Studying composition of the core of neutron stars in nuclear metamodelling approach

Chiranjib Mondal

ECT*, Trento
June 21, 2022

What do we have?

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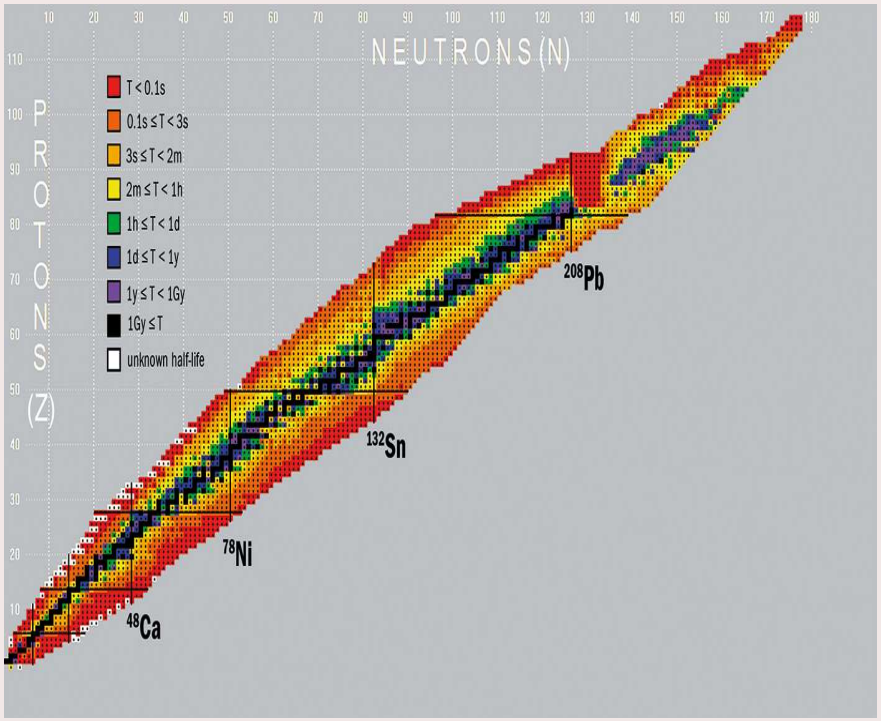
Low energy Nuclear Physics

We have knowledge from Nuclear Physics in the laboratory

Finite nuclear properties



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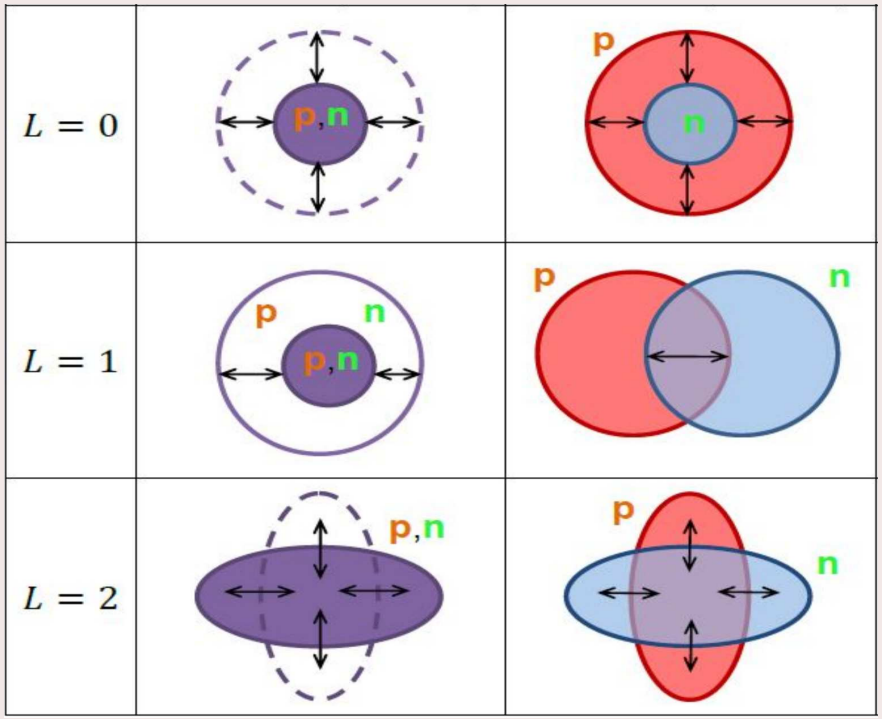

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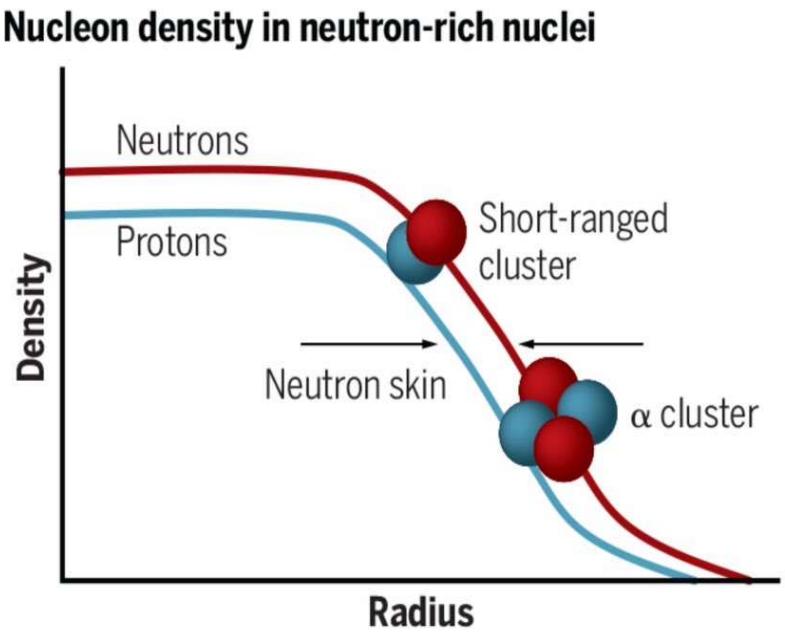

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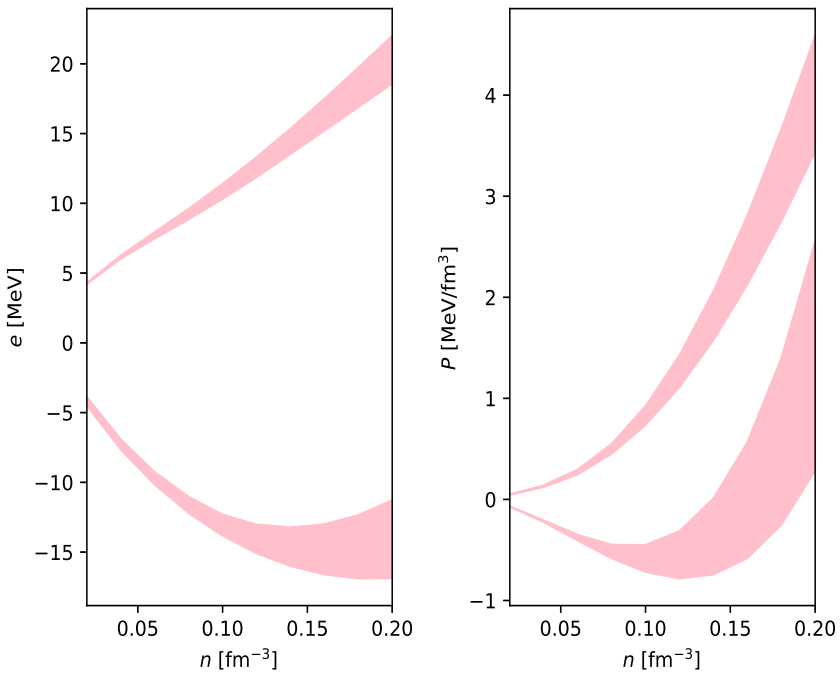

Drischler *et. al.* PRC 93, 05431 (2016)

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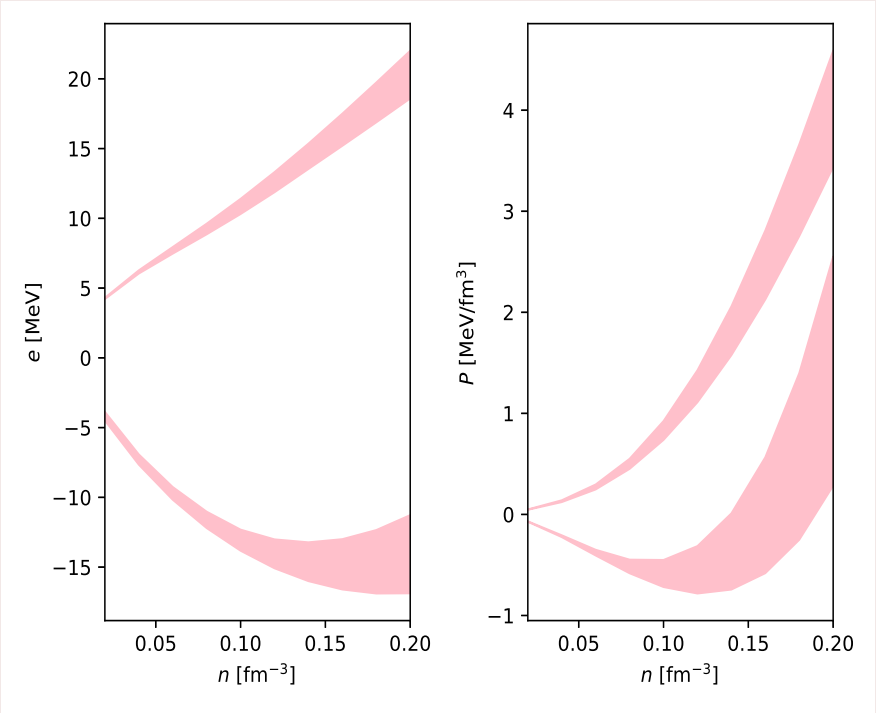

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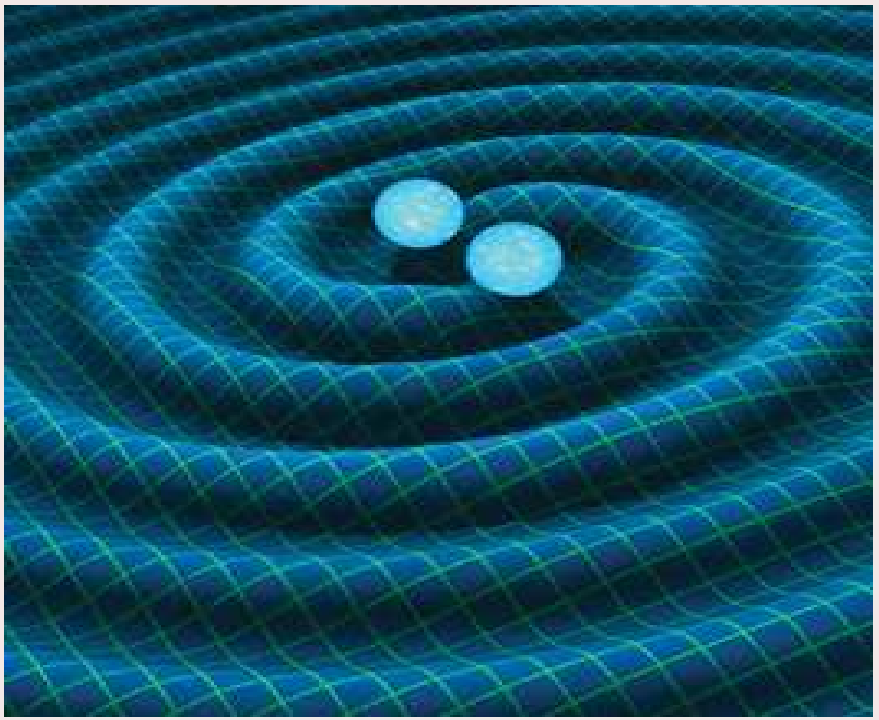
From observation



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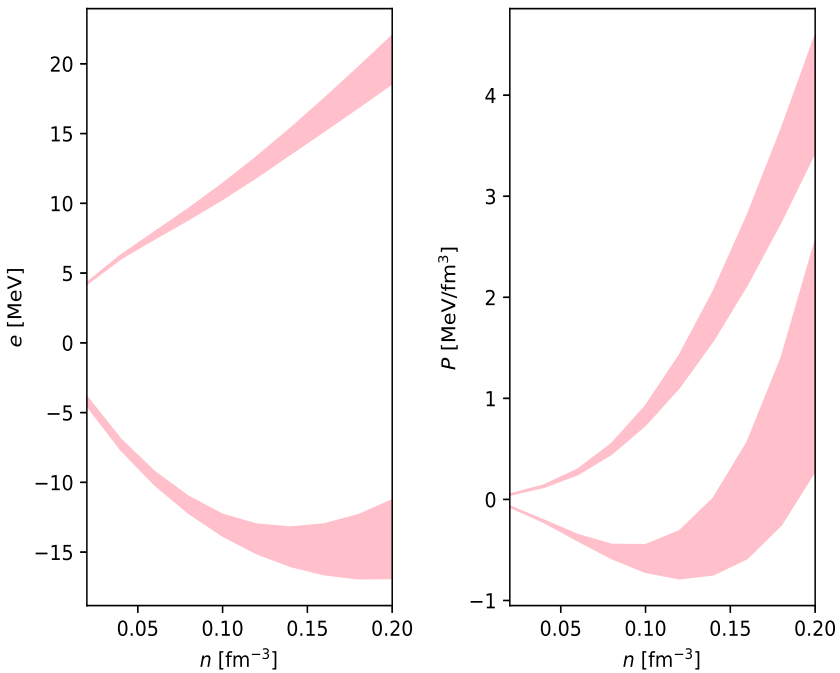

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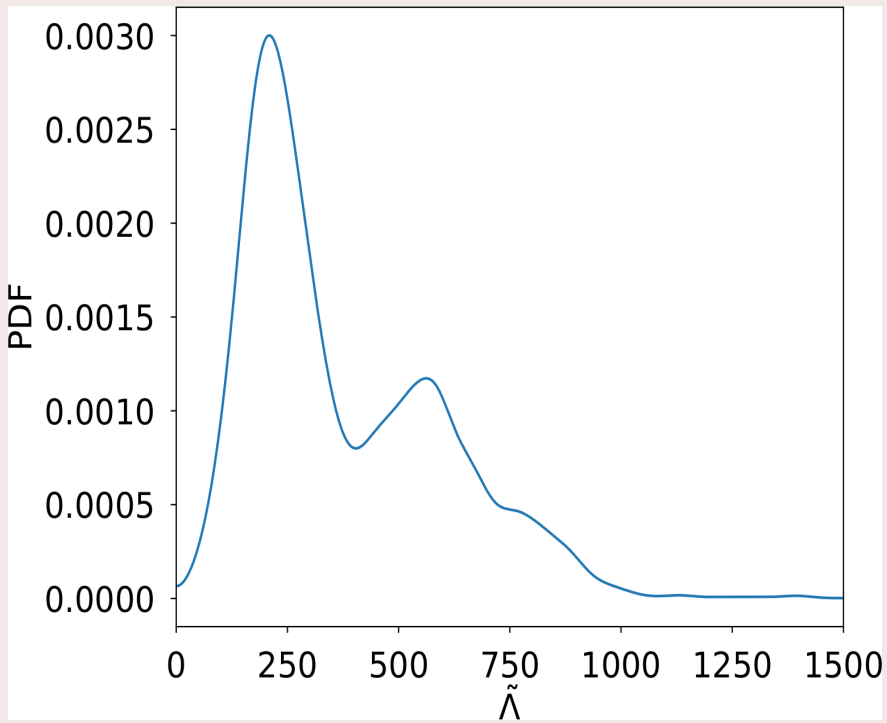

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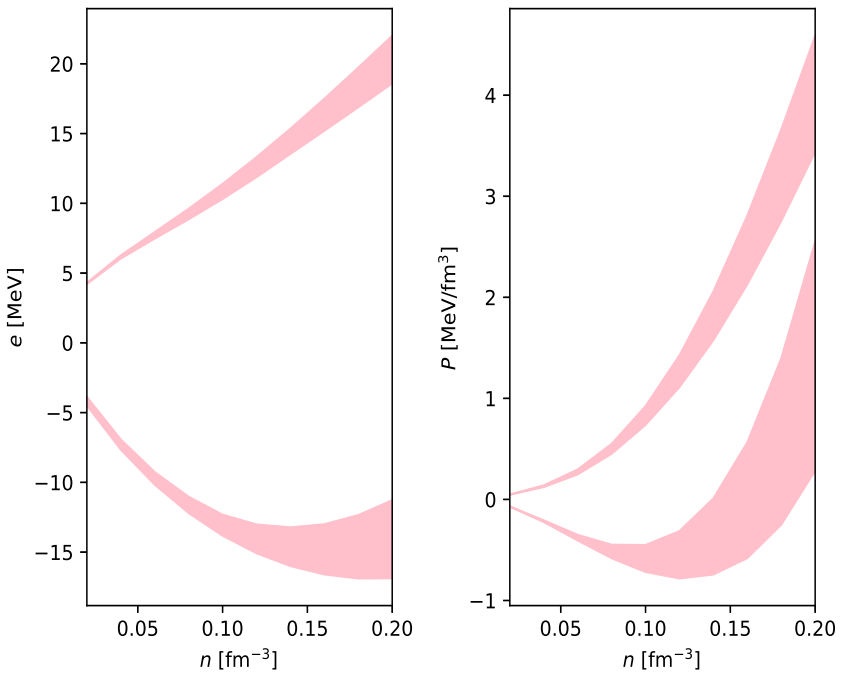

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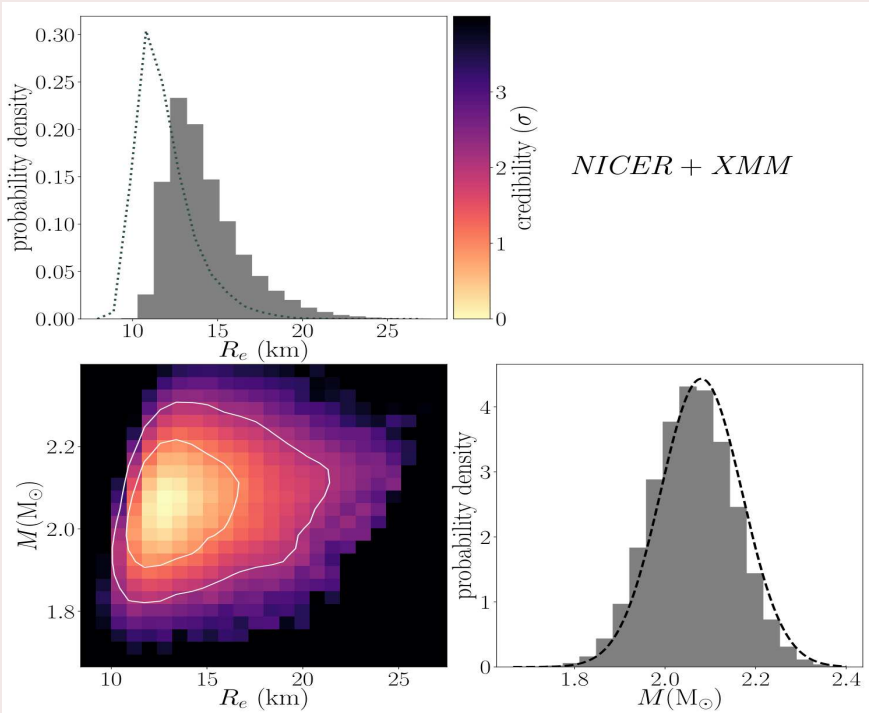

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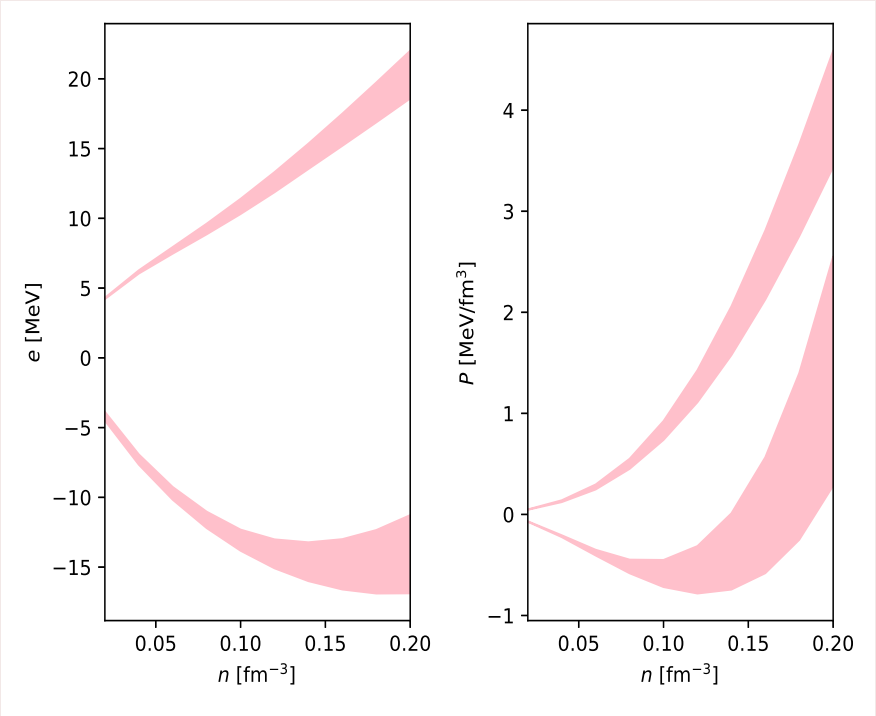

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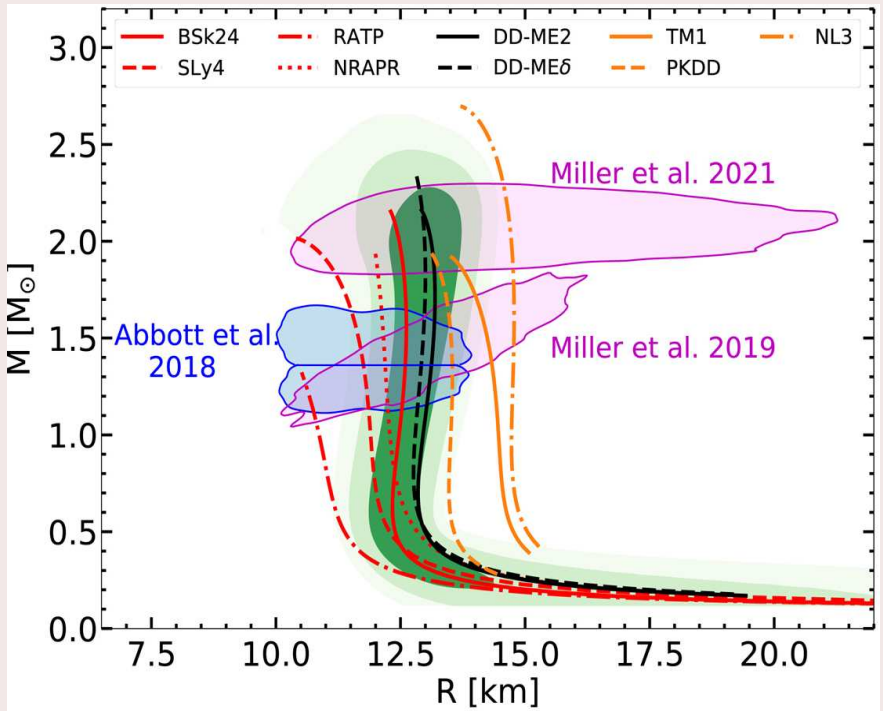

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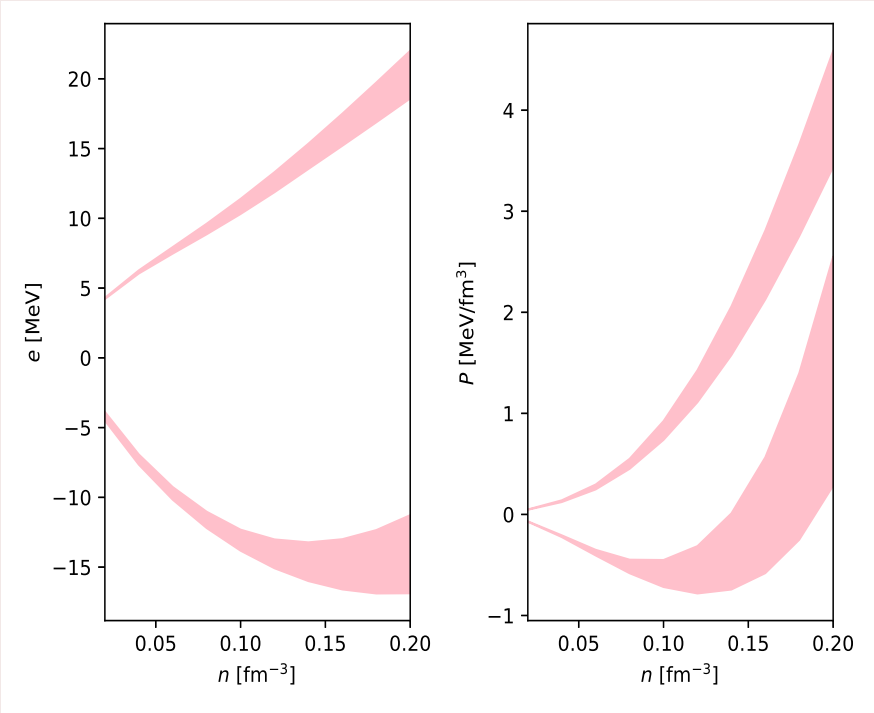

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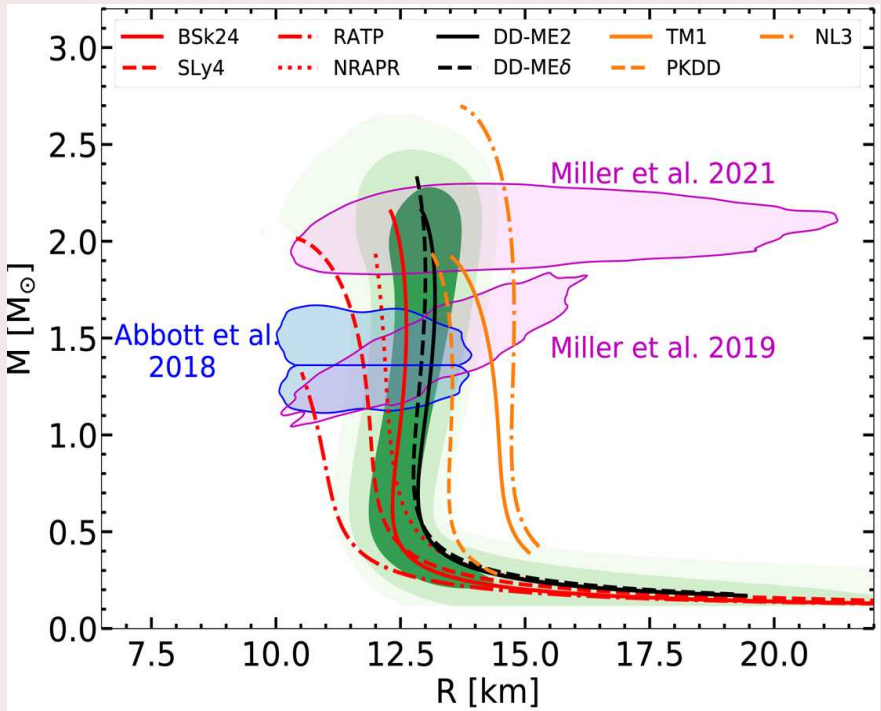

We can construct equation of state (EoS) with nuclear models. (!!!!)

Connecting parameters to "observables"

Equation of state

- **The energy is given by** ($x = \frac{n-n_{\rm sat}}{3n_{\rm sat}}$, $n = n_n + n_p$, $\delta = \frac{n_n - n_p}{n}$)

$$
\begin{aligned}
e(n_n, n_p) &\simeq e_{\rm SNM}(n, 0) + e_{\rm sym}(n)\delta^2 \\
e_{\rm SNM}(n) &\simeq E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{6}Q_{\rm sat}x^3 + \frac{1}{24}Z_{\rm sat}x^4 \\
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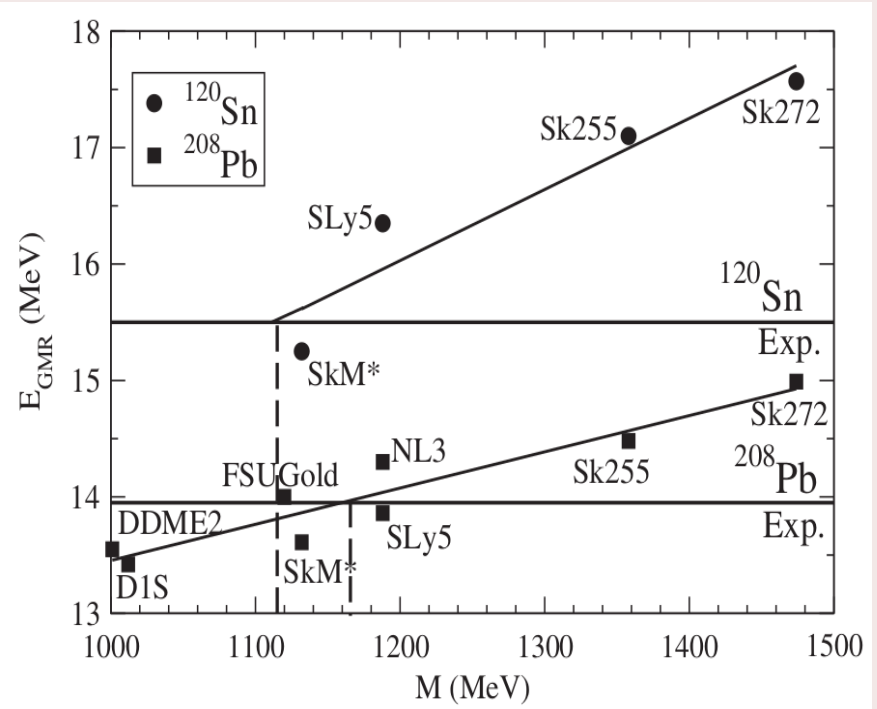
Phys. Rev. Lett. 109, 092501 (2012)



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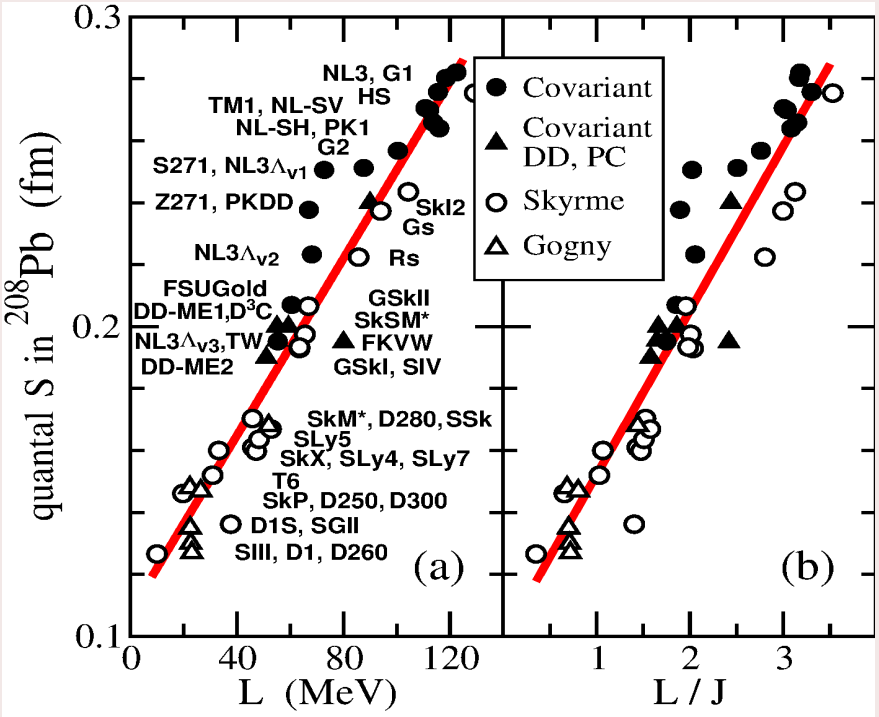
Phys. Rev. Lett. 102, 122502 (2009)



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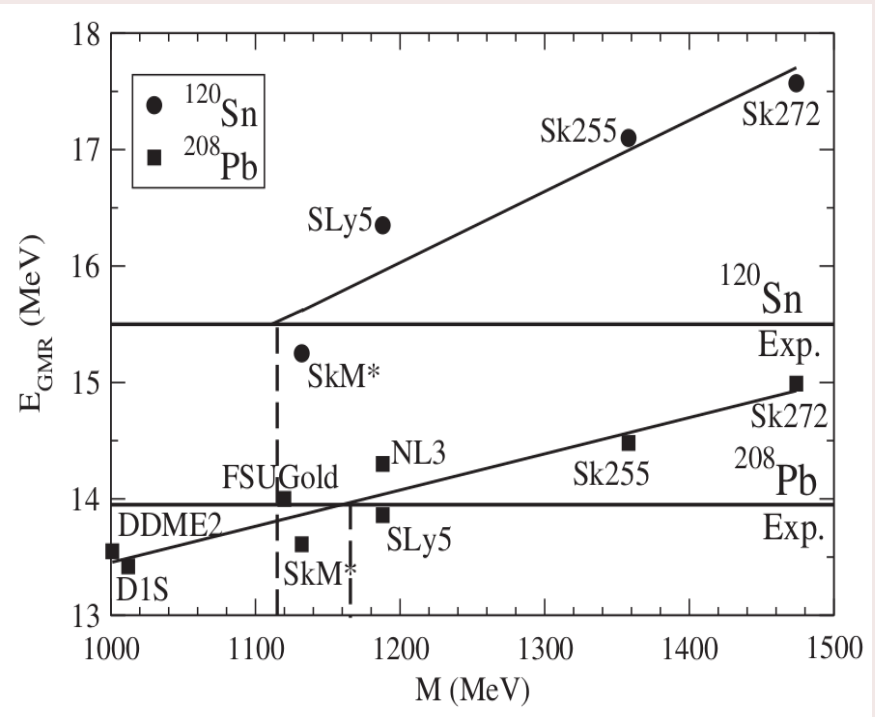
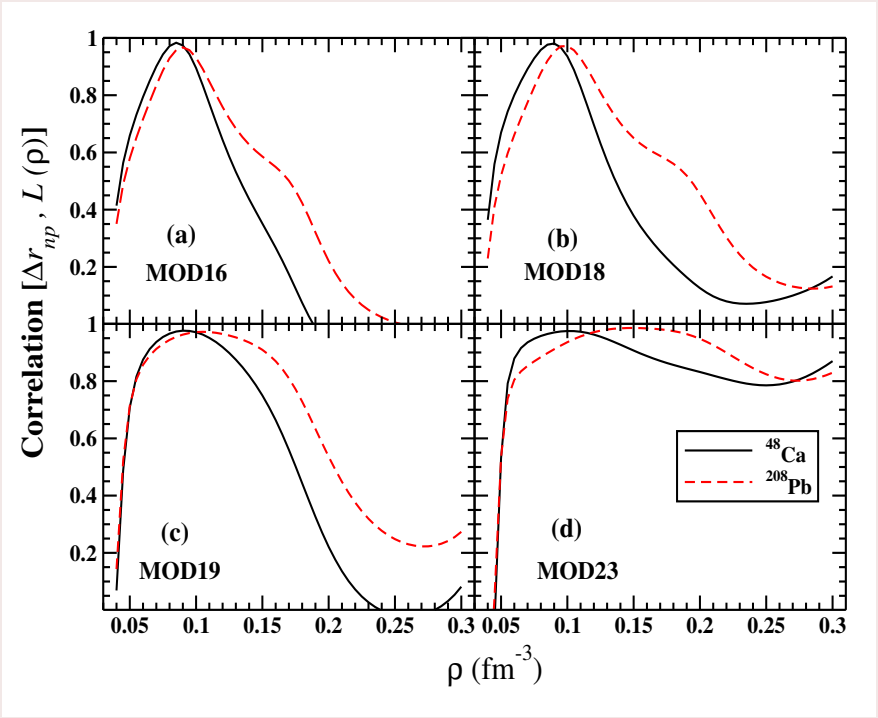


Fictitious correlations??

Equation of state

Δr_{np} - L_{sym} correlation



CM, Phys.Rev.C 105, 034305 (2022).

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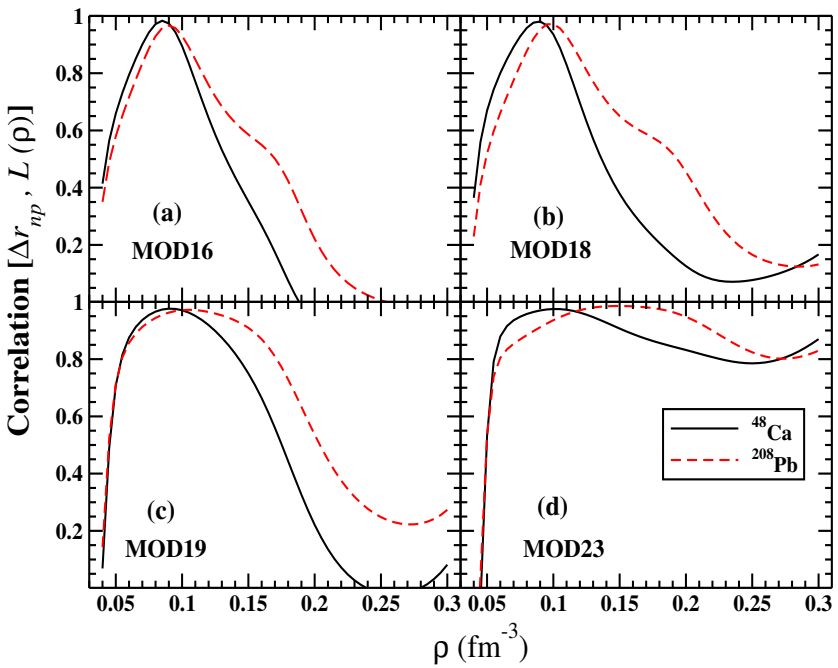

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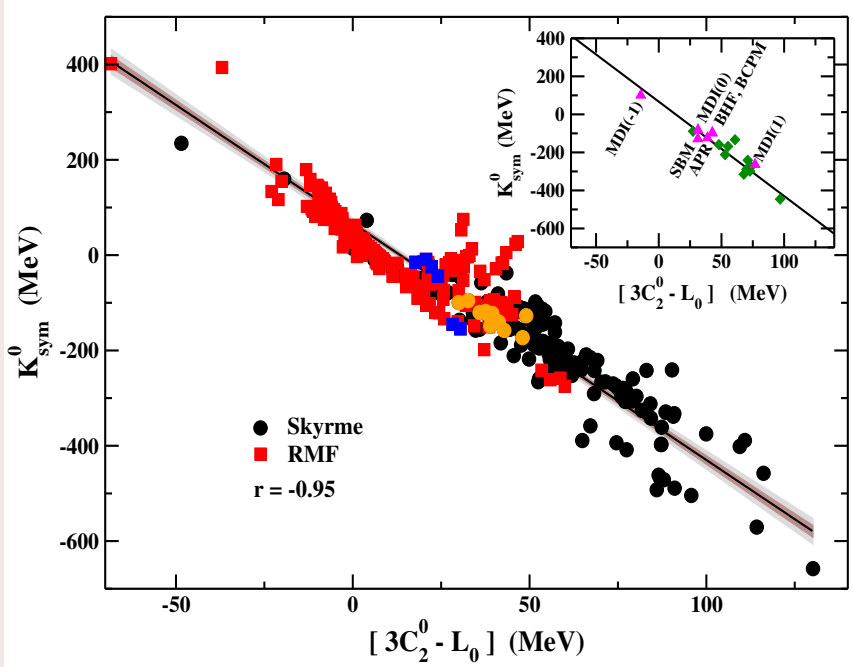
K_{sym} - $(3J_{sym} - L_{sym})$ correlation



CM *et. al.*, PRC 96, 021302 (2017)

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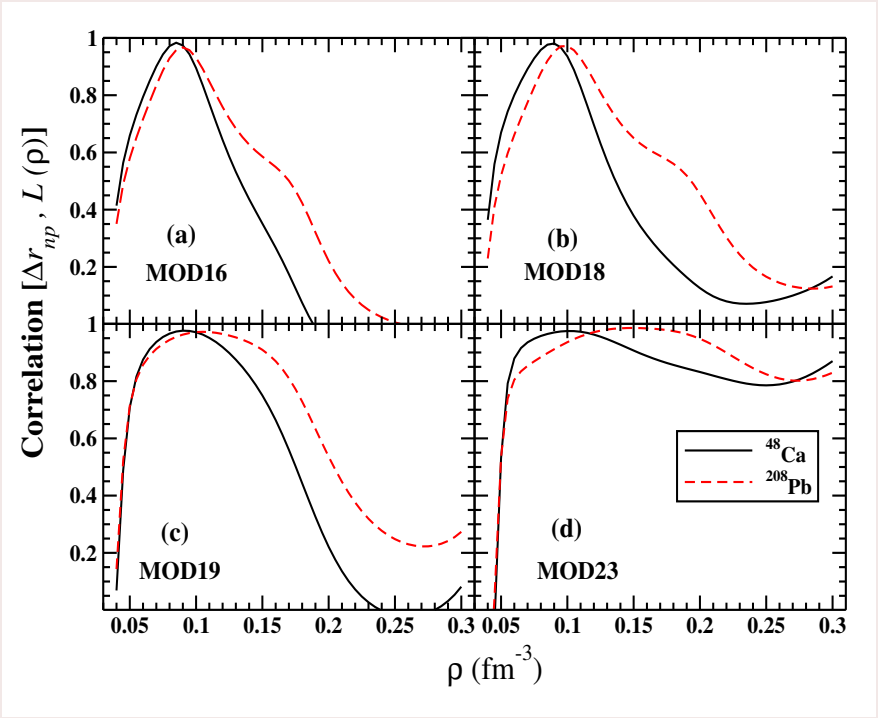

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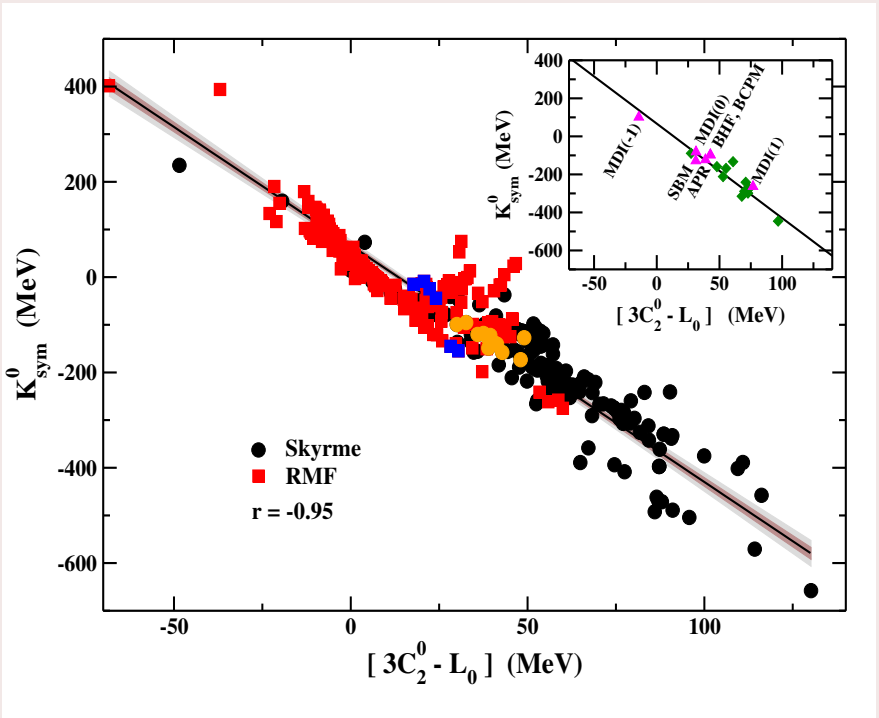

CM *et. al.*, PRC 96, 021302 (2017)

To do list:

- **Systematic exploration of a functional.**
- **Exploring different forms of the functional.**
- **Agnostic approach.**

Nucleonic meta-modelling

Founding aspects [PRC 97, 025805 (2018)]

Features

- **Flexible functional $e(n_n, n_p)$ able to reproduce existing effective nucleonic models and interpolate between them.**
- **Expansion in powers of the Fermi momentum or of the density.**
- **Expansion around saturation: Parameter space = emp. par. $\overrightarrow{X}$.**
- **β-equilibrium!!!**

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- **β-equilibrium!!!**

- **The energy per particle can be rewritten as,**

$$
\begin{aligned}
e(n_n, n_p) &\simeq e_{\rm SNM}(n, 0) + e_{\rm sym}(n)\delta^2 \\
e_{meta}(n_n, n_p) &= KE(n_n, n_p) + \sum_{\alpha \geq 0} \frac{1}{\alpha!} \left(v_\alpha^{is} + v_\alpha^{iv} \delta^2 \right) x^\alpha . \\
v_\alpha^{is(iv)} &\equiv f\left(E_{\rm sat}, K_{\rm sat} \cdots J_{\rm sym}, L_{\rm sym} \cdots \right).
\end{aligned}
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Bayesian Study

Obtaining the filters

Prior = Nuclear physics informed prior with AME2016 fit.

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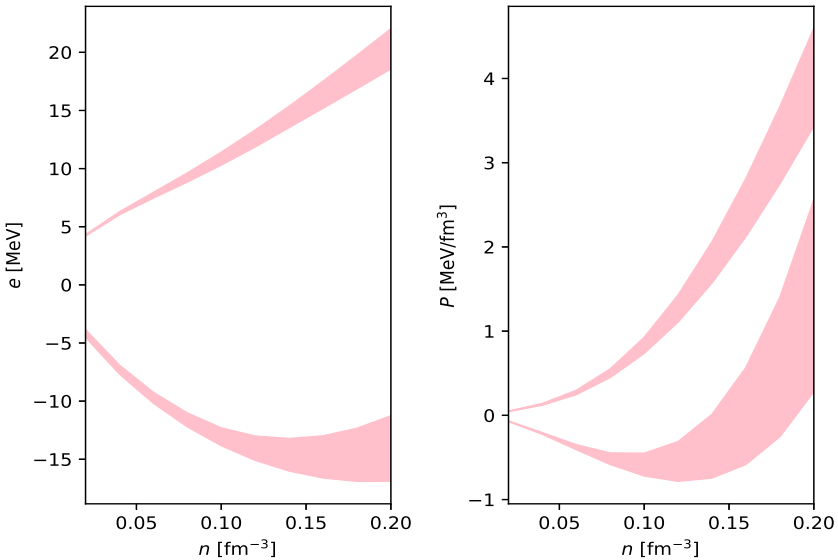

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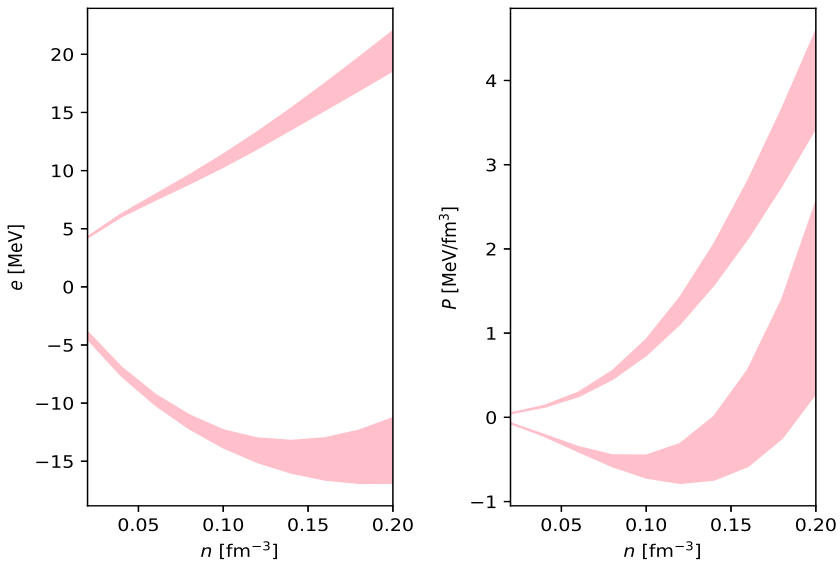

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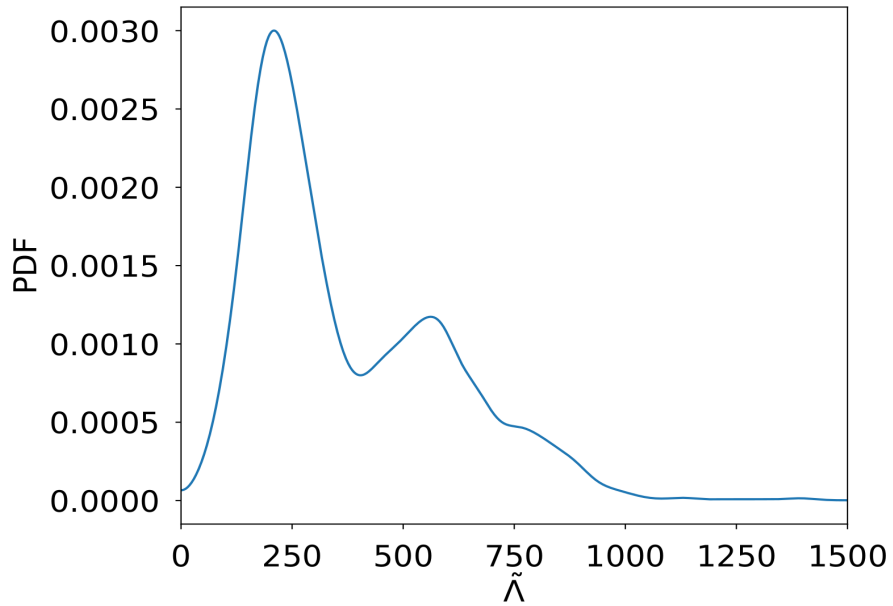

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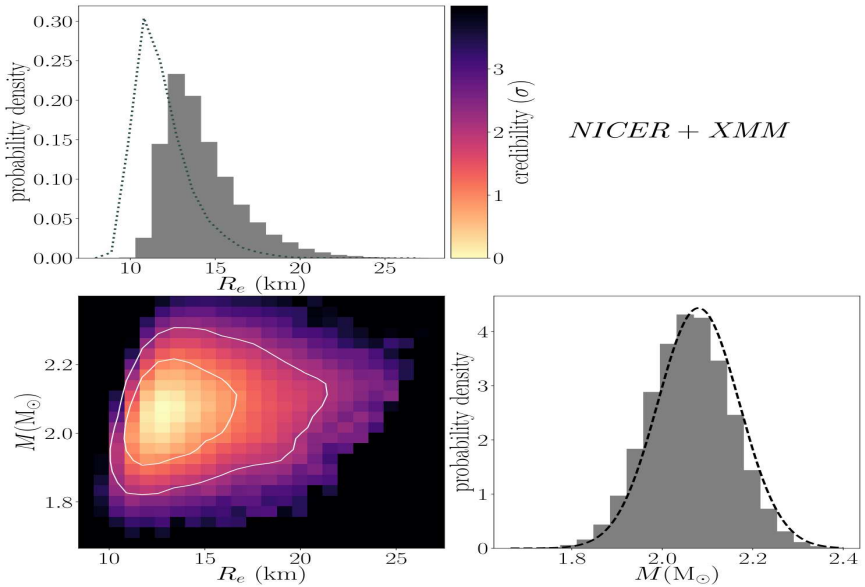
- **All** = EFT + HD + LVC + NICER.

NICER



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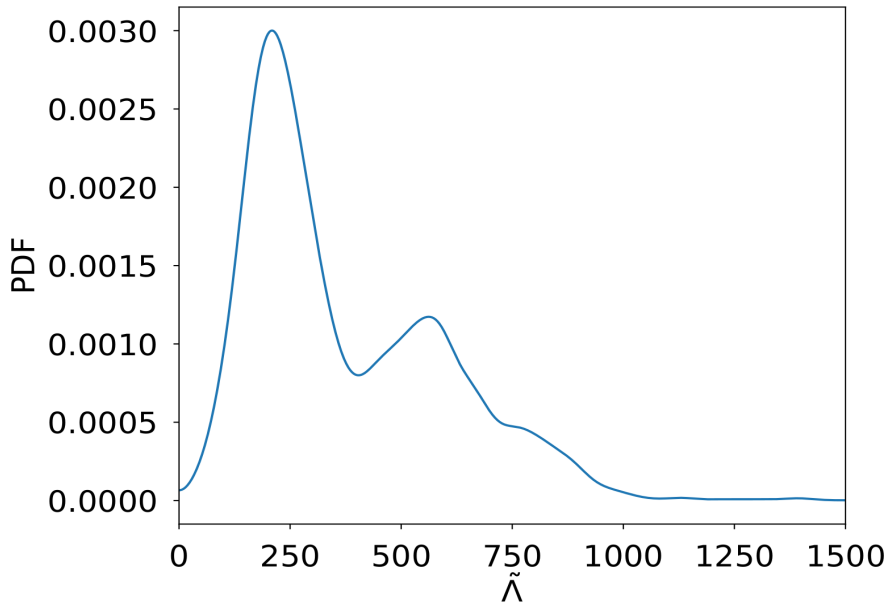
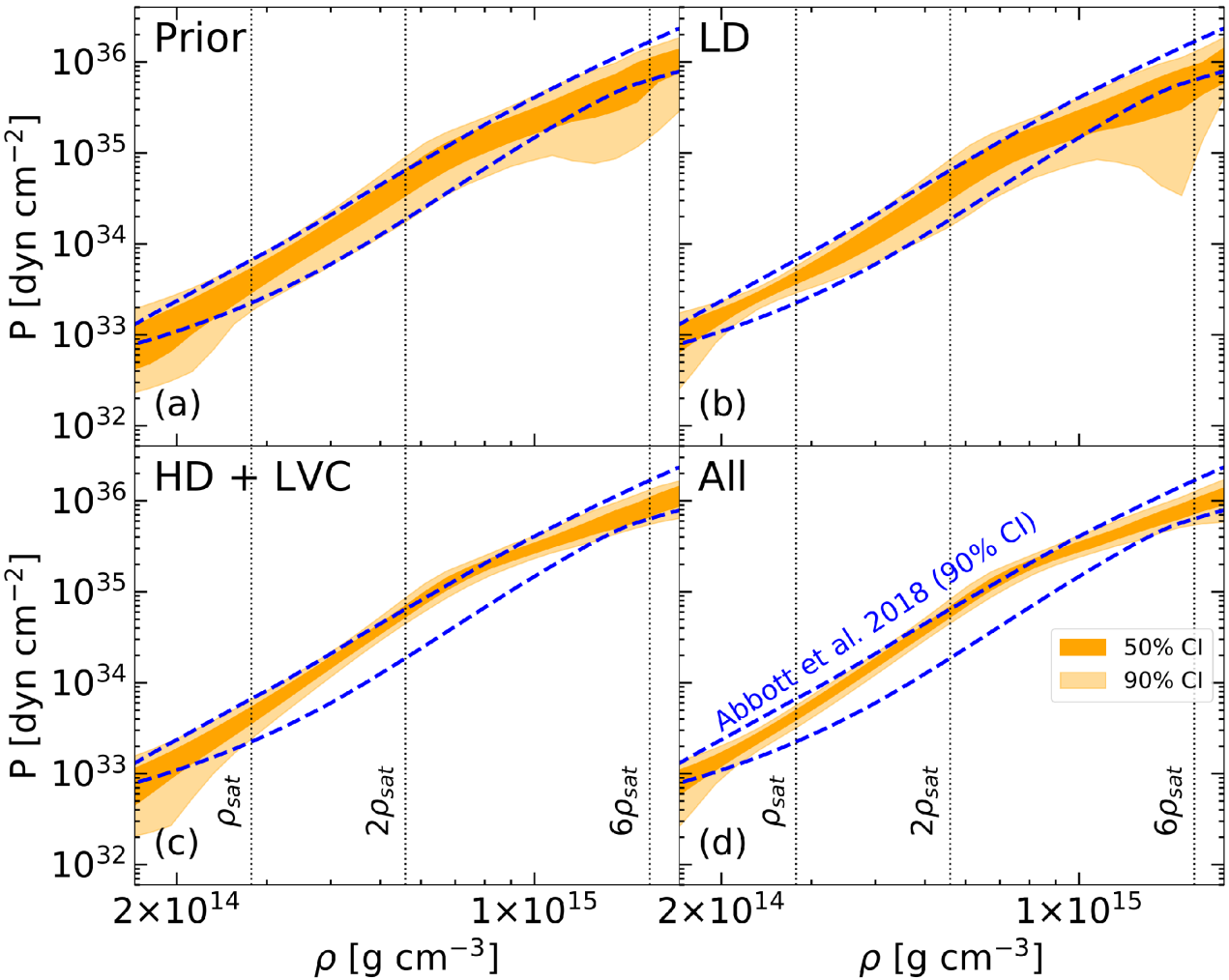


Impact of recent data

EoS

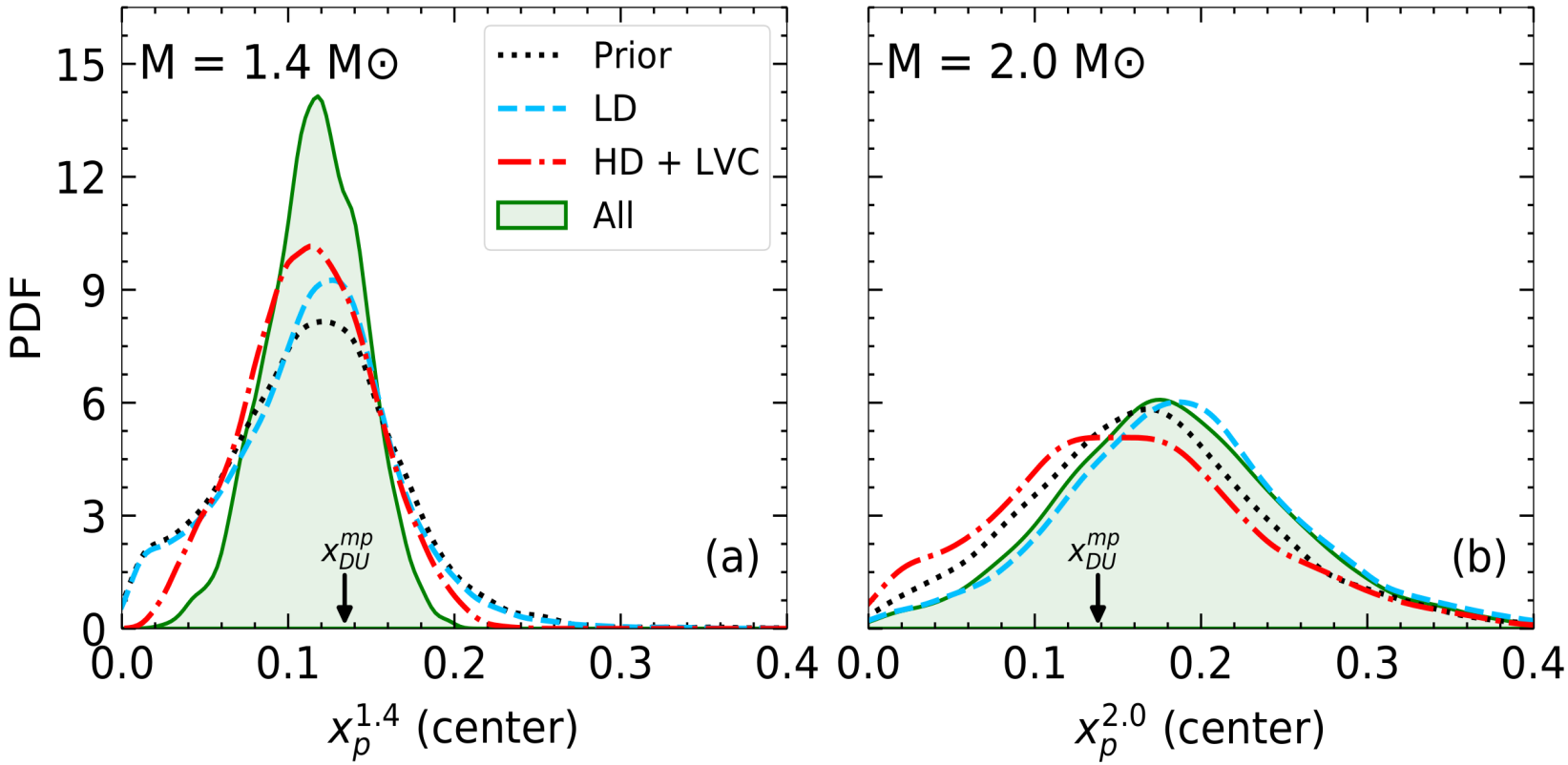


Hoa Dinh Thi, CM & F. Gulminelli, Universe 7, 373 (2021).

Impact of recent data

Proton fraction

$$\boxed{x_{DU} = \frac{1}{1 + (1 + x_{ep}^{1/3})^3}} \text{ with, } x_{ep} = \frac{x_e}{x_p}.$$



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The masquerading problem

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EoS to composition

Solve Tolman-Oppenheimer-Volkoff (TOV) equations, we can construct the unique M-R or Λ-M(R) relations.

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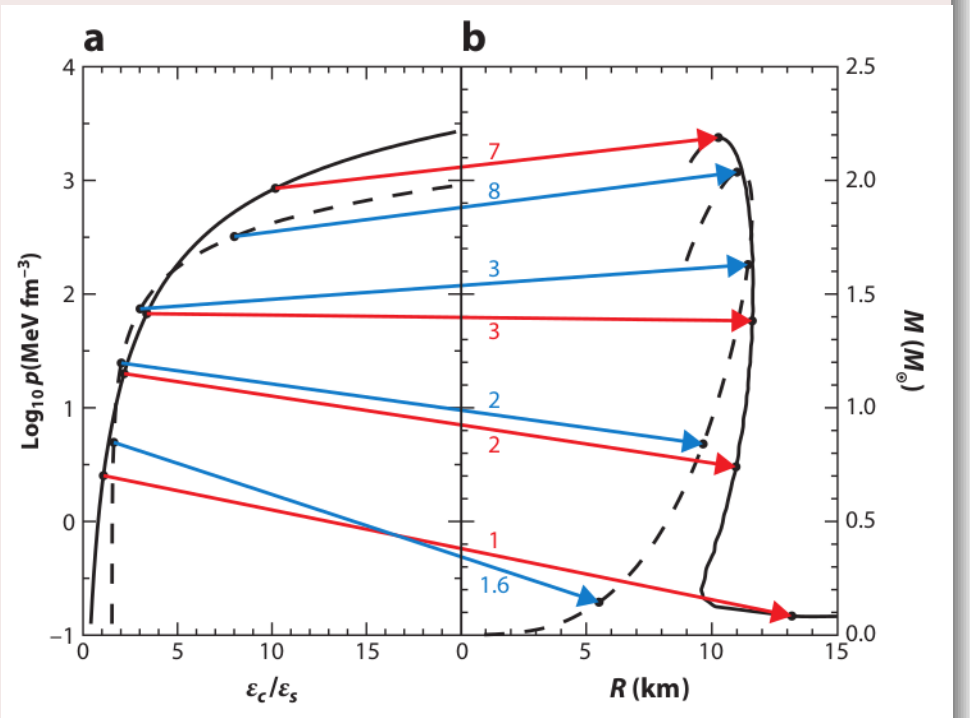
J. Lattimer, ARNPS 62, 485–515 (2012)



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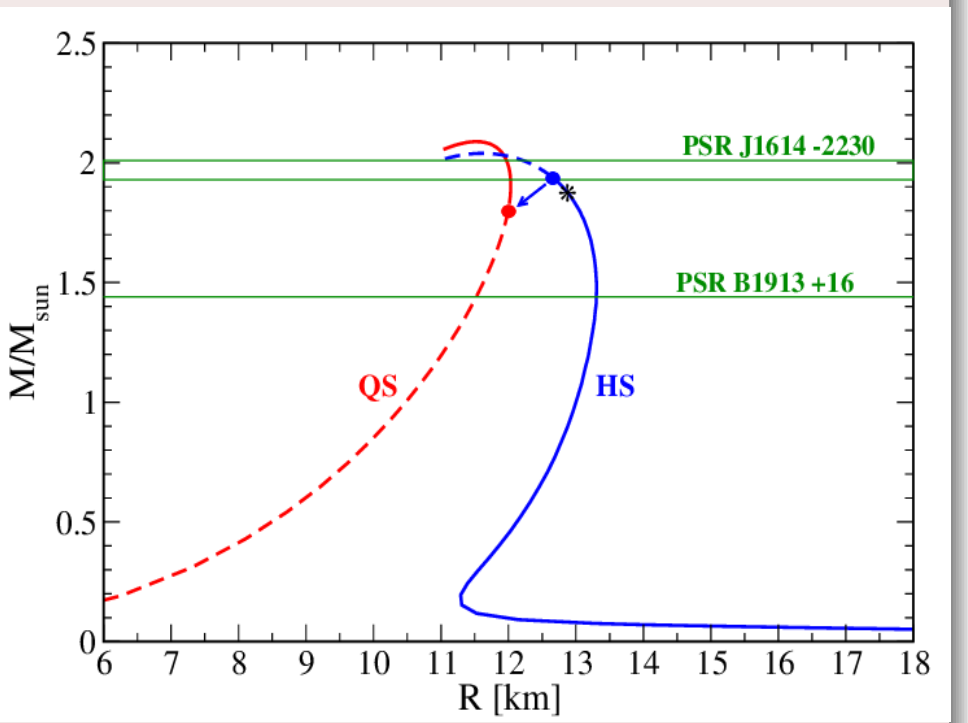

I. Bombaci, conference paper

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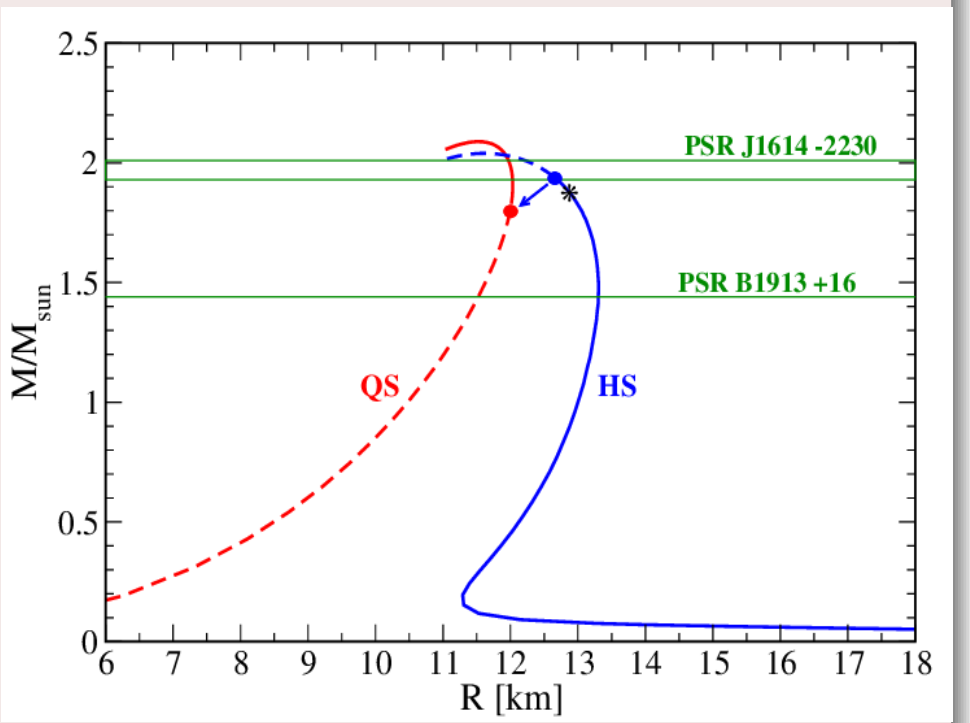

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Proposition

- **Can we predict the composition of the Neutron star matter?**

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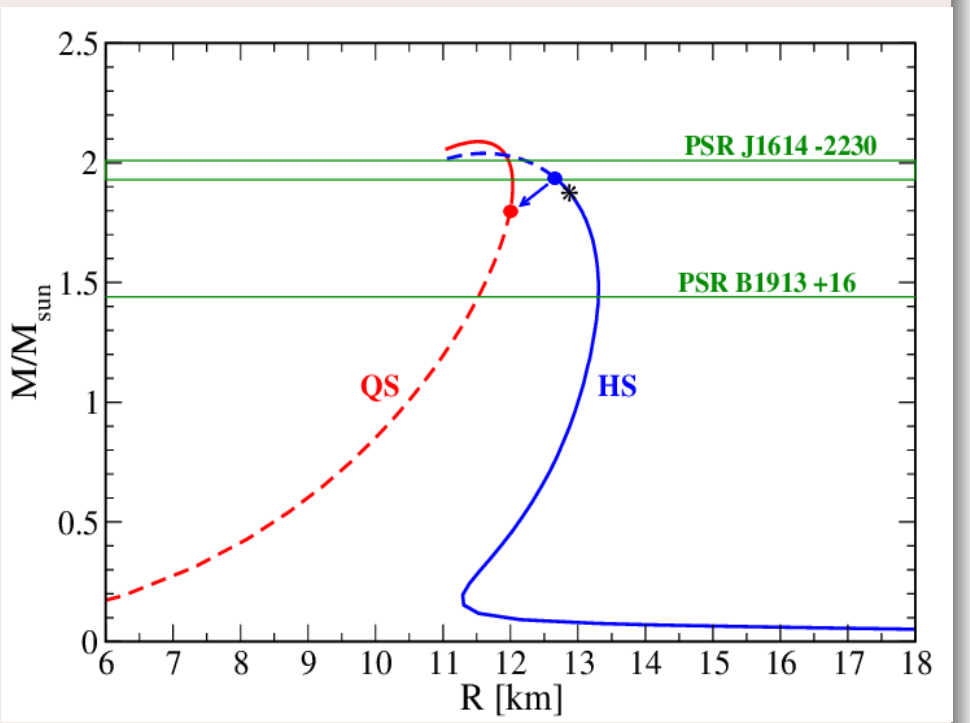


I. Bombaci, conference paper

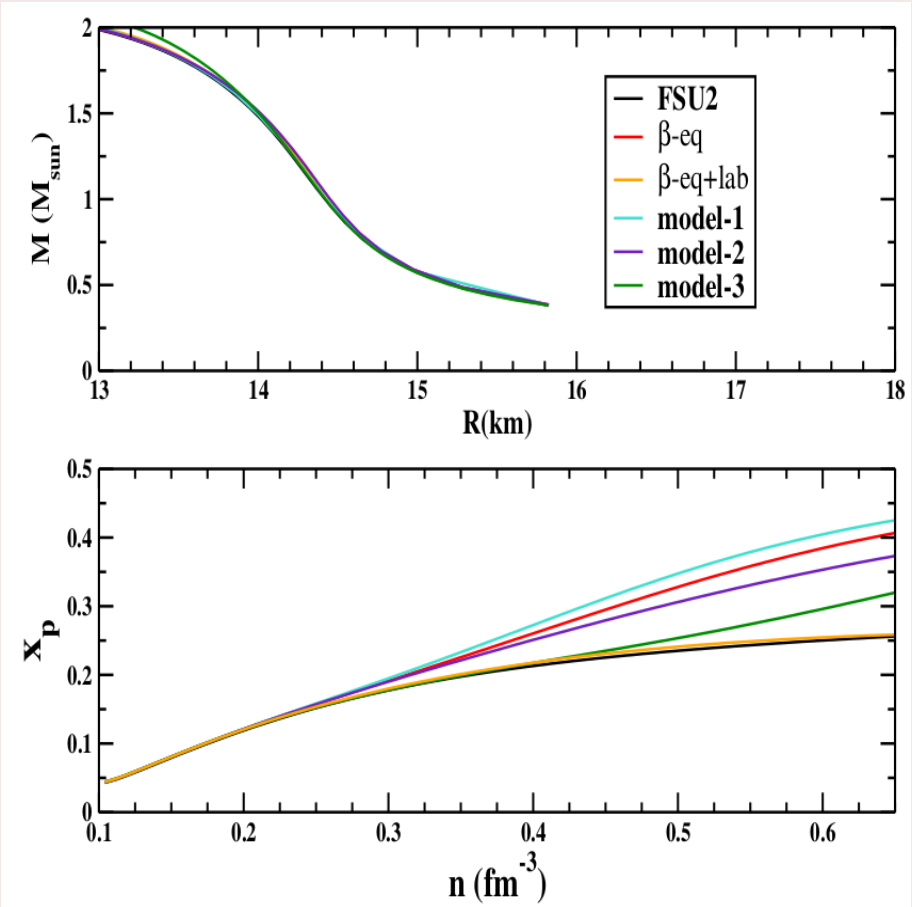
Proposition

- Can we predict the composition of the Neutron star matter?
- We propose a problem of reverse engineering!!

Masquerading in nucleonic hypothesis

FSU2 case

CM, FG Phys.Rev.D 105, 083016 (2022)



The masquerade

- Same in M-R, different in proton fraction x_p.

Possible solution to the Masquerading

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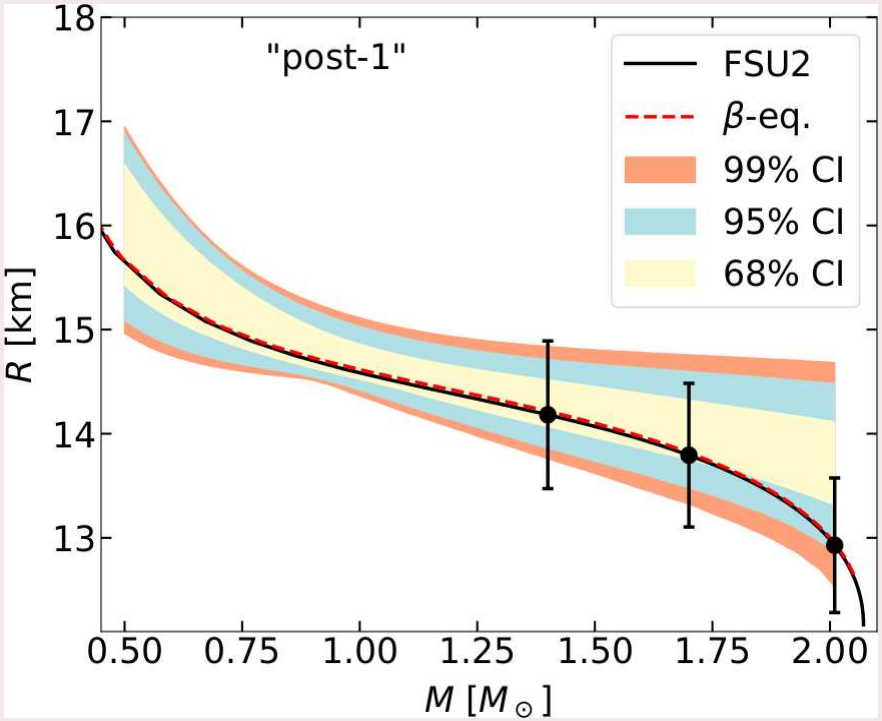
M-R relation

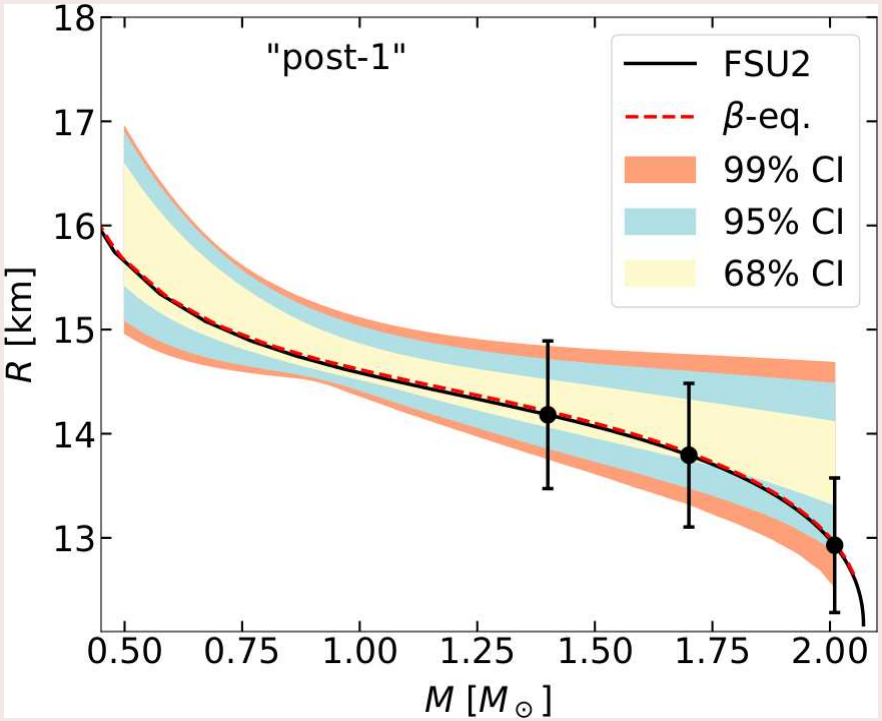


CM, F. Gulminelli, Phys. Rev. D 105, 083016 (2022).

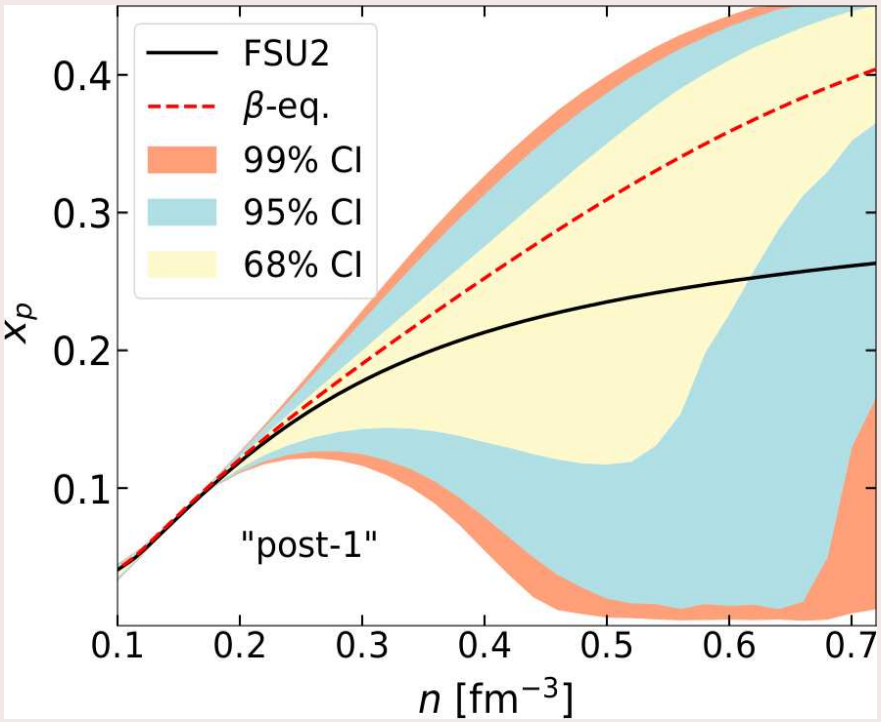
Possible solution to the Masquerading

Laboratory data

M-R relation



Proton fraction x_p



CM, F. Gulminelli, Phys. Rev. D 105, 083016 (2022).

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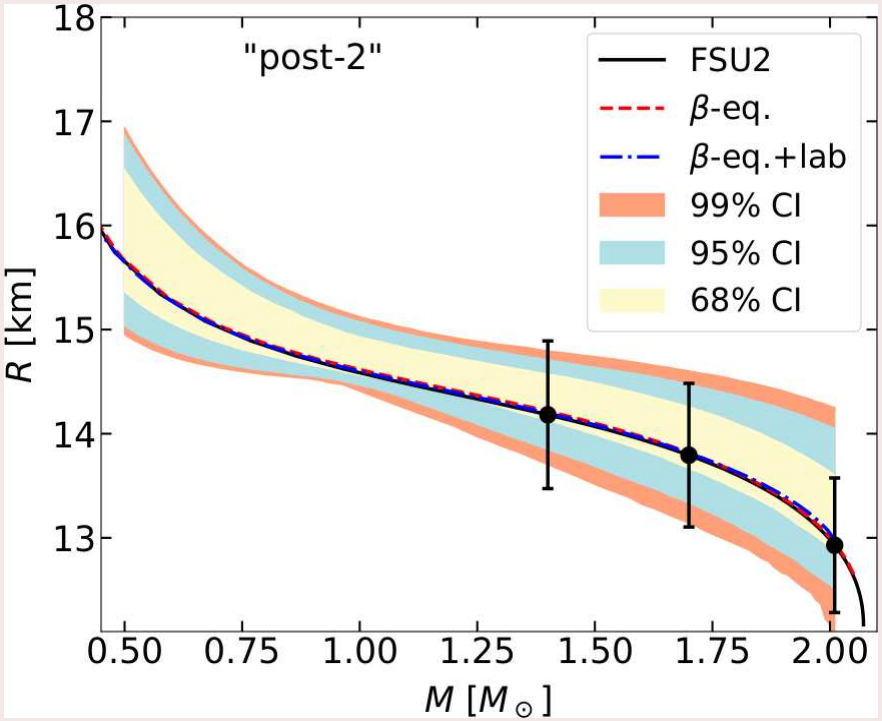
Laboratory data

M-R relation + SNM



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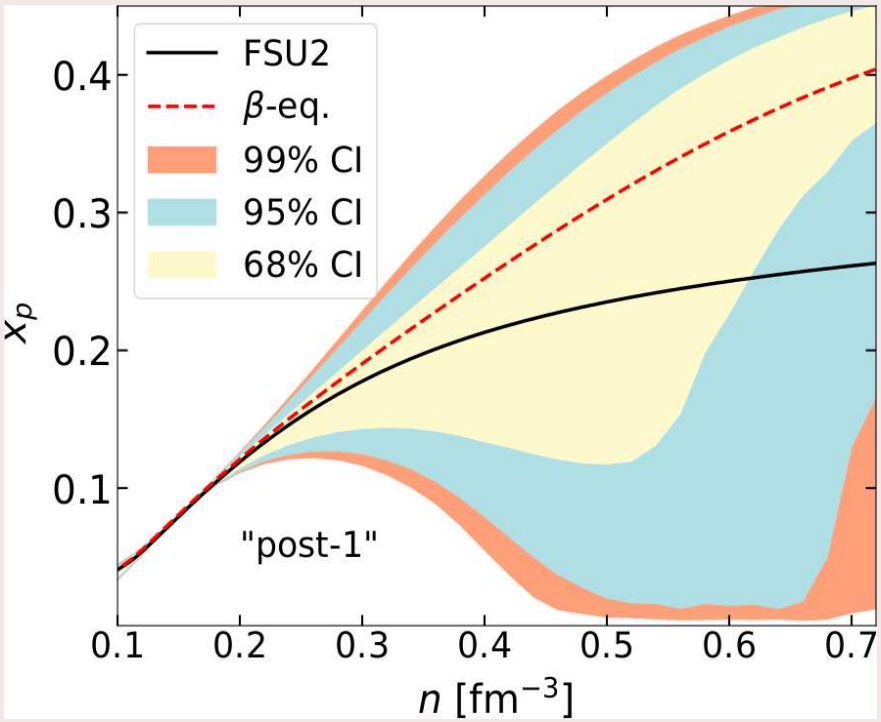

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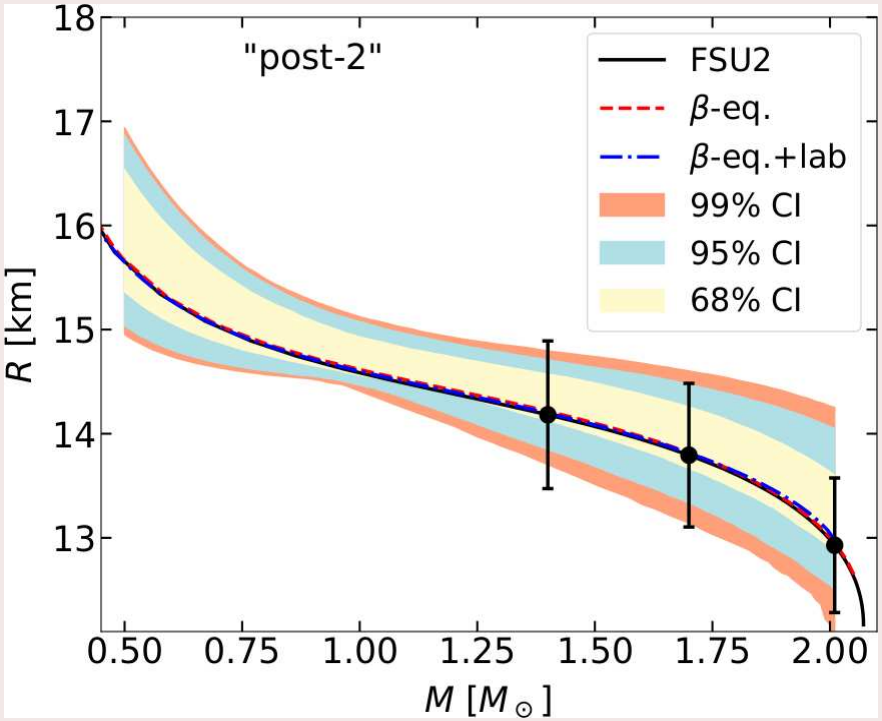
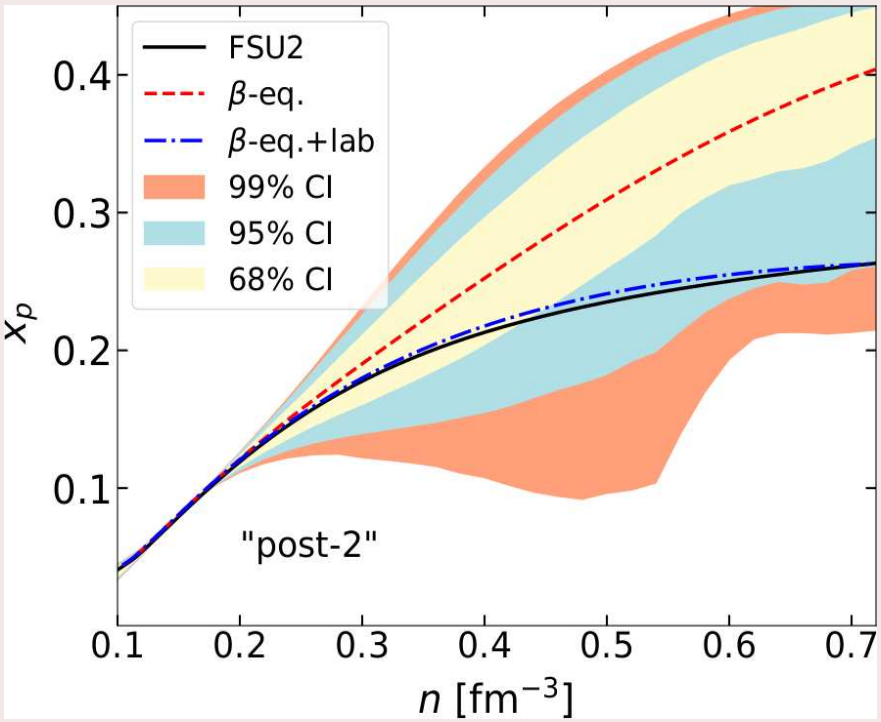
Laboratory data

M-R relation + SNM



Proton fraction x_p

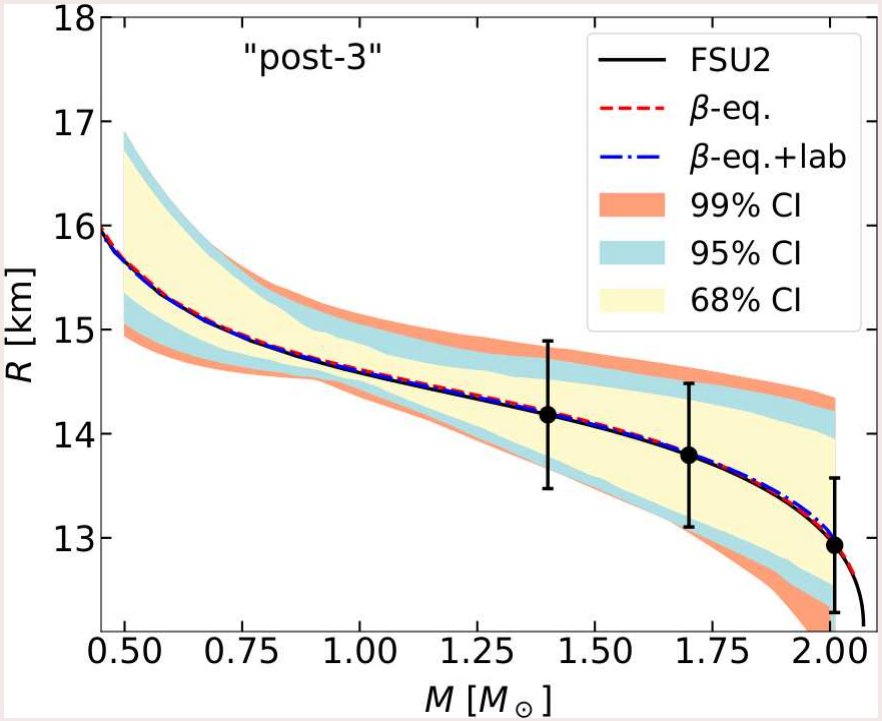


CM, F. Gulminelli, Phys. Rev. D 105, 083016 (2022).

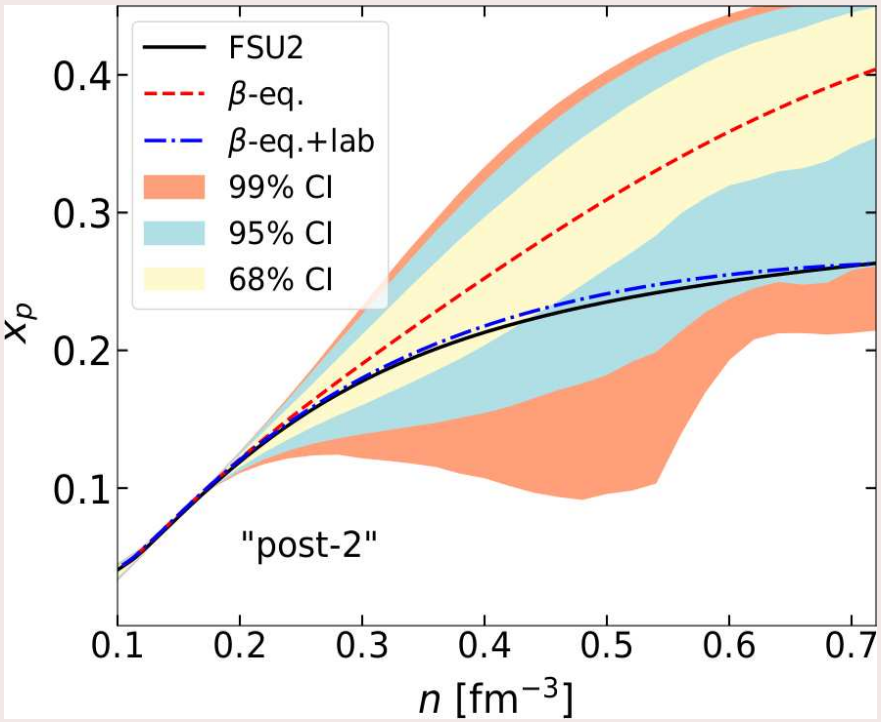
Possible solution to the Masquerading

Laboratory data

M-R relation + SNM + Symm Ener



Proton fraction x_p



CM, F. Gulminelli, Phys. Rev. D 105, 083016 (2022).

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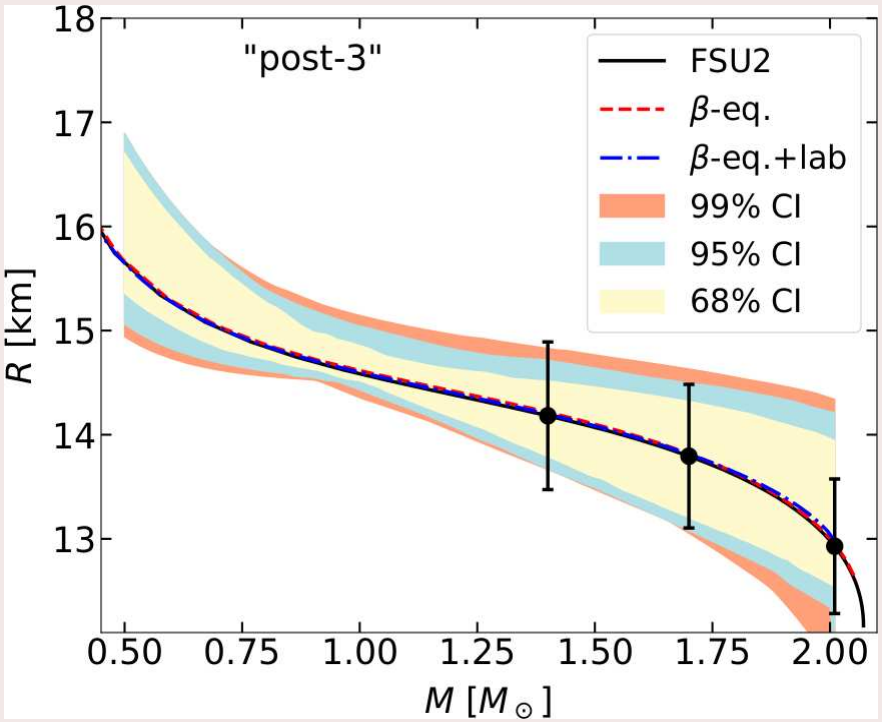
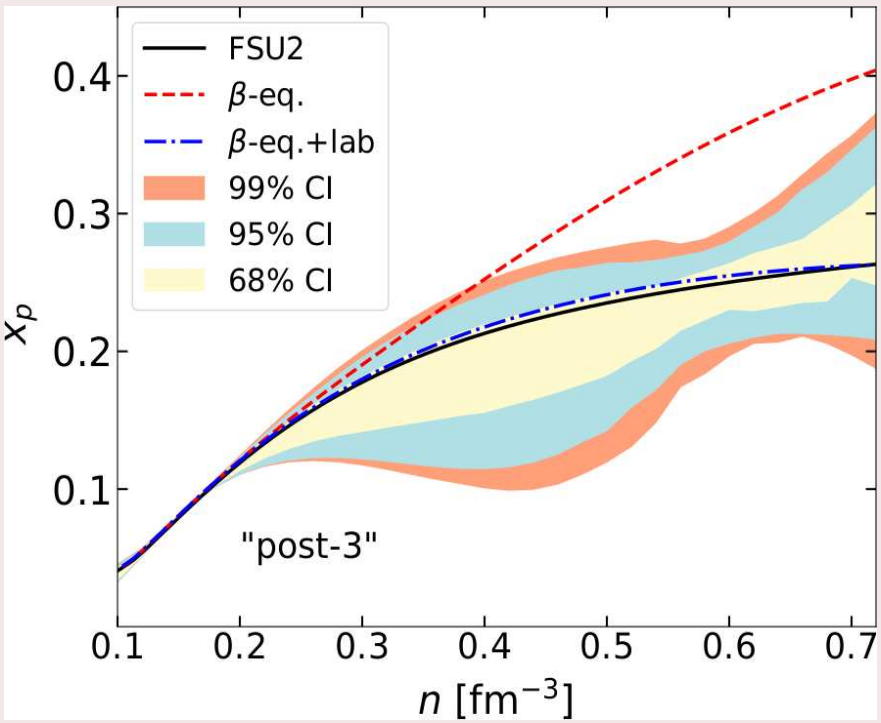


Proton fraction x_p



CM, F. Gulminelli, Phys. Rev. D 105, 083016 (2022).

Collaborators

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- Jadunath De
- Santosh Samaddar
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Remarks and Outlook:

- We have established a semi-agnostic approach that handles nuclear physics and astrophysics constraints at the same footing.
- We obtained a null hypothesis to look for exotic matter. All present constraints can be satisfied with this purely nucleonic assumption.
- We have observed that extracting information on the core composition would need assistance from the laboratory experiments.
- With upcoming facilities there is possibility to find signatures of deconfined phase transition.