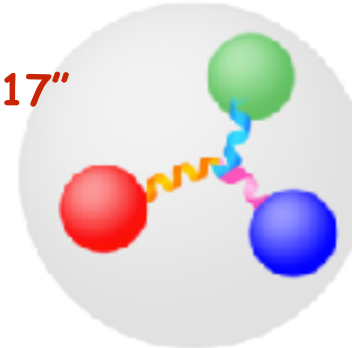
International workshop “Strangeness Nuclear Physics 2017”
March, 12th-14th, 2017,
Osaka Electro-Communication University, Japan



The strangeness quark mean field theory

Jinniu Hu

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J.H, A. Li, H. Shen, and H. Toki, Prog. Theor. Exp. Phys. 2014 (2014) 013D02
J.H, A. Li, H. Toki, and W. Zuo, Phys. Rev. C 89 (2014) 025802
X. Xing, J.H., and H. Shen, Phys. Rev. C 94 (2016) 044308
X. Xing, J.H., and H. Shen, in preparation

Outline

- Introduction
- Strangeness quark mean field theory
- Numerical results and discussions
- Summary and Perspectives

Strangeness nuclear physics

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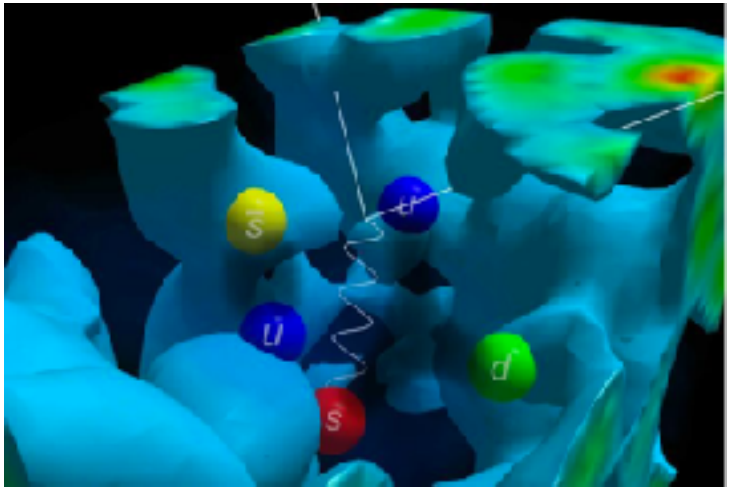
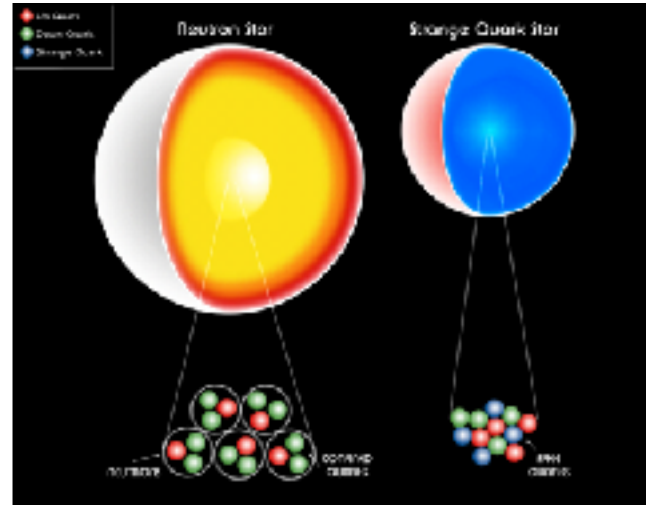
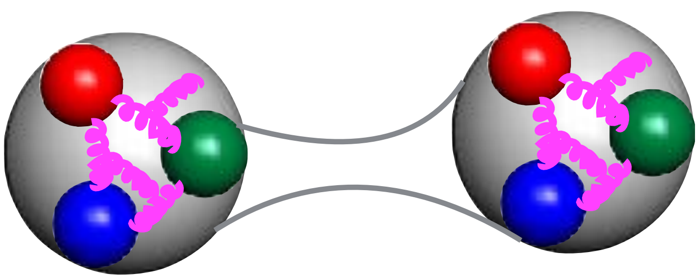
Hadrons



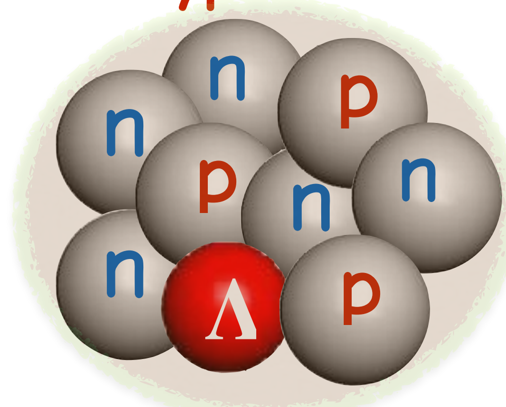
Compact star



Baryon-baryon force



Hypernuclei



A. Gal, E. V. Hungerford, and D. J. Millener, Rev. Mod. Phys. 88(2016)035004

Theoretical methods

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- ✓ ab initio methods

  H. Nemura, Y. Akaishi, and Y. Suzuki, Phys. Rev. Lett. 89(2002)142504

  E. Hiyama and T. Yamada, Prog. Part. Nucl. Phys. 63(2009)339

  D. Lonardoni, S. Gandolfi, and F. Pederiva, Phys. Rev. C 87(2013)041303(R)

  R. Wirth, et al. Phys. Rev. Lett. 113(2014)192502

- ✓ Shell model

  D. J. Millener, Nucl. Phys. A 881(2012)298

- ✓ Skyrme Hartree-Fock model

  M. Rayet, Ann. Phys. (NY) 102(1976)226

  X. R. Zhou, et al. Phys. Rev. C 76(2007)034312

  H.-J. Schulze and T. Rijken, Phys. Rev. C 88(2013)024322

- ✓ Relativistic mean-field model

  R. Brockmann and W. Weise, Phys. Lett. B 69(1977)167

  H. Shen, F. Yang, and H. Toki, Prog. Theor. Phys. 115(2006)325

  R. L. Xu, C. Wu, and Z. Z. Ren, J. Phys. G 39(2012)085107

  T. T. Sun, et al., Phys. Rev. C 94(2016)064319

  ....

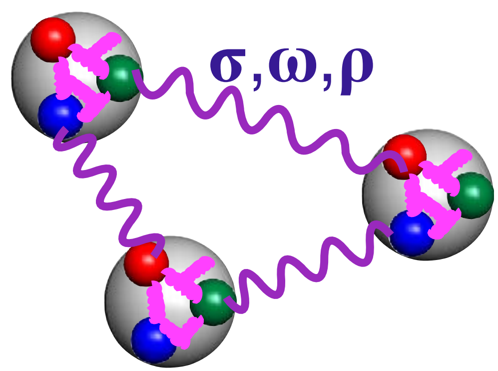
Relativistic many-body theories from quark level

- ✓ baryons are not point particles!
- ✓ baryon properties change in medium!
- ✓ quark-gluon plasma!

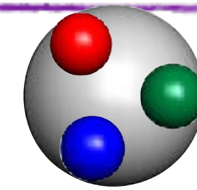
……..

Hadron model ⟷ **many-body method**

Self-consistently



Strangeness system with quark model



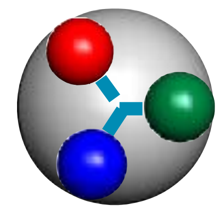
✓ Quark meson coupling (QMC) model

K. Tsushima, et al. Nucl. Phys. A 630(1998)691

✓ Friedberg-Lee model

J. S. Liang and H. Shen, Phys. Rev. C88 (2013) 035208

……



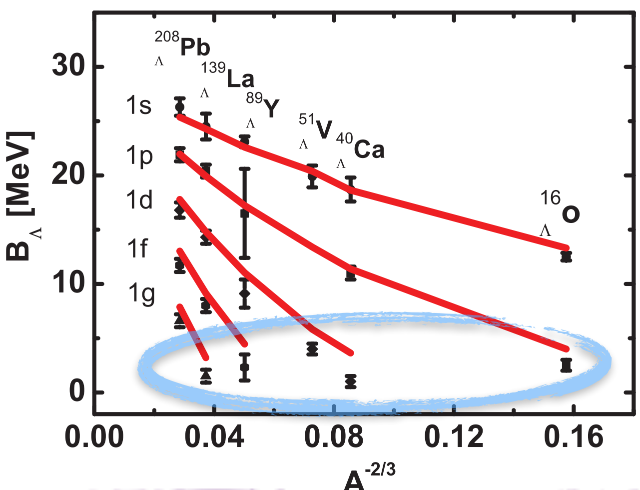
✓ Quark mean field (QMF) model

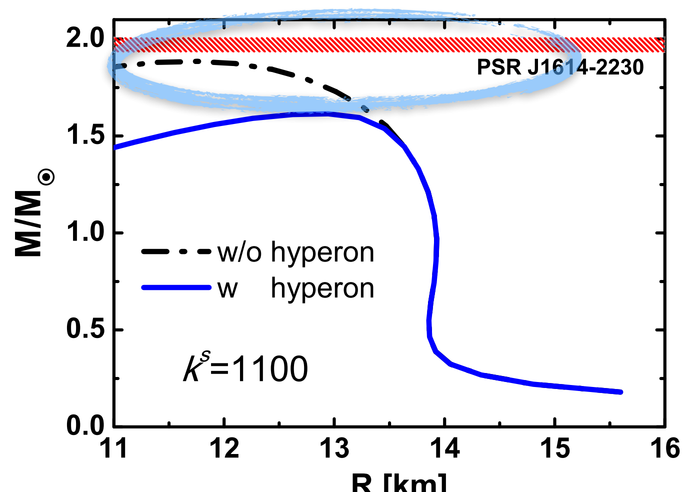
H. Shen, H. Toki, Nucl. Phys. A 707 (2002) 469

J.H, A. Li, H. Shen, and H. Toki, Prog. Theor. Exp. Phys. 2014(2014) 013D02

J.H, A. Li, H. Toki, and W. Zuo, Phys. Rev. C 89(2014) 025802

Properties of hypernuclei and neutron star with QMF model





» Chiral symmetry

» Gluon exchange

Miss!

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Quark level

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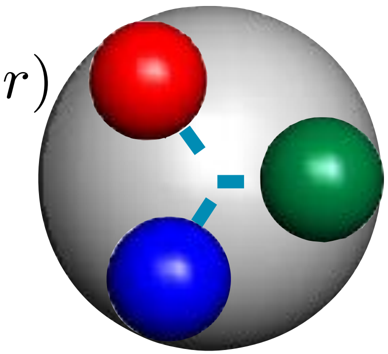
X. Xing, J.H., and H. Shen, Phys. Rev. C 94 (2016) 044308

- **Constituent quark in Dirac equation**

$$[-i\alpha\cdot\nabla+\beta m_i^*+\beta U(r)]q_i(r)=\varepsilon_i^* q_i(r)$$



where, the effective quark mass is

$$m_i^*=m_i+g_\sigma^i\sigma$$

and effective single particle energy is

$$\varepsilon_i^*=\varepsilon_i-g_\omega^i-g_\rho^i\rho\tau_3$$

- **Confinement potential**

$$U(r)=\frac{1}{2}(1+\gamma^0)(ar^2+V_0)$$

- **Center-of-mass corrections**

$$\langle B|\sum_{i=1}^{3}\gamma^0(i)\{\frac{1}{3}\gamma(i)\cdot\sum_{j=1}^{3}\vec{p}_j+\frac{1}{2}(1+\gamma^0(i))[U(r_i)-U(\rho_i)]\}|B\rangle$$

Quark level

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- **Pionic self-energy correction**

$$\delta M_B^\pi = -\sum_k \sum_{B'} \frac{V_j^{\dagger BB'} V_j^{BB'}}{w_k}$$

- **Gluon correction**

Color-electric
$$(\Delta E_B)_g^E = \frac{1}{8\pi} \sum_{i,j} \sum_{a=1}^{8} \int \frac{d^3 r_i d^3 r_j}{|\vec{r}_i - \vec{r}_j|} \langle B | J_i^{0a}(\vec{r}_i) J_j^{0a}(\vec{r}_j) | B \rangle$$

Color-magnetic
$$(\Delta E_B)_g^M = -\frac{1}{8\pi} \sum_{i,j} \sum_{a=1}^{8} \int \frac{d^3 r_i d^3 r_j}{|\vec{r}_i - \vec{r}_j|} \langle B | \vec{J}_i^a(\vec{r}_i) \cdot \vec{J}_j^a(\vec{r}_j) | B \rangle$$

Quark color current density
$$J_i^{\mu a}(x) = g_c \bar{\psi}_q(x) \gamma^\mu \lambda_i^a \psi_q(x)$$

- **Baryon mass**

$$M_B^* = E_B^{*0} - \epsilon_{\mathrm{c.m.}} + \delta M_B^\pi + (\Delta E_B)_g^E + (\Delta E_B)_g^M$$

- **Strangeness QMF Lagrangian**

$$\begin{aligned}\mathcal{L}_{\rm QMF} &= \bar{\psi}\left[i\gamma_\mu\partial^\mu - M_N^* - g_\omega\omega\gamma^0 - g_\rho\rho\tau_3\gamma^0 - e\frac{(1-\tau_3)}{2}A\gamma^0\right]\psi \\ &+\bar{\psi}_H\left[i\gamma_\mu\partial^\mu - M_H^* - g_\omega^H\omega\gamma^0 + \frac{f_\omega^H}{2M_H}\sigma^{0i}\partial_i\omega\right]\psi_H \\ &-\frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\ &+\frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{4}c_3\omega^4 \\ &+\frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla A)^2,\end{aligned}$$

- **Dirac equations for baryons**

$$\left[i\gamma_\mu\partial^\mu - M_N^* - g_\omega\omega\gamma^0 - g_\rho\rho\tau_3\gamma^0 - e\frac{(1-\tau_3)}{2}A\gamma^0\right]\psi = 0,$$

$$\left[i\gamma_\mu\partial^\mu - M_H^* - g_\omega^H\omega\gamma^0 + \frac{f_\omega^H}{2M_H}\sigma^{0i}\partial_i\omega\right]\psi_H = 0.$$

- **Equations of motion for mesons**

$$\Delta\sigma - m_\sigma^2\sigma - g_2\sigma^2 - g_3\sigma^3 = \frac{\partial M_N^*}{\partial\sigma}\langle\bar{\psi}\psi\rangle + \frac{\partial M_H^*}{\partial\sigma}\langle\bar{\psi}_H\psi_H\rangle,$$

$$\Delta\omega - m_\omega^2\omega - c_3\omega^3 = -g_\omega\langle\bar{\psi}\gamma^0\psi\rangle - g_\omega^H\langle\bar{\psi}_H\gamma^0\psi_H\rangle + \frac{f_\omega^H}{2M_H}\partial_i\langle\bar{\psi}_H\sigma^{0i}\psi_H\rangle,$$

$$\Delta\rho - m_\rho^2\rho = -g_\rho\langle\bar{\psi}\tau_3\gamma^0\psi\rangle,$$

$$\Delta A = -e\langle\bar{\psi}\frac{(1-\tau_3)}{2}\gamma^0\psi\rangle.$$

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SQMF parameters

The strength of quark confinement potential

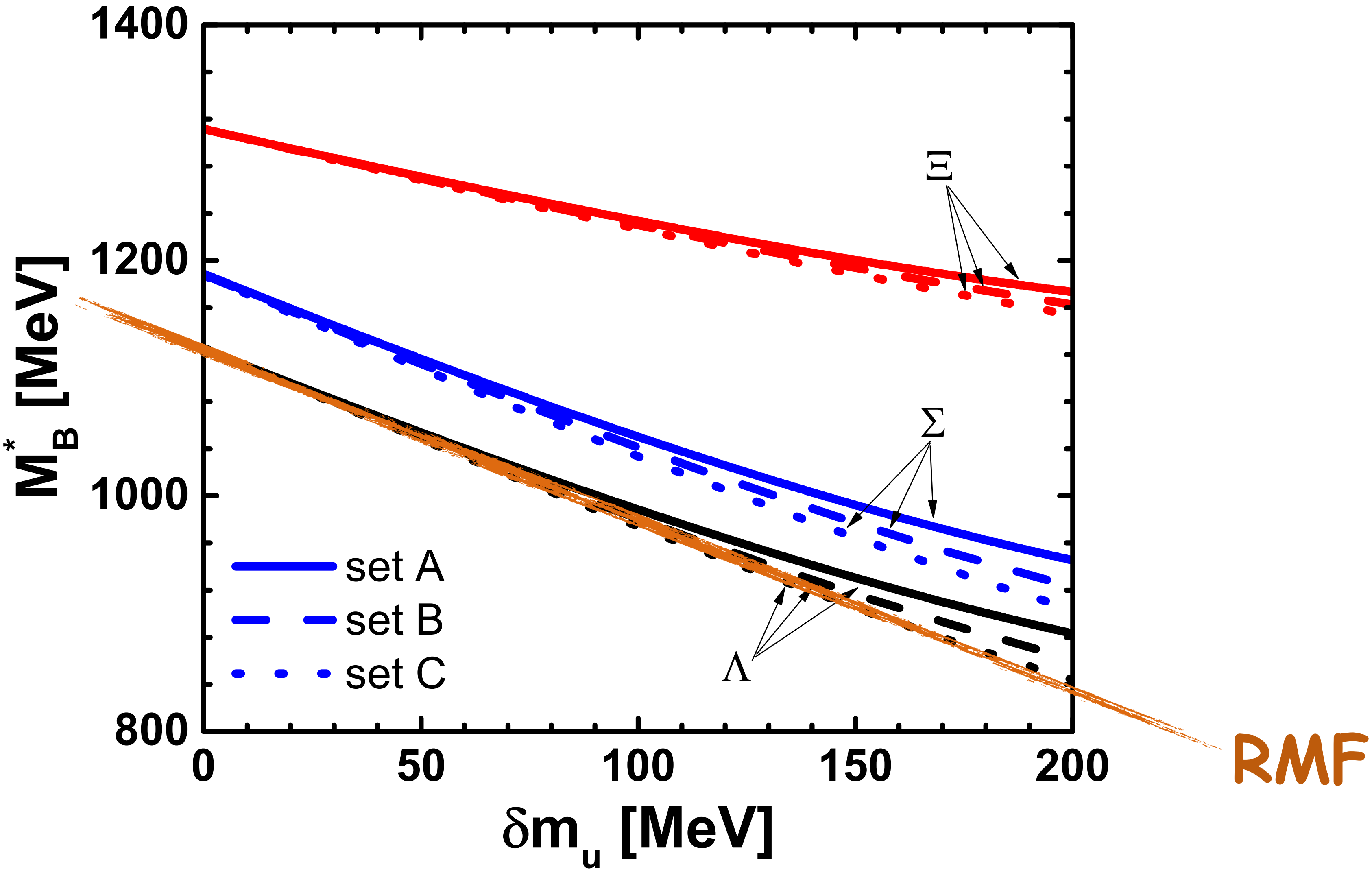
	m_u (MeV)	V_u (MeV)	a_u (fm^{-3})	m_s (MeV)	V_s (MeV)	a_s (fm^{-3})
set A	250	-24.286601	0.579450	330	101.78180	0.097317
set B	300	-62.257187	0.534296	380	54.548210	0.087243
set C	350	-102.041575	0.495596	430	6.802695	0.079534

The coupling constants between meson and baryons

Model	m_u (MeV)	g_σ^u	g_ω	g_ω^Λ	g_ω^Ξ	g_ρ	g_2 (fm^{-1})	g_3	c_3
QMF-NK1S	250	5.15871	11.54726	$0.8258g_\omega$	$0.4965g_\omega$	3.79601	-3.52737	-78.52006	305.00240
QMF-NK2S	300	5.09346	12.30084	$0.8134g_\omega$	$0.4800g_\omega$	4.04190	-3.42813	-57.68387	249.05654
QMF-NK3S	350	5.01631	12.83898	$0.8040g_\omega$	$0.4681g_\omega$	4.10772	-3.29969	-39.87981	221.68240

$$U_\Lambda = -30 \text{ MeV}$$
$$U_\Xi = -12 \text{ MeV}$$

Baryon masses in nuclear medium



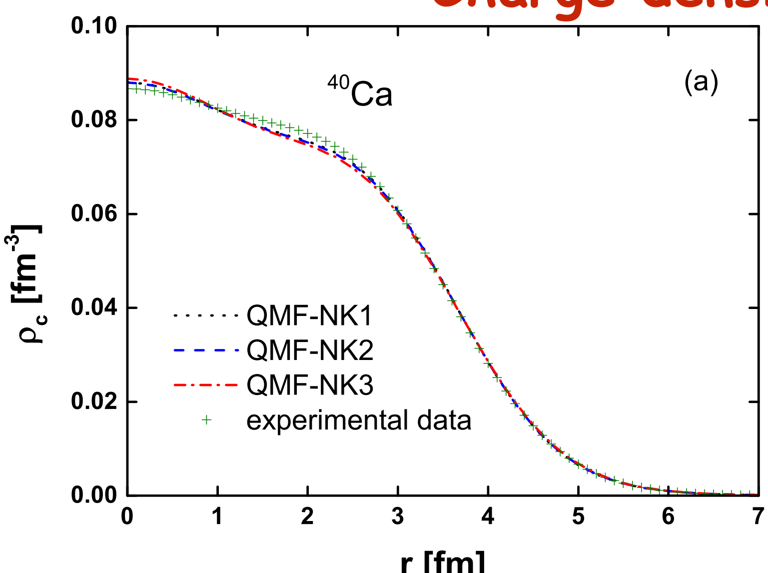
The properties of nuclei

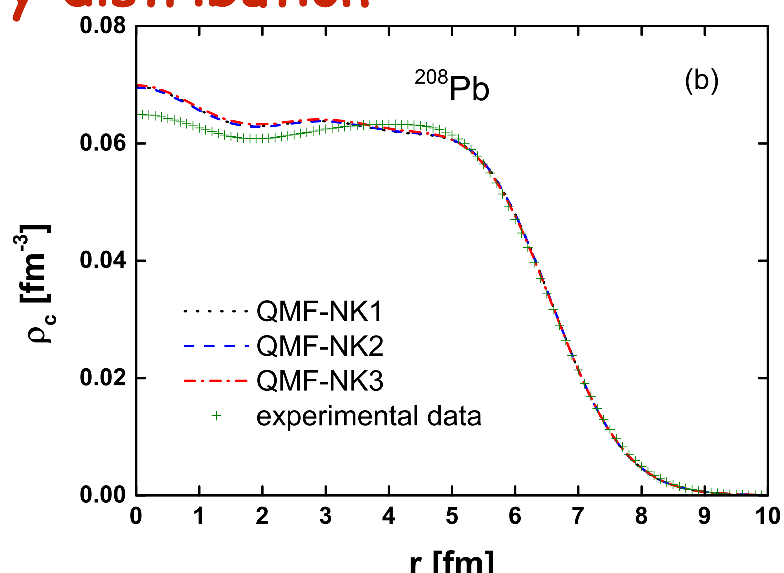
Binding energy and charge radii

Model	E/A (MeV)				R_c(fm)			
	^{40}Ca	^{48}Ca	^{90}Zr	^{208}Pb	^{40}Ca	^{48}Ca	^{90}Zr	^{208}Pb
QMF-NK1	8.62	8.61	8.65	7.92	3.43	3.47	4.26	5.49
QMF-NK2	8.61	8.61	8.67	7.91	3.44	3.47	4.26	5.50
QMF-NK3	8.59	8.63	8.68	7.90	3.44	3.46	4.26	5.50
QMF[18]	8.35	8.43	8.54	7.73	3.44	3.46	4.27	5.53
Expt.	8.55	8.67	8.71	7.87	3.45	3.45	4.26	5.50

Without pion and gluon corrections

Charge density distribution



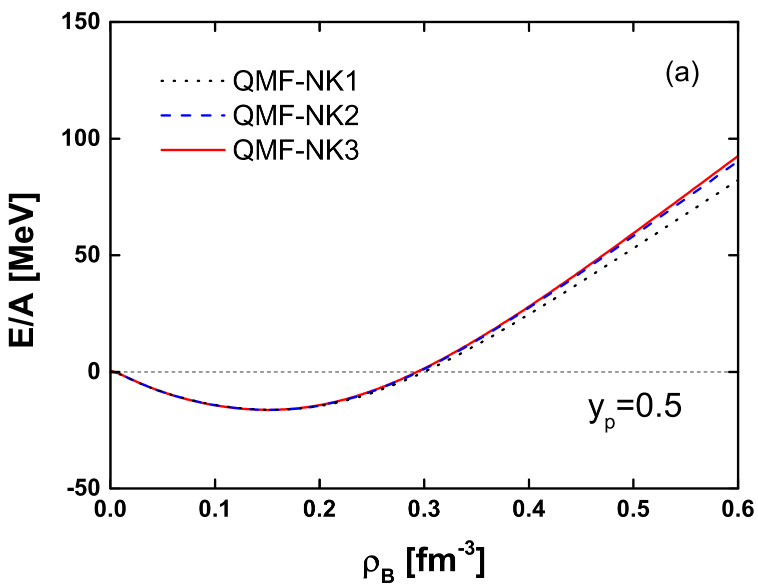


The properties of nuclear matter 南開大學

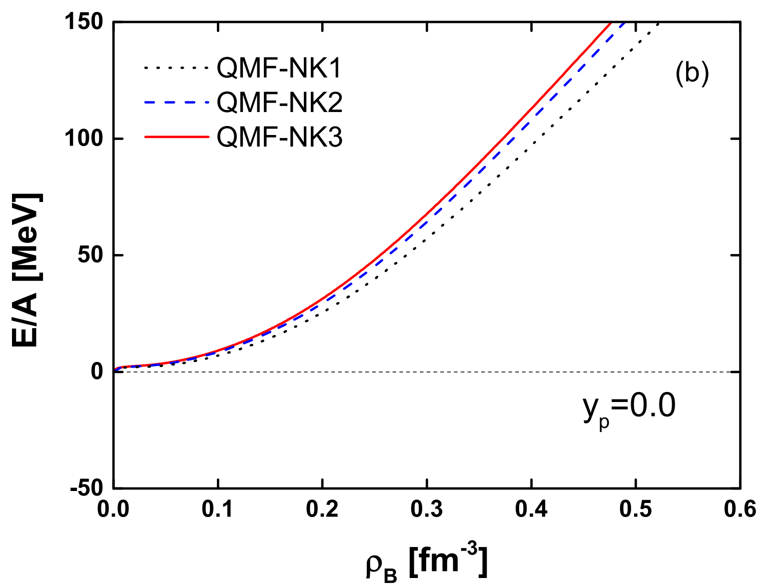
Nuclear saturation properties

Model	ρ_0 (fm^{-3})	E/A (MeV)	K_0 (MeV)	J (MeV)	M_N^*/M_N	L^0 (MeV)	K_{sym}^0 (MeV)	K_{asy} (MeV)	Q_0 (MeV)	K_τ (MeV)
QMF-NK1	0.154	-16.3	323	30.6	0.70	84.8	-28.8	-537.6	495.4	-667.7
QMF-NK2	0.152	-16.3	328	32.9	0.66	93.7	-23.5	-585.7	221.0	-648.8
QMF-NK3	0.150	-16.3	322	33.6	0.64	97.3	-12.0	-595.8	263.0	-675.3

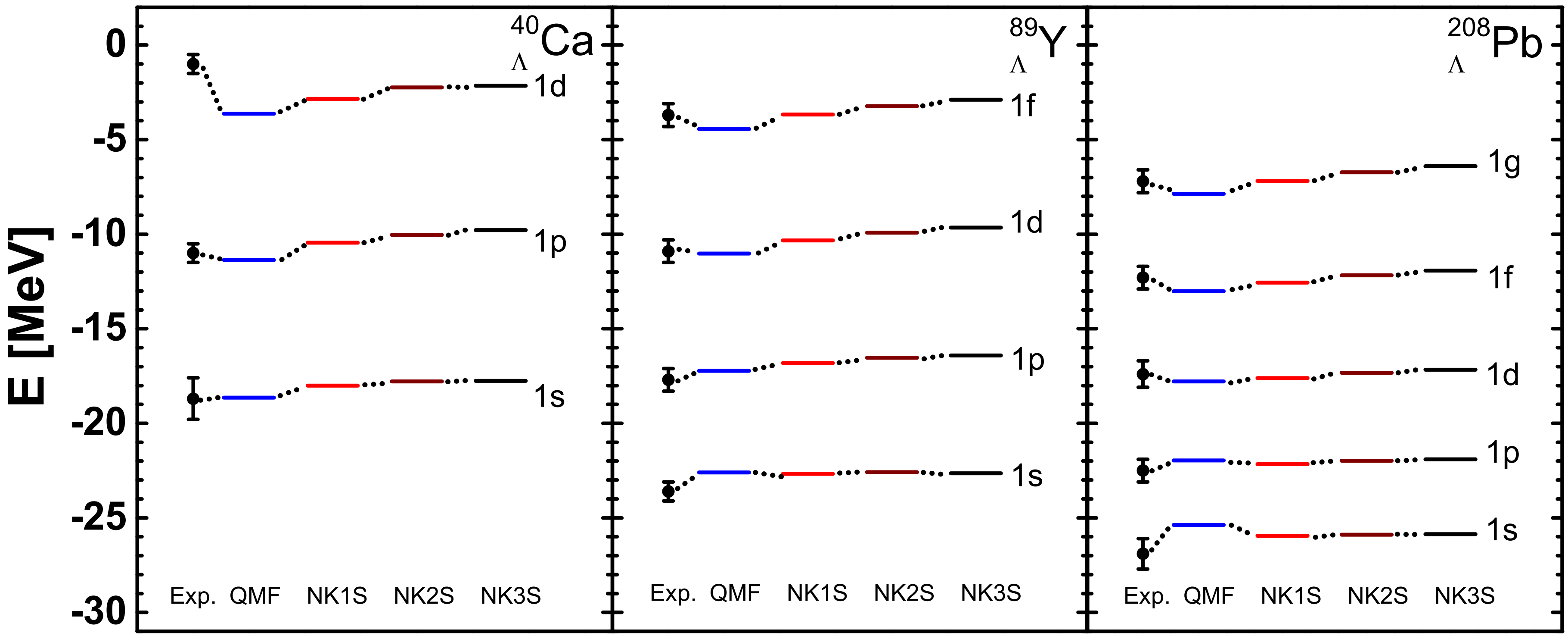
symmetric nuclear matter



pure neutron matter

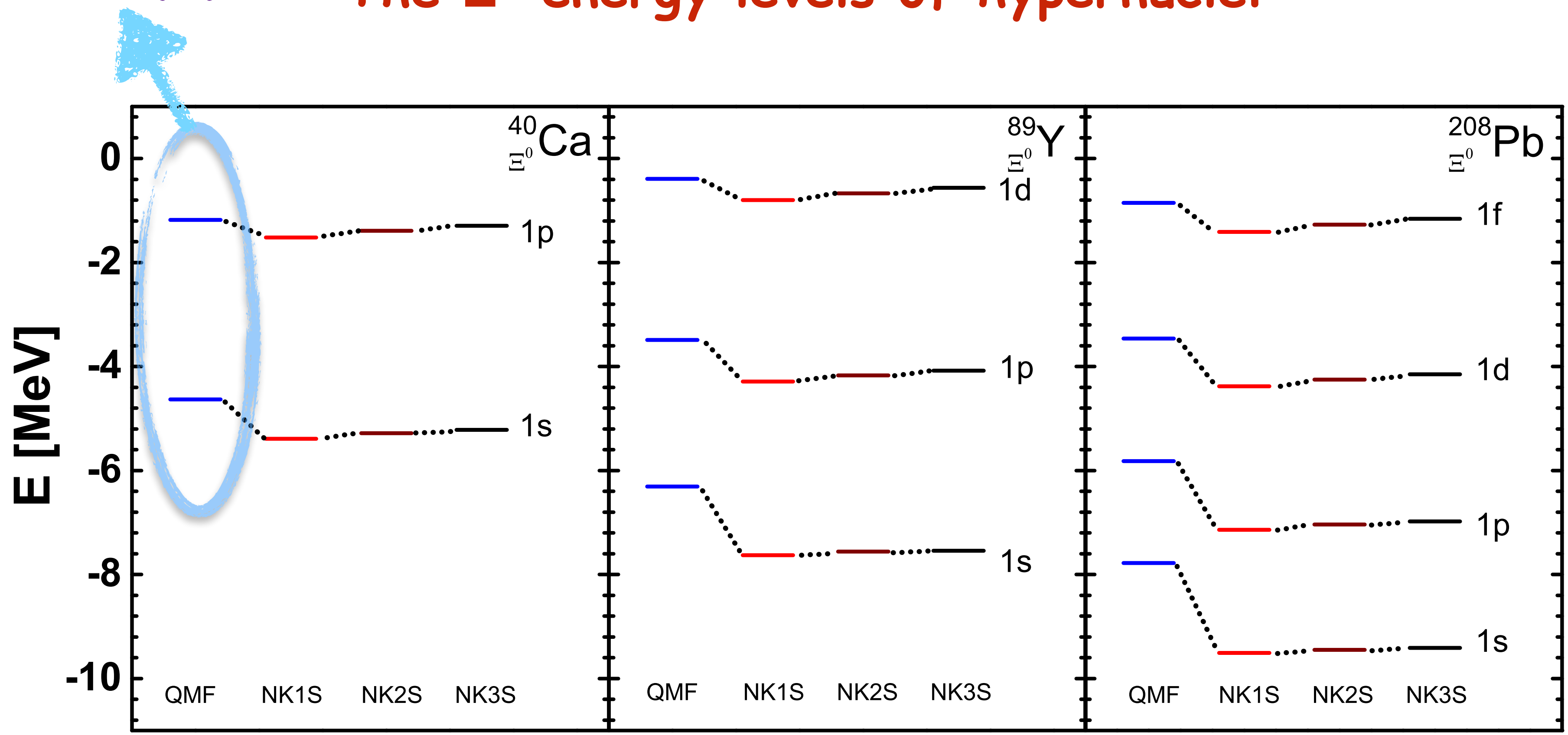


The Λ energy levels of hypernuclei



The Ξ^0 energy levels of hypernuclei

SU(3)



The properties of hypernuclei

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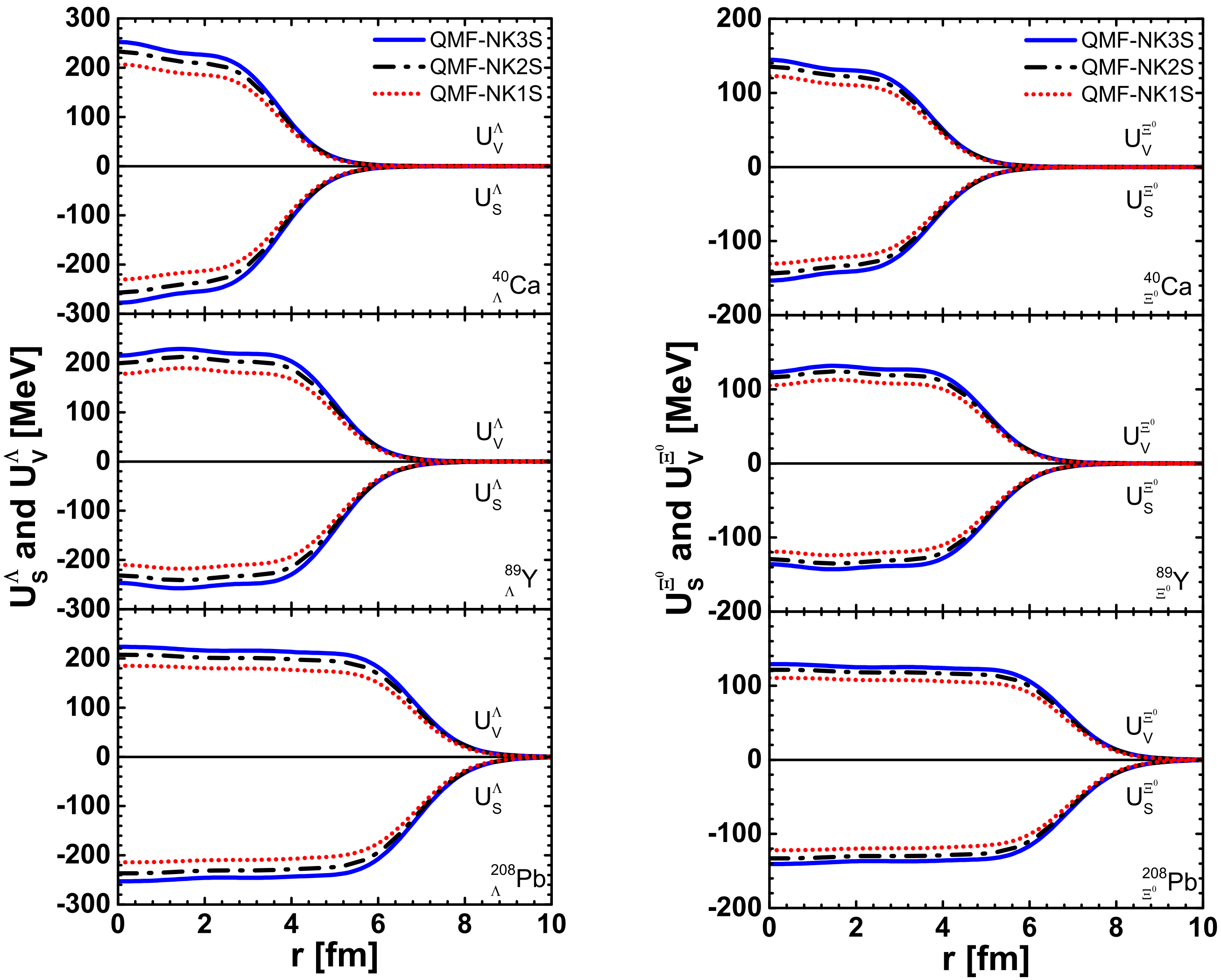
The scalar and vector potentials of Λ and Ξ^0 hypernuclei



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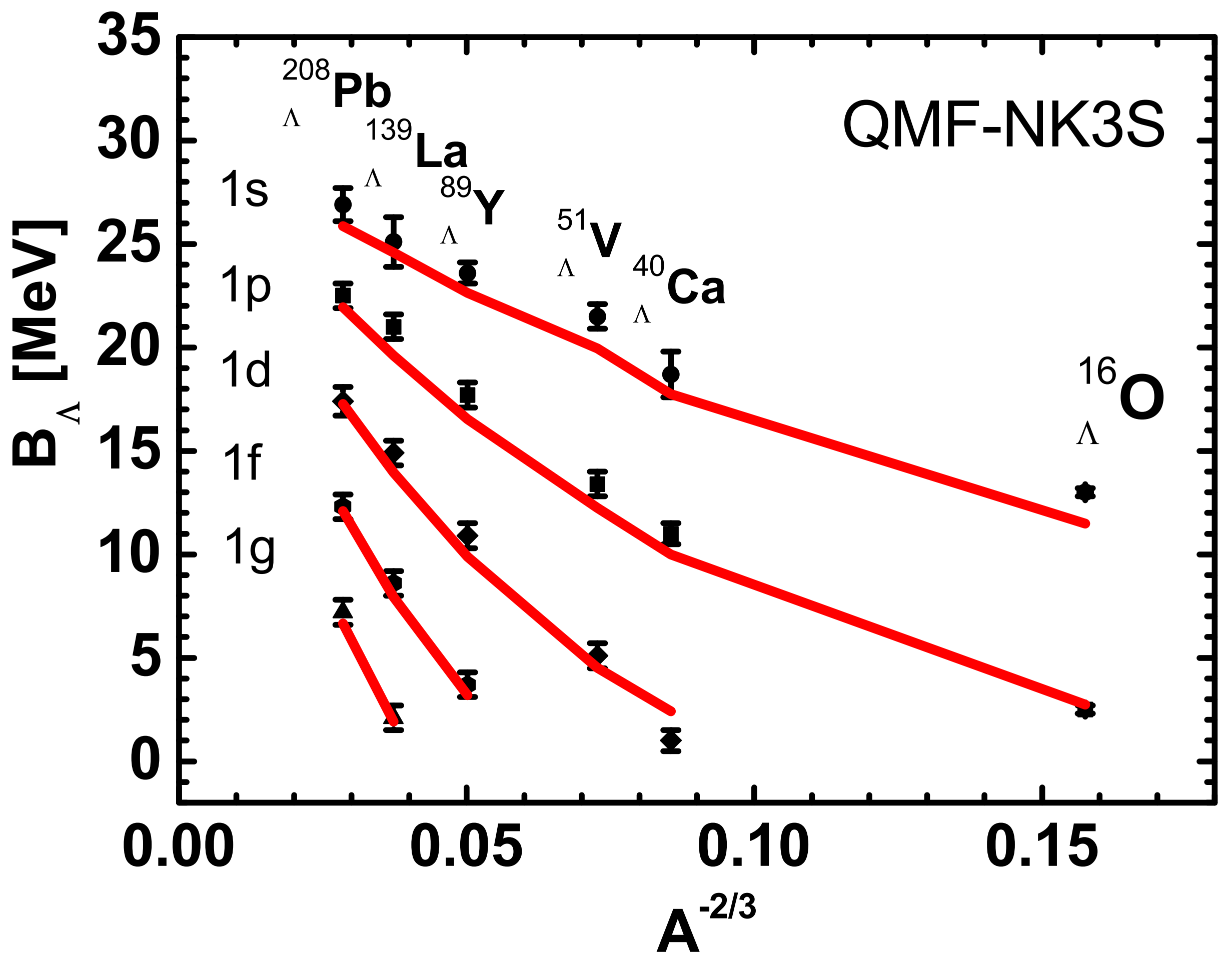
The binding energies of Λ hypernuclei



Exp. Data:A. Gal, E. V. Hungerford and D. J. Millener, Rev. Mod. Phys. 88(2016)035004

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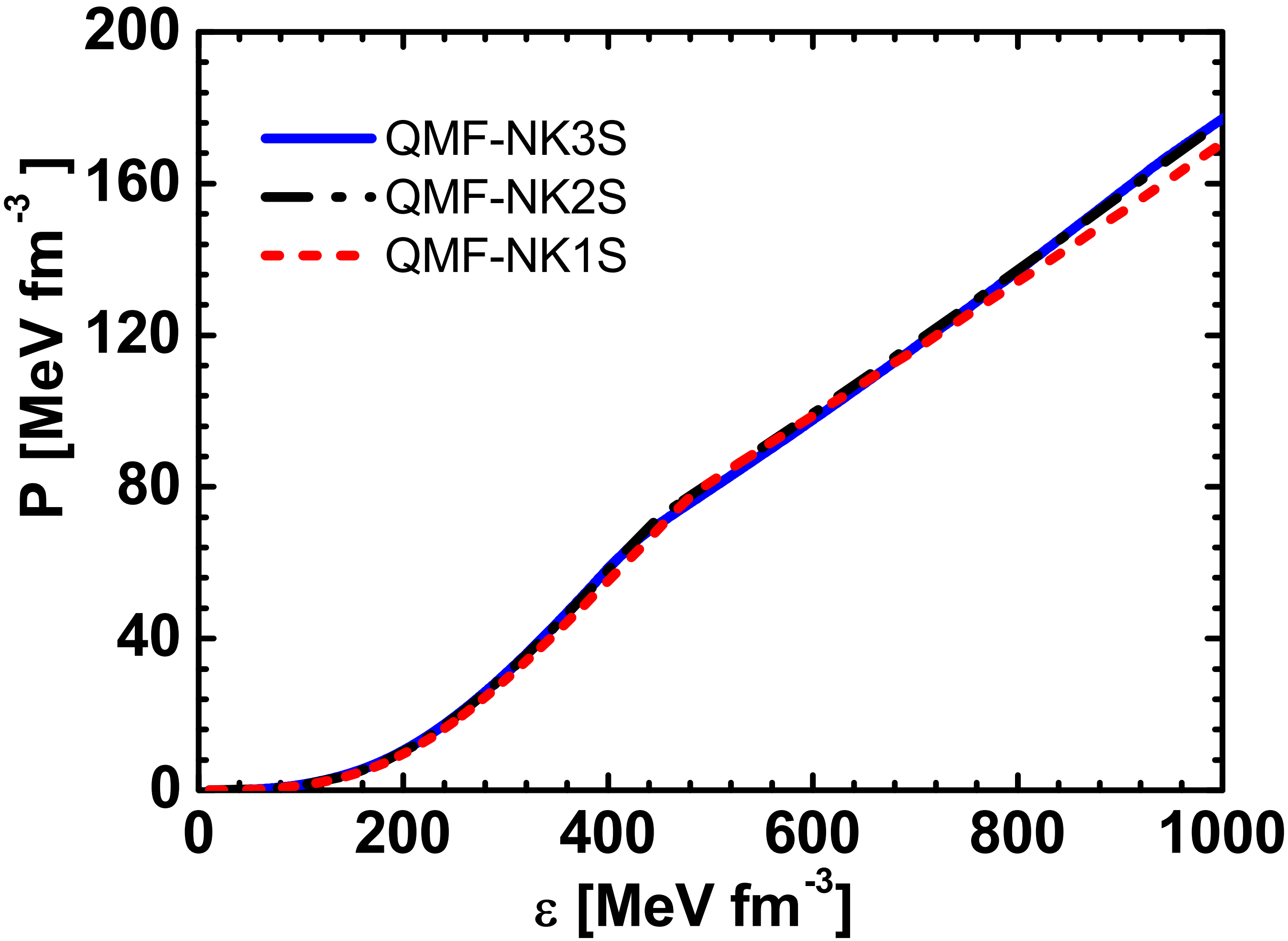
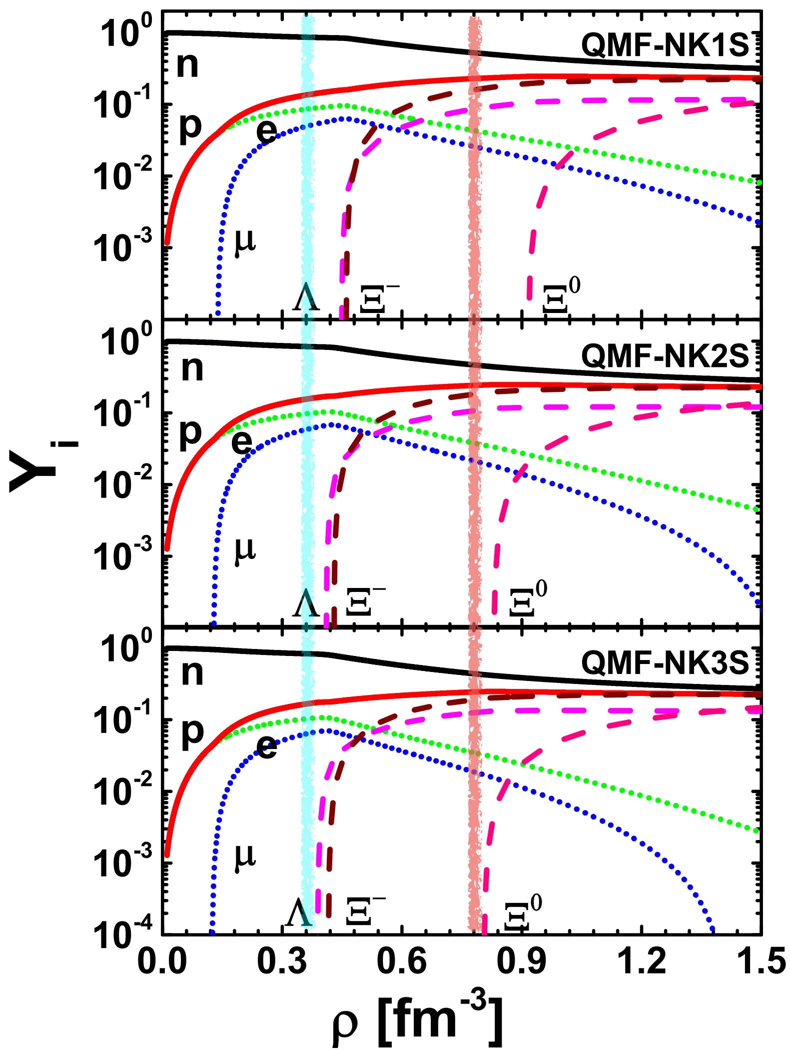
The equations of state of neutron star matter



The particle fractions



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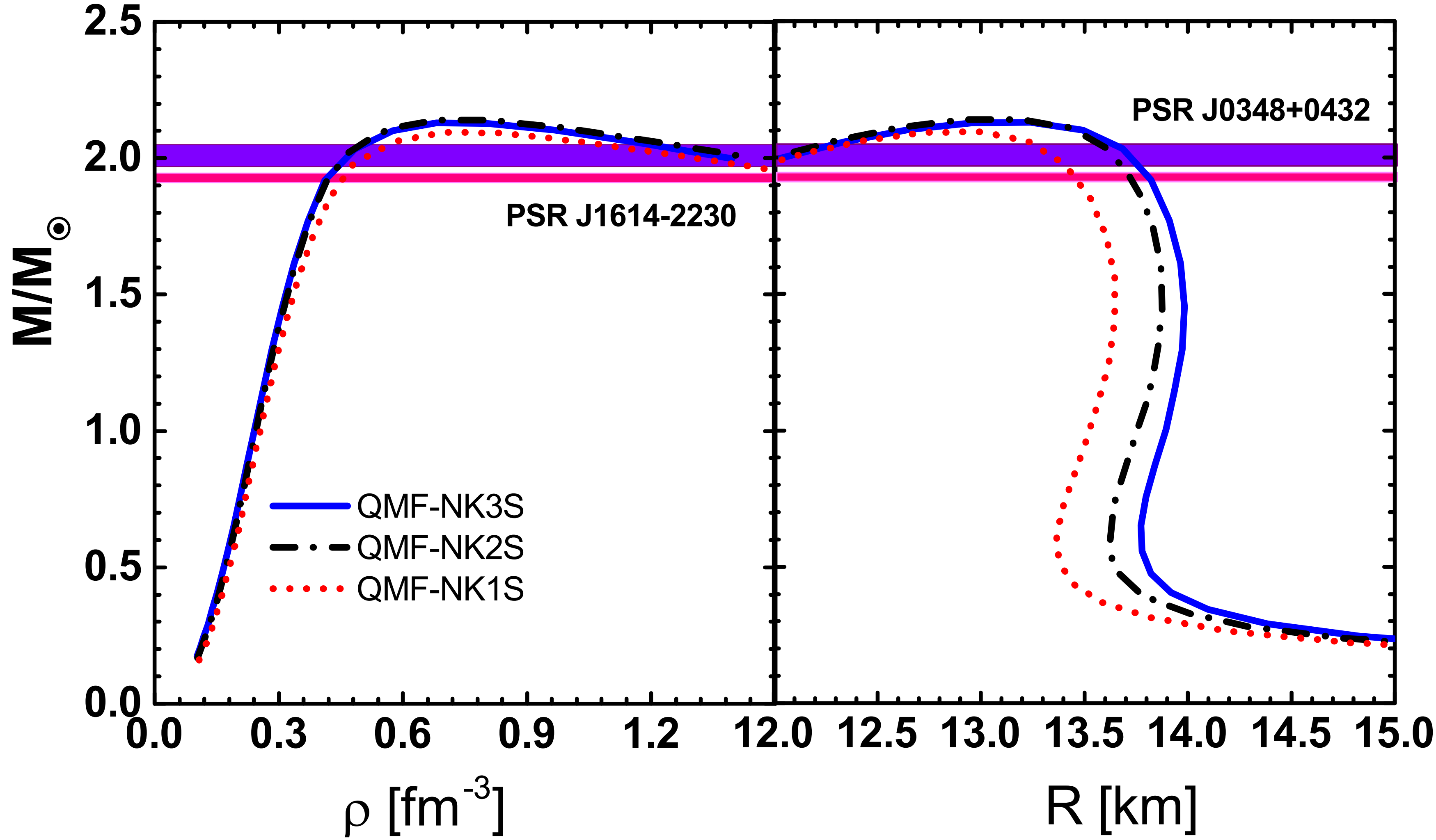
The mass of neutron star



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Summary and Perspective

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- The quark mean field model is extended to strangeness nuclear physics within the pionic and gluonic corrections.

- The binding energies of Λ hypernuclei can be reproduced very well in present framework. The ones of Ξ^0 hypernuclei are also predicted.

- The massive neutron stars are obtained with Λ and hyperon, whose masses are around $2.1 M_{\odot}$.

- The double Λ and Ξ^- hypernuclei will be studied.