Dilatons for Dense Hadronic Matter

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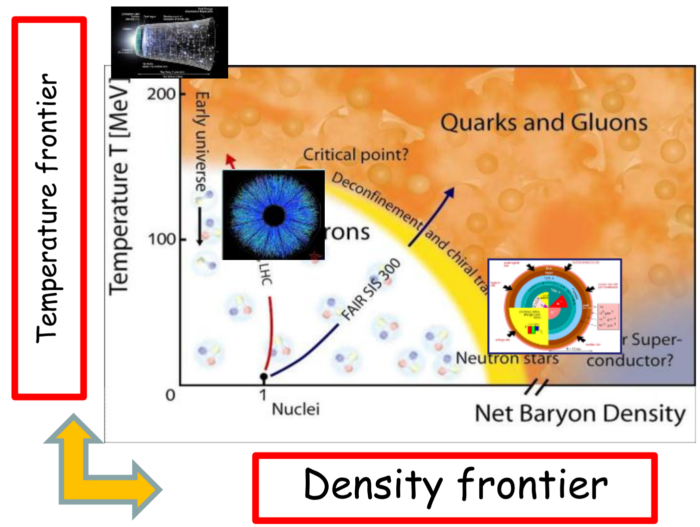
I. Introduction

Manifestations of symmetries of QCD in dense hadronic matter.

1. Chiral symmetry
2. Scale symmetry
3. Hidden local symmetry



Discovery of 125GeV scalar particle
at LHC

Walking Technicolor

SSB of chiral symmetry
→ dilaton as GB

chiral dynamics at finite density

II. Freund –Nambu model

$$V(\psi,\phi) = V_a + V_b$$

$$\begin{aligned} V_a &= \frac{1}{2} f^2 \psi^2 \phi^2 \\ V_b &= \frac{\tau}{4}\left[\frac{\phi^2}{g^2} - \frac{1}{2}\phi^4 - \frac{1}{2g^4}\right] = \frac{\tau}{8g^4}(g^2\phi^2 - 1)^2 \end{aligned}$$

$$\chi = (g^2\phi^2 - 1)/(2g) \qquad \delta\chi = \epsilon(x\cdot\partial + 2)\chi + \frac{\epsilon}{g}$$

$$m_\psi^2 = f^2\phi_0^2, \qquad m_\chi^2 = \tau\phi_0^2$$

matter field   dilaton

(approximate) SSB of scale symmetry:
only the mass of Goldstone boson(dilaton) must be small while all other fields can be arbitrary.

Freund & Nambu, 1968; B. Zumino, 1970

Chiral quartet O(4)

$$\psi, \quad \phi \rightarrow \quad \phi_i, i = 1 - 4$$

$$\begin{aligned} V(\phi_i) &= \lambda(|\phi_i|^2 - v^2)^2 \\ &= \lambda(\pi^2 + \phi^4) + \lambda(\phi^2 - v^2)\pi^2 + \lambda v^2 \phi^2 \end{aligned}$$

$$\phi^2 = v^2$$

- SSB of SU(2) x SU(2) and scale symmetry
- masless pions and light dilaton

Explicit breaking of scale symmetry
→ SSB of chiral symmetry

- pion dynamics in nonlinear realization

$$\pi \qquad F_\pi$$

$$\mathcal{L}(\pi) = \frac{F_\pi}{4} Tr \partial_\mu U \partial^\mu U^\dagger + \ldots.$$

$$\Theta^\mu_\mu|_\pi \neq 0$$

- QCD with trace anomaly

$$\Theta^\mu_\mu|_{QCD} = \frac{\beta(g)}{2g} G^{\mu\nu} G_{\mu\nu}$$

chiral singlet scalar

$$V(\chi) = B\chi^4 \ln \frac{\chi}{\Lambda}$$

$$\Theta^\mu_\mu = -B^4 \chi^4$$

III. Dilaton in dense hadronic matter

Change of $<\chi>$ with baryon number density

Chiral symmetry: nonlinear → linear realization

$$\pi \quad \chi$$

(1) Effective theory for hadronic matter

$$N, \quad \rho, \ldots.$$

hidden local symmetry (HLS)

Harada & Yamawaki(01)

(2) Dilaton limit

Bean & van Kolk(94)

Sasaki,HKL,Paeng,Rho(11)

$$\Sigma \;=\; U\chi\sqrt{\kappa} = \xi_L^\dagger \xi_R \chi\sqrt{\kappa} = s + i\vec{\tau}\cdot\vec{\pi}$$

$< \chi > \to 0$ at higher density

$$\kappa \to 1 \qquad g_A - g_V \to 0 \qquad g_A \sim g_V \to 1$$

$$\begin{aligned}\mathcal{L} \;=\; & \bar{\mathcal{N}} i\partial\!\!\!/ \mathcal{N} - \frac{m_N}{2F_\pi}\bar{\mathcal{N}}\left[\Sigma + \Sigma^\dagger + \gamma_5\left(\Sigma - \Sigma^\dagger\right)\right]\mathcal{N} + \frac{1}{4}\mathrm{tr}\left[\partial_\mu\Sigma\cdot\partial^\mu\Sigma^\dagger\right] \\ & + \frac{a}{2i}\mathrm{tr}\left[\left(\Sigma\partial_\mu\Sigma^\dagger + \Sigma^\dagger\partial_\mu\Sigma\right)V^\mu\right] + \frac{a}{2}\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]\mathrm{tr}\left[V_\mu V^\mu\right] - \frac{1}{2g^2}\mathrm{tr}\left[V_{\mu\nu}V^{\mu\nu}\right] \\ & + \frac{m_s^2}{64F_\pi^2}\left(\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 - \frac{m_s^2}{32F_\pi^2}\left(\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 \ln\left(\frac{\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]}{2F_\pi^2}\right),\end{aligned}$$

Suppression of vector meson –nucleon coulping

$$g_{\rho N}^2 = g^2(1-g_V)^2 \to 0$$

IV. EoS of dense hadronic matter

(a) Suppression of rho-mediated tensor force

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

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

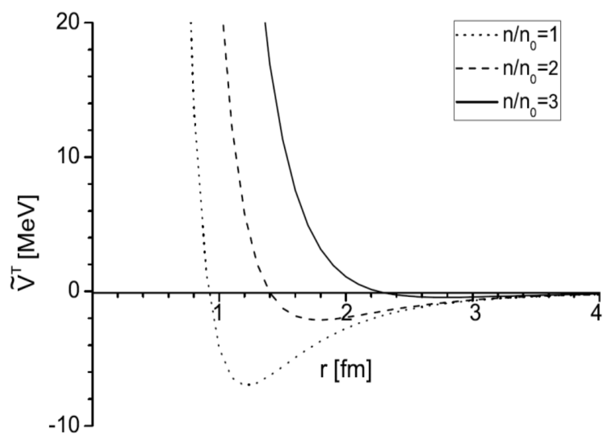


FIG. 1: Sum of π and ρ tensor forces $\tilde{V}^T \equiv (\tau_1 \cdot \tau_2 S_{12})^{-1}(V_\pi^T + V_\rho^T)$ in units of MeV for densities n/n_0 =1, 2 and 3 with the "old scaling," $\Phi \approx 1 - 0.15n/n_0$ and $R \approx 1$ for all n.

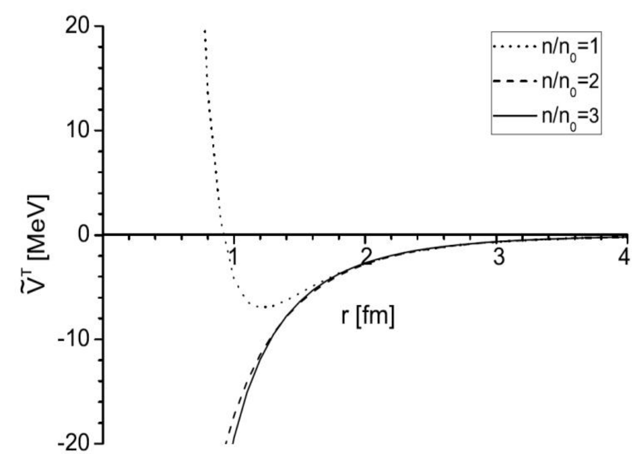


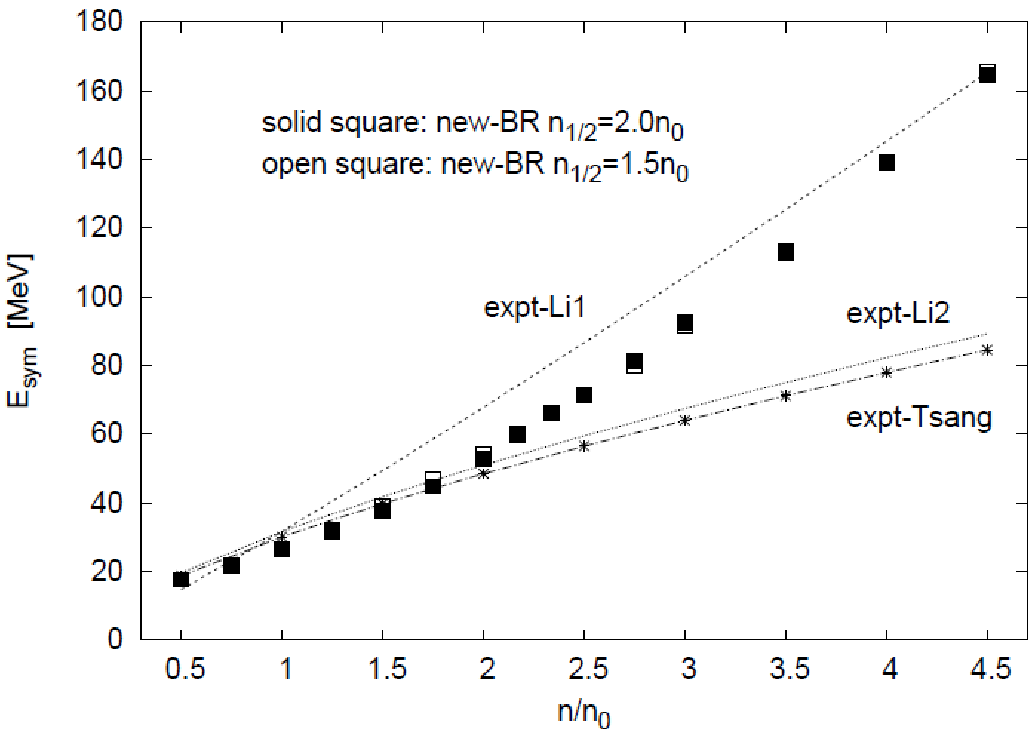
FIG. 2: The same as Fig. 1 with the "new scaling," $\Phi \approx 1 - 0.15n/n_0$ with $R \approx 1$ for $n < n_{1/2}$ and $R \approx \Phi^2$ for $n > n_{1/2}$, assuming $n_0 < n_{1/2} < 2n_0$.

stronger attraction in n-p channel

→ stiffer symmetry energy   S(n)

$$S(n) = E(n, n_p = 0) - E(n, n_n = n_p)$$

Dong, Kuo, HKL,Machleidt, Rho(12)



(b) Baryonic matter : skyrmion on the lattice

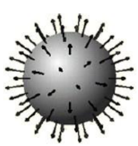
single hedgehog skyrmion

1960, T. H. R. Skyrme

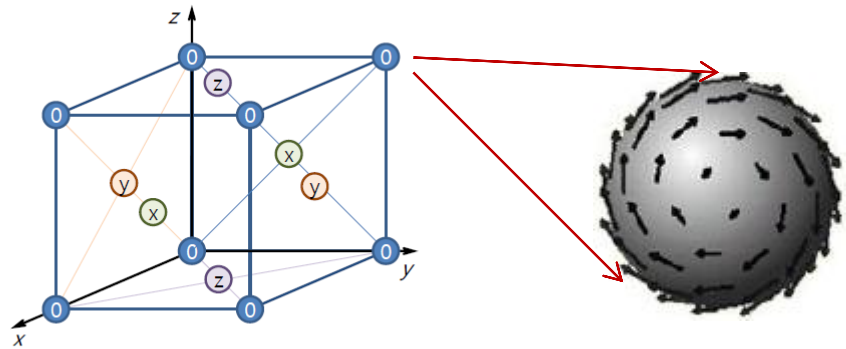
$$\mathcal{L} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) + \frac{1}{32e^2}\,\mathrm{Tr}\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

$U(\bar{x})$: mapping from R^3-{∞}$=S^3$ to $SU(2)=S^3$

→ topological soliton



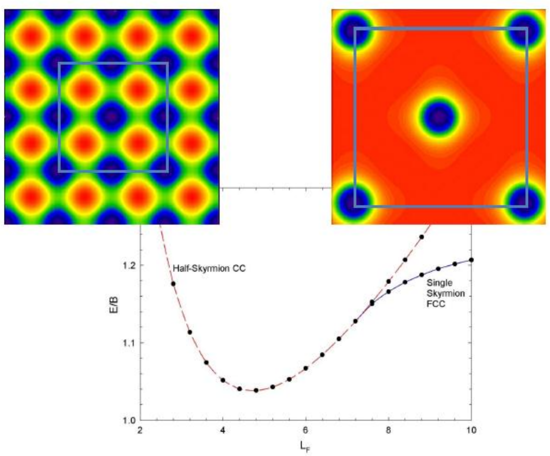
R ~ 1 f m
M ~ 1.5 GeV → baryon ?



Park (2011),

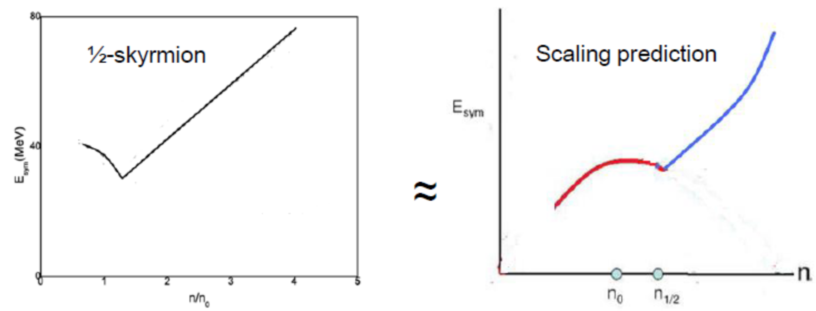
Phase change:
Skyrmion matter → half Skyrmion matter

Skyrmion Crystal



Goldhaber and Manton(1987)
Byung-yoon Park et al. (2003), …

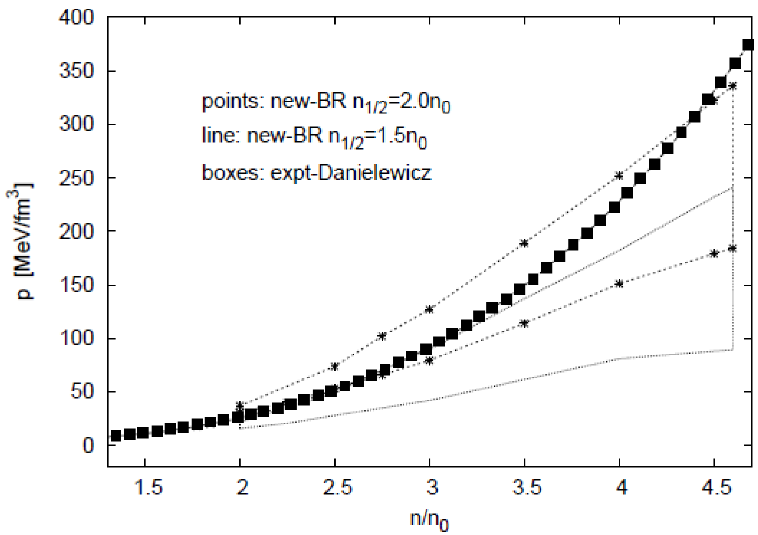
Effect on symmetry energy

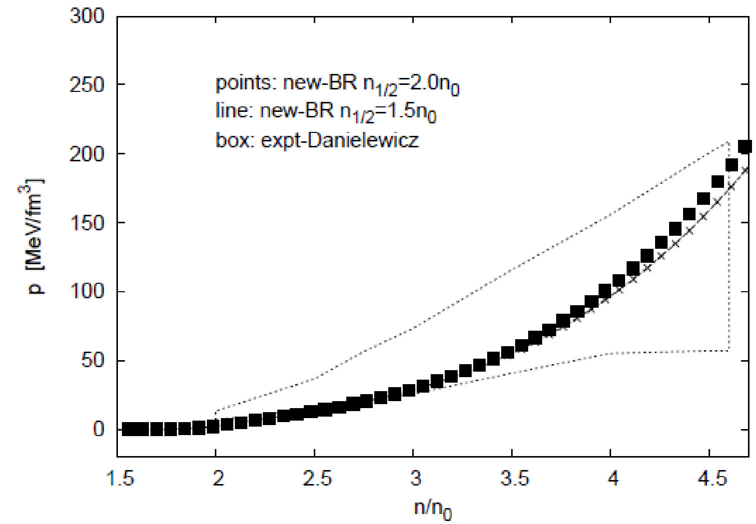


HKL, Park and Rho(2010)

(c) EoS with new scaling

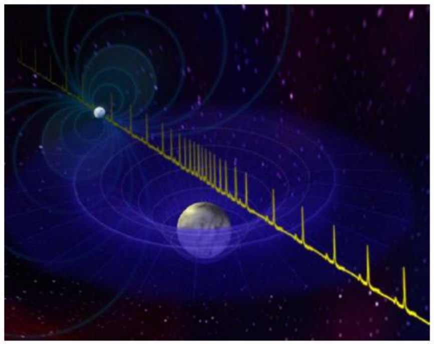
Dong, Kuo, HKL, Machleidt, Rho, 1207.0429



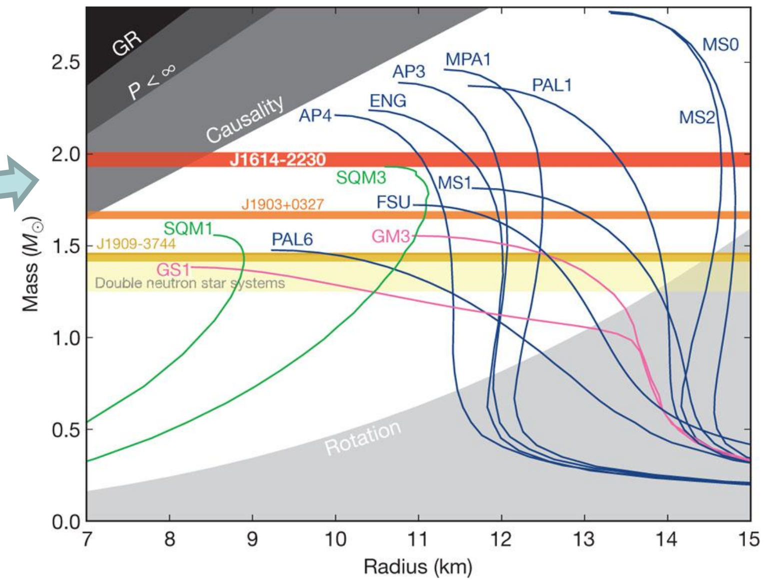


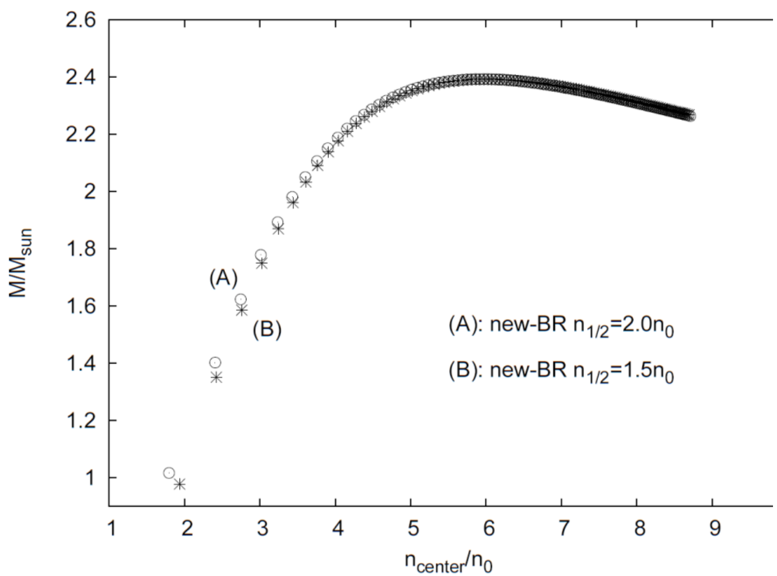
Stiffer EoS for massive neutron star

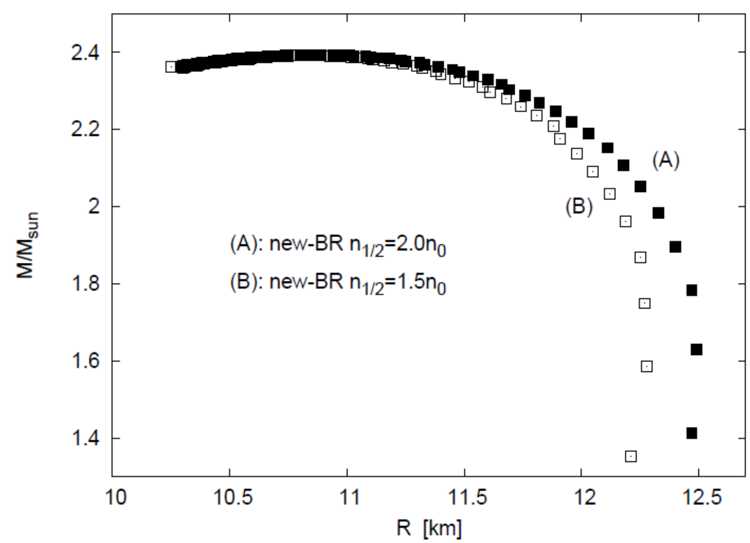
massive neutron star



PSR J1614-2230
$(1.97 \pm 0.04) M_{\odot}$







V. Summary

- Effective theory with chiral and scale symmetry.

  - pion, vector meson, nucleon, dilaton
  - vector mesons introduced through hidden local symmetry (HLS)

- Dilaton → density dependence of hadronic natter
  - skyrmion matter
  - dialton limit

- Stiffer symmetry energy and EoS for star matter

  astrophysical observation : PSR J1614-2230 : $(1.97 \pm 0.04) M_{\odot}$

  new RIB machines, advanced LIGO