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誠樸雄偉 勵學敦行

Properties of Compact Star Matter

--- perspectives based on ChEFT

马永亮

南京大学

2024第九届手征有效场论研讨会
2024.10.18-2024.10.22
湖南，长沙

主要合作者

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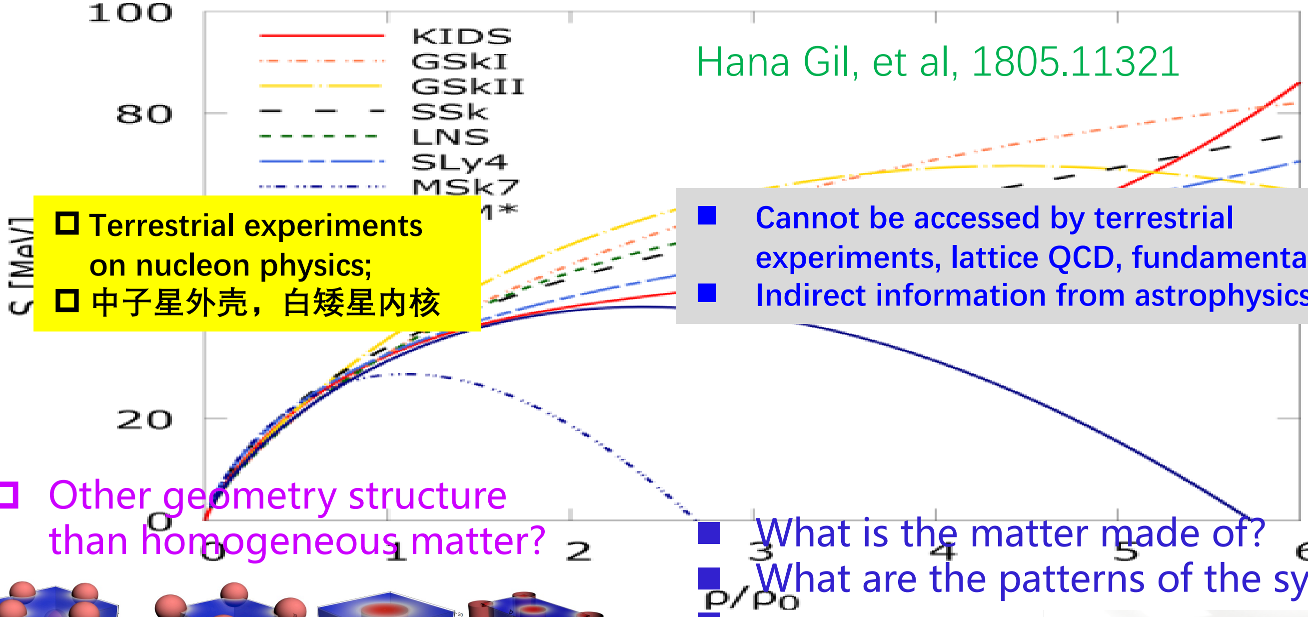
■ Property of nuclear matter has be studied for several decades:

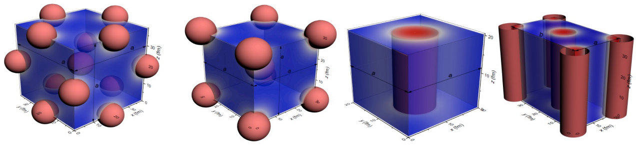


Hana Gil, et al, 1805.11321

- ☐ Terrestrial experiments on nucleon physics;
- ☐ 中子星外壳，白矮星内核

- ■ Cannot be accessed by terrestrial experiments, lattice QCD, fundamental QCD!
- ■ Indirect information from astrophysics.

☐ Other geometry structure than homogeneous matter?



- ■ What is the matter made of?
- ■ What are the patterns of the symmetries involved?
- ■ ……

Constraints from symmetric nuclear matter

	Empirical
$n_0(\mathrm{fm}^{-3})$	0.155 ± 0.050 [37]
$e_0(\mathrm{MeV})$	-15.0 ± 1.0 [37]
$K_0(\mathrm{MeV})$	230 ± 30 [38]
$E_{\mathrm{sym}}(n_c)(\mathrm{MeV})$	26.7 ± 0.2 [39]
$E_{\mathrm{sym}}(n_0)(\mathrm{MeV})$	30.9 ± 1.9 [40]
$E_{\mathrm{sym}}(2n_0)(\mathrm{MeV})$	46.9 ± 10.1 [41]
$L(n_c)(\mathrm{MeV})$	43.7 ± 7.8 [42]
$L(n_0)(\mathrm{MeV})$	52.5 ± 17.5 [40]
$J_0(\mathrm{MeV})$	-700 ± 500 [43]

[37] A. Sedrakian, J.-J. Li, and F. Weber, Prog. Part. Nucl. Phys. **131**, 104041 (2023), arXiv:2212.01086 [nucl-th].
[38] M. Dutra, O. Lourenco, J. S. Sa Martins, A. Delfino, J. R. Stone, and P. D. Stevenson, Phys. Rev. C **85**, 035201 (2012), arXiv:1202.3902 [nucl-th].
[39] Z. Zhang and L.-W. Chen, Phys. Lett. B **726**, 234 (2013), arXiv:1302.5327 [nucl-th].
[40] J. M. Lattimer and Y. Lim, Astrophys. J. **771**, 51 (2013), arXiv:1203.4286 [nucl-th].
[41] B.-A. Li, P. G. Krastev, D.-H. Wen, and N.-B. Zhang, Eur. Phys. J. A **55**, 117 (2019), arXiv:1905.13175 [nucl-th].
[42] Z. Zhang and L.-W. Chen, Phys. Rev. C **90**, 064317 (2014), arXiv:1407.8054 [nucl-th].
[43] M. Farine, J. M. Pearson, and F. Tondeur, Nucl. Phys. A **615**, 135 (1997).

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- Information about the masses of the heaviest neutron stars derives primarily from precise Shapiro time delay measurements of pulsars orbiting in binary systems with white dwarf companions

$$\text{PSR J1614–2230} \qquad M = 1.908 \pm 0.016\, M_\odot\,,$$
$$\text{PSR J0348+0432} \qquad M = 2.01 \pm 0.04\, M_\odot\,,$$
$$\text{PSR J0740+6620} \qquad M = 2.08 \pm 0.07\, M_\odot\,.$$
$$\text{PSR J0952–0607} \qquad M = 2.35 \pm 0.17\, M_\odot\,.$$

- P. B. Demorest, *et al.* Nature 2010, 467, 1081.
- E. Fonseca, *et al.* Astrophys. J. 2016, 832, 167.
- Z. Arzoumanian, *et al.* Astrophys. J. Suppl. 2018, 235, 37.
- J. Antoniadis, *et al.* Science 2013, 340, 448.
- H. T. Cromartie, *et al.* Nat. Astron. 2020, 4, 72.
- E. Fonseca, *et al.* Astrophys. J. Lett. 2021, 915, L12.
- R. W. Romani, *et al.* Astrophys. J. Lett. 2022, 934, L17.

- Together with their masses the radii of neutron stars can be inferred from X-ray profiles of rotating hot-spot patterns measured with the NICER telescope.

$$\text{PSR J0030+0451} \qquad M = 1.34^{+0.15}_{-0.16}\, M_\odot\,, \qquad R = 12.71^{+1.14}_{-1.19}\,\text{km}\,,$$
$$\text{PSR J0740+6620} \qquad M = 2.072^{+0.067}_{-0.066}\, M_\odot\,, \qquad R = 12.39^{+1.30}_{-0.98}\,\text{km}\,.$$

- T. T. Riley, *et al.* Astrophys. J. Lett. 2019, 887, L21.
- T. E. Riley, *et al.* Astrophys. J. Lett. 2021, 918, L27.

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

Editors' Suggestion   Featured in Physics

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

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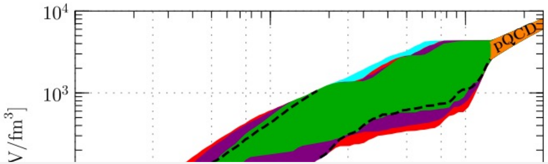
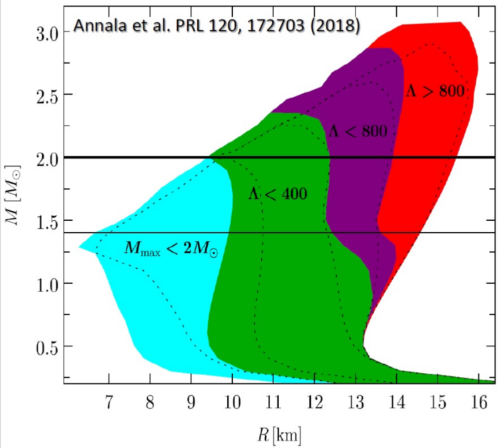
Switzerland
6 Stavanger,

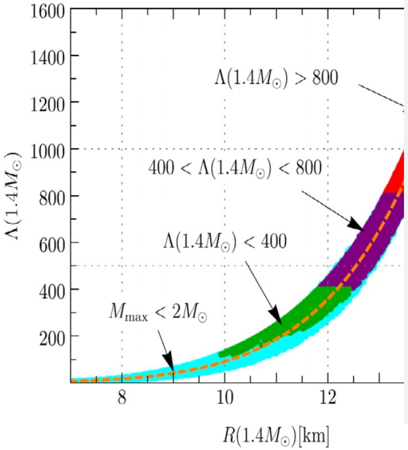
ceived 6 Feb



Impact of $\tilde{\Lambda} < 800$ on NS radius & EOS

- $\Lambda_{1.4} \lesssim 800$: in terms of NS radius $10 \lesssim R_{1.4M_\odot} \lesssim 13.5$ km for an EOS
  - connects to the NNLO pQCD (Kurkela et al. 2010) and chiral EFT (Hebeler et al. 2013)
  - causality $c_s < c$ and $M_{\mathrm{EOS,max}} \gtrsim 2M_\odot$ constraints in the intermediate region





- Tidal deformability(GW170817):

$$\Lambda_{1.4} < 800$$

$$\tilde{\Lambda} = 300^{+420}_{-230} \quad \rightarrow \tilde{\Lambda} = 190^{+390}_{-120}$$

$$R = 11.9^{+1.4}_{-1.4}\ km$$

C. Y. Tsang, *et al.*, 1807.06571

Inset: The same function constructed with tritropic interpolating functions only.

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■ 量子强子动力学是描述低能强相互作用不可缺少的工具

$$\mathcal{L}_{\rm fermion} = \bar{\Psi}\left(i\not{\partial} - m_N\right)\Psi + \bar{\psi}\left(i\not{\partial} - m_e\right)\psi \ ,$$

$$\begin{aligned}\mathcal{L}_{\rm boson} = &\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\ &- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3\left(\omega_\mu\omega^\mu\right)^2 \\ &- \frac{1}{4}\vec{\rm P}_{\mu\nu}\cdot\vec{\rm P}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \ ,\end{aligned}$$

$$\mathcal{L}_{\rm I} = \bar{\Psi}\left(-g_\sigma\sigma - g_\omega\not{\omega} - g_\rho\not{\vec{\rho}}\right)\Psi \ ,$$

➢ B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. 16, 1 (1986);
➢ Y. Sugahara, H. Toki, Nucl.Phys.A 579 (1994) 557-572;
➢ H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, Nucl.Phys.A 637 (1998) 435-450 .

Asymmetric nuclear matter in relativistic mean-field models with isoscalar- and isovector-meson mixing

2202.06468

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[1] Department of Physics and OMEG Institute, Soongsil University, Seoul 06978, Republic of Korea
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ABSTRACT

Using the relativistic mean-field model with nonlinear couplings between the isoscalar and isovector mesons, we study the properties of isospin-asymmetric nuclear matter. Not only the vector mixing, $\omega_\mu\omega^\mu\boldsymbol{\rho}_\nu\boldsymbol{\rho}^\nu$, but also the quartic interaction due to the scalar mesons, $\sigma^2\boldsymbol{\delta}^2$, is taken into account to investigate the density dependence of nuclear symmetry energy, $E_{\rm sym}$, and the neutron-star properties. It is found that the δ meson increases $E_{\rm sym}$ at high densities, whereas the σ-δ mixing makes $E_{\rm sym}$ soft above the saturation density. Furthermore, the δ meson and its mixing have a large influence on the radius and tidal deformability of a neutron star. In particular, the σ-δ mixing reduces the neutron-star radius, and, thus, the present calculation can simultaneously reproduce the dimensionless tidal deformabilities of a canonical $1.4M_\odot$ neutron star observed from the binary neutron star merger, GW170817, and from the compact binary coalescence, GW190814.

The Astrophysical Journal, 929:183 (7pp), 2022 April 20 https://doi.org/10.3847/1538-4357/ac5e2a

Effects of Isoscalar- and Isovector-scalar Meson Mixing on Neutron Star Structure

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Abstract

Based on the accurately calibrated interaction FSUGold, we show that including isovector-scalar δ meson and its coupling to isoscalar-scalar σ meson in the relativistic mean-field (RMF) model can soften the symmetry energy $E_{\rm sym}(n)$ at intermediate densities while stiffening the $E_{\rm sym}(n)$ at high densities. We find this new RMF model can be simultaneously compatible with (1) the constraints on the equation of state of symmetric nuclear matter at suprasaturation densities from flow data in heavy-ion collisions; (2) the neutron skin thickness of ^{208}Pb from the PREX-II experiment; (3) the largest mass of a neutron star (NS) reported so far from PSR J0740+6620; (4) the limit of $\Lambda_{1.4} \leqslant 580$ for the dimensionless tidal deformability of the canonical 1.4 $M_\odot$ NS from the gravitational-wave signal GW170817; (5) the mass–radius relation of PSR J0030+0451 and PSR J0740+6620 measured by NICER. The new model thus removes the tension between PREX-II and GW170817 observed in the conventional RMF model.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Gravitational wave astronomy (675); Nuclear astrophysics (1129)

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■ 量子强子动力学是描述低能强相互作用不可缺少的工具

$$
\begin{aligned}
\mathcal{L}_{\text{fermion}} &= \bar{\Psi}\left(i\not{D} - m_N\right)\Psi + \bar{\psi}\left(i\not{D} - m_e\right)\psi \ , \\
\mathcal{L}_{\text{boson}} &= \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 \\
&\quad - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4} c_3 \left(\omega_\mu \omega^\mu\right)^2 \\
&\quad - \frac{1}{4}\vec{\mathrm{P}}_{\mu\nu} \cdot \vec{\mathrm{P}}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \ , \\
\mathcal{L}_{\mathrm{I}} &= \bar{\Psi}\left(-g_\sigma \sigma - g_\omega \not{\omega} - g_\rho \not{\vec{\rho}}\right)\Psi \ ,
\end{aligned}
$$

- B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. 16, 1 (1986);
- Y. Sugahara, H. Toki, Nucl.Phys.A 579 (1994) 557-572;
- H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, Nucl.Phys.A 637 (1998) 435-450 .

- 更一般地强子动力学模型：考虑到标量介子的夸克组分（马垚的报告）；
- 模型引入大量参数，手动寻找参数空间很困难。机器学习技术提供了有力的工具（郭凌君的报告）。

■ Phenomenological models, results are highly model dependent

- ◆ 很难与粒子物理与核物理中的许多基本问题直接联系起来：

  手征对称性的破缺机制、核子质量的起源……

  $f_\pi^*(\rho)$、m_N^*、m_ρ^*、$g_{\rho NN}^*$、 ……

➢ Models anchored on properties of fundamental QCD!

Chiral symmetry? Scale symmetry? Power counting?

Including σ, ρ, ω in addition to the standard NGB π and nucleon.

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■ GnEFT for NM

- Yan-Ling Li, YLM, Mannque Rho, Phys.Rev.D 95 (2017) 11, 114011.
- *"Effective Field Theories for Nuclei and Compact-Star Matter"*, YLM, Mannque Rho, (World Scientific, Singapore,2019)

Hadron fields:	π	ρ, ω	σ	N
Symmetry	NGBs of CSB	Gauge fields of HLS	NGB of SSB	Chiral multiplets

Implication (in medium)

- Topology of QCD (skyrmion, vortex, ...); （林凡的报告）
- Chiral symm. in-medium;
- Hidden flavor symm. in-medim.

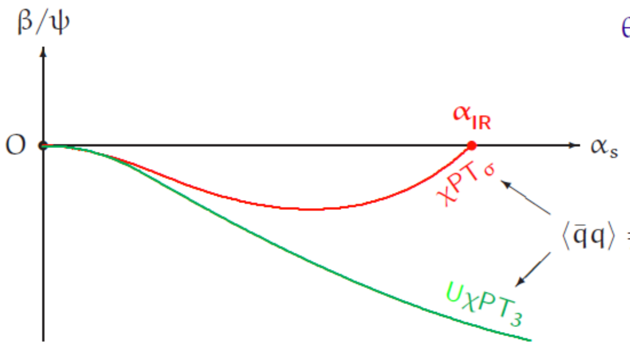
- Scale symm. in-medium; （张璐琦的报告）
- Peak of SV

Power counting: $O(p) \sim O(m_\pi) \sim O(g) \sim O(m_\sigma)$

$f_0(500)$ is a pNGB arising from (noted $m_{f_0} \cong m_K$). The SB of SS associated + an explicit breaking of SI.

Assumption: There is an Nonperturbative IR fixed point in the running QCD coupling constant α_s.

EB of SI: Departure of α_s from IRFP + current quark mass.



$$\theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s} G^2 + (1+\gamma_m) \sum_{q=u,d,s} m_q \bar{q} q$$

IR fixed point: $\beta(\alpha_{IR}) = 0$

$\chi PT_\sigma \Rightarrow$ expand in θ^μ_μ

$\alpha_s \lesssim \alpha_{IR}$, $m_{u,d,s} \sim 0$

about scale-*dependent* $|\text{vac}\rangle$

$\Rightarrow$ NG bosons π, K, η, σ.

$$\mathcal{L}^{\rm LO}_{\chi{\rm PT}_\sigma} = \mathcal{L}^{d=4}_{\rm inv} + \mathcal{L}^{d>4}_{\rm anom} + \mathcal{L}^{d<4}_{\rm mass},$$

$$\begin{aligned}
\mathcal{L}^{d=4}_{\rm inv} &= c_1 \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 {\rm Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) \\
&\quad + \frac{1}{2} c_2 \partial_\mu \chi \partial^\mu \chi + c_3 \left(\frac{\chi}{f_\chi}\right)^4, \\
\mathcal{L}^{d>4}_{\rm anom} &= (1-c_1)\frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^{2+\beta'} {\rm Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) \\
&\quad + \frac{1}{2}(1-c_2)\left(\frac{\chi}{f_\chi}\right)^{\beta'} \partial_\mu \chi \partial^\mu \chi \\
&\quad + c_4 \left(\frac{\chi}{f_\chi}\right)^{4+\beta'}, \\
\mathcal{L}^{d<4}_{\rm mass} &= \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} {\rm Tr}\left(\mathcal{M}^\dagger U + U^\dagger \mathcal{M}\right),
\end{aligned}$$

Crewther and Tunstall , PR**D91**, 034016, e-Print: 1312.3319

Provides an approach to include scalar meson in ChPT.

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$$\mathcal{L} = \mathcal{L}^M_{\chi PT_\sigma}(\pi, \chi, V_\mu) + \mathcal{L}^B_{\chi PT_\sigma}(\psi, \pi, \chi, V_\mu) - V(\chi)$$

$$\mathcal{L}^M_{\chi PT_\sigma}(\pi, \chi, V_\mu) = f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \mathrm{Tr}[\hat{a}_{\perp\mu}\hat{a}^\mu_\perp] + a f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \mathrm{Tr}[\hat{a}_{\parallel\mu}\hat{a}^\mu_\parallel] + \frac{1}{2g^2}\mathrm{Tr}[V_{\mu\nu}V^{\mu\nu}] + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi$$

$$\mathcal{L}^B_{\chi PT_\sigma}(\psi, \pi, \chi, V_\mu) = \mathrm{Tr}(\bar{B} i \gamma_\mu D^\mu B) - \frac{\chi}{f_\sigma}\mathrm{Tr}(\bar{B}B) + \cdots$$

$$V(\chi) \approx \frac{m_\sigma^2 f_\sigma^2}{4}\left(\frac{\chi}{f_\sigma}\right)^4 \left[\ln\left(\frac{\chi}{f_\sigma}\right) - \frac{1}{4}\right].$$

Only in terms of hadrons;
Intrinsic density dependence

- Enters through the VeV of dilaton: scale symmetry;
- Information from topology change is considered;
- Nucleon mass stays as a constant after topology change: parity doublet.
- *The topology change density $n_{1/2}$, parameter.*

Casheire Cat

Quark-Hadron continuity

Qualitative information from topology change

Density dependence of LECs

YLM, M. Rho, PPNP. 113 (2020) 103791

TABLE III. Nuclear matter properties at $n_0 < n_{1/2}$. The empirical values are merely exemplary. n_0 is in unit fm^{-3} and others are in unit MeV.

Parameter	Prediction	Empirical
n_0	0.161	0.16 ± 0.01 [9]
B.E.	16.7	16.0 ± 1.0 [9]
$E_{sym}(n_0)$	30.2	31.7 ± 3.2 [10]
$E_{sym}(2n_0)$	56.4	46.9 ± 10.1 [11];40.2 ± 12.8 [12]
$L(n_0)$	67.8	58.9 ± 16 [11];58.7 ± 28.1 [10]
K_0	250.0	230 ± 20 [13]

Agrees with the empirical values of the nuclear matter properties quite well.

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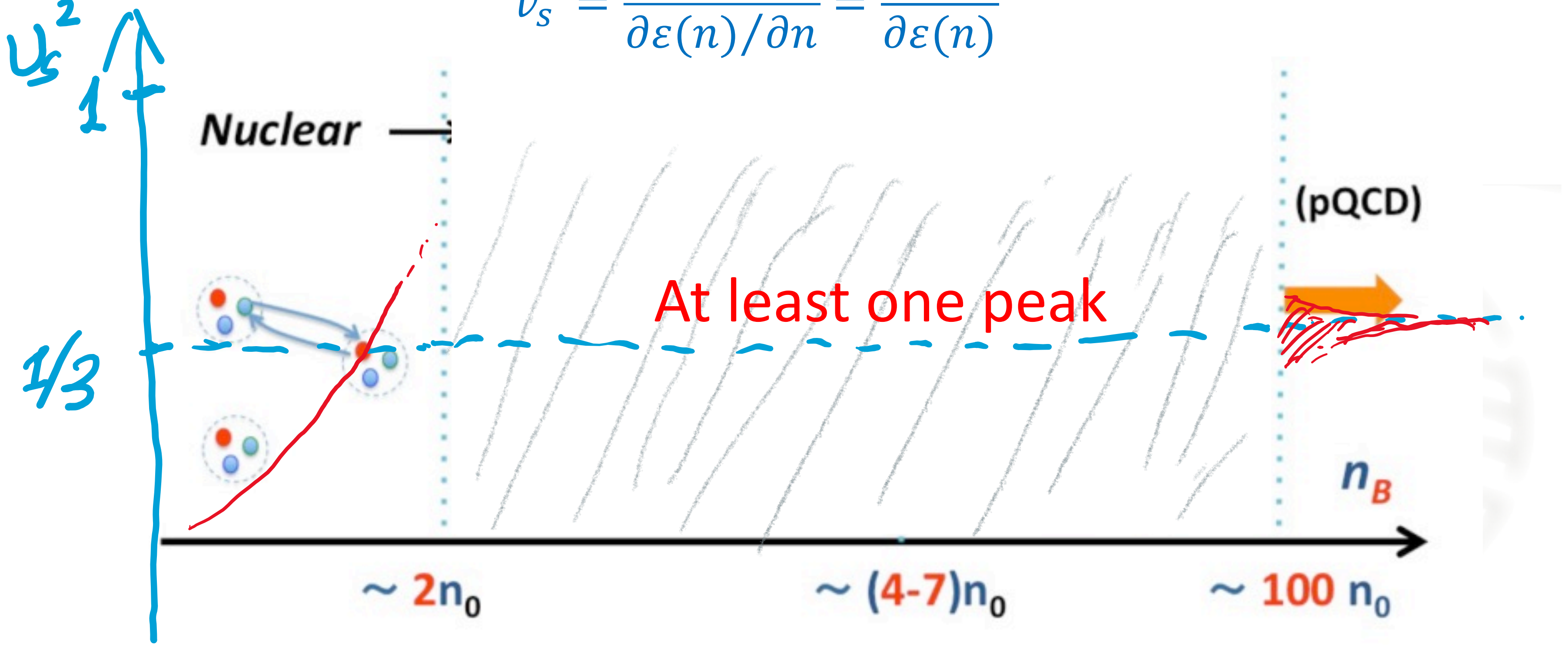
$$v_s^2 = \frac{\partial p(n)/\partial n}{\partial \varepsilon(n)/\partial n} = \frac{\partial p(n)}{\partial \varepsilon(n)}$$



- In the quarkyonic description of dense matter, a peak of SV emerges from the hadronic phase from quarkyonic phase transition when density is increased.

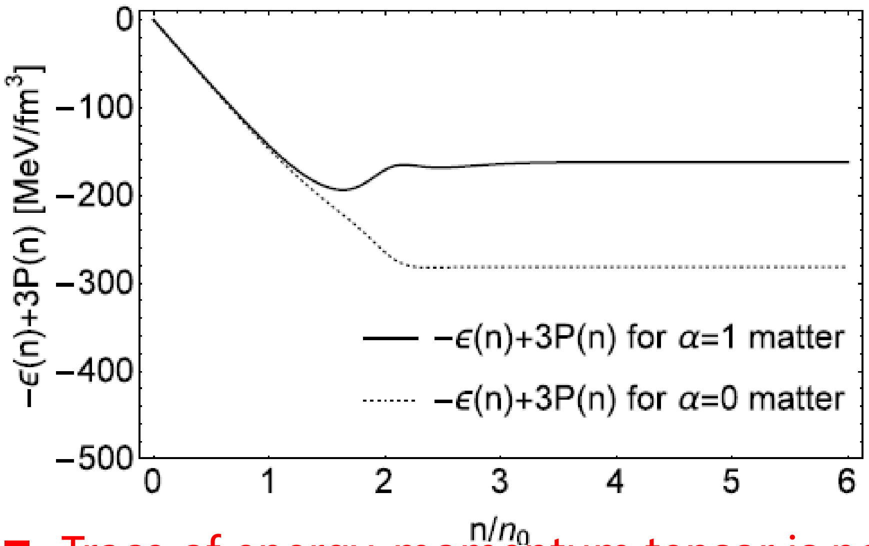
- L. McLerran and S. Reddy, Phys. Rev. Lett. 122, 122701 (2019).
- K. S. Jeong, L. McLerran, and S. Sen, Phys. Rev. C 101, 035201 (2020).
- T. Zhao and J. M. Lattimer, Phys. Rev. D 102, 023021 (2020).
- J. Margueron, H. Hansen, P. Proust, and G. Chanfray, Phys. Rev. C 104, 055803 (2021).

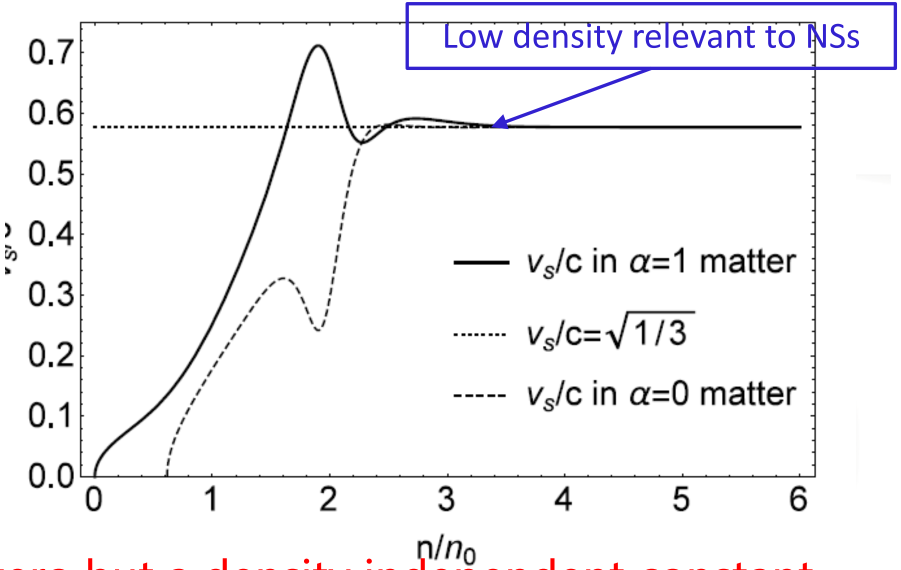
- In a unified approach to nuclei and dense compact star matter based on a GnEFT including pion, rho, omega and the lightest scalar meson regarded as dilaton, we found that the peak emerges at density $(2{\sim}4)n_0$ when the topology change effect was implemented through the Brown-Rho scaling.

- Y.-L. Ma and M. Rho, Phys. Rev. D 99, 014034 (2019).
- Y.-L. Ma and M. Rho, Prog. Part. Nucl. Phys. 113, 103791 (2020).
- Y.-L. Ma and M. Rho, AAPPS Bull. 31, 16 (2021).
- H. K. Lee, Y.-L. Ma, W.-G. Paeng, and M. Rho, Mod. Phys. Lett. A 37, 2230003 (2022).
- Y.-L. Ma and W.-G. Yang, Symmetry 15, 776 (2023).

$$\frac{\partial}{\partial n}\langle\theta^{\mu}_{\mu}\rangle = \frac{\partial\epsilon(n)}{\partial n}(1-3v_s^2) = 0$$

$$v_s^2/c^2 = \frac{\partial P(n)}{\partial n} \Big/ \frac{\partial\epsilon(n)}{\partial n}$$





- Trace of energy-momentum tensor is not zero but a density independent constant at $\gtrsim 2n_0$;

A feature NOT shared by ANY other models or theories in the field

- When $\geq 2n_0$, the sound velocity $\rightarrow 1/\sqrt{3}$ -- conformal sound velocity.

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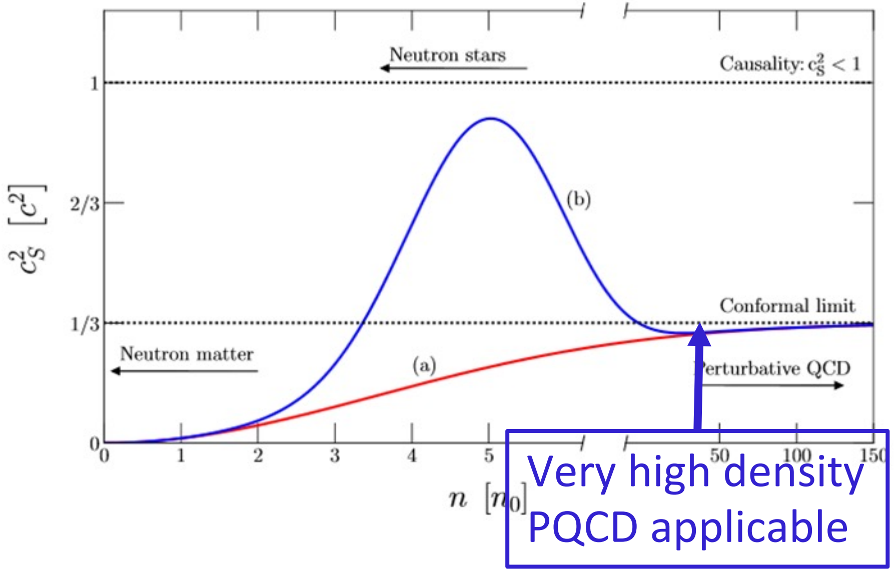
Standard Scenario

We found that the conformal limit of $c_S^2 \leqslant 1/3$ is in tension with current nuclear physics constraints and observations of two-solar-mass NSs, in accordance with the findings of Bedaque & Steiner (2015). If the conformal limit was found to hold at all densities, this would imply that nuclear physics models break down below $2n_0$.



S. Reddy et al, 2018

We are disagreeing!

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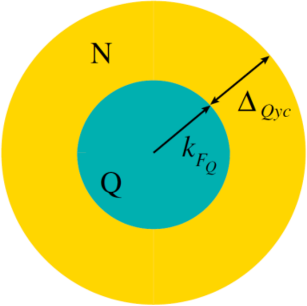
Supported by later publications

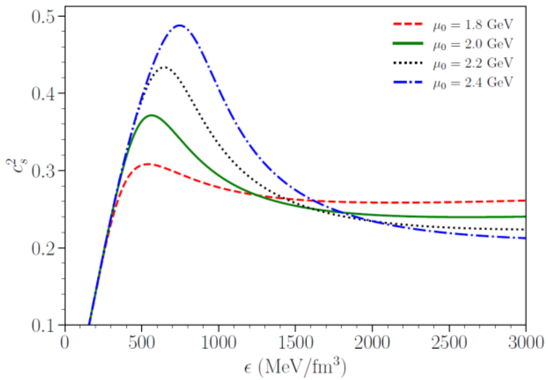
Quark-hadron crossover

$$P(\mu) = S(\mu)P_q(\mu) + (1 - S(\mu))P_h(\mu)$$

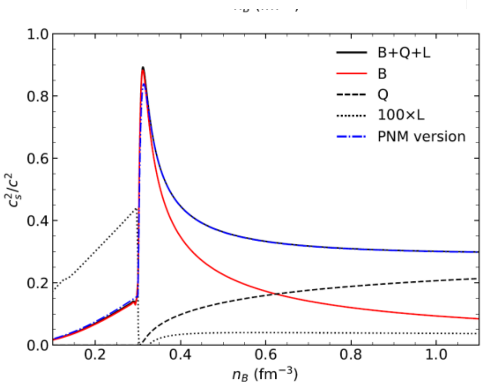
Quarkyonic mat



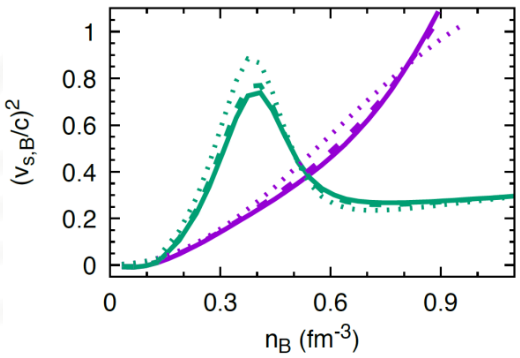
Quarkyonic matter



Kapusta & Welle, 2103.16633



Zhao & Lattimer, 2004.08293



Margueron et al, 2103.10209

- Using a hadron-quark meson model, people found that the peak of SV emerges from the smooth transition from BEC phase of pions to BCS phase with pion condensates on top of the quark Fermi sea which is actually the hadron-quark crossover that had been realized as the trigger of the peak.
  - R. Chiba, T. Kojo, and D. Suenaga, (2024), arXiv:2403.02538 [hep-ph].
  - R. Chiba and T. Kojo, (2023), arXiv:2304.13920 [hep-ph].
  - G. Baym, S. Furusawa, T. Hatsuda, T. Kojo, and H. Togashi, Astrophys. J. 885, 42 (2019).

- By combining the calculation using the chiral NN and 3N interactions with that using a functional RG approach based on QCD, people found the peak of SV is due to the formation of the diquark gap at intermediate density.
  - M. Leonhardt, M. Pospiech, B. Schallmo, J. Braun, C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. 125, 142502 (2020).

Trace Anomaly as Signature of Conformality in Neutron Stars

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We discuss an interpretation that a peak in the sound velocity in neutron star matter, as suggested by the observational data, signifies strongly coupled conformal matter. The normalized trace anomaly is a dimensionless measure of conformality leading to the derivative and the nonderivative contributions to the sound velocity. We find that the peak in the sound velocity is attributed to the derivative contribution from the trace anomaly that steeply approaches the conformal limit. Smooth continuity to the behavior of high-density QCD implies that the matter part of the trace anomaly may be positive definite. We discuss a possible implication of the positivity condition of the trace anomaly on the M-R relation of the neutron stars.

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Define normalized trace anomaly:

$$\Delta \equiv \frac{\langle \Theta \rangle_{T,\mu_B}}{3\varepsilon} = \frac{1}{3} - \frac{P}{\varepsilon}$$

$$v_s^2 = \frac{dP}{d\varepsilon} = v_{s,\mathrm{deriv}}^2 + v_{s,\mathrm{nonderiv}}^2,$$

$$\begin{cases} v_{s,\mathrm{deriv}}^2 \equiv -\dfrac{d\Delta}{d\eta}, \\ v_{s,\mathrm{nonderiv}}^2 \equiv \dfrac{1}{3} - \Delta. \end{cases}$$

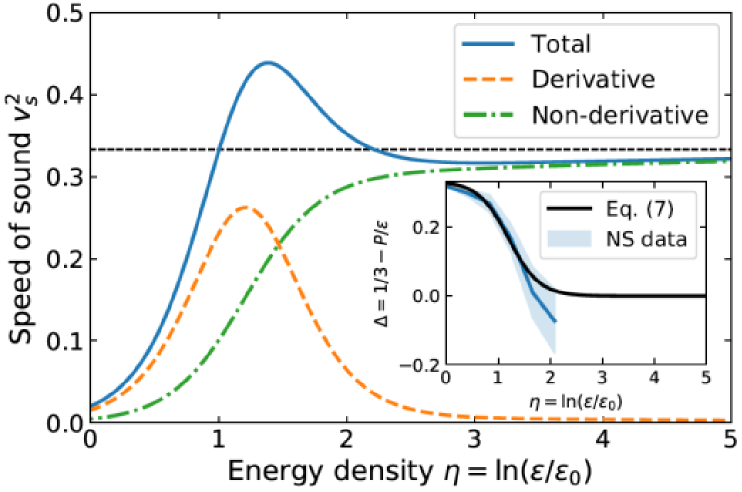

FIG. 2. The speed of sound and its decomposition (6) calculated from (7) as shown in the inset plot. The horizontal axis is the logarithmic energy η normalized to the value at the saturation point, $\varepsilon_0 = 150\,\mathrm{MeV/fm^3}$.

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Reaching percolation and conformal limits in neutron stars

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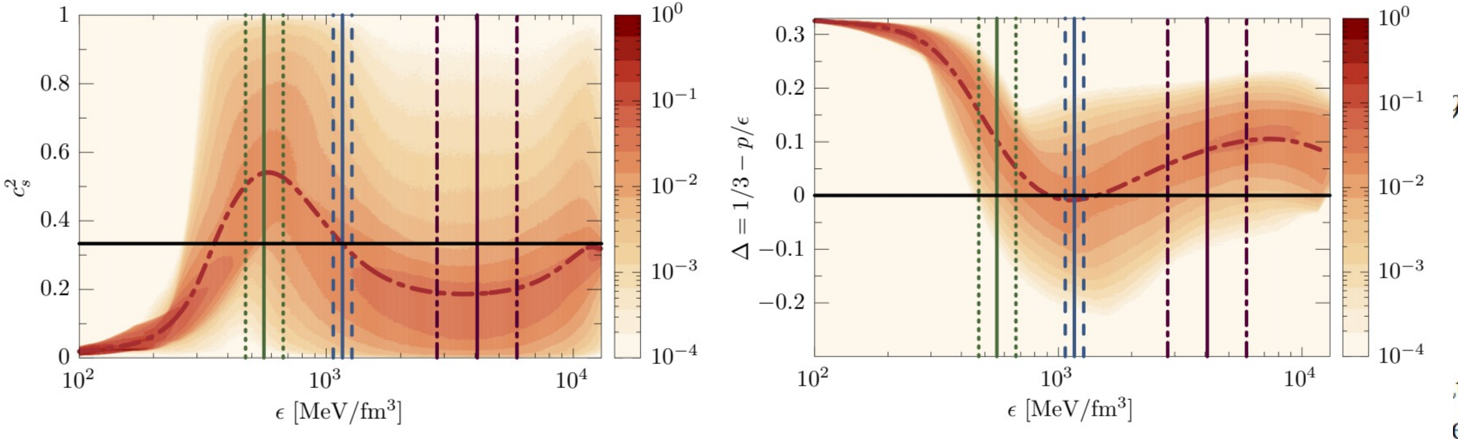

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speed of sound and trace anomaly and demonstrate that they are driven towards their conformal values at the center of maximally massive NSs. The local peak of the speed of sound is shown to be located at values of the energy and particle densities which are consistent with deconfinement and percolation conditions in QCD matter. We also analyze fluctuations of the net-baryon number density in the context of possible remnants of critical behavior. We find that the global maxima of the variance of these fluctuations emerge at densities beyond those found in the interiors of NSs.

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Peak of SV connects to the behavior of trace anomaly in medium.

What will happen when the trace anomaly is implemented in an effective model/theory?

A mean field calculation based on chiral-scale EFT

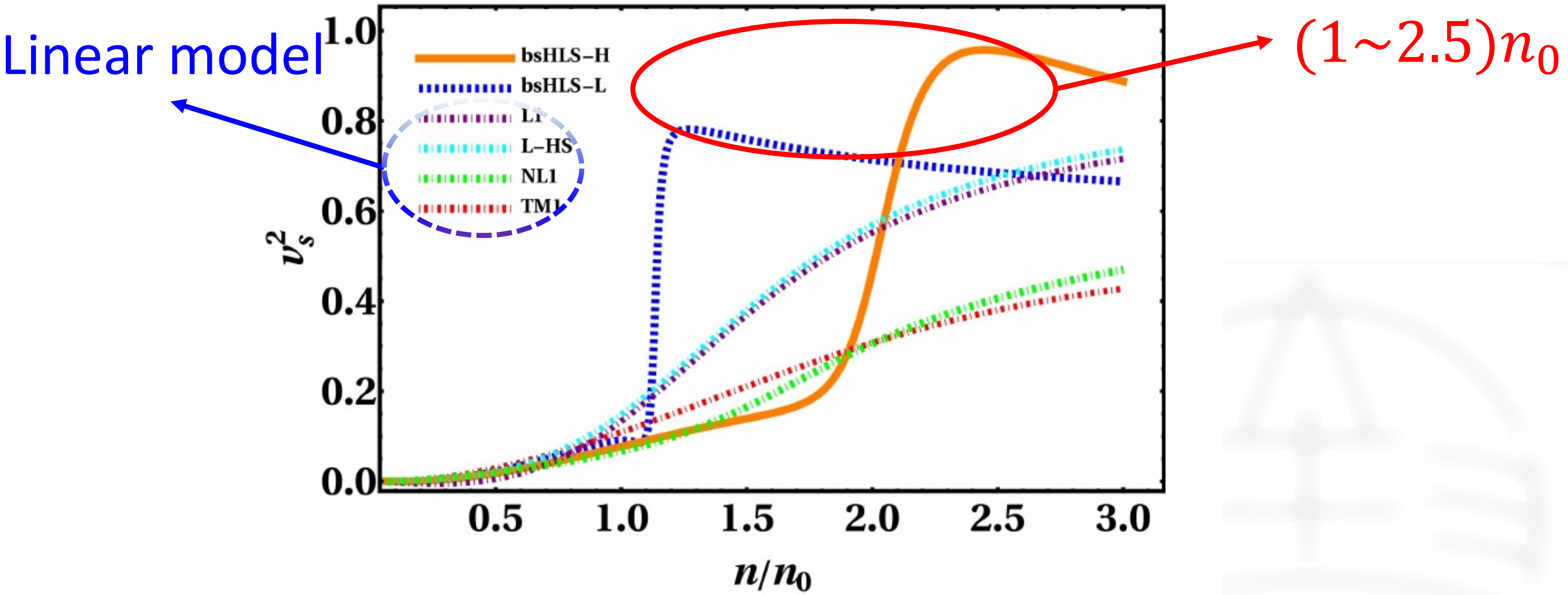
$$
\begin{aligned}
\mathcal{L}_M = & \frac{m_\rho^2}{g_\rho^2}\Phi^2\,\mathrm{Tr}(\hat{\alpha}_{\parallel}^{\mu}\hat{\alpha}_{\mu\parallel}) \\
& + \frac{1}{2}\left(\frac{m_\omega^2}{g_\omega^2} - \frac{m_\rho^2}{g_\rho^2}\right)\Phi^2\,\mathrm{Tr}(\hat{\alpha}_{\parallel}^{\mu})\,\mathrm{Tr}\left(\hat{\alpha}_{\mu\parallel}\right) \\
& - V(\chi) + \cdots , \qquad (1)
\end{aligned}
$$

$$
V(\chi) = -h_5\Phi^4 - h_6\Phi^{4+\beta'},
$$

$$
\begin{aligned}
\mathcal{L}_B = & \bar{N} i\gamma_\mu D^\mu N - m_N \Phi \bar{N} N \\
& - g_{\omega NN}\omega^\mu \bar{N}\gamma_\mu N - g_{\rho NN}\rho^{a\mu}\bar{N}\tau^a\gamma_\mu N \\
& - g_{\omega NN}^{SSB}\left(\Phi^{\beta'} - 1\right)\omega^\mu \bar{N}\gamma_\mu N \\
& - g_{\rho NN}^{SSB}\left(\Phi^{\beta'} - 1\right)\rho^{a\mu}\bar{N}\tau^a\gamma_\mu N \qquad (3)
\end{aligned}
$$

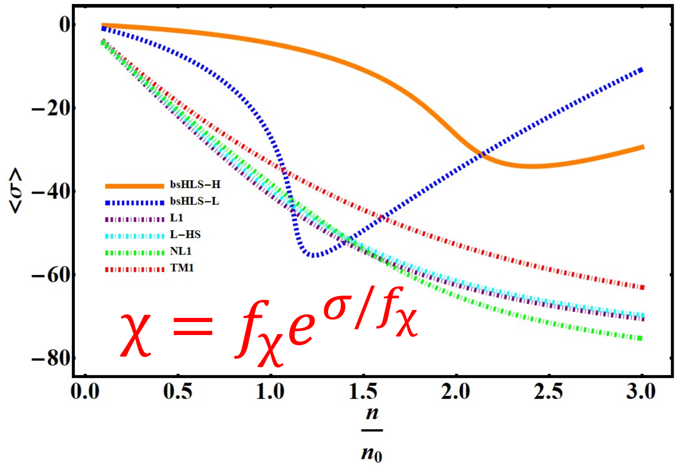
	Empirical	bsHLS-L	bsHLS-H
n_0	0.155 ± 0.050 [45]	0.159	0.159
e_0	-15.0 ± 1.0 [45]	-16.0	-16.0
$K(n_0)$	230 ± 30 [46]	232	284
$E_{\rm sym}(n_0)$	30.9 ± 1.9 [47]	30.5	29.2
$E_{\rm sym}(2n_0)$	46.9 ± 10.1 [48]	51.5	50.2
$L(n_0)$	52.5 ± 17.5 [47]	85.9	68.3
$J(n_0)$	-700 ± 500 [49]	-767	-599

L. Q. Zhang, Y. Ma and YM, 2410.04142.

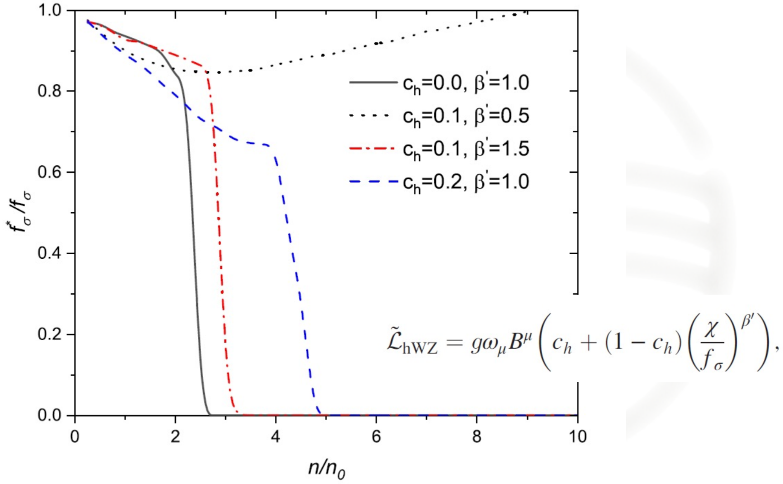


■ There are only hadrons, NO phase/configuration transition!

Why in Chiral-scale EFT?



- Scale symmetry is first partially restored with density, but then broken again. Contradict to naïve expectation!



- Also found in skyrmion crystal approach.

Long-Qi Shao, YM, arXiv:2202.09957

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Nuclear Physics A 807 (2008) 28–37
NUCLEAR PHYSICS A
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$$\left(\frac{E}{B}\right)_{\rm WZ} = \frac{1}{4}\left(\frac{3g}{2}\right)^2 \int_{\rm Box} d^3x \int d^3x'\, B_0(\vec{x}) \frac{\exp(-m_\omega^*|\vec{x}-\vec{x}'|)}{4\pi|\vec{x}-\vec{x}'|} B_0(\vec{x}')$$

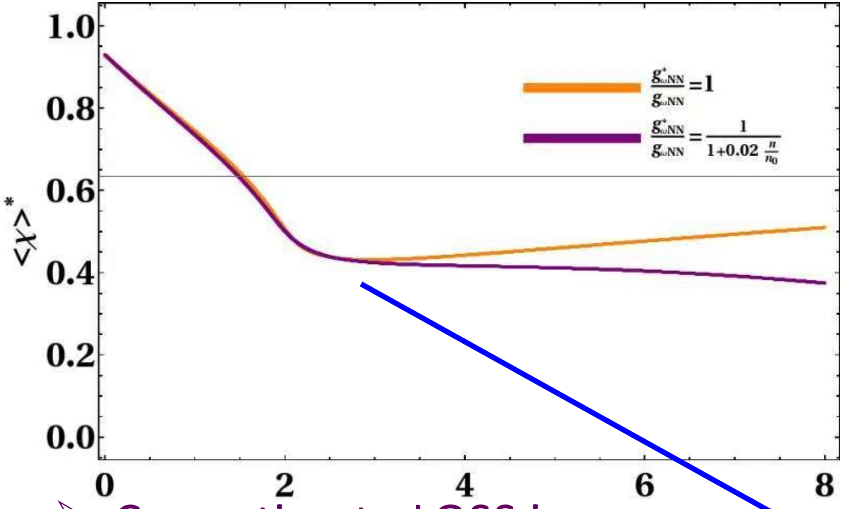
The role of the dilaton in dense skyrmion matter

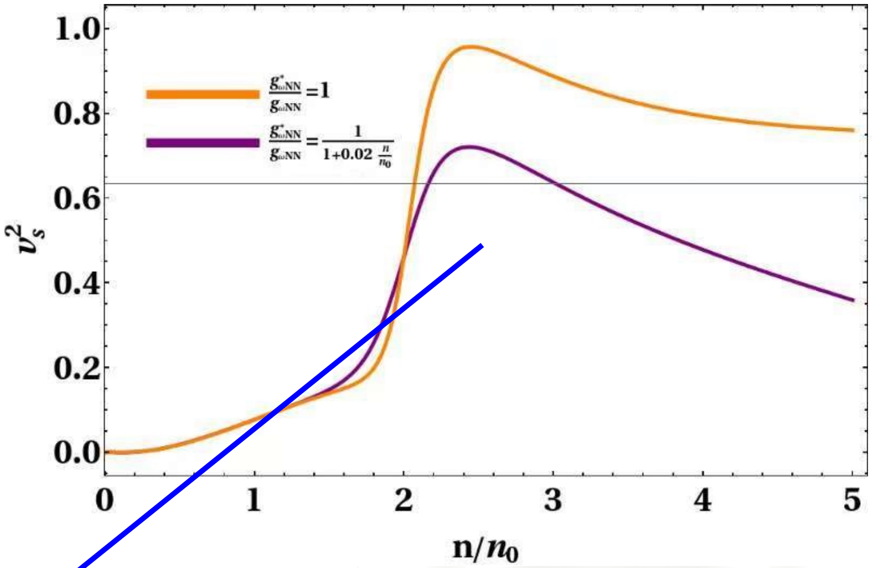
Byung-Yoon Park[a,*], Mannque Rho[b], Vicente Vento[c]

This quantity diverges unless it is screened by m_ω^*. Therefore if the ω mass were to go down as required by the vector manifestation, the skyrmion–skyrmion interactions would become strongly repulsive with increasing density. This forces the ω mass m_ω^* , and hence $\chi*$, to increase. Note that in HLS theory with the vector manifestation, g^2 drops to zero as the density approaches the critical, so the problem is avoided.

- A resolution: $\mathcal{L}'_{an} = \frac{3}{2} g(\chi/f_\chi)^3 \omega_\mu B^\mu.$ New information on compensator approach?

- A scaled $\omega - N - N$ coupling:

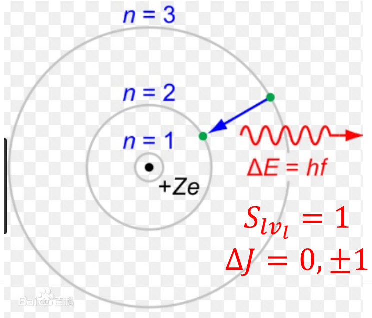




- Correction to LOSS is significant for the restoration of SS!

Locations are locked

- $g_A$quench in Gamov-Taller transition : $g_A^{free} \approx 1.276 \to g_A^{eff} \approx 1$



For $A \leq 60$ nuclei

在壳模型计算中

$$g_A^{eff} = q_{light} \times g_A^{free} \approx 0.98 - 1.18$$

取典型值

$$q_{light} \approx 0.78$$

For $A > 60$ nuclei

Recent RIKEN: $B_{GT}^{RIKEN} = 4.4_{-0.7}^{+0.9}$

D. Lubos, et al., PRL 19'

$$q_{RIKEN}^{ESPM} = 0.46 - 0.55$$

可以一窥核物质中标度对称性表现形式

$$q_{G\sigma EFT}^{ESPM} = q_{SSB} \times q_{SNC}$$

在 $\boldsymbol{GnEFT}$中，相关的轴流为：

$$q_{SSB} g_A \bar{\Psi} \tau^{\pm} \gamma_\mu \gamma_5 \Psi$$

$$q_{SSB} = c_A + (1 - c_A)\Phi^{\beta'}$$

$$\Phi(0) = 1$$
$$\Phi(n_0) = 0.8$$

利用朗道费米流固定点理论： $\boldsymbol{q_{SNC} \approx 0.79}$

For $A \leq 60$ nuclei

$q_{light} \approx 0.78$

↓

$c_A \approx 1$, LOSS是好的近似。

For $A > 60$ nuclei

$q^{ESPM}_{RIKEN} = 0.46 - 0.55$

↑

$q_{SSB} = c_A + (1 - c_A)\Phi^{\beta'} \approx 0.63$

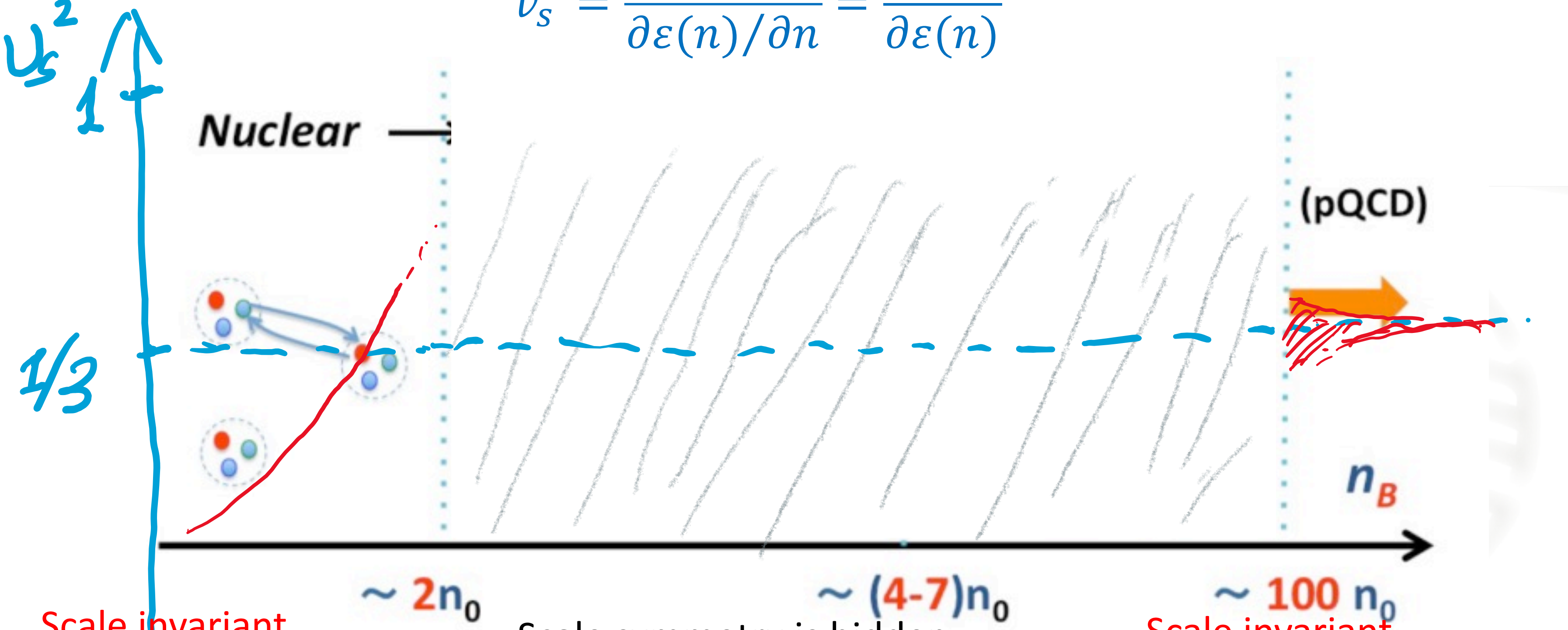
↑

$c_A \approx 0.15, \beta' \approx 2.5$, LOSS 破坏

$\boldsymbol{q_{ssb} = c_A + (1 - c_A)\Phi^{\beta'} \approx 0.64}$

表明了标度对称性在核物质（从低密度到高密度）的实现方式。

$$v_s^2 = \frac{\partial p(n)/\partial n}{\partial \varepsilon(n)/\partial n} = \frac{\partial p(n)}{\partial \varepsilon(n)}$$



Scale invariant.

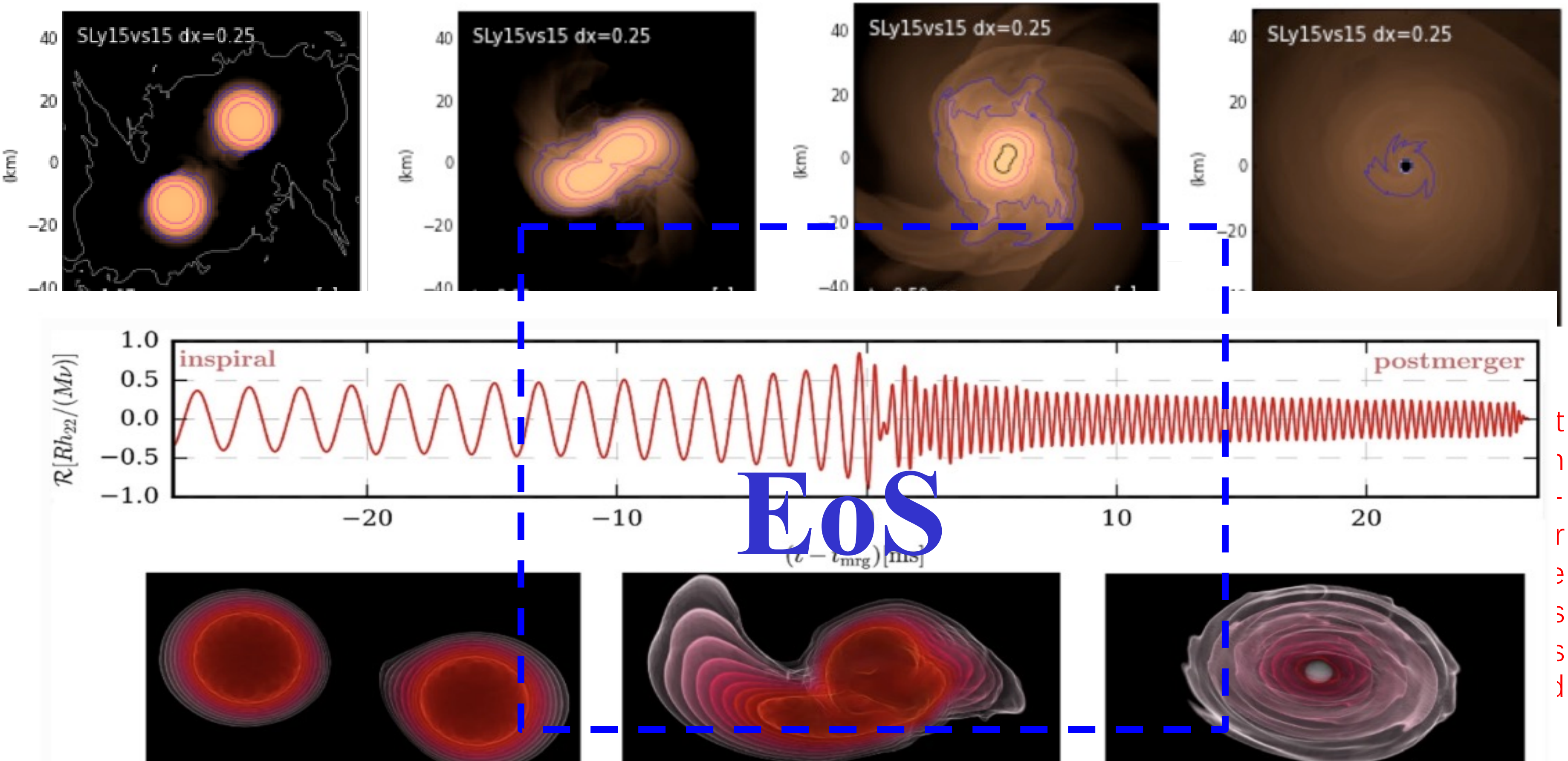
Scale symmetry is hidden.

Scale invariant.

Summary and discussion

- When EFT was used in the study of NM, novel phenomena appear.
- The peak of SV in nuclear matter is due to the nonlinear realization of scale symmetry, NOT the hadron-quark transition or other configuration change.
- The location of the peak is about $(1{\sim}2)n_0$, a density region can be accessed by terrestrial experiments.
- Implementation of SS in omega meson sector, $U(2)_{HLS}$ is badly broken in medium.

Phases of binary neutron star merger



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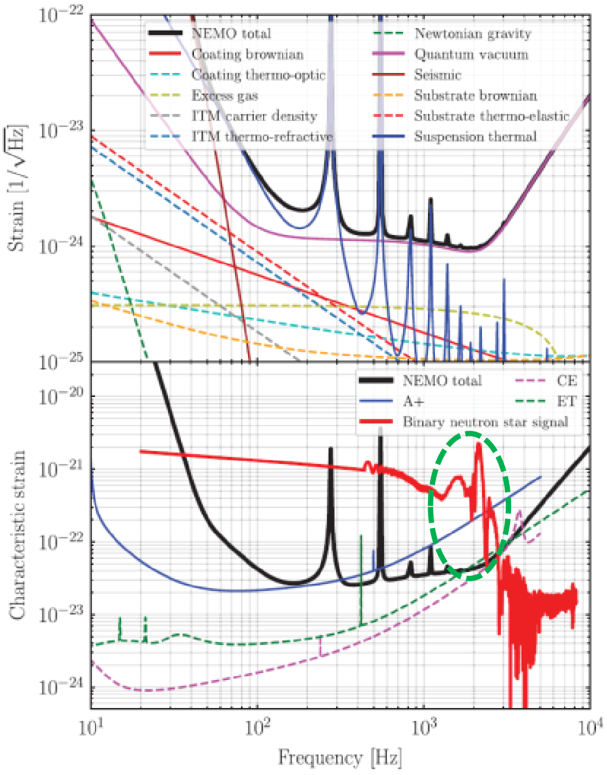
Summary and discussion



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Research Paper

Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network

Figure 1. Noise budget and indicative gravitational-wave signal from a binary neutron star collision. Top panel: we show the amplitude spectral density of the various noise components that make up the total noise budget shown as the black curve. Bottom panel: The black curve is the same total noise budget as the top panel, now shown as the noise amplitude $h_n = \sqrt{f\, S_n(f)}$, where $S_n(f)$ is the power-spectral density. This curve is shown in comparison to design sensitivity of A+ (blue), the Einstein Telescope (ET; green), and Cosmic Explorer (CE; pink). Also shown in red is the predicted characteristic gravitational-wave strain h_c for a typical binary neutron star inspiral, merger, and post-merger at 40 Mpc, where the latter are derived from numerical-relativity simulations.

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Thank you for your attention!