The nuclear matter density functional under the nucleonic hypothesis

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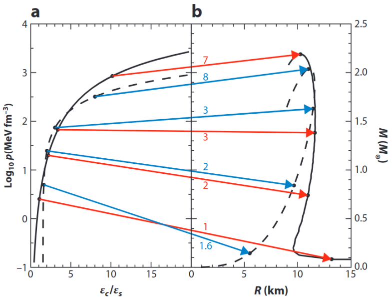
17th Russbach School on Nuclear Astrophysics

Motivations



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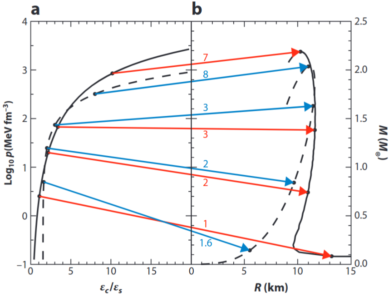

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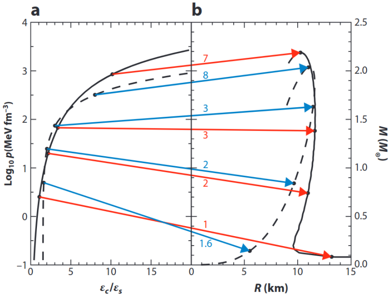

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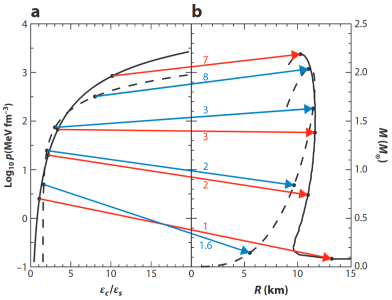

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→ Aim to study the combined implications of these measurements on the **nucleonic EoS** using **meta-modeling** techniques by performing **Bayesian analysis**.

Meta-modeling of the EoS

* Nuclear matter energy per nucleon ($n = n_p + n_n$, $\delta = (n_n - n_p)/n$):

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$$e_{is} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{3!}Q_{sat}x^3 + \frac{1}{4!}Z_{sat}x^4 + \dots$$

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* In meta-modeling:

$$\boxed{e(n,\delta) = t_{FG}(n,\delta) + v(n,\delta).}$$

See Margueron et al. Phys. Rev. C 2018, 97:025806

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- All purely nucleonic models can be nicely reproduced with the metamodel by truncating the expansion at order 4.

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$\rightarrow$ Deviations between observations and metamodel predictions will signal the failure of the nucleonic approximation, and therefore reveal the presence of deconfined matter at high density.

Bayesian analysis

Posterior

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Parameters	Min	Max
E_{sat} (MeV)	-17	-15
n_{sat} (fm^{-3})	0.15	0.17
K_{sat} (MeV)	190	270
Q_{sat} (MeV)	-1000	1000
Z_{sat} (MeV)	-3000	3000
E_{sym} (MeV)	26	38
L_{sym} (MeV)	10	80
K_{sym} (MeV)	-400	200
Q_{sym} (MeV)	-2000	2000
Z_{sym} (MeV)	-5000	5000
$m^\star_{sat}$	0.6	0.8
$\Delta m^\star_{sat}/m$	0.0	0.2
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- Surface and curvature parameters: $\{\sigma_0,\ b_s,\ \sigma_{0c},\ \beta\}$.

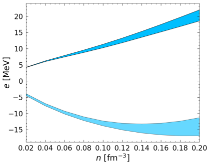
  Fit to AME2016 mass table:

$$\boxed{p_{AME}(\{X\}) = e^{-\chi^2(\{X\})/2}}$$

Huang et al. Chin. Phys. C 2017, 41, 03000

Constraints from nuclear physics and astrophysical observations

1. Chiral EFT calculation:



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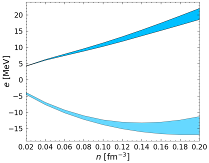

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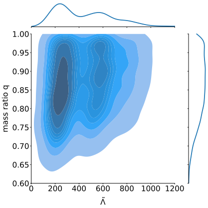

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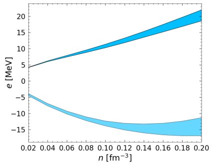

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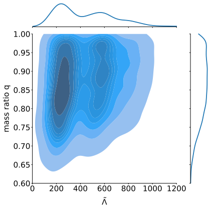

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3. **PSR 0348+0432 mass**: M$= 2.01 \pm 0.04\ M_\odot$
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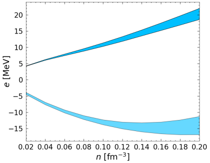

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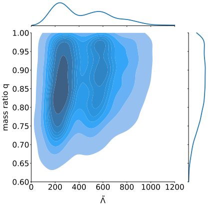

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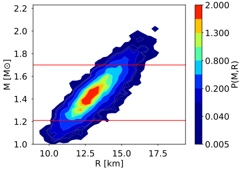
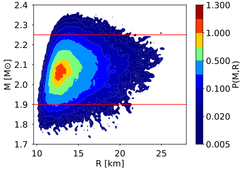
4. PSR J0030+0451 (NICER, 2019) & J0740+6620 (NICER+XMM, 2021) mass and radius measurement





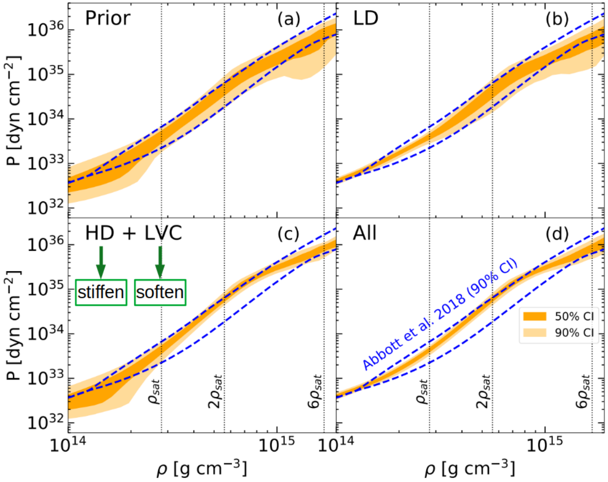
Miller et al, Astrophys. J. Lett. 2019. 887, L24; *Miller et al 2021, arXiv:2105.06979*

Results

1. **Prior**
2. **LD**: EFT calculation
3. **HD+LVC:** (causality, stability, $e_{sym} > 0$)+ NS mass + LVC
4. **All**: EFT calculation + HD + LVC + NICER

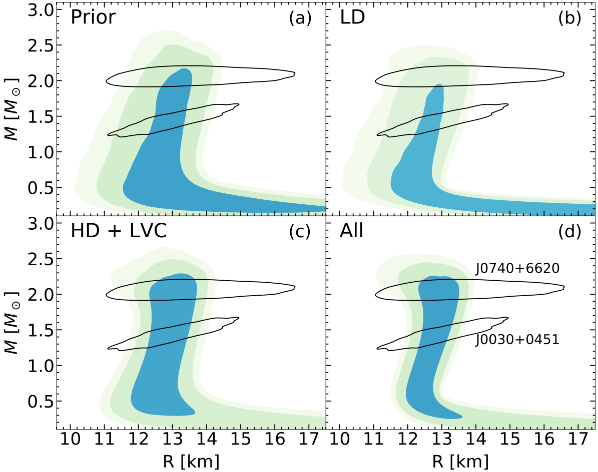
See Dinh Thi, H.; Mondal, C.; Gulminelli, F. Universe 2021, 7, 373.

Equation of State



$\rightarrow$ Good agreement with GW170817.

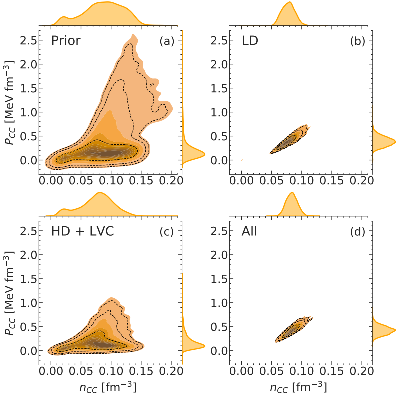
M-R relation



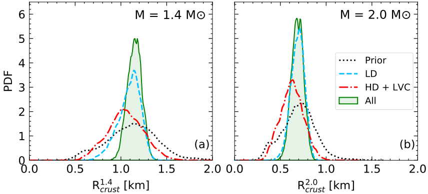
→ Good agreement with NICER measurements.

Crustal properties

Crust-core transition



Crust thickness

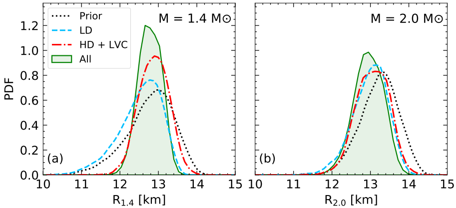


→ Crust properties are mostly constrained by χEFT calculation.

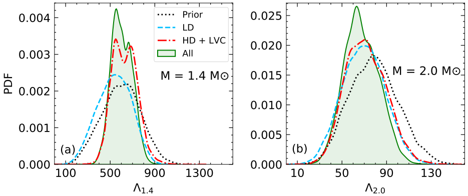
→ $R^{1.4}_{crust} = 1.15^{+0.10}_{-0.08}$ km; $R^{2.0}_{crust} = 0.687^{+0.067}_{-0.067}$ km.

Radius and Tidal deformability

Radius

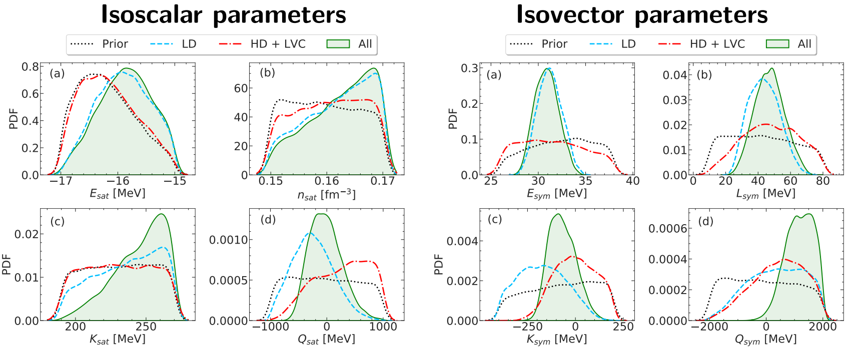


Dim.less tidal deformability



$R_{1.4} = 12.78^{+0.30}_{-0.29}$ km. (Miller et al. 2021: $R_{1.4} = 12.45 \pm 0.65$ km)

Empirical EoS parameters



- χEFT: most effective in low-order isovector parameters (E_{sym}, L_{sym}).
- Astro: most effective in high-order parameters (Q_{sat}, K_{sym}, Q_{sym}).

Correlation between observables and parameters

	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	σ_0	b_s	σ_{0c}	β
n_{CC}	-0.09	-0.05	0.15	-0.11	0.00	-0.34	-0.69	-0.22	0.55	-0.16	0.10	0.43	-0.17	-0.10
P_{CC}	-0.05	-0.02	0.13	-0.03	-0.03	-0.07	-0.62	-0.38	0.41	-0.04	0.05	0.12	-0.02	-0.05
$R^{1.4}_{crust}$	0.09	-0.18	0.19	0.15	0.09	-0.01	-0.14	0.20	0.64	0.01	-0.09	-0.08	0.04	0.08
$R_{1.4}$	0.15	-0.22	0.13	0.20	0.14	-0.03	0.41	0.65	0.42	0.06	-0.14	-0.12	0.02	0.13
$\Lambda_{1.4}$	0.16	-0.24	0.16	0.23	0.14	-0.17	0.26	0.60	0.50	0.10	-0.15	0.00	-0.01	0.14
$x_p^{1.4}$	-0.24	0.32	-0.41	-0.50	-0.09	0.39	0.60	0.75	0.58	0.04	0.22	-0.15	-0.06	-0.20
$R^{2.0}_{crust}$	0.15	-0.23	0.27	0.31	0.19	-0.16	-0.26	0.08	0.53	0.12	-0.14	0.00	0.05	0.14
$R_{2.0}$	0.21	-0.27	0.24	0.38	0.25	-0.19	0.10	0.36	0.37	0.18	-0.19	-0.01	0.04	0.18
$\Lambda_{2.0}$	0.22	-0.29	0.27	0.42	0.27	-0.28	-0.03	0.27	0.36	0.21	-0.20	0.05	0.03	0.19
$x_p^{2.0}$	-0.20	0.19	-0.39	-0.57	-0.29	0.20	0.31	0.51	0.62	0.25	0.19	-0.00	-0.12	-0.18

Conclusions

- Low-density nuclear physics data constrains the crustal properties, while astrophysical data constrains the global NS properties.

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- The nucleonic hypothesis is consistent with all current data.
- We need more stringent constraints from the observations to conclusively establish (reject) the presence of exotic degrees of freedom in high-density matter.