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Manifestation of scale symmetry in dense nuclear matter

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@
2nd Workshop on modern equations of state and spectroscopy in neutron-star matter
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Outline

I. Introduction

II. Scale symmetry and peak of sound velocity

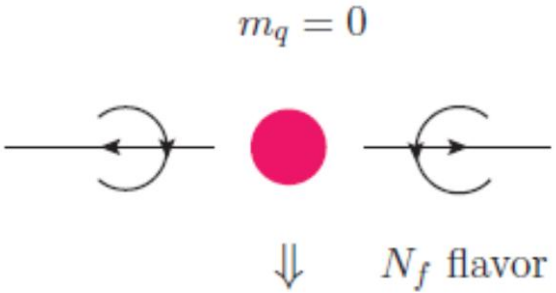
III. Pseudoconformal structure of dense nuclear matter

IV. Summary and conclusion

I. Introduction

Symmetry and symmetry breaking play dominant roles in particle and nuclear physics.

- Chiral symmetry and chiral symmetry breaking have played predominant roles in hadron physics.



$SU(N_f)_L \times SU(N_f)_R \Rightarrow$ Degeneracy of chiral partners;

Chiral symmetry breaking ⇒ Pion as NGBs, splitting of chiral partners.

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I. Introduction

- Scale symmetry and scale symmetry breaking:

Scale transformation: $x_\mu \to \lambda\, x_\mu$

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi} i \not{D} \psi$$

- Invariant at classical level;
- Broken by quantum correction:

$$\partial_\mu J^\mu_D = T^\mu_\mu = \frac{\beta(\alpha_s)}{2\alpha_s} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\eta_{\mu\nu} T^{\mu\nu} = \frac{\beta(g)}{2g} F^2 + \left(1 + \gamma_m(g)\right) m \bar{\psi} \psi$$

Origin of nucleon mass:

$$m_N = \langle N | \theta^\mu_\mu | N \rangle = \frac{\beta(\alpha_s)}{4\alpha_s} \langle N | G^2 | N \rangle + \left(1 + \gamma_m(\alpha_s)\right) \sum_q m_q \langle N | \bar{q} q | N \rangle$$

$$= \qquad\qquad m_0 \qquad + \qquad \Delta(\langle \bar{q} q \rangle)$$

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I. Introduction

Cannot be accessed directly from QCD. Phenomena in nuclear medium:

- Helpful for understanding some fundamental questions in particle and nuclear physics:

  Mechanism of chiral symmetry breaking, origin of nucleon mass, ……

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

- Manifestation/emergence of chiral and scale symmetries.

➢ Models anchored on properties of fundamental QCD!

Chiral symmetry? Scale symmetry? Power counting?

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I. Introduction

	Empirical
n_0	0.155 ± 0.050 [48]
e_0	-15.0 ± 1.0 [48]
K_0	230 ± 30 [49]
$E_{\rm sym}(n_c)$	26.7 ± 0.2 [50]
$E_{\rm sym}(n_0)$	30.9 ± 1.9 [51]
$E_{\rm sym}(2n_0)$	46.9 ± 10.1 [52]
$L(n_c)$	43.7 ± 7.8 [53]
$L(n_0)$	52.5 ± 17.5 [51]
J_0	-700 ± 500 [54]

[48] A. Sedrakian, J.-J. Li, and F. Weber, Prog. Part. Nucl. Phys. 131, 104041 (2023), arXiv:2212.01086 [nucl-th].

[49] 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].

[50] Z. Zhang and L.-W. Chen, Phys. Lett. B 726, 234 (2013), arXiv:1302.5327 [nucl-th].

[51] J. M. Lattimer and Y. Lim, Astrophys. J. 771, 51 (2013), arXiv:1203.4286 [nucl-th].

[52] 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].

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I. Introduction

- 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

PSR J1614–2230 $M = 1.908 \pm 0.016\, M_\odot$,

PSR J0348+0432 $M = 2.01 \pm 0.04\, M_\odot$,

PSR J0740+6620 $M = 2.08 \pm 0.07\, M_\odot$.

PSR J0952–0607 $M = 2.35 \pm 0.17\, M_\odot$.

- 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.

PSR J0030+0451 $M = 1.34^{+0.15}_{-0.16}\, M_\odot$, $R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$,

PSR J0740+6620 $M = 2.072^{+0.067}_{-0.066}\, M_\odot$, $R = 12.39^{+1.30}_{-0.98}\,\mathrm{km}$.

- 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

Eemeli Annala,[1] Tyler Gorda,[1] Aleksi Kurkela,[2] and Aleksi Vuorinen[1]

O. Box 64, FI-00014 University of Helsinki, Finland
Switzerland
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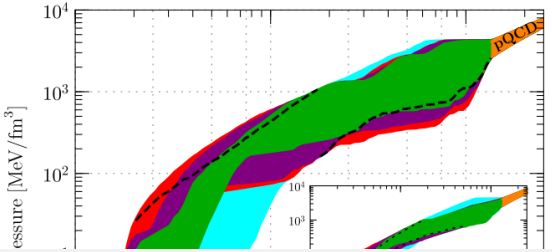
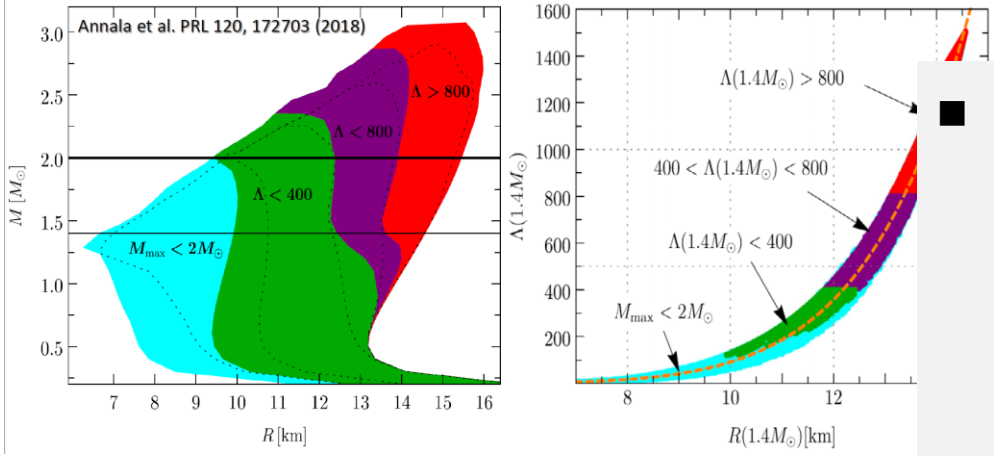
ceived 6 Feb

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):

$$\Lambda_{1.4} < 800$$

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

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

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

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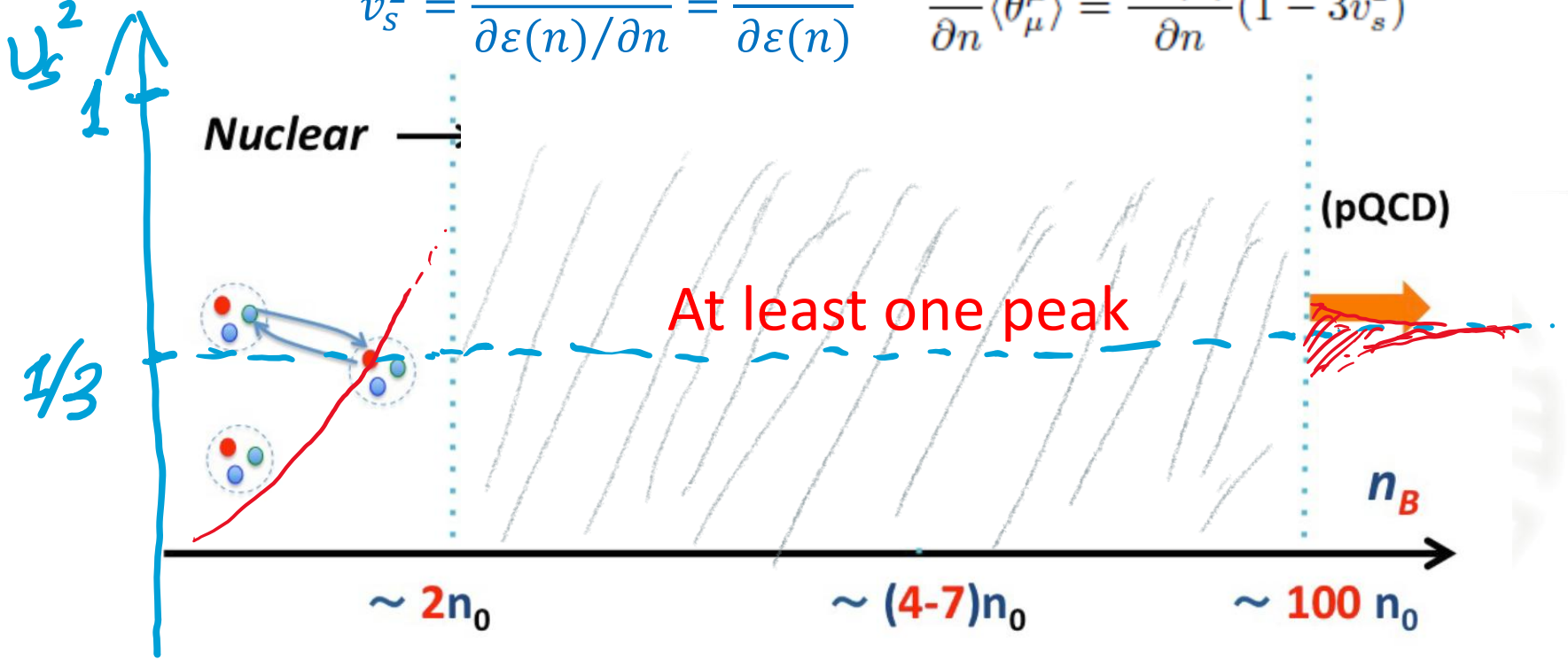
II. Scale symmetry and peak of sound velocity

$$v_s^2 = \frac{\partial p(n)/\partial n}{\partial \varepsilon(n)/\partial n} = \frac{\partial p(n)}{\partial \varepsilon(n)} \qquad \frac{\partial}{\partial n}\langle \theta_\mu^\mu \rangle = \frac{\partial \epsilon(n)}{\partial n}(1 - 3v_s^2)$$



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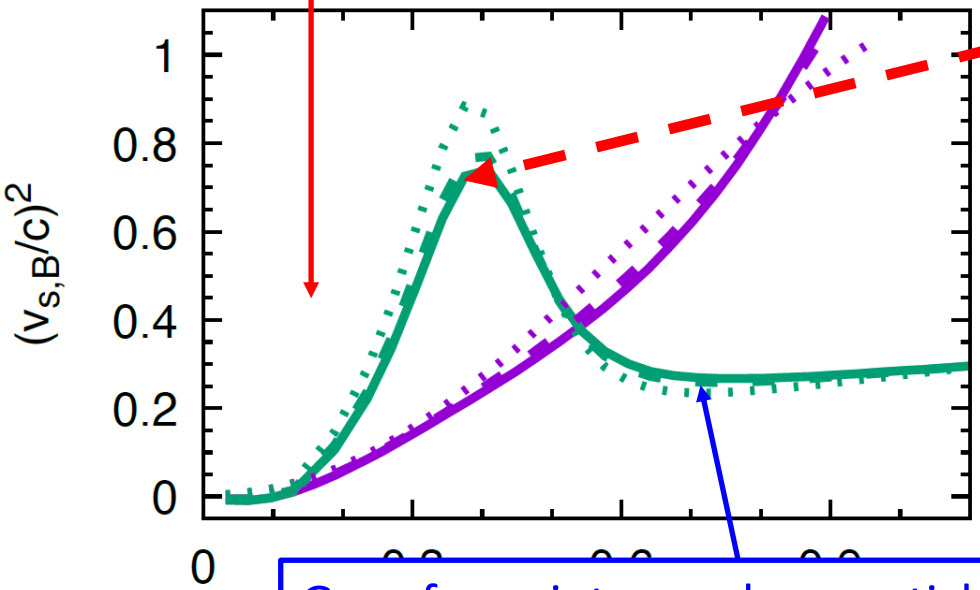
II. Scale symmetry and peak of sound velocity

Hadronic phase



Emerges in the transition from a phase with broken chiral symmetry to one with gapped Fermi surface with the condensation of diquarks and dibaryons.

Hippert, *et al.* , 2105.04535

Gas of non-int. massless particles; zero baryon chemical potential hQCD; LQCD.

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II. Scale symmetry and peak of sound velocity

- 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 $(2\sim4)n_0$ 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.-C. Yang, Symmetry 15, 776 (2023).

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II. Scale symmetry and peak of sound velocity

- 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 C

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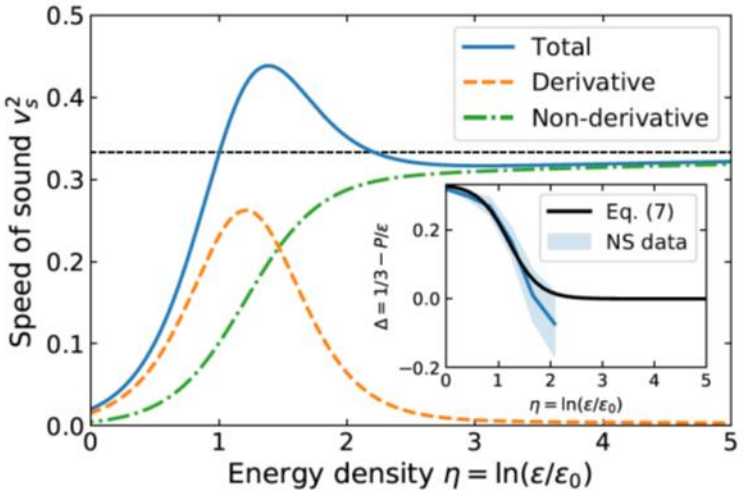

FIG. 2. The speed of sound and its decomposition (6) calculated from (7) as shown in the inset plot. The horizontal axis is the logarithmic energy η normalized to the value at the saturation point, $\varepsilon_0 = 150\,\mathrm{MeV/fm^3}$.

We discuss an interpretation that a peak in the sound v observational data, signifies strongly coupled conforn dimensionless measure of conformality leading to the de 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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II. Scale symmetry and peak of sound velocity

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

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

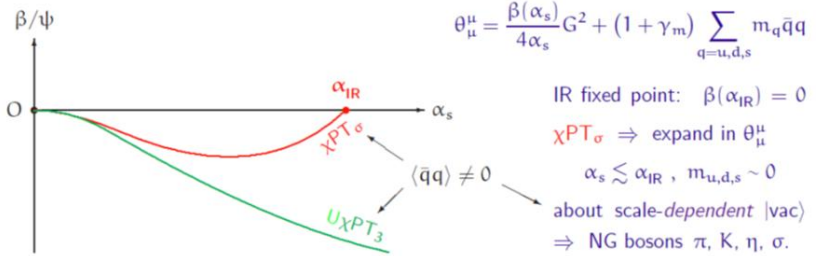
What will happen when the trace anomaly is implemented in an effective model/theory?

- J. Schechter, PRD, 1980, anomaly match;
- Crewther and Tunstall , PRD91(2015), 034016, e-Print: 1312.3319; expansion and power counting.

- Trace anomaly in QCD

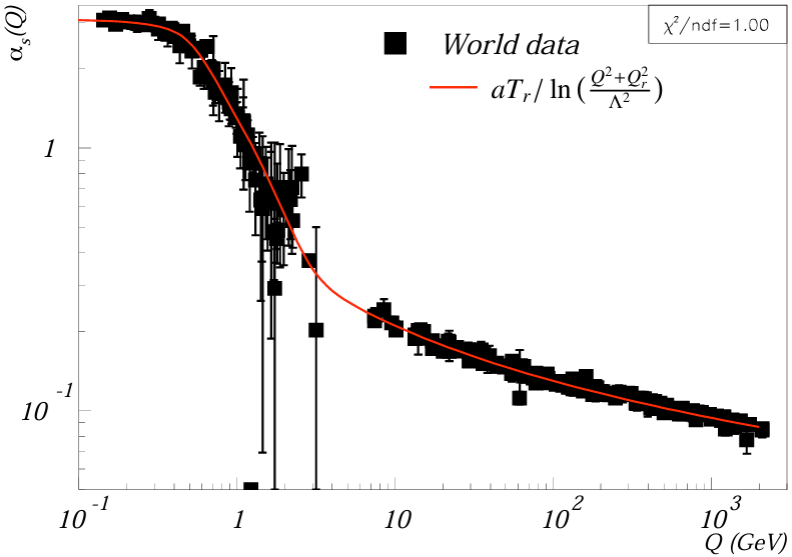
$$\partial_\mu D^\mu = \frac{\beta(\alpha_s)}{4\alpha_s} Tr\,(G_{\mu\nu}G^{\mu\nu}) \propto \chi^4$$

A possible way to introduce a scalar meson.



II. Scale symmetry and peak of sound velocity

➢ A. Deur, e-Print: 2502.06535 [hep-ph].



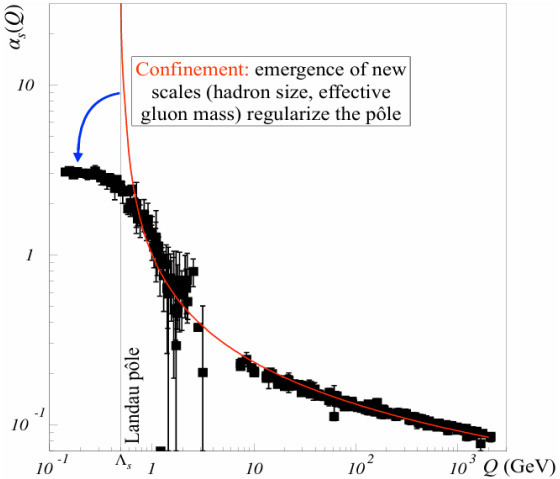


Fig. 8: **Regularization of the Landau pôle.**

➢ The absence of Q^2-dependence of α_s in the IR, i.e., the vanishing QCD β-function, is variously named the freezing of α_s, the conformal window of QCD, or the $Q^2 = 0$ fixed point.

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II. Scale symmetry and peak of sound velocity

Mean field calculation based on chiral-scale EFT

L. Q. Zhang, Y. Ma and *YLM*, 2410.04142; 2412.19023.

$$\chi = f_\chi e^{\sigma/f_\chi} \equiv f_\chi \Phi$$
$$m_\omega^* = \Phi^* m_\omega$$
$$m_N^* = \Phi^* m_N$$

$$\begin{aligned}\mathcal{L}_M =& f_\pi^2\Phi^2\,\mathrm{Tr}\left(\hat{\alpha}_\perp^\mu\hat{\alpha}_{\mu\perp}\right) + f_{\sigma\rho}^2\Phi^2\,\mathrm{Tr}\left(\hat{\alpha}_\parallel^\mu\hat{\alpha}_{\mu\parallel}\right) + f_0^2\Phi^2\,\mathrm{Tr}\left(\hat{\alpha}_\parallel^\mu\right)\mathrm{Tr}\left(\hat{\alpha}_{\mu\parallel}\right)\\ &- \frac{1}{2g_\rho^2}\,\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) - \frac{1}{2g_0^2}\,\mathrm{Tr}\left(V_{\mu\nu}\right)\mathrm{Tr}\left(V^{\mu\nu}\right)\\ &+ \frac{1}{2}\partial_\mu\chi\partial^\mu\chi + \frac{f_\pi^2}{4}\Phi^{3-\gamma_m}\,\mathrm{Tr}\left(\mathcal{M}U^\dagger + U\mathcal{M}^\dagger\right) + h_5\Phi^4 + h_6\Phi^{4+\beta'},\end{aligned}$$

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

	M_σ	β'	r	$g_{\omega NN}$	$g_{\rho NN}$	$g_{\omega NN}^{SSB}$	$g_{\rho NN}^{SSB}$
bsHLS-L	1.05	0.395	0.161	11.5	3.78	16.3	9.45
bsHLS-H	2.30	1.15	0.191	11.0	4.17	8.85	4.85

	Empirical	bsHLS-L	bsHLS-H
n_0	0.155 ± 0.050 [46]	0.159	0.159
e_0	-15.0 ± 1.0 [46]	-16.0	-16.0
$K(n_0)$	230 ± 30 [47]	232	284
$E_{\rm sym}(n_0)$	30.9 ± 1.9 [48]	30.5	29.2
$E_{\rm sym}(2n_0)$	46.9 ± 10.1 [49]	51.5	50.2
$L(n_0)$	52.5 ± 17.5 [48]	85.9	68.3
$J(n_0)$	-700 ± 500 [50]	-767	-599

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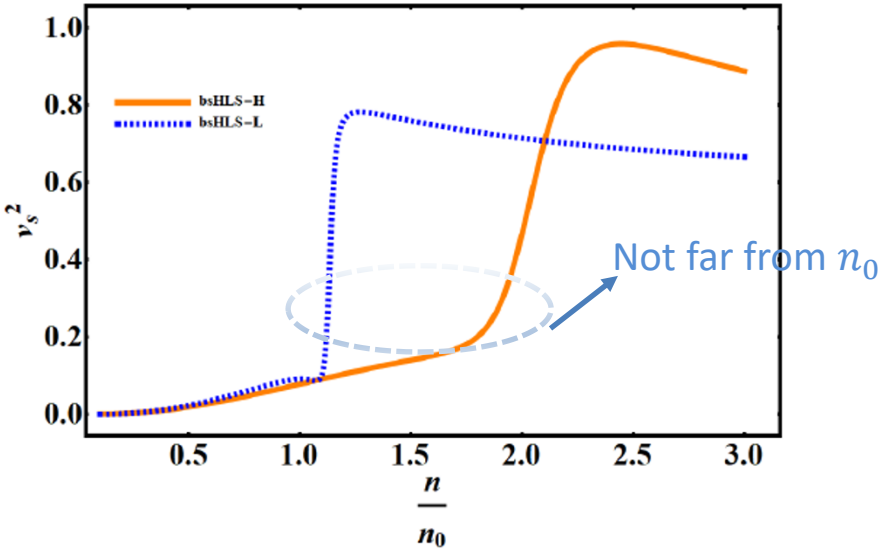
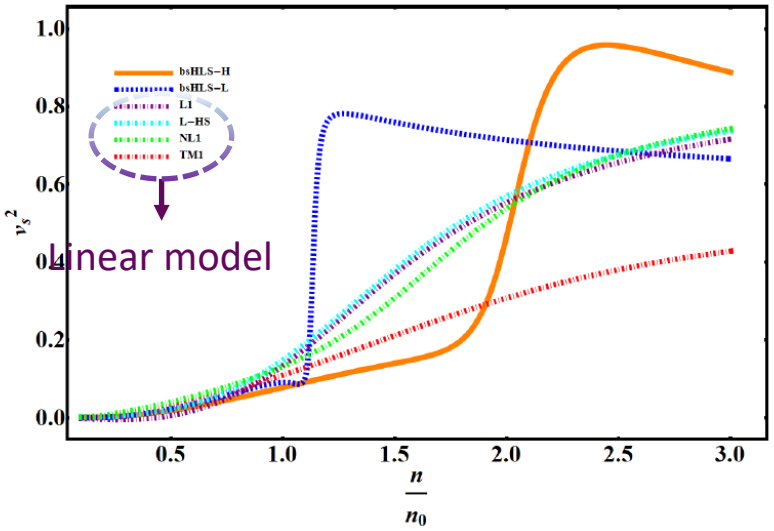
II. Scale symmetry and peak of sound velocity

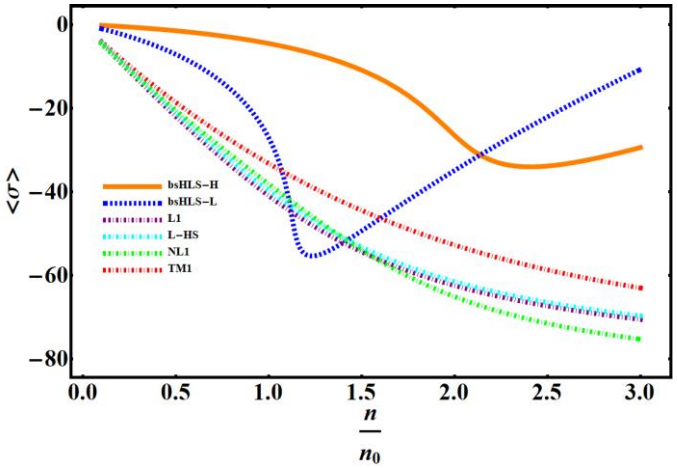




- The peak in the SV is due to the nonlinear realization of scale symmetry NOT due to phase transition/configuration change!

II. Scale symmetry and peak of sound velocity

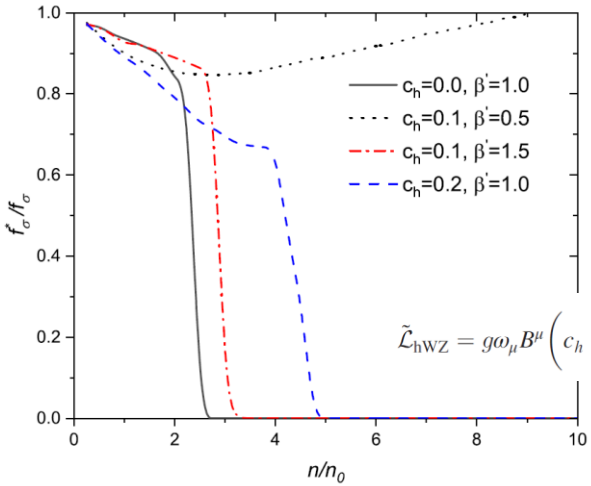
- Why in Chiral-scale EFT?



- Also found in skyrmion crystal approach.

Long-Qi Shao, YM, arXiv:2202.09957

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



$$\tilde{\mathcal{L}}_{\mathrm{hWZ}} = g\omega_\mu B^\mu \left(c_h + (1 - c_h) \left(\frac{\chi}{f_\sigma} \right)^{\beta'} \right),$$

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Nuclear Physics A 807 (2008) 28–37
NUCLEAR PHYSICS A
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II. Scale symmetry and peak of sound velocity

$$\left(\frac{E}{B}\right)_{\mathrm{WZ}} = \frac{1}{4}\left(\frac{3g}{2}\right)^2 \int_{\mathrm{Box}} d^3x \int d^3x'\, B_0(\vec{x}) \frac{\exp(-m_\omega^*|\vec{x}-\vec{x}'|)}{4\pi|\vec{x}-\vec{x}'|} B_0(\vec{x}')$$

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?

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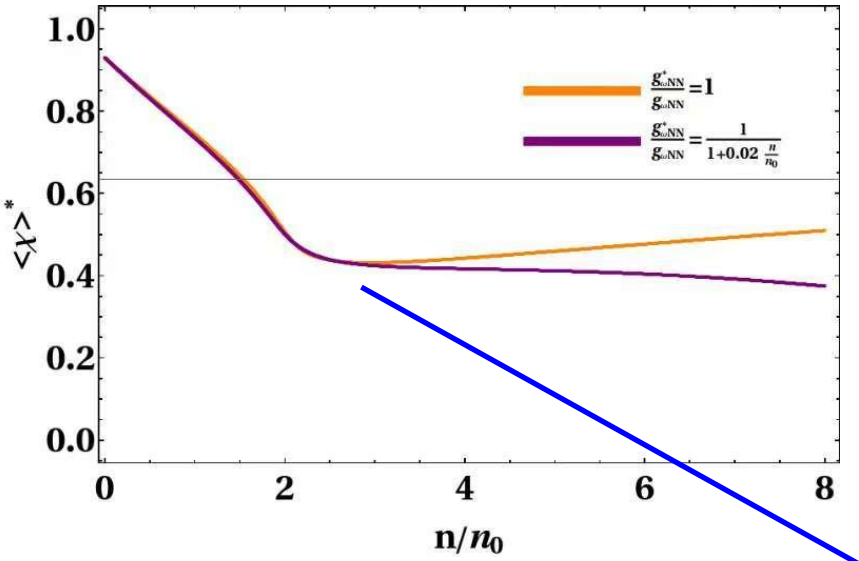
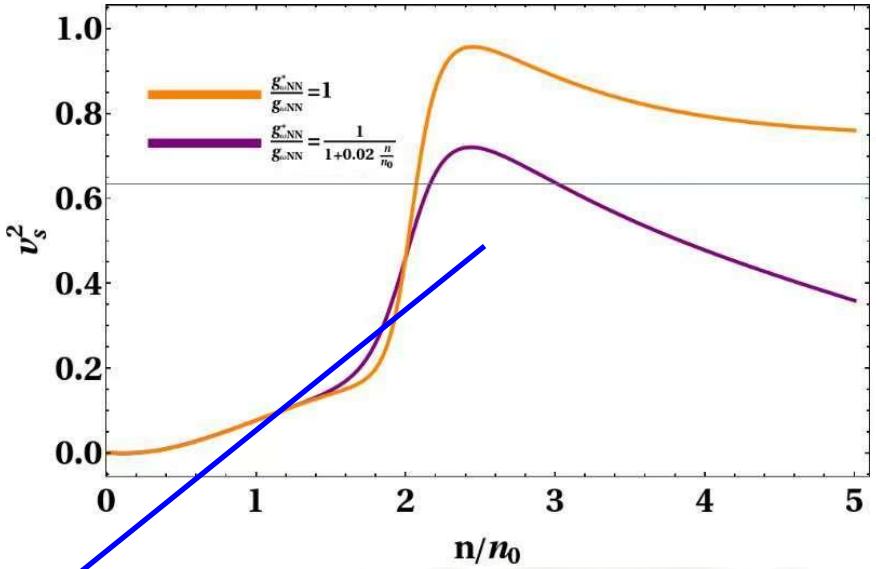
II. Scale symmetry and peak of sound velocity

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

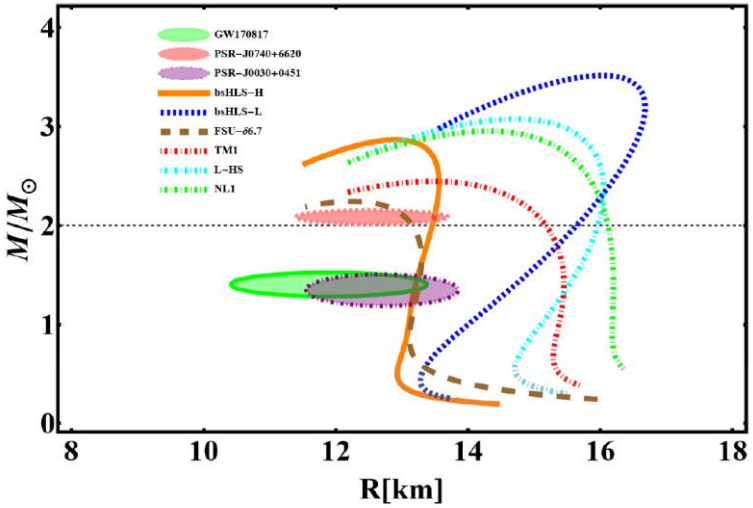




- Correction to LOSS is significant for the restoration of SS!

Locations are locked

II. Scale symmetry and peak of sound velocity



$$\begin{aligned}\mathcal{L}_{\rm RMF} &= \bar{\psi}\left[i\gamma_\mu\partial^\mu - m_N - g_\sigma\sigma - g_{\omega NN}\gamma_\mu\omega^\mu - g_{\rho NN}\gamma_\mu\rho^{\mu a}\tau^a - g_\delta\delta^a\tau^a\right]\psi \\ &+ \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\ &- \frac{1}{2g^2}\,{\rm Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3\left(\omega_\mu\omega^\mu\right)^2 + \frac{1}{2}m_\rho^2\rho^{\mu a}\rho_\mu^a \\ &+ \frac{1}{2}\Lambda_V\rho_\mu^a\rho^{\mu a}\omega_\nu\omega^\nu + \frac{1}{2}\left(\partial_\mu\delta^a\partial^\mu\delta^a - m_\delta^2\delta^a\delta^a\right) + \frac{1}{2}C_{\delta\sigma}\sigma^2\left(\delta^a\right)^2 \ ,\end{aligned}$$

TABLE III. The choice of parameters for Walekca-type models in Eq. (14).

	L-HS [55]	NL1 [56]	TM1 [57]	FSU-δ6.7 [38]
n_0(fm^{-3})	0.149	0.152	0.145	0.148
m_N(MeV)	939	938	938	938
m_σ(MeV)	520	492	511	492
m_ω(MeV)	783	795	783	783
m_ρ(MeV)	770	763	770	763
g_σ	10.5	10.1	10.0	10.2
$g_{\omega NN}$	13.8	13.3	12.6	13.4
$g_{\rho NN}$	4.04	4.98	4.63	7.27
g_2(fm^{-1})	0	-12.2	-7.23	-8.09
g_3	0	-36.3	0.618	5.88

bsHLS-H is preferred!

Consistent with pion-nuclei atom and skyrmion crystal approach.

	M_σ	β'	r	$g_{\omega NN}$	$g_{\rho NN}$	$g_{\omega NN}^{SSB}$	$g_{\rho NN}^{SSB}$
bsHLS-L	1.05	0.395	0.161	11.5	3.78	16.3	9.45
bsHLS-H	2.30	1.15	0.191	11.0	4.17	8.85	4.85

- P. Kienle and T. Yamazaki, PPNP52, 85 (2004).
- YLM and M. Rho, PRD97, 094017 (2018); L. Q. Shao and YLM, PRD106, 014014 (2022).

II. Scale symmetry and peak of sound velocity

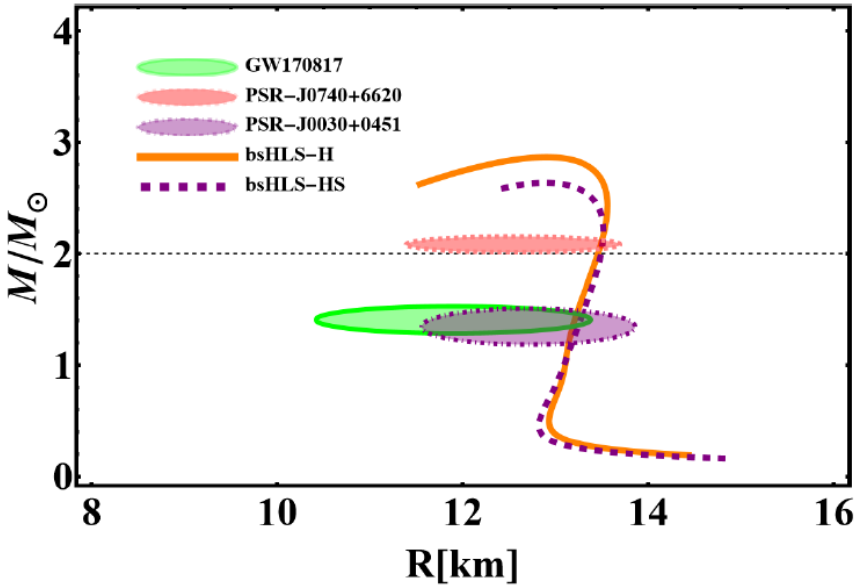


FIG. 3. NS structure results with/without $g_{\omega NN}$ suppression.

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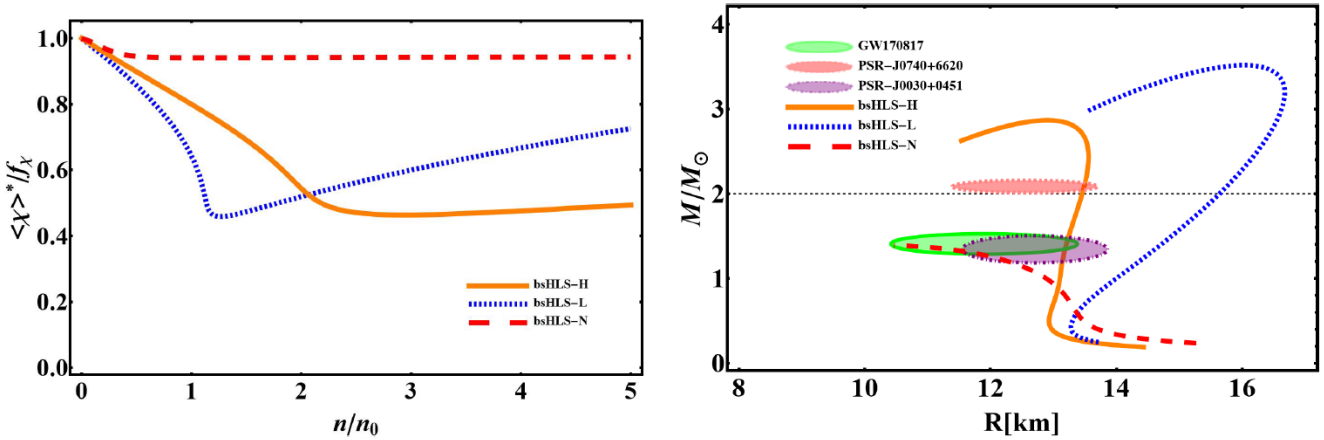
II. Scale symmetry and peak of sound velocity



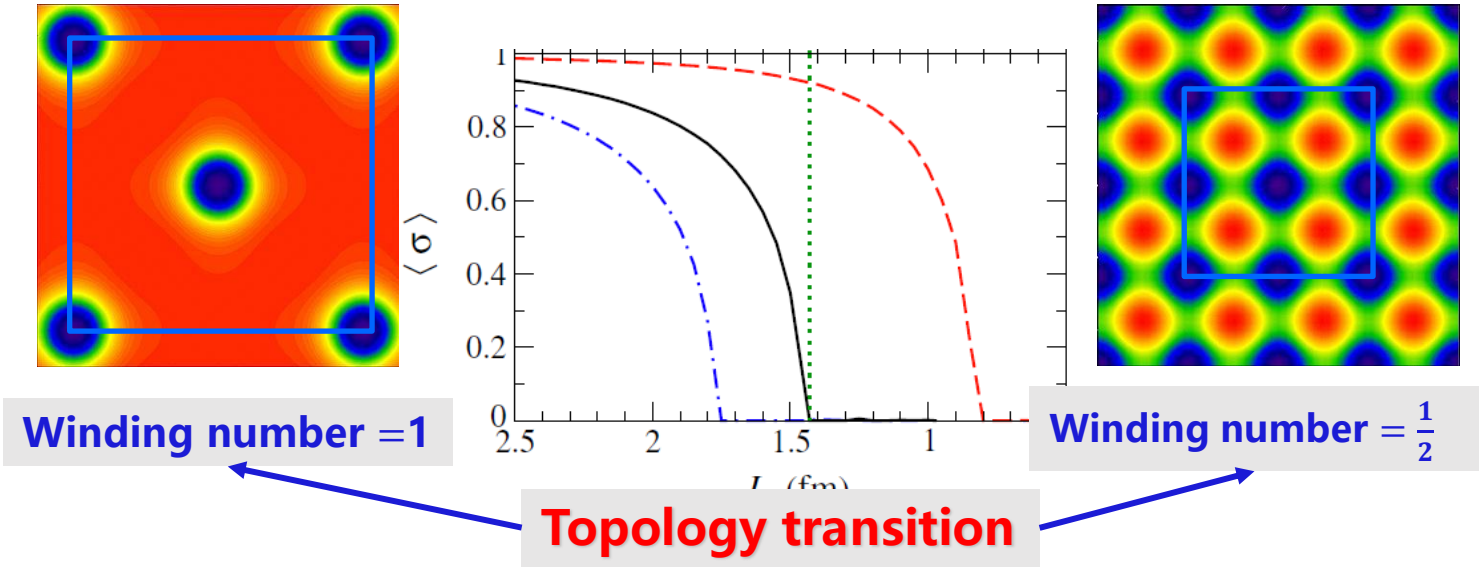
(a)$\langle\chi\rangle^*/f_\chi$ as a function of density.

(b)MR relation of NS.

FIG. 5. The $\langle\chi\rangle^*/f_\chi$ in pure neutron matter and NS structure results with/without B-R scaling.

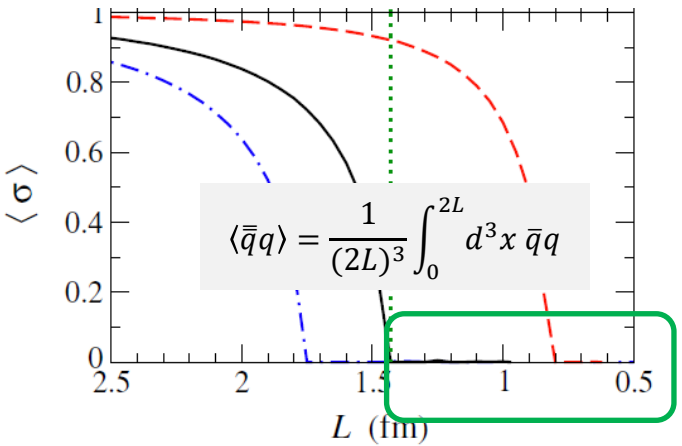
III. PC structure of dense nuclear matter

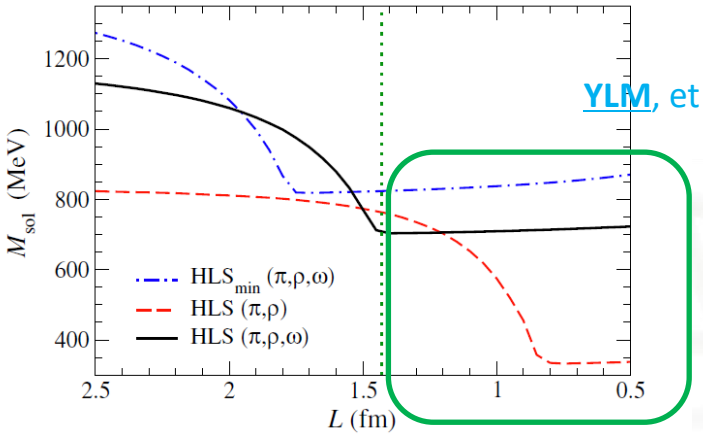
Topology change: Skyrmion-half-skyrmion transition



III. PC structure of dense nuclear matter

Topology change: Parity doublet structure





YLM, et al, PRD 13', 14'

$$\frac{m_N^*}{m_N} \approx \frac{f_\pi^*}{f_\pi},$$

High density region(small L): **Quark condensate vanishes** **However** **Nucleon mass is non-zero**

- **Nucleon mass is not solely from chiral symmetry breaking, it include a chiral invariant part. parity doubling structure.**

Detar & Kunihiro, PRD39, 2805 (1989),
Y. Motohiro, *et al*, 1505.00988

$$m_N = m_0 + \Delta(\bar{q}q),$$

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III. PC structure of dense nuclear matter

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

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

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

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

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.*

Qualitative information from topology change ➡ Density dependence of LECs

- YLM, M. Rho, PPNP113 (2020) 103791 ,e-Print: 1909.05889 [nucl-th];
- H. K. Lee, YLM, W. G. Paeng, M. Rho, MPLA37 (2022), 2230003, e-Print: 2107.01879 [nucl-th];
- YLM, W. C. Yang, Symmetry 15 (2023) 776, e-Print: 2301.02105 [nucl-th].

III. PC structure of dense nuclear matter

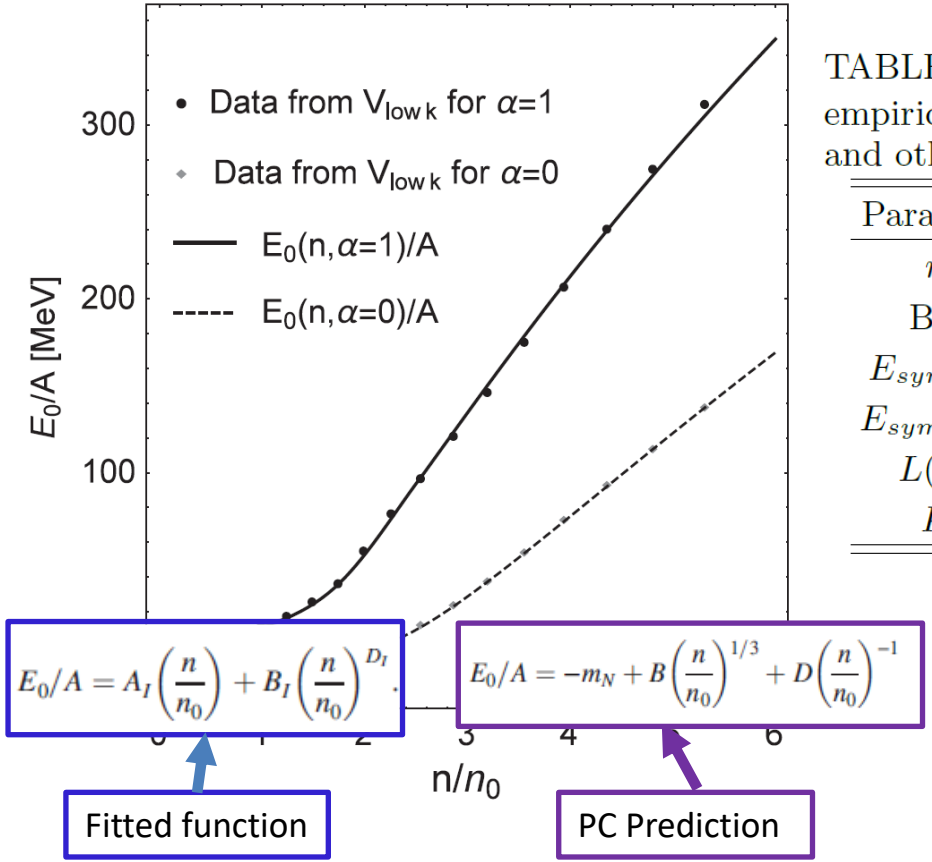

TABLE III. Nuclear matter properties at $n_0 < n_{1/2}$. The empirical values are merely exemplary. n_0 is in unit fm^{-3} and others are in unit MeV.

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]

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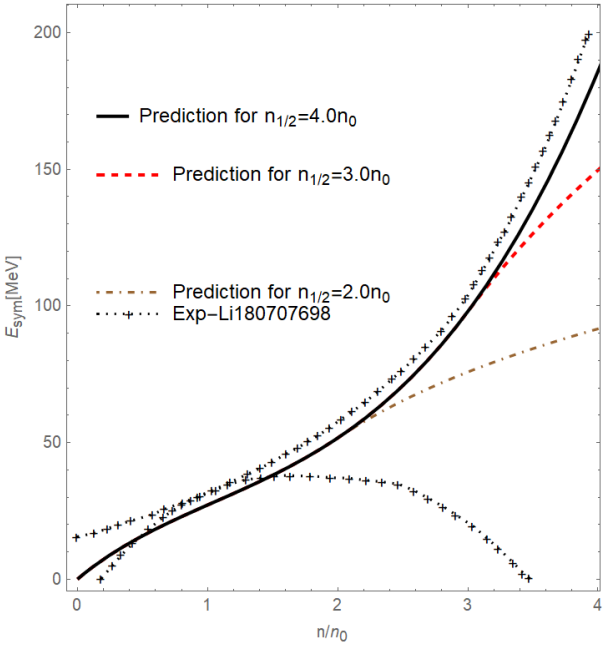
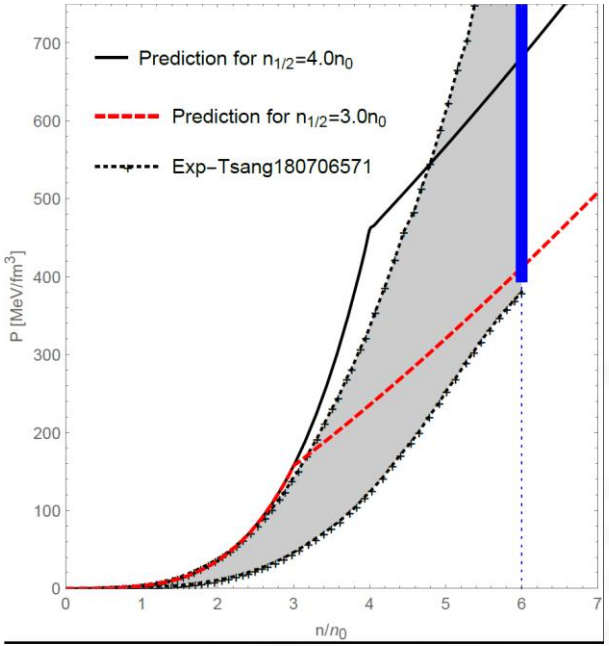
III. PC structure of dense nuclear matter





Agree with the constraints

$n_{1/2}$ is constrained as $\sim(2 - 4)n_0$

YLM, M. Rho, PRD99 (2019), 014034, e-Print: 1810.06062 [nucl-th].

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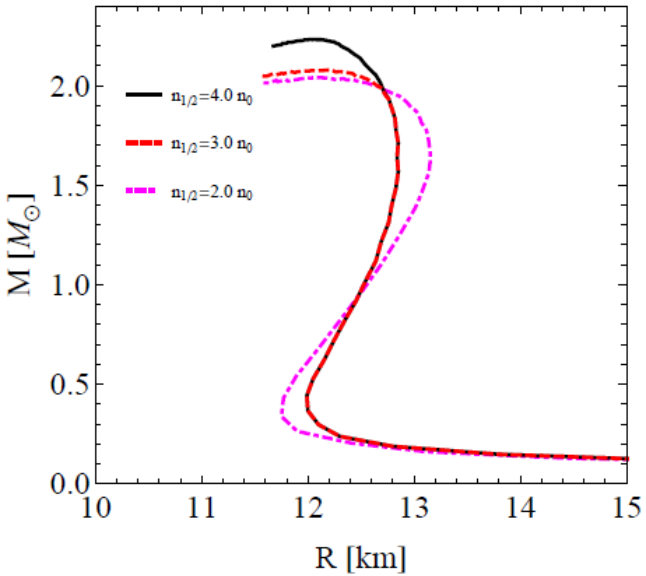
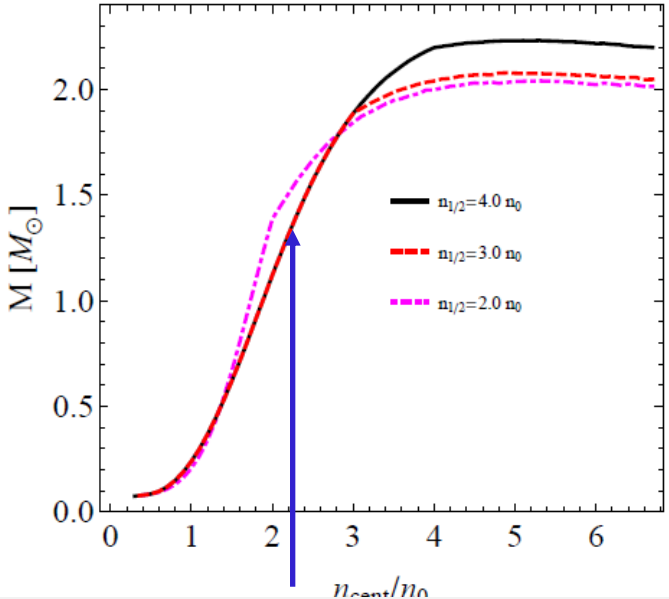
III. PC structure of dense nuclear matter



Accommodate massive star $\geq 2.0\ M_{solar}$

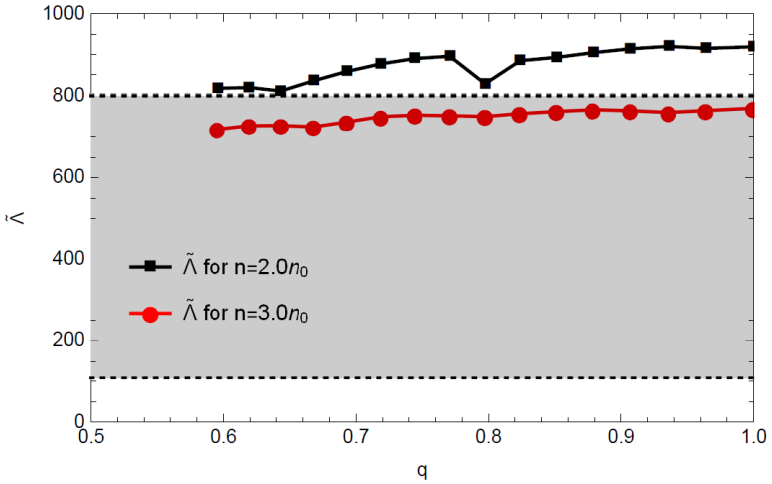


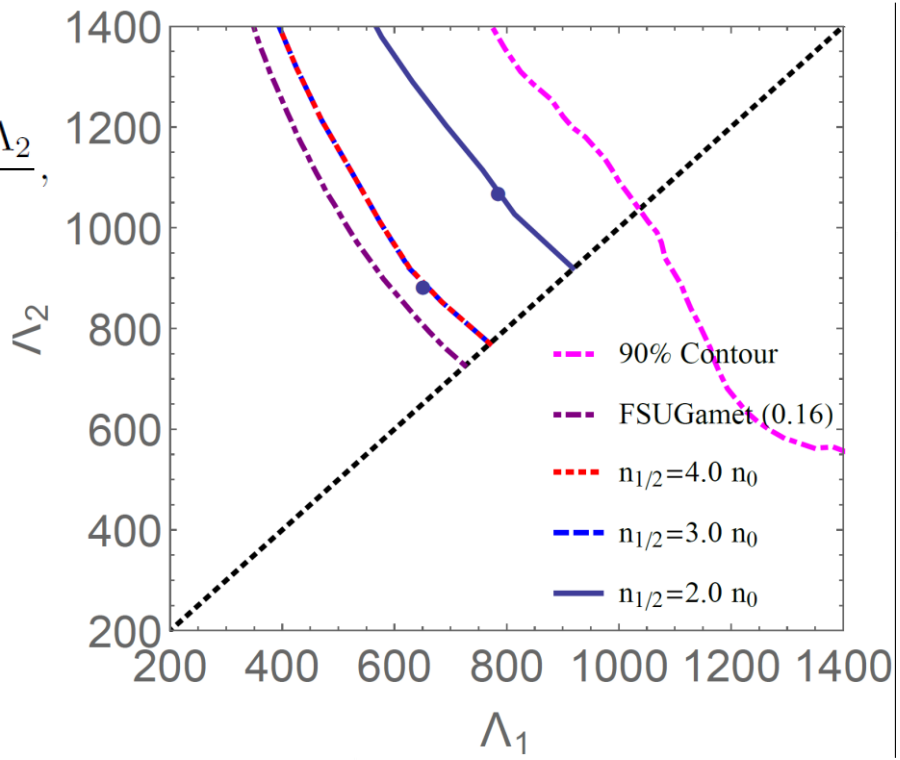
GW data: $\Lambda_{1.4}, R_{1.4}$ ⋯ reflect the EoS for $n < 3n_0$, below the topology change, and hence do not directly control the massive stars of $> 2M_{solar}$.

III. PC structure of dense nuclear matter

$$\mathcal{M}=\frac{(M_1M_2)^{3/5}}{(M_1+M_2)^{1/5}}=1.188\,M_\odot.$$

$$\tilde{\Lambda}=\frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1+(m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5},$$

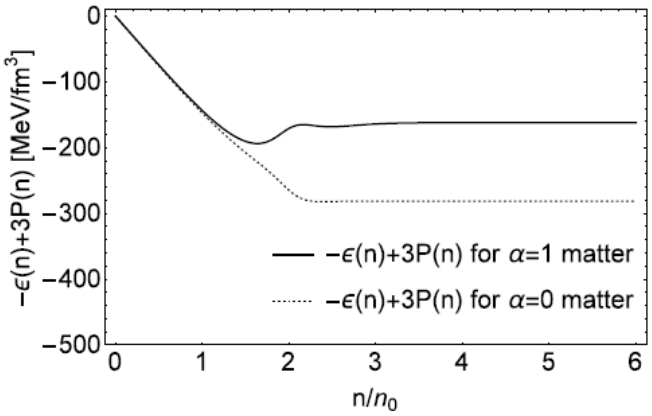


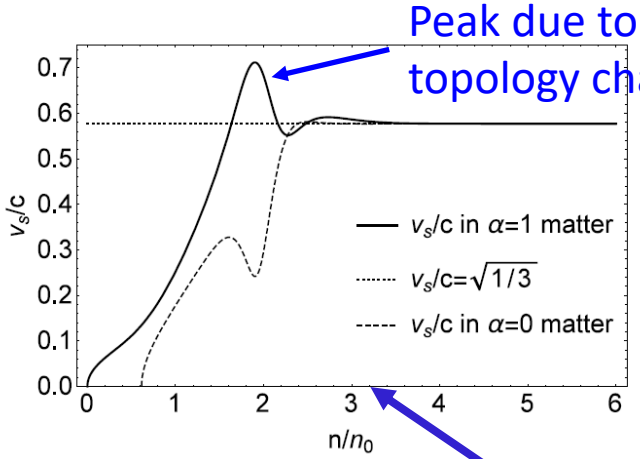


III. PC structure of dense nuclear matter

Pseudoconformal structure

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





- For $\geq 2n_0$, TNMT is a density independent constant;
- For $\geq 2n_0$, SV $\rightarrow 1/\sqrt{3}$—conformal limit.

A feature not observed before.

W. G. Paeng, T. T. S. Kuo, H. K. Lee, *YLM*, M. Rho, PRD96 (2017), 014031, e-Print: 1704.02775 [nucl-th].

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III. PC structure of dense nuclear matter

In the matter system, the sound velocity is defined by

$$v_s^2 = \frac{\partial P(n)}{\partial n} / \frac{\partial \epsilon}{\partial n}, \tag{47}$$

where ϵ and P are, respectively, the energy density and the pressure density. We then have

$$\int \frac{\partial P(n)}{\partial n} dn = \int v_s^2 \frac{\partial \epsilon}{\partial n} dn - \frac{1}{3} C_0 \tag{48}$$

with C_0 being a constant independent of density. For a constant sound velocity, one obtains

$$P(n) = v_s^2 \epsilon(n) - \frac{1}{3} C_0. \tag{49}$$

And for $v_s^2/c^2 = 1/3$, we obtain

$$\epsilon(n) - 3P(n) = C_0. \tag{50}$$

For an ideal liquid system where the nuclear matter is assumed to work, the trace of the energy-momentum tensor (TEMT) is expressed as

$$\theta_\mu^\mu = \epsilon - 3P. \tag{51}$$

Therefore, when $v_s^2/c^2 = 1/3$, one has

$$\langle \theta_\mu^\mu \rangle = C_0, \tag{52}$$

- $C_0 = 0$:

  scale symmetry restoration

- $C_0 = \text{const.}$:

  scale symmetry breaking,

  pseudoconformal

Matters are strongly coupled conformal matter, here, made of baryons.

YLM & M. Rho, 2006.14173
YLM & W. C. Yang, 2301.02105

III. PC structure of dense nuclear matter

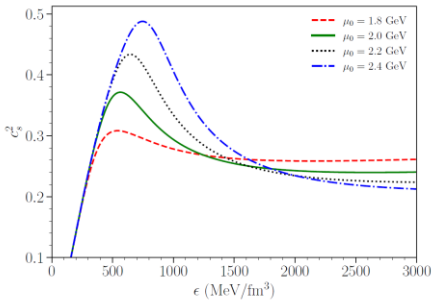
The PCM changed the previous understanding of the EoS:

- The model where the sound velocity saturating the conformal limit at asymptotic density, cannot predicted the maximum value of the NS mass satisfying the observation of the massive NSs.

↓ Predicted in more models

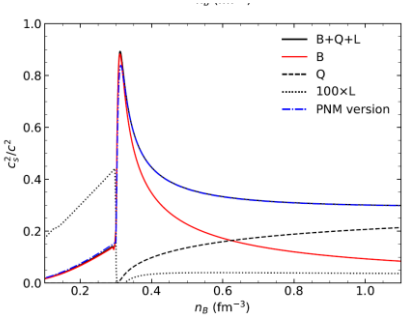
Quark-hadron crossover

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



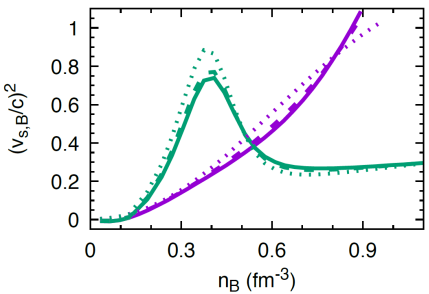
Kapusta & Welle, 2103.16633

Quarkyonic matter



Zhao & Lattimer, 2004.08293

Quarkyonic matter



Margueron et al, 2103.10209

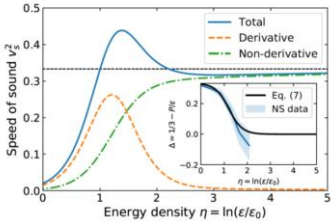


FIG. 2. The speed of sound and its decomposition (6) calculated from (7) as shown in the inset plot. The horizontal axis is the logarithmic energy η normalized to the value at the saturation point, $\varepsilon_0 = 150\,\mathrm{MeV/fm^3}$.

Fujimoto, et al, 2207.06753

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IV. Summary and discussion

- Conformal symmetry plays an interesting role in nuclear matter;
- A mechanism for generating the peak of SV in nuclear matter can be the nonlinear realization of scale symmetry, NOT the hadron-quark transition or other configuration change;
- The location of the peak is about $(1\sim2)n_0$, a density region can be accessed by terrestrial experiments;
- The SV can saturates the conformal limit in the core of massive stars, BUT matter is not conformal. Conformal SV may not be due to the deconfinement phase transition;
- The predictions of the theory agree with all the observations obtained so far. We cannot distinguish it from other models, but cannot be excluded; Maybe mixing of them?

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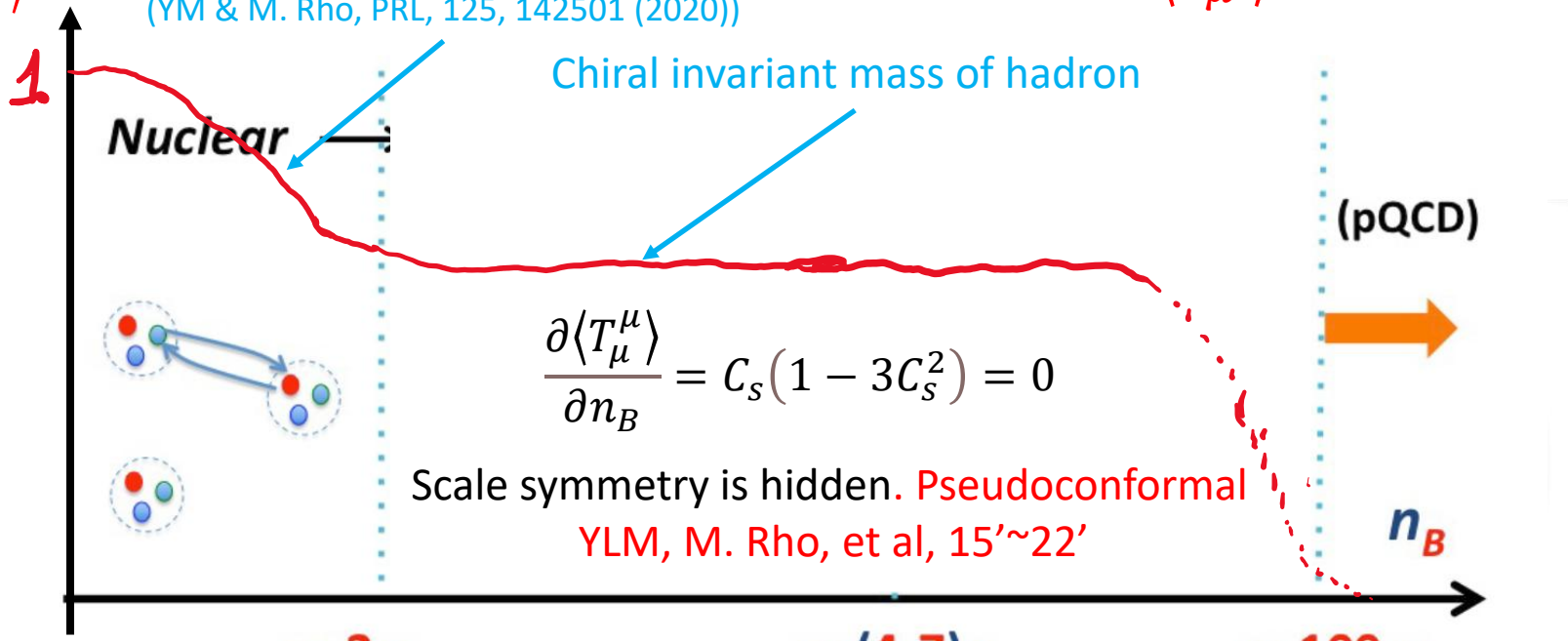
IV. Summary and discussion

$\langle T^{\mu}_{\mu}\rangle^{*}/\langle T^{\mu}_{\mu}\rangle^{*}$

G-T transition of heavy nuclei
(YM & M. Rho, PRL, 125, 142501 (2020))

$\langle T^{\mu}_{\mu}\rangle \sim \langle\chi\rangle \sim m_N$



Scale symmetry is broken

Unnuclear matter made of quasi-DoF?

Scale invariant.

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Thank you for your attention!