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Topology change, emergent symmetry and compact star matter

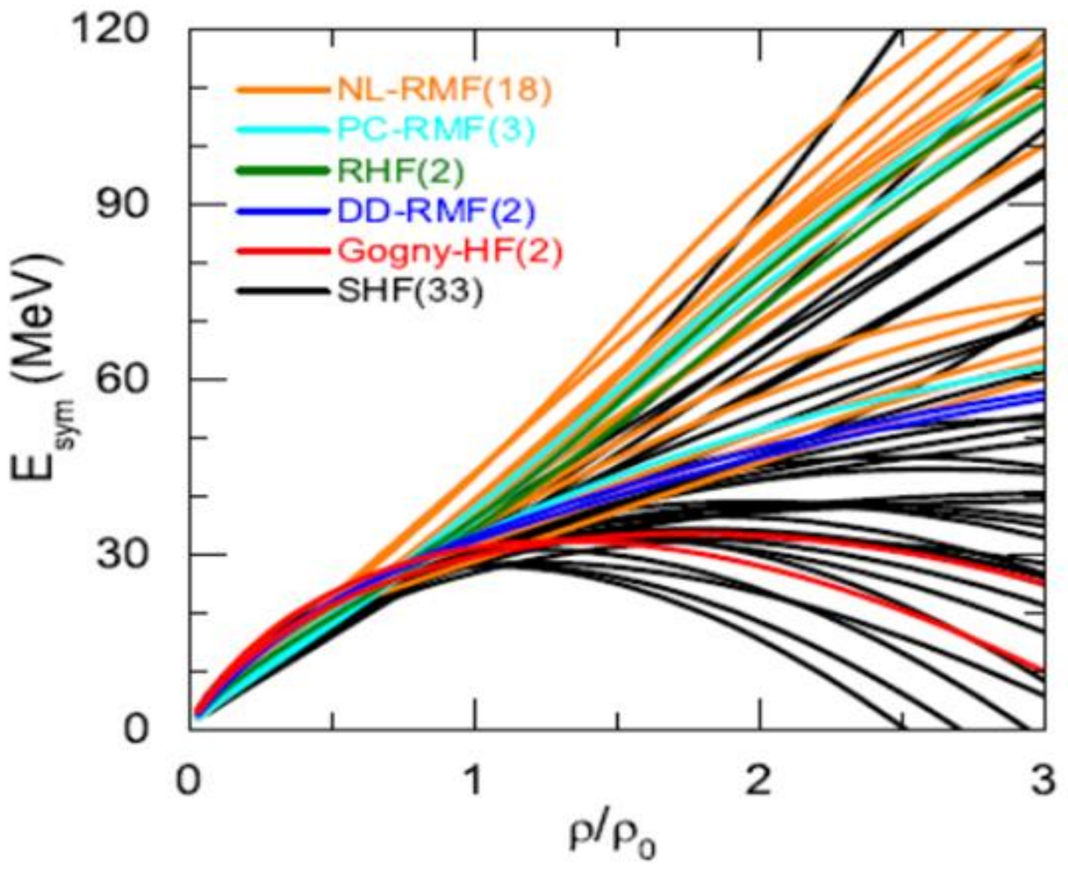
Yong-Liang Ma

In collaboration with
Mannque Rho *et al.*

Colloquium @ ASU, Dec. 09, 2020.

Outline

I、Introduction



L. W. Chen, 1506.09057

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

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

I、Introduction

- ***Finite nuclei as well as infinite nuclear matter*** can be fairly accurately accessed by ***nuclear EFTs***, pionless or pionful, (*s*EFT)" anchored on relevant symmetries and invariances along the line of Weinberg's Folk Theorem.
- *s*EFTs, 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

I、Introduction

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.

- Tidal deformability:

$$\Lambda_{1.4} < 800$$

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

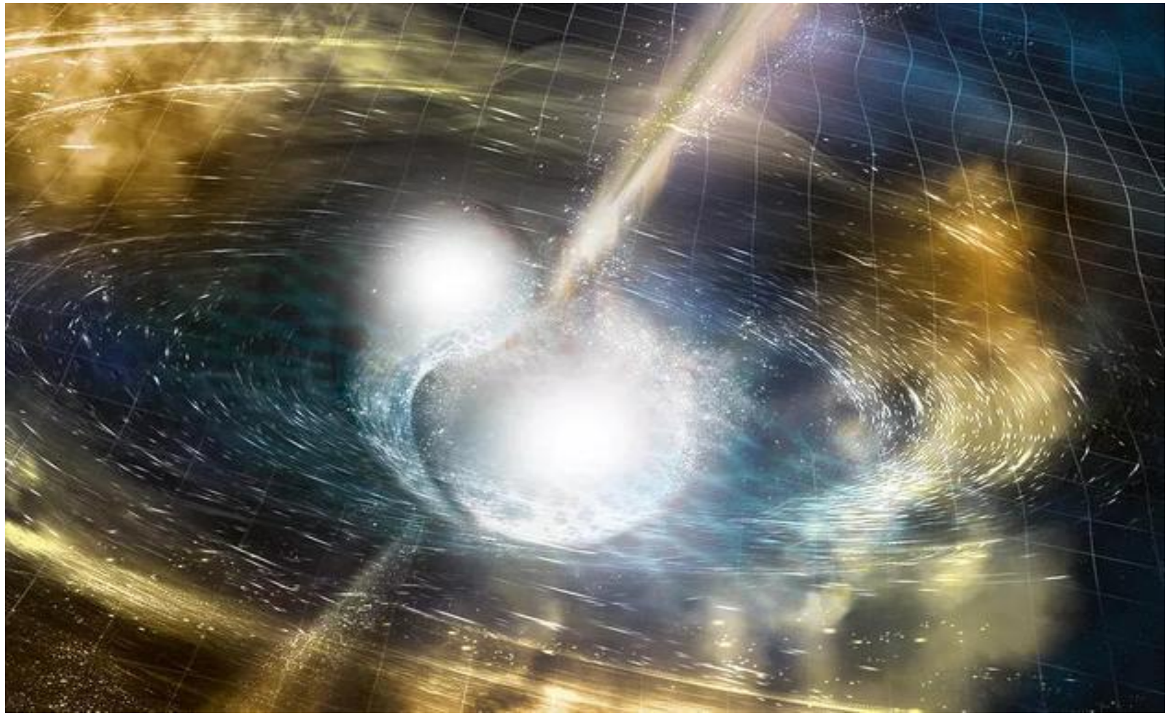
$$R = 11.9^{+1.4}_{-1.4}\ km$$

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

- Pressure:

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

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



- Massive neutron stars:

$(1.97 \pm 0.04) M_\odot$ *Nature, 467(2010),1081.*

$(2.01 \pm 0.04) M_\odot$ *Science, 340(2013), 448.*

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

$\leq 10 n_0$

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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

GnEFT = *s*EFT + ρ and ω + scalar meson $f_0(500)$

ρ and ω ← Hidden local symmetry

scalar meson $f_0(500)$ ← Dilaton/NGB of hidden scale symmetry

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

The former may be verifying the ***Suzuiki 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

$$\langle J(x_1)J(x_2)\cdots J(0)\rangle_{EFT} \overset{match\ at\ \Lambda_M<\Lambda_\chi}{\Longleftrightarrow} \langle J(x_1)J(x_2)\cdots J(0)\rangle_{QCD}$$

Harada and Yamawaki, PRD 01'

$$LECs \Longleftrightarrow Intrinc\ QCD\ quantitiess$$

$$\langle \bar{q}q\rangle,\ \langle G^2\rangle,\cdots$$

*LECs**　　　　Medium modified Vacuum

- **The density dependence involved is intrinsic of QCD, referred to the IDD.**
- **Full density dependence = IDD + $\mathrm{IDD}_{\text{induced}}$**

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

I、Introduction

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

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

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

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

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.*

Cashire Cat

Quark-Hadron continuity ⟷ Qualitative information from topology change → Density dependence of LECs

II、Topology change and quark-hadron continuity

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

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

f_π : pion decay constant

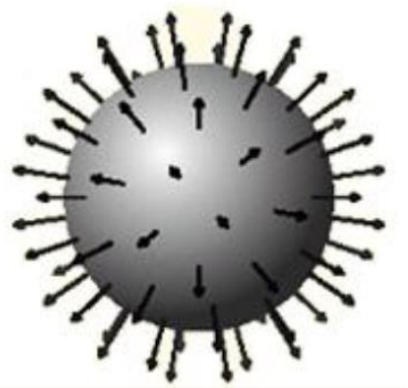
e : Skyrme parameter

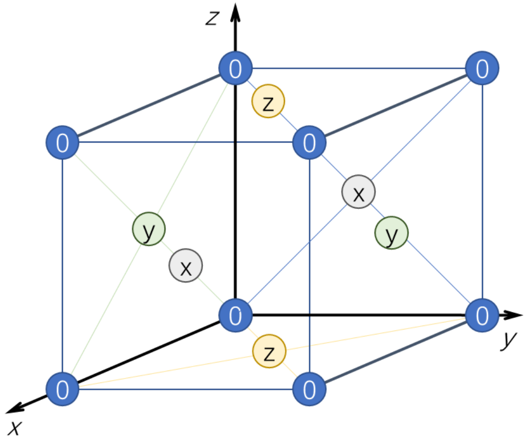
Topological soliton

winding number = baryon number

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

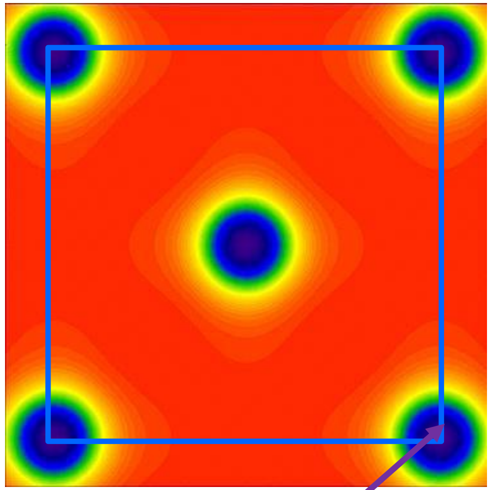
T. R. Skyrme, 1960

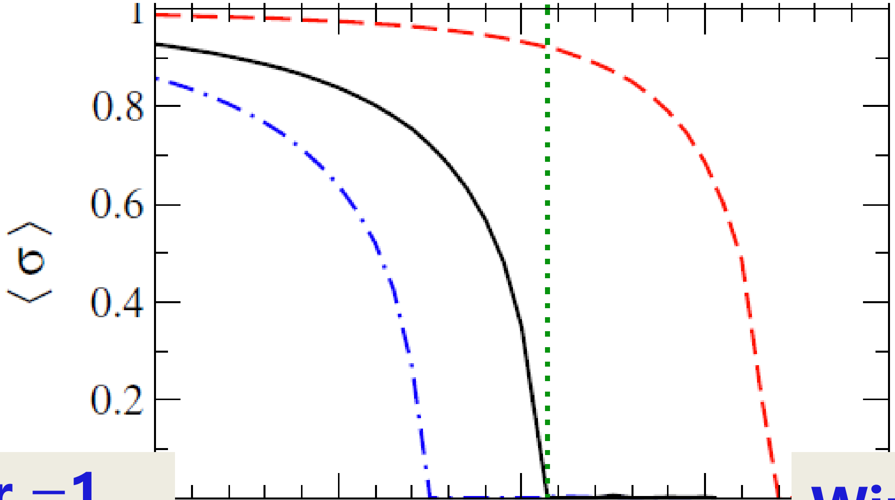


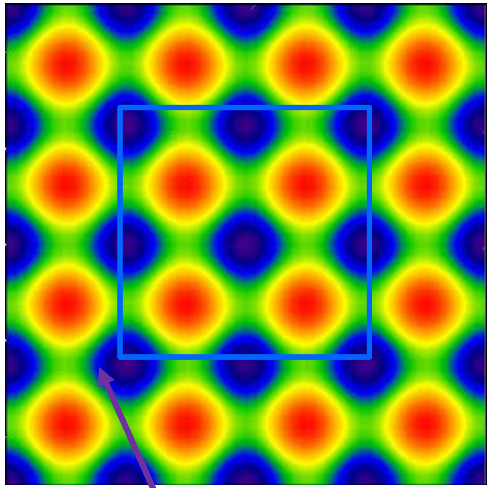


Baryonic interactions in all regimes of density, upto that relevant to the core of CSs, can be accessed.

II、Topology change and quark-hadron continuity







Winding number =1

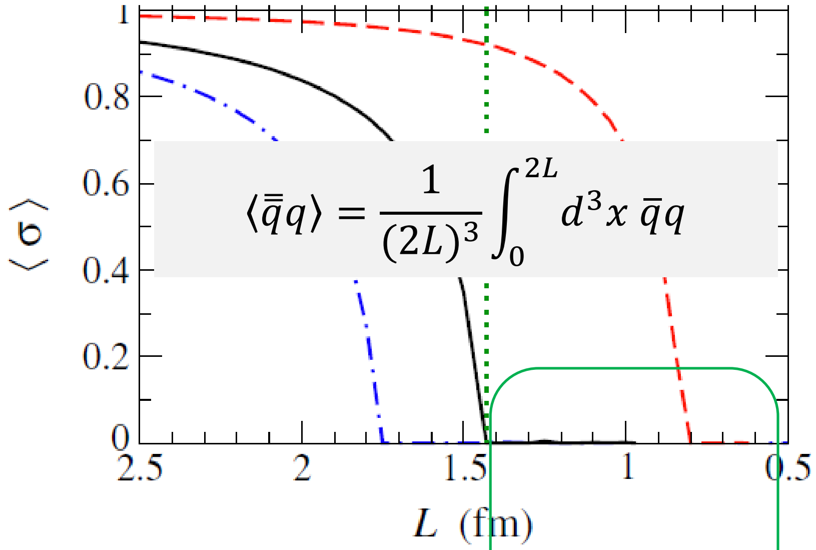
Winding number = $\frac{1}{2}$

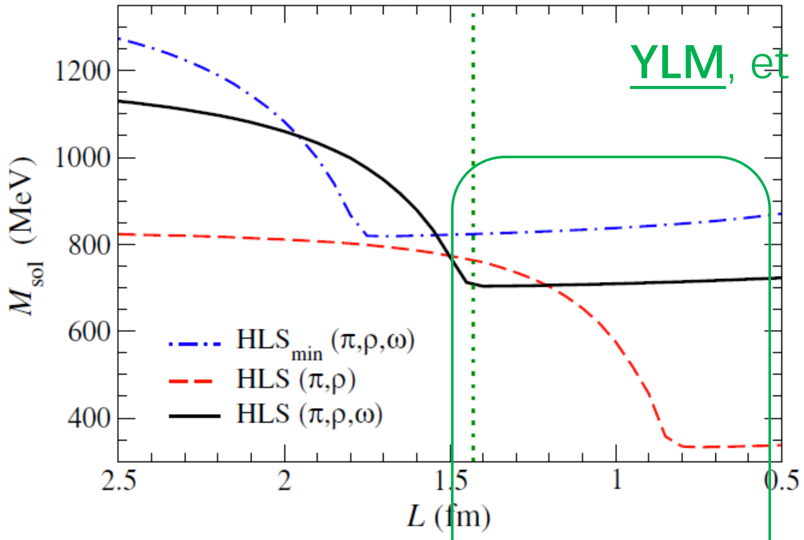
Topology transition

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





YLM, et al, PRD 13', 14'

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.**

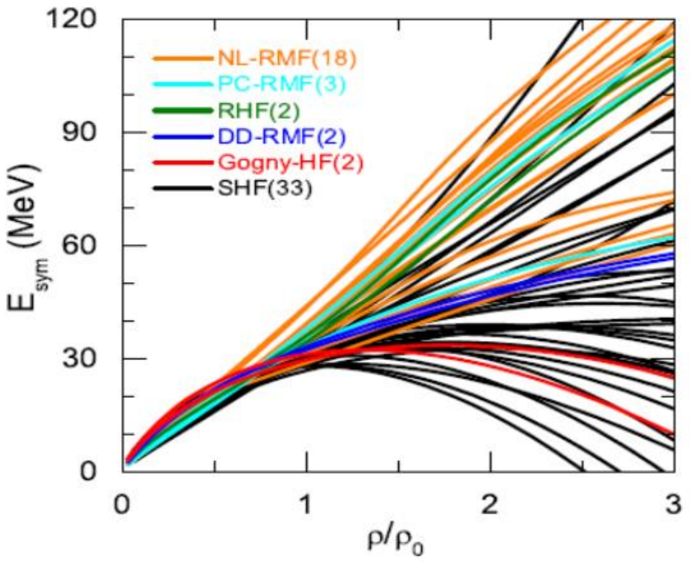
Agree with Y. Motohiro, *et al*, Phys.Rev. C92 (2015), 025201

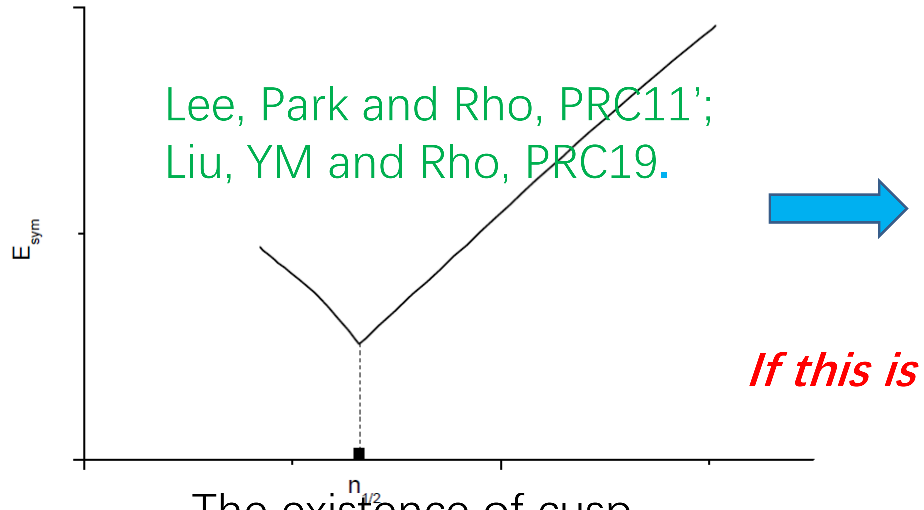
II、Topology change and quark-hadron continuity

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

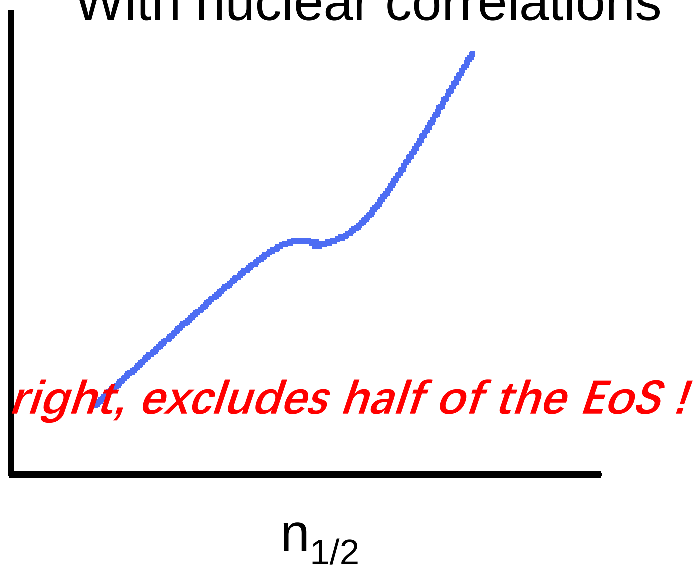
"Symmetry energy is dominated by the tensor forces":

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





The existence of cusp is model independent.

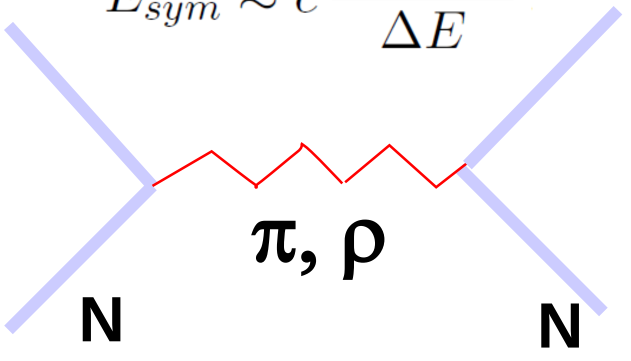


The cusp is associated with the topology change with the emergence of quasiparticle structure with the half-skyrmions.

II、Topology change and quark-hadron continuity

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

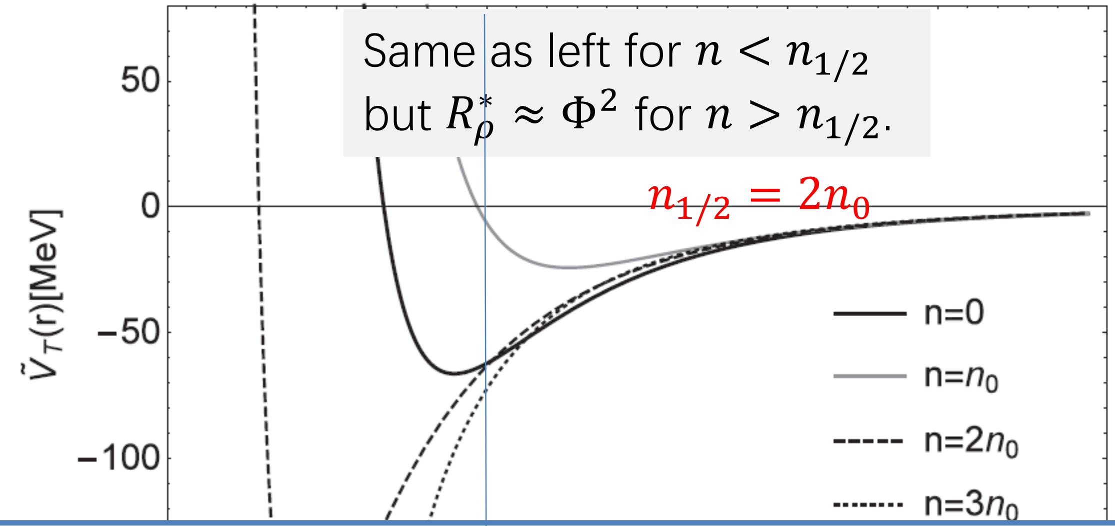
$$E_{sym} \approx c\,\frac{\langle (V^T)^2\rangle}{\Delta E}$$



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

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

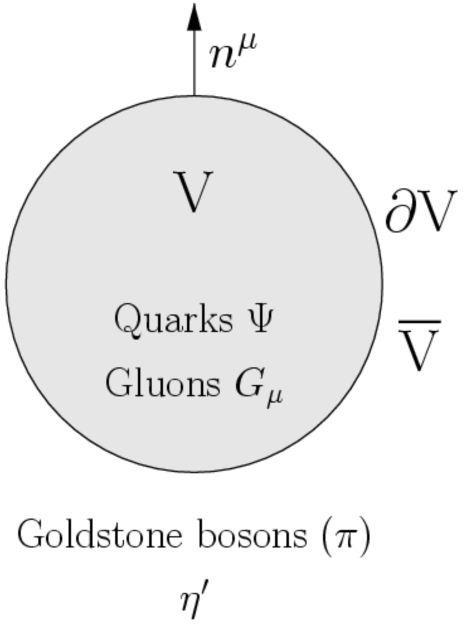
$$R_M^* \equiv \frac{f_{NM}^*}{f_{NM}} \approx \frac{g_{MNN}^*}{g_{MNN}}\frac{m_N}{m_N^*}\frac{m_M^*}{m_M}$$



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 $m_V \to 0$ 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

The Cheshire Cat



"How hadrons transform to quarks"

Baryon charge:

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

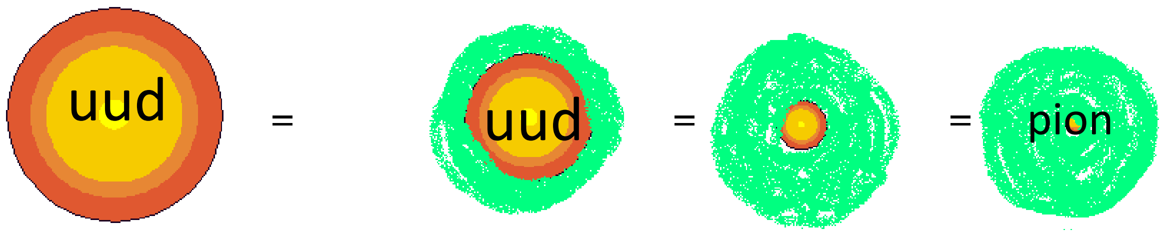
$$B_{in} = 1 - \frac{1}{\pi}[\theta(R) - \frac{1}{2}\sin 2\theta(R)]$$

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

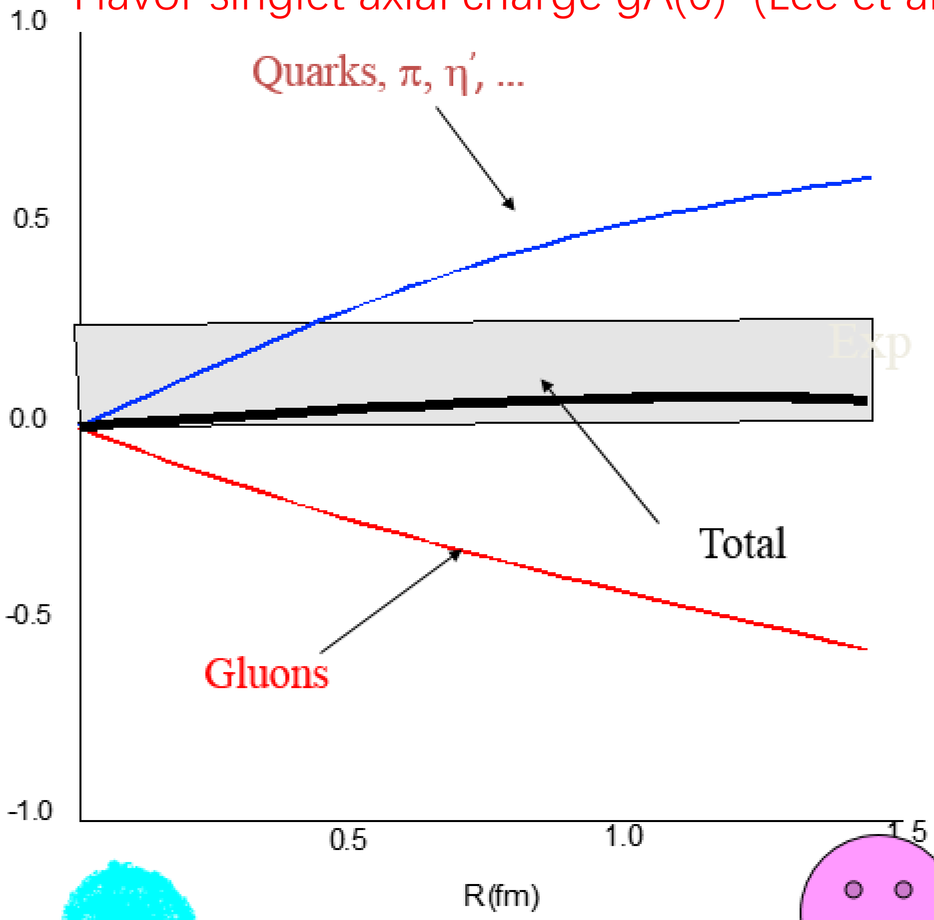
Brown, Goldhaber, Rho 1983
Goldstone, Jaffe 1983

III、Topology change and quark-hadron continuity

Proton



Flavor singlet axial charge gA(0) (Lee et al)



Equivalent description of the proton

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

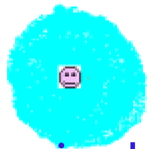
where

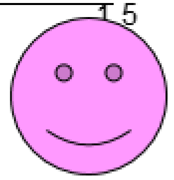
$$S_V = \int_V d^4x \left(\bar{\psi} i \not{D} \psi - \frac{1}{2}\mathrm{tr}\, G_{\mu\nu}G^{\mu\nu}\right) + \cdots,$$

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

$$S_{\delta V} = \frac{1}{2}\int_{\delta V} d\Sigma^\mu \left\{(n_\mu \bar{\psi} U^{\gamma_5} \psi) + i\frac{g_s^2}{16\pi^2} K_{5\mu} (\mathrm{Tr}\,\ln U^\dagger - \mathrm{Tr}\,\ln U)\right\}.$$

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





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

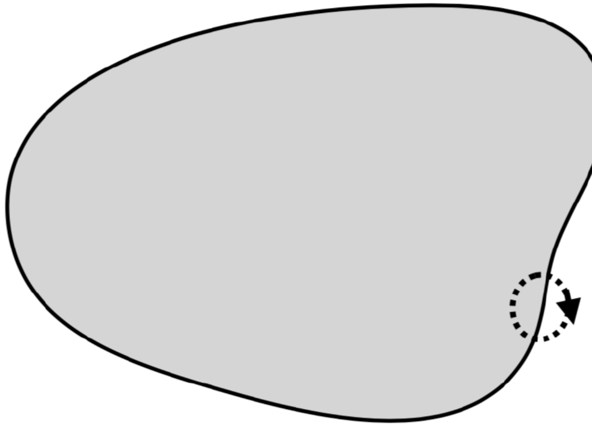
II、Topology change and quark-hadron continuity

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]

ep-th] 6 Feb 2019

Zohar Komargodski

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

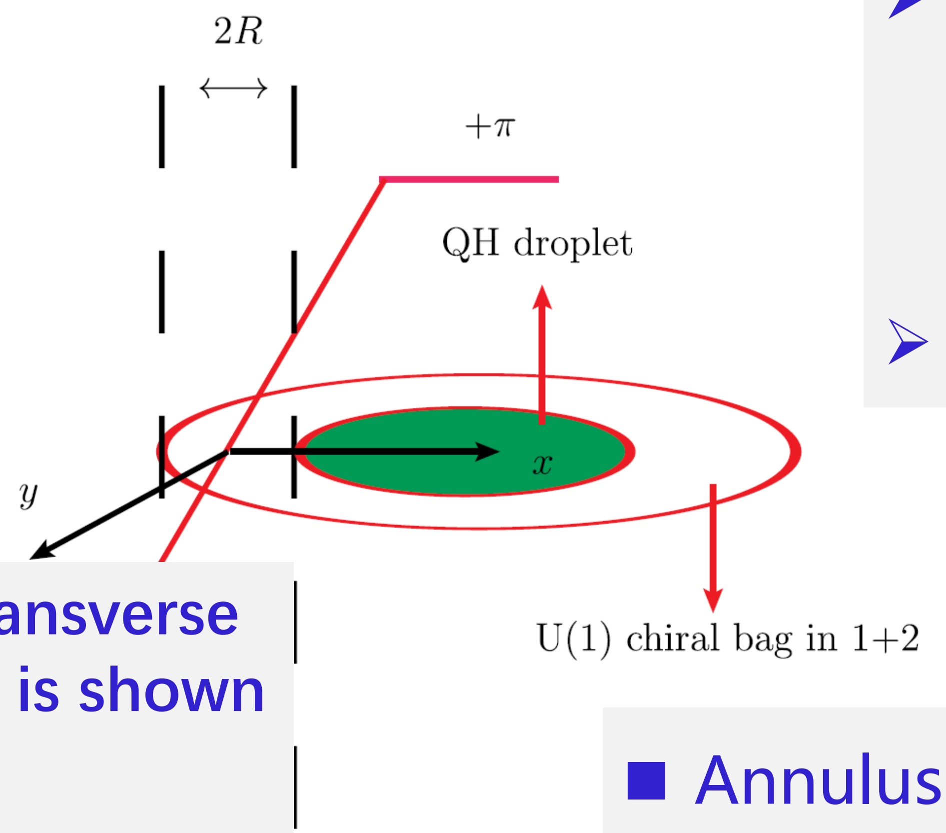
Abstract

$N_f = 1$ 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.

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.

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

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

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

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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

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

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

K. Yamawaki, 2015

$$\mathcal{L}_{L\sigma M} \stackrel{\lambda\to\infty}{\longrightarrow} \mathcal{L}_{NL\sigma} = \frac{f_\pi^2}{4} \cdot \mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)$$

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

$$\mathcal{L}_{L\sigma M} = \mathcal{L}_{\rm sinv} - V(\chi) \qquad\qquad \chi = f_\chi e^{\sigma/f_\chi}\,.$$

with

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

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

Scale invariant

LOSS

Scale noninvariant

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

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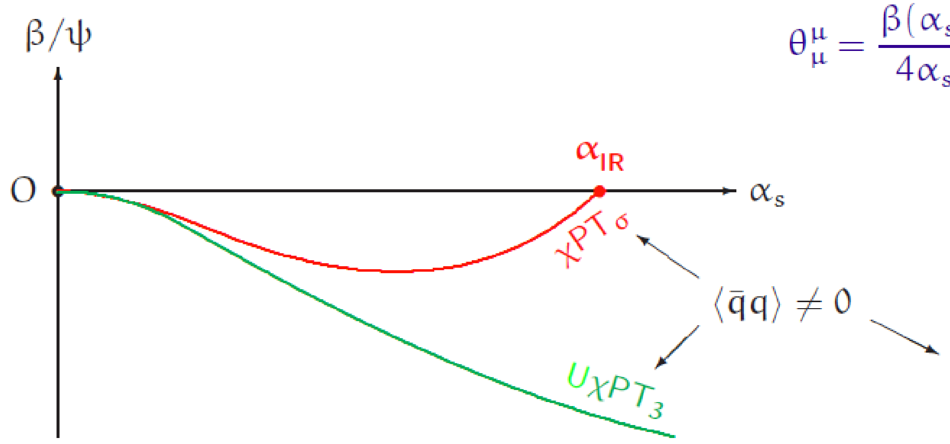
$f_0(500)$ is a pNGB arising from (noted $m_{f_0} \cong m_K$). The SB of SS associated + an explicit breaking of SI.

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* $|vac\rangle$

$\Rightarrow$ 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

Provides an approach to include scalar meson in ChPT.

III、Hidden symmetries of QCD

$$\mathcal{L}_N = \bar{Q} i\gamma^\mu D_\mu Q - g_1 F_\pi \frac{\chi}{F_\chi}\bar{Q}Q + g_2 F_\pi \frac{\chi}{F_\chi}\bar{Q}\rho_3 Q - im_0\bar{Q}\rho_2\gamma_5 Q + g_{V\rho}\bar{Q}\gamma^\mu \hat{\alpha}_{\parallel\mu} Q + g_{V0}\bar{Q}\gamma^\mu \mathrm{tr}[\hat{\alpha}_{\parallel\mu}]Q + g_A\bar{Q}\rho_3\gamma^\mu\hat{\alpha}_{\perp\mu}\gamma_5 Q,$$

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

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

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

$\langle s\rangle \to 0$

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

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

Chiral inv. mass

$$\mathcal{L}_N = \bar{N}i\partial\!\!\!/ N - \bar{N}\hat{M}N - g_1\bar{N}\left(\hat{G}\tilde{s} + \rho_3\gamma_5 i\vec{\tau}\cdot\tilde{\vec{\pi}}\right)N + g_2\bar{N}\left(\rho_3\tilde{s} + \hat{G}\gamma_5 i\vec{\tau}\cdot\tilde{\vec{\pi}}\right)N + (1 - g_{v\omega})\, g_\omega N\frac{\phi\!\!\!/}{2}N\,,$$

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

ρ decouples, HFS emerges.

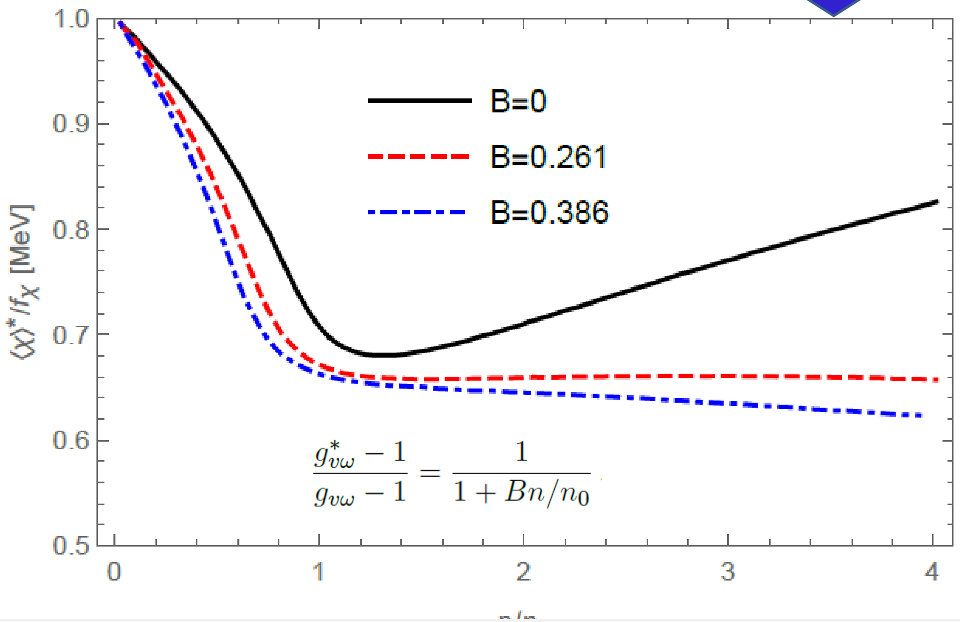
Proposition: *Moving toward to the dilaton-limit fixed point, the fundamental constants in scale-chiral symmetry get transformed as* $f_\pi \to f_\chi, g_A \to g_{v\rho} \to 1$, *and the* ρ *meson decouples while the* ω *remains coupled, breaking the flavor* $U(2)$ *symmetry.*

III、Hidden symmetries of QCD

Emergent from parameter dialing from RMF:

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

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.*

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

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* $m_N^* \to \langle\chi\rangle^* \to m_0$. *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

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

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

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

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

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.*

Cashire Cat

Quark-Hadron continuity

Qualitative information from topology change

Density dependence of LECs

III、Hidden symmetries of QCD

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

$$\langle\theta^\mu_\mu\rangle = \langle\theta^{00}\rangle - \sum_i \langle\theta^{ii}\rangle = \epsilon - 3P$$
$$= 4V(\langle\chi\rangle) - \langle\chi\rangle \frac{\partial V(\chi)}{\partial\chi}\Big|_{\chi=\langle\chi\rangle}$$

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

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 $m_N^* \to \langle\chi\rangle^* \to m_0$. 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}

Imbed the quanlitative conclusion to bsHLS

IDD

Beyond mean field

Calculate $V_{low\ k}$

$DD_{induced}$

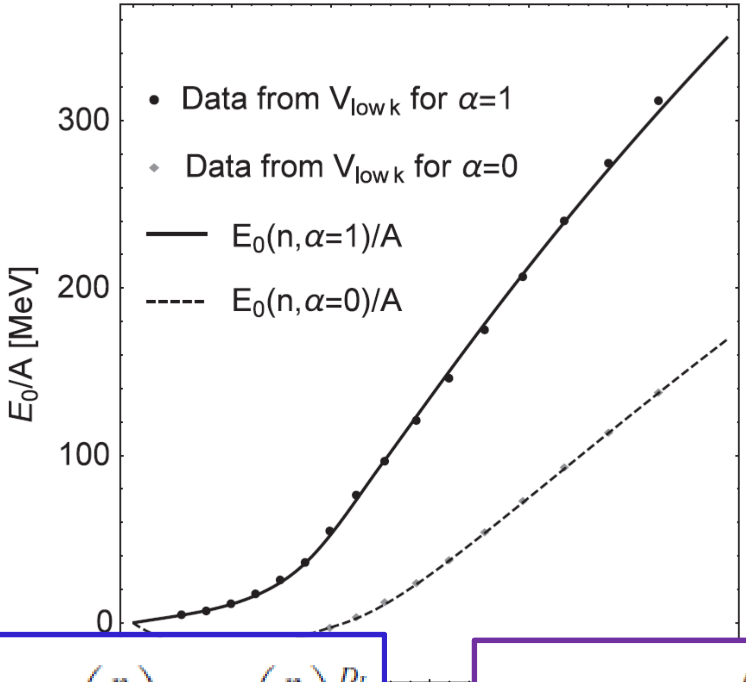
EoS for nuclear matter with IDD

Φ_I: Predictions agree with the nuclear matter at low density.

Φ_{II}: Density independent.

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

IV、The pseudoconformal model of dense nuclear matter

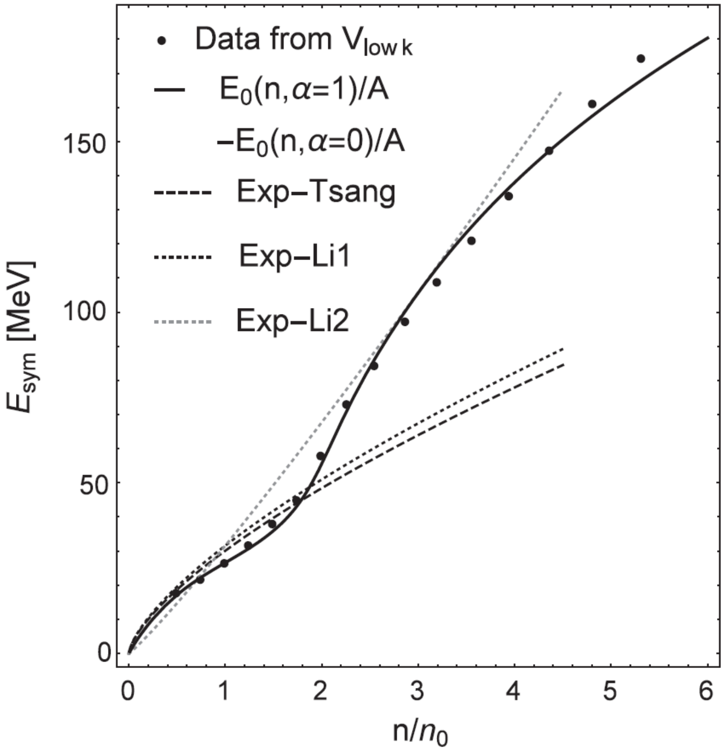


$$E_0/A = A_I\left(\frac{n}{n_0}\right) + B_I\left(\frac{n}{n_0}\right)^{D_I}$$

Fitted function

$$E_0/A = -m_N + B\left(\frac{n}{n_0}\right)^{1/3} + D\left(\frac{n}{n_0}\right)^{-1}$$

PC Prediction



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.

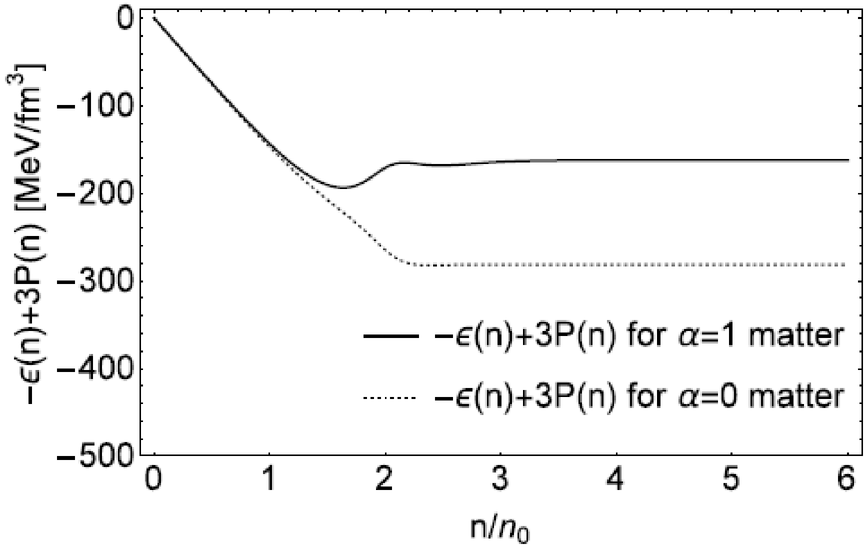
Parameter	Prediction	Empirical
n_0	0.161	0.16 ± 0.01 [9]
B.E.	16.7	16.0 ± 1.0 [9]
$E_{sym}(n_0)$	30.2	31.7 ± 3.2 [10]
$E_{sym}(2n_0)$	56.4	46.9 ± 10.1 [11];40.2 ± 12.8 [12]
$L(n_0)$	67.8	58.9 ± 16 [11];58.7 ± 28.1 [10]
K_0	250.0	230 ± 20 [13]

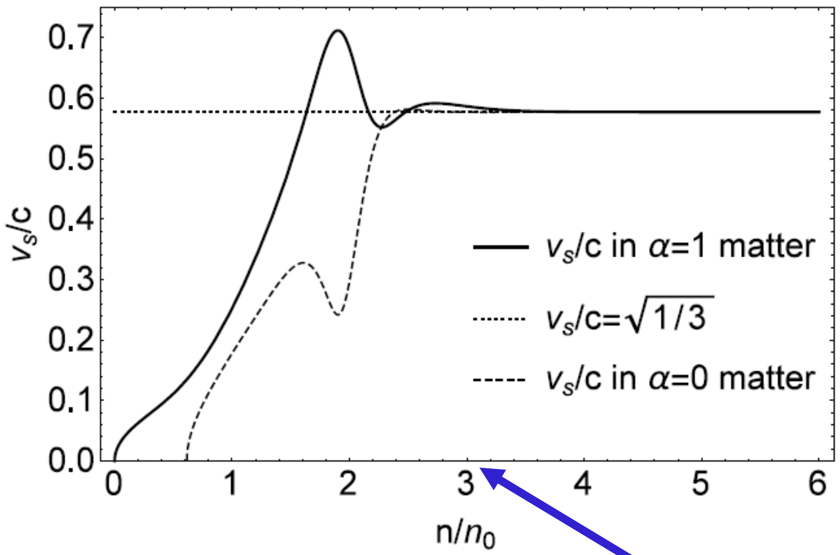
Agrees with the empirical values of the nuclear matter properties quite well.

YLM & M. Rho, 2006.14173 v1

IV、The pseudoconformal model of dense nuclear matter

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





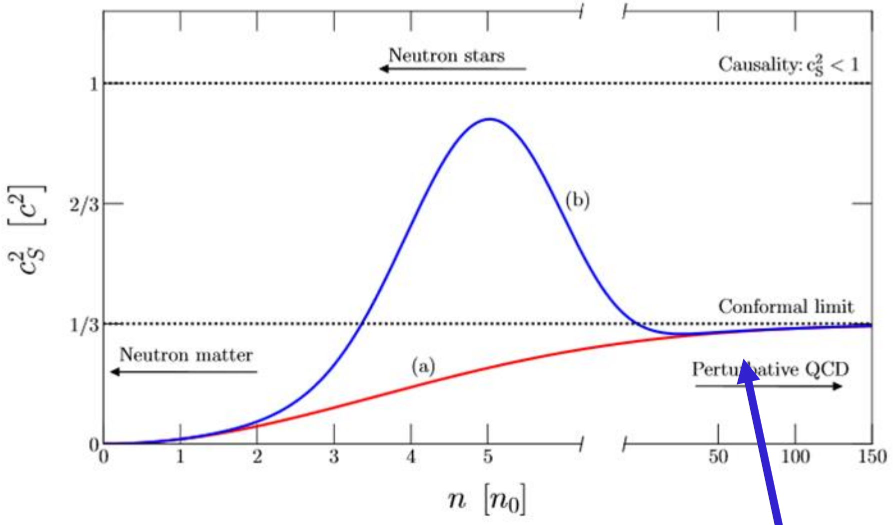
Low density relevant to NSs

- 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.

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

IV、The pseudoconformal model of dense nuclear matter

Standard Scenario



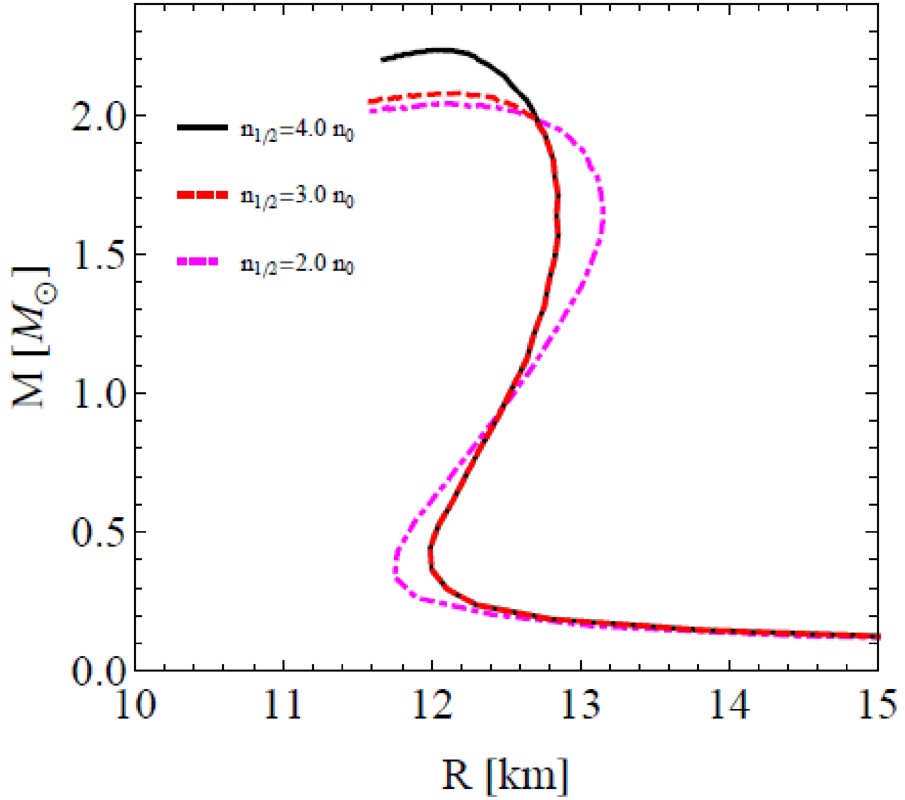
Very high density
PQCD applicable

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 $2n_0$.

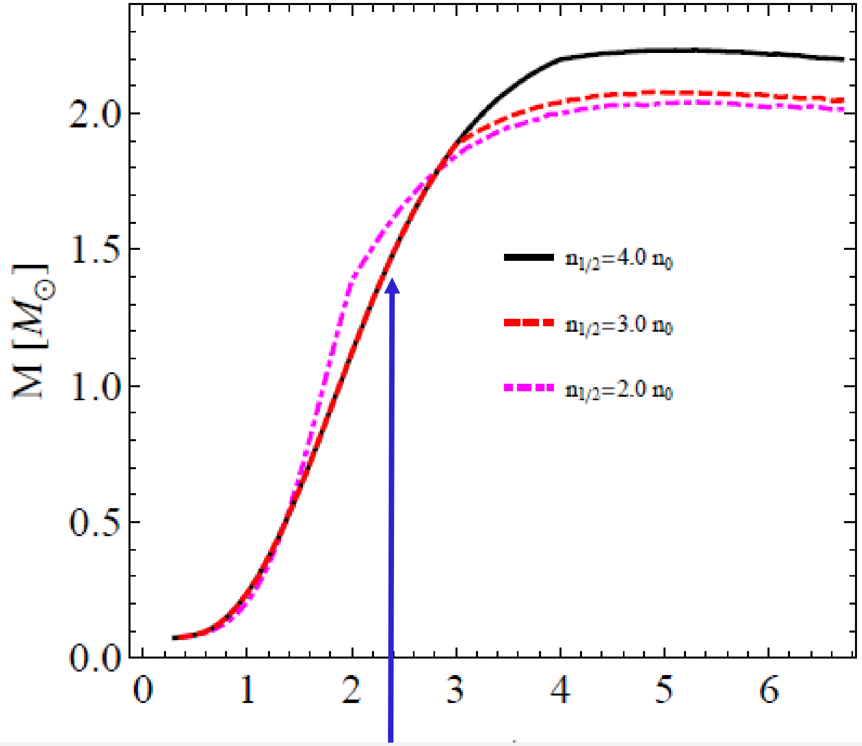
S. Reddy et al, 2018

We are disagreeing!

V、Predictions of the pseudoconformal model



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



GW data: $\Lambda_{1.4}, R_{1.4} \cdots$ 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

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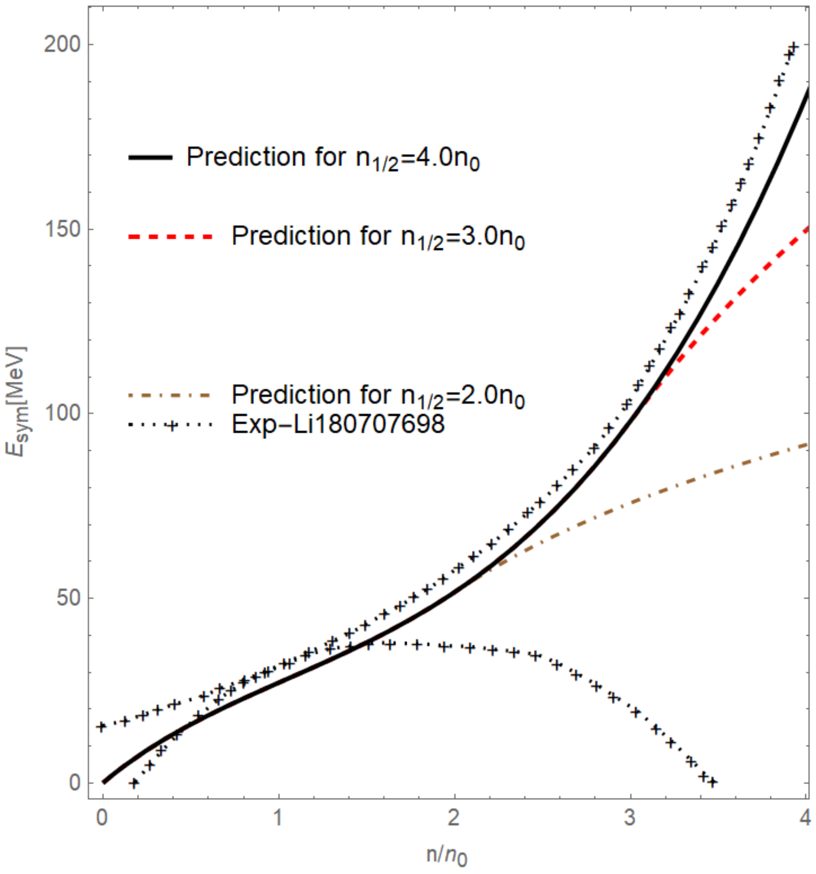
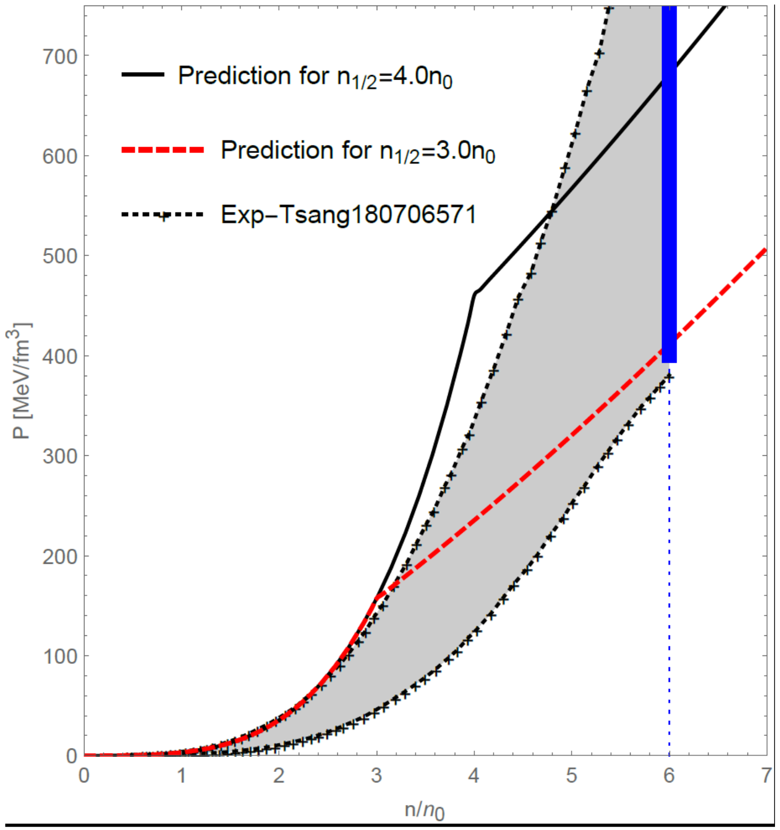




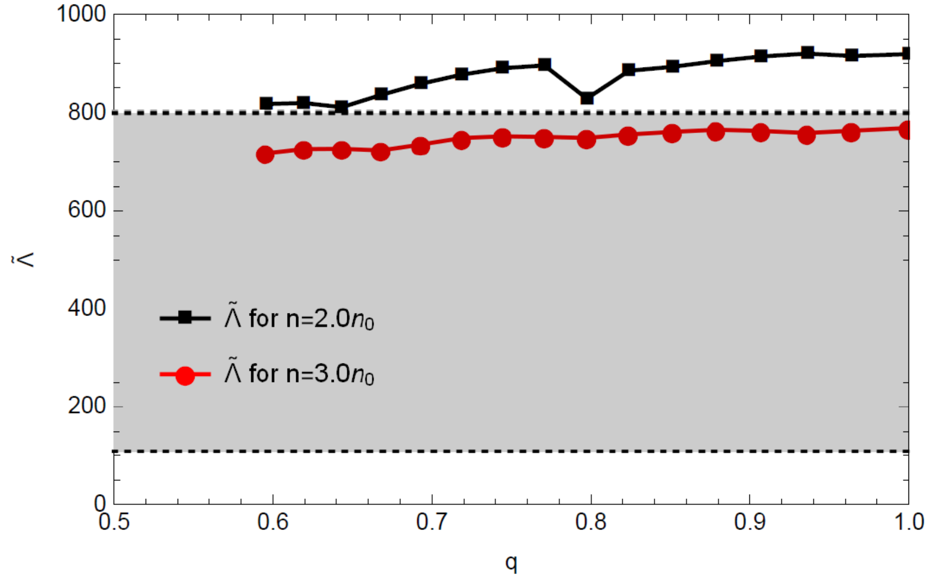
Agree with the constraints

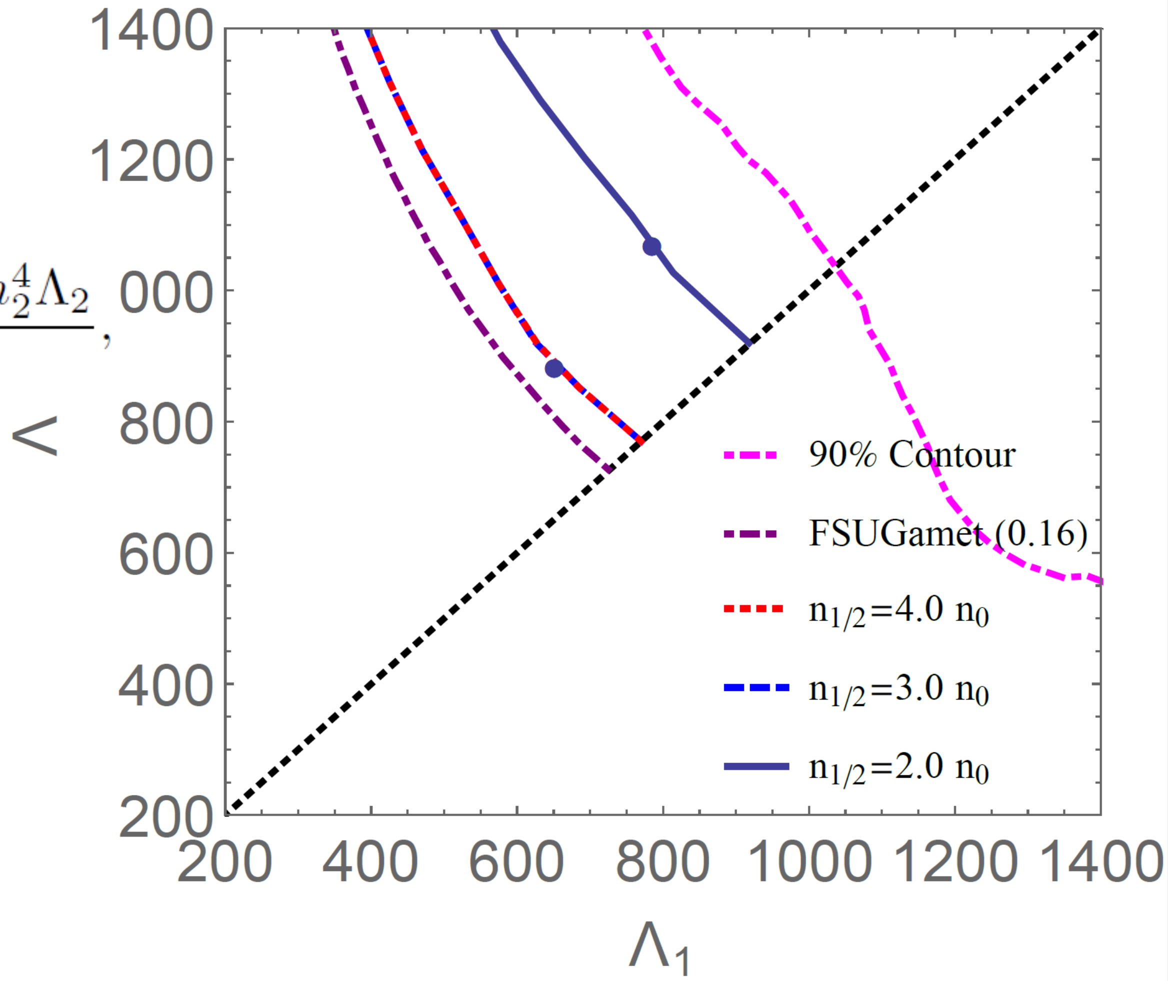
$n_{1/2}$ is constrained as $\sim(2-4)n_0$

V、Predictions of the pseudoconformal model

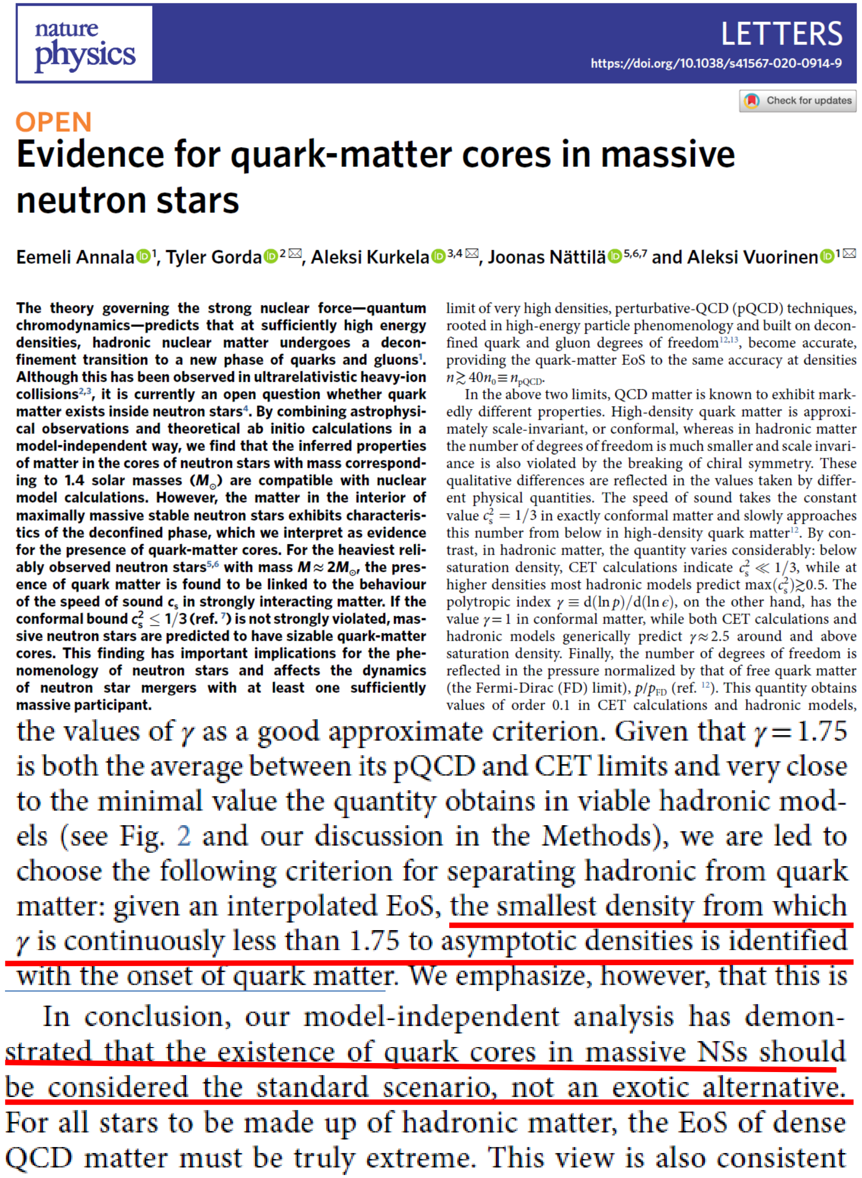
$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} = 1.188\, M_\odot .$$

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





V、Predictions of the pseudoconformal model



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Evidence for quark-matter cores in massive neutron stars

Eemeli Annala[1], Tyler Gorda[2]✉, Aleksi Kurkela[3,4]✉, Joonas Nättilä[5,6,7] and Aleksi Vuorinen[1]✉

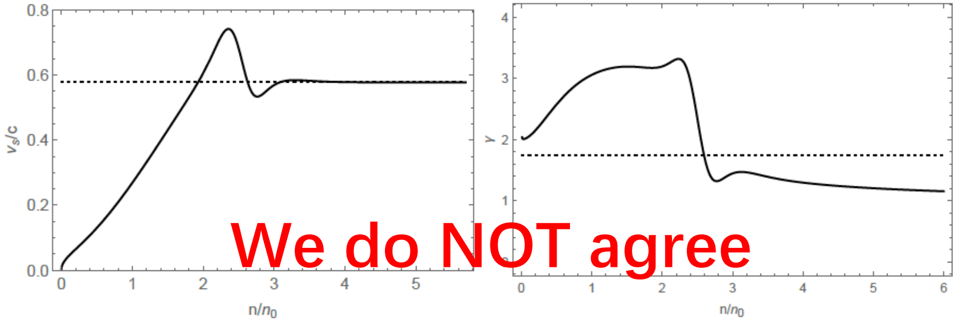
The theory governing the strong nuclear force—quantum chromodynamics—predicts that at sufficiently high energy densities, hadronic nuclear matter undergoes a deconfinement transition to a new phase of quarks and gluons[1]. Although this has been observed in ultrarelativistic heavy-ion collisions[2,3], it is currently an open question whether quark matter exists inside neutron stars[4]. 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 $n \gtrsim 40 n_0 \equiv n_{\rm pQCD}$.

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 matter[12]. 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), $p/p_{\rm FD}$ (ref. [12]). 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



We do NOT agree

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 pannel) in neutron matter.

YLM & M. Rho, 2006.14173

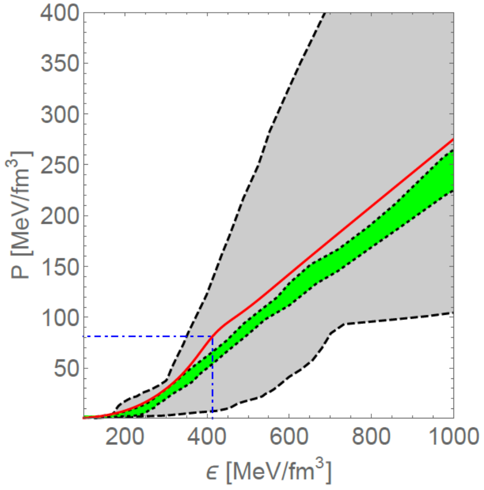


FIG. 2. Comparison of (P/ϵ) between the PCM velocity and the band generated with the SV interpolation method used in [23]. The gray band is from the causality and the green band from the conformality. The red line is the PCM prediction. The dash-dotted line indicates the location of the topology change.

V、Predictions of the pseudoconformal model

Topology change and emergent scale symmetry via gravitational wave detections

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(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 dense nuclear matter 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.

[nucl-th] 7 Nov 2020

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 constitutes 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

...

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 approaching 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 systemat-

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

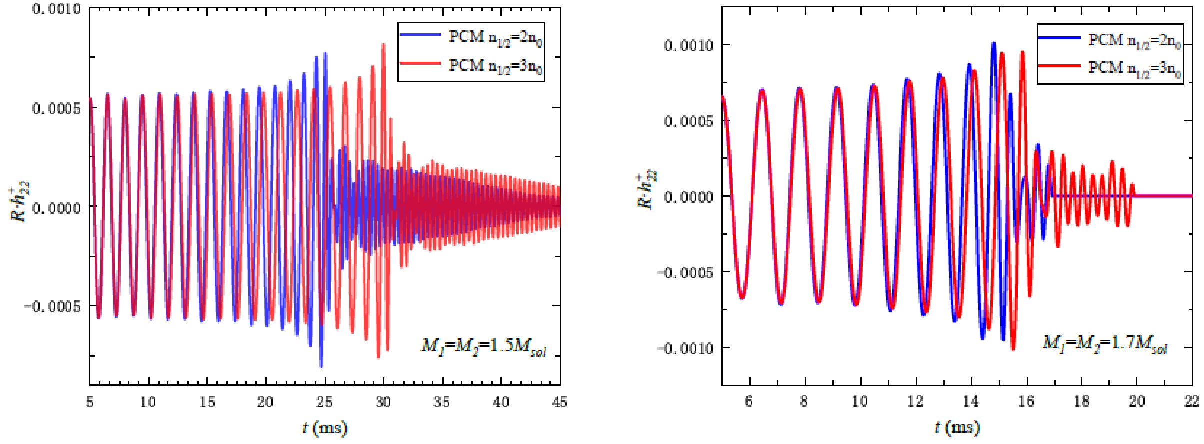
Topology change and emergent symmetry.— One way to do nuclear many body problem is to use the effective theory including mesons only (χmEFT) and regard baryons as topology objects carrying winding number one — skyrmions— and put skyrmions onto a certain crystal lattice. A robust conclusion found in this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

...

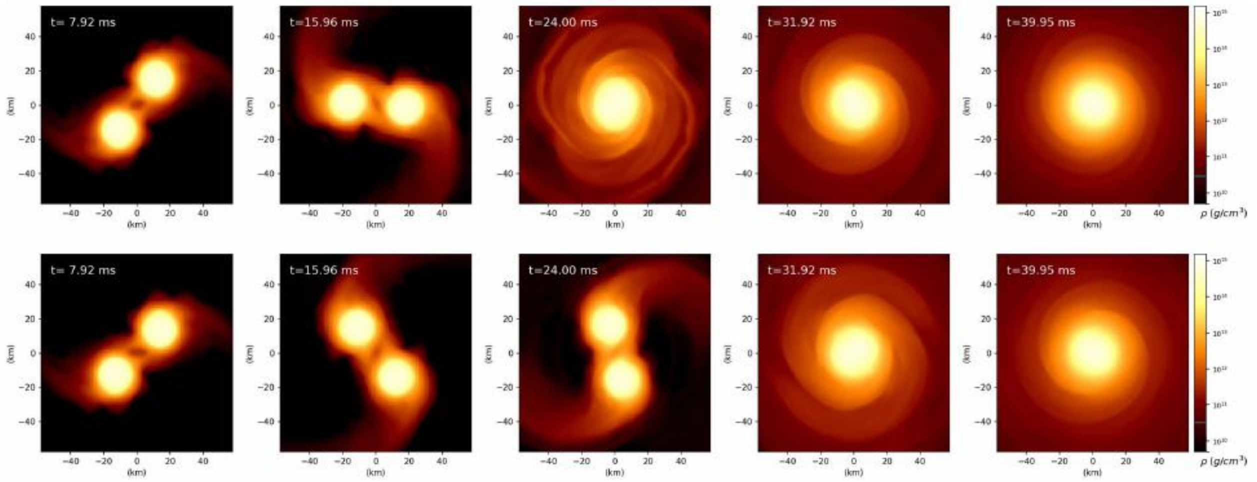
sate vanishes globally but not locally with non-vanishing and nearly density independent pion and dilaton — will be introduced later — decay constants $f_\pi \sim f_\chi \neq 0$, (ii) the baryon mass becomes a density independent constant with magnitude $m_0 \simeq (0.6-0.9)m_N$ which signals the emergence 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.

arXiv:20

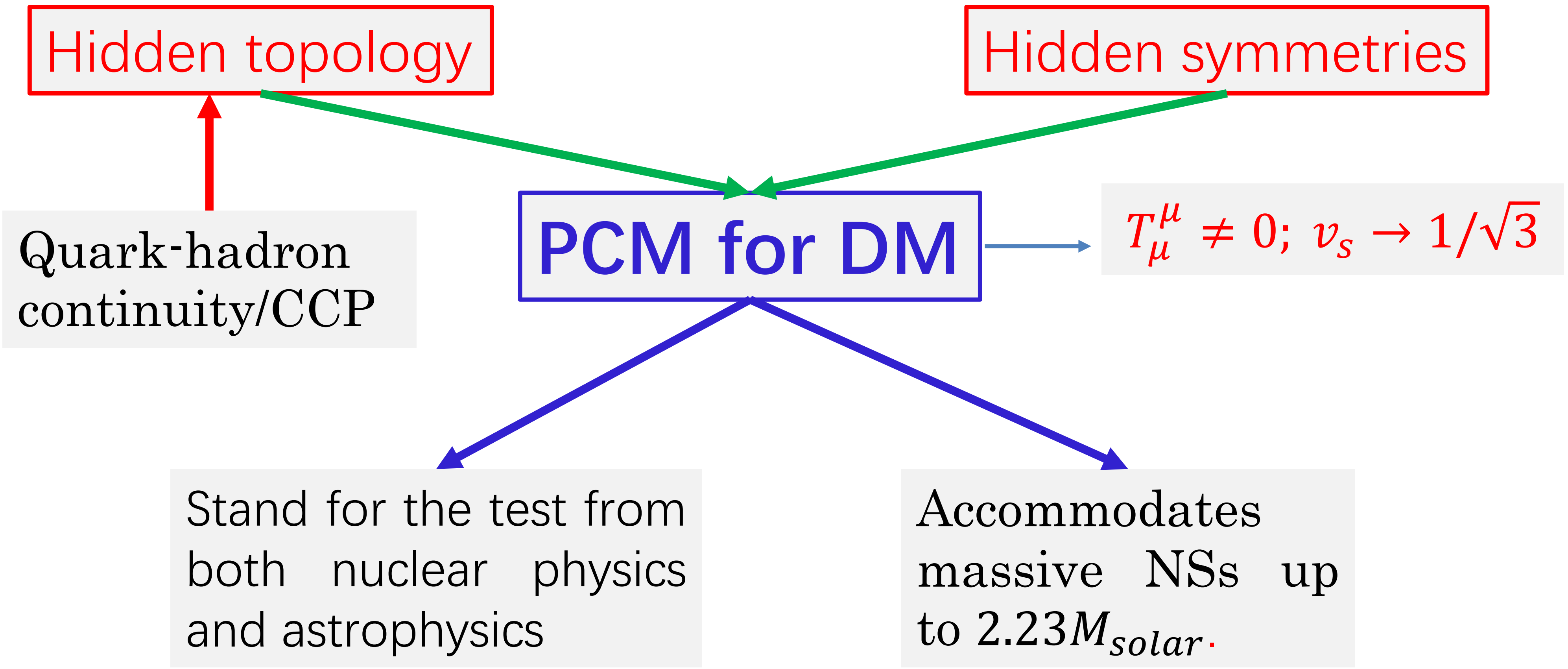
Estimate the location of $n_{1/2}$ using GWs emitted from BNS merger



(a) (b)



VI、 Summary and discussions



Is this pseudo-conformal structure at odds with Nature?

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

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

Thank you for your attention!

Comments are welcome!