

In-medium properties of the low-lying **bottom** baryons in **the QMC model**

Quarks and Nuclear Physics: QNP2018

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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 $\Xi_b(qsb)$,

$$m_{\Sigma_b} > m_{\Xi_b} \rightarrow m_{\Sigma_b}^* < m_{\Xi_b}^*$$

reverses in medium !!!

→ **but issue** of the repulsive **vector potentials**

QMC model 1: Hadron level

$$\begin{aligned}\mathcal{L} &= \bar{\psi}[i\gamma \cdot \partial - m_N^*(\sigma) - g_\omega \omega^\mu \gamma_\mu]\psi + \mathcal{L}_{\text{meson}}, \\ m_N^*(\sigma) &\equiv m_N - g_\sigma(\sigma)\sigma \simeq m_N - g_\sigma \underline{[1 - (a_N/2)(g_\sigma \sigma)]}\sigma \\ g_\sigma &\equiv g_\sigma(\sigma = 0)\end{aligned}$$

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

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

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

QMC model 2: Quark level

$$\mathbf{x} = (t, \vec{r}) \quad (|\vec{r}| \leq \text{bag radius}), \quad \mathbf{V}_\sigma^q = \mathbf{g}_\sigma^q \boldsymbol{\sigma}$$

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

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

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

$$m_h^* = \sum_{j=q, \bar{q}, Q\bar{Q}} \frac{n_j \Omega_j^* - z_h}{R_h^*} + \frac{4}{3} \pi R_h^{*3} B, \quad \left. \frac{\partial m_h^*}{\partial R_h} \right|_{R_h=R_h^*} = 0$$

$$\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_h^* m_q^*)^2]^{1/2}, \text{ with } m_q^* = m_q - g_\sigma^q \boldsymbol{\sigma}$$

$$\Omega_Q^* = \Omega_{\bar{Q}}^* = [x_Q^2 + (R_h^* m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

QMC model 3: From quarks

$$\omega = \frac{g_\omega \rho_B}{m_\omega^2},$$

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

$$= \frac{g_\sigma}{m_\sigma^2} C_N(\sigma) \rho_s \quad (g_\sigma \equiv g_\sigma(\sigma = 0)),$$

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

$$E^{\text{tot}}/A - m_N = \frac{4}{(2\pi)^3 \rho_B} \int d^3k \theta(k_F - |\vec{k}|) \sqrt{m_N^{*2}(\sigma) + \vec{k}^2} \\ + \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2m_\omega^2} - m_N.$$

QMC model 4: Couplings etc.

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

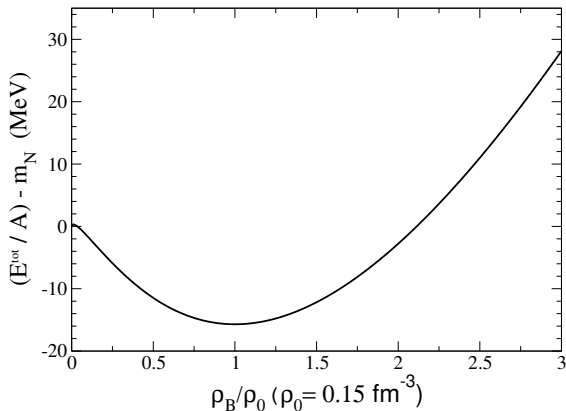
$$\frac{\partial m_N^*(\sigma)}{\partial \sigma} = -3g_\sigma^q \int_{\text{bag}} d^3r \bar{\psi}_q(\vec{r}) \psi_q(\vec{r}) \quad \text{the lowest bag w.f.}$$

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

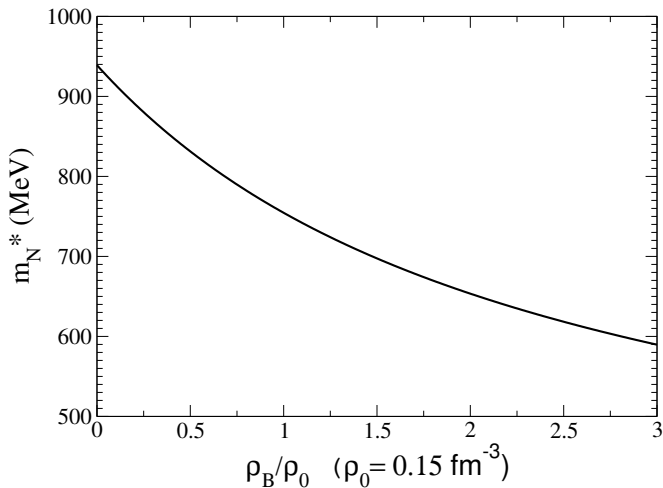
$$C_N(\sigma) = \frac{-1}{g_\sigma(\sigma=0)} \left[\frac{\partial m_N^*(\sigma)}{\partial \sigma} \right],$$

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

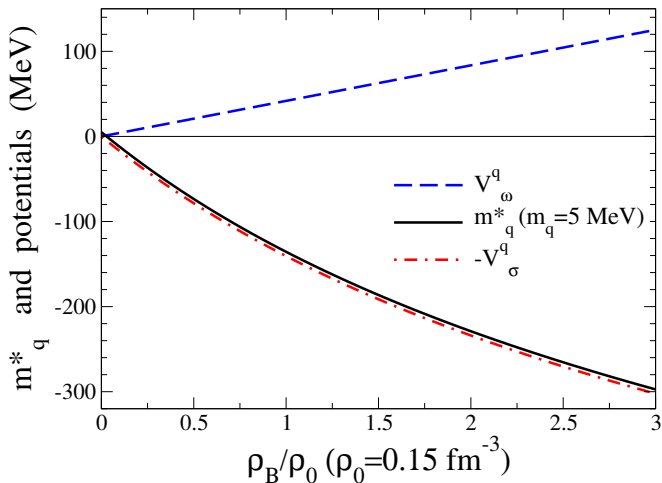
Results: Quark Meson Coupling (Standard)



- Symmetric Nuclear Matter - Binding Energy per Nucleon
- $m_q = 5 \text{ MeV}$, $K = 279.3 \text{ MeV}$

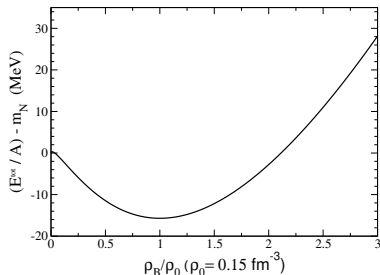
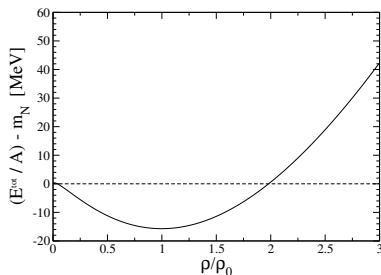


- Nucleon effective mass: $m_q = 5 \text{ MeV}$

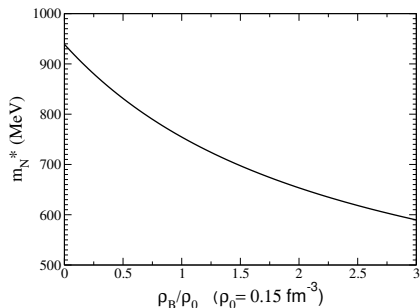
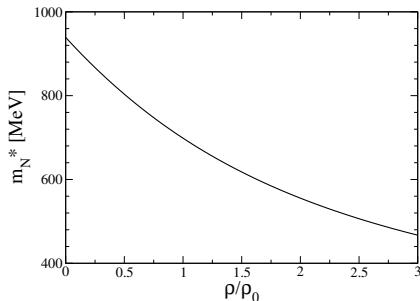


- Effective mass of constituent quarks: $m_q = 5 \text{ MeV}$
- All the light-quarks in any hadrons feel the same potentials !!

Comparison of Energy/nucleon



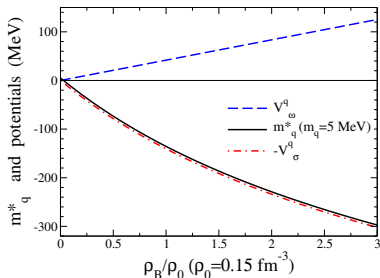
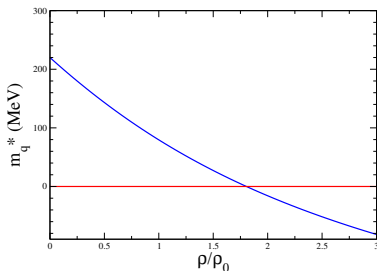
- **Symmetric Nuclear Matter - Binding Energy per Nucleon (scale !!)**
- **LF pion model (left):** $m_q = 220$ MeV, $K = 320.9$ MeV
- **Standard QMC (right):** $m_q = 5$ MeV, $K = 279.3$, MeV



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: $m_q = 220 \text{ MeV}$ (left)
- Standard QMC $m_q = 5 \text{ MeV}$ (right)

Standard QMC, π, ρ in LF model parameters comparison

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

$m_q(\text{MeV})$	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	m_N^*	K	Z_N	$B^{1/4}(\text{MeV})$
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], to appear in Phys. Lett. B

QMC: Hadron masses in medium

$$\mathbf{x} = (t, \vec{r}) \quad (|\vec{r}| \leq \text{bag radius}), \quad \mathbf{V}_\sigma^q = \mathbf{g}_\sigma^q \sigma$$

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

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

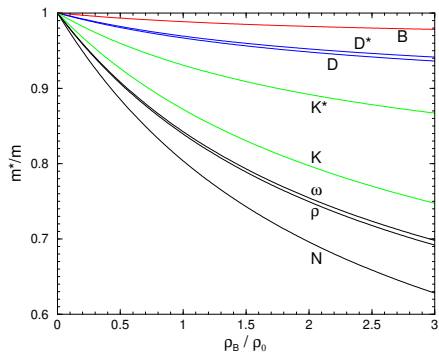
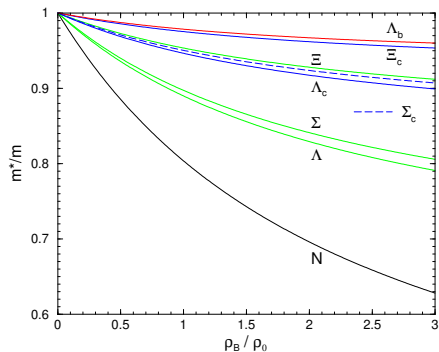
$$[i\gamma \cdot \partial_x - m_Q] \psi_Q(x) \text{ (or } \psi_{\bar{Q}}(x)) = 0$$

$$m_h^* = \sum_{j=q, \bar{q}, Q\bar{Q}} \frac{n_j \Omega_j^* - z_h}{R_h^*} + \frac{4}{3} \pi R_h^{*3} B, \quad \left. \frac{\partial m_h^*}{\partial R_h} \right|_{R_h=R_h^*} = 0$$

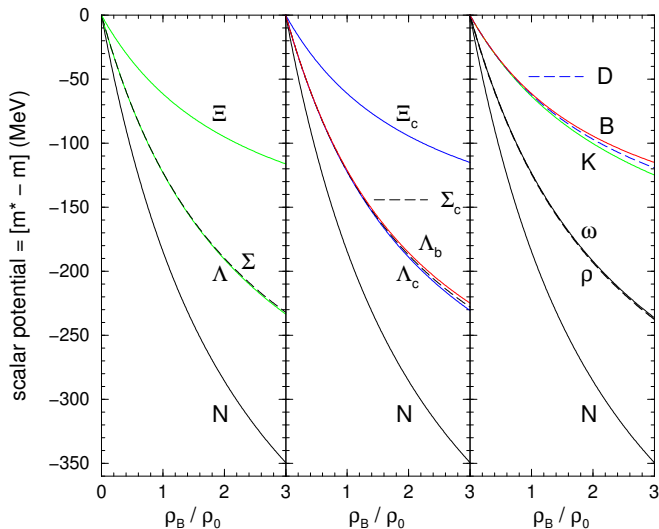
$$\Omega_q^* = \Omega_{\bar{q}}^* = [x_q^2 + (R_h^* m_q^*)^2]^{1/2}, \text{ with } m_q^* = m_q - g_\sigma^q \sigma$$

$$\Omega_Q^* = \Omega_{\bar{Q}}^* = [x_Q^2 + (R_h^* m_Q)^2]^{1/2} \quad (Q = s, c, b)$$

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)

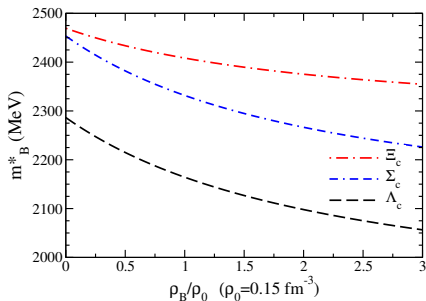
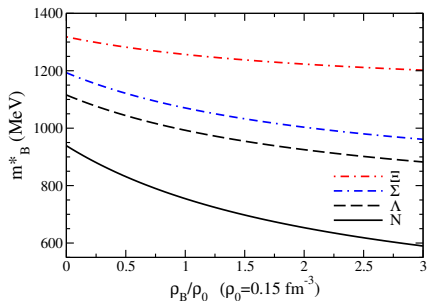
$B(q_1, q_2, q_3)$	z_B	m_B	R_B	x_1	x_2	x_3
$N(qqq)$	3.295	939.0	0.800	2.052	2.052	2.052
$\Lambda(uds)$	3.131	1115.7	0.806	2.053	2.053	2.402
$\Sigma(qqs)$	2.810	1193.1	0.827	2.053	2.053	2.409
$\Xi(qss)$	2.860	1318.1	0.820	2.053	2.406	2.406
$\Omega(sss)$	1.930	1672.5	0.869	2.422	2.422	2.422
$\Lambda_c(udc)$	1.642	2286.5	0.854	2.053	2.053	2.879
$\Sigma_c(qqc)$	0.903	2453.5	0.892	2.054	2.054	2.889
$\Xi_c(qsc)$	1.445	2469.4	0.860	2.053	2.419	2.880
$\Omega_c(ssc)$	1.057	2695.2	0.876	2.424	2.424	2.884
$\Lambda_b(udb)$	-0.622	5619.6	0.930	2.054	2.054	3.063
$\Sigma_b(qqb)$	-1.554	5813.4	0.968	2.054	2.054	3.066
$\Xi_b(qsb)$	-0.785	5793.2	0.933	2.054	2.441	3.063
$\Omega_b(ssb)$	-1.327	6046.1	0.951	2.446	2.446	3.065

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

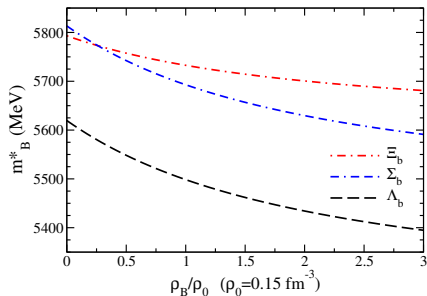
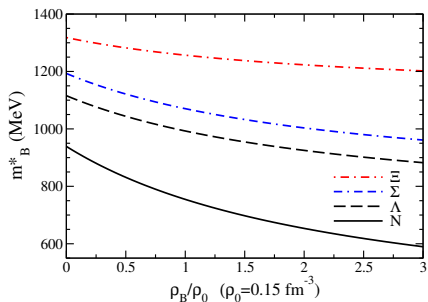
$B(q_1, q_2, q_3)$	m_B^*	R_B^*	x_1^*	x_2^*	x_3^*
$N(qqq)$	754.5	0.786	1.724	1.724	1.724
$\Lambda(uds)$	992.7	0.803	1.716	1.716	2.401
$\Sigma(qqs)$	1070.4	0.824	1.705	1.705	2.408
$\Xi(qss)$	1256.7	0.818	1.708	2.406	2.406
$\Omega(sss)$	—	—	—	—	—
$\Lambda_c(udc)$	2164.2	0.851	1.691	1.691	2.878
$\Sigma_c(qqc)$	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:

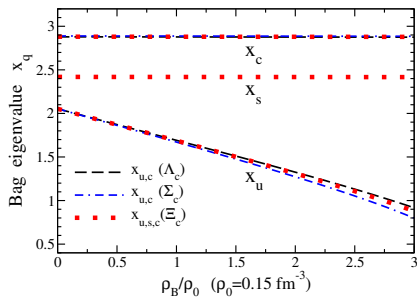
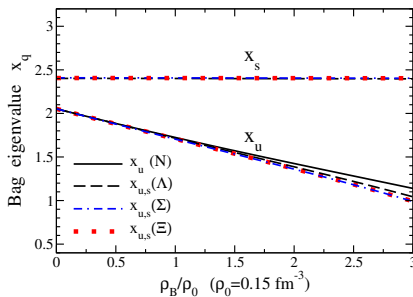
Strange (left), Charm (right) baryons



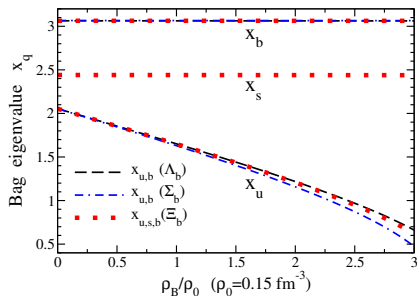
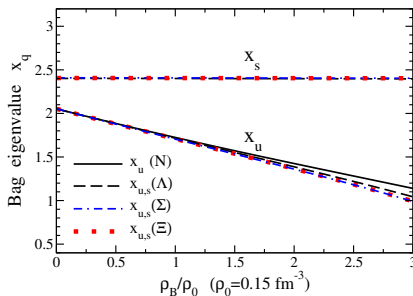
Effective masses:

Strange (left), **Bottom (right)** baryons

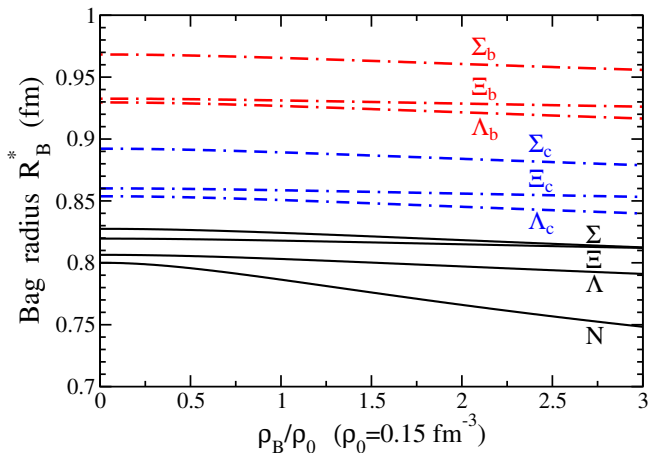
Bag eigenfrequencies: Strange (left), Charm (right) baryons



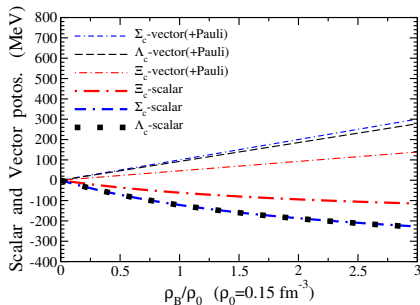
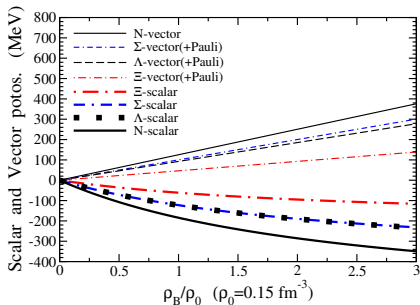
Bag eigenfrequencies: Strange (left), Bottom (right) baryons



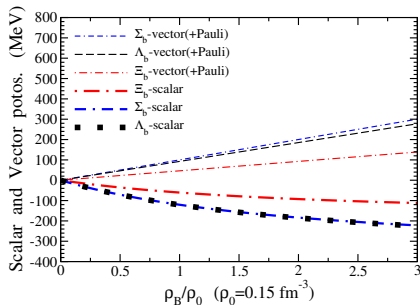
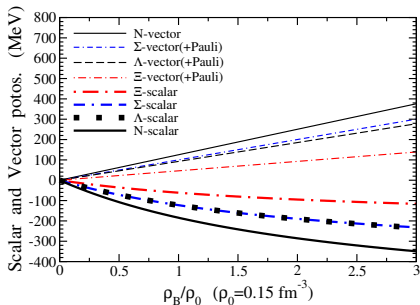
Bag radii: Strange, Charm, Bottom baryons



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

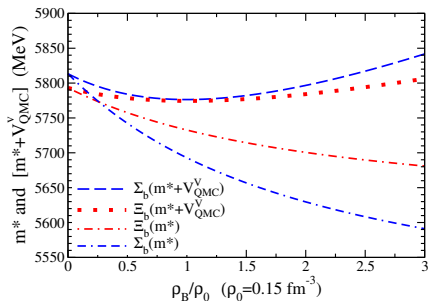
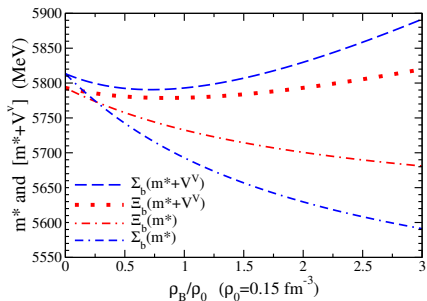


Scalar and (Vector+Pauli) potentials: Strange (left), Bottom (right) baryons



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**

- ⇒ ● Σ_b, Ξ_b baryon **effective masses!!** **excitation energies !!!**
- ⇒ ● **EM FFs., Weak-interaction FFs.** for heavy baryons in medium
- ⇒ ● **in the near future !!**
- ⇒ ● **Heavy ion collisions** involving heavy baryons!!!
- ⇒ ● **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