Debades Bandyopadhyay

Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, Kolkata, India

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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. Pandharipa D.G. Ravenhall, PRC58 (1998) 1804)

ii) Effective Field theory approach:
- Density functional theory (R.J. Furn (2004) 1)
- Chiral perturbation theory (K. Hebeler, PRL105 (2010) 161102)

iii) Phenomenological theories:
- Effective two-body interactions (Skyrme interactions)
- Relativistic Mean Field (RMF) mo Nucl. Phys. 16 (1986) 1)

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

▶ should be consistent with $2M_\odot$ neutron star.

$]^{-1}$

0 0.5 1 1.5 2 2.5 4 6 8 10 12 14 16 R (km)

dp

SFHx SFHo HS(TMA) HS(TM1) BHBΛφ 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

Credit : Shriya Soma

dr = −ε(r)m(r)

r^2

(1 + p(r)

ε(r))(1 + $4\pi r^3$ p(r)

m(r)

)[1 − 2m(r)

r

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

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

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

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

The mass weighted avergare tidal deformability parameter,

$\bar{\Lambda} = 16$

$5 \, (1 - 2C)_2 [2 + 2C(y - 1) - y] \times \{ 2C[6 - 3y + 3C(5y - 8)]$

$+4C^3[13 - 11y + C(3y - 2) + 2C^2(1 + y)] + 3(1 - 2C)^2[2 - y + 2C(y - 1)] \ln(1 - 2C) \}_{-1}.$

$C = {}^{M}$

$_R$ and $y = {}_{RH'}{}_{(R)}$

]

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$k_2 = 8C^5$

13

$[(M_1 + 12M_2)M^4_1\Lambda_1 + (M_2 + 12M_1)M^4_2\Lambda_2$

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

$(M_1 + M_2)_5$

0^3

4000

SFHo SFHx SFHo SFHx HS(TM1)

2000

HS(TMA) PhenomPl

HQ1 HQ2

1000

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: $70 \leq \tilde{\Lambda} \leq$

hadronic EoS (WFF1) compatible with a low value of $\tilde{\Lambda}$? Radius scales with $\tilde{\Lambda}$ as $R = 4.45 \times \tilde{\Lambda}^{1/6}$ [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 interm
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 ~ $2M_\odot$

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

3

DM k(0 GeV)

FDM k(0.02 GeV)

FDM k(0.03 GeV)

FDM k(0.04 GeV)

FDM k(0.05 GeV)

2

F DM k(0.06 GeV)

F 18 12 16 20

R (km)

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

0.08 0.10

R 0.92

4

R 0.75

4

33 220.08 0.10

$k_{2,\,1.4}$

R 0.92

R 0.95

400 800 1200

25 30 35

Energy/particle:

RMF

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

SHF

5

$k_{2,\,1.4}$

5

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

4433 22400 800 1200

800

S_0 DBHF BOB

N93

V18

UIXFSS2CC

FSS2GC [MeV] DBHF FSS2CC

FSS2GC

DBHF

600

BOB

V18

FSS2CC

FSS2GC

BOB

LS220

V18

20 40 60 80

LS220 LS220

N93

SFHO SFHO

UIX

L [MeV]

SFHO
UIX
APR
APR APR
200
0
160 180 200 220 240 260

$6\,y^3 + ...$

▶ Symmetry Energy:

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

$2\,y^2 + ...$

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

$M_0 = Q_0 + 12K_0$

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 $P = P_{cold} + (\Gamma_{th} - 1)(\varepsilon - \varepsilon_{cold})$ ▶ 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

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

E. R. Most et al., arxiv:1807.03684

1600
1600 DD2 BHBΛφ

8 10 12 14 I_1

DDME2 HQ1
1200
HQ2 SFHo SFHx HS(TM1)
1200

HS(TMA)
800
800
400
400
0
0

14 16 18 20 22 24 I_2

Upper bound on $\bar{\Lambda}$ = 720 gives $I_1 \sim 2 \times 10^{45}$ and $I_2 \sim 1 \times 10^{45}$ g cm^2 and R ~ 13 km in both cases (Sajad A. Bhat and D.B., J. Phys. G4

This is comparable to the value coming out of double pulsar system PSR0737-3039 (M. Kramer (private communication)).

0 10 20 30 40 I

DD2 BHBΛφ DDME2 SFHo SFHx HS(TM1) HS(TMA)

0.05 0.1 0.15 0.2 0.25 C

[S. Banik, D.B., arXiv:1712.09760]

$2.01 M_\odot$ % M^{TOV}_{max} % $2.16 M_\odot$.

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

EoS	n_0 [fm^{-3}]	E_0 [MeV]	K [MeV]	S [MeV]	L [MeV]	M_{max} [$M_\odot$]
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.	~ 0.15	~ 16	240 ± 10	29.0 − 32.7	40.5 − 61.9	