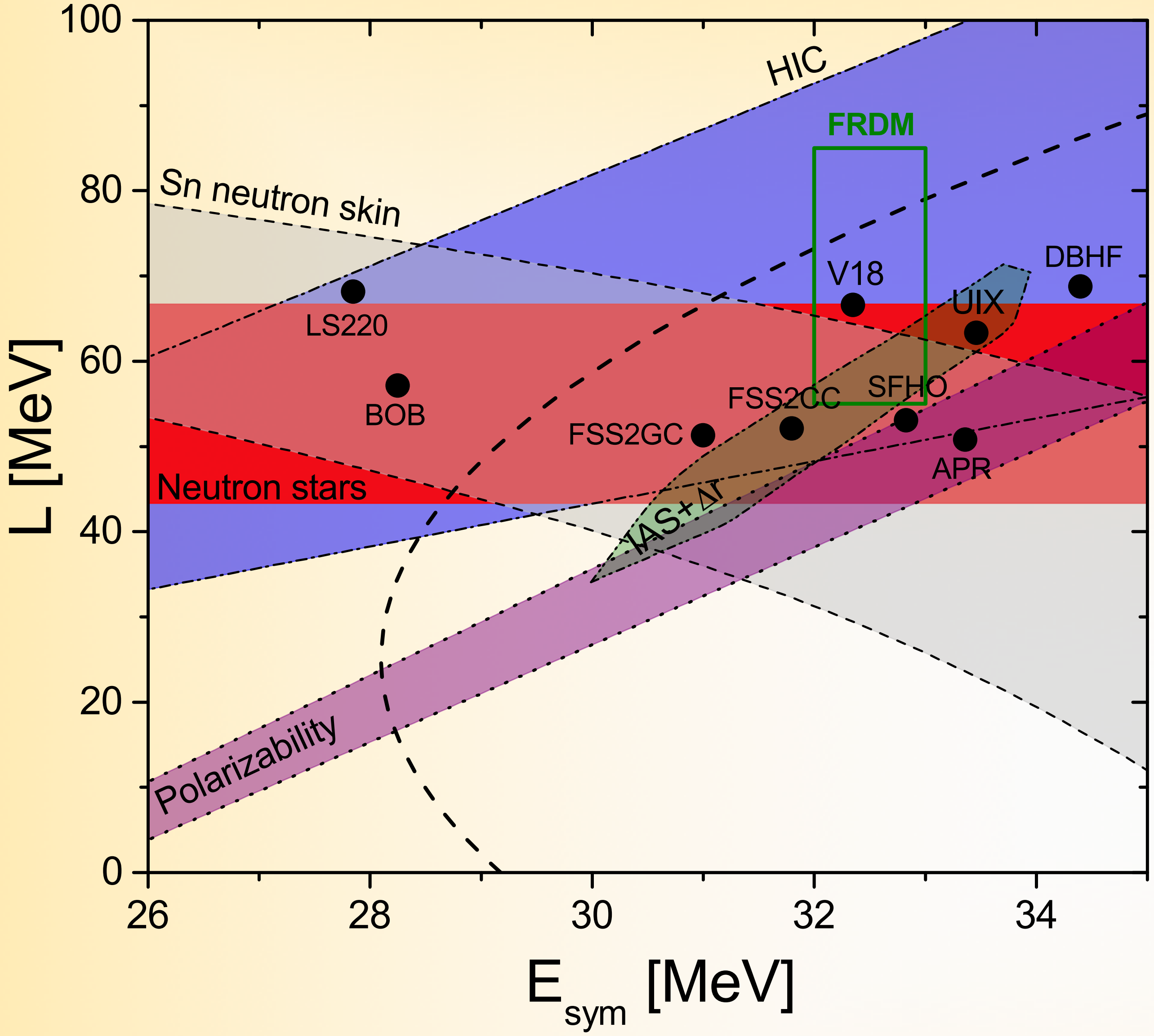
  ➢ LS220 : Matter as mixture of heavy nuclei, alpha particles, free neutrons and protons. Liquid-drop model for nuclei with Skyrme interaction.

  ➢ SFHO : Nucleons described by the RMF model.

Table 1. Saturation properties of the considered EOSs.

EOS	ρ_0	E_0	E_{sym}	L	K_0
BOB	0.170	15.4	28.2	57.1	238.1
V18	0.178	13.9	32.3	66.6	207.4
N93	0.185	16.1	36.5	78.0	224.1
UIX	0.171	14.9	33.5	63.3	171.0
APR	0.159	15.9	33.4	50.8	233.4
DBHF	0.181	16.2	34.4	68.8	217.6
FSS2CC	0.157	16.3	31.8	52.1	219.0
FSS2GC	0.170	15.6	31.0	51.3	185.0
SFHO	0.157	16.2	32.8	53.1	244.4
LS220	0.155	15.8	27.8	68.1	218.9





HIC -> isospin diffusion in HICs (Tsang et al., PRL (2009);

Sn neutron skin from the analysis of neutron skin thickness in Sn isotopes (Chen et al., PRC2010);

Polarizability from the electric dipole polarizability as in Roca-Maza et al., PRC (2015).

FRDM finite-range droplet mass model calculations (Moller, PRL (2012)).

IAS SHF calculations of IAS and the ^{208}Pb neutron-skin thickness (Danielewicz&Lee, NP 2014).

Neutron stars Bayesian analysis of mass and radius measurements of NSs (Steiner et al. ApJL,2013).

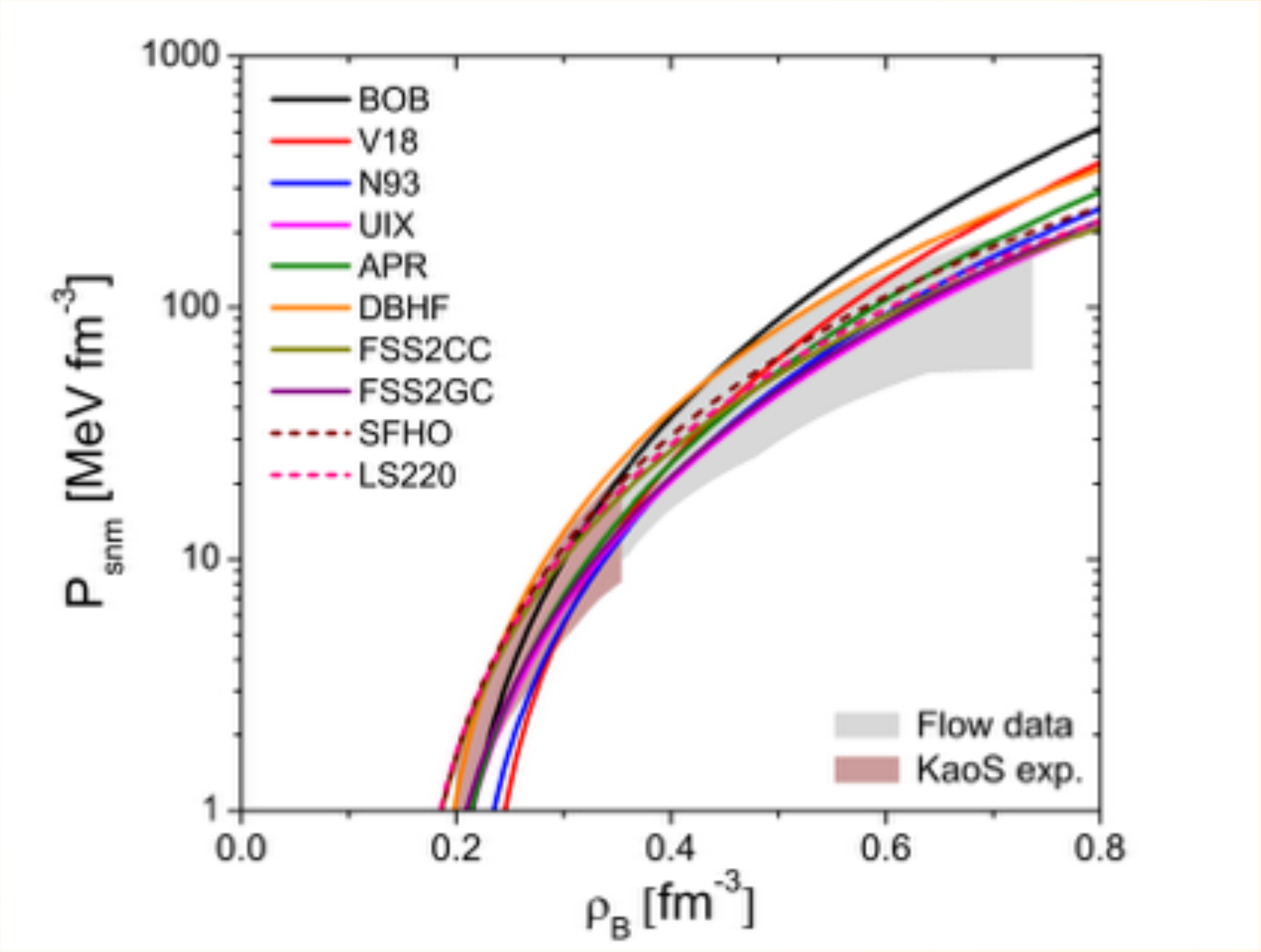
Unitary gas (dashed) (Kolomeitsev et al.2016), only values to the right of the curve are permitted.

No area of the parameter space where all the considered constraints are simultaneously fulfilled !

Combining different constraints reduces the uncertainties in the (S_0,L) parameter space, but no theoretical models can be ruled out a priori on this basis.

SUPRA-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.



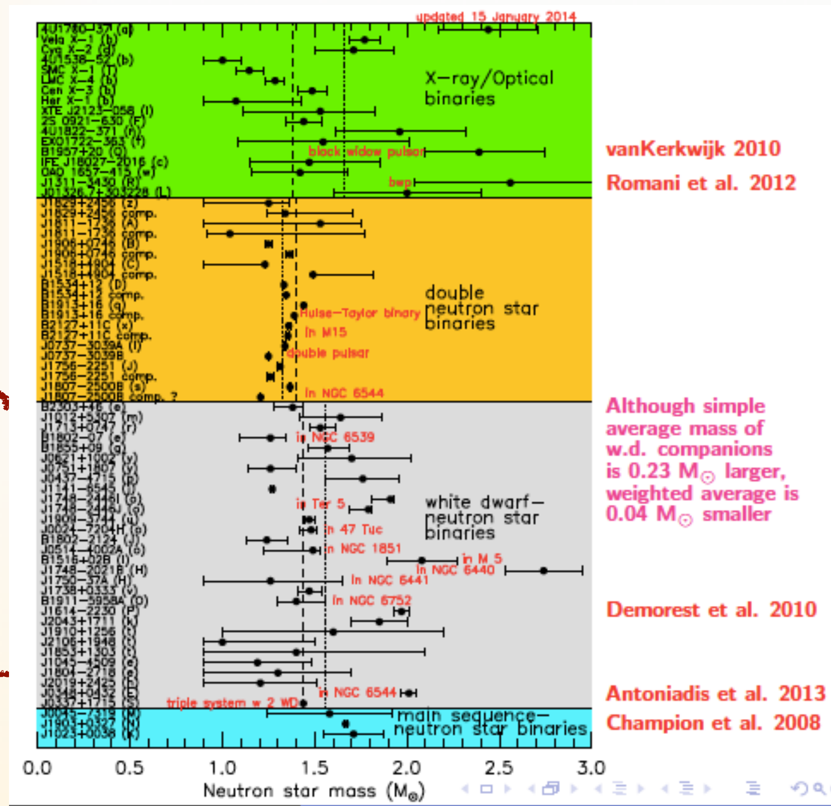
All the chosen EoS are compatible with nuclear saturation properties, and flow data from HIC.

Constraints from astrophysics

Observational Facts

MASSES

Compilation by J. Lattimer



- Best determined masses lie in a narrow interval while several data are still affected by large error bars.

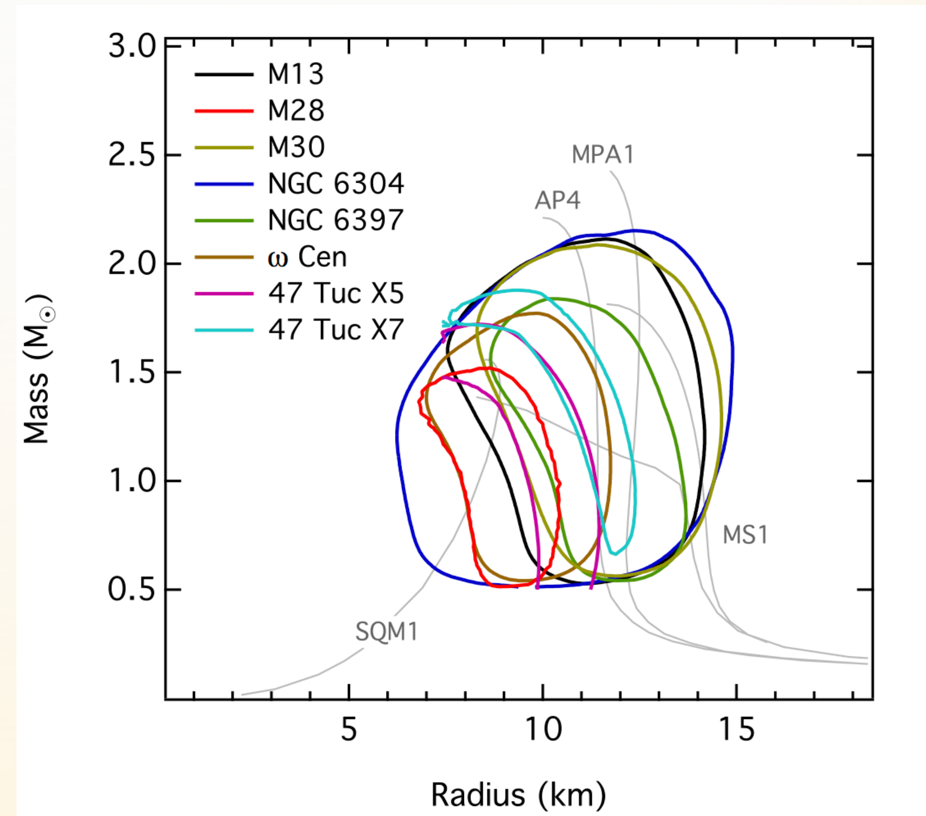
- Typical masses 1<M<2 M0 BUT

  $M \geq 2M_{\odot}$

  impose a very stringent constraint for the nuclear matter EoS !
  A reliable EoS should satisfy

  $M_{max}[EoS] > 2\ M_0$

RADII



- Only indirect measurements.

- Dependence on many parameters :
  - chemical composition of the atmosphere,
  - magnetic field,
  - distance to the source,
  - interstellar absorption.

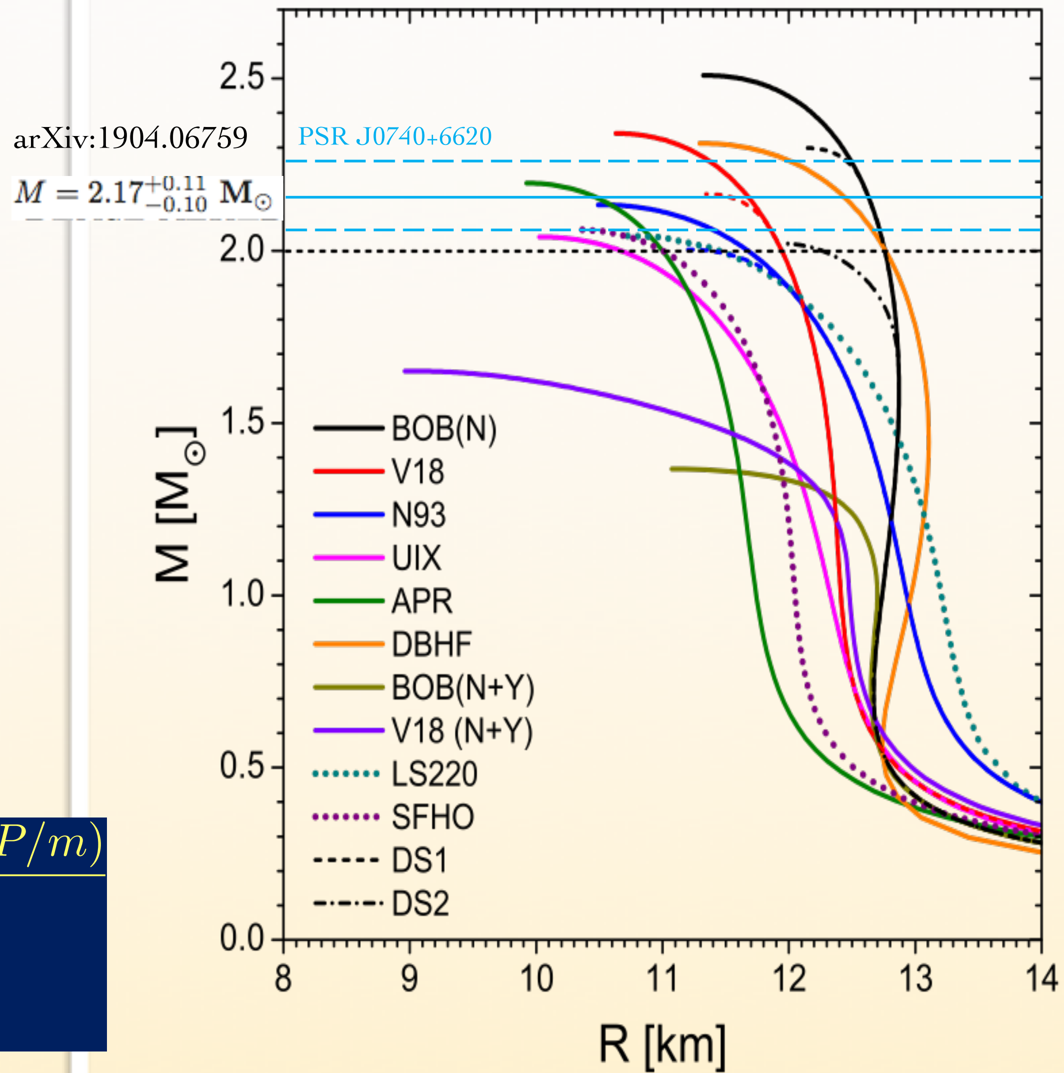
- The estimated radii lie in a range R=12-15 km, with some suggestions indicating lower values of the radius.

Nuclear Matter composition : n, p, e, μ, Λ, Σ …

- Energy density : $\epsilon\,(\rho_i)\,;i = n, p, e, \mu, \Lambda, \Sigma$
- Chemical potentials : $\mu_i = \frac{\partial\epsilon}{\partial\rho_i}$
- Beta-equilibrium : $\mu_i = b_i\mu_n - q_i\mu_e$
- Charge neutrality : $\sum_i x_i q_i = 0$
- Composition : $x_i(\rho)$
- Equation of State : $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$
- TOV equations

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\frac{(\epsilon + P)(1 + 4\pi r^3 P/m)}{1 - \frac{2Gm}{r}}$$

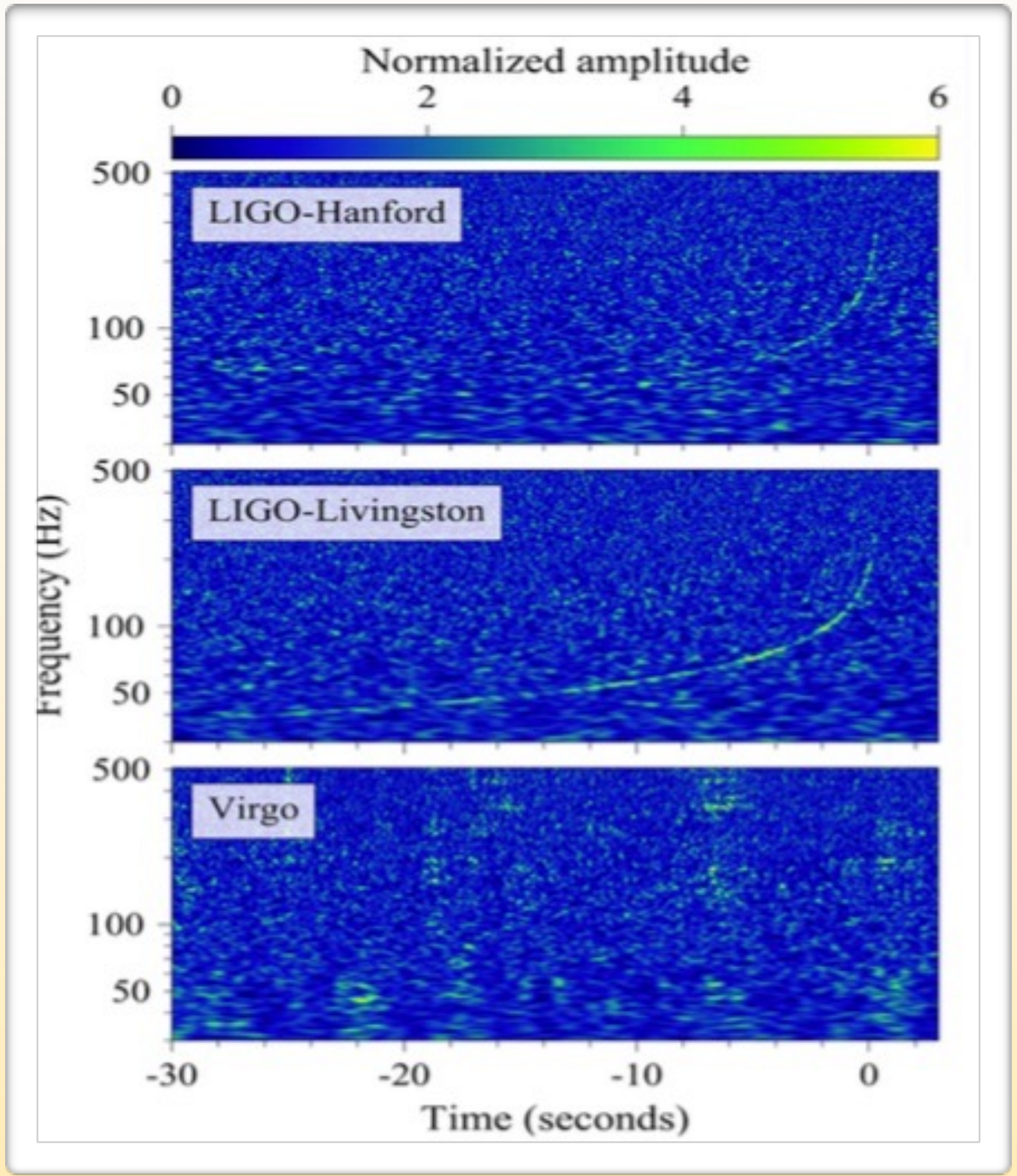
$$\frac{dm}{dr} = 4\pi r^2 \epsilon(r)$$



Problem with the microscopic BHF EoS with hyperons : BOB(N+Y), V18(N+Y).
All EoS give a maximum mass larger than 2 M_0, except the ones with hyperons.

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)

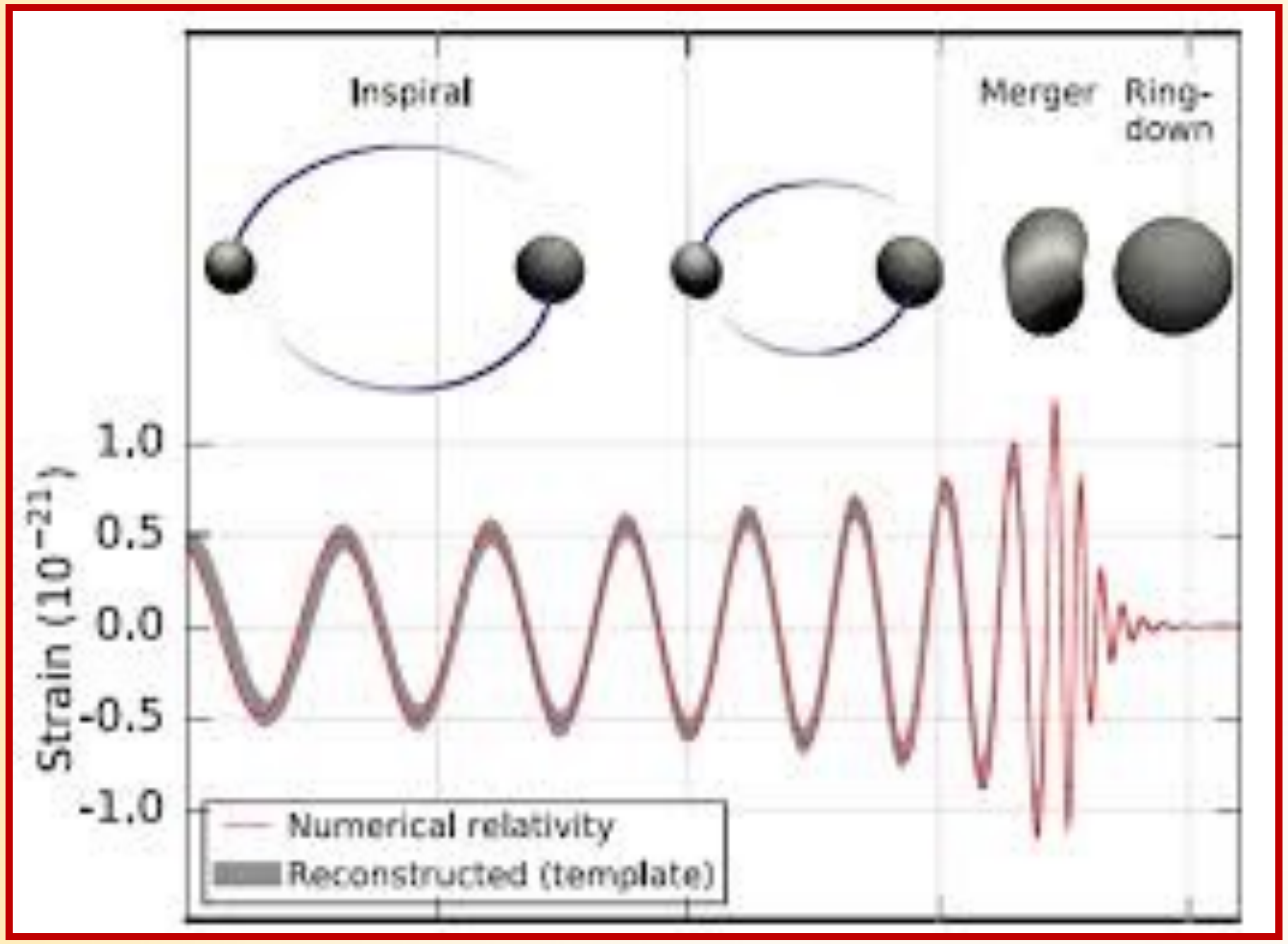
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

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 a NS-NS merger

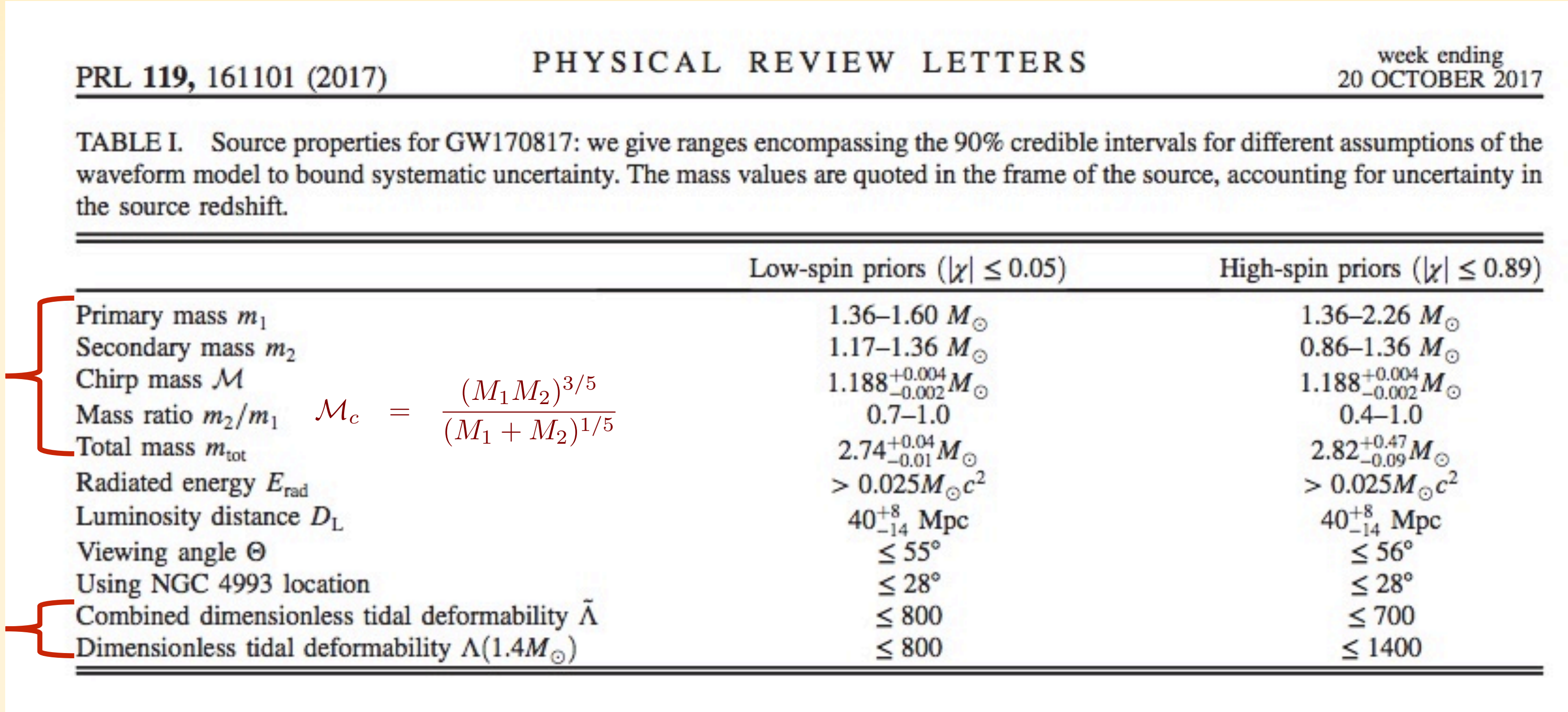


- **Inspiral** decay of the orbital separation with progressive reduction of the orbit. GW emission. Strong tidal forces depending on the compactness M/R, i.e. EoS.
- **Merger** Duration and fate depend on EoS and total mass. Stiffer EoS —-> larger supported mass —-> collapse to BH delayed or avoided.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

Dynamics depend strongly on the EoS,
e.g. tidal deformability, time delay before collapse to BH, etc…

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

Constraints from GW170817

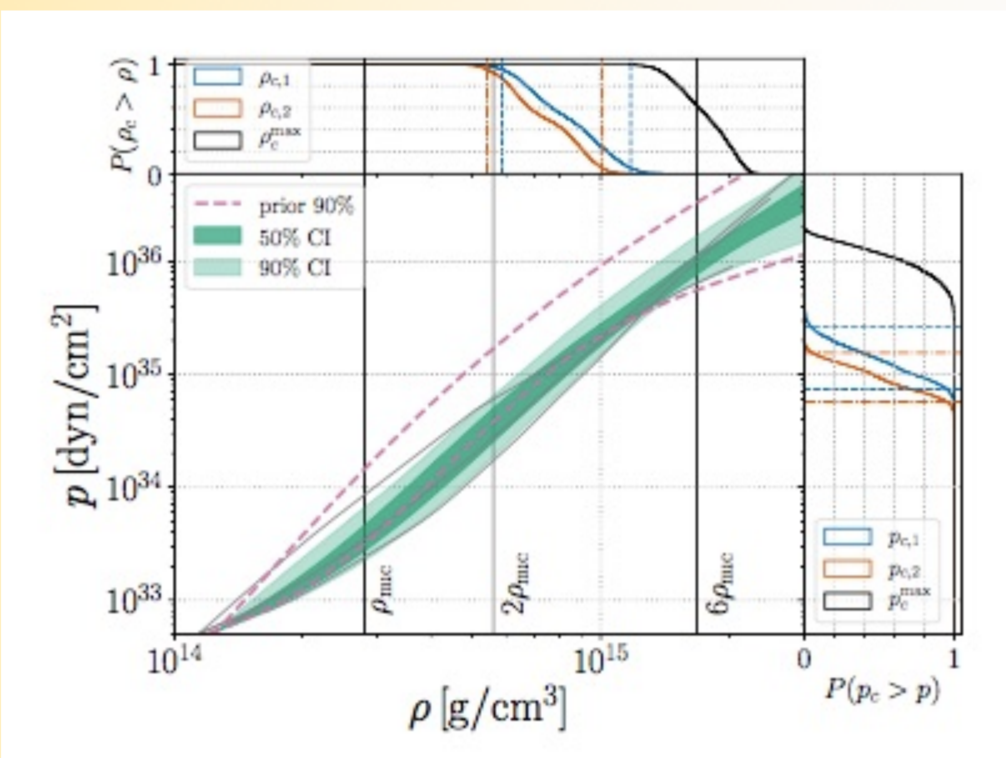


PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

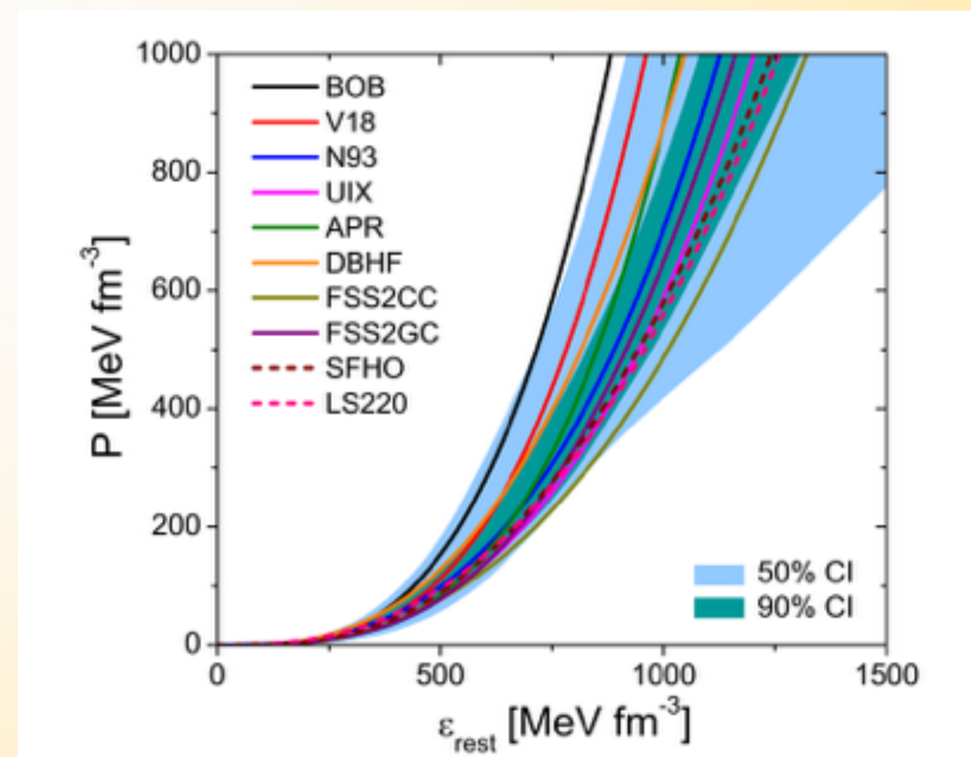
TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\lesssim 800$	$\lesssim 700$
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	$\lesssim 800$	$\lesssim 1400$

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



OUR EOS



The Love number k_2

Solve in GR together with the TOV eqs. for the pressure p and the enclosed mass m

$$k_2 = \frac{8}{5} \frac{\beta^5 z}{6\beta(2-y_R) + 6\beta^2(5y_R-8) + 4\beta^3(13-11y_R) + 4\beta^4(3y_R-2) + 8\beta^5(1+y_R) + 3z\log(1-2\beta)},$$

$$z \equiv (1-2\beta^2)[2-y_R+2\beta(y_R-1)]$$

$$\frac{dp}{dr} = -\frac{m\epsilon}{r^2}\frac{(1+p/\epsilon)\left(1+4\pi r^3 p/m\right)}{1-m/r},$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon,$$

ε being the mass-energy density

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

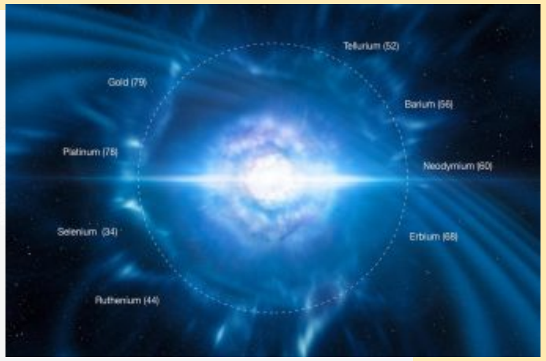
$$Q \equiv 4\pi\frac{(5-y)\epsilon + (9+y)p + (\epsilon+p)/c_s^2}{1-2m/r} - \left[\frac{2(m+4\pi r^3 p)}{r(r-2m)}\right]^2,$$

with $c_s^2 = d\epsilon/dp$ and the EOS $\epsilon(p)$ as input.

$$k_2 = \frac{3G}{2R^5}\lambda$$

The Love number k_2
depends crucially on the compactness β=M/R, hence on the EoS.

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



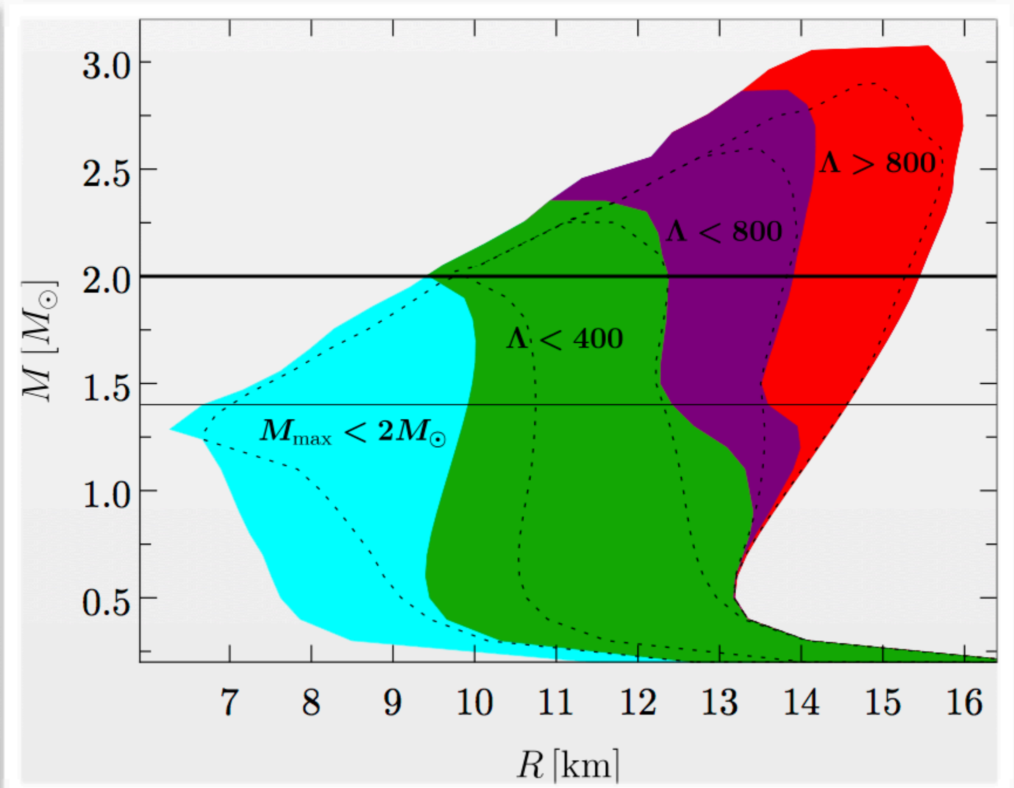
Constraints from GW170817 and the kilonova signal AT2017gfo:

The tidal deformability $\Lambda = \lambda / M^5$

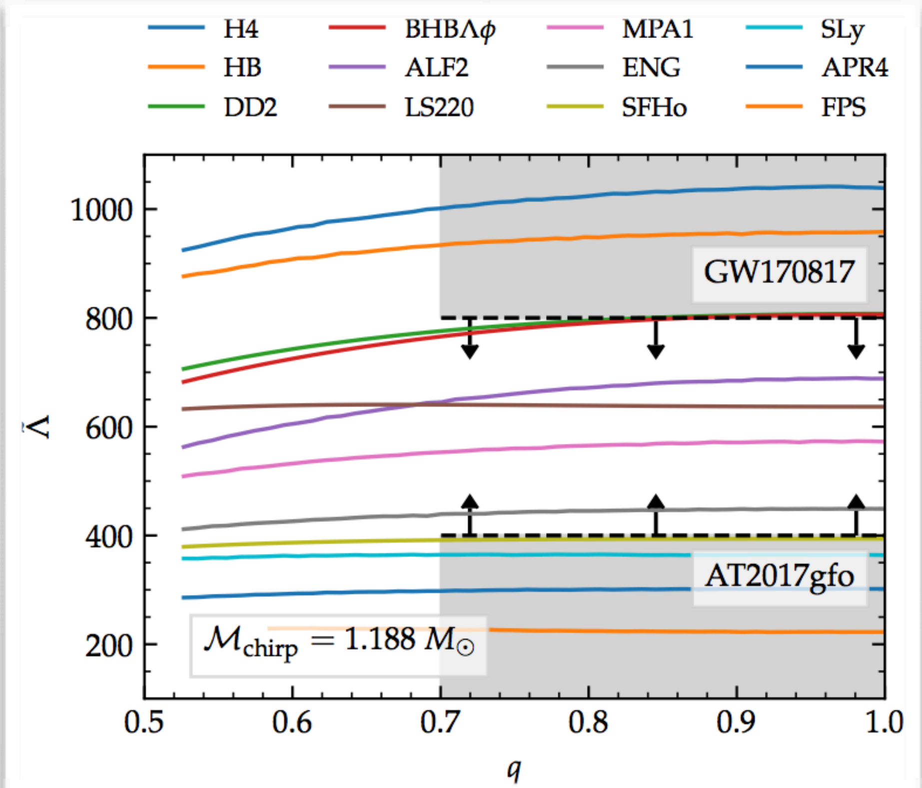
$\Lambda_{1.4} < 800$ at 90% confidence level

$$\tilde{\Lambda} = \frac{16}{13}\left\{\frac{(M_1 + 12 M_2) M_1^4}{(M_1 + M_2)^5}\Lambda_1 + (1 \leftrightarrow 2)\right\} > 400$$

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



Radice et al., ApJ 852, L29 (2018)



- Very stiff EoS are excluded (large radii)
- Limit for the radius $R_{1.4} < 13.6$ km

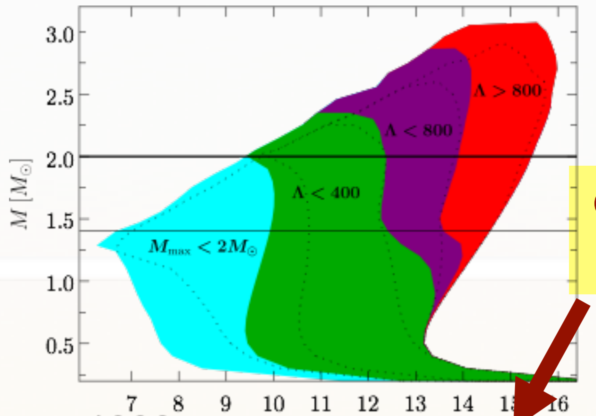
Most et al., arXiv:1803.00549
Lim et al., arXiv:1803.02803

$R_{1.4} \gtrsim 12$ km

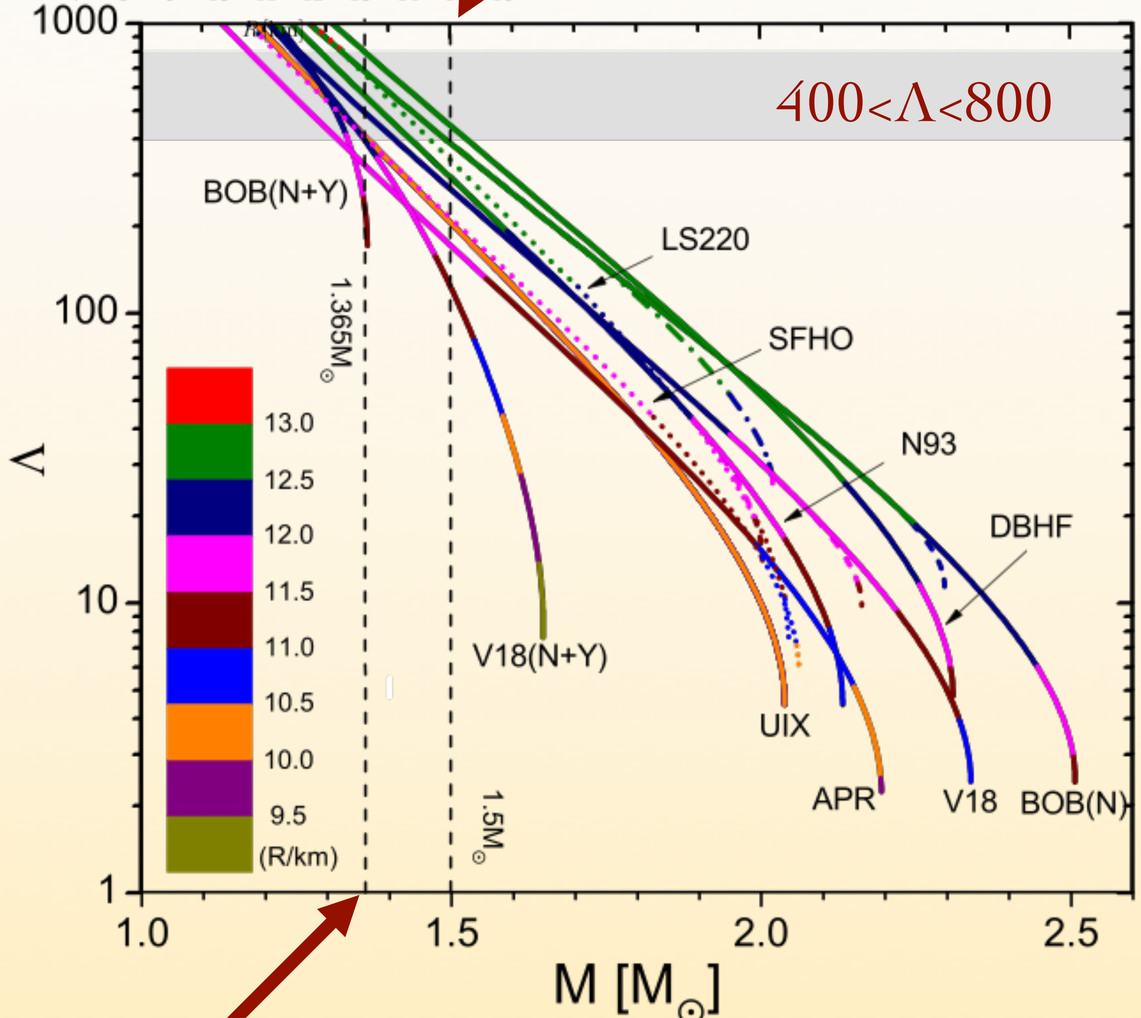
Fattoyev, PREX experiment (neutron skin), PRL 108, 112502 (2012)

Constraining the EoS

Correlations between M, R and Λ



GW170817 : limit derived in Annala et al



GW170817 : mass of each NS for a symmetric binary system

- 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<Λ<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 !

Correlations between M, R and Λ

- Fixed chirp mass

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

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

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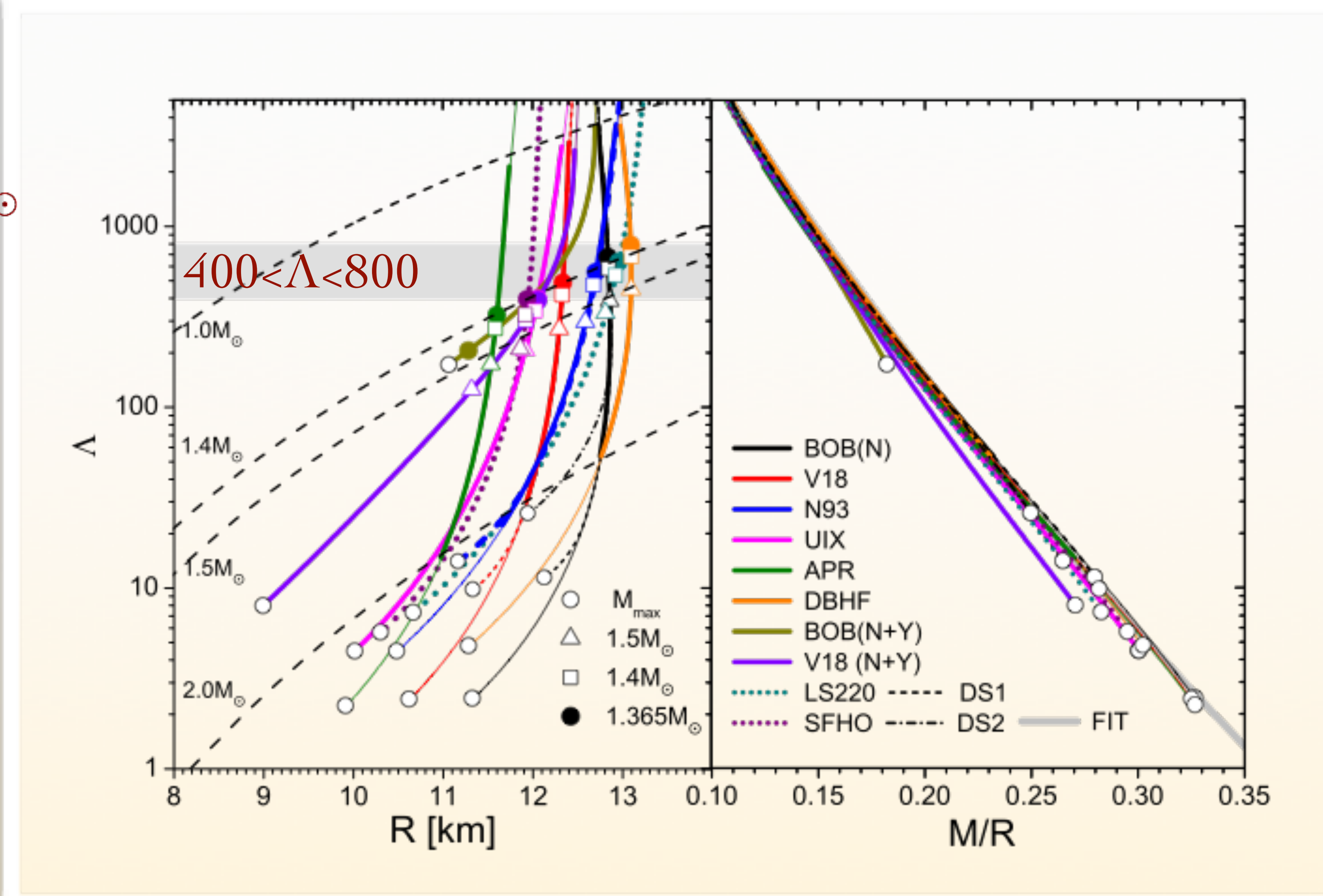
Selection of the EoS !



- Universal relation of Λ vs. the compactness β=M/R

$$\beta = 0.36 - 0.0355 \ln\Lambda + 0.000705 (\ln \Lambda)^2$$

Yagi & Yunes, PRD88, 023009 (2013).

- Fit shown by dashed and solid grey. Holds to within 6.5% for a large set of our NS EoS except for EoS with hyperons.

I-Love-Q Universal relations for Neutron Stars

Universal relations have been shown to exist which establish a link among various quantities, in particular spin-induced quadrupole moment, moment of inertia, tidal deformability.

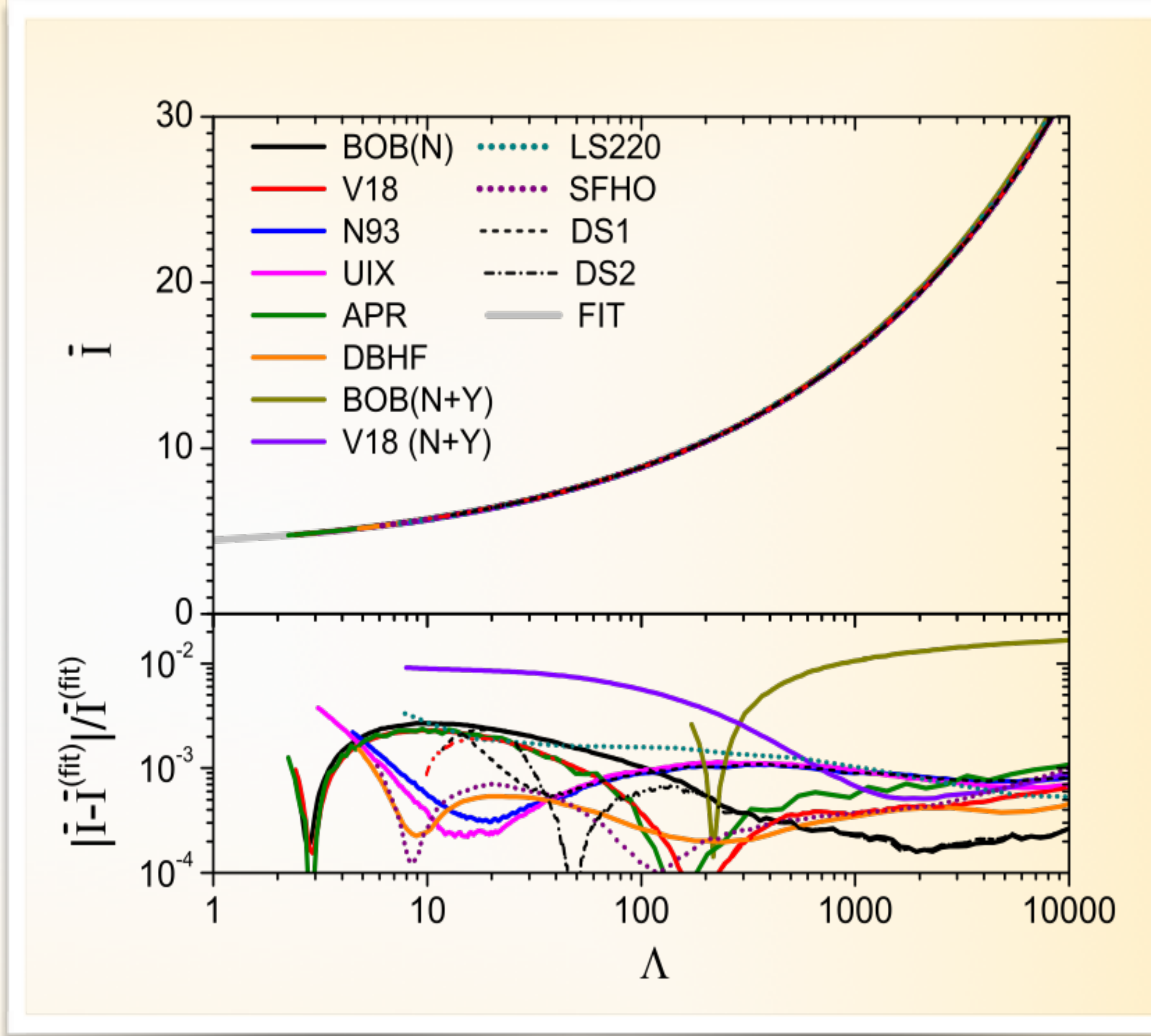
Universal means that these relations are independent on the Equation of State of matter in the neutron star interior.

Since the I-Love-Q relations are EoS independent, measuring one member of the trio gives information on the other two, even if not accessible by observations.

The moment of inertia I

I=I(M,R) therefore a measure of mass and moment of inertia can give access to the radius.

(Lattimer & Schutz, ApJ(2005))



Lower plot : fractional errors less than 1%.

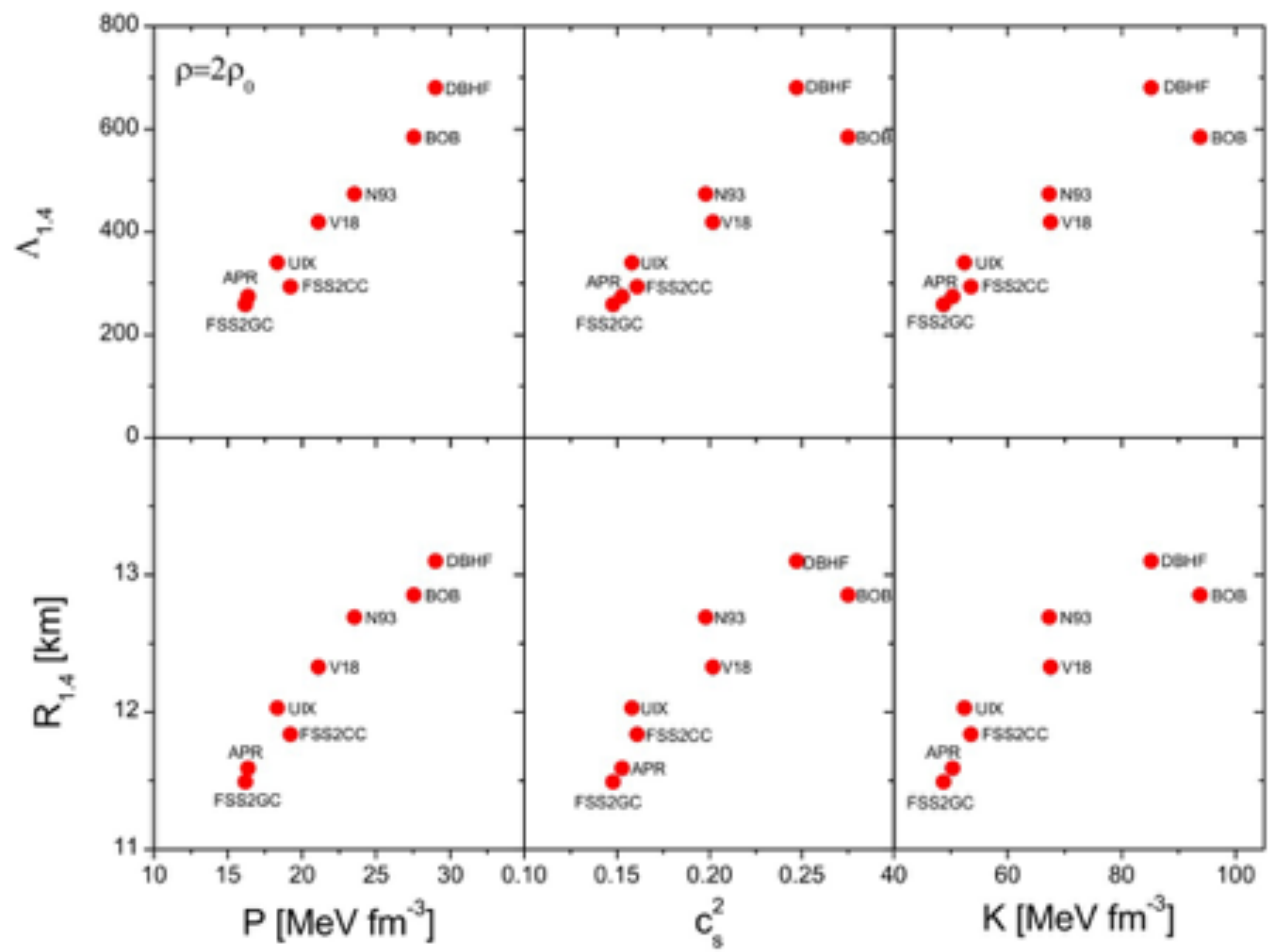
Universal relation I-Λ

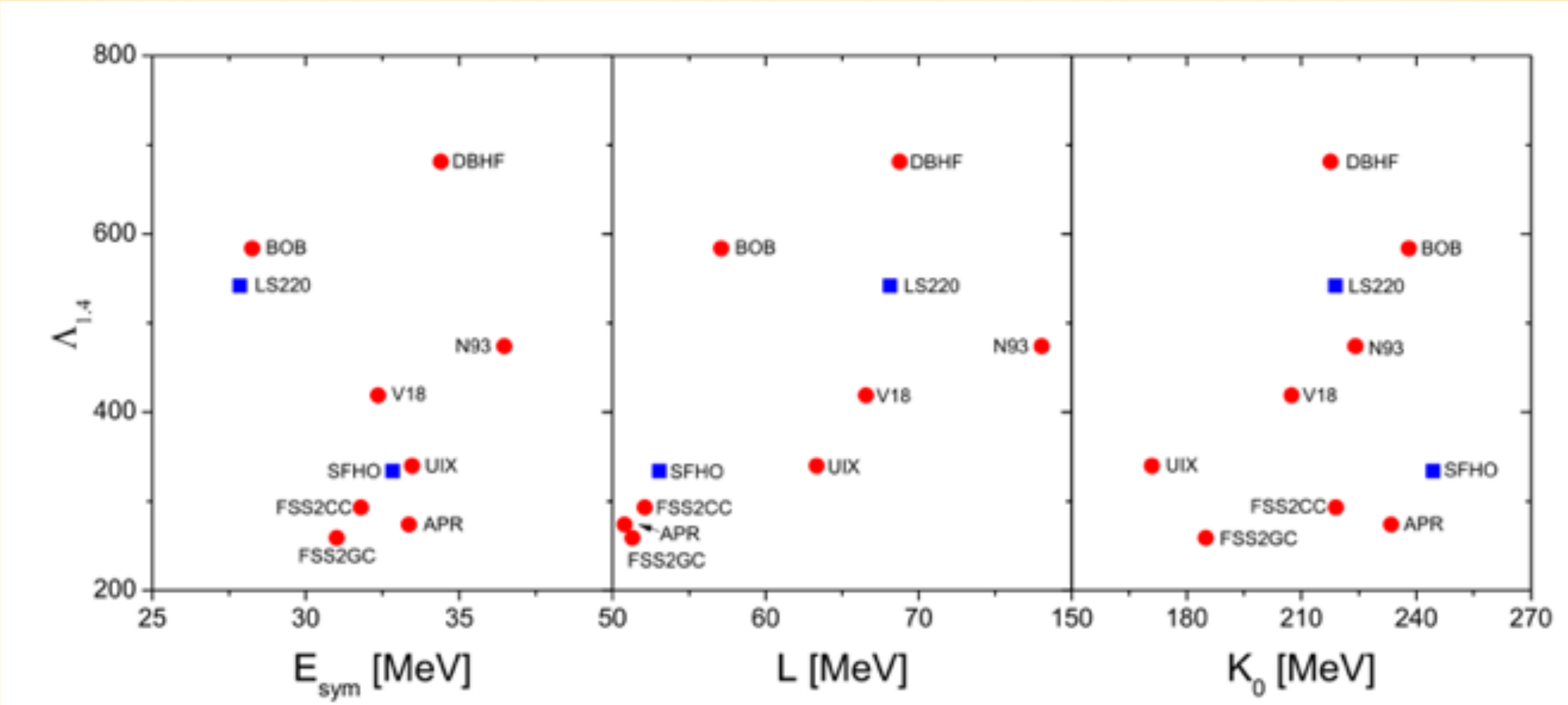
$$\ln(I/M^3) = 1.496 + 0.05951 \ln\Lambda + 0.02238 (\ln\Lambda)^2 - 6.953 \times 10^{-4}(\ln\Lambda)^3 + 8.345 \times 10^{-6}(\ln\Lambda)^4$$

Yagi & Yunes (2017)

Very preliminary results …

How $\Lambda_{1.4}$ is correlated to saturation properties ?
Strong similarities with B.Tsang talk ….





800
600
400
200
$\Lambda_{1.4}$
DBHF
BOB
LS220
N93
V18
SFHO
UIX
FSS2CC
APR
FSS2GC
25
30
35
50
60
70
150
180
210
240
270
E_{sym} [MeV]
L [MeV]
K_0 [MeV]

More in :

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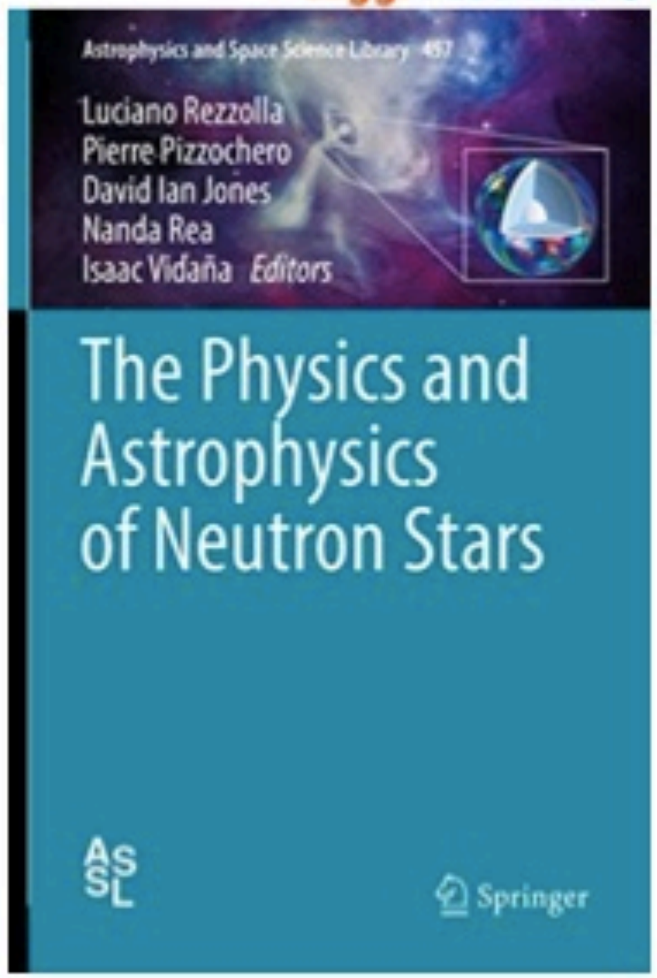

The Physics and Astrophysics of Neutron Stars (Astrophysics and Space Science Library Book 457) (English Edition) 1st ed. 2018 Edition, Formato Kindle

di Luciano Rezzolla (a cura di), Pierre Pizzochero (a cura di), David Ian Jones (a cura di), & 2 altro

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Conclusions

- A large set of microscopic and phenomenological EoS are compatible with several constraints on the EoS from nuclear structure, heavy-ion collisions, and maximum observed mass but still not enough constraining ….

GW170817 event has added further constraints the tidal deformability.

- GW170817 is compatible with the merging of two nucleonic neutron stars with a microscopic EoS with maximum mass >2M0 and 12<R<13 km for 1.4 solar mass. Several compatible EoS.

- Universal relations I-Love-Q are fulfilled by hadronic and hybrid stars. Deviations exhibited by hyperonic EoS.

- More refined constraints from future GW merger events. High-precision telescopes, NICER, ATHENA+, SKA are expected to improve our knowledge of the NS mass-radius relation.

- EoS at finite temperature. Significant work in progress.