



国科大杭州高等研究院
Hangzhou Institute For Advanced Study, UCAS



Topology change, emergent symmetry and compact star matter

Yong-Liang Ma

In collaboration with
Mannque Rho *et al.*

Colloquium @ CCNU, Dec. 16, 2020.



I. Introduction

II. Topology change and quark-hadron continuity

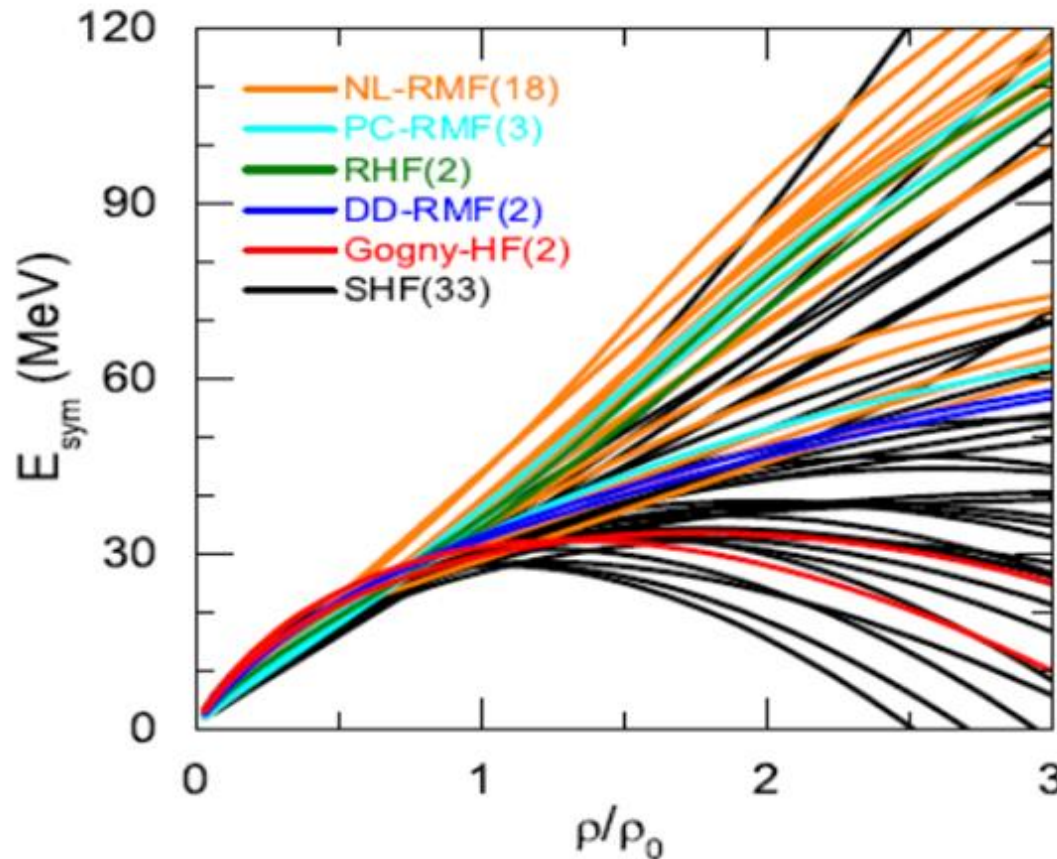
III. Hidden symmetries of QCD

IV. The pseudoconformal model of dense nuclear matter

V. Predictions of the pseudoconformal model

VI. Summary and discussions

I、Introduction



EoS of nuclear matter at high density is a totally mess and uncharted domain.

- ~~Lattice QCD?~~
- ~~Low-temperature terrestrial exp.?~~

L. W. Chen, 1506.09057



- **Finite nuclei as well as infinite nuclear matter** can be fairly accurately accessed by **nuclear EFTs**, “pionless or pionful, (sEFT)” anchored on relevant symmetries and invariances .
- sEFTs, as befits their premise, are expected to **break down at some high density** (and low temperature) relevant to, say, the interior of massive stars.

E.g, In sEFT, the power counting in density is $O(k_F^q)$. For the normal nuclear matter, the expansion requires going to $\sim q = 5$.

J. W. Holt, M. Rho and W.Weise, 1411.6681



Our strategy: Construct “Generalized” nuclear EFT (GnEFT) while capturing fully what s EFT successfully does up to n_0 , can be extrapolated up to a density where s EFT is presumed to break down.

I、Introduction



■ Tidal deformability:

$$\Lambda_{1.4} < 800$$

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

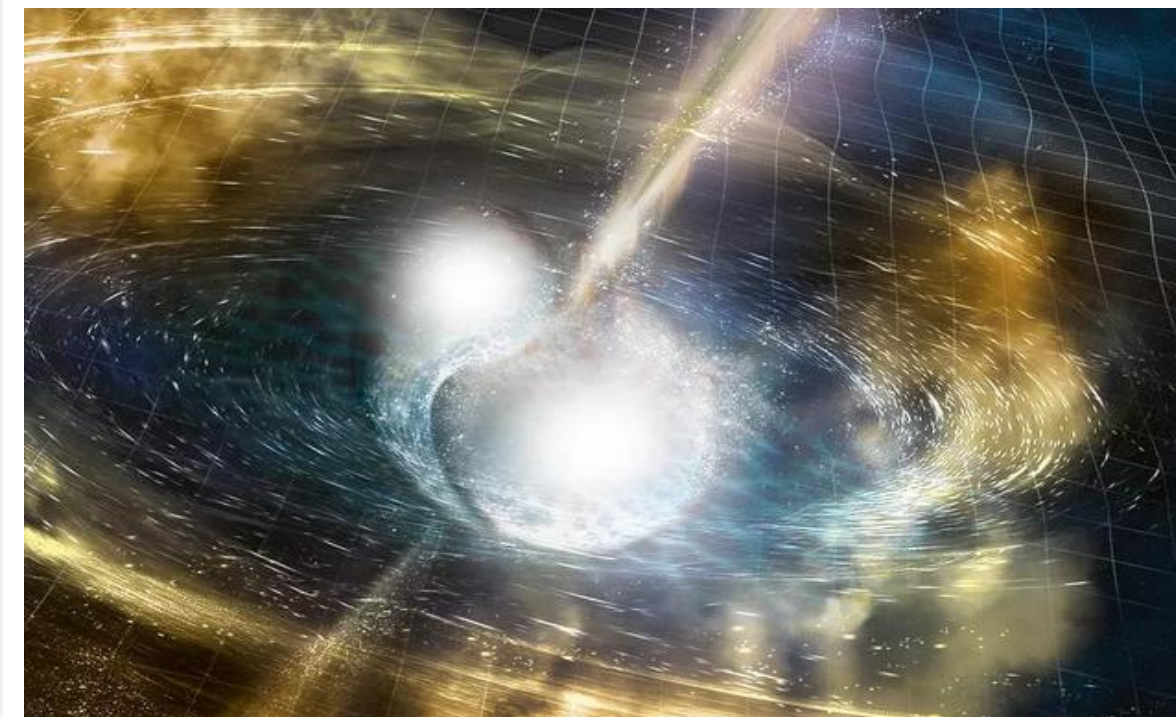
$$R = 11.9_{-1.4}^{+1.4} \text{ km}$$

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

■ Pressure:

$$P(2n_0) = 3.5_{-1.7}^{+2.7} \times 10^{34} \text{ dyn/cm}^2,$$

$$P(6n_0) = 9.0_{-2.6}^{+7.9} \times 10^{34} \text{ dyn/cm}^2.$$



■ Massive neutron stars:

$$(1.97 \pm 0.04)M_{\odot} \quad \textit{Nature, 467(2010),1081.}$$

$$(2.01 \pm 0.04)M_{\odot} \quad \textit{Science, 340(2013), 448.}$$

$$(2.17_{-0.10}^{+0.11})M_{\odot} \quad \textit{arXiv: 1904.06759.}$$

$$\leq 10n_0$$



Basic new physics considered in our approach

■ Hidden topology in QCD

- The microscopic degrees of QCD – quark and gluon – enters the system rephrased using Cheshire Cat Principle

■ Hidden symmetries of QCD

- Hidden scale symmetry
- Hidden local flavor symmetry
- Hidden parity doublet structure of nucleon

I、Introduction



$$\text{GnEFT} = \text{sEFT} + \rho \text{ and } \omega + \text{scalar meson } f_0(500)$$

Hidden local symmetry

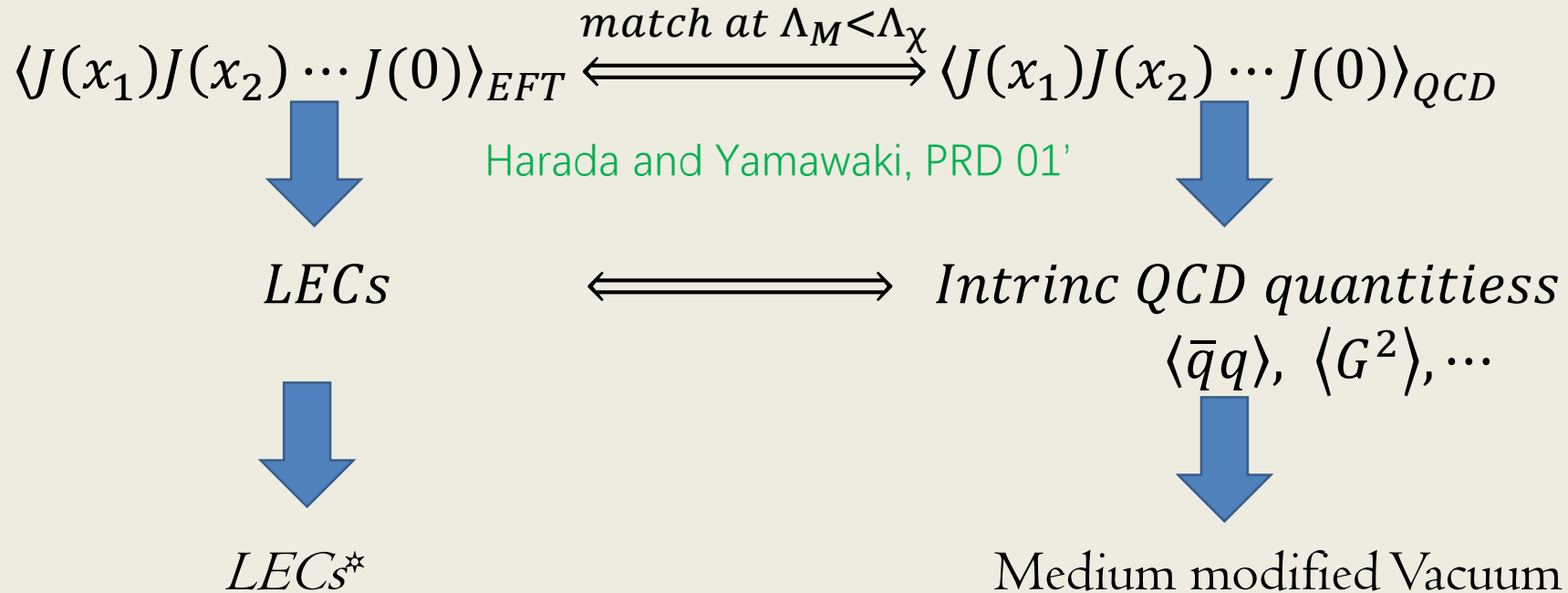
Dilaton/NGB of hidden scale symmetry

- Intrinsic in QCD but not visible in the matter-free vacuum.
- *Get un-hidden by strong nonperturbative nuclear correlations, as nuclear matter is highly compressed.*

The former may be verifying the *Suzuki theorem* and the latter may be indicating an *infrared (IR) fixed point* with both the chiral and scale symmetries realized in the NG mode.

YLM & M. Rho, *PPNP* 20';
W. G. Paeng, et al, *PRD* 17'.

Topology enters through IDD



- The density dependence involved is intrinsic of QCD, referred to the IDD.
- Full density dependence = IDD + IDD_{induced}

Lee, Paeng and Rho (2015); Paeng, Kuo, Lee, Ma and Rho (2017)

I、Introduction



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

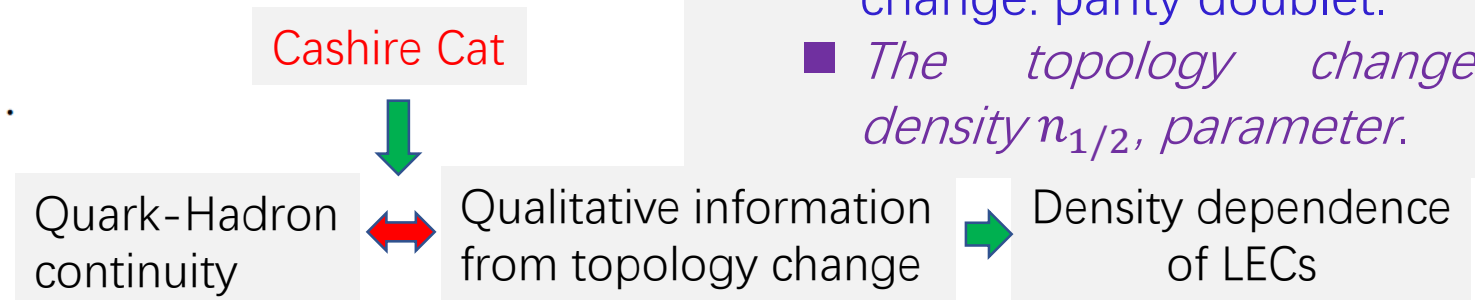
$$\begin{aligned} \mathcal{L}_{\chi PT_\sigma}^M(\pi, \chi, V_\mu) = & f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \text{Tr}[\hat{a}_{\perp\mu} \hat{a}_{\perp}^\mu] + a f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \text{Tr}[\hat{a}_{\parallel\mu} \hat{a}_{\parallel}^\mu] \\ & + \frac{1}{2g^2} \text{Tr}[V_{\mu\nu}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

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

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

**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.*



II、 Topology change and quark-hadron continuity



In large N_c limit, baryon in QCD goes to skyrmion. Witten 79'

$$\mathcal{L} = \frac{f_\pi^2}{4} \text{Tr} (\partial_\mu U^\dagger \partial^\mu U) + \frac{1}{32e^2} \text{Tr} [U^\dagger \partial_\mu U, U^\dagger \partial_\nu U]^2$$

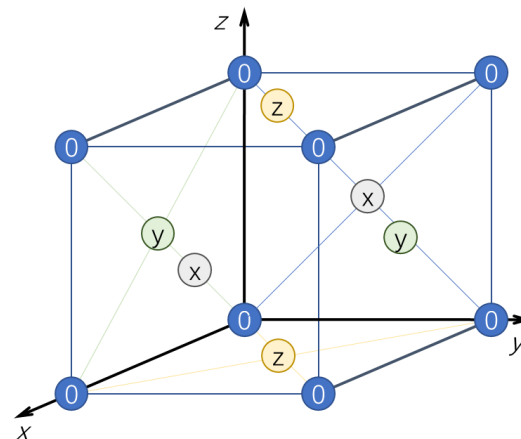
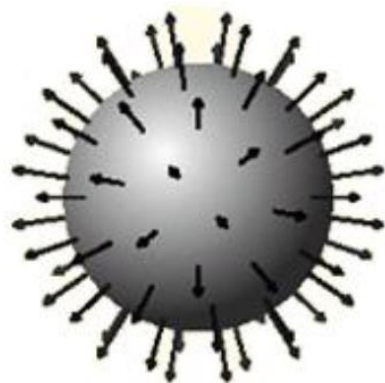
f_π : pion decay constant

e : Skyrme parameter

Topological soliton
winding number = baryon number

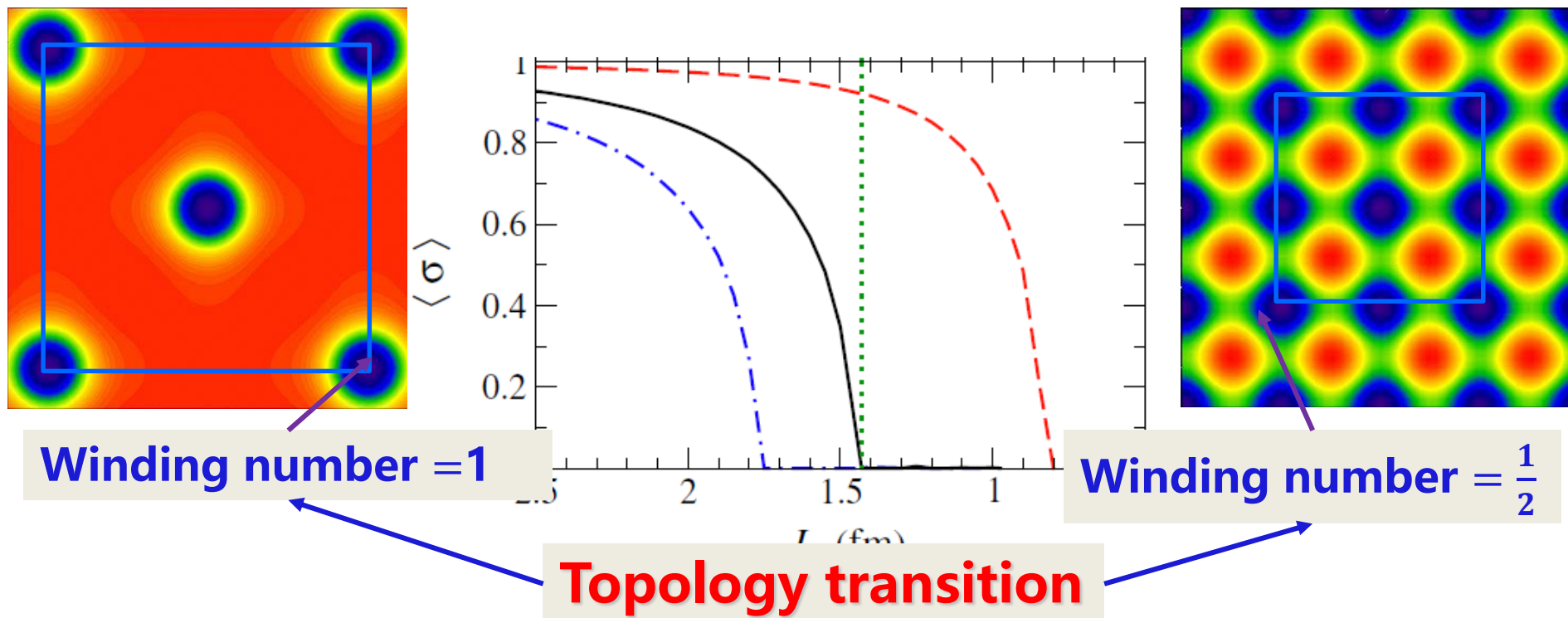
$$B_\mu = \frac{1}{24\pi^2} \epsilon_{\mu\nu\alpha\beta} \text{Tr} (U^\dagger \partial_\nu U U^\dagger \partial_\alpha U U^\dagger \partial_\beta U)$$

T. R. Skyrme, 1960



Baryonic interactions in **all regimes of density**, upto that relevant to the core of CSs, can be accessed.

II、Topology change and quark-hadron continuity

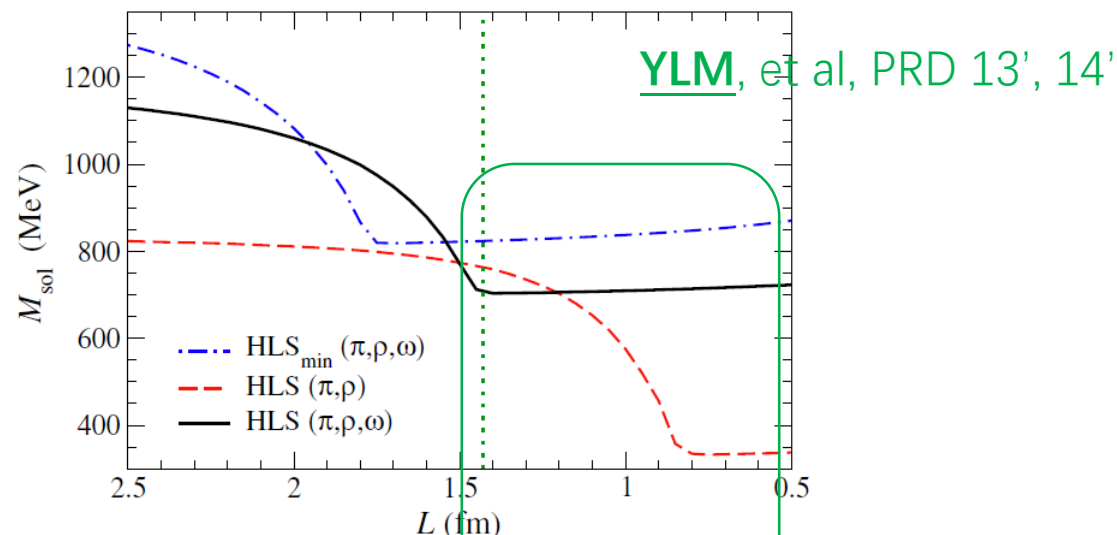
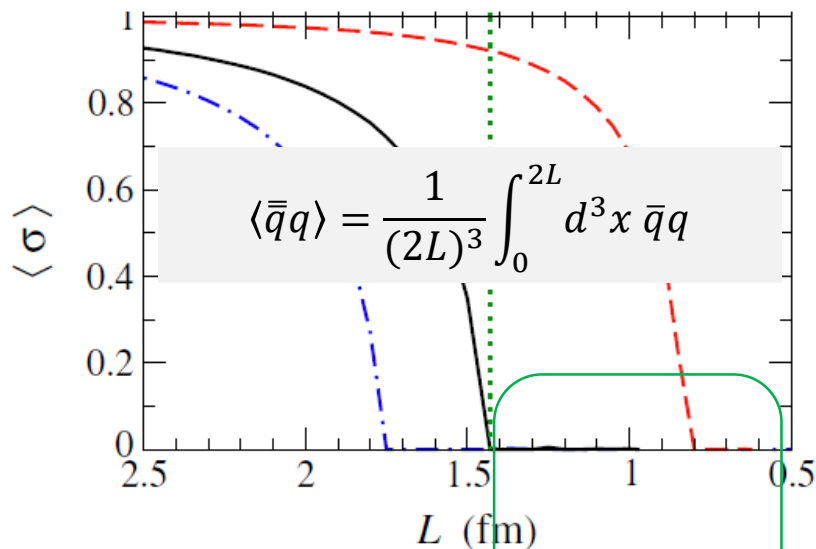


The half-skyrmion phase, characterized by the quark condensate $\Sigma \equiv \langle \bar{q}q \rangle$ vanishing on average but locally nonzero with chiral density wave and non-zero pion decay constant.

No phase transition!



Topology change: Parity doublet structure



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.**

Agree with Y. Motohiro, *et al*, Phys.Rev. C92 (2015), 025201

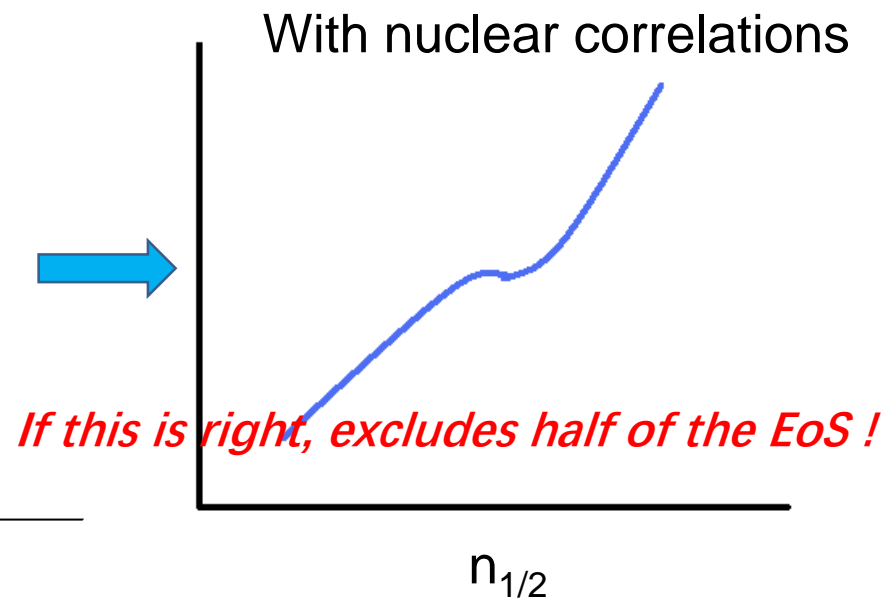
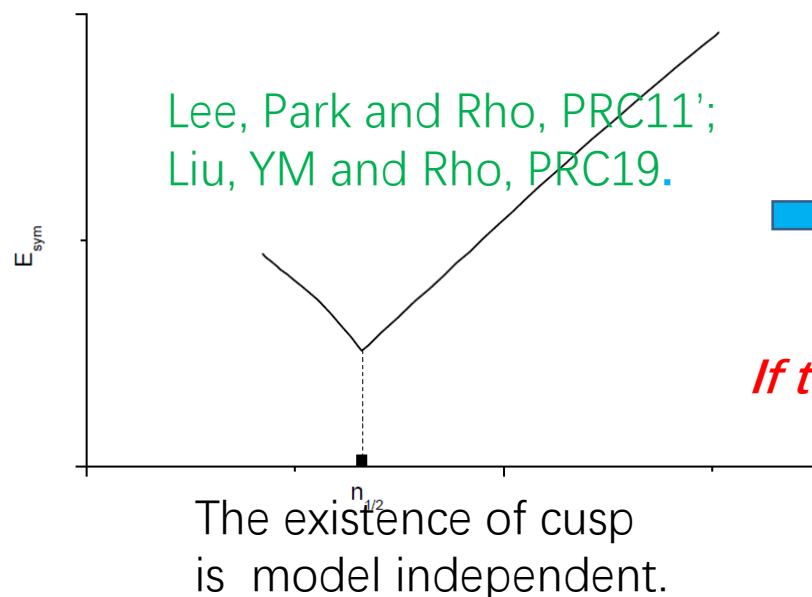
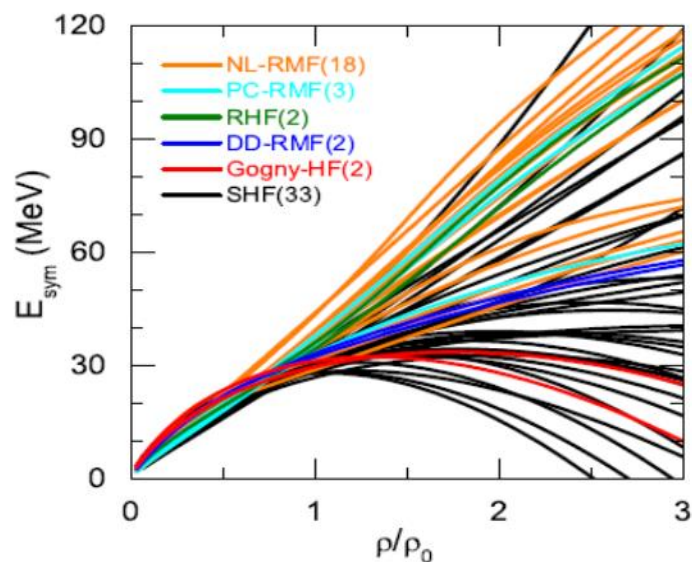
II、Topology change and quark-hadron continuity



$$E(n, \alpha) = E(n, \alpha = 0) + E_{\text{sym}}(n)\alpha^2 + O(\alpha^4) + \dots$$

“Symmetry energy is dominated by the tensor forces”:

$$E_{\text{sym}} \propto 1/\lambda_I + O(1/N_c^2).$$

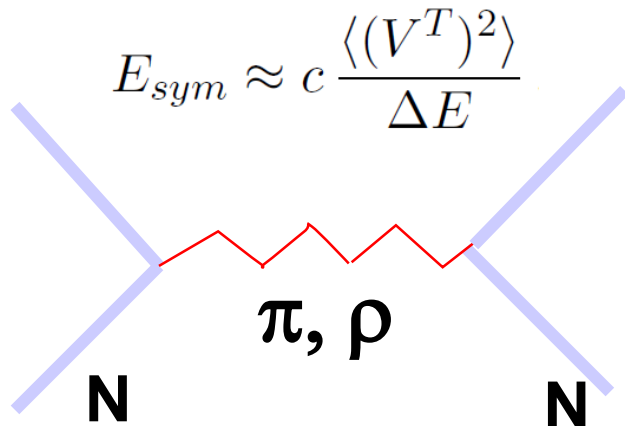


The cusp is associated with the topology change with the emergence of quasiparticle structure with the half-skyrmions.

II、Topology change and quark-hadron continuity



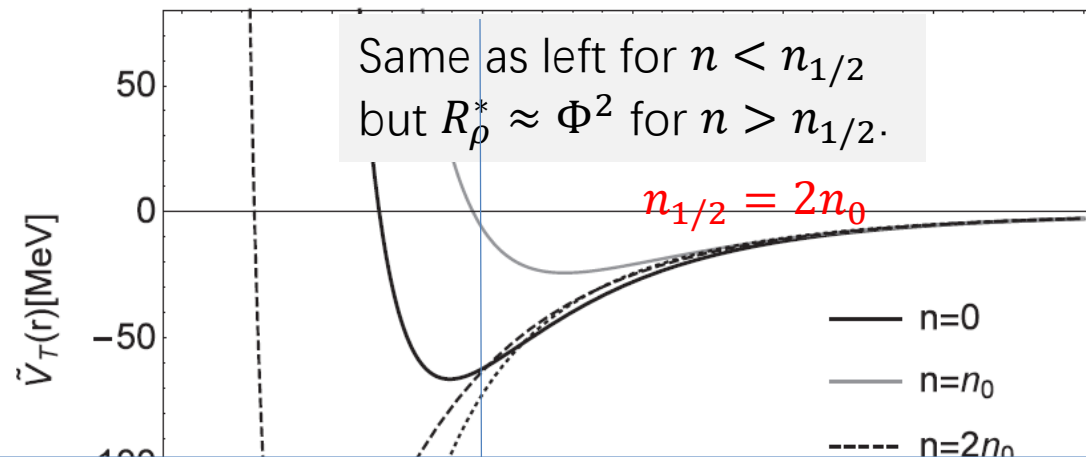
G.E. Brown and R. Machleidt 1994 ... A. Carbone et al 2013



$$V_M^T(r) = S_M \frac{f_{NM}^2}{4\pi} m_M \tau_1 \cdot \tau_2 S_{12} \left(\left[\frac{1}{(m_M r)^3} + \frac{1}{(m_M r)^2} + \frac{1}{3m_M r} \right] e^{-m_M r} \right)$$

$$M = \pi, \rho, S_{\rho(\pi)} = +1(-1)$$

$$R_M^* \equiv \frac{f_{NM}^*}{f_{NM}} \approx \frac{g_{MNN}^* m_N m_M^*}{g_{MNN} m_N^* m_M}$$

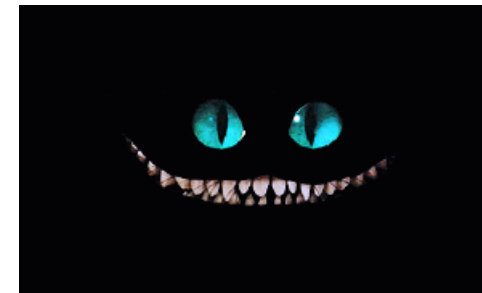


Going toward to $n_{1/2}$ from below, E_{sym} to drop and more or less abruptly turn over at $n_{1/2}$ and then increase beyond $n_{1/2}$.

- Gives precisely the cusp predicted in crystal;
- Produced by the emergent VM with $m_V \rightarrow 0$ at $n > 25n_0$.
- The only density dependence in the TEMT is through the dilaton condensate inherited QCD with vacuum change.
- Cusp structure reflects the NPQCD effect manifested through $\langle \chi \rangle$.
- The TF is RG-invariant in both free space and in medium, which carries the density dependence ONLY through IDD inherited from QCD, NOT nuclear renormalization.



The Cheshire Cat

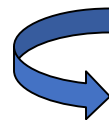


“How hadrons transform to quarks”

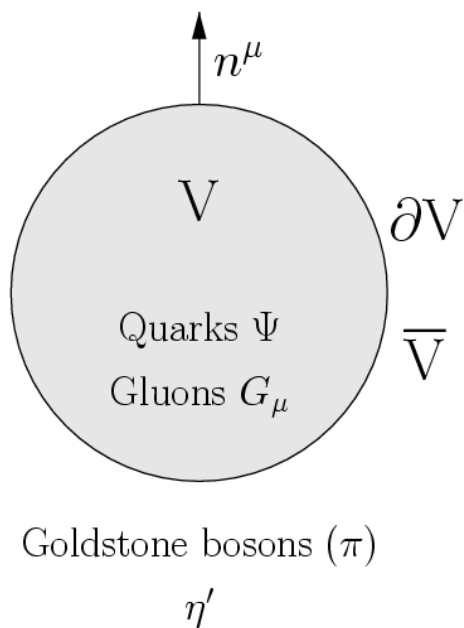
Baryon charge:

$$B_{out} = \frac{1}{\pi} [\theta(R) - \frac{1}{2} \sin 2\theta(R)]$$

$$B_{in} = 1 - \frac{1}{\pi} [\theta(R) - \frac{1}{2} \sin 2\theta(R)]$$



$$B = B_{out} + B_{in} = 1$$



III、Topology change and quark-hadron continuity



Equivalent description of the proton

$$S = S_V + S_{\bar{V}} + S_{\delta V},$$

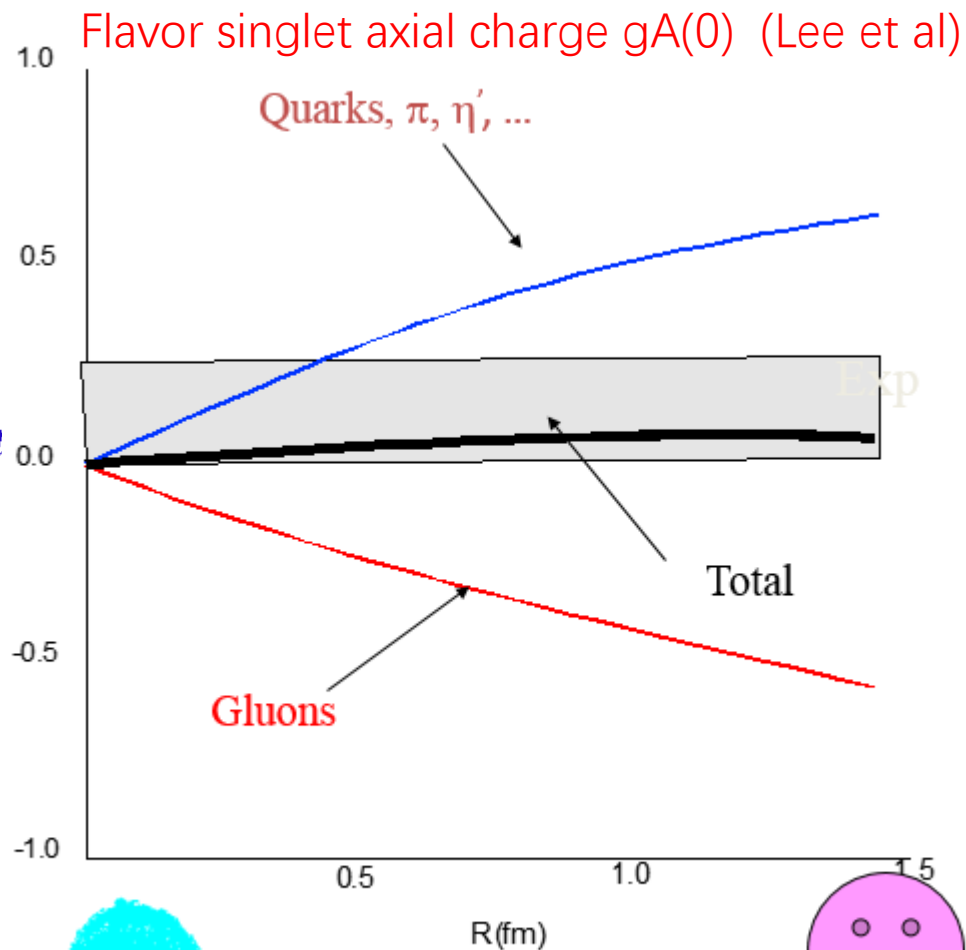
where

$$S_V = \int_V d^4x \left(\bar{\psi} i \not{D} \psi - \frac{1}{2} \text{tr} G_{\mu\nu} G^{\mu\nu} \right) + \dots,$$

$$S_{\bar{V}} = \frac{f^2}{4} \int_{\bar{V}} d^4x \left(\text{Tr} \partial_\mu U^\dagger \partial^\mu U + \frac{1}{4N_f} m_{\eta'}^2 (\text{Tr} \ln U - \text{Tr} \ln U^\dagger)^2 \right) + S_{WZ} + \dots,$$

$$S_{\delta V} = \frac{1}{2} \int_{\delta V} d\Sigma^\mu \left\{ (n_\mu \bar{\psi} U \gamma^5 \psi) + i \frac{g_s^2}{16\pi^2} K_{5\mu} (\text{Tr} \ln U^\dagger - \text{Tr} \ln U) \right\}.$$

$$K_5^\mu = \epsilon^{\mu\nu\alpha\beta} (G_\nu^a G_{\alpha\beta}^a - \frac{2}{3} g_s f^{abc} G_\nu^a G_\alpha^b G_\beta^c),$$



When the bag radius is shrunk to zero, only the smile of the cat is left with spinning gapless quarks running luminally

II、 Topology change and quark-hadron continuity

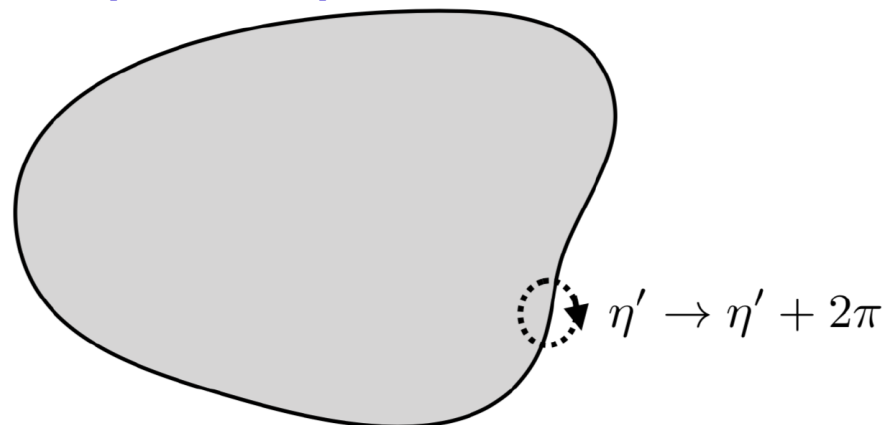


When $N_f = 1$,

Since $\pi_3(U(1)) = 0$;

Rule out the skyrmion approach?

$$J_{\alpha\beta\gamma} = \epsilon_{\alpha\beta\gamma\delta} \partial^\delta \eta' / 2\pi$$



Baryons as Quantum Hall Droplets

1812.09253 [hep-th]

Zohar Komargodski

*Simons Center for Geometry and Physics, Stony Brook, New York, USA
and Weizmann Institute of Science, Rehovot 76100, Israel*

Abstract

$N_f = 1$ baryon can be interpreted as quantum Hall droplet. An important element in the construction is an extended, 2 + 1 dimensional, meta-stable configuration of the η' particle. Baryon number is identified with a magnetic symmetry on the 2 + 1 sheet.

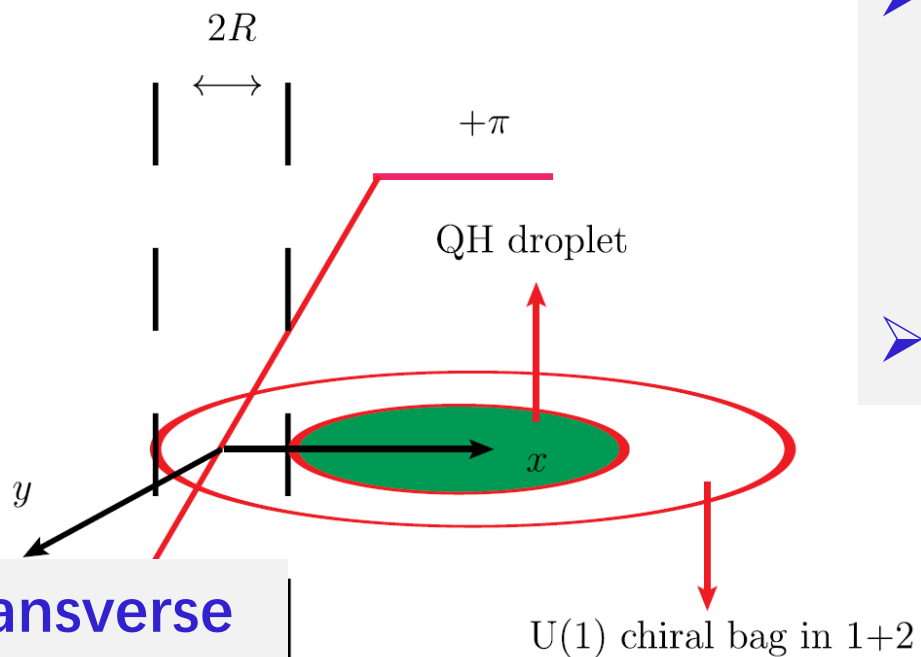
are able to determine the spin, isospin, and certain excitations of the droplet. In addition, balancing the tension of the droplet against the energy stored at the boundary we estimate the size and mass of the baryons. The mass, size, spin, isospin, and excitations that we find agree with phenomenological expectations.

[hep-th] 6 Feb 2019

II、Topology change and quark-hadron continuity



YLM, Nowak, Rho & Zahed, 1907.00958



A current transverse to the smile is shown to appear.
Hall current.

- Consists of free 2-dim quarks, charge e , and subject to a chiral bag BC along the radial x -direction.
- Leaks most quantum numbers.

- Annulus of radius R and clouded by an η' -field with a monodromy of 2π .
- The bag radius is immaterial thanks to CCP.



PHYSICAL REVIEW LETTERS 123, 172301 (2019)

Baryon as a Quantum Hall Droplet and the Quark-Hadron Duality

Yong-Liang Ma^{1,*}, Maciej A. Nowak^{2,†}, Mannque Rho^{3,‡} and Ismail Zahed^{4,§}

¹Center for Theoretical Physics and College of Physics, Jilin University, Changchun 130012, China

²Marian Smoluchowski Institute of Physics and Mark Kac Complex Systems Research Center, Jagiellonian University, ulica Stanisława Łojasiewicza 11, PL 30-348 Kraków, Poland

³Institut de Physique Theorique, CEA Saclay, 91191 Gif-sur-Yvette cedex, France

⁴Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794–3800, USA



(Received 12 July 2019; revised manuscript received 2 September 2019; published 22 October 2019)

We show that the recent proposal to describe the $N_f = 1$ baryon in the large number of the color limit as a quantum Hall droplet can be understood as a chiral bag in a $(1 + 2)$ -dimensional strip using the Cheshire Cat principle. For a small bag radius, the bag reduces to a vortex line which is the smile of the cat with flowing massless quarks all spinning in the same direction. The disk enclosed by the smile is described by a

- 利用重子的手征口袋模型阐明了致密核物质中的夸克-强子对偶机制;
- 给出了在强子物理中实现凝聚态物理中的一些概念的范例。

III、 Hidden symmetries of QCD

Rho and omega mesons play an important role in our formalism of compact star structure

Redundancy in the decomposition

$$U(x) = \xi_L h(x) h(x)^\dagger \xi_R^\dagger$$

$$h(x) \in SU(2)_{L+R} \times U(1)_{L+R}$$

ρ meson

ω meson

$$\hat{\alpha}_{\parallel\mu} = \frac{1}{2i} (D_\mu \xi_R \cdot \xi_R^\dagger + D_\mu \xi_L \cdot \xi_L^\dagger),$$

$$\hat{\alpha}_{\perp\mu} = \frac{1}{2i} (D_\mu \xi_R \cdot \xi_R^\dagger - D_\mu \xi_L \cdot \xi_L^\dagger),$$

$$V_\mu(x) = \frac{g_\rho}{2} \rho_\mu^a \tau^a + \frac{g_\omega}{2} \omega_\mu I_{2 \times 2},$$

The idea -- that is totally different from what one could call “standard” in nuclear community -- is that ρ (and ω, in a different way) is “hidden gauge field”.

Bando, *et al*/89; Harada & Yamawaki, 03

$$\begin{aligned} \mathcal{L}_M = & f_\pi^2 \text{tr} [\hat{\alpha}_{\perp\mu} \hat{\alpha}_{\perp}^\mu] + a_\rho f_\pi^2 \text{tr} [\hat{\alpha}_{\parallel\mu} \hat{\alpha}_{\parallel}^\mu] \\ & + (a_\omega - a_\rho) f_\pi^2 \text{tr} [\hat{\alpha}_{\parallel\mu}] \text{tr} [\hat{\alpha}_{\parallel}^\mu] \\ & - \frac{1}{2} \text{tr} [\rho_{\mu\nu} \rho^{\mu\nu}] - \frac{1}{2} \text{tr} [\omega_{\mu\nu} \omega^{\mu\nu}]. \end{aligned}$$

It captures extremely well certain strong interaction dynamics even at tree order.



Suzuki Theorem:

PHYSICAL REVIEW D **96**, 065010 (2017)

Inevitable emergence of composite gauge bosons

Mahiko Suzuki

*Department of Physics and Lawrence Berkeley National Laboratory University of California,
Berkeley, California 94720, USA*

(Received 18 July 2017; published 15 September 2017)

A simple theorem is proved: When a gauge-invariant local field theory is written in terms of matter fields alone, a composite gauge boson or bosons must be formed dynamically. The theorem results from the fact

This theorem holds for rho if there is a sense of massless rho at some parameter space. The HLS with the redundancy elevated to gauge theory, treated à la Wilsonian RG, has (Harada & Yamawaki,01') a fixed point at $g_\rho = 0$. The KSRF relation $m_\rho^2 \propto f_\pi^2 g_\rho^2$ holds to all loop orders, hence at the fixed point, called vector manifestation (VM) fixed point, there “emerges” a gauge field.

Proposition: *Hidden local symmetry can emerge in nuclear dynamics with the vector meson mass driven to zero at the vector manifestation fixed point by high density.* Indeed in SUSY QCD, Komargodski, JHEP 1102, 019 (2011).

III、 Hidden symmetries of QCD



$SU(2)_L \times SU(2)_R$ linear sigma model

$$\mathcal{L}_{L\sigma M} = \frac{1}{2} \text{Tr}(\partial_\mu M \partial^\mu M^\dagger) - \frac{\mu^2}{2} \text{Tr}(M M^\dagger) - \frac{\lambda}{4} (\text{Tr}(M M^\dagger))^2 \quad M \rightarrow g_L M g_R^\dagger, \quad g_{R,L} \in SU(2)_{R,L}$$

- (1) In the strong coupling limit, $\lambda \rightarrow \infty$, $\langle \sigma \rangle \rightarrow f = f_\pi$, so one simply gets the familiar non-linear sigma model

K. Yamawaki, 2015

$$\mathcal{L}_{L\sigma M} \xrightarrow{\lambda \rightarrow \infty} \mathcal{L}_{NL\sigma} = \frac{f_\pi^2}{4} \cdot \text{Tr}(\partial_\mu U \partial^\mu U^\dagger)$$

- (2) Now we turn to the weak coupling limit $\lambda \rightarrow 0$. Define the scale-dimension-1 and mass-dimension-1 field χ , the conformal compensator

$$\mathcal{L}_{L\sigma M} = \mathcal{L}_{\text{sinv}} - V(\chi)$$

$$\chi = f_\chi e^{\sigma/f_\chi}.$$

with

$$\mathcal{L}_{\text{sinv}} = \frac{1}{2} (\partial_\mu \chi)^2 + \frac{f_\pi^2}{4} \left(\frac{\chi}{f_\phi} \right)^2 \cdot \text{Tr}(\partial_\mu U \partial^\mu U^\dagger),$$

$$V(\chi) = \frac{\lambda}{4} f_\phi^4 \left[\left(\left(\frac{\chi}{f_\phi} \right)^2 - 1 \right)^2 - 1 \right],$$

Scale invariant

Scale noninvariant

LOSS

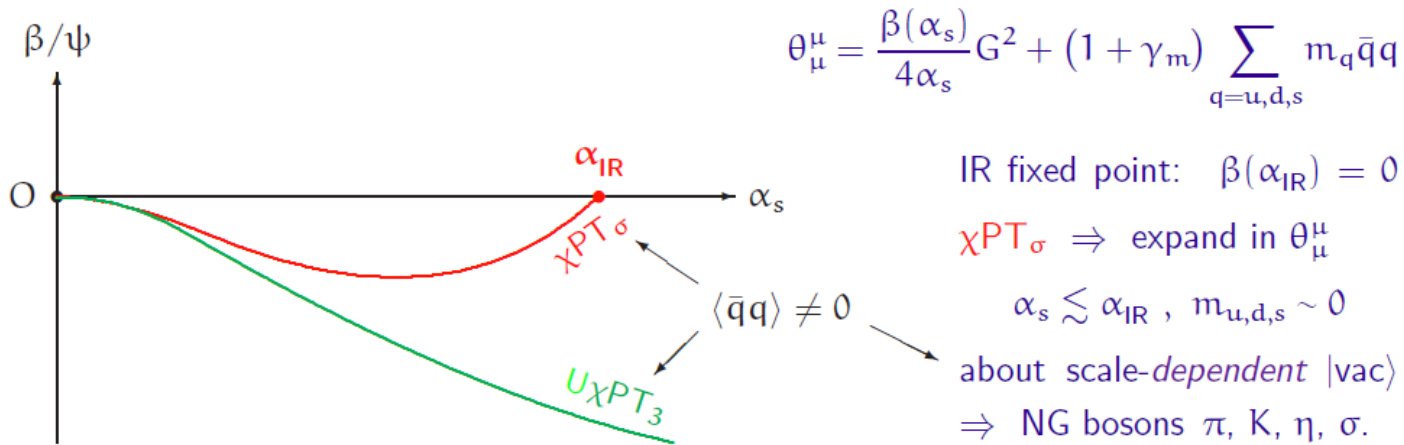
Proposition: *Baryonic matter can be driven by increasing density from Nambu-Goldstone mode in scale-chiral symmetry to the dilaton-limit fixed point in pseudo-conformal mode.*

III、 Hidden symmetries of QCD

$f_0(500)$ 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.



Crewther and Tunstall, PRD91, 034016

Provides an approach to include scalar meson in ChPT.

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

$$\mathcal{L}_{inv}^{d=4} = c_1 \frac{f_\pi^2}{4} \left(\frac{\chi}{f_\chi} \right)^2 \text{Tr} \left(\partial_\mu U \partial^\mu U^\dagger \right) + \frac{1}{2} c_2 \partial_\mu \chi \partial^\mu \chi + c_3 \left(\frac{\chi}{f_\chi} \right)^4,$$

$$\mathcal{L}_{anom}^{d>4} = (1 - c_1) \frac{f_\pi^2}{4} \left(\frac{\chi}{f_\chi} \right)^{2+\beta'} \text{Tr} \left(\partial_\mu U \partial^\mu U^\dagger \right) + \frac{1}{2} (1 - c_2) \left(\frac{\chi}{f_\chi} \right)^{\beta'} \partial_\mu \chi \partial^\mu \chi + c_4 \left(\frac{\chi}{f_\chi} \right)^{4+\beta'},$$

$$\mathcal{L}_{mass}^{d<4} = \frac{f_\pi^2}{4} \left(\frac{\chi}{f_\chi} \right)^{3-\gamma_m} \text{Tr} \left(\mathcal{M}^\dagger U + U^\dagger \mathcal{M} \right),$$

III、Hidden symmetries of QCD



$$\begin{aligned} \mathcal{L}_N = & \bar{Q} i \gamma^\mu D_\mu Q - g_1 F_\pi \frac{\chi}{F_\chi} \bar{Q} Q + g_2 F_\pi \frac{\chi}{F_\chi} \bar{Q} \rho_3 Q \\ & - i m_0 \bar{Q} \rho_2 \gamma_5 Q + g_{V\rho} \bar{Q} \gamma^\mu \hat{\alpha}_{\parallel\mu} Q \\ & + g_{V0} \bar{Q} \gamma^\mu \text{tr}[\hat{\alpha}_{\parallel\mu}] Q + g_A \bar{Q} \rho_3 \gamma^\mu \hat{\alpha}_{\perp\mu} \gamma_5 Q, \end{aligned}$$

- Beane and Klock, PLB, 94'
- Paeng, Lee, Rho and Sasaki, 12'

$$\Sigma = U \chi \frac{F_\pi}{F_\chi} = s + i \vec{\tau} \cdot \vec{\pi}$$

$$m_{N_\pm} = \mp g_2 \langle s \rangle + \sqrt{(g_1 \langle s \rangle)^2 + m_0^2},$$

$\langle s \rangle \rightarrow 0$

$$g_{v\rho} - g_A \rightarrow 0, \quad \alpha - 1 \rightarrow 0. \quad \alpha \equiv f_\pi^2 / f_\chi^2$$

$$m_{N_\pm} \rightarrow m_0.$$

Chiral inv. mass

$$g_\rho NN = g_\rho (g_{v\rho} - 1) \rightarrow 0.$$

ρ decouples, HFS emerges.

$$\begin{aligned} \mathcal{L}_N = & \bar{N} i \not{\partial} N - \bar{N} \hat{M} N - g_1 \bar{N} (\hat{G} \tilde{s} + \rho_3 \gamma_5 i \vec{\tau} \cdot \vec{\pi}) N \\ & + g_2 \bar{N} (\rho_3 \tilde{s} + \hat{G} \gamma_5 i \vec{\tau} \cdot \vec{\pi}) N \\ & + (1 - g_{v\omega}) g_\omega N \frac{\not{\omega}}{2} N, \end{aligned}$$

Proposition: Moving toward to the dilaton-limit fixed point, the fundamental constants in scale-chiral symmetry get transformed as $f_\pi \rightarrow f_\chi, g_A \rightarrow g_{v\rho} \rightarrow 1$, and the ρ meson decouples while the ω remains coupled, breaking the flavor $U(2)$ symmetry.

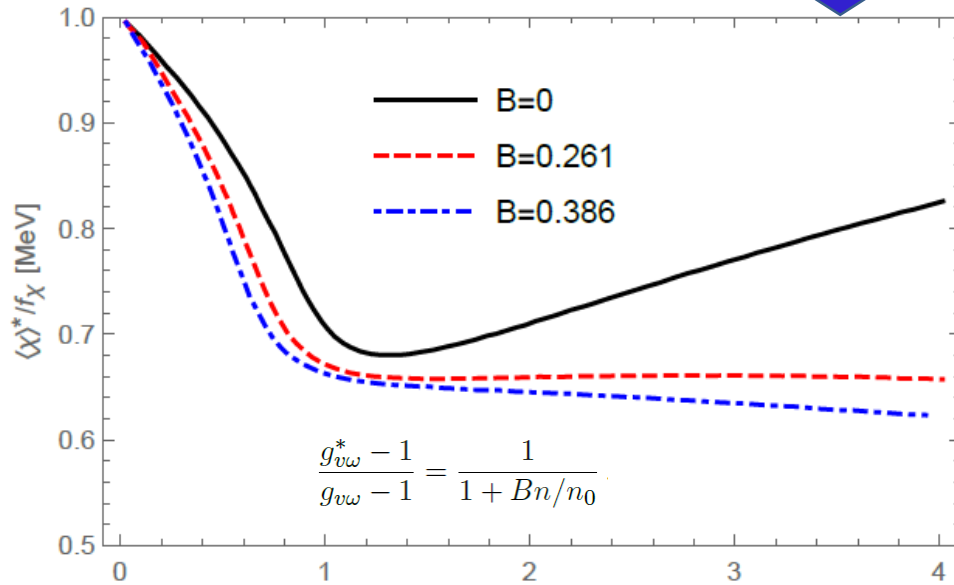
III、Hidden symmetries of QCD



Emergent from parameter dialing from RMF:

$$\mathcal{L} = \bar{N}i\gamma^\mu D_\mu N - hf_\pi \frac{\chi}{f_\chi} \bar{N}N + g_{v\rho} \bar{N}\gamma^\mu \hat{\alpha}_{\parallel\mu} N + g_{v0} \bar{N}\gamma^\mu \text{Tr} [\hat{\alpha}_{\parallel\mu}] N + g_A \bar{N}\gamma^\mu \hat{\alpha}_{\perp\mu} \gamma_5 N + V(\chi)$$

Paeng, Lee, Rho and Sasaki, PRD 13'



Parity doubling emerges via an interplay between ω -N coupling -- with U(2) symmetry strongly broken -- and the dilaton condensate.

$$\begin{aligned} \langle \theta_\mu^\mu \rangle &= \langle \theta^{00} \rangle - \sum_i \langle \theta^{ii} \rangle = \epsilon - 3P \\ &= 4V(\langle \chi \rangle) - \langle \chi \rangle \left. \frac{\partial V(\chi)}{\partial \chi} \right|_{\chi=\langle \chi \rangle} \end{aligned}$$

In the MF of bsHLS, the TEMT is given solely by the dilaton condensate.

Proposition: Going toward the DLFP with the ρ decoupling from the nucleons, the parity doubling emerges and $m_N^* \rightarrow \langle \chi \rangle^* \rightarrow m_0$. Consequently the TEMT in medium in $V_{low k}$ RG theory is a function of only m_0 which is independent of density. This leads to the "pseudo-conformal" sound velocity $v_s^2 \approx 1/3$ in compact stars

IV、 The pseudoconformal model of dense nuclear matter



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

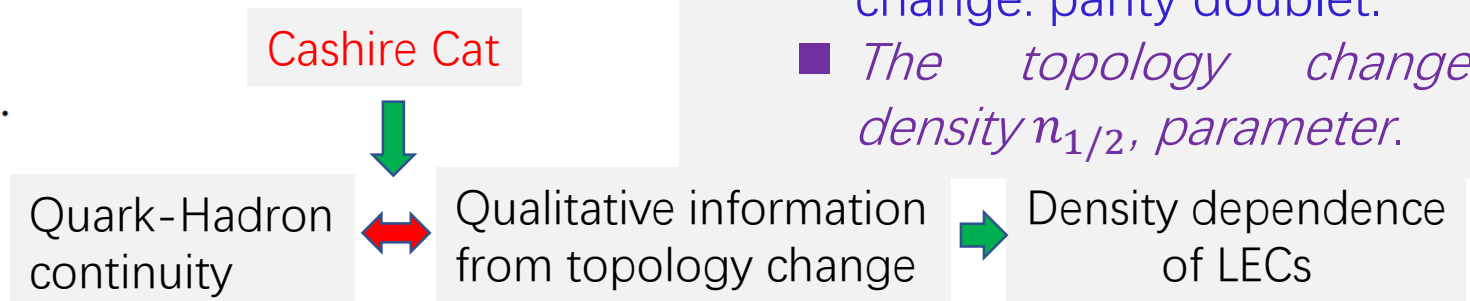
$$\begin{aligned} \mathcal{L}_{\chi PT_\sigma}^M(\pi, \chi, V_\mu) = & f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \text{Tr}[\hat{a}_{\perp\mu} \hat{a}_{\perp}^\mu] + a f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \text{Tr}[\hat{a}_{\parallel\mu} \hat{a}_{\parallel}^\mu] \\ & + \frac{1}{2g^2} \text{Tr}[V_{\mu\nu}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

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

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

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.*





PHYSICAL REVIEW LETTERS **125**, 142501 (2020)

Quenched g_A in Nuclei and Emergent Scale Symmetry in Baryonic Matter

Yong-Liang Ma^{1,2,3,*} and Mannque Rho^{4,†}

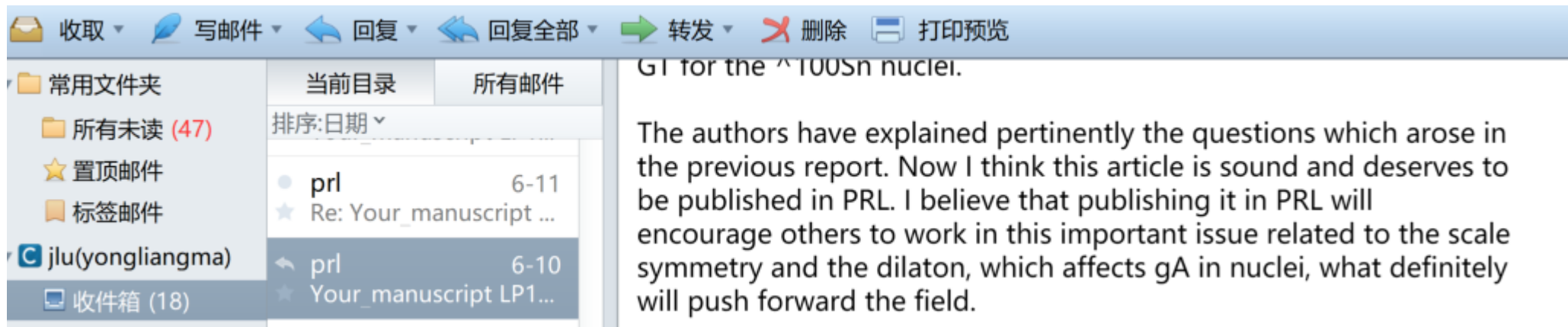
¹*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China*

²*International Centre for Theoretical Physics Asia-Pacific (ICTP-AP) (Beijing/Hangzhou), UCAS, Beijing 100190, China*

³*Center for Theoretical Physics and College of Physics, Jilin University, Changchun, 130012, China*

⁴*Department of Physics, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea*

- 证明了原子核壳模型中核子 Gamow Teller 跃迁中 g_A 淬火问题可以利用费米流体固定点理论中的强子关联来解释；
- 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。



III、 Hidden symmetries of QCD



$$\begin{aligned}\langle \theta_{\mu}^{\mu} \rangle &= \langle \theta^{00} \rangle - \sum_i \langle \theta^{ii} \rangle = \epsilon - 3P \\ &= 4V(\langle \chi \rangle) - \langle \chi \rangle \left. \frac{\partial V(\chi)}{\partial \chi} \right|_{\chi=\langle \chi \rangle}\end{aligned}$$

$$m_N^* = h\bar{\chi}.$$

In GNEFT, the TEMT is given solely by the dilaton condensate.

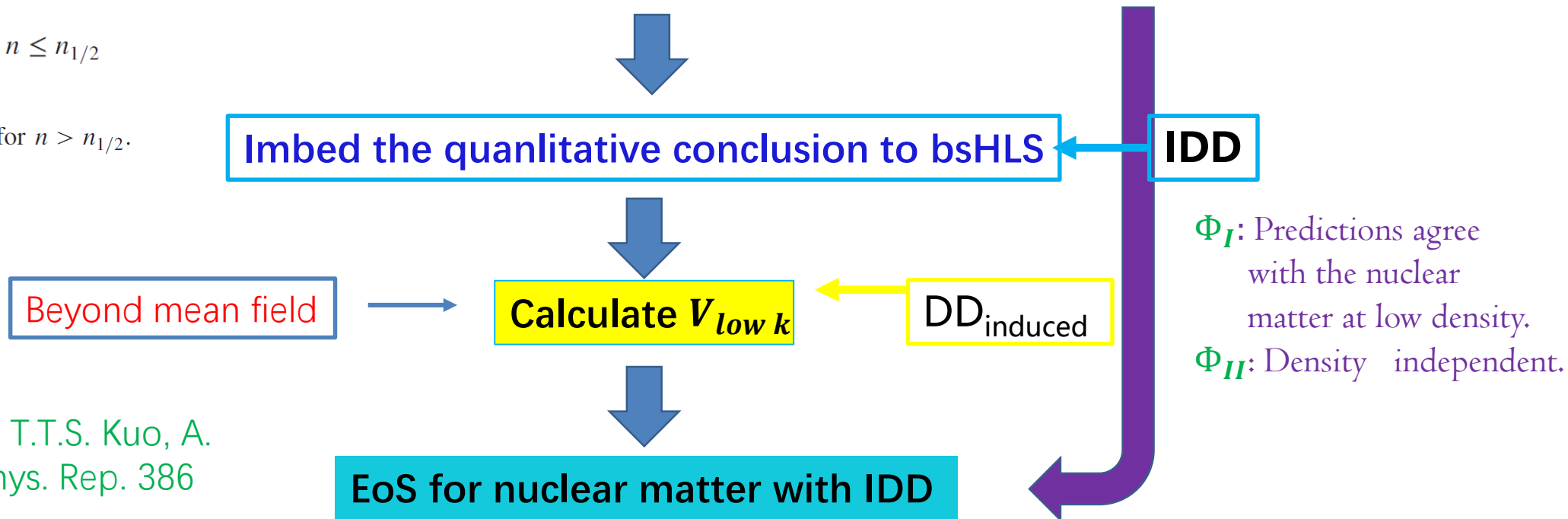
Going toward the DLFP with the ρ decoupling from the nucleons, the parity doubling emerges and $m_N^ \rightarrow \langle \chi \rangle^* \rightarrow m_0$. Consequently the TEMT in medium is a function of only m_0 which is independent of density. This leads to the "pseudo-conformal" sound velocity $v_s^2 \approx 1/3$ in compact stars*

Implement topology transition to EoS

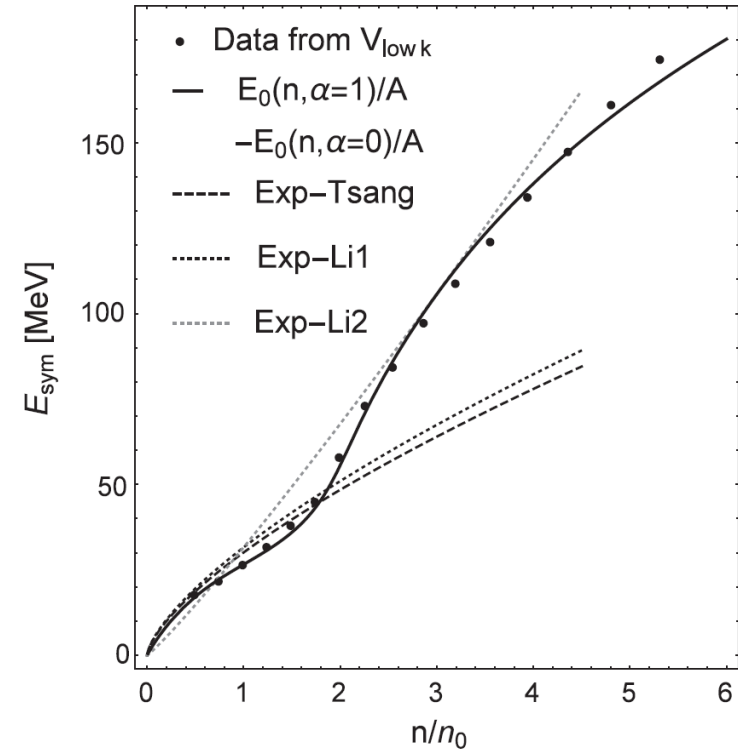
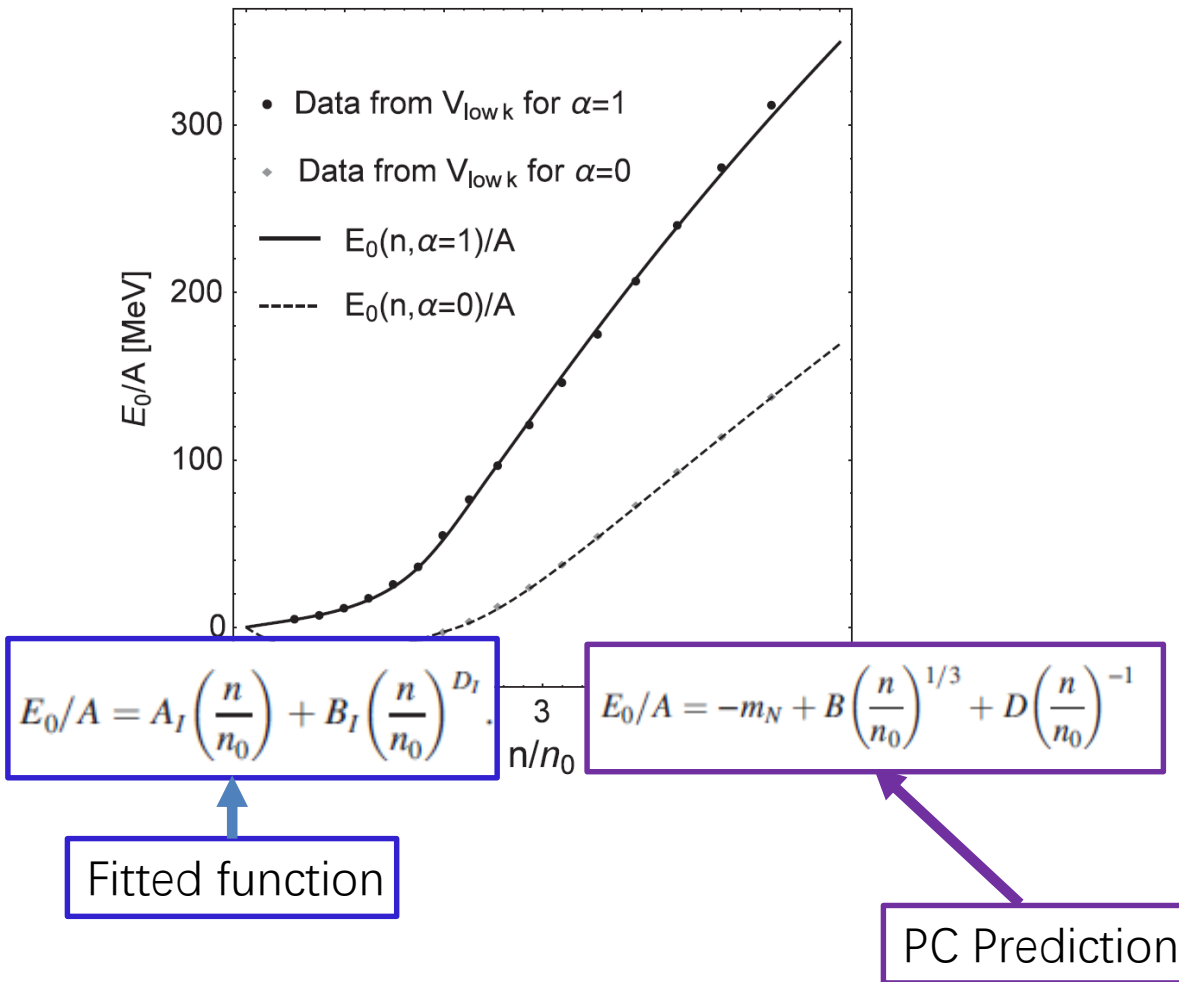
Hadron properties have different scales in $n < n_{1/2}$ and $n > n_{1/2}$
Different scaling behavior: Φ_I and Φ_{II}

$$\Phi^* = \frac{1}{1 + c_I(n/n_0)} \quad \text{for } n \leq n_{1/2}$$

$$\Phi^* \approx \kappa \approx \frac{1}{1 + c_I(n_{1/2}/n_0)} \quad \text{for } n > n_{1/2}.$$



S.K. Bogner, T.T.S. Kuo, A. Schwenk, Phys. Rep. 386 (2003).



IV、 The pseudoconformal model 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.

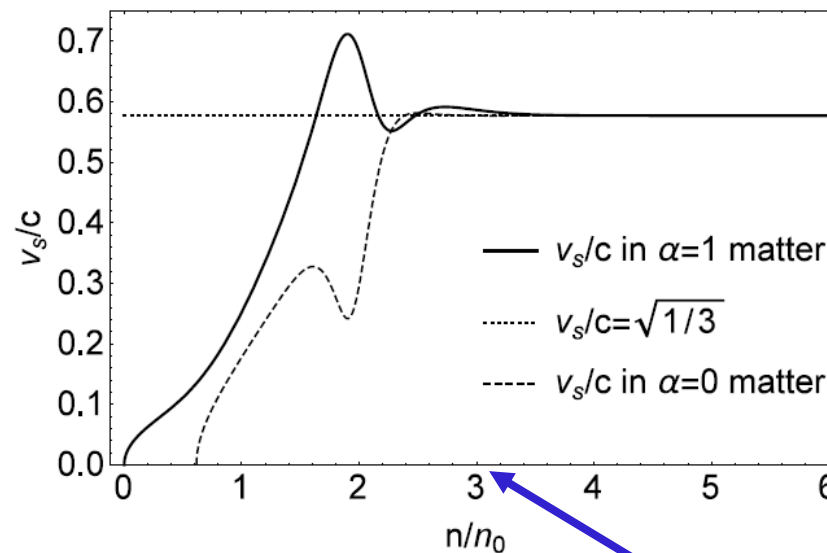
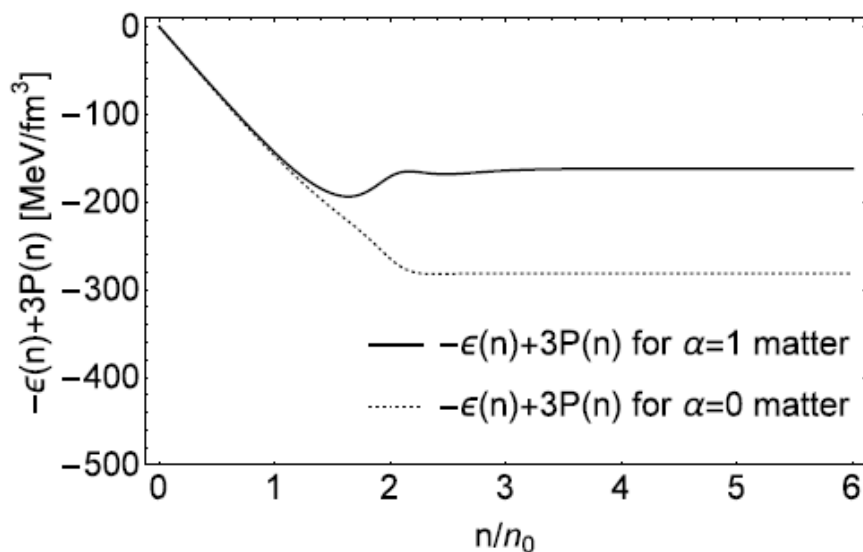
Parameter	Prediction	Empirical
n_0	0.161	0.16 ± 0.01 [9]
B.E.	16.7	16.0 ± 1.0 [9]
$E_{sym}(n_0)$	30.2	31.7 ± 3.2 [10]
$E_{sym}(2n_0)$	56.4	46.9 ± 10.1 [11]; 40.2 ± 12.8 [12]
$L(n_0)$	67.8	58.9 ± 16 [11]; 58.7 ± 28.1 [10]
K_0	250.0	230 ± 20 [13]

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



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

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

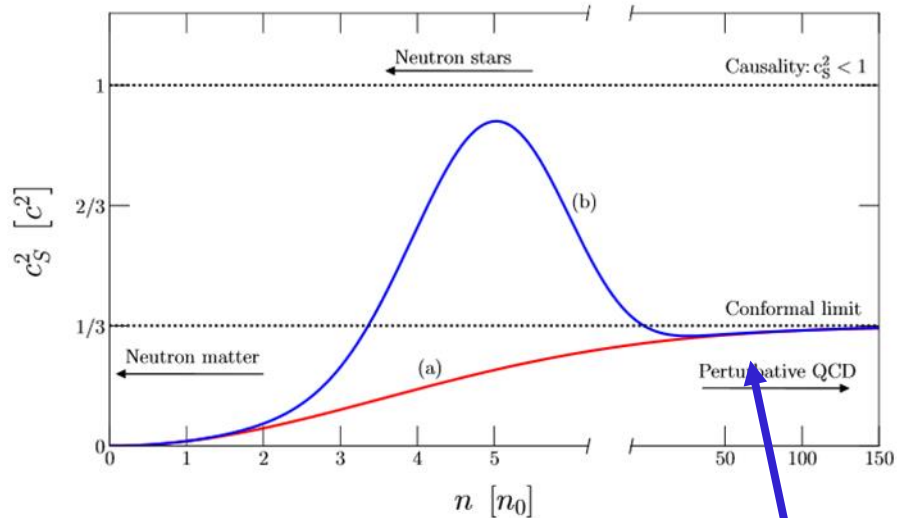


- Trace of energy-momentum tensor is not zero but a density independent constant at $\geq 2n_0$;
- When $\geq 2n_0$, the sound velocity $\rightarrow 1/\sqrt{3}$ -- conformal sound velocity.

Low density relevant
to NSs

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

Standard Scenario



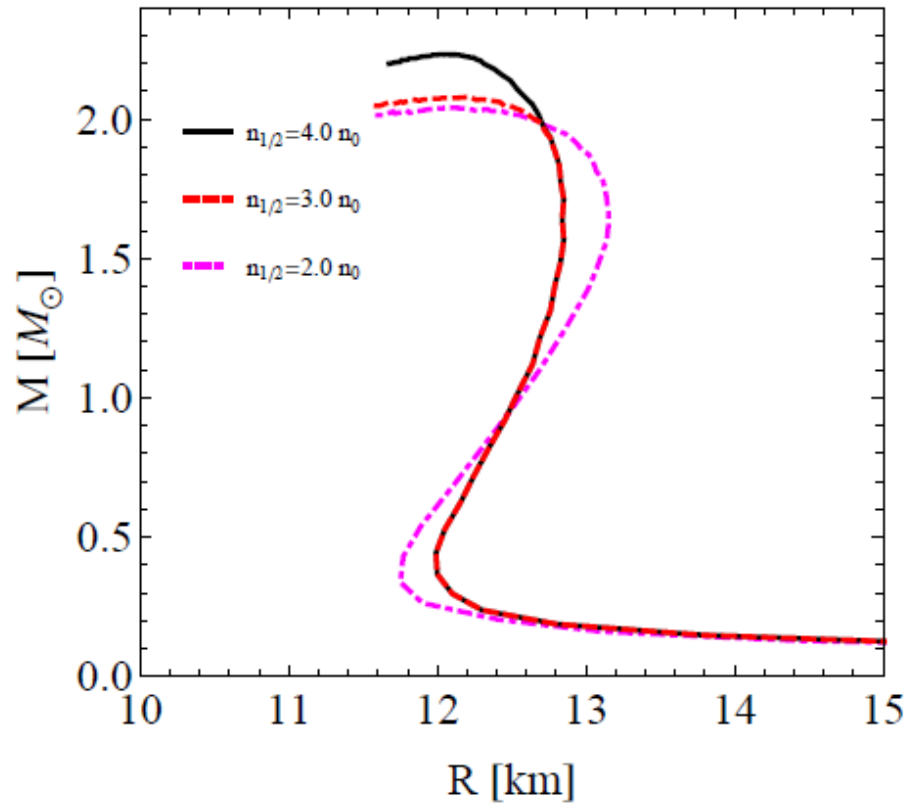
Very high density
PQCD applicable

We found that the conformal limit of $c_s^2 \leq 1/3$ 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 $2n_0$.

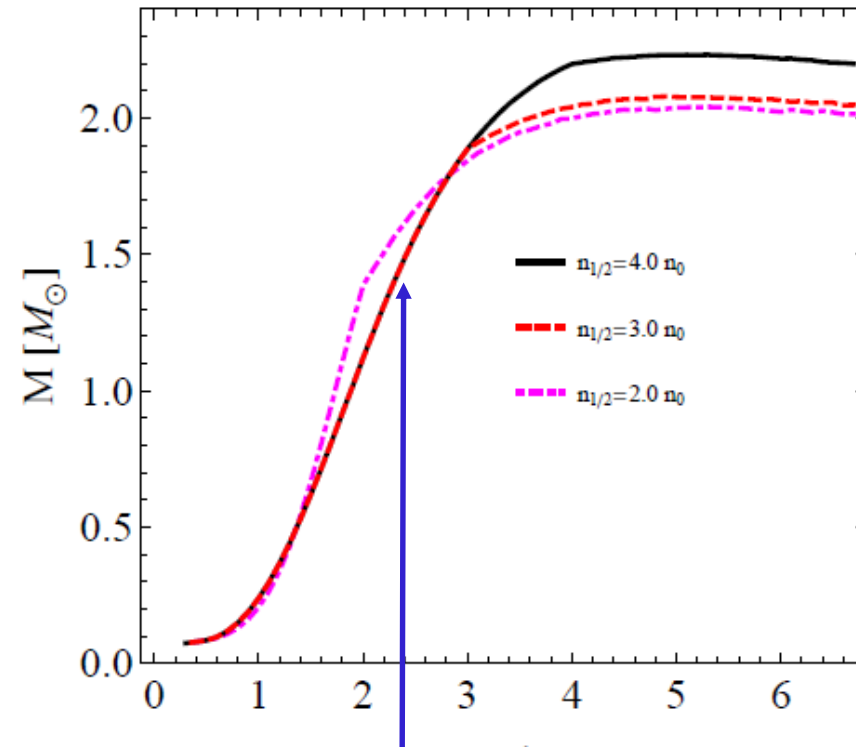
S. Reddy et al, 2018

We are disagreeing!

V、 Predictions of the pseudoconformal model

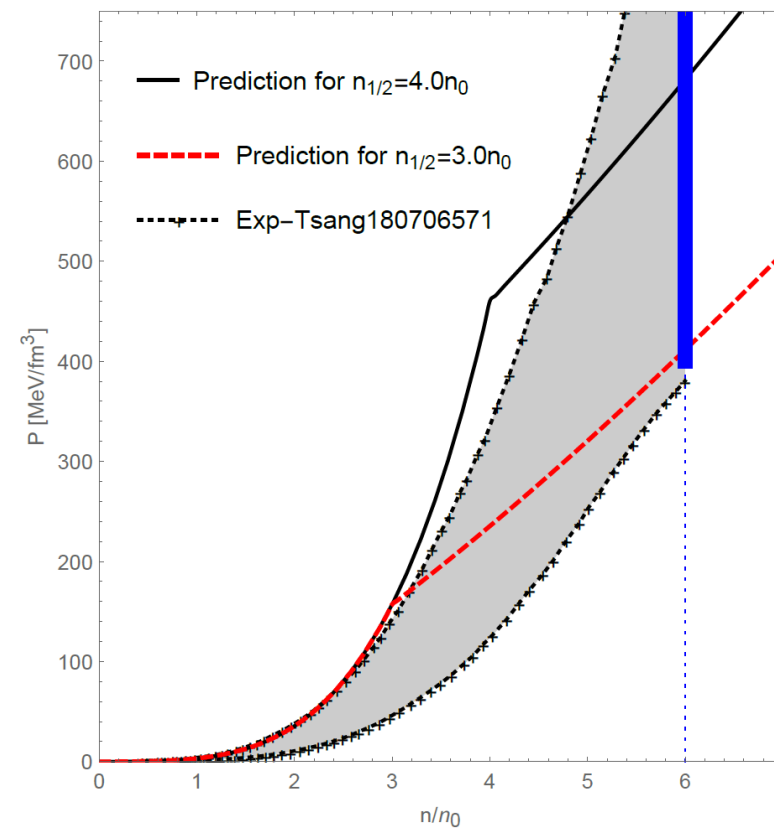
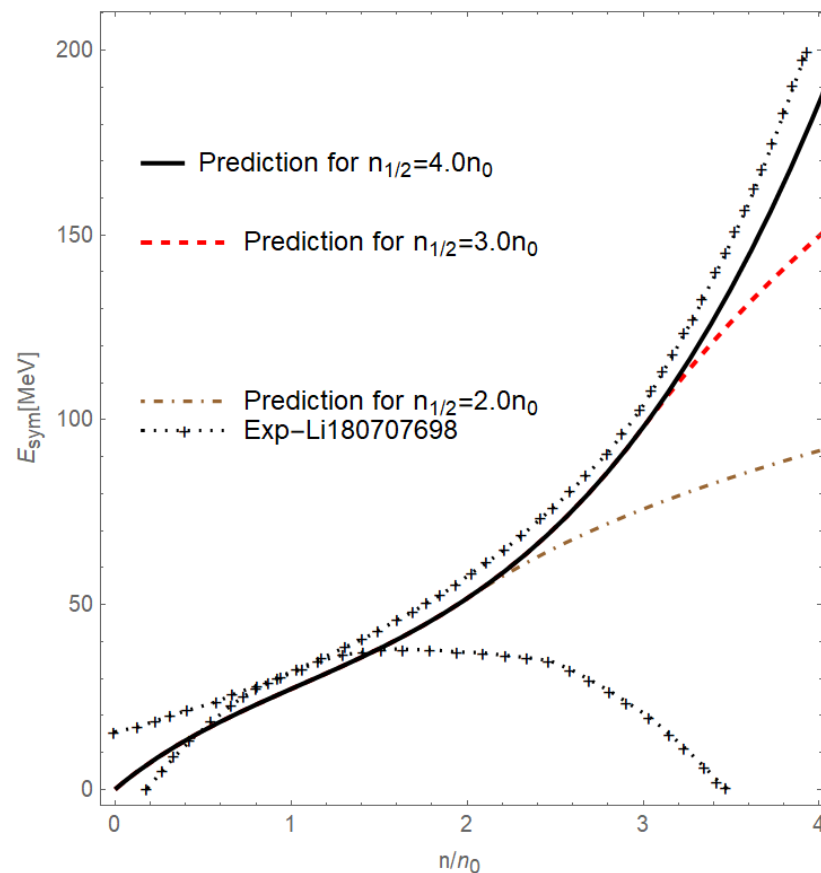


Accommodate massive star
 $\geq 2.0 M_{solar}$



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

V、 Predictions of the pseudoconformal model



Agree with the constraints

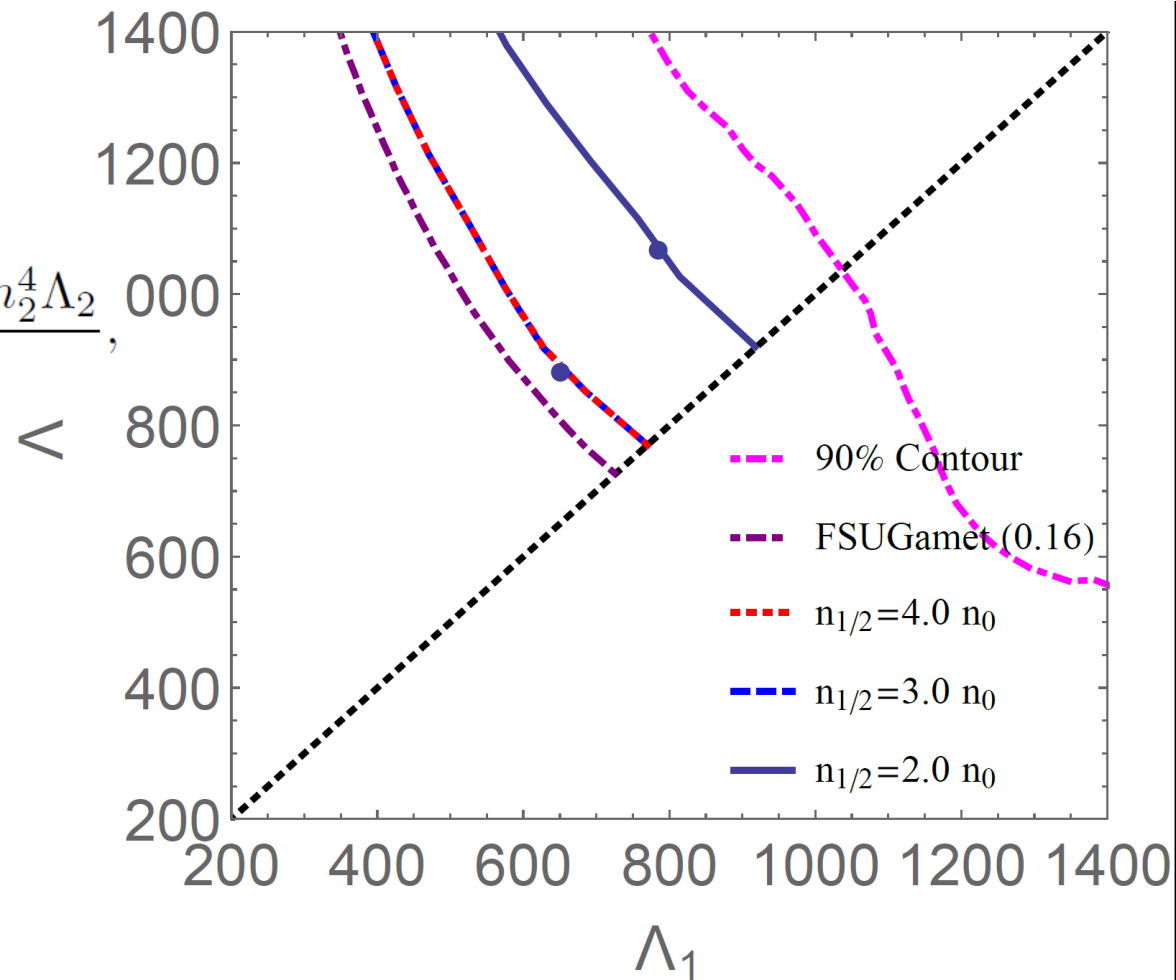
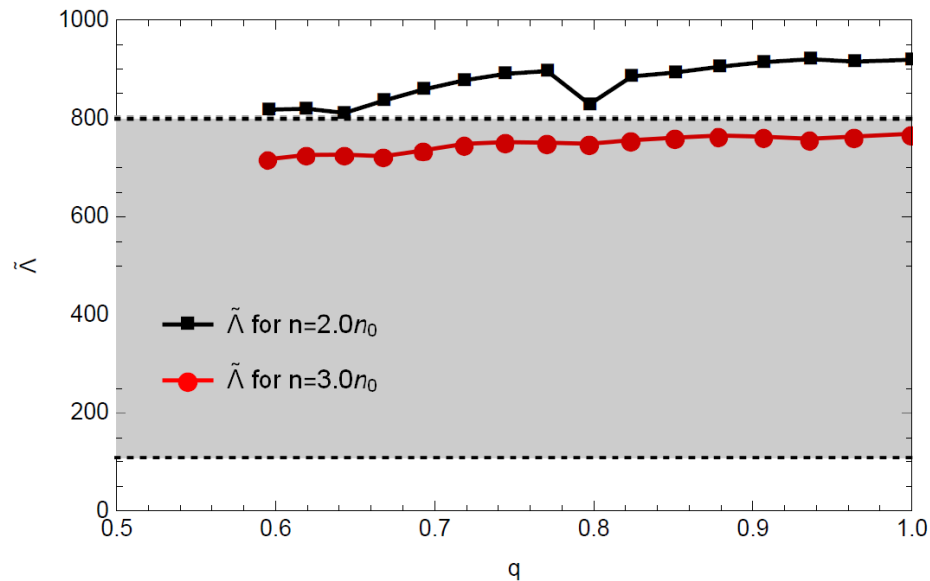
$n_{1/2}$ is constrained as $\sim(2 - 4)n_0$

V、Predictions of the pseudoconformal model



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

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



V、 Predictions of the pseudoconformal model



nature physics LETTERS
https://doi.org/10.1038/s41567-020-0914-9
Check for updates

OPEN Evidence for quark-matter cores in massive neutron stars

Eemeli Annala¹, Tyler Gorda², Alekski Kurkela^{3,4}, Joonas Nättilä^{5,6,7} and Alekski Vuorinen^{1,8}

The theory governing the strong nuclear force—quantum chromodynamics—predicts that at sufficiently high energy densities, hadronic nuclear matter undergoes a deconfinement transition to a new phase of quarks and gluons. Although this has been observed in ultrarelativistic heavy-ion collisions^{2,3}, it is currently an open question whether quark matter exists inside neutron stars⁴. By combining astrophysical observations and theoretical ab initio calculations in a model-independent way, we find that the inferred properties of matter in the cores of neutron stars with mass corresponding to 1.4 solar masses (M_{\odot}) are compatible with nuclear model calculations. However, the matter in the interior of maximally massive stable neutron stars exhibits characteristics of the deconfined phase, which we interpret as evidence for the presence of quark-matter cores. For the heaviest reliably observed neutron stars^{5,6} with mass $M \approx 2M_{\odot}$, the presence of quark matter is found to be linked to the behaviour of the speed of sound c_s in strongly interacting matter. If the conformal bound $c_s^2 \leq 1/3$ (ref. 7) is not strongly violated, massive neutron stars are predicted to have sizable quark-matter cores. This finding has important implications for the phenomenology of neutron stars and affects the dynamics of neutron star mergers with at least one sufficiently massive participant.

limit of very high densities, perturbative-QCD (pQCD) techniques, rooted in high-energy particle phenomenology and built on deconfined quark and gluon degrees of freedom^{12,13}, become accurate, providing the quark-matter EoS to the same accuracy at densities $n \gtrsim 40n_0 \equiv n_{\text{pQCD}}$. In the above two limits, QCD matter is known to exhibit markedly different properties. High-density quark matter is approximately scale-invariant, or conformal, whereas in hadronic matter the number of degrees of freedom is much smaller and scale invariance is also violated by the breaking of chiral symmetry. These qualitative differences are reflected in the values taken by different physical quantities. The speed of sound takes the constant value $c_s^2 = 1/3$ in exactly conformal matter and slowly approaches this number from below in high-density quark matter¹². By contrast, in hadronic matter, the quantity varies considerably: below saturation density, CET calculations indicate $c_s^2 \ll 1/3$, while at higher densities most hadronic models predict $\max(c_s^2) \gtrsim 0.5$. The polytropic index $\gamma \equiv d(\ln p)/d(\ln \epsilon)$, on the other hand, has the value $\gamma = 1$ in conformal matter, while both CET calculations and hadronic models generically predict $\gamma \approx 2.5$ around and above saturation density. Finally, the number of degrees of freedom is reflected in the pressure normalized by that of free quark matter (the Fermi-Dirac (FD) limit), p/p_{FD} (ref. 13). This quantity obtains values of order 0.1 in CET calculations and hadronic models,

the values of γ as a good approximate criterion. Given that $\gamma = 1.75$ is both the average between its pQCD and CET limits and very close to the minimal value the quantity obtains in viable hadronic models (see Fig. 2 and our discussion in the Methods), we are led to choose the following criterion for separating hadronic from quark matter: given an interpolated EoS, the smallest density from which γ is continuously less than 1.75 to asymptotic densities is identified with the onset of quark matter. We emphasize, however, that this is

In conclusion, our model-independent analysis has demonstrated that the existence of quark cores in massive NSs should be considered the standard scenario, not an exotic alternative. For all stars to be made up of hadronic matter, the EoS of dense QCD matter must be truly extreme. This view is also consistent

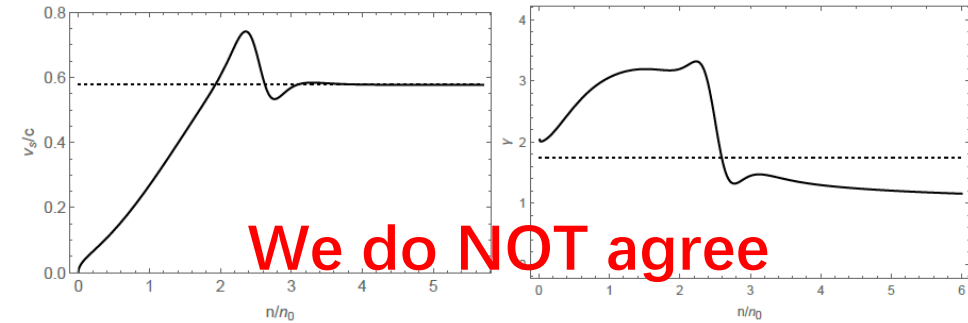


FIG. 1. Density dependence of the SV of stars v_s (left panel) and the polytropic index $\gamma = d \ln P / d \ln \epsilon$ (right panel) in neutron matter.

YLM & M. Rho, 2006.14173

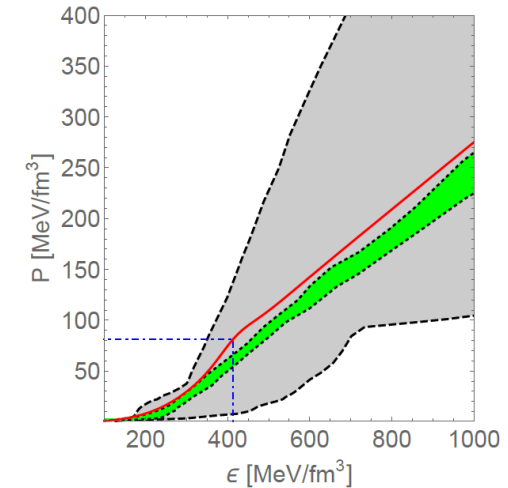


FIG. 2. Comparison of (P/ϵ) between the PCM velocity and the band generated with the SV interpolation method used in [23]. The gray band is from the causality and the green band from the conformality. The red line is the PCM prediction. The dash-dotted line indicates the location of the topology change.

V、 Predictions of the pseudoconformal model



Topology change and emergent scale symmetry via gravitational wave detections

Wen-Cong Yang,¹ Yong-Liang Ma,^{2,3,*} and Yue-Liang Wu^{2,3,4,5,†}

¹Center for Theoretical Physics and College of Physics, Jilin University, Changchun, 130012, China

²School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou, 310024, China

³International Centre for Theoretical Physics Asia-Pacific (ICTP-AP) (Beijing/Hangzhou), UCAS, Beijing 100190, China

⁴Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing, 100190, China

⁵School of Physical Sciences, University of Chinese Academy of Sciences, Beijing, 100049, China

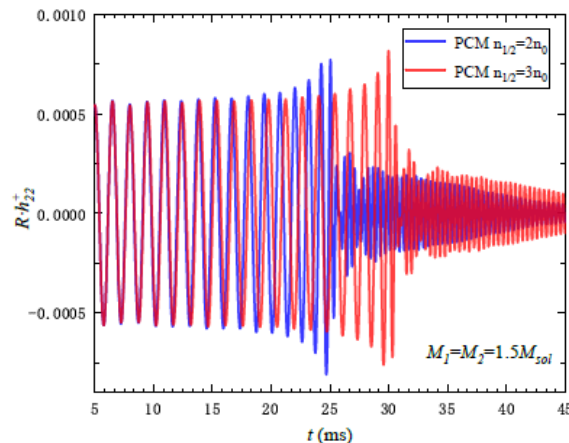
(Dated: November 10, 2020)

Topological structure has been extensively studied and confirmed in highly correlated condensed matter physics. We explore the gravitational waves emitted from the binary neutron star mergers using the pseudoconformal model for compact stars which regards the topology change and the possible emergent scale symmetry and satisfies all the constraint from astrophysics. We find that the location of the topology change affects the gravitational waves dramatically due to its effect on the equation of state. And, the effect on the waveforms of the gravitational waves are within the ability of the on-going and upcoming facilities and therefore gives the possible way to measure the topology structure in nuclear physics.

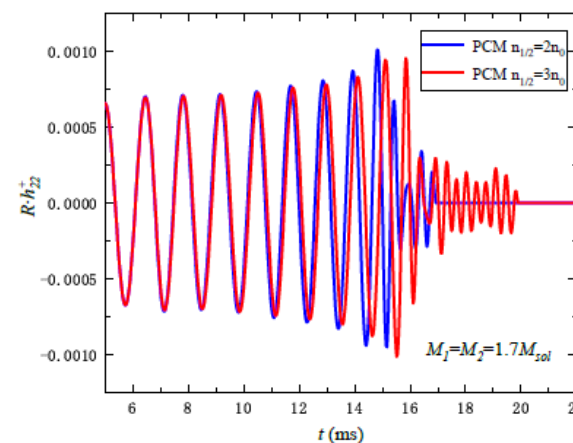
Introduction.— The nature of strongly interacting matter at high baryon number density is one of the outstanding open problems in both nuclear and astrophysics. What are the symmetry patterns involved in this region? What are the constituents at high density relevant to the cores of the compact stars? Are there any novel phenomena inside the massive compact stars? For some discussions on these aspects, we suggest, e.g., [1–5] and some relevant references therein. At this moment, these puzzles can neither be clarified from fundamental QCD—even using the lattice simulation—nor be judged from

quasi-fermions of fractional baryon charge [9]. As before and clarified later, we call this model as pseudoconformal model (PCM).

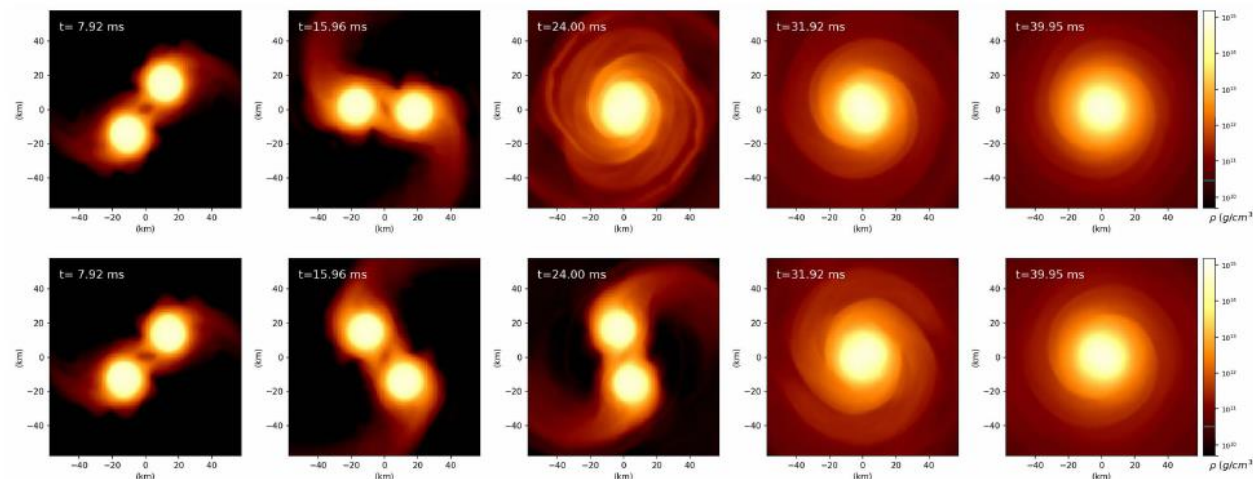
Topology change and emergent symmetry.— One way to do nuclear many body problem is to use the effective theory including mesons only (χ mEFT) and regard baryons as topology objects carrying winding number one — skyrmions — and put skyrmions onto a certain crystal lattice. A robust conclusion found in this approach is that there is a topology change corresponding to the skyrmion-half-skyrmion transition with half-



(a)



(b)



[nucl-th] 7 Nov 2020

Estimate the location of $n_{1/2}$ using GWs emitted from BNS merger

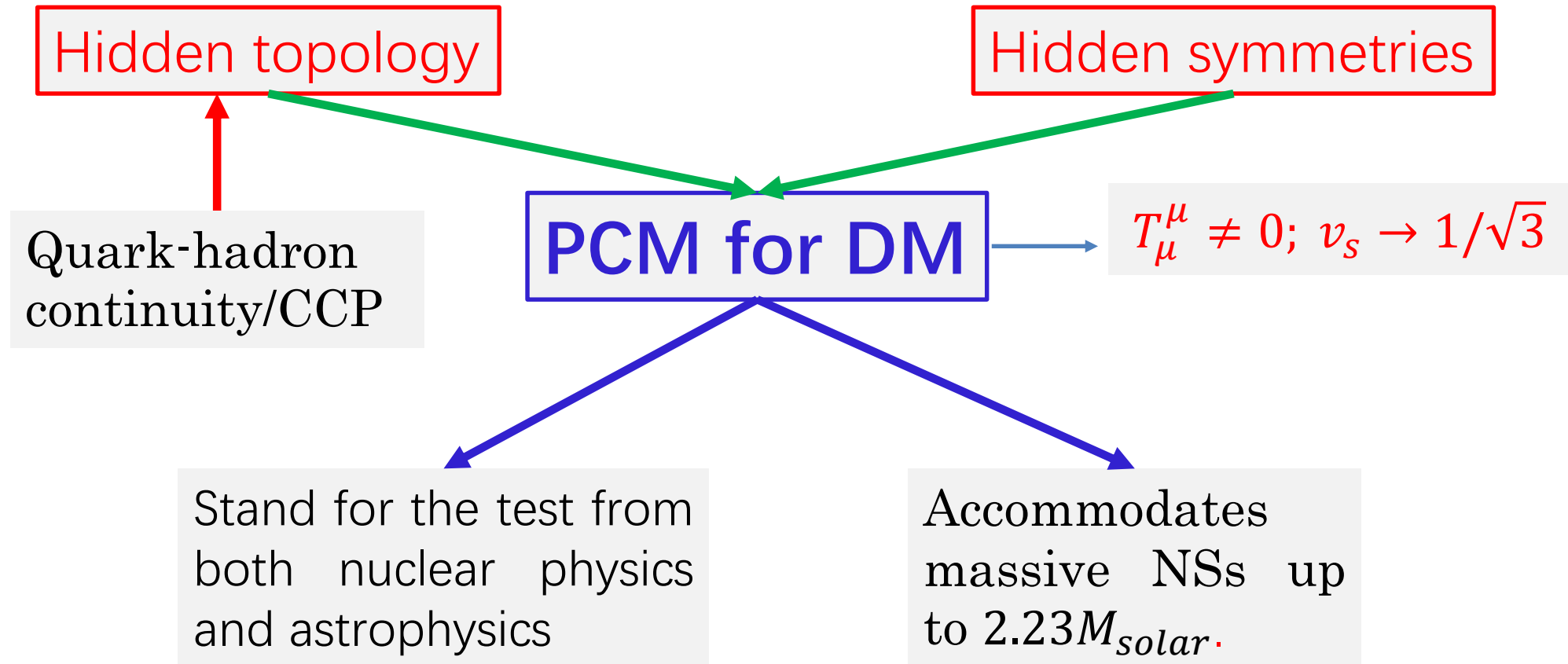
arXiv:2011.05000

of state (EoS) of the nuclear matter and the nature of the strongly interacting baryonic matter. In addition, the GWs emitted in the post-merger stage decay very fast and give the information of the baby star mass and spin which also depend on the EoS of the nuclear matter.

We study in this paper the GWs emitted from the neutron star merger using a conceptionally novel approach to dense nuclear matter anchored on some symmetries emerged at high density region as well as a particular topological structure of baryonic matter embodying both nucleonic and quarkonic properties [4, 8] (for a systematic

state vanishes globally but not locally with non-vanishing and nearly density independent pion and dilaton — will be introduced later — decay constants $f_\pi \sim f_X \neq 0$, (ii) the baryon mass becomes a density independent constant with magnitude $m_0 \simeq (0.6 - 0.9)m_N$ which signals the emergence of the parity-doubling structure of nucleons and (iii) the hidden gauge coupling associated with the ρ meson mass to be introduced later starts to drop and flows to zero at the vector manifestation fixed point [11], therefore the vector meson becomes massless and the hidden gauge symmetry emerges.

VI、 Summary and discussions





Is this pseudo-conformal structure
at odds with Nature?

Not with what's measured (or known)
up to now

$$\text{Constraint to: } 2.0n_0 \leq n_{\frac{1}{2}} < 4.0 n_0$$



Thank you for your attention!

Comments are welcome!