Topology change, emergent symmetry and compact star matter

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In collaboration with Mannque Rho et al.
Outline

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.?
I. Introduction

- **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 along the line of Weinberg's Folk Theorem.

- 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 $\sim q = 5$.

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J. W. Holt, M. Rho and W. Weise, 1411.6681
Our strategy: Construct “Generalized” nuclear EFT (GnEFT) while capturing fully what sEFT successfully does up to $n_0$, can be extrapolated up to a density where sEFT is presumed to break down.
I. Introduction

- Tidal deformability:
  \[ \Lambda_{1.4} < 800 \]
  \[ \tilde{\Lambda} = 300^{+420}_{-230} \rightarrow \tilde{\Lambda} = 190^{+390}_{-120} \]
  \[ R = 11.9^{+1.4}_{-1.4} \text{ km} \]
  \[ \text{C. Y. Tsang, et al., 1807.06571} \]

- Pressure:
  \[ P(2n_0) = 3.5^{+2.7}_{-1.7} \times 10^{34} \text{ dyn/cm}^2, \]
  \[ P(6n_0) = 9.0^{+7.9}_{-2.6} \times 10^{34} \text{ dyn/cm}^2. \]

- Massive neutron stars:
  \[ (1.97 \pm 0.04)M \odot \]
  \[ (2.01 \pm 0.04)M \odot \]
  \[ (2.17^{+0.11}_{-0.10})M \odot \]
  \[ \leq 10n_0 \]
  \[ \text{Nature, 467(2010), 1081.} \]
  \[ \text{Science, 340(2013), 448.} \]
  \[ \text{arXiv: 1904.06759.} \]
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
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 **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';
I. Introduction

Topology enters through IDD

\[
\langle J(x_1)J(x_2)\ldots J(0) \rangle_{EFT} \leftrightarrow \langle J(x_1)J(x_2)\ldots J(0) \rangle_{QCD}
\]

match at \( \Lambda_M < \Lambda_X \)

Harada and Yamawaki, PRD 01'

LECs

\[ \langle \bar{q}q \rangle, \langle G^2 \rangle, \ldots \]

Intrinsic QCD quantities

LECs*

Medium modified Vacuum

➢ The density dependence involved is intrinsic of QCD, referred to the IDD.

➢ Full density dependence = IDD + IDD\text{induced}

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

\[ \mathcal{L} = \mathcal{L}^M_{\chi \text{PT}}(\pi, \chi, V_\mu) + \mathcal{L}^B_{\chi \text{PT}}(\psi, \pi, \chi, V_\mu) - V(\chi) \]

\[ \mathcal{L}^M_{\chi \text{PT}}(\pi, \chi, V_\mu) = f_\pi^2 \left( \frac{\chi}{f_\sigma} \right)^2 \text{Tr}[\hat{a}_{\perp \mu} \hat{a}_\mu] + a f_\pi^2 \left( \frac{\chi}{f_\sigma} \right)^2 \text{Tr}[\hat{a}_{\parallel \mu} \hat{a}_\mu] \]

\[ + \frac{1}{2g^2} \text{Tr}[V_{\mu \nu} V^{\mu \nu}] + \frac{1}{2} \partial_\mu \chi \partial_\mu \chi \]

\[ \mathcal{L}^B_{\chi \text{PT}}(\psi, \pi, \chi, V_\mu) = \text{Tr}(\bar{B} i \gamma_\mu D_\mu B) - \frac{\chi}{f_\sigma} \text{Tr}(\bar{B} B) + \cdots \]

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

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.

Quark-Hadron continuity

Qualitative information from topology change

Density dependence of LECs

Cashire Cat
Π、Topology change and quark-hadron continuity

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

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

- $f_\pi$: pion decay constant
- $e$: Skyrme parameter

Topological soliton
winding number = baryon number

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

T. R. Skyrme, 1960

Baryonic interactions in all regimes of density, upto that relevant to the core of CSs, can be accessed.
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!
II、Topology change and quark-hadron continuity

Topology change: Parity doublet structure

\[ \langle \bar{q}q \rangle = \frac{1}{(2L)^3} \int_0^{2L} d^3 x \bar{q}q \]

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.**

Ⅱ、Topology change and quark-hadron continuity

\[ E(n, \alpha) = E(n, \alpha = 0) + E_{\text{sym}}(n)\alpha^2 + O(\alpha^4) + \cdots \]

“Symmetry energy is dominated by the tensor forces”:

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

The cusp is associated with the topology change with the emergence of quasiparticle structure with the half-skyrmions.
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 from QCD, NOT nuclear renormalization.
The Cheshire Cat

"How hadrons transform to quarks"

Baryon charge:

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

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

\[ B = B_{\text{out}} + B_{\text{in}} = 1 \]

Goldstone bosons (\(\pi\))

\[ \eta' \]

Quarks \(\Psi\)

Gluons \(G_{\mu}\)

\[ n^\mu \]

\[ \partial V \]

\[ V \]
III、Topology change and quark-hadron continuity

Proton = uud = pion

Flavor singlet axial charge $g_A(0)$ (Lee et al)

Equivalent description of the proton

When the bag radius is shrunk to zero, only the smile of the cat is left with spinning gapless quarks running luminally...
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 \( \eta' \) 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

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

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

- Annulus of radius $R$ and clouded by an $\eta'$-field with a monodromy of $2\pi$.
- The bag radius is immaterial thanks to CCP.

YLM, Nowak, Rho & Zahed, 1907.00958
Rho and omega mesons play an important role in our formalism of compact star structure

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

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

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

Inevitable emergence of composite gauge bosons

Mahiko Suzuki

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

\[
\mathcal{L}_{\sigma \chi} = \frac{1}{2} \frac{\mu^2}{2} \text{Tr}(M M^\dagger) - \frac{\lambda}{4} \left( \text{Tr}(M M^\dagger) \right)^2 \quad M \rightarrow g_L M g_R^\dagger, \quad g_{R,L} \in SU(2)_{R,L}
\]

(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

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

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

\[
\mathcal{L}_{\sigma \chi} = \mathcal{L}_{\text{inv}} - V(\chi)
\]

with

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

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

K. Yamawaki, 2015

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 $\alpha_s$.

EB of SI: Departure of $\alpha_s$ from IRFP + current quark mass.

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

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

$\chi_{PT}\sigma \Rightarrow$ expand in $\theta^\mu_\mu$

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

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

$\Rightarrow$ NG bosons $\pi$, $K$, $\eta$, $\sigma$.

Crewther and Tunstall, PRD91, 034016

Provides an approach to include scalar meson in ChPT.
Proposition: Moving toward to the dilaton-limit fixed point, the fundamental constants in scale-chiral symmetry get transformed as $f_\pi \to f_X$, $g_A \to g_{v\rho} \to 1$, and the $\rho$ meson decouples while the $\omega$ remains coupled, breaking the flavor $U(2)$ symmetry.
Emergent from parameter dialing from RMF:

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

Paeng, Lee, Rho and Sasaki, PRD 13’.

\[
\langle \theta_{\mu}^i \rangle = \langle \theta^{00} \rangle - \sum_i \langle \theta^{ii} \rangle = \epsilon - 3P
\]

\[
= 4V(\langle \chi \rangle) - \langle \chi \rangle \left. \frac{\partial V(\chi)}{\partial \chi} \right|_{\chi = \langle \chi \rangle}
\]

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

Proposition: Going toward the DLFP with the \( \rho \) decoupling from the nucleons, the parity doubling emerges and \( m_N^* \rightarrow \langle \chi \rangle^* \rightarrow m_0 \). Consequently the TEMT in medium in \( V_{\text{low } k} \text{RG theory} \) 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.

Parity doubling emerges via an interplay between \( \omega-N \) coupling -- with \( U(2) \) symmetry strongly broken -- and the dilaton condensate.
IV、The pseudoconformal model of dense nuclear matter

\[ \mathcal{L} = \mathcal{L}^{M}_{\chi PT} (\pi, \chi, V_{\mu}) + \mathcal{L}^{B}_{\chi PT} (\psi, \pi, \chi, V_{\mu}) - V(\chi) \]

\[ \mathcal{L}^{M}_{\chi PT} (\pi, \chi, V_{\mu}) = f^2 \pi \left( \frac{\chi}{f_{\sigma}} \right)^2 \text{Tr}[\hat{a} \gamma_{\mu} \hat{a}^\dagger] + af^2 \pi \left( \frac{\chi}{f_{\sigma}} \right)^2 \text{Tr}[\hat{a} \gamma_{\mu} \hat{a}^\dagger] + \frac{1}{2} g^2 \text{Tr}\left[ V_{\mu \nu} V^{\mu \nu} \right] + \frac{1}{2} \partial_{\mu} \chi \partial^{\mu} \chi \]

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

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

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

2020/12/09

Colloquium@ASU, UCAS
\[ \langle \theta^\mu \rangle = \langle \theta^{00} \rangle - \sum_i \langle \theta^{ii} \rangle = \epsilon - 3P \]

\[ = 4V(\langle \chi \rangle) - \langle \chi \rangle \frac{\partial V(\chi)}{\partial \chi} \bigg|_{\chi = \langle \chi \rangle} \]

\[ m_N^* = h\chi. \]

Going toward the DLFP with the $\rho$ 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.

In GNEFT, the TEMT is given solely by the dilaton condensate.
IV、The pseudoconformal model of dense nuclear matter

Implement topology transition to EoS

Hadron properties have different scales in $n < n_{1/2}$ and $n > n_{1/2}$

Different scaling behavior: $\Phi_I$ and $\Phi_{II}$

Imbed the quantitative conclusion to bsHLS

Beyond mean field

Calculate $V_{low k}$

EoS for nuclear matter with IDD

$\Phi_I$: Predictions agree with the nuclear matter at low density.
$\Phi_{II}$: Density independent.

IV、The pseudoconformal model of dense nuclear matter

\[ E_0/A = A_I \left( \frac{n}{n_0} \right) + B_I \left( \frac{n}{n_0} \right)^{\alpha I} \]

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

Fitted function

PC Prediction
The pseudoconformal model of dense nuclear matter

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

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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prediction</th>
<th>Empirical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_0$</td>
<td>0.161</td>
<td>0.16 ± 0.01 [9]</td>
</tr>
<tr>
<td>B.E.</td>
<td>16.7</td>
<td>16.0 ± 1.0 [9]</td>
</tr>
<tr>
<td>$E_{sym}(n_0)$</td>
<td>30.2</td>
<td>31.7 ± 3.2 [10]</td>
</tr>
<tr>
<td>$E_{sym}(2n_0)$</td>
<td>56.4</td>
<td>46.9 ± 10.1 [11]; 40.2 ± 12.8 [12]</td>
</tr>
<tr>
<td>$L(n_0)$</td>
<td>67.8</td>
<td>58.9 ± 16 [11]; 58.7 ± 28.1 [10]</td>
</tr>
<tr>
<td>$K_0$</td>
<td>250.0</td>
<td>230 ± 20 [13]</td>
</tr>
</tbody>
</table>
IV、The pseudoconformal model of dense nuclear matter

\[
\frac{\partial}{\partial n} \langle \theta^\mu \rangle = \frac{\partial \varepsilon(n)}{\partial n} (1 - 3v_s^2) = 0
\]

\[
v_s^2/c^2 = \frac{\partial P(n)}{\partial n} / \frac{\partial \varepsilon(n)}{\partial n}
\]

- 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.

A feature NOT shared by ANY other models or theories in the field of nuclear matter.
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
Accommodate massive star $\geq 2.0 \ M_{solar}$

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

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

Agree with the constraints
V. Predictions of the pseudoconformal model

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

\[ \tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4 \Lambda_1 + (m_2 + 12m_1)m_2^4 \Lambda_2}{(m_1 + m_2)^5} \]
V、Predictions of the pseudoconformal model

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We do NOT agree

YLM & M. Rho, 2006.14173

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.

FIG. 2. Comparison of $(P/\epsilon)$ 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.
Estimate the location of $n_{1/2}$ using GWs emitted from BNS merger
VI. Summary and discussions

Hidden topology

Quark-hadron continuity/CCP

PCM for DM

Hidden symmetries

$T^\mu_\mu \neq 0; \nu_s \to 1/\sqrt{3}$

Stand for the test from both nuclear physics and astrophysics

Accommodates massive NSs up to $2.23M_{\odot}$. 
Is this pseudo-conformal structure at odds with Nature?

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

Constraint to: $2.0n_0 \leq \frac{n_1}{2} < 4.0n_0$
Thank you for your attention!

Comments are welcome!