The 7th Symposium on Symmetries & Emergence of Structure in QCD
Jul 19-22, 2023, Rizhao, Shandong

Strangeness in nuclear systems (B6)

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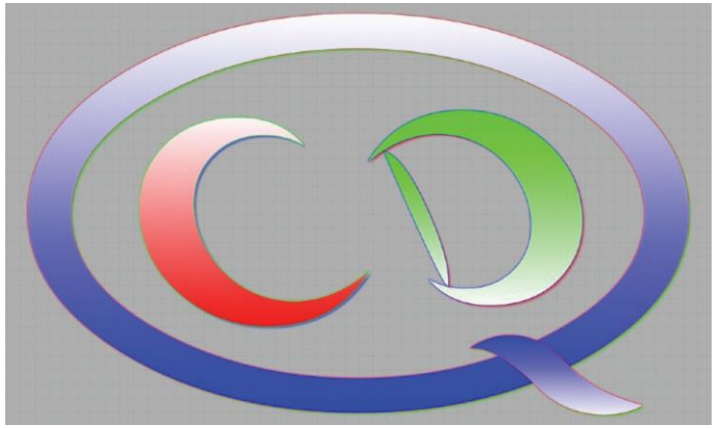

Publications (NSFC No. 12070131001)

- X.-X. Sun, S.-G. Zhou, Angular momentum projection in the deformed relativistic Hartree-Bogoliubov theory in continuum, Phys. Rev. C. 104 (2021) 064319.
- X.-X. Sun, S.-G. Zhou, Rotating deformed halo nuclei and shape decoupling effects, Science Bulletin. 66 (2021) 2072–2078.
- Y.-T. Rong, Z.-H. Tu, S.-G. Zhou, New effective interactions for hypernuclei in a density-dependent relativistic mean field model, Phys. Rev. C. 104 (2021) 054321.
- G.G. Adamian, N.V. Antonenko, H. Lenske, L.A. Malov, S.-G. Zhou, Self-consistent methods for structure and production of heavy and superheavy nuclei, Eur. Phys. J. A. 57 (2021) 89.
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- Z.-H. Tu, S.-G. Zhou, Effects of the ϕ Meson on the Properties of Hyperon Stars in the Density-dependent Relativistic Mean Field Model, Astrophys. J. 925 (2022) 16.
- Z.-H. Tu, $^{1}S_{0}$ hyperon superfluidity in neutron stars from a separable pairing force of finite range, Phys. Rev. C. 106 (2022) 025806.
- C. Pan, M.-K. Cheoun, Y.-B. Choi, J. Dong, X. Du, X.-H. Fan, W. Gao, L. Geng, E. Ha, X.-T. He, J. Huang, K. Huang, S. Kim, Y. Kim, C.-H. Lee, J. Lee, Z. Li, Z.-R. Liu, Y. Ma, J. Meng, M.-H. Mun, Z. Niu, P. Papakonstantinou, X. Shang, C. Shen, G. Shen, W. Sun, X.-X. Sun, J. Wu, X. Wu, X. Xia, Y. Yan, T.C. Yiu, K. Zhang, S. Zhang, W. Zhang, X. Zhang, Q. Zhao, R. Zheng, S.-G. Zhou, DRHBc Mass Table Collaboration, Deformed relativistic Hartree-Bogoliubov theory in continuum with a point-coupling functional. II. Examples of odd Nd isotopes, Phys. Rev. C. 106 (2022) 014316.
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Outline

- Introduction
- New effective interactions for hypernuclei in density-dependent relativistic mean field model
- Effects of ϕ meson on properties of hyperon stars in density-dependent relativistic mean field model
- Summary & perspectives

Covariant Density Functional Theory (CDFT)

$$\mathcal{L} = \sum_B \bar{\psi}_B \Big(i\gamma_\mu \partial^\mu - M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^* - g_{\omega B}\gamma_\mu \omega^\mu - g_{\phi B}\gamma_\mu \phi^\mu - g_{\rho B}\gamma_\mu \vec{\tau}\cdot\vec{\rho}^\mu - e\gamma_\mu \frac{1-\tau_3}{2} A^\mu \Big) \psi_B$$

$$+ \psi_\Lambda \frac{f_{\omega\Lambda\Lambda}}{4M_\Lambda} \sigma_{\mu\nu}\Omega^{\mu\nu}\psi_\Lambda + \frac{1}{2}\partial^\mu\sigma\,\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}\sigma^{*2} - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu$$

$$- \frac{1}{4}S^{\mu\nu}S_{\mu\nu} + \frac{1}{2}m_\phi^2\phi^\mu\phi_\mu - \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^\mu\vec{\rho}_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu},$$

$$[\boldsymbol{\alpha}\cdot\boldsymbol{p} + V_B + T_B + \Sigma_R + \beta(M_B + S_B)]\psi_{iB} = \varepsilon_i\psi_{iB},$$

$$\left(-\Delta + m_\sigma^2\right)\sigma = -g_{\sigma N}\rho_N^s - g_{\sigma\Lambda}\rho_\Lambda^s,$$

$$\left(-\Delta + m_{\sigma^*}^2\right)\sigma^* = -g_{\sigma^*\Lambda}\rho_\Lambda^s,$$

$$\left(-\Delta + m_\omega^2\right)\omega_0 = g_{\omega N}\rho_N^v + g_{\omega\Lambda}\rho_\Lambda^v - \frac{f_{\omega\Lambda\Lambda}}{2M_\Lambda}\rho_\Lambda^T,$$

$$\left(-\Delta\phi + m_\phi^2\right)\phi = g_{\phi\Lambda}\rho_\Lambda^v,$$

$$\left(-\Delta + m_\rho^2\right)\rho_0 = g_{\rho N}\left(\rho_n^v - \rho_p^v\right),$$

$$-\Delta A_0 = e\rho_p^v.$$

Serot_Walecka1986_ANP16-1

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MDC-CDFT (β_{20}, β_{22}, β_{30}, β_{32}, β_{40}, …)

- Axially deformed harmonic oscillator (ADHO) basis

Ring_Gambhir_Lalazissis1997_CPC105-77

$$\left[-\frac{\hbar^2}{2M}\nabla^2 + V_B(z,\rho)\right]\Phi_\alpha(\boldsymbol{r}\sigma) = E_\alpha\Phi_\alpha(\boldsymbol{r}\sigma) \qquad V_B(z,\rho) = \frac{1}{2}M(\omega_\rho^2\rho^2 + \omega_z^2 z^2)$$

$$\Phi_\alpha(\boldsymbol{r}\sigma) = C_\alpha\phi_{n_z}(z)R_{n_\rho}^{m_l}(\rho)\frac{1}{\sqrt{2\pi}}e^{im_l\varphi}\chi_{s_z}(\sigma)$$

- Fourier expansion for densities & potentials

$$f(\rho,\varphi,z) = f_0(\rho,z)\frac{1}{\sqrt{2\pi}} + \sum_{n=1}^{\infty} f_n(\rho,z)\frac{1}{\sqrt{\pi}}\cos(2n\varphi) \qquad f = V \text{ or } \rho$$

- A modified linear constraint method

$$E' = E_{\mathrm{RMF}} + \sum_{\lambda\mu}\frac{1}{2}C_{\lambda\mu}Q_{\lambda\mu} \qquad C_{\lambda\mu}^{(n+1)} = C_{\lambda\mu}^{(n)} + k_{\lambda\mu}\left(\beta_{\lambda\mu}^{(n)} - \beta_{\lambda\mu}\right)$$

Lu_Zhao_Zhao_SGZ 2014_PRC89-014323 Zhao_Lu_Zhao_SGZ 2017_PRC95-014320

MDC-CDFT (β_{20}, β_{22}, β_{30}, β_{32}, β_{40}, …)

ph channel	Non-linear	Density-dependent
Meson exchange	NL3, NL3*, PK1, …	DD-ME1, DD-ME2, …
Point Coupling	PC-F1, PC-PK1, …	DD-PC1, …

MDC-RMF MDC-RHB

pp channel	BCS	Bogoliubov
Constant gap	√	-
Constant strength	√	-
Delta force	√	√
Separable force	√	√

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2017_PRC95-014320

Applications of MDC-CDFTs

- Potential energy surface, ground state & fission properties
  - (β_{20}, β_{22}, β_{30}): 1-, 2- & 3-dim PES of ^{240}Pu & B_f's of actinides
  - (β_{20}, β_{22}): Shape polarization effect of Λ
  - (β_{20}): Superdeformed shapes in Λ hypernuclei
  - (β_{20}): Third barriers in light actinides
  - (β_{20}, β_{30}): Octupole correlations & shape transitions
  - (β_{20}, β_{22}, β_{30}): Octupole correlations in MχD
  - (β_{20}, β_{32}): Nuclear Tetrahedral shapes
  - (β_{20}, β_{22}, β_{30}): 1-, 2-, & 3-dim PES of ^{270}Hs
  - ($\beta_{\lambda\mu}$, R): Clustering, bubble & toroidal structure; GMR
- Fission dynamics based on PES from MDC-CDFTs
  - Spontaneous fission
  - Induced fission
- Angular momentum & parity projected MDC-CDFTs
  - Clustering & exotic shapes

MultiDimensionally-Constrained Covariant Density Functional Theories

MDC-CDFT (β_{20}, β_{22}, β_{30}, β_{32}, β_{40}, …)

ph channel	Non-linear	Density-dependent
Meson exchange	**NL3, NL3*, PK1, …**	**DD-ME1, DD-ME2, …**
Point Coupling	**PC-F1, PC-PK1, …**	**DD-PC1, …**

- Motivation of the present work
  - Not many effective DD interactions for hypernuclei
  - Spherical shapes assumed when these effective interactions were obtained though most observed hypernuclei are deformed
- Aim of the present work
  - New effective DD interactions for hypernuclei with deformation effects considered in fitting

Density dependent (DD) coupling constants

$$\mathcal{L} = \sum_B \bar{\psi}_B \left(i\gamma_\mu \partial^\mu - M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^* - g_{\omega B}\gamma_\mu \omega^\mu - g_{\phi B}\gamma_\mu \phi^\mu - g_{\rho B}\gamma_\mu \vec{\tau}\cdot\vec{\rho}^\mu - e\gamma_\mu \frac{1-\tau_3}{2} A^\mu \right) \psi_B$$

$$+ \psi_\Lambda \frac{f_{\omega\Lambda\Lambda}}{4M_\Lambda} \sigma_{\mu\nu}\Omega^{\mu\nu}\psi_\Lambda + \frac{1}{2}\partial^\mu\sigma\,\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}\sigma^{*2} - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu$$

$$- \frac{1}{4}S^{\mu\nu}S_{\mu\nu} + \frac{1}{2}m_\phi^2\phi^\mu\phi_\mu - \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^\mu\vec{\rho}_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu},$$

$$g_{mB}(\rho^\upsilon) = g_{mB}(\rho_{\text{sat}}) f_{mB}(x), \quad x = \rho^\upsilon/\rho_{\text{sat}},$$

$$R_m = g_{m\Lambda}(\rho_{\text{sat}})/g_{mN}(\rho_{\text{sat}})$$

R_σ and R_ω

$$f_{mN}(x) = \begin{cases} a_m \dfrac{1 + b_m(x + d_m)^2}{1 + c_m(x + d_m)^2}, & m = \sigma \text{ or } \omega \\ e^{-a_\rho(x-1)}, & m = \rho, \end{cases}$$

$$f_\sigma(1) = 1,\ f_\omega(1) = 1,\ f_\sigma''(0) = 0,\ f_\omega''(0) = 0,\ \text{and}\ f_\sigma''(1) = f_\omega''(1)$$

New effective DD interactions

Rong(荣宇婷)_ Tu(涂中豪)_
SGZ 2021_PRC104-054321

Hypernucleus	Expt.	DD-ME-Yi				PKDD-Yi			
		$i=0$	$i=1$	$i=2$	$i=3$	$i=0$	$i=1$	$i=2$	$i=3$
${}^{12}_{\Lambda}$C	11.36 ± 0.20	25.514	**10.789**	10.588	10.120	25.566	**10.854**	10.514	10.013
${}^{13}_{\Lambda}$C	12.0 ± 0.2	28.080	**12.262**	12.023	11.422	27.814	**11.932**	11.534	10.944
${}^{16}_{\Lambda}$O	13.0 ± 0.2	27.516	**12.849**	**12.643**	12.174	27.771	**13.089**	**12.684**	12.105
${}^{28}_{\Lambda}$Si	17.2 ± 0.2	34.724	**17.643**	**17.560**	17.450	34.857	**17.731**	**17.578**	17.469
${}^{32}_{\Lambda}$S	17.5 ± 0.5	36.814	**18.865**	**18.895**	18.827	36.341	**18.824**	**18.695**	18.640
${}^{40}_{\Lambda}$Ca	18.7 ± 1.1	36.600	**19.566**	**19.448**	**19.265**	36.730	**19.756**	**19.493**	**19.235**
${}^{51}_{\Lambda}$V	21.5 ± 0.6	39.126	**21.227**	**21.228**	**21.401**	39.095	**21.251**	**21.221**	**21.407**
${}^{52}_{\Lambda}$V	21.8 ± 0.3	39.429	**21.422**	**21.440**	**21.662**	39.348	**21.400**	**21.402**	**21.649**
${}^{89}_{\Lambda}$Y	23.6 ± 0.5	41.882	**23.511**	**23.576**	**23.974**	41.788	**23.501**	**23.578**	**24.018**
${}^{139}_{\Lambda}$La	25.1 ± 1.2	42.691	**24.306**	**24.479**	**25.215**	42.226	**23.987**	**24.295**	**25.210**
${}^{208}_{\Lambda}$Pb	26.9 ± 0.8	44.489	**25.687**	**25.893**	**26.746**	44.029	**25.337**	**25.694**	**26.729**
$\bar{\chi}^2$			2.543	1.867	0.185		2.580	1.889	0.211
$\bar{\chi}^2_{\text{all}}$		2956.907	2.543	3.009	6.690	2954.595	2.580	3.666	9.233
Δ		17.175	0.711	0.672	0.668	17.048	0.816	0.712	0.716
δ		98.221	3.759	3.840	4.817	97.776	4.018	4.060	5.419
R_σ		0.667	0.366	0.417	0.577	0.667	0.367	0.464	0.659
R_ω		0.667	0.352	0.415	0.611	0.667	0.353	0.472	0.712
$\sigma^+_{R_\sigma}$			0.053	0.036	0.080		0.080	0.092	0.084
$\sigma^-_{R_\sigma}$			0.079	0.071	0.082		0.088	0.093	0.085

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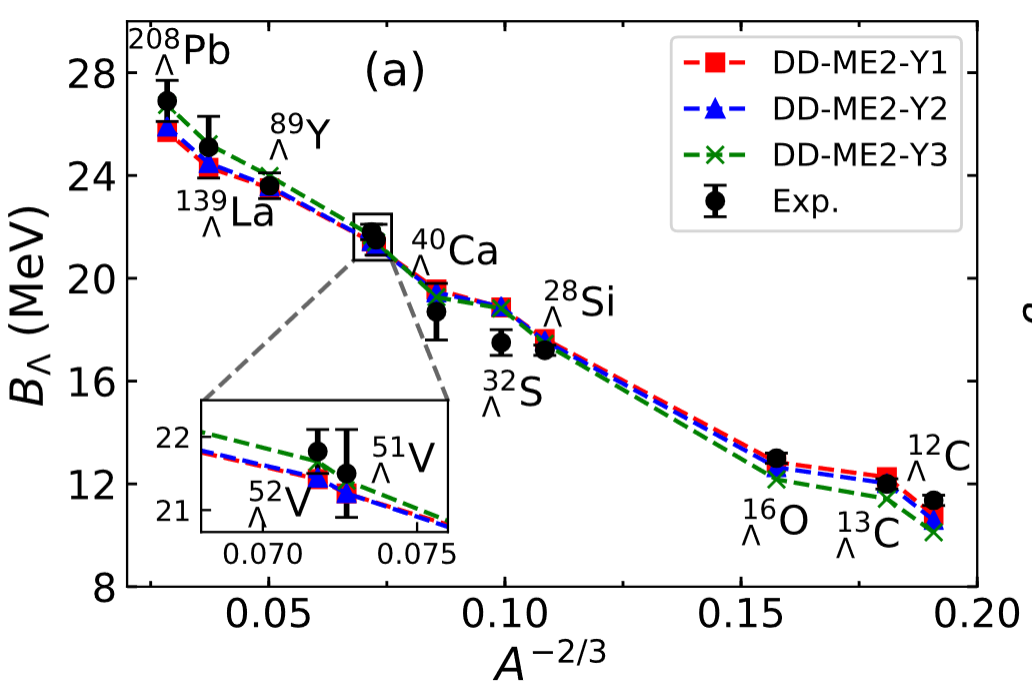
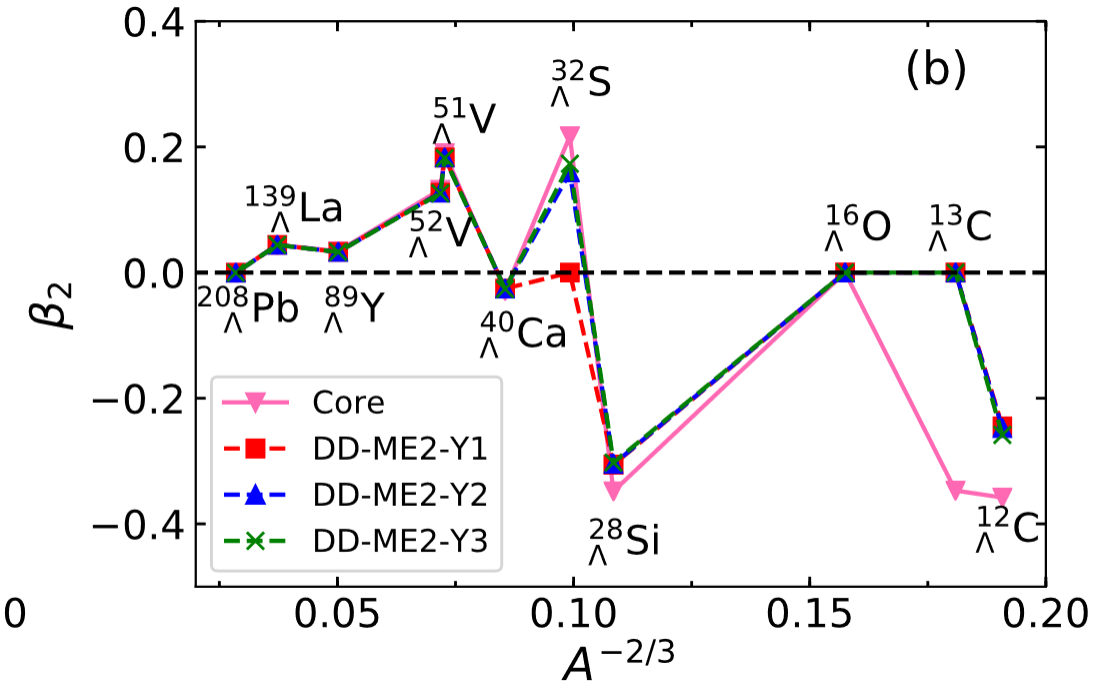
Ground state properties





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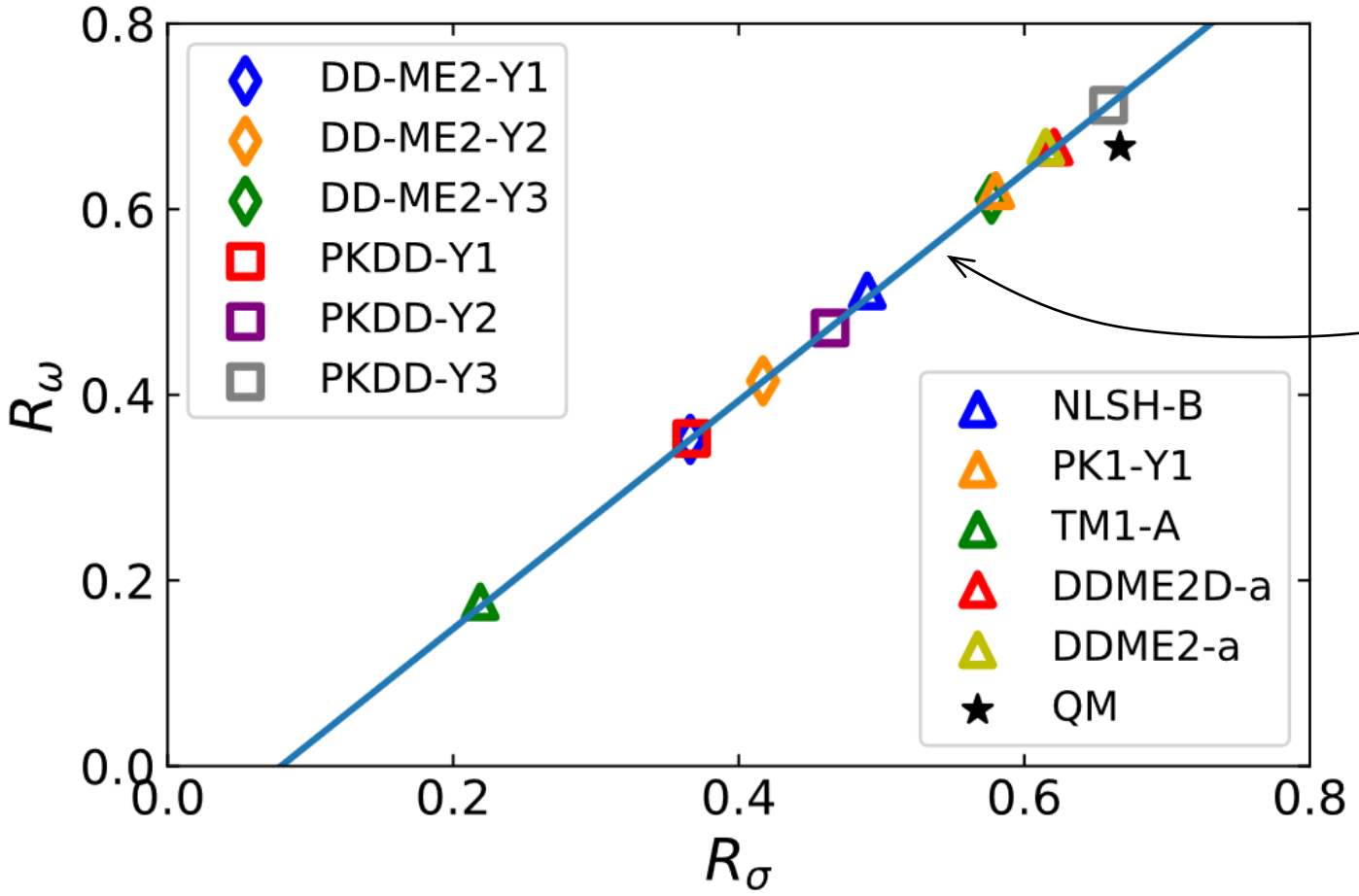
Linear relation between R_σ & R_ω



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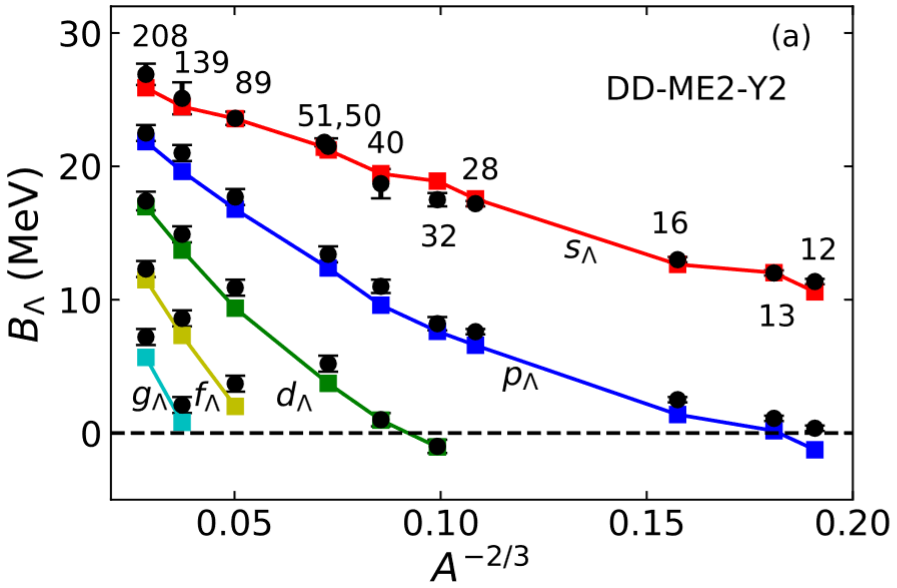
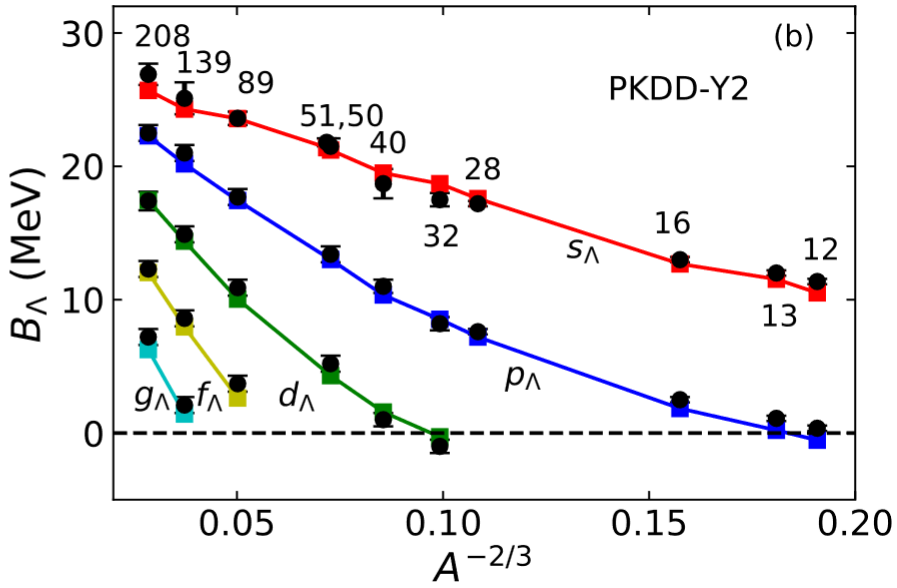
Single Λ states





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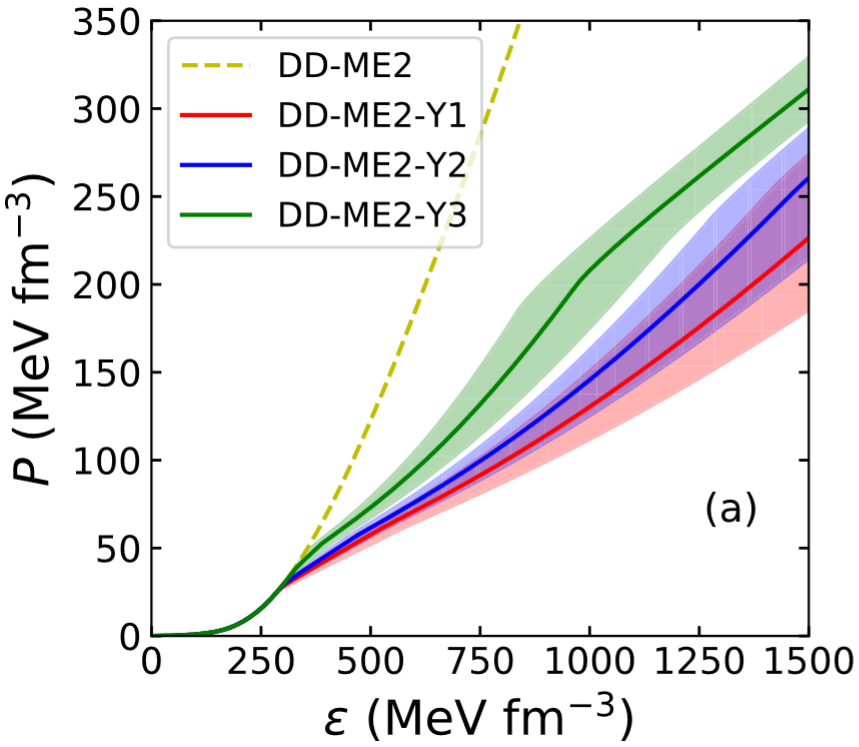
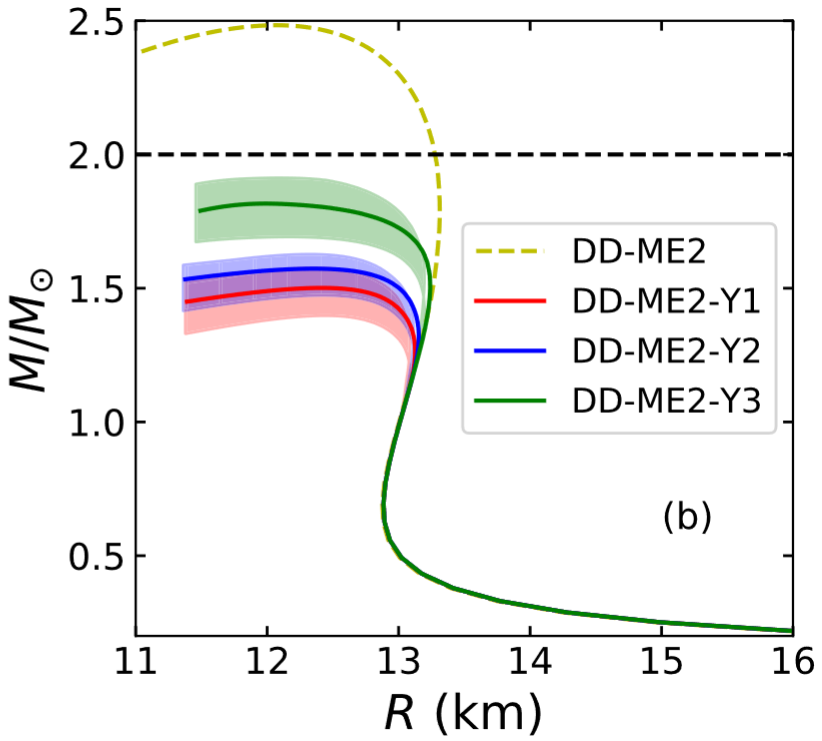
Neutron (hyperon) stars: Hyperon puzzle





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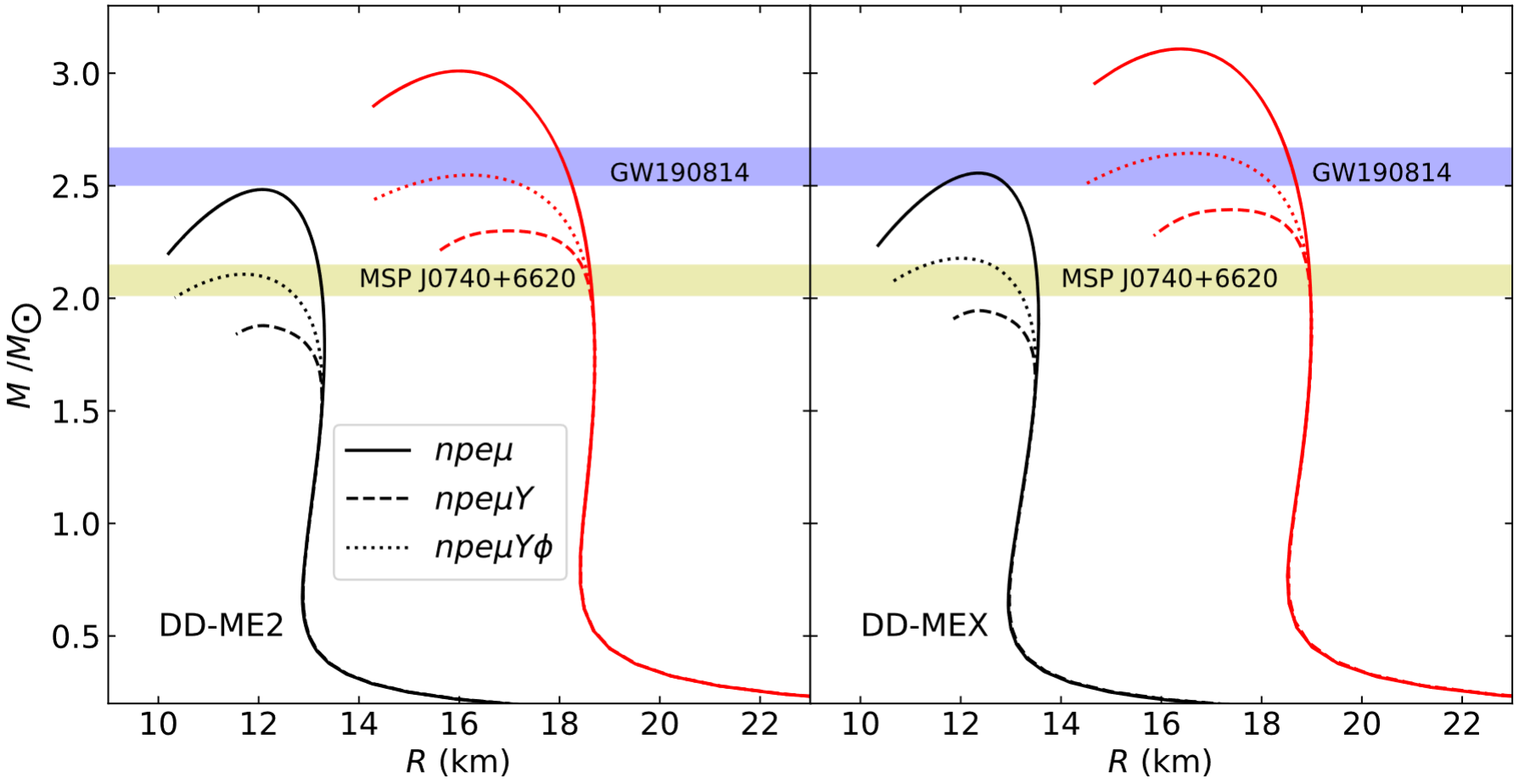
An attempt toward solving hyperon puzzle

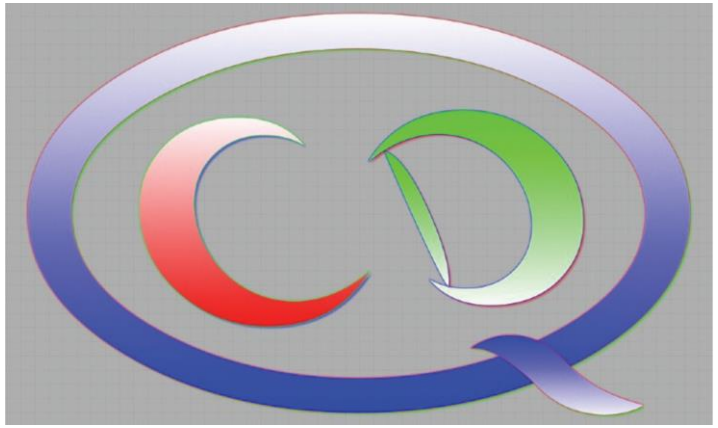


Tu(涂中豪)_SGZ2022_ApJ925-16

Summary & perspectives

- Summary
  - New effective interactions for hypernuclei in density-dependent relativistic mean field model
  - Effects of ϕ meson on properties of hyperon stars in density-dependent relativistic mean field model

- Perspectives
  - More on shape effects in hypernuclei
  - Connection with no-core shell model calculations
  - …



Summary & perspectives

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Thanks

谢谢