Mesons in nuclei and partial restoration of chiral symmetry

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KEK Tokai campus, Tokai, Japan

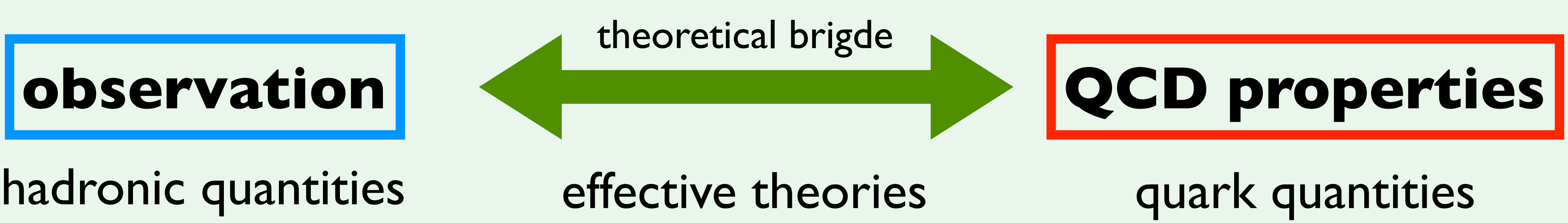
Contents

- introduction
  partial restoration of chiral symmetry in nuclear medium
- what we expect in partial restoration
- η' meson in nuclear medium
- other topics
  role of anomaly term in spontaneous breaking
  diquark-quark potential in heavy baryon

Motivation

hadrons in nuclei = systems of hadron and nucleus

- as **hadron physics**
    - a tool to investigate QCD vacuum structure, such as mechanism of spontaneous **chiral symmetry** breaking
    - QCD vacuum structure can change in different environments
    - nucleus provides us a finite density system
- for **other research areas**
    - we obtain important constraints on high density physics with controlled experiments on the earth



Partial restoration of chiral symmetry

- nuclear matter is a finite density system
- its density is not high enough for complete restoration of symmetry
- partial (or incomplete) restoration takes place in nuclear matter with sufficient reduction of the magnitude of the quark condensate $\langle \bar{q}q \rangle$

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model-independent theoretical relation

$$\langle \bar{q} q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2} \rho \right) \langle \bar{q} q \rangle + \mathcal{O}(\rho^{n>1})$$

$\sigma_{\pi N}$: πN sigma term, $O(m_q)$, obtained from $T_{\pi N}$ at soft limit

low density expansion

$$\langle \bar{q} q \rangle^* = \langle 0 | \bar{q} q | 0 \rangle + \rho \langle N | \bar{q} q | N \rangle + \mathcal{O}(\rho^{n>1})$$

negative **$\sigma_{\pi N}$: positive**

Drukarev, Levin,
Prog. Part. Nucl. Phys. 27, 77 (1991)

$\pi N \sigma$ term

$$2 m_q \langle N | \bar{q} q | N \rangle = \sigma_{\pi N}$$

Gell-Mann Oakes Renner relation

$$m_\pi^2 f_\pi^2 = -2 m_q \langle \bar{q} q \rangle$$

- 30-40 % reduction at saturation density, if one believes linear extrapolation
- quark condensate is not direct observable, but hadronic quantities like fpi are.

Partial restoration of chiral symmetry

phenomenological confirmation

- pionic atom and pion-nucleus scattering experiments, together with theoretical consideration, have suggested that chiral symmetry is partially restored in nuclear matter with 35% reduction of quark condensate

pionic atom

K. Suzuki et al. PRL92, 072302 (04)

pion-nucleus scattering

Friedman et al. PRL93, 122302 (04)

+

theoretical consideration

Kolomeitsev, Kaiser, Weise, PRL90, 092501 (03). → 35% reduction

DJ, Hatsuda, Kunihiro, PLB 670, 109 (08).

spectrum/cross section
→ π-A optical potential

effective theory
translates more fundamental quantities

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effective theory
translates more fundamental quantities

theoretical issue density dependence of quark condensate
(beyond the linear density approximation)

phenomenological issue other phenomena expected by partial restoration
(other meson-nucleus system than pion)

Expectations in partial restoration

- reduction of mass generated by chiral symmetry breaking

- masses of some hadrons are generated by ChSB
- (a part of) nucleon mass is generated by ChSB
  in-medium effective mass of nucleon is 0.7m_N in RMF

η'

- a part of η' mass is generated by ChSB
- large scalar potential for in-medium η'

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

- reduction of mass difference between chiral partners

- chiral partners should degenerate in chiral restoration limit
- reduce the mass difference in partial restoration
  (more precisely, their spectral functions tend to degenerate)

η

η meson has strong coupling to N*(1535)
in medium η meson probes chiral symmetry of N and N*

DJ, Nagahiro, Hirenzaki, PRC66, 045202 (02).
Nagahiro, DJ, Hirenzaki, PRC68, 035805 (03); NPA761, 92 (05)
DJ, Kolomeitsev, Nagahiro, Hirenzaki, NPA811,158 (08)

Expectations in partial restoration

- wave function renormalization for Nambu-Goldstone boson

- NG bosons are described by chiral effective theory
  ChPT : expansion of NG boson momentum (and quark mass)
- energy dependent interactions with nucleon
  vanish in the soft limit (q -> 0) and chiral limit (Adler zero)
- large wave function renormalization

$$Z = \left(1 - \frac{\partial \Sigma}{\partial p_0^2}\right)^{-1}$$

Σ : self-energy

in medium, various quantities changes

K^+, π^0

Aoki, DJ, PTEP 2017, 103D01.

- enhancement of K^+-nucleus elastic scattering
- 40% enhancement of $\pi^0 \rightarrow \gamma\gamma$ decay

Goda, DJ, PTEP 2014, 033D03.

η' meson

η' meson and chiral symmetry

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

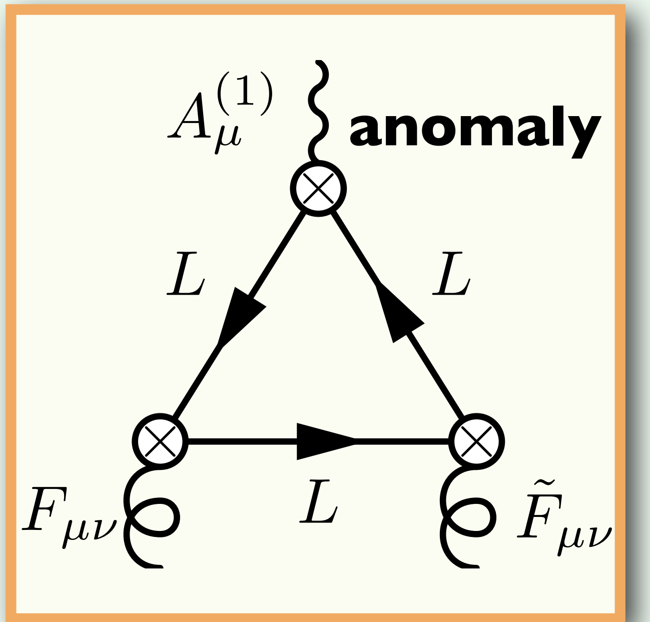
$\eta'(958)$ $I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

- η' meson would be a Nambu-Goldstone boson associated with the spontaneous $U_A(1)$ chiral symmetry breaking.
- $U_A(1)$ symmetry is actually broken by quantum effect (quantum anomaly).
  thus, η' meson is NOT a Nambu-Goldstone boson.
  this is the reason that η' meson has a large mass.
- thanks to vector couplings,
  chirality does not change in anomaly diagram
- pseudoscalar meson is composed of a pair of right and left quarks.

$$\bar{q}\gamma_5 q = \bar{q}_L q_R - \bar{q}_R q_L$$

- **SU(3) chiral symmetry is necessarily broken, when the anomaly affects η' mass**



anomaly breaks $U_A(1)$ without changing chirality

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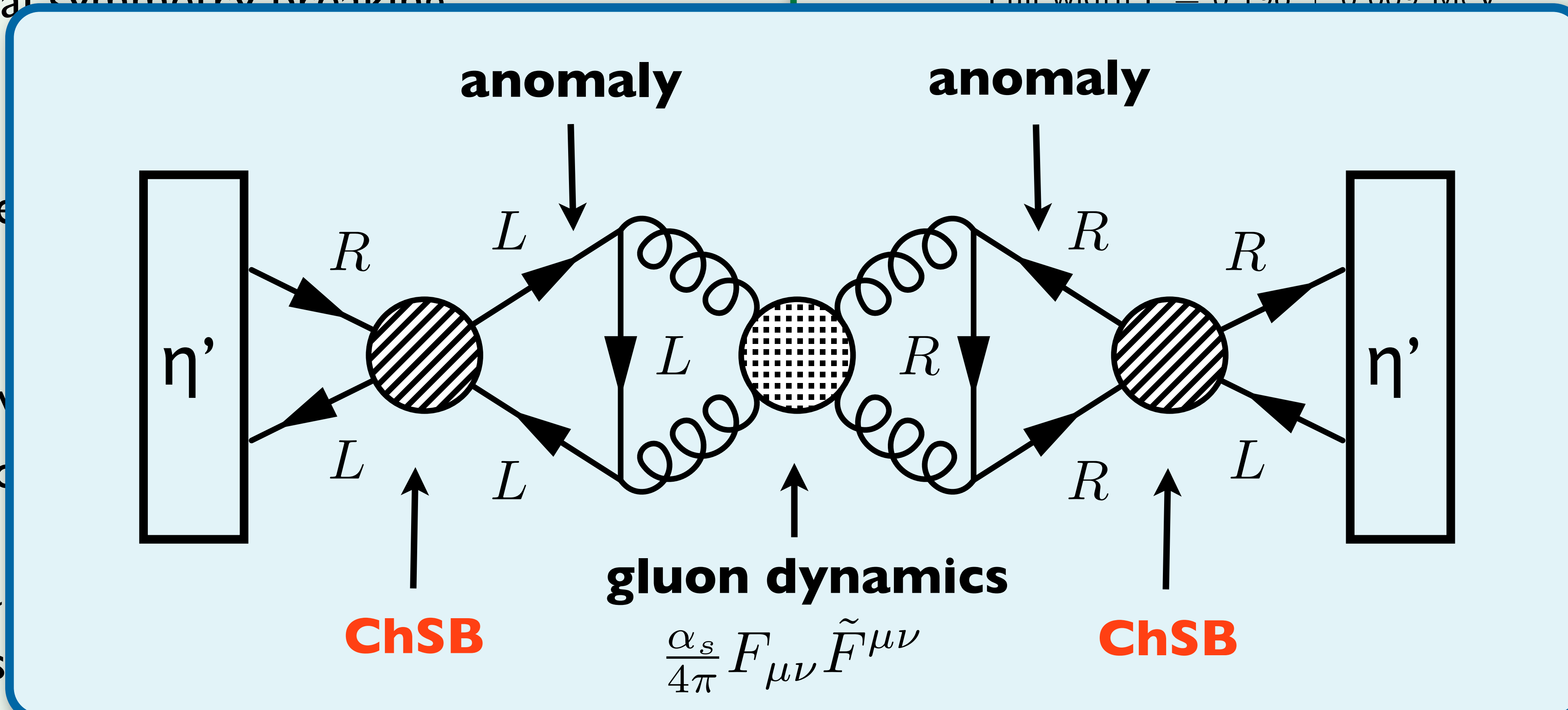

aly

$\tilde{F}_{\mu\nu}$

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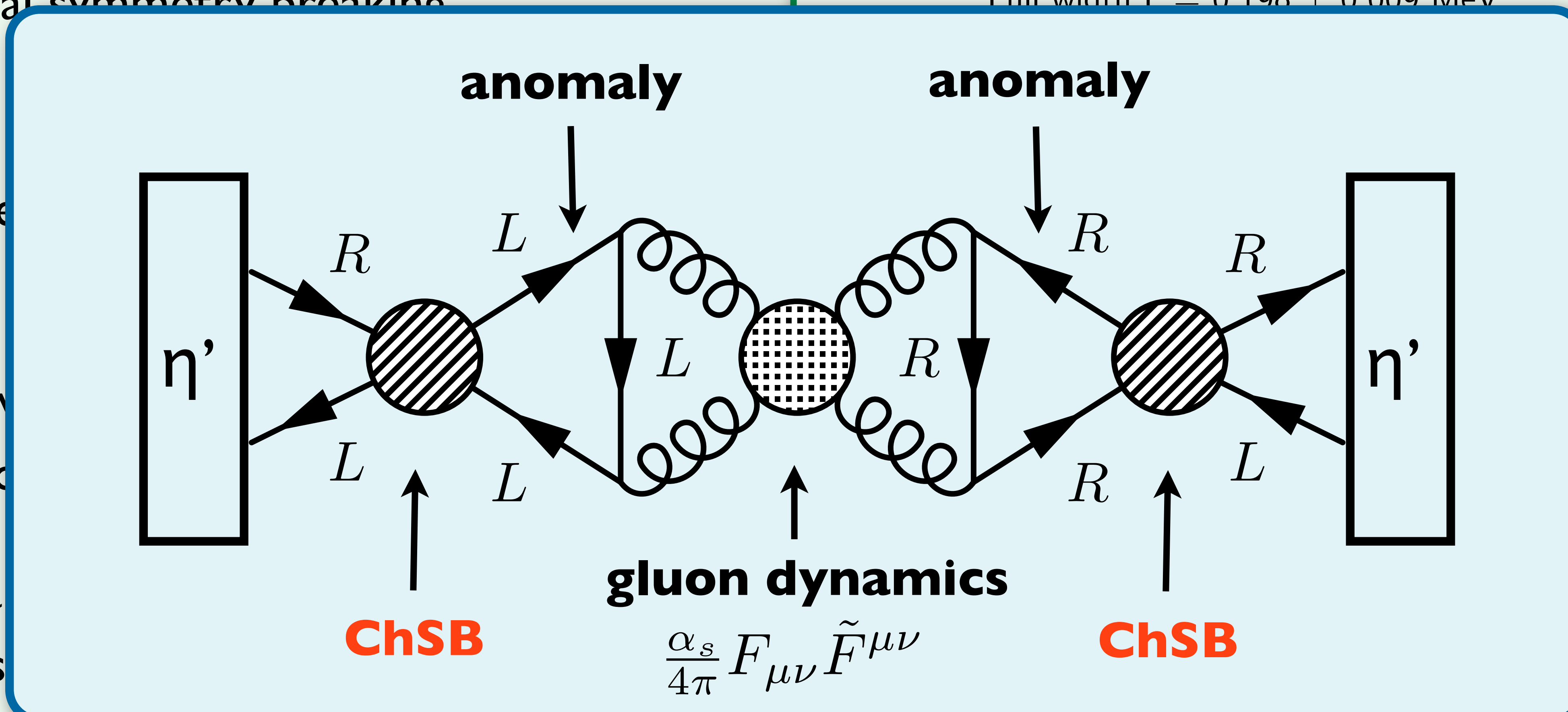

- **SU(3) chiral symmetry is necessarily broken, when the anomaly affects η' mass**

anomaly breaks $U_A(1)$ without changing chirality

- because quark masses are small, spontaneous breaking induces the η' mass generation. therefore, once partial restoration takes place, η' mass should be reduced.

η' meson in chiral restoration

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)
DJ, Sakai, Nagahiro, Hirenzaki, Ikeno, NPA914 (13) 354

a group theoretical argument

- Let us consider chiral $SU(3)_L \times SU(3)_R$ symmetry, because **$U_A(1)$ is always broken by anomaly**

Scalar and Pseudoscalar mesons

$$(\bar{\mathbf{3}}, \mathbf{3}) \oplus (\mathbf{3}, \bar{\mathbf{3}}) \qquad \bar{q}_i^L q_j^R \qquad \bar{q}_i^R q_j^L$$

parity eigenstate

9 scalar and 9 pseudoscalar

$$\bar{q}_i \gamma_5 q_j \, , \bar{q}_i q_j$$

$$\bar{\mathbf{3}} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8}$$

contains both octet and singlet

σ_0	π, K, η_8	η_0	a_0, κ, f_0
scalar singlet	**pseudoscalar octet**	**pseudoscalar singlet**	**scalar octet**

- In fact, η0 and η8 are in the same multiplet even **without $U_A(1)$ symmetry**

Therefore, when chiral symmetry is restored,
η_8 and η_0 get degenerate in chiral limit

dynamical study was performed by Cohen and Lee-Hatsuda

Cohen, PRD54, 1867 (1996)
Lee, Hatsuda, PRD54, 1871 (1996)

η' meson in nuclear matter

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

the mass gap of η' and η is generated by chiral symmetry breaking

the η' mass get reduced when chiral symmetry is being restored in nuclear medium

simple order estimation

assumptions

η'-η mass difference (400 MeV) be dependent on quark condensate linearly

partial restoration of ChS take place with 30% at ρ_0

we expect strong η' mass reduction $\Delta m_{\eta'} \sim 120$ MeV @ $\rho = \rho_0$

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chiral effective theories tell similar results.

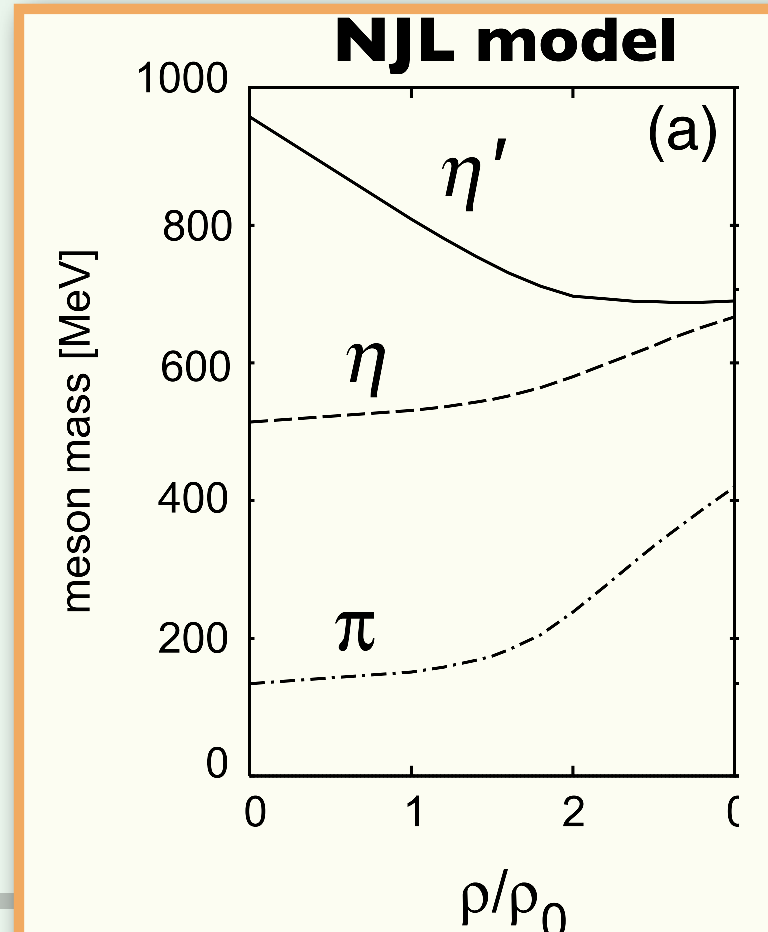
linear sigma model Sakai, DJ, PRC88 (13) 064906

$\Delta m_{\eta'} \sim 80$ MeV @ $\rho = \rho_0$

$\Delta(m_{\eta'} - m_\eta) \sim 130$ MeV @ $\rho = \rho_0$

NJL model P. Costa, M. C. Ruivo, and Y. L. Kalinovsky, PLB560, 171 (03). Nagahiro, Takizawa, Hirenzaki, PRC74,045203 (2006)

$\Delta m_{\eta'} \sim 150$ MeV @ $\rho = \rho_0$



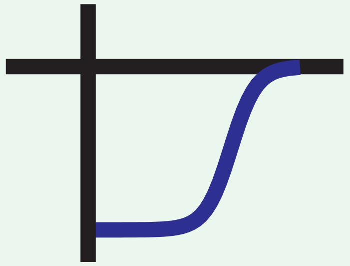
Hadrons in nuclei

- **mass reduction in infinite matter implies attractive scalar potential for finite systems**
- mass modification is described as in-medium self-energy

$$m^2(\rho) = m_0^2 + \Sigma(m^2, \rho)$$

mass reduction → attractive interaction

mass enhancement → repulsive interaction



position-dependent self-energy → potential

- for finite system, with local density approximation

$$\Sigma(\rho) \to \Sigma(\rho(r))$$

- interaction with medium corresponds to a potential in finite system
- mass modification provides a (Lorentz) scalar potential
- **for η', we expect about 100 MeV mass reduction in nuclear matter. this corresponds to a 100 MeV attractive scalar potential**.
- with this attractive potential, one expects some η' bound states in nucleus.

Possible bound state spectra

DJ, Nagahiro, Hirenzaki,
PRC85 (12) 032201(R)

mass reduction in nuclear matter provides a scalar potential in finite nucleus

a simple η’ optical potential
(Woods-Saxon type)

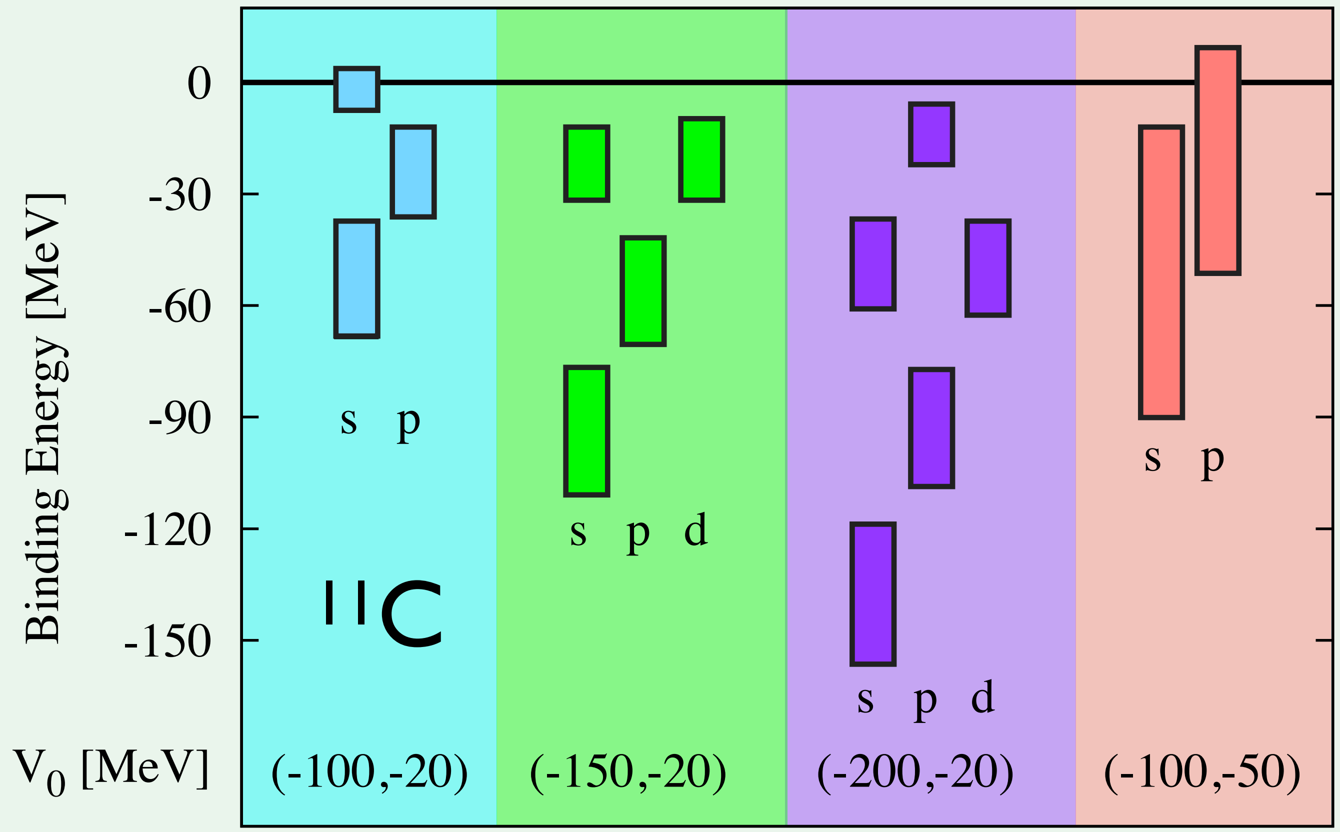
proportional to nuclear density

$$V_{\eta'}(r) = V_0 \frac{\rho(r)}{\rho_0}$$

Δm = 150 MeV
Γ/2 = 20 MeV

Re: theoretical expectation

Im: phenomenological observation



currently, no distinct structure was observed in formation experiment at GSI

Tanaka et al. (η-PRiME/Super-FRS Collaboration),
PRL117 (16) 202501; PRC97 (18) 015202

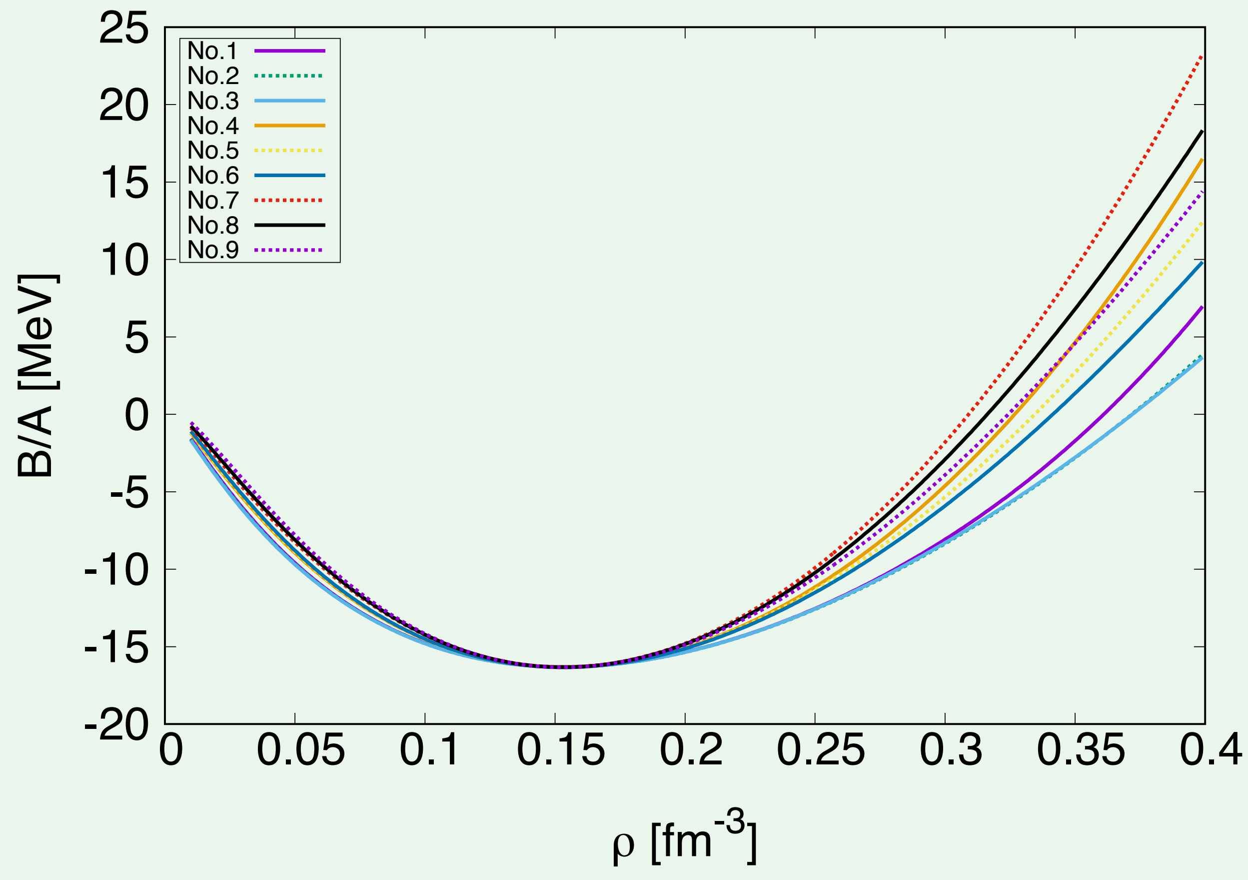
nuclear structure can be changed by strong attraction of η’-A interaction

Relativistic mean field theory

DJ, Masutani, Hirenzaki, arXiv:1808.10140 [nucl-th]

relativistic mean field theory (RMF), σ-ω model, or Walecka model

- **reproduces saturation properties of nuclear matter within the model**
- using nucleus model reproducing normal nuclei, we investigate η' mesonic nuclei
- **η' meson is treated as a matter field like nucleon** and interacts with mean fields
- η' interacts with nucleons through the σ field
- **η'σ coupling is adjusted to have 80 MeV mass reduction of η' meson at saturation density**

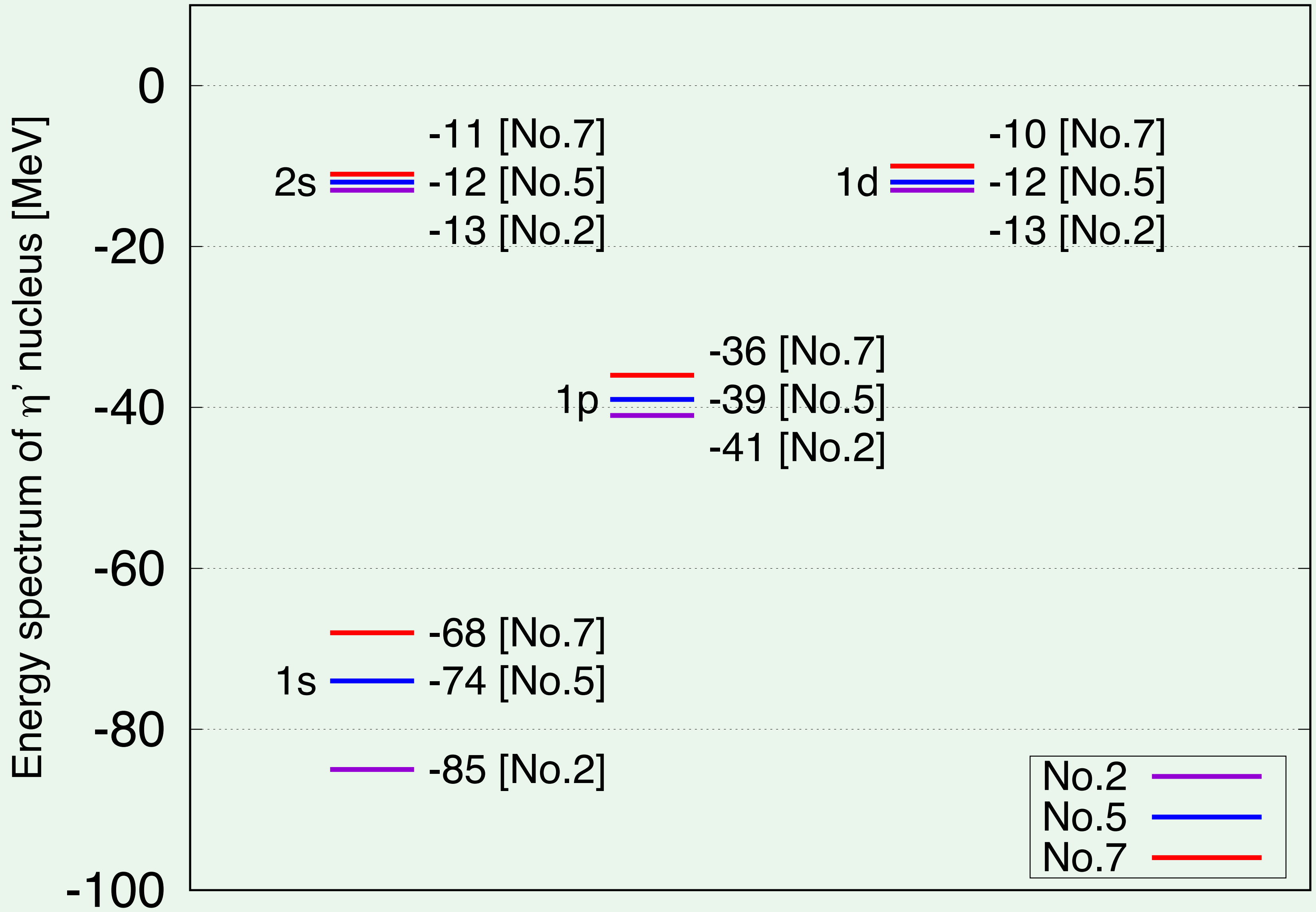


Glendenning, Compact Star, (Springer)

Relativistic mean field theory

DJ, Masutani, Hirenzaki, arXiv:1808.10140 [nucl-th]

η' bound states in ^{16}O



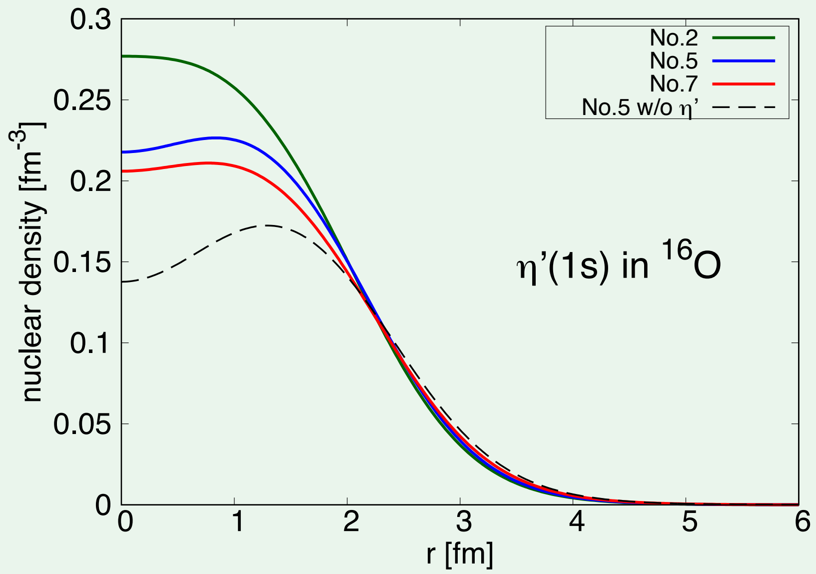
nuclear EoS
no.2: soft
no.5: medium
no.7: hard

- four bound states
- binding energies depend slightly on parameters of nuclear matter

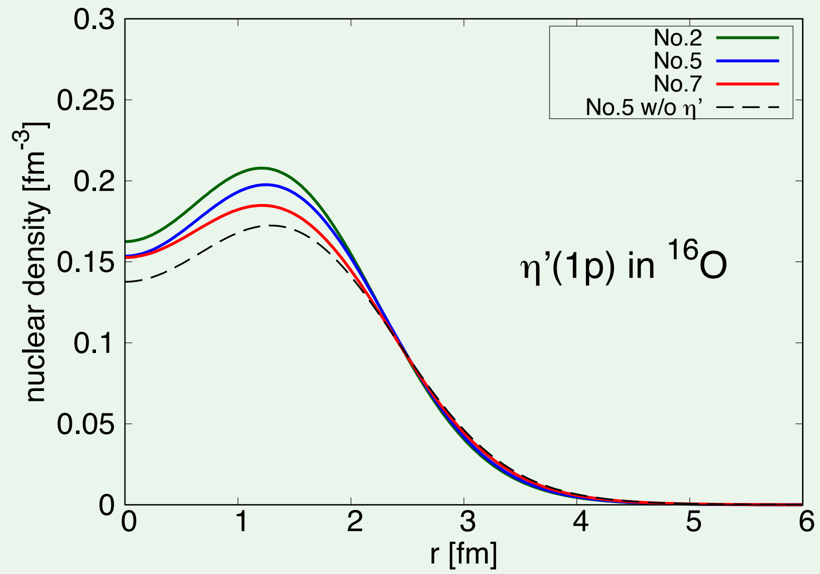
Relativistic mean field theory

DJ, Masutani, Hirenzaki, arXiv:1808.10140 [nucl-th]

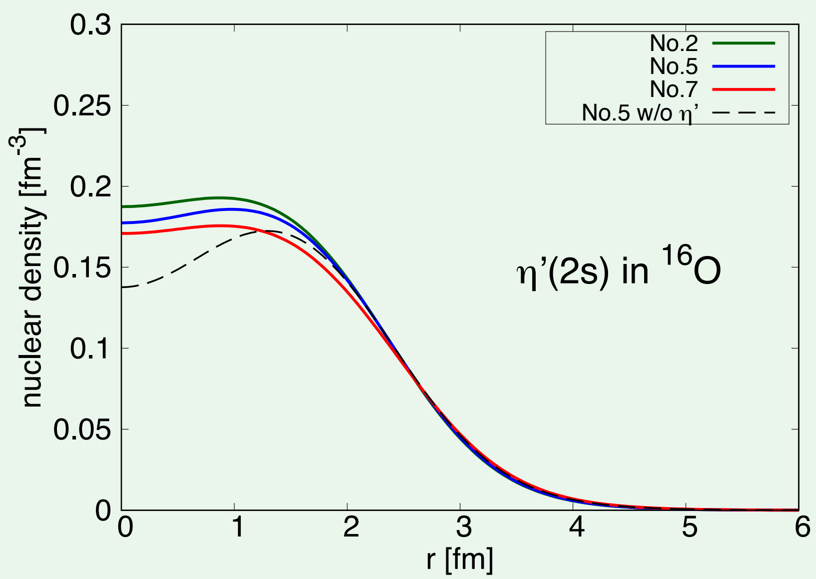
nuclear density distribution for each η' bound state



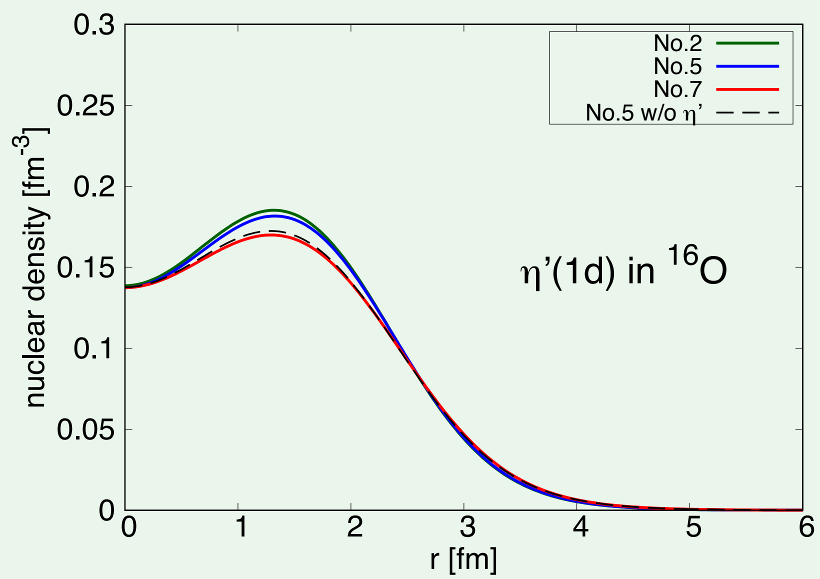
(a) 1s



(b) 1p



(c) 2s



(d) 1d

- density distribution for 1s bound state is quite different from one without η'
- it could be hard to produce such state by nuclear reaction

η'-N interaction

Sakai, DJ, PRC88 (13) 064906; PTEP2017, 013D01 (17).

linear sigma model picture

nucleon mass is generated also by spontaneous breaking of ChS

$$m_N = g\langle\sigma_0\rangle$$

→ presence of strong coupling σNN

this is the origin of the strong scalar attraction in NN interaction

in the same way

chiral symmetry breaking generates a part of eta' meson with help of anomaly

$$m_{\eta_0}^2 - m_{\eta_8}^2 = 6B\langle\sigma_0\rangle$$

→ presence of strong coupling ση'η'

B term : anomaly effect

we expect strong attraction in η'-N in scalar-isoscalar exchange

this is the origin of the mass reduction in nuclear matter

remark

some repulsion could be present in vector potential like ω exchange in nuclear force

Weinberg-Tomozawa type interaction vanishes for neutral mesons
induced by vector meson exchange

DJ, Masutani, Hirenzaki, arXiv:1808.10140 [nucl-th]

Role of anomaly term for ChS breaking

Kono (Tokyo Metropolitan University)
Jido (Tokyo Institute of Technology)
Kuroda, Harada (Nagoya University)

Role of anomaly term for ChS breaking

we believe that anomaly term plays minor role for ChS breaking

chiral symmetry is broken without anomaly term

Kono, DJ, Kuroda, Harada, in preparation

SU(3) linear σ model

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2}\mathrm{Tr}[MM^\dagger] - \frac{\lambda}{4}\mathrm{Tr}[(MM^\dagger)^2] - \frac{\lambda'}{4}\left(\mathrm{Tr}[MM^\dagger]\right)^2$$
$$- A\mathrm{Tr}[\chi M^\dagger + \chi^\dagger M] + \sqrt{3}B(\det M + \det M^\dagger)$$

explicit ChS breaking
flavor symmetry breaking

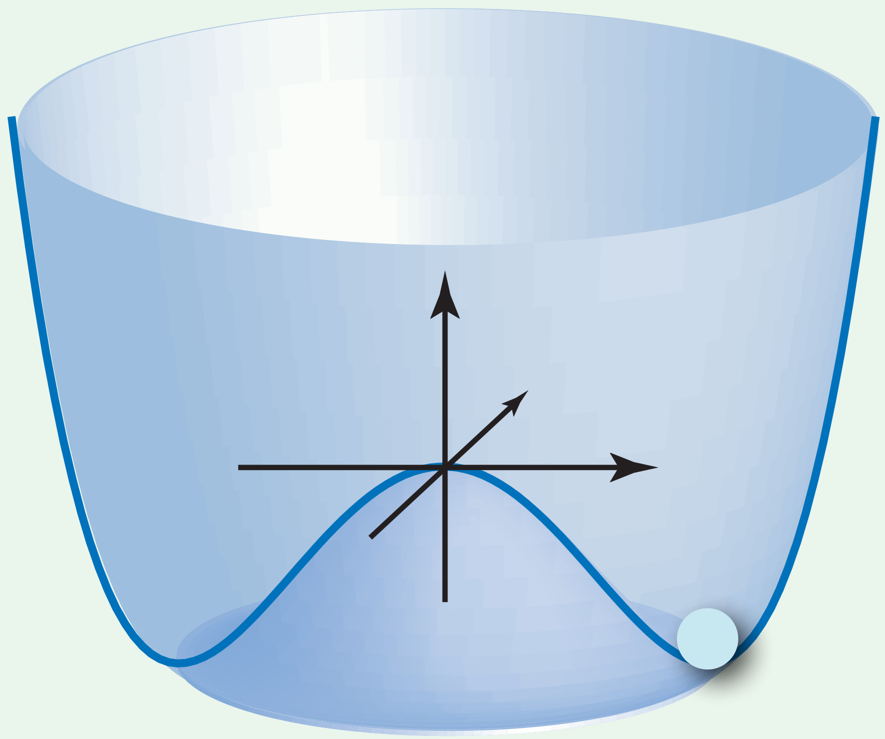
anomaly term
breaks $U_A(1)$ symmetry

- **$\mu^2 < 0$ → spontaneous breaking**

SU(3) NJL model

$$\mathcal{L} = \bar{q}(\partial\!\!\!/ - m)q + g_s\left[\left(\bar{q}\frac{\lambda_a}{2}q\right)^2 + \left(\bar{q}i\gamma_5\frac{\lambda_a}{2}q\right)^2\right]$$
$$+ \frac{g_d}{2}\{\det[\bar{q}(1+\gamma_5)q] + \det[\bar{q}(1-\gamma_5)q]\}$$

- **$g_s > g_{s\,\mathrm{crit}}$ → spontaneous breaking**

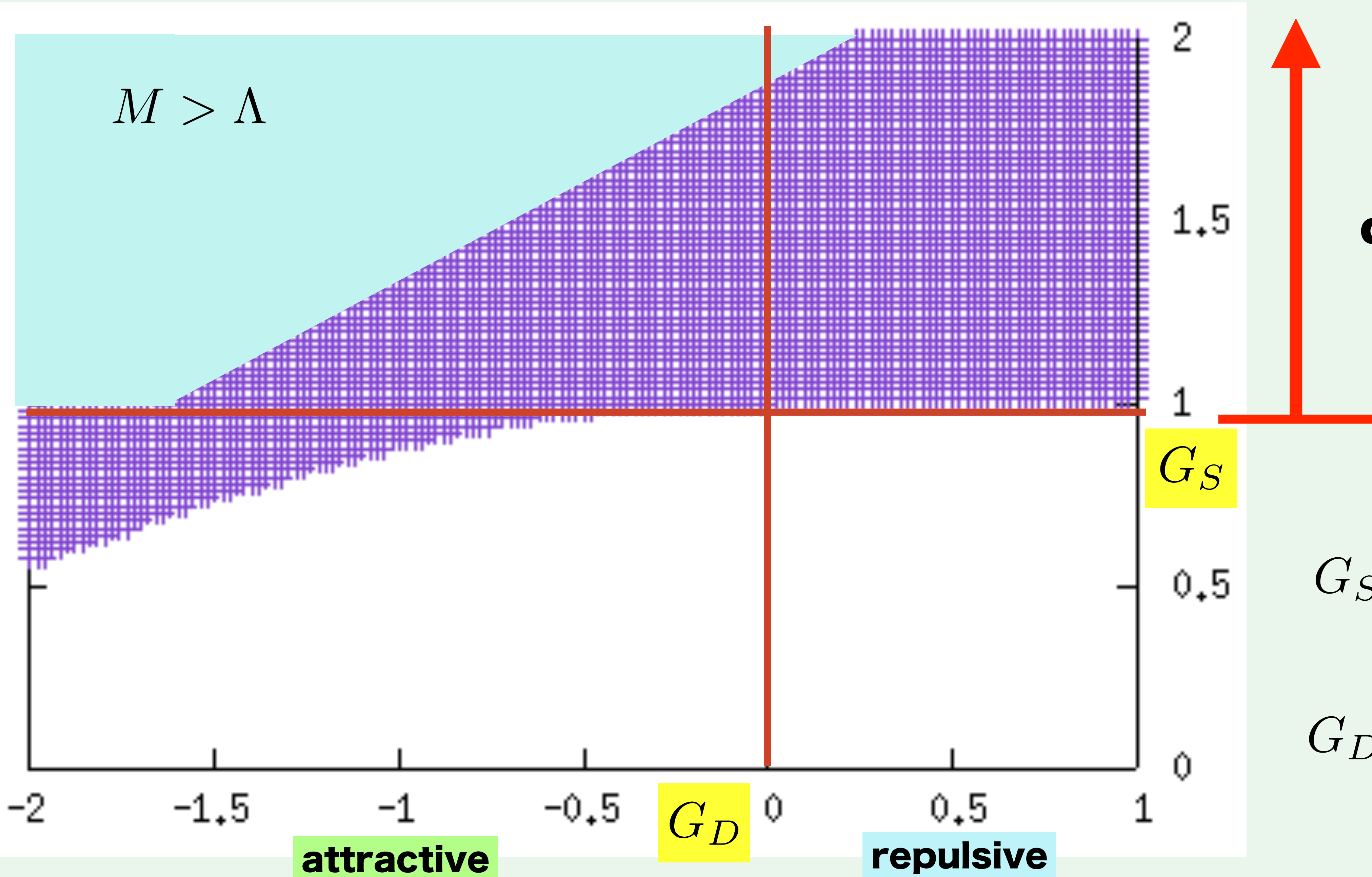


with anomaly term, ChS can be broken even if above conditions is not satisfied

NJL phase diagram **chiral limit**

Kono, DJ, Kuroda, Harada, in preparation

dynamical breaking takes place in the purple region



$$G_S = g_s \left(\frac{3\Lambda^2}{2\pi^2}\right)$$

$$G_D = g_d \Lambda \left(\frac{3\Lambda^2}{2\pi^2}\right)^2$$

- dynamical breaking takes place even below the critical value of G_s
- in such a case, η' mass is larger than sigma mass (2M in chiral limit)

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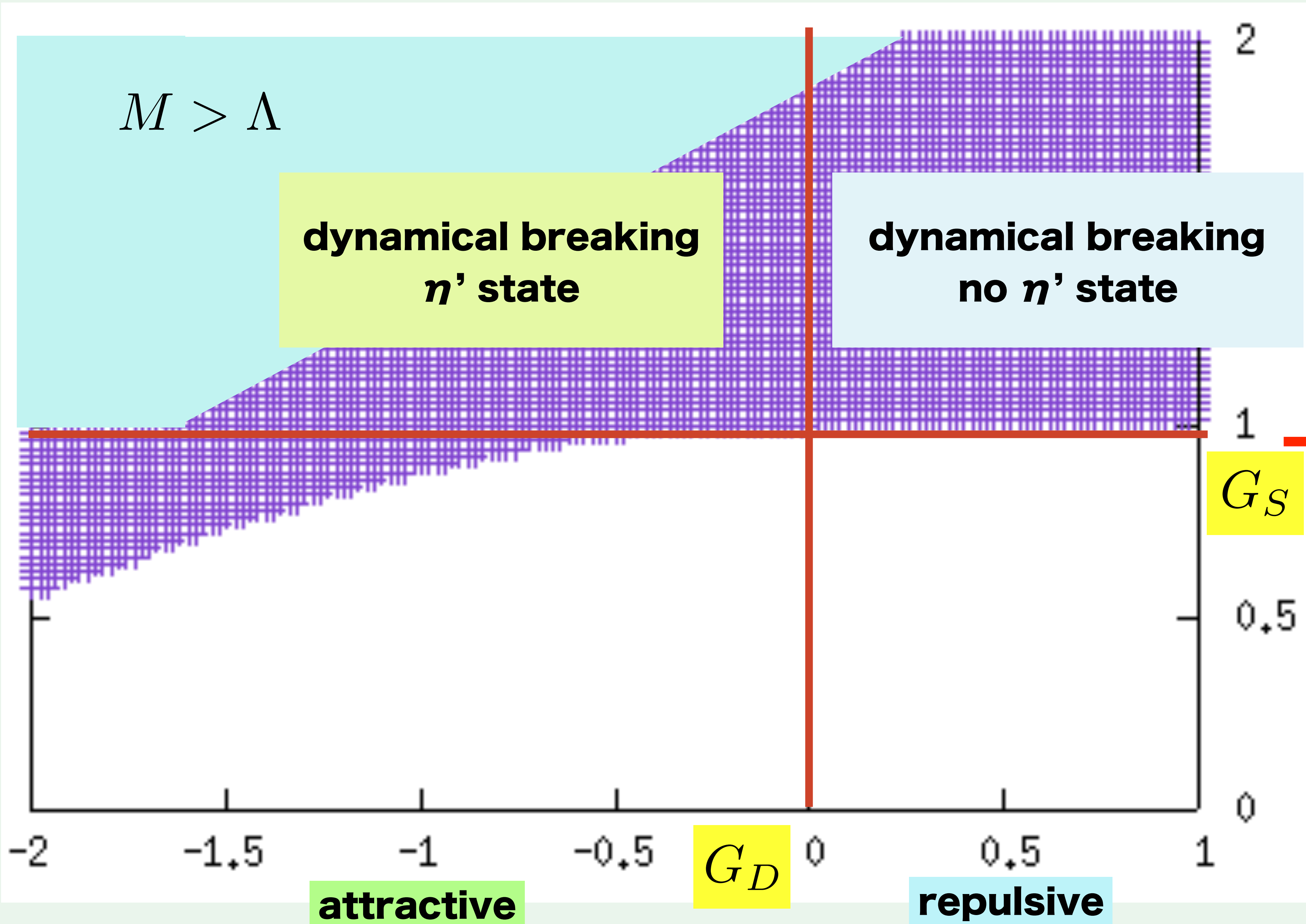

usual dynamical breaking

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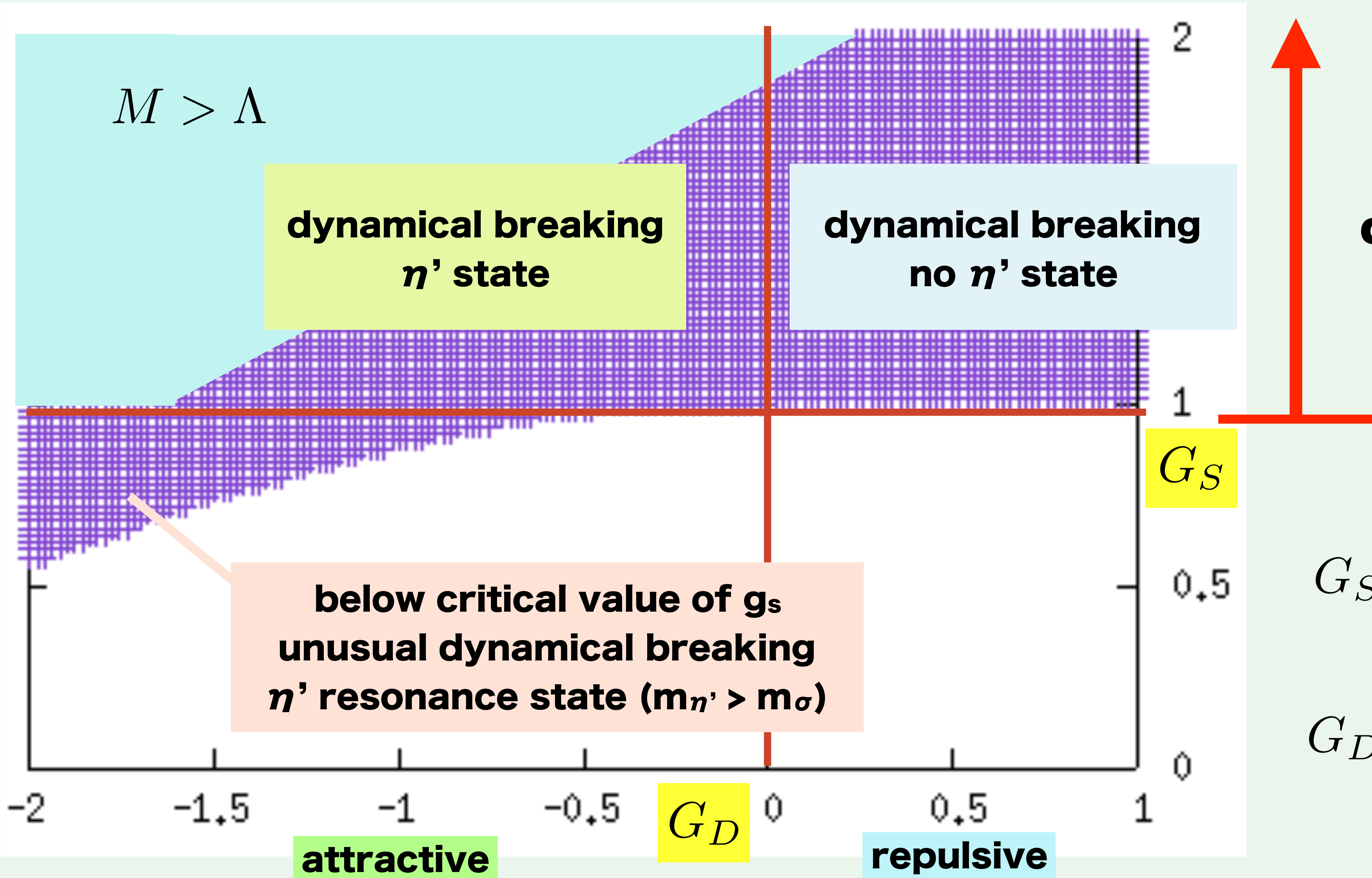

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explicit ChS breaking
flavor symmetry breaking

anomaly term
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chiral limit

vacuum condition at tree level + mass formula

relation between σ and η' masses and μ²

$$6\mu^2 = m_{\eta_0}^2 - 3m_{\sigma_0}^2$$

usual breaking $\mu^2 < 0$ $m_{\eta'}^2 < 3m_{\sigma_0}^2$

unusual breaking $\mu^2 > 0$ $m_{\eta'}^2 > 3m_{\sigma_0}^2$ consistent with NJL model

we do not know η' mass at chiral limit

SU(3) linear σ model

Kono, DJ, Kuroda, Harada, in preparation

off chiral limit

chiral symmetry and SU(3) breaking is introduced by $m_q \neq m_s$

SU(3) breaking parameter $\epsilon = \frac{\langle \sigma_8 \rangle}{\langle \sigma_0 \rangle} = \frac{f_\pi - f_K}{f_\pi + 2 f_K} = -0.12$

vacuum condition at tree level + mass formula

mass relation

$$6\mu^2 \left(1 - \frac{1}{2}\epsilon\right) = m_{\eta_0}^2 \left(1 - \frac{1}{2}\epsilon - 6\epsilon^2 + \epsilon^3 - 8\epsilon^4\right) - 3 m_{\sigma_0}^2 \left(1 - \frac{1}{2}\epsilon + 2\epsilon^2 - \epsilon^3\right) + m_{\eta_8}^2 \left(4 - 5\epsilon + 6\epsilon^2 - 8\epsilon^3 + 4\epsilon^4\right) + m_\pi^2 \left(4 + \epsilon + 6\epsilon^2 + 4\epsilon^3 + 4\epsilon^4\right)$$

$$6\mu^2 = 0.92 m_{\eta_0}^2 - 3.08 m_{\sigma_0}^2 + 4.42 m_{\eta_8}^2 + 3.96 m_\pi^2$$

usual breaking $\mu^2 < 0$ $m_{\sigma_0} > 860 \text{ MeV}$

unusual breaking $\mu^2 > 0$ $m_{\sigma_0} < 860 \text{ MeV}$

$m_{\eta_8} = 550 \text{ MeV}$

$m_{\eta_0} = 958 \text{ MeV}$

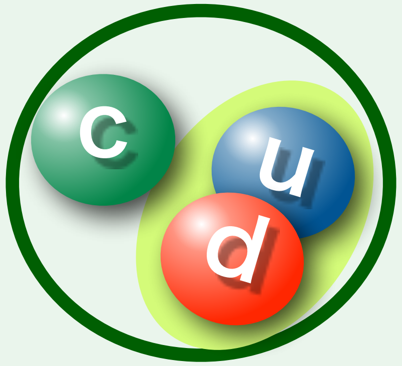
$m_\pi = 140 \text{ MeV}$

unusual spontaneous breaking is possible,
if singlet sigma mass is smaller than 860 MeV.

diquark models for heavy baryon

to discuss possibility of existence
and investigate properties of diquark

Λ_c



Kumakawa, Sakashita (Tokyo Metropolitan University)
Jido (Tokyo Institute of Technology)

diquark-quark model

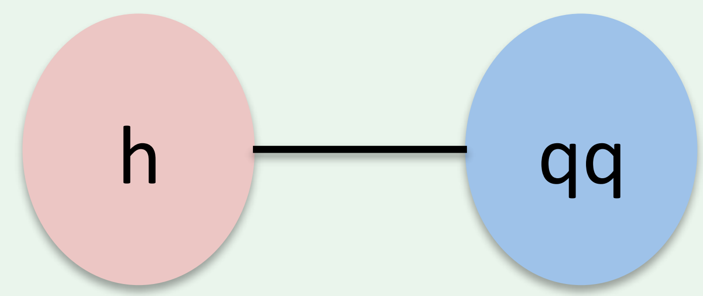
diquark as a point-like particle

D. Jido and M. Sakashita,
PTEP 2016 (2016) no.8, 083D02

two-body nonrelativistic quantum mechanics

$$H = m_d + m_h + \left[-\frac{\hbar^2}{2\mu}\frac{1}{r}\frac{d^2}{dr^2}r + \frac{\hat{L}_\lambda^2}{2\mu r^2} + V_{\bar{3}3}(r) \right]$$

effective potential between diquark and quark

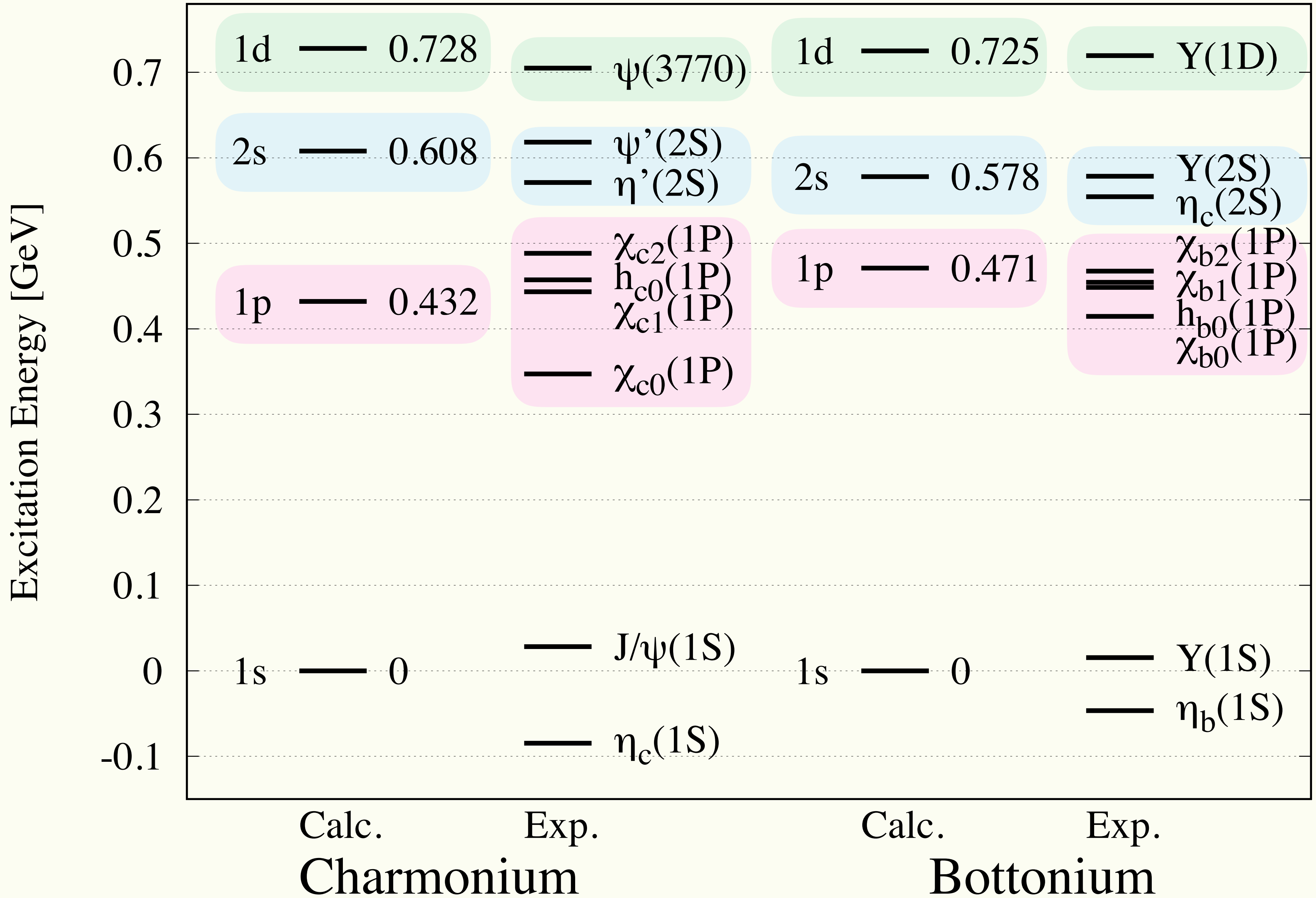


$$V_{\bar{3}3}(r) = -\frac{4}{3}\frac{\alpha}{r}\hbar c + kr + V_0$$

potential paramters are determined by spectra of charmonium and bottonium

→α:0.4 k:0.9 [GeV/fm]

without LS, SS interaction to see global structure of spectra



$\alpha = 0.4,$

$k = 0.9$ [GeV/fm]

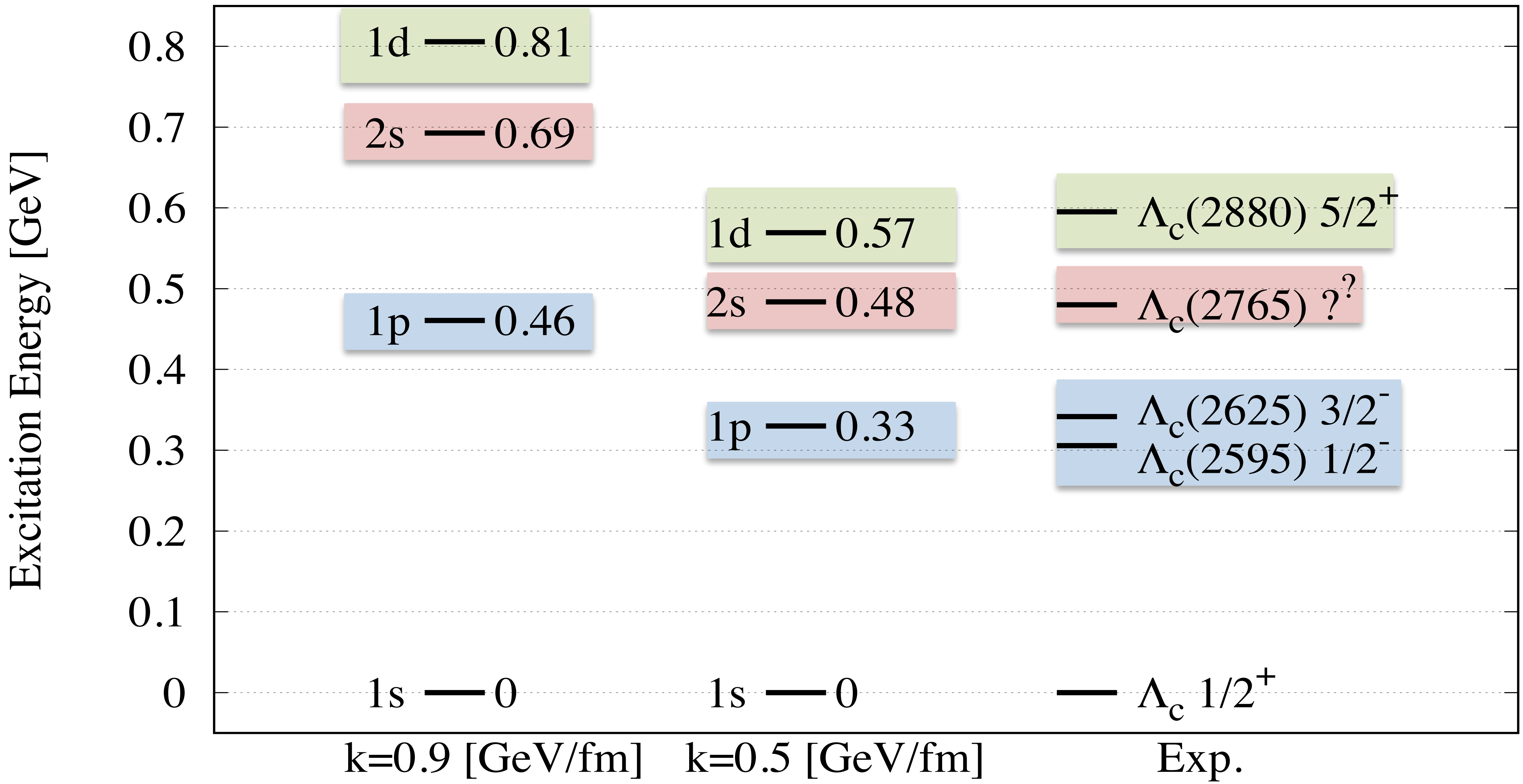
$m_c = 1.5$ GeV

$m_b = 4.0$ GeV

Λ_c (Point like model)

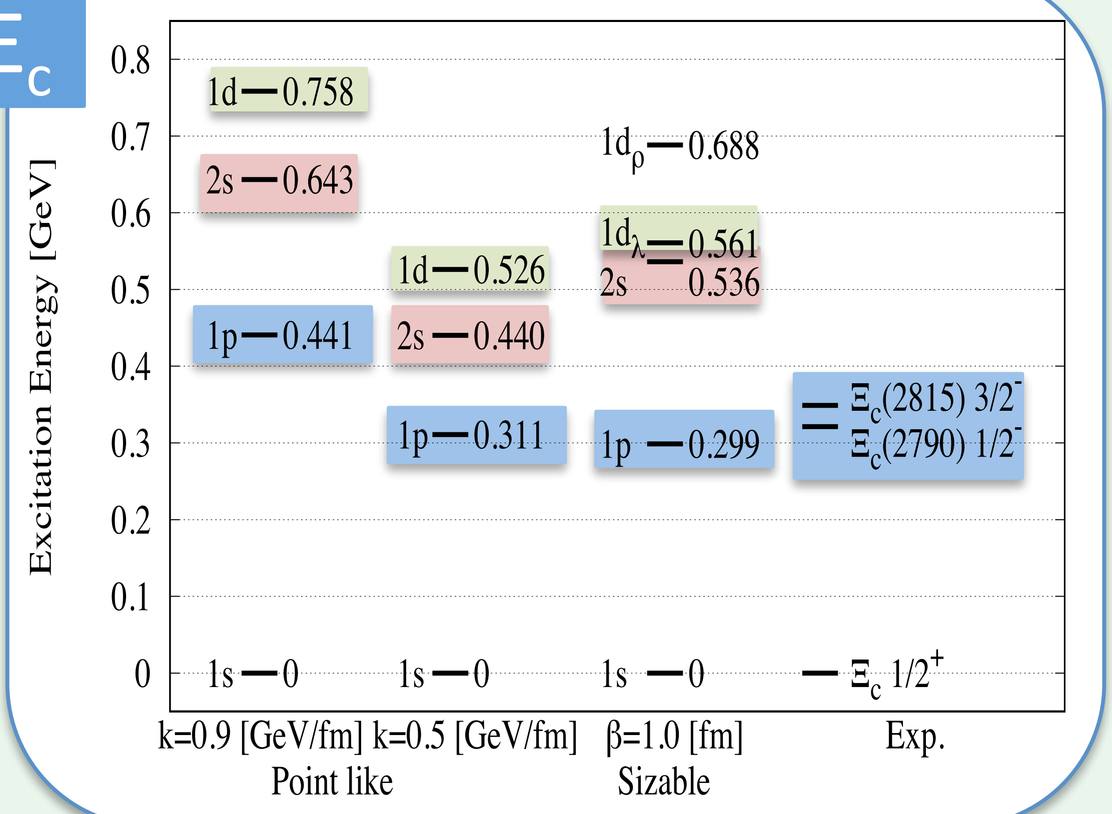
D. Jido and M. Sakashita,
PTEP 2016 (2016) no.8, 083D02

Λ_c Excitation energy

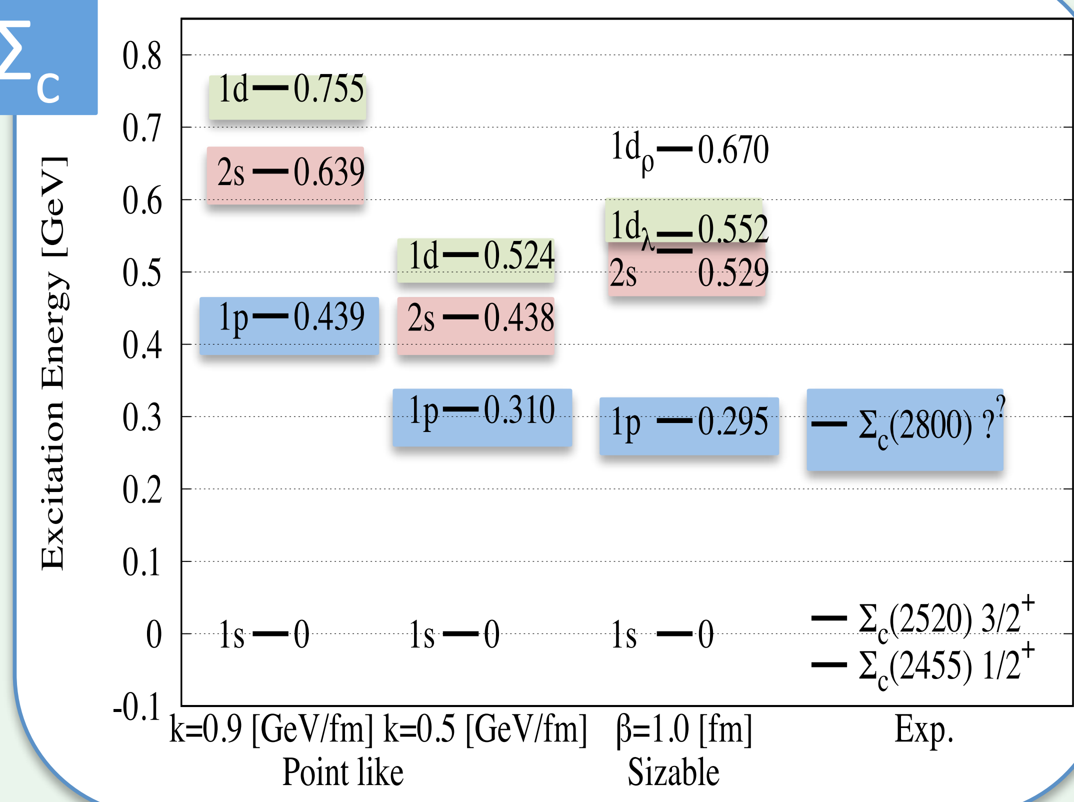


Kumakawa, DJ,
PTEP2017, 123D01; in preparation

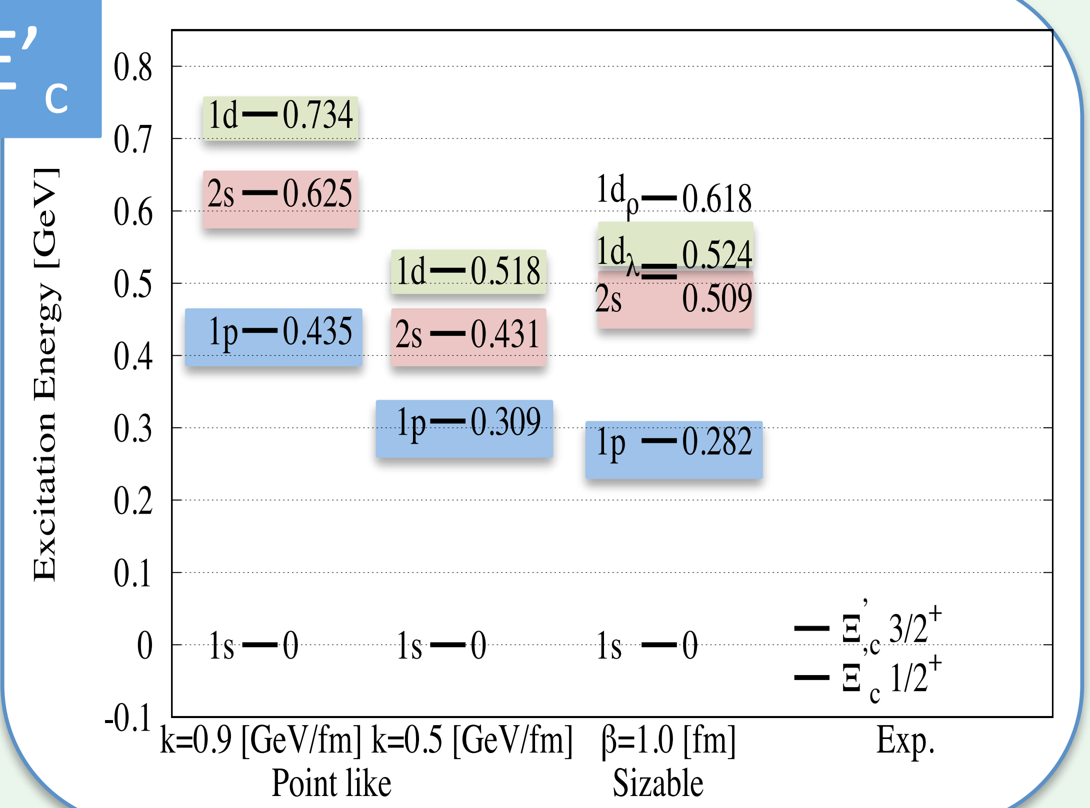
Ξ_c



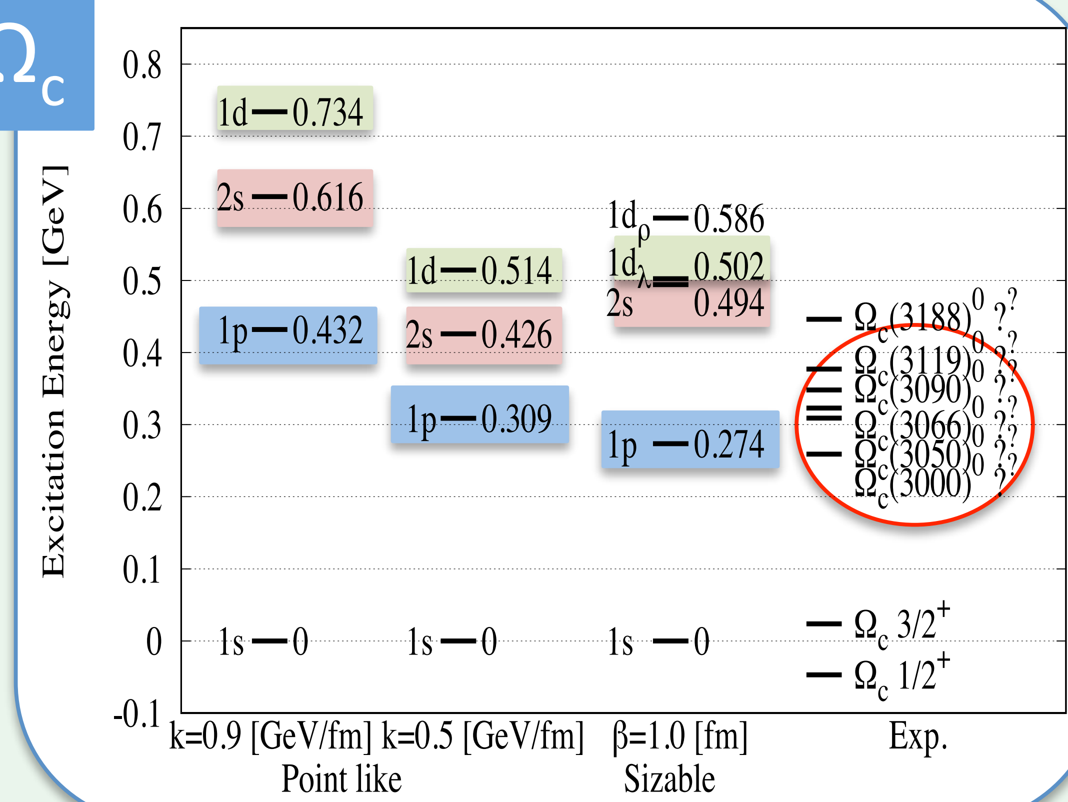
Σ_c



Ξ'_c



Ω_c



Summary

- partial restoration of chiral symmetry = reduction of magnitude of quark condensate
  in-medium modification of pion properties → change of quark condensate
  change of quark condensate → possible property changes of other hadrons
- expectations when partial restoration of chiral symmetry takes place in nuclear matter
  - **reduction of hadron mass** η'
  - **reduction of mass difference of chiral partners** η
  - **wave function renormalization of NG bosons** K^+, π^0
- η' meson in nuclear matter
  - singlet η and octet η belong to the same multiplet in SU(3) chiral group and get degenerate when chiral symmetry is restored
  - a part of η' meson mass is generated by chiral symmetry breaking as for nucleon
  - 100 MeV reduction of eta' mass is expected in nuclear density
  - strong attractive scalar potential in nucleus from isoscalar-scalar σ exchange
  - strong η' attraction could change the nuclear structure
- anomaly term can induce spontaneous breaking of chiral symmetry
- diquark-quark interaction could be weaker than antiquark-quark interaction