Constraining the dense matter EOS

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Collaborators: Chun Huang, Bikai Gao, Chen Zhang, Enping Zhou, Yan Yan, Renxin Xu et. al.

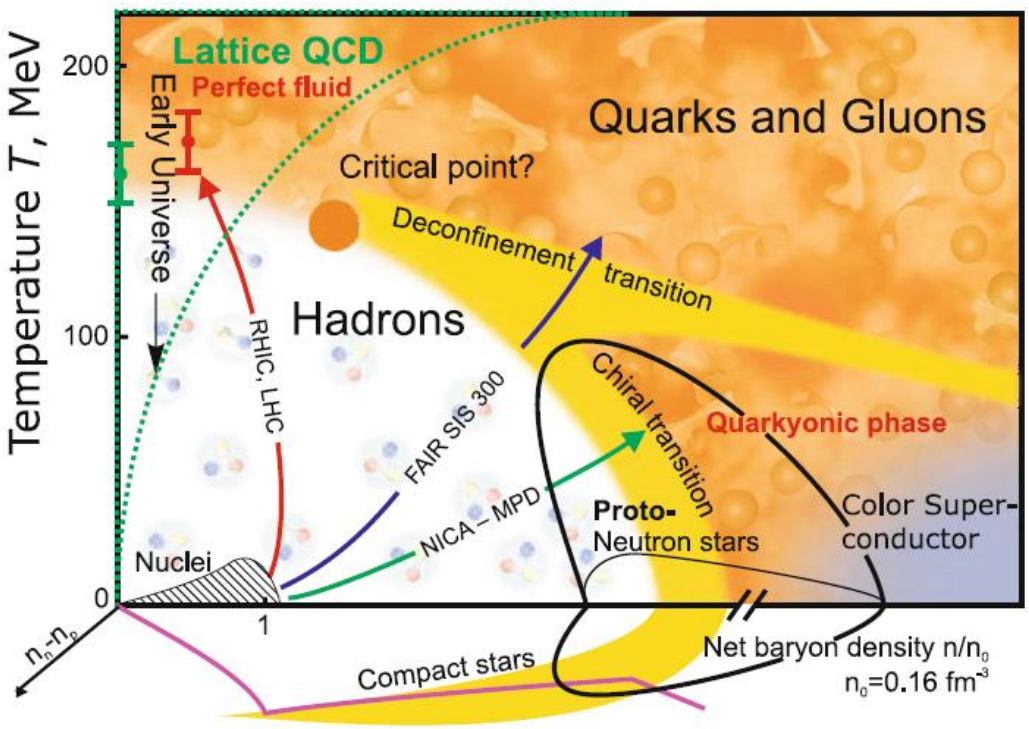
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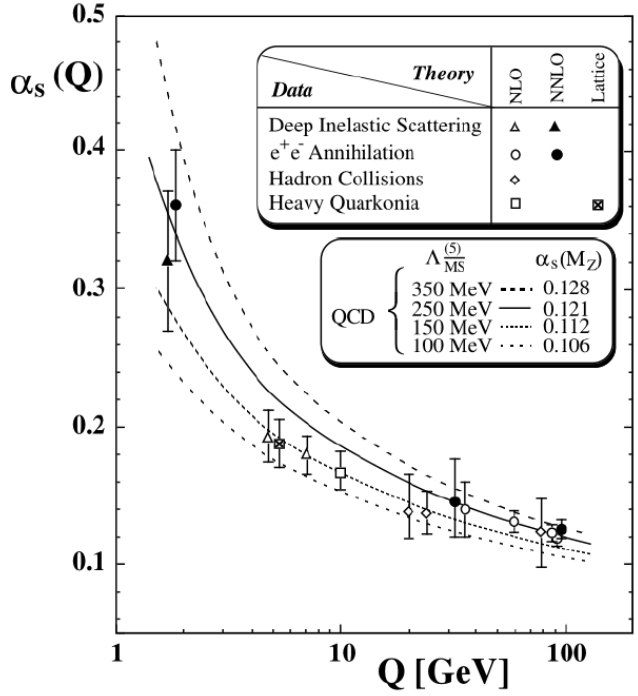
What is the nature of dense matter?

QCD phase diagram

NICA White paper



QCD running coupling





Hadron star: quarks confined *gravity-bound*

Quark star: quarks de-confined *self-bound on surface*

Hybrid/mixed star: quarks de-con./con. *gravity-bound*

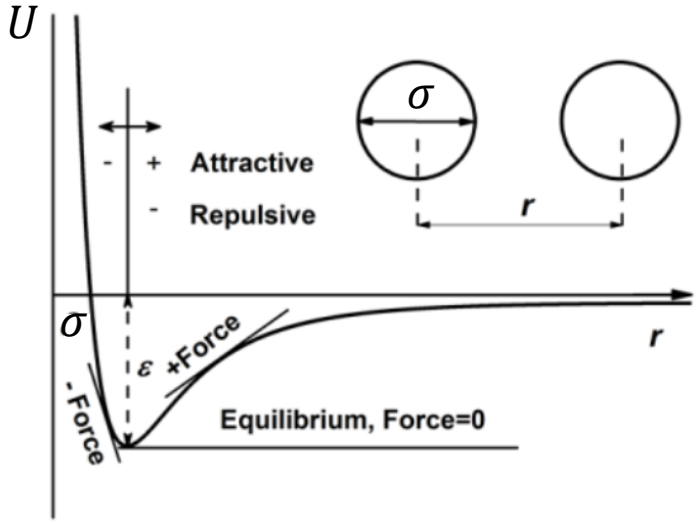
Strangeon star: quarks localized *self-bound on surface*

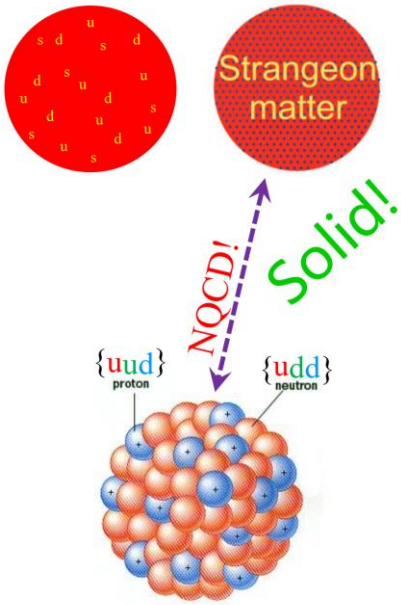
Lai Xiaoyu and Xu Renxin 2017

Strangeon matter EOS and Bayes theorem

Lennard-Jones potential:

$$U(r) = 4\epsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$





Credit Renxin Xu

Strangeon matter equation of state (EOS):

Three-parameter model: $(N_q, \varepsilon, n_{sur})$

X. Y. Lai and R. X. Xu (2009)

$$\rho = \frac{1}{9}\epsilon\frac{A_6^2}{A_{12}}\left(\frac{N_{\rm q}{}^4}{18n_{\rm sur}^4}n^5 - \frac{N_{\rm q}^2}{n_{\rm sur}^2}n^3\right) + m_{\rm q}N_{\rm q}n,$$

$$P = \frac{2}{9}\epsilon\frac{A_6^2}{A_{12}}\left(\frac{N_{\rm q}^4}{9n_{\rm sur}^4}n^5 - \frac{N_{\rm q}^2}{n_{\rm sur}^2}n^3\right).$$

Two-parameter model: $(\tilde{\epsilon}, \bar{n})$

C. Zhang, Y. Gao, C. J. Xia, and R. Xu (2023)

$$\frac{\rho}{n_{\rm sur}} = \frac{a}{9}\tilde{\epsilon}\left(\frac{1}{18}\bar{n}^5 - \bar{n}^3\right) + m_{\rm q}\bar{n},$$

$$\frac{P}{n_{\rm sur}} = \frac{2a}{9}\tilde{\epsilon}\left(\frac{1}{9}\bar{n}^5 - \bar{n}^3\right),$$

Astronomical observations:

GW170817 (the 'golden' event)

- PSR J0030+0451

$M = 1.44^{+0.15}_{-0.14} M_\odot$, $R = 13.02^{+1.24}_{-1.06}$ km (Miller et al. 2019)

$M = 1.34^{+0.15}_{-0.16} M_\odot$, $R = 12.71^{+1.14}_{-1.19}$ km (Riley et al. 2019)

- PSR J0740+6620

(currently most massive NS)

$M = 2.062^{+0.090}_{-0.091} M_\odot$, $R = 13.71^{+2.61}_{-1.50}$ km (Miller et al. 2021)

$M = 2.072^{+0.067}_{-0.066} M_\odot$, $R = 12.39^{+1.30}_{-0.98}$ km (Riley et al. 2021)

- **PSR J0437-4715 new measurement 2024**

(the brightest rotation-powered millisecond x-ray pulsar)

$M = 1.418 \pm 0.037\ M_\odot$, $R = 11.36^{+0.95}_{-0.63}$ km

- GW190814 mass gap

$2.59^{+0.08}_{-0.09} M_\odot$

the likelihood function of the data

the prior probability of the parameter set

the posterior distribution of a set of model parameters

$$p(\boldsymbol{\theta}|\boldsymbol{d}, \mathcal{M}) = \frac{p(\boldsymbol{d}|\boldsymbol{\theta}, \mathcal{M})\, p(\boldsymbol{\theta}|\mathcal{M})}{p(\boldsymbol{d}|\mathcal{M})}$$

- **How can astronomical observations help us constrain this unclear parameter?**
- **Can the dimensionality of the model's degrees of freedom affect the result?**

Choice of priors for model parameters:

Three-parameter model: $(N_q, \varepsilon, n_{sur})$ (PSR J0030 + 0451 and PSR J0740 + 6620)

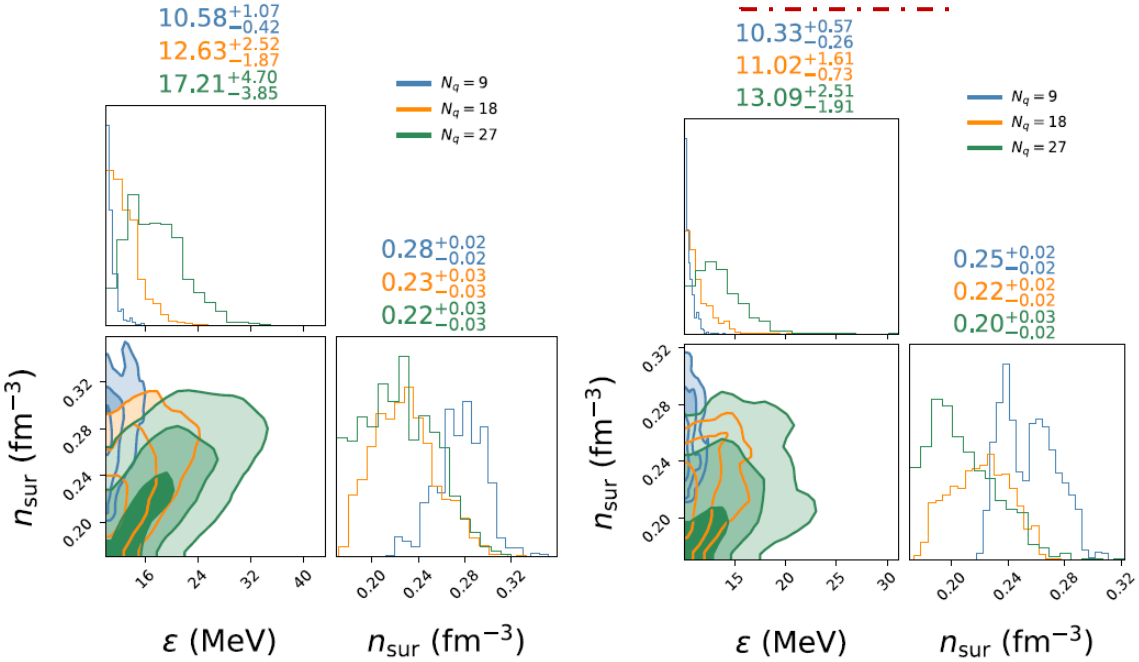
N_q: 9, 18, 21, 24, 27 (satisfy the color neutrality requirement)

ε: 10-170 MeV (nucleon-nucleon scattering data)

n_{sur}: 1 n_0-2.25 n_0 (self-bound property)

TABLE I. The Bayesian evidence with and without PSR J0437-4715 for different N_q. The N_q^* denotes the relatively supported EOS parameter by comparing the Bayes factor with the analysis under identical observational data, which will be discussed in detail below.

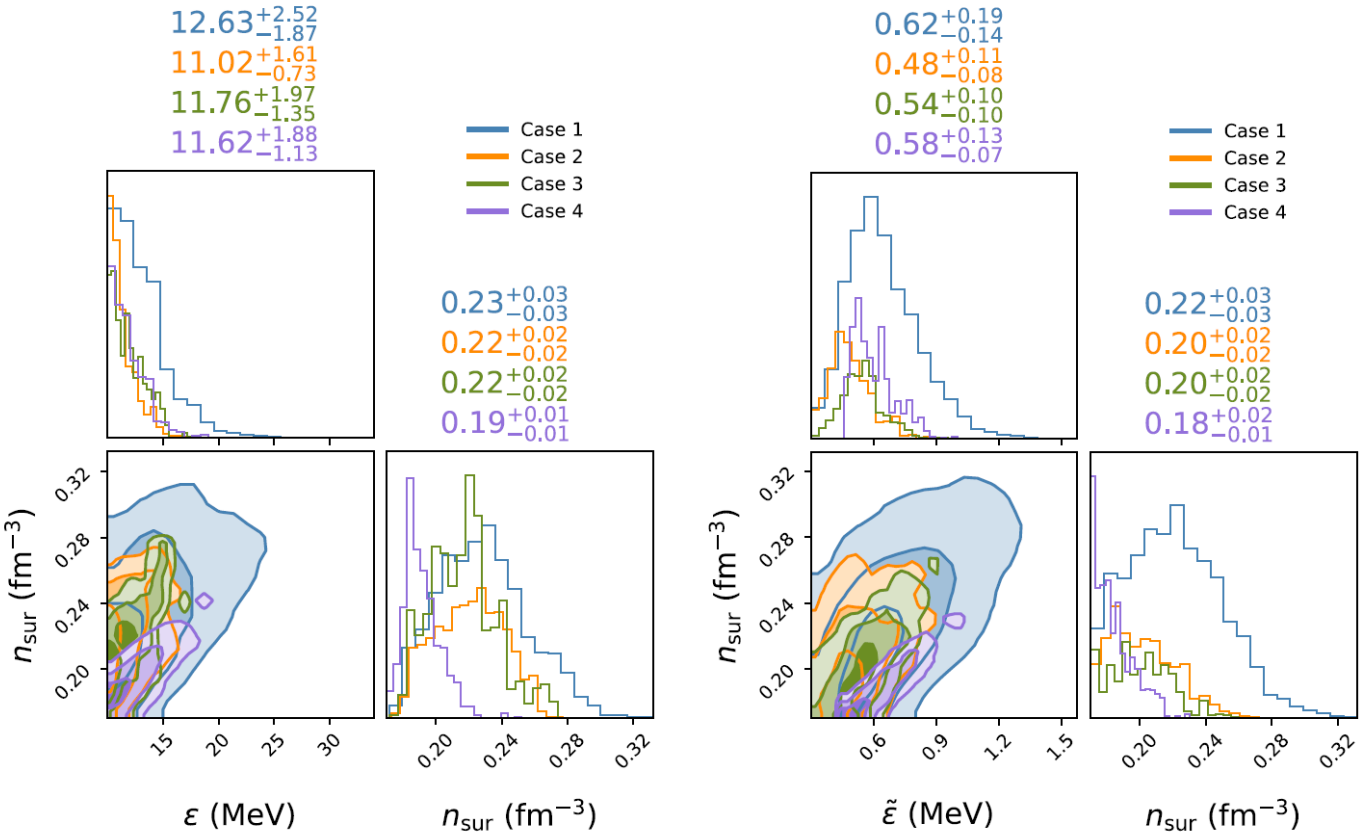
Evidence	Three-parameter model	$N_q = 9$	$N_q^* = 18$	$N_q = 24$	$N_q = 27$
Log Z	without PSR J0437-4715	−34.4	−29.8	−28.9	−29.0
Log Z	with PSR J0437-4715	−48.1	−36.7	−37.5	−36.0



The statistical evidence favors the $N_q = 18$ model for the strangeon matter, a strangeon consisting of 18 quarks, which is completely symmetric in spin, flavor, and color spaces.

Three-parameter model: $(N_q, \varepsilon, n_{sur})$

Two-parameter model: $(\widetilde{\epsilon}, \overline{n})$

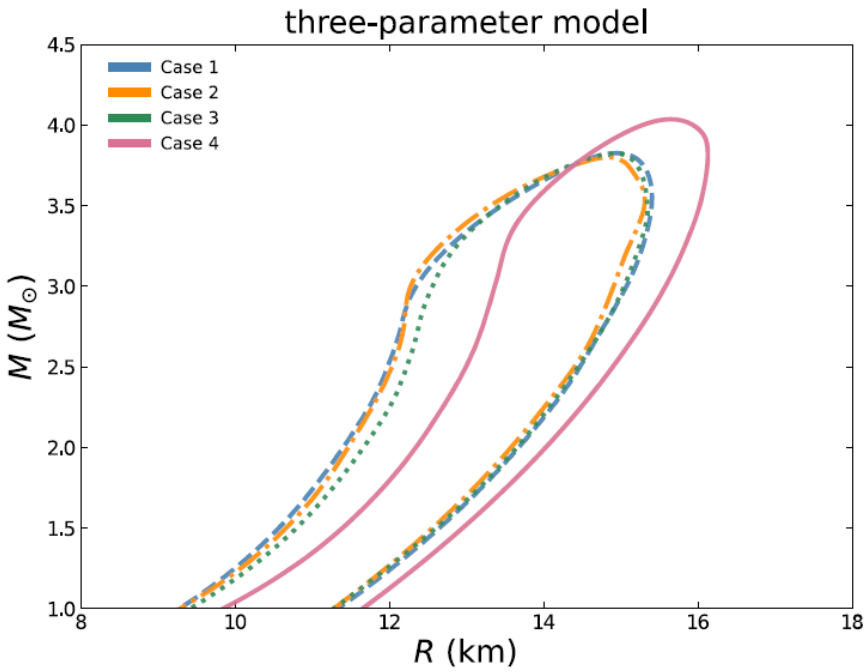


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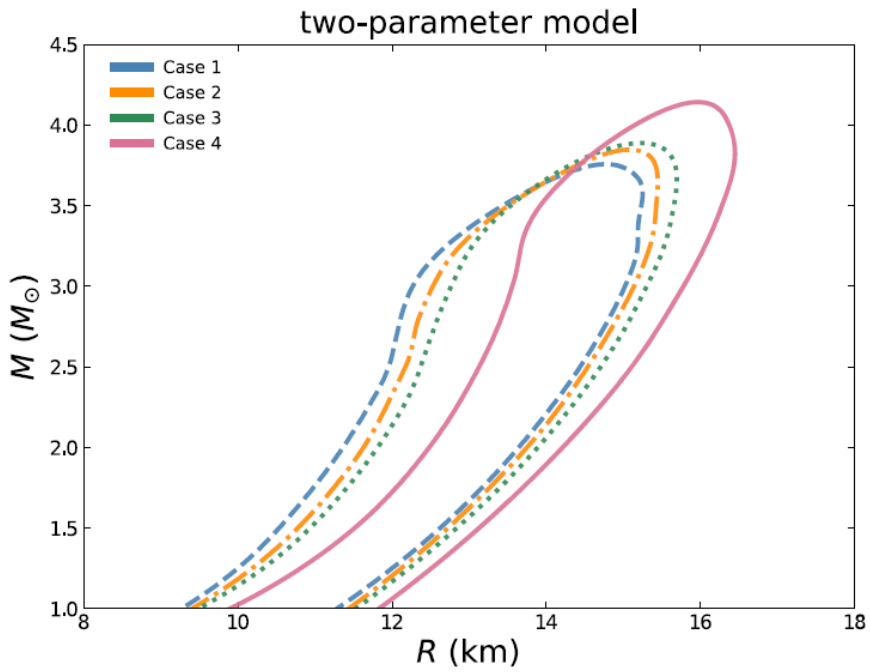


FIG. 4. The M-R posterior distributions at 90% confidence level resulting from the three-parameter and two-parameter models.

$N_q = 18$

https://chunhuangphy.github.io/CompactObject/

CompactObject

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Usage of download_compose Module

Unit Convention for Developer

MCMC INFERENCE WORKFLOW

RMF EOS emcee workflow

CompactObject

An Open-Source Package for Neutron Stars Comprehensive Workflow for Bayesian Inference Constraining Neutron Star EOS Package

CompactObject is an open-source package designed to perform Bayesian inference on neutron star equation of state (EOS) constraints. It offers a comprehensive workflow that integrates astrophysical observations and nuclear measurements to explore the interior composition of neutron stars. The package is built to be user-friendly, easily extendable, and thoroughly documented, making it an essential tool for researchers in nuclear astrophysics. The package integrates three independent modules:

1. **Tolman–Oppenheimer–Volkoff (TOV) Equation Solver** A user-friendly solver for determining neutron star structure based on a given EOS.
2. **Neutron Star EOS Generator** Generates EOS across the full density range. Currently, it includes the relativistic mean field theory EOS solver and will support polytropes and additional EOS models in the future.
3. **Bayesian Inference Workflow** A complete package for constraining the EOS of neutron stars. This includes defining the likelihood from observations (X-ray timing, gravitational waves, radio timing) and nuclear experiments (nuclear quantities, pQCD, chiral EFT), as well as from simulated astrophysical observations. It also involves defining priors for the parameters and running nested sampling of the posterior space.

These three components are independent, allowing users to integrate them into their workflows seamlessly. The package's functionality extends beyond inference studies, and we welcome contributions of new features.

CompactObject: An open-source Python package for full-scope neutron star equation of state inference

Chun Huang, Tuhin Malik, João Cartaxo, Shashwat Sourav, Wenli Yuan, Tianzhe Zhou, Xuezhi Liu, John Groger, Xieyuan Dong, Nicole Osborn, Nathan Whitsett, Zhiheng Wang, Constança Providência, Micaela Oertel, Alexander Y. Chen, Laura Tolos, Anna Watts

The CompactObject package is an open-source software framework developed to constrain the neutron star equation of state (EOS) through Bayesian statistical inference. It integrates astrophysical observational constraints from X-ray timing, gravitational wave events, and radio measurements, as well as nuclear experimental constraints derived from perturbative Quantum Chromodynamics (pQCD) and Chiral Effective Field Theory (χEFT). The package supports a diverse range of EOS models, including meta-model like and several physics-motivated EOS models. It comprises three independent components: an EOS generator module that currently provides seven EOS choices, a Tolman-Oppenheimer-Volkoff (TOV) equation solver, that allows the determination of the Mass Radius and Tidal deformability as observables, and a comprehensive Bayesian inference workflow module, including a complete pipeline for implementing EOS Bayesian inference. Each component can be used independently in different scientific research contexts, such as nuclear physics and astrophysics. In addition, CompactObject is designed to work in synergy with existing software such as CompOSE, allowing the use of the CompOSE EOS database to extend the EOS options available.

https://chunhuangphy.github.io/CompactObject/

arXiv:2411.14615 (Submitted to JOSS 2025)



Hybrid stars with large quark cores

Theoretical method

arXiv: 2502.17859 (PRD accepted)

We are currently unable to describe the hadronic phase and the quark phase in a unified theoretical model from a first-principle approach.



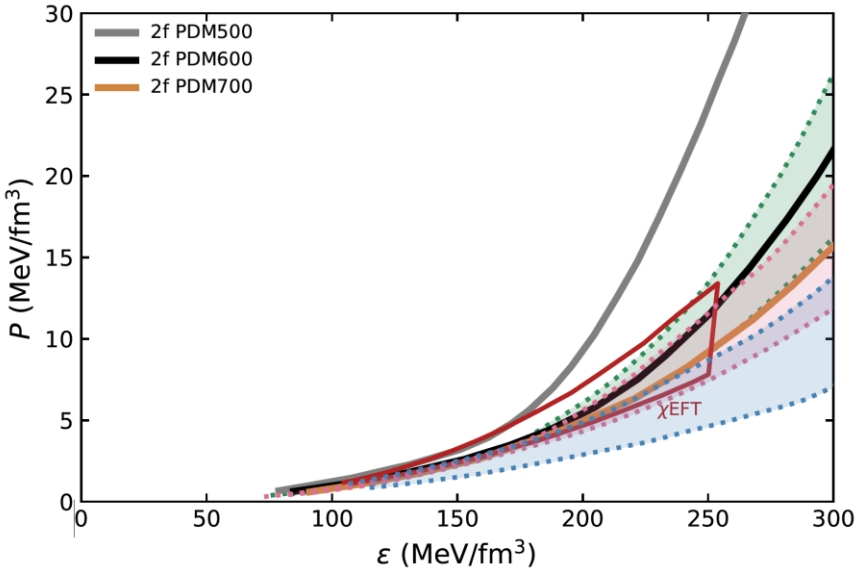
Although unified model is not yet available from a first-principle approach, **effective models that incorporate key aspects of QCD, such as chiral symmetry, provide a viable alternative.**

Quark phase: We use Nambu-Jona-Lasinio (NJL) model, which effectively captures the dynamics of spontaneous chiral symmetry breaking of QCD, successfully reproduces the spectrum of low-lying mesons. This model has been widely used and extended to describe the quark matter in compact star physics.

Hadronic phase: It is desirable to have a Lagrangian for the hadronic phase which also respects chiral symmetry. Then, the parity doublet model (PDM) is particularly well-suited for this purpose!

Pressures as functions of baryon chemical potential for hadronic matter and quark matter.
We also compare the EOS derived from PDM and predicted from χEFT.

Incorporating the details of the microscopic physics within our models result in different behaviors in the $P(\mu_B)$ intersections.



Hybrid stars with large quark cores

Theoretical method

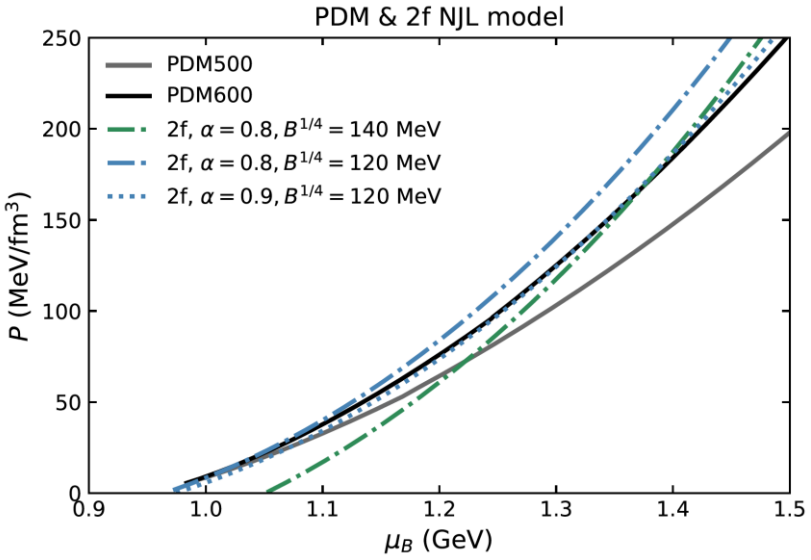
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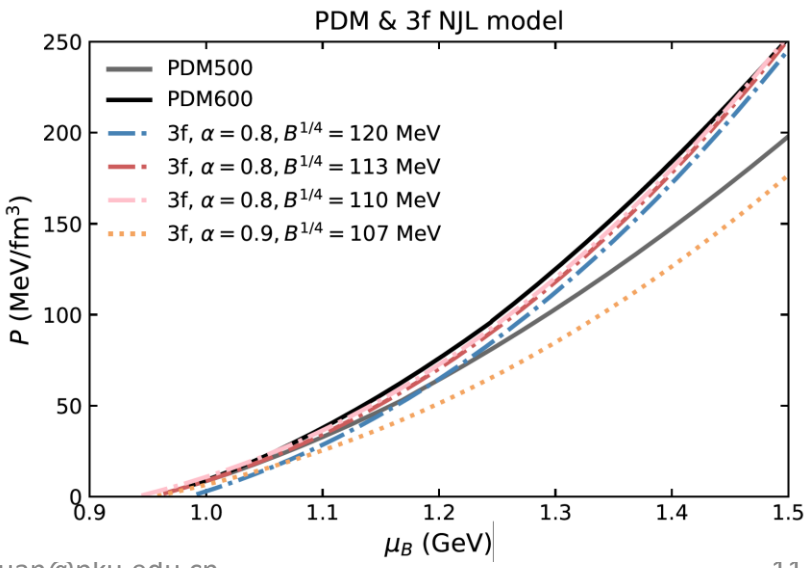


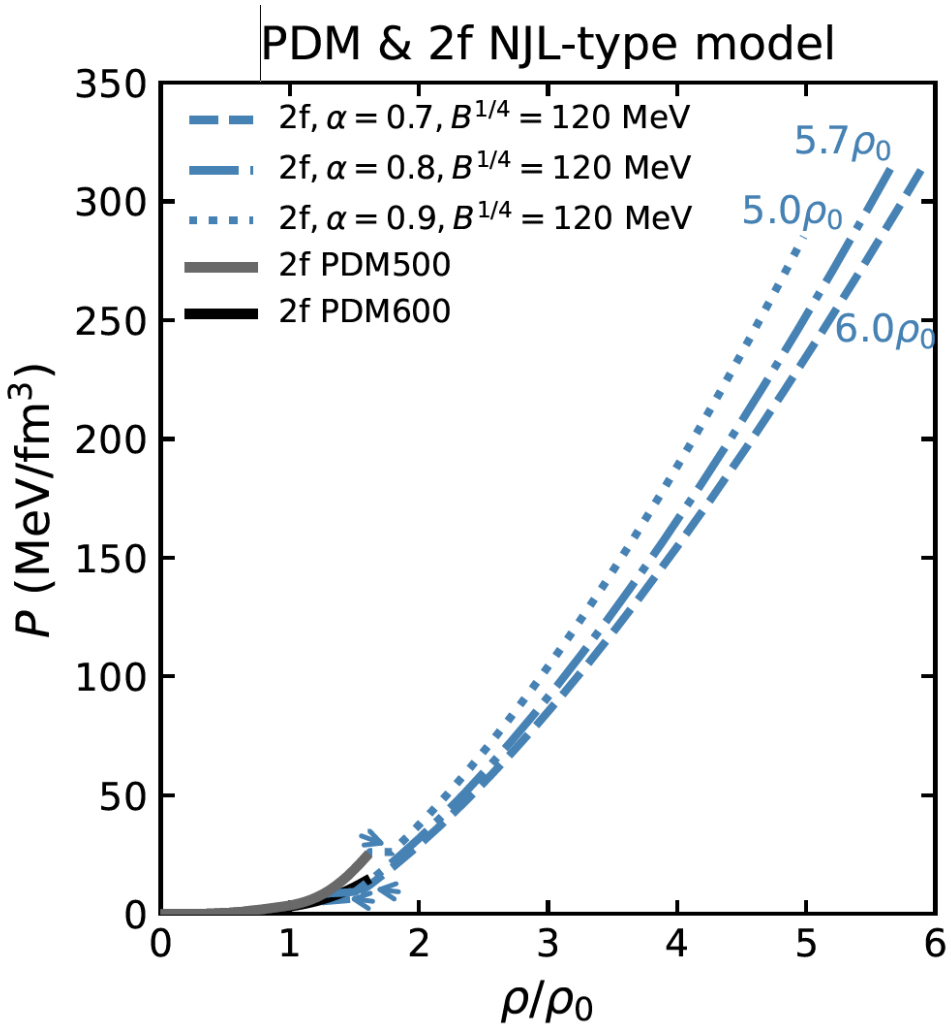
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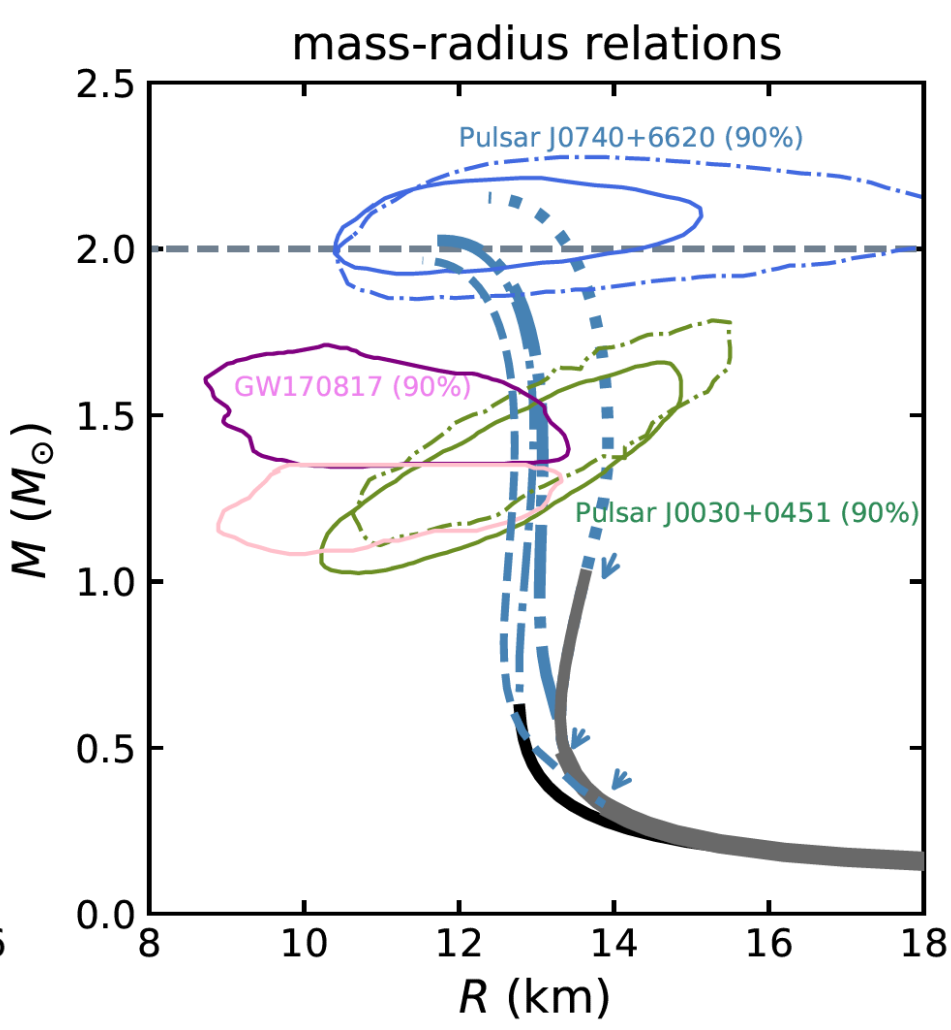
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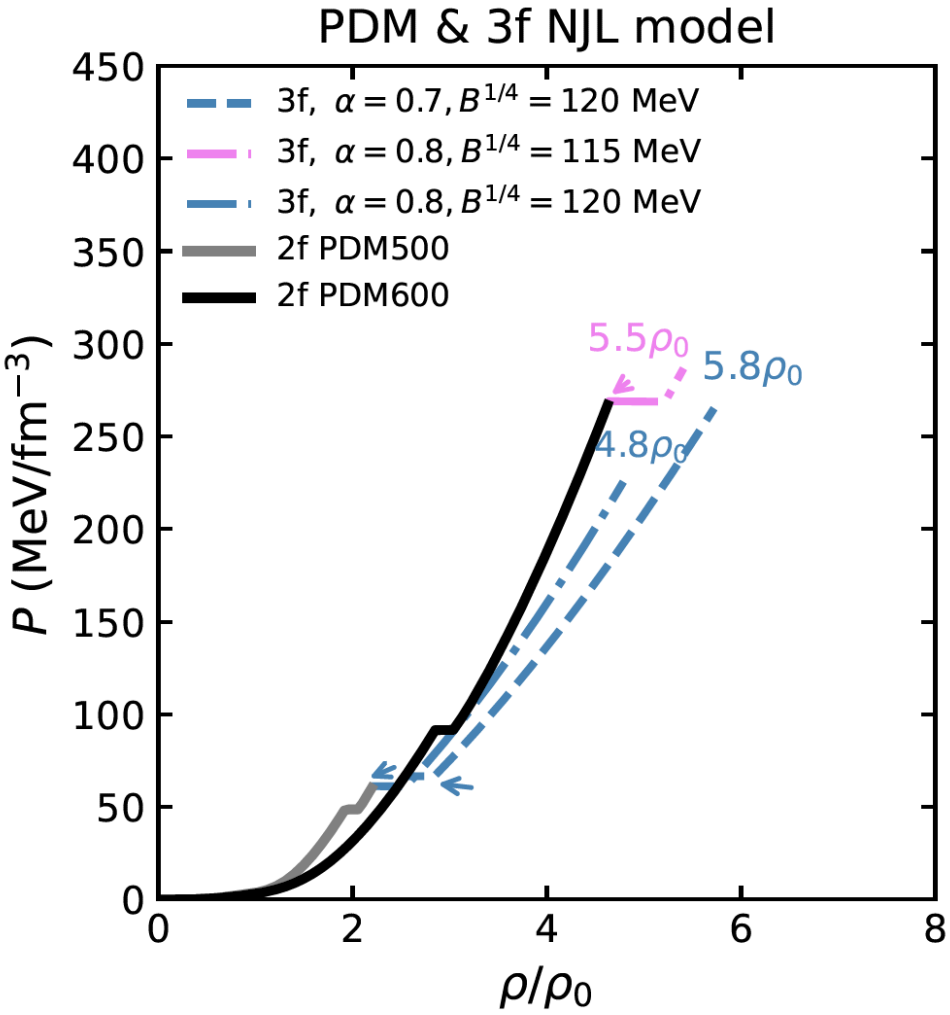
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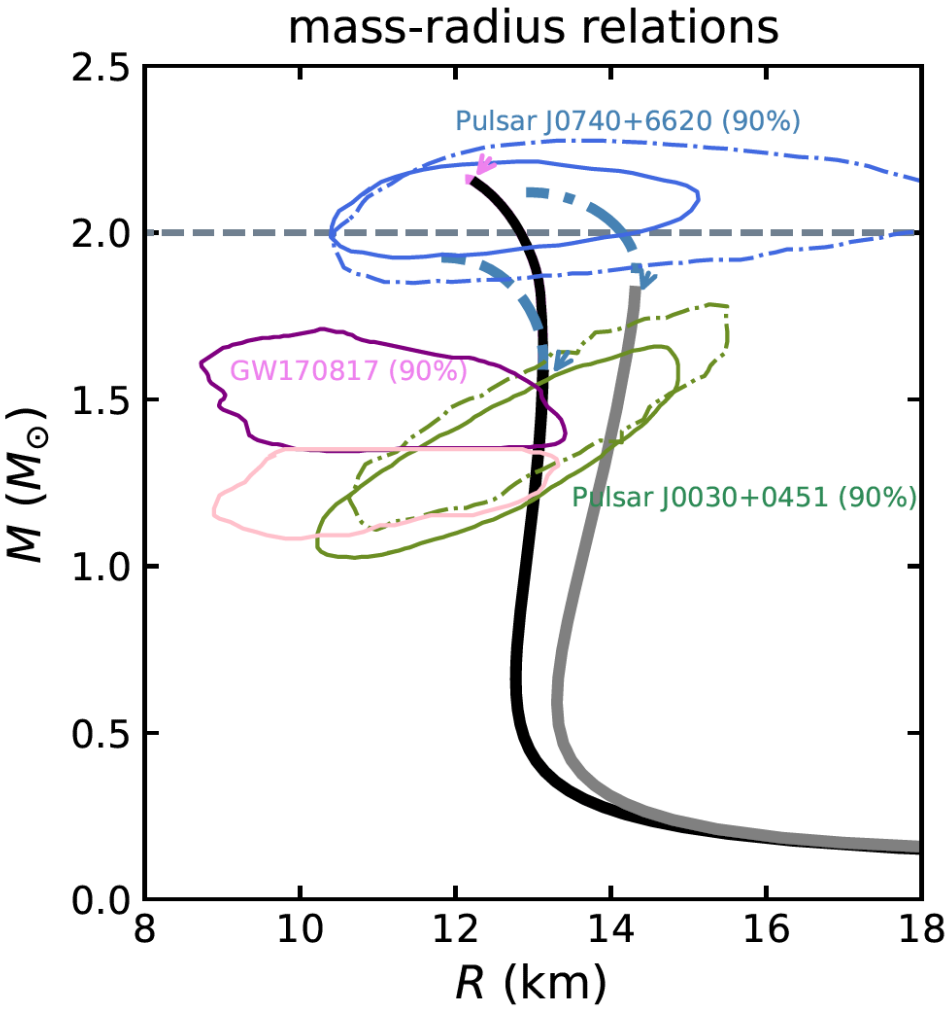





PDM & 2f NJL-type model
2f, $\alpha = 0.7, B^{1/4} = 120$ MeV
2f, $\alpha = 0.8, B^{1/4} = 120$ MeV
2f, $\alpha = 0.9, B^{1/4} = 120$ MeV
2f PDM500
2f PDM600
$5.7\rho_0$
$5.0\rho_0$
$6.0\rho_0$
P (MeV/fm^3)
ρ/ρ_0


mass-radius relations
Pulsar J0740+6620 (90%)
GW170817 (90%)
Pulsar J0030+0451 (90%)
M ($M_\odot$)
R (km)


PDM & 3f NJL model
3f, $\alpha = 0.7, B^{1/4} = 120$ MeV
3f, $\alpha = 0.8, B^{1/4} = 115$ MeV
3f, $\alpha = 0.8, B^{1/4} = 120$ MeV
2f PDM500
2f PDM600
$5.5\rho_0$
$5.8\rho_0$
$4.8\rho_0$
P (MeV/fm^{-3})
ρ/ρ_0


mass-radius relations
Pulsar J0740+6620 (90%)
GW170817 (90%)
Pulsar J0030+0451 (90%)
M ($M_\odot$)
R (km)

Summary

- Under the prior assumption of a finite number of quarks in a strangeon, Nq, our analysis reveals that current mass-radius measurements favor a larger Nq. Specifically, the results support the scenario where a strangeon forms a stable bound state with Nq=18, symmetric in color, flavor, and spin spaces, with a relatively strong Bayesian evidence.

- The comparative analyses of the posterior EOS parameter spaces derived from the three-parameter model and two-parameter model demonstrate a consistent prediction under identical observational constraints.

- We find stable neutron stars (NSs) with large quark cores within a specific parameter space. Typical NSs with masses around 1.4 solar mass may possess defined quark matter in their centers.

Thank you!