Halo formation in ^{11}Li: The Role of Pairing and Tensor Correlations nuclei

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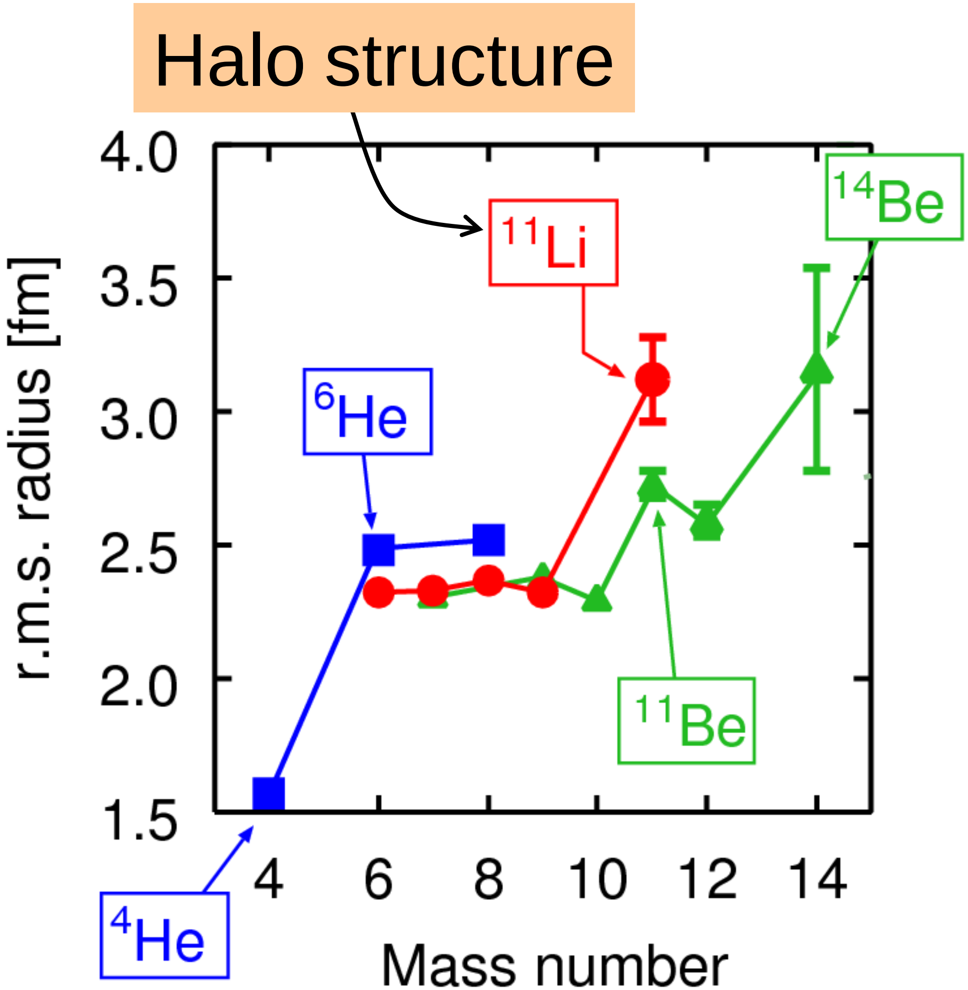
Outline

- **Role of V_{tensor}** in the nuclear structure by describing strong tensor correlation explicitly.
- Tensor Optimized Shell Model (TOSM) to describe tensor correlation.
- Halo formation in ^{11}Li
  - Coexistence of tensor and pairing correlations
- Unitary Correlation Operator Method (UCOM) to describe short-range correlation.
- TOSM+UCOM to He & Li isotopes with V_{bare}

Characteristics of Li-isotopes

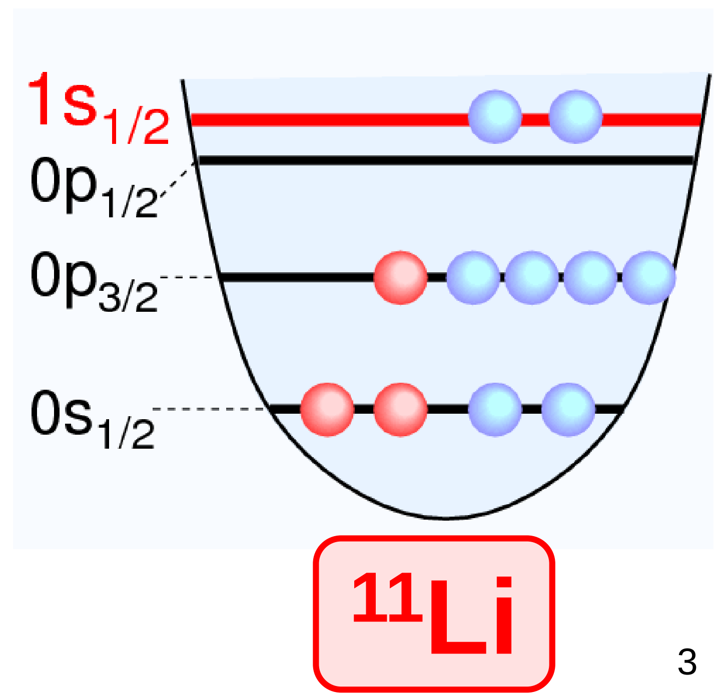


Tanihata et al., PRL55(1985)2676.
PLB206(1998)592.

✓ Breaking of magicity N=8

- $^{10\text{-}11}$Li, $^{11\text{-}12}$Be
- ^{11}Li … $(1s)^2 \sim 50\%$.

  (Expt by Simon et al.,PRL83)
- Mechanism is unclear

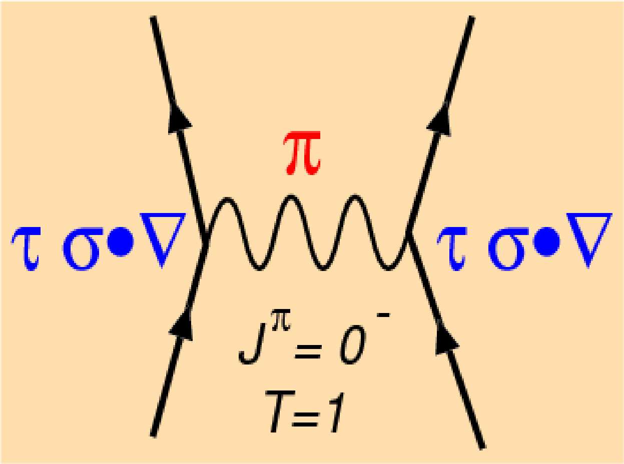


Importance of tensor force

- Tensor force (V_{tensor}) plays a significant role in the nuclear structure.
  - In ^{4}He, $\langle V_{tensor} \rangle \sim \langle V_{central} \rangle$

    $P(D) \sim 15\%$ (AV18, GFMC)

    R.B. Wiringa, S.C. Pieper, J. Carlson, V.R. Pandharipande, PRC62(2001)



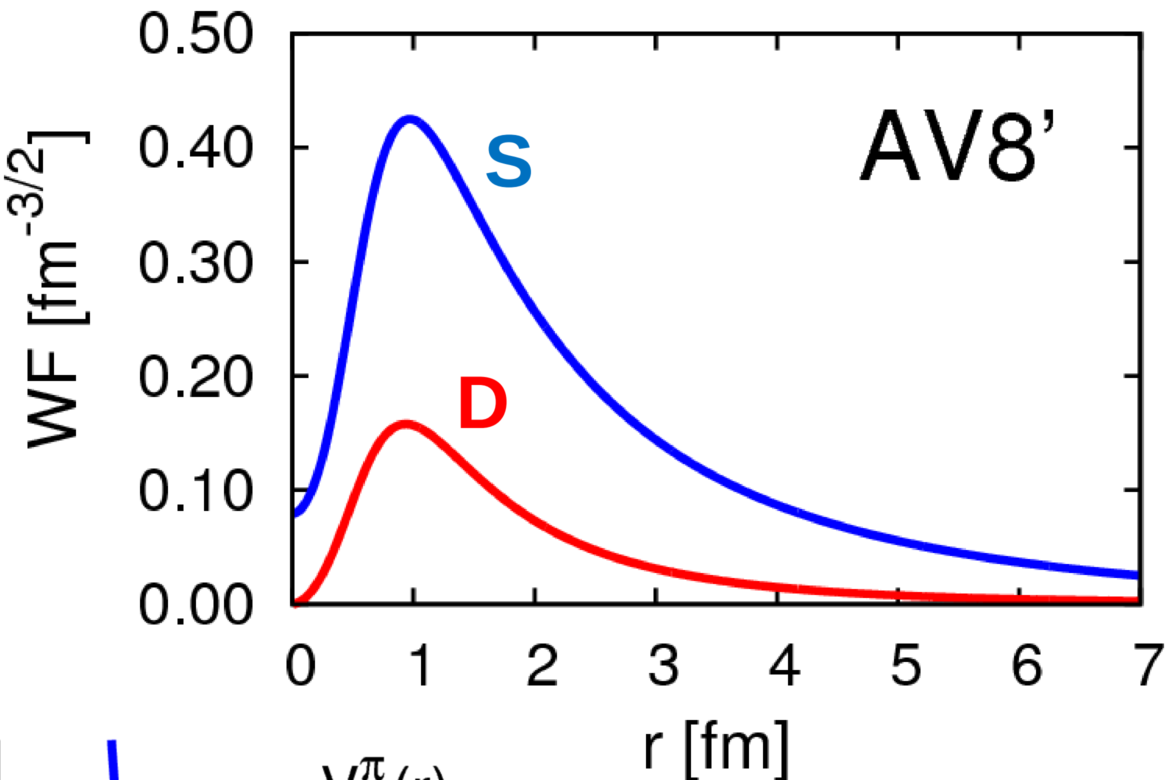
- We would like to understand **role of V_{tensor}** in the nuclear structure by describing tensor correlation explicitly.

  ✓ wave function : shell model, cluster model

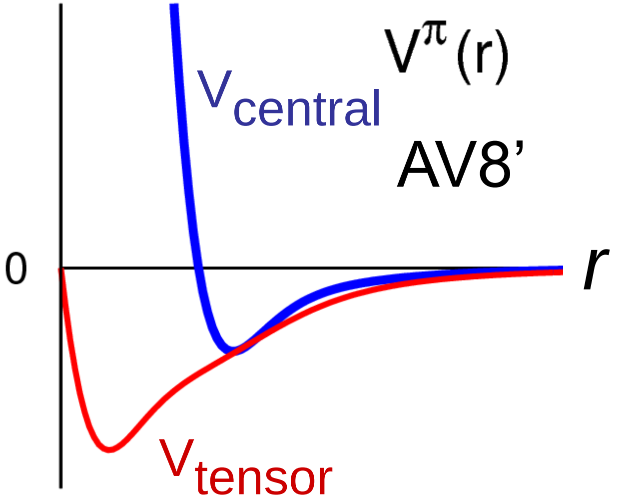
  ✓ *LS* splitting, halo formation, level inversion, etc,…

Li isotopes

Deuteron properties & tensor force



Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P(L=2)	5.77%
Radius	1.96 fm



$R_m(s)$=2.00 fm

$R_m(d)$=1.22 fm

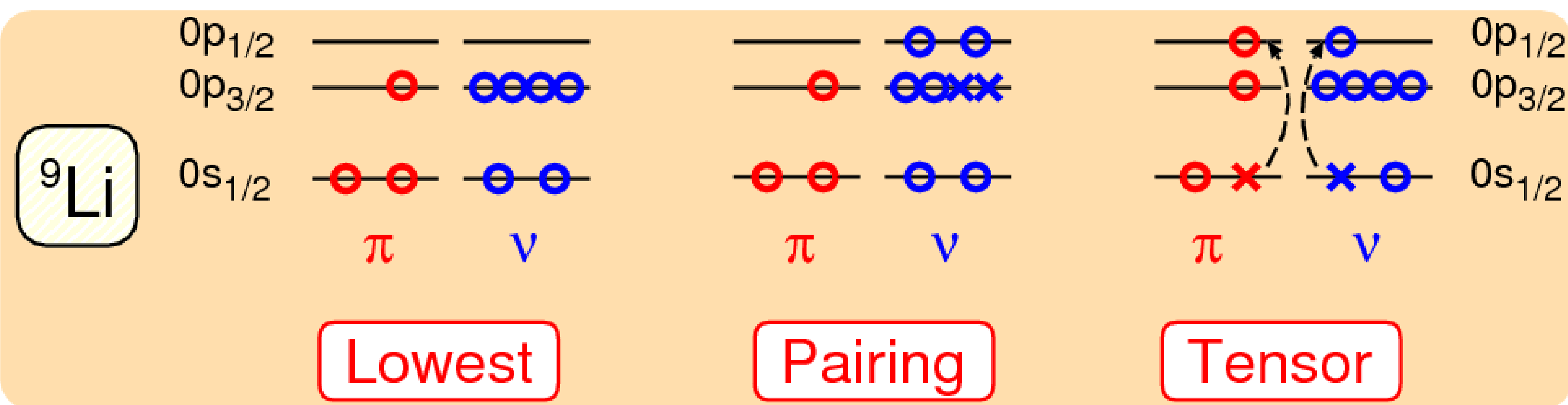
d-wave is
"**spatially compact**"
(high momentum)

^{9}Li in TOSM

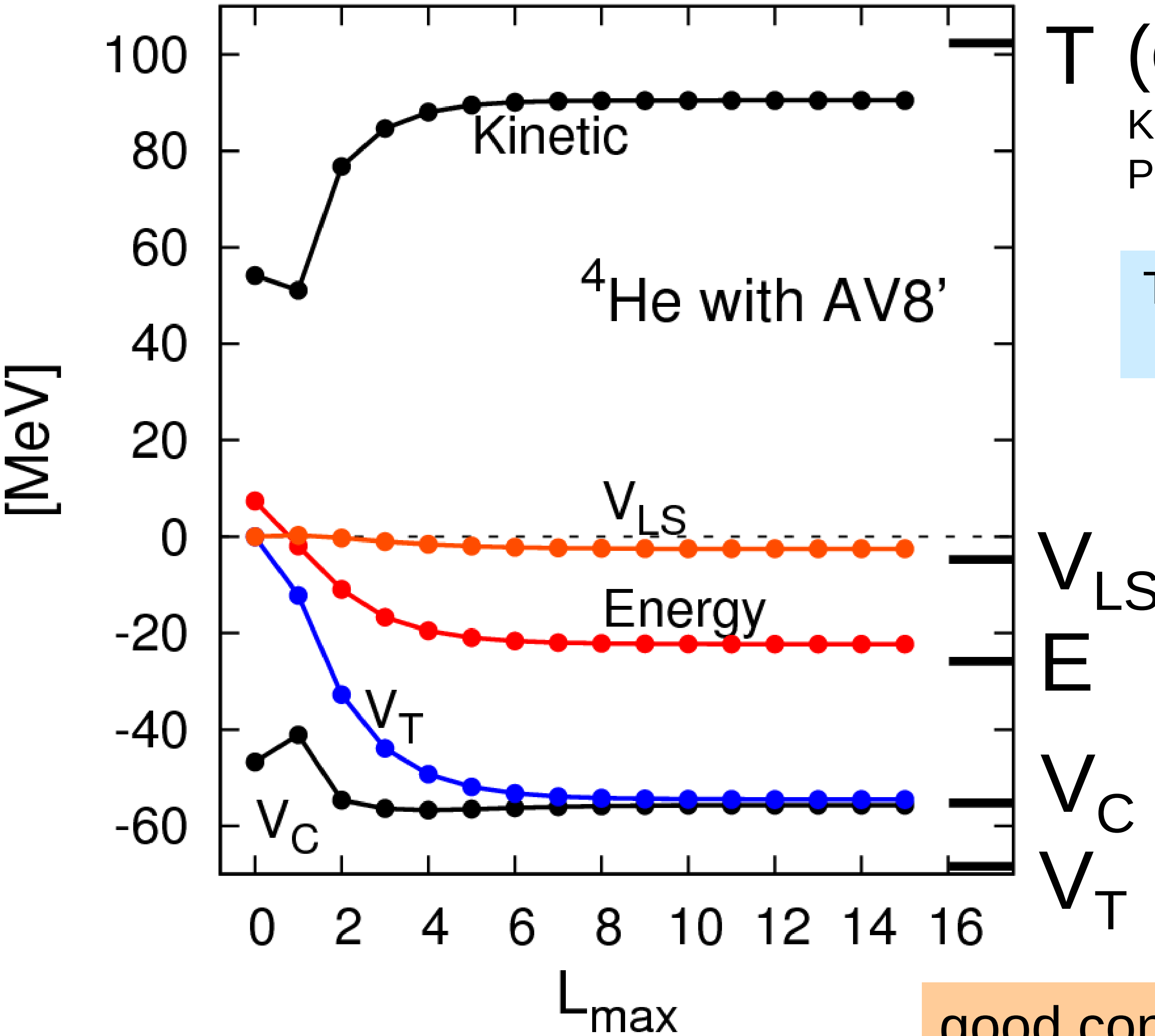
- Tensor-optimized shell model
  TM et al., PTP121(2009), PTP117(2007).

- 0s+0p+1s0d within 2p2h excitations, *G*-matrix (Akaishi)

- Length parameters b_{0s}, $b_{0p1/2}$, $b_{0p3/2}$, … are determined independently and variationally (Gaussian expansion).
  - Describe high momentum component from V_{tensor}
    cf. CPP-HF by Sugimoto et al.,NPA740 / Akaishi NPA738



^{4}He in TOSM + short-range UCOM



Kamada et al.
PRC64 (Jacobi)

TM, H. Toki, K. Ikeda
PTP121(2009)511

- variational calculation
- Gaussian expansion with 9 Gaussians

good convergence

Configurations of ^{4}He with AV8'

TM, H. Toki, K. Ikeda
PTP121(2009)511

$(0s_{1/2})^4$	83.0 %
$(0s_{1/2})^{-2}{}_{JT}(p_{1/2})^2{}_{JT}$ ***JT*=10**	2.6
JT=01	0.1
$(0s_{1/2})^{-2}{}_{10}(1s_{1/2})(d_{3/2})_{10}$	2.3
$(0s_{1/2})^{-2}{}_{10}(p_{3/2})(f_{5/2})_{10}$	1.9
Radius [fm]	1.54

- deuteron correlation with $(J,T)=(1,0)$

Cf. R.Schiavilla et al. (VMC) PRL98(2007)132501
R. Subedi et al. (JLab) Science320(2008)1476
$^{12}C(e,e'pN)$

S.C.Simpson, J.A.Tostevin PRC83(2011)014605
$^{12}C \rightarrow {}^{10}B+pn$

- ^{4}He contains $p_{1/2}$ of "***pn*-pair**"
  - Same feature in ^{5}He-^{8}He ground state

^{9}Li in TOSM

- Tensor-optimized shell model
  TM et al., PTP121(2009), PTP117(2007).

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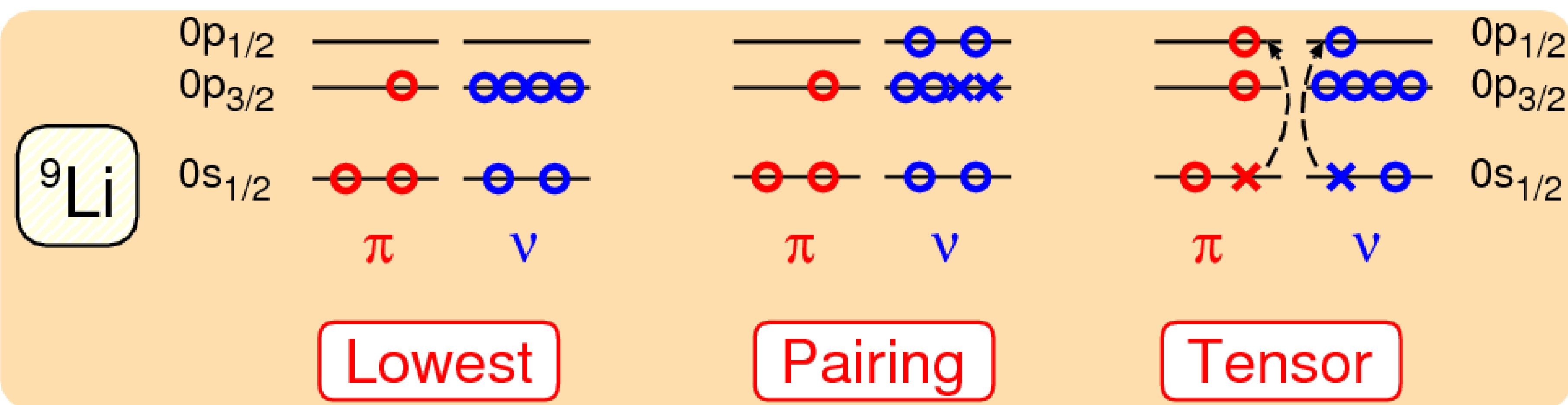
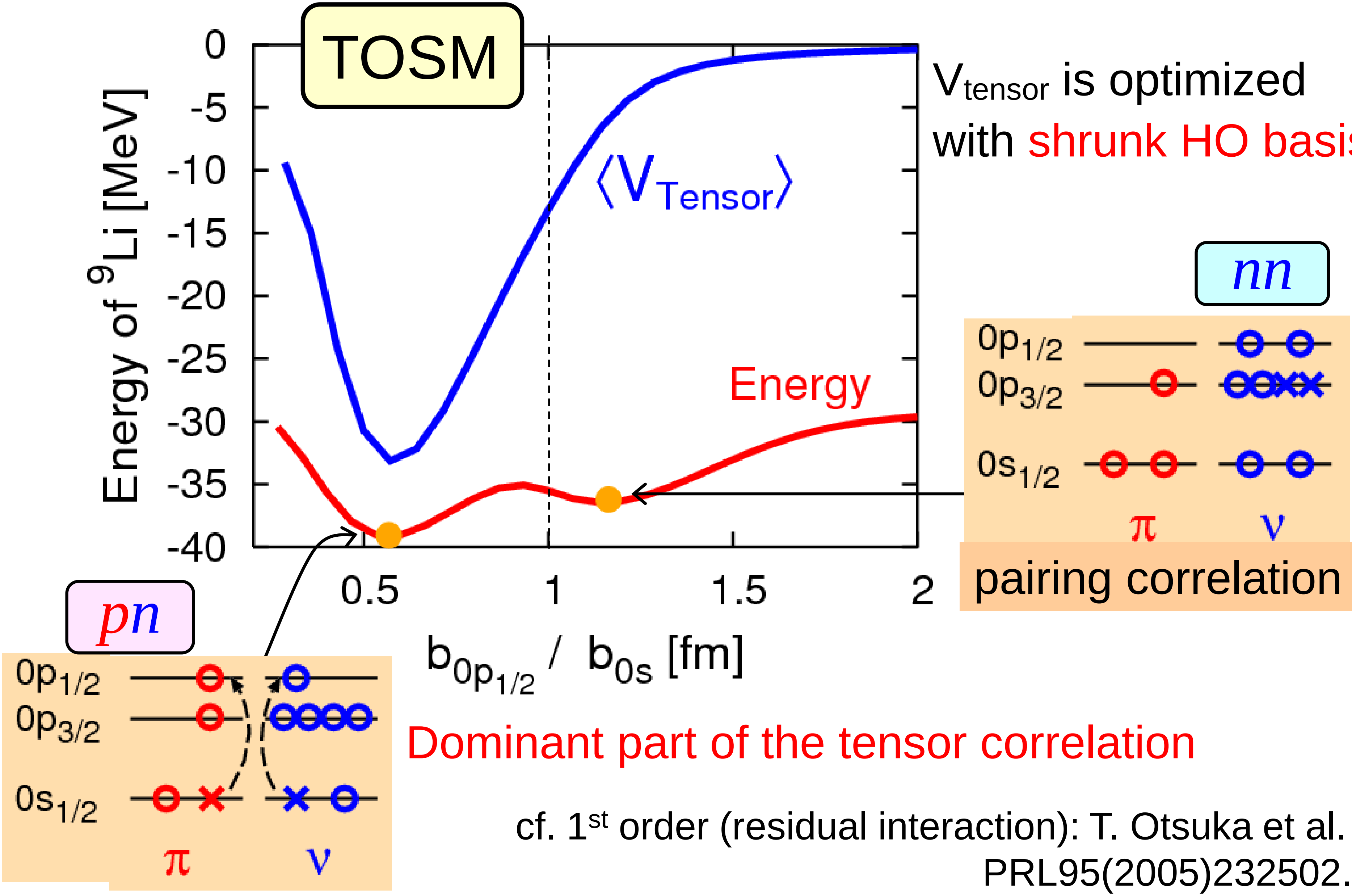


Energy surface for *b*-parameter in ^{9}Li

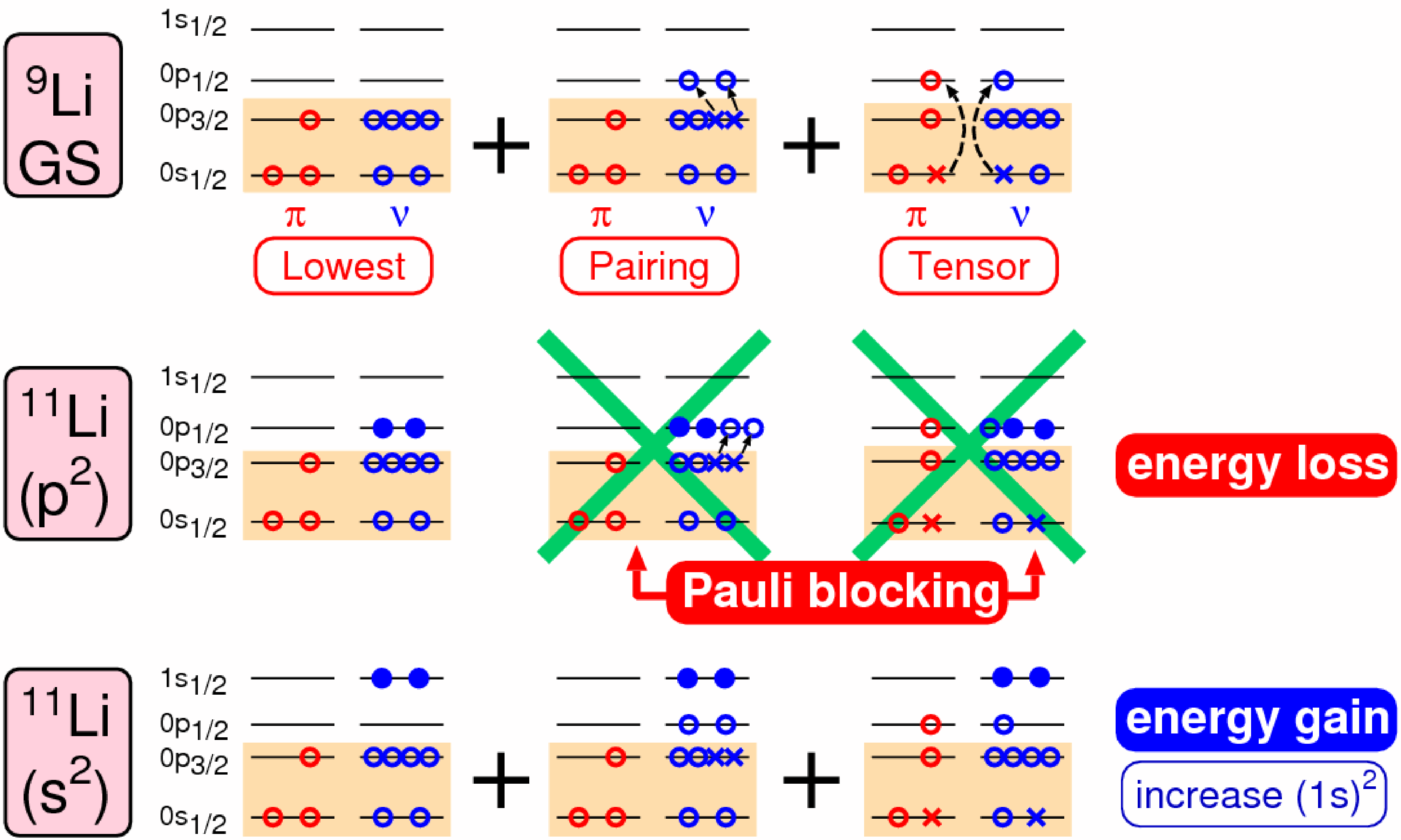


V_{tensor} is optimized with shrunk HO basis

Dominant part of the tensor correlation

cf. 1st order (residual interaction): T. Otsuka et al. PRL95(2005)232502.

Expected effects of pairing and tensor correlations in ^{11}Li



Pairing-blocking :

K.Kato,T.Yamada,K.Ikeda,PTP101('99)119, Masui,S.Aoyama,TM,K.Kato,K.Ikeda,NPA673('00)207.
TM,S.Aoyama,K.Kato,K.Ikeda,PTP108('02)133, H.Sagawa,B.A.Brown,H.Esbensen,PLB309('93)1.

^{11}Li in coupled ^{9}Li+n+n model

- System is solved based on RGM

$$H(^{11}\mathrm{Li}) = H(^{9}\mathrm{Li}) + H_{nn} \qquad \Phi(^{11}\mathrm{Li}) = \mathcal{A}\left\{\sum_{i=1}^{N} \psi_i(^{9}\mathrm{Li}) \cdot \chi_i(nn)\right\}$$

$$\sum_{i=1}^{N} \left\langle \psi_j(^{9}\mathrm{Li}) \middle| H(^{11}\mathrm{Li}) - E \middle| \mathcal{A}\left\{\psi_i(^{9}\mathrm{Li}) \cdot \chi_i(nn)\right\}\right\rangle = 0$$

$\psi_i(^{9}\mathrm{Li})$: shell model type configuration $\rightarrow$ TOSM

- Orthogonality Condition Model (OCM) is applied.

$$\sum_{i=1}^{N} \left[H_{ij}(^{9}\mathrm{Li}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12}) \cdot \delta_{ij} \right] \chi_j(nn) = E\chi_i(nn)$$

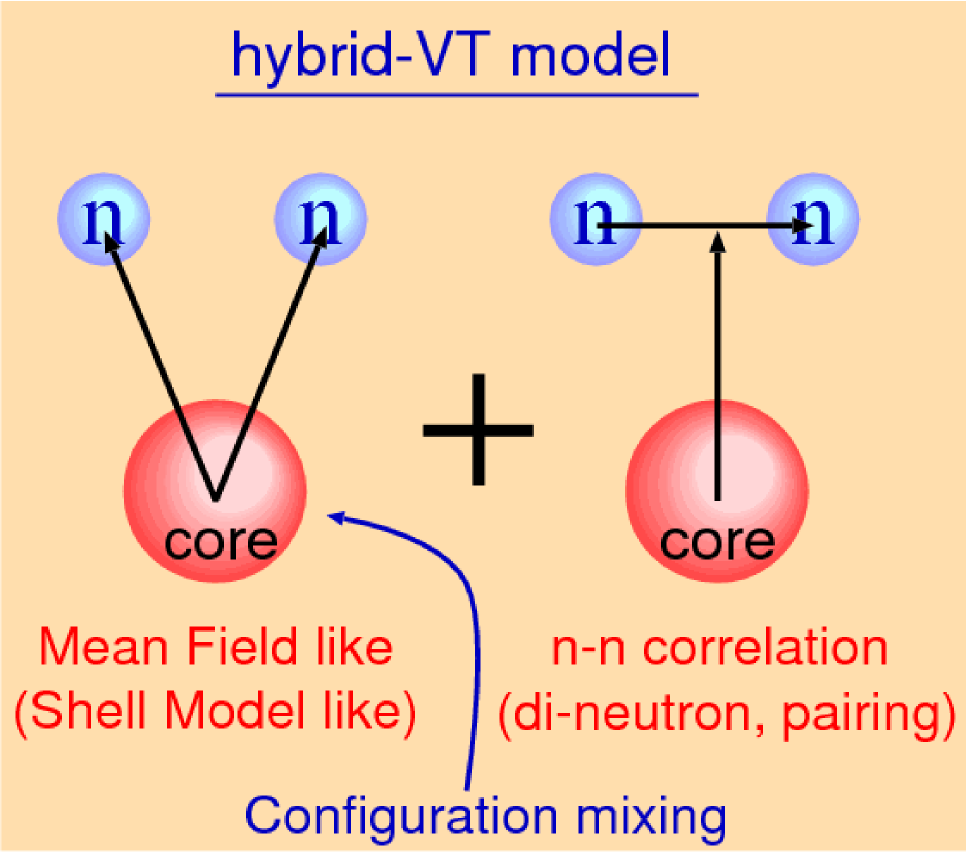
$H_{ij}(^{9}\mathrm{Li}) = \left\langle \psi_i \middle| H(^{9}\mathrm{Li}) \middle| \psi_j \right\rangle$: Hamiltonian for ^{9}Li

$\chi(nn) = \mathcal{A}\{\varphi_1 \varphi_2\}$: hybrid-TVmodel with Gaussian expansion

$\left\langle \varphi_i \middle| \phi_\alpha \right\rangle = 0,\ \{\phi_\alpha \in {}^{9}\mathrm{Li}\}$: Orthogonality to the Pauli-forbidden states

Hamiltonian of ^{11}Li

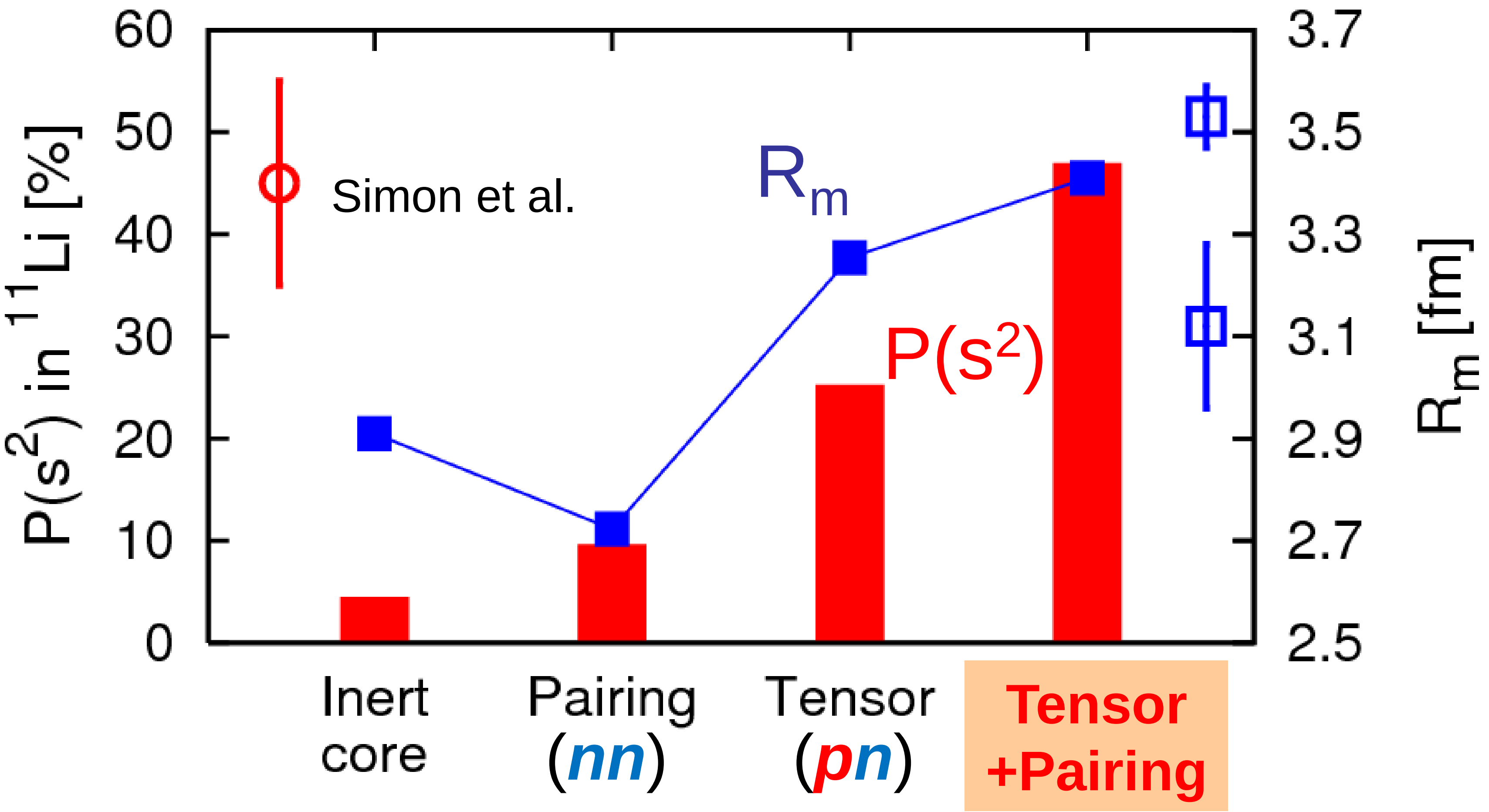
- $V_{\text{core-n}}$: folding potential
  - Same strength for *s*- and *p*-waves
  - Adjust to reproduce S_{2n}=0.31 MeV
- V_{nn} : Argonne (AV8')
- 2n : Gaussian expansion



TM, K.Kato, H.Toki, K.Ikeda, PRC76('07)024305.

TM. Y.Kikuchi, K.Kato, H.Toki, K.Ikeda, PTP119('08)561.

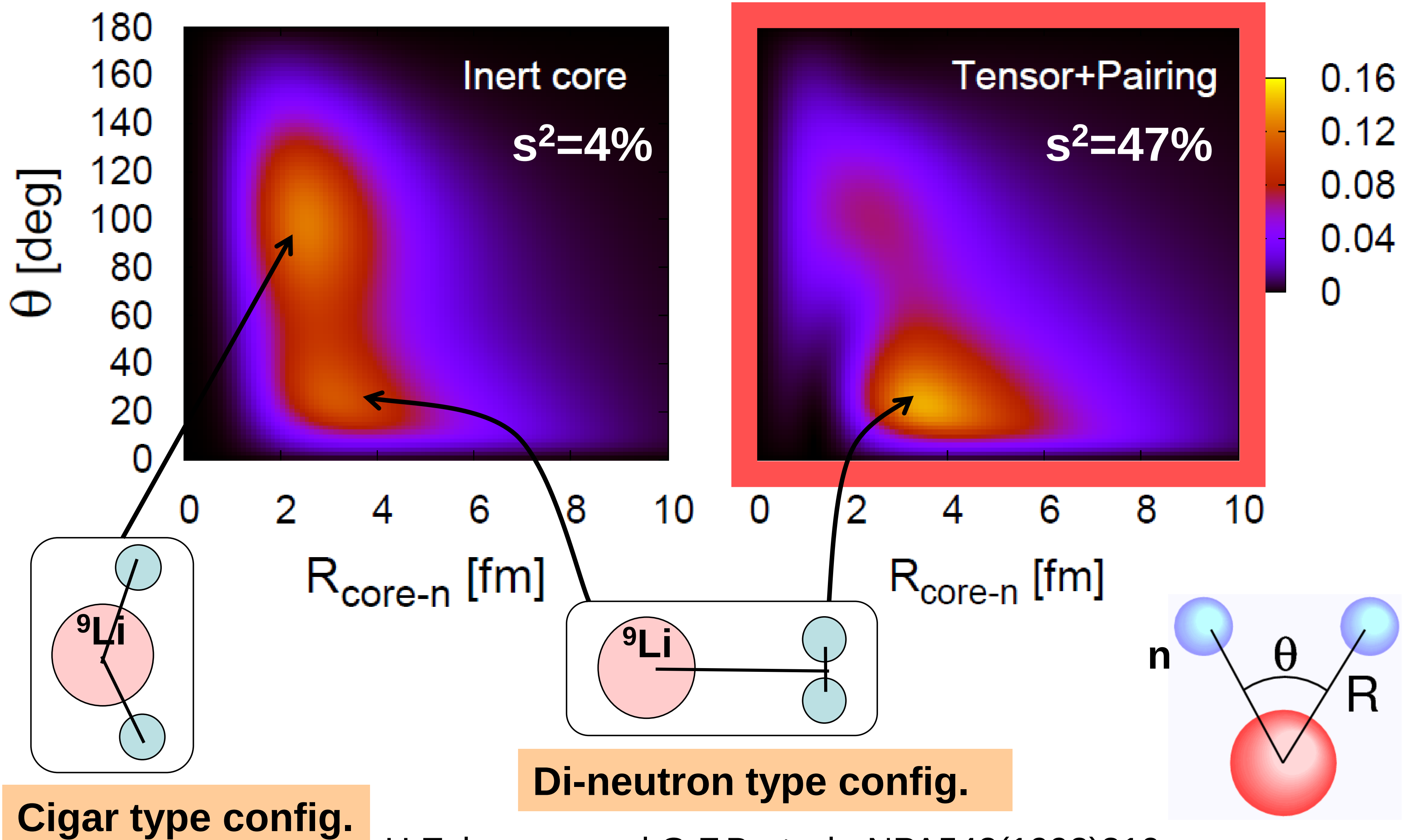
^{11}Li G.S. properties (S_{2n}=0.31 MeV)



$E(s^2)-E(p^2)$	2.1	1.4	0.5	-0.1	[MeV]

Pairing correlation couples $(0p)^2$ and $(1s)^2$ for last 2n

2n correlation density in ^{11}Li

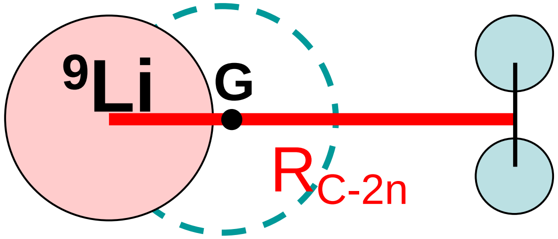


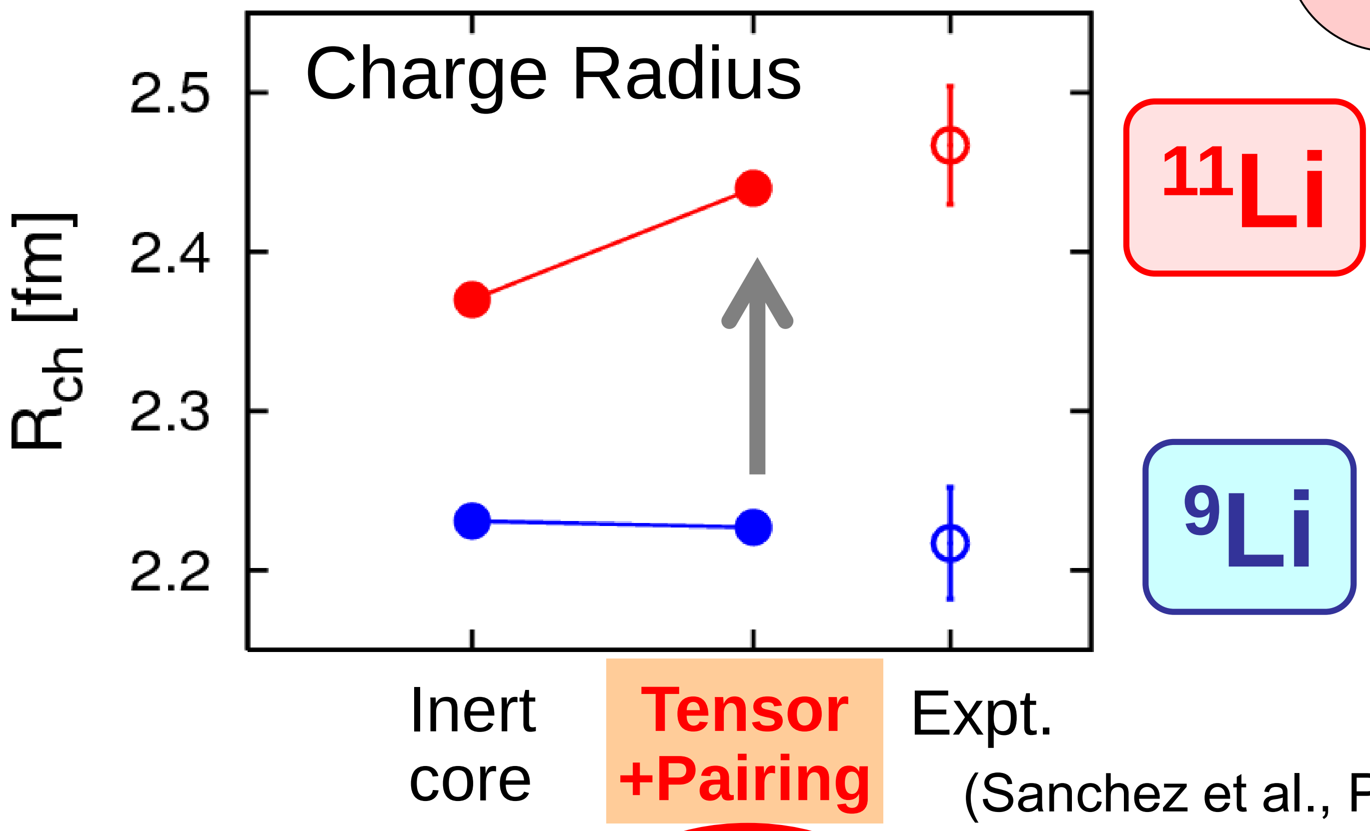
H.Esbensen and G.F.Bertsch, NPA542(1992)310

K. Hagino and H. Sagawa, PRC72(2005)044321

Charge Radii of Li isotopes

$$R^2_{\text{proton}}(^{11}\text{Li}) = R^2_{\text{proton}}(^{9}\text{Li}) + \left(\frac{2}{11}\right)^2 R^2_{\text{C-2n}}$$



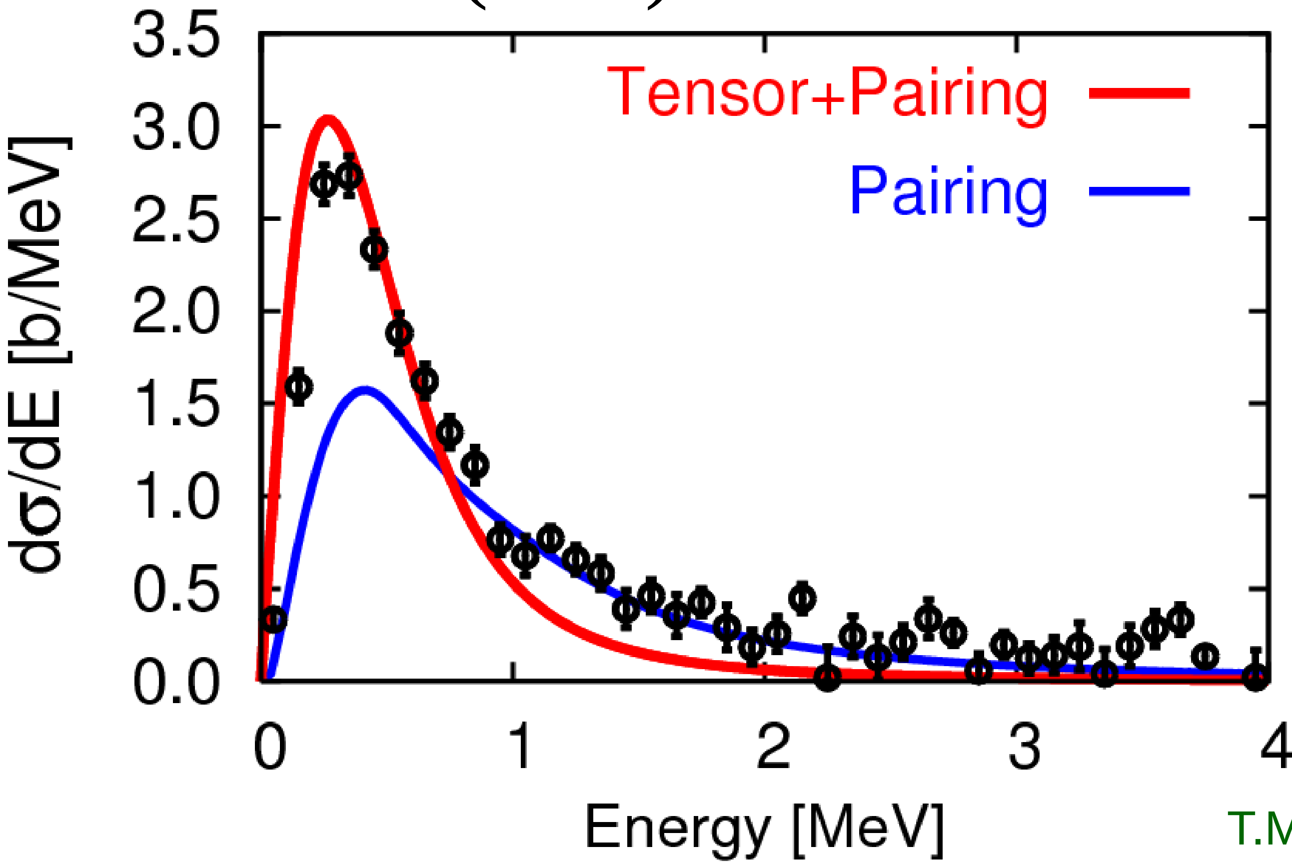


(Sanchez et al., PRL96('06))

	Inert core	Tensor +Pairing	
$R_{\text{C-2n}}$	4.67	5.69	[fm]
$P(s^2)$	4	47	%

Coulomb breakup strength of ^{11}Li

$$^{11}\mathrm{Li}\,(\mathrm{G.S.}) \rightarrow {}^{9}\mathrm{Li} + n + n$$



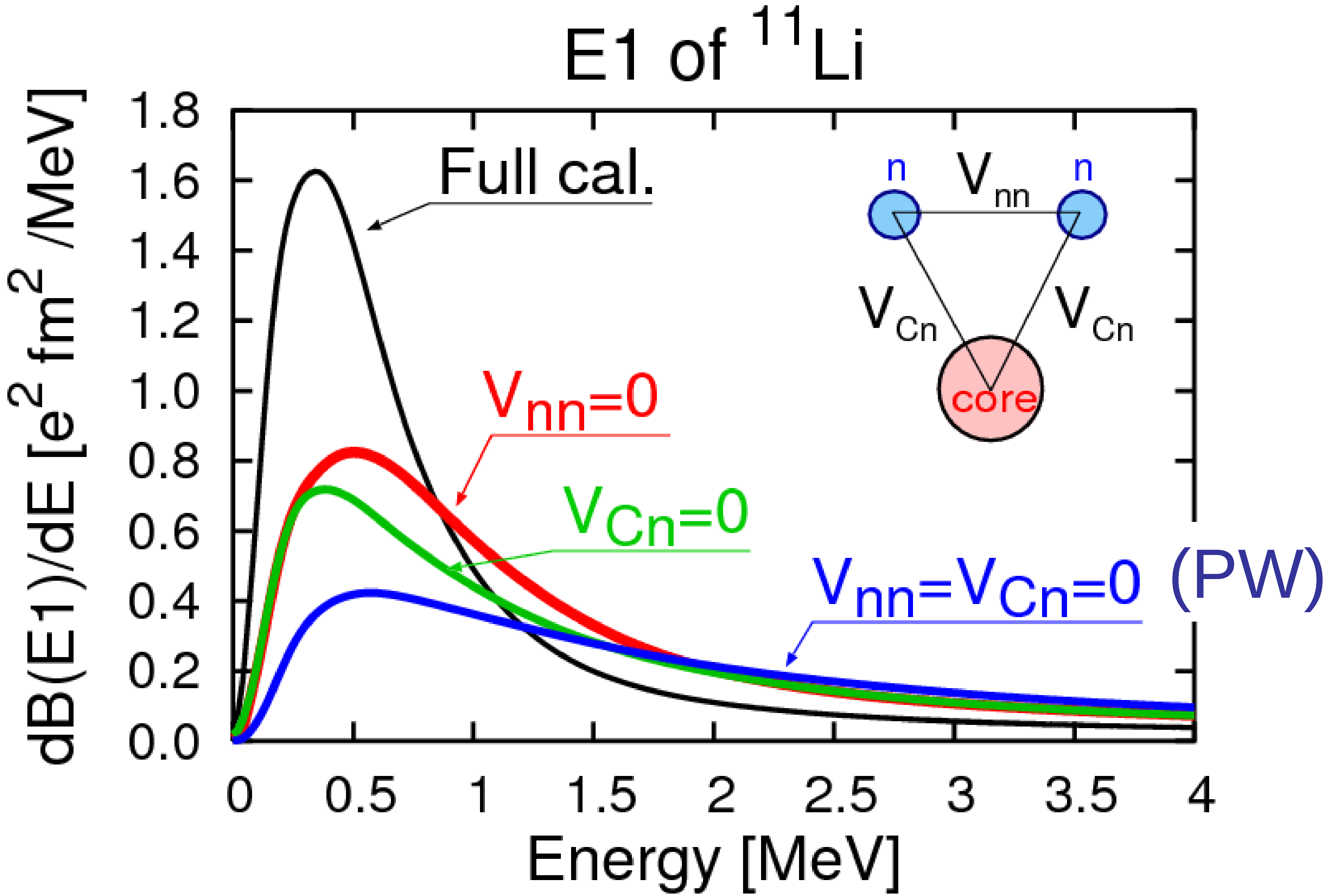
No three-body resonance

E1 strength by using the Green's function method
+Complex scaling method
+Equivalent photon method
(TM et al., PRC63('01))

T.Myo, K.Kato, H.Toki, K.Ikeda
PRC76(2007)024305

- Expt: T. Nakamura et al. , PRL96,252502(2006)
- Energy resolution with $\sqrt{E}$ =0.17 MeV.

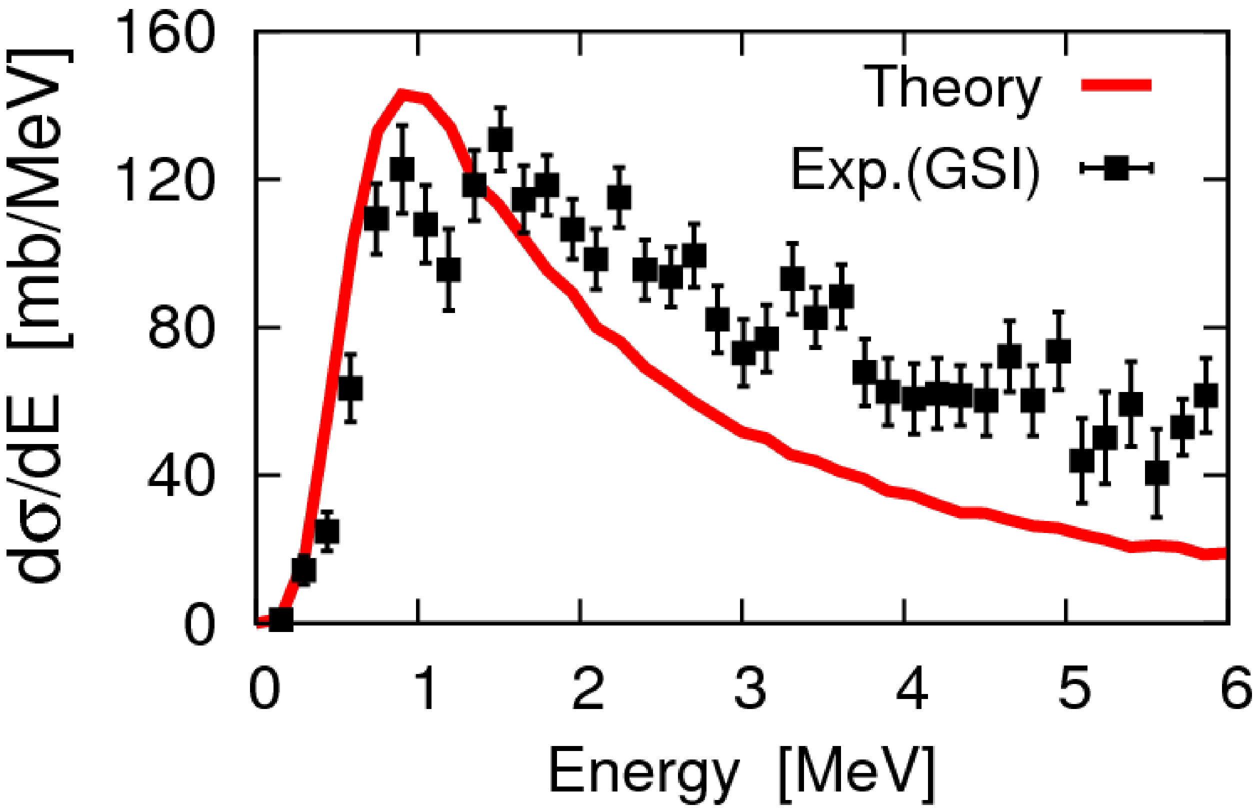
Correlations in the final states of ^{11}Li breakup



TM, K.Kato, H.Toki, K.Ikeda, PRC76('07)024305.
TM. Y.Kikuchi, K.Kato, H.Toki, K.Ikeda, PTP119('08)561.

Coulomb breakup strength of ^{6}He

$$^{6}\mathrm{He}\,(\mathrm{G.S.}) \rightarrow\ ^{4}\mathrm{He} + n + n$$



E1+E2
Equivalent photon method

TM, K. Kato, S. Aoyama and K. Ikeda PRC63(2001)054313.

Kikuchi, TM, Takashina, Kato, Ikeda
PTP122(2009)499
PRC81(2010)044308.
(+invariant mass of α-n, and n-n)

^{6}He : 240MeV/A, Pb Target (T. Aumann et.al, PRC59(1999)1252)

Virtual *s*-wave states in ^{10}Li

- **$1s_{1/2}$ virtual state:**

$$(0p_{3/2})_\pi (1s_{1/2})_\nu \rightarrow 1^-, 2^-$$

a_s : scattering length of ^{9}Li+n

J^π	Inert core	Tensor +Pairing
1^-	+1.4 fm	–5.6 fm
2^-	+0.8 fm	–17.4 fm

T.M. et al., PTP119('08)561
arXiv:0803.0590

Expt. M. Thoennessen et al., PRC59 (1999)111.
M. Chartier et al. PLB510(2001)24.
H.B. Jeppesen et al. PLB642(2006)449.

a_s = –10 ~ –25 fm

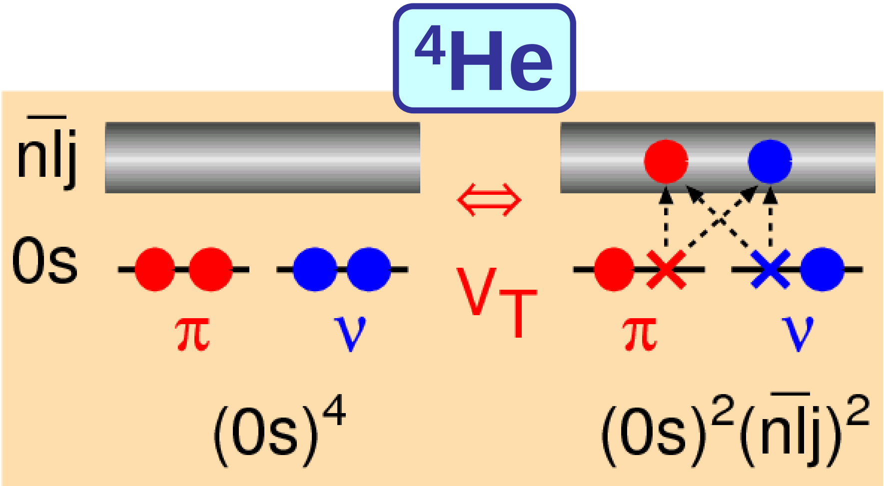
cf. $a_s(nn)$: -18.5 ± 0.5 fm

Pauli-blocking naturally describes virtual s-state in ^{10}Li

Tensor-optimized shell model (TOSM)

TM, Sugimoto, Kato, Toki, Ikeda   PTP117(2007)257

- Configuration mixing within 2p2h excitations with high-L orbits.
  TM et al., PTP113(2005)
  TM et al., PTP117(2007)



- Length parameters such as b_{0s}, b_{0p}, … are optimized independently, or superposed by many Gaussian bases.
  - Spatial shrinkage of ***D*-wave** as seen in deuteron
    HF by Sugimoto et al,(NPA740) / Akaishi (NPA738)
    RMF by Ogawa et al.(PRC73), AMD by Dote et al.(PTP115)
- Satisfy few-body results with Minnesota central force (^{4,6}He)

Hamiltonian and variational equations in TOSM

$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij},$$

(0p0h+1p1h+2p2h)

$$\Phi(A) = \sum_k C_k \cdot \psi_k(A)$$

$\psi_k(A)$: shell model type configuration with mass number A

Particle state : Gaussian expansion for each orbit

$$\varphi_{lj}^{n}(\mathbf{r}) = \sum_{m=1}^{N} C_{lj,m}^{n} \cdot \phi_{lj,m}(\mathbf{r}) \qquad \phi_{lj,m}(\mathbf{r}) = N_l(b_{lj,m}) \cdot r^l e^{-\left(r/b_{lj,m}\right)^2} \left[Y_l(\hat{\mathbf{r}}), \chi_{1/2}^{\sigma}\right]_j$$

Gaussian basis function

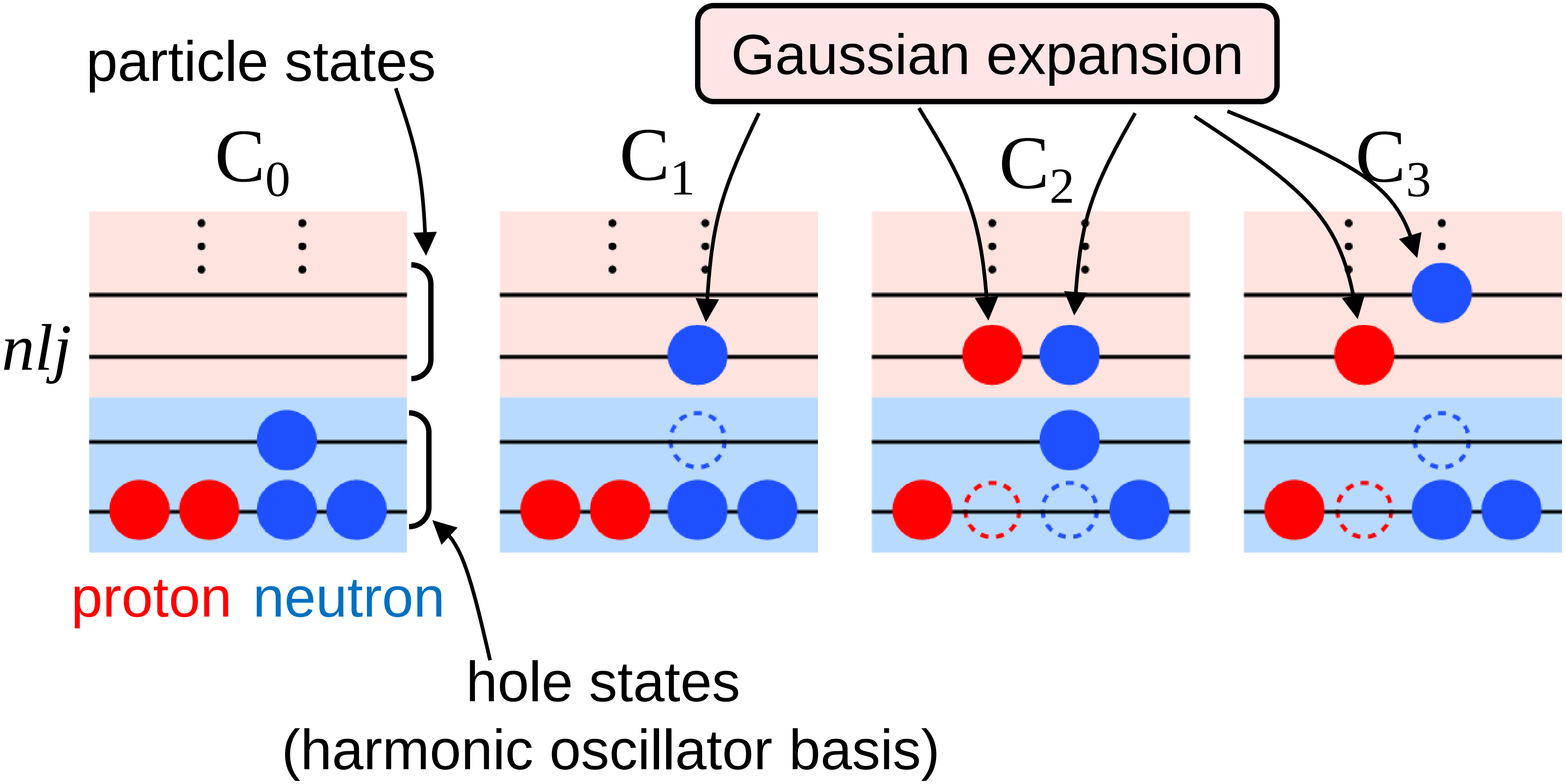
$$\left\langle \varphi_{lj}^{n} \middle| \varphi_{lj}^{n'} \right\rangle = \delta_{n,n'}$$

$$\frac{\partial \langle H - E \rangle}{\partial C_k} = 0, \qquad \frac{\partial \langle H - E \rangle}{\partial b_{lj,m}} = 0$$

TOSM code : *p*-shell region

c.m. excitation is excluded by Lawson’s method

Configurations in TOSM



Application to Hypernuclei by Umeya (NIT)
to investigate ΛN-ΣN coupling

Unitary Correlation Operator Method

(short-range part)

$$\Psi_{\text{corr.}} = C \cdot \Phi_{\text{uncorr.}}$$

TOSM

short-range correlator

$C^\dagger = C^{-1}$ (Unitary trans.)

$$H\Psi = E\Psi \;\rightarrow\; C^\dagger H C \Phi \equiv \hat{H}\Phi = E\Phi$$

Bare Hamiltonian

Shift operator depending on the relative distance

$$C = \exp(-i\sum_{i<j} g_{ij}), \qquad g_{ij} = \tfrac{1}{2}\{ p_r s(r_{ij}) + s(r_{ij}) p_r \} \qquad \vec{p} = \vec{p}_r + \vec{p}_\Omega$$

Amount of shift, variationally determined.

$$C^\dagger r C \simeq r + s(r) + \tfrac{1}{2} s(r) s'(r) \cdots$$

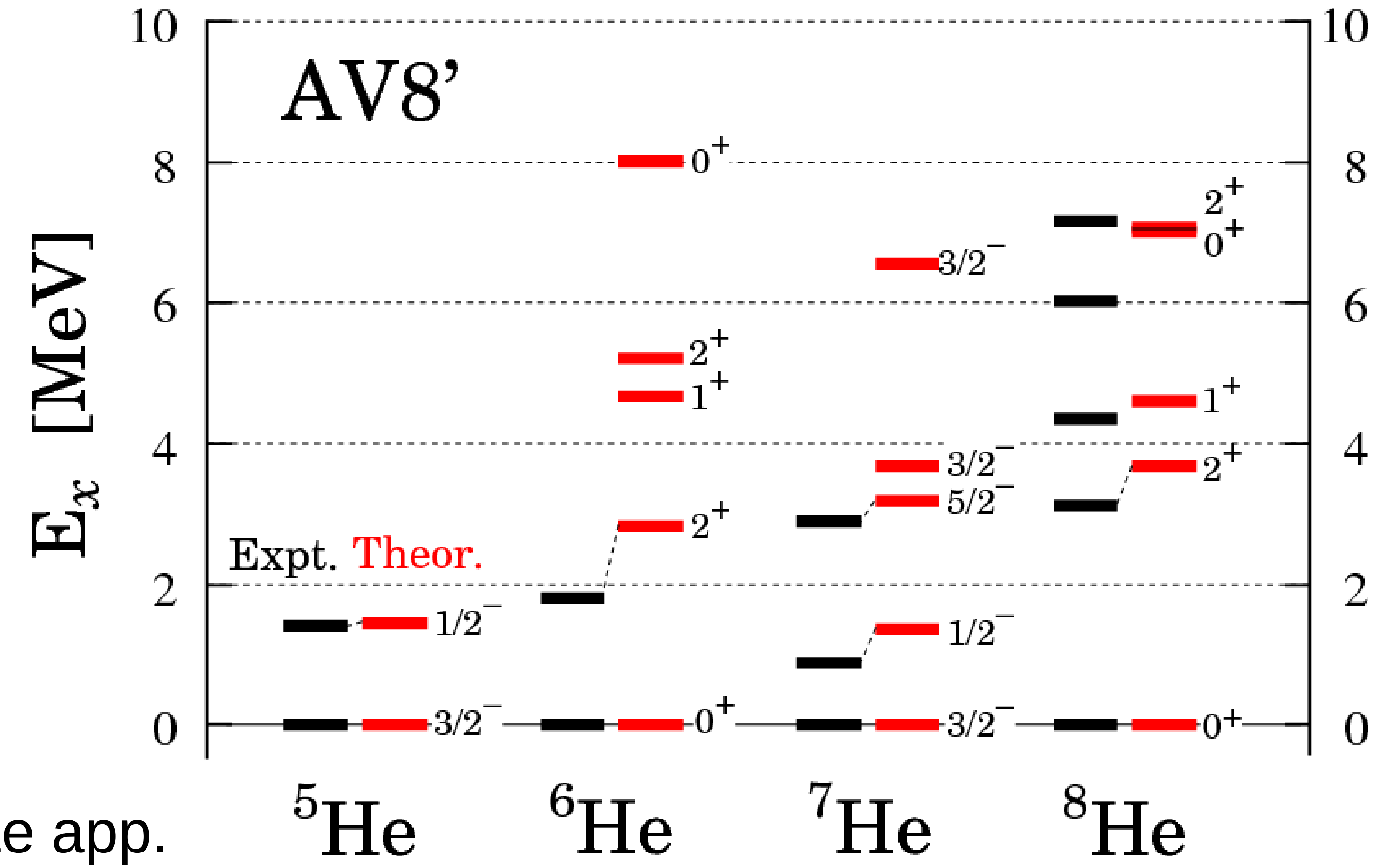
2-body cluster expansion

H. Feldmeier, T. Neff, R. Roth, J. Schnack, NPA632(1998)61

$^{4\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV

TM, A. Umeya, H. Toki, K. Ikeda
PRC84 (2011) 034315

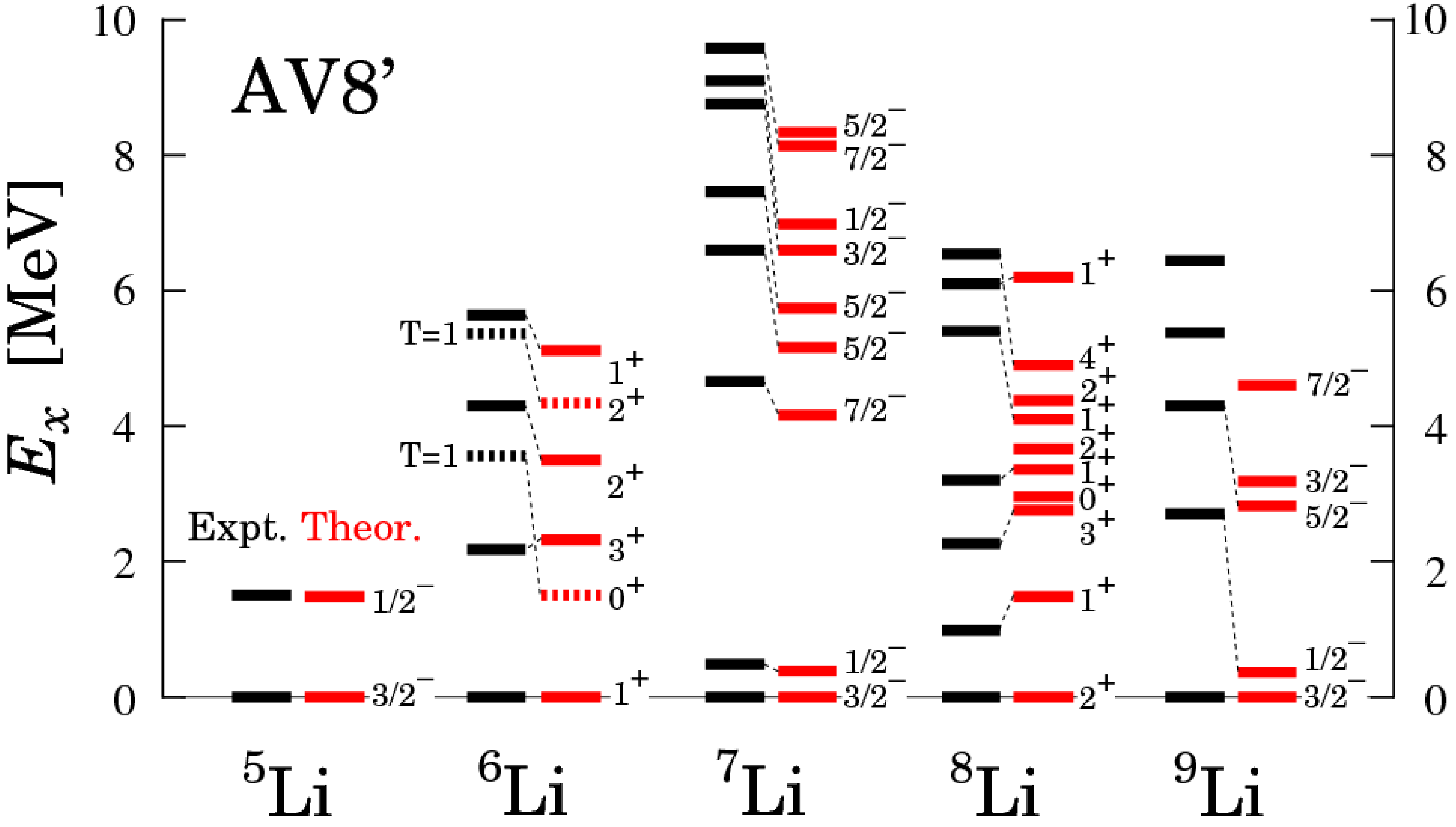


- Bound state app.
- No continuum
- No V_{NNN}

- Excitation energy spectra are reproduced well

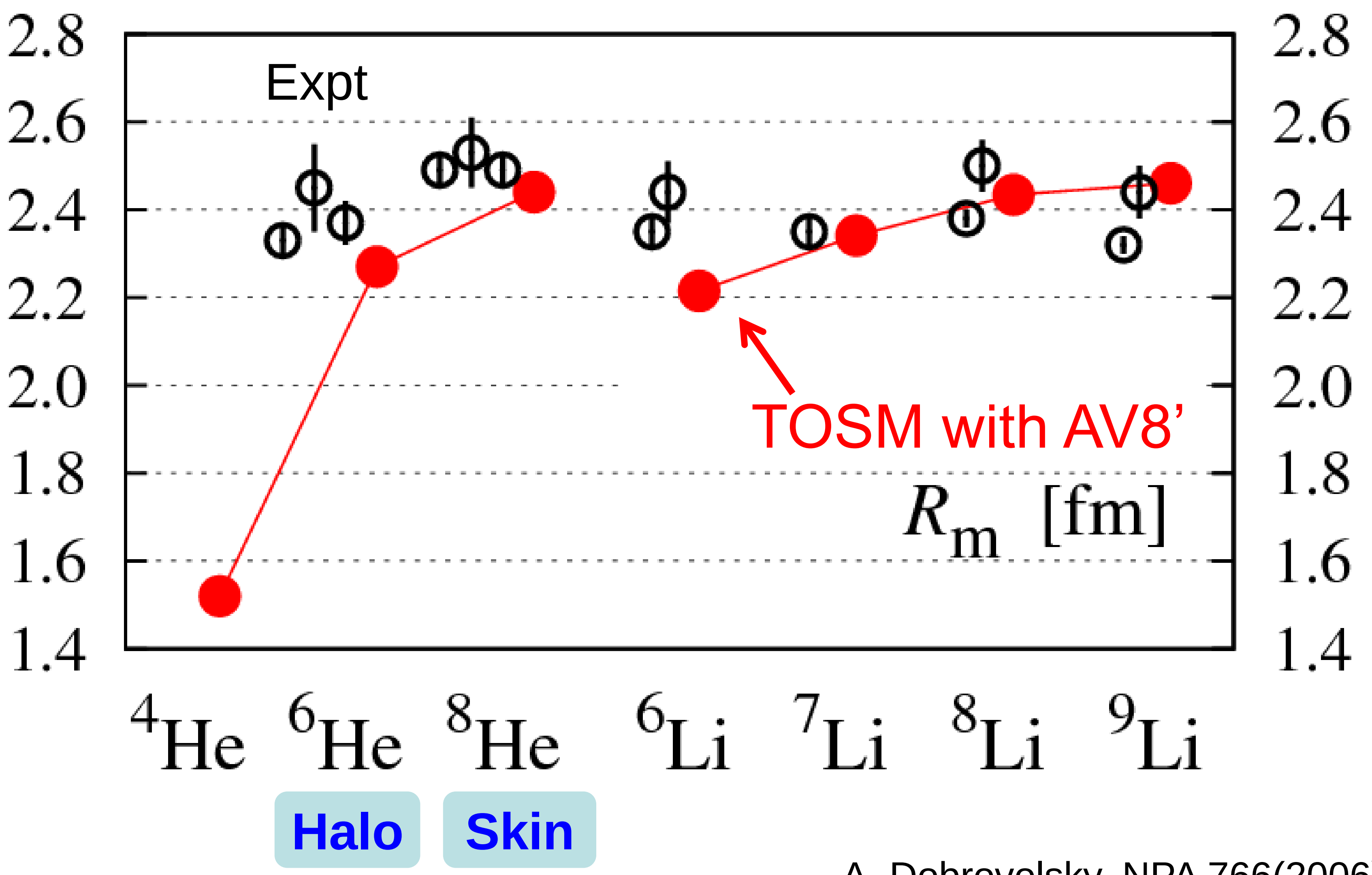
$^{5-9}$Li with TOSM+UCOM

- Excitation energies in MeV



- Excitation energy spectra are reproduced well

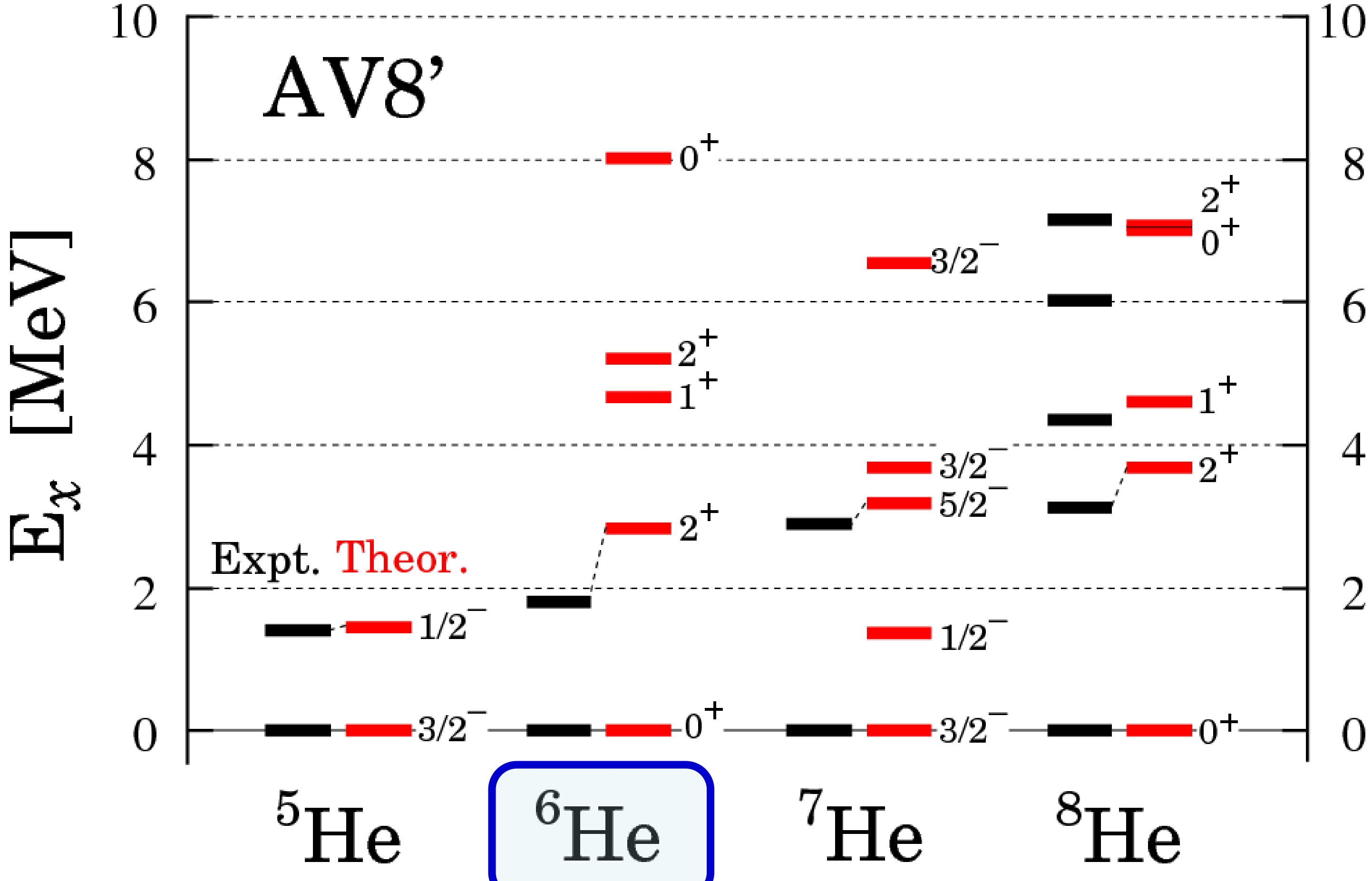
Matter radius of He & Li isotopes



A. Dobrovolsky, NPA 766(2006)1
I. Tanihata et al., PLB289('92)261
G. D. Alkhazov et al., PRL78('97)2313
O. A. Kiselev et al., EPJA 25, Suppl. 1('05)215.
P. Mueller et al., PRL99(2007)252501

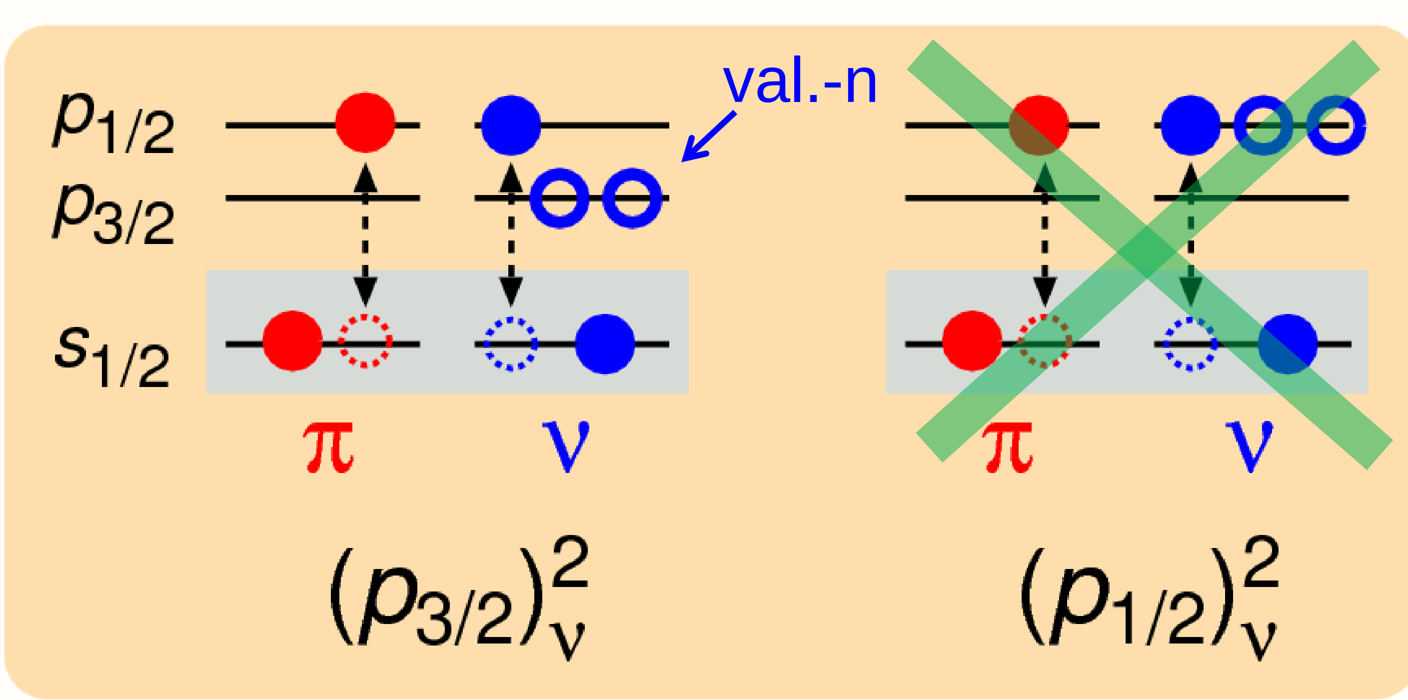
$^{4\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV



- No V_{NNN}
- No continuum
- Excitation energy spectra are reproduced well

Tensor correlation in ^{6}He



Ground state

halo state (0^+)

Excited state

Tensor correlation is **suppressed** due to Pauli-Blocking

TM, K. Kato, K. Ikeda, J. Phys. G31 (2005) S1681

^{6}He : Hamiltonian component in TOSM

- Difference from ^{4}He in MeV

^{6}He	0^+_1	0^+_2
n^2 config	$(p_{3/2})^2$	$(p_{1/2})^2$

b_{hole}=1.5 fm

$\hbar\omega$=18.4 MeV (hole)

same trend in $^{5-8}$He

LS splitting energy in ^{5}He

•Terasawa, Arima PTP23 ('60)
•Nagata, Sasakawa, Sawada, Tamagaki, PTP22('59)
•Myo, Kato, Ikeda, PTP113 ('05)

Summary

- **Halo formation in ^{11}Li** with tensor and pairing correlations.
  - Coexistence of tensor and pairing correlations
  - Pauli-blocking caused by halo neutrons
- ^{4}He contains "***pn*-pair of $p_{1/2}$**" than $p_{3/2}$.
- **TOSM+UCOM** with bare nuclear force.
- **He isotopes with $p_{3/2}$** has large contributions of V_{tensor} & Kinetic energy.

Review **Di-neutron clustering and deuteron-like tensor correlation in nuclear structure focusing on ^{11}Li**

K. Ikeda, T. Myo, K. Kato and H. Toki
Springer, Lecture Notes in Physics 818 (2010)
"Clusters in Nuclei" Vol.1, 165-221.