In-medium properties of the low-lying strange, charm, and bottom baryons in the QMC model

"Hadron Mass, Confinement, from JLab Expts. in 12-GeV Era"

APCTP, July, 2018

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Interesting Results for Bottom Baryons, Σ_b, Ξ_b

QMC model (related) reviews:

1. G. Krein, A. W. Thomas, K. Tsushima (Quarkonia-A) Prog. Part. Nucl. Phys. 100 (2018) 161
2. K. Saito, K. Tsushima and A. W. Thomas (QMC model) Prog. Part. Nucl. Phys. 58 (2007) 1

References:

Quarkonia-nuclear bindings (QMC summary):

G. Krein, A. W. Thomas, K. Tsushima

Prog. Part. Nucl. Phys. 100 (2018) 161

QMC model:

K. Saito, K. Tsushima and A. W. Thomas

Prog. Part. Nucl. Phys. 58 (2007) 1

1. Motivations
2. Introduction: QMC
3. Low-lying Strange, Charm, Bottom baryons
4. Summary, Perspective

Motivations, and Introduction of QMC model

- Complete and update the in-medium properties of the low-lying strange, charm, bottom baryons (in the QMC model)

- Detailed comparison of the strange, charm, and bottom sectors

- To get idea, opinions, and suggestions from audiences

- Highlight: Effective masses of $\Sigma_b(qqb)$ and $\Xi_b(qsb)$,

$\boxed{m_{\Sigma_b} > m_{\Xi_b} \rightarrow m^*_{\Sigma_b} < m^*_{\Xi_b}}$ reverses in medium !!!

$\rightarrow$ but issue of the repulsive vector potentials

Introduction, Motivations: QMC model

Motivations

•**(Large) nuclei, and nuclear matter** in terms of **quarks** and **gluons**

(**eventually** by **QCD**) **???!!!**

•**NN**,NNN,NNNN... interactions →

Nucleus ? ← shell model, MF model,...

•**Lattice QCD**: still extracting **NN, NY and YY** interactions, [**Y**=hyperons:**Λ,Σ,Ξ**]

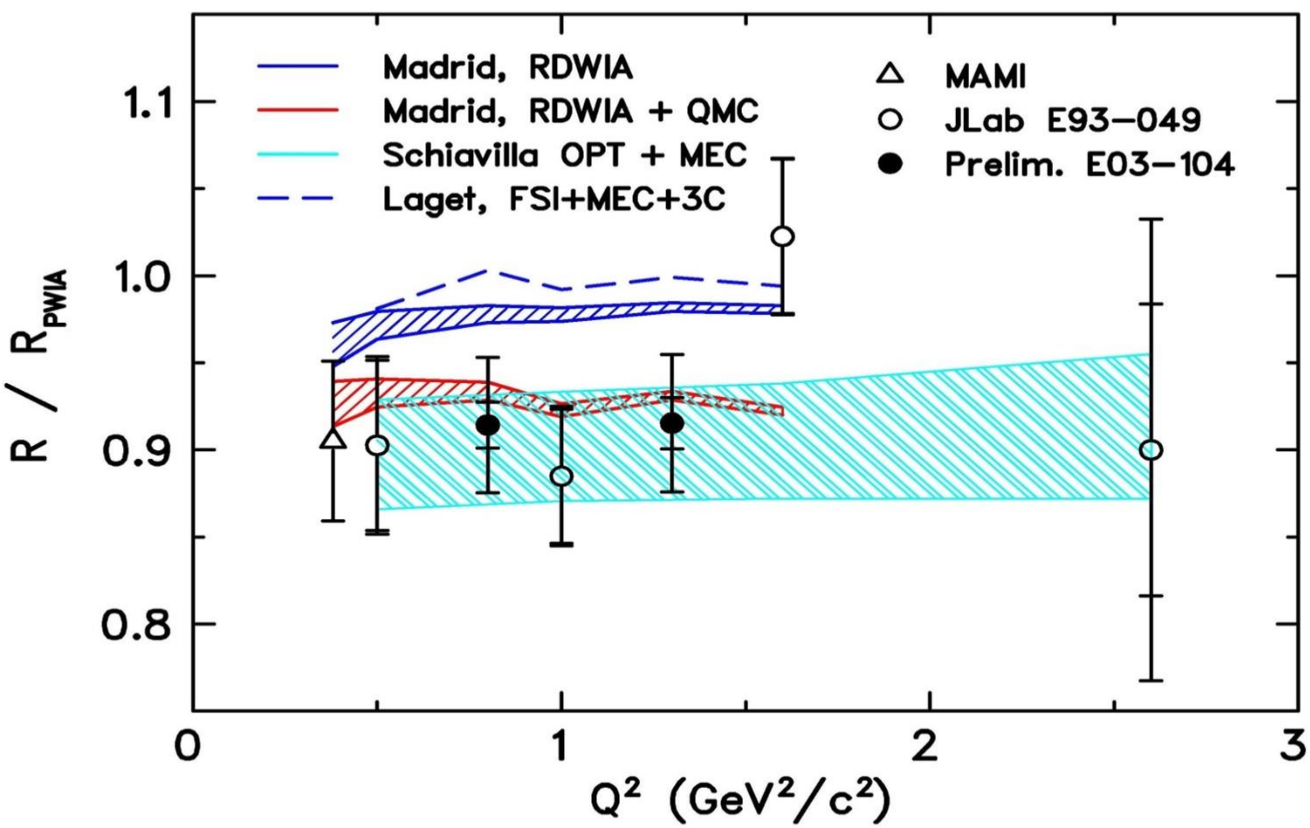
•**Quark model** based description of **nucleus**

•**Hadron** properties **in a nuclear medium**

$R=(p'_x/p'_z)=(G_E^p/G_M^p): {}^4He/{}^1H$

S. Malace, M. Paolone and S. Strauch, arXiv:0807.2251 [nucl-ex]

S. Strauch *et al., Phys. Rev. Lett.* ***91, 052301 (2003)***

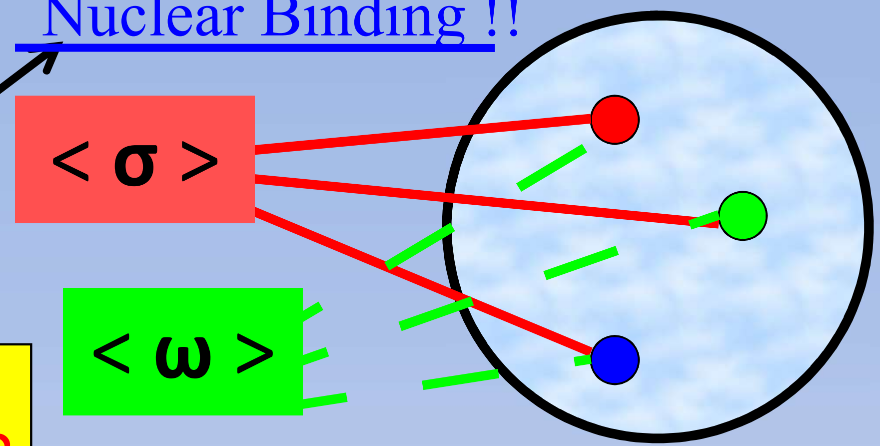


The QMC model P. Guichon, PLB 200, 235 (1988)

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

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

Nuclear Binding !!



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

↓ nonlinear in **σ**

$M^*_N \approx M_N - g^N_\sigma \sigma + \underline{(d/2)\,(g^N_\sigma \sigma)^2}$

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

1. Start

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

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

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

Self-consistent !

(Applied quark model !)

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

Quark Dirac spinor in a **bound hadron:**

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

Lower component is **enhanced** !

$\Rightarrow$ $g_A^* < g_A$: ~ |U|**2 – (1/3) |L|**2,

$\Rightarrow$ **Decrease** of scalar density $\Rightarrow$

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 !

⇒ **Novel Saturation** mechanism !

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…

$$M^*(\vec{R}) \approx M - g_\sigma \sigma(\vec{R}) + (d/2)\,(g_\sigma \sigma(\vec{R}))^{**2}$$

Non-linear dependence **scalar polarizability**

0.22 d**¼ 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.**

Nuclear (Neutron) matter, E/A

Novel saturation mechanism !

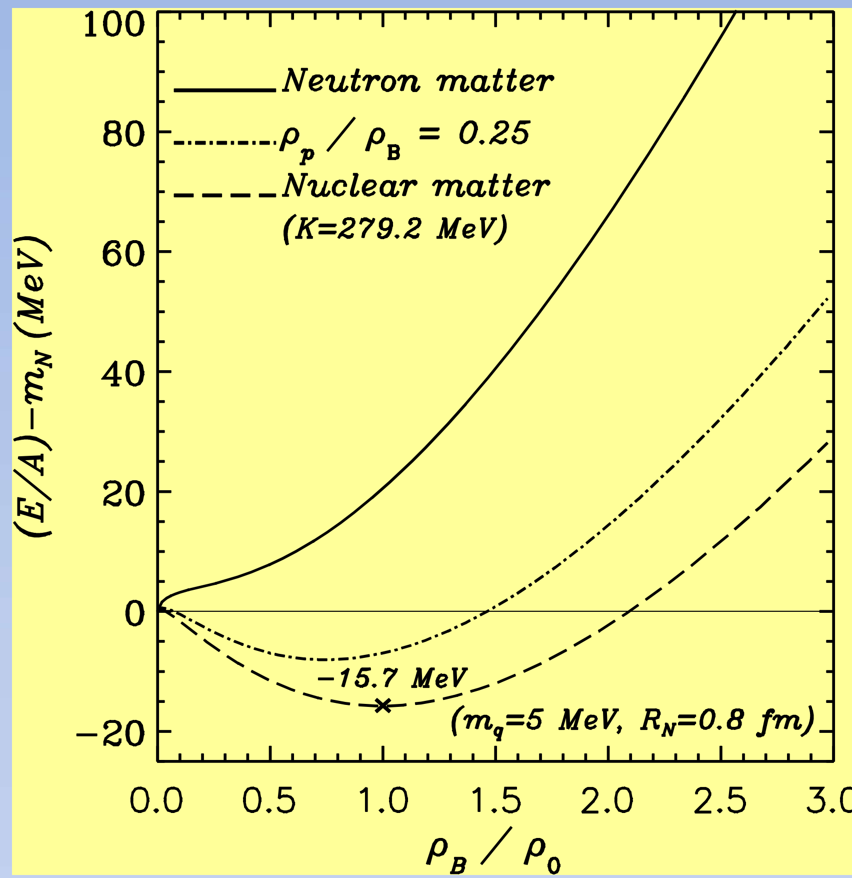
Incompressibility

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**

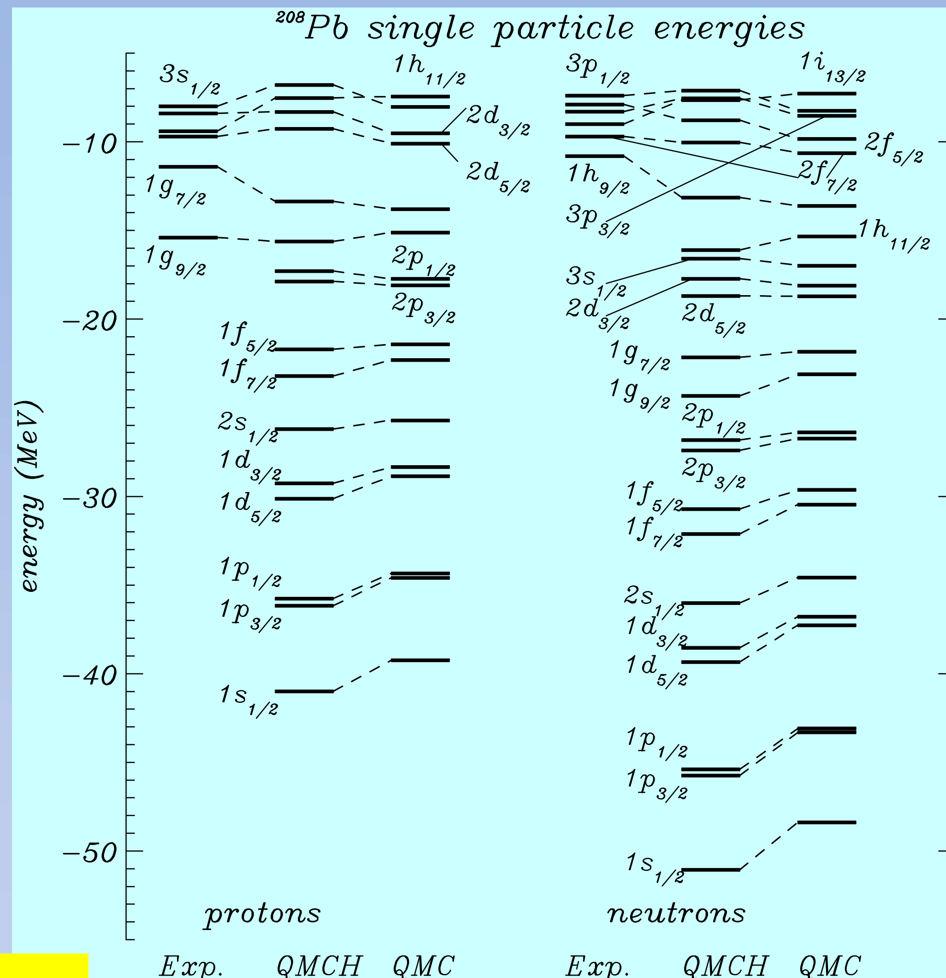
Nuclear matter

<u>Based on **quarks**</u> !

↓

Hadrons

Hypernuclei



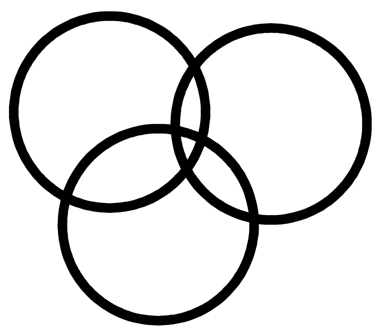
latest QMC, NPA 814, 66 (2008)

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**:



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

QMC · · 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

- 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** · 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 $\sigma = 0$)

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:

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

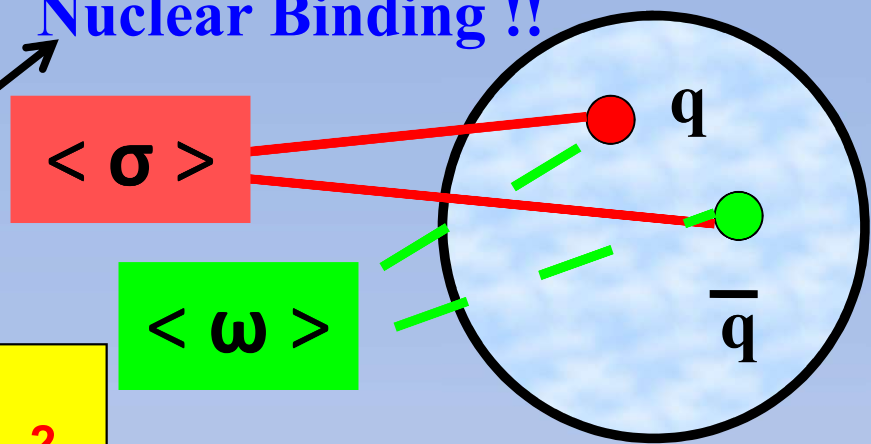
highlights scalar polarizability

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 !!



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

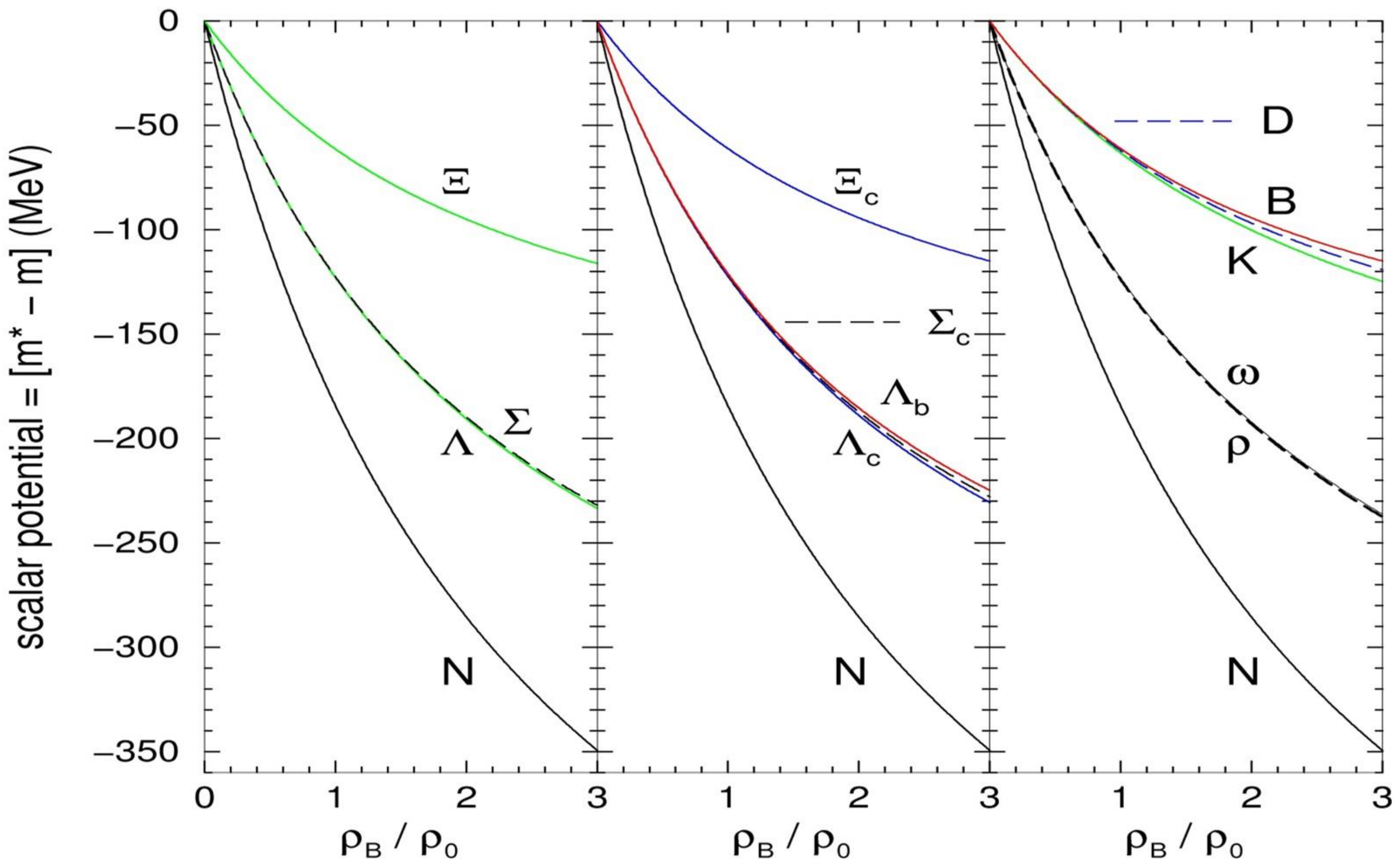
↓ **nonlinear** in **σ**

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

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

σ,ω fields: **no couplings** with **s,c,b** quarks!!

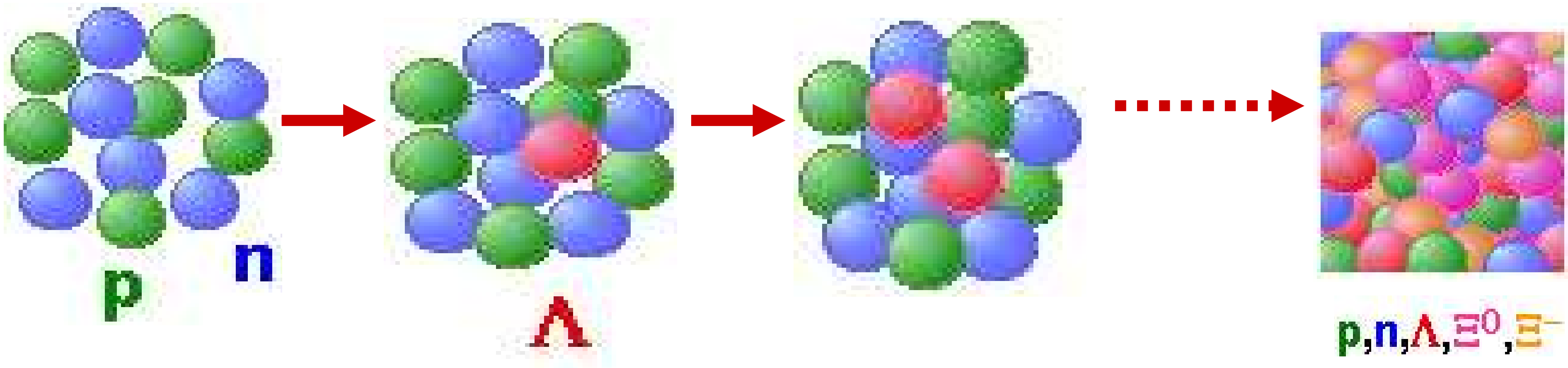
Scalar potentials in **QMC** respects **SU(3)** (**light quark # !**)



Hypernuclei
(Introduction)

What are Hypernuclei ?

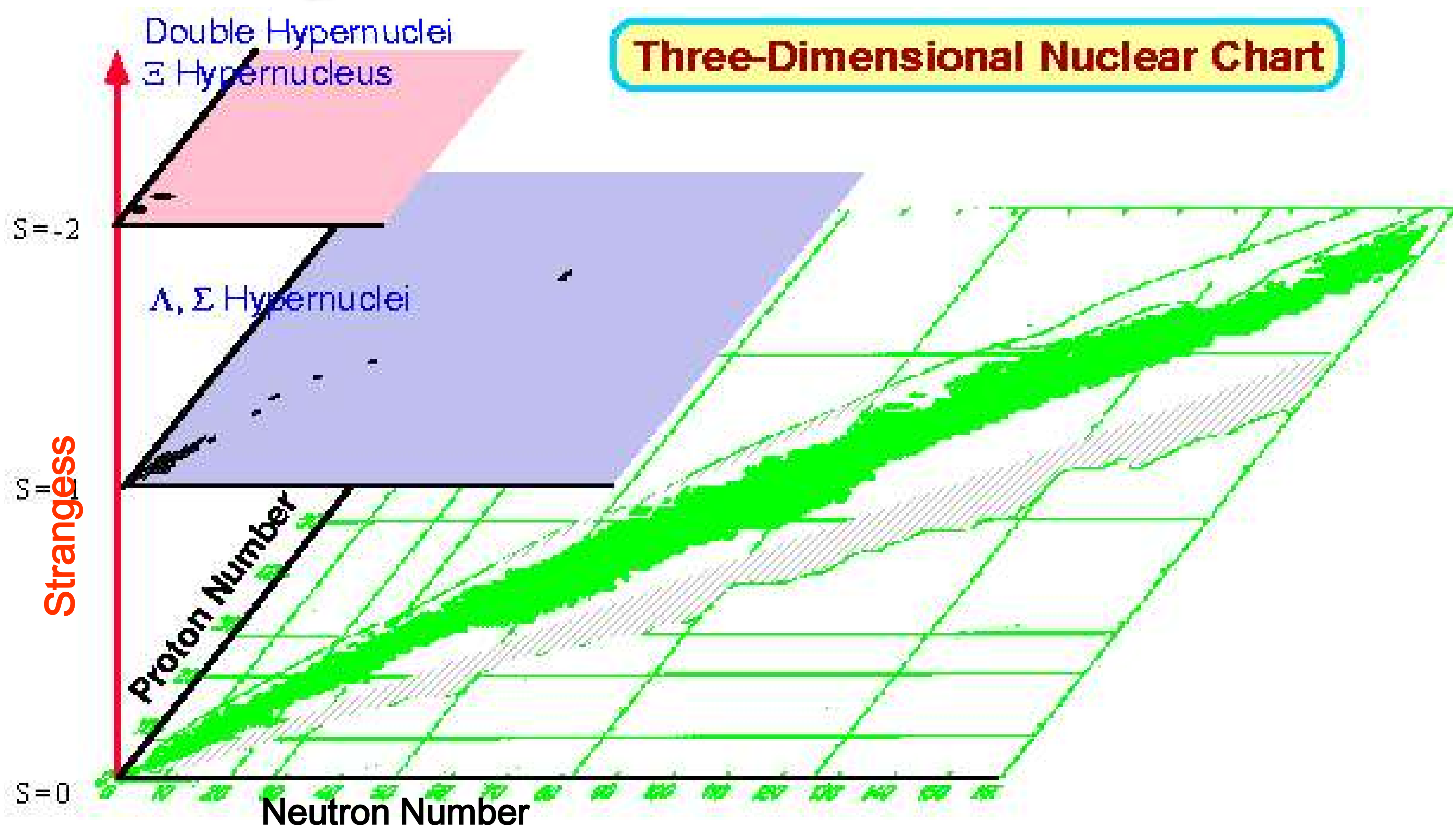
Hypernuclei are nuclear systems where at least one nucleon is replaced by a hyperon (e.g. Λ).

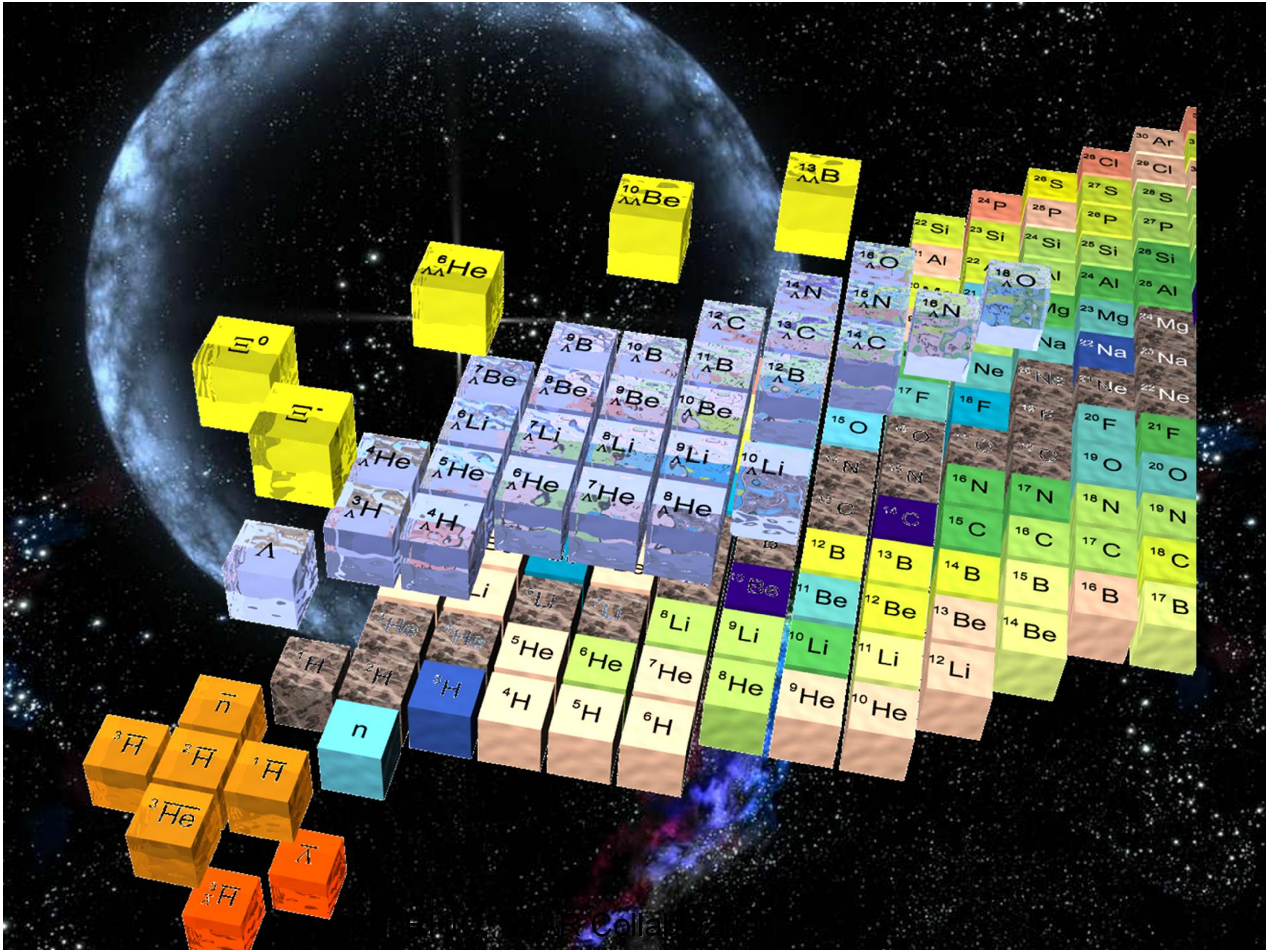


${}^{A}_{\Lambda}Z$ is a bound state of Z protons (A-Z-1) neutrons and a Λ hyperon

Hypernuclei are a laboratory to study the hyperon-nucleon, Hyperon-hyperon interactions.

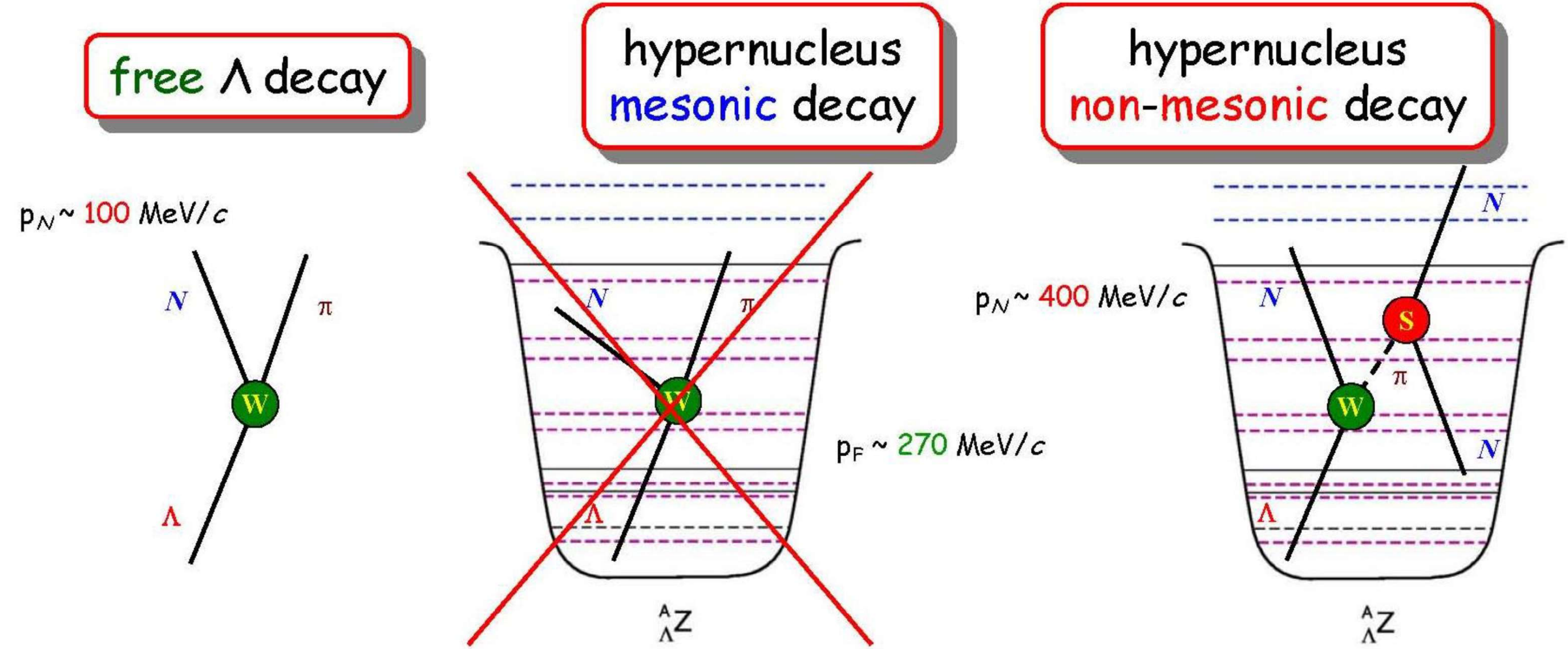
S = - 2, Ξ-Hypernuclei at J-PARC, JAPAN
by (K^-, K^+) reaction, the first evidence.
(KISO Event, Ξ^- - ^{14}N system)





10 ΛΛBe
13 ΛΛB
6 ΛΛHe
Ξ0
Ξ-
Λ
3 ΛH
4 ΛH
4 ΛHe
5 ΛHe
6 ΛHe
7 ΛHe
8 ΛHe
6 ΛLi
7 ΛLi
8 ΛLi
9 ΛLi
10 ΛLi
7 ΛBe
8 ΛBe
9 ΛBe
10 ΛBe
9 ΛB
10 ΛB
11 ΛB
12 ΛB
12 ΛC
13 ΛC
14 ΛC
14 ΛN
15 ΛN
16 ΛN
16 ΛO
18 ΛO
n
1H
2H
3H
4H
5H
6H
5He
6He
7He
8He
9He
10He
8Li
9Li
10Li
11Li
12Li
11Be
12Be
13Be
14Be
12B
13B
14B
15B
16B
17B
14C
15C
16C
17C
18C
16N
17N
18N
19N
15O
19O
20O
17F
18F
20F
21F
22Na
23Na
23Mg
24Mg
24Al
25Al
22Si
23Si
24Si
25Si
26Si
24P
25P
26P
27P
26S
27S
28S
28Cl
29Cl
30Ar
n̄
1H̄
2H̄
3H̄
3Hē
Λ̄

Λ hyperon can stay in contact with nucleons inside a Nucleus



$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

$\tau_\Lambda = 263$ ps

suppressed by Pauli blocking

$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

Why are Hypernuclei interesting!

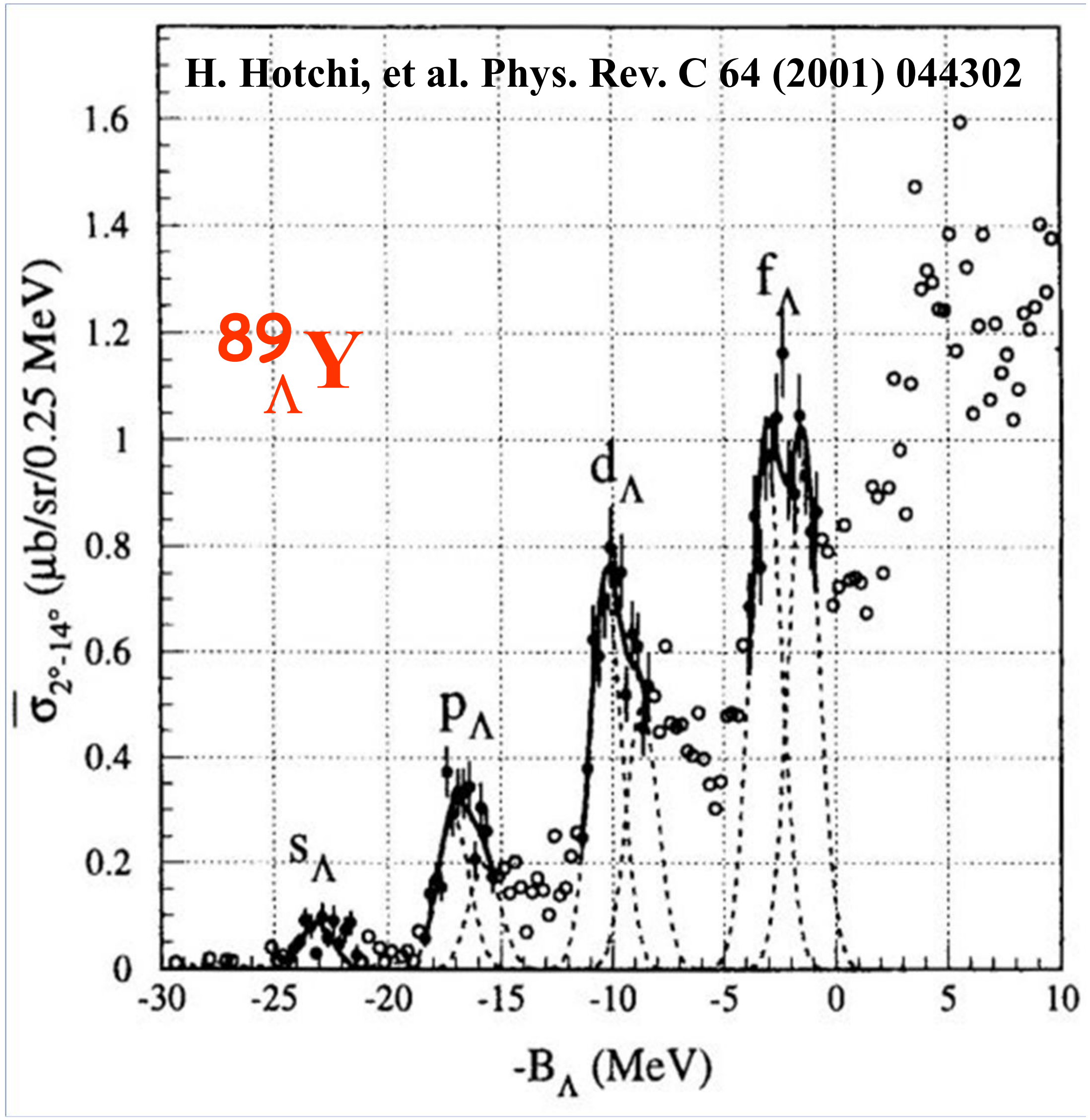
New type of nuclear matter, new symmetries, New selection rules. First kind of flavored nuclei.

Hyperons are free from Pauli principle restrictions

Can occupy quantum states already filled up with nucleons

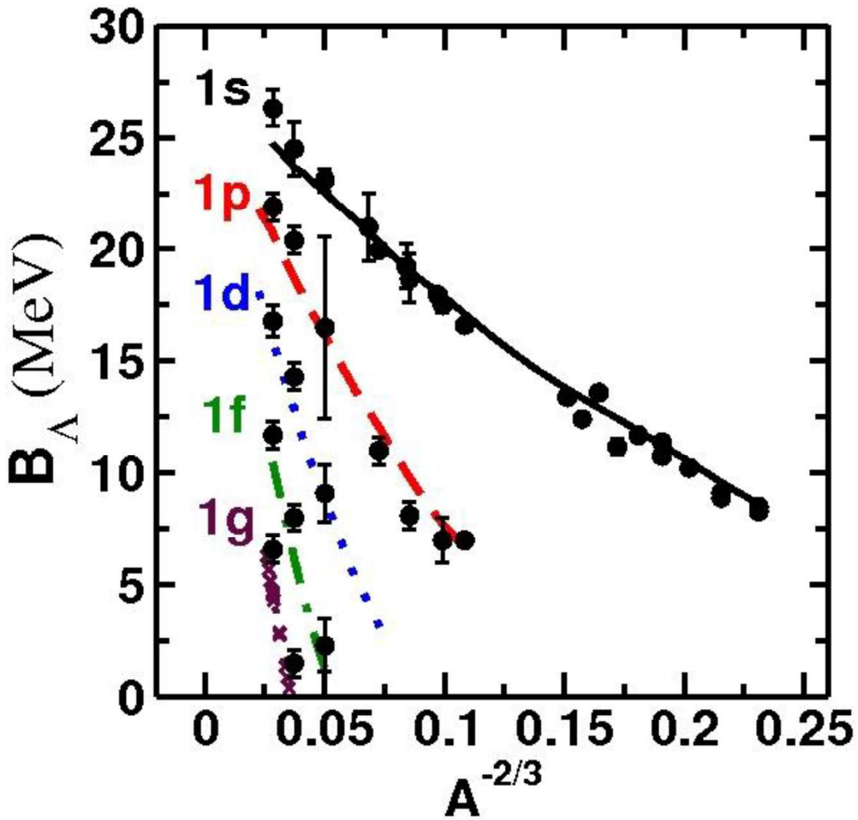
This makes a hyperon embedded in the nucleus a unique tool for exploring the nuclear structure.

Good probe for deeply bound single particle states.



Study of S = -1 hypernuclei (Λ or Σ)

The nuclear structure and the many body nuclear dynamics is extended to new non conventional symmetries, due to the inclusion of an S≠ 0 degree of freedom in the nucleus, YN interaction



The Skyrme type ΛN interaction from the known BE of Λ hypernuclei.

Neelam Guleria, S.K. Dhiman and R. Shyam, Nucl. Phys. A 886, 71 (2012)

The role played by quark degrees of freedom in nuclear phenomena: Quark-Meson coupling model, extended for hypernuclei

Guichon, KT, Saito, Thomas

The study of four fermion, strangeness changing, baryon-baryon weak interaction YN→NN, which can occur only inside hypernuclei

S = -2 systems

New Physics items

- For a detailed understanding of the quark aspect of the baryon-baryon forces in the SU(3) space, information on the YY channel is essential.

- Are there S=-2 deeply bound multi $\bar{K}$ states??

- Search for *H particle*

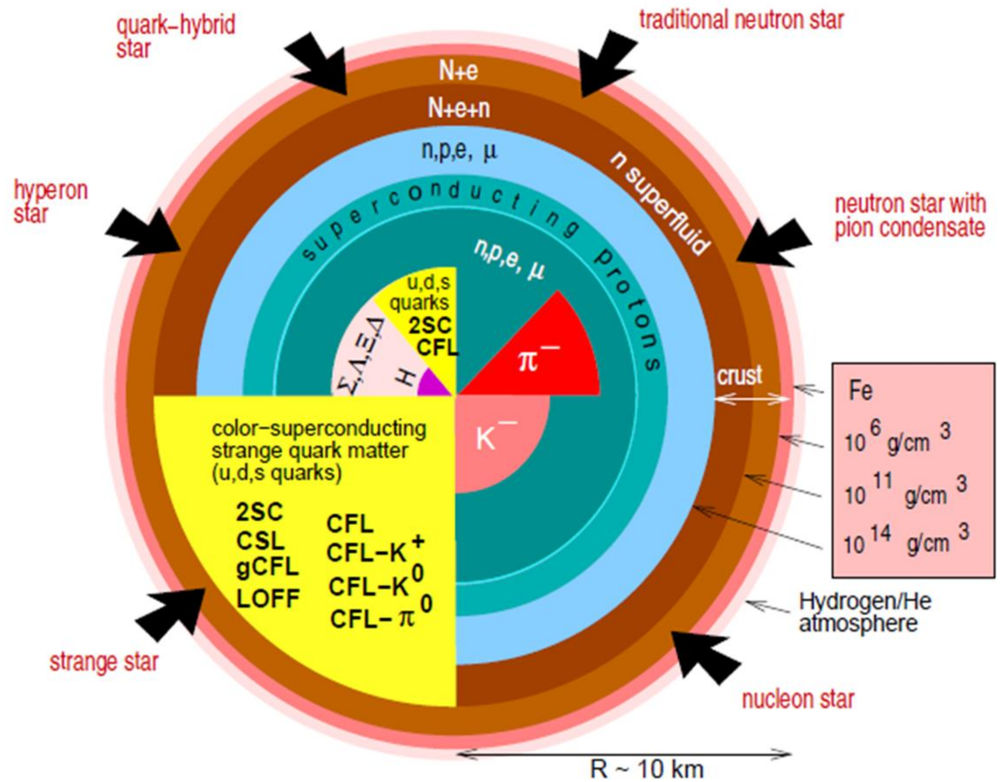
  six-quark system uuddss

Conjectured

composition of a neutron star

Neutron star composition

- Formation of compact stars depends On the nature of the YY interaction.



Juergen Schaffner-Bielich, Nucl. Phys. A804 (2008) 309

Experiments

No! Σ-Hypernuclei

Naïve SU(3) based model

yield **Σ**-Hypernuclei !

→ QMC ?

Λ, Σ ⇔ Self-consistent **OGE** color hyperfine interaction

Λ and Σ hypernuclei are more or less similar (channel couplings) ⇔ **improve !**

Ξ potential: **weaker (~1/2)** of Λ and Σ (**Light quark #**)

Very **small spin-orbit splittings** for Λ hypernuclei ⇔ **SU(6) quark model**

Bag mass and **color mag. HF** int. contribution (**OGE**)

T. DeGrand *et al*., PRD 12, 2060 (1975)

$$M = [N_q\Omega_q + N_s\Omega_s]/R - Z_0/R + 4\pi B R^3/3$$

$$+ \underline{(F_s)^n}\Delta E_M(f) \qquad (f = N, \Delta, \Lambda, \Sigma, \Xi \ldots)$$

$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j M(m_i, m_j, R)$$

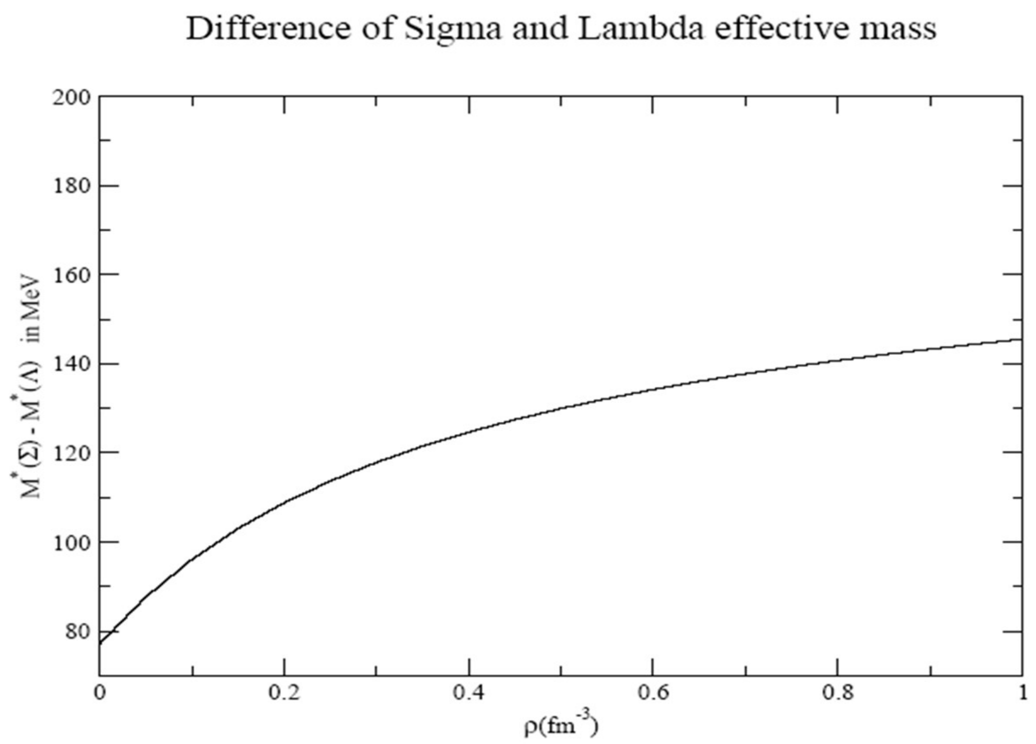
$$\Delta E_M(\Lambda) = -3\alpha_c M(m_q, m_q, R), \quad (q = u, d)$$

$$\Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R)$$

$$-4\alpha_c M(m_q, m_s, R)$$

Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

N - Δ and **Σ - Λ** splitting arise from **one-gluon-exchange** in MIT Bag Model : as "σ" so does this splitting…



Σ - Λ splitting

Σ-hypernuclei unbound!!

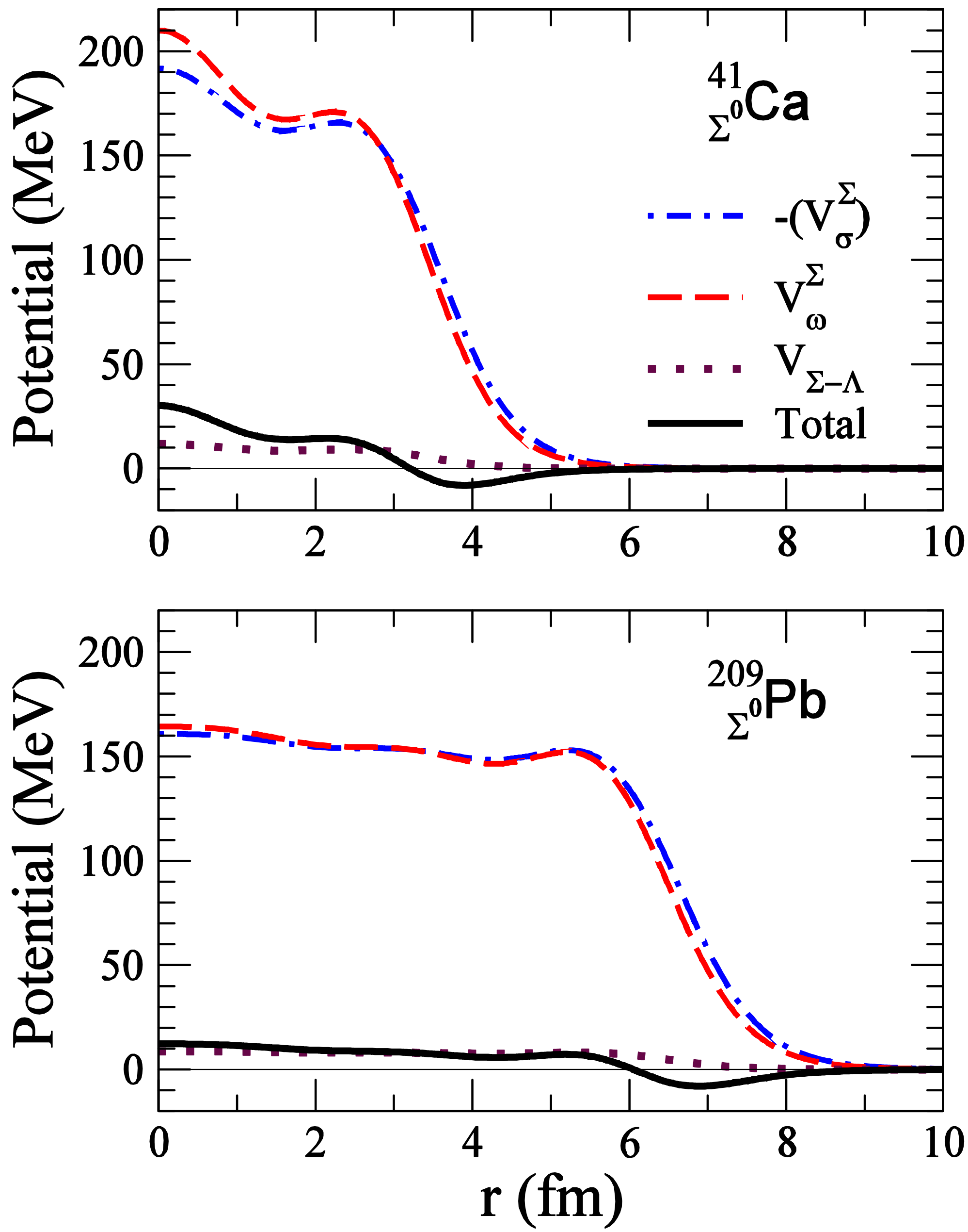
Guichon, Thomas, Tsushima, Nucl. Phys. A841 (2008) 66

Σ^0 potentials
($1s_{1/2}$)

Repulsion
in center
Attraction
in surface

No Σ nuclear bound state!

HF couplings for hyperons ⇔ successful for high density neutron star
(NPA 792, 341 (2007))



Hypernuclei spectra 1

NPA 814, 66 (2008)

	$^{16}_{\Lambda}$O Exp.	$^{17}_{\Lambda}$O	$^{17}_{\Xi^0}$O	$^{40}_{\Lambda}$Ca Exp.	$^{41}_{\Lambda}$Ca	$^{41}_{\Xi^0}$Ca	$^{49}_{\Lambda}$Ca	$^{49}_{\Xi^0}$Ca
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9	-1.9	-15.4	-5.6
$1d_{5/2}$					-5.5		-7.4	
$2s_{1/2}$					-1.0		-3.1	
$1d_{3/2}$					-5.5		-7.3	

Hypernuclei spectra 2

NPA 814, 66 (2008)

	$^{89}_{\Lambda}$Yb Exp.	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb Exp.	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-23.1	-24.0	-9.9	-26.3	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.5	-19.4	-7.2	-21.9	-24.0	-12.7
$1d_{5/2}$	-9.1	-13.4	-3.1	-16.8	-20.1	-9.6
$2s_{1/2}$		-9.1	–		-17.1	-8.2
$1d_{3/2}$	(-9.1)	-13.4	-3.4	(-16.8)	-20.1	-9.8

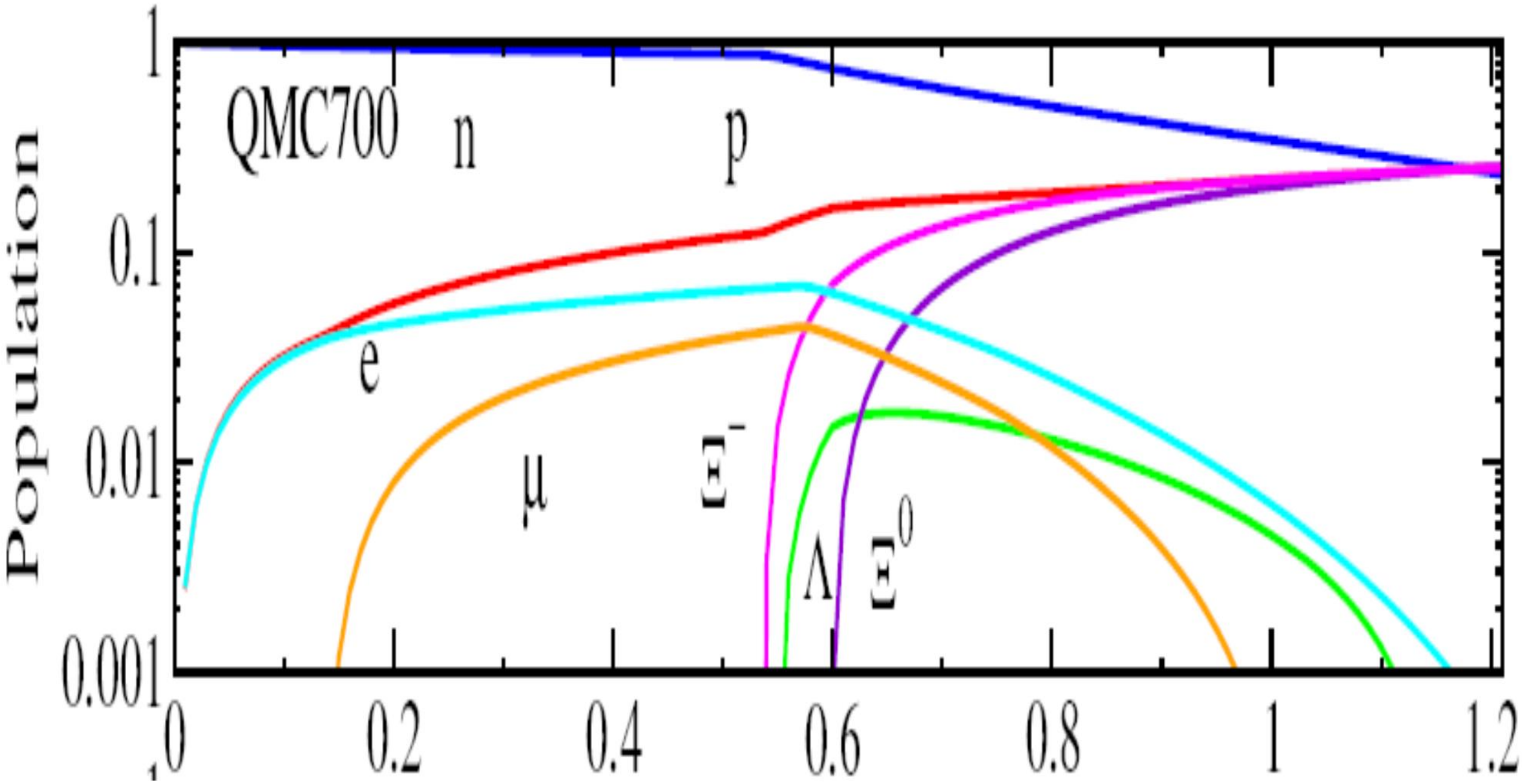
Summary: hypernuclei

- The latest version of QMC (**OGE** color **hyperfine** interaction included self-consistently in matter) ⇒
- Λ single-particle energy **$1s_{1/2}$ in Pb** is **-26.9** MeV (Exp. **-26.3** MeV) ⇐ **no extra parameter!**
- **Small** spin-orbit splittings for the Λ
- **No Σ nuclear bound state !!**
- Ξ is expected to form nuclear bound state

Consequences for Neutron Star ⇒

D.L.Whittenbury et.al., Phys.Rev. C89 (2014) 06580

New QMC model, relativistic, Hartree-Fock treatment



Stone et al., Nucl. Phys. A792 (2007) 341

QMC model 1: Hadron level

$$\mathcal{L} = \bar{\psi}[i\gamma\cdot\partial - m_N^*(\sigma) - g_\omega\omega^\mu\gamma_\mu]\psi + \mathcal{L}_{\mathrm{meson}},$$

$$m_N^*(\sigma) \equiv m_N - g_\sigma\underline{(\sigma)}\sigma \simeq m_N - g_\sigma\underline{[1-(a_N/2)(g_\sigma\sigma)]}\sigma$$

$$g_\sigma \equiv g_\sigma(\sigma=0)$$

$$\mathcal{L}_{\mathrm{meson}} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2 - \frac{1}{2}\partial_\mu\omega_\nu(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu) + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\ ,$$

$$\rho_B = \frac{4}{(2\pi)^3}\int d^3k\ \theta(k_F - |\vec{k}|) = \frac{2k_F^3}{3\pi^2},$$

$$\rho_s = \frac{4}{(2\pi)^3}\int d^3k\ \theta(k_F - |\vec{k}|)\frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}},$$

QMC model 2: Quark level

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius)

$$\left[i\gamma \cdot \partial_x - (m_q - V^q_\sigma) \mp \gamma^0 \left(V^q_\omega + \frac{1}{2} V^q_\rho\right)\right] \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} = 0$$

$$\left[i\gamma \cdot \partial_x - (m_q - V^q_\sigma) \mp \gamma^0 \left(V^q_\omega - \frac{1}{2} V^q_\rho\right)\right] \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} = 0$$

$$[i\gamma \cdot \partial_x - m_Q]\, \psi_Q(x) \ (\text{or } \psi_{\overline{Q}}(x)) = 0$$

$$m^*_h = \sum_{j=q,\bar{q},Q\overline{Q}} \frac{n_j \Omega^*_j - z_h}{R^*_h} + \frac{4}{3}\pi R^{*3}_h B, \quad \left.\frac{\partial m^*_h}{\partial R_h}\right|_{R_h = R^*_h} = 0$$

$$\Omega^*_q = \Omega^*_{\bar{q}} = [x^2_q + (R^*_h m^*_q)^2]^{1/2}, \text{with } m^*_q = m_q - g^q_\sigma \sigma$$

$$\Omega^*_Q = \Omega^*_{\overline{Q}} = [x^2_Q + (R^*_h m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

QMC model 3: From quarks

$$
\begin{aligned}
\omega &= \frac{g_\omega \rho_B}{m_\omega^2}, \\
\sigma &= \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \frac{4}{(2\pi)^3} \int d^3k \; \theta(k_F - |\vec{k}|) \frac{m_N^*(\sigma)}{\sqrt{m_N^{*2}(\sigma) + \vec{k}^2}} \\
&= \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \rho_s \quad (g_\sigma \equiv g_\sigma(\sigma = 0)), \\
C_N(\sigma) &= \frac{-1}{g_\sigma(\sigma = 0)} \left[\frac{\partial m_N^*(\sigma)}{\partial \sigma} \right], \\
E^{tot}/A - m_N &= \frac{4}{(2\pi)^3 \rho_B} \int d^3k \; \theta(k_F - |\vec{k}|) \sqrt{m_N^{*2}(\sigma) + \vec{k}^2} \\
&\quad + \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2 m_\omega^2} - m_N.
\end{aligned}
$$

QMC model 4: Couplings etc.

m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148

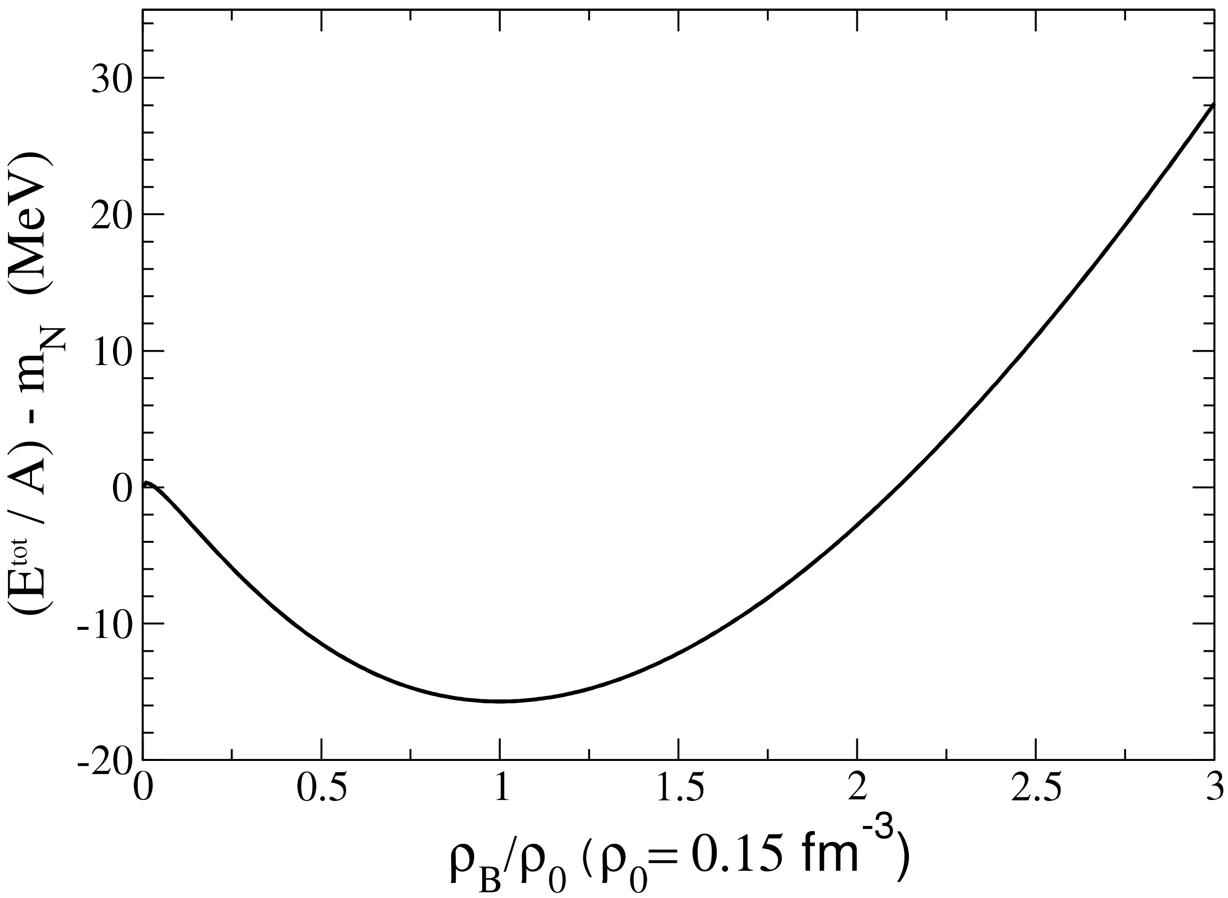
$$\frac{\partial m_N^*(\sigma)}{\partial\sigma} = -3g_\sigma^q \int_{bag} d^3r\, \overline{\psi}_q(\vec{r})\psi_q(\vec{r}) \quad \text{the lowest bag w.f.}$$

$$\equiv -3g_\sigma^q S_N(\sigma) = -\frac{\partial}{\partial\sigma}\left[g_\sigma(\sigma)\sigma\right],$$

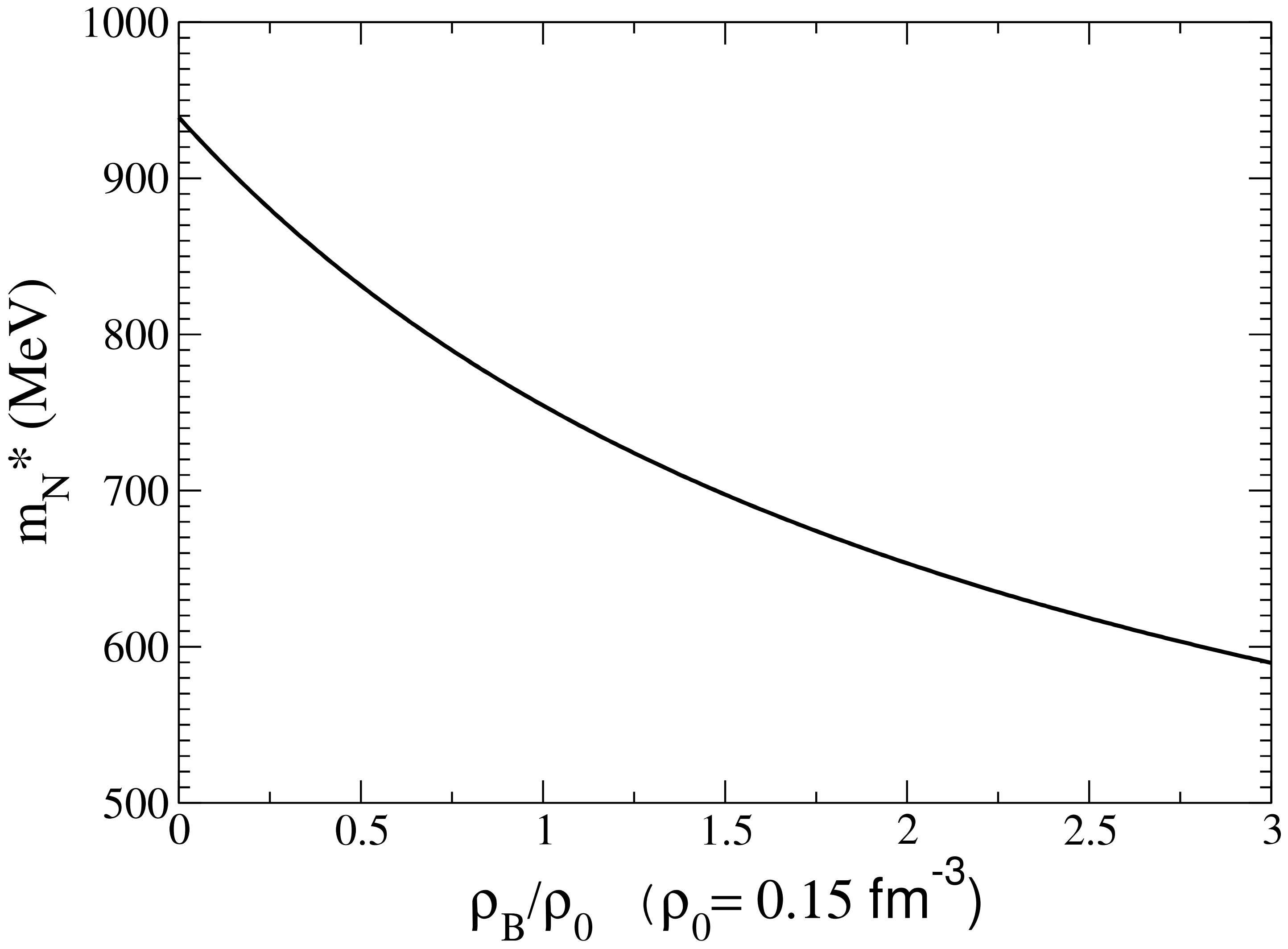
$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma=0)}\left[\frac{\partial m_N^*(\sigma)}{\partial\sigma}\right],$$

$$g_\sigma \equiv g_\sigma^N \equiv 3g_\sigma^q S_N(\sigma=0).$$

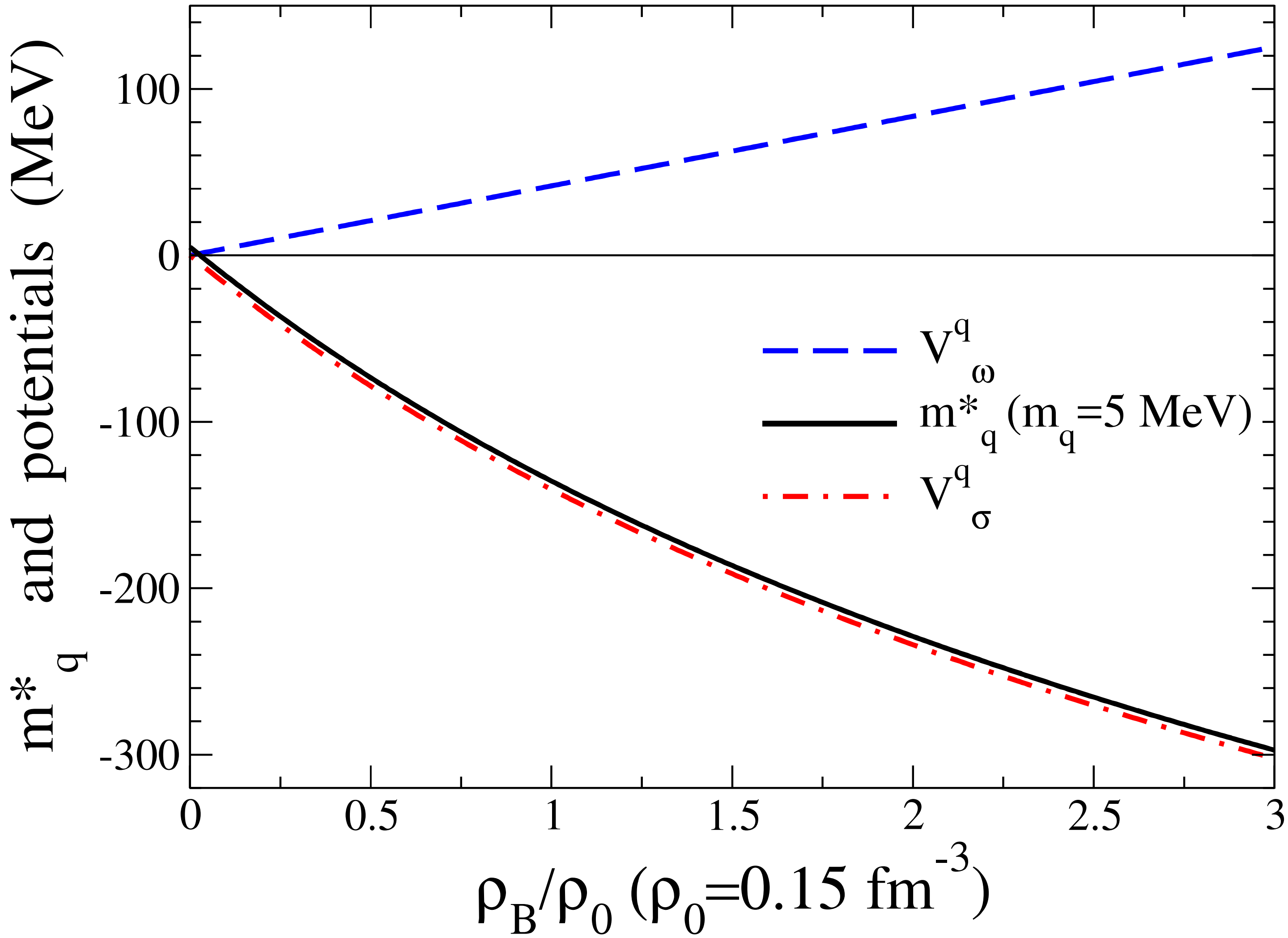
Results: Quark Meson Coupling (Standard)



- **Symmetric Nuclear Matter - Biding Energy per Nucleon**
- **m_q = 5 MeV, K = 279.3 MeV**

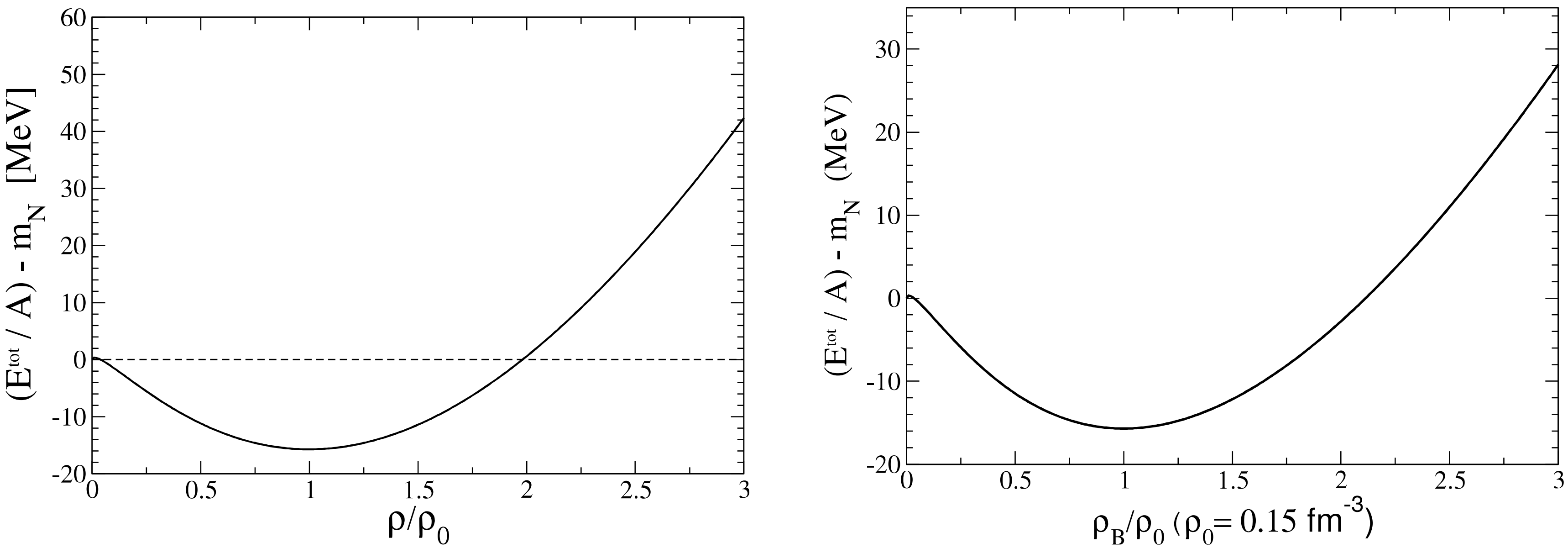


- **Nucleon effective mass: $m_q = 5$ MeV**

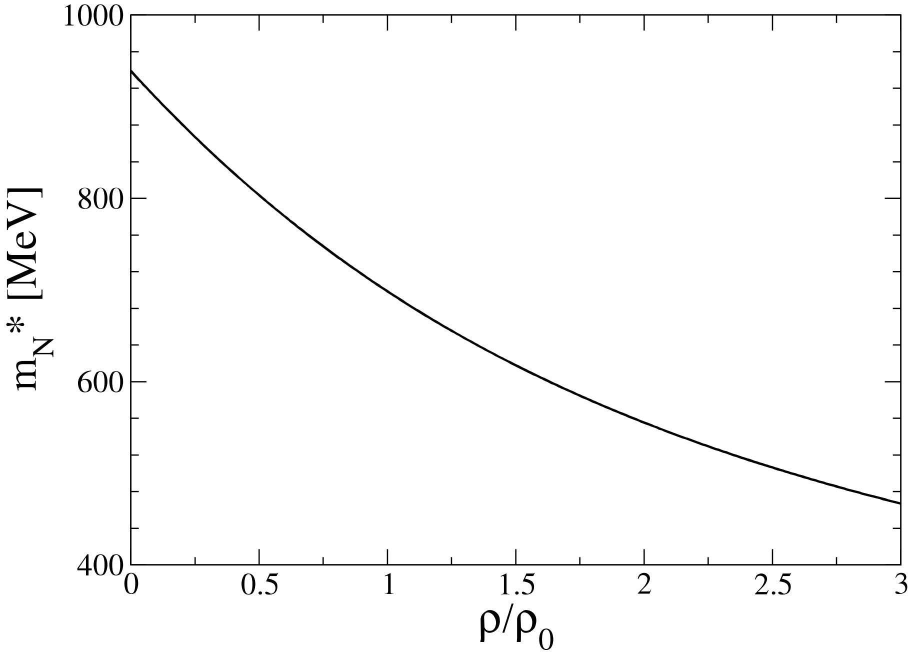


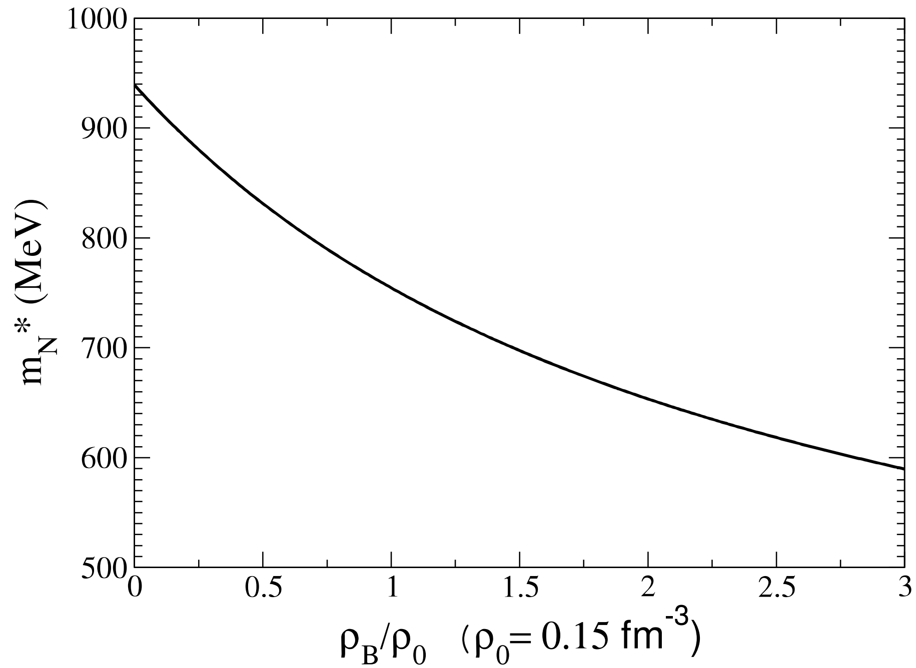
- **Effective mass of constituent quarks: $m_q = 5$ MeV**
- **All the light-quarks in any hadrons feel the same potentials !!**

Comparison of Energy/nucleon



- Symmetric Nuclear Matter - Biding Energy per Nucleon (scale !!)
- LF pion model (left): $m_q = 220$ MeV, $K = 320.9$ MeV
- Standard QMC (right): $m_q = 5$ MeV, $K = 279.3$, MeV

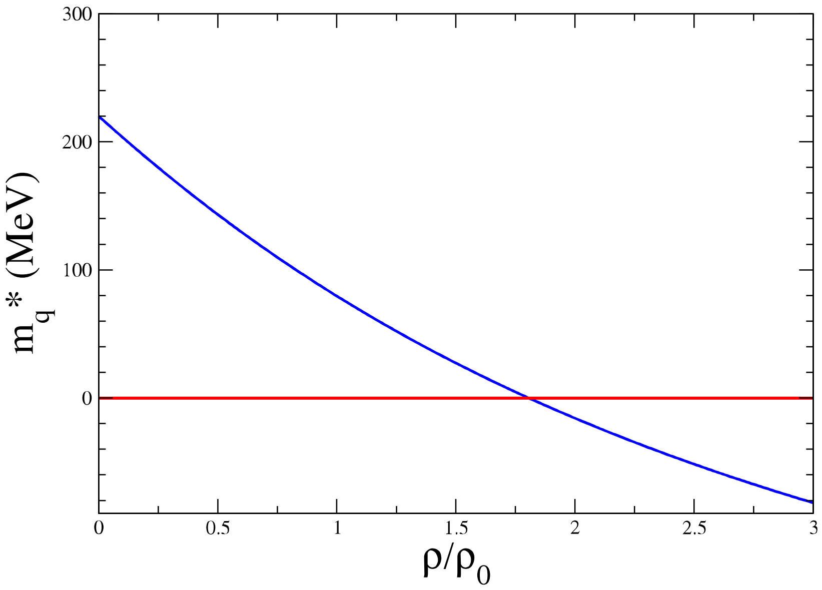


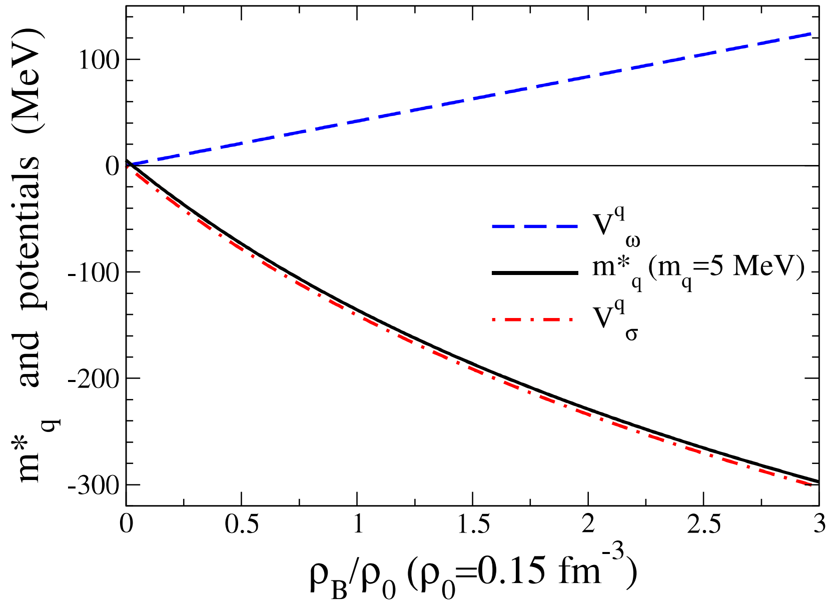


Nucleon effective mass

- **LF pion model** **(left: $m_q = 220$MeV)**
- **Standard QMC** **(right: $m_q = 5$MeV)**

LF pion model and Standard QMC: m_q^* (potentials)





- Effective mass of constituent quarks, up and down
- LF pion model: $m_q = 220$ MeV (left)
- Standard QMC $m_q = 5$ MeV (right)

Standard QMC, π, ρ in LF model parameters comparison

- **Motivation:** The present model works well (Symmetric Vertex)!

m_q(MeV)	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}$(MeV)
5	5.39	5.30	754.6	279.3	3.295	170
220	6.40	7.57	698.6	320.9	4.327	148
430	8.73	11.93	565.25	361.4	5.497	69.75

- Refs. LF π, ρ model:

J.P.B.C. de Melo, KT et al.,
LF π model ($m_q = 220$ MeV): Phys.Rev. C90 (2014) no.3, 035201;
Phys.Lett. B766 (2017) 125;
Few Body Syst. 58 (2017) no.2, 85
LF ρ model ($m_q = 430$ MeV): Few Body Syst. 58 (2017) no.2, 82;
arXiv:1802.06096 [hep-ph]

QMC: Hadron masses in medium

$x = (t, \vec{r})$ ($|\vec{r}| \leq$ bag radius)

$$\left[i\gamma \cdot \partial_x - (m_q - V^q_\sigma) \mp \gamma^0 \left(V^q_\omega + \frac{1}{2}V^q_\rho\right)\right] \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} = 0$$

$$\left[i\gamma \cdot \partial_x - (m_q - V^q_\sigma) \mp \gamma^0 \left(V^q_\omega - \frac{1}{2}V^q_\rho\right)\right] \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} = 0$$

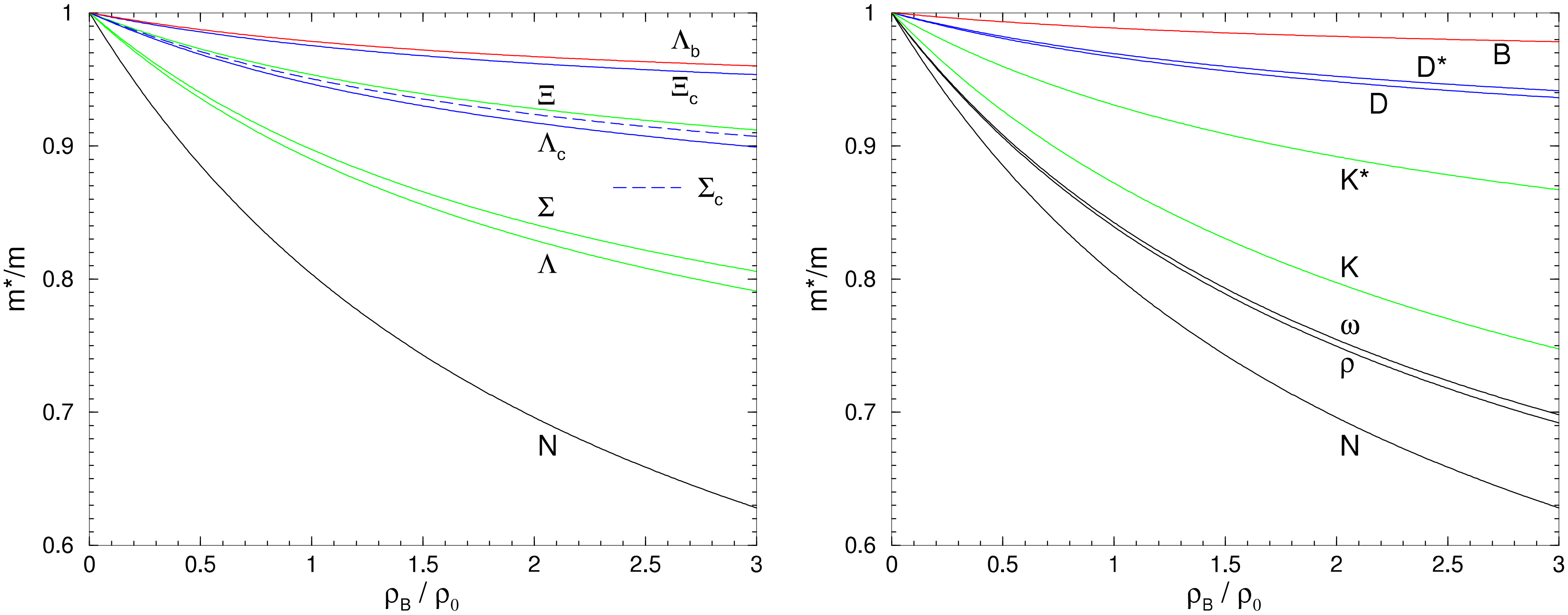
$$[i\gamma \cdot \partial_x - m_Q]\, \psi_Q(x) \;\; (\text{or } \psi_{\overline{Q}}(x)) = 0$$

$$m^*_h = \sum_{j=q,\bar{q},Q\overline{Q}} \frac{n_j \Omega^*_j - z_h}{R^*_h} + \frac{4}{3}\pi R^{*3}_h B, \quad \left.\frac{\partial m^*_h}{\partial R_h}\right|_{R_h = R^*_h} = 0$$

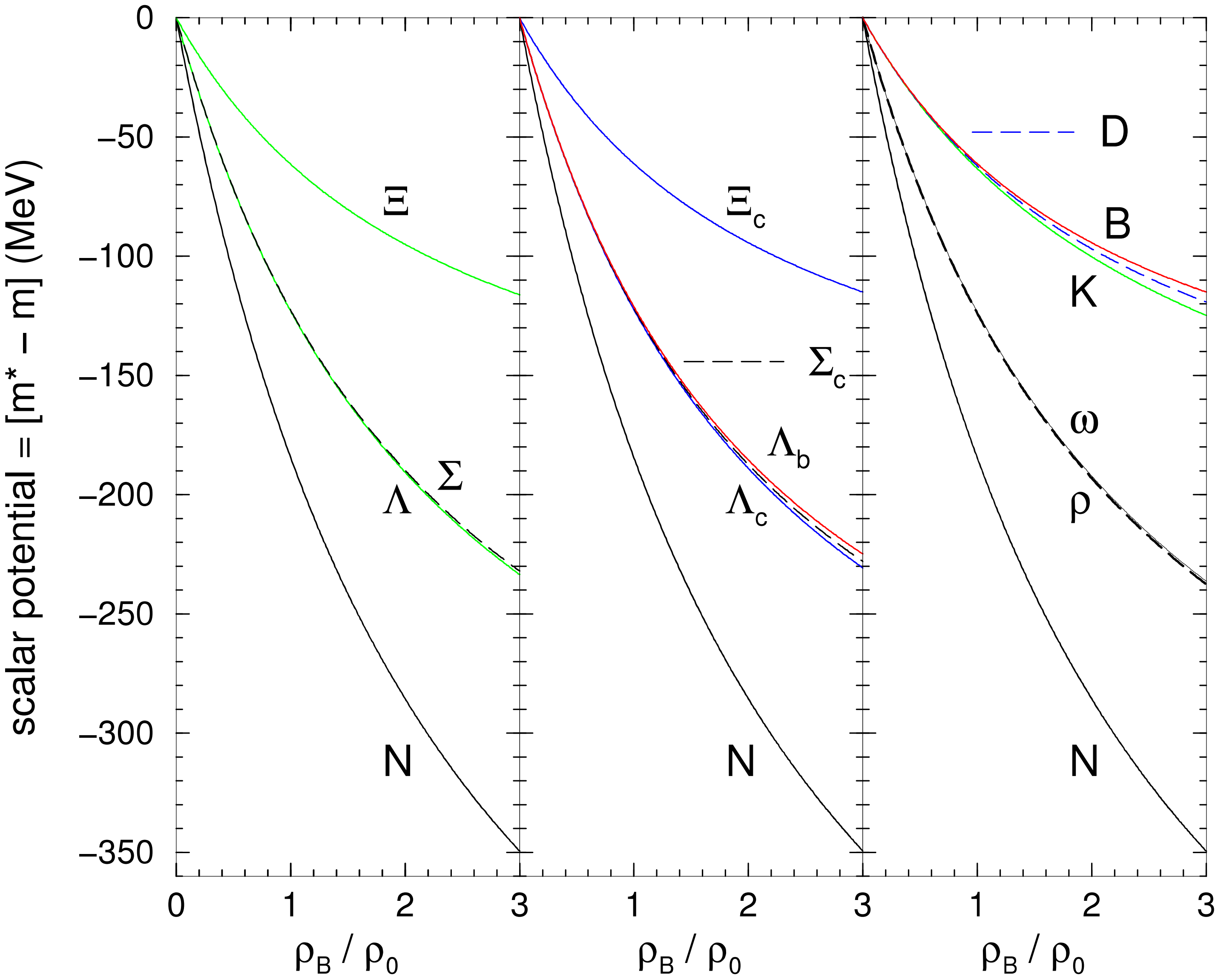
$$\Omega^*_q = \Omega^*_{\bar{q}} = [x_q^2 + (R^*_h m^*_q)^2]^{1/2}, \text{with } m^*_q = m_q - g^q_\sigma \sigma$$

$$\Omega^*_Q = \Omega^*_{\overline{Q}} = [x_Q^2 + (R^*_h m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

Hadron masses (ratios) in medium



Scalar potentials: $m_h^* - m_h$ (in medium)



In-medium properties of the low-lying Strange, Charm, Bottom baryons

- **Effective masses** (Σ_b, Ξ_b !!)
- **In-medium bag radii**
- **In-medium bag eigenfrequencies**
- **Scalar and vector (plus Pauli) potentials**
- **Excitation (total) energies** (Σ_b, Ξ_b !!)

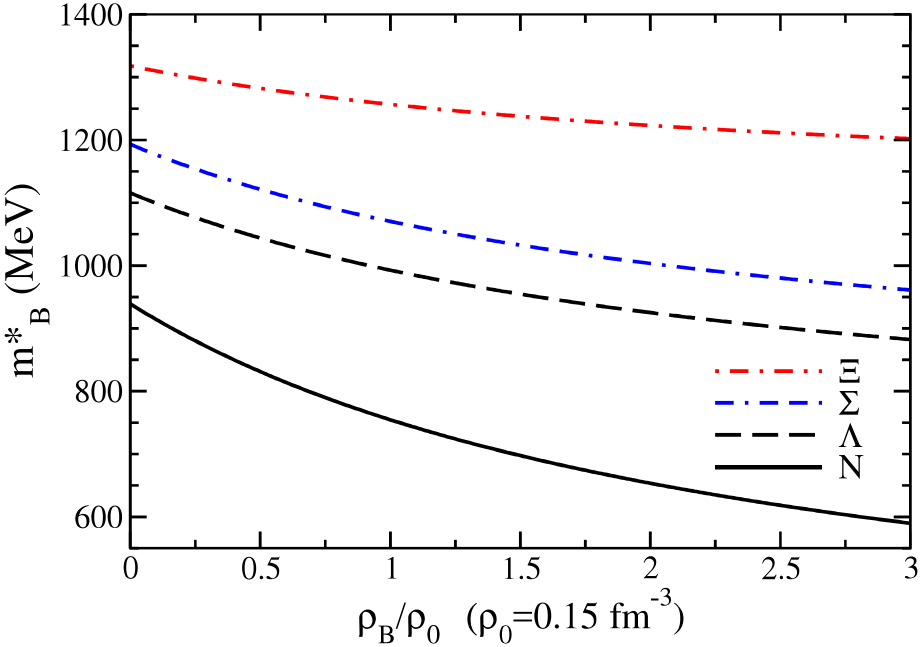
In vacuum (inputs)

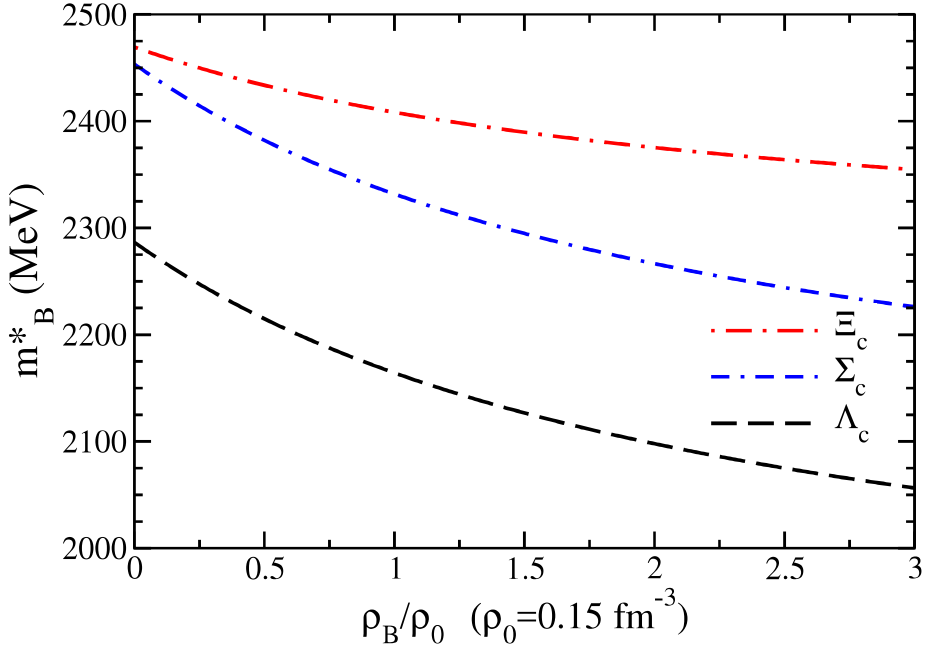
$B(q_1, q_2, q_3)$	z_B	m_B	R_B	x_1	x_2	x_3
N(qqq)	3.295	939.0	0.800	2.052	2.052	2.052
Λ(uds)	3.131	1115.7	0.806	2.053	2.053	2.402
Σ(qqs)	2.810	1193.1	0.827	2.053	2.053	2.409
Ξ(qss)	2.860	1318.1	0.820	2.053	2.406	2.406
Ω(sss)	1.930	1672.5	0.869	2.422	2.422	2.422
Λ_c(udc)	1.642	2286.5	0.854	2.053	2.053	2.879
Σ_c(qqc)	0.903	2453.5	0.892	2.054	2.054	2.889
Ξ_c(qsc)	1.445	2469.4	0.860	2.053	2.419	2.880
Ω_c(ssc)	1.057	2695.2	0.876	2.424	2.424	2.884
Λ_b(udb)	-0.622	5619.6	0.930	2.054	2.054	3.063
Σ_b(qqb)	-1.554	5813.4	0.968	2.054	2.054	3.066
Ξ_b(qsb)	-0.785	5793.2	0.933	2.054	2.441	3.063
Ω_b(ssb)	-1.327	6046.1	0.951	2.446	2.446	3.065

In medium at $\rho_0 = 0.15\ \mathrm{fm}^3$

$B(q_1, q_2, q_3)$	m_B^*	R_B^*	x_1^*	x_2^*	x_3^*
$N(qqq)$	754.5	0.786	1.724	1.724	1.724
$\Lambda(uds)$	992.7	0.803	1.716	1.716	2.401
$\Sigma(qqs)$	1070.4	0.824	1.705	1.705	2.408
$\Xi(qss)$	1256.7	0.818	1.708	2.406	2.406
$\Omega(sss)$	—	—	—	—	—
$\Lambda_c(udc)$	2164.2	0.851	1.691	1.691	2.878
$\Sigma_c(qqc)$	2331.8	0.889	1.671	1.671	2.888
$\Xi_c(qsc)$	2408.3	0.859	1.687	2.418	2.880
$\Omega_c(ssc)$	—	—	—	—	—
$\Lambda_b(udb)$	5498.5	0.927	1.651	1.651	3.063
$\Sigma_b(qqb)$	5692.8	0.966	1.630	1.630	3.066
$\Xi_b(qsb)$	5732.7	0.931	1.649	2.440	3.063
$\Omega_b(ssb)$	—	—	—	—	—

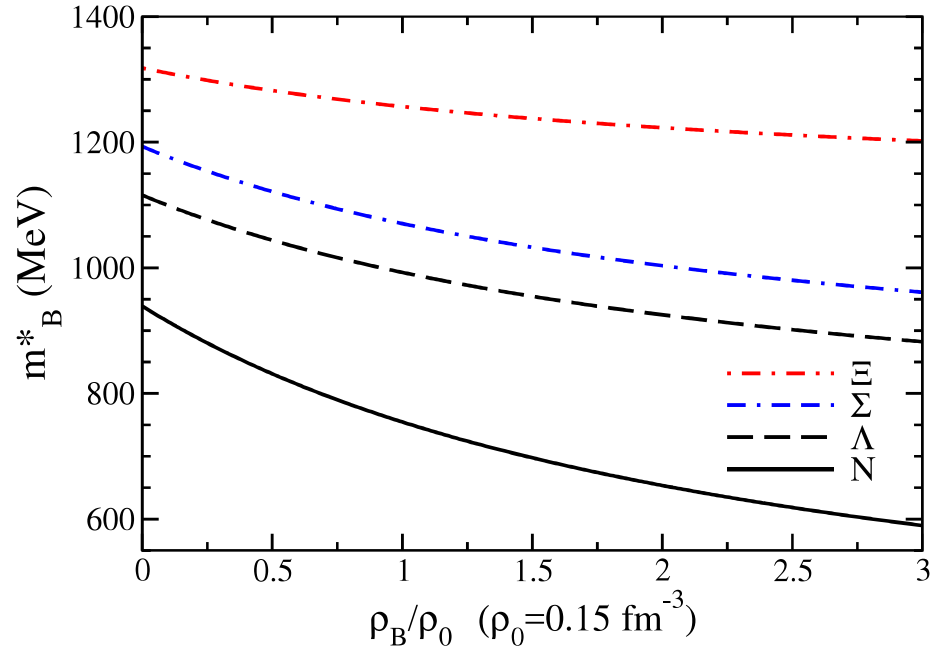
Effective masses:
Strange (left), Charm (right) baryons

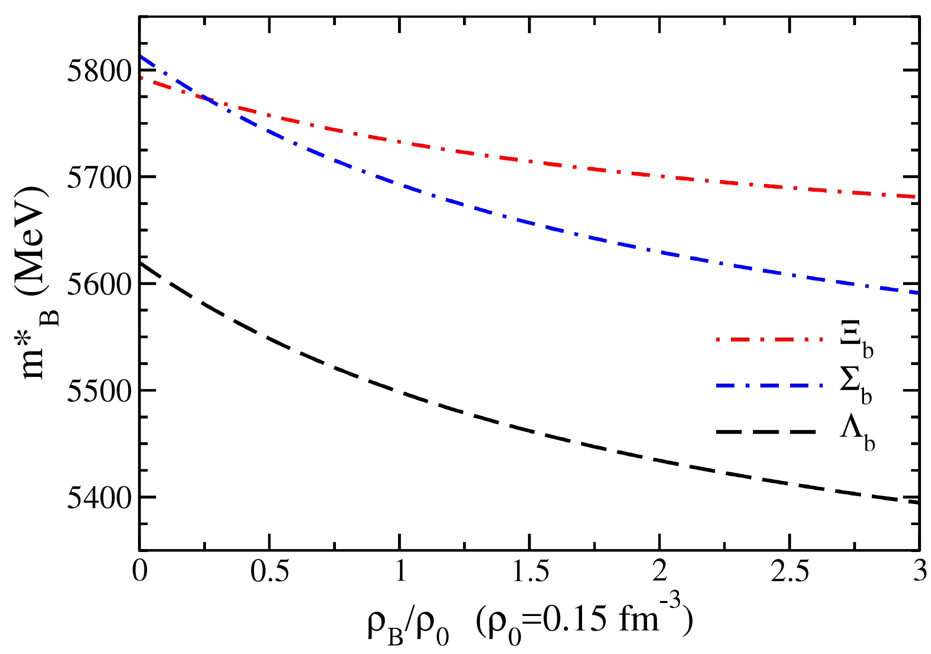




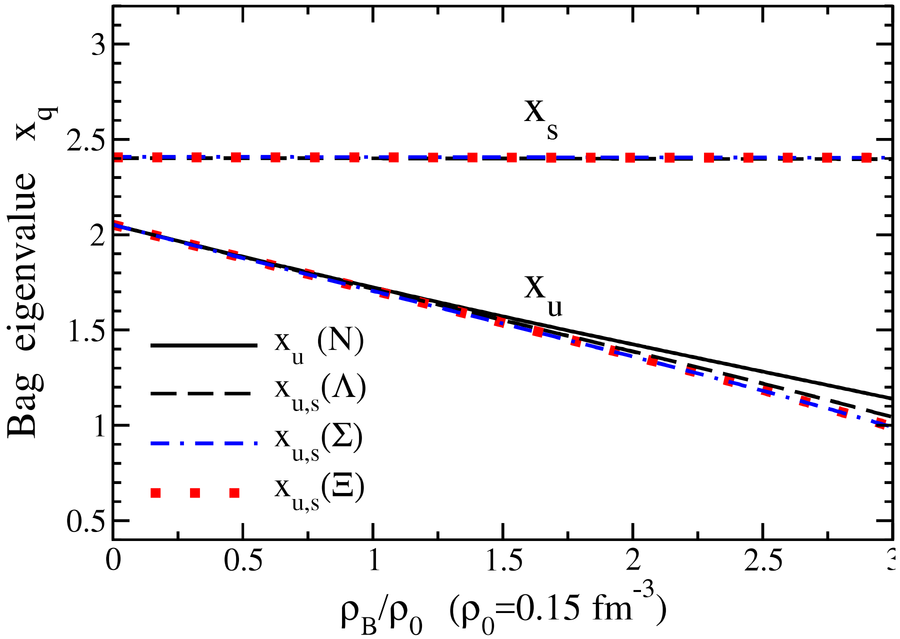
Effective masses:

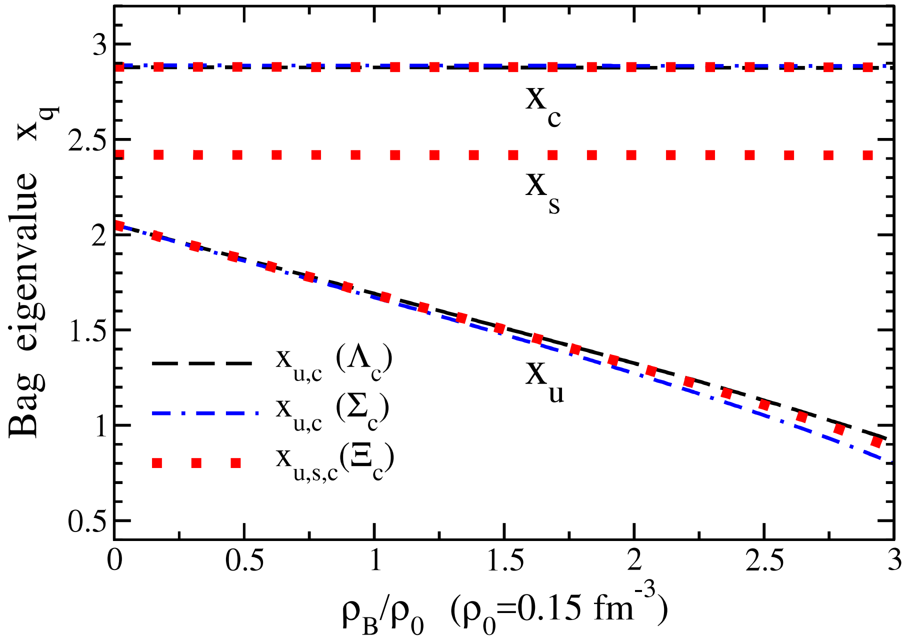
Strange (left), Bottom (right) baryons



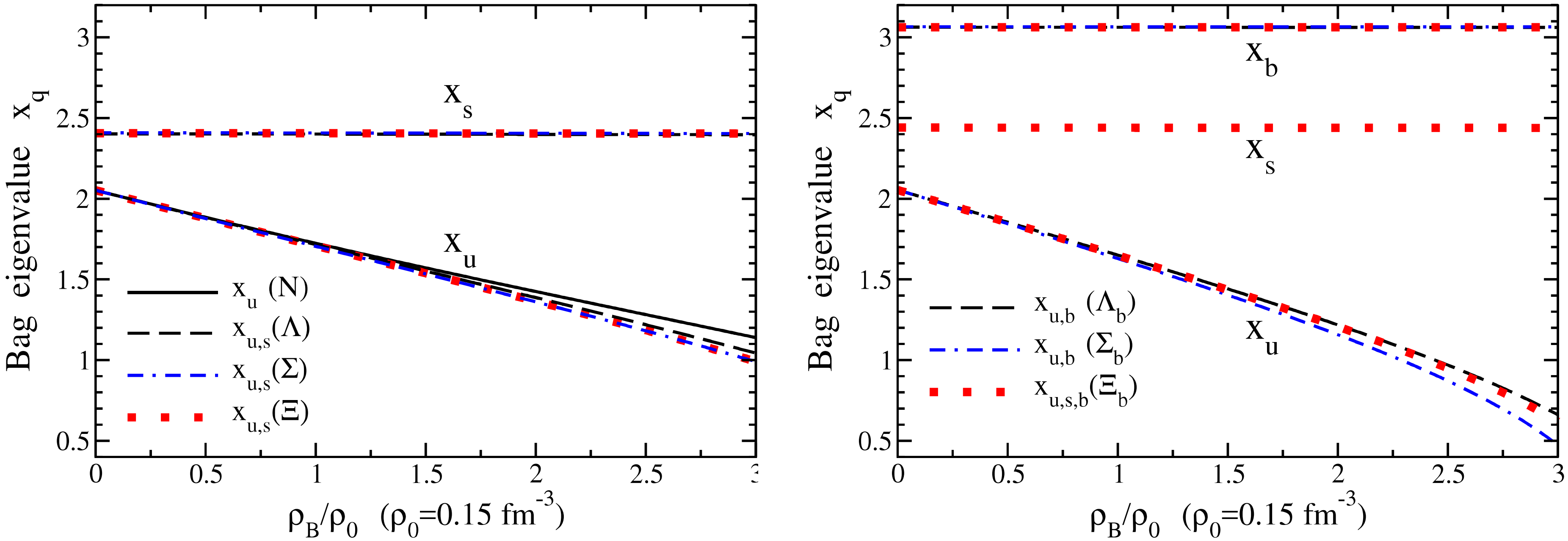


Bag eigenfrequencies:
Strange (left), Charm (right) baryons

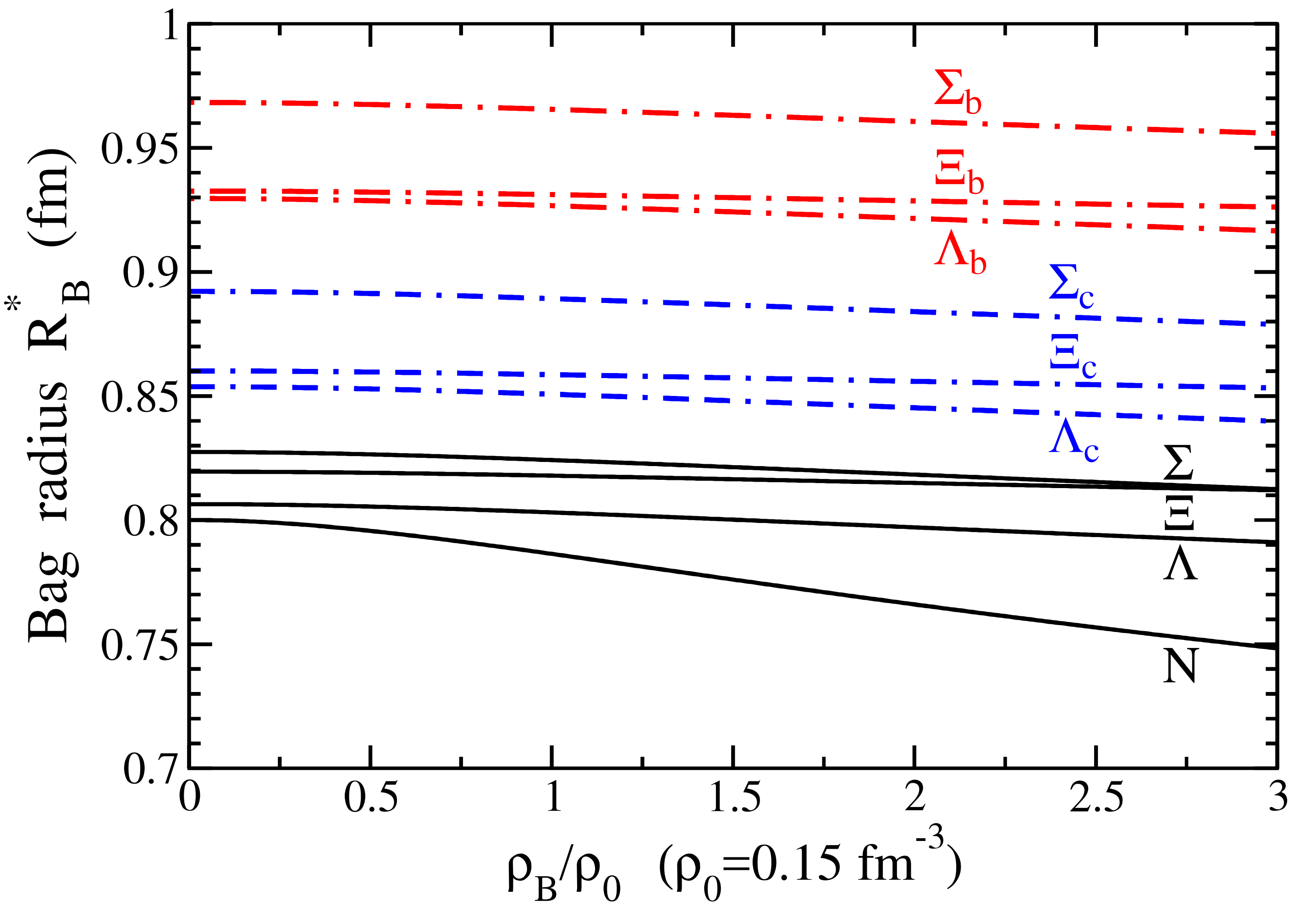




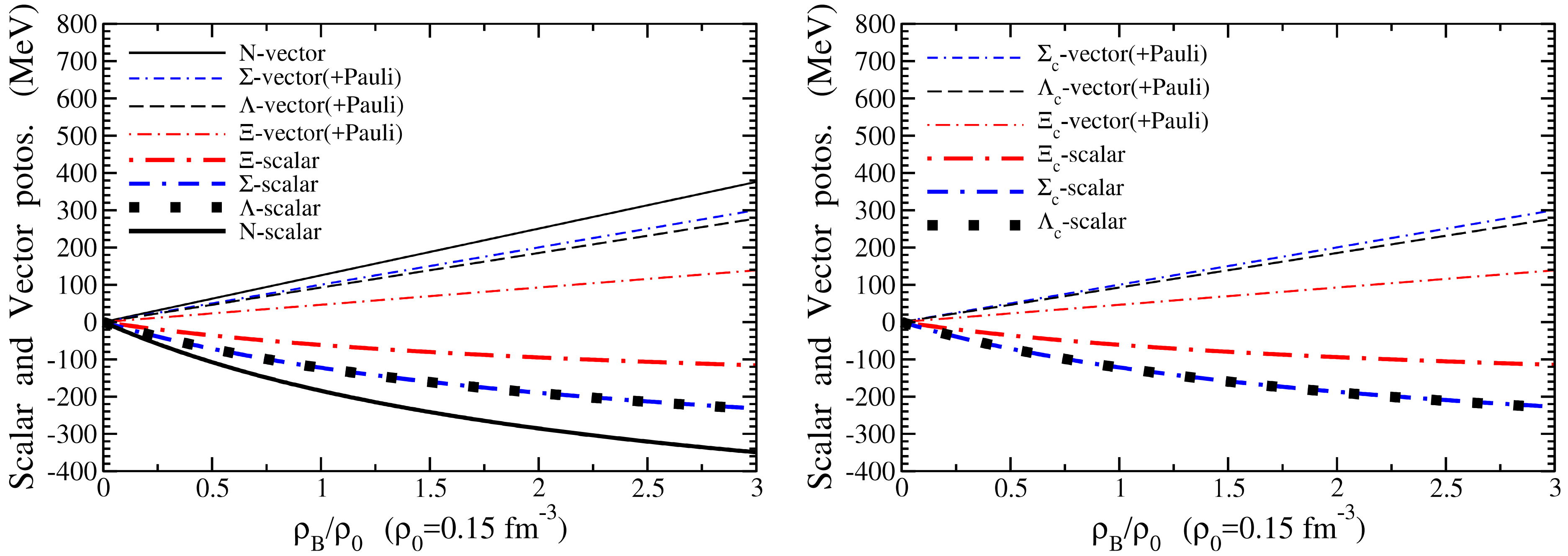
Bag eigenfrequencies: Strange (left), Bottom (right) baryons



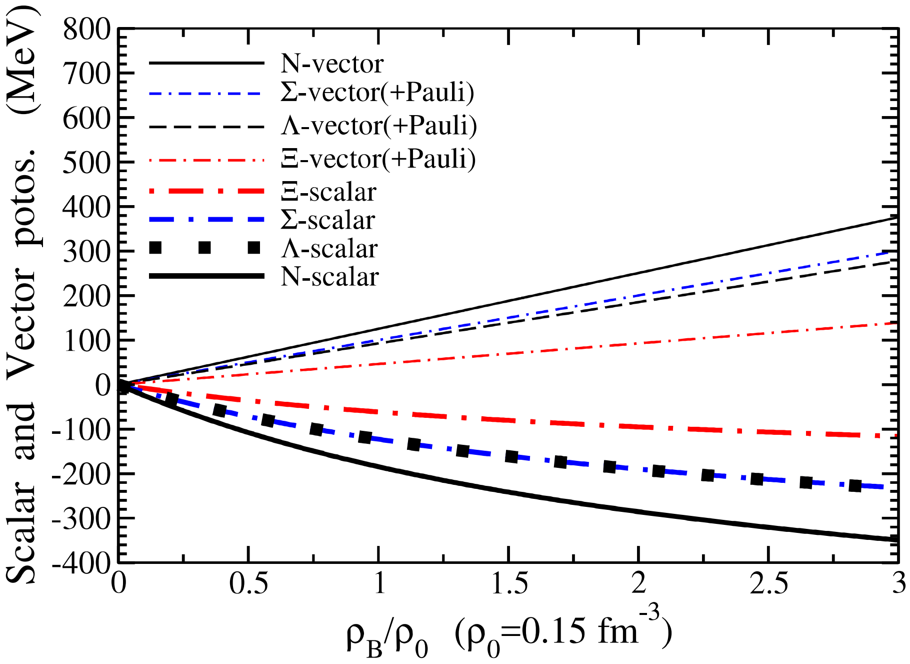
Bag radii: Strange, Charm, Bottom baryons

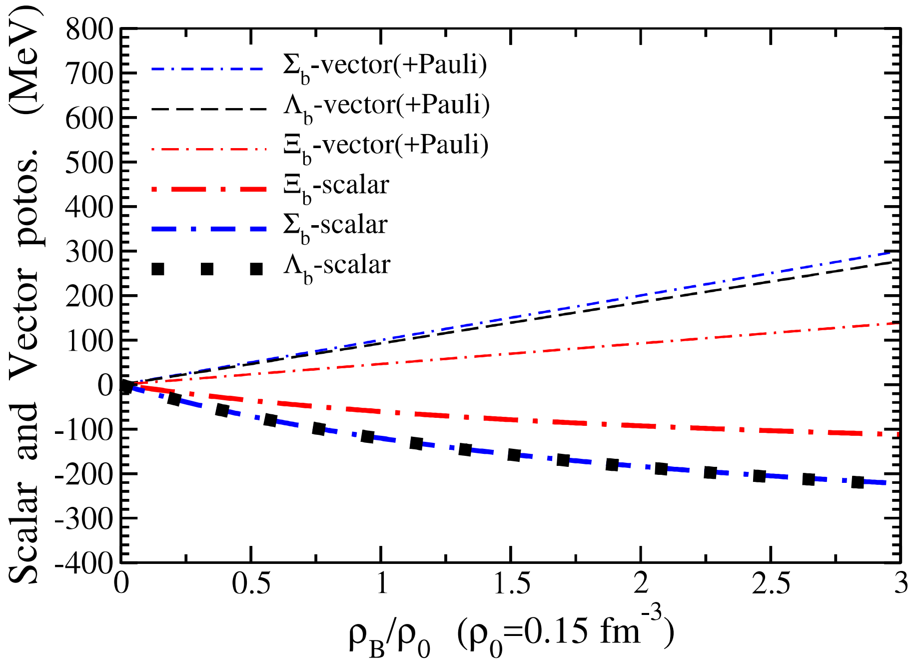


Scalar and (Vector+Pauli) potentials: Strange (left), Charm (right) baryons

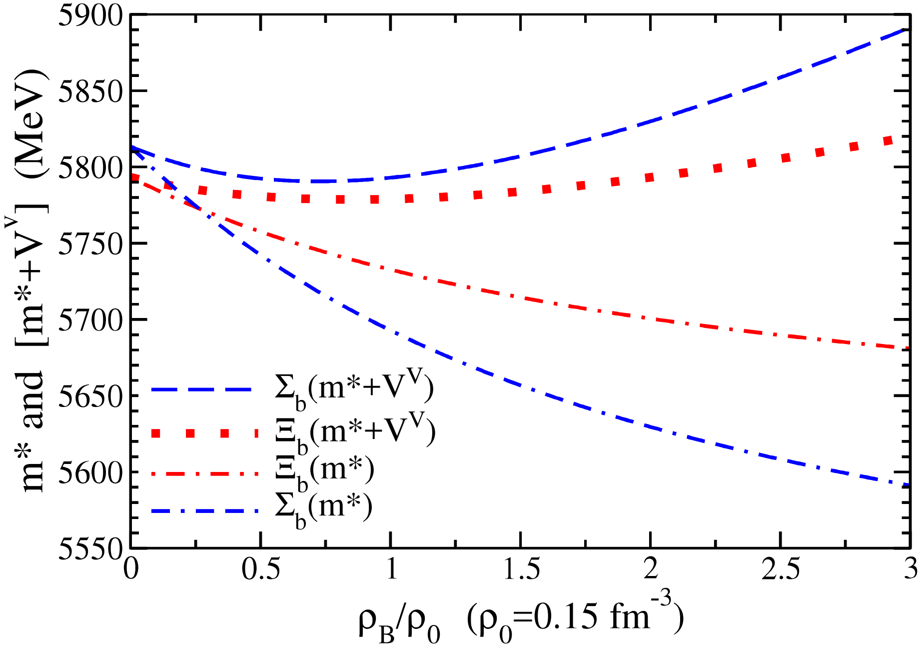


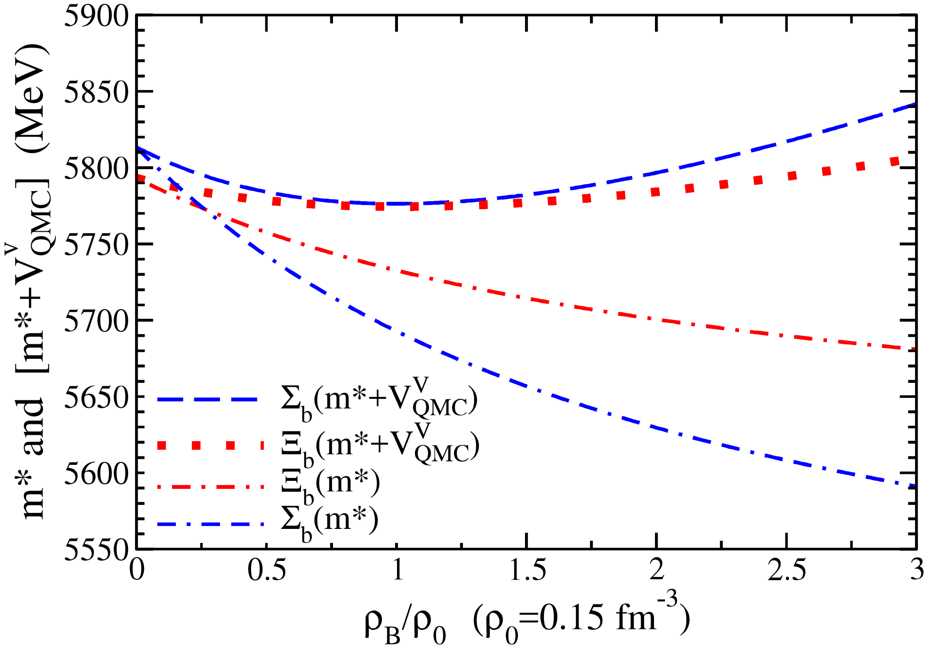
Scalar and (Vector+Pauli) potentials: Strange (left), Bottom (right) baryons





Excitation energies (scalar + vector pots.): Σ_b, Ξ_b Vector + "Pauli" (left), Vector (right)





Summary, Perspective

•QMC model: In-medium properties of the low-lying Strange, Charm, Bottom baryons (completed) effective masses, bag radii, bag eigenfrequencies, (two different) vector potentials, excitation (total) energies

$\Longrightarrow$• Σ_b, Ξ_b baryon effective masses!! excitation energies !!!

$\Longrightarrow$• EM FFs., Weak-interaction FFs. for heavy baryons in medium

$\Longrightarrow$•in the near future !!

$\Longrightarrow$• Heavy ion collisions involving heavy baryons!!!

$\Longrightarrow$•Other interesting applications ??!! Your Suggestions !!!

Thank You Very Much !!!

References:

Quarkonia-nuclear bindings (QMC summary):

G. Krein, A. W. Thomas, K. Tsushima

Prog. Part. Nucl. Phys. 100 (2018) 161

QMC model:

K. Saito, K. Tsushima and A. W. Thomas

Prog. Part. Nucl. Phys. 58 (2007) 1