Systematics on the high-density nuclear equation of state from relativistic Hartree-Fock theory with Brown-Rho scaling

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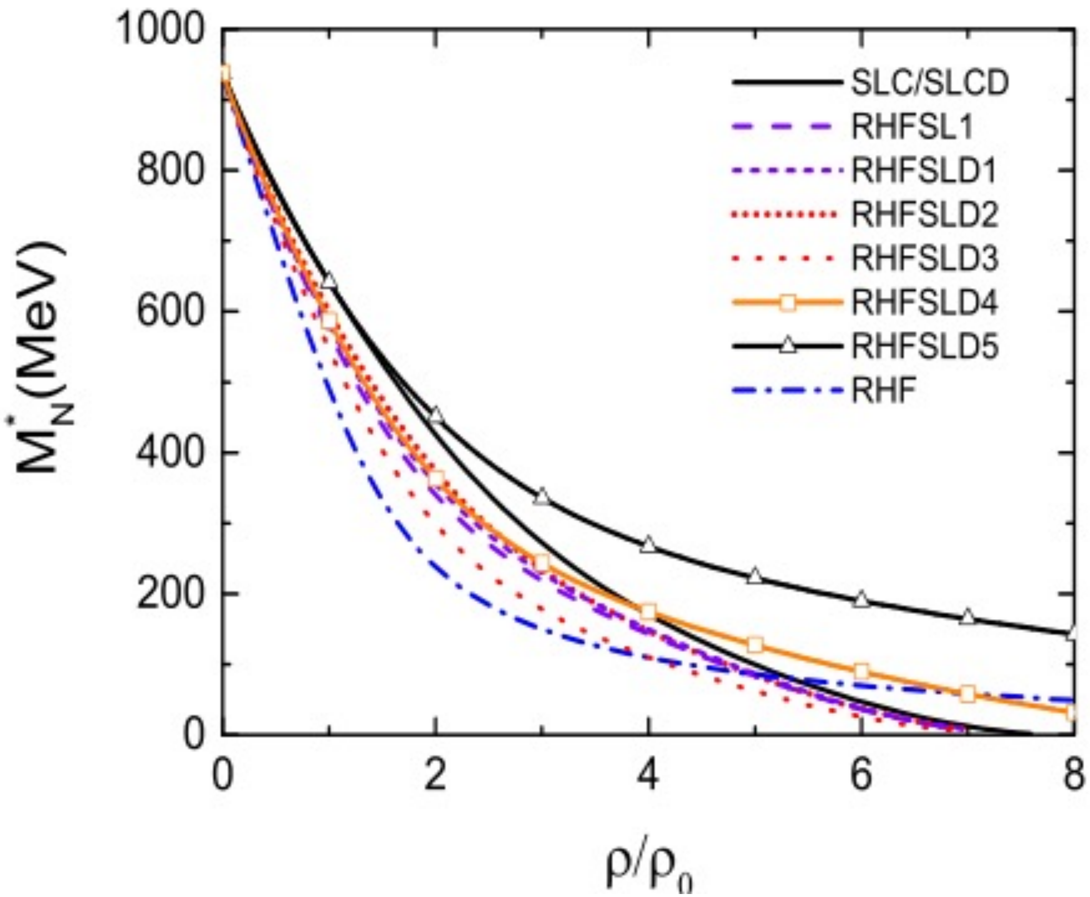
$$\frac{m_\sigma^*}{m_\sigma} = \frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = \frac{f_\pi^*}{f_\pi} = 1 - x\frac{\rho}{\rho_0},$$

G. E. Brown and M. Rho,
Phys. Rev.Lett. **66**,2720 (1991).



PRL **94,** 192303 (2005) PHYSICAL REVIEW LETTERS week ending 20 MAY 2005

Observation of In-Medium Modifications of the ω Meson

D. Trnka,[1] G. Anton,[2] J. C. S. Bacelar,[3] O. Bartholomy,[4] D. Bayadilov,[4,8] Y. A. Beloglazov,[8] R. Bogendörfer,[2] R. Castelijns,[3] V. Crede,[4,†] H. Dutz,[5] A. Ehmanns,[4] D. Elsner,[5] R. Ewald,[5] I. Fabry,[4] M. Fuchs,[4] K. Essig,[4] Ch. Funke,[4] R. Gothe,[5,*] R. Gregor,[1] A. B. Gridnev,[8] E. Gutz,[4] S. Höffgen,[5] P. Hoffmeister,[4] I. Horn,[4] J. Hössl,[2] I. Jaegle,[7] J. Junkersfeld,[4] H. Kalinowsky,[4] Frank Klein,[5] Fritz Klein,[5] E. Klempt,[2] M. Konrad,[5] B. Kopf,[6,9] M. Kotulla,[7] B. Krusche,[7] J. Langheinrich,[5,*] H. Löhner,[3] I. V. Lopatin,[8] J. Lotz,[4] S. Lugert,[1] D. Menze,[5] J. G. Messchendorp,[3] T. Mertens,[7] V. Metag,[1] C. Morales,[5] M. Nanova,[1] R. Novotny,[1] M. Ostrick,[5] L. M. Pant,[1,||] H. van Pee,[1] M. Pfeiffer,[1] A. Roy,[1,¶] A. Radkov,[8] S. Schadmand,[1,‡] Ch. Schmidt,[4] H. Schmieden,[5] B. Schoch,[5] S. Shende,[3] G. Suft,[2] V. V. Sumachev,[8] T. Szczepanek,[4] A. Süle,[5] U. Thoma,[1,4] R. Varma,[1,¶] D. Walther,[5] Ch. Weinheimer,[4,§] and Ch. Wendel[4]

$$\frac{m_\omega^*}{m_\omega} = 1 - x\,\frac{\rho}{0.6\rho_0} \qquad x = 0.13$$

PRL **96,** 092301 (2006) PHYSICAL REVIEW LETTERS week ending 10 MARCH 2006

Experimental Signature of Medium Modifications for ρ and ω Mesons in the 12 GeV $p + A$ Reactions

M. Naruki,* Y. Fukao, H. Funahashi, M. Ishino,† H. Kanda,‡ M. Kitaguchi,§ S. Mihara,† K. Miwa, T. Miyashita, T. Murakami, T. Nakura, F. Sakuma, M. Togawa, S. Yamada,|| and Y. Yoshimura
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$$\frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = 1 - x\,\frac{\rho}{\rho_0} \qquad x = 0.092 \pm 0.002$$

PHYSICAL REVIEW C **78**, 015201 (2008)

Light vector mesons in the nuclear medium

M. H. Wood,[1] R. Nasseripour,[17] D. P. Weygand,[2] C. Djalali,[1] C. Tur,[1] U. Mosel,[3] P. Muehlich,[3] G. Adams,[34] M. J. Amaryan,[32] P. Ambrozewicz,[15] M. Anghinolfi,[21] G. Asryan,[41] H. Avakian,[2] H. Bagdasaryan,[32,41] N. Baillie,[40] J. P. Ball,[5] N. A. Baltzell,[1] S. Barrow,[16] M. Battaglieri,[21] I. Bedlinskiy,[23] M. Bektasoglu,[31] M. Bellis,[8] N. Benmouna,[17] B. L. Berman,[17] A. S. Biselli,[8,14,34] L. Blaszczyk,[16] S. Bouchigny,[22] S. Boiarinov,[2] R. Bradford,[8] D. Branford,[13] W. J. Briscoe,[17] W. K. Brooks,[2] V. D. Burkert,[2] C. Butuceanu,[40] J. R. Calarco,[29] S. L. Careccia,[32] D. S. Carman,[2] B. Carnahan,[9] L. Casey,[9] S. Chen,[16] L. Cheng,[9] P. L. Cole,[19] P. Collins,[5] P. Coltharp,[16] D. Crabb,[39] H. Crannell,[9] V. Crede,[16] J. P. Cummings,[34] N. Dashyan,[41] R. De Vita,[21] E. De Sanctis,[20] P. V. Degtyarenko,[2] H. Denizli,[33] L. Dennis,[16] A. Deur,[2] K. V. Dharmawardane,[32] R. Dickson,[8] G. E. Dodge,[32] D. Doughty,[2,11] M. Dugger,[5] S. Dytman,[33] O. P. Dzyubak,[1] H. Egiyan,[29] K. S. Egiyan,[41] L. El Fassi,[4] L. Elouadrhiri,[2] P. Eugenio,[16] G. Fedotov,[28] G. Feldman,[17] R. J. Feuerbach,[8] A. Fradi,[22] H. Funsten,[40] M. Garçon,[10] G. Gavalian,[29,32] G. P. Gilfoyle,[36] K. L. Giovanetti,[24] F. X. Girod,[10] J. T. Goetz,[6] C. I. O. Gordon,[18] R. W. Gothe,[1] K. A. Griffioen,[40] M. Guidal,[22] N. Guler,[32] L. Guo,[2] V. Gyurjyan,[2] C. Hadjidakis,[22] K. Hafidi,[4] H. Hakobyan,[41] R. S. Hakobyan,[9] C. Hanretty,[16] J. Hardie,[2,11] N. Hassall,[18] F. W. Hersman,[29] K. Hicks,[31] I. Hleiqawi,[31] M. Holtrop,[29] C. E. Hyde-Wright,[32] Y. Ilieva,[17] D. G. Ireland,[18] B. S. Ishkhanov,[28] E. L. Isupov,[28] M. M. Ito,[2] D. Jenkins,[38] H. S. Jo,[22] J. R. Johnstone,[18] K. Joo,[12] H. G. Juengst,[17,32] N. Kalantarians,[32] J. D. Kellie,[18] M. Khandaker,[30] P. Khetarpal,[34] W. Kim,[25] A. Klein,[32] F. J. Klein,[9] A. V. Klimenko,[32] M. Kossov,[23] Z. Krahn,[8] L. H. Kramer,[2,15] V. Kubarovsky,[2,34] J. Kuhn,[8] S. E. Kuhn,[32] S. V. Kuleshov,[23] J. Lachniet,[8,32] J. M. Laget,[2,10] J. Langheinrich,[1] D. Lawrence,[27] Ji Li,[34] K. Livingston,[18] H. Y. Lu,[1] M. MacCormick,[22] N. Markov,[12] P. Mattione,[35] S. McAleer,[16] B. McKinnon,[18] J. W. C. McNabb,[8] B. A. Mecking,[2] S. Mehrabyan,[33] J. J. Melone,[18] M. D. Mestayer,[2] C. A. Meyer,[8] T. Mibe,[31] K. Mikhailov,[23] R. Minehart,[39] M. Mirazita,[20] R. Miskimen,[27] V. Mokeev,[28] K. Moriya,[8] S. A. Morrow,[10,22] M. Moteabbed,[15] J. Mueller,[33] E. Munevar,[17] G. S. Mutchler,[35] P. Nadel-Turonski,[17] S. Niccolai,[17,22] G. Niculescu,[24,31] I. Niculescu,[24] B. B. Niczyporuk,[2] M. R. Niroula,[32] R. A. Niyazov,[2,32] M. Nozar,[2] M. Osipenko,[21,28] A. I. Ostrovidov,[16] K. Park,[1] E. Pasyuk,[5] C. Paterson,[18] S. Anefalos Pereira,[20] J. Pierce,[39] N. Pivnyuk,[23] D. Pocanic,[39] O. Pogorelko,[23] S. Pozdniakov,[23] B. M. Preedom,[1] J. W. Price,[7] Y. Prok,[26] D. Protopopescu,[18,29] B. A. Raue,[2,15] G. Riccardi,[16] G. Ricco,[21] M. Ripani,[21] B. G. Ritchie,[5] F. Ronchetti,[20] G. Rosner,[18] P. Rossi,[20] F. Sabatié,[10] J. Salamanca,[19] C. Salgado,[30] J. P. Santoro,[2,9,38] V. Sapunenko,[2] R. A. Schumacher,[8] V. S. Serov,[23] Y. G. Sharabian,[2] D. Sharov,[28] N. V. Shvedunov,[28] E. S. Smith,[2] L. C. Smith,[39] D. I. Sober,[9] D. Sokhan,[13] A. Stavinsky,[23] S. Stepanyan,[2] S. S. Stepanyan,[25] B. E. Stokes,[16] P. Stoler,[34] I. I. Strakovsky,[17] S. Strauch,[1,17] M. Taiuti,[21] D. J. Tedeschi,[1] A. Tkabladze,[17] S. Tkachenko,[32] L. Todor,[36] M. Ungaro,[12,34] M. F. Vineyard,[36,37] A. V. Vlassov,[23] D. P. Watts,[13] L. B. Weinstein,[32] M. Williams,[8] E. Wolin,[2] A. Yegneswaran,[2] L. Zana,[29] B. Zhang,[26] J. Zhang,[32] B. Zhao,[12] and Z. W. Zhao[1]

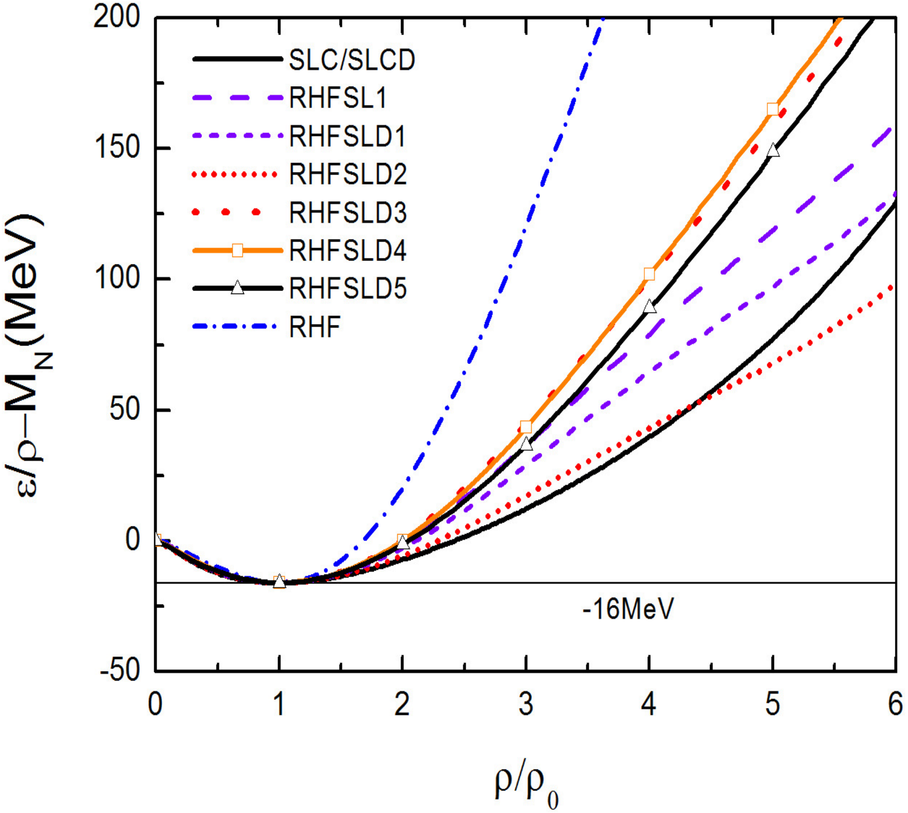
$$\frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = 1 - x\,\frac{\rho}{\rho_0} \qquad x \leq 0.053$$

Quantum Electrodynamics(QED)： 电磁相互作用的媒介粒子是光子

Quantum Hadron Dynamics(QHD): 核相互作用的媒介粒子可以是σ，ω，π，ρ介子等等。情况更为复杂。

以核物质状态方程(EOS)为例：

$$E(\rho,\delta)=\frac{\epsilon(\rho,\delta)}{\rho}=E_0(\rho)+E_{sym}(\rho)\delta^2+O(\delta^4),$$



$$P = \rho^2 \frac{dE_0(\rho)}{d\rho}\Big|_{\rho=\rho_0} = 0$$

$$E_0(\rho_0) - E_0^{vac}(\equiv M_N^{vac}) = -16MeV$$

$$K_0 = 9\rho_0^2\, \frac{d^2 E_0(\rho)}{d\rho^2}\Big|_{\rho=\rho_0}$$

$$K_0 \equiv 240 \pm 20MeV$$

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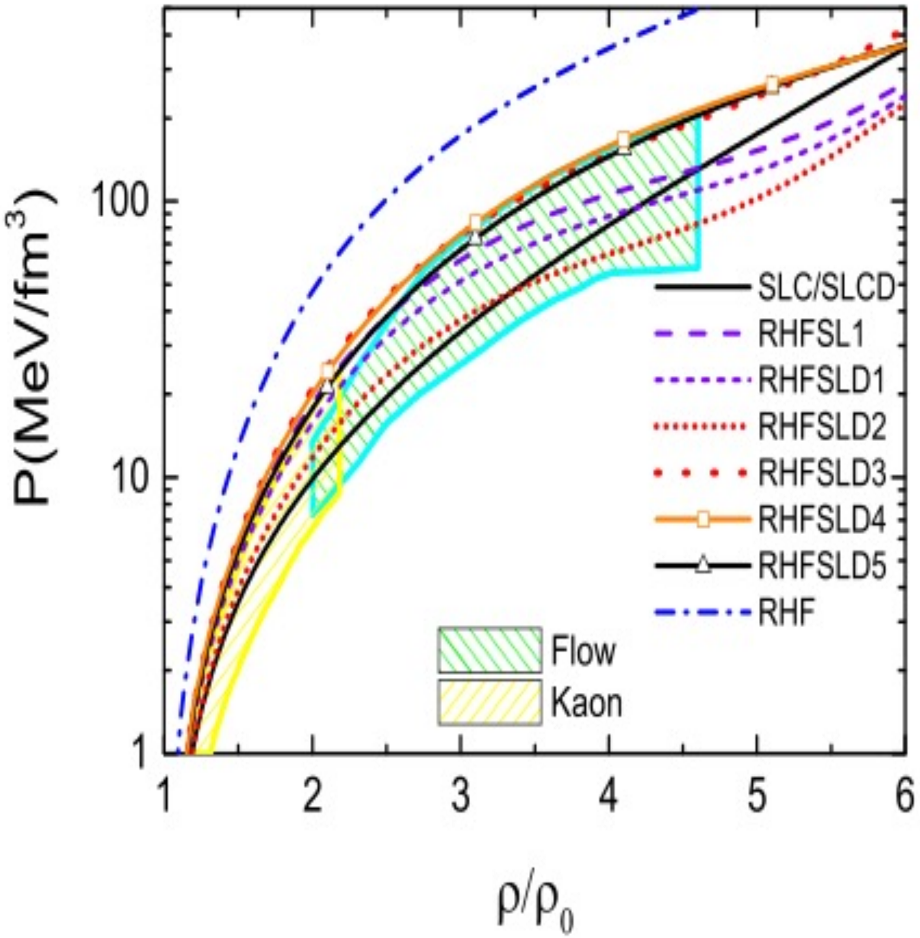
$$K_0 \equiv 210 - 300MeV$$

P. Danielewicz, et al., Science, **298**,1592–1596(2002).

$$P = \rho^2 \frac{dE_0(\rho)}{d\rho}$$



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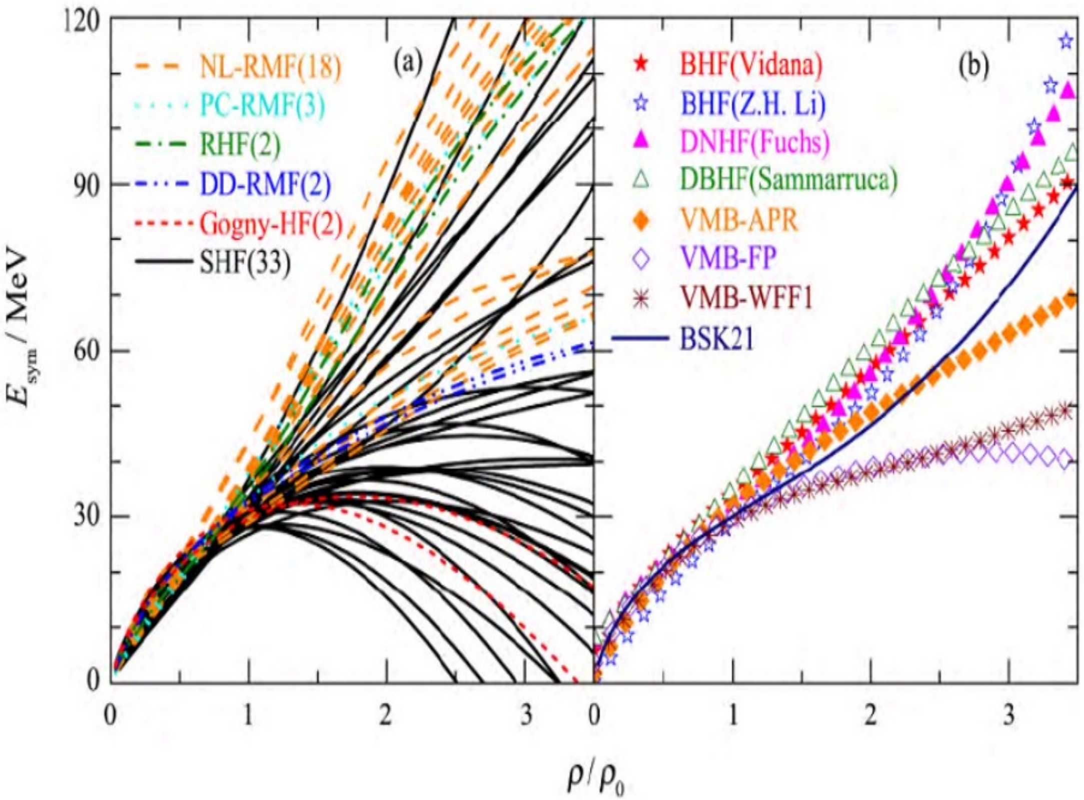
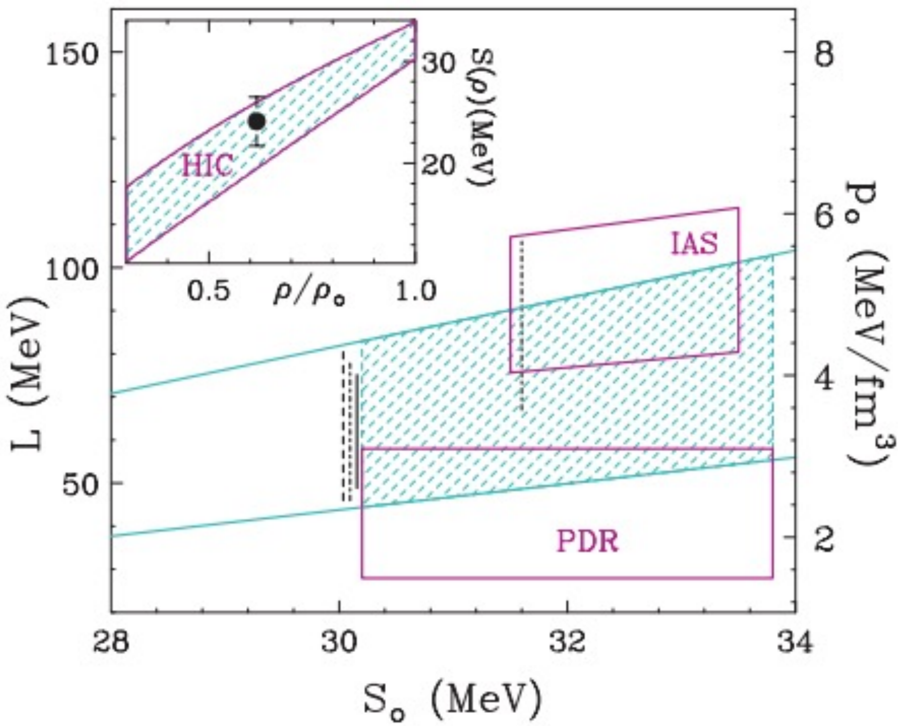
Z.Q. Feng, Phys. Rev. C83, 067604 (2011).



L.W. Chen Nucl. Phys. Rev., **34**, 20–28 （2017）



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PHYSICAL REVIEW LETTERS **126,** 172503 (2021)

Editors' Suggestion

Implications of PREX-2 on the Equation of State of Neutron-Rich Matte

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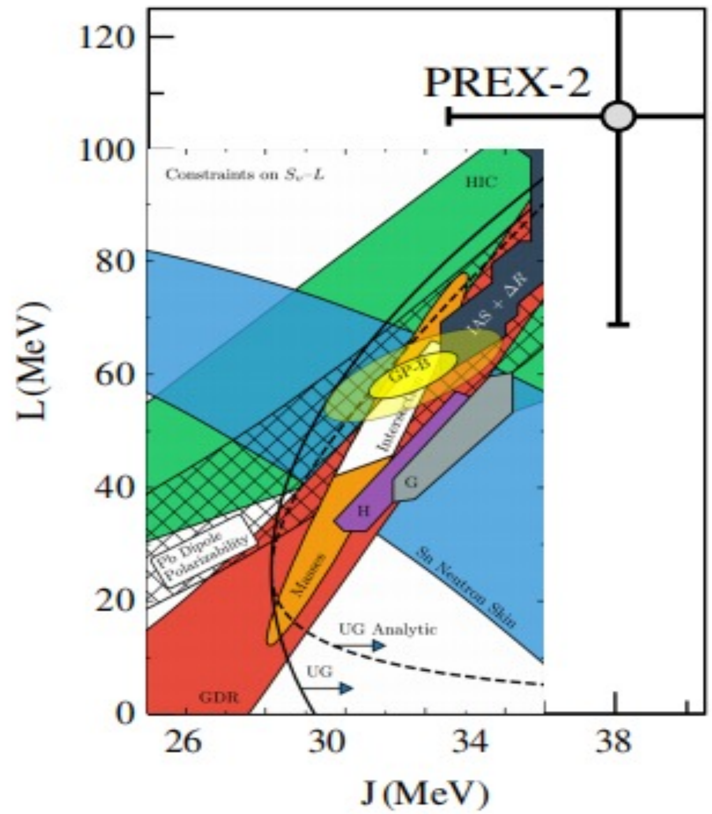
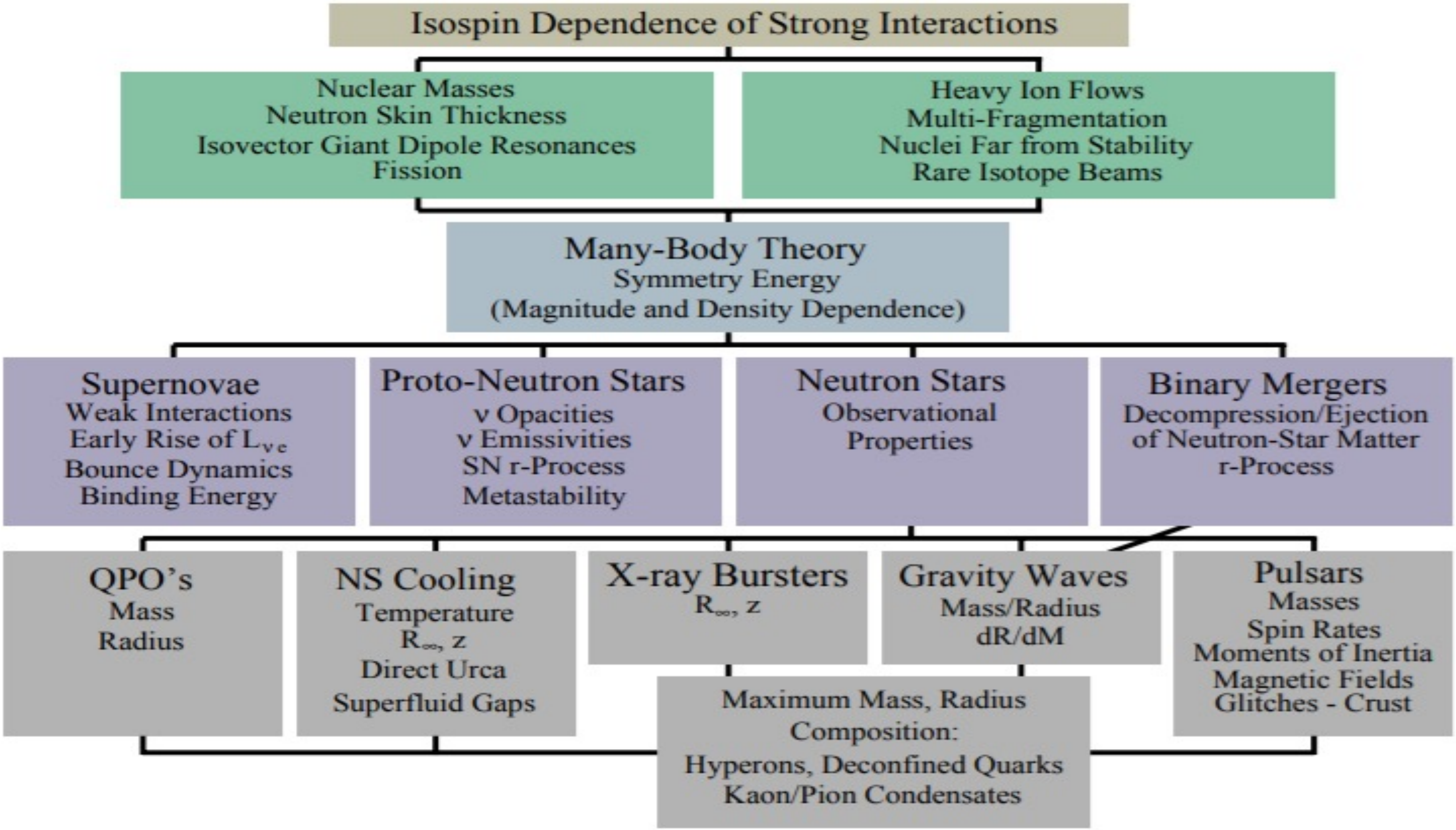
Laboratory experiments sensitive to the equation of state of neutron rich matter in the vicinity of nuclea saturation density provide the first rung in a "density ladder" that connects terrestrial experiments t astronomical observations. In this context, the neutron skin thickness of ^{208}Pb (R^{208}_{skin}) provides a stringen laboratory constraint on the density dependence of the symmetry energy. In turn, an improved value of R^{20}_{ski} has been reported recently by the PREX collaboration. Exploiting the strong correlation between R^{208}_{skin} an the slope of the symmetry energy L within a specific class of relativistic energy density functional we report a value of $L = (106 \pm 37)$ MeV—which systematically overestimates current limits based o both theoretical approaches and experimental measurements. The impact of such a stiff symmetry energ on some critical neutron-star observables is also examined.





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nature astronomy

LETTERS

https://doi.org/10.1038/s41550-019-0880-2

Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

H. T. Cromartie[1*], E. Fonseca[2], S. M. Ransom[3], P. B. Demorest[4], Z. Arzoumanian[5], H. Blumer[6,7], P. R. Brook[6,7], M. E. DeCesar[8], T. Dolch[9], J. A. Ellis[10], R. D. Ferdman[11], E. C. Ferrara[12,13], N. Garver-Daniels[6,7], P. A. Gentile[6,7], M. L. Jones[6,7], M. T. Lam[6,7], D. R. Lorimer[6,7], R. S. Lynch[14], M. A. McLaughlin[6,7], C. Ng[15,16], D. J. Nice[8], T. T. Pennucci[17], R. Spiewak[18], I. H. Stairs[15], K. Stovall[4], J. K. Swiggum[19] and W. W. Zhu[20]

MSP J0740+6620

$$M_P = 2.14^{+0.10}_{-0.09} M_s$$

Astrophys. J. Lett. **915**, L12(2021).

Refined Mass and Geometric Measurements of the High-Mass PSR J0740+6620

E. Fonseca,[1,2,3,4] H. T. Cromartie,[5,6] T. T. Pennucci,[7,8] P. S. Ray,[9] A. Yu. Kirichenko,[10,11] S. M. Ransom,[7] P. B. Demorest,[12] I. H. Stairs,[13] Z. Arzoumanian,[14] L. Guillemot,[15,16] A. Parthasarathy,[17] M. Kerr,[9] I. Cognard,[15,16] P. T. Baker,[18] H. Blumer,[3,4] P. R. Brook,[3,4] M. DeCesar,[19] T. Dolch,[20,21] F. A. Dong,[13] E. C. Ferrara,[22,23,24] W. Fiore,[3,4] N. Garver-Daniels,[3,4] D. C. Good,[13] R. Jennings,[25] M. L. Jones,[26] V. M. Kaspi,[1,2] M. T. Lam,[27,28] D. R. Lorimer,[3,4] J. Luo,[29] A. McEwen,[26] J. W. McKee,[29] M. A. McLaughlin,[3,4] N. McMann,[30] B. W. Meyers,[13] A. Naidu,[31] C. Ng,[32] D. J. Nice,[33] N. Pol,[30] H. A. Radovan,[34] B. Shapiro-Albert,[3,4] C. M. Tan,[1,2] S. P. Tendulkar,[35,36] J. K. Swiggum,[33] H. M. Wahl,[3,4] and W. W. Zhu[37]

MSP J0740+6620

$$M_P = 2.08^{+0.07}_{-0.07} M_s$$

PHYSICAL REVIEW LETTERS **120,** 172703 (2018)

ditors' Suggestion | Featured in Physics

Gravitational-Wave Constraints on the Neutron-Star-Matter Equation of State

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The detection of gravitational waves originating from a neutron-star merger, GW170817, by the LIGO and Virgo Collaborations has recently provided new stringent limits on the tidal deformabilities of the stars involved in the collision. Combining this measurement with the existence of two-solar-mass stars, we generate a generic family of neutron-star-matter equations of state (EOSs) that interpolate between state-of-the-art theoretical results at low and high baryon density. Comparing the results to ones obtained without the tidal-deformability constraint, we witness a dramatic reduction in the family of allowed EOSs. Based on our analysis, we conclude that the maximal radius of a 1.4-solar-mass neutron star is 13.6 km, and that the smallest allowed tidal deformability of a similar-mass star is $\Lambda(1.4\ M_\odot) = 120$.

PHYSICAL REVIEW LETTERS **120,** 261103 (2018)

New Constraints on Radii and Tidal Deformabilities of Neutron Stars from GW170817

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We explore in a parameterized manner a very large range of physically plausible equations of state (EOSs) for compact stars for matter that is either purely hadronic or that exhibits a phase transition. In particular, we produce two classes of EOSs with and without phase transitions, each containing one million EOSs. We then impose constraints on the maximum mass ($M < 2.16\ M_\odot$) and on the dimensionless tidal deformability ($\tilde{\Lambda} < 800$) deduced from GW170817, together with recent suggestions of lower limits on $\tilde{\Lambda}$. Exploiting more than 10^9 equilibrium models for each class of EOSs, we produce distribution functions of all the stellar properties and determine, among other quantities, the radius that is statistically most probable for any value of the stellar mass. In this way, we deduce that the radius of a purely hadronic neutron star with a representative mass of 1.4 $M_\odot$ is constrained to be $12.00 < R_{1.4}/\mathrm{km} < 13.45$ at a 2σ confidence level, with a most likely value of $\bar{R}_{1.4} = 12.39$ km; similarly, the smallest dimensionless tidal deformability is $\tilde{\Lambda}_{1.4} > 375$, again at a 2σ level. On the other hand, because EOSs with a phase transition allow for very compact stars on the so-called "twin-star" branch, small radii are possible with such EOSs although not probable, i.e., $8.53 < R_{1.4}/\mathrm{km} < 13.74$ and $\bar{R}_{1.4} = 13.06$ km at a 2σ level, with $\tilde{\Lambda}_{1.4} > 35.5$ at a 3σ level. Finally, since these EOSs exhibit upper limits on $\tilde{\Lambda}$, the detection of a binary with a total mass of 3.4 $M_\odot$ and $\tilde{\Lambda}_{1.7} > 461$ can rule out twin-star solutions.

PHYSICAL REVIEW LETTERS **120,** 172702 (2018)

Editors' Suggestion | Featured in Physics

Neutron Skins and Neutron Stars in the Multimessenger Era

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(Received 17 November 2017; revised manuscript received 8 January 2018; published 25 April 2018)

The historical first detection of a binary neutron star merger by the LIGO-Virgo Collaboration [B. P. Abbott *et al.*, Phys. Rev. Lett. **119**, 161101 (2017)] is providing fundamental new insights into the astrophysical site for the *r* process and on the nature of dense matter. A set of realistic models of the equation of state (EOS) that yield an accurate description of the properties of finite nuclei, support neutron stars of two solar masses, and provide a Lorentz covariant extrapolation to dense matter are used to confront its predictions against tidal polarizabilities extracted from the gravitational-wave data. Given the sensitivity of the gravitational-wave signal to the underlying EOS, limits on the tidal polarizability inferred from the observation translate into constraints on the neutron-star radius. Based on these constraints, models that predict a stiff symmetry energy, and thus large stellar radii, can be ruled out. Indeed, we deduce an upper limit on the radius of a 1.4$M_\odot$ neutron star of $R_\star^{1.4} < 13.76$ km. Given the sensitivity of the neutron-skin thickness of ^{208}Pb to the symmetry energy, albeit at a lower density, we infer a corresponding upper limit of about $R_{\rm skin}^{208} \lesssim 0.25$ fm. However, if the upcoming PREX-II experiment measures a significantly thicker skin, this may be evidence of a softening of the symmetry energy at high densities—likely indicative of a phase transition in the interior of neutron stars.

PHYSICAL REVIEW LETTERS **121,** 161101 (2018)

uggestion

GW170817: Measurements of Neutron Star Radii and Equation of State

B. P. Abbott *et al.*[*]

(The LIGO Scientific Collaboration and the Virgo Collaboration)

(Received 5 June 2018; revised manuscript received 25 July 2018; published 15 October 2018)

On 17 August 2017, the LIGO and Virgo observatories made the first direct detection of gravitational waves from the coalescence of a neutron star binary system. The detection of this gravitational-wave signal, GW170817, offers a novel opportunity to directly probe the properties of matter at the extreme conditions found in the interior of these stars. The initial, minimal-assumption analysis of the LIGO and Virgo data placed constraints on the tidal effects of the coalescing bodies, which were then translated to constraints on neutron star radii. Here, we expand upon previous analyses by working under the hypothesis that both bodies were neutron stars that are described by the same equation of state and have spins within the range observed in Galactic binary neutron stars. Our analysis employs two methods: the use of equation-of-state-insensitive relations between various macroscopic properties of the neutron stars and the use of an efficient parametrization of the defining function $p(\rho)$ of the equation of state itself. From the LIGO and Virgo data alone and the first method, we measure the two neutron star radii as $R_1 = 10.8^{+2.0}_{-1.7}$ km for the heavier star and $R_2 = 10.7^{+2.1}_{-1.5}$ km for the lighter star at the 90% credible level. If we additionally require that the equation of state supports neutron stars with masses larger than 1.97 $M_\odot$ as required from electromagnetic observations and employ the equation-of-state parametrization, we further constrain $R_1 = 11.9^{+1.4}_{-1.4}$ km and $R_2 = 11.9^{+1.4}_{-1.4}$ km at the 90% credible level. Finally, we obtain constraints on $p(\rho)$ at supranuclear densities, with pressure at twice nuclear saturation density measured at $3.5^{+2.7}_{-1.7} \times 10^{34}$ dyn cm^{-2} at the 90% level.

PHYSICAL REVIEW C VOLUME 36, NUMBER 1 JULY 1987

Relativistic description of nuclear systems in the Hartree-Fock approximation

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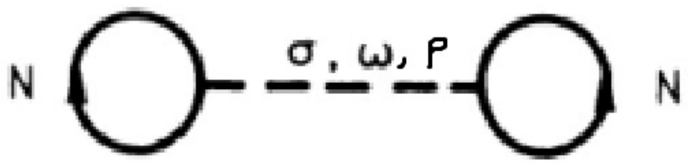

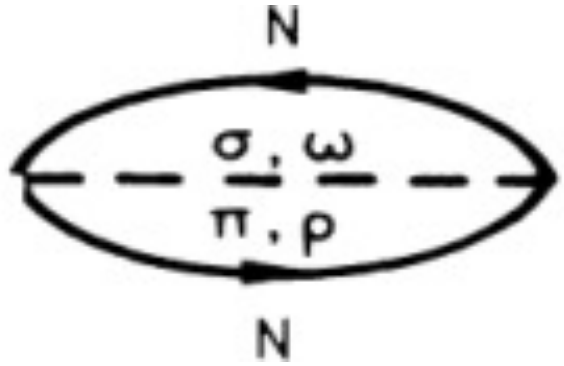

	K (MeV)	a_4 (MeV)	M^*/M	$\langle v/c \rangle$
(a)	540	19.5	0.54	0.35
(b)	615	29.5	0.51	0.30
(c)	545	29.5	0.51	0.33
(d)	355	28	0.63	0.42
(e)	465	28	0.56	0.37

PHYSICAL REVIEW C VOLUME 48, NUMBER 6 DECEMBER 1993

Relativistic Hartree-Fock approximation in a nonlinear model for nuclear matter and finite nuclei

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$$\mathcal{L}_0=\bar{\psi}(i\gamma_\mu\partial^\mu-M)\psi+\tfrac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma)-U(\sigma)+\tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}+\tfrac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu-\tfrac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} +\tfrac{1}{2}(\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi}-m_\pi^2\boldsymbol{\pi}^2)-\tfrac{1}{4}H_{\mu\nu}H^{\mu\nu},$$

$$\mathcal{L}_I=-g_\sigma\bar{\psi}\sigma\psi-g_\omega\bar{\psi}\gamma^\mu\omega_\mu\psi-\frac{f_\omega}{2M}\bar{\psi}\sigma^{\mu\nu}\partial_\mu\omega_\nu\psi -g_\rho\bar{\psi}\gamma^\mu\boldsymbol{\rho}_\mu\cdot\boldsymbol{\tau}\psi-\frac{f_\rho}{2M}\bar{\psi}\sigma^{\mu\nu}\partial_\mu\boldsymbol{\rho}_\nu\cdot\boldsymbol{\tau}\psi -e\bar{\psi}\gamma^\mu\tfrac{1}{2}(1+\tau_3)A_\mu\psi-\frac{f_\pi}{m}\bar{\psi}\gamma_5\gamma^\mu\partial_\mu\boldsymbol{\pi}\cdot\boldsymbol{\tau}\psi,$$

$$U(\sigma)=\tfrac{1}{2}m_\sigma^2\sigma^2+\tfrac{1}{3}b\sigma^3+\tfrac{1}{4}c\sigma^4 .$$

Model	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_σ (MeV)	$10^3\bar{b}$	$10^3\bar{c}$	K (MeV)	M^*/M	a_4 (MeV)
Ref. [18]	4.16	11.18	440	0	0	465	0.56	38.6
HF(δ)	7.19	8.22	525	0	0	399	0.60	35.0
HFSI	4.005	10.4	412	−6.718	−14.61	250	0.61	35.0
HFSI(δ)	6.92	7.5	515	−1.52	−2.62	300	0.63	33.9

PHYSICAL REVIEW C **78**, 065805 (2008)

Neutron star properties in density-dependent relativistic Hartree-Fock theory

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$$g_\phi(\rho_b)=g_\phi(\rho_0)\,f_\phi(x)$$

$$g_\rho(\rho_b)=g_\rho(0)\,e^{-a_\rho x},\quad f_\pi(\rho_b)=f_\pi(0)\,e^{-a_\pi x}.\qquad f_\phi(x)=a_\phi\frac{1+b_\phi(x+d_\phi)^2}{1+c_\phi(x+d_\phi)^2}.$$

	ρ_0	E_B/A	K	J	M_S^*/M
PKO1	0.1520	−15.996	250.239	34.371	0.5900
PKO2	0.1510	−16.027	249.597	32.492	0.6025
PKO3	0.1530	−16.041	262.469	32.987	0.5862

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_I$$

$$\begin{aligned}
\mathcal{L}_0 \;=\; & \sum_B \bar{\psi}_B(i\gamma_\mu\partial^\mu - M_B)\psi_B + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^{*2}\sigma^2) \\
& + \frac{1}{2}m_\omega^{*2}\omega_\mu\omega^\omega - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\rho^{*2}\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu \\
& - \frac{1}{4}\boldsymbol{G}_{\mu\nu}\cdot\boldsymbol{G}^{\mu\nu} + \frac{1}{2}(\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi} - m_\pi^{*2}\boldsymbol{\pi}^2),
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_I \;=\; & -g_\sigma^*\bar{\psi}\sigma\psi - g_\omega^*\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho^*\bar{\psi}\gamma_\mu\boldsymbol{\rho}^\mu\cdot\boldsymbol{\tau}\psi \\
& - \frac{f_\pi^*}{m_\pi^*}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\boldsymbol{\pi}\cdot\boldsymbol{\tau}\psi,
\end{aligned}$$

$$\frac{m_\sigma^*}{m_\sigma} = \frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = \frac{f_\pi^*}{f_\pi} = 1 - x\frac{\rho}{\rho_0},$$

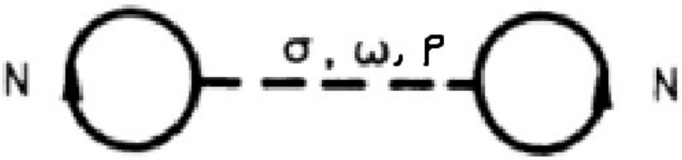
G. E. Brown and M. Rho,
Phys. Rev.Lett. **66**,2720 (1991).

$$\frac{g_\sigma^*}{g_\sigma} = \frac{1}{1+y\rho/\rho_0}, \qquad \frac{g_\omega^*}{g_\omega} = \frac{1-x\rho/\rho_0}{1+w\rho/\rho_0},$$
$$\frac{g_\rho^*}{g_\rho} = \frac{1-x\rho/\rho_0}{1+z\rho/\rho_0}.$$

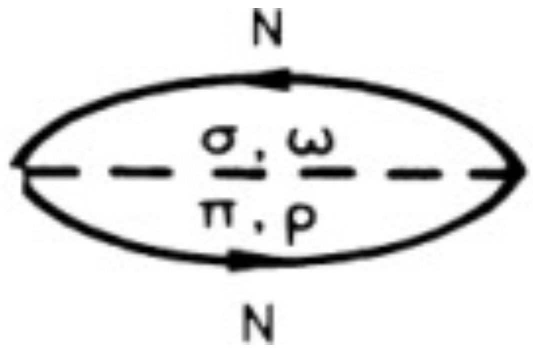
W. Z. Jiang, B. A. Li, and L. W. Chen,
Phys. Lett. B 653, 184-189(2007).

$$\epsilon = \epsilon_K + \epsilon_D + \epsilon_E,$$

$$\epsilon_K = \sum_{B=n,p} \frac{1}{\pi^2} \int_0^{k_{F,B}} k^2 dk (k\hat{K} + M_B \hat{M}_B),$$



$$\epsilon_D = -\frac{1}{2}\frac{g_\sigma^{*2}}{m_\sigma^{*2}}\rho_s^2 + \frac{1}{2}\frac{g_\omega^{*2}}{m_\omega^{*2}}\rho^2 + \frac{1}{2}\frac{g_\rho^{*2}}{m_\rho^{*2}}\rho_3^2,$$



$$\begin{aligned}\epsilon_E = \frac{1}{2}\frac{1}{(2\pi)^4} \sum_{\alpha,B,B'} \int_0^{k_{F,B}} \int_0^{k_{F,B'}} kk'dkdk' \\ \times\{\delta_{BB'}[A_\alpha(k,k') + \hat{M}_B(k)\hat{M}_{B'}(k')B_\alpha(k,k') \\ +\hat{K}(k)\hat{K}(k')C_\alpha(k,k')]_{\sigma,\omega} + (2-\delta_{BB'})[A_\alpha(k,k') \\ +\hat{M}_B(k)\hat{M}_{B'}(k')B_\alpha(k,k') \\ +\hat{K}(k)\hat{K}(k')C_\alpha(k,k')]_{\rho,\pi}\}.\end{aligned}$$

$$\Sigma(p)u(p,s,\tau) = \frac{\delta}{\delta \bar{u}(p,s,\tau)} \sum_{\sigma,\omega,\rho,\pi} \left[\varepsilon_\phi^D + \varepsilon_\phi^E\right]$$

$$\Sigma_B^S(k) = -\frac{g_\sigma^{*2}}{m_\sigma^{*2}}\rho_S + \frac{1}{(4\pi)^2 k}\sum_{\alpha,B'}\int_0^{k_{F,B'}} k' dk' \times$$

$$\hat{M}_{B'}(k')[\delta_{BB'}B_\alpha(k,k')_{\sigma,\omega} + (2-\delta_{BB'})B_\alpha(k,k')_{\rho,\pi}],$$

$$\Sigma_B^0(k) = \frac{g_\omega^{*2}}{m_\omega^{*2}}\rho + \frac{g_\rho^{*2}}{m_\rho^{*2}}\rho_3 + \frac{1}{(4\pi)^2 k}\sum_{\alpha,B'}\int_0^{k_{F,B'}} k' dk'$$

$$\times[\delta_{BB'}A_\alpha(k,k')_{\sigma,\omega} + (2-\delta_{BB'})A_\alpha(k,k')_{\rho,\pi}],$$

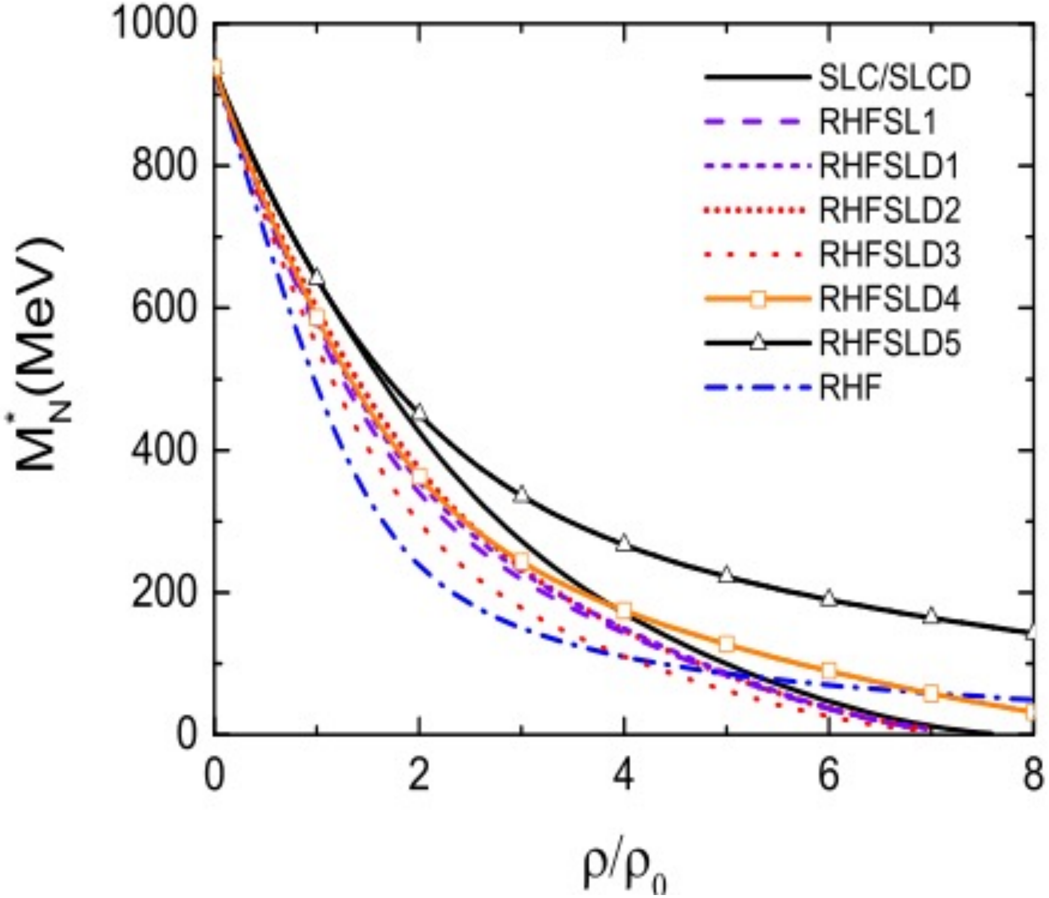
$$\Sigma_B^V(k) = \frac{1}{(4\pi)^2 k}\sum_{\alpha,B'}\int_0^{k_{F,B'}} \hat{K}(k')k' dk' \times$$

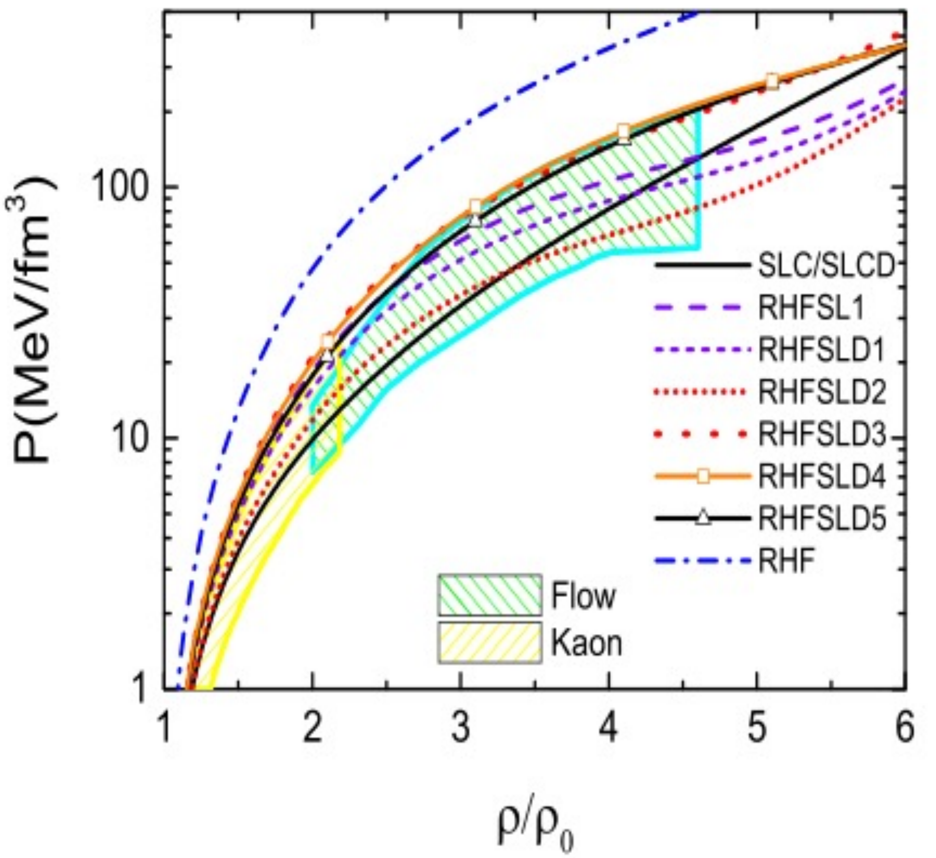
$$[\delta_{BB'}C_\alpha(k,k')_{\sigma,\omega} + (2-\delta_{BB'})C_\alpha(k,k')_{\rho,\pi}].$$

$$M_B^*(k) = M_B + \Sigma_B^S(k),$$

$$\boldsymbol{k}^* = \boldsymbol{k} + \hat{\boldsymbol{k}}\Sigma_B^V(k),$$

$$E_B^*(k) = \sqrt{M_B^{*2} + \boldsymbol{k}^{*2}},$$





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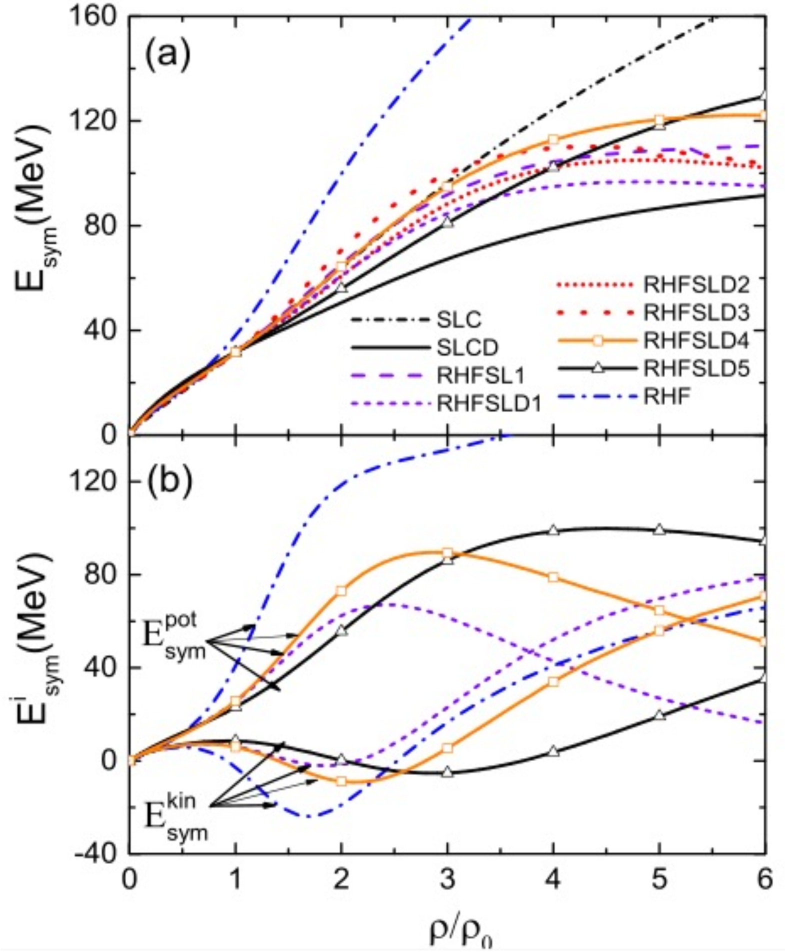
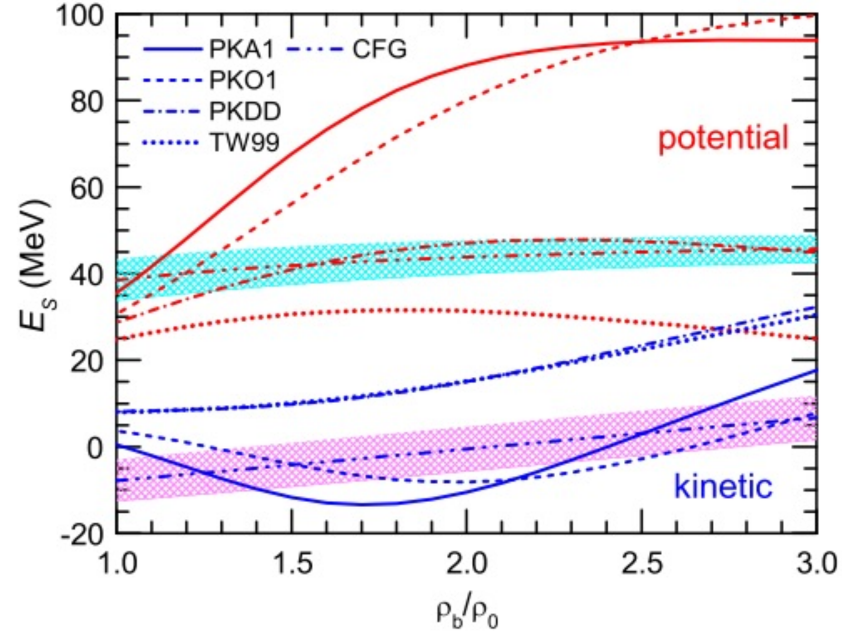


$$\epsilon = \epsilon_K + \epsilon_D + \epsilon_E,$$

$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2(\epsilon/\rho)}{\partial\delta^2}|_{\delta=0},$$

$$E^{pot}_{sym} = \frac{1}{2}\frac{\partial^2((\epsilon_D+\epsilon_E)/\rho)}{\partial\delta^2}|_{\delta=0}$$

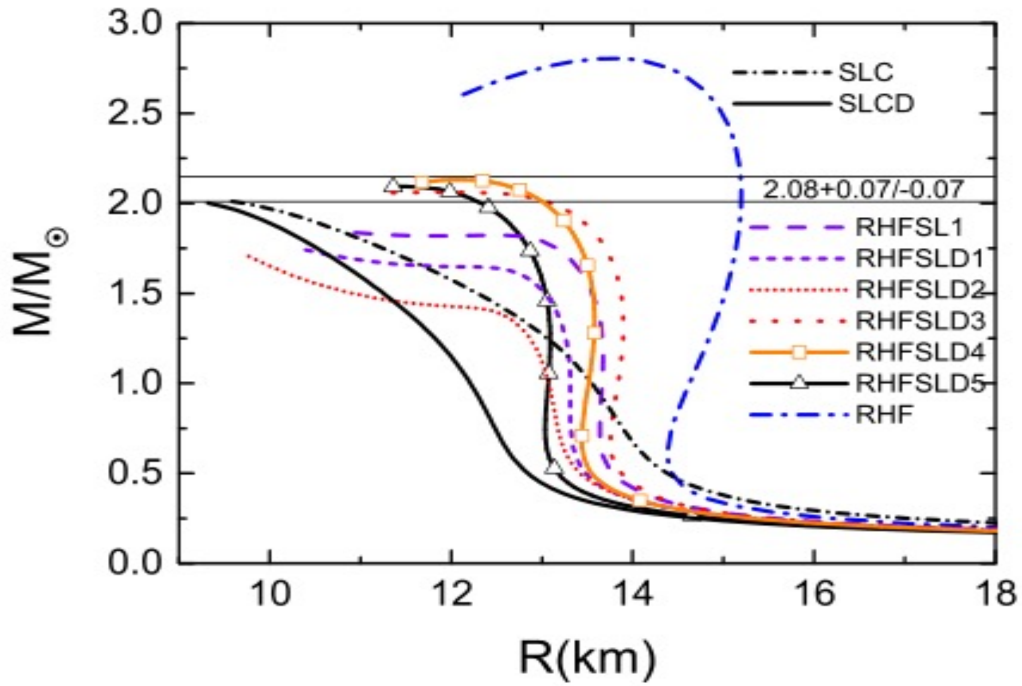
$$E^{kin}_{sym} = \frac{1}{2}\frac{\partial^2(\epsilon_K/\rho)}{\partial\delta^2}|_{\delta=0}$$



Q. Zhao et al., J. Phys. G: Nucl. Part. Phys. **42**, 095101(2015).

Model	g_σ	g_ω	g_ρ	f_π	x	y	z	E_B/A(MeV)	κ(MeV)	E_{sym}(MeV)	L(MeV)	$M_{max}/M_\odot$	$R(1.4M_\odot)$
SLC	10.1408	10.3261	3.8021	-	0.126	0.239	-	-16.3	230.0	31.6	92.3	2.01	12.6
SLCD	10.1408	10.3261	5.7758	-	0.126	0.239	0.5191	-16.3	230.0	31.6	61.5	2.00	11.5
RHFSL1	10.410	10.190	1.721	-	0.126	0.239	-	-16.0	300.6	31.6	90.4	1.84	13.6
RHFSLD1	10.236	9.978	2.832	-	0.126	0.239	0.5191	-16.0	276.3	31.6	79.7	1.74	13.2
RHFSLD2	9.863	9.798	2.468	1.000	0.126	0.239	0.5191	-16.0	237.8	31.6	76.9	1.71	12.5
RHFSLD3	10.485	10.838	0.130	1.000	0.126	0.210	0.5191	-16.0	301.0	31.6	96.0	2.06	13.9
RHFSLD4	9.898	10.063	1.905	1.000	0.092	0.170	0.5191	-16.0	303.8	31.6	84.7	2.13	13.6
RHFSLD5	9.148	8.922	2.789	1.000	0.053	0.140	0.5191	-16.0	292.3	31.6	73.1	2.09	13.1
RHF	10.607	11.759	-	1.000	-	-	-	-16.0	524.7	37.9	149.2	2.80	15.0

$$\frac{m_\sigma^*}{m_\sigma} = \frac{m_\omega^*}{m_\omega} = \frac{m_\rho^*}{m_\rho} = \frac{f_\pi^*}{f_\pi} = 1 - x\frac{\rho}{\rho_0},$$



Si-Na Wei, Wei-Zhou Jiang, and Zhao-Qing Feng,
Phys. Rev. C 104, 045804(2021).

总结

1.在RHF中考虑BR scaling，可以使得核物质状态方程变软。考虑BR scaling，对称核物质的状态方程可以符合由重离子碰撞提取得到限制区间。此外，非对称核物质状态方程(对称能)在核物质密度比较高时会变得比较平甚至有些许下降。

2.当质量下降比较快的时候($x = 0.126$),1.4倍太阳质量的中子星的半径会超过GW170817给出的上限限制($R_{1.4M_s} \approx 13.7km$)。当$x = 0.092$时，1.4倍太阳质量的中子星的半径为$13.6km$，接近于GW170817给出的上限限制。所以，介子质量下降$x \leq 0.092$时，RHF的计算结果更合理些。