Towards a Cheshire Cat for Hadron-Quark Continuity in Compact Stars

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Towards a Cheshire Cat for Hadron-Quark Continuity in Compact Stars

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We review an effective field theory approach to dense compact-star matter that exploits the Cheshire Cat Principle for hadron-quark continuity at high density, adhering only to hadronic degrees of freedom, hidden topology and hidden symmetries of QCD. No Landau-Ginzburg-Wilsonian-type phase transition is involved in the range of densities involved. The microscopic degrees of freedom of QCD, i.e., quarks and gluons, possibly intervening at high baryonic density are traded in for fractionalized topological objects. Essential in the description are symmetries invisible in QCD in the matter-free vacuum: Scale symmetry, flavor local symmetry and parity-doubling. The partial emergence of scale symmetry is signaled by a dilatonic scalar in a "pseudo-conformal" structure. Flavor gauge symmetry manifests with the ρ meson mass going toward a Wilsonian RG fixed point identified with the "vector manifestation fixed point (VMFP)" at which the flavor gauge boson mass goes to zero. Parity doubling is to take place as the quasi-nucleon mass converges to the chiral invariant m_0. The theory with a few controllable parameters accounts satisfactorily for *all* known properties of normal nuclear matter and makes certain predictions that are drastically different from what's available in the literature. In particular, it provides a topological mechanism, argued to be robust, for the cross-over from soft-to-hard equation of state that predicts the star properties in overall agreement with the presently available data, including the maximum star mass $M_{max} \sim 2.3 M_{\odot}$ and the recent LIGO/Virgo gravity-wave data. What is most glaringly different from *all other* approaches known, however, is the prediction for the *rapid convergence* to a sound velocity of star $v_s^2 \approx 1/3$ (in unit $c = 1$) at a density $n \gtrsim 3n_0$, far from the asymptotic density $\gtrsim 50n_0$ expected in perturbative QCD. We interpret this to signal the precocious emergence in compact-star matter of a pseudo-conformal structure associated with the hidden symmetries.

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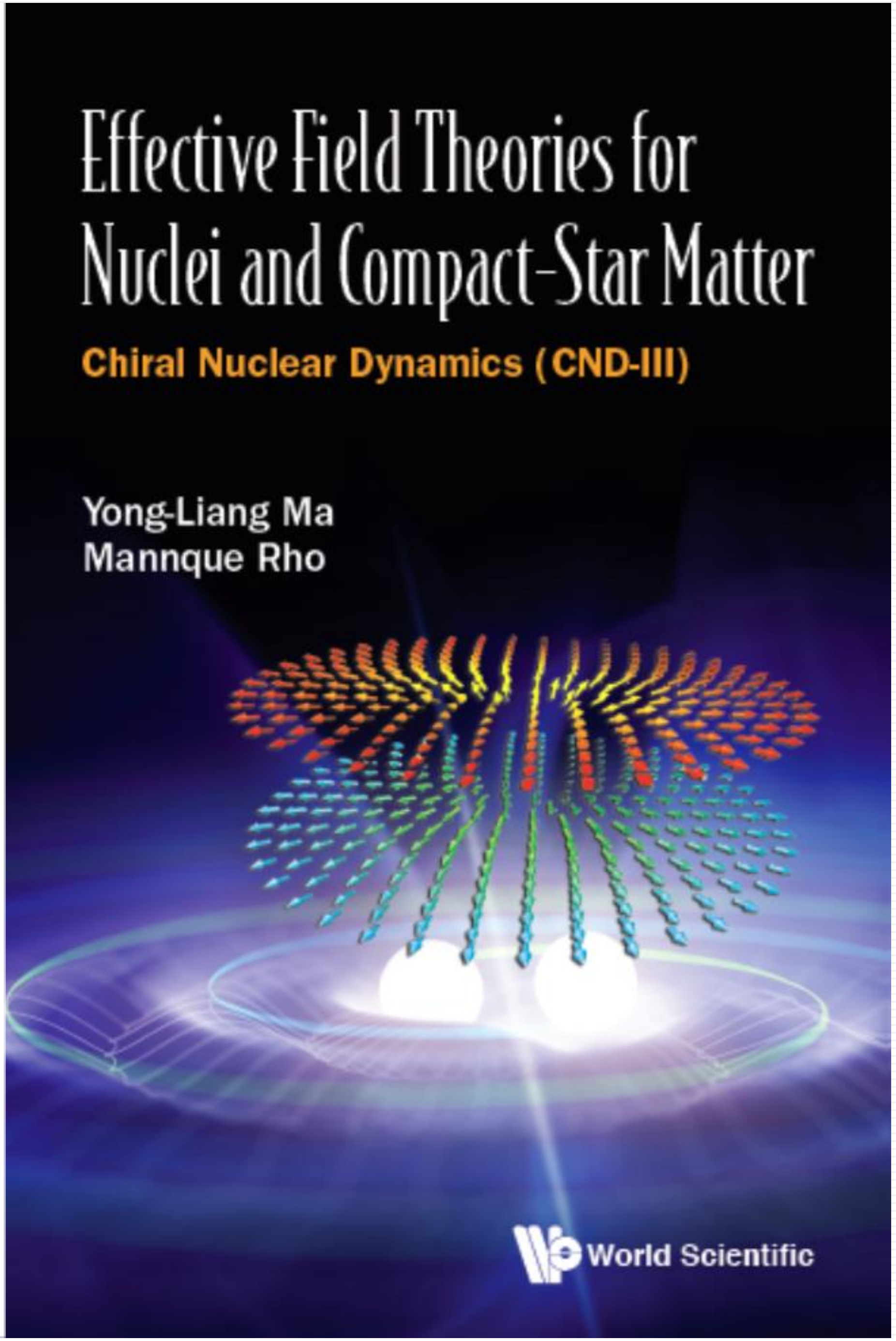


Opportunities and approaches in nuclear physics

There have been some remarkable developments in nuclear astrophysics

Maximum mass of compact stars / GWs from coalescing neutron stars.

A great event for astrophysical science

matter in heaven ⟷ matter on earth

Strong impacts on the most fundamental issue of nuclear physics:

State of matter under extreme conditions.

Main thrusts

- Phenomenological/effective models that purport to explain the data.
  - Using constraints from experiments. Contain a number of parameters to be adjusted so as to accommodate on-coming more precise data.
- **In terms of a framework based on a precisely defined theory, new physics from on-going observations.**
  - **Less successful in confronting Nature. Aiming at uncovering hitherto unexplored aspects of the strongly-interacting state of matter**

Developments in astrophysics

■ 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.*

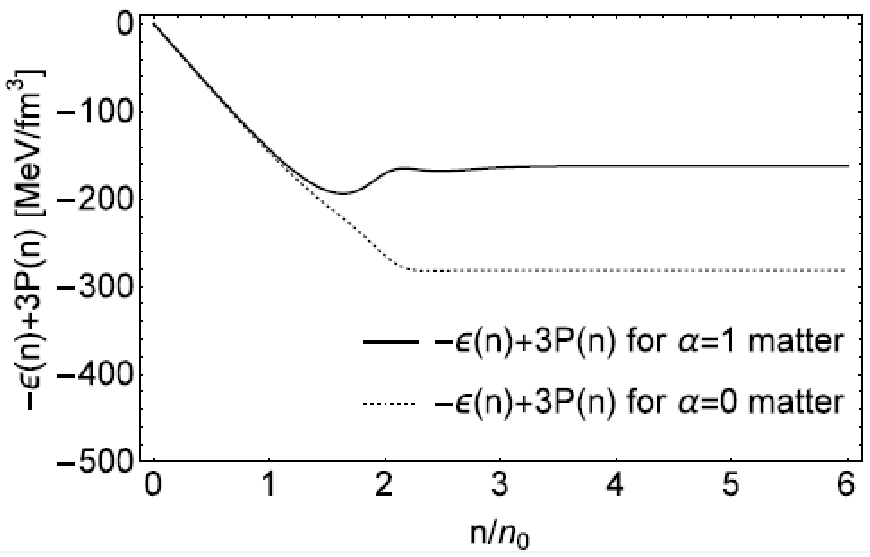
$(2.17^{+0.11}_{-0.10}) M_\odot$ *arXiv: 1904.06759.*

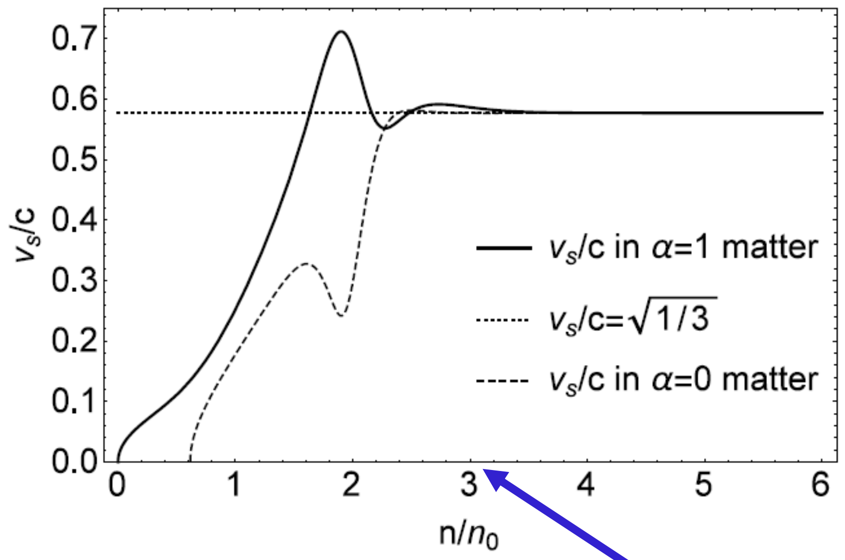
Basic new physics considered in our approach

- 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

Pseudoconformal model for dense nuclear matter

Paeng, Kuo, Lee, Ma and Rho, PRD17'; Paeng, Lee, Ma and Rho, SCPMA19' Ma and Rho, PRD19'.





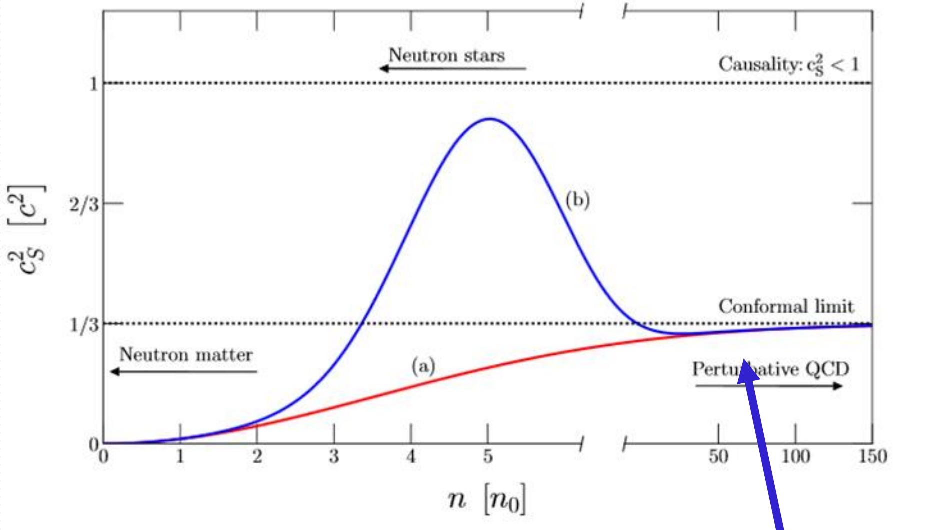
- Trace of energy-momentum tensor is not zero but a density independent constant at $\geq 2n_0$;
- When $\geq 2n_0$, the sound velocity $\to 1/\sqrt{3}$ -- conformal sound velocity.

Very high density
PQCD applicable

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

Issues on Sound velocity in 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!

Hidden symmetries of QCD: Local flavor symmetry

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.

Hidden symmetries of QCD: Local flavor symmetry

Suzuki Theorem：

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

Inevitable emergence of composite gauge bosons

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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 I: *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).

Hidden symmetries of QCD: Scale symmetry

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

$$\mathcal{L}_{L\sigma M} = \frac{1}{2}\, Tr\left(\partial_\mu M\, \partial^\mu M^\dagger\right) - \frac{\mu^2}{2}\, Tr(M\, M^\dagger) - \frac{\lambda}{4}\, (Tr(M\, M^\dagger))^2$$

$M \to g_L\, M\, g_R^\dagger\,, \quad g_{R,L} \in SU(2)_{R,L}$

(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

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

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

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

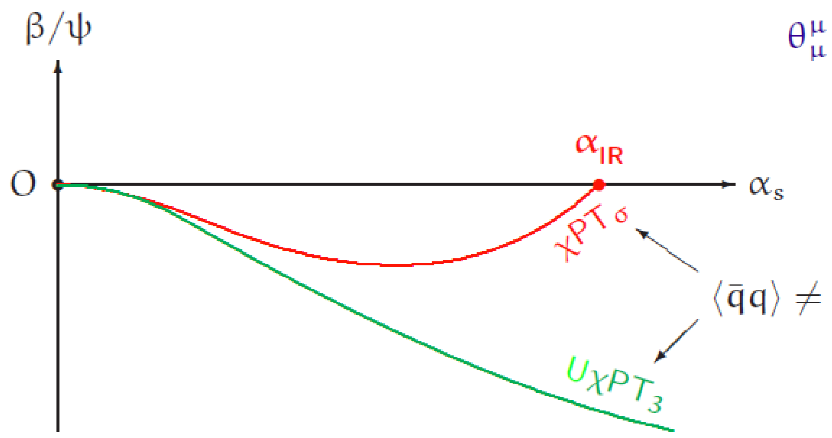
Proposition II: *Baryonic matter can be driven by increasing density from Nambu-Goldstone mode in scale-chiral symmetry to the dilaton-limit fixed point, in pseudo-conformal mode*

Hidden symmetries of QCD: Scale symmetry

$f_0(500)$ 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.

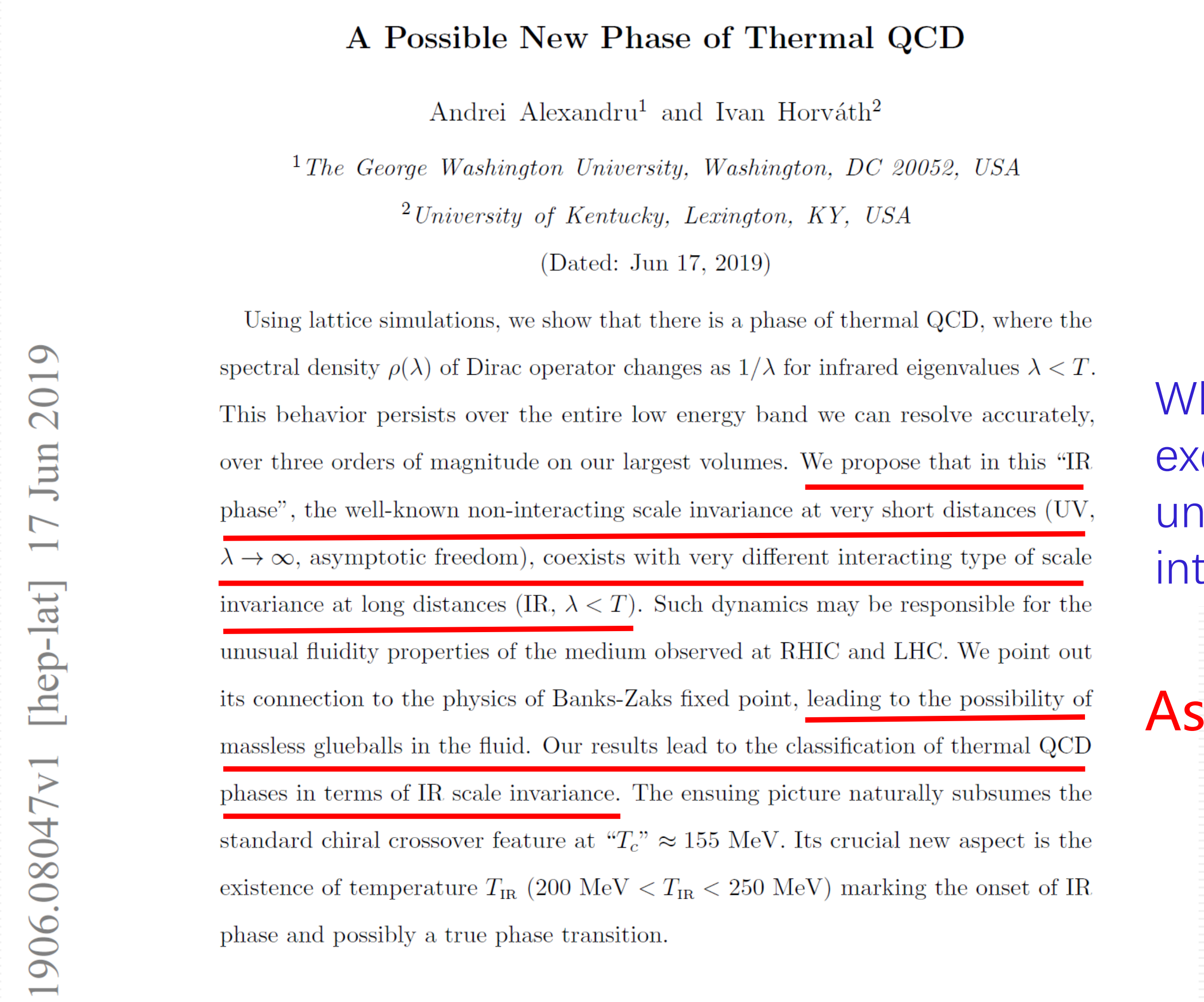
$$\mathcal{L}^{\rm LO}_{\chi{\rm PT}_\sigma} = \mathcal{L}^{d=4}_{\rm inv} + \mathcal{L}^{d>4}_{\rm anom} + \mathcal{L}^{d<4}_{\rm mass},$$

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

Crewther and Tunstall , PR**D91**, 034016

Provides an approach to include scalar meson in ChPT.

Hidden symmetries of QCD: Scale symmetry



1906.08047v1 [hep-lat] 17 Jun 2019

A Possible New Phase of Thermal QCD

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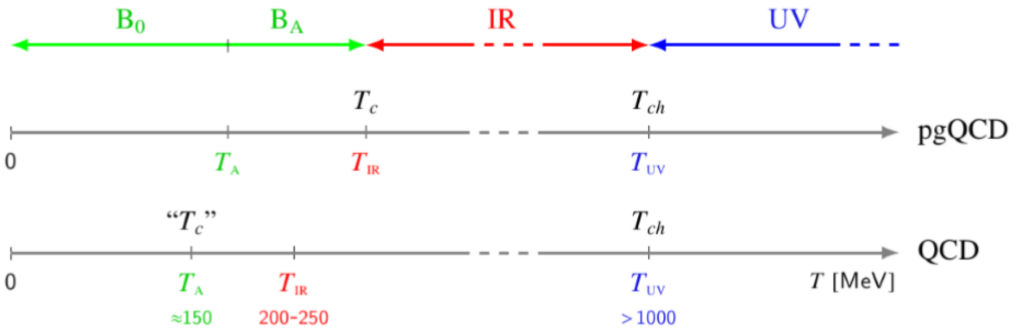
(Dated: Jun 17, 2019)

Using lattice simulations, we show that there is a phase of thermal QCD, where the spectral density $\rho(\lambda)$ of Dirac operator changes as $1/\lambda$ for infrared eigenvalues $\lambda < T$. This behavior persists over the entire low energy band we can resolve accurately, over three orders of magnitude on our largest volumes. We propose that in this "IR phase", the well-known non-interacting scale invariance at very short distances (UV, $\lambda \to \infty$, asymptotic freedom), coexists with very different interacting type of scale invariance at long distances (IR, $\lambda < T$). Such dynamics may be responsible for the unusual fluidity properties of the medium observed at RHIC and LHC. We point out its connection to the physics of Banks-Zaks fixed point, leading to the possibility of massless glueballs in the fluid. Our results lead to the classification of thermal QCD phases in terms of IR scale invariance. The ensuing picture naturally subsumes the standard chiral crossover feature at "T_c" $\approx$ 155 MeV. Its crucial new aspect is the existence of temperature T_{IR} (200 MeV $< T_{IR} <$ 250 MeV) marking the onset of IR phase and possibly a true phase transition.



What may be significant is the possible zero-mass glueball excitation which may or may not be a dilaton. It is however unclear whether this observation can be given an interpretation in terms of the CT theory

Assumption: Same picture happens in dense system

↓

Chiral-Scale EFT

Hidden symmetries of QCD: DLFP and parity-doubling

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

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

$\langle s\rangle \to 0$

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

$$m_{N_\pm} \to m_0\,.$$ Chiral inv. mass

$$g_{\rho NN} = g_\rho(g_{v\rho} - 1) \to 0.$$ ρ decouples, HFS emerges.

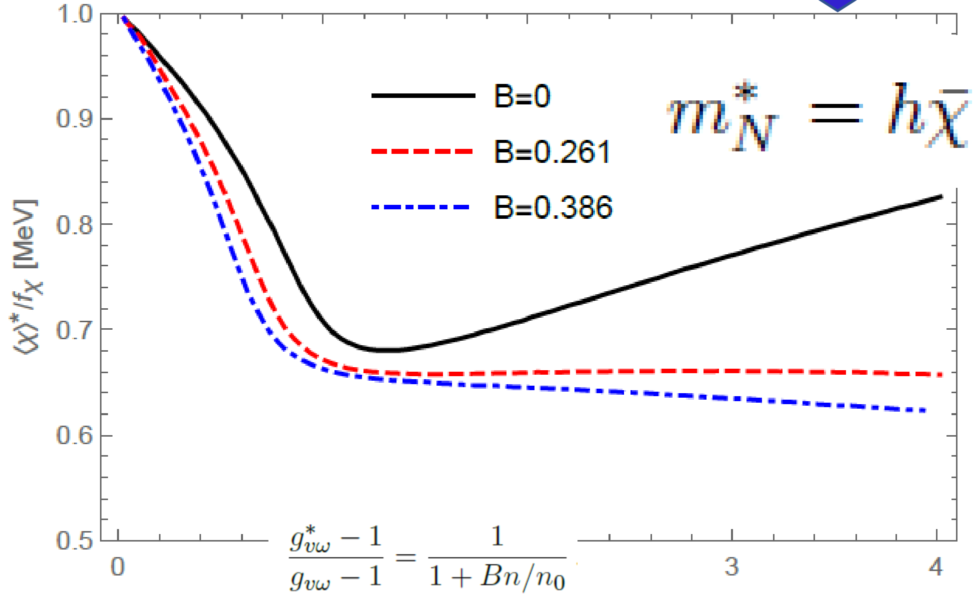
Proposition III: *Moving toward to the dilaton-limit fixed point, the fundamental constants in scale-chiral symmetry get transformed as $f_\pi \to f_\chi, g_A \to g_{v\rho} \to 1$, and the ρ meson decouples while the ω remains coupled, breaking the flavor $U(2)$ symmetry.*

Hidden symmetries of QCD: Emergent parity-doubling

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'.



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

$$\frac{g_{v\omega}^* - 1}{g_{v\omega} - 1} = \frac{1}{1 + Bn/n_0}$$

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 IV: *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*

Topology in nuclear interactions

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

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

Skyrme, 1960

- Baryonic interactions in all regimes of density can be given a robust description in terms of topology that can access the highly nonperturbative dense baryonic matter relevant to the core of compact stars, which cannot be accessed directly by QCD.

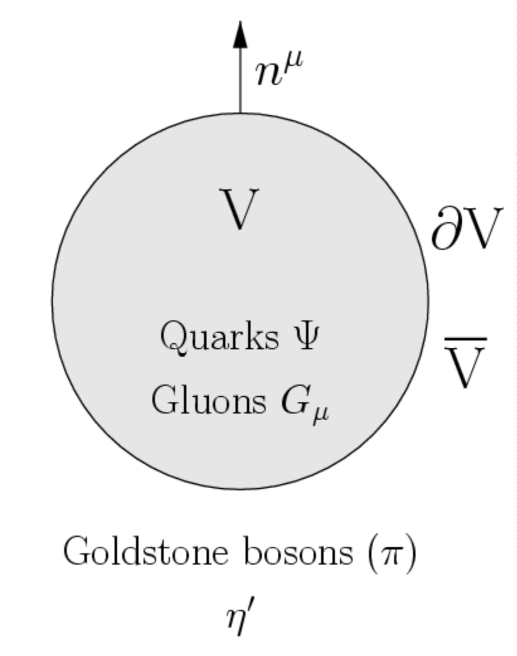
Microscopic QCD degrees of freedom, i.e., quarks and gluons.

The Cheshire Cat Principle that exploits the ``chiral bag".

Macroscopic DoFs, hadrons, given in terms of topological object.

Chashire Cat principle

The Cheshire Cat



"How hadrons transform to quarks"

Baryon charge:

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

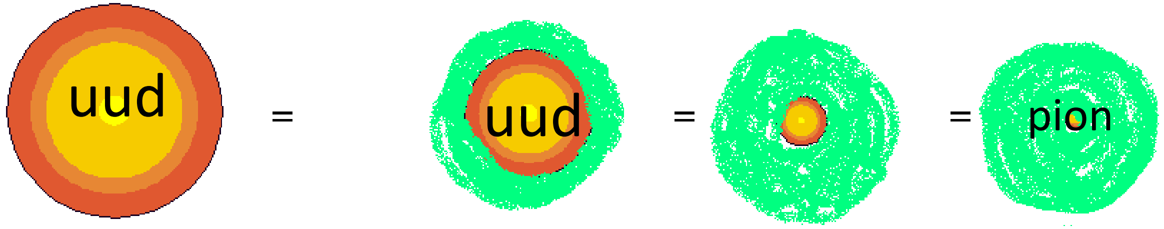
$$B_{in} = 1 - \frac{1}{\pi}[\theta(R) - \frac{1}{2}\sin 2\theta(R)]$$

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

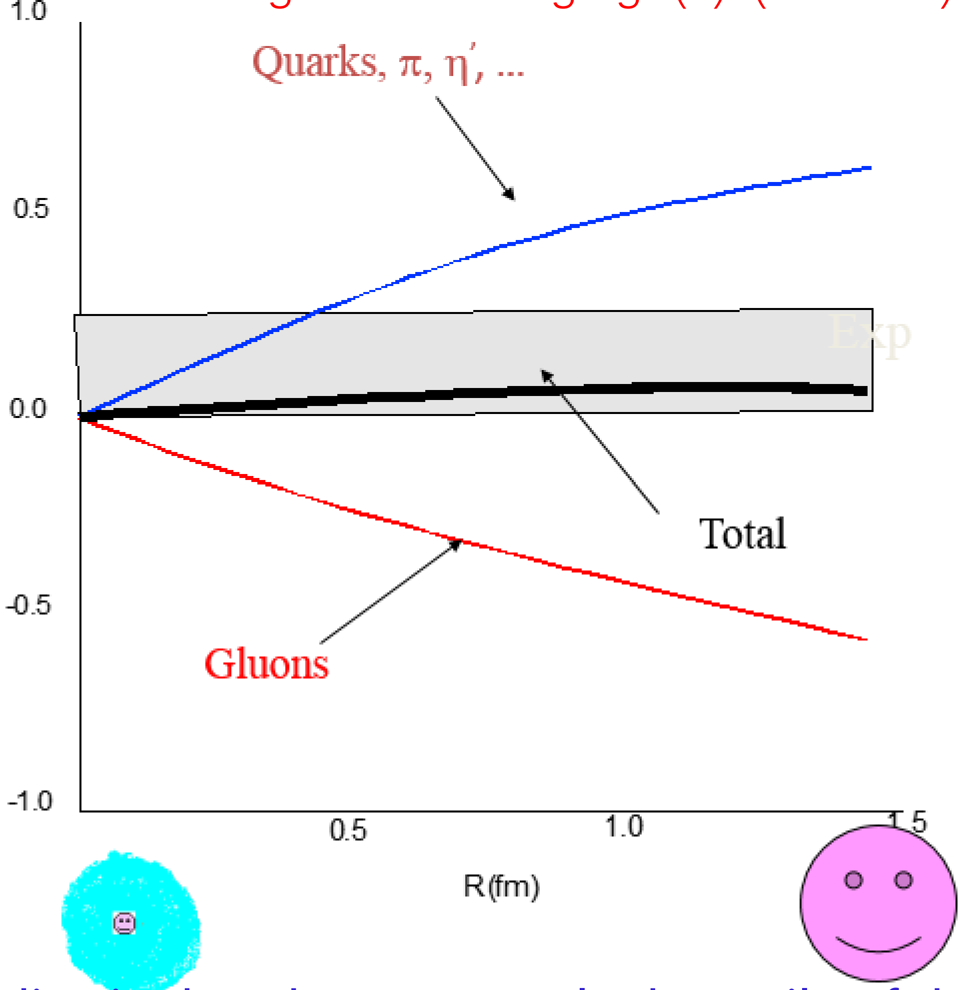
Brown, Goldhaber, Rho 1983
Goldstone, Jaffe 1983

Chashire Cat principle

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

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

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

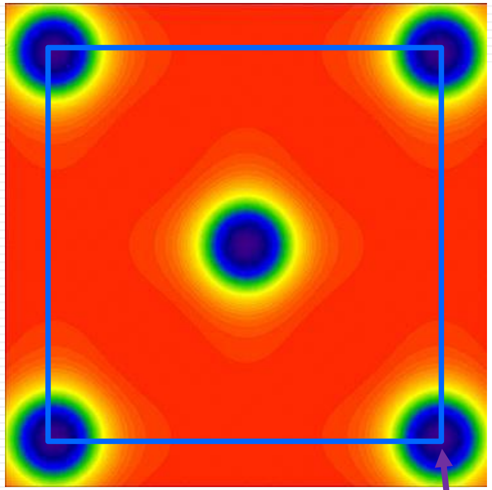
$$S_{\delta V} = \frac{1}{2} \int_{\delta V} d\Sigma^\mu \left\{ (n_\mu \bar{\psi} U^{\gamma_5} \psi) + i \frac{g_s^2}{16\pi^2} K_{5\mu} (\mathrm{Tr}\, \ln U^\dagger - \mathrm{Tr}\, \ln U) \right\} .$$

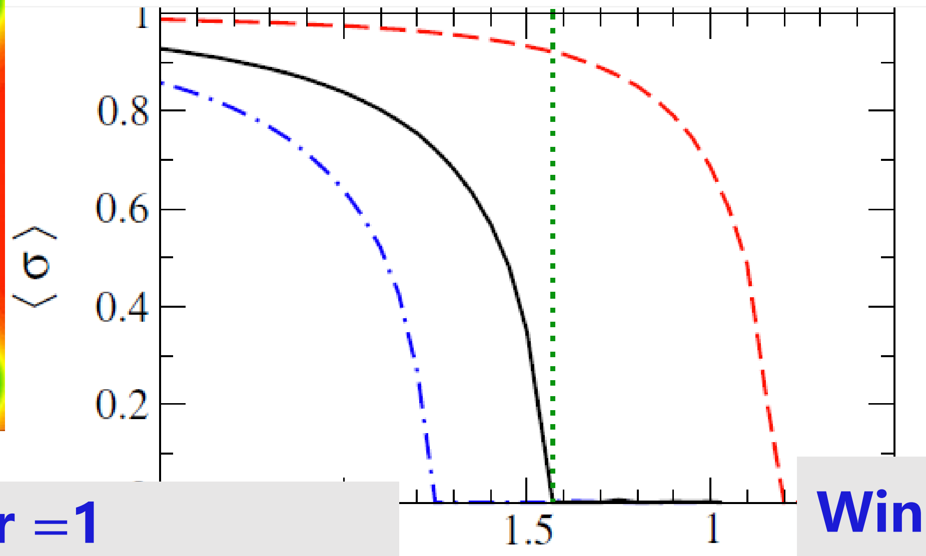
$$K_5^\mu = \epsilon^{\mu\nu\alpha\beta} (G_\nu^a G_{\alpha\beta}^a - \frac{2}{3} g_s f^{abc} G_\nu^a G_\alpha^b G_\beta^c),$$

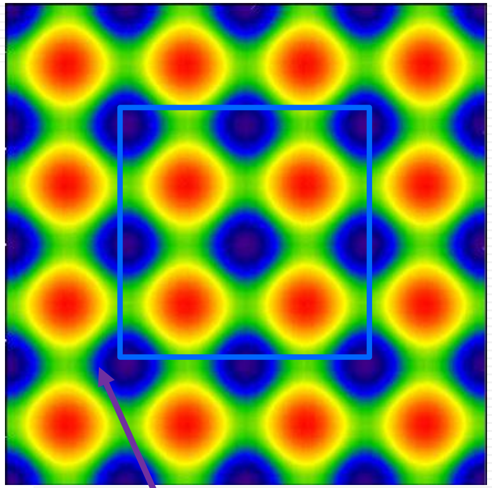
When the bag radius is shrunk to zero, only the smile of the cat is left with spinning gapless quarks running luminally

Topology change: **Skyrmion-half-skyrmion transition**

Ma, Harada, Oh, Park and Rho, 13'







Winding number =1

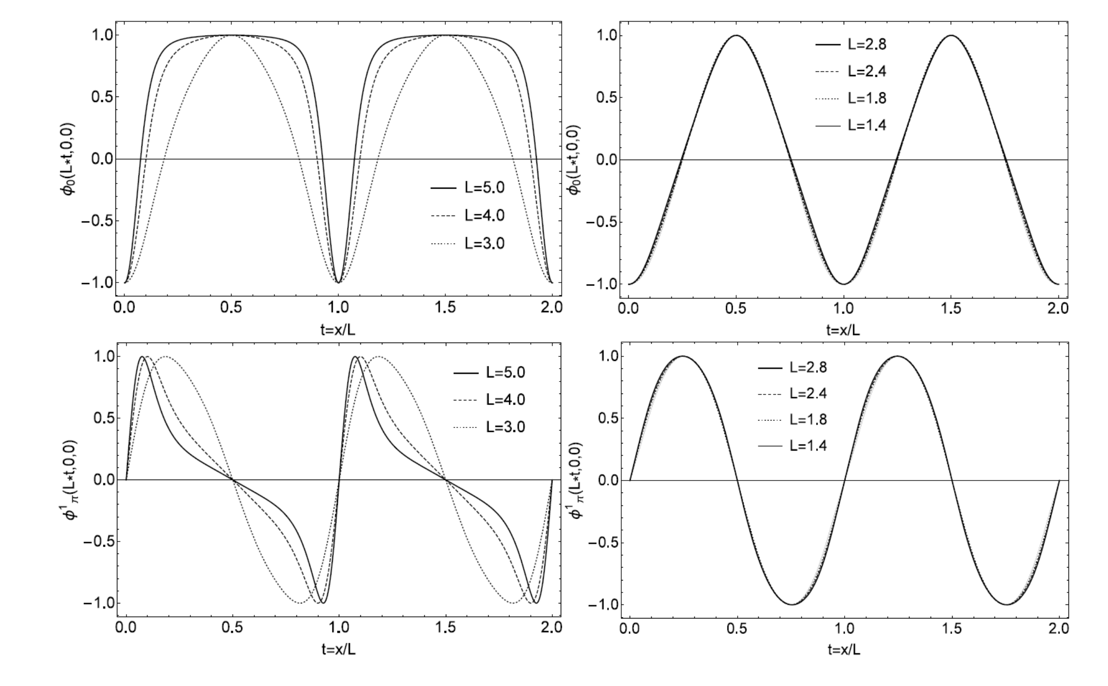
Winding number $= \frac{1}{2}$

Topology transition

- **Proposition VI:** *The half-skyrmion phase in a solitonic description of dense baryonic matter is 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, resembling the pseudogap phase in condensed matter.*

Topology change: Quansiparticle in half-skymrion phase

The half-skyrmion phase in the skyrmion-crystal simulation is in a state that can be described almost entirely by mean fields, largely undistorted by strong interactions. This resembles Landau-Fermi liquid fixed point theory where the β function for the quasiparticle interactions is suppressed.



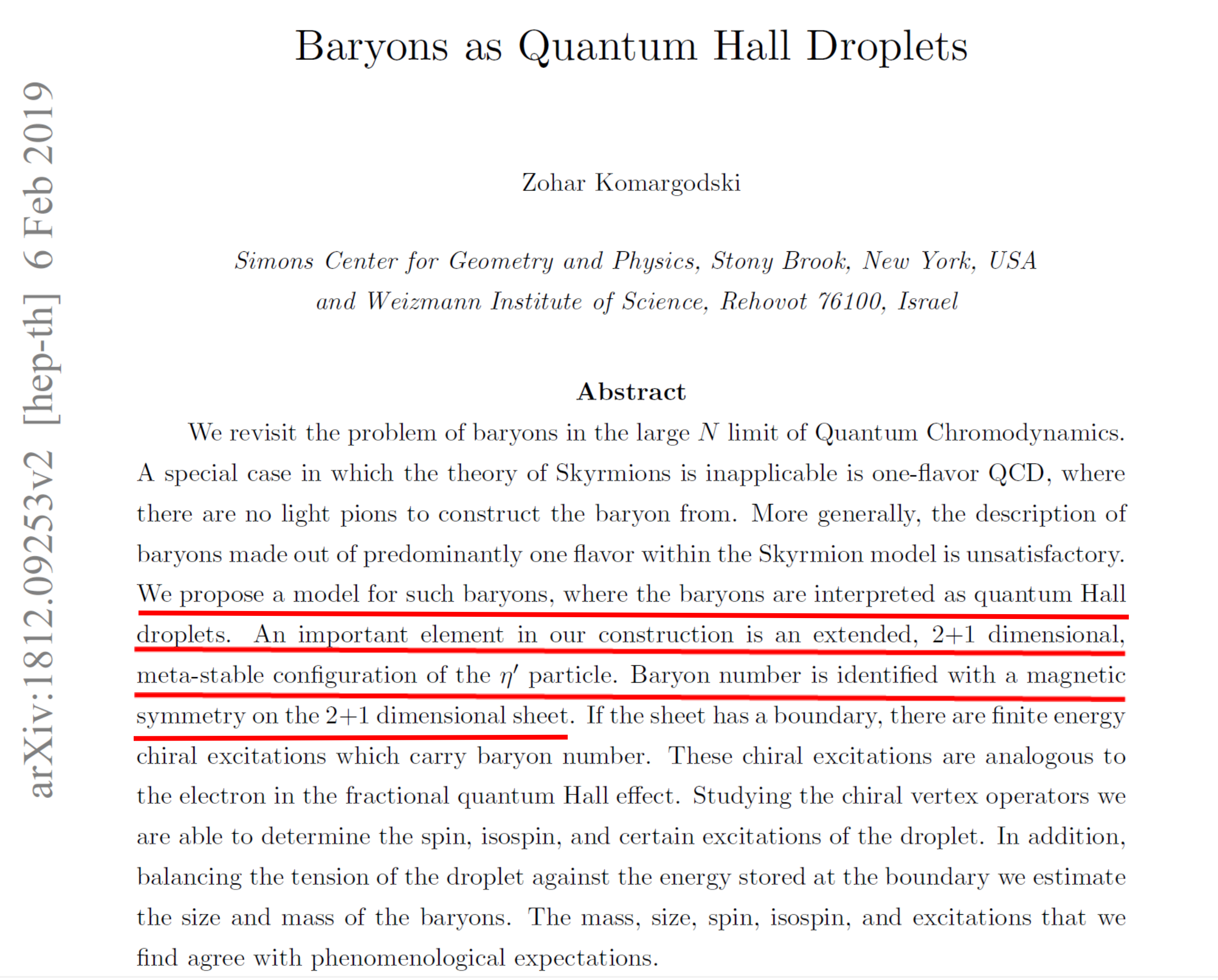
Paeng, Kuo, Lee, Ma, Rho, 17'

Topology change: Cheshire Cat for hadron-quark continuity

When $N_f = 1$,

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

Rule out the skyrmion approach?



arXiv:1812.09253v2 [hep-th] 6 Feb 2019

Baryons as Quantum Hall Droplets

Zohar Komargodski

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Abstract

We revisit the problem of baryons in the large N limit of Quantum Chromodynamics. A special case in which the theory of Skyrmions is inapplicable is one-flavor QCD, where there are no light pions to construct the baryon from. More generally, the description of baryons made out of predominantly one flavor within the Skyrmion model is unsatisfactory. We propose a model for such baryons, where the baryons are interpreted as quantum Hall droplets. An important element in our 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 dimensional sheet. If the sheet has a boundary, there are finite energy chiral excitations which carry baryon number. These chiral excitations are analogous to the electron in the fractional quantum Hall effect. Studying the chiral vertex operators we 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/1907.00958

Baryon as a Quantum Hall Droplet and the Cheshire Cat Principle

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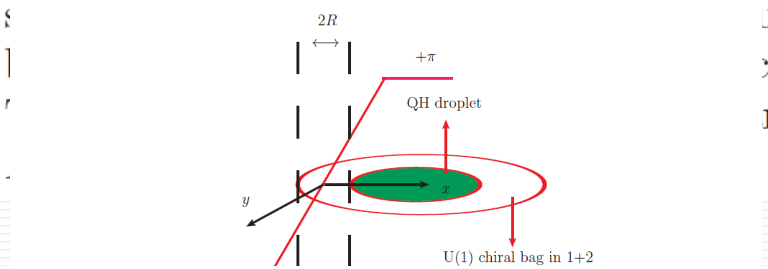
(Dated: July 2, 2019)

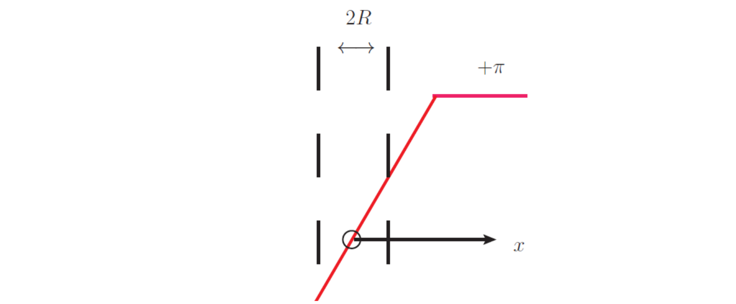
We show that the recent proposal to describe the $N_f = 1$ baryon in the large number of color limit as a quantum Hall droplet, can be understood as a chiral bag in a 1+2 dimensional strip using the Cheshire cat principle. For a small bag radius, the bag red

uarks all spinning in the

cal field theory due to the

ryon number and spin $\frac{1}{2}N$





- **Proposition VIII:** *The topology change with the cusp singularity at $n_{1/2}$ is a dual, via Cheshire Cat, to the hadron-quark continuity in QCD responsible for the soft-to-hard change in the EoS.*

Effective field theory for baryonic matter

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

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

Intrinsic density dependence (IDD) enters through the VeV of dilaton.

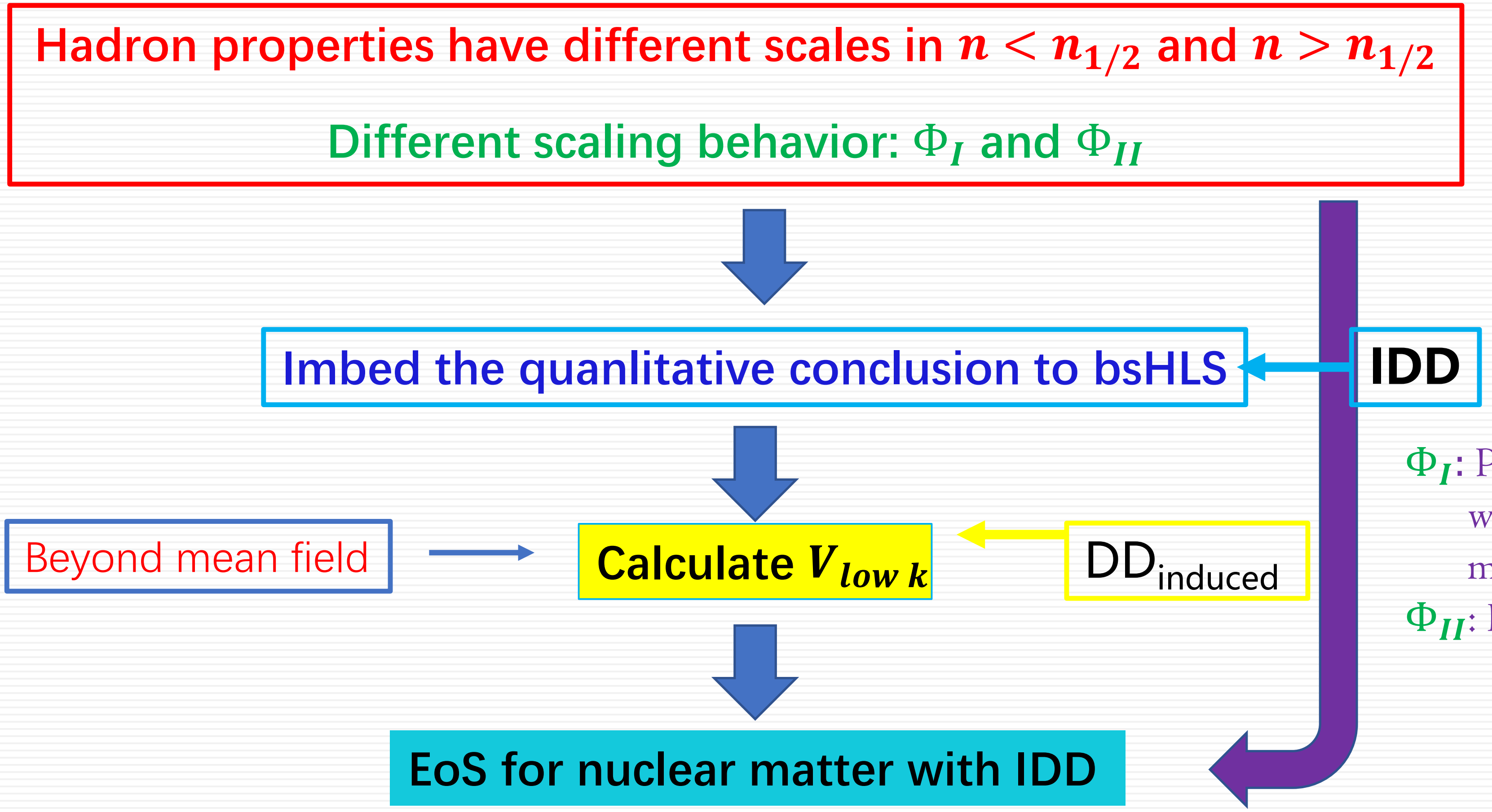
$$\mathcal{L}^{B}_{\chi PT_\sigma}(\psi,\pi,\chi,V_\mu) = \mathrm{Tr}(\bar{B} i\gamma_\mu D^\mu B) - \frac{\chi}{f_\sigma}\mathrm{Tr}(\bar{B}B) + \cdots$$

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

Li, Ma and Rho, PRD95,114011 (2017);

- **Proposition IX:** *In baryonic matter, scale symmetry is "intrinsically" locked to chiral symmetry so that the pion decay constant scales in density as does the dilaton decay constant.*

Implement topology transition to EoS



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

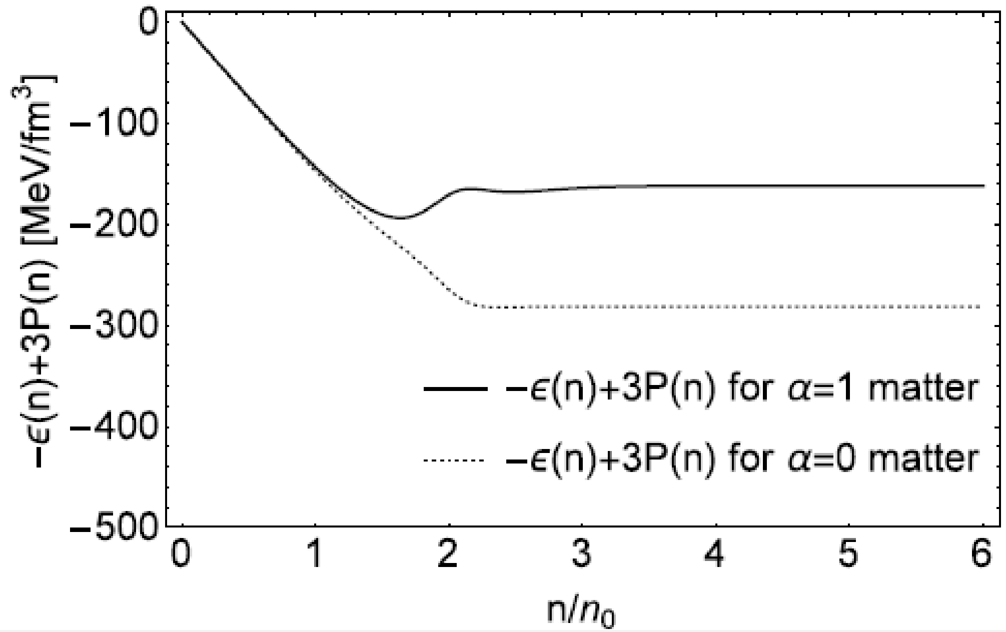
Φ_{II}: Density independent.

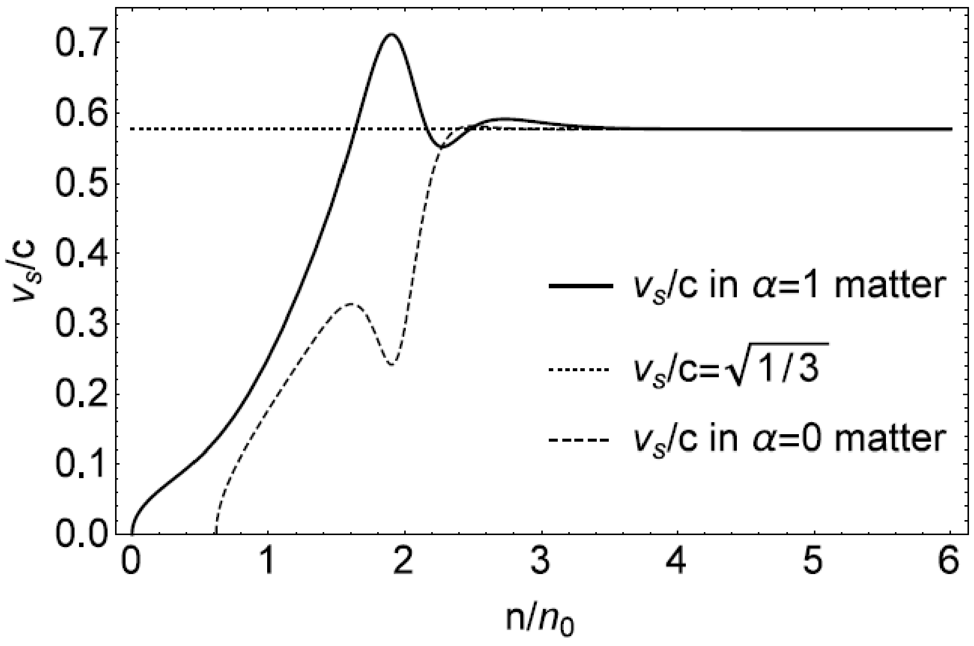
Parameter free EoS for DM: $E/A = -m_N + X^{\alpha} x^{1/3} + Y^{\alpha} x^{-1},\ n \gtrsim n_{1/2}.$

Pseudo-conformal model

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

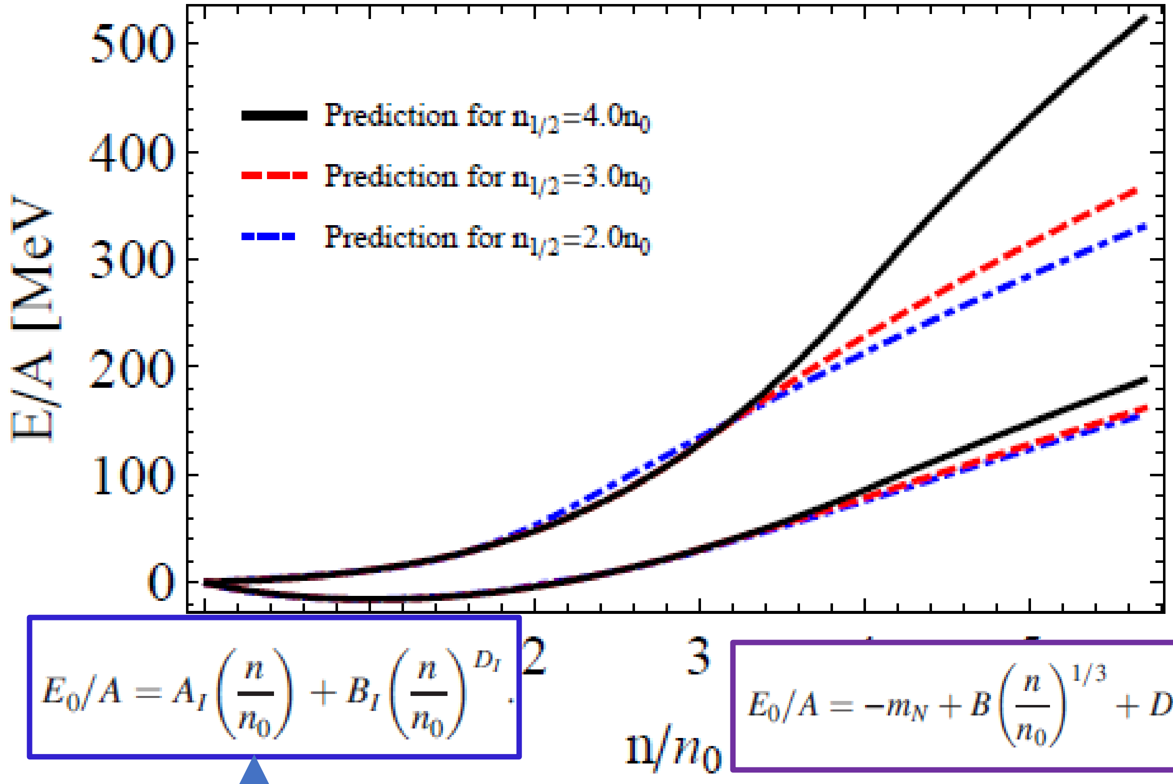
$$v_s^2/c^2 = \frac{\partial P(n)}{\partial n} \Big/ \frac{\partial \epsilon(n)}{\partial n}$$





Paeng, Kuo, Lee, Ma and Rho, PRD17'.

Emergent scale symmetry in medium

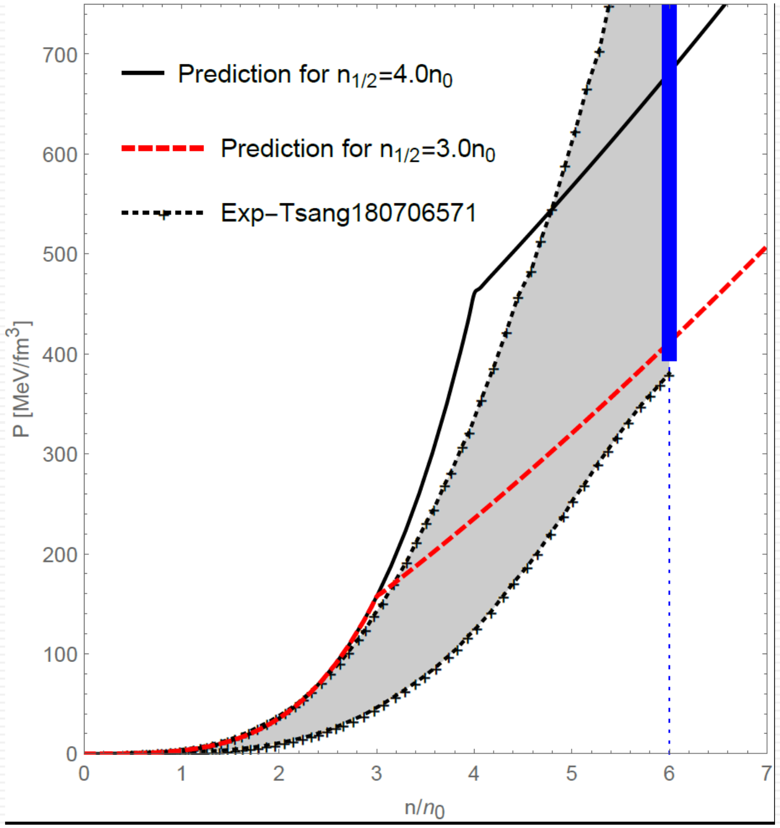


$$E_0/A = A_I\left(\frac{n}{n_0}\right) + B_I\left(\frac{n}{n_0}\right)^{D_I}.$$

Fitted function

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

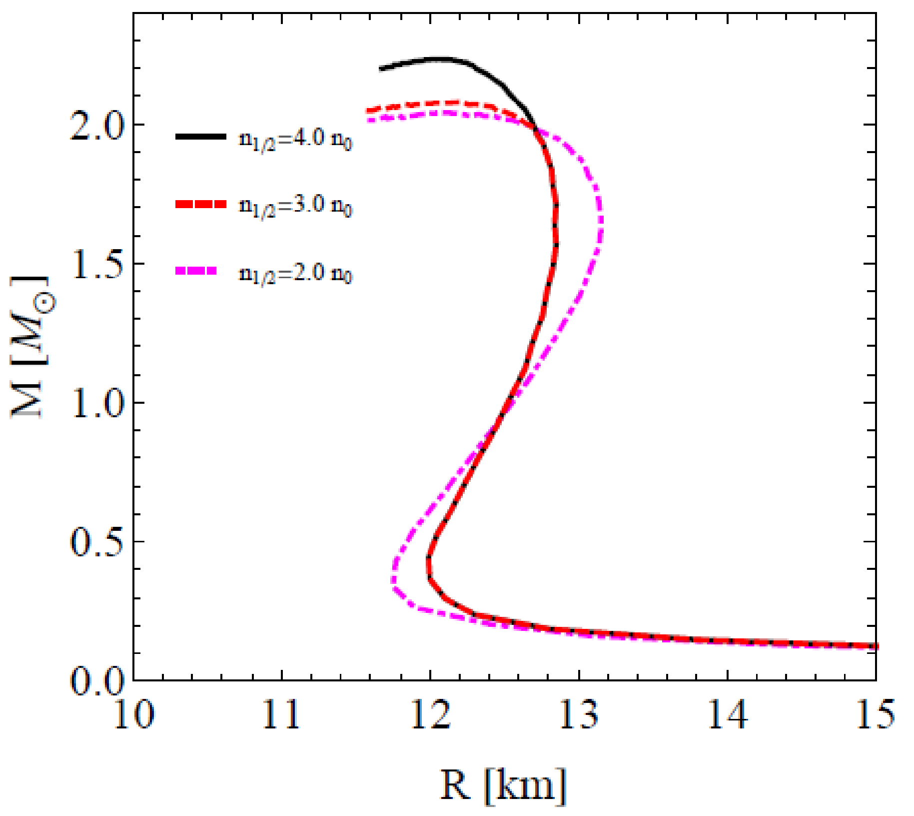
PC Prediction

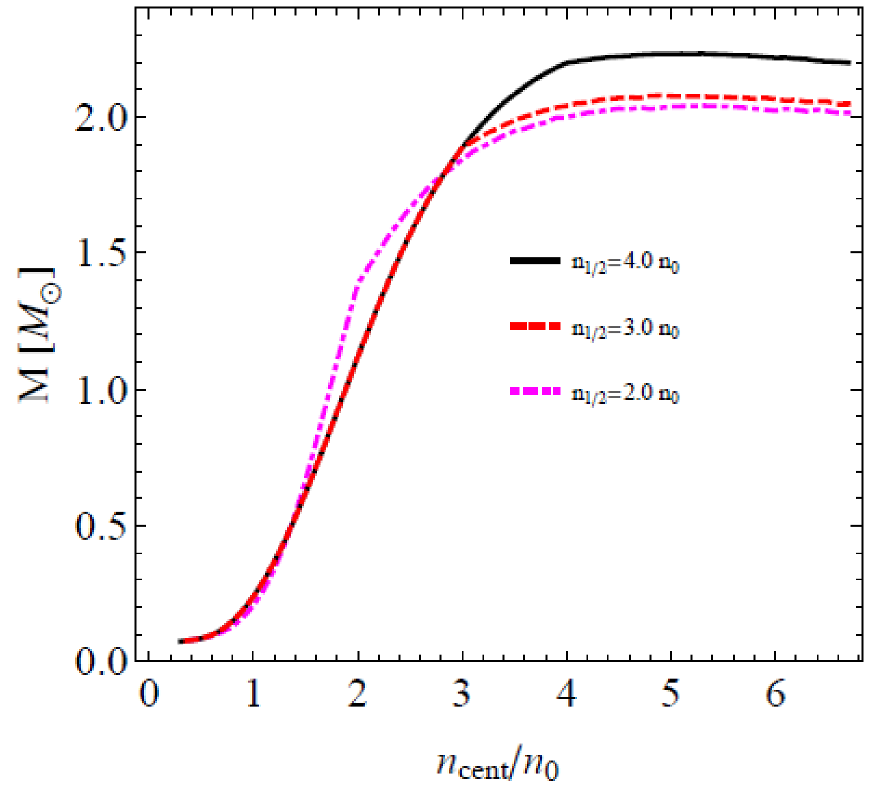


The value of $n_{1/2}$, to be constraint by observation.

Paeng, Kuo, Lee, Ma and Rho, PRD17'; Ma and Rho 18', Ma and Rho, 19'.

Massive star properties





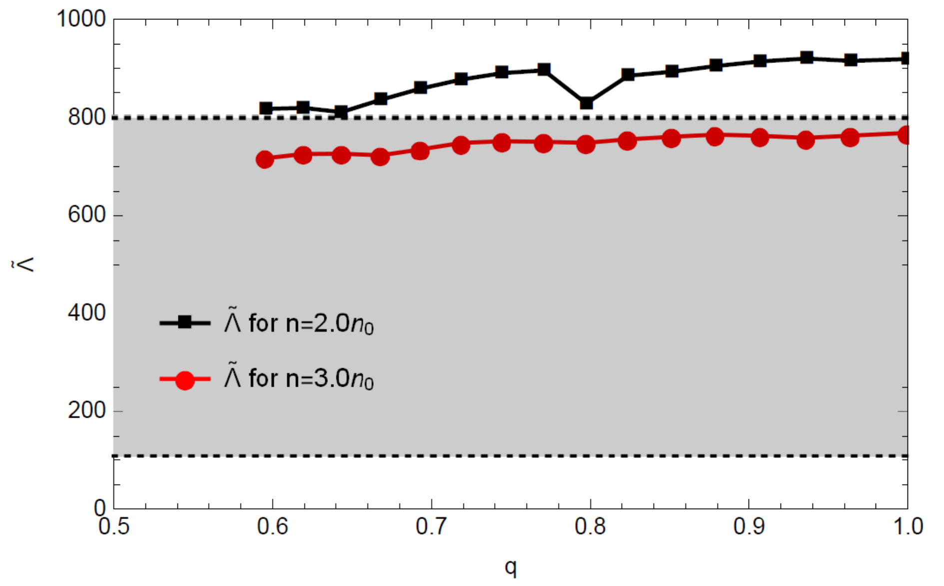
Accommodate massive star $\geq 2.0\ M_{solar}$

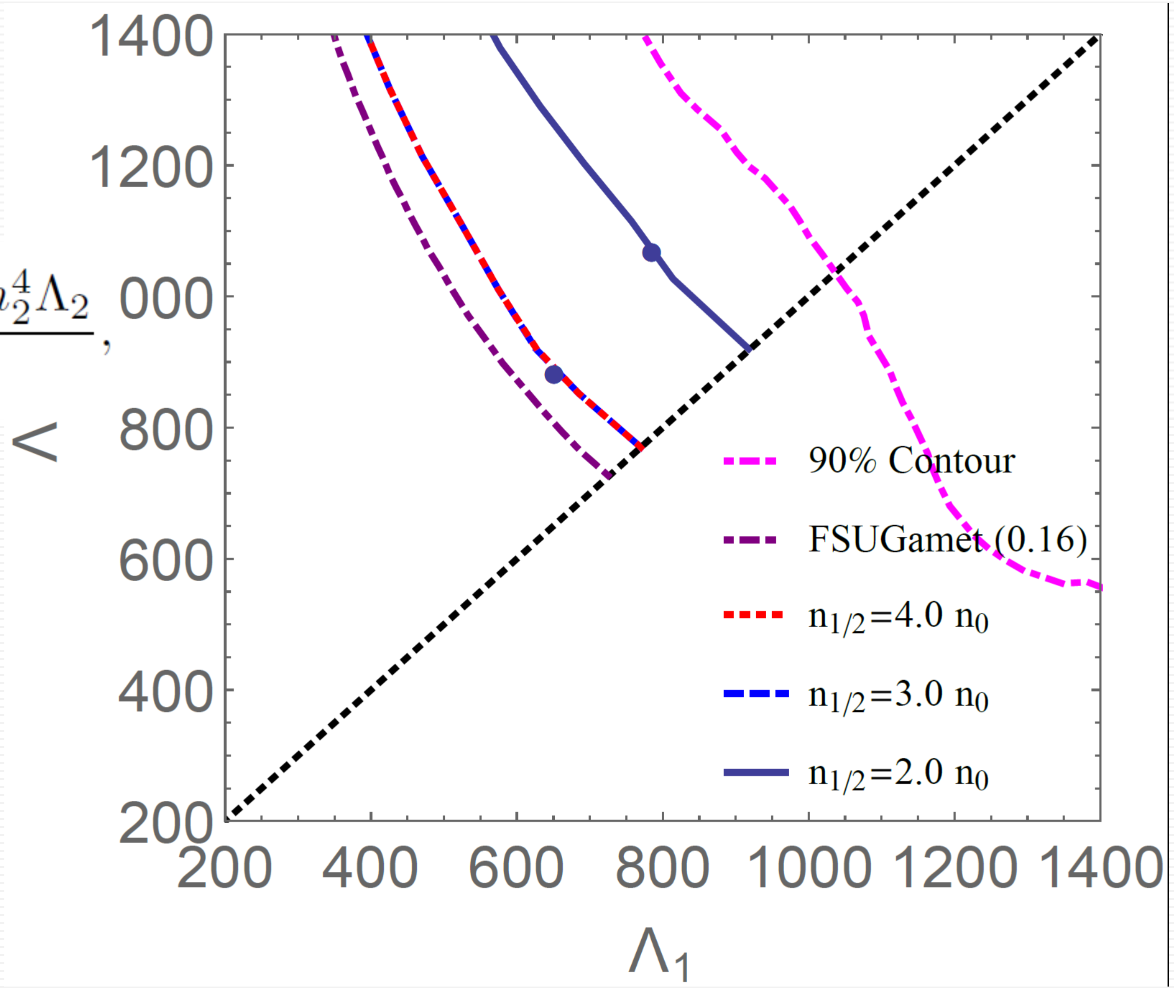
Ma and Rho, 18'; Ma, Lee, Paeng and Rho, 18'; Paeng, Kuo, Lee, YM and Rho PRD17'

Tidal deformability

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

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





Summary and discussion

- Hidden topology + hidden symmetries emerge at high density inspired us to propose a simple structure – PC – of DM.
- The quark-hadron continuity is descried through the topology change thanks to the Cheshire Cat principle.
- Continuity in conformality: low density (unitarity business) --> high density (PConformailty)
- In stark contrast to what was found in the literature, the PCM, which works well for normal nuclear matter density, gives $v_s \to 1/\sqrt{3}$ --- the conformal limit --- at a density $\geq n_{1/2}$and accommodates massive neutron stars up to $2.23M_{solar}$, which is consistent with the present observation.
- So far, our model has stood the test from both the nuclear physics and astrophysics.

Summary and discussion

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