APCTP-JINR Joint Workshop
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Dense Baryonic Matter in the Hidden Local Symmetry

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Works with
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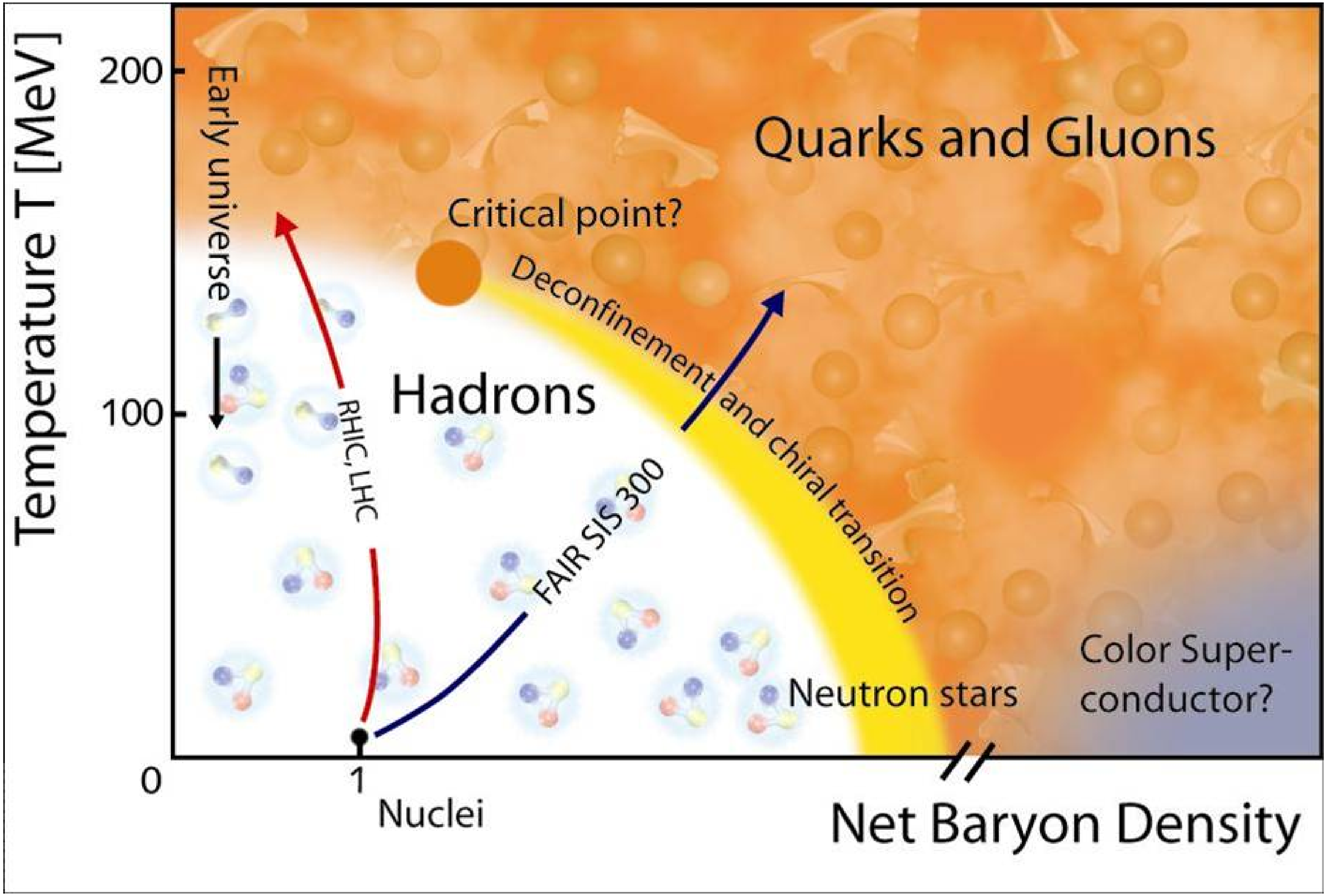
D.-P. Min, H.-J. Lee, J.-I. Kim, V. Vento

Contents

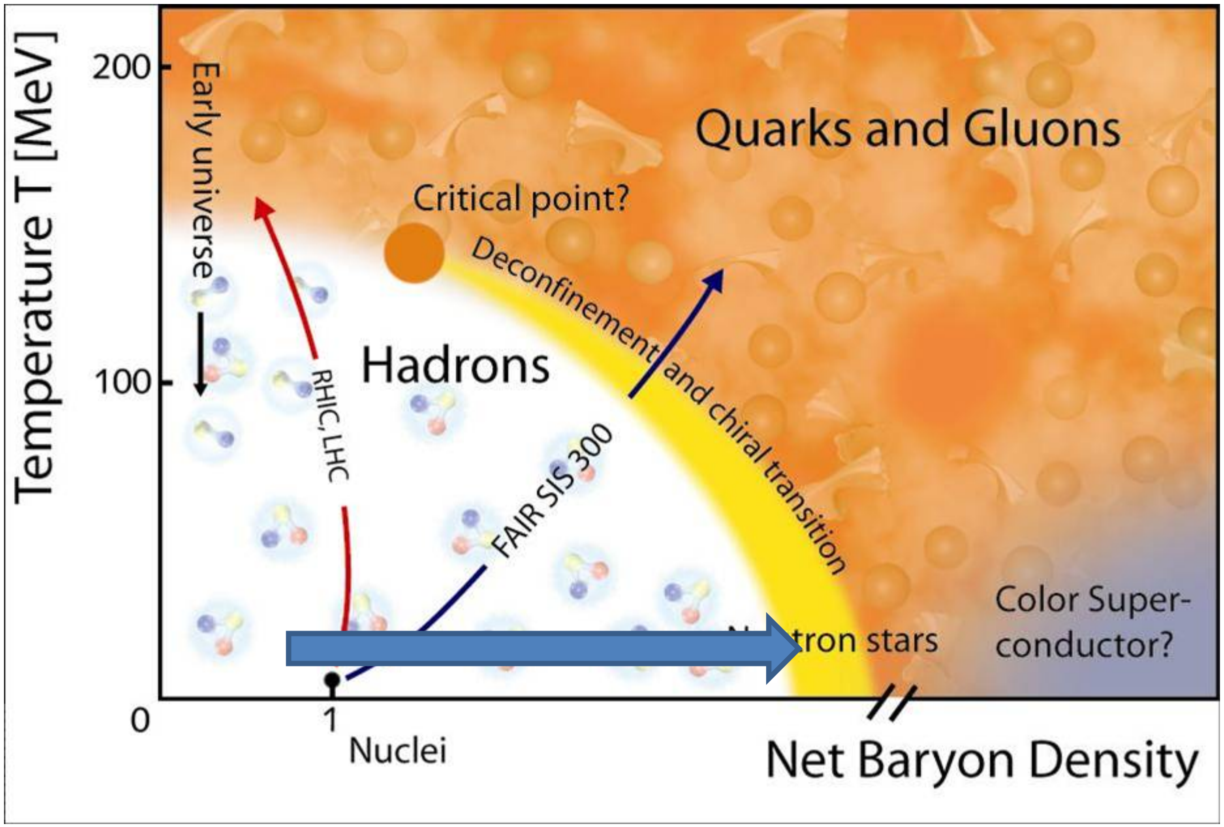
- What?
- How?
- Recent results
- Discussions

I. What are all about?


Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
FAIR SIS 300
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
Neutron stars
Color Super-
conductor?

We study

- the dense baryonic matter



- the properties of hadrons in dense baryonic matter

Ⅱ. How we do it?

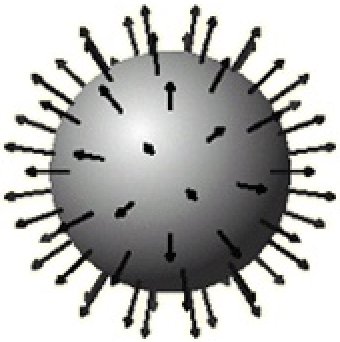
Skyrme Model

1960, T. H. R. Skyrme

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

$U(\vec{x}) = exp(i\tau\pi/f_\pi)$: mapping from $R^3 - \{\infty\} = S^3$ to $SU(2) = S^3$

⟶ topological soliton



R ~ 1 f m
M ~ 1.5 GeV ⟶ baryon ?

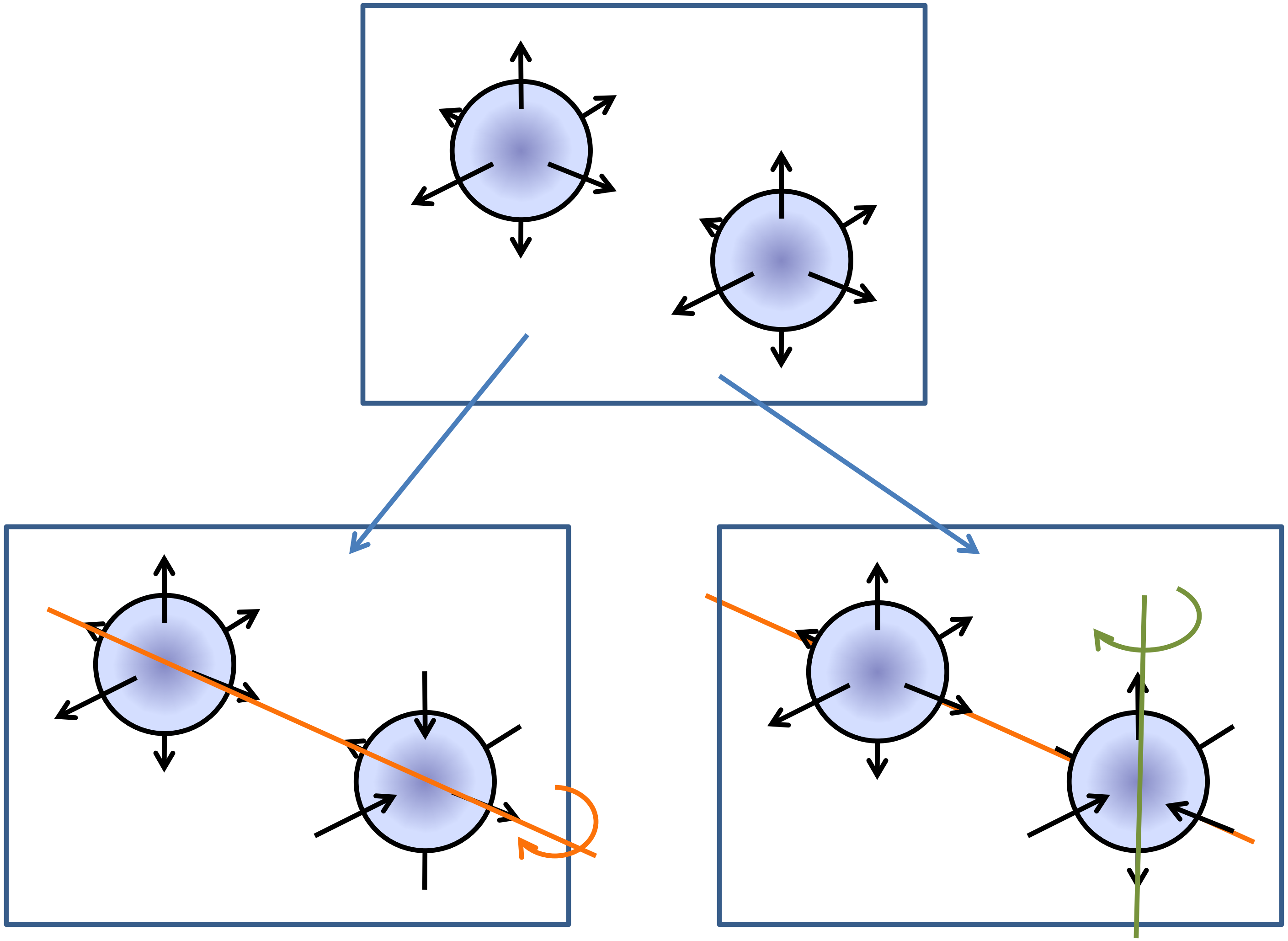
Classical object!

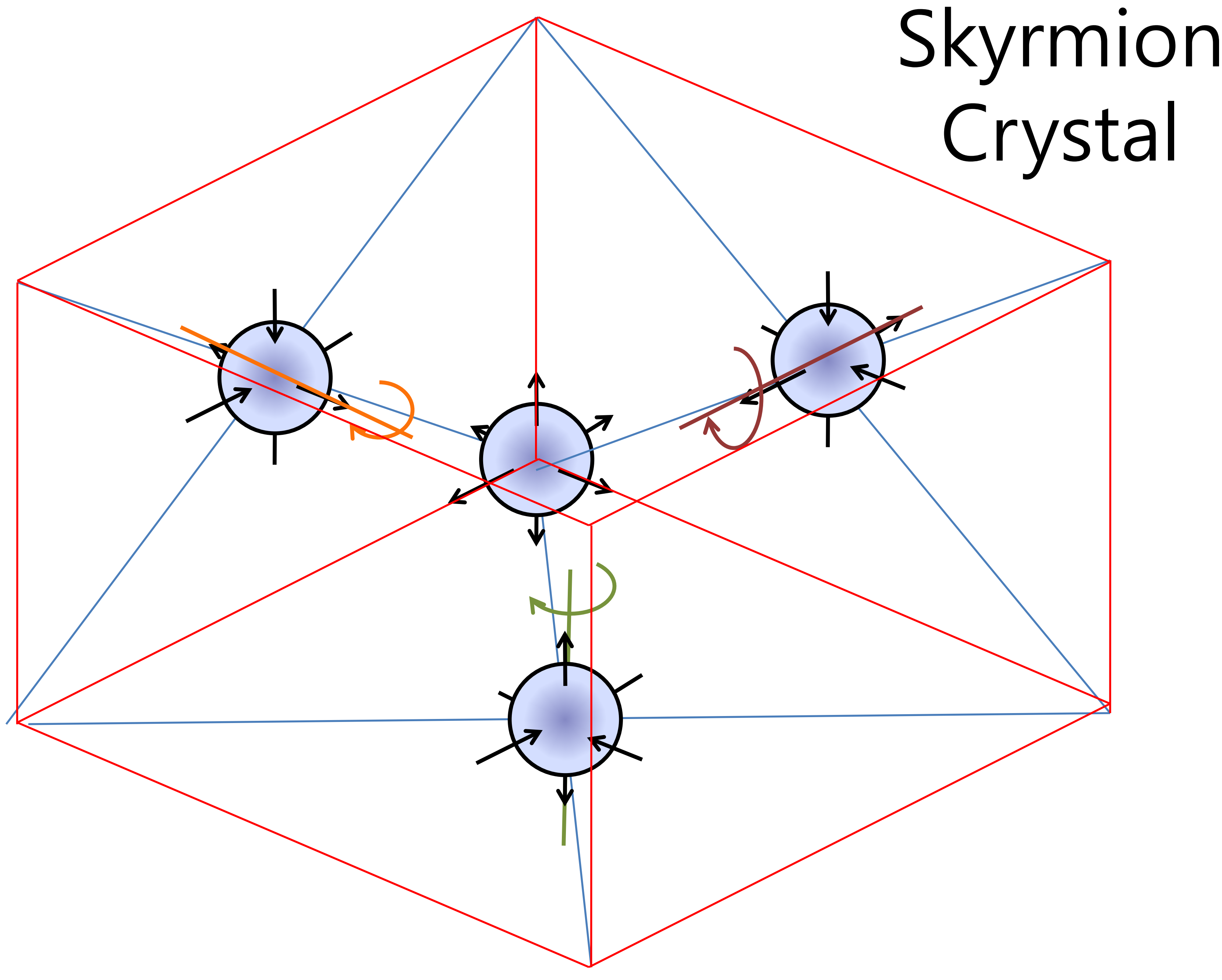
↓

Easy to construct
many-body system

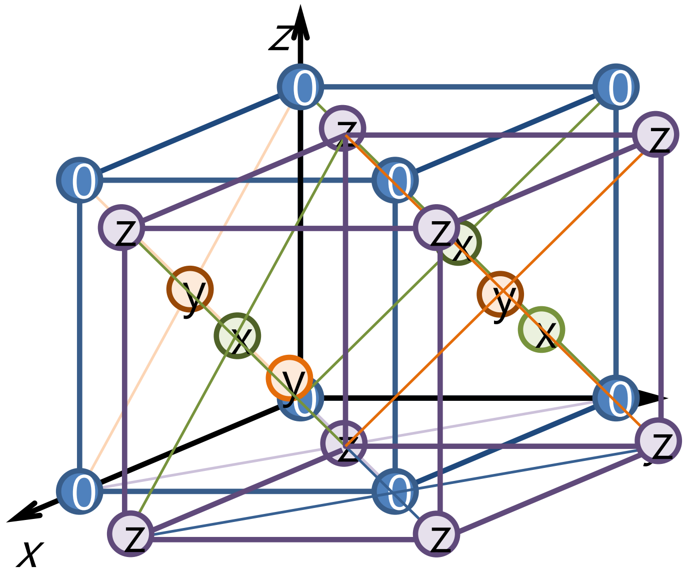
Two skyrmions

1960, T. H. R. Skyrme




Skyrmion
Crystal

FCC Skyrmion crystal

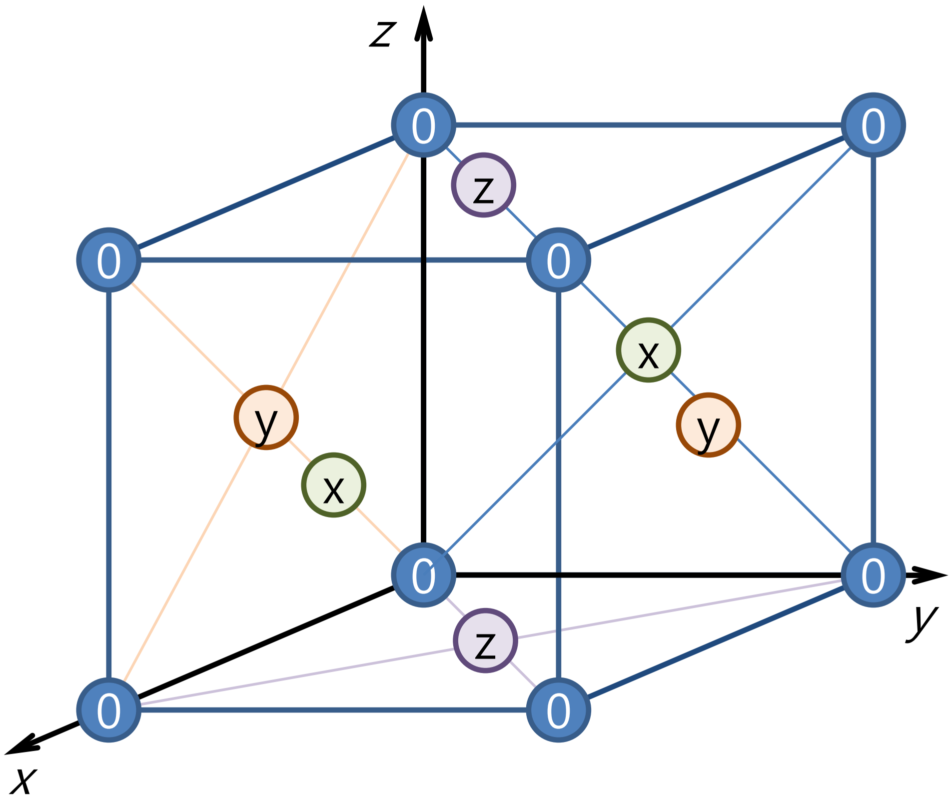


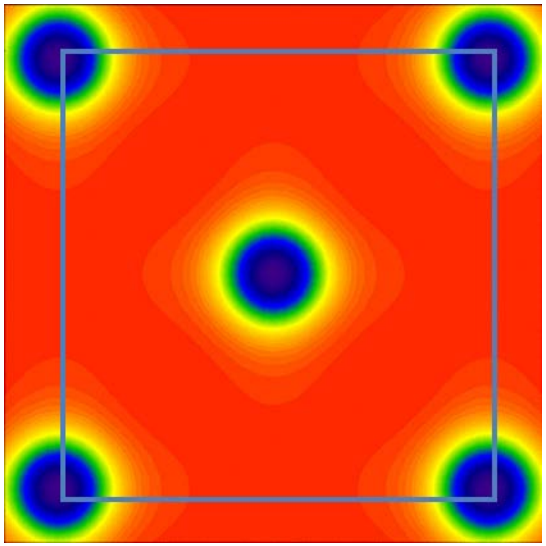
$$U(x+L/2, y+L/2, z) = \tau_z \, U(x,y,z) \, \tau_z$$

$$U(x+L/2, y, z+L/2) = \tau_y \, U(x,y,z) \, \tau_y$$

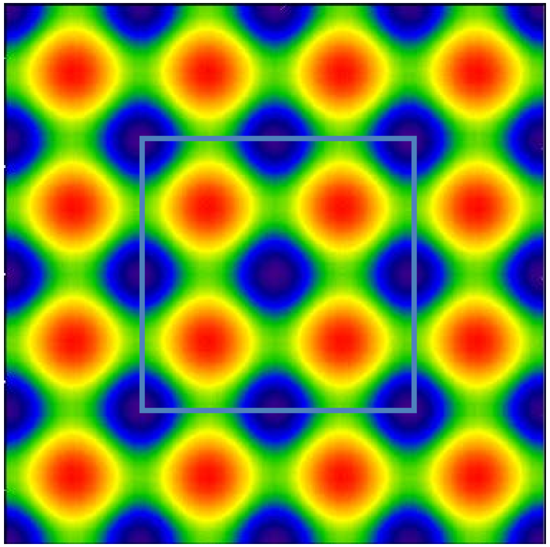
$$U(x, y+L/2, z+L/2) = \tau_x \, U(x,y,z) \, \tau_x$$

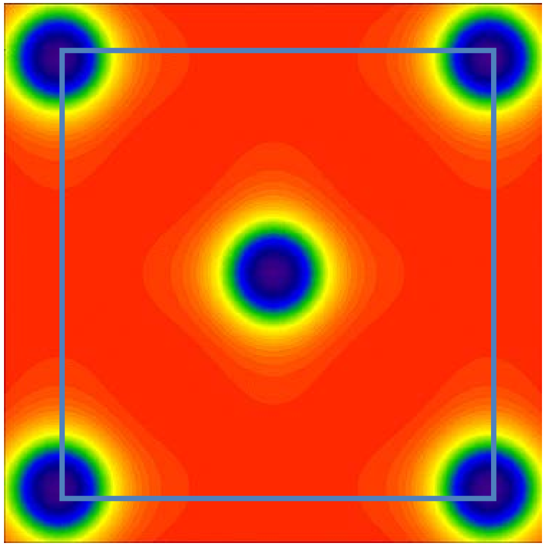
Skyrmion crystal(FCC)

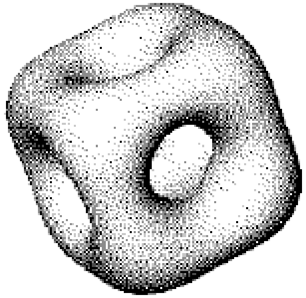


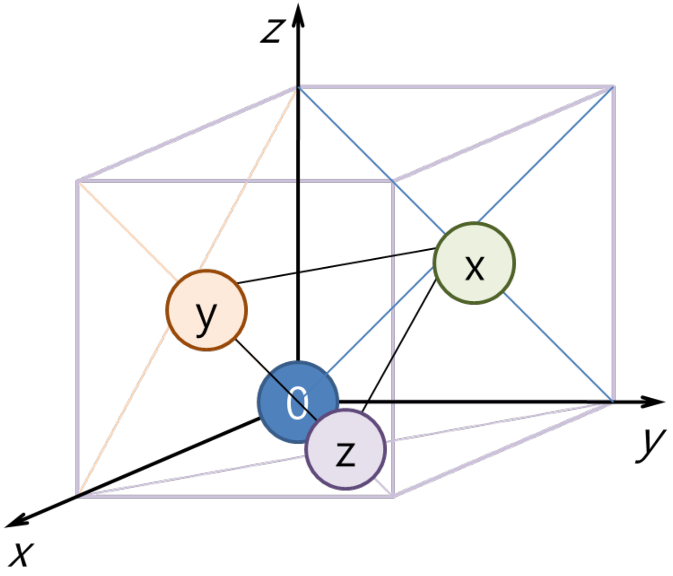


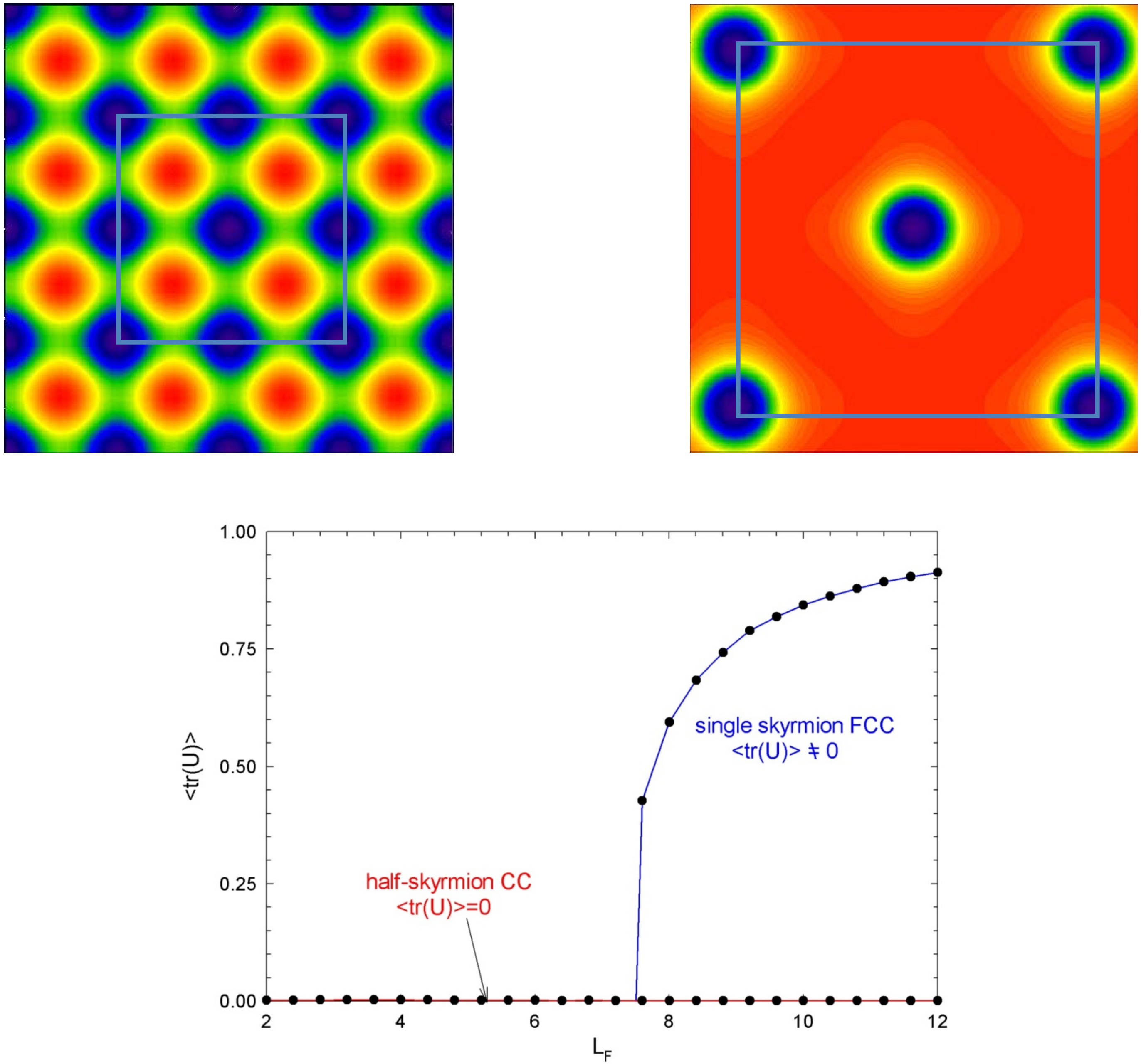
Phase transition











1.00
0.75
0.50
0.25
0.00
<tr(U)>
2
4
6
8
10
12
L_F
single skyrmion FCC
<tr(U)> ≠ 0
half-skyrmion CC
<tr(U)>=0

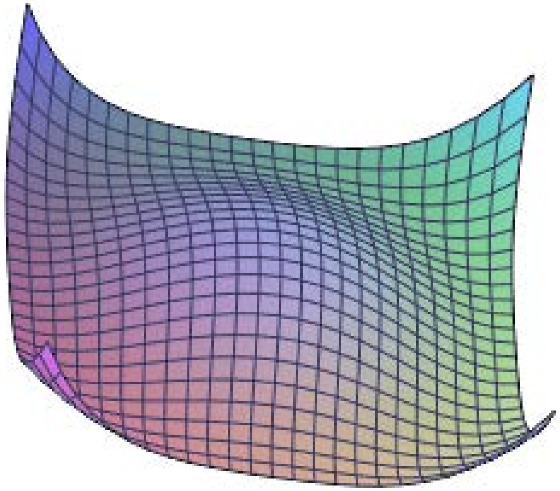
What we have found is the classical solution of the meson Lagrangian!

↓

In-medium properties of the mesons

Analogy

$$\lambda\phi^4 - \mu^2\phi^2$$



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

$$\downarrow \quad U_\pi = \exp(i\vec{\tau}\cdot\vec{\pi})$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \vec{\pi}\cdot\partial^\mu \vec{\pi} + \cdots$$

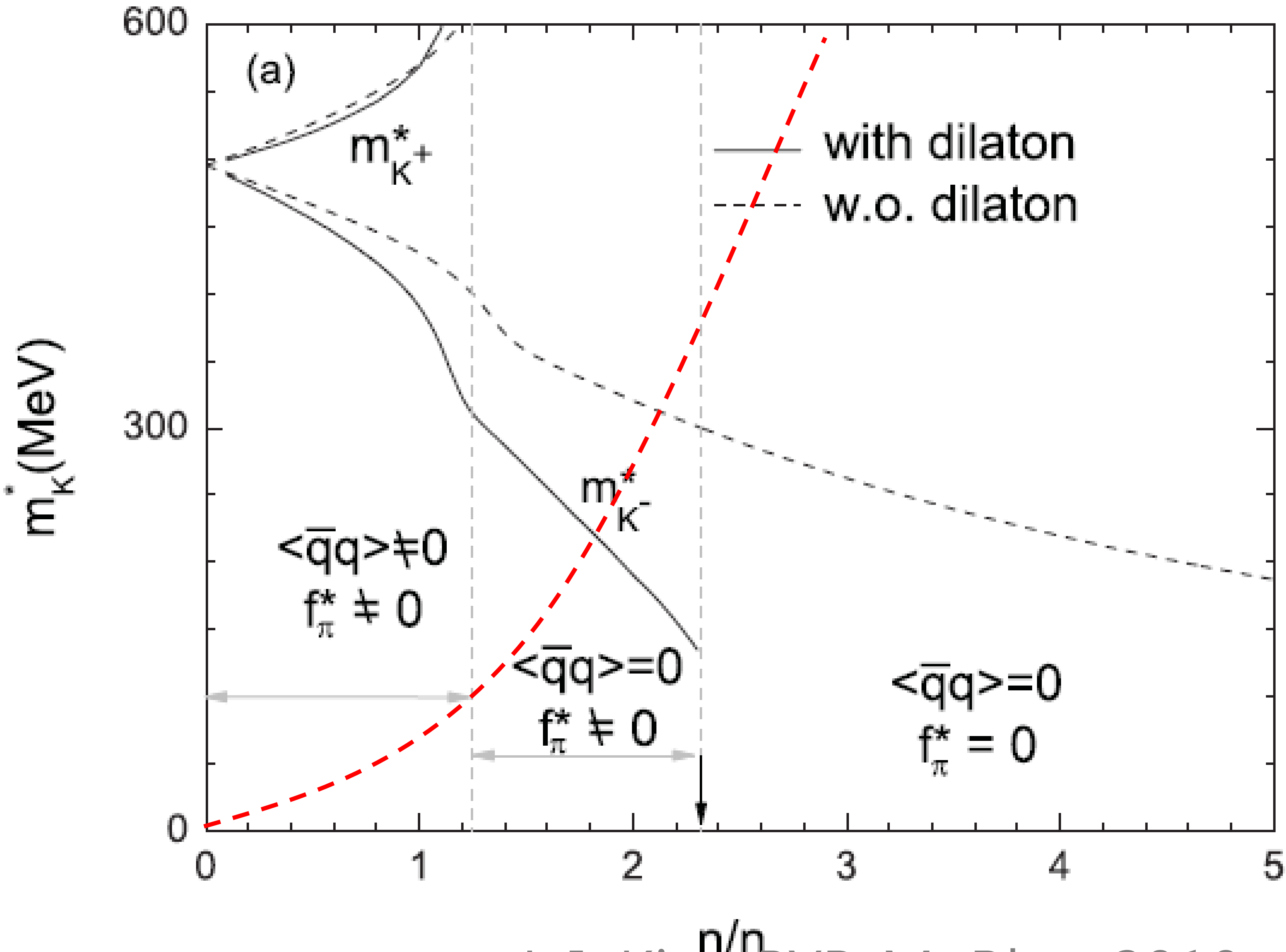
$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{1}{32e^2}\mathrm{Tr}\left[U^\dagger\partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

$$U = \sqrt{U_\pi} U_B \sqrt{U_\pi}$$

$$\mathcal{L} = \frac{1}{2} G_{ab}(U_B)\partial_\mu \pi^a \partial^\mu \pi^b + \cdots$$

$$\frac{f_\pi^*}{f_\pi} = \sqrt{\langle G_{aa}(U_B)\rangle}$$

Consequence?



J. I. Kim, BYP, M. Rho, 2010

In-Medium Modification of Tensor Force

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

Ⅲ. Recent Work

Y. Ma, M. Harada, H. K. Lee, Y. Oh, B.-Y. Park, M. Rho, to appear in Phys. Rev. D the density $n_{1/2}$ at which the ~~skyrmions~~ Skyrmions in medium fractionize into ~~half-skyrmions~~ half-Skyrmions , bringing in a drastic change in the equation of state of dense baryonic matter. We find that the $U(1)$ field that figures in the Chern-Simons term in the ~~5-D~~ five-dimensional holographic QCD action or equivalently the ω field in the homogeneous Wess-Zumino term in the dimensionally reduced hidden local symmetry action plays a crucial role in the ~~half-skyrmion~~ half-Skyrmion phase. The importance of the ω degree of freedom may be connected to what happens in the instanton structure of elementary baryon noticed in holographic QCD. The most striking and intriguing in what is found in the model is that the pion decay constant that smoothly drops with increasing density in the ~~skyrmion~~ Skyrmion phase stops decreasing at $n_{1/2}$ and remains nearly constant in the ~~half-skyrmion~~ half-Skyrmion phase. In accordance with the large N_c consideration,

Full HLS Lagrangian up to O(p^4)

$$\mathcal{L}_{\rm HLS} = \mathcal{L}_{(2)} + \mathcal{L}_{(4)} + \mathcal{L}_{\rm anom}$$

$$\mathcal{L}_{(2)} = f_\pi^2 \,\mathrm{Tr}\,\left(\hat{a}_{\perp\mu}\hat{a}_{\perp}^{\mu}\right) + a f_\pi^2 \,\mathrm{Tr}\,\left(\hat{a}_{\parallel\mu}\hat{a}_{\parallel}^{\mu}\right) - \frac{1}{2g^2}\mathrm{Tr}\,\left(V_{\mu\nu}V^{\mu\nu}\right)$$

$$\begin{aligned}
\mathcal{L}_{(4)y} = {} & y_1 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp}^{\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_{\perp}^{\nu}\right] + y_2 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_{\perp}^{\mu}\hat{\alpha}_{\perp}^{\nu}\right] + y_3 \mathrm{Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_{\parallel}^{\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_{\parallel}^{\nu}\right] + y_4 \mathrm{Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_{\parallel}^{\mu}\right. \\
& + y_5 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp}^{\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_{\parallel}^{\nu}\right] + y_6 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_{\parallel}^{\mu}\hat{\alpha}_{\parallel}^{\nu}\right] + y_7 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_{\parallel}^{\nu}\hat{\alpha}_{\parallel}^{\mu}\right] \\
& + y_8 \left\{\mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel}^{\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_{\parallel}^{\nu}\right] + \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_{\perp}^{\nu}\hat{\alpha}_{\parallel}^{\mu}\right]\right\} + y_9 \mathrm{Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_{\perp}^{\mu}\hat{\alpha}_{\parallel}^{\nu}\right],
\end{aligned}$$

$$\mathcal{L}_{(4)z} = i z_4 \mathrm{Tr}\left[V_{\mu\nu}\hat{\alpha}_{\perp}^{\mu}\hat{\alpha}_{\perp}^{\nu}\right] + i z_5 \mathrm{Tr}\left[V_{\mu\nu}\hat{\alpha}_{\parallel}^{\mu}\hat{\alpha}_{\parallel}^{\nu}\right].$$

$$\mathcal{L}_{\rm anom} = \frac{N_c}{16\pi^2}\left[\, i\,\mathrm{Tr}\left[\hat{\alpha}_{\rm L}^3\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}^3\hat{\alpha}_{\rm L}\right] + i\,\mathrm{Tr}\left[\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}\right] + \mathrm{Tr}\left[F_{\rm V}\left(\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L}\right)\right]\right]$$

$$f_\pi^2 = N_c G_{\rm YM} M_{\rm KK}^2 \int dz K_2(z) \left[\dot\psi_0(z)\right]^2, \quad a f_\pi^2 = N_c G_{\rm YM} M_{\rm KK}^2 \lambda_1 \langle \psi_1^2 \rangle,$$

$$\frac{1}{g^2} = N_c G_{\rm YM} \langle \psi_1^2 \rangle,$$

$$y_1 = -y_2 = -N_c G_{\rm YM} \langle (1+\psi_1-\psi_0^2)^2 \rangle, \quad y_3 = -y_4 = -N_c G_{\rm YM} \langle \psi_1^2 (1+\psi_1)^2 \rangle,$$

$$y_5 = 2y_8 = -y_9 = -2N_c G_{\rm YM} \langle \psi_1^2 \psi_0^2 \rangle, \quad y_6 = -y_5 - y_7,$$

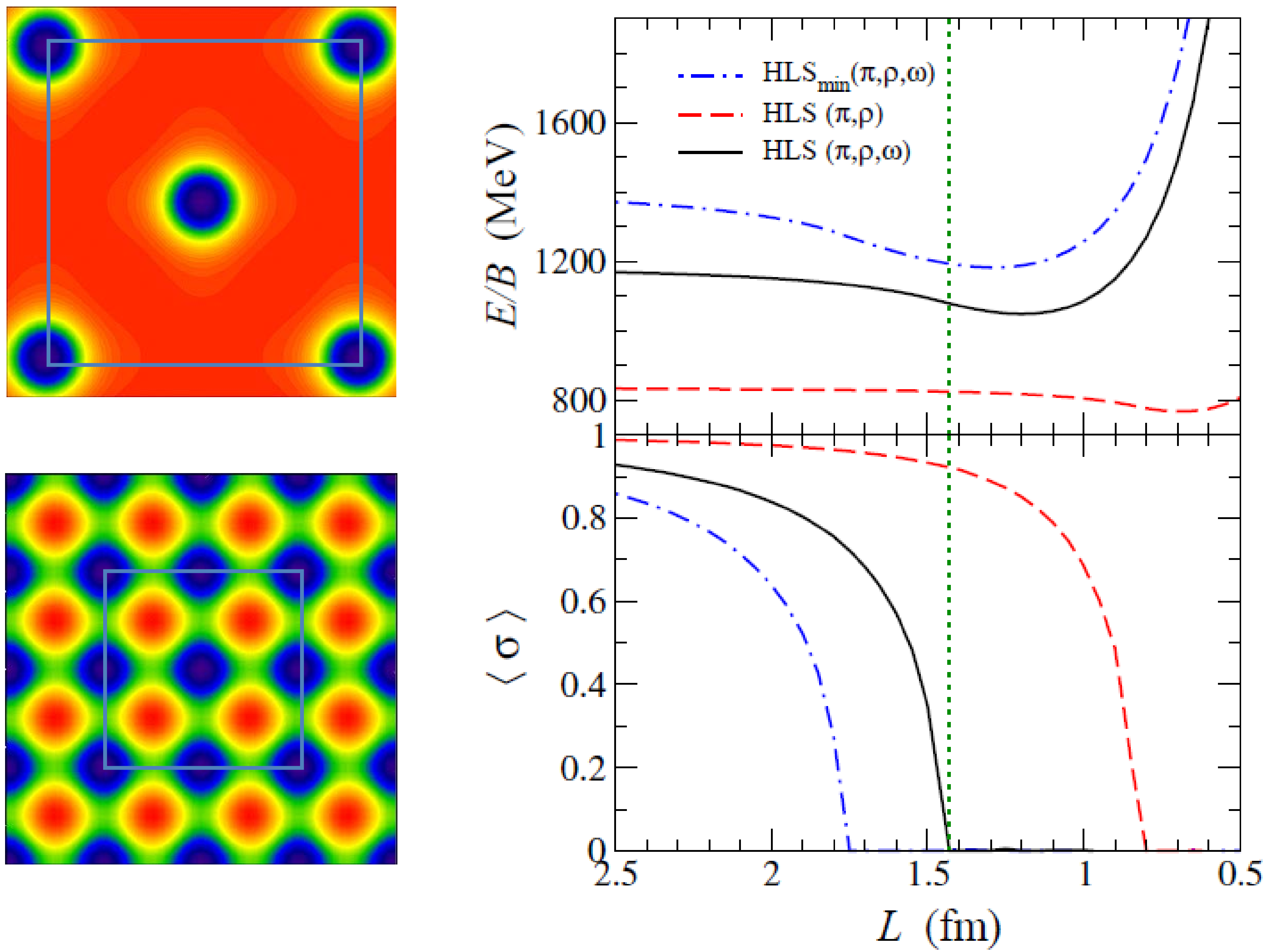
$$y_7 = 2N_c G_{\rm YM} \langle \psi_1 (1+\psi_1) (1+\psi_1-\psi_0^2) \rangle,$$

$$z_4 = 2N_c G_{\rm YM} \langle \psi_1 (1+\psi_1-\psi_0^2) \rangle, z_5 = -2N_c G_{\rm YM} \langle \psi_1^2 (1+\psi_1) \rangle,$$

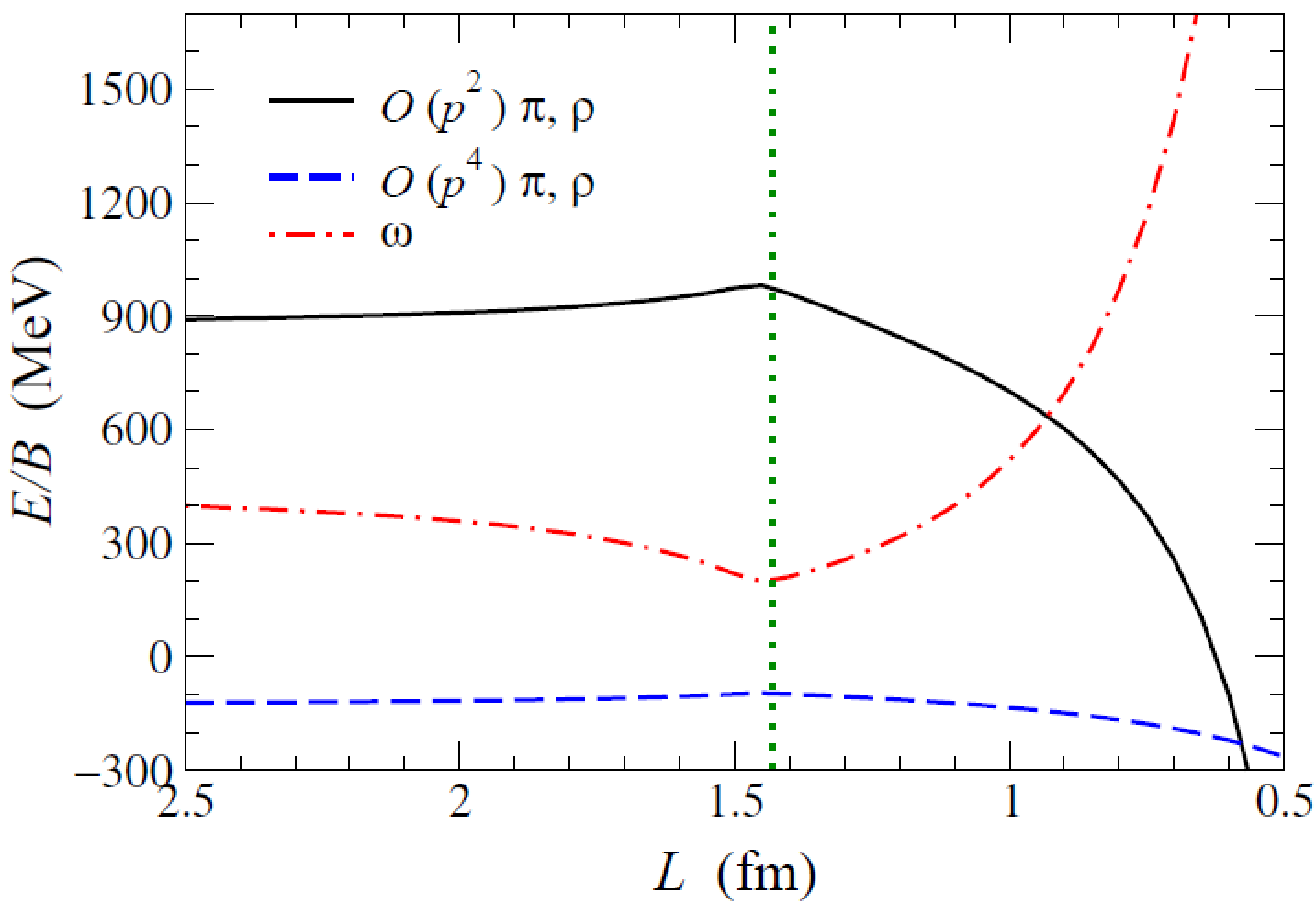
$$c_1 = \left\langle\left\langle \dot\psi_0 \psi_1 \left(\frac{1}{2}\psi_0^2 + \frac{1}{6}\psi_1^2 - \frac{1}{2} \right) \right\rangle\right\rangle,$$

$$c_2 = \left\langle\left\langle \dot\psi_0 \psi_1 \left(-\frac{1}{2}\psi_0^2 + \frac{1}{6}\psi_1^2 + \frac{1}{2}\psi_1 + \frac{1}{2} \right) \right\rangle\right\rangle$$

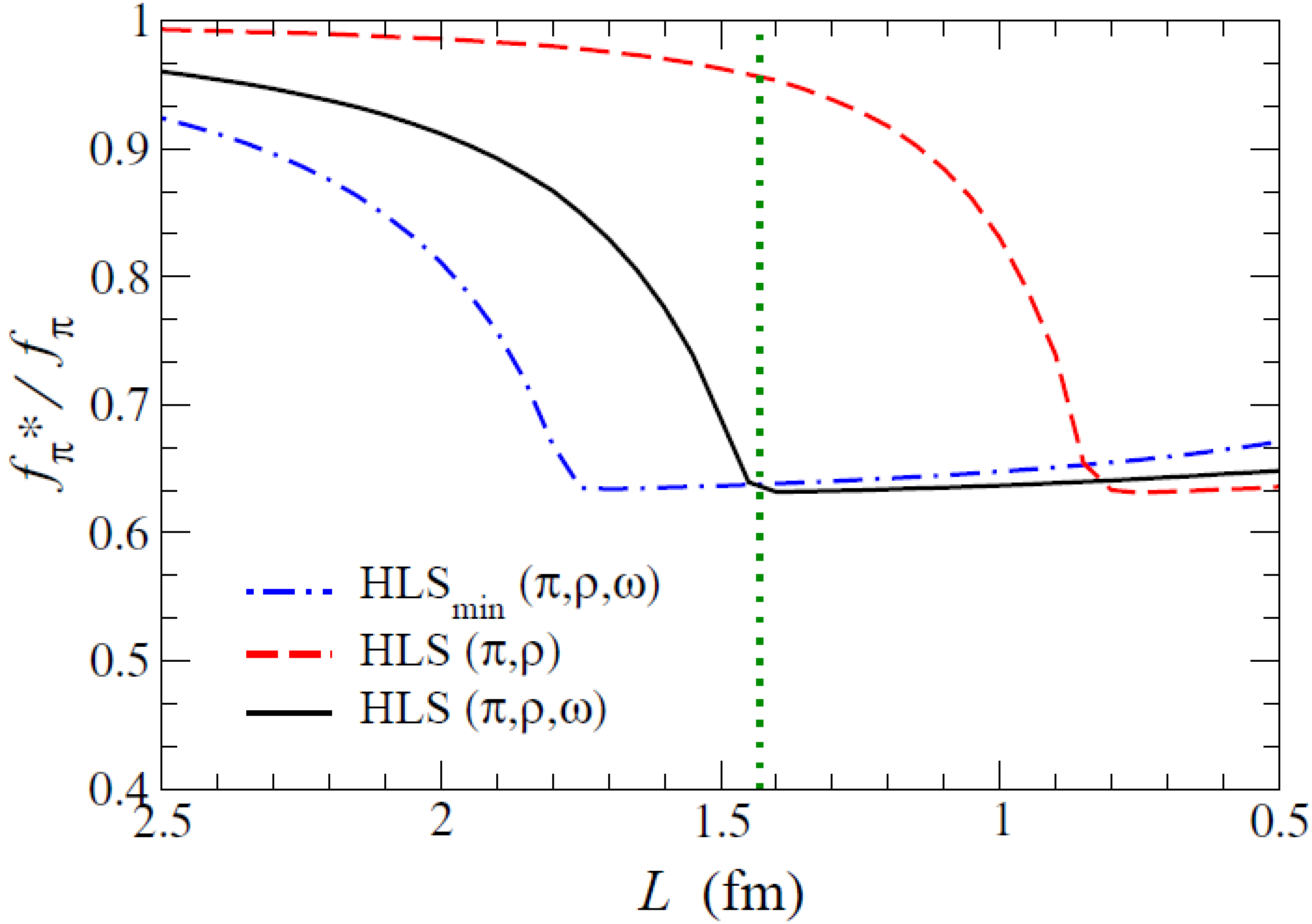
$$c_3 = \left\langle\left\langle \dot\psi_0 \psi_1 \left(\frac{1}{2}\psi_1 \right) \right\rangle\right\rangle,$$



HLS$_{min}$(π,ρ,ω)
HLS (π,ρ)
HLS (π,ρ,ω)
E/B (MeV)
1600
1200
800
1
0.8
0.6
0.4
0.2
0
⟨σ⟩
2.5
2
1.5
1
0.5
L (fm)

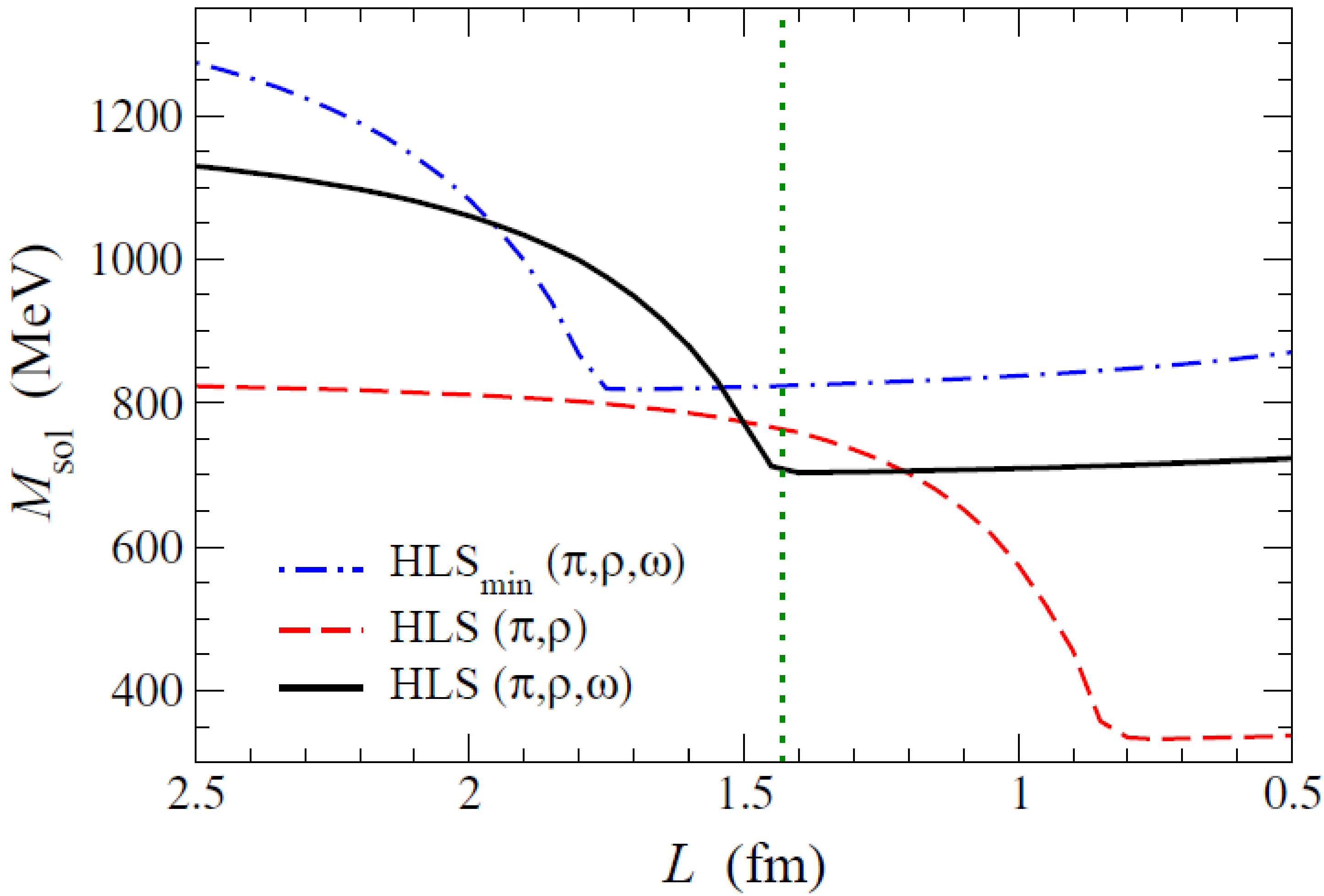


1500
1200
900
600
300
0
−300
2.5
2
1.5
1
0.5
E/B (MeV)
L (fm)
O (p^2) π, ρ
O (p^4) π, ρ
ω



1
0.9
0.8
0.7
0.6
0.5
0.4
2.5
2
1.5
1
0.5
f_π^* / f_π
L (fm)
HLS$_{min}$ (π,ρ,ω)
HLS (π,ρ)
HLS (π,ρ,ω)

f_π^* & m_ρ^*



1200
1000
800
600
400
M_{sol} (MeV)
2.5
2
1.5
1
0.5
L (fm)
HLS$_{min}$ (π,ρ,ω)
HLS (π,ρ)
HLS (π,ρ,ω)

Dilaton

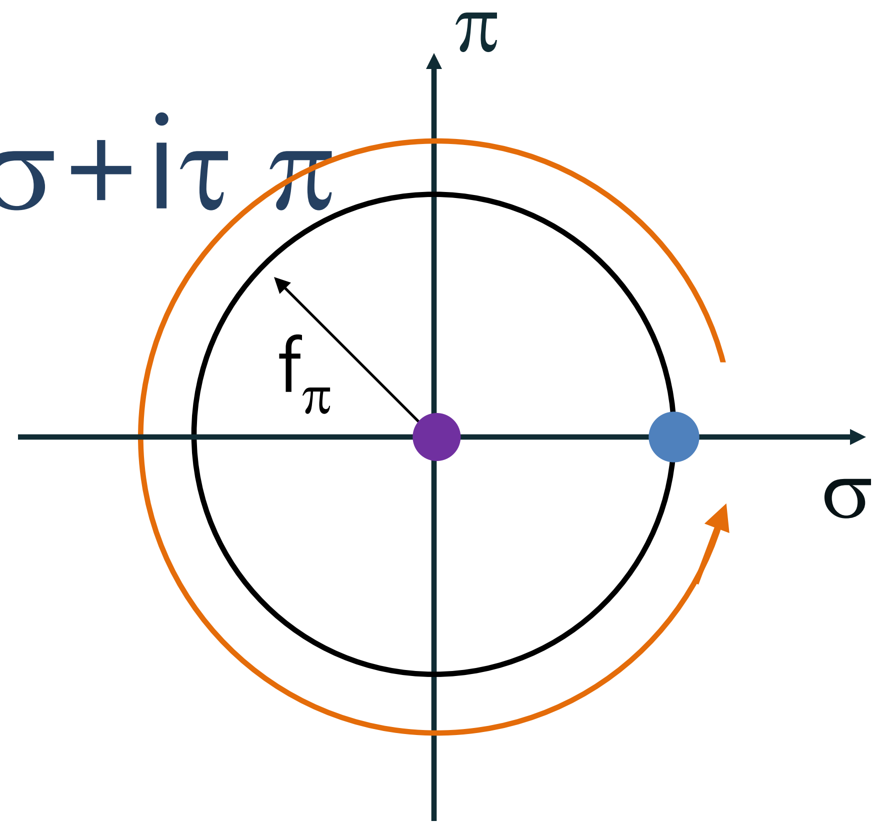
Y. Ma, M. Harada, H. K. Lee, Y. Oh, B.-Y. Park, M. Rho, in preparation

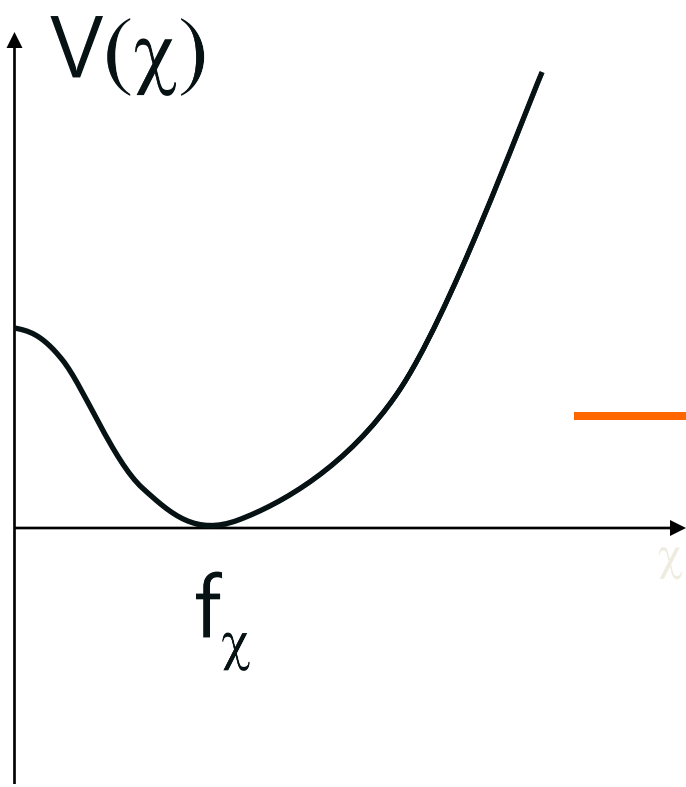
$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{1}{32e^2}\mathrm{Tr}[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U]^2$$
$$+ \frac{f_\pi^2 m_\pi^2}{4}\mathrm{Tr}(U + U^\dagger - 2)$$

← Trace Anomaly of QCD

$$\mathcal{L} = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}(\partial_\mu U \partial^\mu U) + \frac{1}{32e^2}\mathrm{Tr}[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U]^2$$
$$+ \frac{f_\pi^2 m_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^3 \mathrm{Tr}(U^\dagger + U - 2)$$
$$+ \tfrac{1}{2}\partial_\mu \chi \partial^\mu \chi - \tfrac{1}{4} m_\chi^2 f_\chi^2 \left((\chi / f_\chi)^4 (\ln(\chi/f_\chi) - \tfrac{1}{4}) + \tfrac{1}{4}\right)$$

$U \rightsquigarrow \chi U \sim \sigma + i\tau\pi$



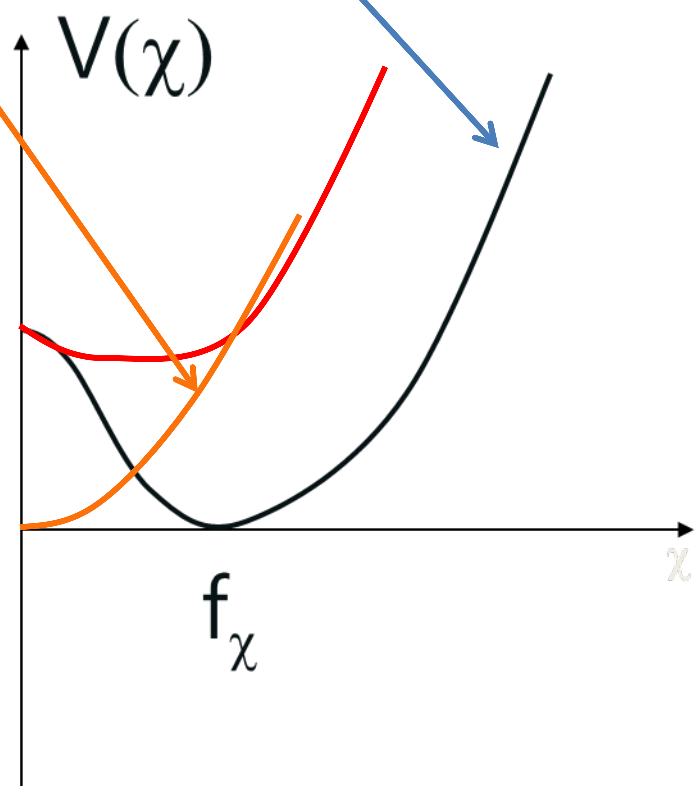


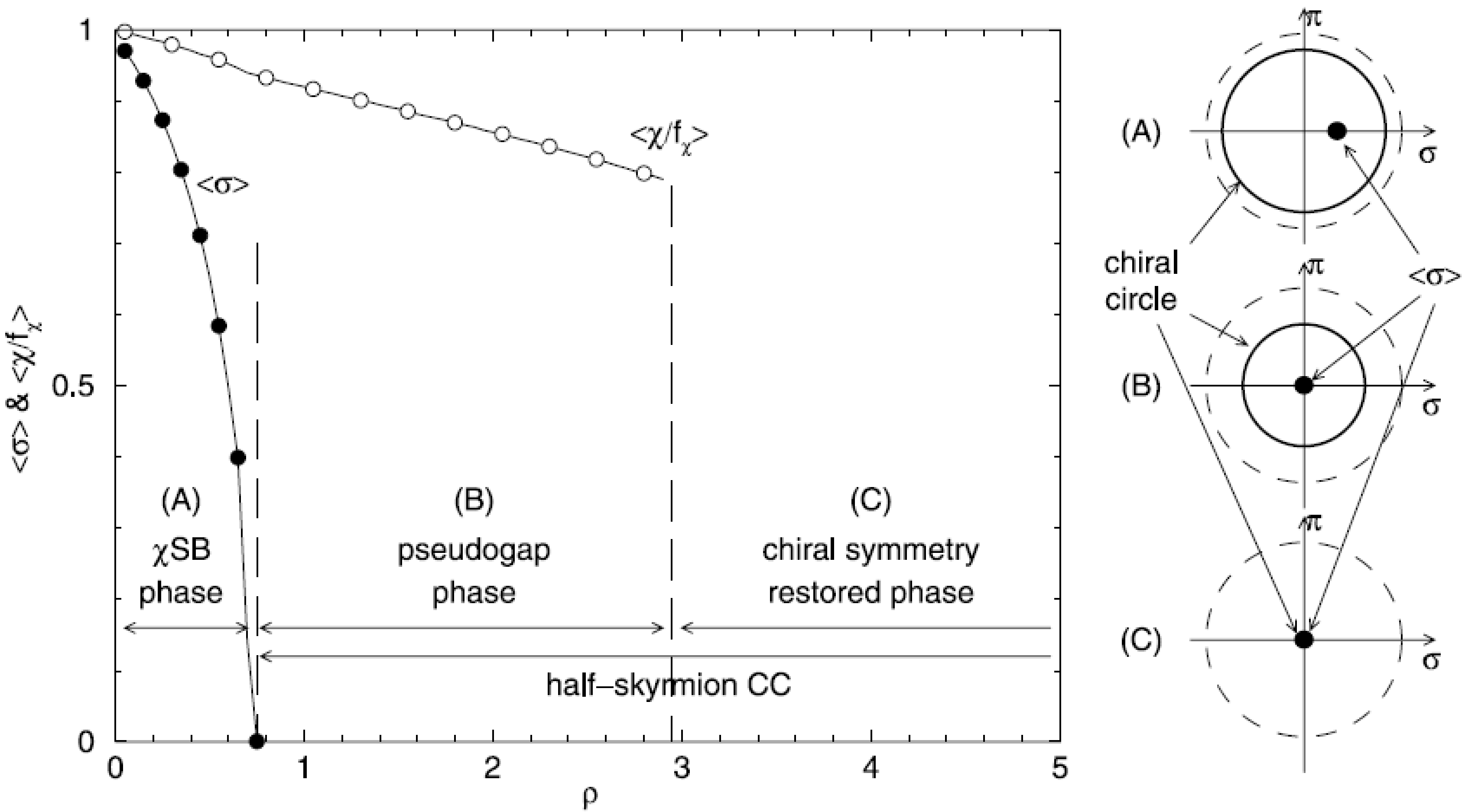
Vacuum ($\rho=0$)

$U=1$

$\chi=f_\chi$

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





1
0.5
0
0
1
2
3
4
5
ρ
<σ> & <χ/fχ>
<χ/fχ>
<σ>
(A)
χSB
phase
(B)
pseudogap
phase
(C)
chiral symmetry
restored phase
half−skyrmion CC
(A)
(B)
(C)
π
σ
chiral
circle
<σ>

omega & dilaton

Minimal HLS

$$\mathcal{L} = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) \cdot$$

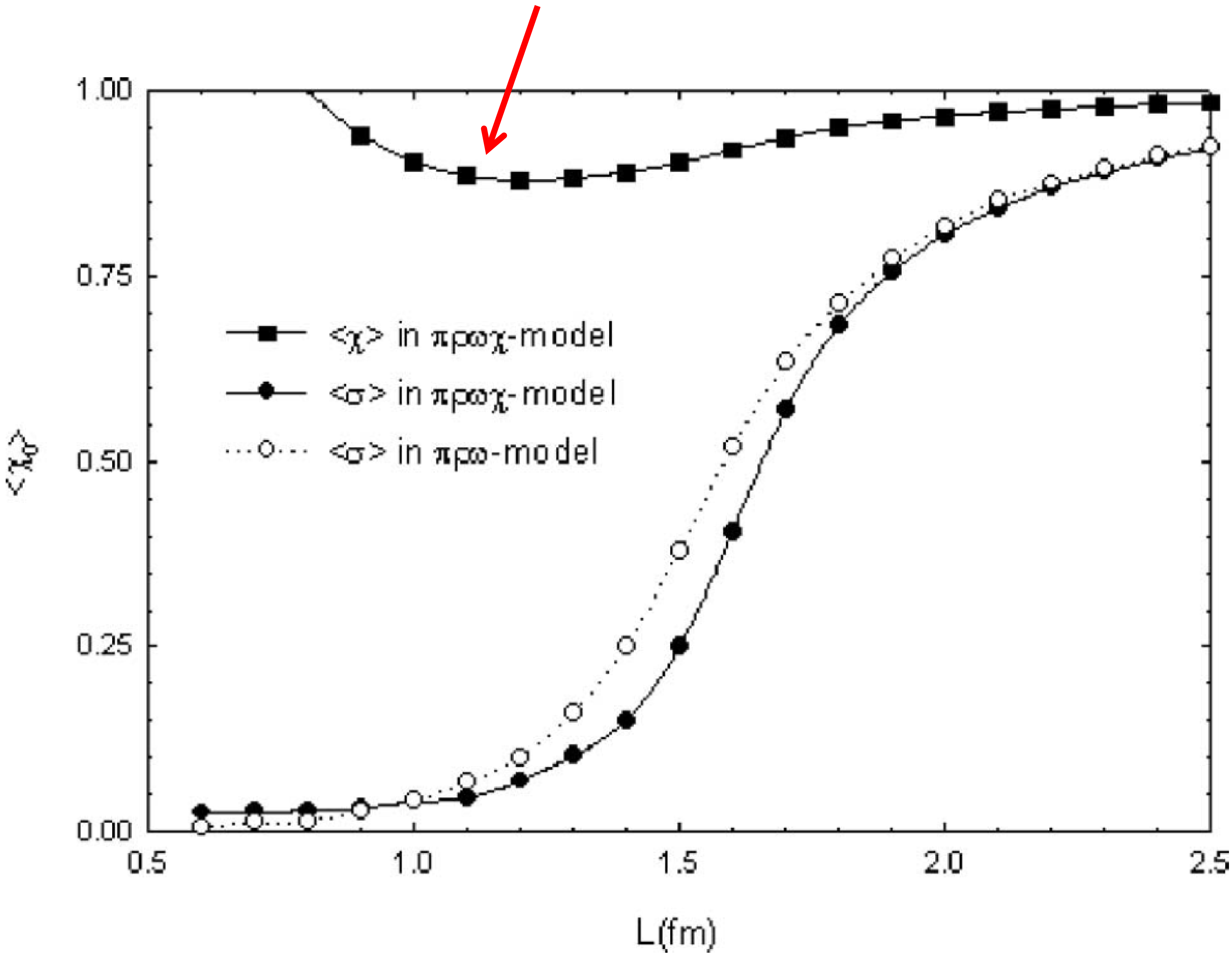
$$- \frac{f_\pi^2}{4} a \left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}[\ell_\mu + r_\mu + i(g/2)(\vec{\tau}\cdot\vec{\rho}_\mu + \omega_\mu)]^2$$

$$-\frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{3}{2}g\omega_\mu B^\mu$$

$$+\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{m_\chi^2 f_\chi^2}{4}\left[(\chi/f_\chi)^4(\ln(\chi/f_\chi) - \frac{1}{4}) + \frac{1}{4}\right]$$

KSRF relation : $m_V^2 = a f_\pi^2 g^2$ → m_V^*

BYP, M. Rho, V. Vento, 2003, 2008



1.00
0.75
0.50
0.25
0.00
0.5
1.0
1.5
2.0
2.5
<χσ>
L(fm)
<χ> in πρωχ-model
<σ> in πρωχ-model
<σ> in πρω-model

$$\mathcal{L} = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{f_\pi^2 m_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^3 \mathrm{Tr}(U + U^\dagger - 2)$$
$$- \frac{f_\pi^2}{4} a \left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}[\ell_\mu + r_\mu + i(g/2)(\vec{\tau}\cdot\vec{\rho}_\mu + \omega_\mu)]^2$$
$$- \frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{3}{2} g\omega_\mu B^\mu + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi$$
$$- \frac{m_\chi^2 f_\chi^2}{4}\left[(\chi/f_\chi)^4\left(\ln(\chi/f_\chi) - \frac{1}{4}\right) + \frac{1}{4}\right],$$

↓

$$(-\partial_i^2 + m_\omega^{*2})w = -\frac{3g}{2f_\pi^2} B_0$$

↓

$$(E/B)_{\mathrm{WZ}} = \frac{1}{4}\int_{\mathrm{Box}} d^3x \int d^3x' \left(\frac{3g}{2}\right)^2 B_0(\vec{x}) \frac{\exp(-m_\omega^*|\vec{x}-\vec{x}'|)}{4\pi|\vec{x}-\vec{x}'|} B_0(\vec{x}')$$

$$\mathcal{L} = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{f_\pi^2 m_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^3 \mathrm{Tr}(U + U^\dagger - 2)$$

$$- \frac{f_\pi^2}{4} a \left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}[\ell_\mu + r_\mu + i(g/2)(\vec{\tau}\cdot\vec{\rho}_\mu + \omega_\mu)]^2$$

$$- \frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{3}{2} g \omega_\mu B^\mu \left(\frac{\chi}{f_\chi}\right)^3 \chi \partial^\mu \chi$$

2008

$$- \frac{m_\chi^2 f_\chi^2}{4}\left[(\chi/f_\chi)^4\left(\ln(\chi/f_\chi) - \frac{1}{4}\right) + \frac{1}{4}\right],$$

$$(-\partial_i^2 + m_\omega^{*2}) w = -\frac{3g^*}{2f_\pi^2} B_0$$

$$w = -\frac{3g^*}{2f_\pi^2}\int d^3x' \frac{\exp(-m_\omega^*|\vec{x} - \vec{x}'|)}{4\pi|\vec{x} - \vec{x}'|} B_0(\vec{r}')$$

$$\mathcal{L} = \frac{f_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) + \frac{f_\pi^2 m_\pi^2}{4}\left(\frac{\chi}{f_\chi}\right)^3 \mathrm{Tr}(U + U^\dagger - 2)$$
$$- \frac{f_\pi^2}{4} a \left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}[\ell_\mu + r_\mu + i(g/2)(\vec{\tau}\cdot\vec{\rho}_\mu + \omega_\mu)]^2$$
$$- \frac{1}{4}\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{3}{2} g \omega_\mu B^\mu + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi$$
$$- \frac{m_\chi^2 f_\chi^2}{4}\left[(\chi/f_\chi)^4\left(\ln(\chi/f_\chi) - \frac{1}{4}\right) + \frac{1}{4}\right],$$

U(2) sym. Breaking? 2013

$$\left(-\partial_i^2 + m_\omega{}^2\right) w = -\frac{3g}{2 f_\pi^2} B_0$$

$$w = -\frac{3g}{2 f_\pi^2}\int d^3x' \frac{\exp(-m_\omega|\vec{x} - \vec{x}'|)}{4\pi|\vec{x} - \vec{x}'|} B_0(\vec{r}')$$

Full HLS Lagrangian up to O(p^4)

$$\mathcal{L}_{\rm HLS} = \mathcal{L}_{(2)} + \mathcal{L}_{(4)} + \mathcal{L}_{\rm anom}$$

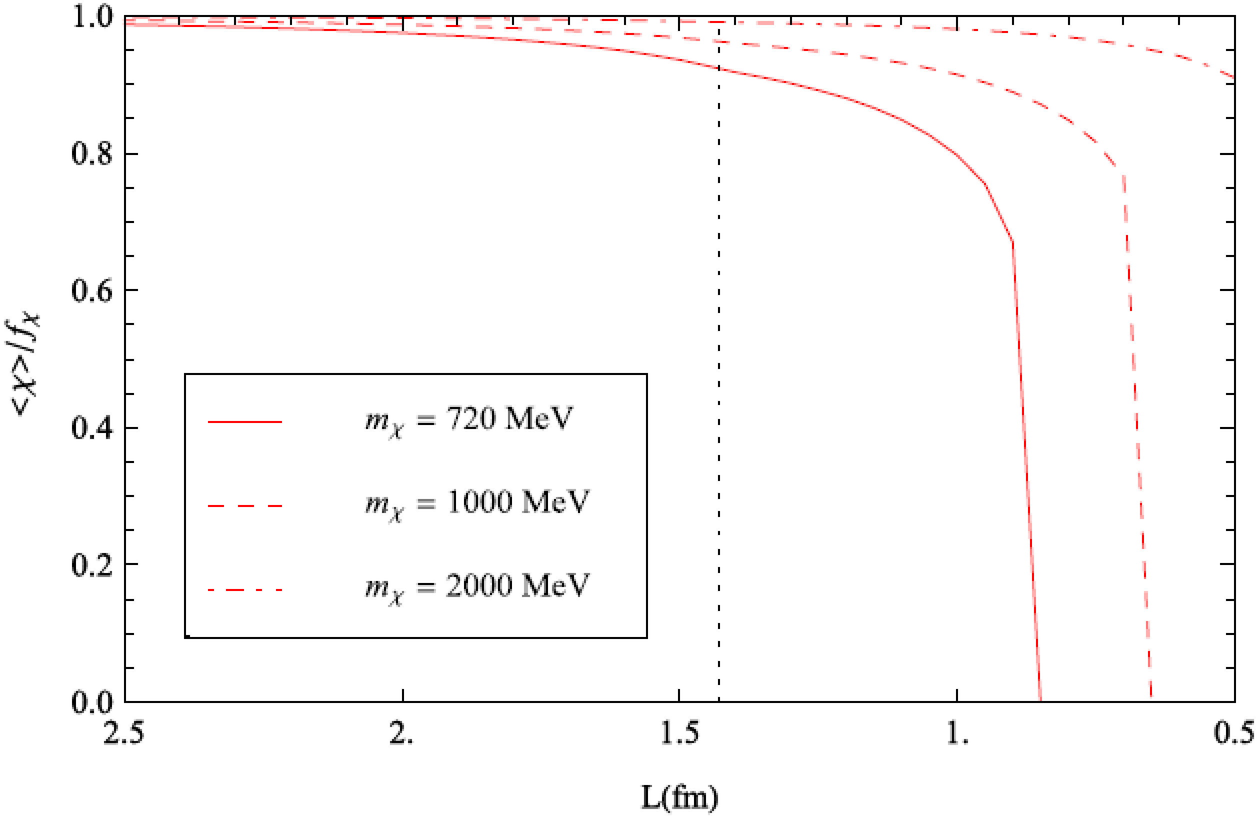
$$\left(\frac{\chi}{f_\chi}\right)^2$$

$$\mathcal{L}_{(2)} = f_\pi^2 \,{\rm Tr}\,(\hat{a}_{\perp\mu}\hat{a}_\perp^\mu) + a f_\pi^2\,{\rm Tr}\,\left(\hat{a}_{\parallel\mu}\hat{a}_\parallel^\mu\right) - \frac{1}{2g^2}{\rm Tr}\,(V_{\mu\nu}V^{\mu\nu})$$

$$\begin{aligned}\mathcal{L}_{(4)y} = {} & y_1 {\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\hat{\alpha}_{\perp\nu}\hat{\alpha}_\perp^\nu\right] + y_2{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\perp^\nu\right] + y_3{\rm Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\nu\right] + y_4{\rm Tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\mu \right.\\ & + y_5{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\parallel^\nu\right] + y_6{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_\parallel^\nu\right] + y_7{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\nu\hat{\alpha}_\parallel^\mu\right]\\ & + y_8\left\{{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_{\perp\nu}\hat{\alpha}_\parallel^\nu\right] + {\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\perp^\nu\hat{\alpha}_\parallel^\mu\right]\right\} + y_9{\rm Tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_{\parallel\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\parallel^\nu\right],\end{aligned}$$

$$\mathcal{L}_{(4)z} = iz_4{\rm Tr}\left[V_{\mu\nu}\hat{\alpha}_\perp^\mu\hat{\alpha}_\perp^\nu\right] + iz_5{\rm Tr}\left[V_{\mu\nu}\hat{\alpha}_\parallel^\mu\hat{\alpha}_\parallel^\nu\right].$$

$$\mathcal{L}_{\rm anom} = \frac{N_c}{16\pi^2}\left[\, i\,{\rm Tr}[\hat{\alpha}_{\rm L}^3\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}^3\hat{\alpha}_{\rm L}] + i\,{\rm Tr}[\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R}] + {\rm Tr}[F_{\rm V}\,(\hat{\alpha}_{\rm L}\hat{\alpha}_{\rm R} - \hat{\alpha}_{\rm R}\hat{\alpha}_{\rm L})]\right]$$



1.0
0.8
0.6
0.4
0.2
0.0
2.5
2.
1.5
1.
0.5
L(fm)
<χ>/f_χ
m_χ = 720 MeV
m_χ = 1000 MeV
m_χ = 2000 MeV

Ⅳ. Summary & Discussion

Summary

We have applied the skyrmion picture to

- dense baryonic matter
- in-medium hadron properties

Skyrmion picture provides us

- simple & easy tools
- non-trivial information (to be checked by experiments)

If you need to modify the hadron properties to analyze or fit data from experiments or the observations related to dense matter, please remember

감사합니다!