从中子星天文观测到致密物质物态

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2024年11月

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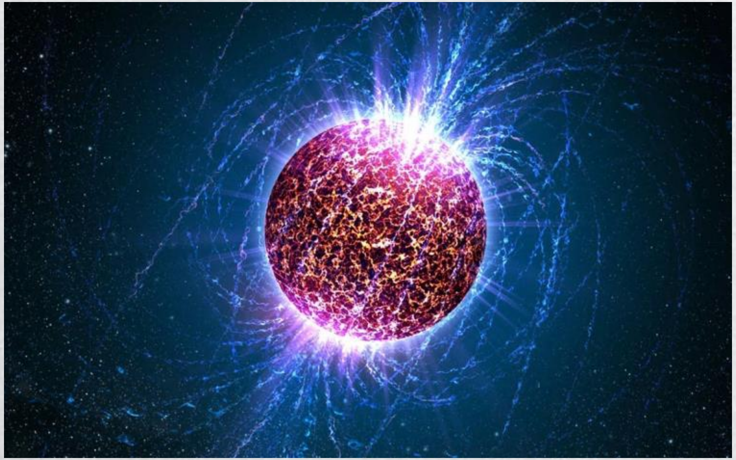
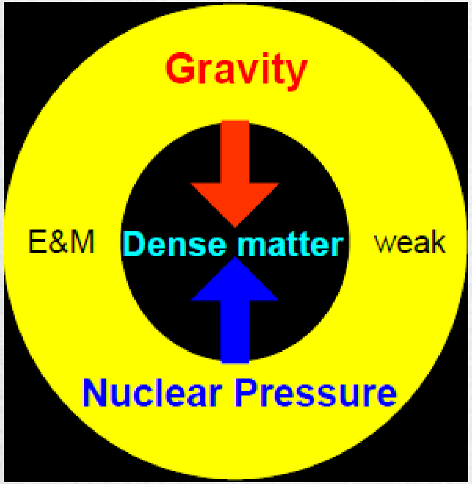
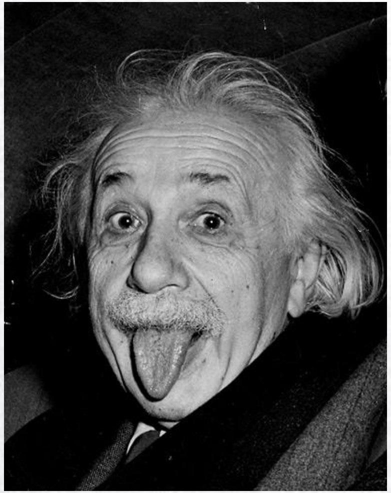
中子星研究概述

➢ Neutron stars are a remarkable marriage of Einstein's theory of general relativity with nuclear physics.



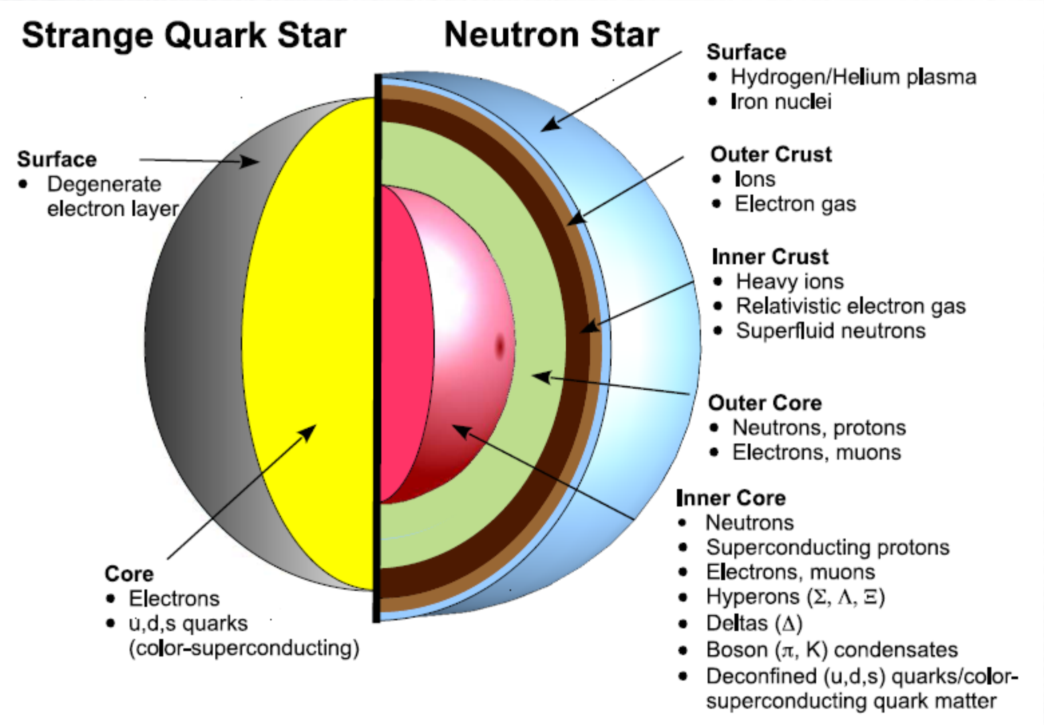




Yunes, N. et al., *Nat Rev Phys* **4**, 237 (2022).

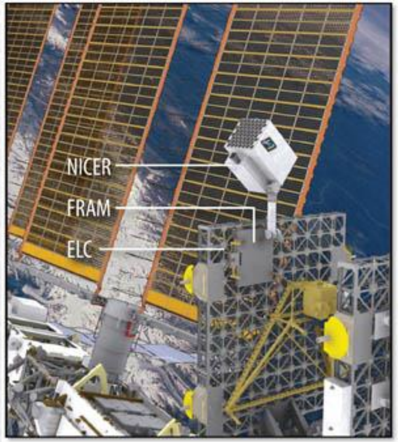
中子星研究概述

- The interiors of neutron star harbor extreme matter that cannot be probed in the laboratory. At such high densities and pressures, their cores may consist predominantly of exotic matter such as free quarks or hyperons.

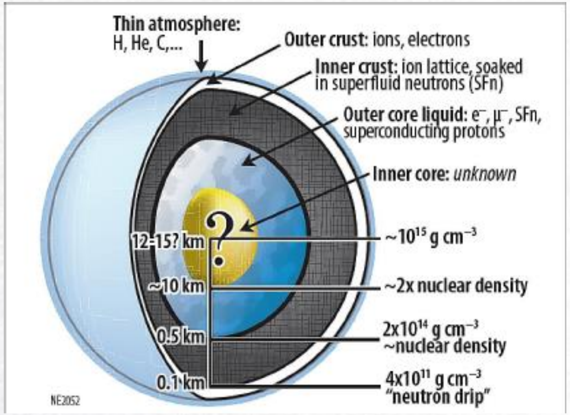


中子星研究概述 observations

- Neutron star observation related installation: Gravitational wave observations from the Laser Interferometer Gravitational-wave Observatory (LIGO), Neutron star observations from Five-hundred-meter Aperture Spherical radio Telescope (FAST), and X-ray observations from the Neutron Star Interior Composition Explorer (NICER), are beginning to run.



中子星研究概述 Structure and Matter



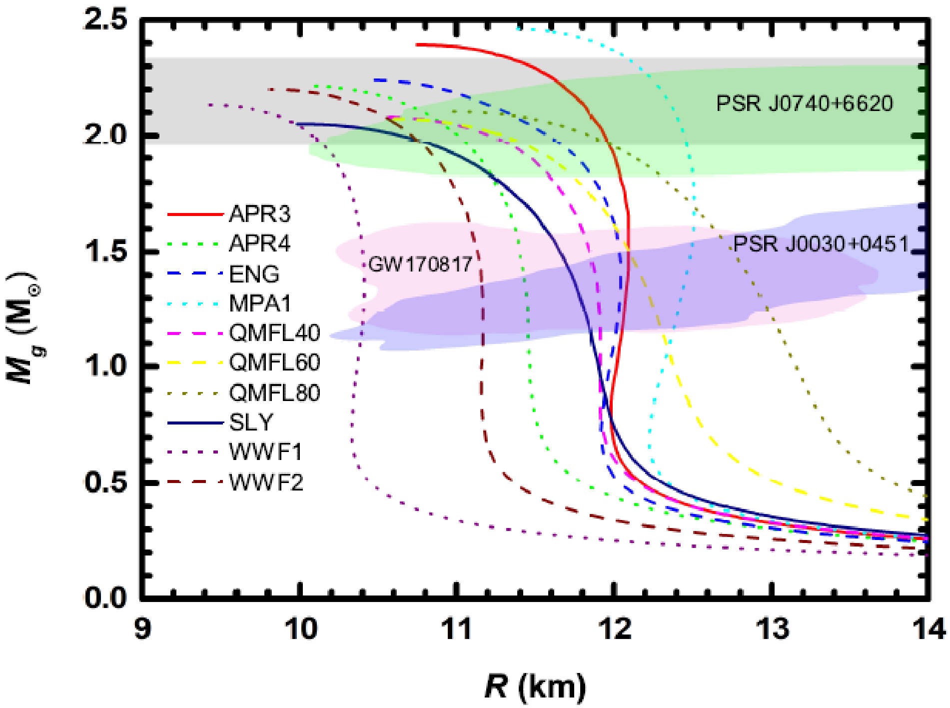
- Atmospheres (only a few centimeters closest to the surface) can have atoms.

- At densities greater than $\sim10^7$g/cm^3, the Fermi energy of electrons becomes high enough that the matter becomes progressively richer in neutrons.

- At densities greater than 4×10^{11}g/cm^3 it becomes possible for neutrons to "drip out" of the nucleus, which means that matter is a mix of free neutrons, free electrons, and nuclei. At about "nuclear saturation density" 2.7×10^{14}g/cm^3, there are no longer any isolated nuclei, and we now have the neutron soup.

- Pushing to yet higher densities, it may be energetically favorable to form other baryons with at least one strange quark, such as hyperons, until eventually close to the center of the star, quarks may become deconfined and one may encounter a degenerate quark-gluon plasma.

中子星研究概述　Observation constraints on the M-R relation



Mass–radius relations, where the gray area denotes the range of maximum mass accurately observed so far. The light red area denotes the marginalized posterior (*M*g, *R*) of the merged binary neutron star released by LIGO and VIRGO collaboration in GW170817. The light blue and green areas denote the marginalized posterior (*M*g, *R*e) released by NICER for PSR J0030 + 0451 and PSR J0740 + 6620, respectively.

Yuxi Li, Jue Wang, Zehan Wu and Dehua Wen Class. Quantum Grav. 39 (2022) 035014

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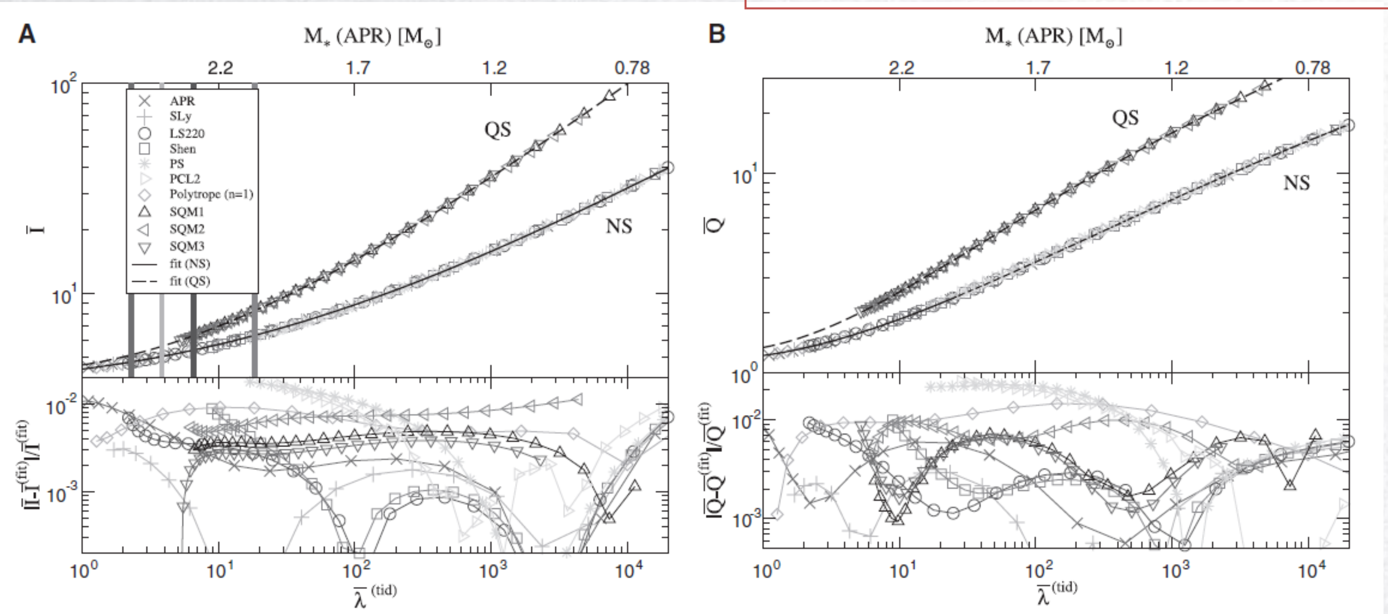
中子星研究概述

Universal relations among neutron star property (such as I-LOVE-Q)

Kent Yagi* and Nicolás Yunes, Science 341, 365 (2013)



- These universal relations can be used to learn about neutron star deformability through observations of the moment of inertia (and vice versa), distinguish neutron stars from quark stars, and test general relativity.

One of the few purely theoretical studies of neutron stars to be published in SCIENCE.

Why do we study the universal relations?

- There is considerable uncertainty in understanding the equation of state for the super dense nuclear matter in neutron stars.

- The universal relation reflects the nature that some relations between the global properties of NS are not dependent on the EOS.

- This relation can be used to constrain the properties that cannot be directly observed (such as the gravitational binding energy) or cannot be accurately observed (such as the radius).

- The universal relation can be further used to constrain the EOS (such as the symmetry energy).

参量之间的关联性

The linear correlation, which reflects the strength of linear correlation between two quantities, can be expressed as

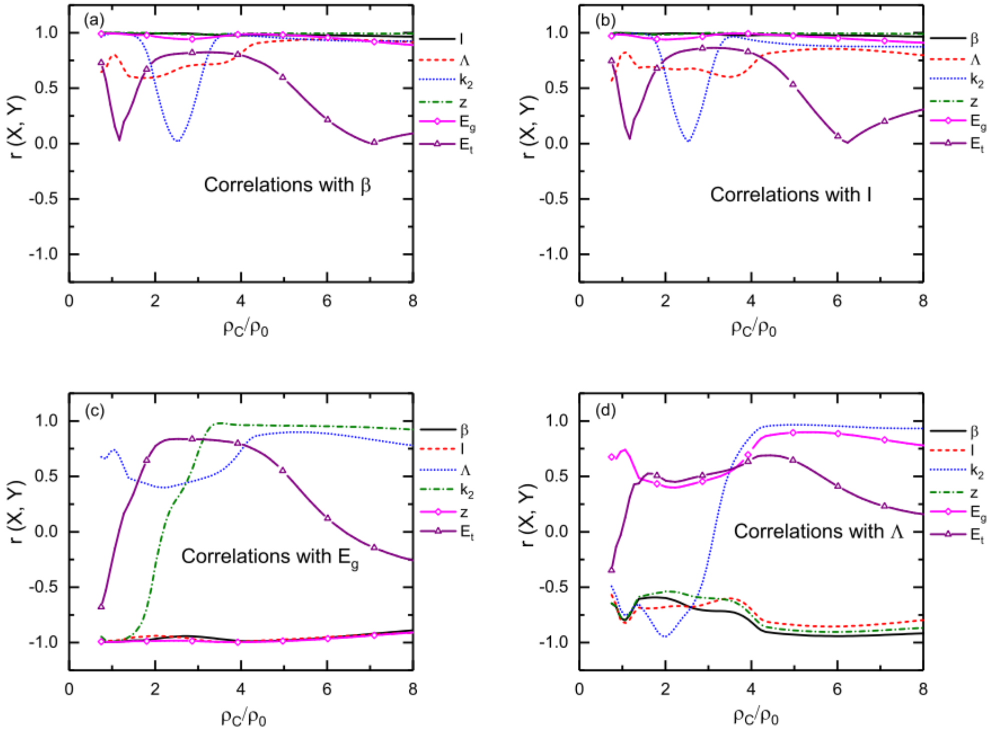
$$r(X,Y)=\frac{N\sum_{i=1}^{N}X_iY_i-\sum_{i=1}^{N}X_i\sum_{i=1}^{N}Y_i}{\sqrt{N\sum_{i=1}^{N}X_i^2-\left(\sum_{i=1}^{N}X_i\right)^2}\sqrt{N\sum_{i=1}^{N}Y_i^2-\left(\sum_{i=1}^{N}Y_i\right)^2}}$$

Briefly: $$r(X,Y)=\frac{\mathrm{Cov}(X,Y)}{\sqrt{D(X)}\sqrt{D(Y)}}$$

The closer the absolute value of the correlation coefficient |r| is to 1, the greater the correlation strength between the two quantities will be.

M. Ferreira, M. Fortin, T. Malik, B. K. Agrawal, and C. Providencia, Phys. Rev. D 101, 043021 (2020).

中子星性质参量之间的关联性

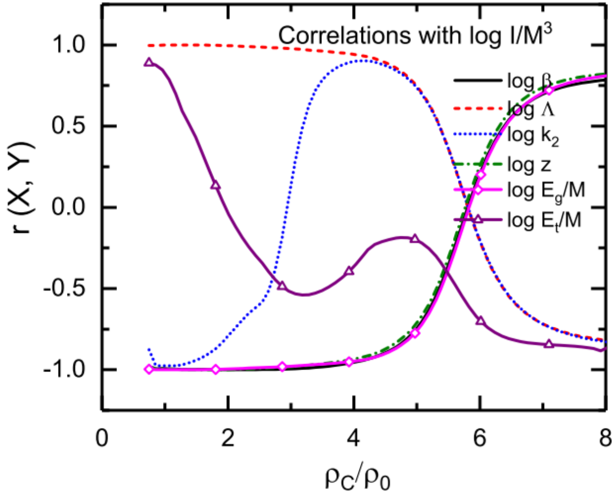


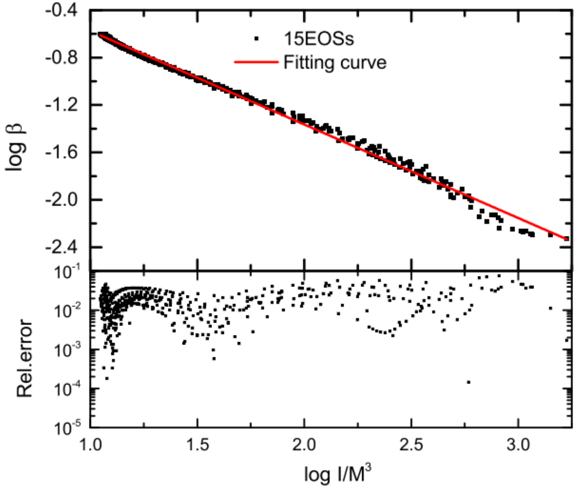
Linear correlation properties of the neutron star properties. It is shown that the quantities possessing desired linear correlation properties are the compactness β, moment of inertia I, gravitational redshift z and gravitational binding energy Eg.

Shen Yang, DHW∗, Jue Wang and Jing Zhang, Phys. Rev. D 105, 063023 (2022)

中子星性质参量之间的关联性

Predicting the new universal (I/M^3– β) relations based on the linear correlation analysis





The universal relation I/M^3- β can be expressed as

$$\log I/M^3 = -1.261 \log \beta + 0.277$$

Shen Yang, DHW∗, Jue Wang and Jing Zhang, Phys. Rev. D 105, 063023 (2022)

中子星性质与核物质参量的关联分析

- 饱和点处的核物质参量，L: 对称能斜率

$$e(\rho,\delta) = e(\rho) + S(\rho)\delta^2,$$

$$e(\rho) = e_0(\rho_0) + \frac{K_0}{2}x^2 + \frac{J_0}{6}x^3 + O(x^4),\ \ x = \frac{\rho-\rho_0}{3\rho_0},$$

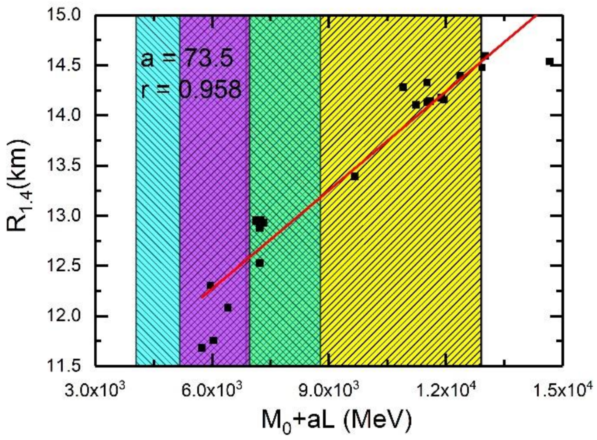
$$S(\rho) = E_{\rm sym}(\rho_0) + Lx + \frac{K_{\rm sym}}{2}x^2 + O(x^3).$$

- 目标：对中子星各种性质与核物质参量的关联特征进行系统性分析，找出较好的关联，并联合地面实验给出的核物质参量数据来对中子星性质进行约束，并同天文观测数据进行比较分析其中的物理机制。

- 方法：Pearson 线性关联系数

Shen Yang & DHW, PRD **107**, 063009 (2023)

对称能斜率L对$1.4M_{\odot}$中子星性质的约束



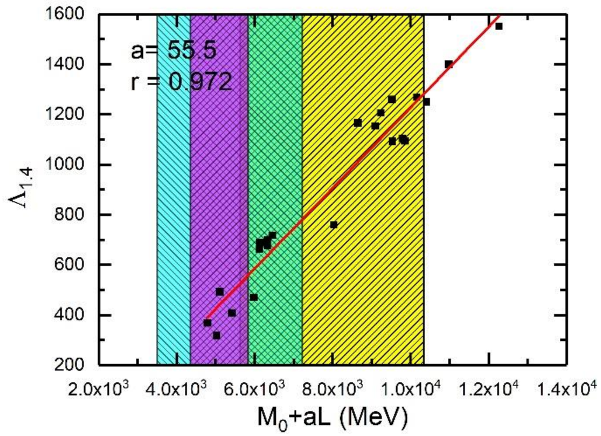


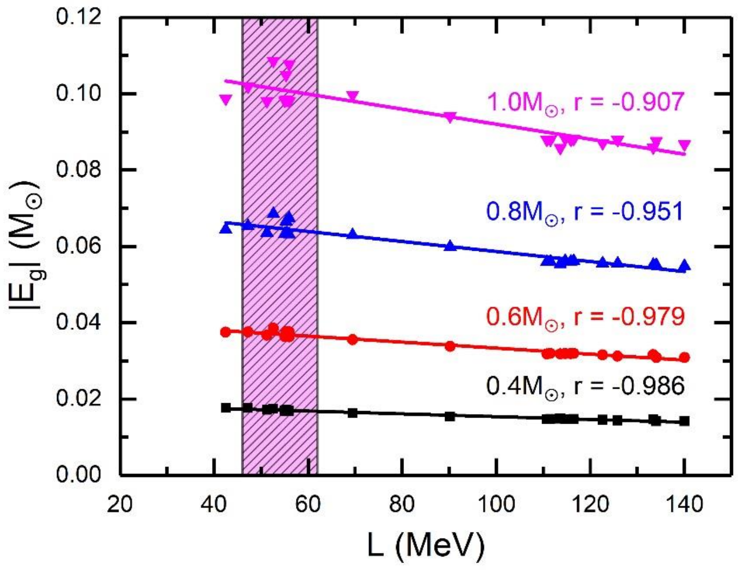
TABLE I: The correlations between NS properties and $M_0 + aL$ (a represents the coefficient of maximal correlation). r represents the linear correlation coefficient, and L_1 = 58.7 ± 28.1MeV, L_2 = 106 ± 37MeV, L_3 = 54 ± 8MeV, respectively.

	$M_0 + aL$				
	a	r	L_1	L_2	L_3
$R_{1.4}$	73.5	0.958	11.63-13.18	12.56-14.54	12.00-12.58
$\Lambda_{1.4}$	55.5	0.972	182.1-782.9	527.3-1285.1	321.7-561.3

由地面实验提取的$L = 54 \pm 8$MeV(Reinhard2021PRL)给出的中子星$R_{1.4}$，$\Lambda_{1.4}$的约束范围能够与GW170817($R_{1.4} < 13.5$km, $70 \leq \Lambda_{1.4} \leq 580$),NICER的天文观测数据较好的符合

Shen Yang & DHW, PRD **107**, 063009 (2023)

对称能斜率L对低质量中子星引力结合能$|E_\mathrm{g}|$的约束



$$
\begin{aligned}
|E_{g,0.4}| &= -\,3.653\times10^{-5}L+0.019\\
&= 0.017\ M_\odot,\\
|E_{g,0.6}| &= -\,7.864\times10^{-5}L+0.041\\
&= 0.036-0.037\ M_\odot,\\
|E_{g,0.8}| &= -\,1.311\times10^{-4}L+0.072\\
&= 0.064-0.066\ M_\odot,\\
|E_{g,1.0}| &= -\,1.968\times10^{-4}L+0.112\\
&= 0.100-0.103\ M_\odot.
\end{aligned}
$$

低质量中子星的引力结合能$|E_\mathrm{g}|$在理论上可以被L的约束范围较好的约束，其能够与超新星爆发中的总释放能量联系起来以用来预测低质量中子星的形成。

Shen Yang & DHW, PRD **107**, 063009 (2023)

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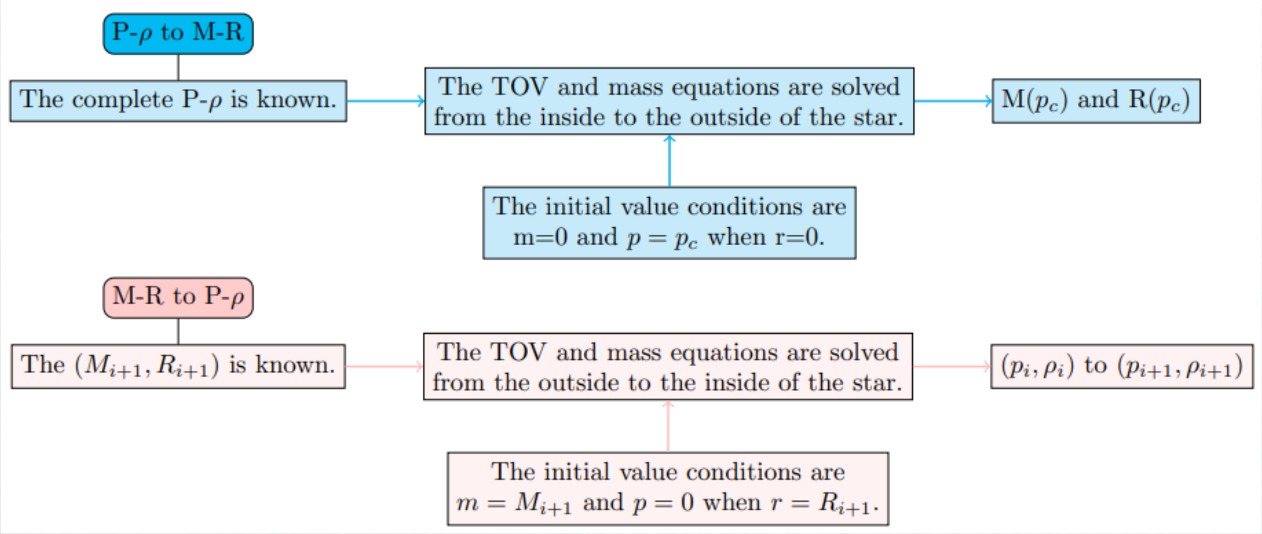
神经网络算法下中子星质量半径对EoS的约束

EOS: $P(\rho)$ $\underset{逆TOV映射}{\overset{TOV映射}{\rightleftarrows}}$ TOV方程：

$$\frac{dP}{dr} = -\frac{G\rho m(r)}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{m(r)c^2}\right)\left(1-\frac{2Gm(r)}{rc^2}\right)^{-1}$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho$$



如果将EOS到M-R的映射称为TOV映射，则M-R到EOS的映射可视为**逆TOV映射**

Zehan Wu, DHW *, From masses and radii of neutron stars to EOS of nuclear matter through neural network， Chin. Phys. C 48, 024101（2024）

1.神经网络算法下中子星质量半径对EoS的约束

Parameter range (MeV)		
parameter	range	interval
L	30 ~ 143	+1
K_s	-400 ~ 100	+1
J_s	-200 ~ 800	+100
J_0	-300~400	+100
K_0	240	
$E_{sym}(\rho_0)$	31.7	

总样本量约：5,026,032

筛选条件

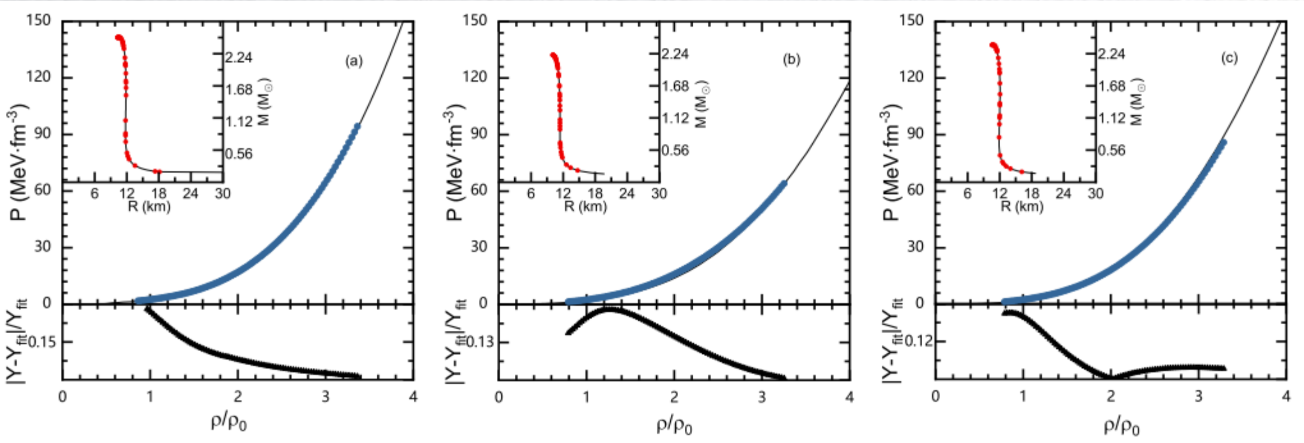
Maximum mass	$2.14M_\odot$
tidal deformation	70~580($1.4M_\odot$)
Mass radius corresponding	1.29~1.59$M_\odot$/11.2~13.3km

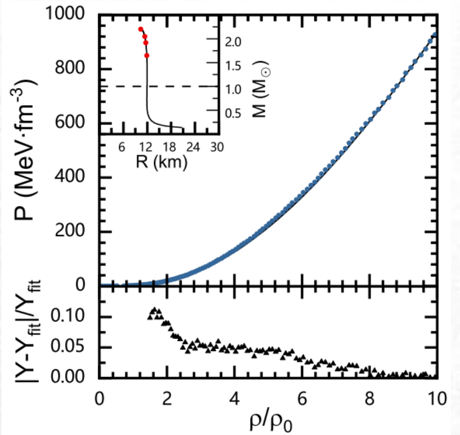
筛选后剩余样本量884,294

$$\begin{cases} E_0(\rho)=E_0(\rho_0)+\frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2+\frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 \\ E_{sym}(\rho)=E_{sym}(\rho_0)+L\left(\frac{\rho-\rho_0}{3\rho_0}\right)+\frac{K_{sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2+\frac{J_{sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 \end{cases}$$

Zehan Wu, DHW*, From masses and radii of neutron stars to EOS of nuclear matter through neural network， Chin. Phys. C 48, 024101（2024）

神经网络算法下中子星质量半径对EoS的约束





40 points　　APR3　　APR4　　4 points

40对（M,R）点作为输入，NN能够给出比较准确的结果，当输入点降低至35点时相对误差显著变大。

只变化L-K_{sym}时，生成样本量约8,000。输入点数降低至**4**

Zehan Wu, DHW*, From masses and radii of neutron stars to EOS of nuclear matter through neural network，Chin. Phys. C 48, 024101（2024）

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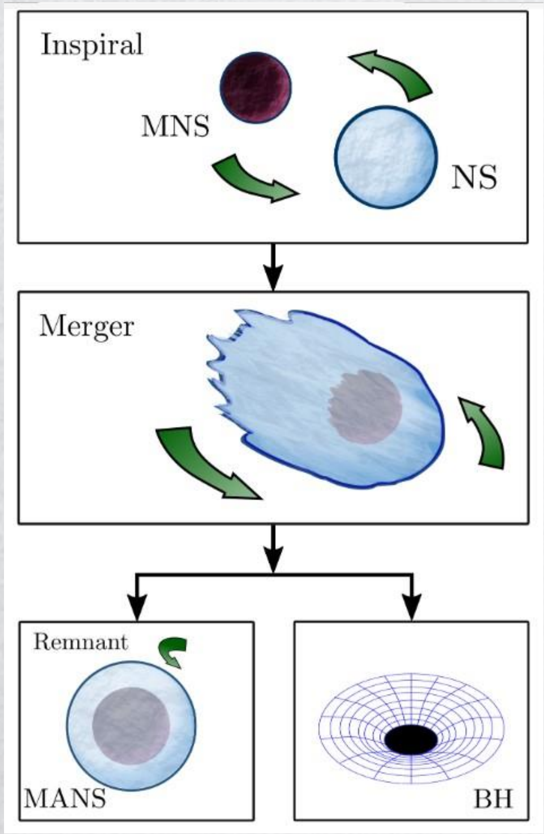
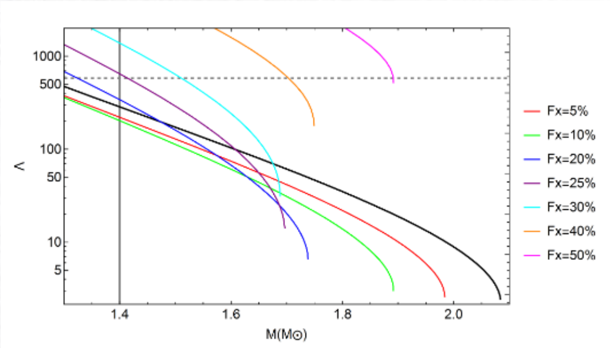
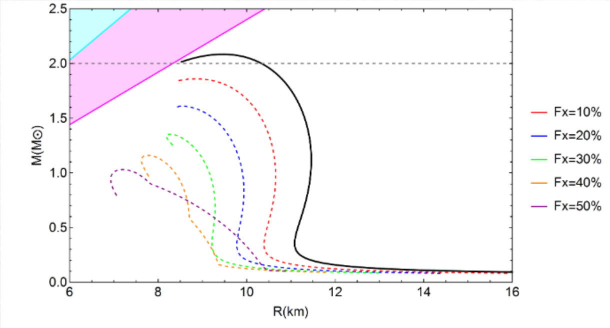
含暗物质中子星



由于中子星极强的引力，它可能会吸收其附近的暗物质，或者与纯暗物质星合并形成含暗物质中子星。





暗物质对中子星潮汐形变以及半径的影响

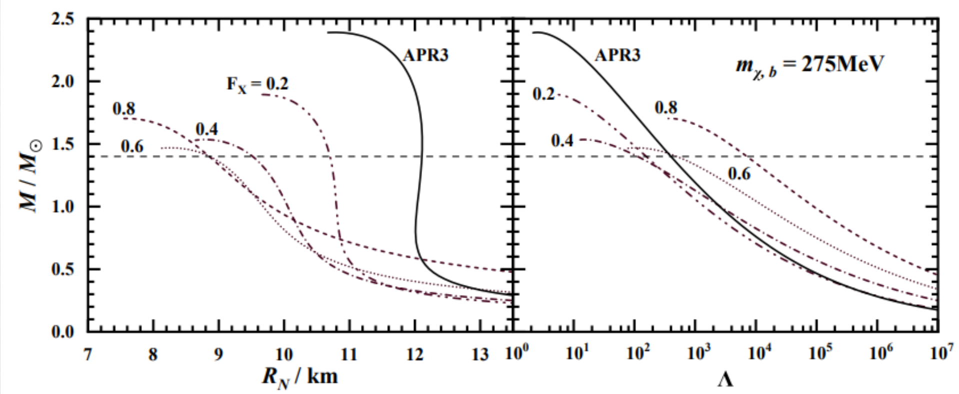
Physical Review D, 2023, 107(11): 115028.

Physical Review D, 2022, 105(2): 023001.

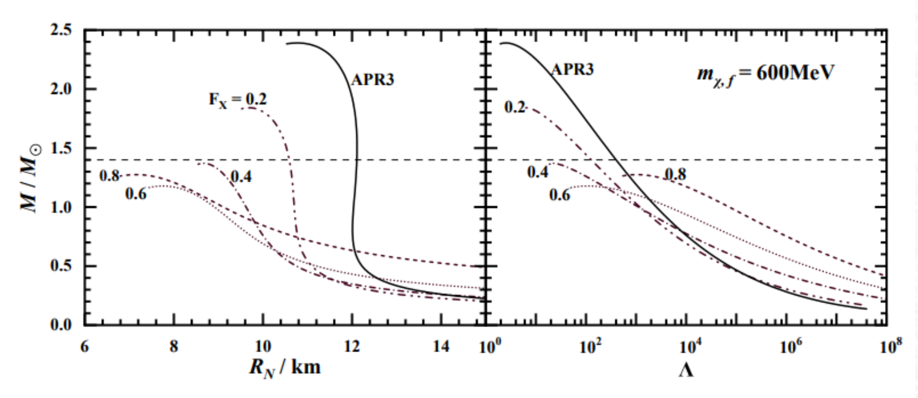
含暗物质中子星的宏观性质

Hongyi Sun and DHW*, Phys. Rev. D 109, 123037 (2024)

自相互作用玻色暗物质



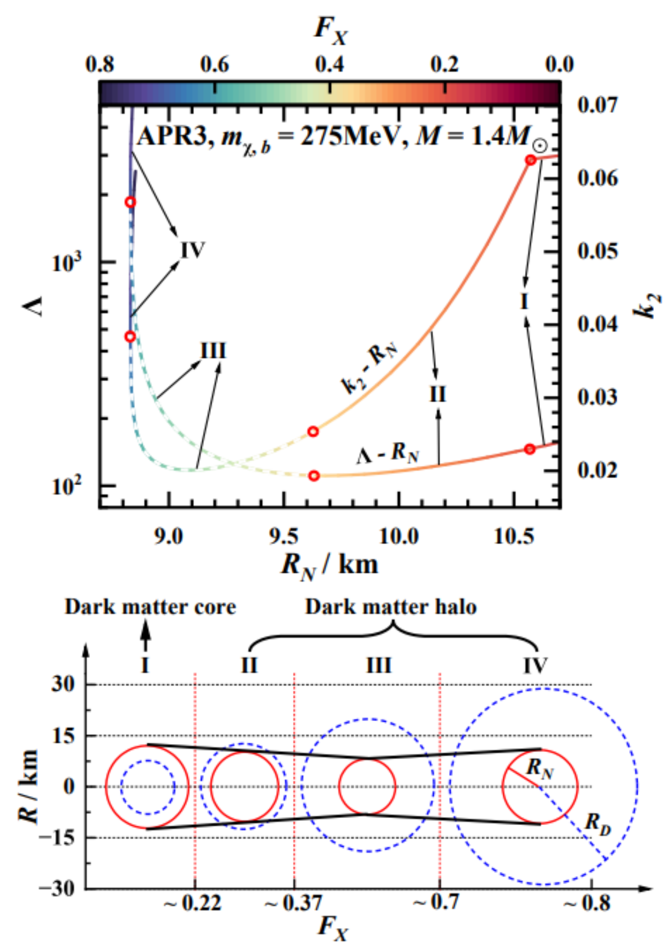
理想费米气暗物质



1. 潮汐形变Λ与普通物质半径R_N随F_X的变化；
2. 不同暗物质模型下含暗物质中子星的差别。

含暗物质中子星的宏观性质

Hongyi Sun and DHW*, Phys. Rev. D 109, 123037 (2024)



R_N和Λ的负相关关系

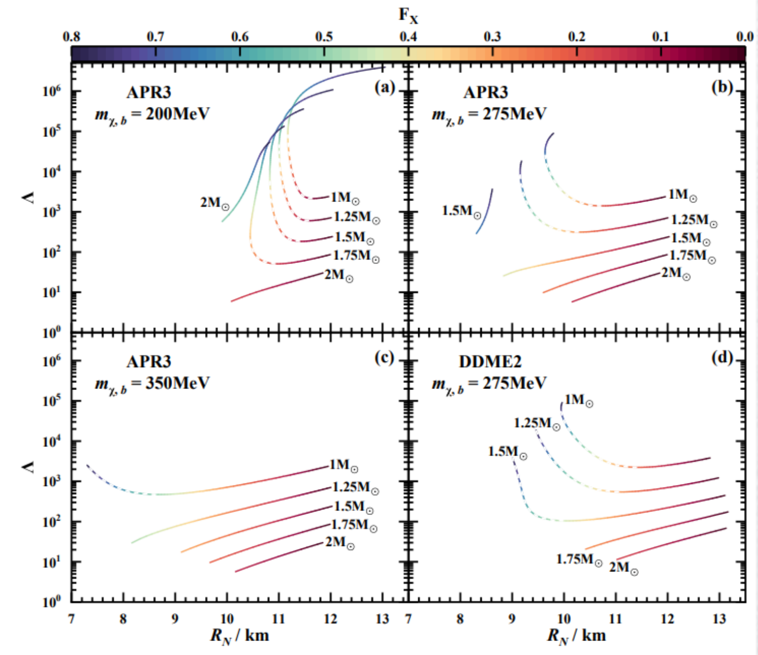
当暗物质质量分数较大时，会出现普通物质半径R_N和潮汐形变Λ的负相关关系（虚线）

本质原因：增大暗物质质量分数时R_N减小，但是Λ随$R = R_D$的增大而增大（III和IV）。

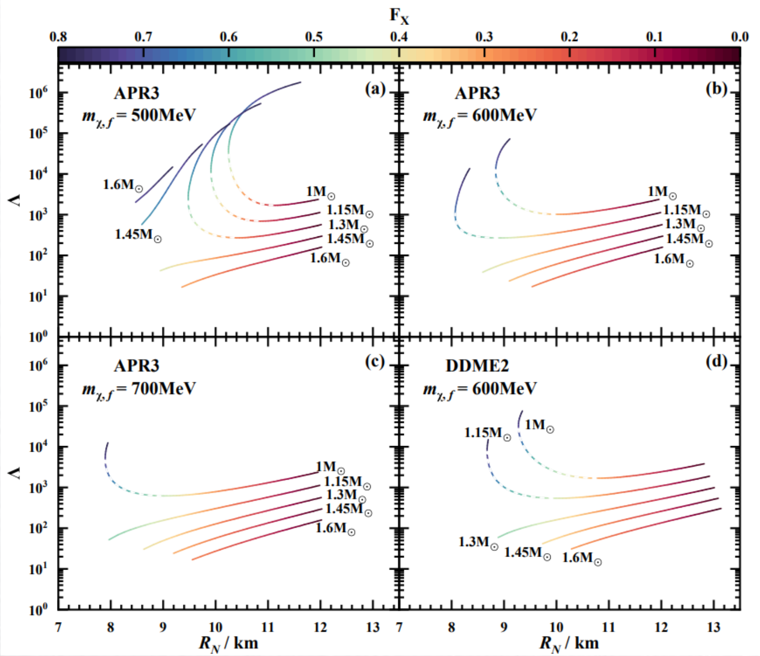
含暗物质中子星的宏观性质 —— R_N和Λ负相关关系的普遍性

Hongyi Sun and DHW*, Phys. Rev. D 109, 123037 (2024)

自相互作用玻色暗物质



理想费米气暗物质



R_N和Λ的负相关关系在改变暗物质模型及其物态参数的情况下是普遍存在的，而且可以利用该负相关关系来限制暗物质物态的参数。

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结 论

- 采用线性相关性的分析方法可以更高效、更精确地预测中子星性质参量的普遍性关系。
- 利用构建的普适性关系，可以对无法观测或难以观测的中子星性质参量进行有效约束。引力结合能是一种构建中子星性质参量普适性关系的理想参量。
- 利用神经网络算法，根据一定数量、一定精度的中子星质量-半径观测值可以给出较为精确的物态方程。
- 含暗物质中子星潮汐形变与普通物质半径之间的负相关关系可以作为中子星内是否含有暗物质的观测证据。

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