Constraining the equation of state of neutron stars using multimessenger observations

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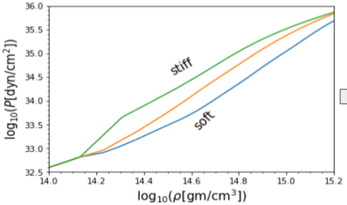
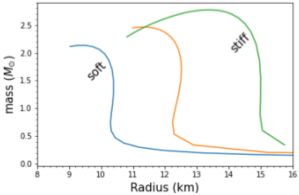
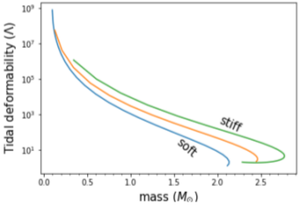
Equation of state (EoS) and observables







GW observables - mass, tidal deformability
(event name: GW170817 & GW190425)

X-ray observables - mass, radius
(PSR J0030+0451, PSR J0740+6620)

Radio observables - mass
(massive pulsar mass measurement)

Hybrid nuclear+PP EoS parameterization

- We improve piecewise-polytope ($\log p$, $\Gamma_1, \Gamma_2, \Gamma_3$) parameterization combining information coming from our nuclear physics knowledge.
  - In outer crust BPS EoS is used
  - Then below $1.25\rho_0$ saturation properties of nuclear matter is used

symmetric nuclear matter

symmetry energy

$$e_0(\rho, \delta) \approx e_0(\rho) + e_{sym}\delta^2$$

$$e_0(\rho) = e_0(\rho_0) + \frac{K_0}{2}\chi^2 + \frac{J_0}{6}\chi^3$$

$$e_{sym}(\rho) = e_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \frac{J_{\rm sym}}{6}\chi^3$$

$\delta =$ "symmetry parameter" $= (\rho_{\rm n} - \rho_{\rm p})/\rho$,
$\chi = (\rho - \rho_0)/3\rho_0$

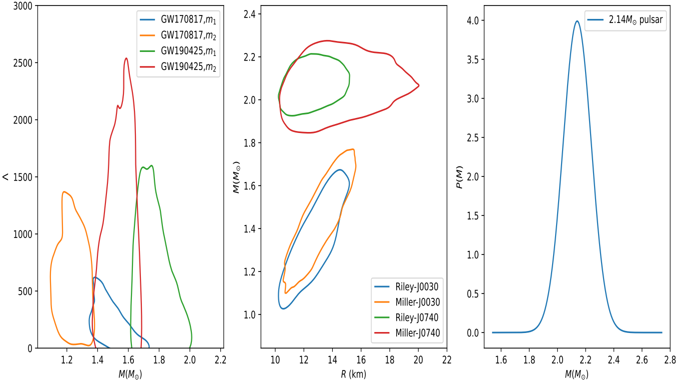
  - At high densities piecewise-polytrope is used

BB, P. Char, R. Nandi, and S. Bose, Phys. Rev. D **103**, 103015 (2021)

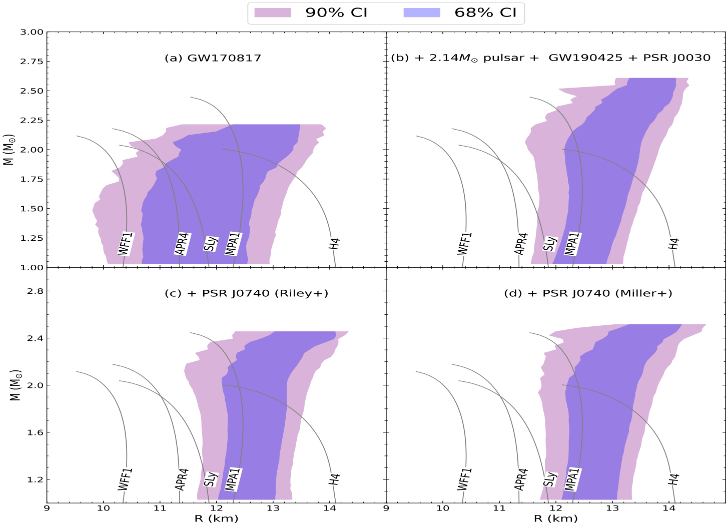
Bayes' theorem and Datasets

Bayes' theorem:

$$P(\theta|d) \propto P(\theta)\Pi_i P(d_i|\theta)\,,$$
$$d = (d_{\rm GW}, d_{\rm X-ray}, d_{\rm Radio})$$



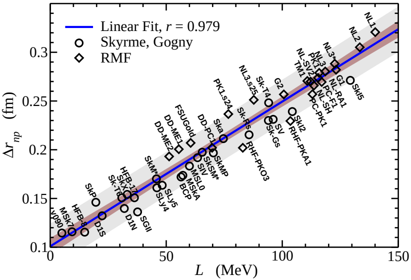
Mass-radius constraints



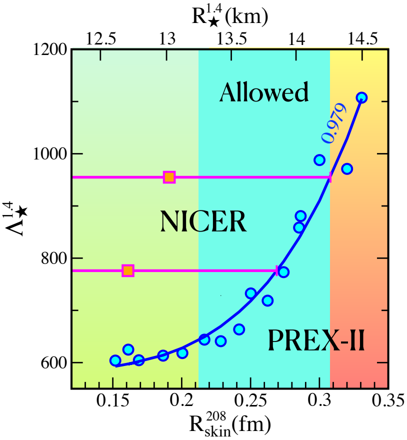
BB, arXiv: 2105.02886, Astrophys. J. **921**, 63 (2021)

PREX-II result

Reed+21 infer $L = 106 \pm 37$ MeV based on $^{208}\mathrm{Pb}$, $R^{208}_{\mathrm{skin}} = 0.29 \pm 0.07$ fm. Suggest this implies $13.25 \leq R_{1.4} \leq 14.26$ km

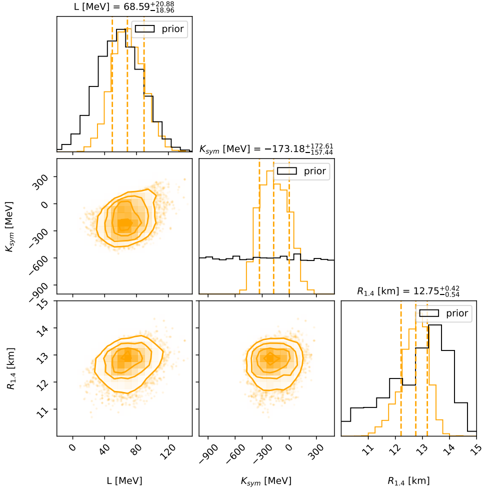


Vinas+13



Reed+21, PRL 126, 172503

Empirical parameters after PREX-II



BB, arXiv: 2105.02886, Astrophys. J. **921**, 63 (2021)

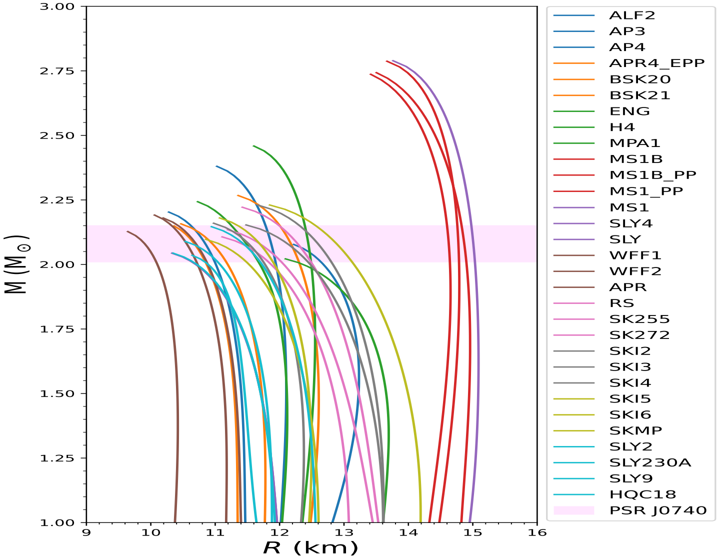
- The value of L slightly larger than previous
- Weak correlation (~ 0.27) between L and $R_{1.4}$
- PREX-II does not require large radius

EoS model-selection

- There is an exhaustive literature on constraining NS properties either using phenomenological or nuclear-physics motivated EoS parameterization (Raaijmakers+19,Landry+20,Jiang+19,Traversi+20, Biswas+20,Al-Mamun+20,Dietrich+20,.....)
- However in a complementary approach the following question can be asked:

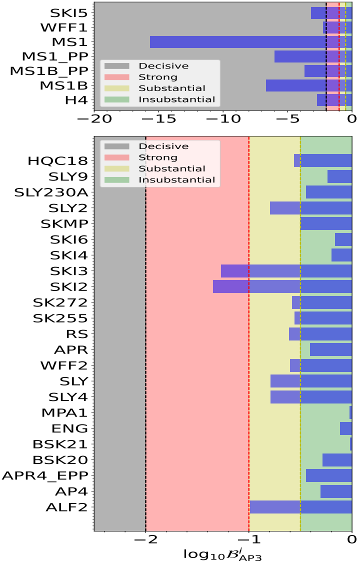
  Given a variety of NS EoS model in the literature based on nuclear-physics, which one is the most preferred by the current observation in a statistical sense?
- To provide the current status of various NS EoS models, a Bayesian model-selection study is needed using multi-messenger observations

EoS catalog



3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
M (M⊙)
9
10
11
12
13
14
15
16
R (km)
ALF2
AP3
AP4
APR4_EPP
BSK20
BSK21
ENG
H4
MPA1
MS1B
MS1B_PP
MS1_PP
MS1
SLY4
SLY
WFF1
WFF2
APR
RS
SK255
SK272
SKI2
SKI3
SKI4
SKI5
SKI6
SKMP
SLY2
SLY230A
SLY9
HQC18
PSR J0740

Result



- Bayes' factor, $\mathcal{B}^i_j = \prod_k \frac{P(d_k|\mathrm{EoS}_i)}{P(d_k|\mathrm{EoS}_j)}$; if $\mathcal{B}^i_j > 0$, then model i is preferred over j
- AP3 is the most preferred model
- Decisive when $\log_{10}\mathcal{B}^i_{\rm AP3} \leq -2$ (R.E.Kass and A.E.Raftery, 1995)
- SKI5, WFF1, MS1,MS1_PP, MS1B_PP, MS1B, and H4 are ruled out; both extreme soft and stiff EoSs are ruled out now

BB, arXiv: 2106.02644, Astrophys. J. **926**, 75 (2022)

Summary and Future plans

- We have developed a hybrid EoS formulation which connects low density nuclear physics information with a generic parameterization at higher densities
- Novel constraint on NS EoS is obtained combining multiple astrophysical observations
- PREX-II data does not require large radius of NS
- model-selection study is performed for EoS ranking
- Any upcoming astrophysical observations can be used to put further constraints on NS EoS