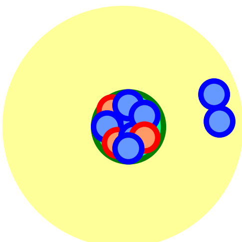
# Di-neutron correlation in light neutron-rich nuclei



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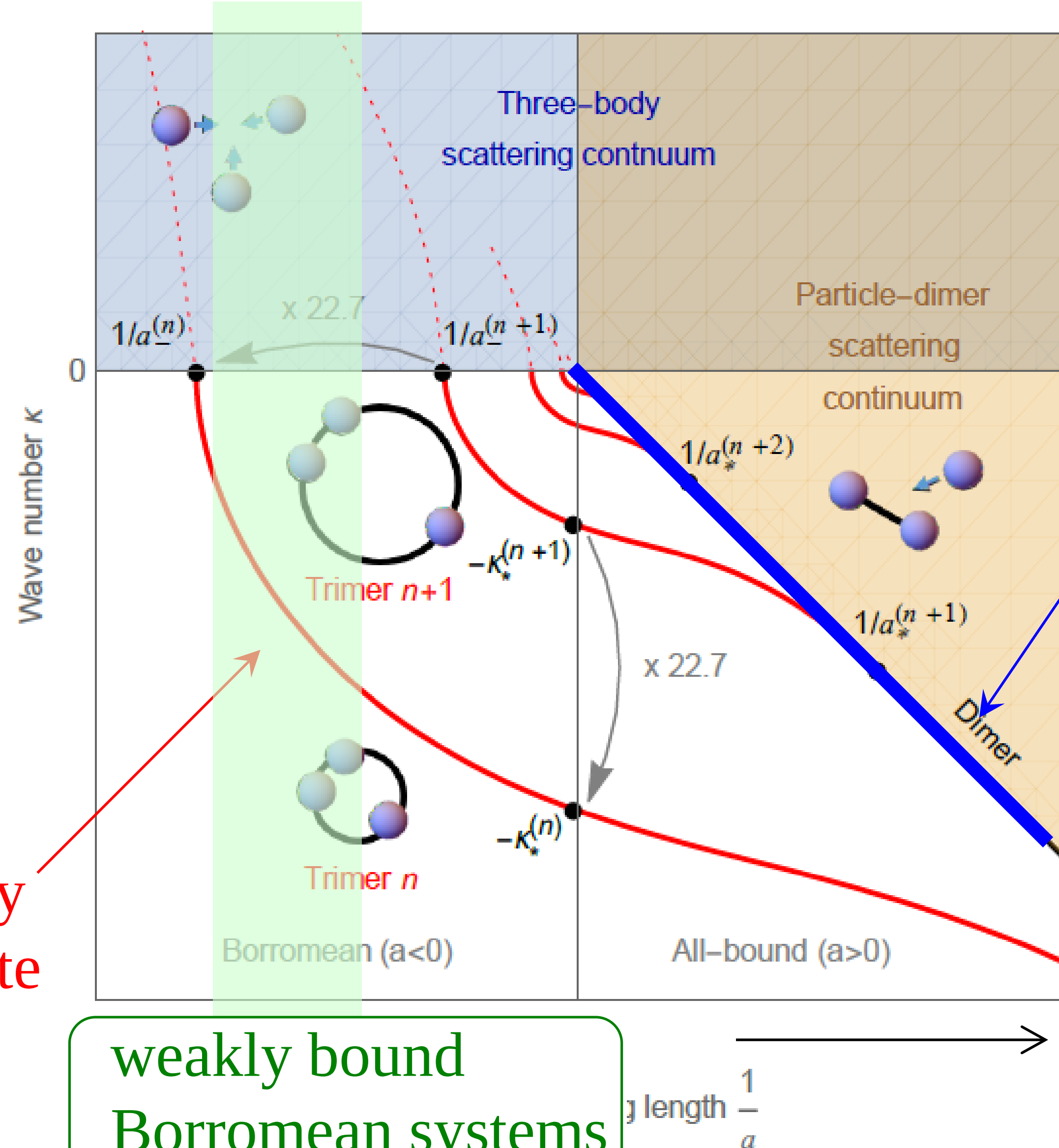
TOHOKU UNIVERSITY

1. Borromean systems in atomic nuclei
2. Three-body model and di-neutron correlation
3. Dipole excitations
4. Three-body resonance states
5. Summary

Reimei workshop on “Universal Physics in Many-Body Quantum Systems”,
Dec. 12-14, 2018, Tokai, Japan

# Borromean systems in atomic nuclei




two-body
bound state

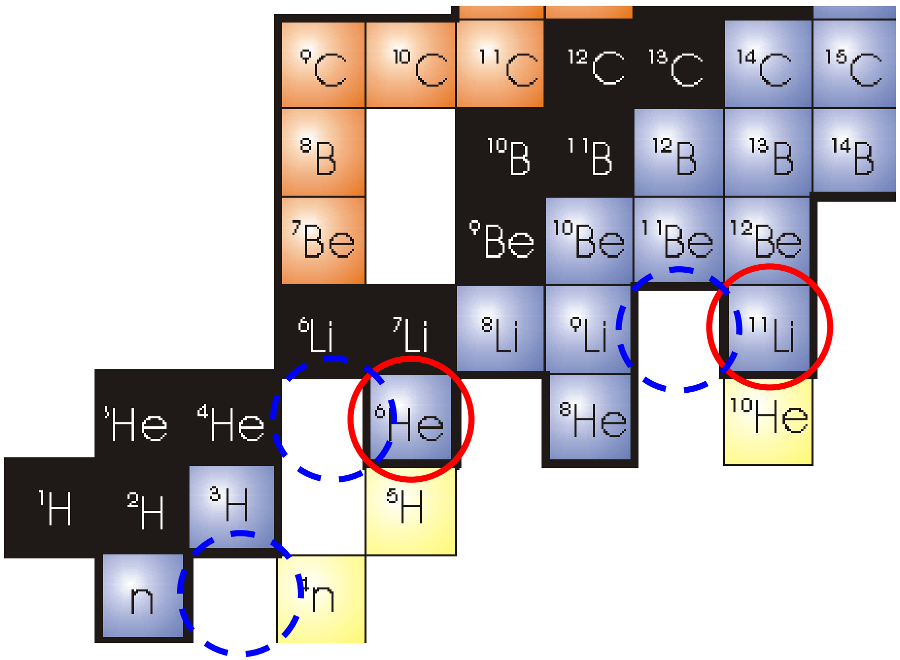
three-body
bound state

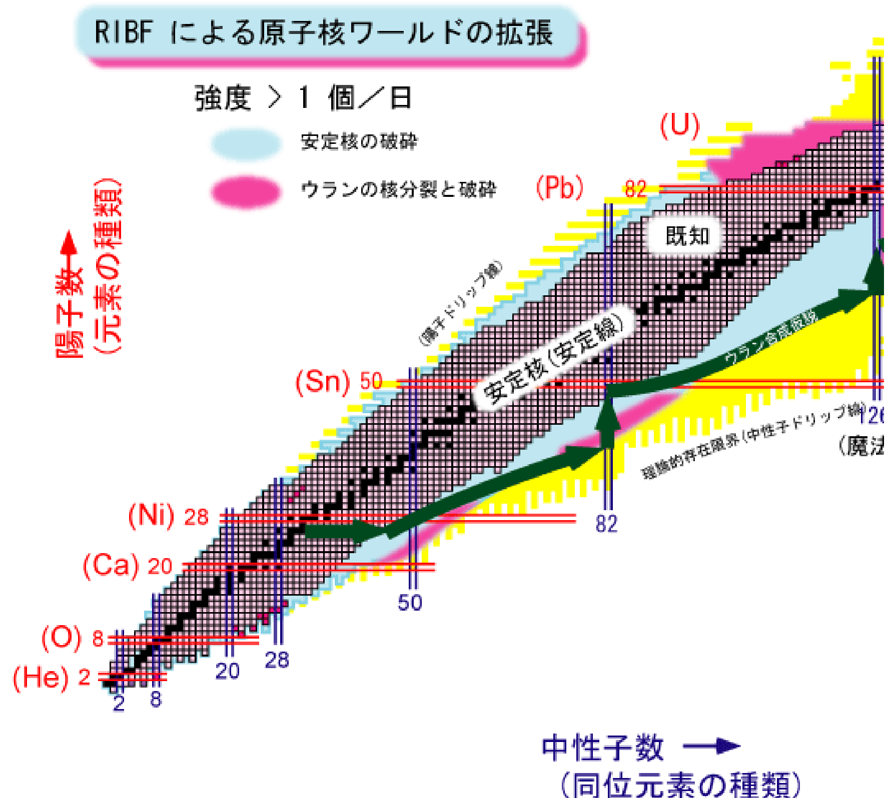
weakly bound
Borromean systems

→ $1/a$

P. Naidon and S. Endo, Rep. Prog. Phys. 80 (‘17)056001

# Borromean nuclei




$^{11}Li = {}^{9}Li + n + n$ : bound

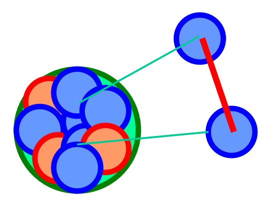
$^{9}Li + n$ : unbound

$n + n$ : unbound

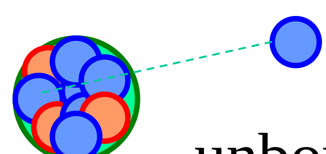
$^{6}He = {}^{4}He + n + n$ : bound

$^{4}He + n$ : unbound

$n + n$ : unbound



bound



unbound

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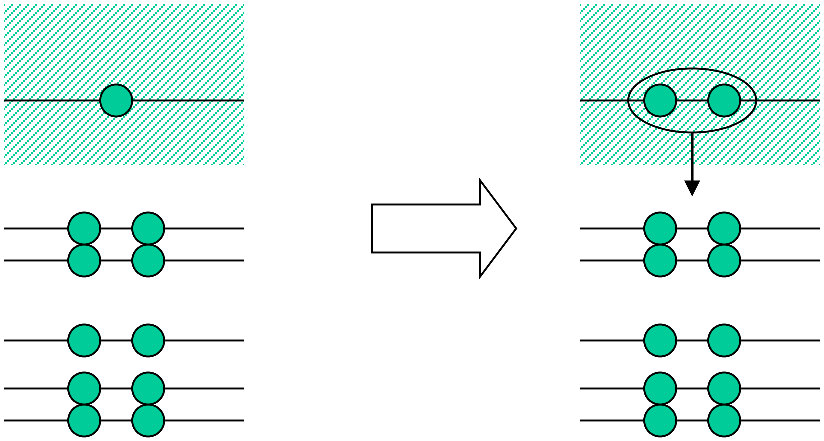
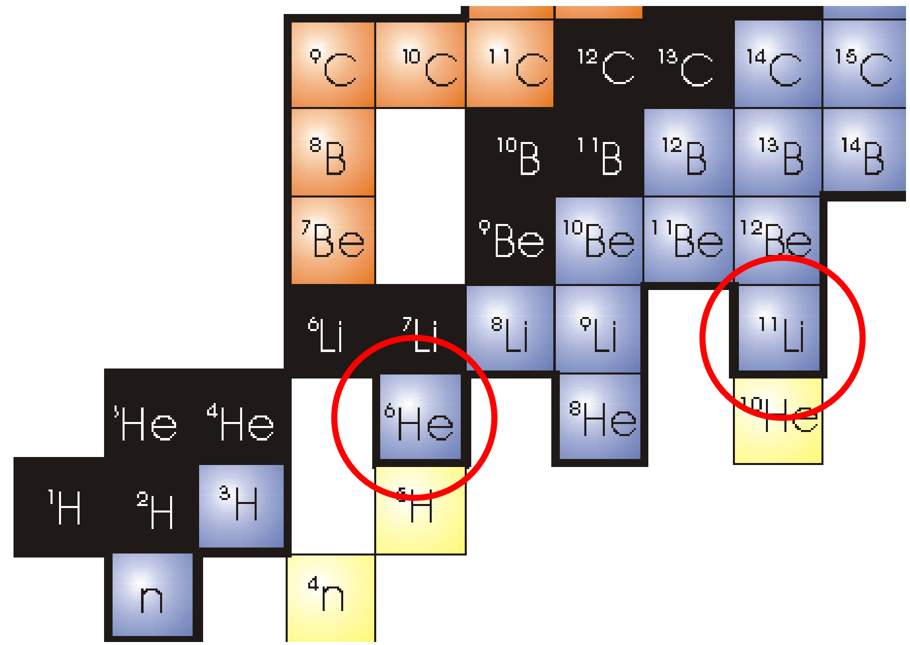
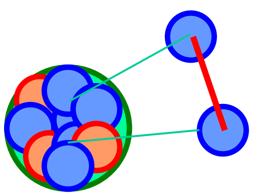
# Borromean nuclei

residual interaction → attractive



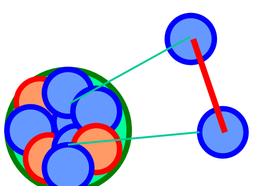
particle unstable particle stable



nn attraction

bound



nn attraction

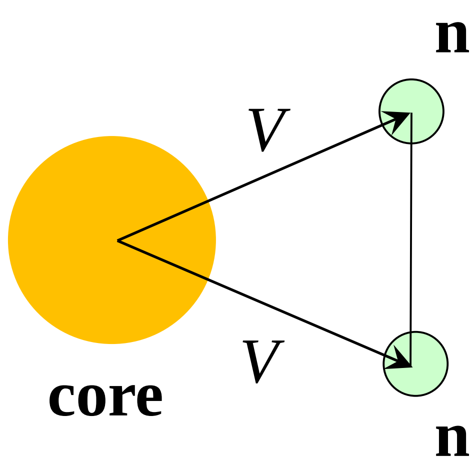
unbound, but almost bound: $^{26}$O

Questions to ask: the role of nn-correlation?

- Spatial structure?
- Excitation modes?
- Decay dynamics of unbound nuclei?
- Influence to nuclear reactions?

# Three-body model and di-neutron correlation

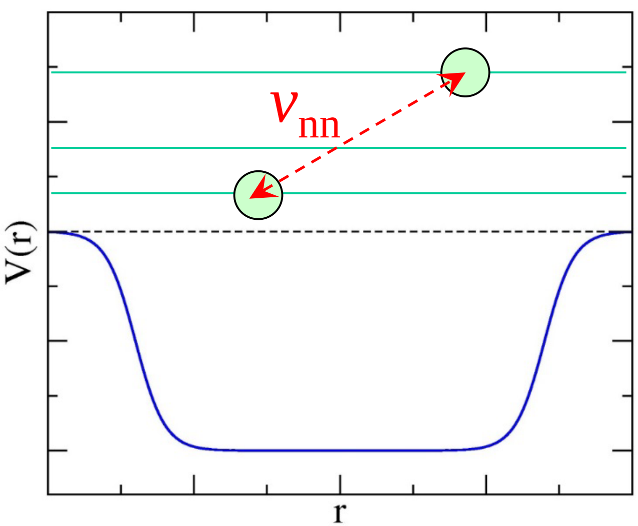
$^{11}$Li, $^{6}$He




Density-dependent delta-force

$$v(\boldsymbol{r}_1, \boldsymbol{r}_2) = v_0(1 + \alpha\rho(r)) \times\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

$v_0 \leftarrow$ scatt. length




continuum states:
discretized in a large box

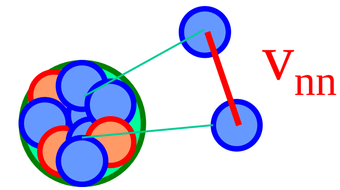
$$\Psi_{gs}(\boldsymbol{r}, \boldsymbol{r}') = \mathcal{A} \sum_{nn'lj} \alpha_{nn'lj} \Psi^{(2)}_{nn'lj}(\boldsymbol{r}, \boldsymbol{r}')$$

$\longrightarrow$ diagonalize the $H_{3bd}$

G.F. Bertsch and H. Esbensen, Ann. of Phys. 209 ('91) 327
K.H. and H. Sagawa, PRC72 ('05) 044321

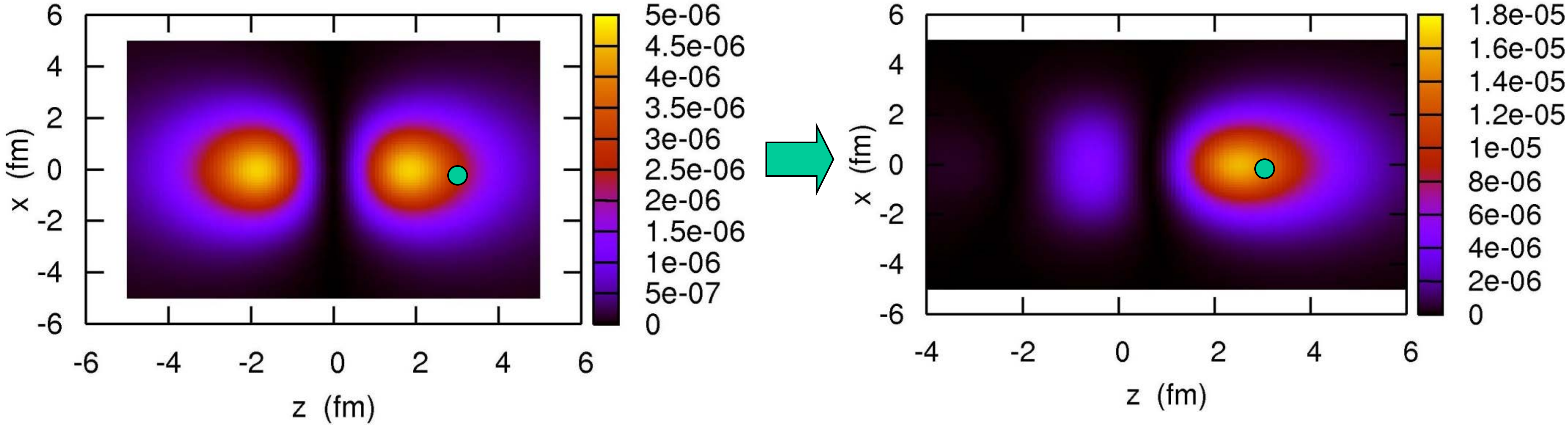
# The ground state density: $^{11}$Li = $^{9}$Li + n + n

K.H. and H. Sagawa, PRC72('05)044321




without nn interaction

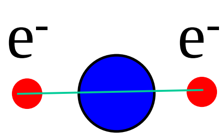
with nn interaction

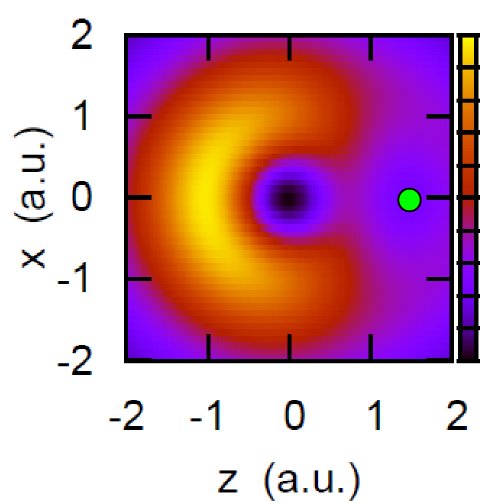



large asymmetry in density distribution = **<u>di-neutron correlation</u>**

cf. Matsuo-san's talk

cf. Coulomb hole in He atom
(He nucleus + e$^-$ + e$^-$)

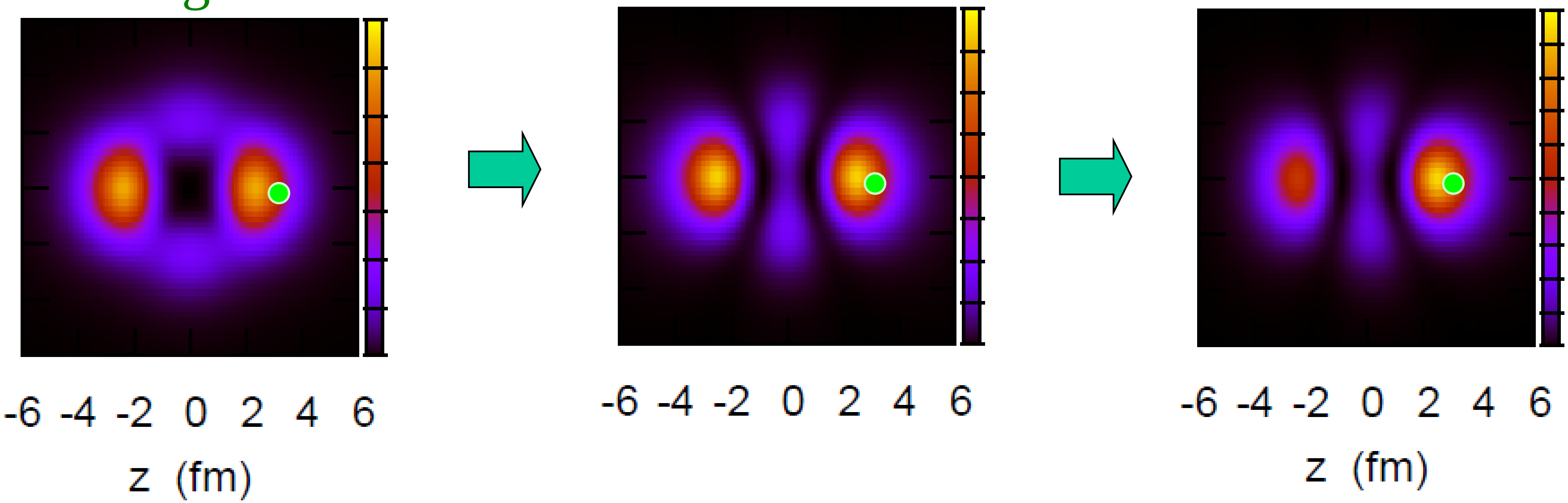


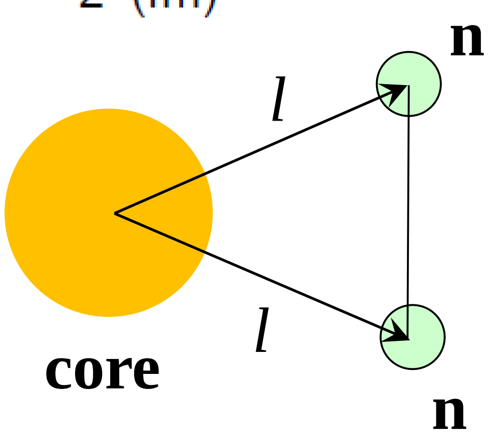



## role of parity mixing

$^{18}O = {}^{16}O + n + n \rightarrow \quad \rho_2(\boldsymbol{r}) = |\Psi_{\rm g.s.}(\boldsymbol{r}, \boldsymbol{r}')|^2_{\boldsymbol{r}'=z_0}$

single-*l* → multi-*l*, but even *l* only → multi-*l*, both even and odd *l*



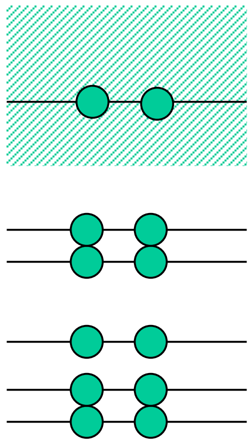




cf. F. Catara, A. Insolia, E. Maglione, and A. Vitturi, PRC29('84)1091

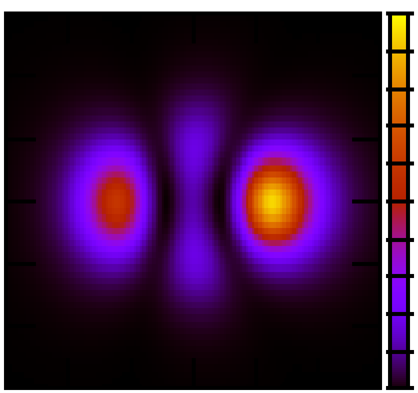
# weakly bound systems

✓ continuum states

several *l*'s

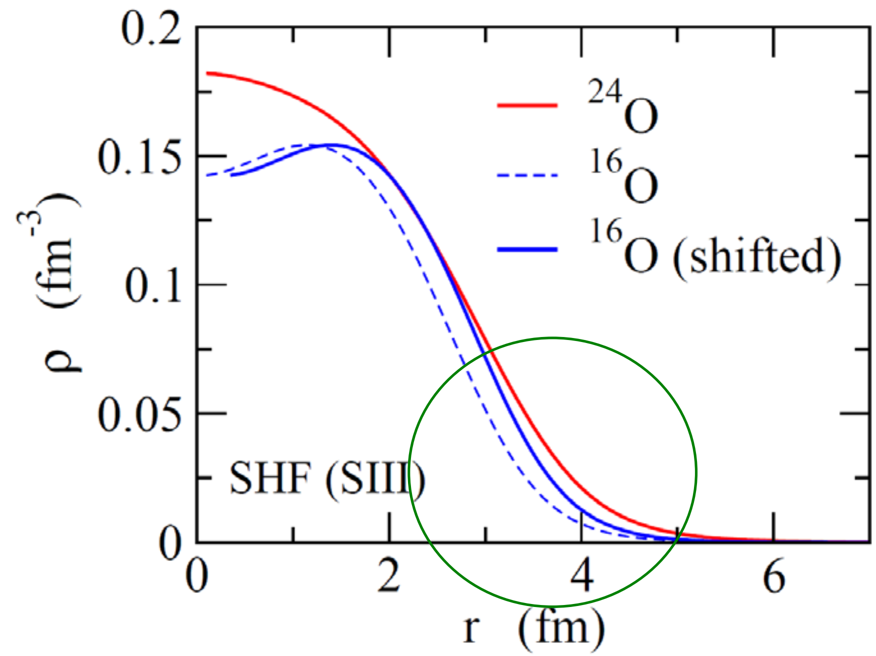


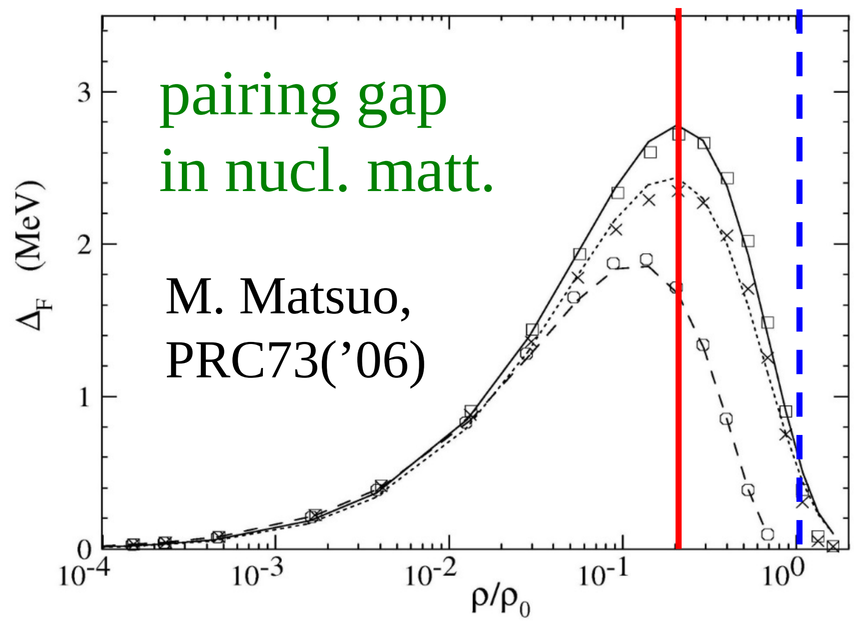
parity mixing: easy



➡ enhanced dineutron correlation

✓ extended density distribution



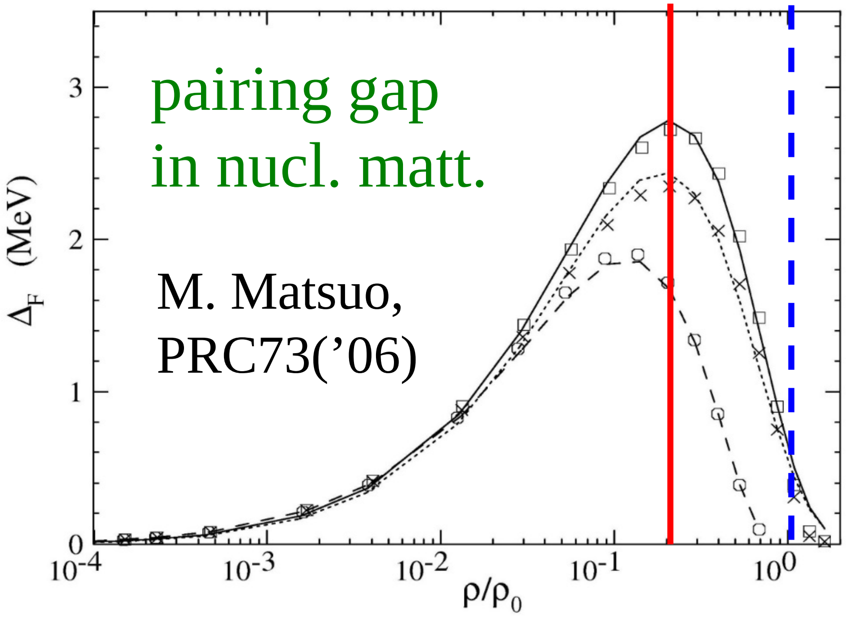



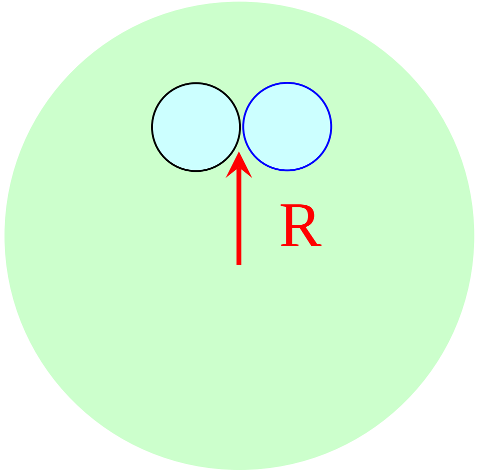
# probing several density regions

K.H. et al., PRL99 ('07) 022506

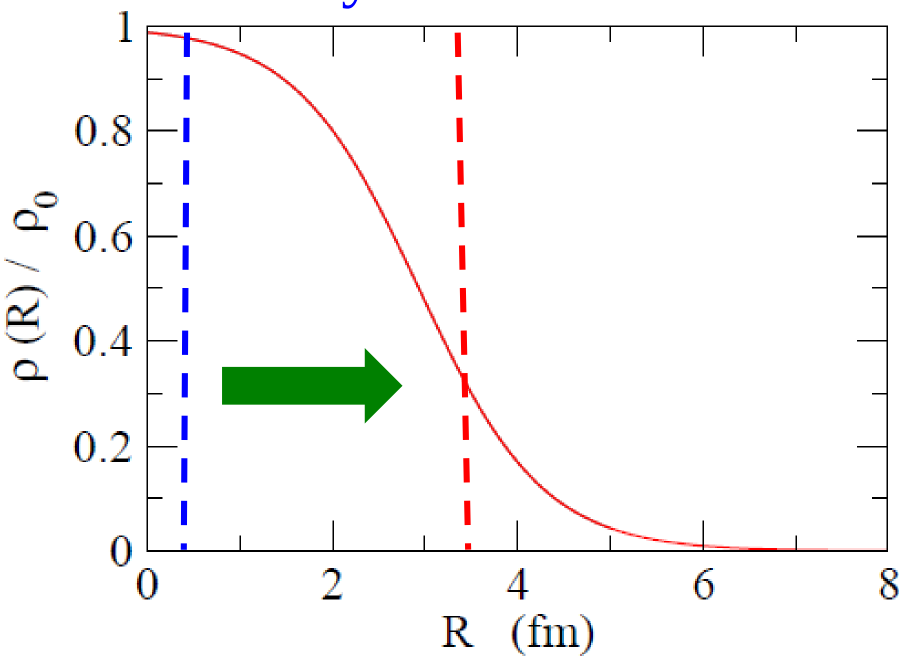
pairing gap in nucl. matt.

M. Matsuo, PRC73('06)

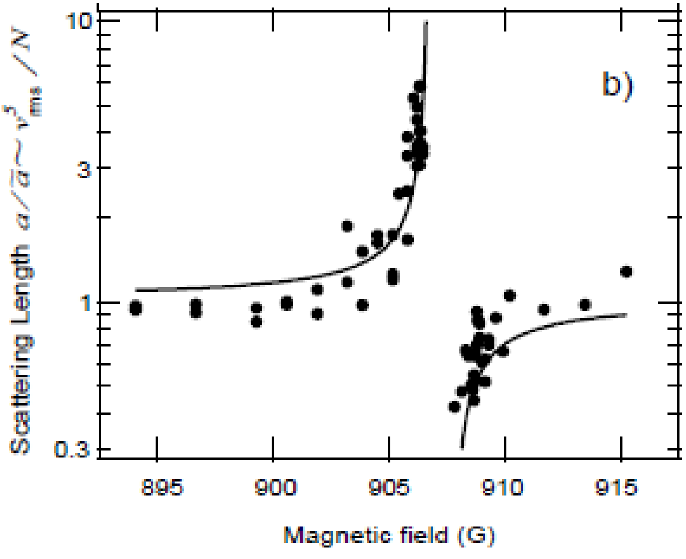



Density distribution

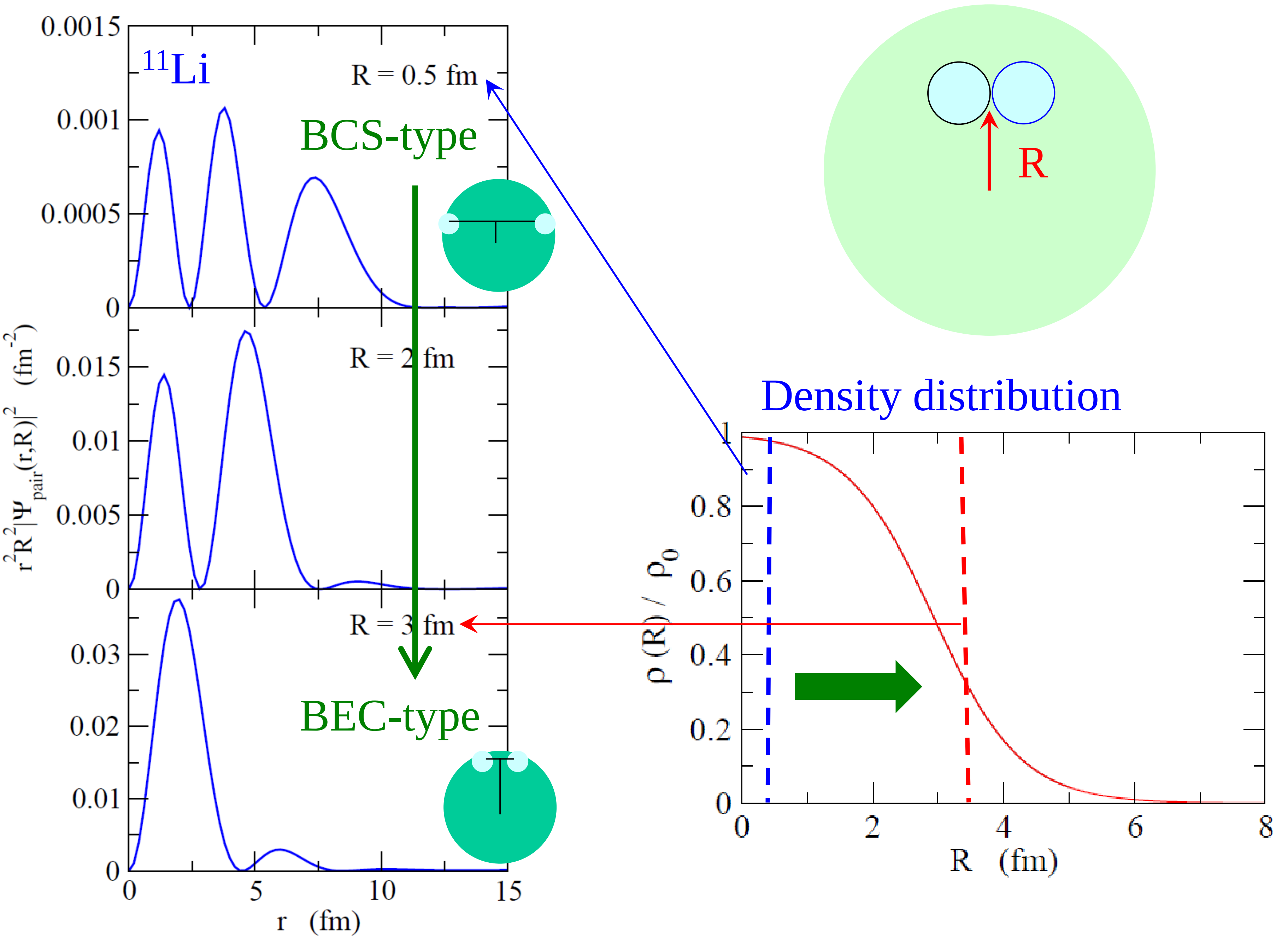



effective change in an interaction



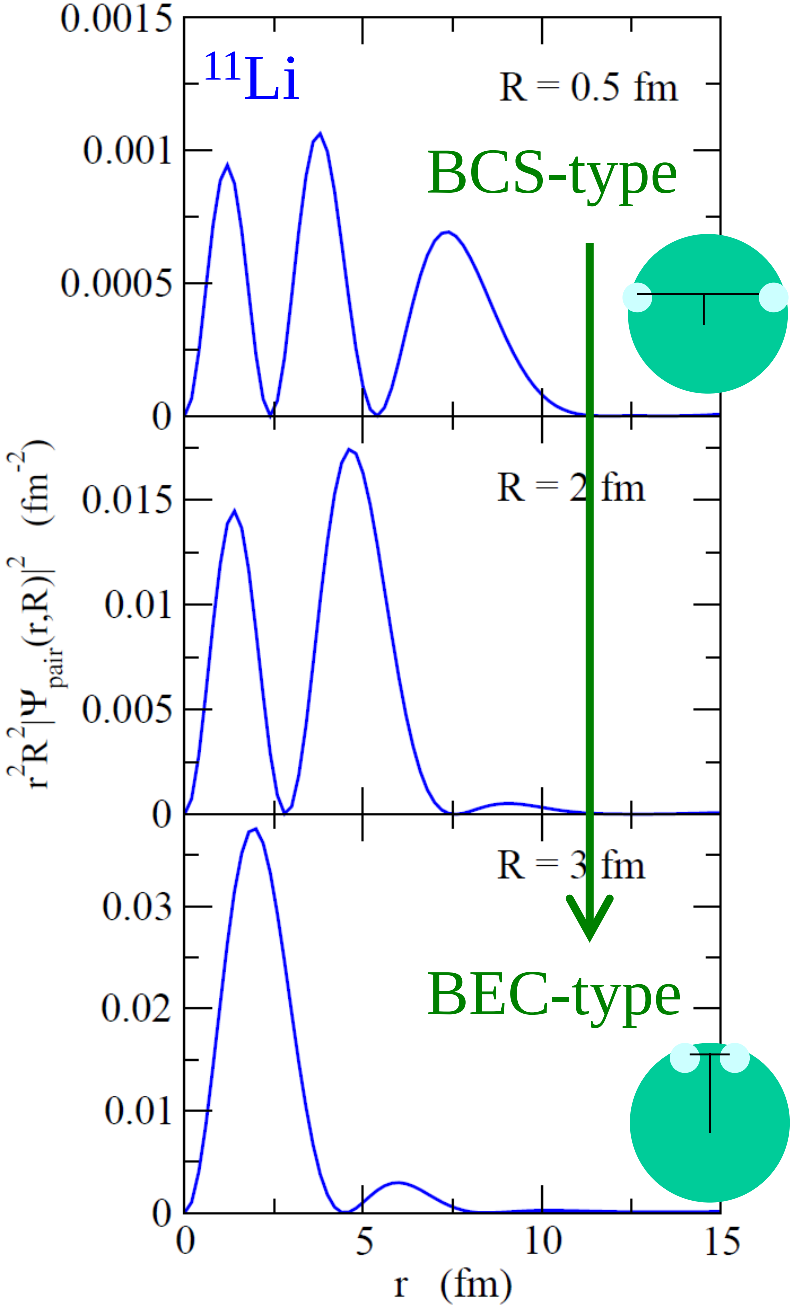
# probing several density regions

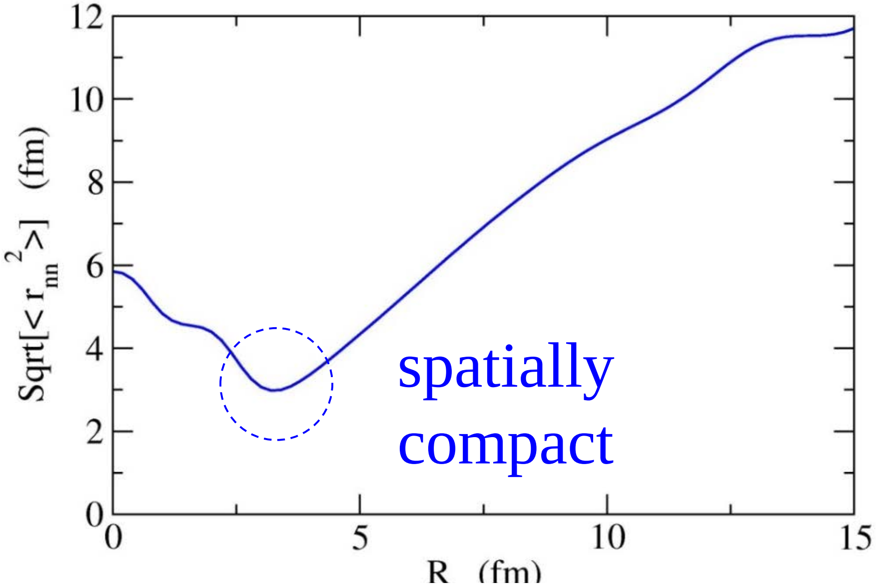
K.H. et al., PRL99 ('07) 022506

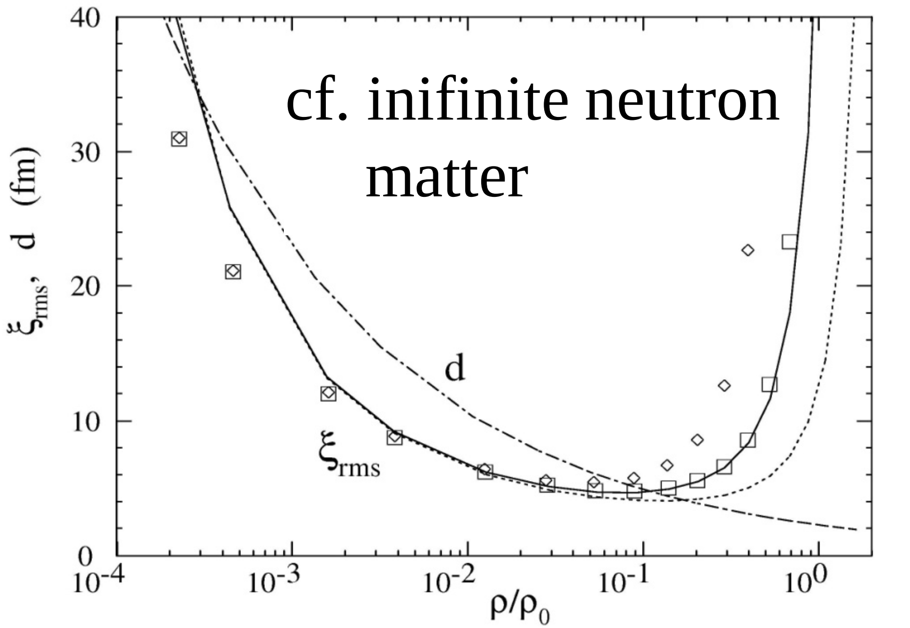


## probing several density regions

K.H. et al., PRL99 ('07) 022506



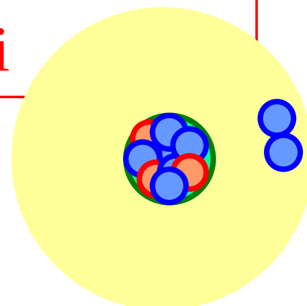




M. Matsuo, PRC73('06)044309

# Di-neutron correlations in neutron-rich nuclei

Strong di-neutron correlations
in neutron-rich nuclei



✓ Borromean nuclei (3body calc.)

Bertsch-Esbensen (‘91)
Zhukov et al. (‘93)
Hagino-Sagawa (‘05)
Kikuchi-Kato-Myo (‘10)

✓ Heavier nuclei (HFB calc.)

Matsuo et al. (‘05)
Pillet-Sandulescu-Schuck (‘07)

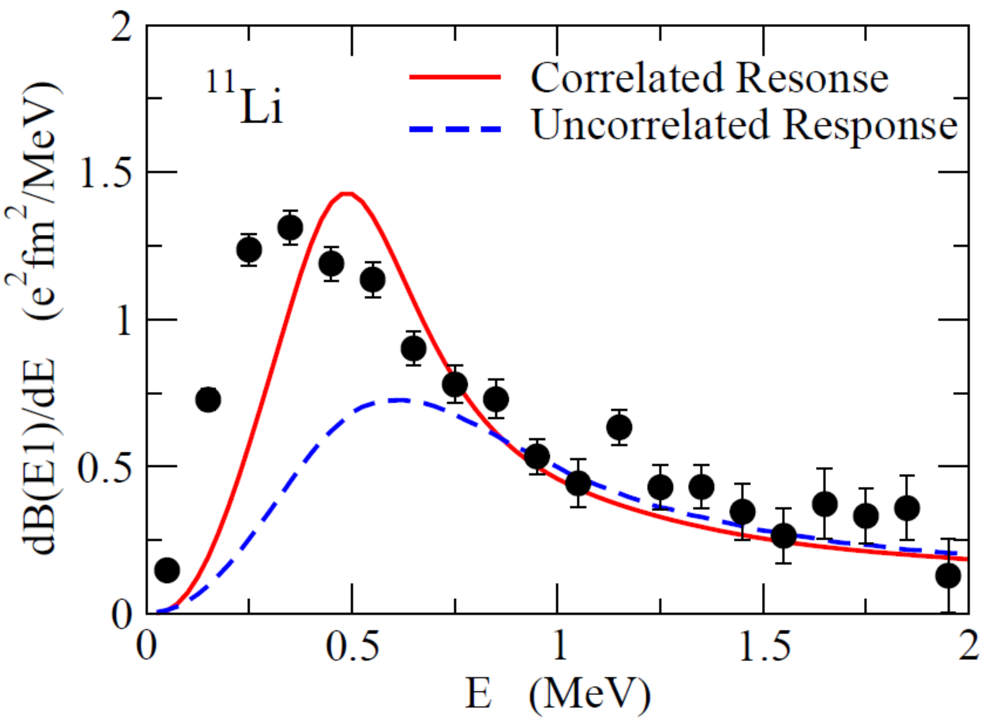
How to probe it experimentally?

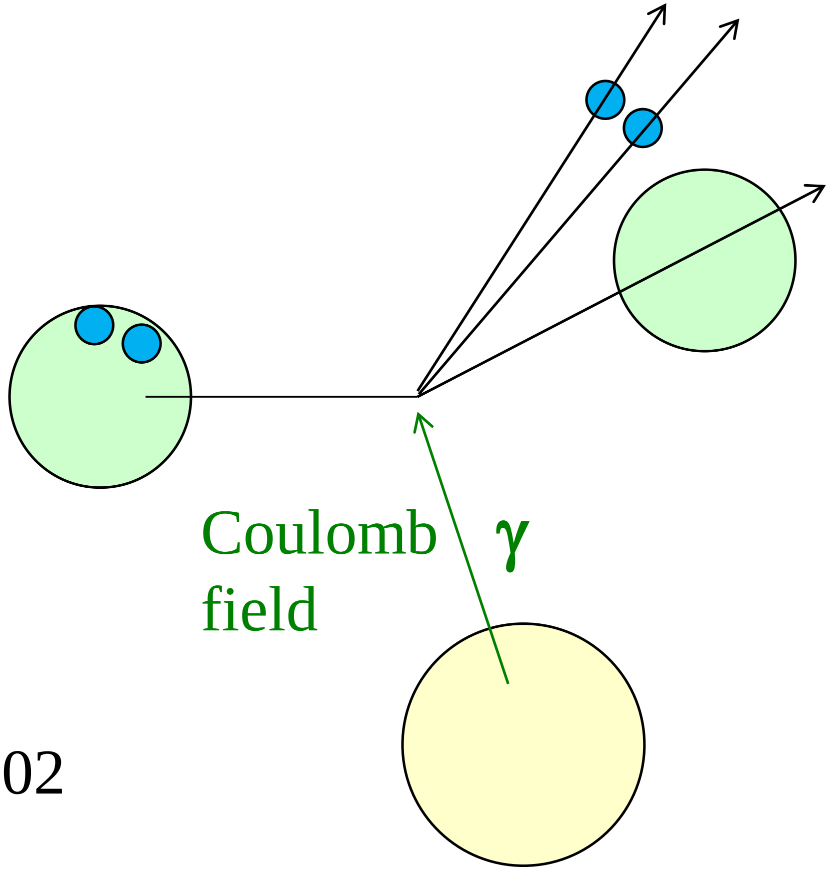
➢ Coulomb breakup
T. Nakamura et al.
cluster sum rule
(mean value of $\theta_{nn}$)

➢ Two-neutron decays
3-body resonance due to
a centrifugal barrier
MoNA ($^{16}$Be, $^{13}$Li, $^{26}$O)
**SAMURAI ($^{26}$O)**
GSI ($^{26}$O)

# Coulomb breakup of 2-neutron halo nuclei

How to probe the di-neutron correlation? ⟶ Coulomb breakup



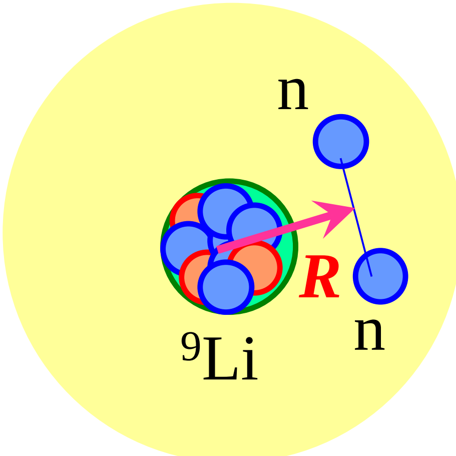

Experiments:

T. Nakamura et al., PRL96 (’06) 252502

3-body model calculations:

K.H. et al., PRC80 (‘09) 031301(R)

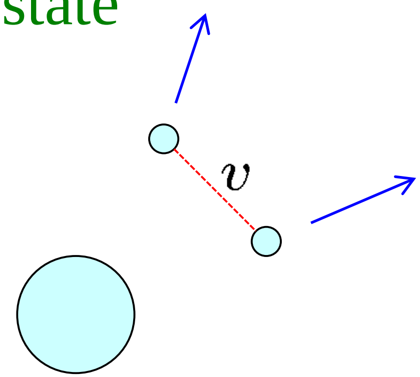
# A possible connection to hadron physics



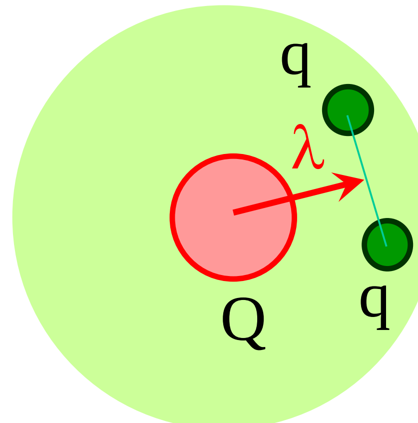

E1excitation

$$\hat{T}_{\mathrm{E1}} \propto \boldsymbol{R}$$

final state

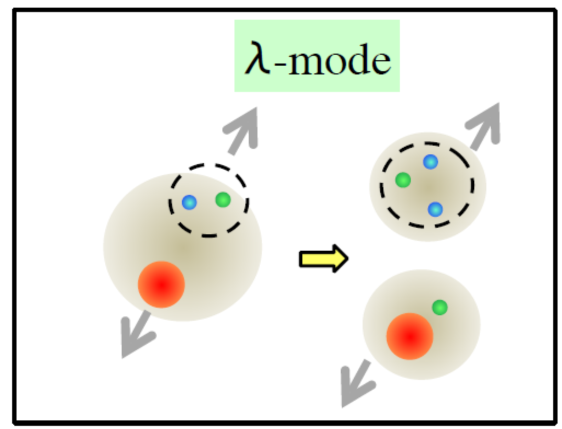


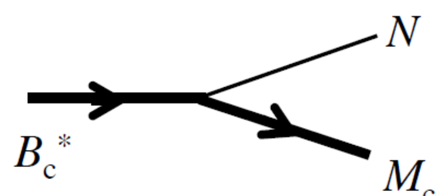

## Baryons with a charm quark




λ mode

final state: confinement




any universality?

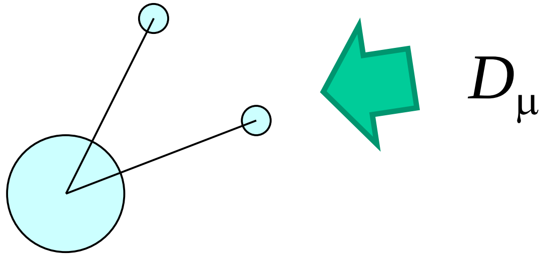
the same discussion

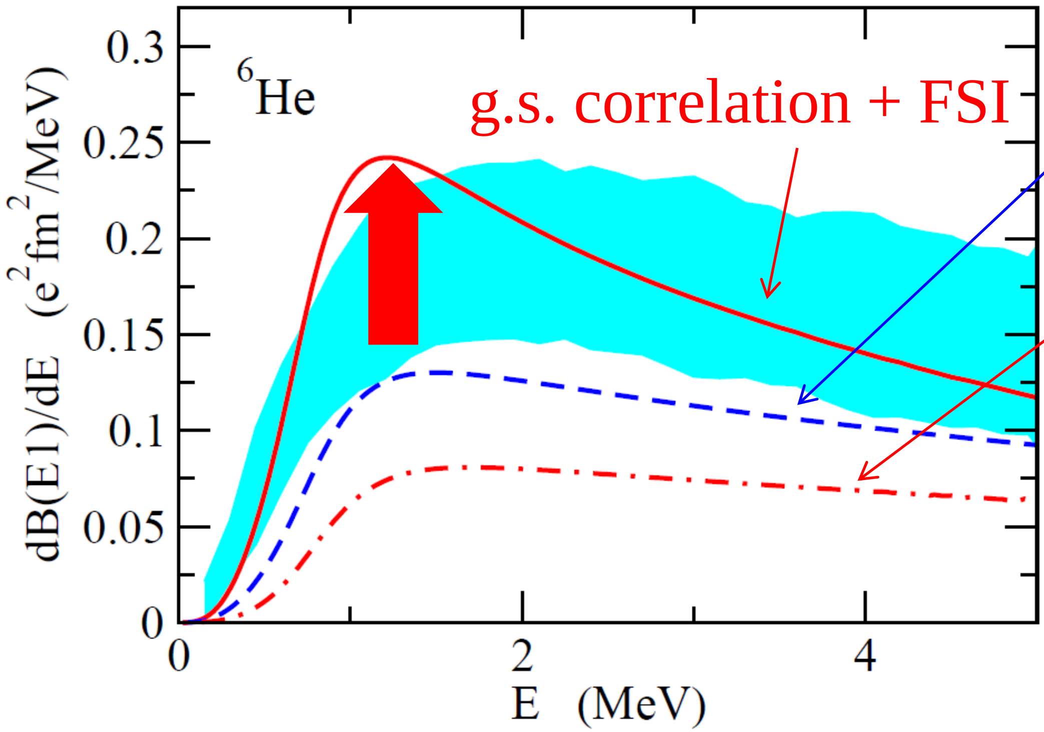
using invariant mass?

courtesy: A. Hosaka

# g.s. correlation? or correlation in excited states?

$^6He(0^+) \rightarrow {}^6He(1^-) \rightarrow \alpha + n + n$



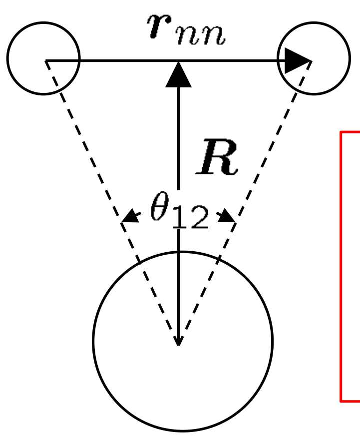

g.s. correlation only
(no nn interaction in
the final state)

g.s.：odd-*l* only
(no dineutron correlation)
＋FSI

Expt.: T. Aumann et al., PRC59('99)1252

✓Both FSI and dineutron correlations: important role in E1 strength

# Geometry of Borromean nuclei




Cluster sum rule

$$B_{\rm tot}(E1) = \sum_f |\langle \Psi_f | \hat{T}_{\rm E1} | \Psi_0 \rangle|^2 \sim \frac{3}{\pi} \left( \frac{Z_c e}{A_c + 2} \right)^2 \langle R^2 \rangle$$

reflects the g.s. correlation

“experimental data” for opening angle

$\sqrt{\langle R^2 \rangle} \longleftarrow$ $B_{tot}(E1)$

$\sqrt{\langle r^2_{\rm nn} \rangle} \longleftarrow$ matter radius

$$\langle \theta_{12} \rangle = 65.2 \pm 12.2 \;\; (^{11}\text{Li}) \qquad = 74.5 \pm 12.1 \;\; (^{6}\text{He})$$

$\Longleftrightarrow \langle \theta_{12} \rangle_{\rm no-corr.} = 90$

$\longrightarrow$ di-neutron correlation

K.H. and H. Sagawa,PRC76(’07)047302

# Geometry of Borromean nuclei

"experimental data" for opening angle

$\sqrt{\langle R^2 \rangle} \longleftarrow B_{tot}(E1)$

$\sqrt{\langle r_{nn}^2 \rangle} \longleftarrow$ matter radius

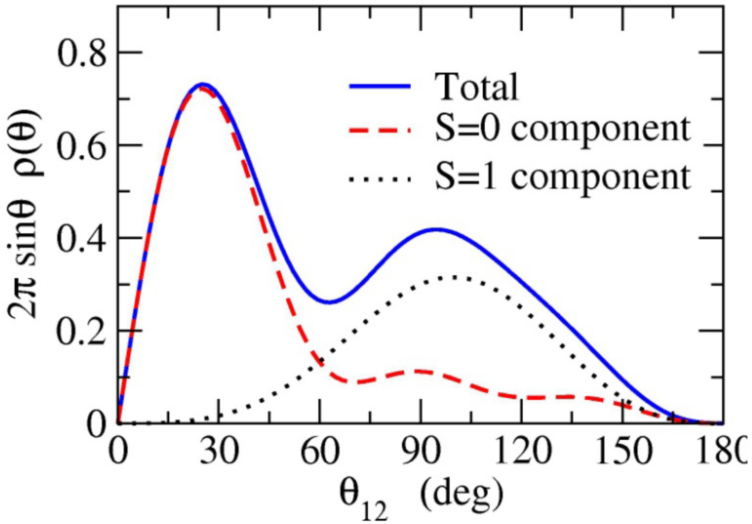
$$\langle \theta_{12} \rangle = 65.2 \pm 12.2 \; (^{11}\mathrm{Li})$$
$$= 74.5 \pm 12.1 \; (^{6}\mathrm{He})$$

$\Longleftrightarrow \langle \theta_{12} \rangle_{\mathrm{no-corr.}} = 90$

⟶ di-neutron correlation

K.H. and H. Sagawa,PRC76 ('07) 047302

3-body model calculations

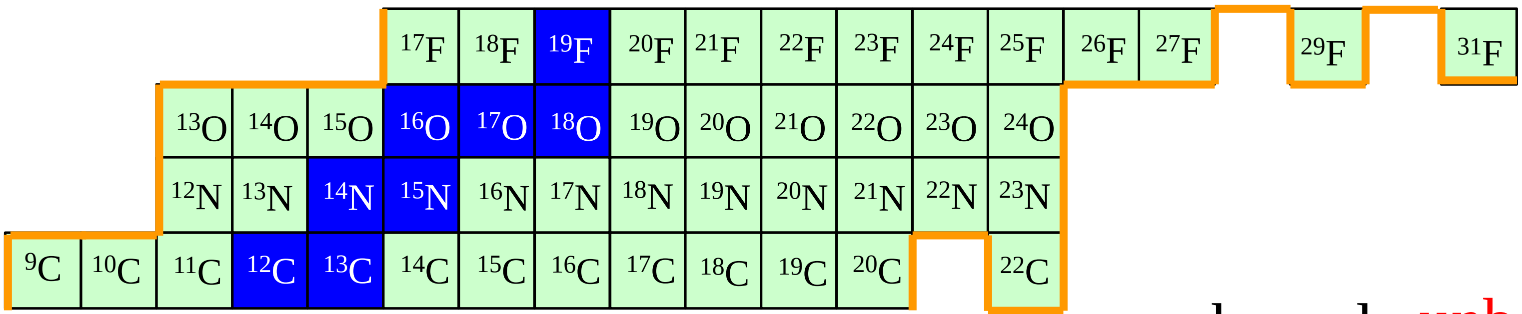


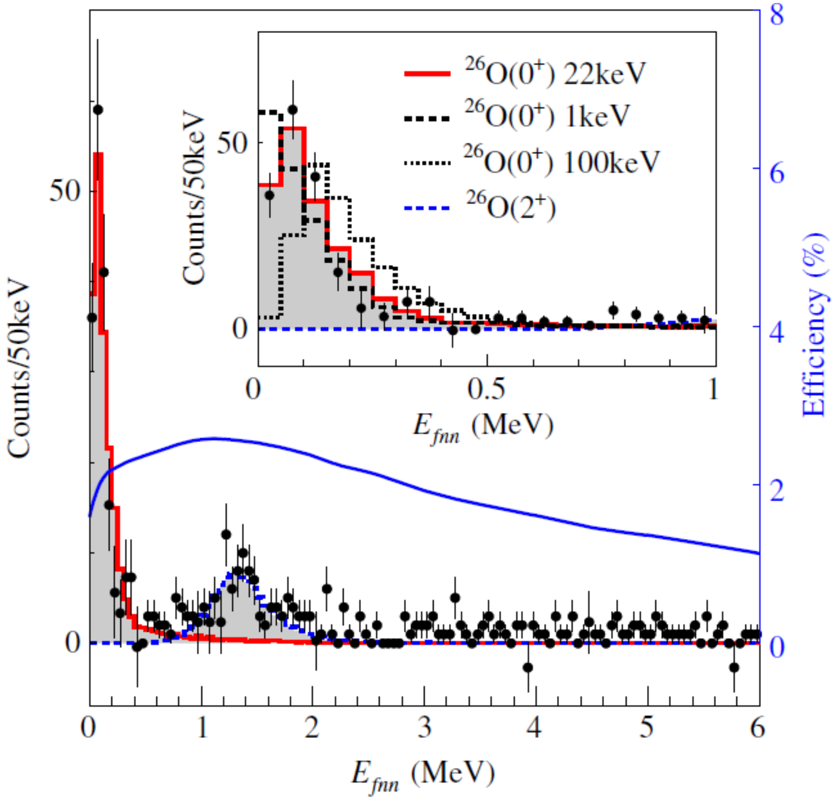

✓ but, average value only

✓ no accessible to the detailed structure

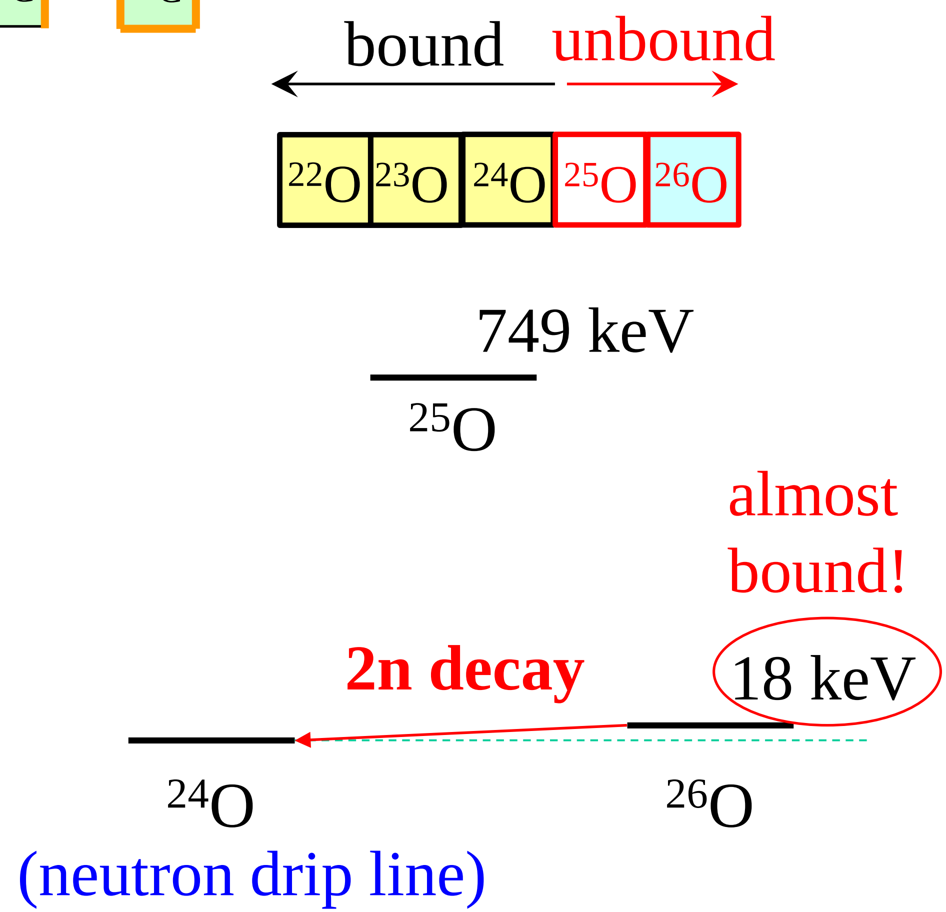
⟶ other probes?

# Two-neutron decay of $^{26}$O

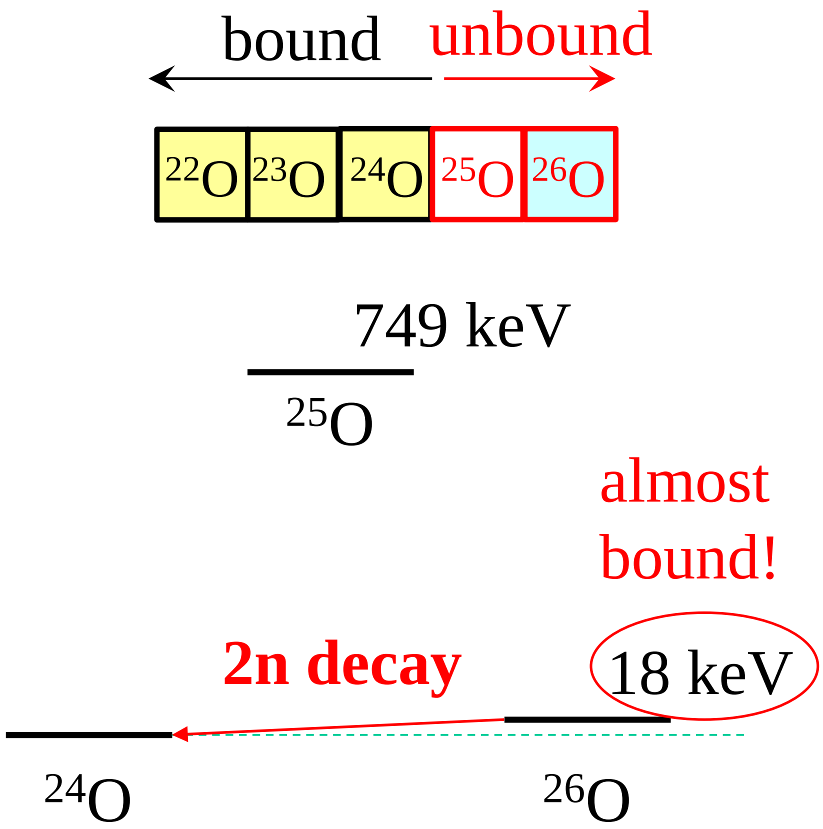


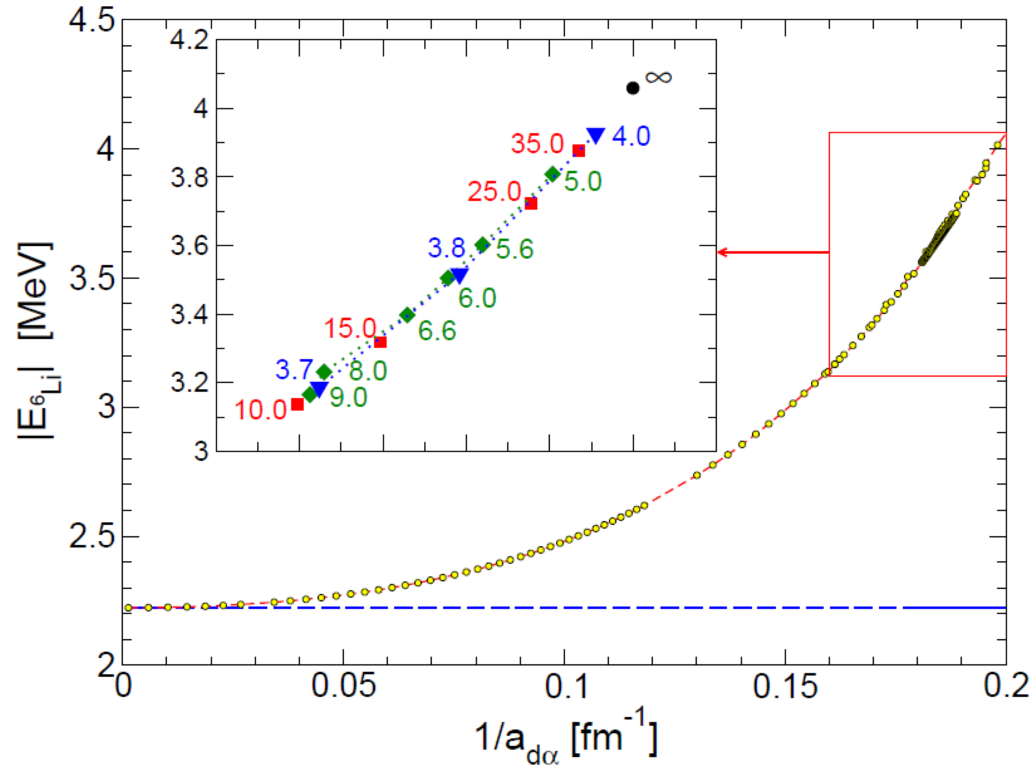




Y. Kondo et al., PRL116('16)102503



# cf. a few-body universality in $^6$Li = α + p + n



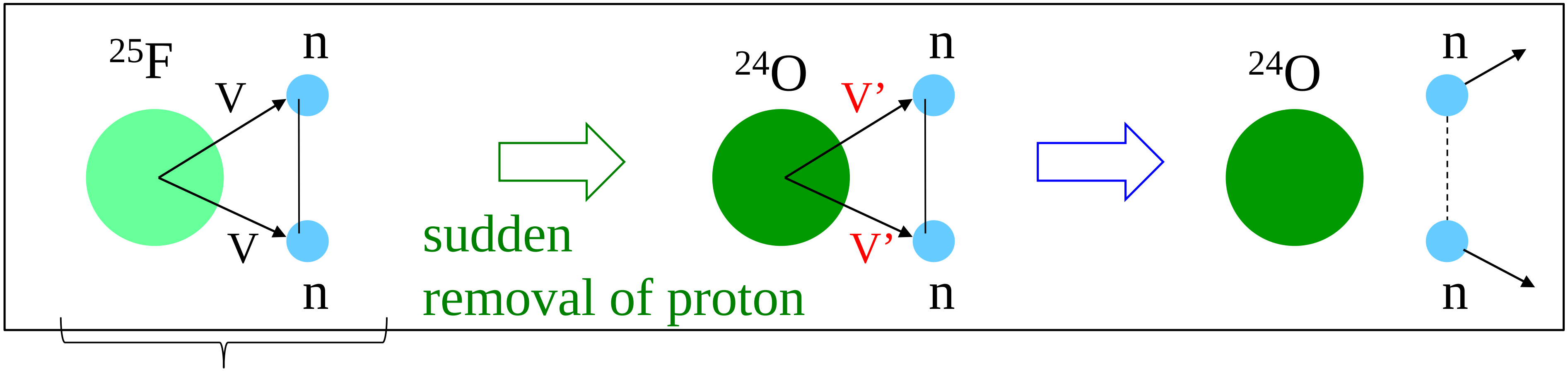




J. Lei, L. Hlophe, Ch. Elster,
A. Nogga, F.M. Nunes and D.R. Phillips,
Phys. Rev. C98 ('18) 051001(R)

## 3-body model analysis for $^{26}$O decay

K.H. and H. Sagawa,
PRC89 ('14) 014331
PRC93('16) 034330

cf. Expt. : $^{27}$F + $^{9}$Be → $^{26}$O → $^{24}$O + n + n




g.s. of $^{27}$F (bound)

$$\Psi_{nn}(^{27}\mathrm{F}) \otimes |^{25}\mathrm{F}\rangle \Rightarrow \Psi_{nn}(^{27}\mathrm{F}) \otimes |^{24}\mathrm{O}\rangle \Rightarrow$$

spontaneous decay

→ the same config. (the reference state)

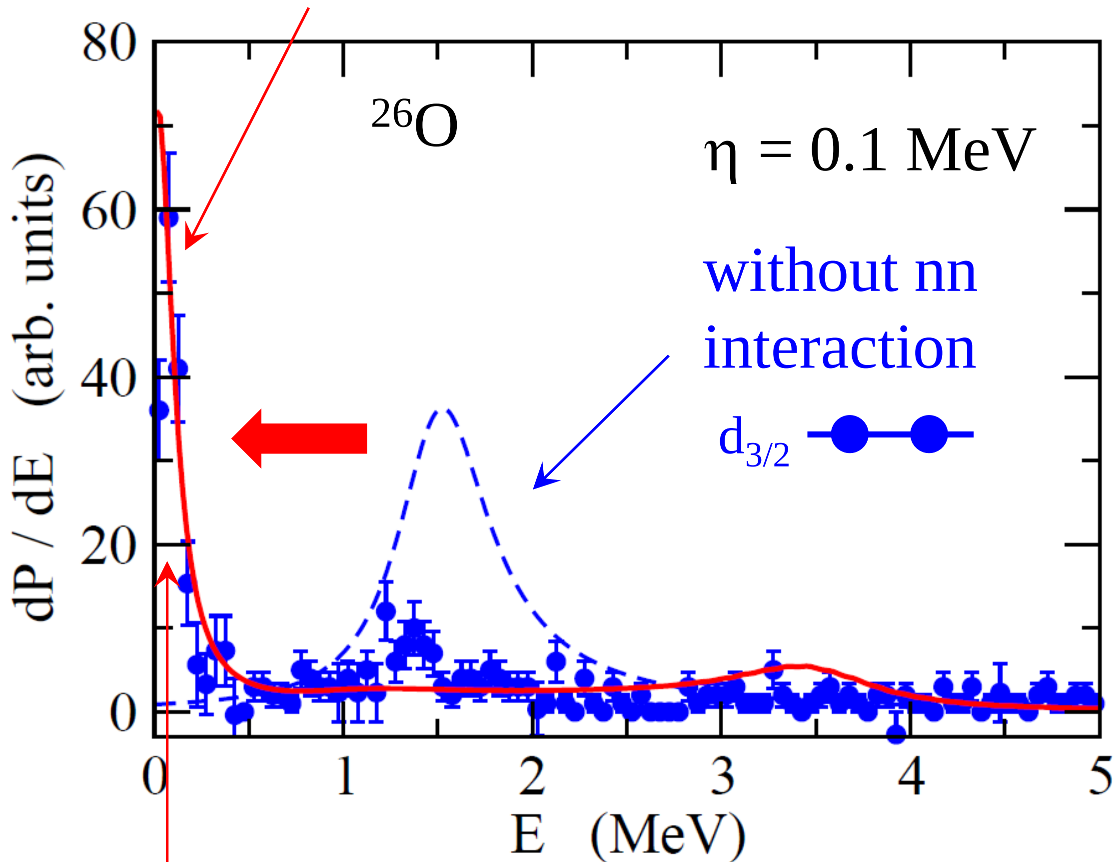
$$\frac{dP}{dE} = |\langle\Psi_{nn}(^{27}\mathrm{F})|\Psi_{nn}(^{26}\mathrm{O};E)\rangle|^2$$

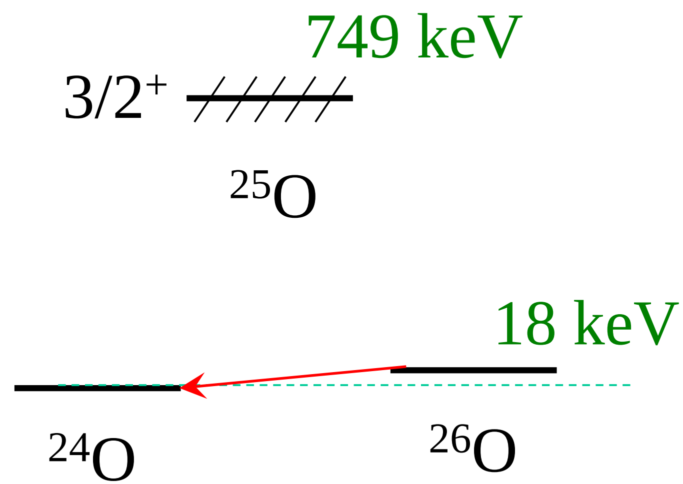
# Decay energy spectrum

$$|\Phi_{\rm ref}\rangle = \left|[1d_{3/2}]^2\right\rangle \text{ in } {}^{27}\text{F}$$

K.H. and H. Sagawa,
PRC89 ('14) 014331
PRC93('16) 034330

with nn interaction



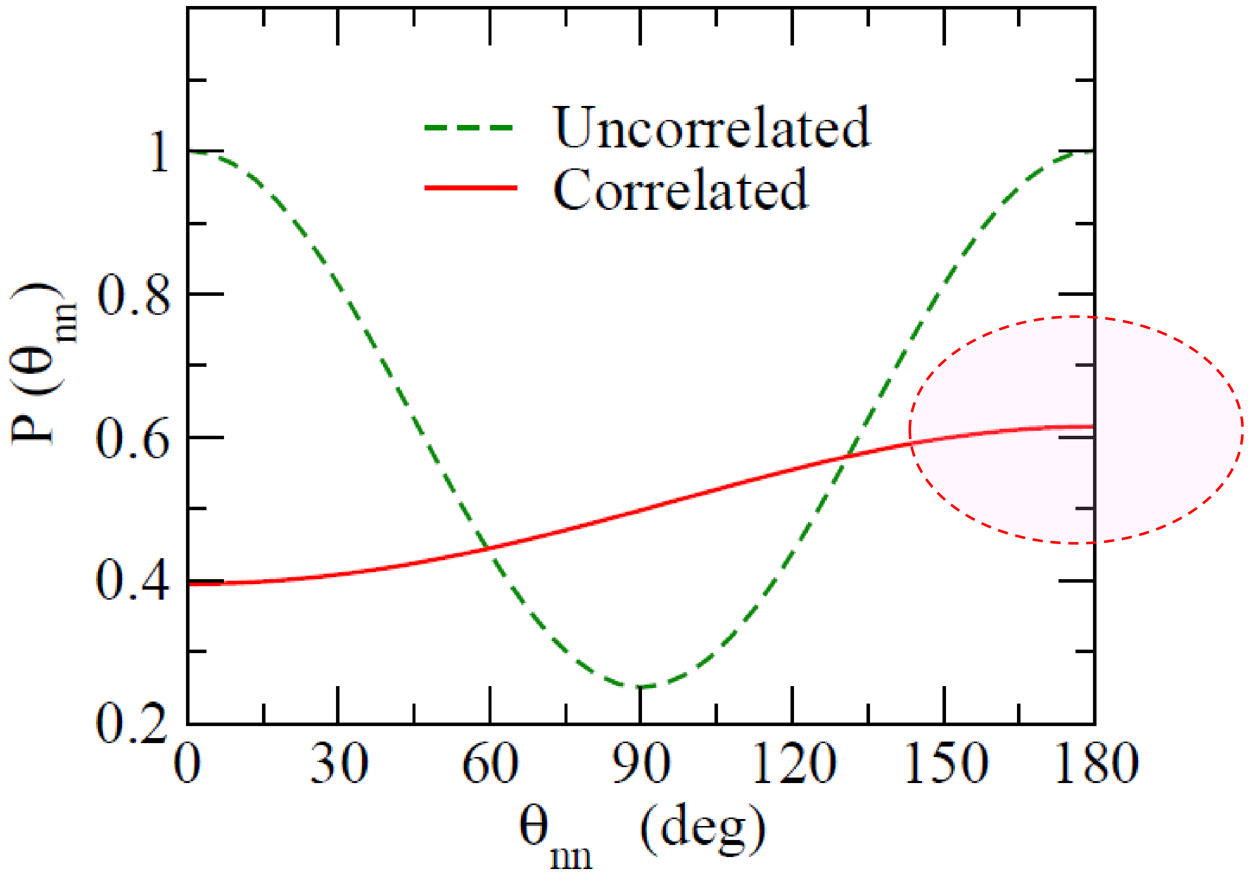

$E_{\rm peak}$ = 18 keV

Data: Y. Kondo et al., PRL116('16)102503

K.H. and H. Sagawa,
PRC89 ('14) 014331
PRC93('16) 034330

## Angular correlation of two emitted neutrons

$$P(\theta) \sim |\langle \boldsymbol{k}_1 \boldsymbol{k}_2 | \Psi_{\mathsf{3bd}}(E) \rangle|^2$$




**correlation → enhancement of back-to-back emissions**

# Dineutron correlation in the momentum space

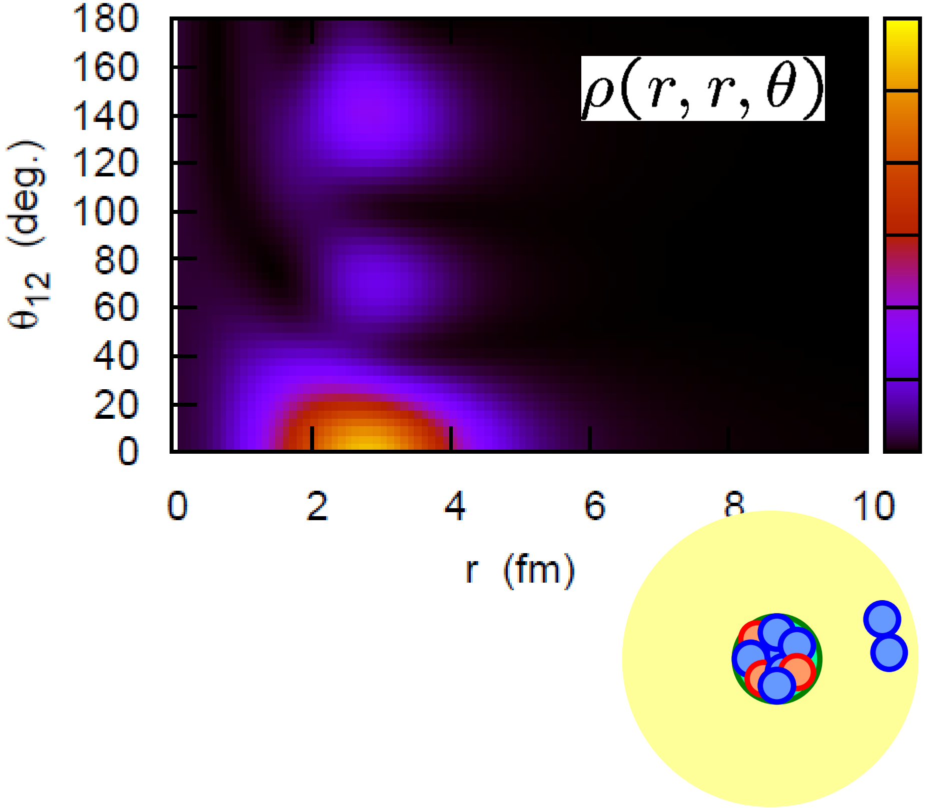
$$\Psi(\boldsymbol{r},\boldsymbol{r}') = \alpha\,\Psi_{s^2}(\boldsymbol{r},\boldsymbol{r}') + \beta\,\Psi_{p^2}(\boldsymbol{r},\boldsymbol{r}')$$

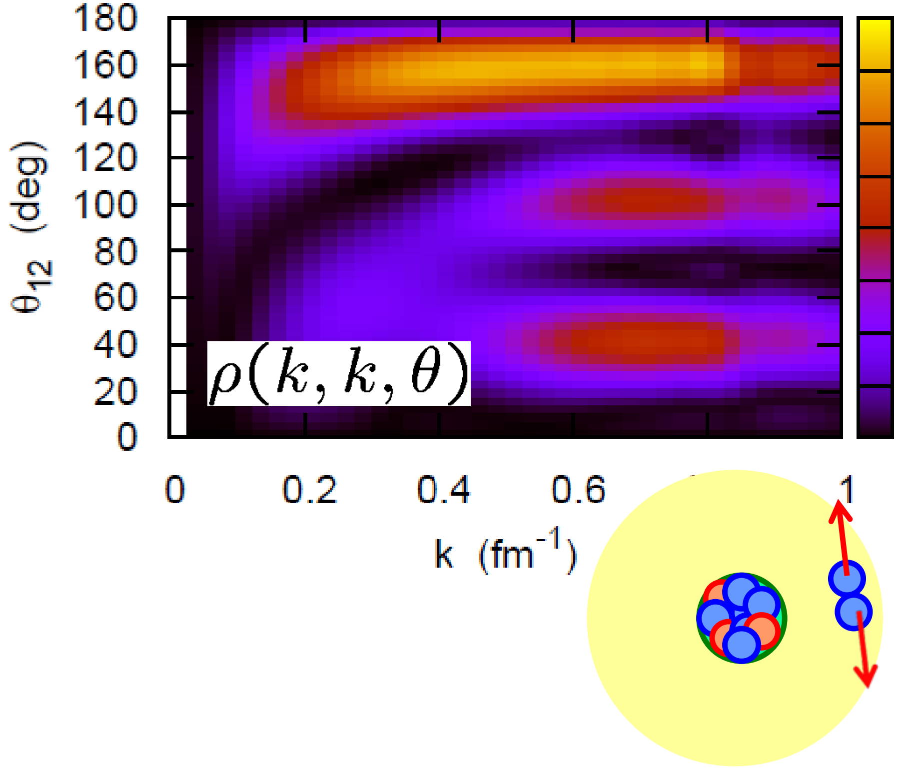
→ $\theta_r = 0$: enhanced

→ Fourier transform

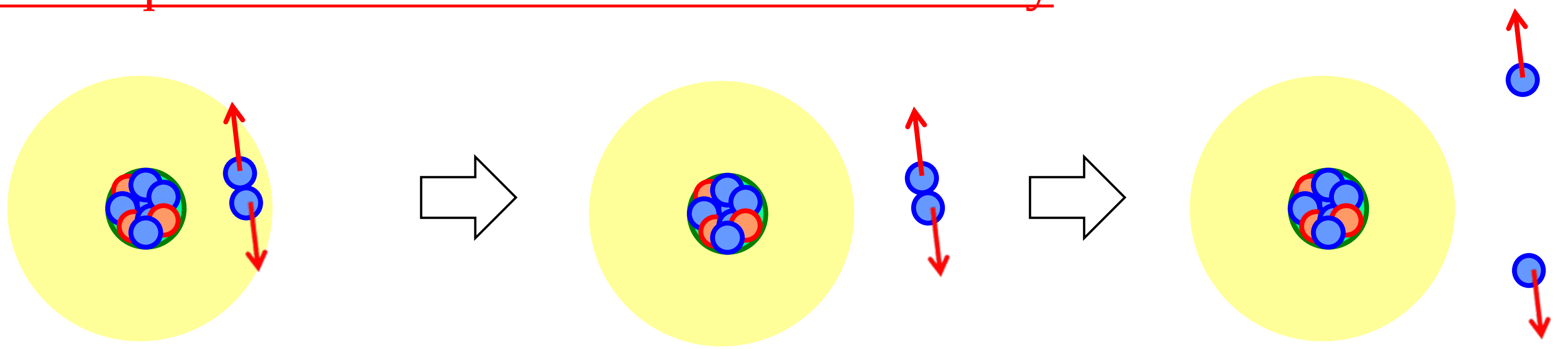
$$\tilde{\Psi}(\boldsymbol{k},\boldsymbol{k}') = \alpha\,\tilde{\Psi}_{s^2}(\boldsymbol{k},\boldsymbol{k}') - \beta\,\tilde{\Psi}_{p^2}(\boldsymbol{k},\boldsymbol{k}')$$

→ $\theta_k = \pi$: enhanced

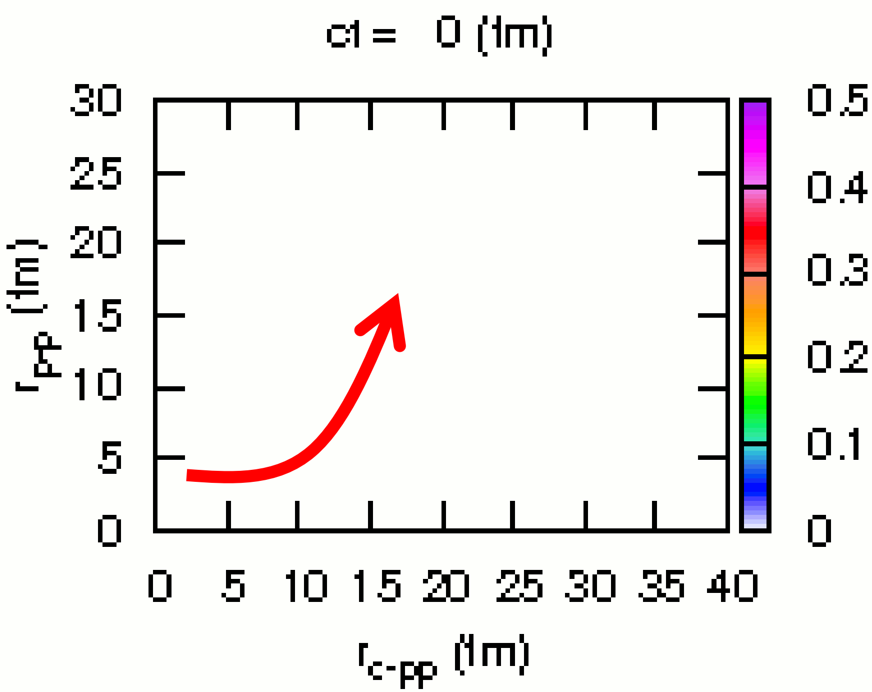


# Consequence to a two-nucleon emission decay



2p decay of $^{6}$Be : time-dependent calculations

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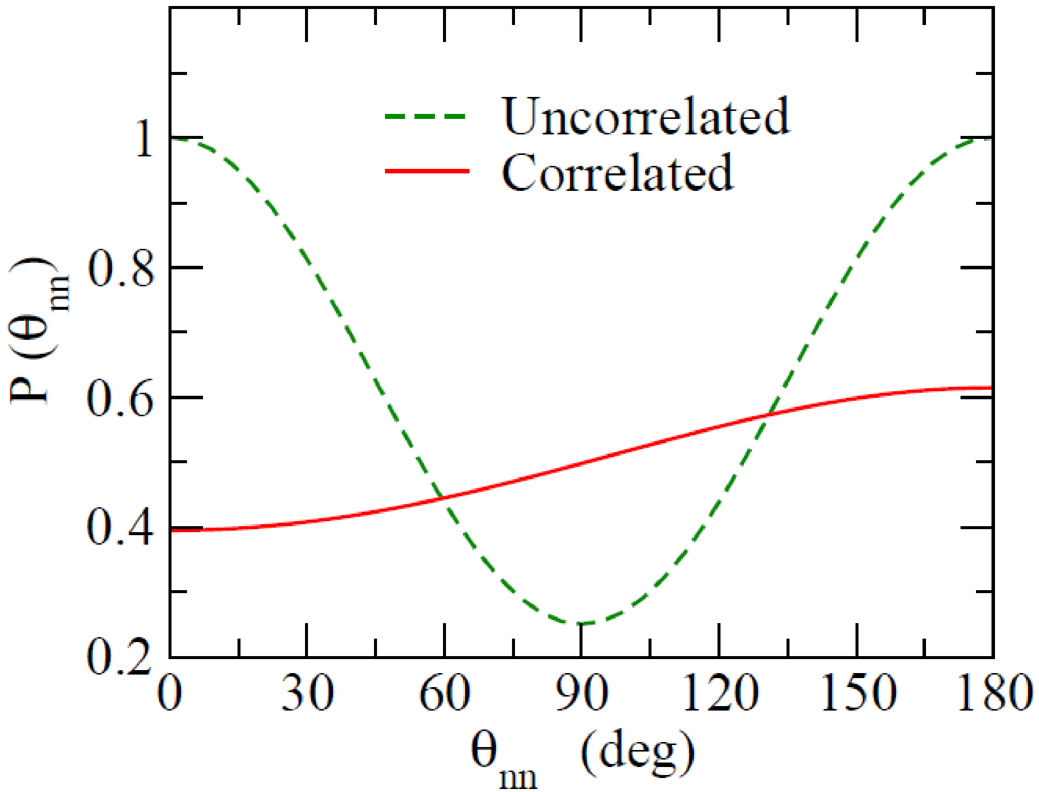
# Di-neutron correlation in the momentum space

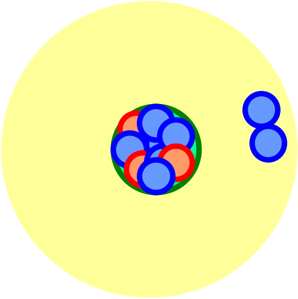



enhancement of back-back emission

→ a clear evidence for di-neutron correlation

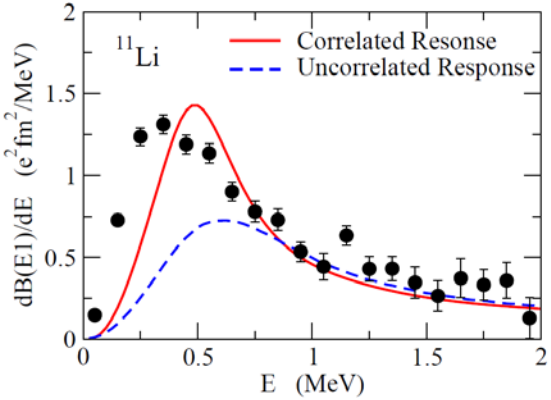
experiment?

# Summary



Di-neutron correlation : spatial localization of two neutrons

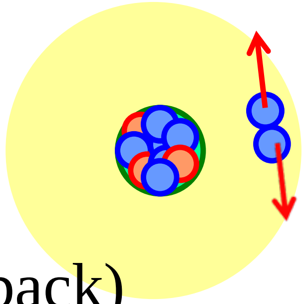
✓parity mixing
✓neutron-rich nuclei: enhanced




how to probe it?

- Coulomb breakup

✓enhancement of B(E1) due to the correlation
✓Cluster sum rule (only with the g.s. correlation)



•two-neutron emission decay

✓ opening angle of two emitted neutrons (back-to-back)

⟷ a clear evidence for dineutron correlation

**$^{26}$O: almost bound three-body system ← a few-body universality?**