



第一届超子物理研讨会 惠州

超核结构中 相对论有效核力的介质效应

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兰州大学 教育部稀有同位素前沿科学中心

兰州大学 核科学与技术学院

2024年4月13日

背景

交换项效应

密度依赖性

介子自由度

小结

白
強
不
息
獨
樹
一
幟

◆ 超核：原子核中包含超子（奇异自由度）

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

◆ 超核结构（与反应）

➤ 重子-重子相互作用

B. F. Gibson, Phys. Rep. 257 (1995) 349

E. Epelbaum, RMP 81 (2009) 1773

➤ 中子星内部结构

M. Prakash, Phys. Rep. 280 (1997) 1

L. Tolos, PPNP 112 (2020) 103770

◆ 超核结构模型

结团模型

壳模型

密度泛函理论

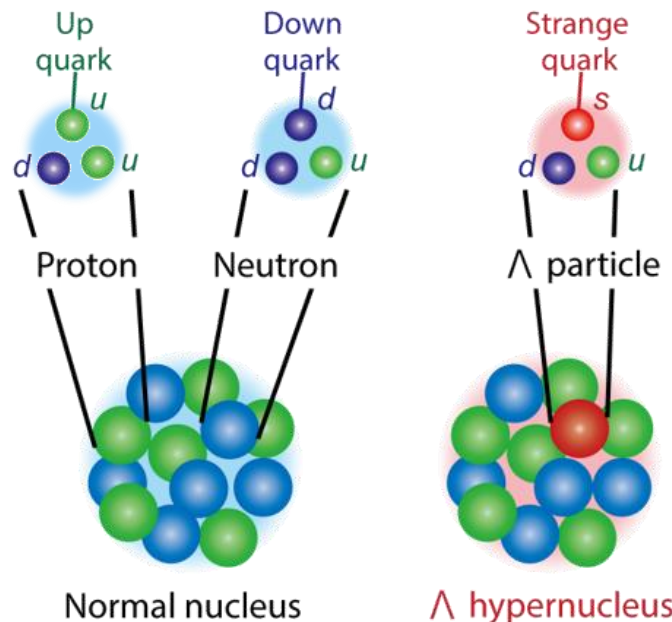
E. Hiyama, PPNP 63 (2009) 339

R. Wirth, R. Roth, PRL 117 (2016) 182501

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

R. Brockmann, W. Weise, PLB 69 (1977) 167

H. Toki, Phys. Rev. C 58 (1998) 3749



协变密度泛函理论

核力介子交换 (点耦合) 图像 + 密度泛函思想
自旋-轨道耦合、(赝) 自旋对称性的自治描述

Walecka(1974), Serot(1986), Reinhard(1989), Ring(1996), Meng(2006)

CDFT开展超核研究

H. Shen, PTP 2006; Y. Tanimura, PRC 2012; B. N. Lu, PRC 2014;

T. T. Sun, PRC 2016; J. M. Yao, PRC 2017; J. N. Hu, PRC 2018;

Y. T. Rong, PLB 2020; Y. Zhang, PRC 2021; S. Y. Ding, PRC 2022

.....

◆ 构建超子-核子、超子-超子相互作用

超子寿命 $\sim 10^{-10}$ s

现实核力

利用自由空间散射等实验数据提取相移、散射长度等

- 介子交换, 考虑对称性: Nijmegen, Bonn-Jülich
- 手征有效场
- 格点QCD

超子相关的数据匮乏

K.W. Li et al., 科学通报 63 (2018) 38

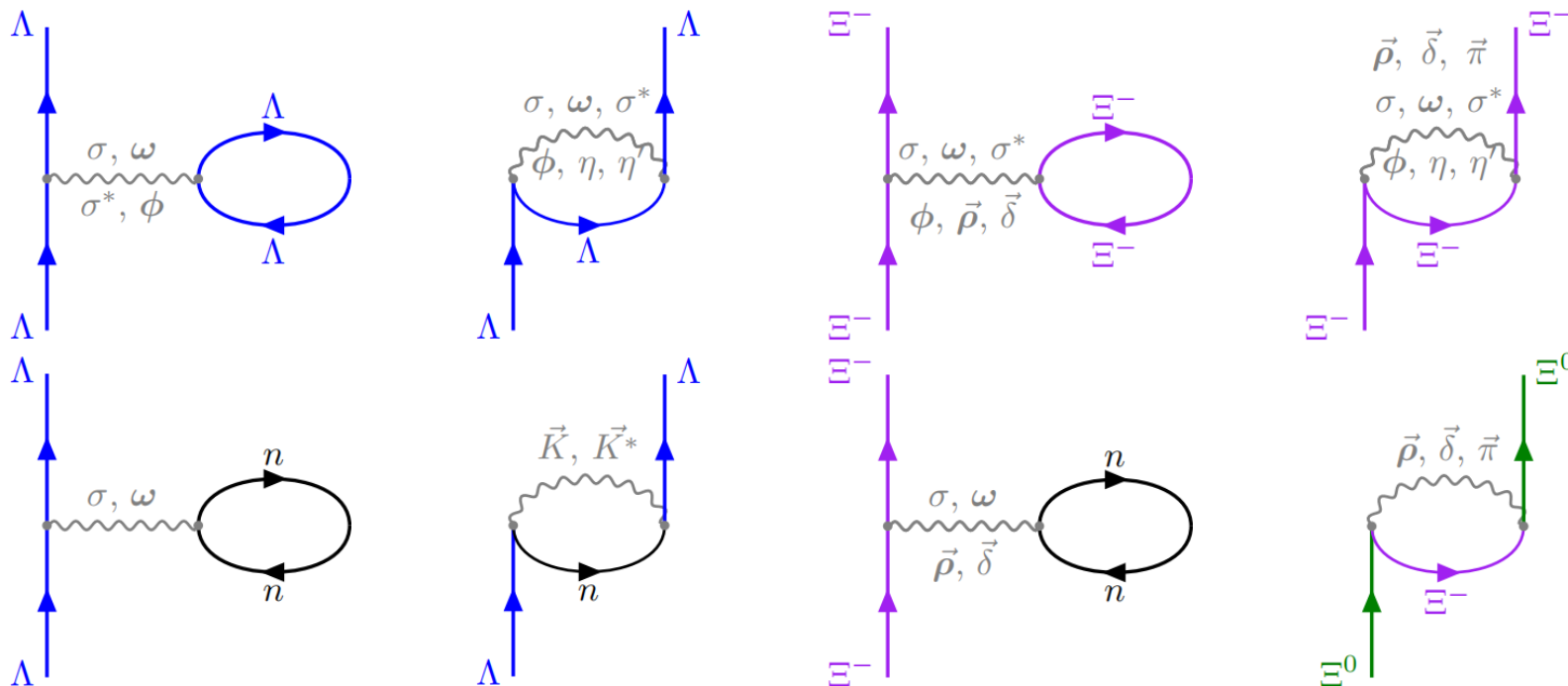
T.A. Rijken, PRC 59 (1999) 21; J. Haidenbauer, PRC 72 (2005) 044005

H. Polinder, NPA 779 (2006) 244; K.W. Li, CPC 42 (2018) 014105

NPLQCD Collaboration, PRL 109 (2012) 172001; HAL QCD Collaboration

有效相互作用

利用超核结合能、单粒子分离能、衰变寿命等约束

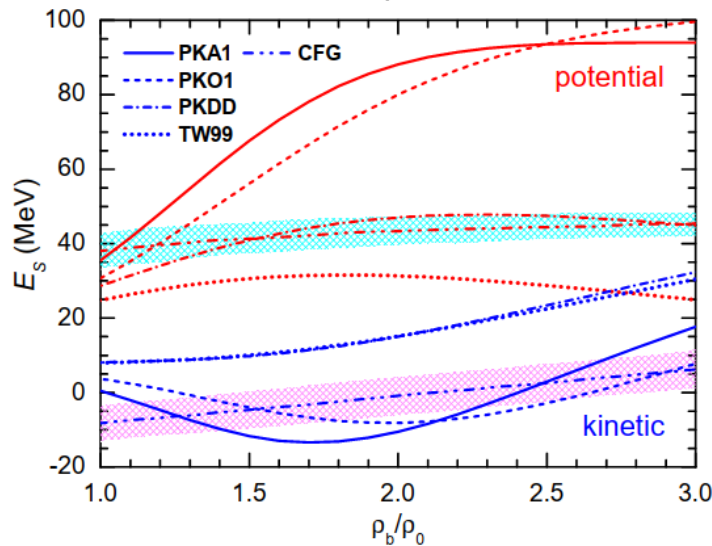
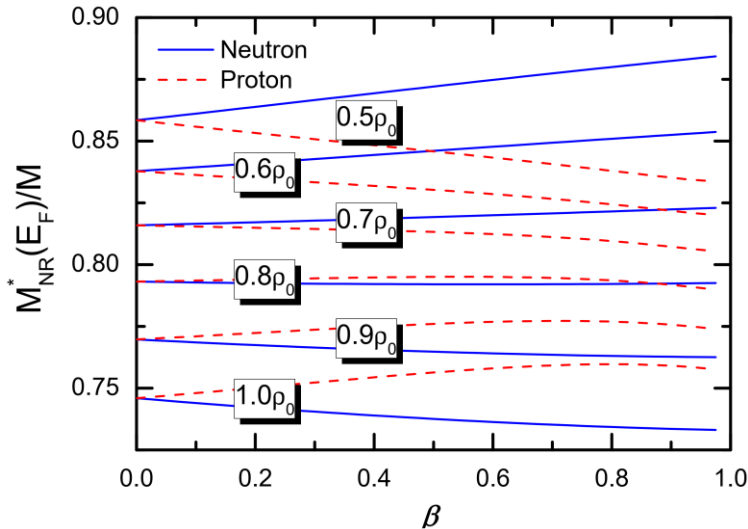
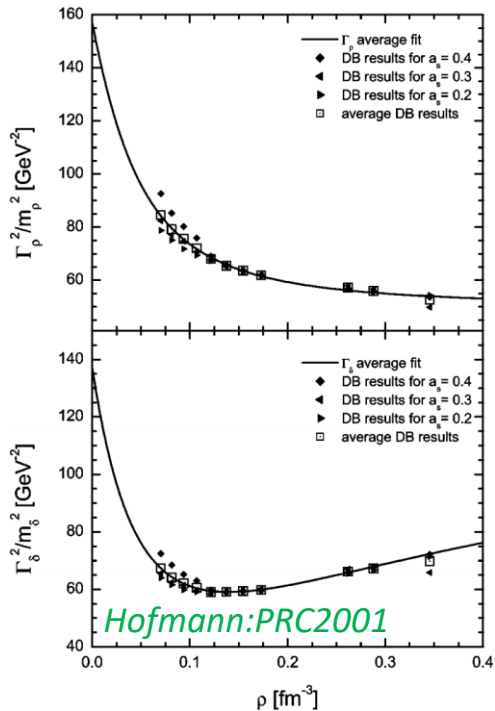
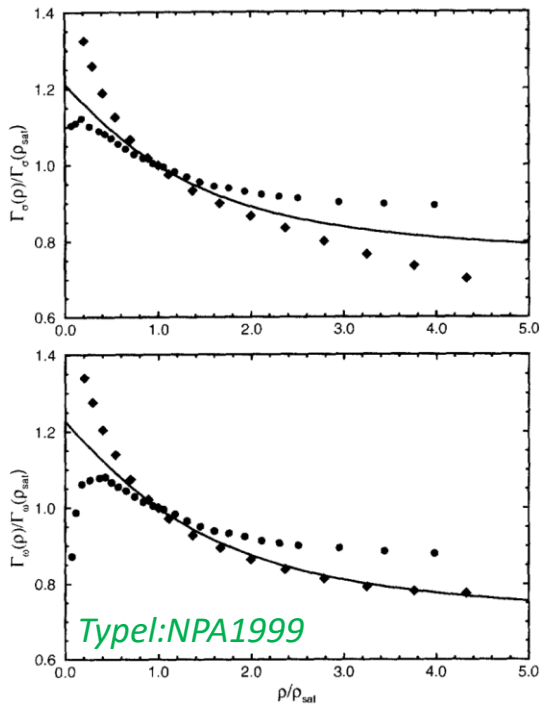


DDRMF

Brockmann1992; Lenske1995; Fuchs1995

Impact on nuclear matter properties:

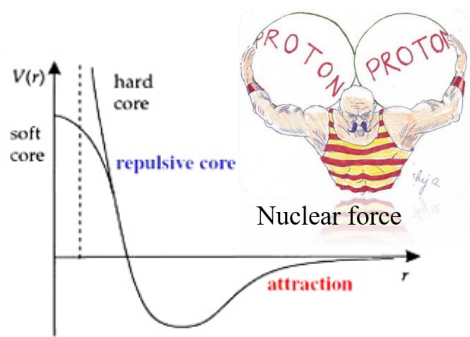
W.H.Long:PLB2006, B.Y.Sun:PRC2008, Z.W.Liu:PRC2018



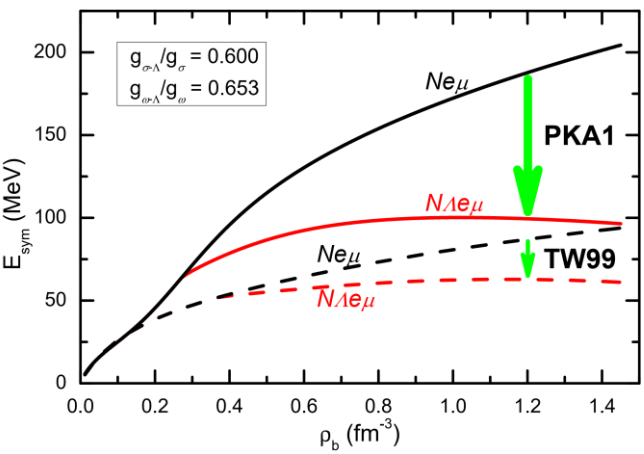
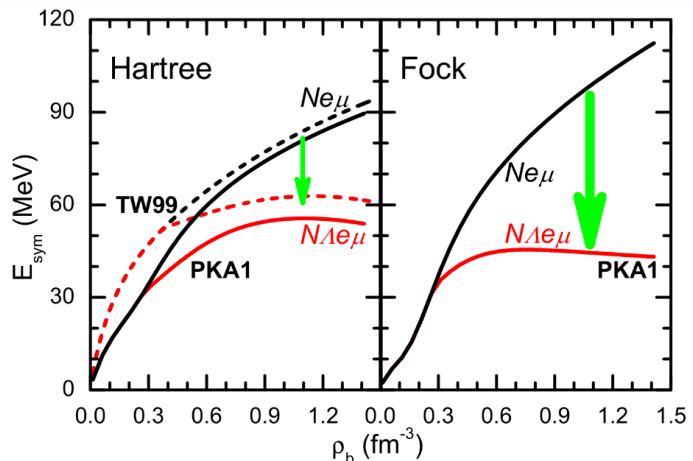
发展与思考

- 完整的两体相互作用
- 新的密度依赖关系
- 新的介子交换自由度

介质中核力的动力学平衡



1. 完整的两体相互作用——交换项

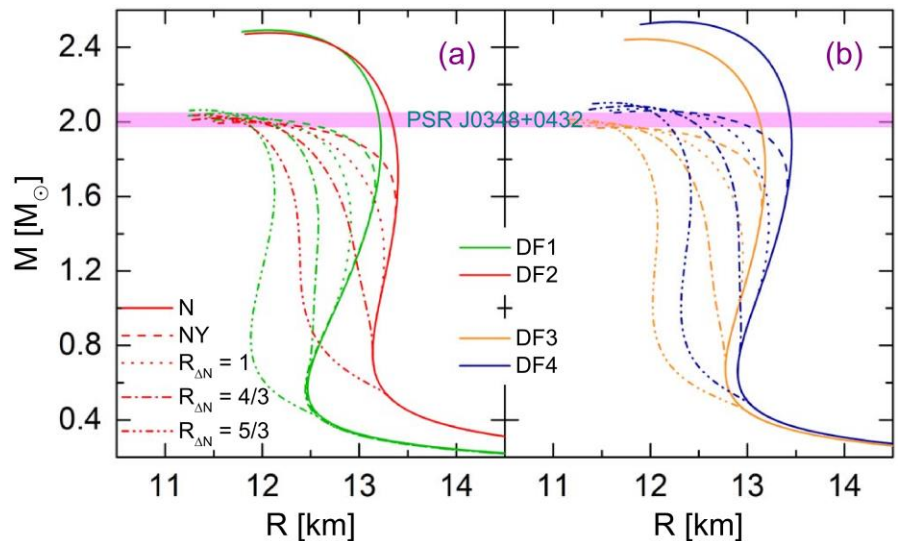
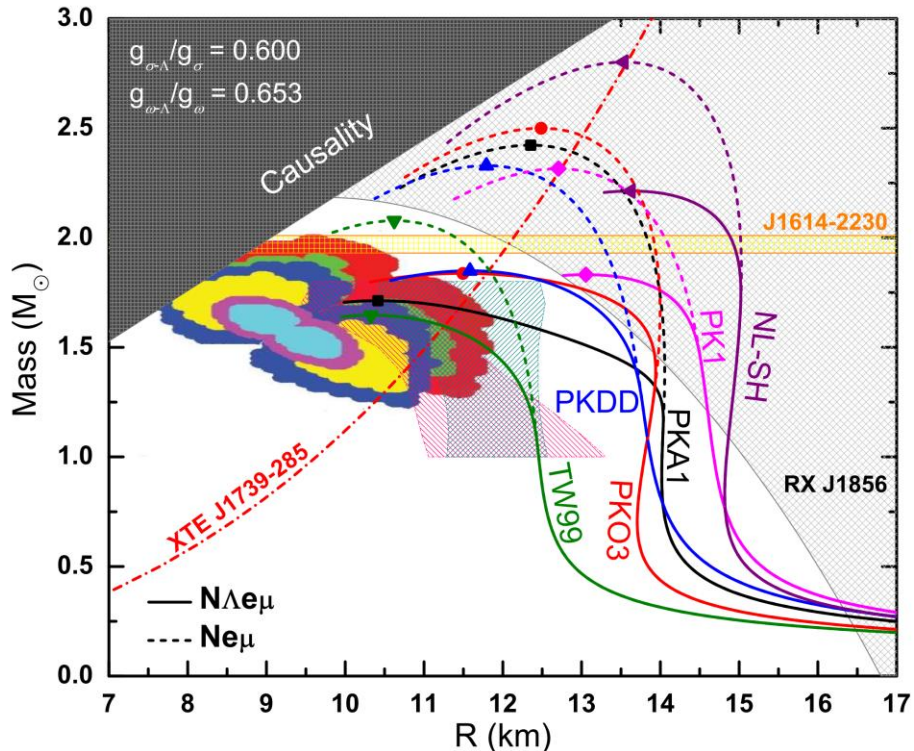


超子引起的交换项效应

- ◆ 额外的对称能软化影响中子星半径
- ◆ 超子耦合强度变化可能再现大质量

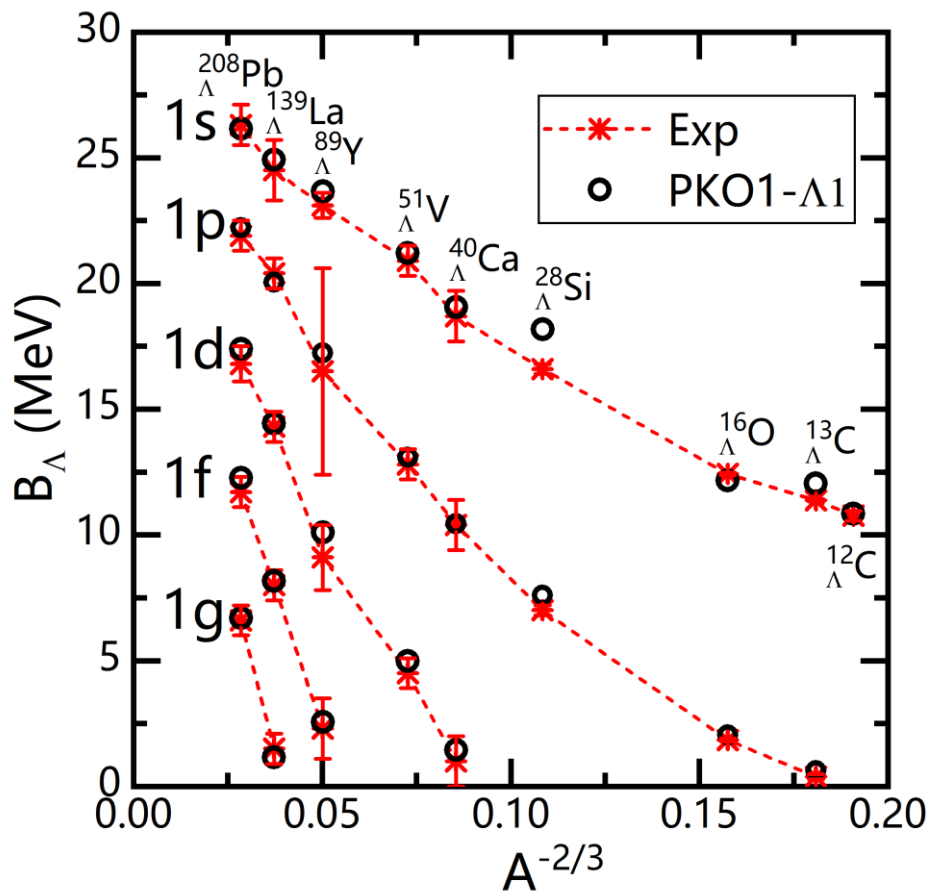
孙保元, 中国科学: 物理学 力学 天文学 46 (2016) 012018

交换项在核物质、有限核性质描述中的作用:
改变耦合强度密度依赖、核介质中动力学平衡



W. H. Long, BYS, K. Hagino, H. Sagawa, PRC 85 (2012) 025806

A. Sedrakian, J. J. Li, F. Weber, PPNP 131 (2023) 104041



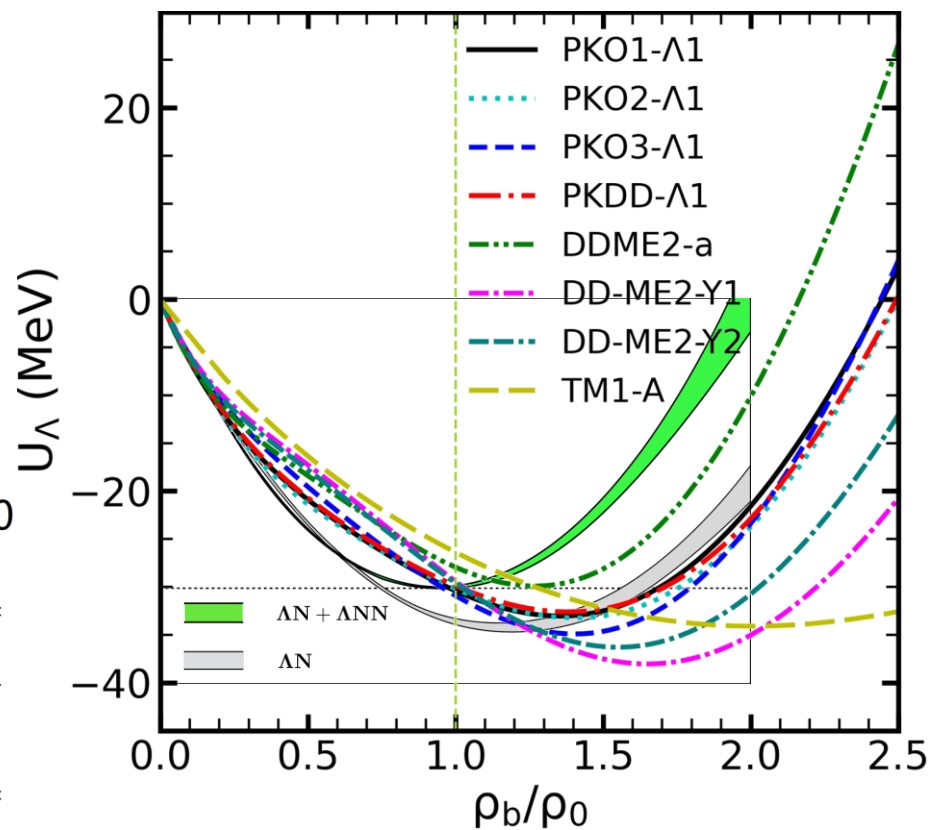
	PKO1- Λ 1	PKO2- Λ 1	PKO3- Λ 1	PKDD- Λ 1
$g_{\sigma\Lambda}/g_{\sigma N}$	0.596	0.591	0.594	0.620
Δ	0.265	0.260	0.407	0.347

单 Λ 超子分离能:

$$B_\Lambda({}^A_\Lambda Z) = E({}^{A-1}Z) - E({}^A_\Lambda Z)$$

A. Gal et al., Rev. Mod. Phys. 88 (2016) 035004

O.Hashimoto and H.Tamura, PPNP 57 (2006) 564



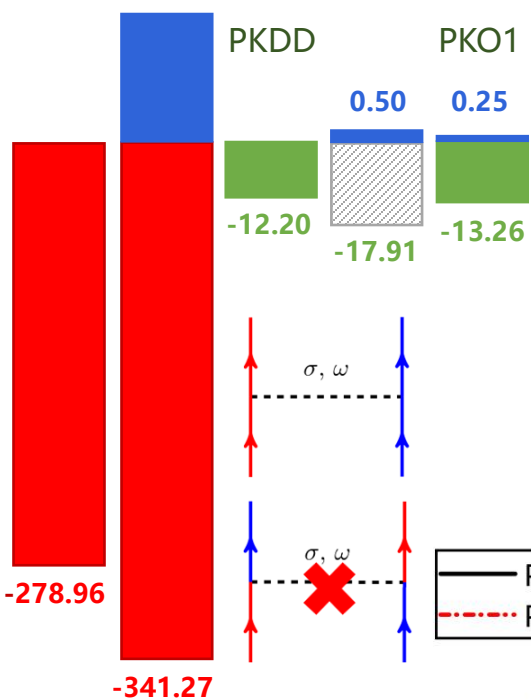
S.Y. Ding, Z. Qian, BYS, W.H. Long, Phys. Rev. C 106 (2022) 054311

SU(3) chiral EFT at NLO

D. Gerstung, Eur. Phys. J. A (2020) 56:175

超核结构中交换项效应

PKDD PKO1

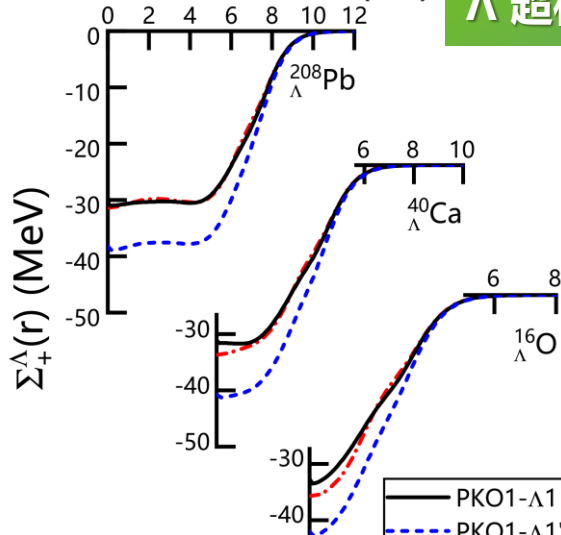


$$\chi \equiv \left| \frac{E_{\sigma}^E + E_{\omega}^E}{E_{\sigma}^D + E_{\omega}^D} \right|$$

$$\chi_N \approx 24.6\%$$

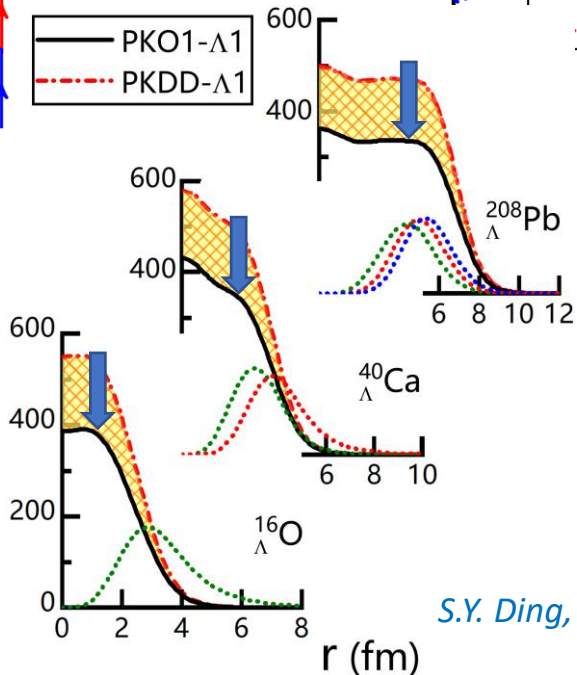
$$\chi_{\Lambda} \approx 1.8\%$$

r (fm)



PKO1- Λ 1
PKDD- Λ 1

$\Sigma_{-}^{\Lambda}(r)$ (MeV)

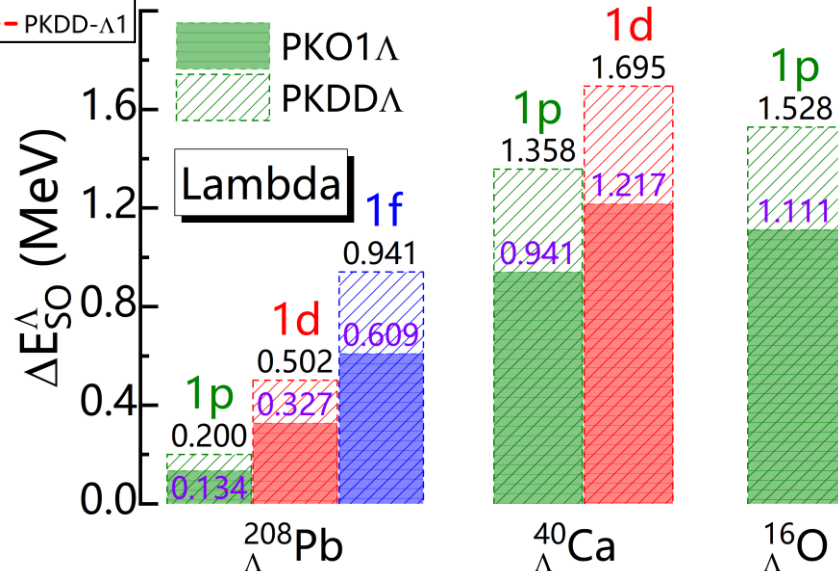


r (fm)

Λ 超核动力学平衡主要由同位旋标量道主导

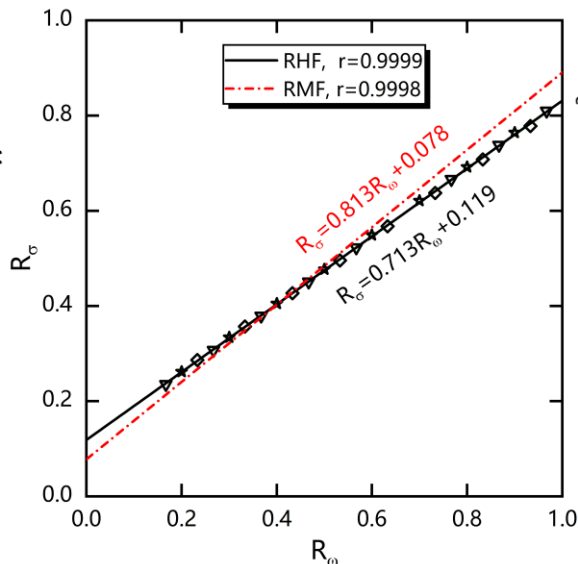
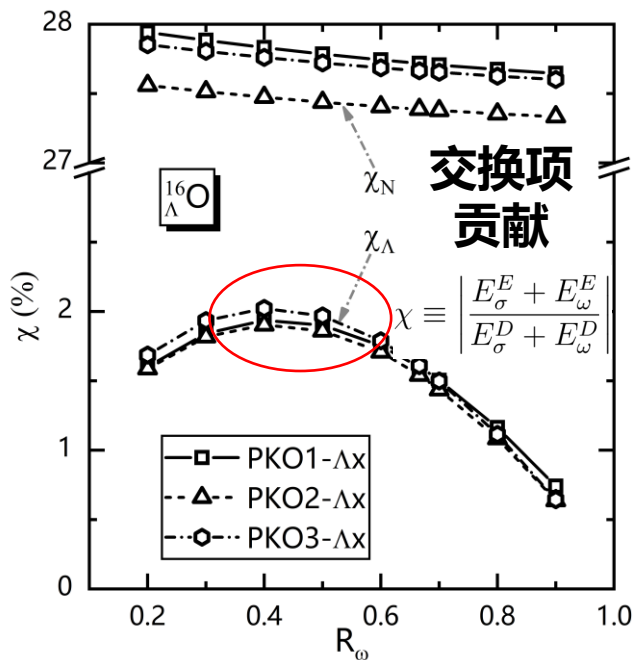
超子部分交换项贡献弱，难以抵消更强的直接项吸引，为合理给出结合能需**弱化**直接项，导致耦合强度 $g_{\sigma\Lambda}/g_{\sigma N}$ **减小**

RHF 中 Σ^{Λ} 斜率更缓
导致相对 RMF 更小的自旋-轨道势

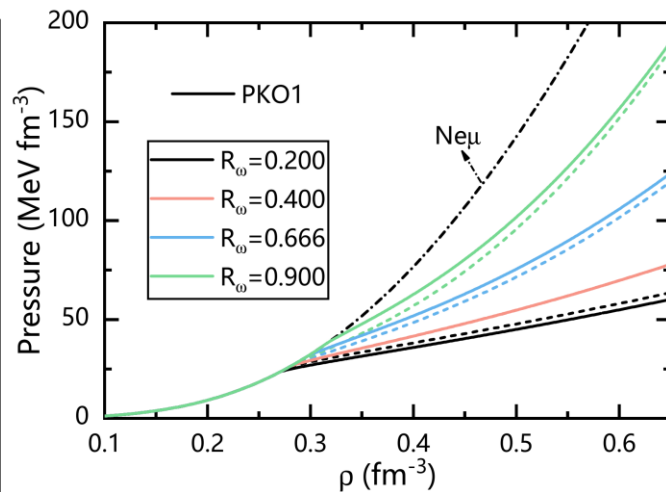


S.Y. Ding, Z. Qian, B.Y.S., W.H. Long, *Phys. Rev. C* 106 (2022) 054311
ChinaXiv: T202307.00031; T202307.00172

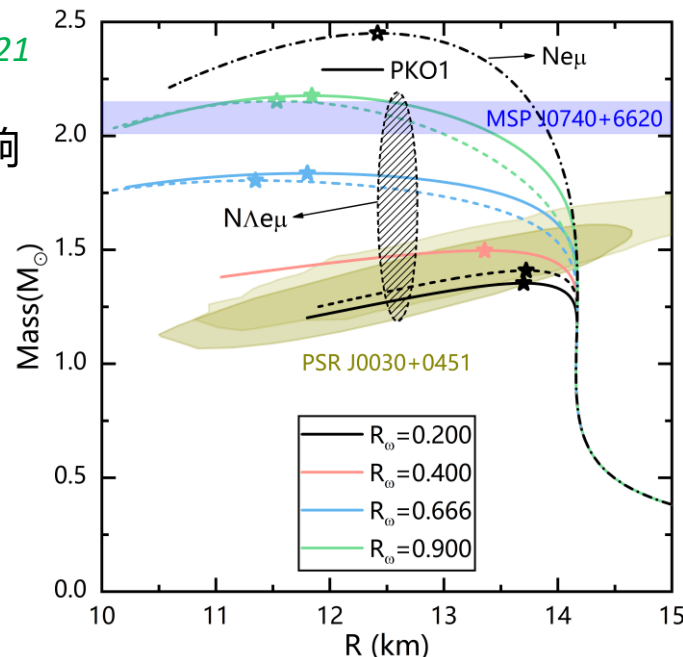
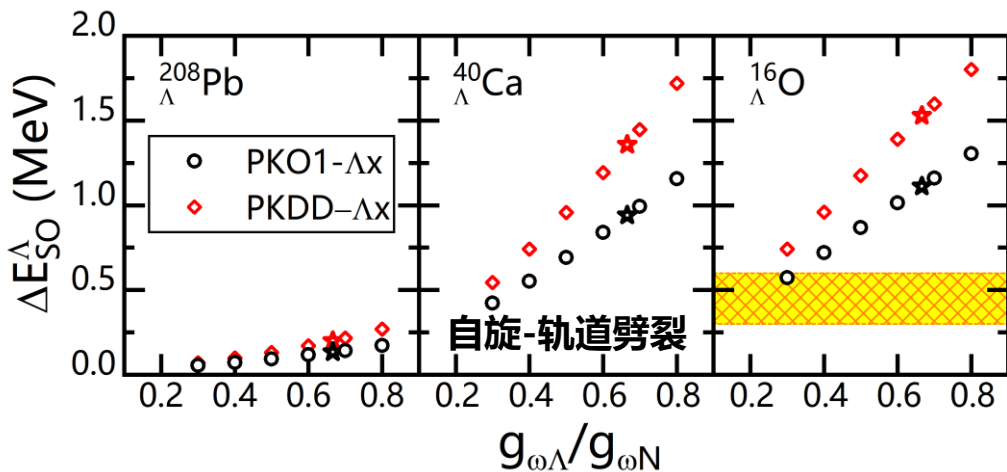
同位旋标量介子耦合强度的线性关联



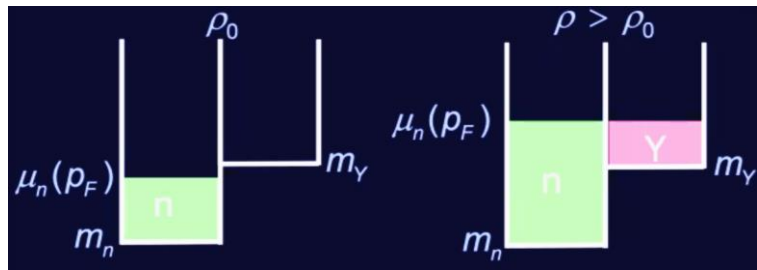
Rong et al, PRC 104 (2021) 054321



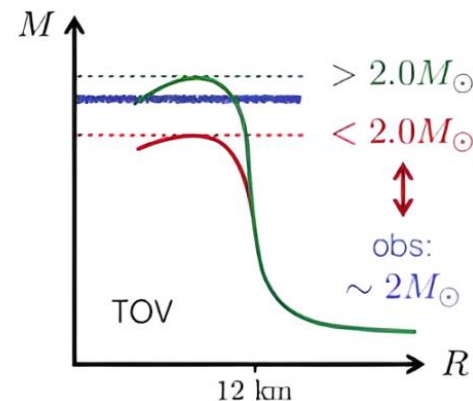
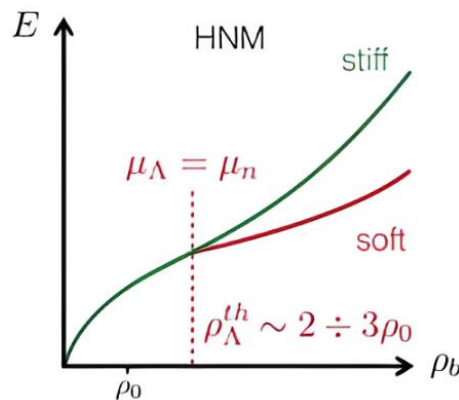
交换项对于超核与中子星的具体作用受到耦合强度比值影响



中子星 Hyperon Puzzle

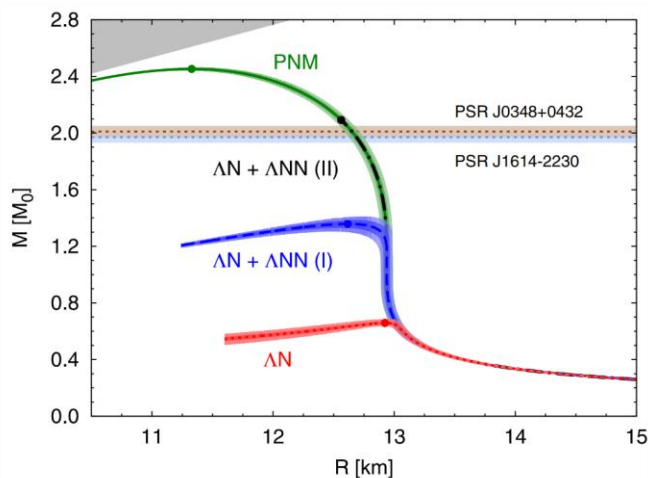


$$e^- + p \rightarrow \nu_e + \Lambda \quad p_{F,n}^2 + m_n^2 \geq m_\Lambda^2$$

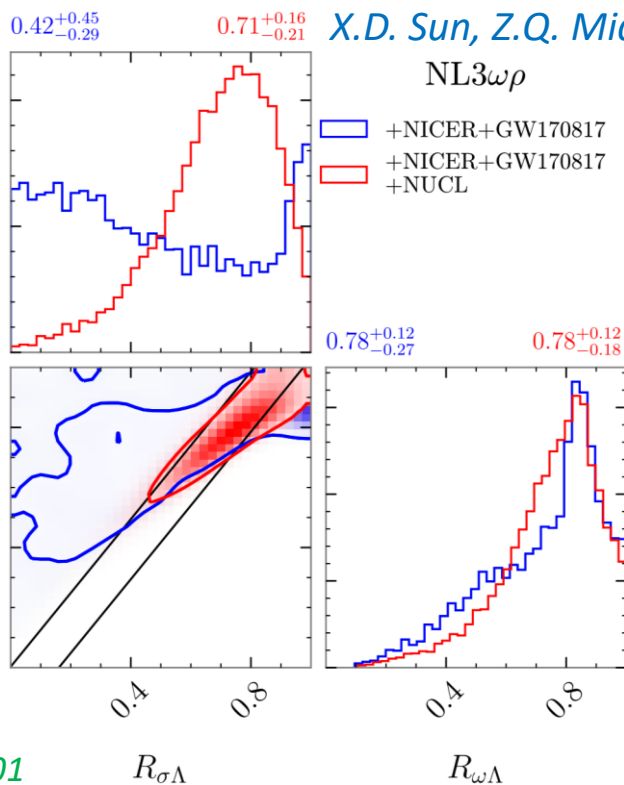


The appearance of hyperons

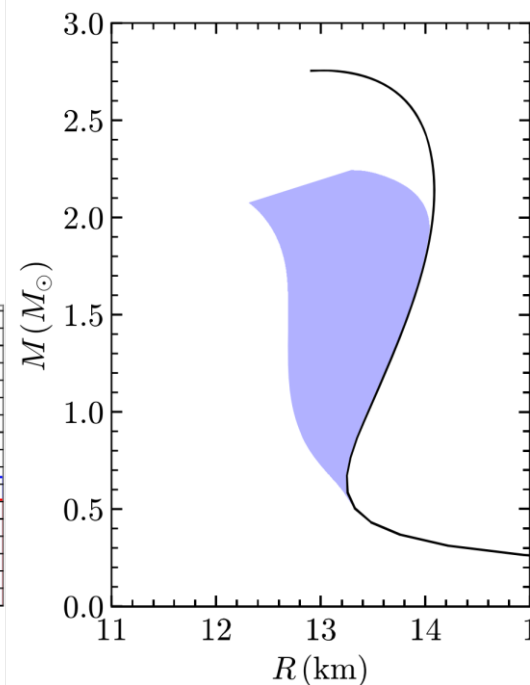
- Relieve of Fermi pressure
- Softer equation of state
- Reduction of maximal mass

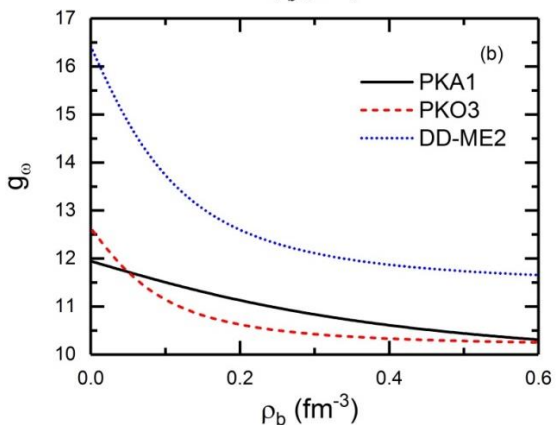
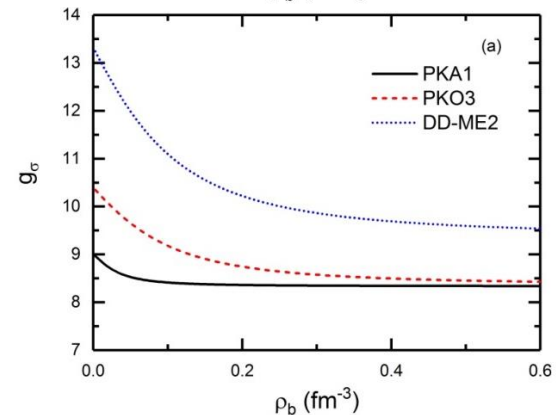
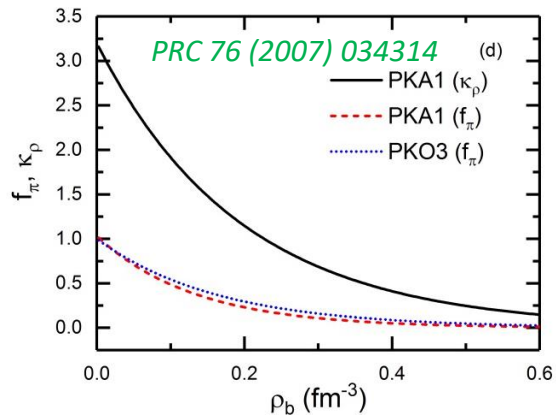


Lonardonì, Diego et al., PRL 114 (2015) 092301



X.D. Sun, Z.Q. Miao, BYS, A. Li, ApJ 942 (2023) 55





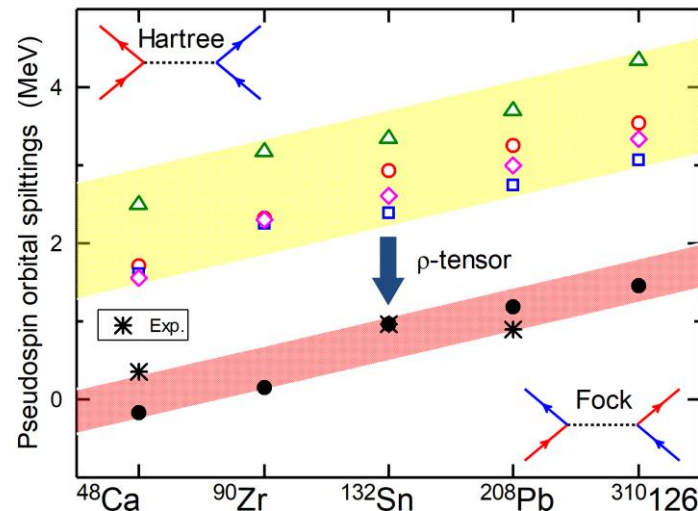
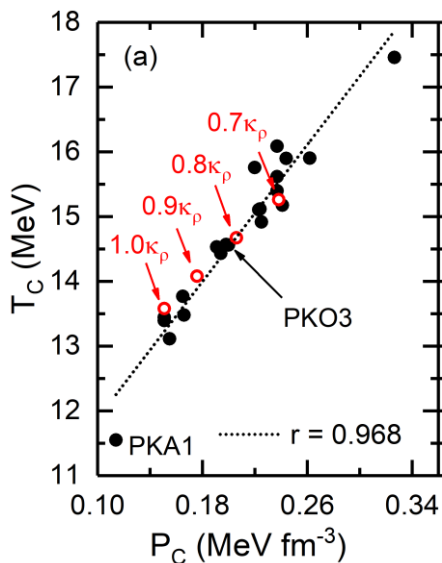
ρ 介子张量

σ 吸引与 ω 排斥关系改变

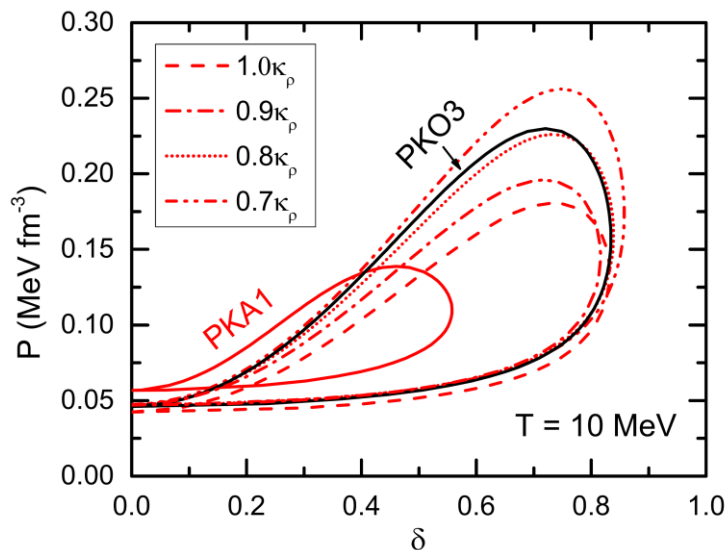
σ 与 ω 密度依赖行为改变

σ 、 ω 耦合常数恢复平行

ρ 张量强度减小为原始的x倍

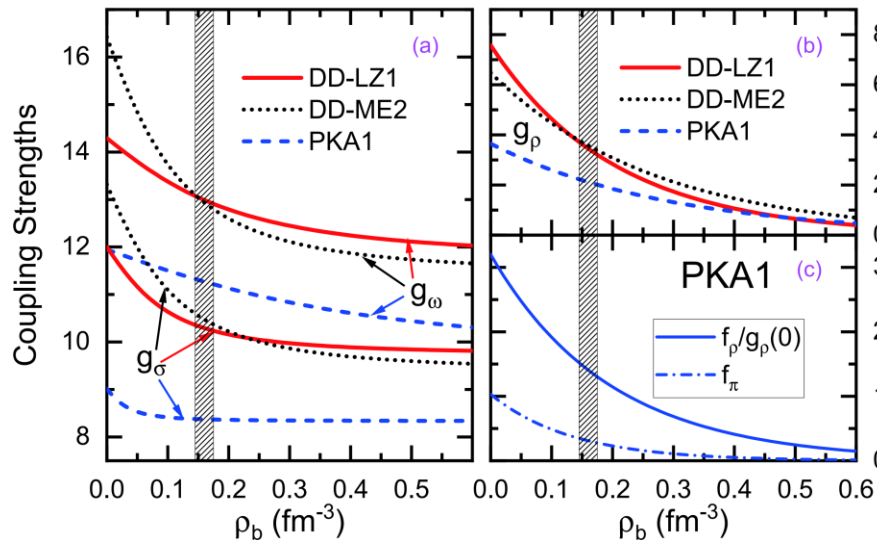


J. Geng et al., PRC 100 (2019) 051301(R)

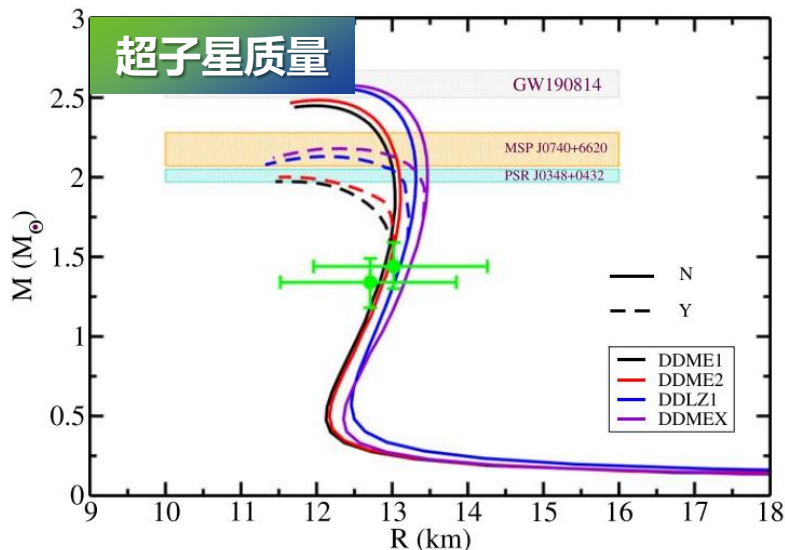


S. Yang, X. D. Sun, J. Geng, BYS, W. H. Long, Phys. Rev. C 103 (2021) 014304

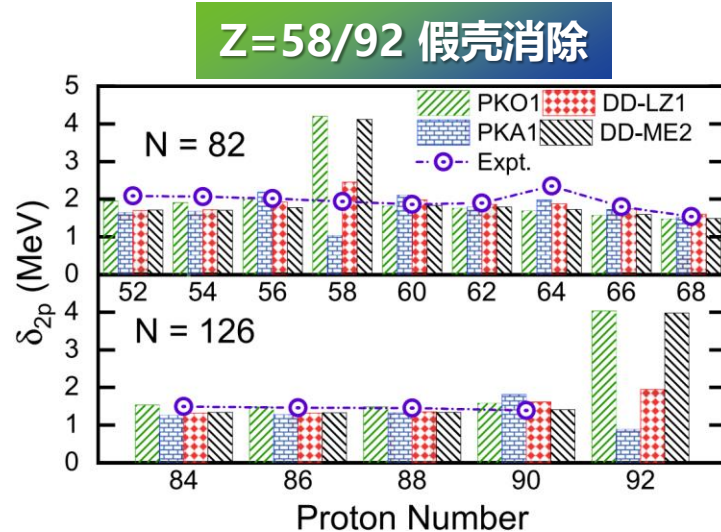
2. 新的密度依赖关系



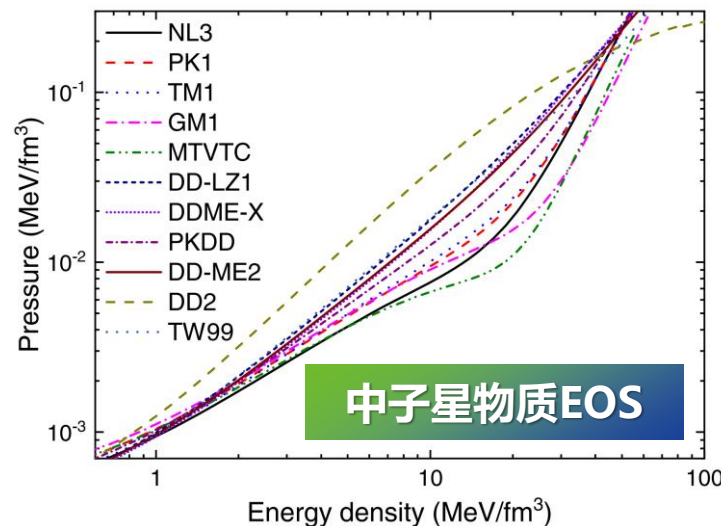
B. Wei et al., CPC 44 (2020) 074107



I. A. Rather, APJ 917 (2021) 46



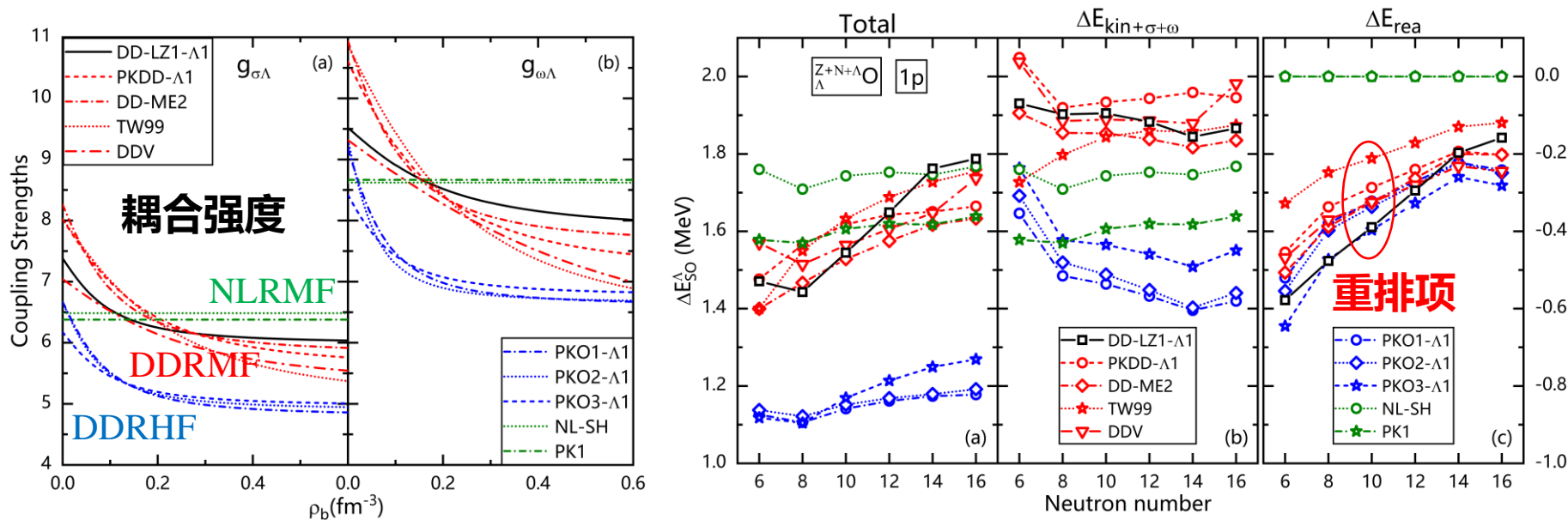
Unified nuclear matter equations of state constrained by the in-medium balance in density-dependent covariant density functionals



C.J. Xia, BYS, T. Maruyama, W.H.Long, A. Li, PRC 105 (2022) 045803

C.J. Xia, T. Maruyama, A. Li, BYS, WHL, Y.X. Zhang, CTP 74 (2022) 095303

	DD-LZ1- Λ 1	PKDD- Λ 1	DD-ME2	TW99	DDV	PKO1- Λ 1	PKO2- Λ 1	PKO3- Λ 1	NL-SH	PK1
$g_{\sigma\Lambda}/g_{\sigma N}$	0.615	0.620	0.620	0.617	0.622	0.596	0.591	0.594	0.621	0.618
Δ_1	0.319	0.363	0.245	0.375	0.473	0.265	0.260	0.407	0.916	0.519
Δ_2	1.810	0.734	0.710	0.684	3.460	0.683	0.527	0.881	1.614	1.184



- 随同位旋演化，超子环境密度改变，耦合强度变化，动能加势能总体稳定或减小
- 环境密度增大，耦合强度导数减小，重排项贡献随同位旋演化减小

S.Y. Ding, W. Yang, BYS, *Chin. Phys. C* 47 (2023) 124103

密度依赖的有效
相互作用:重排项



减小超子自旋-轨道劈裂,
增强同位旋依赖性

◆ 构建超子-核子相互作用

缺乏含粲超核实验信息，关于 $\Lambda_c N$ 有效相互作用主要通过以下方式得到

利用 SU(4) 对称性

根据已知相互作用强度推测含粲重子-核子相互作用

C. B. Dover, Phys. Rev. D 16 (1977) 3; I. Vidaña, PRC 99 (2019) 045208

Lattice QCD Simulation

$Y_c N$ interaction with different pion mass ($m_\pi \sim 410, 570, 700\text{MeV}$)

T. Miyamoto, Nucl. Phys. A 971 (2018) 113

Chiral Effective Field

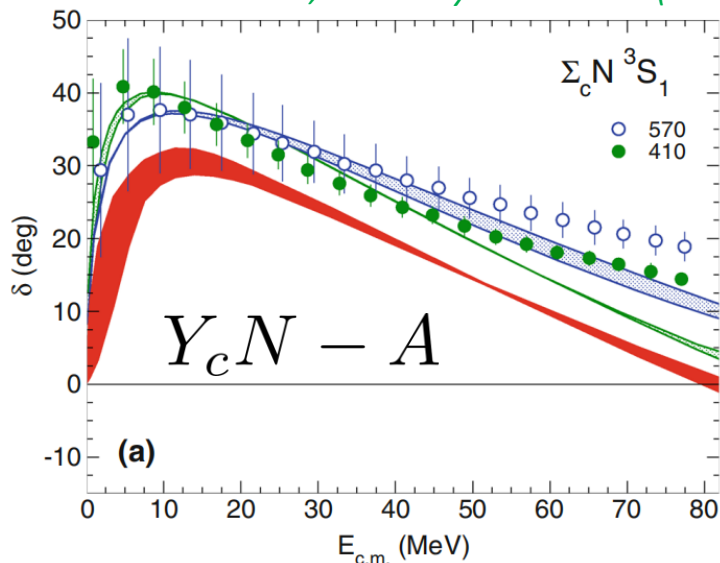
$\Sigma_c N$ coupling

$m_\pi = 138\text{MeV}$

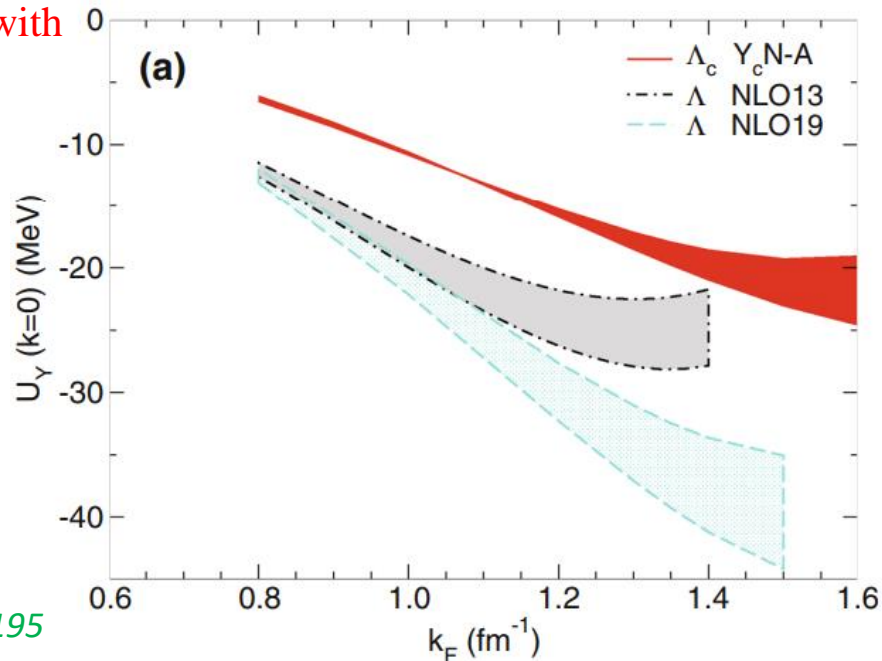
J. Haidenbauer, Euro. Phys. Jour. A 54 (2018) 199

J. Haidenbauer, Euro. Phys. Jour. A 56 (2020) 195

without
with



J. Haidenbauer, A. Nogga, et al., Euro. Phys. Jour. A 56 (2020) 195



◆ 含粲超核结构模型

➤ Few-body methods

H. Garcilazo, Phys. Rev. C 92 (2015) 024006, ...

➤ Perturbative many-body approach

J. Haidenbauer, Euro. Phys. Jour. A 56 (2020) 195,

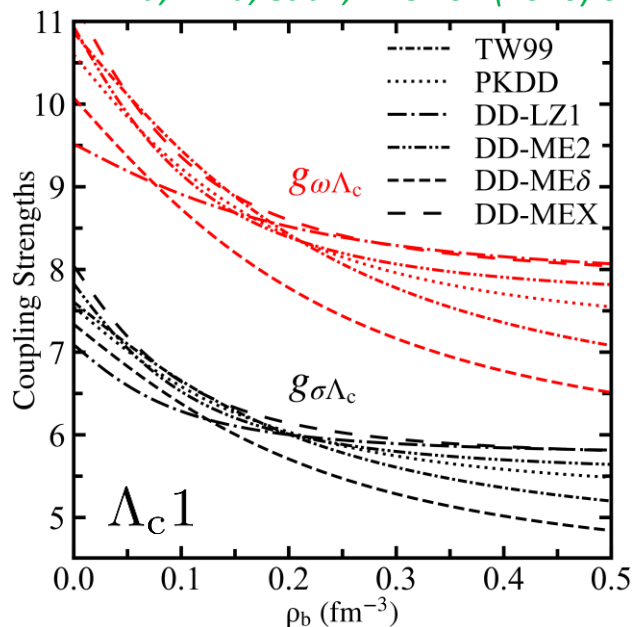
I. Vidaña, Phys. Rev. C 99 (2019) 045208, ...

➤ Density functional theory

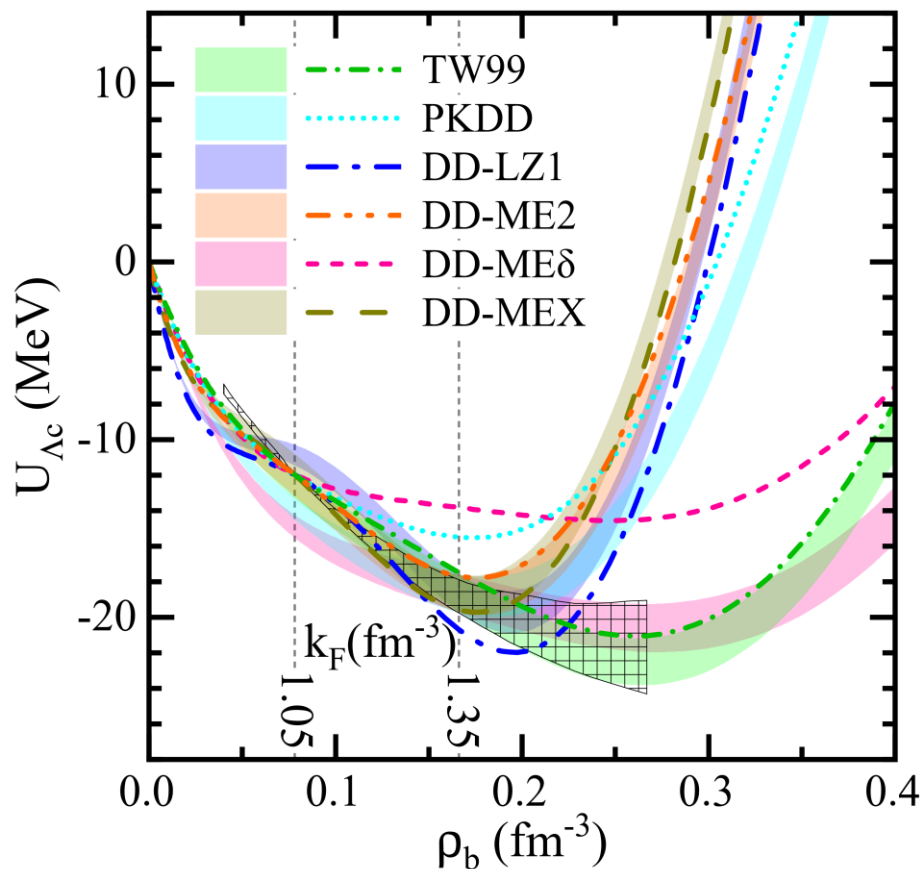
R. Shyam and K. Tsushima, PLB 770 (2017) 236

Y.-X. Liu, C. F. Chen, et al., PRC 108 (2023) 064312

L. Wu, J. Hu, et al., PRC 101 (2020) 024303



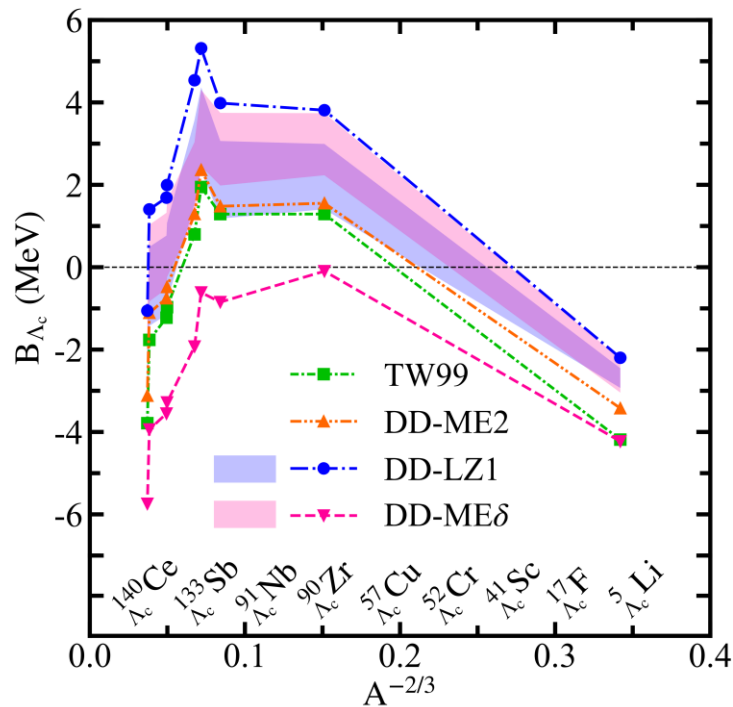
$$R_{\omega\Lambda_c} = g_{\omega\Lambda_c} / g_{\omega N} = 0.666$$



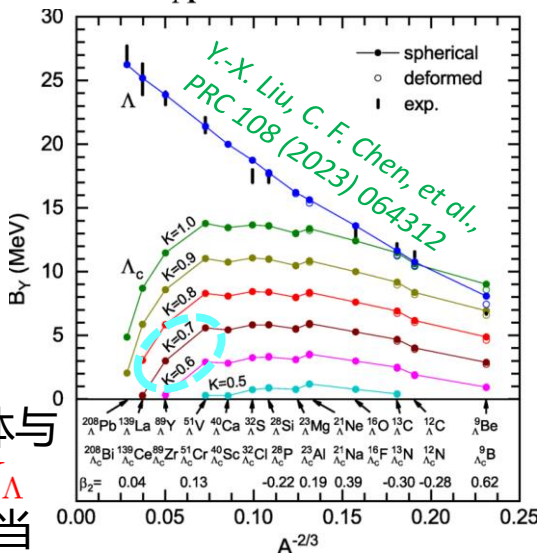
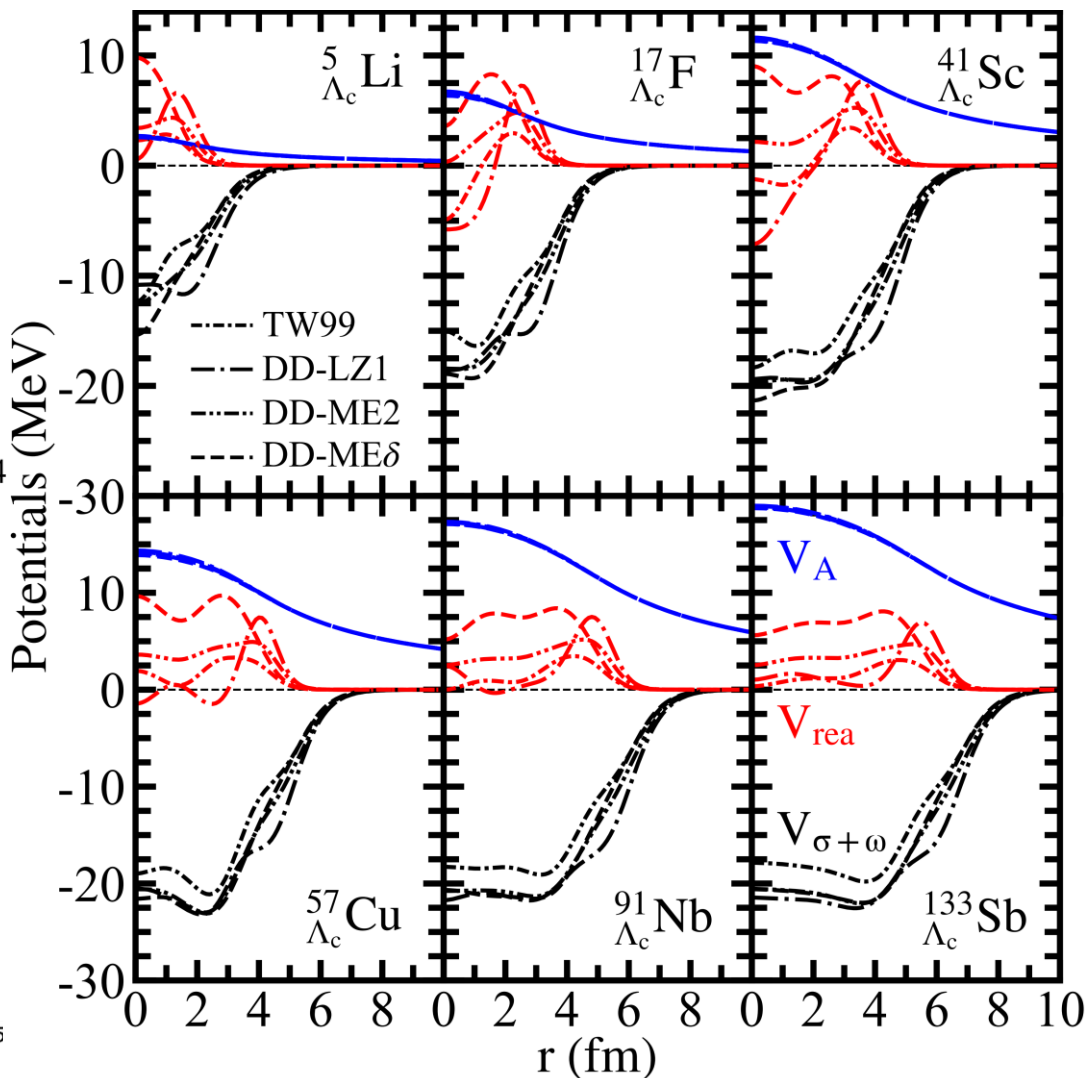
势场强度演化与耦合强度的密度依赖行为密切相关

低密度时二者斜率差距较大，势场吸引势较强；
随密度增加差距减小，势场深度增加缓慢甚至排斥

含粲超核结构的稳定性



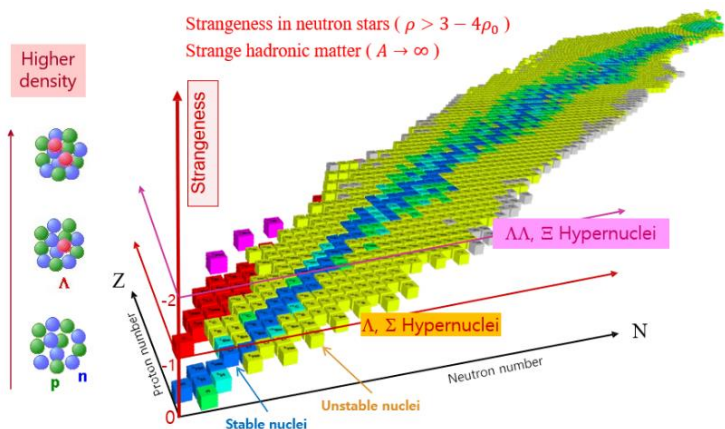
- 含粲超核额外的库仑相互作用效应
- 耦合强度的密度依赖性影响轻质量超核稳定性



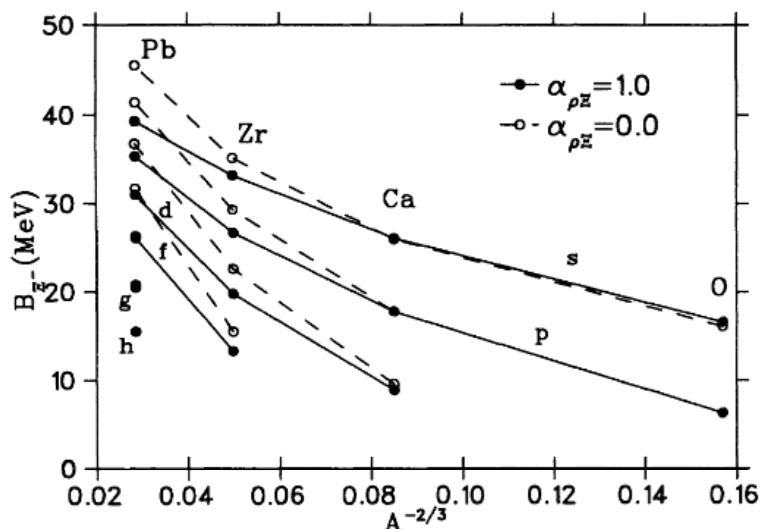
计算结果大体与
 $U_{\Lambda_c} = 0.6U_{\Lambda}$
SHF结果相当

3. 新的介子交换自由度

Ξ 超核: 相比 Λ 超核 寿命更短 反应截面更小 \rightarrow 更难产生及观测



O.Hashimoto and H.Tamura, PNP 57 (2006) 564
A. Gal et al., Rev. Mod. Phys. 88 (2016) 035004



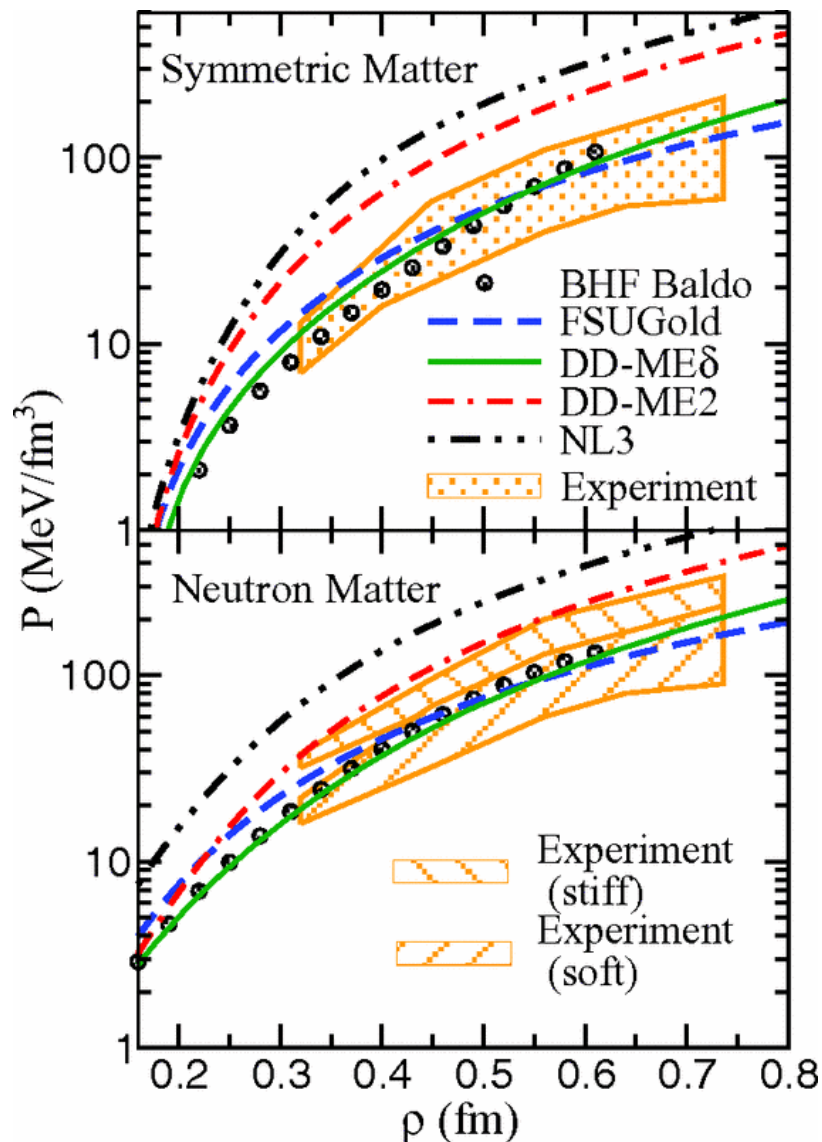
J. Mareš, B. K. Jennings, PRC 49 (1994) 2472

Experiment	Event	Target	Decay mode	B_{Ξ^-} (MeV)
BNL-E885		^{12}C	$^{12}_{\Xi^-}\text{Be} + K^+$	$4.50(V_{WS} = -14)$
J-PARC-E05		^{12}C	$^{12}_{\Xi^-}\text{Be} + K^+$	6.30
		^{12}C	$^{12}_{\Xi^-}\text{Be} + K^+$	9.00(2.00)
KEK E176	10-09-06	^{12}C	$^9_{\Lambda}\text{Be} + ^4_{\Lambda}\text{H}$	0.82 ± 0.17
KEK E176	13-11-14	^{12}C	$^9_{\Lambda}\text{Be}^* + ^4_{\Lambda}\text{H}$	0.82 ± 0.14
KEK E373	T2 KISO	^{14}N	$^{10}_{\Lambda}\text{Be} + ^5_{\Lambda}\text{He}$	3.87 ± 0.21
		^{14}N	$^{10}_{\Lambda}\text{Be}^* + ^5_{\Lambda}\text{He}$	1.03 ± 0.18
J-PARC E07	T006 IBUKI	^{14}N	$^{10}_{\Lambda}\text{Be} + ^5_{\Lambda}\text{He}$	1.27 ± 0.21 (1.13 ± 0.14)
KEK E373	T3 KINKA	^{14}N	$^9_{\Lambda}\text{Be} + ^5_{\Lambda}\text{He} + n$	8.00 ± 0.77
		^{14}N	$^9_{\Lambda}\text{Be}^* + ^5_{\Lambda}\text{He} + n$	4.96 ± 0.77
J-PARC E07	T010 IRRAWADDY	^{14}N	$^5_{\Lambda}\text{He} + ^5_{\Lambda}\text{He} + ^4\text{He} + n$	6.27 ± 0.27

S. H. Hayakawa et al., PRL 126 (2021) 062501 M. Yoshimoto et al., PTEP 2021 (2021) 073D02

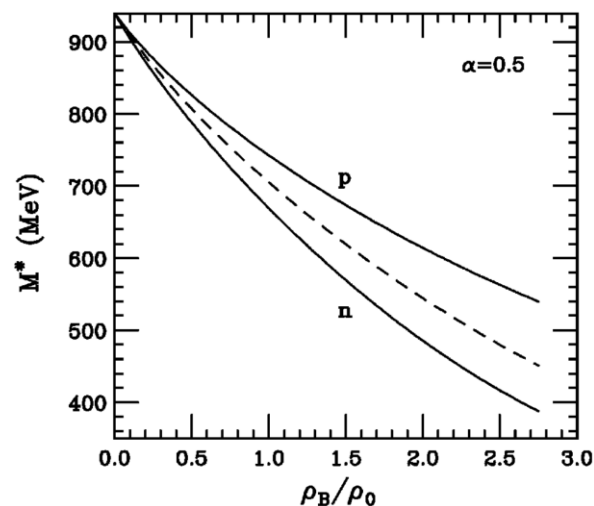
	$^{15}_{\Xi^-s}\text{C}$	$^{15}_{\Xi^-p}\text{C}$	$^{13}_{\Xi^-s}\text{B}$	$^{12}_{\Xi^-s}\text{Be}$
PK1	8.000	0.951	7.481	4.843
TW99	8.000	0.576	7.074	4.422
PKDD	8.000	0.776	7.154	4.501
DD-ME2	8.000	0.733	7.390	4.718
DD-MEX	8.000	0.478	7.577	4.610
DD-LZ1	8.000	0.068	8.953	5.622
	8.00 ± 0.77	1.13 ± 0.14		4.50
Expt. or empirical data				6.30
				9.00(2.00)

同位旋标量道动力学平衡效应



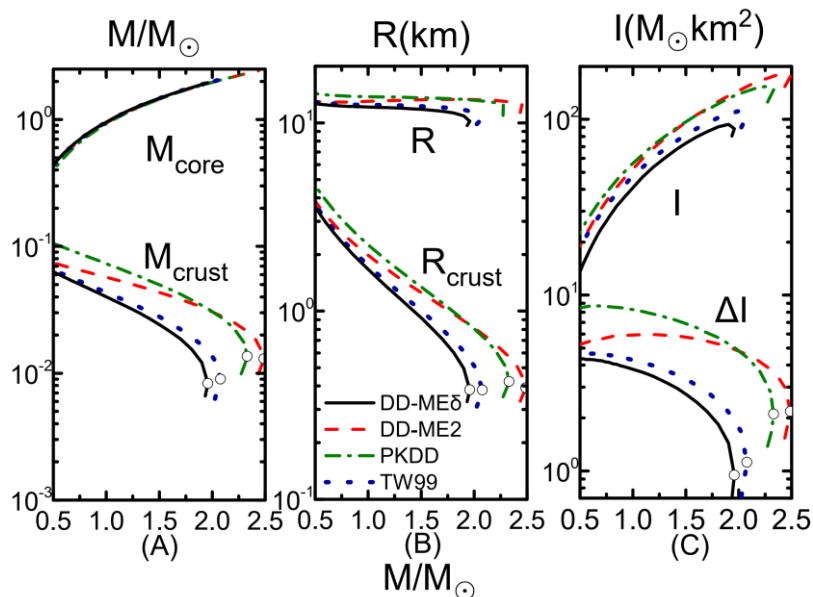
X. Roca-Maza et al, *Phys. Rev. C* 84 (2011) 054309

◆ 影响同位旋相关性质
◆ 产生新的动力学平衡



核子有效质量劈裂
(高密显著)

B. Liu et al, *PRC* 65 (2002) 045201

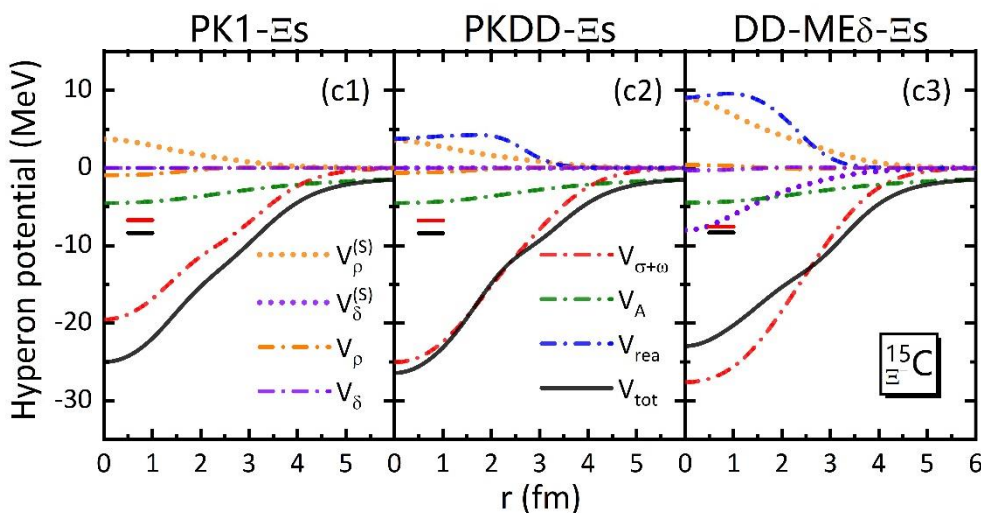
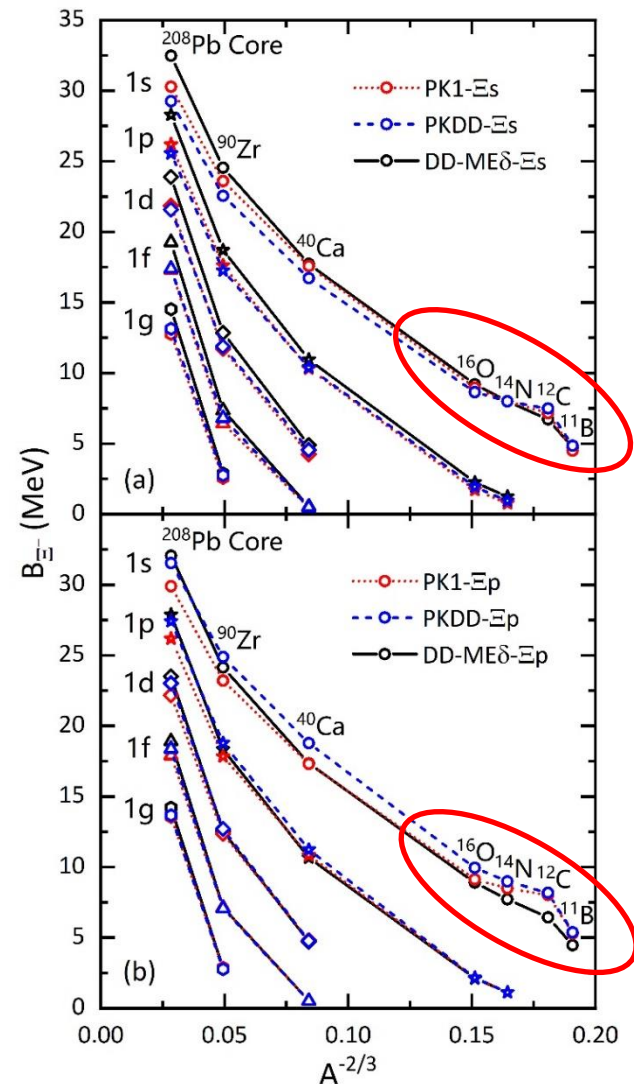


Z. Qian, R. Y. Xing and BYS, *Sci. Chin. PMA* 61 (2018) 082011

对 Ξ 超核结构的影响

RMF-Ξ_s	$^{15}_{\Xi-s}\text{C}$	$^{15}_{\Xi-p}\text{C}$	$^{13}_{\Xi-s}\text{B}$	$^{12}_{\Xi-s}\text{Be}$
PK1	8.000	0.951	7.481	4.843
PKDD	8.000	0.776	7.154	4.501
DD-ME δ	8.000	1.251	6.707	4.708
	8.00 ± 0.77	1.13 ± 0.14		4.50

RMF-Ξ_p	$^{15}_{\Xi-s}\text{C}$	$^{15}_{\Xi-p}\text{C}$	$^{13}_{\Xi-s}\text{B}$	$^{12}_{\Xi-s}\text{Be}$
PK1	8.495	1.130	8.025	5.301
PKDD	8.989	1.130	8.168	5.377
DD-ME δ	7.716	1.130	6.437	4.460
	8.00 ± 0.77	1.13 ± 0.14		4.50



DD-ME δ 显著的重排项贡献

- 核力具体特征依赖于核物质密度、自旋、同位旋、核子动量等，呈现出复杂的演化行为，影响不同能标、尺度下核结构相关物理。超核是包含了奇异自由度重子（超子）的核多体系统，其特性是理解重子-重子相互作用的重要途径。
- 在协变密度泛函理论中，通过在介子交换图像中采用密度依赖的耦合强度，可以有效地考虑核力的介质相关性，改善模型对一些核结构特性的描述。核介质中核子与超子道不同的动力学平衡机制，影响耦合常数取值，进而影响超核及含超子中子星性质的描述。

完整的两体相互作用

新的密度依赖关系

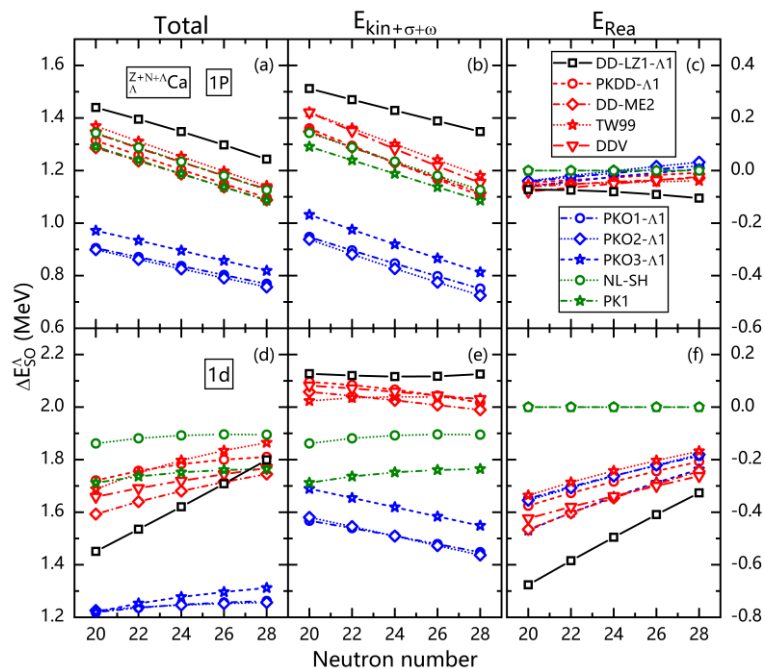
新的介子交换自由度

- 期待粒子物理与原子核物理同行更密切的合作

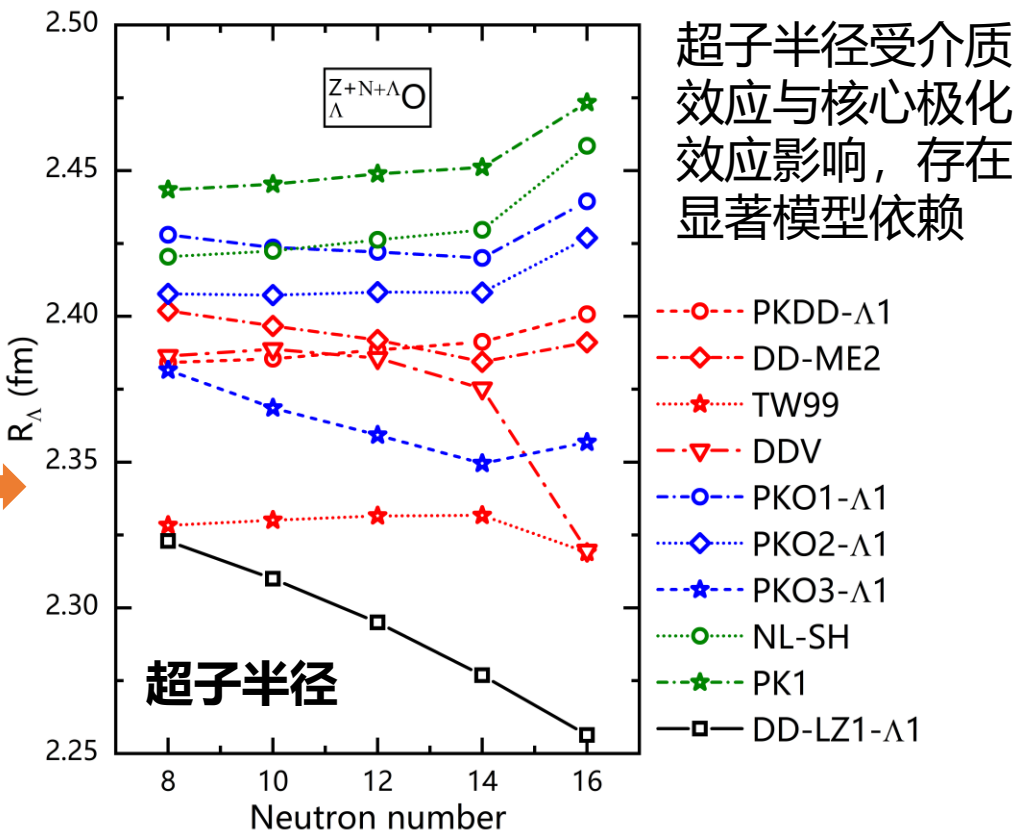
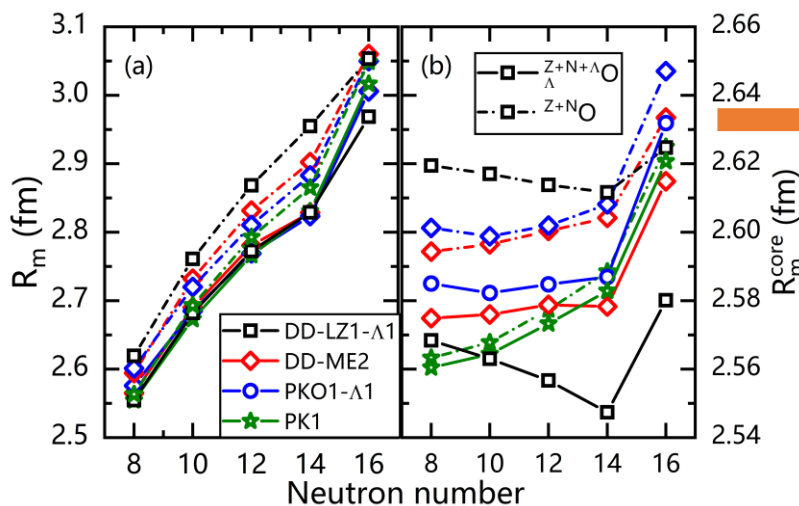
《粲重子衰变与相互作用机制研究》

- 期望推进HIAF高能实验站（超核研究装置）未来建设



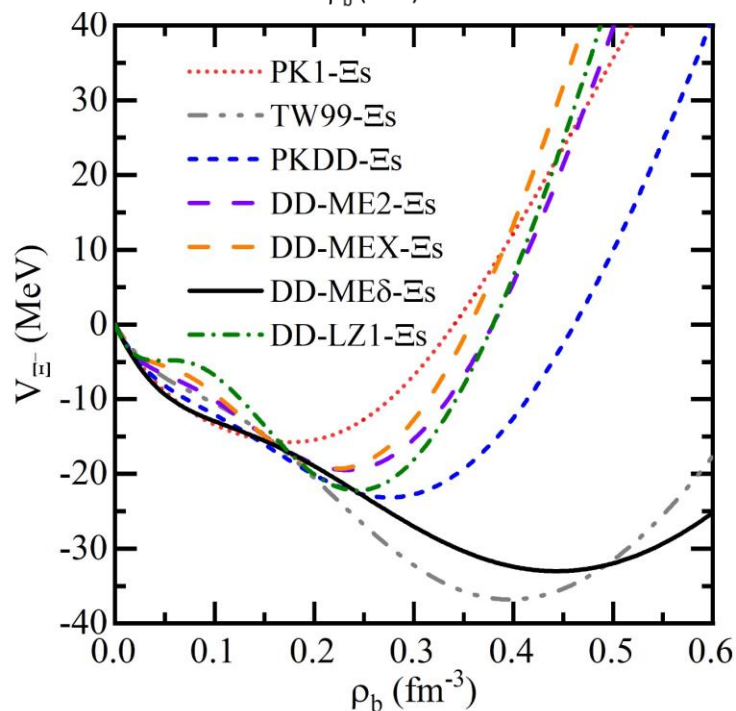
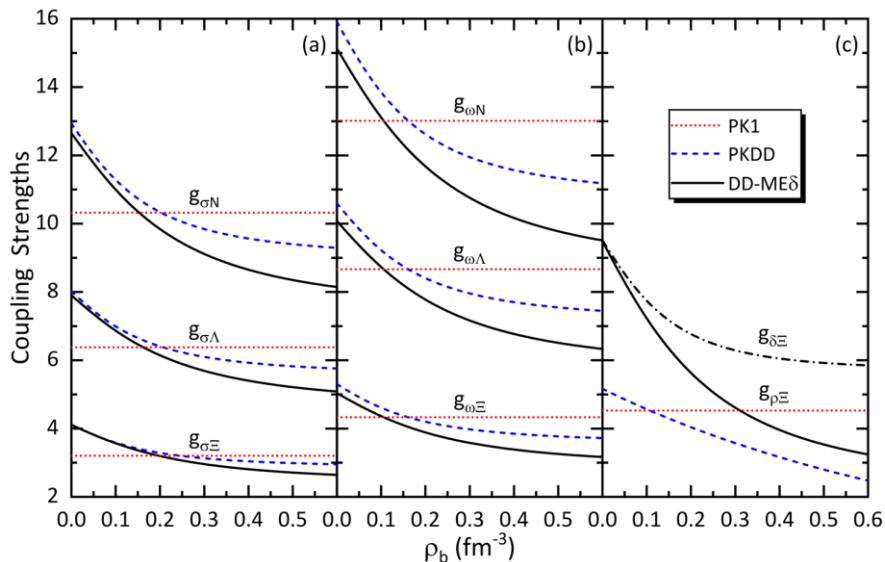


- 超子 $1p$ 态为**深束缚态**，重排项不敏感依赖于密度，耦合强度导数较小，重排项随同位旋演化变动不大
- 超子 $1d$ 态为**浅束缚态**，耦合强度敏感依赖于密度，耦合强度导数较大，重排项随同位旋演化急剧减小

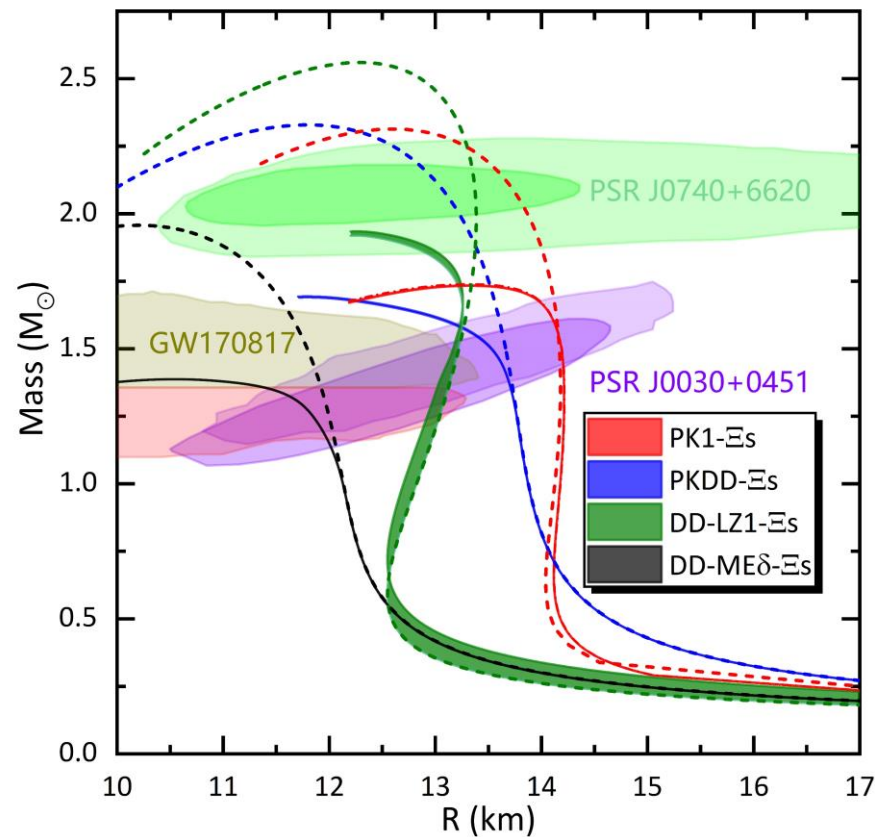
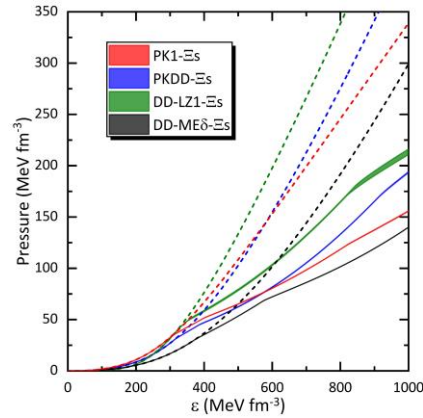


超子半径受介质效应与核心极化效应影响，存在显著模型依赖

ΞN 耦合强度的密度依赖性



- ΛN 耦合强度:
 $U_{\Lambda} \approx -30 \text{ MeV}$
- ΞN 耦合强度:
RMF- Ξs
- ΣN 耦合强度:
 $U_{\Sigma} = +30 \text{ MeV}$



超核光谱学实验

O.Hashimoto and H.Tamura, PPNP 57 (2006) 564

A. Gal et al., Rev. Mod. Phys. 88 (2016) 035004

Feliciello, A, Nagae, T, Rep. Prog. Phys. 78 (2015) 096301

➤ 高分辨率 γ 射线光谱实验 (H. Tamura 及其合作组)

PRC 40 (1989) R479; PRL 84 (2000) 5963;

NPA 754 (2005) 58c; NPA 914 (2013) 99; PRL 115 (2015) 222501

➤ 乳胶实验 (K. Nakazawa 及其合作组)

NPA 835 (2010) 207; PRL 126 (2021) 062501;

PTEP 2015 (2015) 033D02; PTEP 2021 (2021) 073D02

