Equation of state and Nuclear parameter inference with GW detections of NS mergers

Neuvième assemblée du GdR Ondes Gravitationnelles 13/10/2025

Suleiman & Read 2024 (Phys. Rev. D 109)
Davis et al. 2024 (A&A, 687, A44),
Ng. et al. 2025 (arXiv:2507.0323 in press)

In collaboration with LPC Caen, GANIL, Observatoire de Strasbourg, CSUF

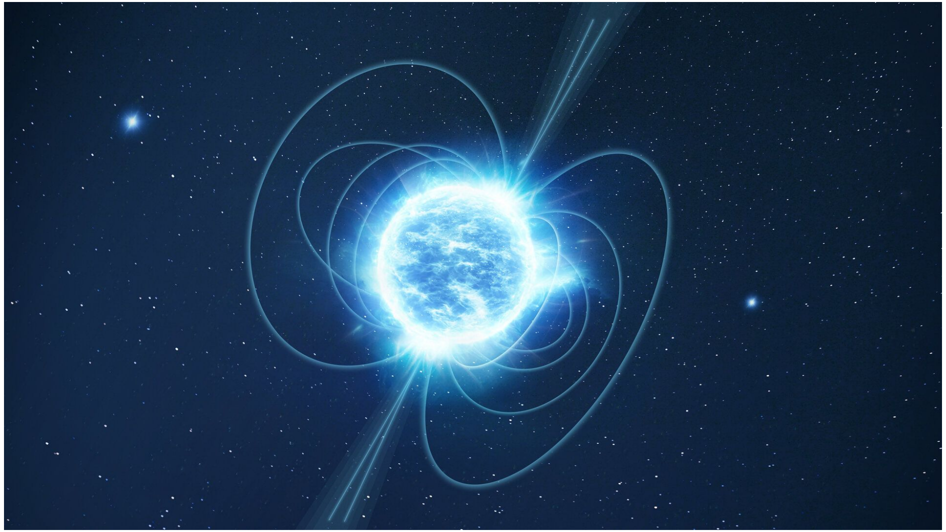
Lami Suleiman
Deutsches Elektronen-Synchrotron

Neutron Stars as probes for Dense Matter Physics

Limited understanding of **strong interaction**

- Non-perturbative nature of strong interaction
- **Experimental data** is limited by thermodynamic conditions

Dense matter properties are poorly know.
Thankfully, we have **Neutron Stars** (NSs)!



Credit ESA website

Neutron Stars as probes for Dense Matter Physics

Limited understanding of **strong interaction**

- Non-perturbative nature of strong interaction
- **Experimental data** is limited by thermodynamic conditions

Dense matter properties are poorly know.
Thankfully, we have **Neutron Stars** (NSs)!

- Highly **compact objects** M~Msol, R~10km
- Matter in their interior is very dense (several times ρ_{nuc}) and neutron rich
- Astro. parameters (M, R, Λ) are modeled with
  - theory of gravitation, mostly GR
  - theory for the **Equation of State** (EoS) i.e. P(ρ) or P(ϵ), mostly T=0 and β-equilibrium.

BNS merger quantities: mass/tidal deformation

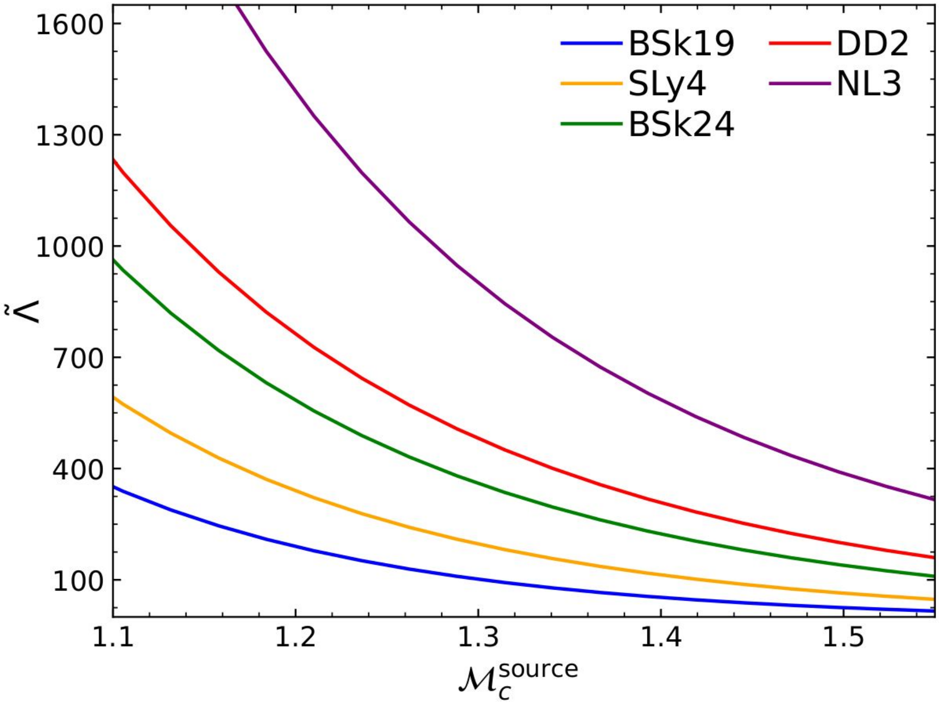


Figure for MANITOU book

Neutron Stars as probes for Dense Matter Physics

Limited understanding of **strong interaction**

- Non-perturbative nature of strong interaction
- **Experimental data** is limited by thermodynamic conditions

Dense matter properties are poorly know. Thankfully, we have **Neutron Stars** (NSs)!

- Highly **compact objects** M~Msol, R~10km
- Matter in their interior is very dense (several times ρ_{nuc}) and neutron rich
- Astro. parameters (M, R, Λ) are modeled with
  - theory of gravitation, mostly GR
  - theory for the **Equation of State** (EoS) i.e. P(ρ) or P(ϵ), mostly T=0 and β-equilibrium.
- **Comparing modeling and observations**, we can probe dense matter Physics.

BNS merger quantities: mass/tidal deformation

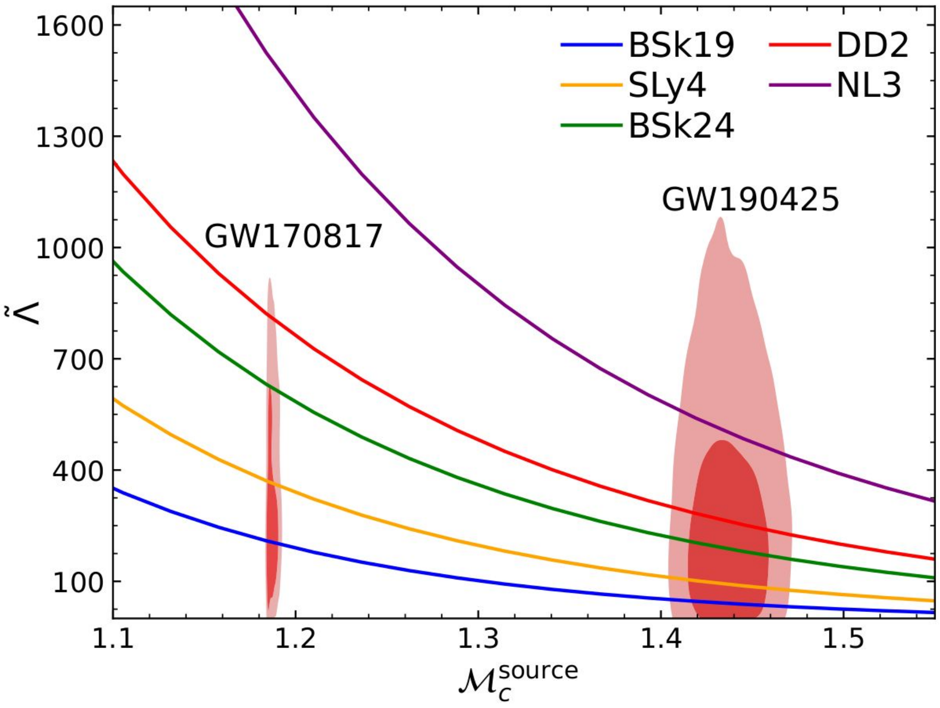
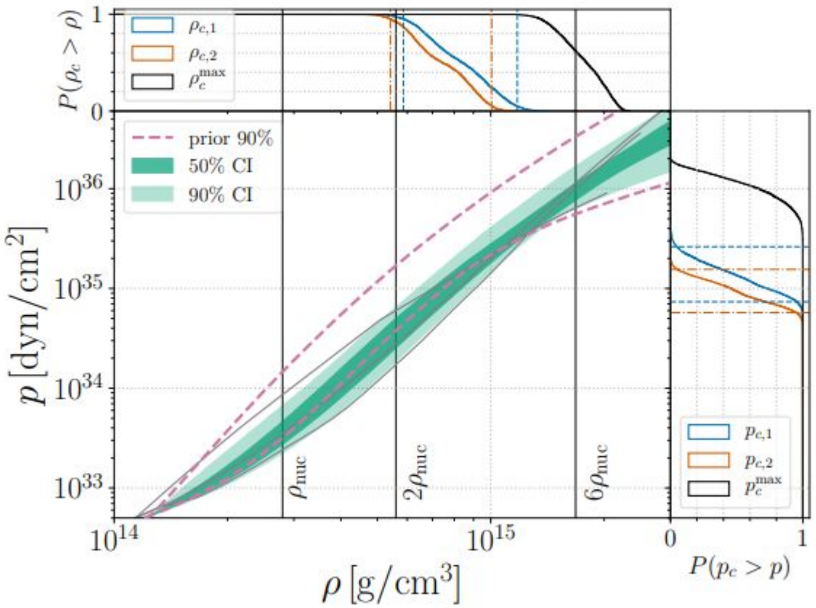


Figure for MANITOU book

Equation of State inference from GW detections

Instead of testing EoS by EoS, we use **Bayesian approach for inference** that relies on priors of EoSs.



Abbott et al. 2018 Phys. Rev. Lett. 121, 161101

Equation of State inference from GW detections

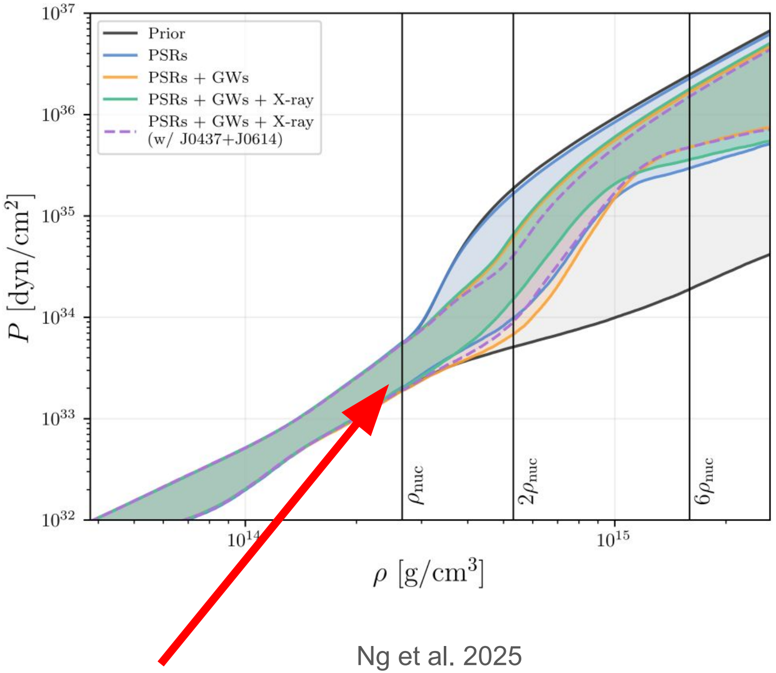
Instead of testing EoS by EoS, we use **Bayesian approach for inference** that relies on priors of EoSs.

Prior preferences:
- Large **agnostic priors** for astrophysicists
- Priors **linked to nuclear physics** quantities.

We have a solution to combine both:
semi-agnostic priors

Crust Unified Tool for Eos Reconstruction (CUTER)
Davis et al. 2024 (A&A, 687, A44)
- **low density** based on the **meta-model**
  - EoS based on nuclear parameters
  - experimental/theory data dictate the prior
  - describes npeμ matter only
- **high density** based on **agnostic approach**
  - Piecewise Polytropes or Gaussian Processes

GW data paired with other astrophysical data



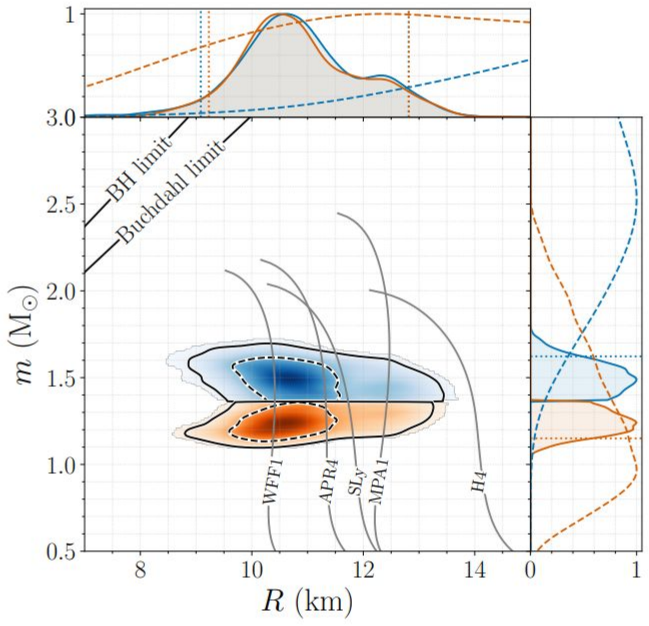
Ng et al. 2025

Nuclear parameters only dictate the EoS up to ρ_{nuc}

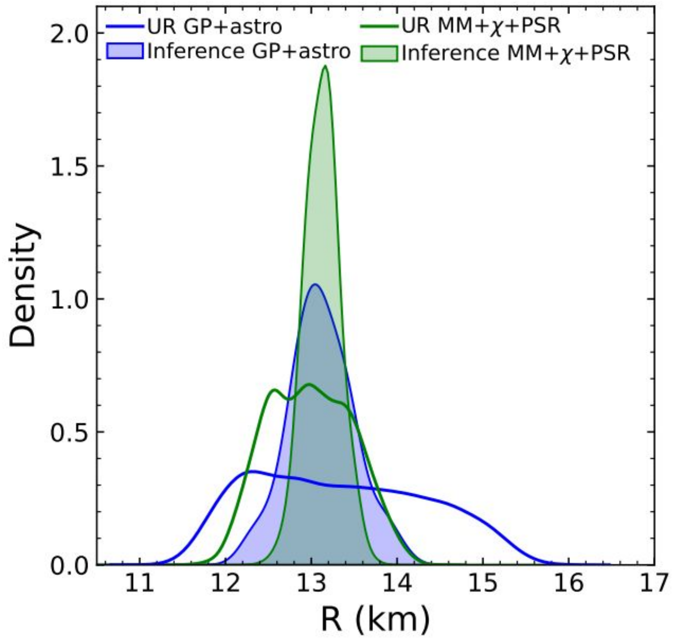
Neutron Star parameter extraction from GW detections

Extract a measure of **R** using:

- quasi-universal relations vs direct EoS inference
- careful in the future [Suleiman & Read 2024]



Abbott et al. 2018 Phys. Rev. Lett. 121, 161101



Suleiman & Read 2024, Phys. Rev. D 109, 103029

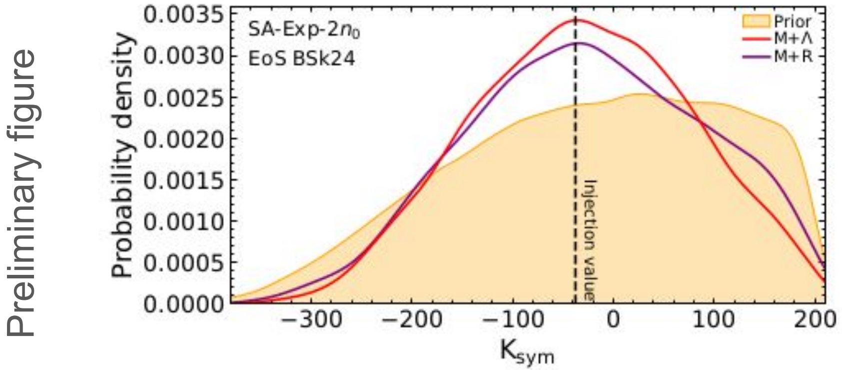
Going beyond the EoS: nuclear parameter inference

If nuclear parameters are used to build the prior, we can design **posteriors** for them **given astrophysical data**.

Challenge of semi-agnostic approach:

- Sources must constrain low density EoS
- Careful to have a large prior
- Not all parameters can be constrained

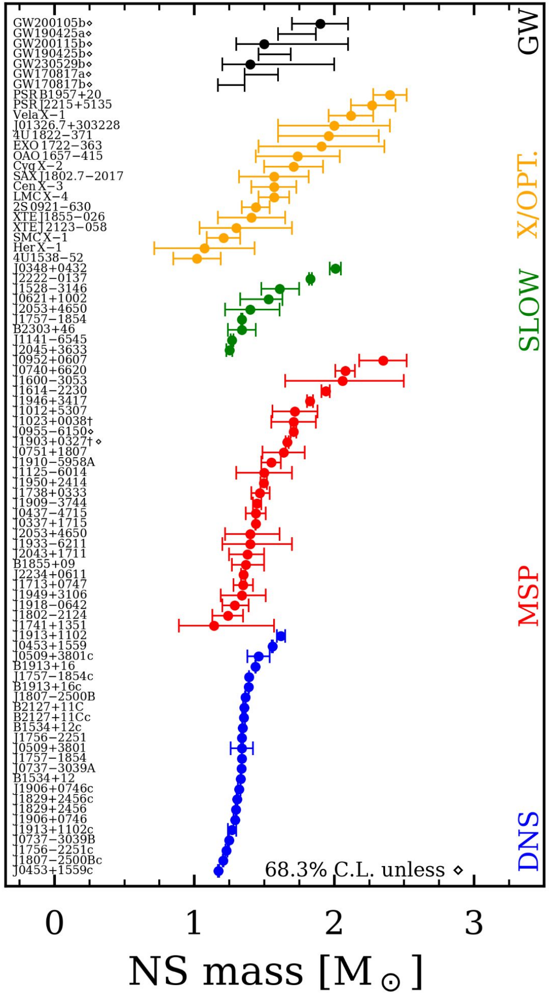
Simulated data with injection study:
BSk24 EoS used to simulate NSs
$n_0 = n_{nuc} = \rho_{nuc} / mn$



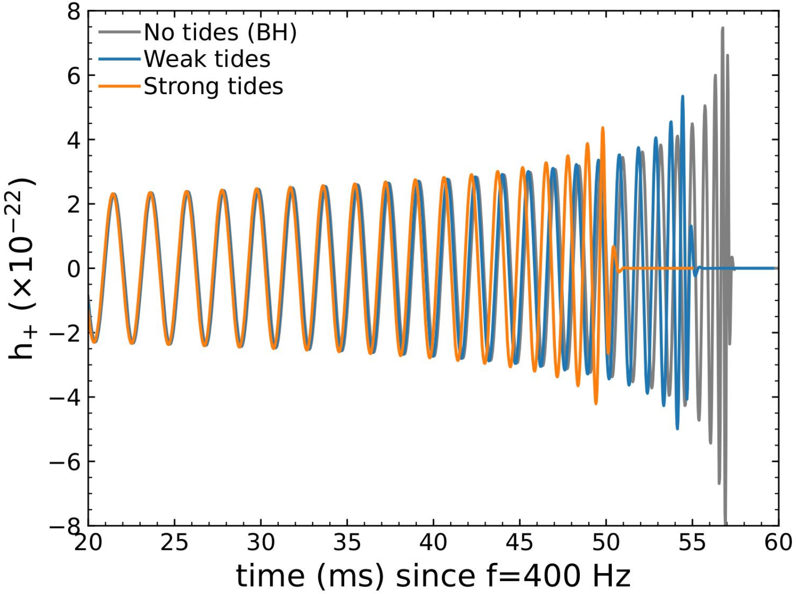
Conclusion

- ➔ GW detections of BNS mergers help probe neutron rich and dense matter Physics.
- ➔ **CUTER** builds EoSs priors partly based on nuclear parameters, with nuclear physics knowledge.
- ➔ With semi-agnostic EoS priors in a Bayesian inference, we can constrain SOME **nuclear parameters.**

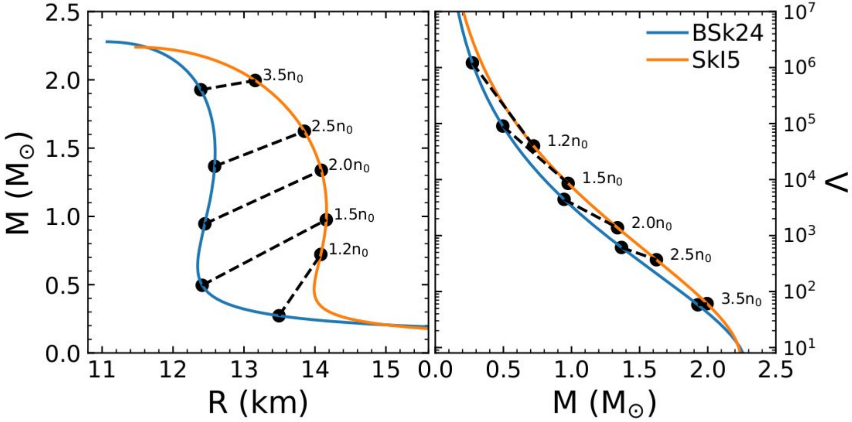
Thank you for your attention.



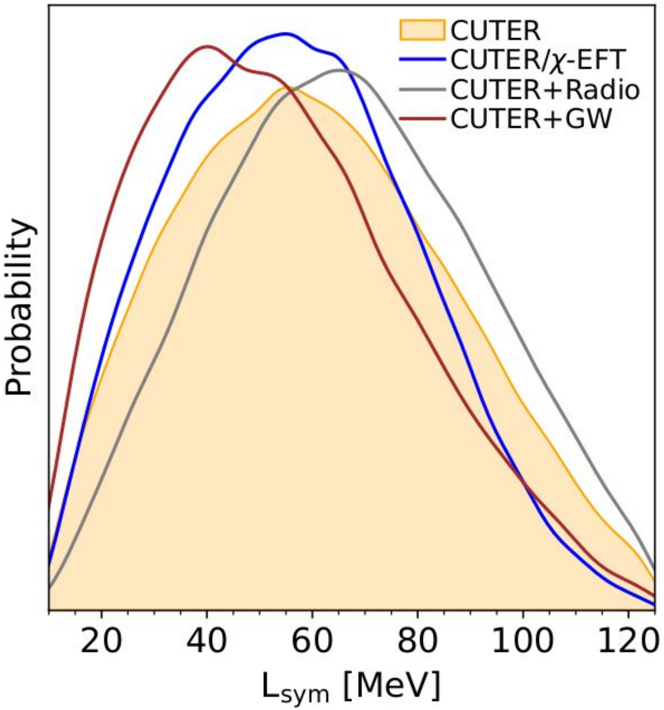
GW200105b⋄
GW190425a⋄
GW200115b⋄
GW190425b⋄
GW230529b⋄
GW170817a⋄
GW170817b⋄
PSR B1957+20
PSR J2215+5135
Vela X−1
J01326.7+303228
4U 1822−371
EXO 1722−363
OAO 1657−415
Cyg X−2
SAX J1802.7−2017
Cen X−3
LMC X−4
2S 0921−630
XTE J1855−026
XTE J2123−058
SMC X−1
Her X−1
4U1538−52
J0348+0432
J2222−0137
J1528−3146
J0621+1002
J2053+4650
J1757−1854
B2303+46
J1141−6545
J2045+3633
J0952+0607
J0740+6620
J1600−3053
J1614−2230
J1946+3417
J1012+5307
J1023+0038†
J0955−6150⋄
J1903+0327† ⋄
J0751+1807
J1910−5958A
J1125−6014
J1950+2414
J1738+0333
J1909−3744
J0437−4715
J0337+1715
J2053+4650
J1933−6211
J2043+1711
B1855+09
J2234+0611
J1713+0747
J1949+3106
J1918−0642
J1802−2124
J1741+1351
J1913+1102
J0453+1559
J0509+3801c
B1913+16
J1757−1854c
B1913+16c
J1807−2500B
B2127+11C
B2127+11Cc
B1534+12c
J1756−2251
J0509+3801
J1757−1854
J0737−3039A
B1534+12
J1906+0746c
J1829+2456c
J1829+2456
J1906+0746
J1913+1102c
J0737−3039B
J1756−2251c
J1807−2500Bc
J0453+1559c
GW
X/OPT.
SLOW
MSP
DNS
68.3% C.L. unless ⋄
0
1
2
3
NS mass [M⊙]

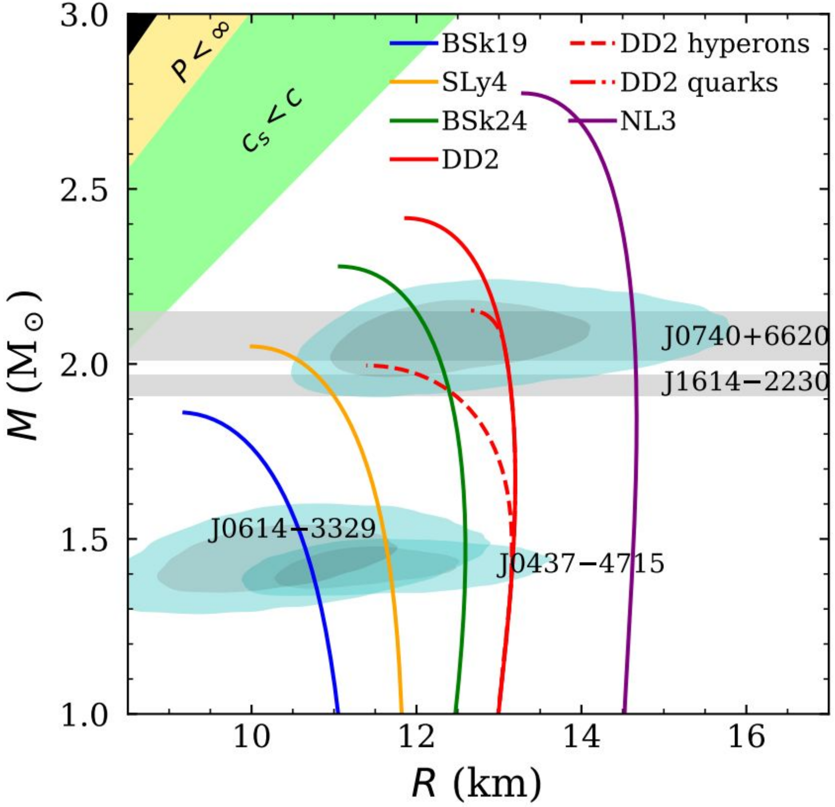


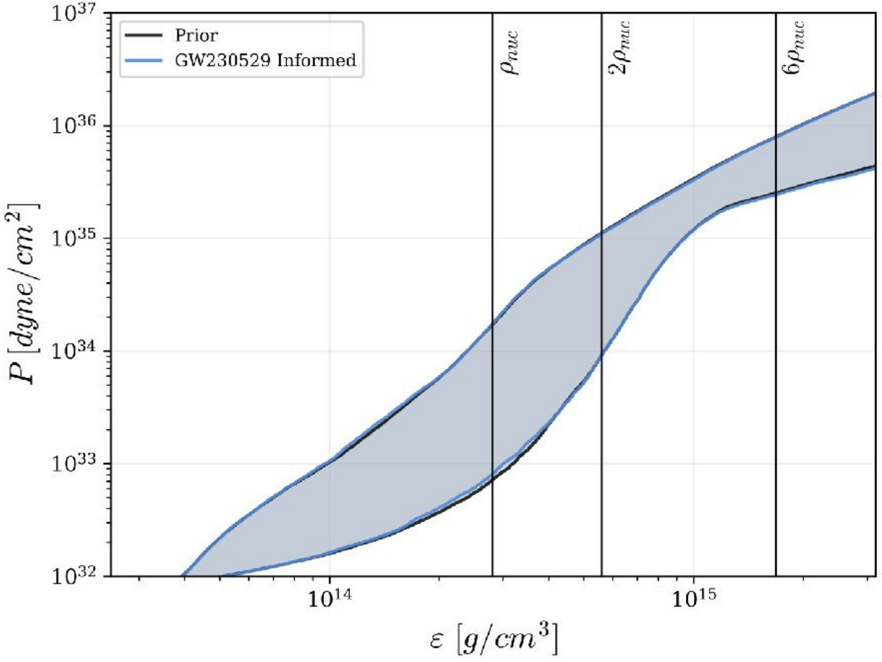
No tides (BH)
Weak tides
Strong tides
8
6
4
2
0
−2
−4
−6
−8
h+ (×10−22)
20
25
30
35
40
45
50
55
60
time (ms) since f=400 Hz



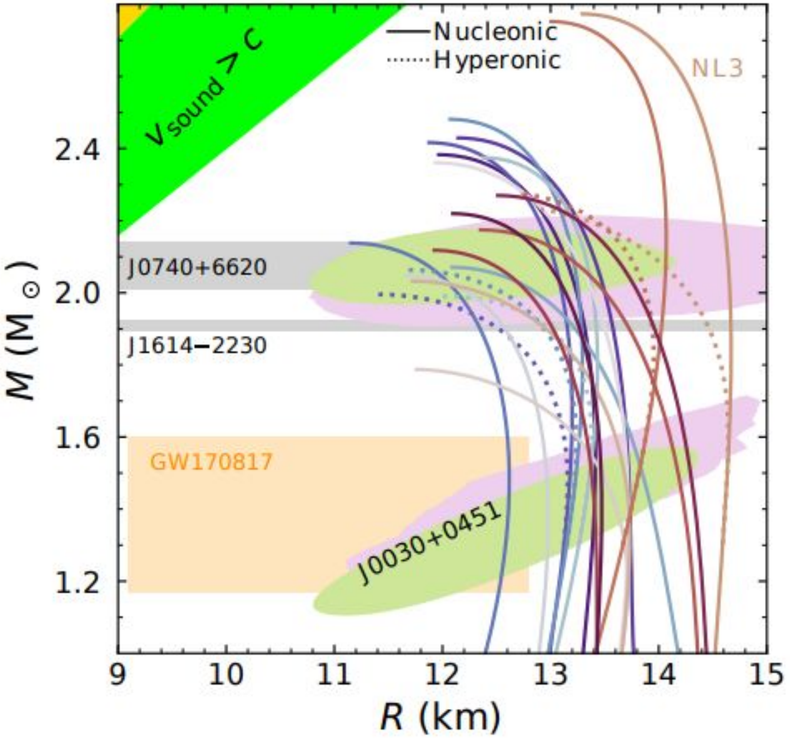
2.5
2.0
1.5
1.0
0.5
0.0
M (M⊙)
3.5n0
2.5n0
2.0n0
1.5n0
1.2n0
11
12
13
14
15
R (km)
BSk24
SkI5
1.2n0
1.5n0
2.0n0
2.5n0
3.5n0
0.0
0.5
1.0
1.5
2.0
2.5
M (M⊙)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Λ


CUTER
CUTER/χ-EFT
CUTER+Radio
CUTER+GW
Probability
20
40
60
80
100
120
L_sym [MeV]


P < ∞
c_s < c
BSk19
SLy4
BSk24
DD2
DD2 hyperons
DD2 quarks
NL3
J0740+6620
J1614−2230
J0614−3329
J0437−4715
M (M_⊙)
R (km)
1.0
1.5
2.0
2.5
3.0
10
12
14
16



Prior
GW230529 Informed
ρnuc
2ρnuc
6ρnuc
P [dyne/cm²]
ε [g/cm³]



Vsound > C
Nucleonic
Hyperonic
NL3
J0740+6620
J1614−2230
GW170817
J0030+0451
M (M⊙)
R (km)

$$e_{\rm nuc}(n,\delta) = e_{\rm is}(n) + e_{\rm iv}(n)\delta^2 + t^*_{\rm FG}(n,\delta)$$

$$e_{\rm is}(n) = e_{\rm is}(n; n_{\rm sat}, \{X_{\rm is}\}, m^*_{\rm sat}, \Delta m^*_{\rm sat}, b) \ ,$$

$$e_{\rm iv}(n) = e_{\rm iv}(n; n_{\rm sat}, \{X_{\rm iv}\}, m^*_{\rm sat}, \Delta m^*_{\rm sat}, b) \ ,$$

$$\{X_{\rm is}\} = \{E_{\rm sat}, K_{\rm sat}, Q_{\rm sat}, Z_{\rm sat}\} \ ,$$

$$\{X_{\rm iv}\} = \{E_{\rm sym}, L_{\rm sym}, K_{\rm sym}, Q_{\rm sym}, Z_{\rm sym}\}$$

	$X_{\rm min}$	$X_{\rm max}$
$n_{\rm sat}$	0.15	0.17
$E_{\rm sat}$	−17.0	−15.0
$K_{\rm sat}$	190.0	270.0
$Q_{\rm sat}$	−1000.0	1000.0
$Z_{\rm sat}$	−3000.0	3000.0
$E_{\rm sym}$	26.0	38.0
$L_{\rm sym}$	10.0	80.0
$K_{\rm sym}$	−400.0	200.0
$Q_{\rm sym}$	−2000.0	2000.0
$Z_{\rm sym}$	−5000.0	5000.0
$m^\star_{\rm sat}/m$	0.6	0.8
$\Delta m^\star_{\rm sat}/m$	0.0	0.2
b	1	10