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▣ Equation of State (EoS) before GW170817 ▣ EoS after GW170817 ▣ Outlook

Neutron star matter is a many-body system

▣ Two classes of models: non-relativistic and relativistic models

i) **Microscopic models** : ▣ Brueckner Hartree-Fock and Dirac-Brueckner-Hartree-Fock

theories (R. Brockmann and R. Machleidt, PRC42 (1990) 1965) ▣ Variational many-body approach (A. Akmal, V. Pandharipande,

D.G. Ravenhall, PRC58 (1998) 1804) ii) **Effective Field theory approach**: ▣ Density functional theory (R.J. Furnstberg,

(2004) 1) ▣ Chiral perturbation theory (K. Hebeler, PRL105 (2010) 161102)

iii) **Phenomenological theories**: ▣ Effective two-body interactions (Skyrme interactions) ▣ Relativistic Mean Field (RMF) models

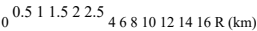
Nucl.

Phys. 16 (1986) 1)

☑ should satisfy the experimental constraint on nuclear parameters such as binding energy, effective mass, compression modulus, symmetry at the saturation density,

☑ should be consistent with $2M_{\odot}$ neutron star.

$$]^{-1}$$



$$dp$$

SFHx SFHo HS(TMA) HS(TM1) BHB $\Lambda\phi$ Hybrid DD2 K=300MeV, m*/m=0.70 K=240MeV, m*/m=0.70 K=230MeV, m*/m=0.70 K=300MeV, m*/m=0.78 K=240MeV, m*/m=0.78 K=230MeV, m*/m=0.78 K=220MeV, m*/m=0.78
Credit : [Shriya Soma](#)

$$dr = -\epsilon(r)m(r)$$

$$r^2$$

$$(1 + p(r))\epsilon(r)\left(1 + \frac{4\pi r^3}{3}p(r)\right)$$

$$m(r)$$

$$)[1 - 2m(r)]$$

$$r$$

1. Late stage inspiral in the binary: The tidal deformability λ is defined as

$$\lambda = -\frac{Q_{ij}}{\epsilon_{ij}}$$
 Dimensionless tidal deformability,

$$\Lambda_{i=1,2} = \frac{k_2}{3G^2} (R_i/M_i)^5$$

2. Post Merger Oscillations of the remnant: This signal is buried in the noise as detectors are not sensitive enough! 3. EM observations: Kilonova

The mass weighted average tidal deformability parameter,

$$\bar{\Lambda} = \frac{1}{5} (1 - 2C)^2 [2 + 2C(y - 1) - y] \times \{ 2C[6 - 3y + 3C(5y - 8)] + 4C^3[13 - 11y + C(3y - 2) + 2C^2(1 + y)] + 3(1 - 2C)^2[2 - y + 2C(y - 1)] \ln(1 - 2C) \}^{-1}.$$

$$C = \frac{M}{M_R} \text{ and } y = \frac{R}{R_{H(R)}}$$

$$k_2 = \frac{8C^5}{13} [(M_1 + 12M_2)M_1^4 \Lambda_1 + (M_2 + 12M_1)M_2^4 \Lambda_2]$$

$$H(R) \text{ ; T. Hinderer, ApJ 677 (2008) }$$


$$(M_1 + M_2)^5$$



$$\frac{0^3}{4000}$$

$$\frac{SFHo \ SFHx \ SFHo \ SFHx \ HS(TM1)}{2000}$$

$$\frac{HQ1 \ HQ2}{1000}$$

$$\frac{8 \ 12 \ R \ (km)}{16 \ 20 \ 0}$$

0 500 1000 Λ_1 1500 2000  M-R relation probes the overall EoS where as $\Lambda_1 - \Lambda_2$ plot is

sensitive to certain regions of an EoS, (S.A. Bhat and D.B., JPG46 (2019) 014003)  Constraint on combined tidal deformability: $70 \leq \bar{\Lambda} \leq 1100$ hadronic EoS (WFF1) compatible with a low value of $\bar{\Lambda}$?  Radius scales with $\bar{\Lambda}$ as $R = 4.45 \times \bar{\Lambda}^{1/6}$ [S. Soma, DB (in preparation)]

Baye’s Theorem: $p(\theta|d) \propto p(\theta)p(d|\theta)$ For EoS related part of the parameter space and corresponding priors
deformability parameters; Universal Relation ($\Lambda - C$) ii. Direct sampling of EoS $p(\rho)$ (P. B. Abbott et al., PRL 121 (2018) 161101)

► Parametrizing the EoSs in the intermediate range of State are

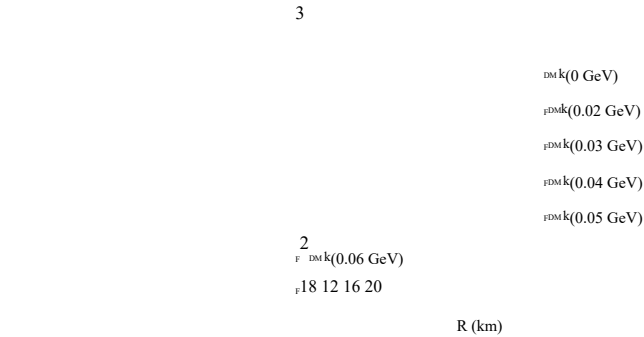
Credit: Yuki Fugimoto et al., arXiv:1903.03400

on maximum mass and tidal deformability are imposed, ► EoS with hadron-quark
causal, ► Those should support $\sim 2M_{\odot}$
Neutron Stars, ► Constraints of upper bound

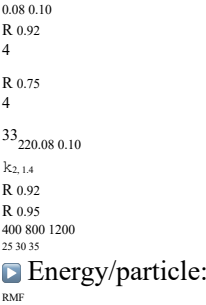
phase transition could explain small value of $\tilde{\Lambda}$

E. R. Most et al., PRL120 (2018) 261103

Small Radius: $8.53 \leq R_{1.4}/\text{km} \leq 13.74$ and $\tilde{\Lambda}_{1.4} \geq 35$ (E. R. Most et al., PRL120) LVC: 11.9 ± 1.4 km; NICER (preliminary): $\sim 12 - 15$ km for PS



More compact stars, lower tidal deformabilities [T. Malik et al., PRD99 (2019) 043016 ; J. Ellis et al., PRD97 (2018) 123007]



$$e(n,x) = e(n,0) + S_2(n)x^2 +$$



$$e(n,0) = e_0 + K_0$$



FSS2GC [MeV] DBHF FSS2CC

SHO
 LUX
 APR
 APR APR
 200
 0
 160 180 200 220 240 260

$$_6 y_3 + \dots$$

► Symmetry Energy:

$$S_2(n) = J_0 + L_0 y + K_{\text{symm},0}$$

$$_2 y_2 + \dots$$

$$x = (n_n - n_p)/n; y = (n - n_0)/3n_0;$$

$$M_0 = Q_0 + 12K_0$$

T. Malik et al., arXiv:1805.11963

J-B Wei et al., arXiv:1907.08761

$$_2 y_2 + Q_0$$

Credit: C. Raithel et al., ApJ875 (2019) 12

► Cold Equations of State are

not appropriate for post merger phase, ► Ad hoc temperature

dependence is introduced in EoS $P = P_{\text{cold}} + (\Gamma_{\text{th}} - 1)(\epsilon - \epsilon_{\text{cold}})$ ► Finite temperature field

theory models for EoS

▣ More merger events tighten neutron star EoS! ▣ We shall see activities to study EoS using machine learning technique ▣ Is neutron star made of only nucleons or can we see the imprint of exotic components of matter say, hyperons, Bose condensate, quarks?

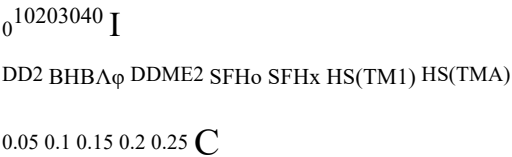
Exciting time ahead!

B. Margalit and B.D. Metzger, arxiv:1904.1199

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Upper bound on $\Lambda^- = 720$ gives $l_1 \sim 2 \times 10^{45}$ and $l_2 \sim 1 \times 10^{45}$ g cm² and $R \sim 13$ km in both cases ([Sajad A. Bhat and D.B., J. Phys. G46](#)). This is comparable to the value coming out of double pulsar system PSR0737-3039 ([M. Kramer \(private communication\)](#)).



[[S. Banik, D.B., arXiv:1712.09760](#)]

$2.01 M_{\odot} \leq M_{\text{TOV max}} \leq 2.16 M_{\odot}.$

Non-relativistic EoSs (LS200, SLy etc) violate causality i.e. $c_s > c$ at densities 5-7 n_0 .

SFHo	0.1583	16.19	245	31.57	47.10	2.06	BHBΛφ	0.1491	16.02	243	31.67	55.04	2.11
LS220	0.1550	16.00	220	28.61	73.82	2.06	SLy	0.160	15.97	230	31.98	47.11	2.05
MS1	0.1484	15.75	250	35.00	110	2.77	APR4	0.160	16.00	266	32.59	58.46	2.19

Exp. $\sim 0.15 \sim 16 \text{ }^{240}_{\pm 10} \text{ }^{29.0}_{-32.7} \text{ }^{40.5}_{-61.9}$

n_0	E ₀	K	S	L	M _{max}	EoS	[fm ⁻³]	[MeV]	[MeV]	[MeV]	[MeV]	[M _⊙]
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