Binding of Charmed Mesons (D, $\bar{D}$) and J/Ψ in **Nuclei**

CIPANP 2009, **San Diego, California, 05/27/2009**

K. Tsushima (JLab)

KT *et al*., Phys. Rev. C 59, 2824 (1999)

G. Krein, KT, A.W. Thomas (work in progress)

For other mesons and review of QMC:

K. Saito, KT, A.W. Thomas, PPNP, 58, 1 (2007)

Outline

- Introduction
- **QMC** model, **finite nuclei**
- **D, $\bar{D}$** in a nuclear medium
- **J/Ψ** in a nuclear medium
- Summary, outlook

Introduction

- (Large) **nuclei**, and **nuclear matter** in terms of quarks and gluons (or QCD) ???!!!
- NN,NNN,NNNN... interactions $\Longrightarrow$ Nucleus ? $\Longleftarrow$ shell model, MF model,...
- Lattice QCD: still extracting NN and NY interactions, [Y=hyperons: Λ,Σ,Ξ]
- **Quark model** based description of nucleus
- Hadron properties **in a nuclear medium**

The **QMC** model P.A.M. Guichon, PLB 200, 235 (1988)

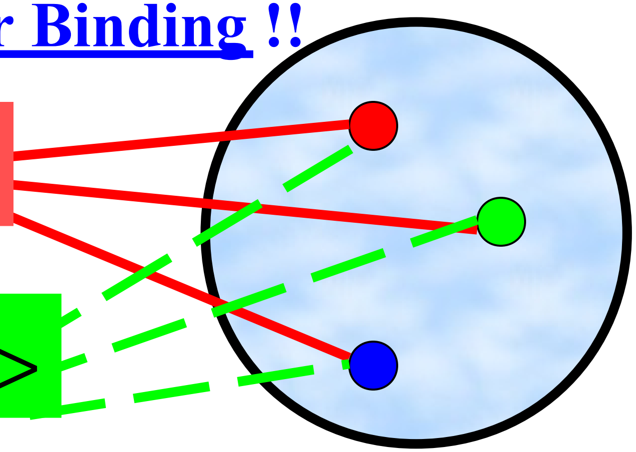
(For a review, PPNP 58, 1 (2007))

Light (u,d) quarks interact self-consistently with mean **σ** and **ω** fields

Nuclear Binding !!

< **σ** >

< **ω** >



$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

⇓ **nonlinear** in σ

$M^*_N \cong M_N - g^N_\sigma \sigma + (d/2)(g^N_\sigma \sigma)^2$

$$[i\,\partial\cdot\gamma - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega]\, q = 0$$

$M^*_N = M_N - V^N_\sigma$

1. Start

$$[i\,\partial\cdot\gamma - M^*_N + \gamma_0 V^N_\omega]\, \mathbf{N} = 0$$

$V^N_\omega = 3V^q_\omega$

Applied quark model (lattice) mass formula

Self-consistent !

At Nucleon Level Response to the Applied Scalar Field is the Scalar Polarizability

Nucleon response to **a chiral invariant scalar field** is then a nucleon property of great interest…

$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2$$

Non-linear dependence **scalar polarizability**

d ¼ 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the **ONLY place the response of the internal structure of the nucleon enters.**

Bound quark Dirac spinor ($1s_{1/2}$)

Quark Dirac spinor in a bound hadron:

$$q_{1s}(r) = \begin{pmatrix} U(r) \\ i\,\vec{\sigma}\cdot\hat{r}\,L(r) \end{pmatrix} \chi$$

Lower component is enhanced !

$\Longrightarrow$ $g_A^* < g_A$: $\sim |U|^2 - (1/3)\,|L|^2$,

$\Longrightarrow$ Decrease of scalar density $\Longrightarrow$

Decrease in **Scalar Density**

Scalar density (quark): ~ |U|^2 - |L|^2,

⇓

M_N*, N wave function, Nuclear scalar density etc., are **self-consistently** modified due to the N internal structure change !

⟹ <u>Novel Saturation mechanism !</u>

Nuclear (Neutron) matter, E/A

Novel saturation mechanism !

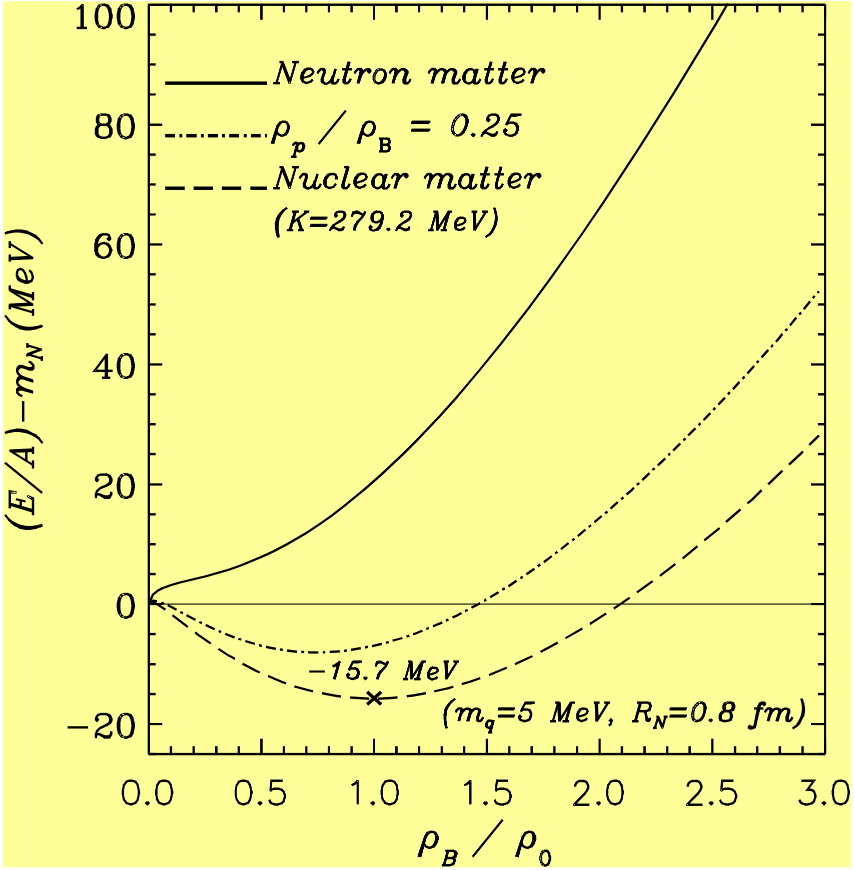
Incompressibility

QHD: K ≈ 500 MeV

QMC: K ≈ 280 MeV

(Exp. 200 ~ 300 MeV)

PLB 429, 239 (1998)

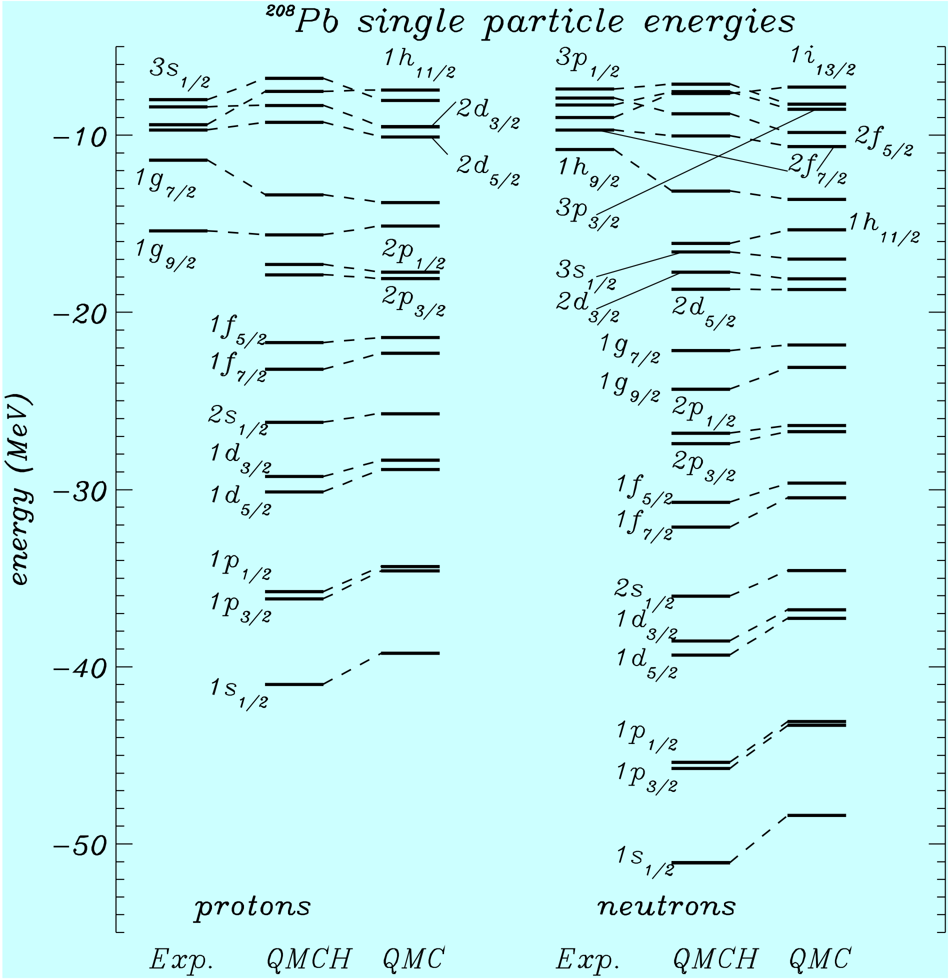


Finite nuclei (^{208}Pb energy levels)

NPA 609, 339 (1996)

Large mass **nuclei**

Nuclear matter



Based on **quarks** !

↓

Hadrons

Hypernuclei

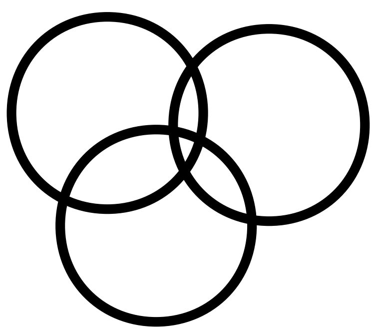
(the latest QMC)

Summary : Scalar Polarizability

- Can always rewrite **non-linear coupling** as linear coupling plus non-linear scalar self-coupling – **likely physical origin of non-linear versions of QHD**

- In nuclear matter this is **the only place** the internal structure of the nucleon enters in MFA

- Consequence of **polarizability** in atomic physics is **many-body forces:**



$$V = V_{12} + V_{23} + V_{13} + \mathbf{V_{123}}$$

QMC $\Longleftrightarrow$ QHD

- **QHD** shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron **internal structure**

- Minimal model couples these mesons to **quarks** in relativistic quark model – e.g. MIT bag, or confining NJL... **any other quark models**

- g_σ^q , g_ω^q, g_ρ^q fitted to ρ_0 , **E/A** and **symmetry energy**

- ***No additional parameters*** predict change of structure and **binding in nuclear matter of all hadrons**:
  e.g. **ω, ρ, η, J/ψ, N, Λ, Σ, Ξ** $\Longrightarrow$ see later !

Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work in nuclear theory is based upon **effective forces**

- Used for everything from nuclear astrophysics to collective excitations of nuclei
- **Skyrme Force**: Vautherin and Brink

In Paper : **Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)**

explicitly obtained effective force, 2- plus 3- body, of **Skyrme type**

- equivalent to QMC model (required expansion around $\boldsymbol{\sigma} = 0$)

Physical Origin of Density Dependent Force of the Skyrme Type within the QMC model

That is, apply new **effective force** directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

» 4%

» 1%

- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[\frac{-3\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\sigma}{2\,(1 + d\rho\,G_\sigma)} + \frac{3\,G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[\frac{5\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

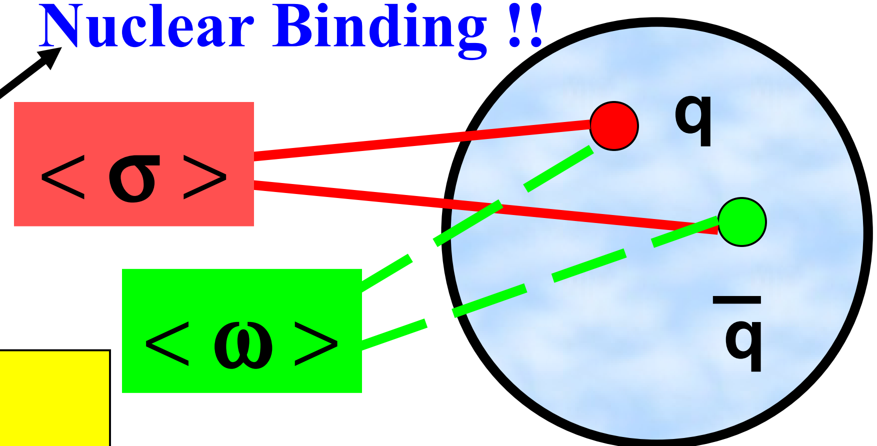
highlights scalar polarizability

Mesons in nuclear medium in **QMC**

(For a review, PPNP 58, 1 (2007))

Light (u,d) quarks interact self-consistently with mean **σ** and **ω** fields

Nuclear Binding !!



$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

⇓ **nonlinear** in σ

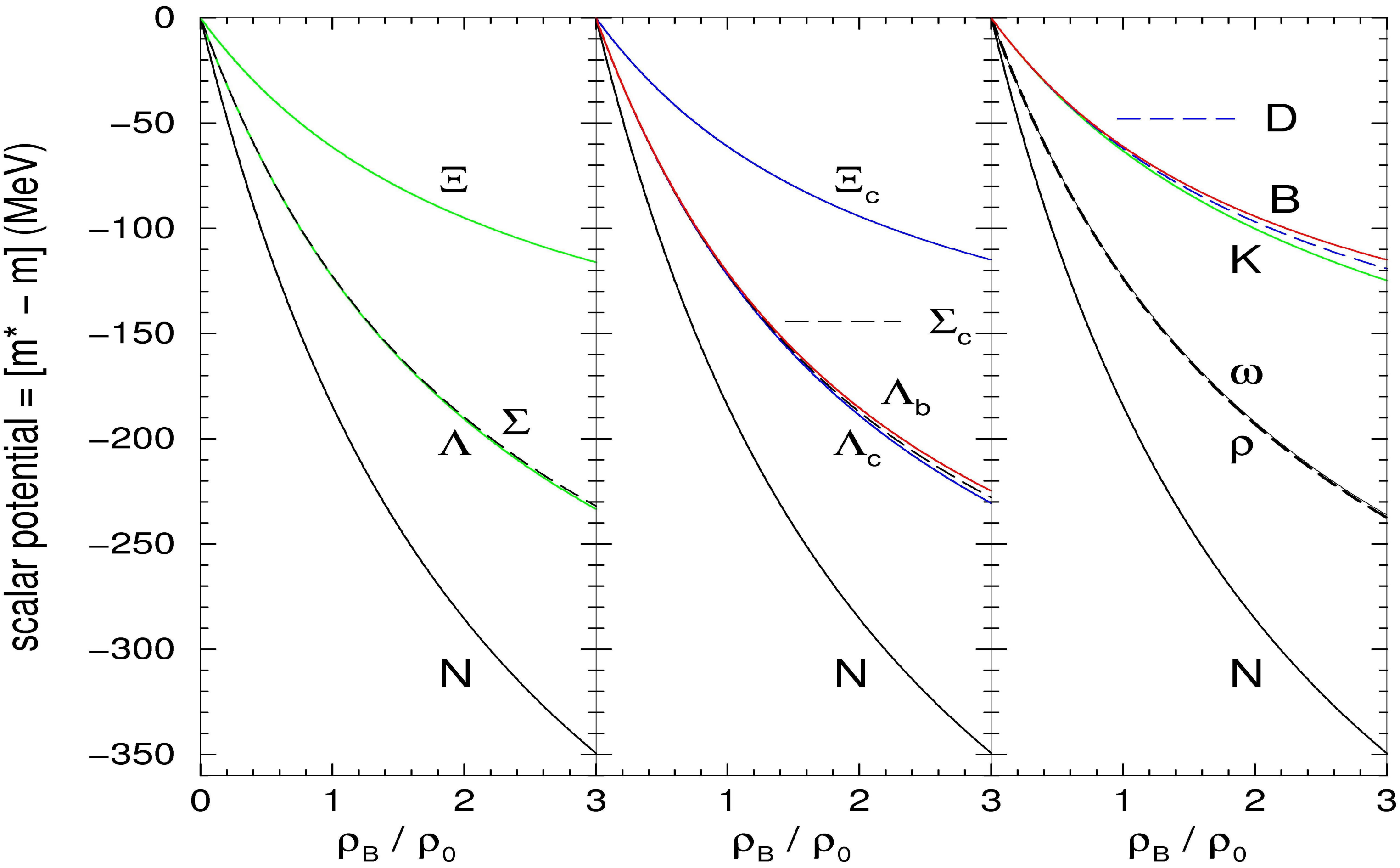
$M^*_M \cong M_M - g^M_\sigma \sigma + (d^M/2)(g^M_\sigma \sigma\ )$

$$[i\,\partial\cdot\gamma - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega\,]\,q = 0$$

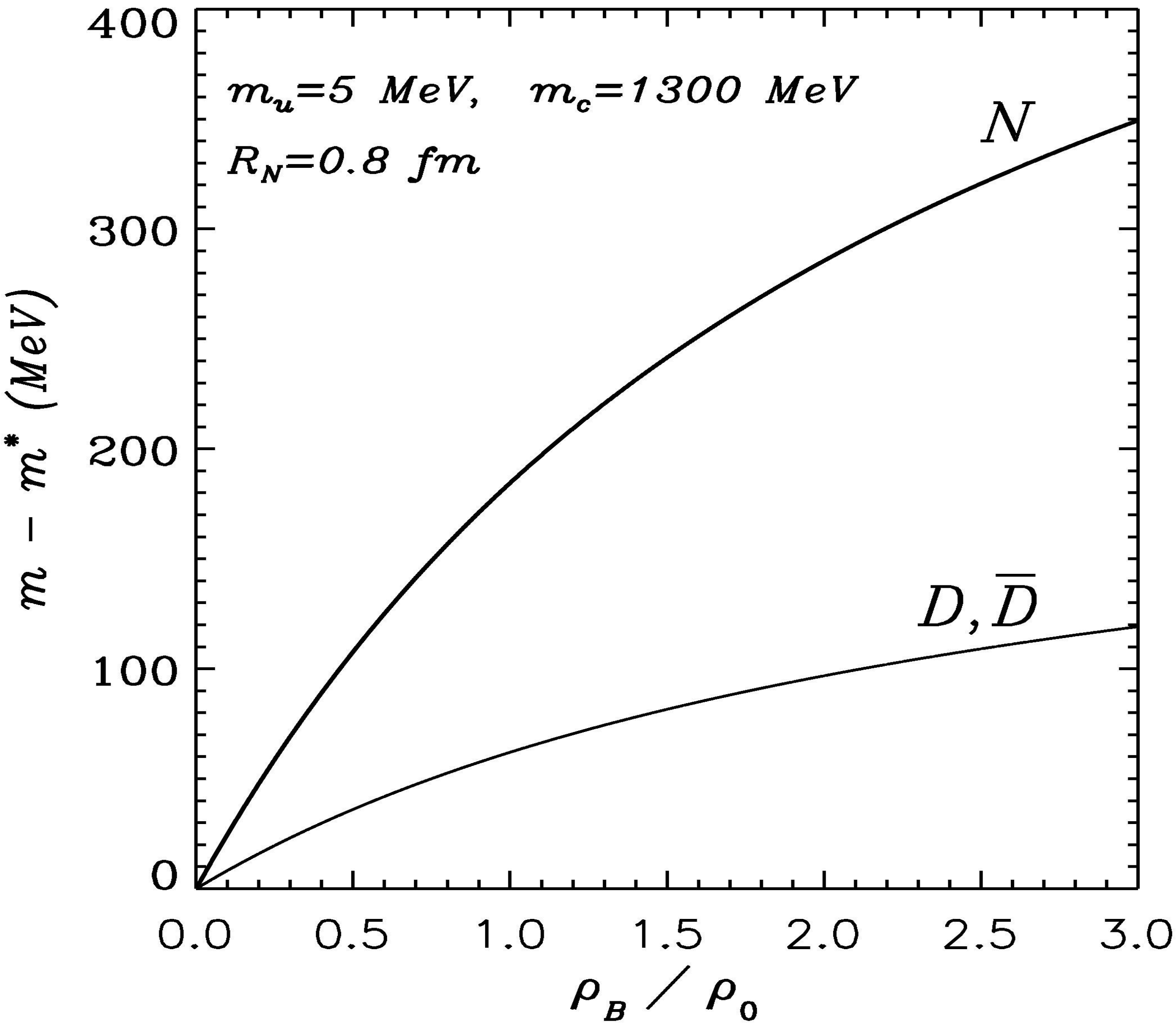
σ, ω fields: **<u>no couplings</u>** with **s,c,b** quarks**!!**

Applied quark model (lattice) mass formula

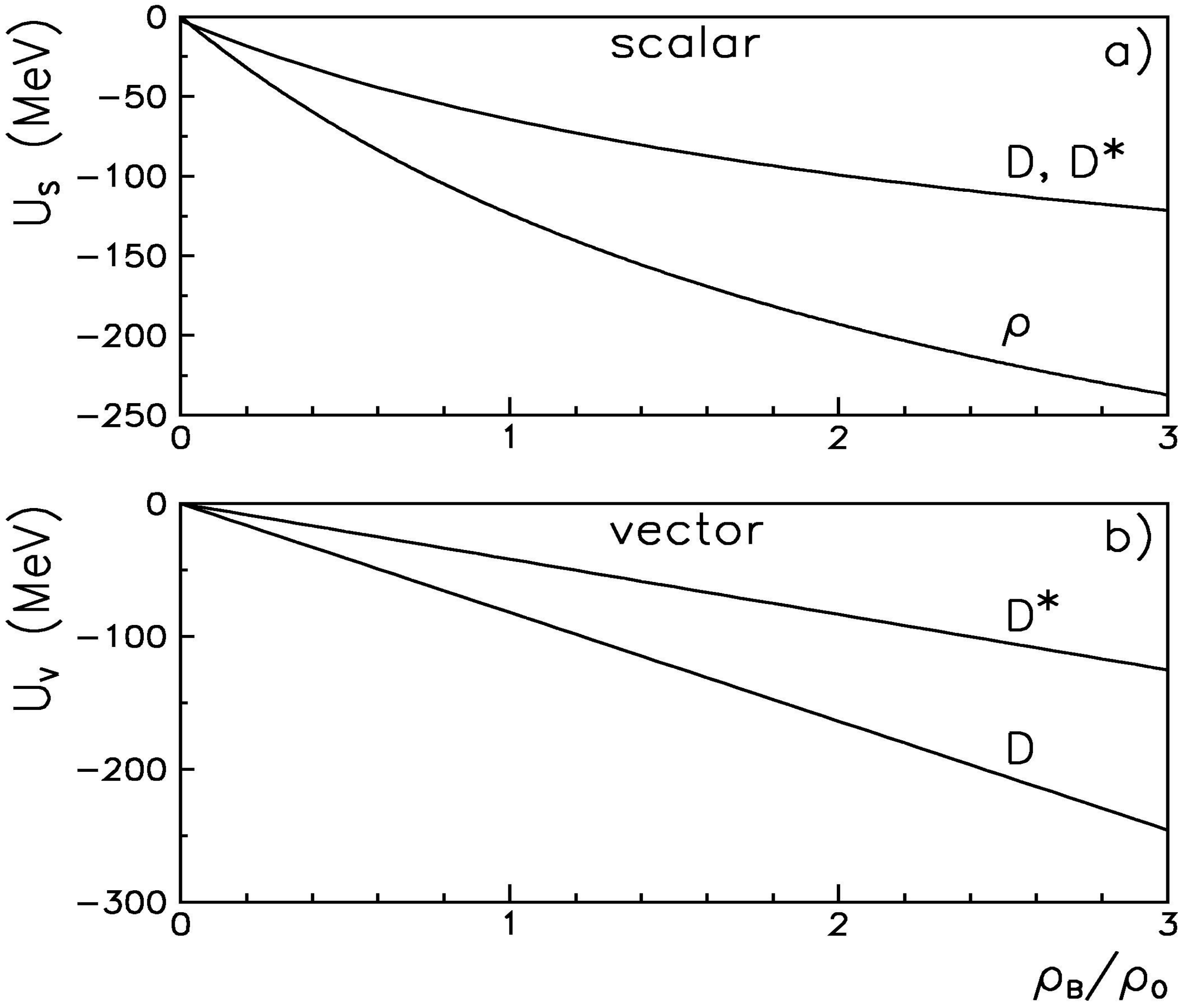
Scalar potentials in **QMC** respects SU(3) (**light quark # !**)



D meson scalar potential



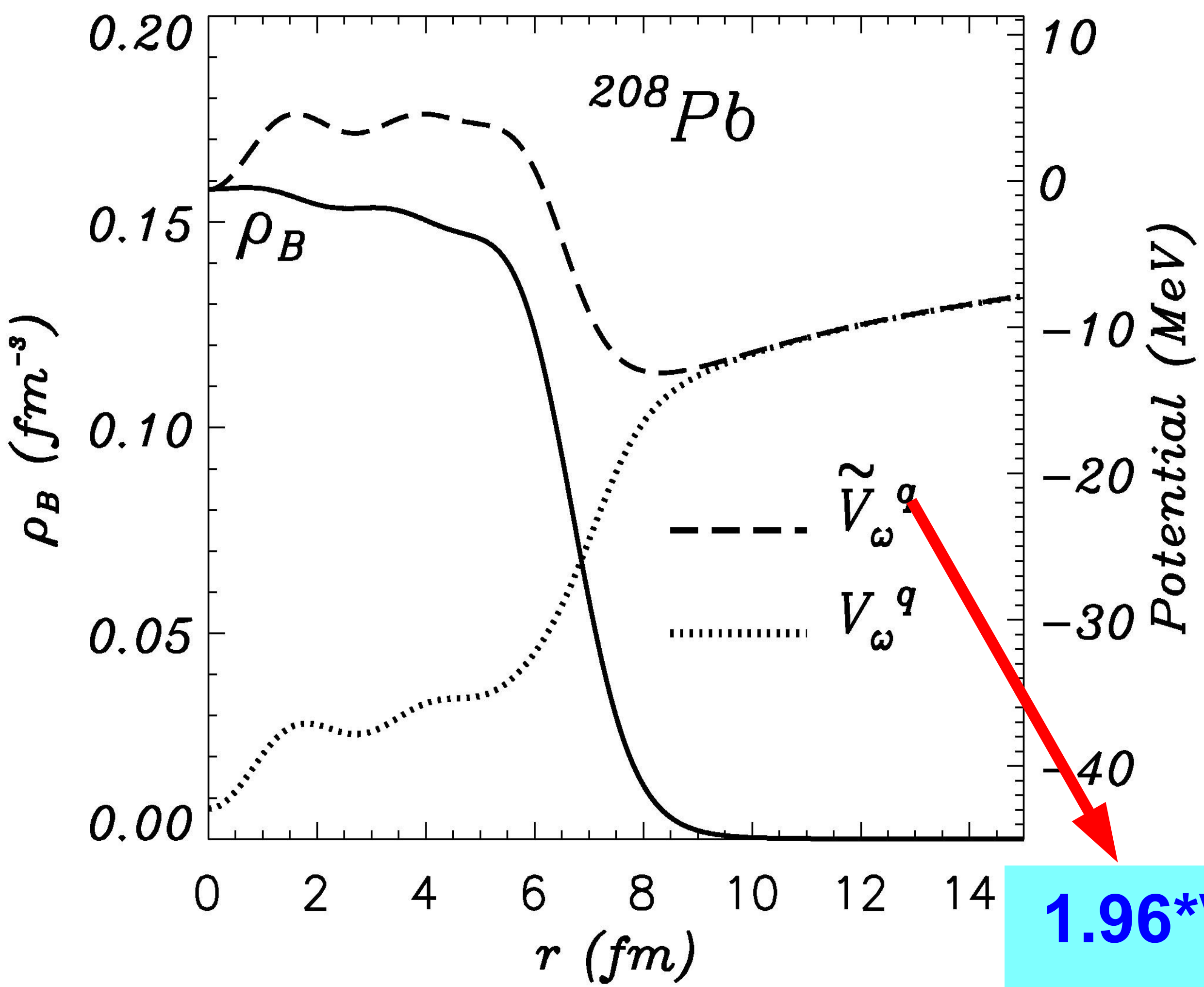
D and D* potentials in nuclear matter



$D^+ = c\,\bar{d}$

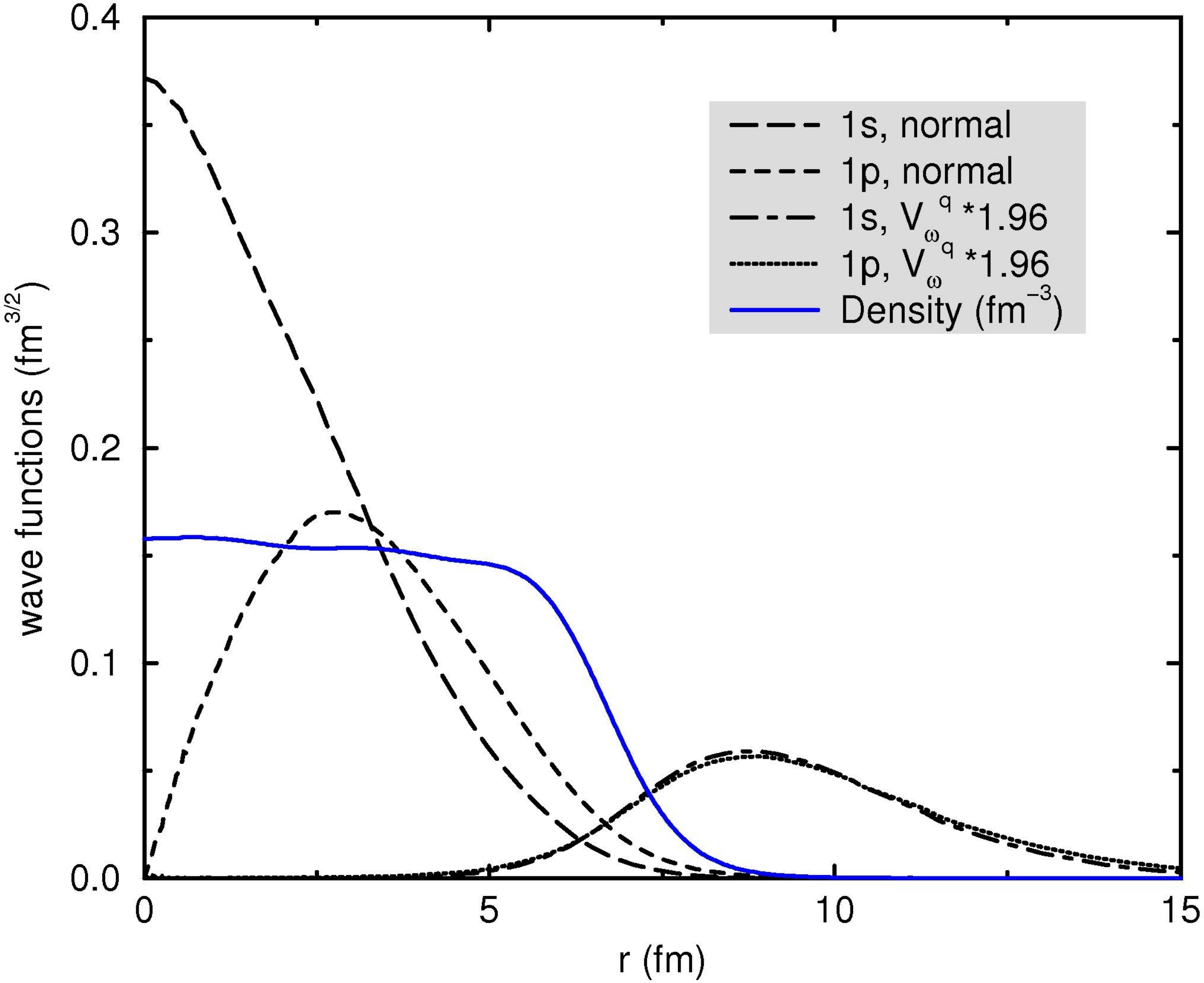
$D^0 = c\,\bar{u}$

D^- ($\bar{c}d$) **total** potential in **Pb**



$1.96*V_\omega^q$

D^- ($\bar{c}d$) bound state wave functions in Pb



$\bar{D}$ bound state energy in Pb

state	D^- 1.96 *Vqω	D^- Vqω	D^- Vqω No Coulomb	$\bar{D}0$ 1.96 *Vqω	$\bar{D}0$ Vqω	D0 Vqω
1s	-10.6	-35.2	-11.2	unbound	-25.4	-96.2
1p	-10.2	-32.1	-10.0	unbound	-23.1	-93.0
2s	-7.7	-30.0	-6.6	unbound	-19.7	-88.5

J/ψ pot. in matter (color octet)

$H = \alpha_\psi/2 \langle N| \vec{E}_a \cdot \vec{E}_a |N\rangle$

M.B. Voloshin: chromo-polarizability

at ρ_0, **V< -21** (α_ψ/2 GeV $^{-3}$) [MeV],

PPNP 61, 455 (2008)

S.H. Lee, C.M. Ko: QCD Stark effect

V = - 8 + 3 (D-loop) [MeV], **PRC 67, 038202 (2003)**

M. Luke, A.V. Manohar, M.J. Savage: EFT

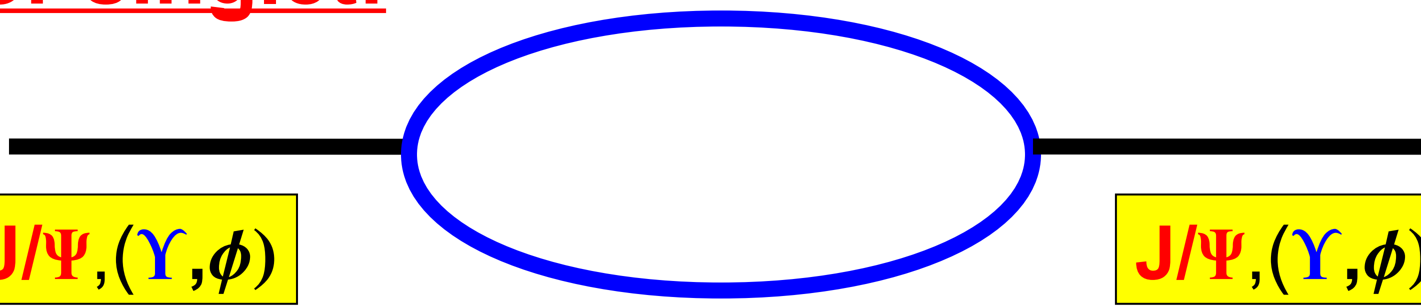
V = -11 ~ - 8 [MeV], **PLB 288, 355 (1992)**

J/Ψ (ϒ,ϕ) mass in medium (loop!)

J/Ψ (ϒ,ϕ) bound in large nuclei ?

D, B, K (in medium!)

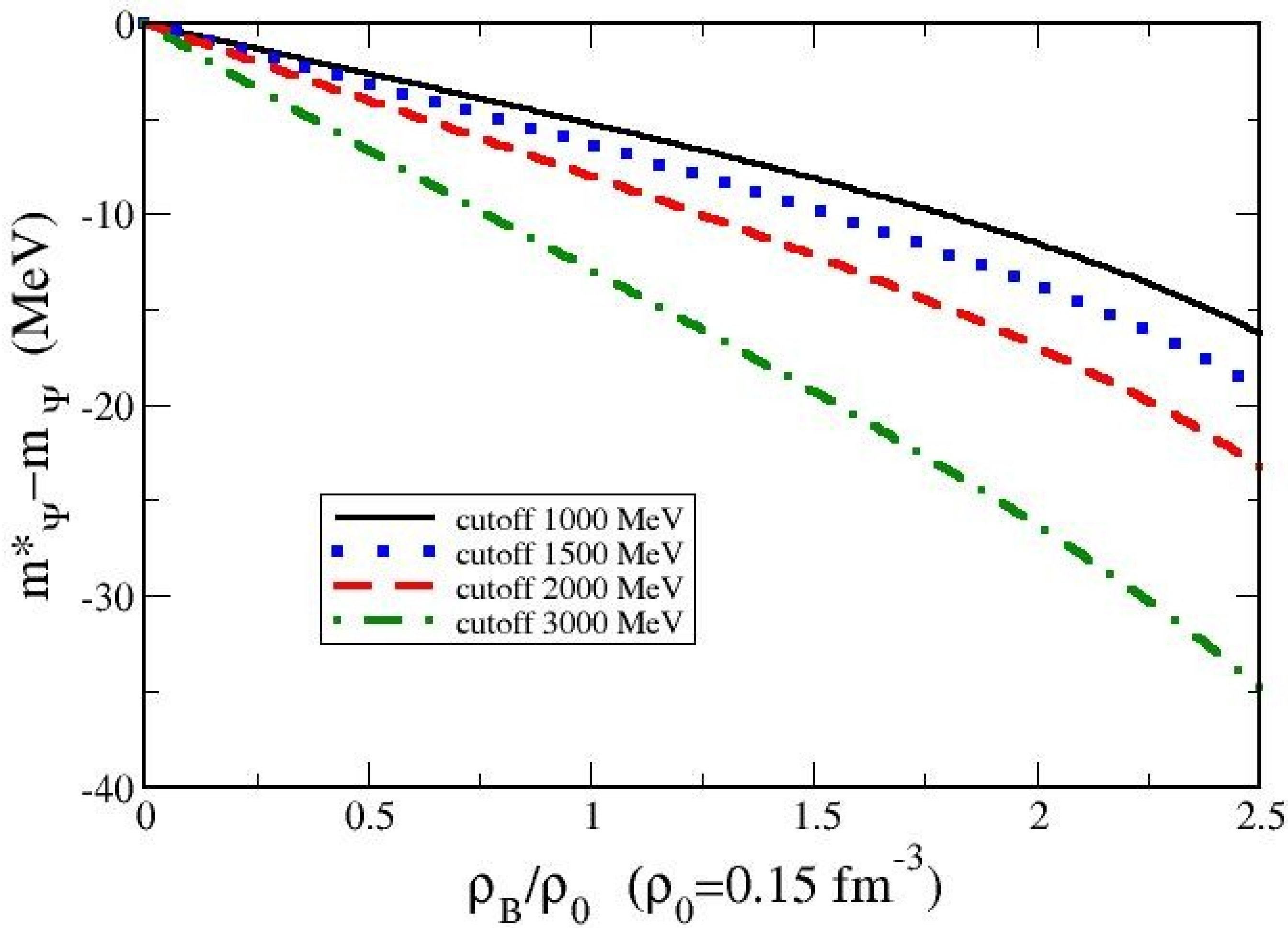
Color singlet!



J/Ψ,(ϒ,ϕ) **J/Ψ,(ϒ,ϕ)**

$\bar{D}$, $\bar{B}$, $\bar{K}$ (in medium!)

D-$\overline{\text{D}}$ loop: J/Ψ potential in matter



Summary, outlook

1. **D^-** will form nuclear (atomic) **bound state**
2. **J/Ψ** potential in nuclear matter

   Color octet, **QCD Stark** ⟹ **attraction!**

   Color singlet, **D-$\bar{D}$ loop** ⟹ **attraction!**

   (Loops with **D*** ⟹ **additional attraction!**)
3. **J/Ψ** will be **bound** in (large mass) nuclei
4. Loops involve **D*** must be added
5. Υ, Φ ?

Spin-Orbit Splitting

	Neutrons (Expt)	Neutrons (QMC)	Protons (Expt)	Protons (QMC)
^{16}O $1p_{1/2}$-$1p_{3/2}$	**6.10**	**6.01**	**6.3**	**5.9**
^{40}Ca $1d_{3/2}$-$1d_{5/2}$	**6.15**	**6.41**	**6.0**	**6.2**
^{48}Ca $1d_{3/2}$-$1d_{5/2}$	**6.05 (Sly4)**	**5.64**	**6.06 (Sly4)**	**5.59**
^{208}Pb $2d_{3/2}$-$2d_{5/2}$	**2.15 (Sly4)**	**2.04**	**1.87 (Sly4)**	**1.74**

Agreement generally very satisfactory – NO parameter adjusted to fit