What can Skyrme Model Predict for Dense Nuclear Matter?

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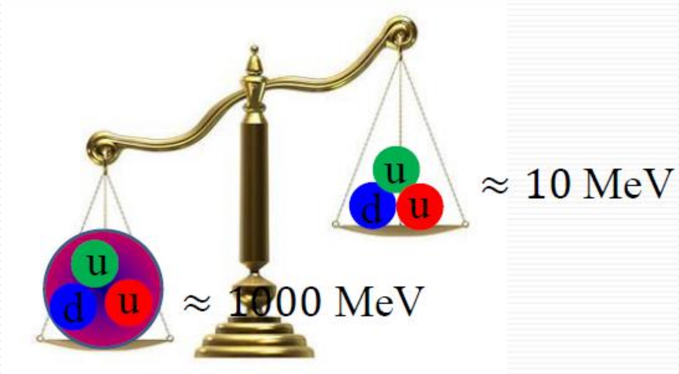
Talk given @ QCD Phase Structure III workshop, June 6-9, 2016, Wuhan, China.

Some challenges in particle and nuclear physics

Where is the nucleon mass from ?



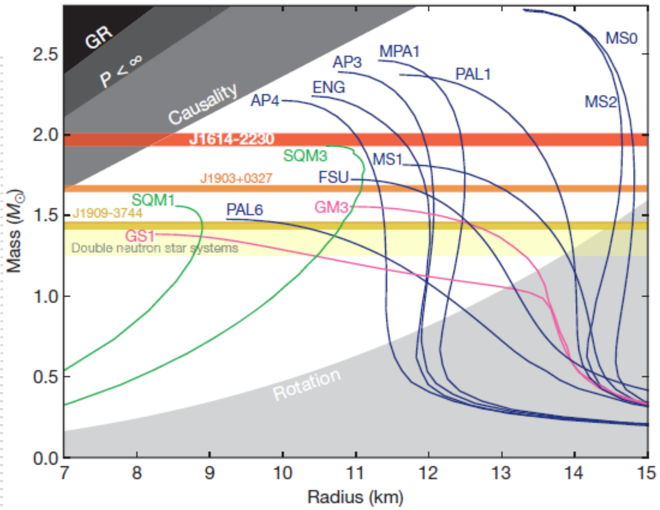
In marked contrast to the next scale hadron, nucleus. The mass of a nucleus of mass number A is given almost entirely, say, ~98%, by the sum of the masses of A nucleons.

- Mechanism of χSSB. However, difficult to explore in free space. Nuclear matter is a good environment.

EoS of nuclear matter ?

A two-solar-mass neutron star measured using Shapiro delay Nature, vol.467(2010), 1081

precision[8,9]. Here we present radio timing observations of the binary millisecond pulsar J1614-2230[10,11] that show a strong Shapiro delay signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_{\odot}$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_{\odot}$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks[12].



Effective theory point of view in nuclear physics

"What is quantum field theory, and what did we think it is?" hep-th/9702027.

- When you use QFT to study low-energy phenomena, any assumption satisfying Lorentz invariance or QM or cluster decomposition could NOT be wrong, provided you don't say specifically what the Lagr. is.
- As long as you let it be the most general possible Lagr. consistent with the symmetries of the theory, you're simply writing down the most general theory you could possibly write down.

--- Weinberg's Folk Theorem

Approaches to dense baryonic system via W theorem

1. Put baryon fields as explicit degrees of freedom, coupled to meson fields via Weinberg (e.g., nucl-EFT) $\rightarrow$ chiral perturbation theory (χPT).

2. Baryons as skyrmions: multi-skyrmion system (e.g., skyrmion crystal).

Effective field theory of nuclear physics

$$\mathcal{L} = \bar{\psi}\left(i\gamma_\mu\partial^\mu - m\right)\psi$$

$$\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) + \frac{1}{2}\left(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - m_\sigma^2\vec{\delta}^2\right)$$

$$-\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} - \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu$$

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$g_\sigma\bar{\psi}\sigma\psi + g_\delta\bar{\psi}\vec{\tau}\vec{\delta}\psi$$

$$-g_\omega\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho\bar{\psi}\gamma_\mu\vec{\tau}\vec{\rho}^\mu\psi - e\bar{\psi}\gamma_\mu A^\mu\psi$$

With

Heavy-mesons

Without

$$\bar{\mathcal{L}} = \bar{\psi}(i\gamma\cdot\partial - m)\psi$$

$$-\frac{1}{2}\alpha_S(\hat{\rho})(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\hat{\rho})(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi) - \frac{1}{2}\alpha_{TV}(\hat{\rho})(\bar{\psi}\vec{\tau}\gamma^\mu\psi)(\bar{\psi}\vec{\tau}\gamma_\mu\psi)$$

$$-\frac{1}{2}\delta_S(\partial_\nu\bar{\psi}\psi)(\partial^\nu\bar{\psi}\psi) - e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi\ .$$

What has been accomplished

Pions: Interacting with the protons and neutrons subject to chiral symmetry with small symmetry breaking.
→ Do mean field/Derive KSDF from chiral Lagrangian
→ Present industry in nuclear physics.

Aim: To go from chiral Lagrangian to nuclear forces to nuclei to nuclear matter density (n_0) then to >> n_0 *e.g.*, 1.97 M_{sun} with density ~ $6n_0$.

Success: ~ 2000 nuclei with deviation ~ ½ MeV, up to ~ n_0 .
Price to pay: ~ 50 parameters.

Higher density: unknown, QCD uncontrollable.

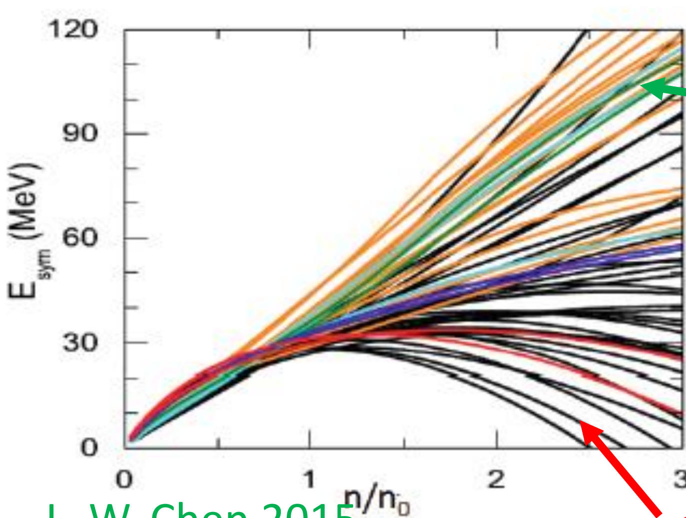
At high density it is *totally* wild

Example: “Symmetry energy”

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

$$\alpha = (n_n - n_p)/(n_n + n_p)$$

Wilderness at $n>n_0$



L. W. Chen 2015

“Very Stiff”

“Supersoft”

Even with hidden gauge symmetry things go wild!!

Enter topology
Skyrmion

A non-linear field theory

BY T. H. R. SKYRME

Atomic Energy Research Establishment, Harwell

(*Communicated by Sir Basil Schonland, F.R.S.—Received* 5 *September* 1960)

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

f_π : pion decay constant

e : Skyrme parameter

EDITORIALS

NATURE|Vol 465|17 June 2010

Skyrmion makeover

Celebrating the treasures of topological twists.

After re-emerging from the depths of obscurity several times over, the spotlight is back on skyrmions And a reader can only wonder what other neglected gems of mathematical ideas are tucked away in the literature, awaiting a creative scientist to recognize their value to the physical world? ■

Vol 465 | 17 June 2010 | doi:10.1038/nature09124 nature

LETTERS

Real-space observation of a two-dimensional skyrmion crystal

X. Z. Yu[1,2], Y. Onose[2,3], N. Kanazawa[3], J. H. Park[4], J. H. Han[4], Y. Matsui[1], N. Nagaosa[3,5] & Y. Tokura[2,3,5]

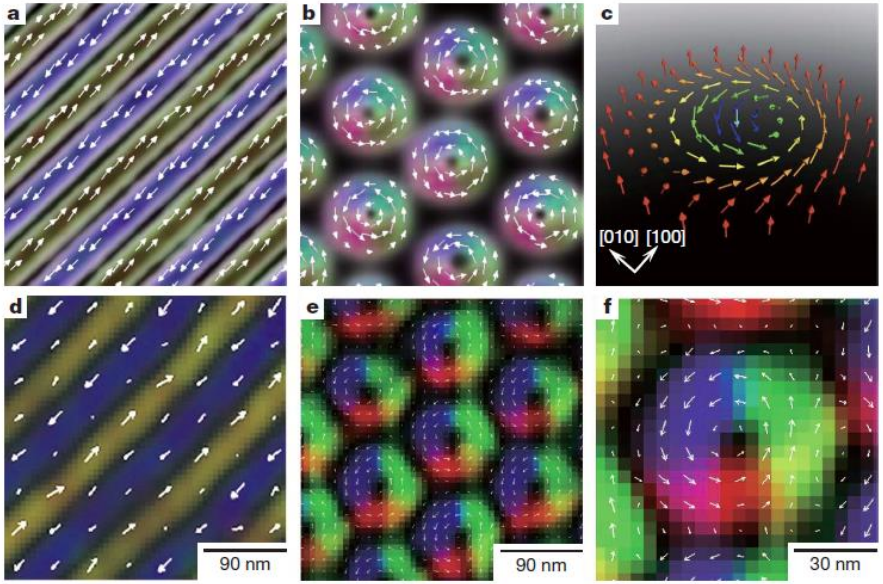


Figure 1 | Topological spin textures in the helical magnet $Fe_{0.5}Co_{0.5}Si$. **a**, **b**, Helical (**a**) and skyrmion (**b**) structures predicted by Monte Carlo simulation. **c**, Schematic of the spin configuration in a skyrmion. **d–f**, The experimentally observed real-space images of the spin texture, represented by the lateral magnetization distribution as obtained by TIE analysis of the

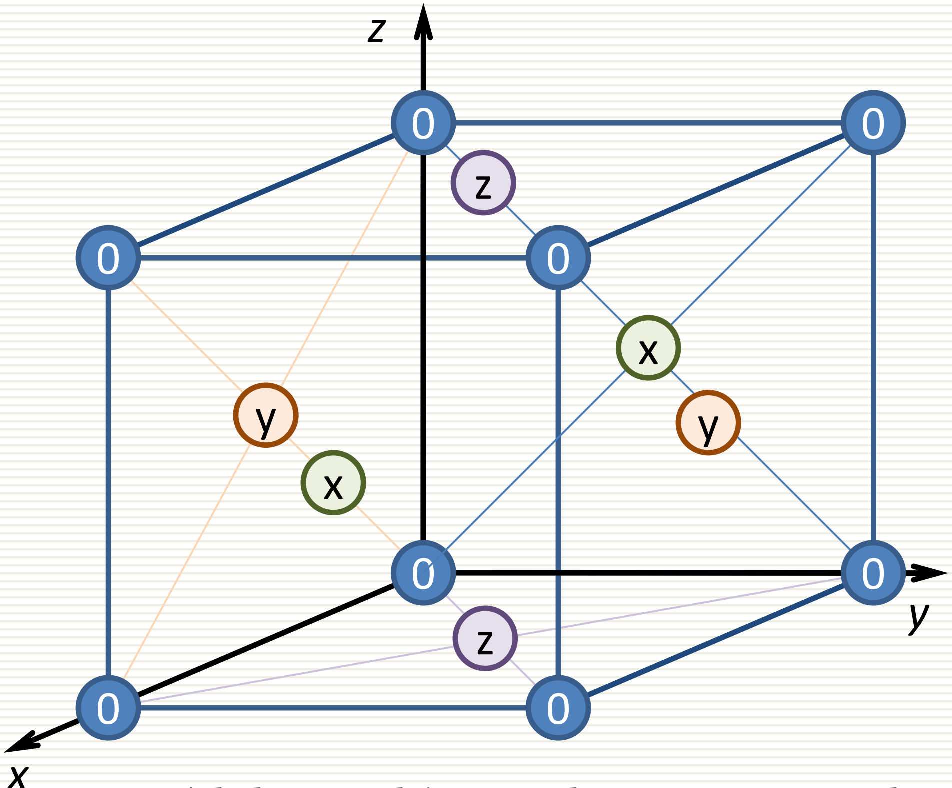
What χPT cannot do: Topology
Skyrmions on Crystal

- Topology changes at high density, with the skyrmion fractionizing into ½- skyrmions.
- Drastic effect on the nuclear tensor forces.
- Parity-doublet symmetry "emerges" at high density: Nucleon mass in medium has two components, i.e.,

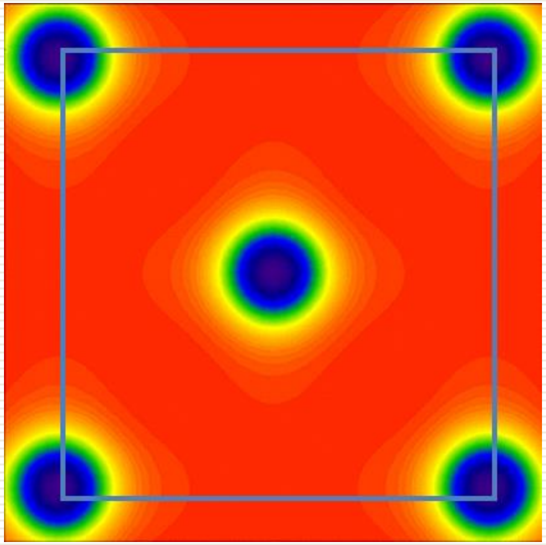
$$m^*_N = m_0 + \Delta(\Sigma^*) \rightarrow m_0 \text{ as } \Sigma^* \rightarrow 0.$$

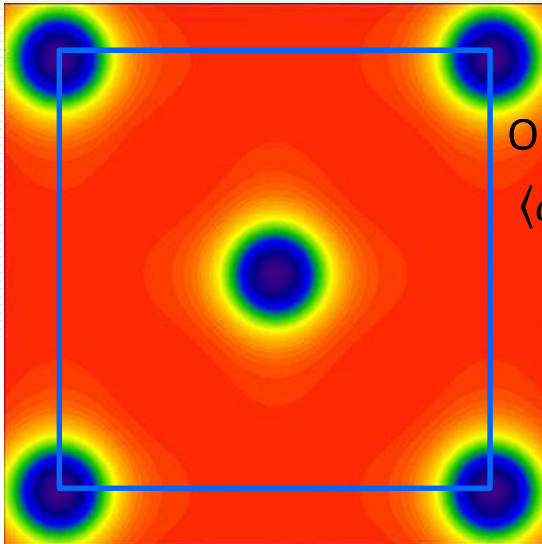
Skyrmion matter from crystal

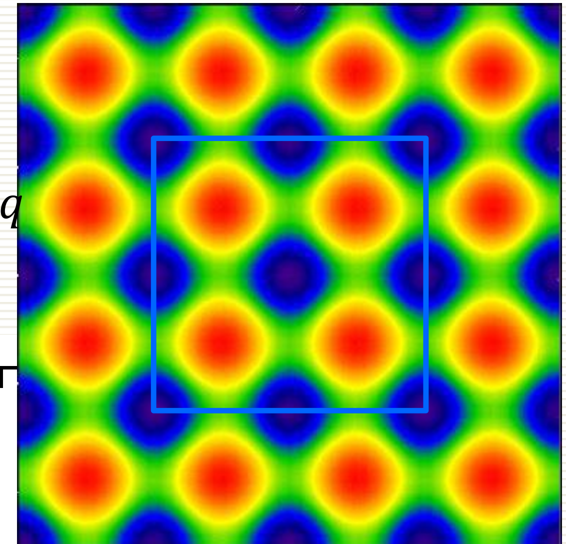
- Originally: I. Klebanov, Nucl. Phys. B262(1985) 133-143. CC
- Kugler & Shtrikman, PLB208 (1988) 491; PRD40 (1989) 3421.



Widely used in condense matter physics

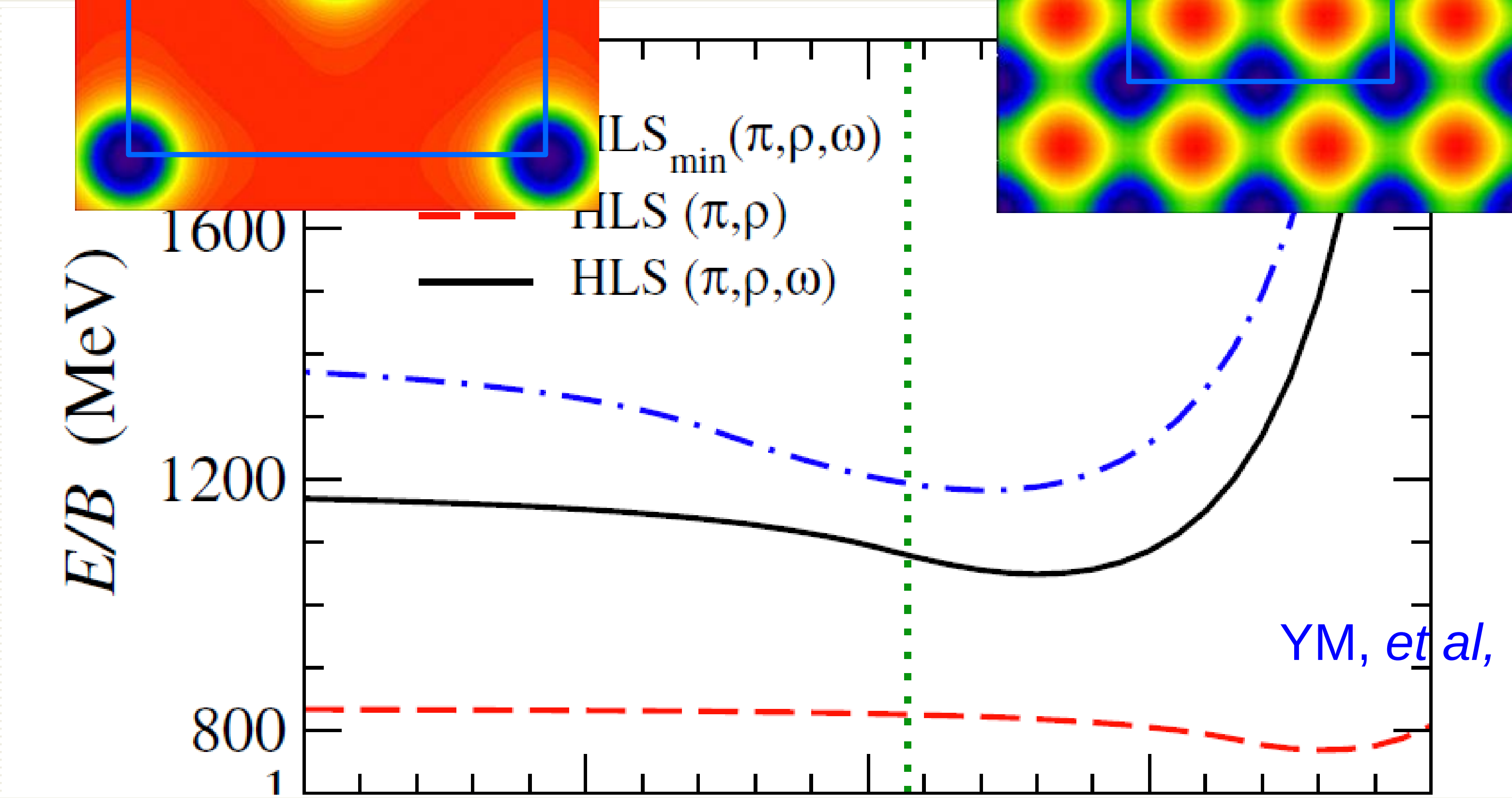






Order parameter:

$$\langle\sigma\rangle = \frac{1}{(2L)^3}\int_0^{2L} d^3x\, \bar{q}q$$



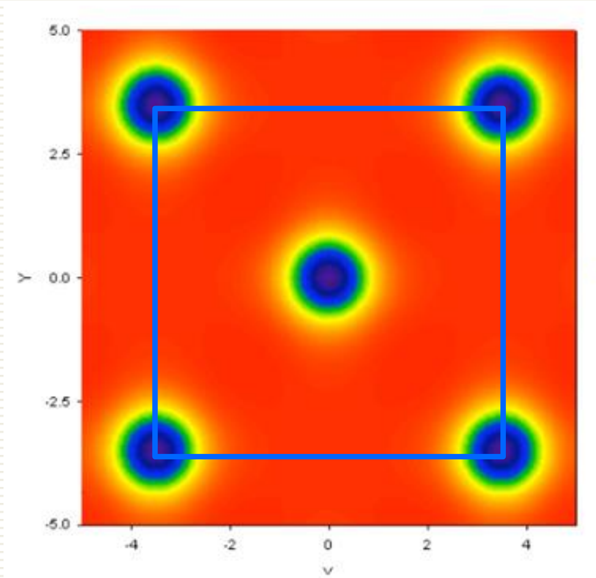
YM, *et al*, 2013

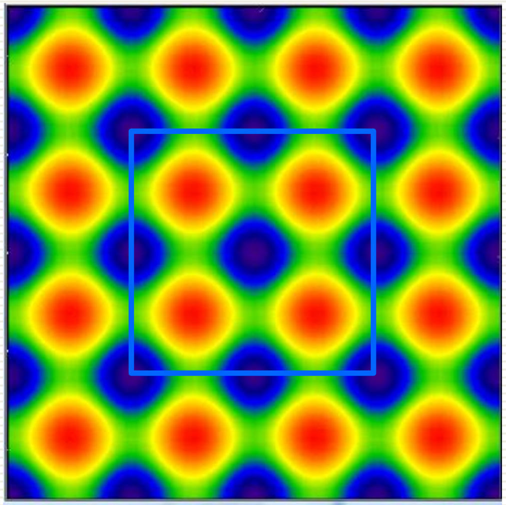
Appearance of ½-skyrmions is robust

$\mathbf{U = e^{2i\pi/f_\pi}}$ ⟶ skyrmion

$\mathbf{U} = \xi_{\mathbf{L}}\xi_{\mathbf{R}}^{\dagger}, \quad \xi_{\mathbf{L,R}}$ ⟶ half-skyrmion

$$\mathcal{L}_\xi = \frac{f_\pi^2}{2}\{\mathrm{Tr}\left[|D_\mu \xi_L|^2 + |D_\mu \xi_R|^2\right]$$



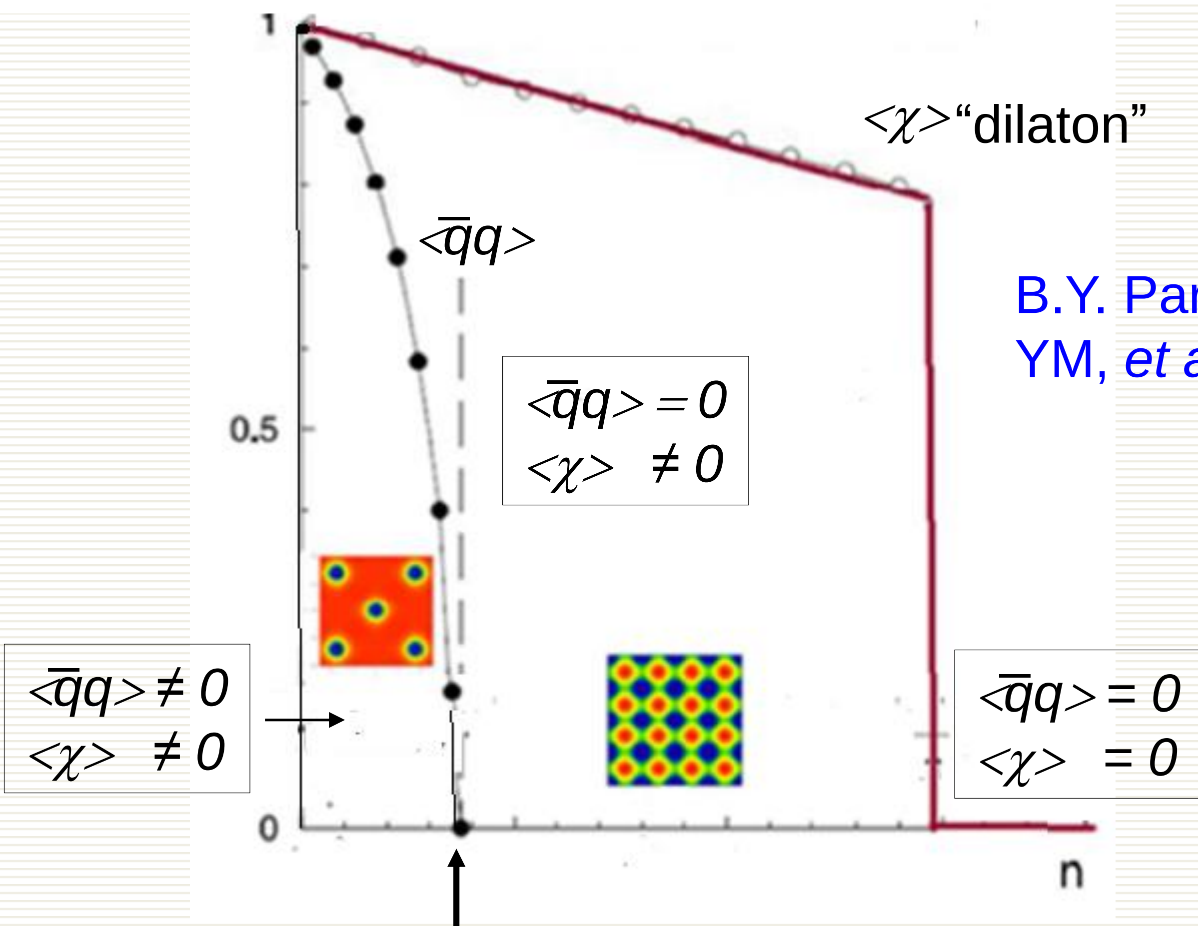


skyrmions

Half-skyrmions

Topology change = Phase Change

$$\mathcal{L}_{\text{dHLS-I}} = \mathcal{L}_{(2)}^{\text{dHLS-I}} + \mathcal{L}_{(4)}^{\text{HLS}} + \mathcal{L}_{\text{anom}}^{\text{HLS}} + \mathcal{L}_{\text{dilaton}},$$



B.Y. Park, *et al*, 2004
YM, *et al*, 2013

Estimate: $n_{1/2} \sim (1.3 – 2)\, n_0$

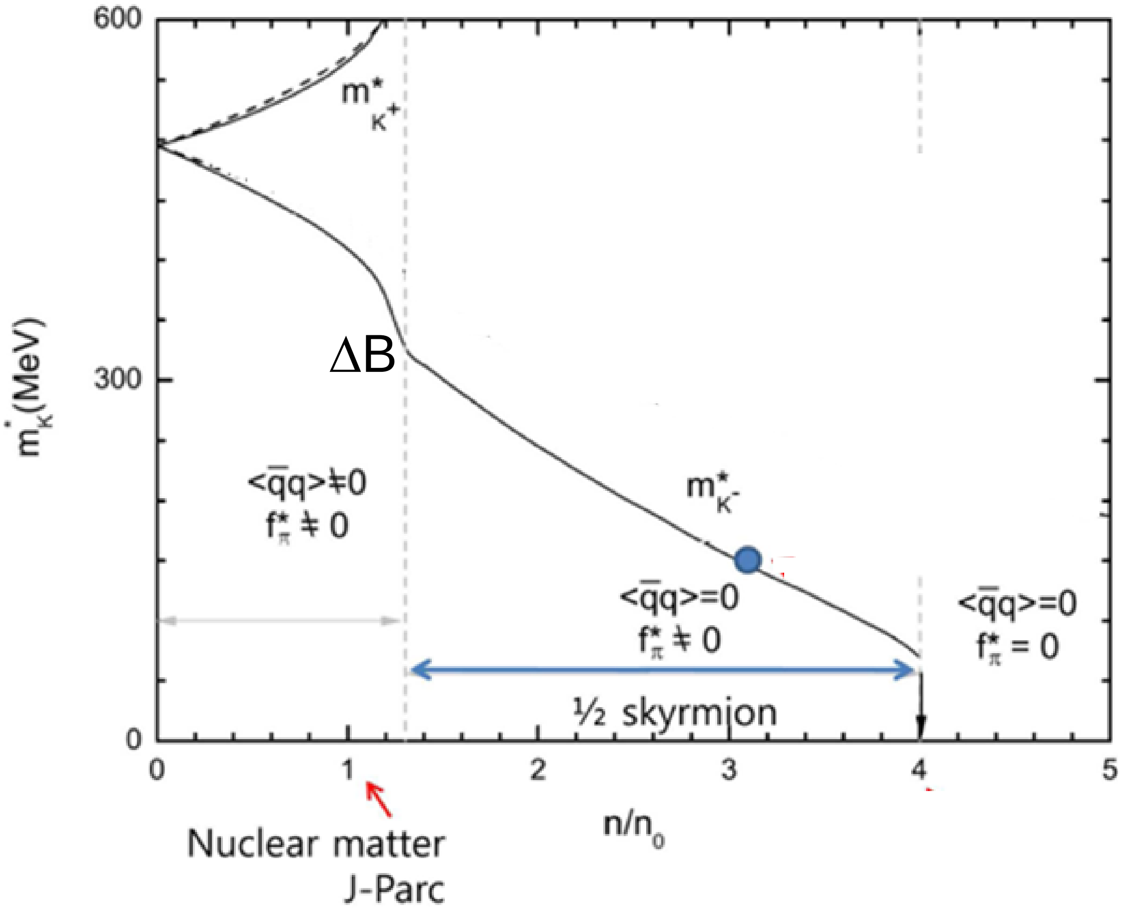
Predictions in the skyrmion approach

Skyrmions on crystal make certain predictions that are not in standard nuclear field theory based on chiral symmetry. We would like to see whether these predictions are

- Trustworthy (or falsifiable) and
- presaging new physics.

Prediction-I

Anti-kaon "roaming" through ½-skyrmion matter: Wess-Zumino term



B.-Y. Park, *et al,* 2010
YM, *et al*, in preparation

△B ~ 100 MeV

- **Issues:**

(1) Dense kaon nuclei

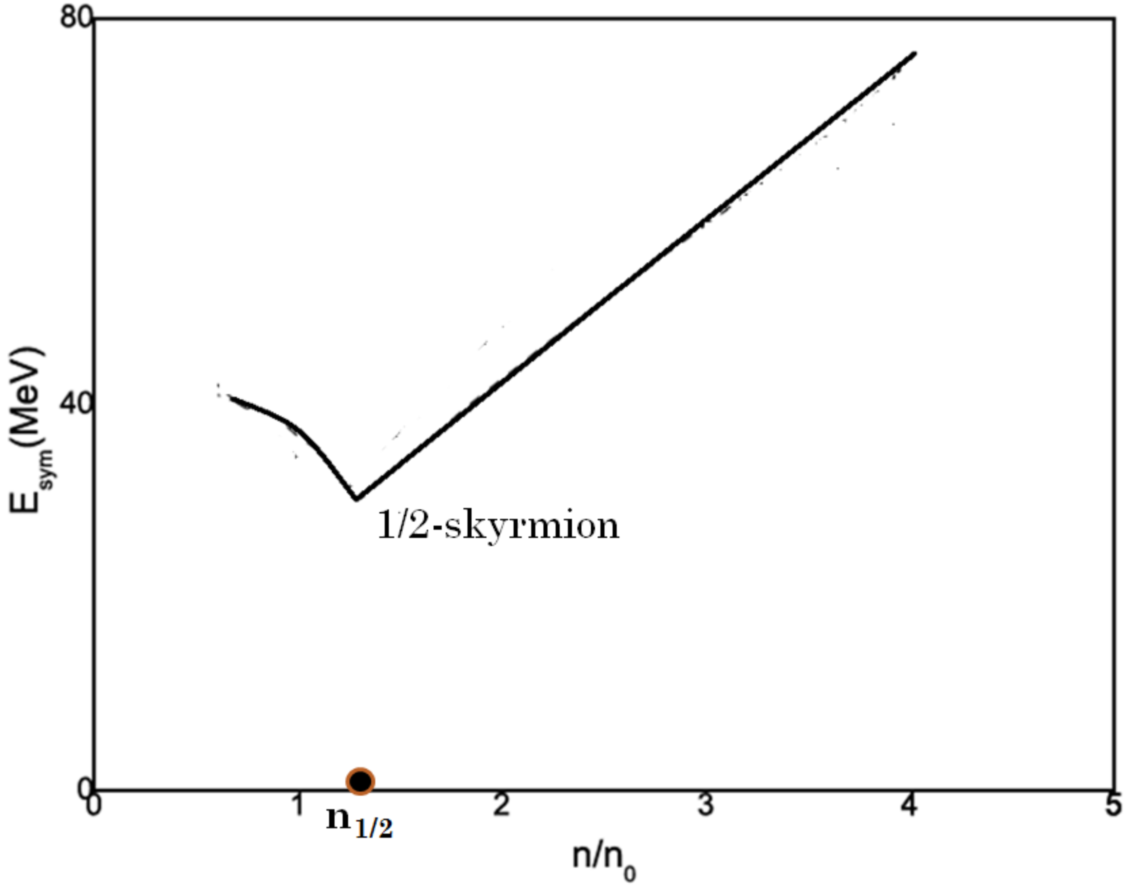
(2) 1.97 M_{solar} star.

Prediction-II

Nuclear symmetry energy

$$E(n,\delta) = E(n,0) + E_{sym}\delta^2 + \mathcal{O}(\delta^4)$$

$$\delta = (n_p - n_n)/(n_n + n_p)$$



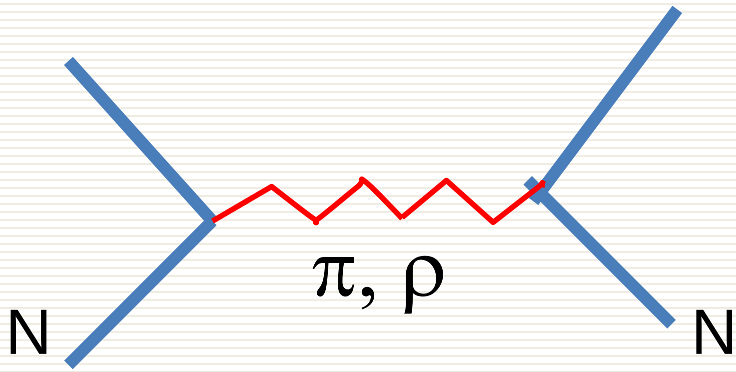
$$E_{sym} = \frac{1}{8\lambda_I} \propto N_c^{-1}$$

Is the cusp real?

Answer: Yes

E_{sym} is dominated by the tensor forces

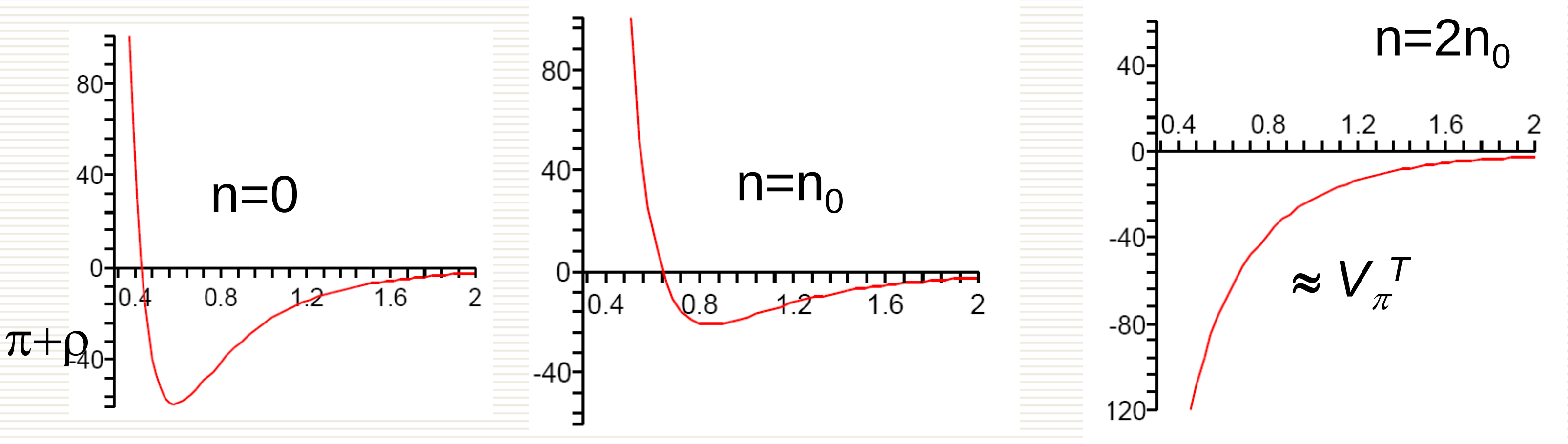
G.E. Brown and R. Machleidt 1994 … A. Carbone et al 2013



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

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

Tensor forces are drastically modified in the ½-skyrmion phase



Above $n_{1/2,}$ the ρ tensor gets "killed,"

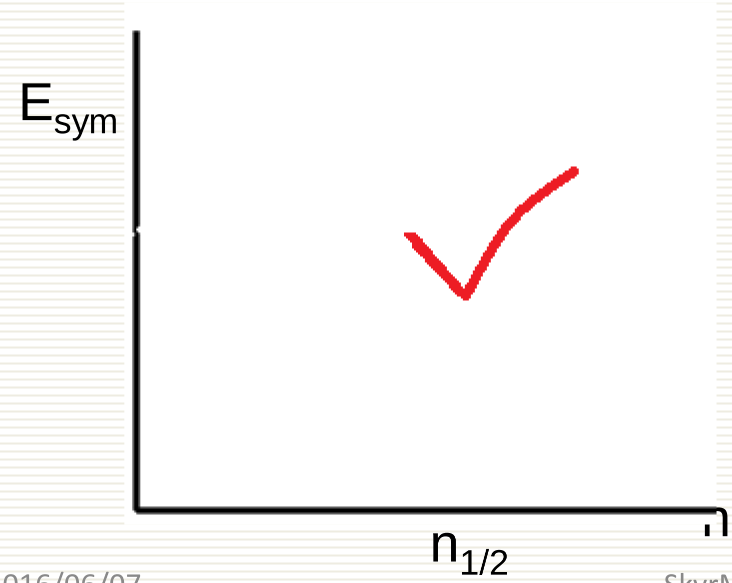
Has a significant effect on:

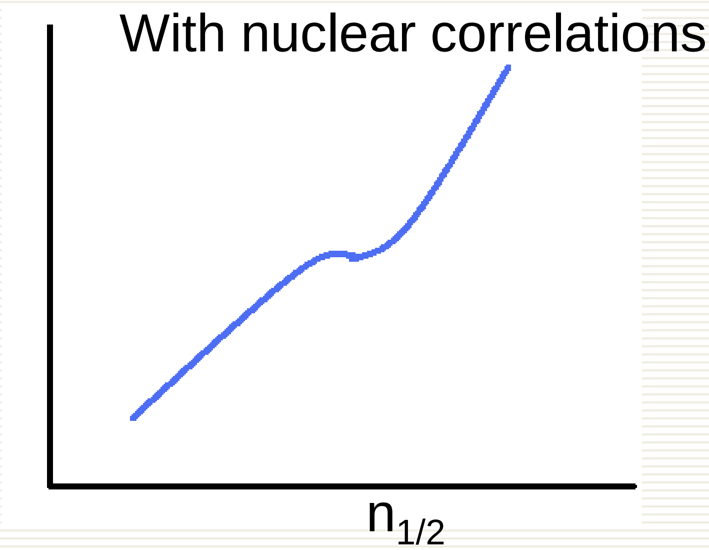
- Beta decay of C-14; W.G. Paeng, YM and T. T. S. Kuo, in preparation;
- 2νββ and 0νββ of nuclei, YM and T. T. S. Kuo, in preparation.

Symmetry Energy

"Symmetry energy is dominated by the tensor forces":

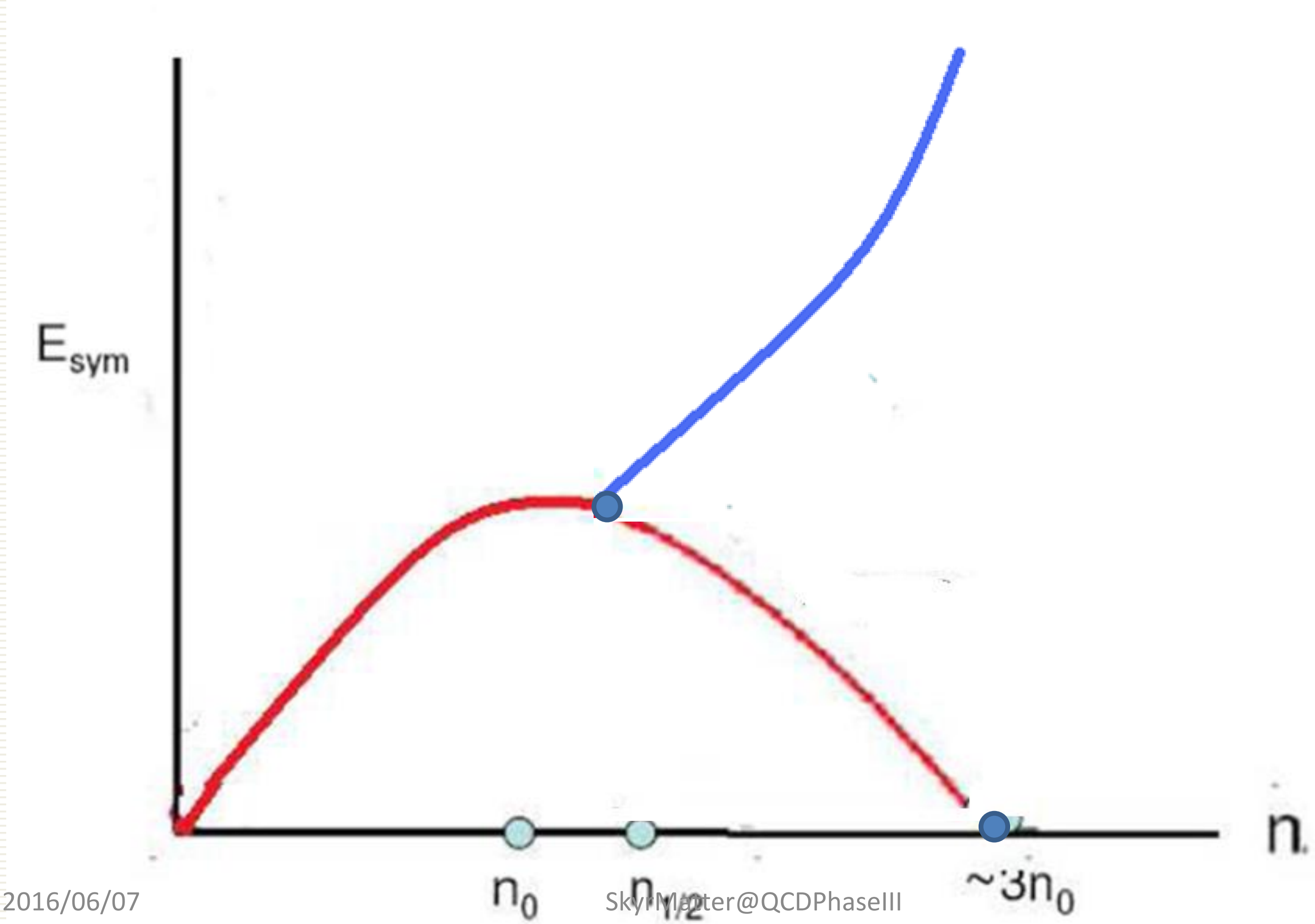
Skyrmion $\Longleftrightarrow$ $E_{sym} \propto \frac{|V_T|^2}{\overline{E}}$



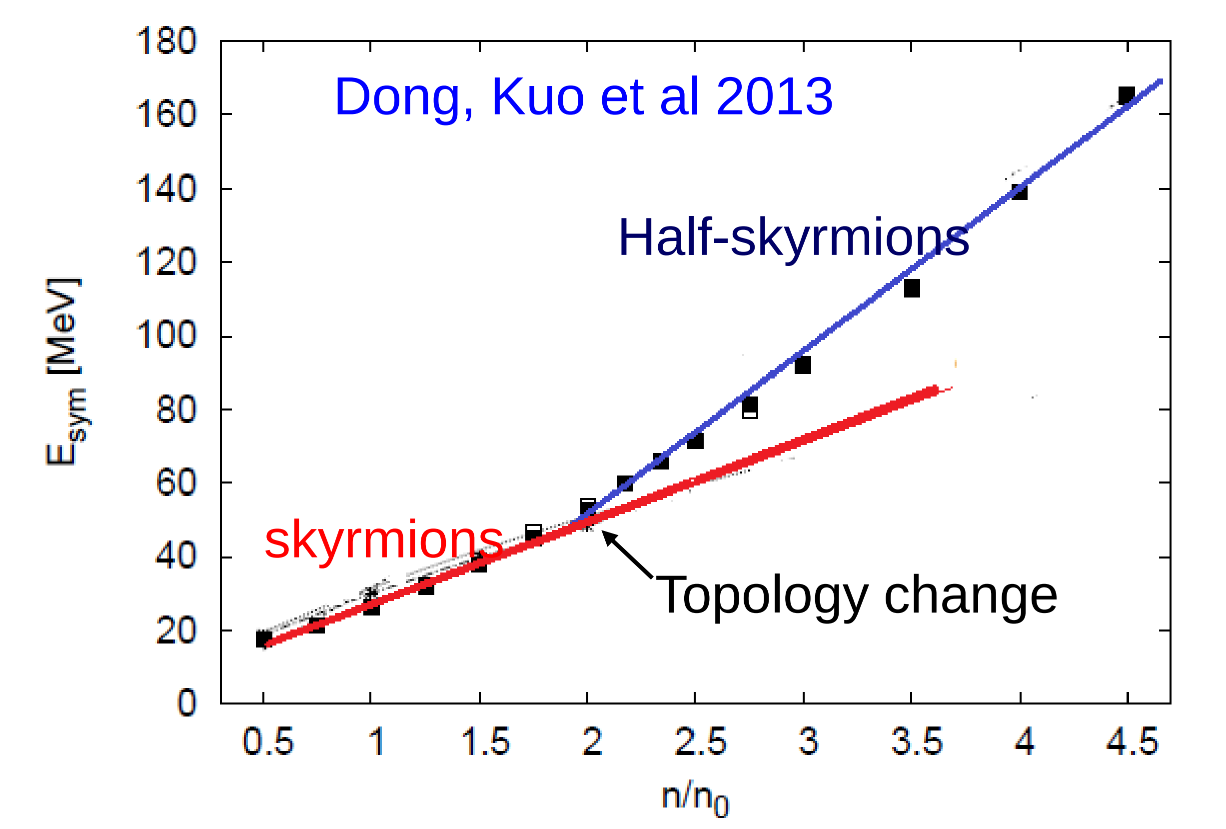


Predicts

How the ½-skyrmions act on E_{sym}



“Embed” in many-body correlations
To go above n_0

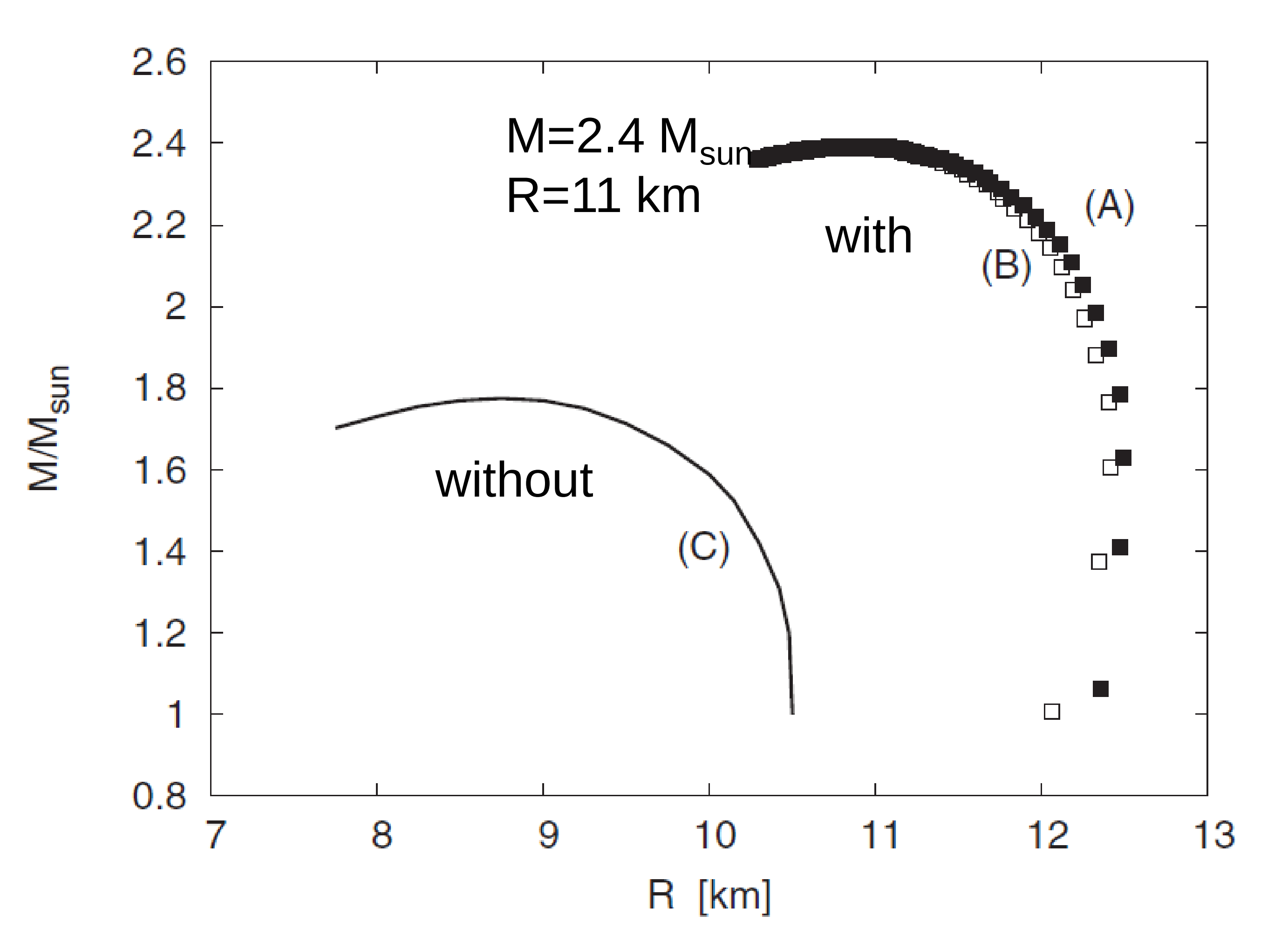


Consistent with $M_\odot$ star

If correct, signal for something new in hadron physics.

Hatsuda et al 2013

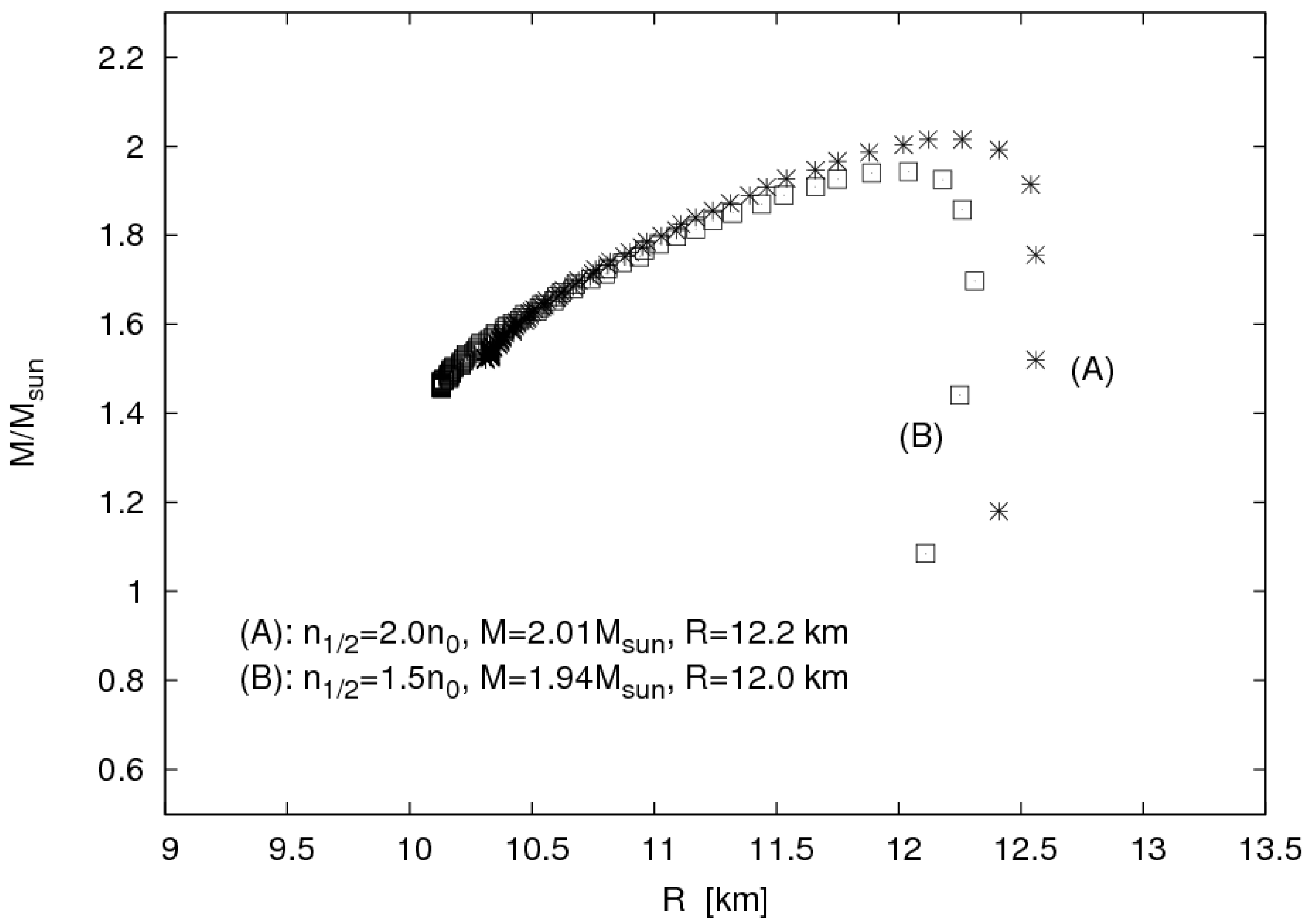
Compact stars w/wo topology change



Observations: M=1.97±0.04, 2.01±0.04 M_{sun} , R~ (11-15) km

Compact Star $M_{\odot}^{max}$ vs. R

Dong, Kuo, Lee, Rho 2012



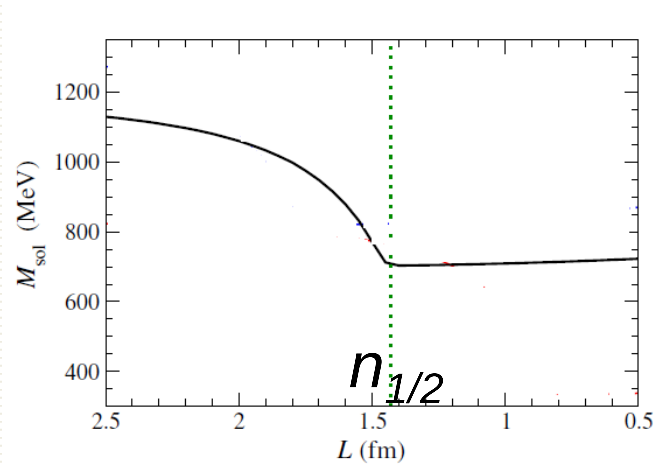
Shapiro measure
$M = 1.97 \pm 0.04\ M_{\odot}$
$R = 11\text{-}15$ km

Prediction – III

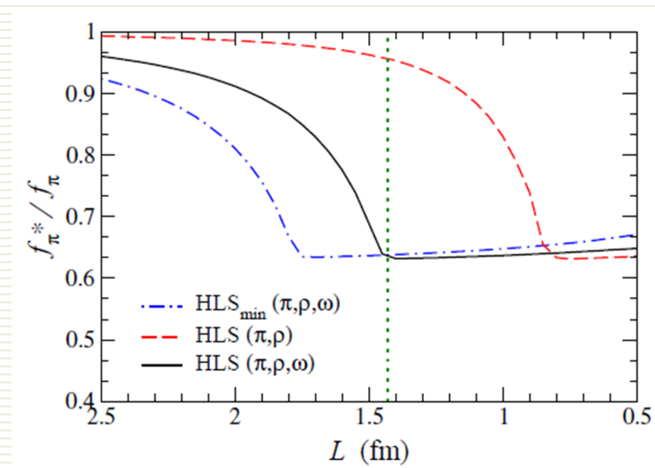
Origin nucleon mass and pattern of χSB

- "Emergent" parity-doublet symmetry for nucleons: $m^* = m_0 + \Delta(\Sigma^*)$

YM *et, al,* 2013



m_0



- In the half-skyrmion phase, chiral symmetry is broken due to the multi-quark condensate. Kogan-Kovner-Shifman's mechanism of χSB.

Prediction – IV

Inhomogeneous quark condensates

M. Rho, H. K. Lee, YM and M. Harada, PRD(2015).

1. Local chiral symmetry breaking (dense effect):

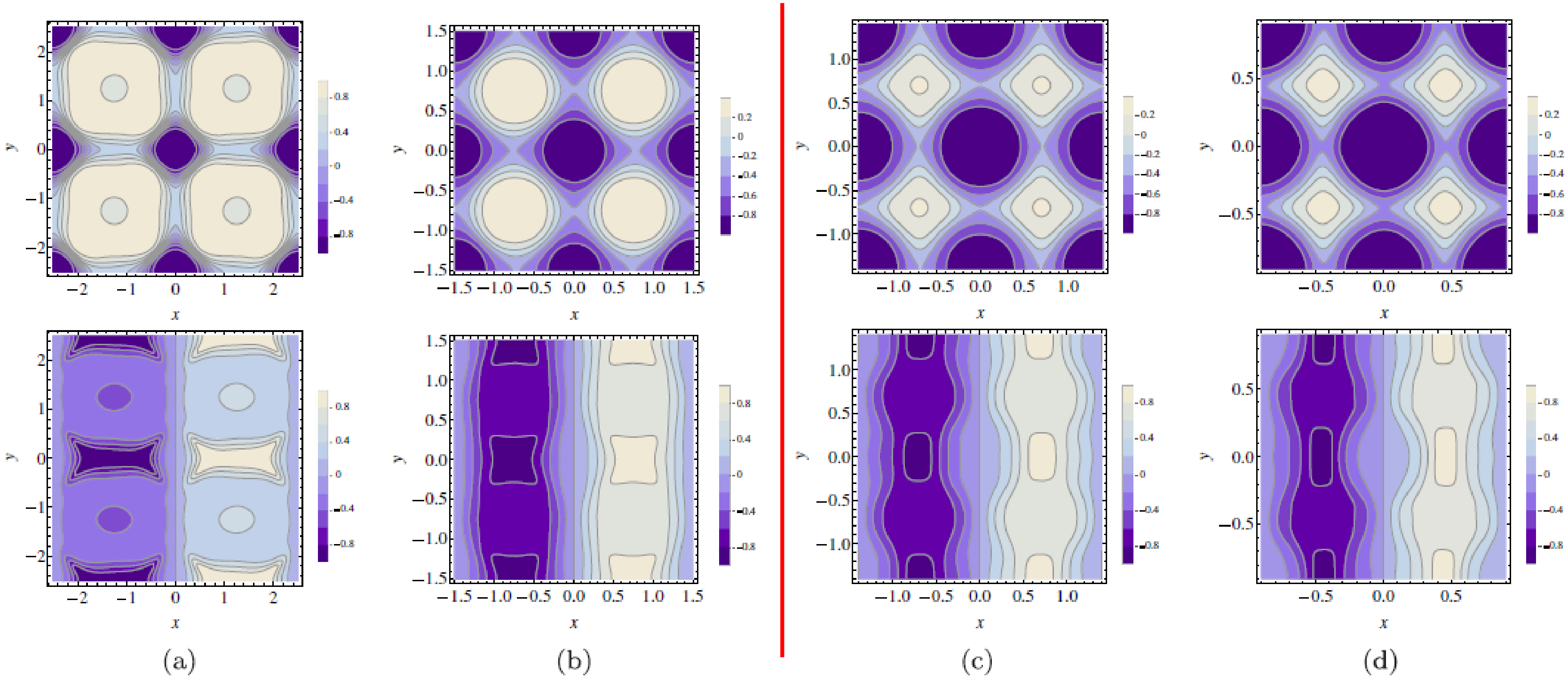


FIG. 1 (color online). The density effect on $\phi_0(x, y, 0)$ (first row) and $\phi_1(x, y, 0)$ (second row). The half-Skyrmion phase appears at $L = 1.45$ fm. (a) $L = 2.5$ fm. (b) $L = 1.5$ fm. (c) $L = 1.4$ fm. (d)$L = 0.9$ fm.

Prediction – IV

Parity doublet of heavy-light mesons

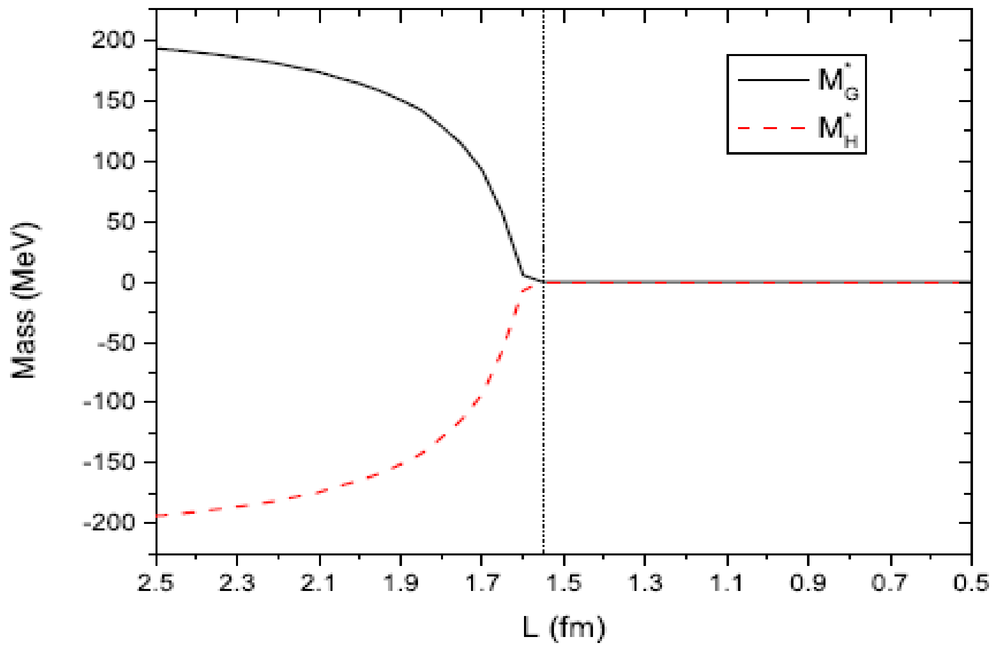


FIG. 1. (Color online) Medium modified heavy-light meson mass splitting as a function of the crystal size L. The vertical line indicates the critical density of the skyrmion-half-skyrmion phase transtion.

D. Suenaga, B. R. He, YM, M. Harada, PRD(2015);

Further discussions

- Skyrme model provides a unified approach to the single baryon, baryonic matter and medium modified hadron properties.
- Skyrmion approach to dense baryonic matter predicts several things that chiral effective theory including baryon as an explicit degree of freedom cannot do.
- To match the reality, extra contribution? Loop correction? In Skyrme model, contribution ≈500 MeV. Meier &Walliser, 1997. A consistent way to include scalar effect?
- Resonance effect on Symmtery energy, Kaon, self-consistently obtain medium modified hadron properties and like to fundemantal QCD? In progress.
- Skyrmion might provide a bridge between nuclear physics and condensed matter physics.