北京大学物理学院
School of Physics, Peking University

Furong Xu (许甫荣)

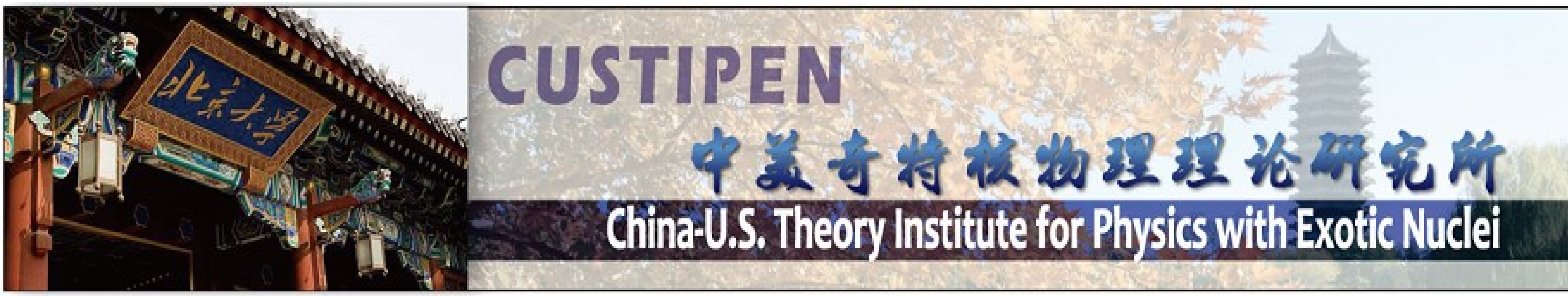
(I) Nuclear theoretical researches in China (incompletely)

(II) Nuclear education in China (incompletely)

(III) Resonance and continuum in atomic nuclei

-- Core Gamow shell model with realistic nuclear forces --

ANPhA symposium (Nov. 23-25, 2016, Sendai Japan)



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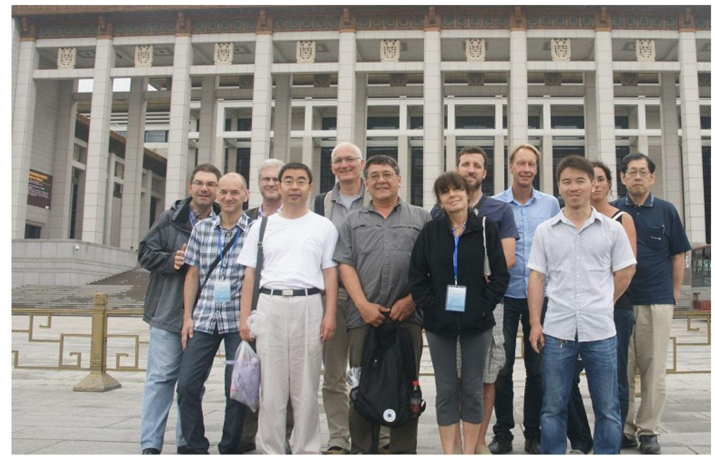
The 2nd CUSTIPEN Workshop, PKU,2013.12


PKU-CUSTIPEN Nuclear Reaction Conference
Peking University, August 10-14, 2014


PKU-CUSTIPEN Nuclear Reaction Conference, PKU, 2014.8



Nuclear theory researches in China

In Beijing

PKU (structure)

Ab initio **(MBPT, GSM, BHF, SM): excited-state spectra, binding energies …**

DFT (relativistic and non-relativistic): halo, rotations …

ITP–CAS (structure)

DFT (relativistic): halo, fission, superheavy …

BNU (structure and reaction)

Transport model: superheavy, heavy ion collision

CIAE (structure and reaction)

DFT (relativistic), PSM, QMD: structure, rotations, heavy ion collision

Beihang (structure and reaction)

Reaction models, DFT, nuclear forces

……

In other cities

Nanjing

Clustering

Nuclear symmetry energy

SJU

Algebra model, masses…

PSM, rotations…

Symmetry energy, heavy ion collision

SIAP-CAS

Heavy ion collision, clustering

IMP-CAS

Nuclear matter…

Huzhou

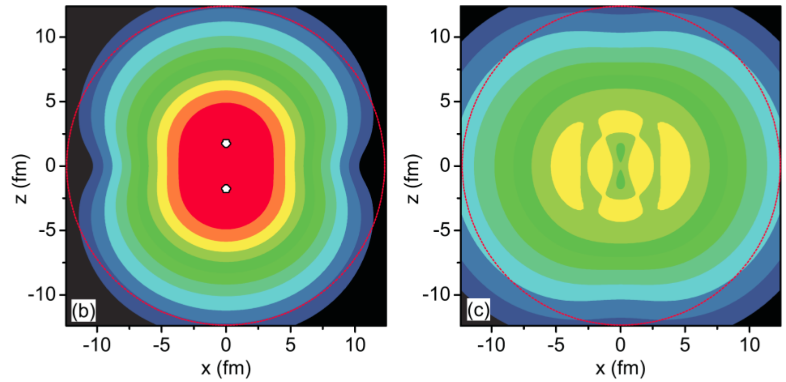
Structure, rotations, QMD heavy ion collision …

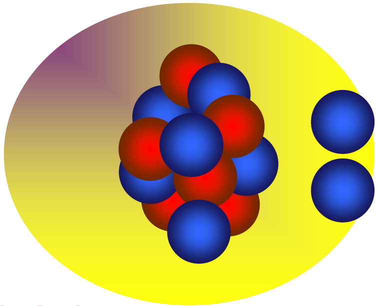
Some other theory groups in China

Some examples in theoretical researches in China

Relativistic HB model

^{44}Mg: Prolate Core + Oblate Halo

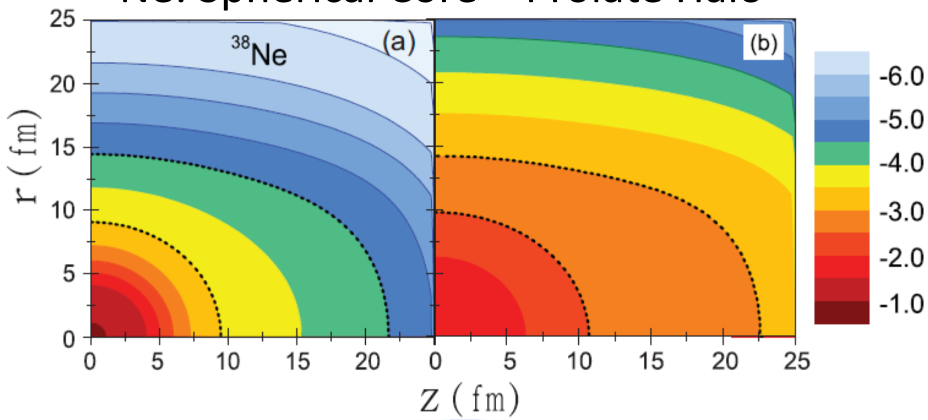


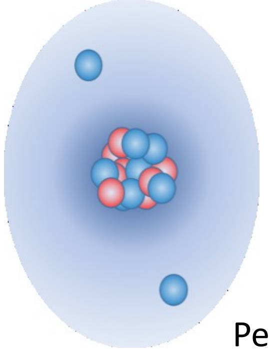


SGZ+2010
PRC82-011301R
Li+2012_PRC85-024312

Skyrme HFB model

^{38}Ne: Spherical Core + Prolate Halo





Pei_Zhang_Xu2013
PRC87-051302R
Pei+2014_PRC90-024317

Shape Decoupling in Deformed Halo Nuclei

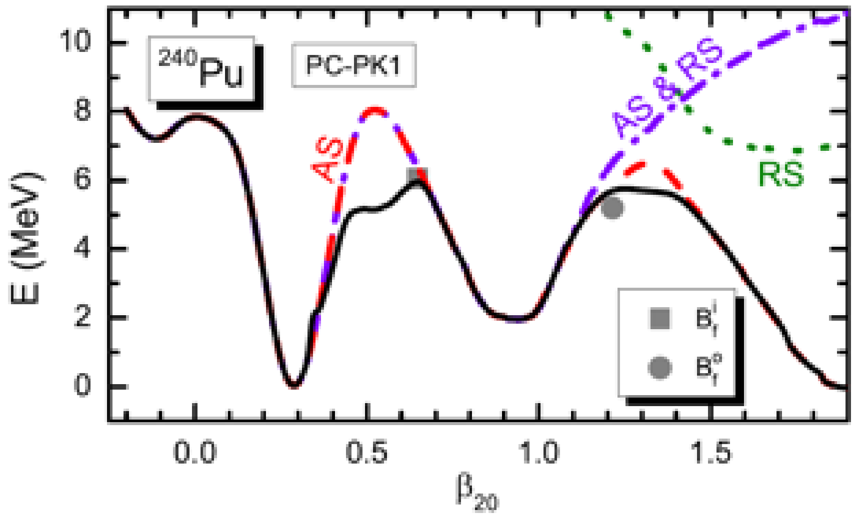
Nuclear shape & fission barrier from MDC-CDFT

A multidimensionally-constrained covariant density functional theory (MDC-CDFT) was developed

- Including all shape degrees of freedom $\beta_{\lambda\mu}$ with even μ, e.g., β_{20}, β_{22}, β_{30}, β_{32}, β_{40}, β_{42}, β_{44}, …
- Used to study fission barriers & exotic shapes, e.g., β_{32} (tetrahedral) shape

Example: Lowering effect of triaxiality (β_{22} or γ) on the 2nd fission barrier of actinides

Lu_Zhao_Zhou2011_PRC84-014328
Lu_Zhao_Zhou2012_PRC85-011301R
Zhao_Lu_Zhao_Zhou2012_PRC86-057304
Lu_Zhao_Zhao_Zhou2012_PRC85-024312
Lu_Zhao_Zhao_Zhou2014_PRC89-014323
Lu_Hiyama_Sagawa_Zhou2014_PRC89-044307
Zhao_Lu_Vretenar_Zhao_Zhou2015_PRC91-014321
Zhao_Lu_Niksic_Vretenar_Zhou2016_PRC93-044315
Zhou2016_PhysScr91-063008(Review)
……

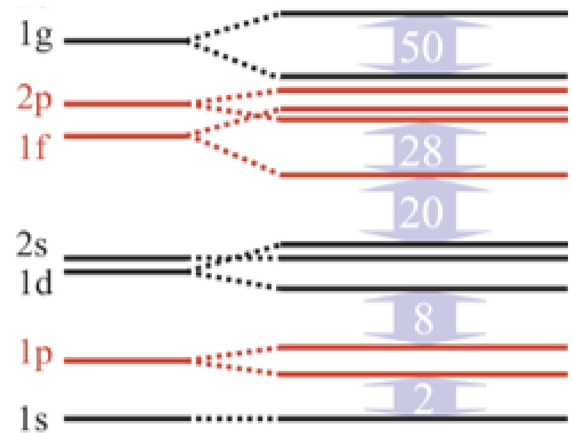


Relativistic Hartree(-Fock)-Bogoliubov models

	Spherical Nuclei	Deformed Nuclei
Box Boundary	Meng_Ring1996_PRL77-3963 Meng1998_NPA635-3 Poschl+1997_PRL79-3841 Long+2010_PRC81-024308	SGZ+2010_PRC82-011301R Li+2012_PRC85-024312 Li+2012_ChinPhysLett29-042101 Chen+2012_PRC85-067301

^{31}Ne

- Spherical models
  - Ren et al.: DDRMF Ren_Chen_Ma_Xu2001_CTP35-717
  - Zhang et al.: RMF+ACCC+BCS
    Zhang_Smith_Kang_Zhao2014_PLB730-30
- Deformed models
  - Qiu & Zhou: deformed Skyrme HF+BCS, tensor
    Qiu_Zhou2014_CTP61-101
- Experiment
  - Nakamura et al.: Deformation-driven p-wave halos at the drip-line: ^{31}Ne
    Nakamura … 2014_PRL112-142501



Liang_Meng_SGZ2015PhysRep

Clustering in nuclei

PRL **110,** 262501 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Zhou+2013_PRL111-103604

Nonlocalized Clustering: A New Concept in Nuclear Cluster Structure Physics

Bo Zhou,[1,2,3,*] Y. Funaki,[3,†] H. Horiuchi,[2,4] Zhongzhou Ren,[1,5,‡] G. Röpke,[6] P. Schuck,[7,8] A. Tohsaki,[2] Chang Xu,[1] and T. Yamada[9]

Cluster model
Container picture

PRL **113,** 032506 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

He2014_PRL113-032506

Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

W. B. He (何万兵),[1,2] Y. G. Ma (马余刚),[1,3,*] X. G. Cao (曹喜光),[1,†] X. Z. Cai (蔡翔舟),[1] and G. Q. Zhang (张国强)[1]

QMD model
GDR connected
to clusterring

PRL **115,** 022501 (2015) PHYSICAL REVIEW LETTERS week ending 10 JULY 2015

Zhao_Itagaki_Meng2015
PRL115-022501

Rod-shaped Nuclei at Extreme Spin and Isospin

P. W. Zhao (赵鹏巍),[1,2,3] N. Itagaki (板垣直之),[1] and J. Meng (孟杰)[3,4,5,*]

Cranking RMF model
Clustering at extreme
spin & isospin

(II) Nuclear Science Education in China

Recent History:

- In 1990s, we had hard time for nuclear science (not only nuclear physic) : less funding, less students…
- Many departments of nuclear physics were closed down
- Nuclear physics was no longer a major for undergraduate programs (NOT allowed to recruit new undergraduates!)

➢ Beginning from 2002, we started struggling, argued, discussed…
➢ Air pollution became more serious, and nuclear power stations become important in China.
➢ This is the big point with that we talked to Education Ministry.
➢ Many activities for nuclear science future…

Steering committee for high education in nuclear engineering and technology, Ministry of Education of China

核工程与核技术专业教学指导委员会

姓名	学校	任职
康克军	清华大学 副校长	主任
许甫荣	北京大学 系主任	副主任
张福宝	国防科工委 司长	副主任
张建民	西安交大 系主任	副主任
程建平	清华大学 常务副校长	秘书长

核科学与技术人才培养的紧迫性

到2020年需要本科以上专业人才情况是:

- 核工程6600人（核反应堆工程2600人）
- 放射化工工艺与放射化学2600人
- 核燃料工程1500人
- 核技术应用及基础学科5000人（核技术应用2400人）
- 辐射防护与环境保护1300人
- 核物理等基础学科1300人
- 核地质与铀矿冶1300人

Nuclear physics is the basic major for whole nuclear science and engineering

由于实际输送到核科技工业系统就业的学生远低于核专业毕业生数，对某些专业方向尤其如此；根据目前发展形势，到2020年需要培养核专业人才要比上述预测数字还要大，因此，核工业面临艰巨的人才培养任务

Situation started changing around 2005 !

普通高等学校本科专业目录

（2013年教育部公布）

0702	物理学类	0702	物理学类
070201	物理学	070201	物理学
070202	应用物理学	070202	应用物理学
070203	核物理	070204S	核物理

Year 2013

Year 2006

2007年全国核专业本科招生规模

清华大学	工程物理	90	成都理工大学	辐射防护与环境工程	30
清华大学	核工程与核技术	60	东华理工学院	辐射防护与环境工程	40
西安交通大学	核工程与核技术	65	兰州大学	辐射防护与环境工程	32
上海交通大学	核工程与核技术	75	西南科技大学	辐射防护与环境工程	70
哈尔滨工程大学	核工程与核技术	250	南华大学	核反应堆工程	40
成都理工大学	核工程与核技术	60	东华理工学院	核化工与核燃料工程	40
东华理工学院	核工程与核技术	60	兰州大学	核化工与核燃料工程	25
华北电力大学	核工程与核技术	60	南华大学	核化工与核燃料工程	45
南华大学	核工程与核技术	130	东华理工学院	核技术	40
南华大学	核工程与核技术（核防护方向）	45	兰州大学	核技术	30
沈阳工程学院	核工程与核技术	35	南华大学	核技术	45
四川大学	核工程与核技术	60	南华大学	核物理	30
西南科技大学	核工程与核技术	80	四川大学	核物理	40
重庆大学	核工程与核技术	30		合计	1607

Up to date: more than 50 new schools of nuclear science and technology, established in China…

目前设有核专业的高校（不完全统计）

北京大学	清华大学	东华理工学院	黑龙江大学
中国科技大学	北京师范大学	沈阳工学院	上海大学
西安交通大学	郑州大学	武汉大学	华北电力大学
上海交通大学	东北师范大学	南京大学	西南大学
哈尔滨工程大学	兰州大学	南华大学	西南科技大学
浙江大学	南京航天航空大学	成都理工大学	重庆大学
四川大学	新疆大学	吉林大学	天津大学

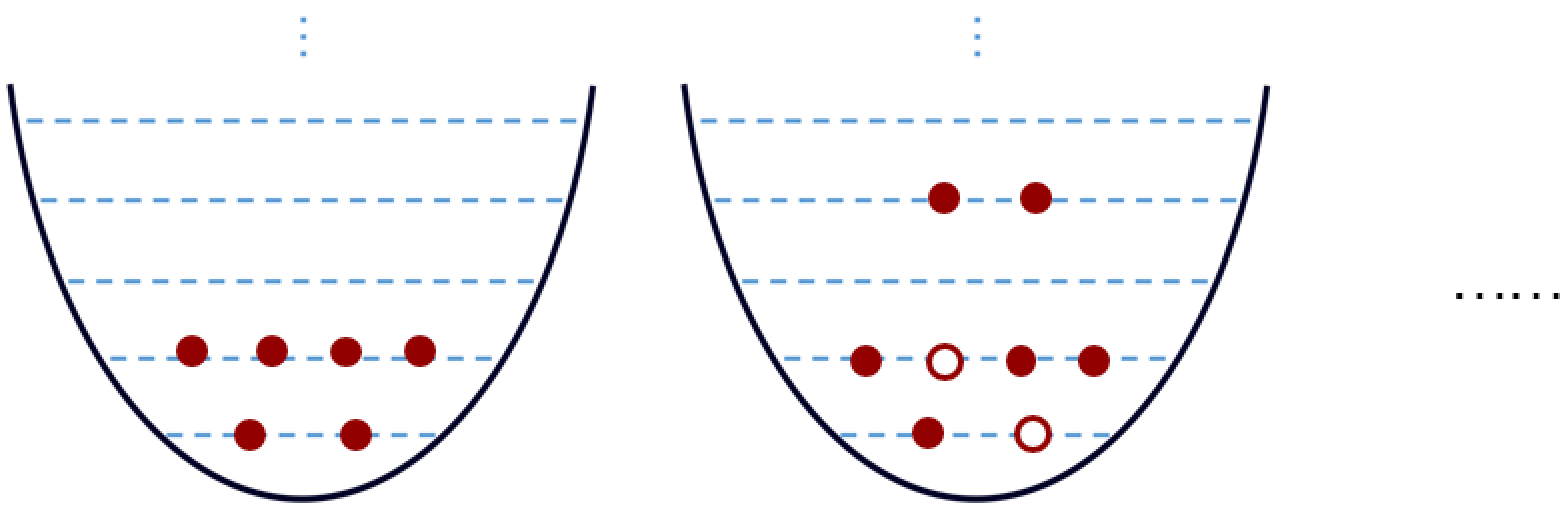
(III) Our group's works on :
Resonances and continua in atomic nuclei

Two most fundamental problems in nuclear structure calculations

1. Nuclear Force ?

Realistic *NN* forces *vs* phenomenological potentials

2. Many-Body Problems (Correlations)



HF **_ph_ excitations beyond mean field (HF)**

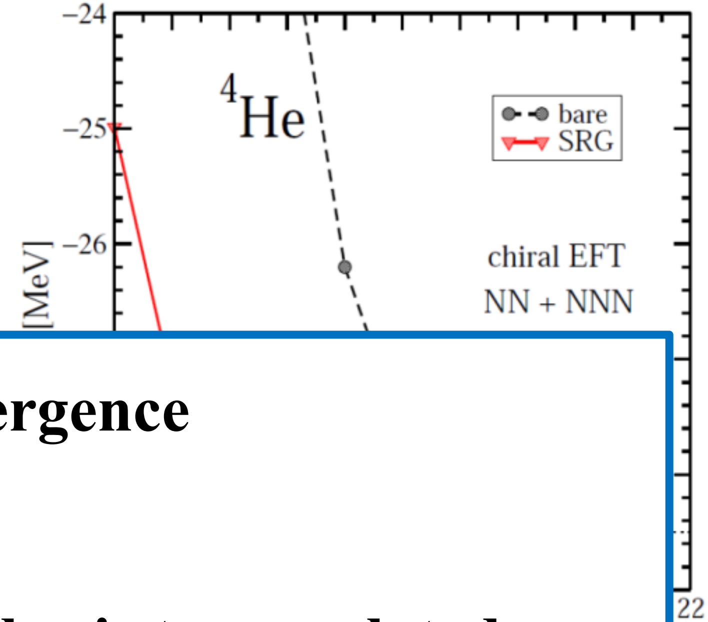
Our HF-MBPT calculations for binding energies with N^3LO + SRG

^{4}He	SRG flow parameter λ (fm^{-1})			
	1.5	2.0	2.5	3.0
Expt. [60]	-28.296	-28.296	-28.296	-28.296
NCSM [61]	-28.20	-28.41	-27.43	-26.80
SHF	-25.754	-21.864	-15.854	-10.278
PT2	-1.788	-5.088	-9.652	-13.783
PT3	-0.391	-0.899	-1.523	-1.953
SHF+PT2+PT3	-27.933	-27.850	-27.029	-26.013

^{16}O	SRG flow parameter λ (fm^{-1})			
	1.5	2.0	2.5	3.0
Expt. [60]	-127.619	-127.619	-127.619	-127.619
SHF	-169.968	-133.169	-85.173	-44.102
PT2	-10.132	-29.497	-59.617	-88.326
PT3	-0.794	-1.931	-4.630	-7.339
SHF+PT2+PT3	-180.893	-164.597	-149.419	-139.767

N_{shell}=13, $\hbar\Omega$=35 MeV

Q: **Realistic bare forces + advanced many-**

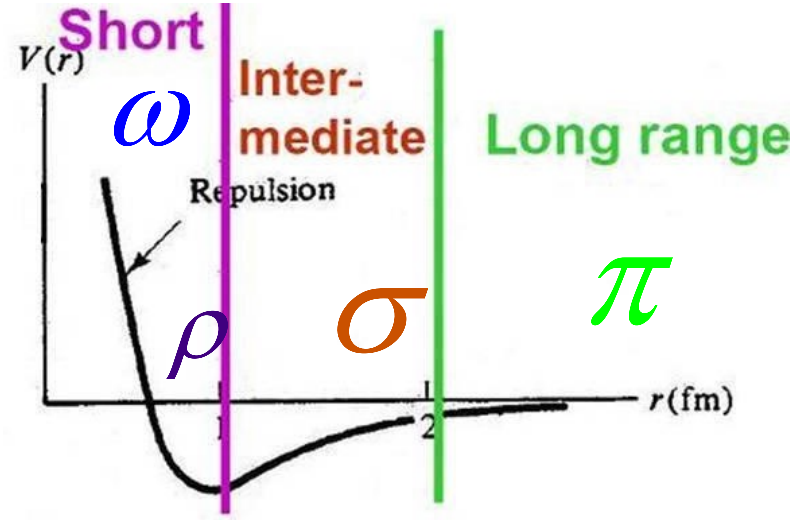


A: **Yes !** **BUT the convergence is slow !**

- **An intermediate step to speed up convergence**
- **Renormalization of bare forces**
- **Transfer bare force from uncorrelated basis to correlated basis**
- **Renormalized interaction includes already some many-body correlations, e.g., induced-3NFs**

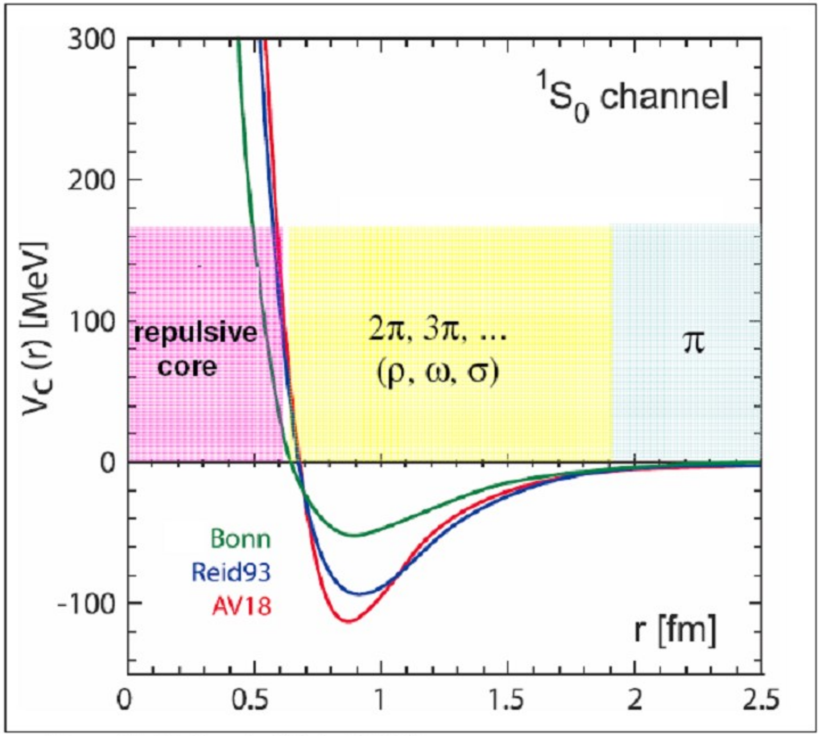
G-matrix, $V_{low\text{-}k}$, LS, UCOM, SRG

✓ **Realistic forces + renormalization + many-body correlations**



One-Boson exchange potential

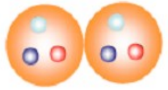
QCD-based Chiral EFT



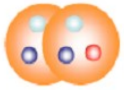
From T. Hatsuda (Oslo 2008)

One-pion exchange
by Yukawa (1935)

Multi-pions
by Taketani (1951)



Repulsive core
by Jastrow (1951)



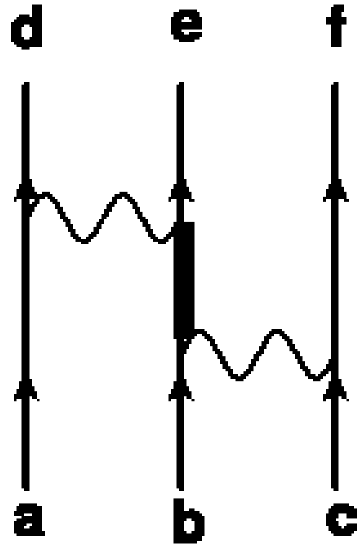
Renormalization: uncorrelated basis → correlated basis

Unitary transformation:

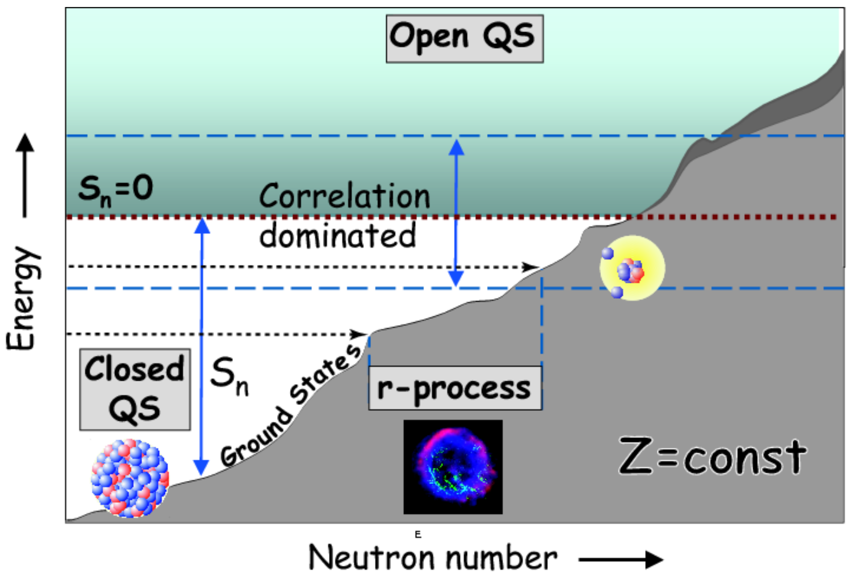
$$\widetilde{A} = C^{\dagger} A C = \widetilde{A}^{[1]} + \widetilde{A}^{[2]} + \widetilde{A}^{[3]} + \cdots$$

Induced many-body correlations (forces)

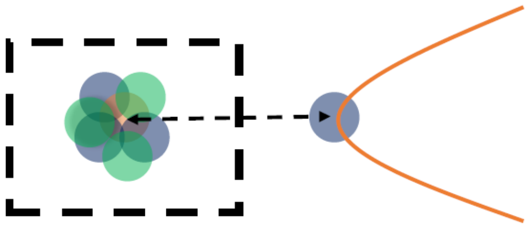
e.g., induced-3NFs



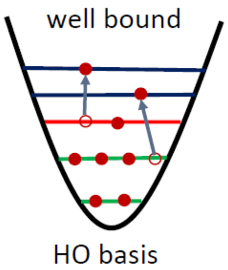
Core Gamow Shell Model with realistic nuclear forces

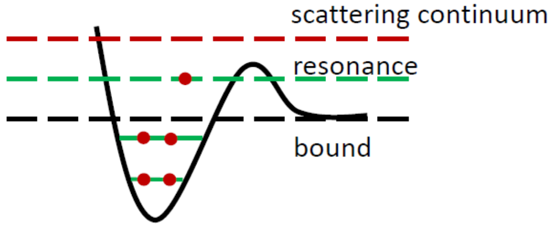


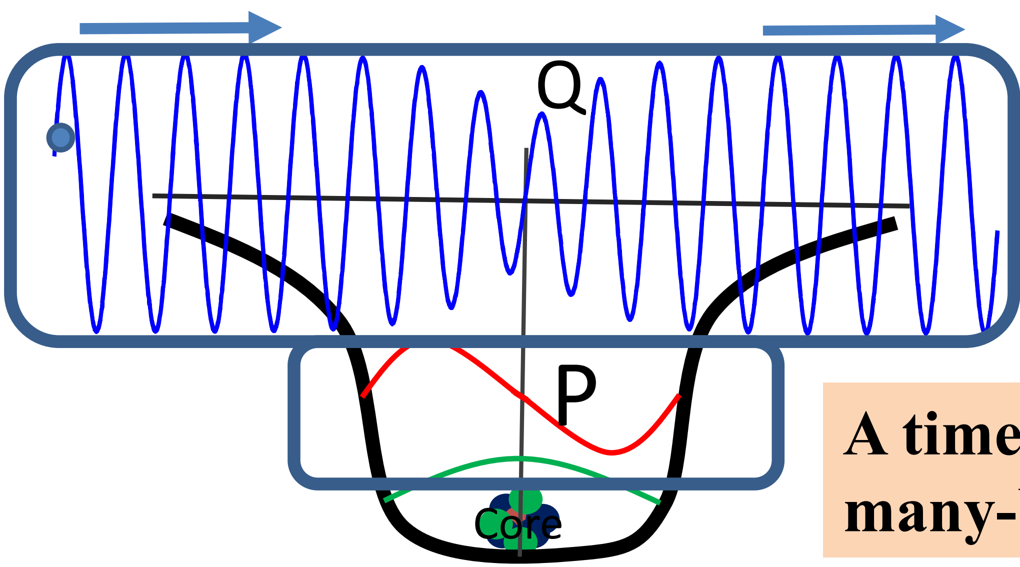
Closed quantum system



Open quantum system







A time-dependent many-body problem

Michel, Nazarewicz, Ploszajczak, Rotureau *et al.*, 2003--

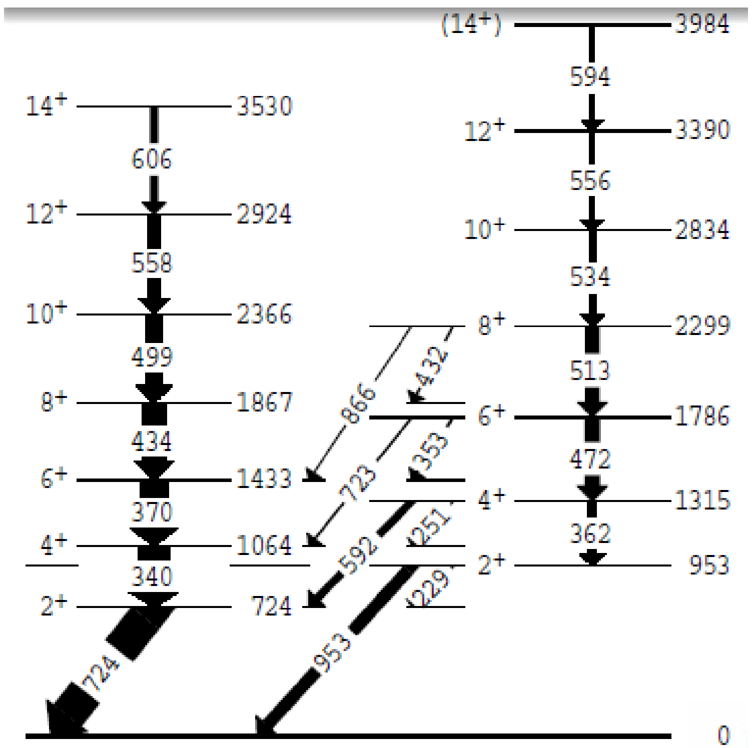
$$V = V_{WS} + V_{J,T}(\vec{r}_1, \vec{r}_2)$$

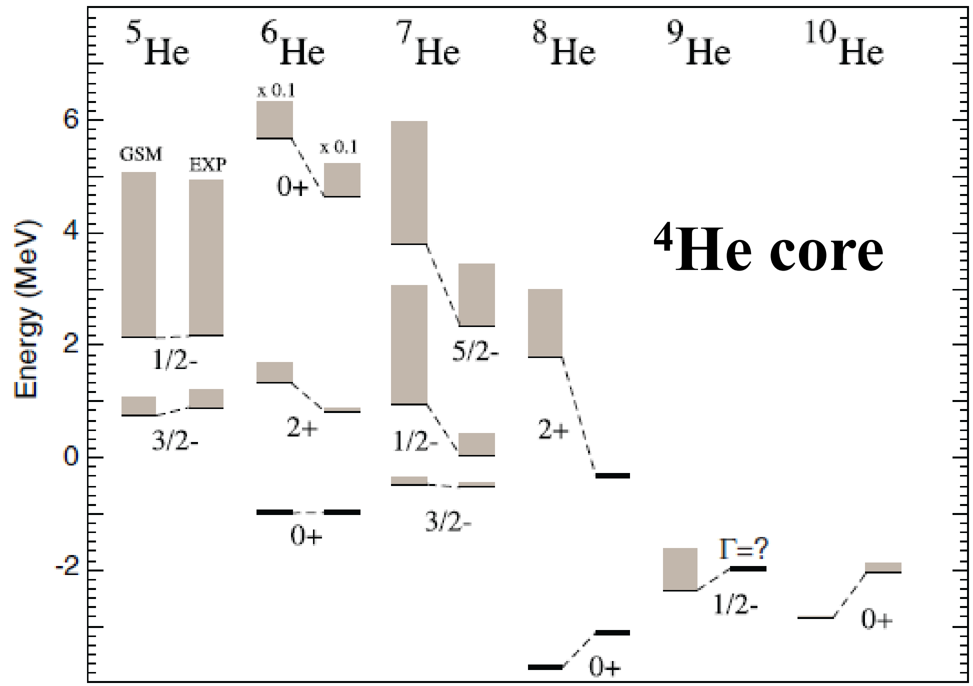
$$V(\mathbf{r}_i, \mathbf{r}_j) = -V_{\mathrm{SGI}}^{(J,T)} \exp\left[-\left(\frac{\mathbf{r}_i - \mathbf{r}_j}{\mu}\right)^2\right] \delta(r_i + r_j - 2R_0)$$

conventional γ-ray spectra

$V_{\mathrm{SGI}}^{(J)}$ is the strength in the JT channel

^{188}Pb: prolate and oblate bands





J. Pakarinen et al., PRC 72, 011304(R) (2005)

Michel, Nazarewicz, Płoszajczak, Vertse,

Phys. G: Nucl. Part. Phys. 36 (2009) 013101

Our Gamow shell model with an inert core

1. Start from realistic nuclear forces;
2. No limitation on the number of valence particles;
3. Extend Q-box + folded diagrams to complex-k space to construct model-space effective interaction in Gamow basis
4. Calculate excited-state spectra including resonance widths.

Realistic CGSM with CD-Bonn

Realistic nuclear forces ⇨ Gamow shell model calculations

Taking a doubly closed core

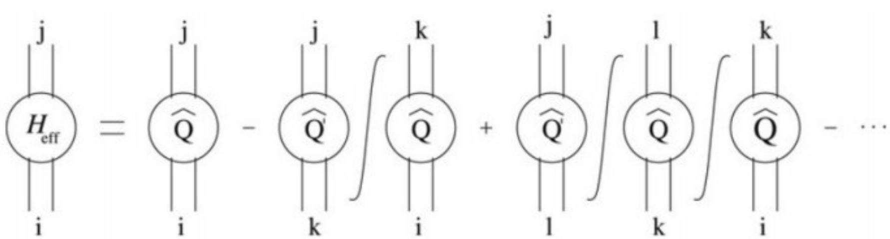
Bare forces: Strong repulsion, slow convergence → $V_{low\,k}$ or SRG → **To remove hard core, but still keep good descriptions of NN scattering phase shifts**

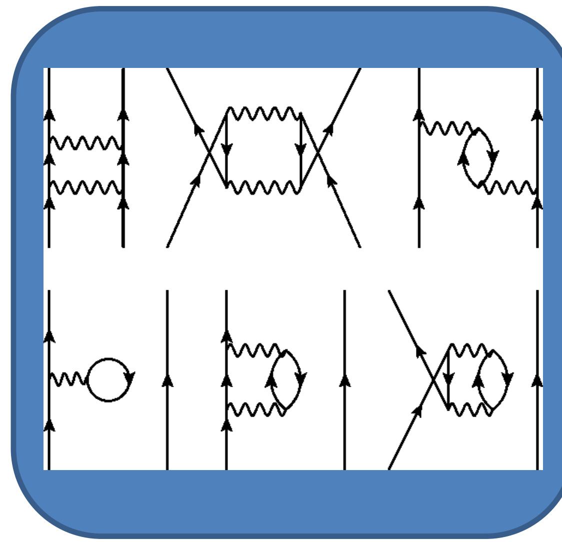
$$\langle \alpha_P | \bar{H}_{\rm eff} | \alpha_{P'} \rangle = \sum_{\alpha_{P''}} \sum_{\alpha_{P'''}} \sum_{kk'k''\in\mathcal{K}} \langle \alpha_P | \tilde{k}'' \rangle \langle \tilde{k}'' | \alpha_{P''} \rangle \langle \alpha_{P''} | \tilde{k} \rangle E_k \langle \tilde{k} | \alpha_{P'''} \rangle \langle \alpha_{P'''} | \tilde{k}' \rangle \langle \tilde{k}' | \alpha_{P'} \rangle$$

$$\frac{dH_\lambda}{d\lambda} = -\frac{4}{\lambda^5}[[T_{\rm rel}, H_\lambda], H_\lambda]$$

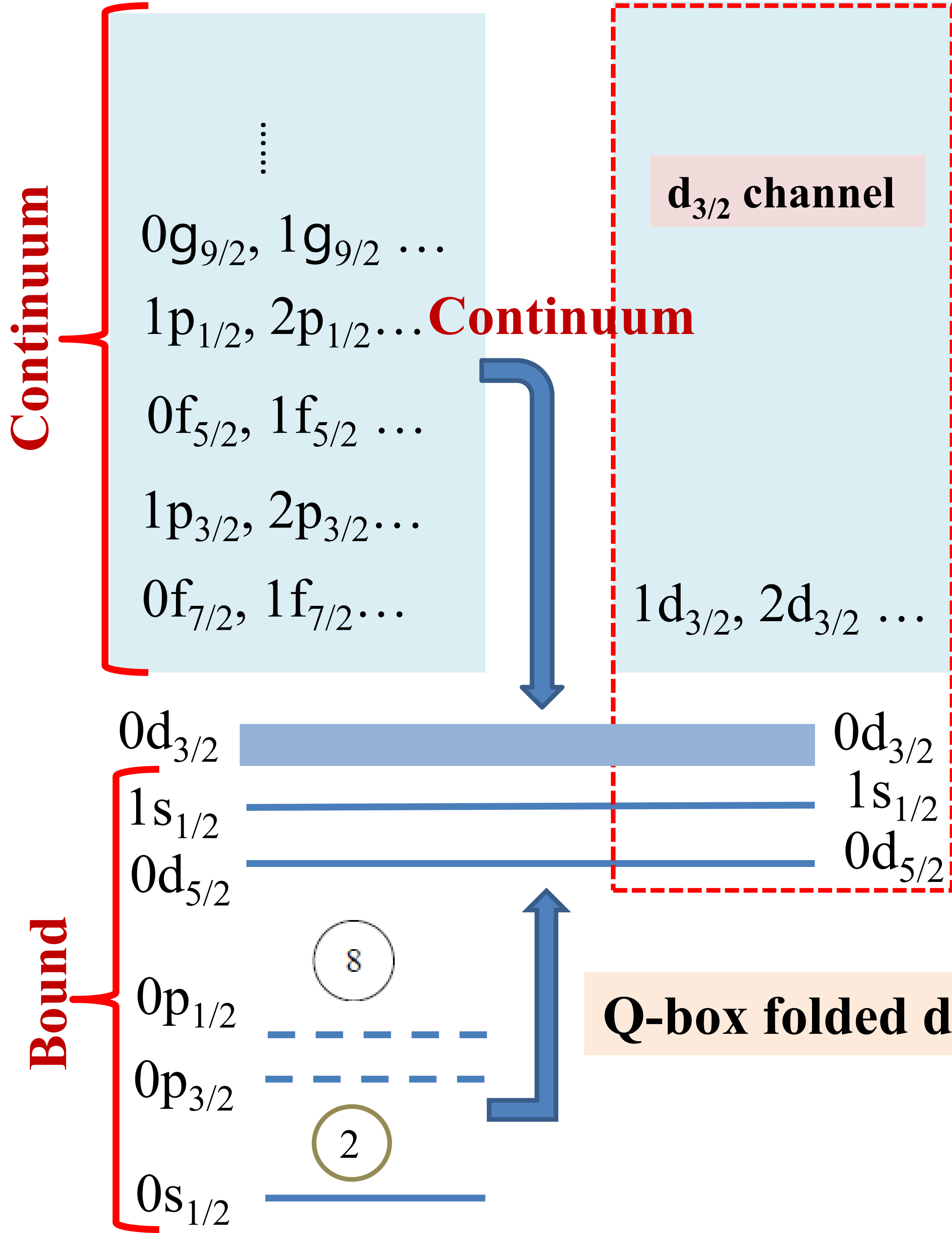
Q

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E-H}QVP,$$





Nondegenerated extended Kuo-Krenciglowa folded-diagram method (EKK) by Takayanagi, NPA 852, 61 (2011)



Model space

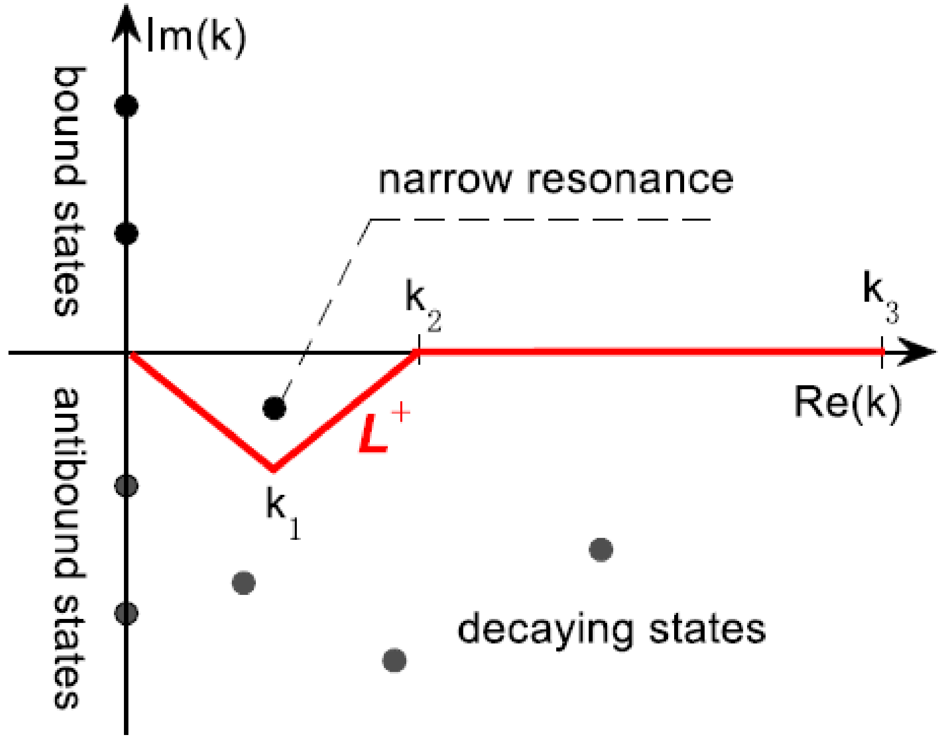
For each given channel,

Berggren completeness relation

$$\sum_{n} |u_n\rangle\langle\widetilde{u_n}| + \int_{L_+} |u_k\rangle\langle\widetilde{u}_k| dk = 1$$

Q-box folded diagrams in complex-k basis

Convergence against discretization number N_L

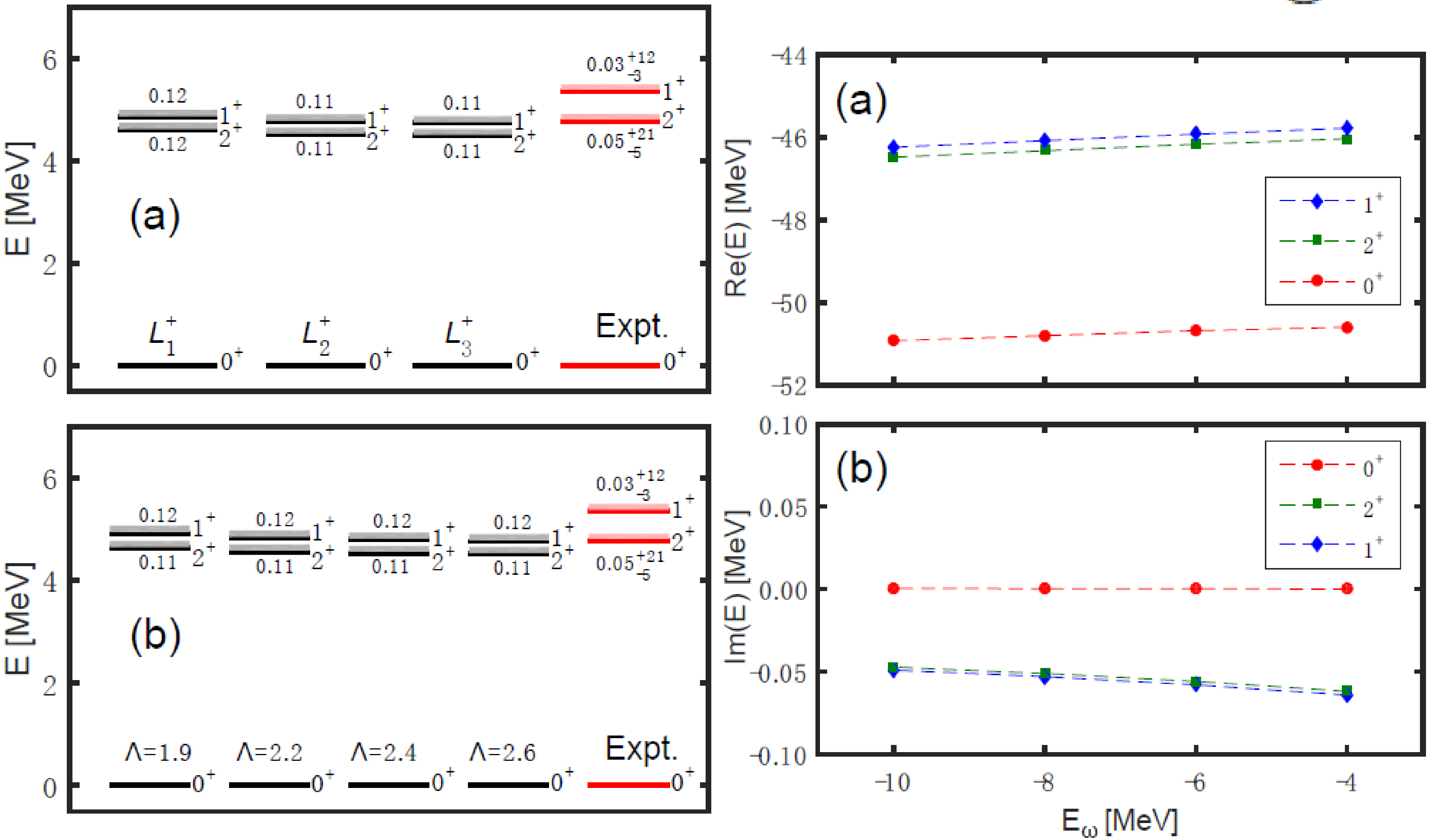


$\tilde{E}_n = E_n - i\Gamma/2$ $\quad$ ^{24}O $\quad$ $\Lambda = 2.6\ \mathrm{fm}^{-1}$

N_L	0^+	2^+	1^+
16	$-50.642 + 0.013i$	$-46.172 - 0.004i$	$-45.922 - 0.009i$
18	$-50.716 + 0.002i$	$-46.262 - 0.046i$	$-46.017 - 0.049i$
20	$-50.711 - 0.001i$	$-46.219 - 0.054i$	$-45.976 - 0.056i$
22	$-50.712 + 0.000i$	$-46.218 - 0.053i$	$-45.974 - 0.056i$

Convergences of spectroscopic calculations

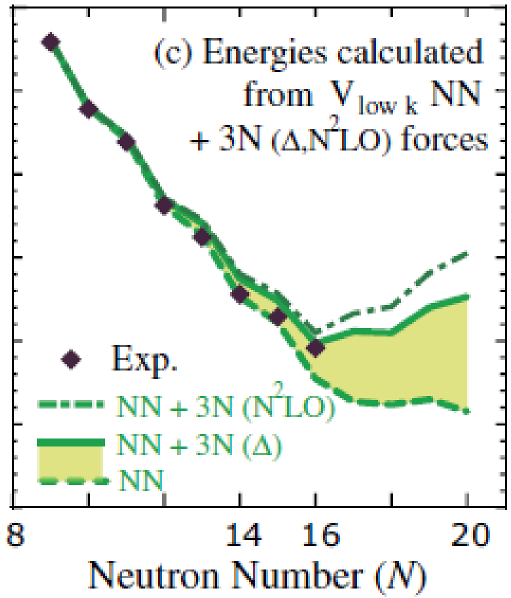
^{24}O



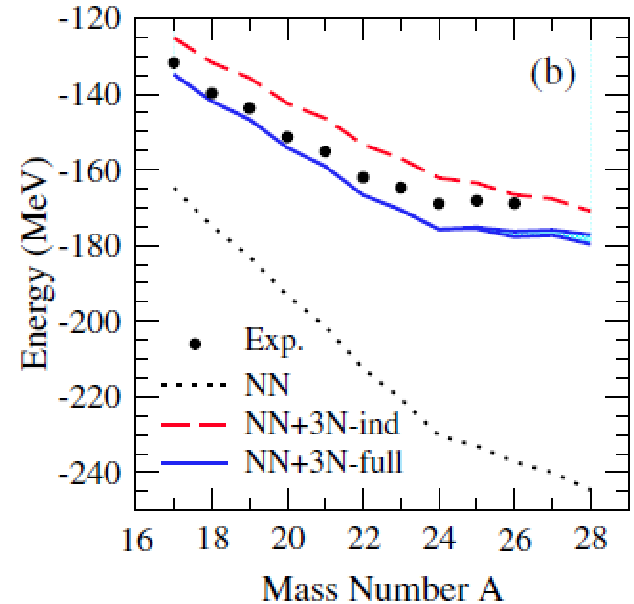
Binding energy: CGSM= - 50.7 MeV; Expt= - 41.3 MeV

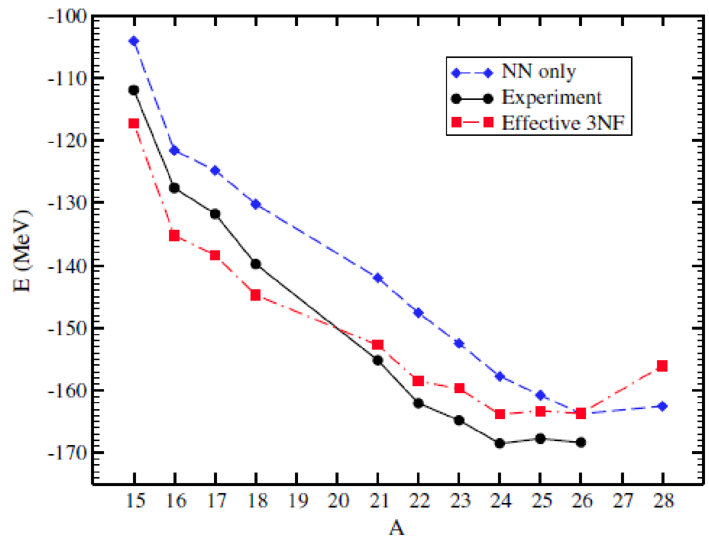
3NFs are important for binding energy calculations

Otsuka *et al.*, PRL 105, 032501 (2010): SM, N^3LO, N^2LO 3NF



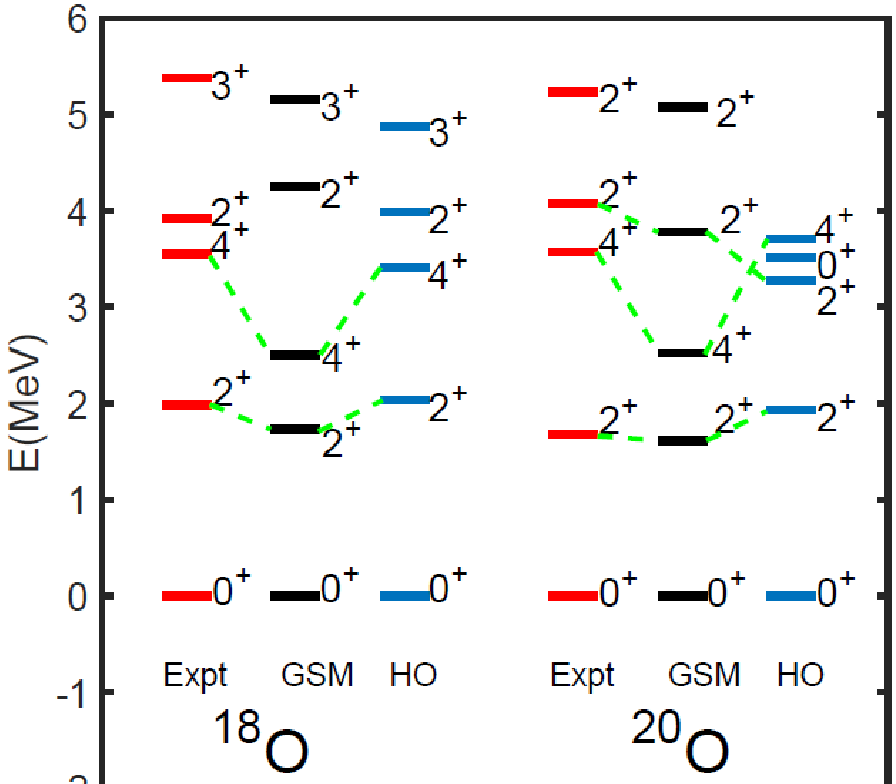
Bogner *et al.*, PRL 113, 142501 (2014): In-medium SRG, N^3LO, 3NF=induced / initial (N^2LO)



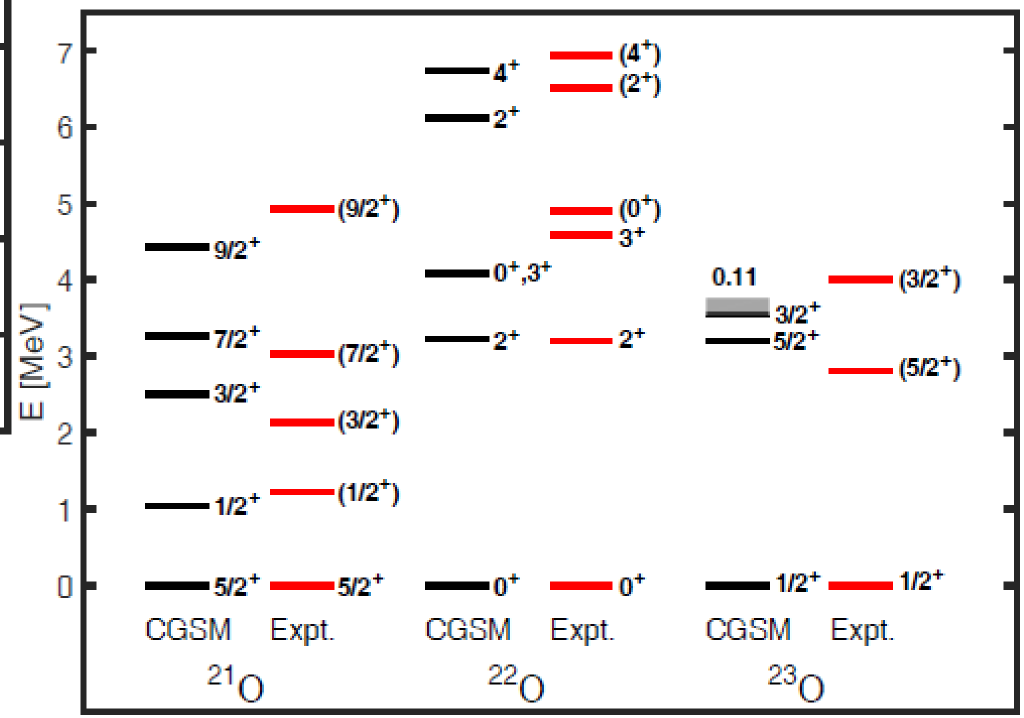


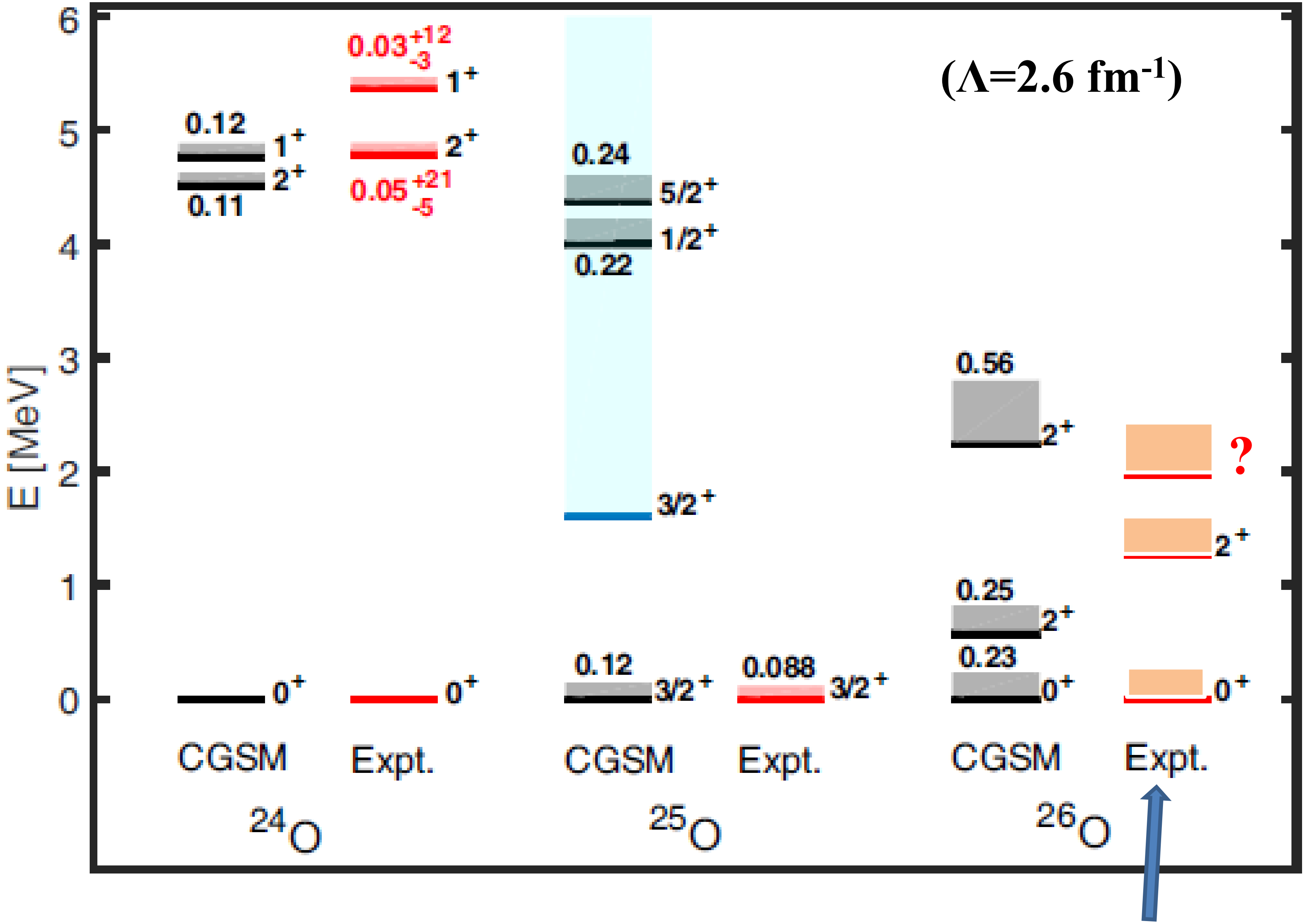
G. Hagen *et al.*, PRL 108, 242501 (2012): Continuum CC, N^3LO, N^2LO 3NF

Our CD-Bonn CGSM, compared with conventional H.O. SM



Hard cutoff Λ=2.6 fm^{-1} to reduce 3NFs

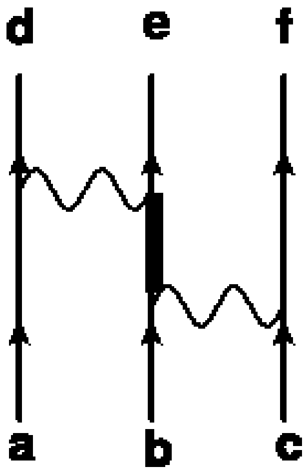


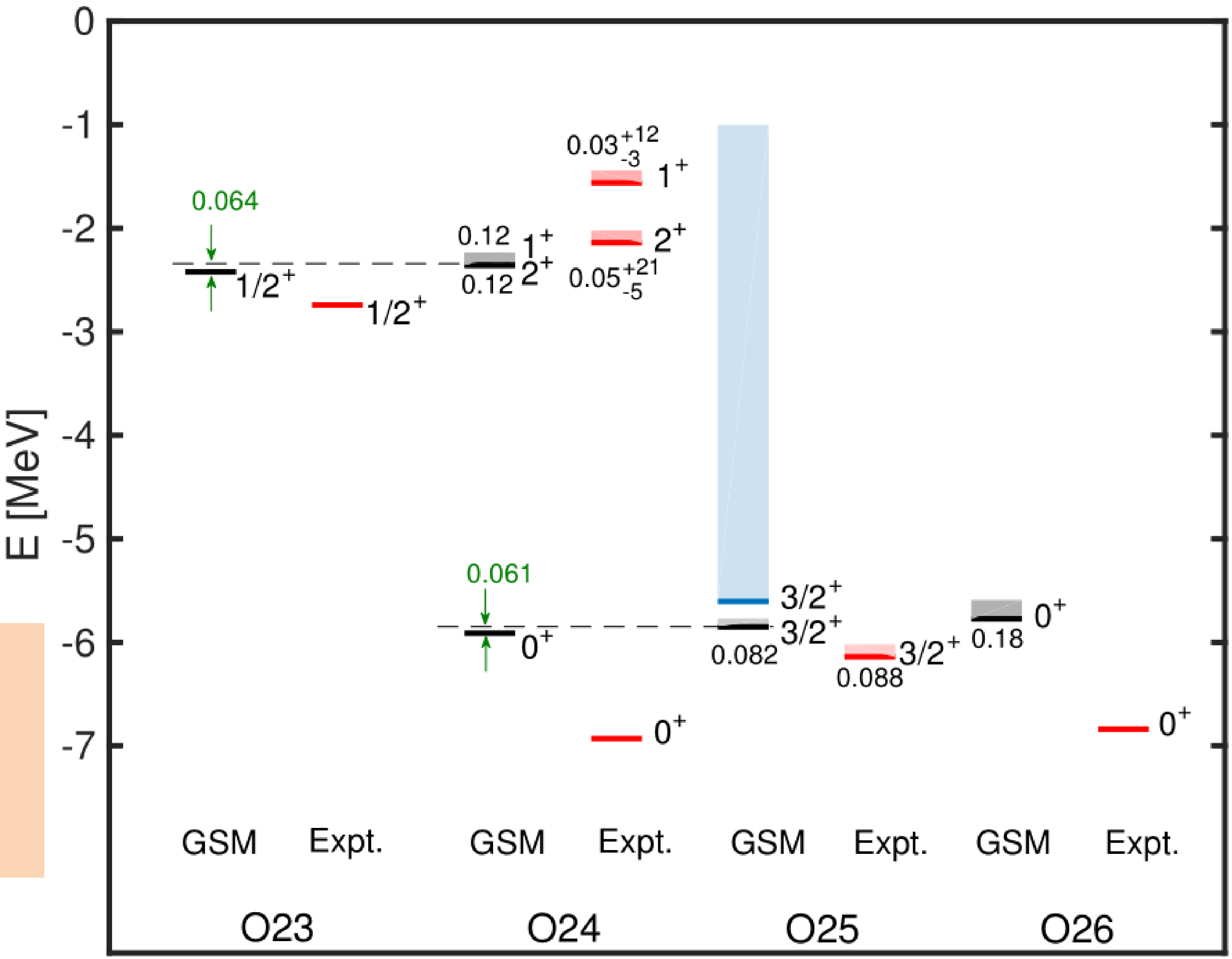


Y. Kondo *et al.*, PRL 116, 102503 (2016)

3NF effects

^{22}O core (N=14, 16 new closed shells)





Perfect should be:

1. ^{16}O core
2. 3NF included

Summary

I. Nuclear theory researches in China

II. Nuclear education in China (last 15 years)

Ab initio nuclear structure calculations of my group

Realistic nuclear forces (CD Bonn)

↓

Renormalizations ($V_{\text{low-}k}$)

↓

Many-body correlations (CGSM)

→ **We have developed the full Q-box folded diagrams to nondegenerate complex-*k* space, which includes contributions from core polarization and excluded Q space.**

✓ **Successfully applied to excited-state spectra of weakly-bound or unbound oxygen isotopes.**

Thank you for your attention !

ANPhA symposium (Nov. 23-25, 2016, Sendai Japan)