# QCD Symmetries in eta and etaprime mesic nuclei

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Looking for evidence of gluonic degrees of freedom in low energy QCD:

Confinement and dynamical (chiral) symmetry breaking

$$SU_L(3) \times SU_R(3) \times U_A(1)$$

Expect nonet of pseudoscalar Goldstone bosons

Pions and Kaons fit in this picture

The masses of the eta and eta´ are 300-400 MeV too big !

→ Famous axial U(1) problem of QCD

Additional mass is associated with non-perturbative gluon dynamics

Using nuclei to probe singlet degrees of freedom and QCD symmetries:

→ How should the eta and eta-prime masses be modified in nuclei ?

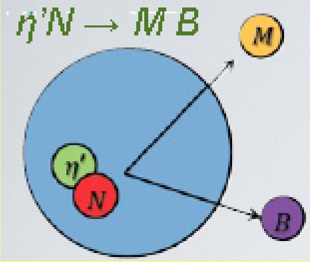
→ *Possible bound states and eta(-prime) nucleon scattering lengths*

Cracow, September 23 2013

# Experiments: What to expect ?

- ELSA

## search for η'-mesic states - exclusive measurement




measurement of η'N formation and decay

BGO-OD@ELSA

H. Schmieden, P. Levi Sandri

$^{12}C(\gamma,p)\ \eta' X$ @ 2.8 GeV

4π acceptance

- GSI

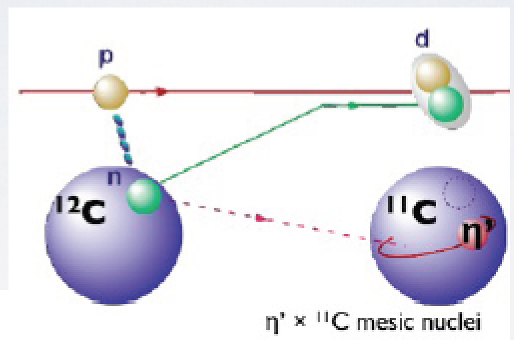
## spectroscopy of η'-mesic state: inclusive measurement

η'PRiME

missing mass measurement
of (p,d) reaction with FRS@GSI

K. Itahashi *et al.*, Prog. Theo. Phys. 128(2012) 601

$^{12}C(p,d)\ \eta' X$ @ 2.5 GeV

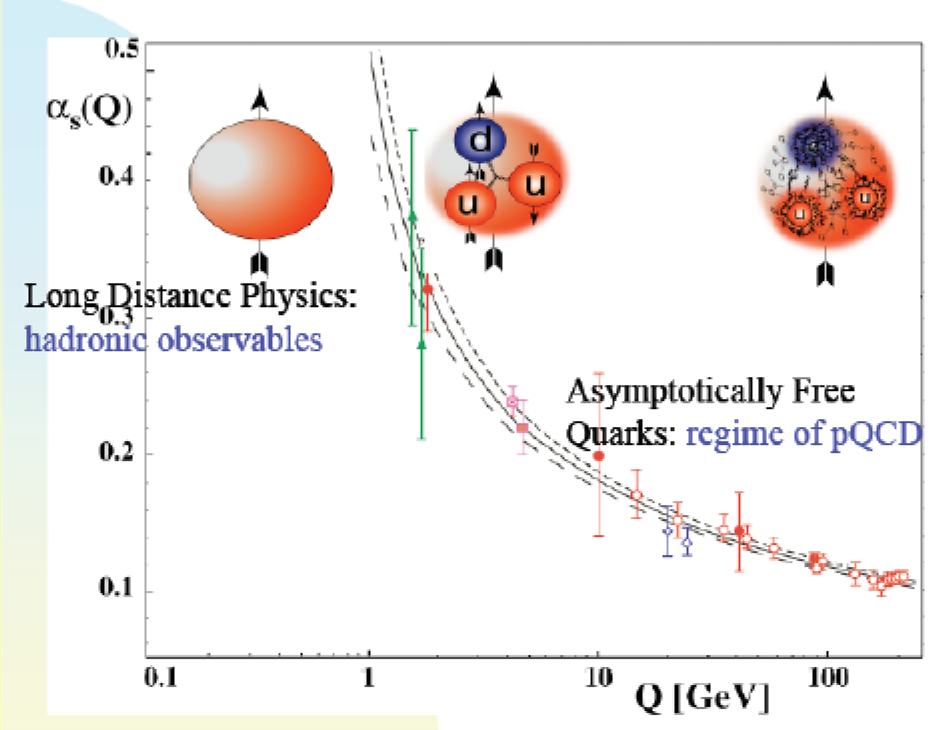



- COSY
  WASA, ANKE ...

Channels: $dd \to (^4\text{He-}\eta)_{bs} \to {}^3\text{He}p\pi^-$
$dd \to (^4\text{He-}\eta)_{bs} \to {}^3\text{He}n\pi^0 \to {}^3\text{He}n\gamma\gamma$

## Search for $\eta$-mesic nuclei with WASA-at-COSY

# From Quarks to Hadrons




- Confinement
- Dynamical chiral symmetry breaking:
  - » Chiral condensate, pions, kaons, … Goldstone bosons
- Axial U(1) Symmetry breaking … Big masses for eta and etaprime
- Using nuclei to probe symmetries and possible restoration (both quark and gluonic effects)

# Chiral symmetry

- QCD Lagrangian with massless quarks exhibits chiral symmetry

$$\mathcal{L}_{QCD} = \sum_q \bar{q}_L \left(i\hat{D} - g\hat{A}\right) q_L + \bar{q}_R \left(i\hat{D} - g\hat{A}\right) q_R - \sum_q m_q \left(\bar{q}_L q_R + \bar{q}_R q_L\right) - \frac{1}{2} G_{\mu\nu} G^{\mu\nu}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\alpha}.\vec{\tau}\gamma_5} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad , \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\beta}.\vec{\tau}\gamma_5} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

- Noether currents

$$J^{(3)}_{\mu 5} = \left[\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d\right] \qquad \partial^\mu J^{(3)}_{\mu 5} = 2m_u \bar{u} i\gamma_5 u - 2m_d \bar{d} i\gamma_5 d$$

- No parity doublets in hadron spectrum → Spontaneous Chiral symmetry breaking: non zero condensate $\langle \text{ vac } | \bar{q}q | \text{ vac } \rangle < 0$ spontaneously breaks the symmetry

  → Nonet of near massless Goldstone bosons with $J^P = 0^-$

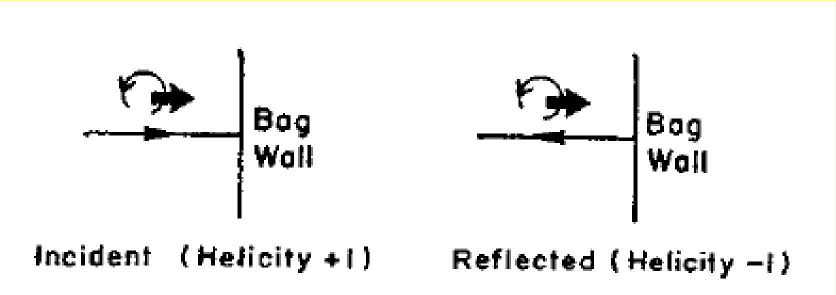
- Identify with pion, kaon, eta with meson mass squared proportional to $m_q$

$$m^2_{\eta_8} = \frac{4}{3} m^2_K - \frac{1}{3} m^2_\pi$$

… where is the singlet boson ?

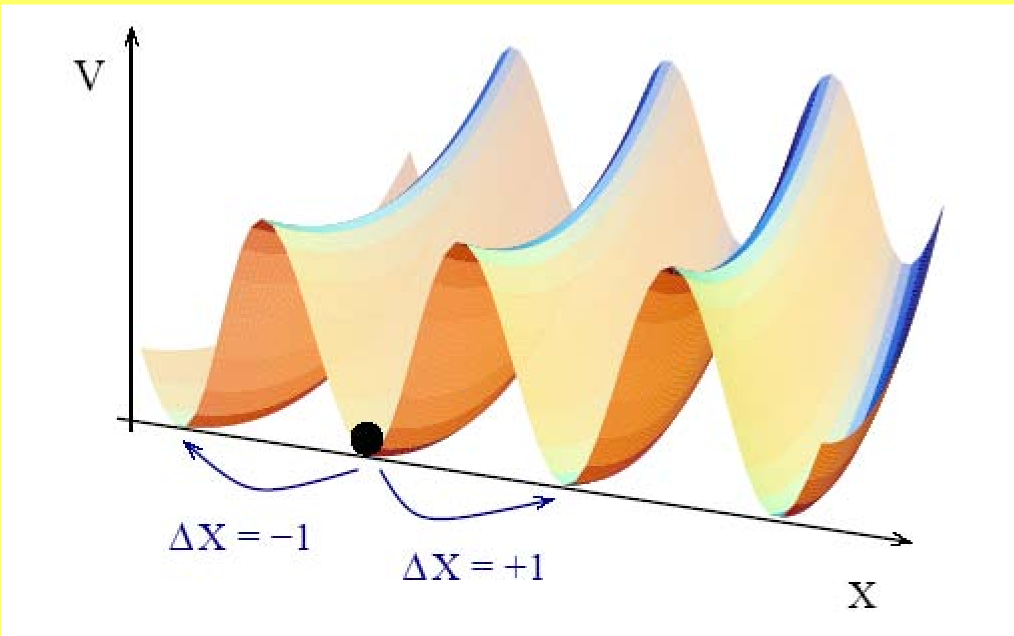
# Confinement and chiral symmetry

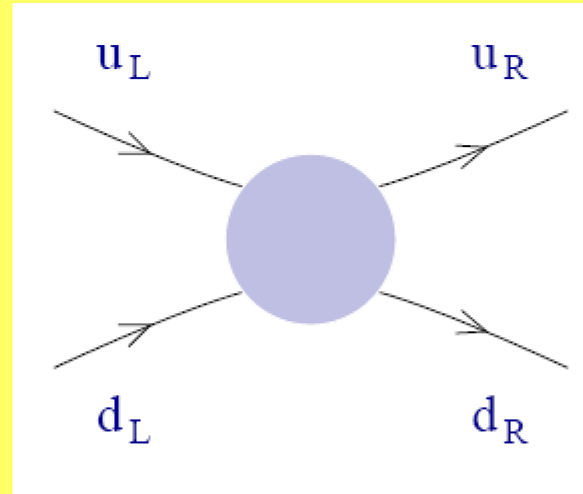
- Scalar confinement dynamically breaks chiral symmetry,
  - E.g. Bag model confinement
- Pions, kaons, eta ... as Goldstone bosons

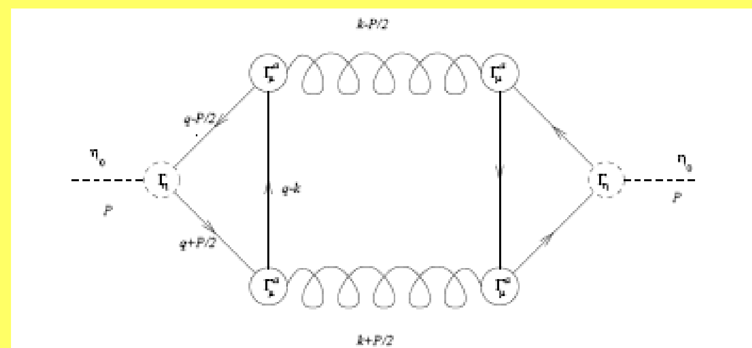


# Chirality and anomalous glue

- Perturbative QCD conserves chirality for massless quarks
- Confinement and vacuum tunneling processes (instantons, …) connect left and right handed quarks



$$\Gamma_\mu D^{\mu\nu} \Gamma_\nu \propto 1/k^4$$

# Eta and Etaprime masses

- Mass matrix

$$M^2_{\eta-\eta'} = \begin{pmatrix} \frac{4}{3}m^2_{\rm K} - \frac{1}{3}m^2_\pi & -\frac{2}{3}\sqrt{2}(m^2_{\rm K} - m^2_\pi) \\ -\frac{2}{3}\sqrt{2}(m^2_{\rm K} - m^2_\pi) & [\frac{2}{3}m^2_{\rm K} + \frac{1}{3}m^2_\pi + \tilde{m}^2_{\eta_0}] \end{pmatrix}$$

- Diagonalize

$$\begin{aligned} |\eta\rangle &= \cos\theta\ |\eta_8\rangle - \sin\theta\ |\eta_0\rangle \\ |\eta'\rangle &= \sin\theta\ |\eta_8\rangle + \cos\theta\ |\eta_0\rangle \end{aligned}$$

- Eigenvalues

$$m^2_{\eta',\eta} = (m^2_{\rm K} + \tilde{m}^2_{\eta_0}/2) \pm \frac{1}{2}\sqrt{(2m^2_{\rm K} - 2m^2_\pi - \frac{1}{3}\tilde{m}^2_{\eta_0})^2 + \frac{8}{9}\tilde{m}^4_{\eta_0}}.$$

$$m^2_\eta + m^2_{\eta'} = 2m^2_K + \tilde{m}^2_{\eta_0}.$$

- With no glue:
  chiral symmetry „predicts" eigenstates with masses 300 MeV „too small"
  - » „eta" $(\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle)$ degenerate with the pion
  - » „etaprime" $|\bar{s}s\rangle$ with mass $\sqrt{2m^2_K - m^2_\pi}$

# Axial U(1) symmetry

- Extra gluonic mass term is associated with the QCD axial anomaly

$$J_{\mu 5} = \left[\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s\right]$$

$$\partial^\mu J_{\mu 5} = \sum_{k=1}^{f} 2i\left[m_k \bar{q}_k \gamma_5 q_k\right] + N_f\left[\frac{\alpha_s}{4\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

- plus gluon topology (note the difference with „perturbative glue")

- ´t Hooft, Veneziano, Witten, Crewther, …
  - possible connection to confinement (Kogut and Susskind)

*Can we observe physical manifestation of this anomalous glue in low-energy physical processes involving eta and eta´ mesons ?*

→ For review see SDB, Acta Phys Pol B Suppl 2 (2009) 11.

# Glue in etaprime physics

- Glue enters through the anomaly equation …
- Three important places it can contribute
    - » Gluonic potential associated with QCD vacuum gives the etaprime a big mass
    - » The etaprime has a large singlet component
      → coupling to gluonic intermediate states (OZI violation)
    - » Gluonic Fock components in the etaprime wavefunction

# Eta(prime) bound states in nuclei

[SDB + AW Thomas, Phys Lett B634 (2006) 368]

- New experiments + big effort ...
- Binding energies and effective masses in nuclei are sensitive to
  - Coupling to scalar sigma field in the nuclei in mean field approx.
  - Nucleon-nucleon and nucleon-hole excitations in the medium
- TH: Solve for the meson self-energy in the medium

$$k^2 - m^2 = \text{Re }\Pi(E, \vec{k}, \rho)$$

$$\Pi(E, \vec{k}, \rho)\Big|_{\{\vec{k}=0\}} = -4\pi\rho\left(\frac{b}{1 + b\langle\frac{1}{r}\rangle}\right). \qquad b = a(1 + \frac{m}{M})$$

  - Where a is the „eta(prime)-nucleon scattering length“

# Eta bound-states in nuclei

- Sigma mean field couples to light quarks and not to strange quarks
  → Flavour-singlet component is important !
  The bigger the eta-eta´ mixing angle, the bigger the singlet component in the eta
  → greater the attraction
  → more binding
  → bigger eta-N scattering length
  Likewise, more mixing gives smaller singlet component in the eta'
  → reduced binding and smaller eta'N scattering length

QCD arguments

→ gluonic mass term is suppressed in the medium

but TH technology to calculate the size of the effect direct from QCD still some time away

→ look at QCD inspired models

# QCD and models

- Include key aspects of QCD as input motivation
  - » Confinement
  - » Chiral symmetry
  - » Eta-etaprime mixing

- Quark-meson coupling, chiral coupled channels, NJL, linear sigma model... include different aspects of QCD input with very different predictions

- Suppose we see a bound state or mass shift ☺
  - » What do we learn about QCD ?

# U(1) extended chiral Lagrangian

- Low energy effective Lagrangian

$$\mathcal{L}_{\rm m} = \frac{F_\pi^2}{4}{\rm Tr}(\partial^\mu U \partial_\mu U^\dagger) + \frac{F_\pi^2}{4}{\rm Tr}\left[\chi_0 \left(U + U^\dagger\right)\right] + \frac{1}{2} i Q {\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2.$$

$$U = \exp\left(i\frac{\phi}{F_\pi} + i\sqrt{\frac{2}{3}}\frac{\eta_0}{F_0}\right)$$

- Q represents the topological charge density.

  The gluonic potential

$$\frac{1}{2} i Q {\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2 \;\; \mapsto \;\; -\frac{1}{2}\tilde{m}_{\eta_0}^2 \eta_0^2$$

  yields the gluonic contribution to the etaprime mass term

- Couple to sigma mean field and repeat …

$$\mathcal{L}_\sigma = \frac{F_\pi^2}{4}{\rm Tr} M \, \left(U + U^\dagger\right) \, g_\sigma^M \sigma + Q^2 \, g_\sigma^Q \sigma$$

$$\tilde{m}_{\eta_0}^2 \mapsto \tilde{m}_{\eta_0}^{*2} = \tilde{m}_{\eta_0}^2 \, \frac{1+2x}{(1+x)^2} \; < \tilde{m}_{\eta_0}^2$$

where

$$x = \frac{1}{3} g_\sigma^Q \sigma \; \tilde{m}_{\eta_0}^2 F_0^2 .$$

# QCD Inspired Models

- Quark Meson Coupling Model:
  - Can vary the mixing angle !
  - Use large eta and eta´ masses to treat the eta and eta´ as MIT Bags embedded in the medium with coupling between the light-quarks and the sigma mean field

Solve for in-medium mass and binding energy

→ Extract an „effective“ scattering length for the model

→ Increases with increasing singlet component in the eta !

| | $m$ (MeV) | $z$ | $m^*$ (MeV) | Re$a$ (fm) |
|---|---|---|---|---|
| $\eta_8$ | 547.75 | 3.31 | 500.0 | 0.43 |
| $\eta$ (-10°) | 547.75 | 3.15 | 474.7 | 0.64 |
| $\eta$ (-20°) | 547.75 | 3.00 | 449.3 | 0.85 |
| $\eta_0$ | 958 | 1.46 | 878.6 | 0.99 |
| $\eta'$ (-10°) | 958 | 1.62 | 899.2 | 0.74 |
| $\eta'$ (-20°) | 958 | 1.76 | 921.3 | 0.47 |

For etaprime $V_{\text{real}} \sim -48 \pm 11 \ MeV$

# Eta-etaprime mixing and mass shift

- Phenomenological fits to EP data
  - » On-shell Re[a_eta] ~ 0.9 fm [Green + Wycech, Arndt et al]
  - » COSY-11 ~ 0.7 fm from FSI in pp → pp eta
  - » Re[a_eta´] < 0.8fm, prefer |a_eta´|~ 0.1 fm

- Chiral coupled channels treating the eta as a pure octet state
  - » Small mass shift and small Re[a_eta] ~ 0.2 fm
  - » For etaprime: new Nagahiro et al., consider range of |a_eta´|

- N*(1535)
  - 3 quark state (1s)2(1p) in Quark model and lattice calculations

    or

    K-Sigma quasi-bound state from Chiral coupled channels in octet approx.

  - In data and in both QMC and chiral coupled channels models, negligible shift in excitation energy in nuclei

# Bound states in finite nuclei

NH
ELSEVIER
Nuclear Physics A670 (2000) 198c–201c

Study of $\omega$-, $\eta$-, $\eta'$- and $D^-$-mesic nuclei

K. Tsushima[a] *

Table 1
$\eta$, $\omega$ and $\eta'$ bound state energies (in MeV), $E_j = Re(E_j^* - m_j)$ $(j = \eta, \omega, \eta')$, where a
widths for the $\eta'$ are set to zero. The eigenenergies are given by, $E_j^* = E_j + m_j - i\Gamma_j/2$

| | | $\gamma_\eta = 0.5$ | | $\gamma_\omega$=0.2 | | $\gamma_{\eta'} = 0$ |
|---|---|---|---|---|---|---|
| | | $E_\eta$ | $\Gamma_\eta$ | $E_\omega$ | $\Gamma_\omega$ | $E_{\eta'}$ |
| $^6_j$He | 1s | -10.7 | 14.5 | -55.6 | 24.7 | * (not calculated) |
| $^{11}_j$B | 1s | -24.5 | 22.8 | -80.8 | 28.8 | * |
| $^{26}_j$Mg | 1s | -38.8 | 28.5 | -99.7 | 31.1 | * |
| | 1p | -17.8 | 23.1 | -78.5 | 29.4 | * |
| | 2s | — | — | -42.8 | 24.8 | * |
| $^{16}_j$O | 1s | -32.6 | 26.7 | -93.4 | 30.6 | -41.3 |
| | 1p | -7.72 | 18.3 | -64.7 | 27.8 | -22.8 |
| $^{40}_j$Ca | 1s | -46.0 | 31.7 | -111 | 33.1 | -51.8 |
| | 1p | -26.8 | 26.8 | -90.8 | 31.0 | -38.5 |
| | 2s | -4.61 | 17.7 | -65.5 | 28.9 | -21.9 |
| $^{90}_j$Zr | 1s | -52.9 | 33.2 | -117 | 33.4 | -56.0 |
| | 1p | -40.0 | 30.5 | -105 | 32.3 | -47.7 |
| | 2s | -21.7 | 26.1 | -86.4 | 30.7 | -35.4 |
| $^{208}_j$Pb | 1s | -56.3 | 33.2 | -118 | 33.1 | -57.5 |
| | 1p | -48.3 | 31.8 | -111 | 32.5 | -52.6 |
| | 2s | -35.9 | 29.6 | -100 | 31.7 | -44.9 |

- -10 degrees mixing angle
- Eta Binding energy
  -10.7 MeV in $^6$He
  - (14-15) MeV with -20 degrees

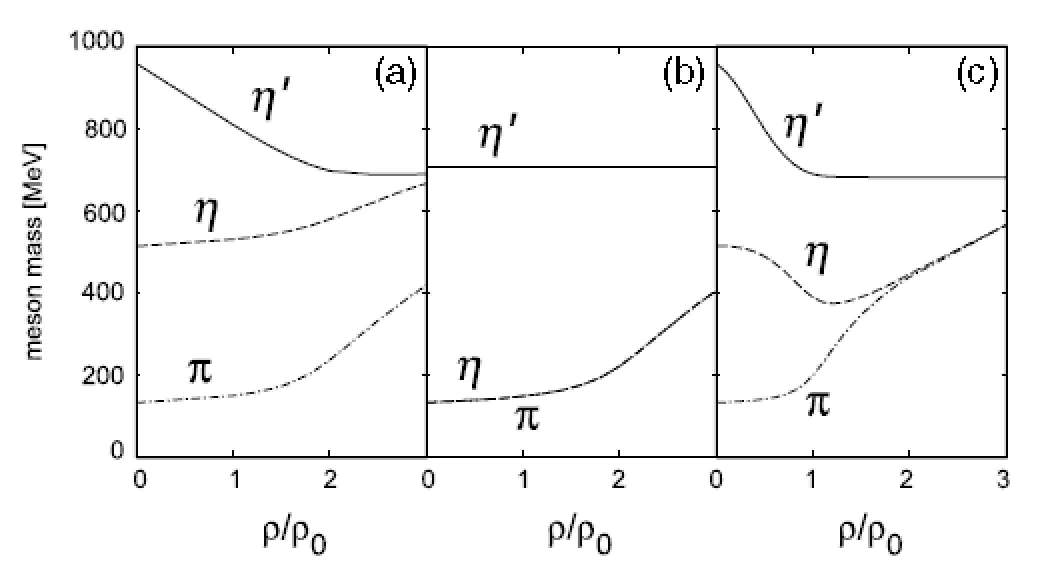
- For etaprime in Carbon 12
- Binding energy
  - (22-37) MeV for mixing angles -20 and -10 degrees

# Comparison with NJL

- NJL model using density dependent instanton interaction
  - QCD input: chiral symmetry, no confinement, medium a Fermi gas of quarks instead of nucleons, mass shift for the eta´ up to ~ 150 MeV
    - » Phys Rev C74 (2006) 045203

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_4 + \mathcal{L}_6,$$
$$\mathcal{L}_0 = \bar{\psi}\left(i\partial_\mu\gamma^\mu - \hat{m}\right)\psi,$$
$$\mathcal{L}_4 = \frac{g_S}{2}\sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}\lambda^a i\gamma_5\psi)^2],$$
$$\mathcal{L}_6 = g_D\{\det[\bar{\psi}_i(1-\gamma_5)\psi_j] + \text{h.c.}\}.$$

$$\text{(a) } g_D(\rho) = g_D$$
$$\text{(b) } g_D(\rho) = 0$$
$$\text{(c) } g_D(\rho) = g_D\exp[-(\rho/\rho_0)^2],$$




- Suppose eta-eta´ mass splitting comes just from anomaly, proportional to quark condensate → 80-100 MeV mass shift
  - » Phys Rev C85 (2012) 032201, arXiv:1309.4845

# Outlook and Conclusions

- Eta and etaprime physics probes the role of long range gluonic dynamics
- Etas and etaprimes in nuclei:
  - Aspects of Confinement, chiral symmetry and their interplay
  - Binding energies and scattering lengths sensitive to the flavour-singlet component in the eta
  - QMC model:
    - » Factor of 2 increase in the eta-nucleon scattering length and binding energy in nuclei with eta-etaprime mixing cf. Theory prediction with a pure octet eta
    - » N*(1535) as 3 quark state $(1s)^2(1p)$

... Awaits experimental input!

.. ELSA, GSI (etaprime), COSY (eta).