FRIB

# Experimental Nuclear Physics II

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT of ENERGY | Office of Science

# Today’s menu for experimental nuclear physics I & II

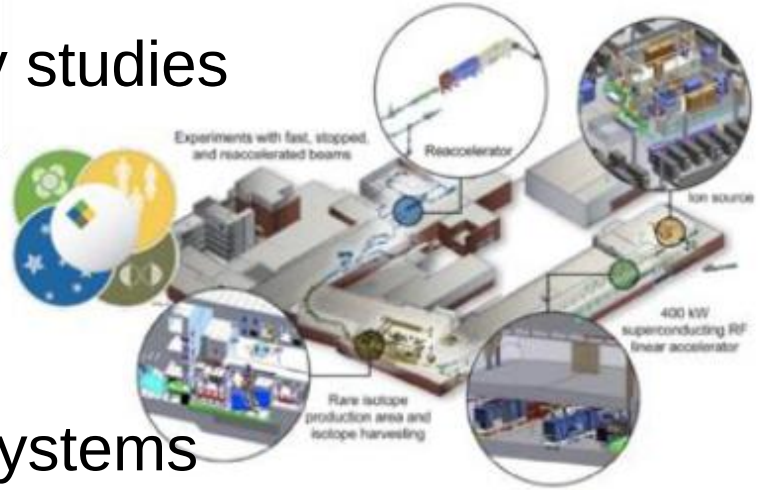
- To understand complex structure of atomic nuclei, various experimental methods need to be combined
- Experiments with rare isotopes pose additional challenges to achieve required precision and sensitivity

Be familiar with representative experimental methodology and approaches
Be aware of recent highlights in our field at FRIB era

This (first) lecture :
- RI-beam production for new isotope search and decay studies
- In-beam Gamma Spectroscopy with fast RI beams

to track structural changes

Next (second) lecture:
- Invariant-mass Spectroscopy to study weakly bound systems



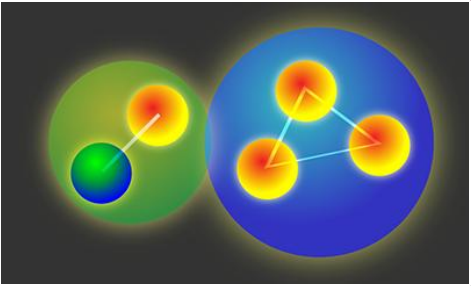
# Halo at different scales

## Nuclear Halo: Quantum Tunneling Effects for $\ell$ =0,1

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2\mu r^2}+V(r)-\epsilon_l\right]u_l(r)=0$$

### Unique features

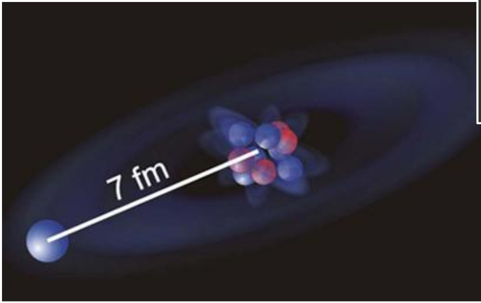
- Interactions between halo neutrons (pairing)
- Core deformation



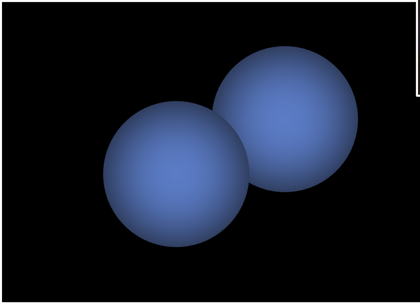
$10^{-15}$ m
QCD

A narrow **penta-quark** state Pc(4312)$^+$ close to the $\Sigma_c^+\bar{D}_0$ threshold

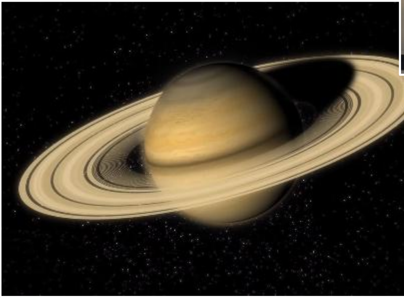
LHCb collaboration, PRL122(19)222001



$10^{-14}$ m
Strong force



$10^4$ m
Electromagnetic

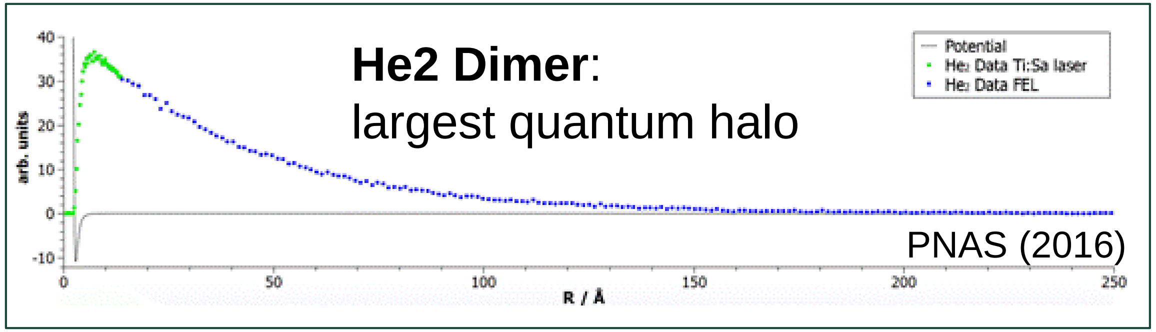


$10^8$ m

Gravity

heaviest

$10^{21}$ m



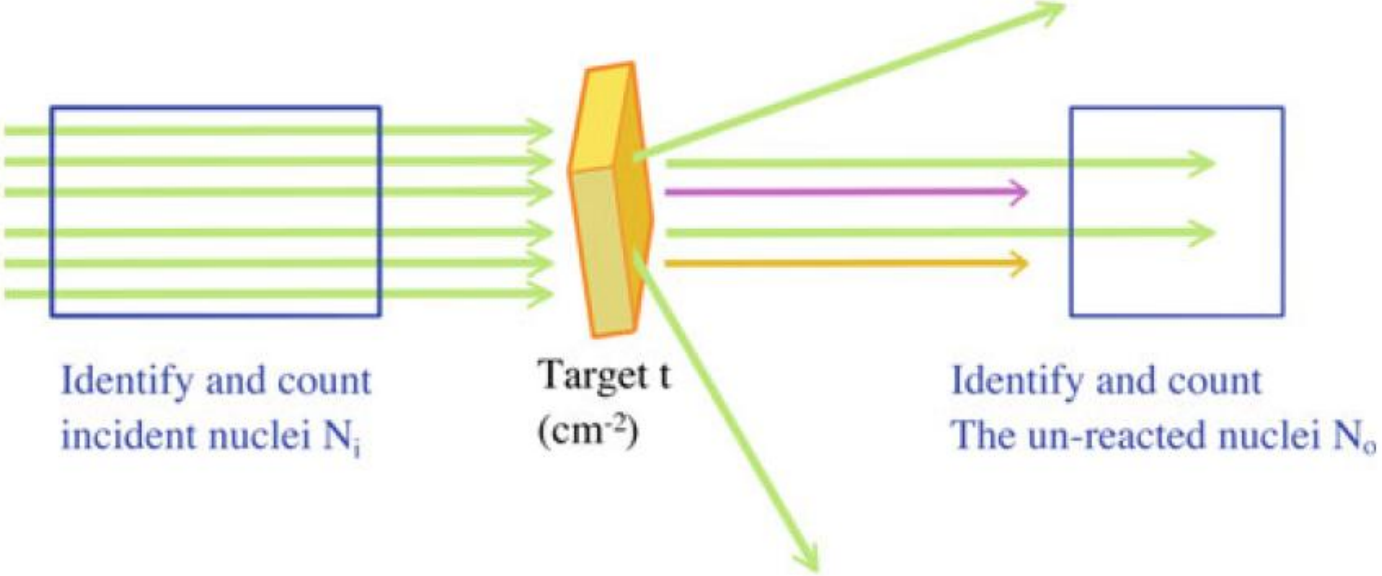
**He2 Dimer**:
largest quantum halo

PNAS (2016)

# Transmission method

Interaction cross sections can be determined based on the transmission method by measuring the number of incoming beams ($N_{in}$) and outgoing beams ($N_{out}$).

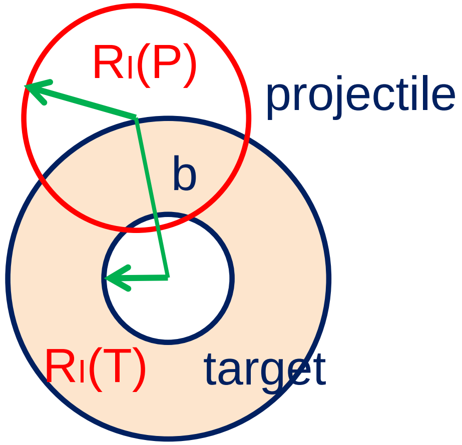
$$\sigma_I = \frac{1}{L_t \rho} \ln \left( \frac{N_i}{N_0} \right)$$



from A.Obertelli and H. Sagawa, Modern Nuclear Physics (Springer)

# Discovery of halo nuclei

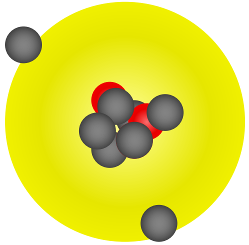
## 1. Interaction cross section measurements



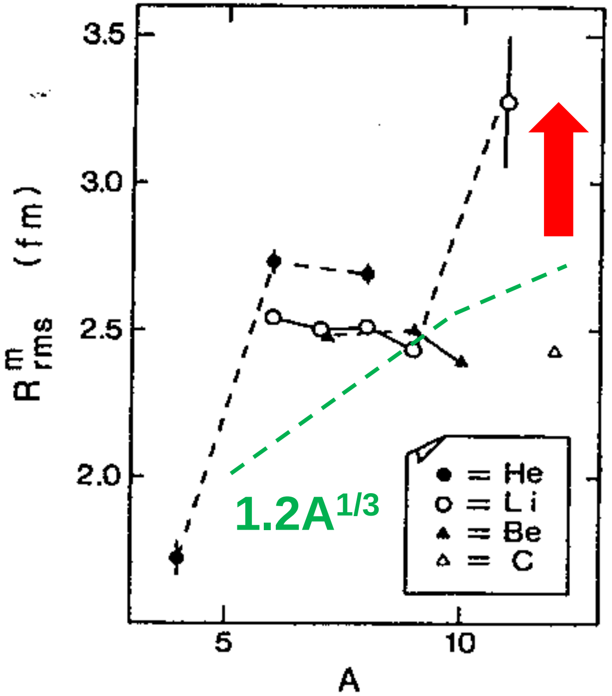
It is assumed that reaction occurs when the impact parameter becomes

$$b < R_I(P) + R_I(T)$$

$$\sigma_I = \pi \left( R_I(P) + R_I(T) \right)^2$$



$^{11}$Li
(neutron-rich)

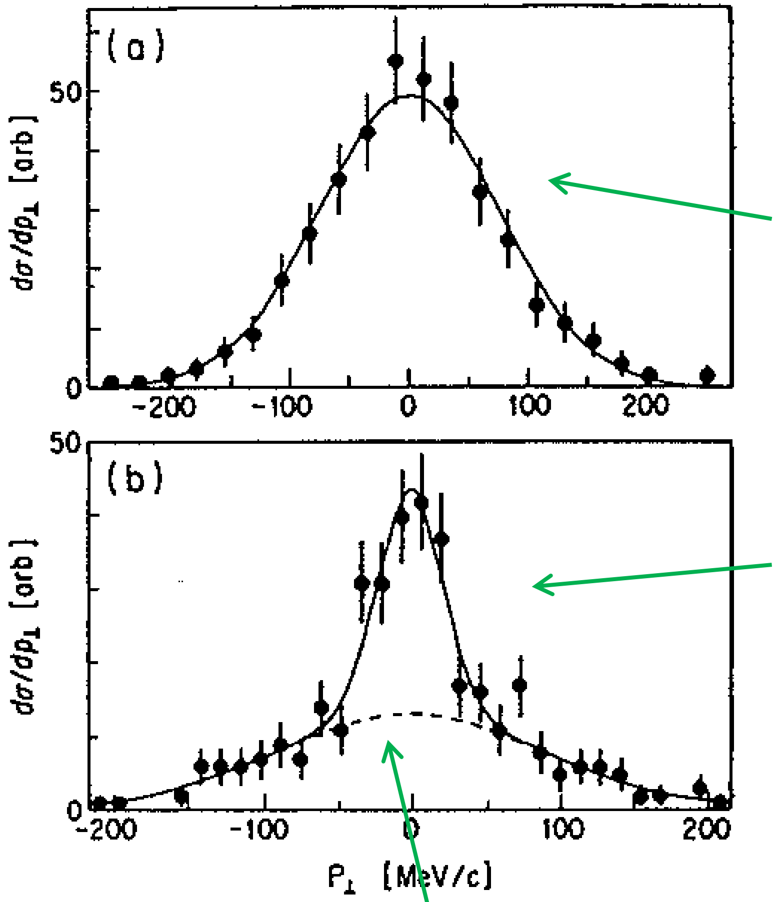


**Large enhancement in $^{11}$Li**

I.Tanihata et al., PRL55, 2676 (1985)

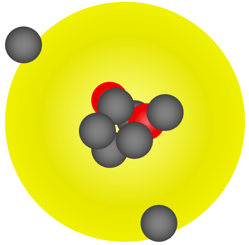
# Confirmation of halo structure

## 2. Momentum distribution of $^{11}$Li



$^{6}$He distribution from $^{8}$He

similar to Goldhaber model



$^{11}$Li
(neutron-rich)

$^{9}$Li distribution from $^{11}$Li (very narrow!)

uncertainty principle

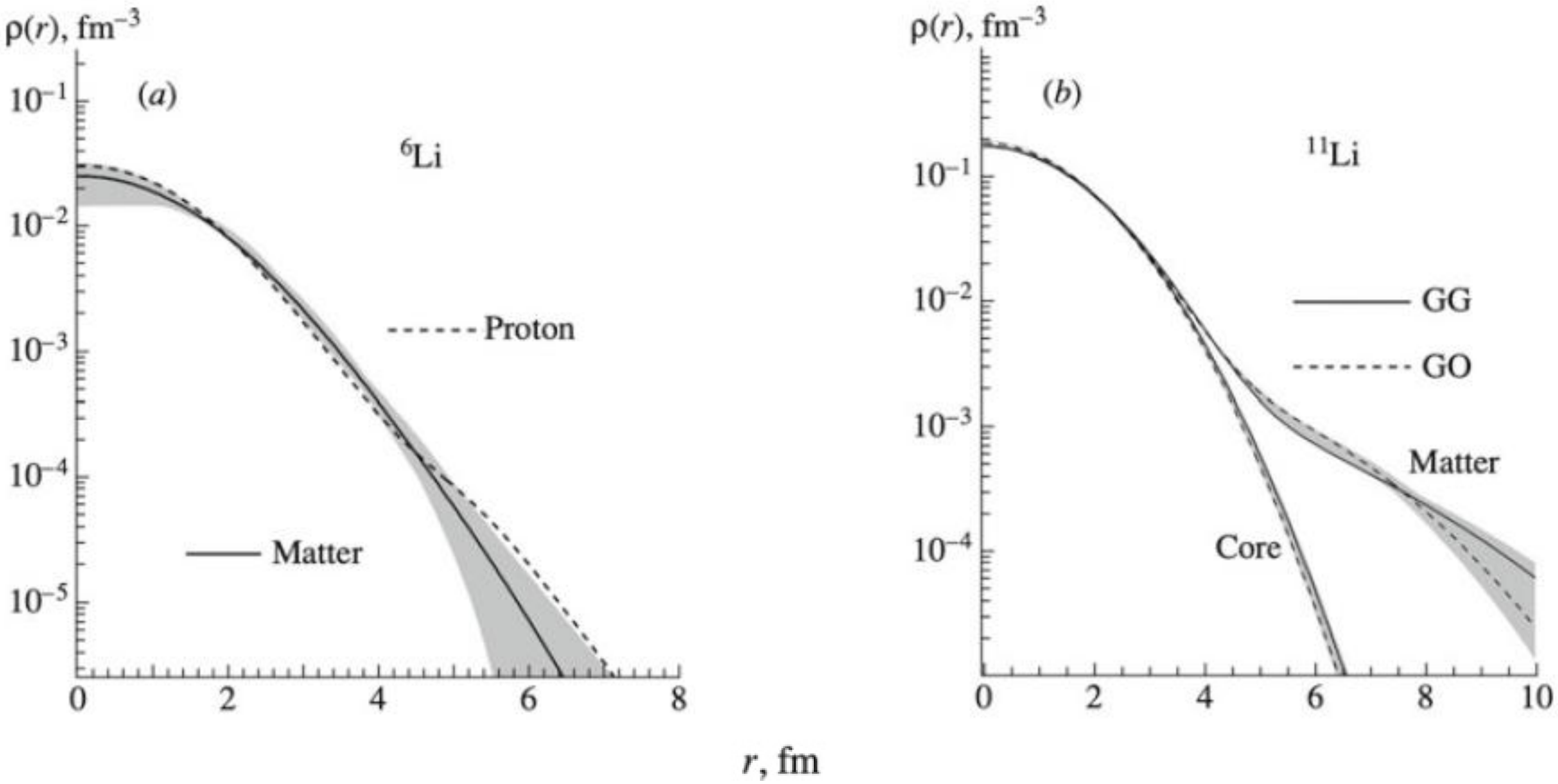
$$\underline{\Delta p} \cdot \underline{\Delta x} \geq \hbar$$

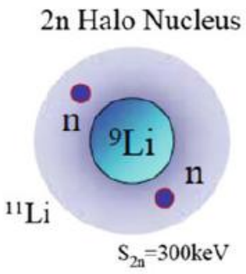
small → large

a wider part is similar to Goldhaber model

T.Kobayashi et al., PRL69, 2599 (1988)

# Borromean nucleus





2n (n+n) ⋯ unbound
$^{10}$Li ($^{9}$Li+n) ⋯ unbound
$^{11}$Li ($^{9}$Li+n+n) ⋯ **bound**

Knot theory
Borromean Ring

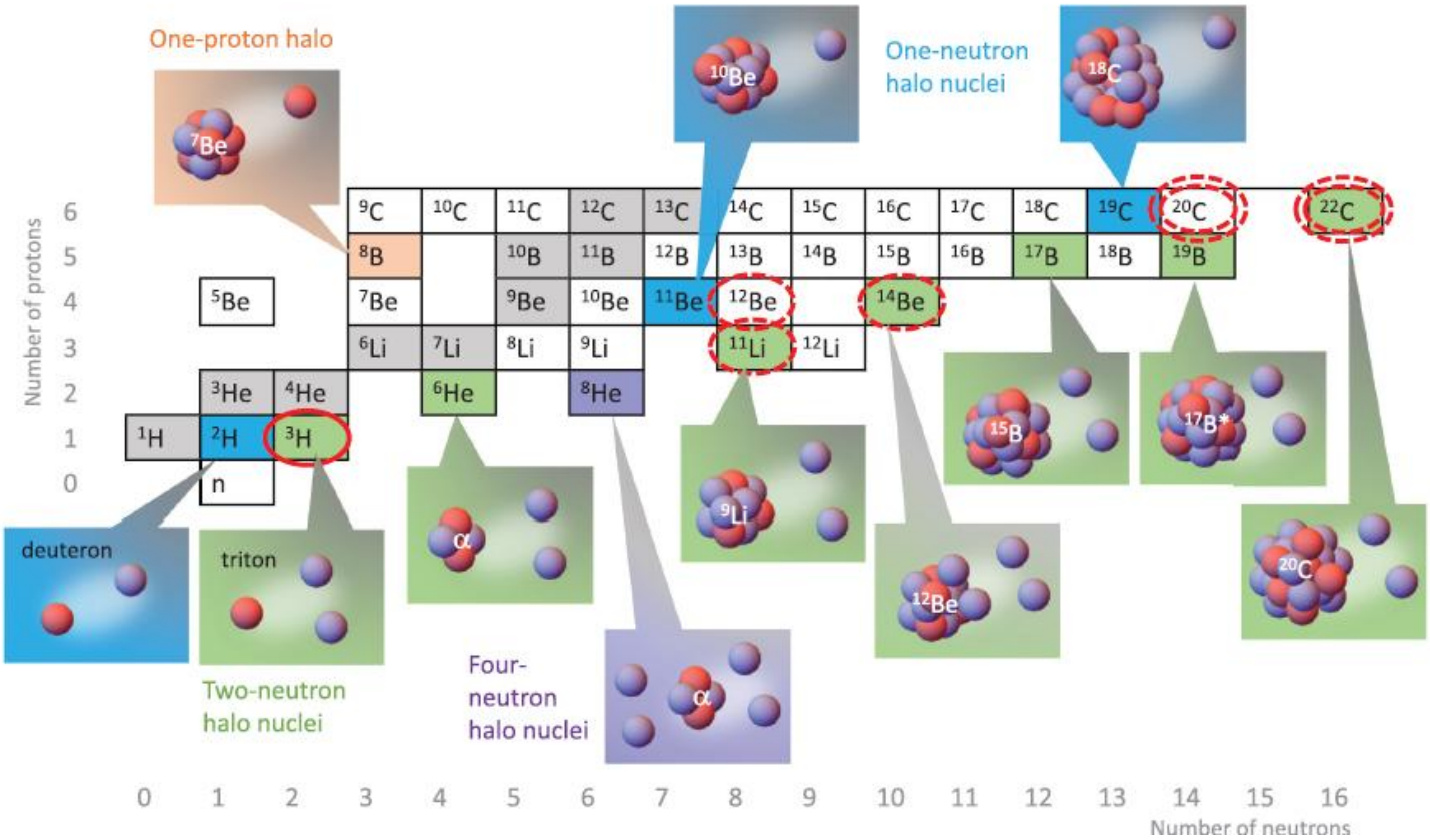
Emblem of Borromeo
Family, Italy

from A.Obertelli and H. Sagawa, Modern Nuclear Physics (Springer)

# Universal halo structure at dripline

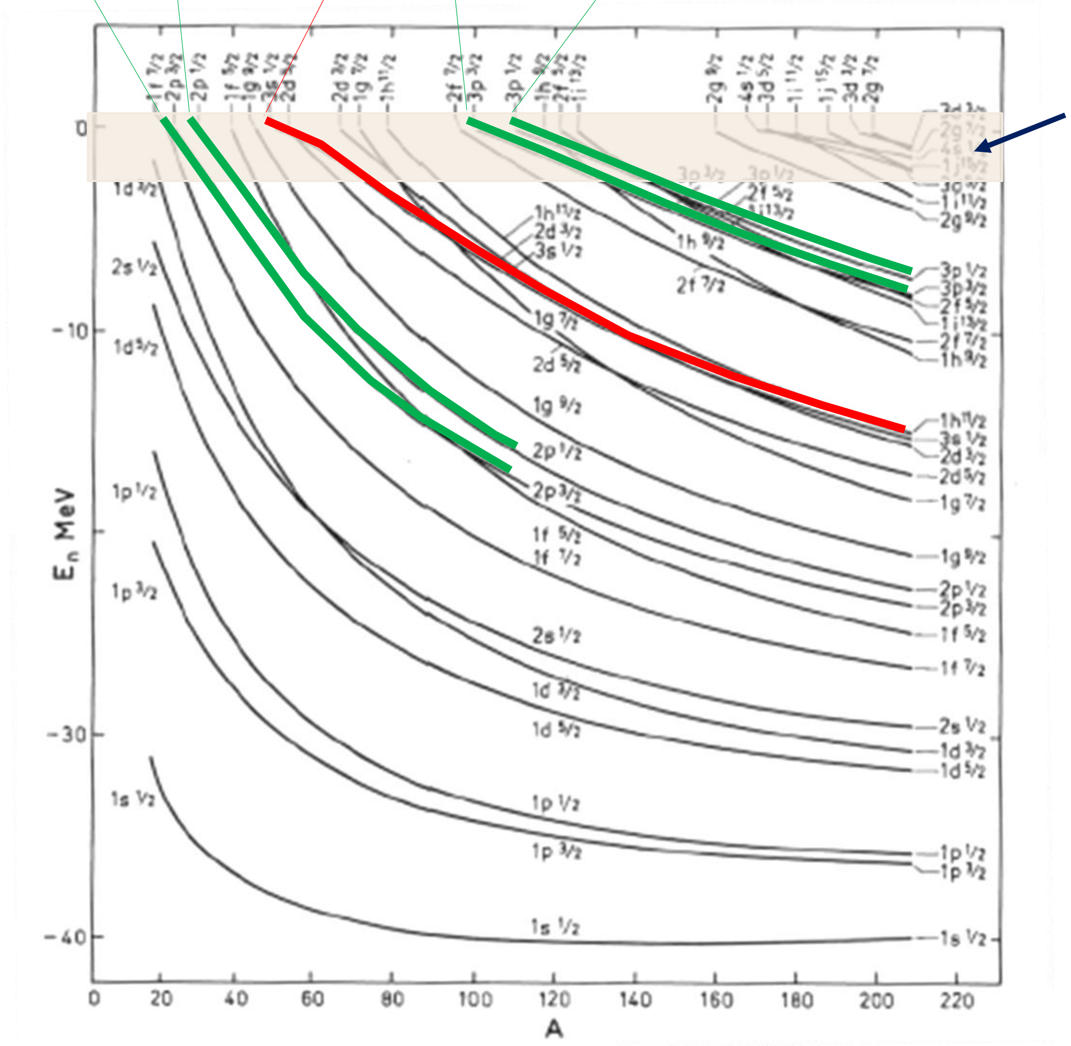
Pascal Naidon and Shimpei Endo “Efimov physics: a review”

Rep. Prog. Phys. **80** (2017) 056001 Review



# Low $\ell$ dominance at the drip lines

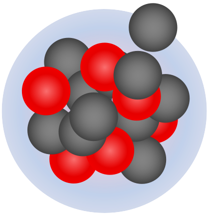
$2p_{3/2}$ $2p_{1/2}$ $3s_{1/2}$ $3p_{3/2}$ $3p_{1/2}$ $\ell$ = 0 (s) $\ell$ = 1 (p)



at driplines (<1MeV)

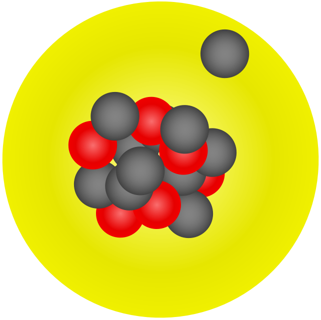
High-$\ell$ orbits

($\ell$=2 (d) and above )



Low-$\ell$ orbits

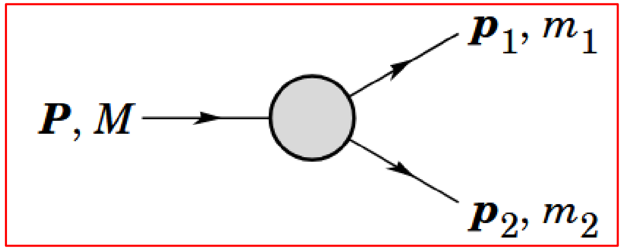
($\ell$ =0, 1 (s,p) )



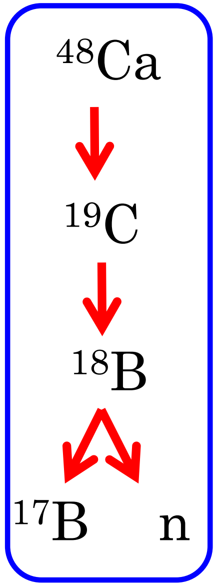
Energies of neutron orbits in a spherical nuclear potential

Aage Bohr and Ben R. Mottelson,
Volume I Fig.2.30

# Invariant mass spectroscopy – MoNA-Sweeper setup



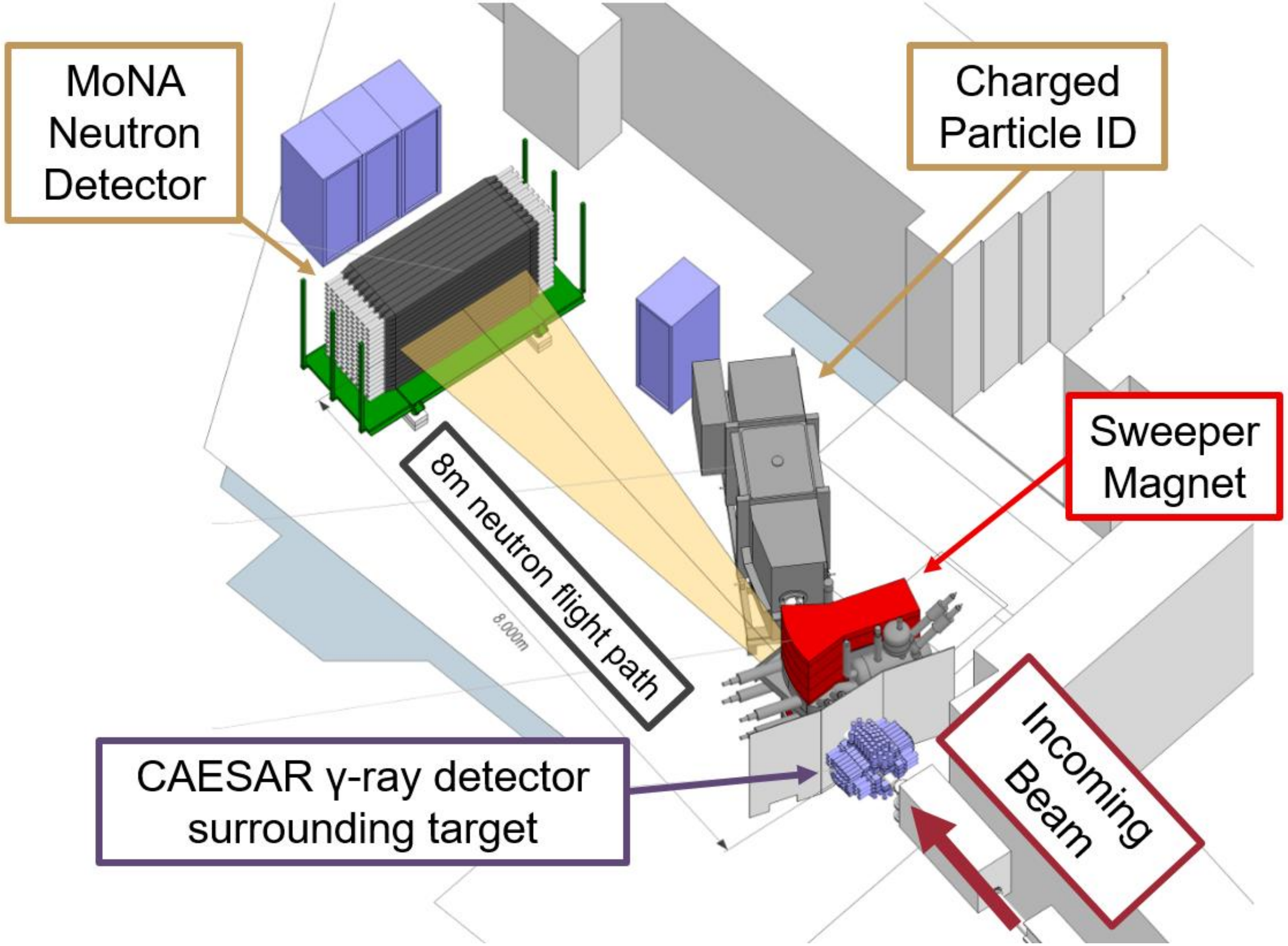
Particle Data Group (2022)



$$E_{\mathrm{cm}} = \left[(E_1 + E_2)^2 - (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2\right]^{1/2} ,$$

$$= \left[m_1^2 + m_2^2 + 2E_1 E_2 (1 - \beta_1 \beta_2 \cos\theta)\right]^{1/2}$$

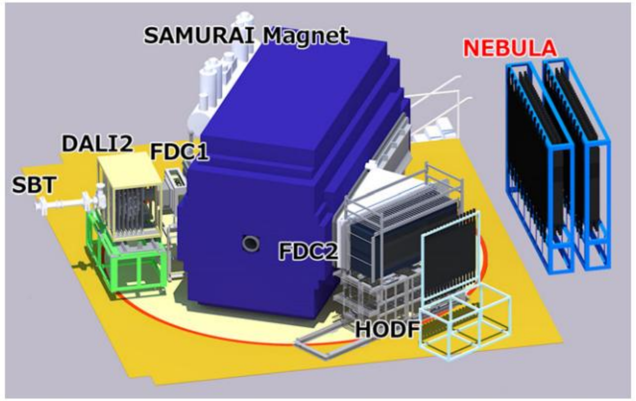
in the Lorentz-invariant form



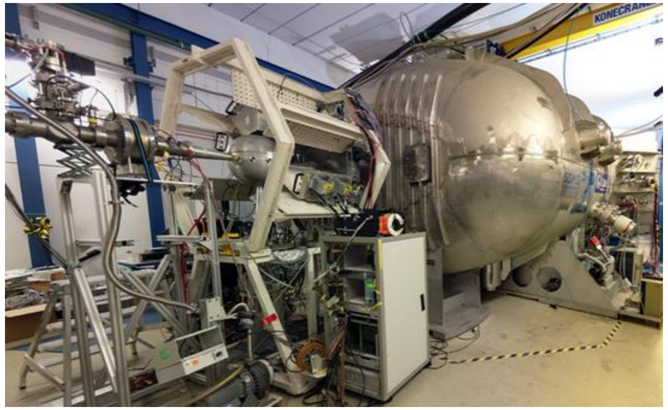
Courtesy of Aldric Revel (FRIB)

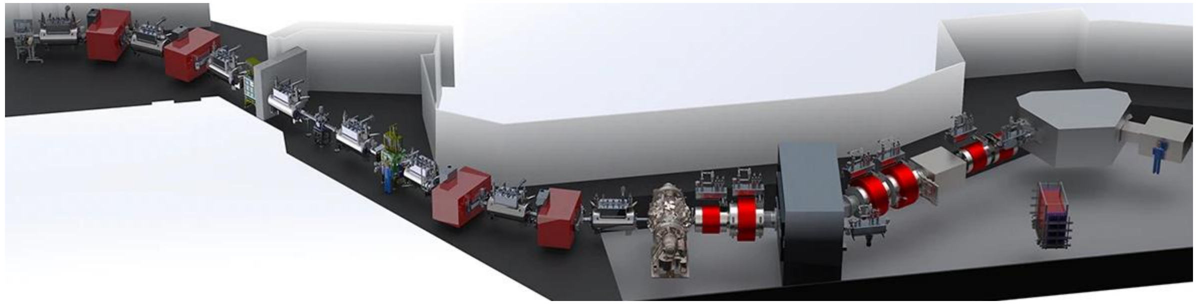
# Advanced setup – SAMURAI/ R3B /HRS

## SAMURAI at RIBF



## R3B (GLAD) at GSI/FAIR

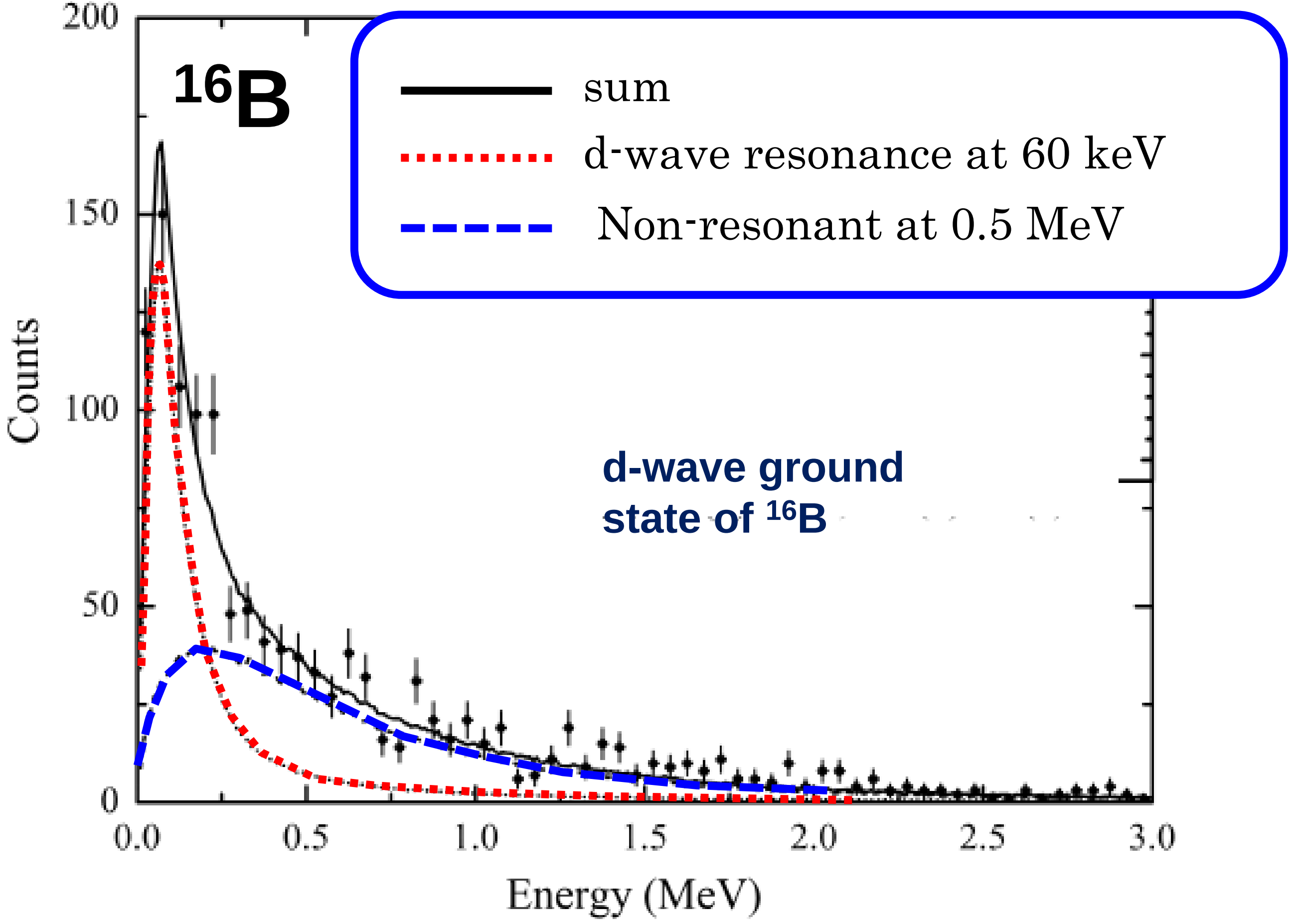




… HRS under construction at FRIB

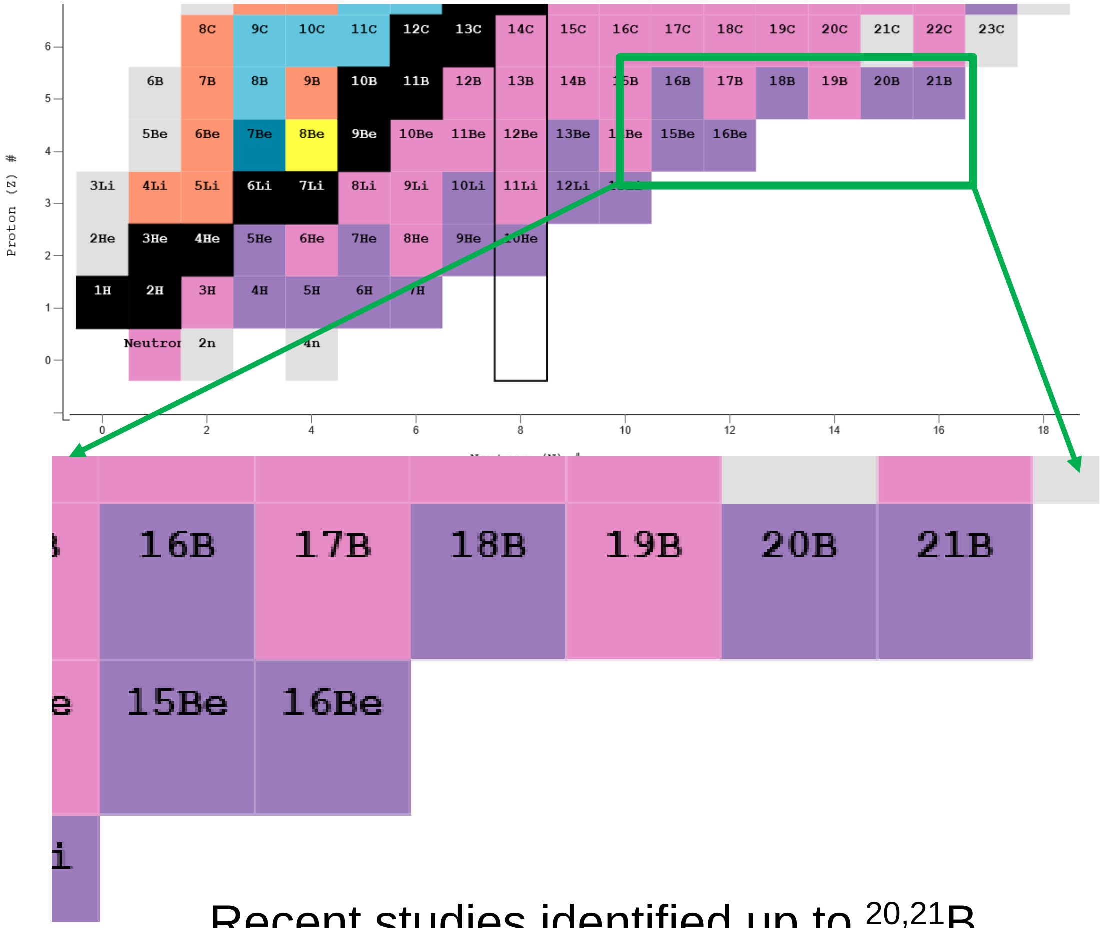
# Invariant-mass spectroscopy – $^{16}$B spectrum

$$E_d = \sqrt{M_f^2 + M_n^2 + 2(E_f E_n - p_f p_n cos(\Theta_{open}))} - M_f - M_n$$



d-wave ground state of $^{16}$B

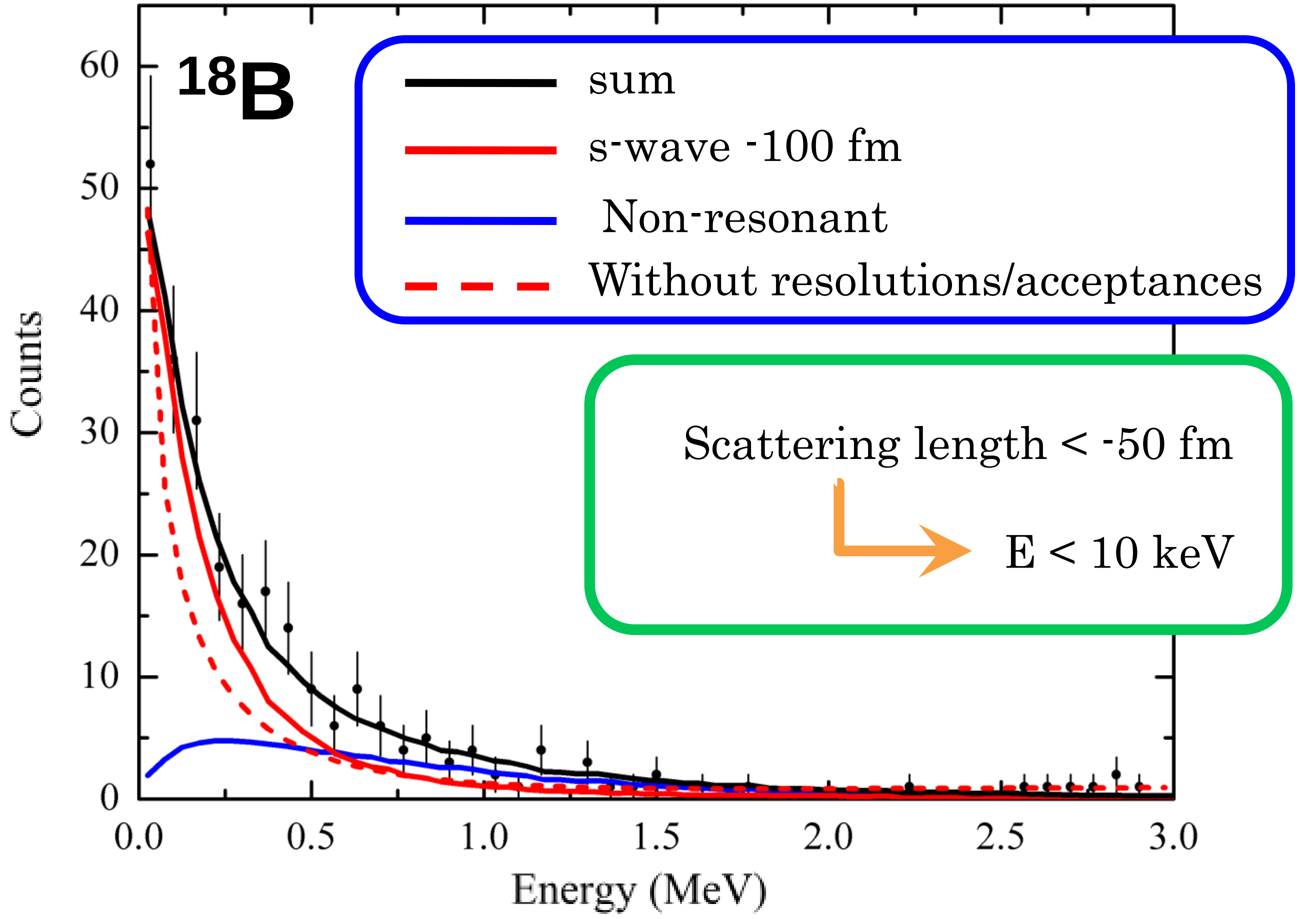
A. Spyrou et al., Phys. Lett. B. 683, 129 (2010)



Recent studies identified up to $^{20,21}$B
S.Leblond et al., PRL121, 262502 (2018)

# Invariant-mass spectroscopy – $^{18}$B spectrum

$$E_d = \sqrt{M_f^2 + M_n^2 + 2(E_f E_n - p_f p_n cos(\Theta_{open}))} - M_f - M_n$$



Scattering length < -50 fm

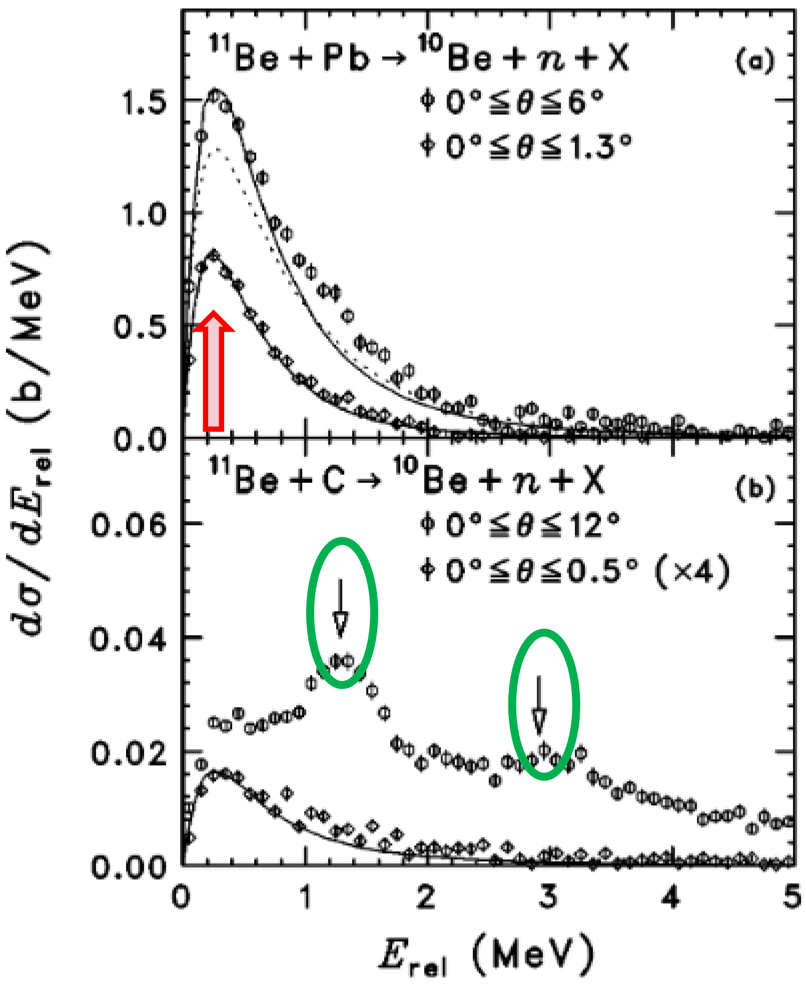
$\rightarrow$ E < 10 keV

**Virtual state:
s-wave close to
the threshold**

G. Blanchon, A. Bonaccorso *et al.*, Nucl. Phys. A 784, 49 (2007)
A. Spyrou et al., Phys. Lett. B. 683, 129 (2010)

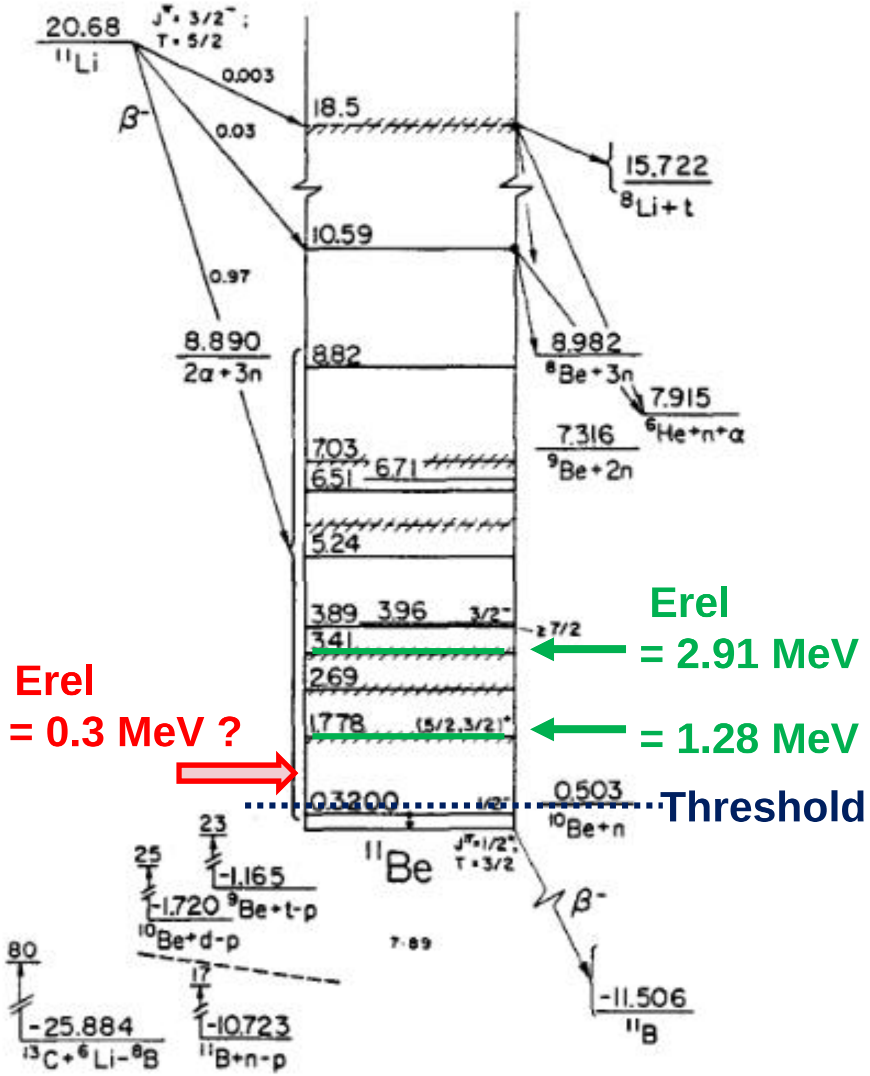
# Resonant vs non-resonant *states*

Coulomb and nuclear breakup of $^{11}$Be



N. Fukuda et al., Phys. Rev. C70, 054606 (2004)

**Any resonance at Erel = 0.3 MeV?**



Erel
= 2.91 MeV

= 1.28 MeV

Erel
= 0.3 MeV ?

Threshold

# Direct break up model

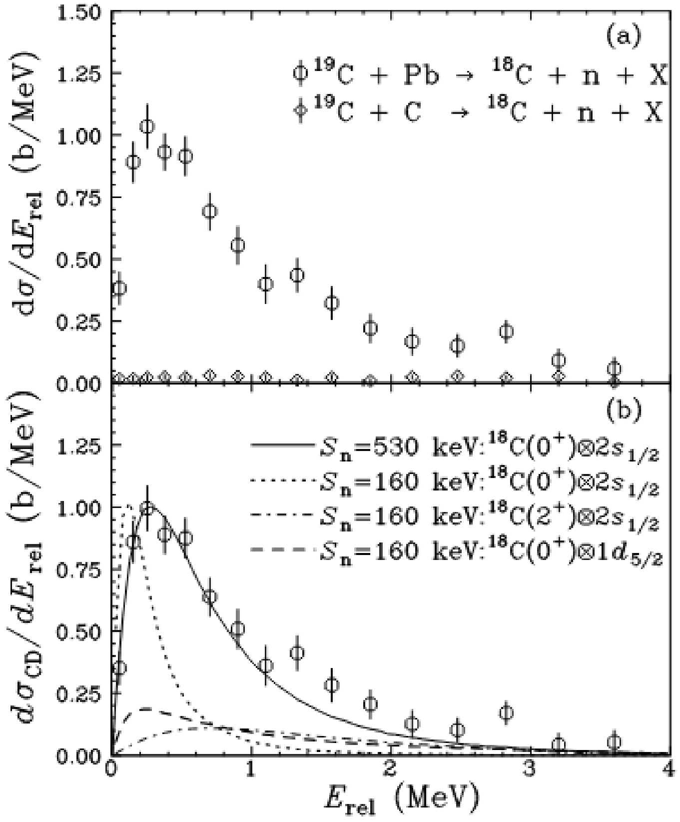
**The B(E1) distribution of Coulomb breakup is the Fourier transform of *r*R(r), where R(r) is the radial part of the initial wave function of the ground state.**

$$\frac{d\sigma_{\mathrm{CD}}}{dE_{\mathrm{rel}}} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_{\mathrm{rel}}}$$

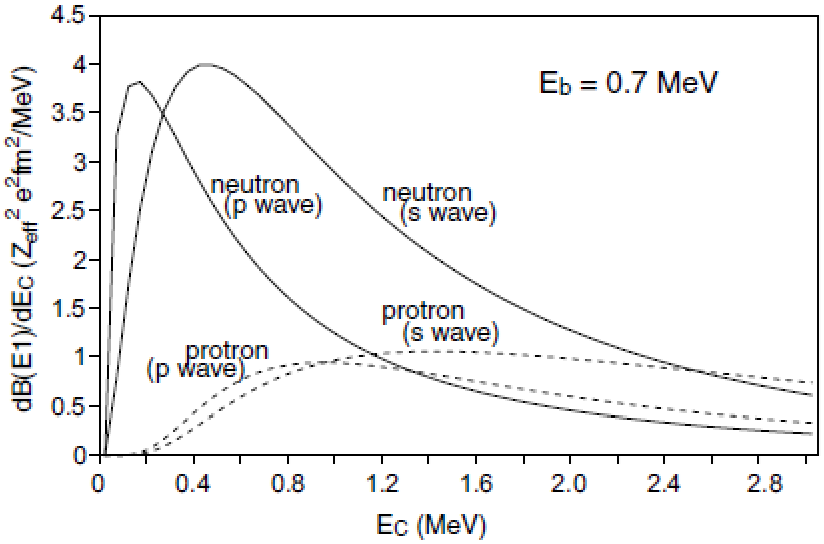
$$\frac{dB(E1)}{dE_{\mathrm{rel}}} = \left| \langle \mathbf{q} | \frac{Ze}{A} r Y^1_m | \Phi(\mathbf{r}) \rangle \right|^2$$

final state $\langle \mathbf{q} | = \sqrt{\frac{2\mu q}{\hbar^2 \pi}}\, j_{\ell_f}(qr)$ **or $e^{ik\cdot r}$**

**(plane wave with $q = \sqrt{2\mu E_{\mathrm{rel}}}/\hbar$ )**



**data sensitive to $\ell$ and Sn**
**Of the ground (initial) state**



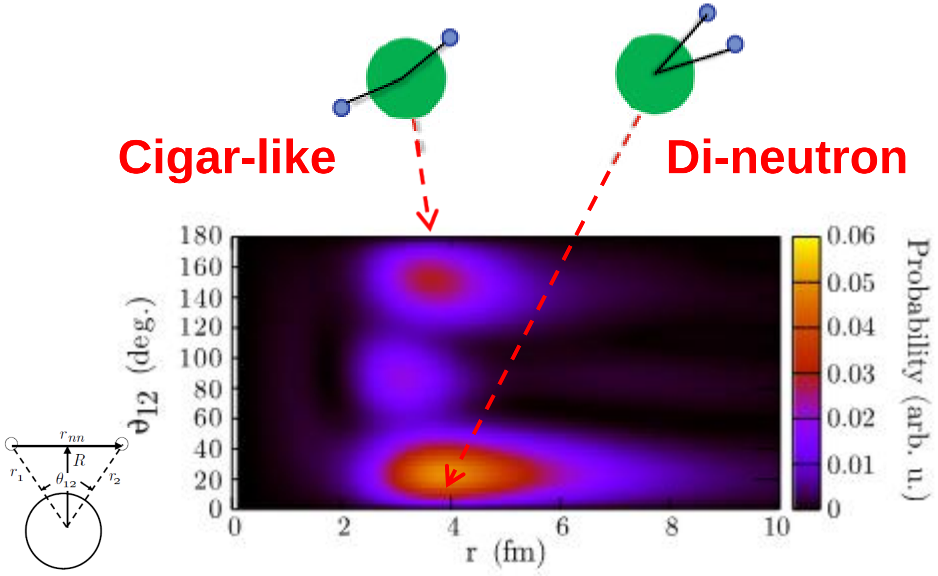
T. Nakamura et al., Phys. Rev. Lett. 83, 1112 (1999)
M.A. Nagarajan, S.M.Lenzi, and A. Vitturi, Eur. Phys. J. A. 24, 63 (2005)

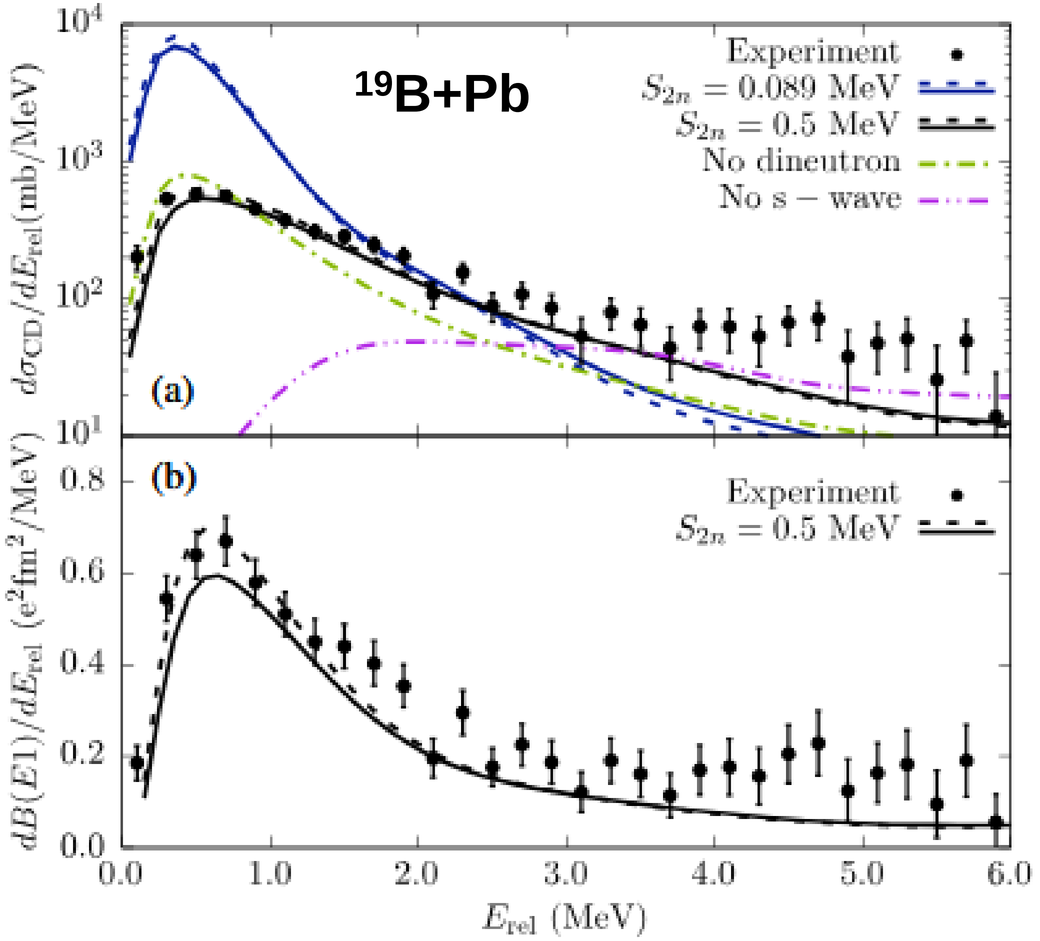
# 2n halo $^{19}$B and Coulomb breakup

The measured Coulomb breakup cross sections have a low-energy peak characteristic of halo with small separation energy ($S_{2n}$ = 0.5MeV).

The summed B(E1) gives an estimate of the root-mean-square distance 5.75 fm between the core and 2n.

$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1^2 + r_2^2 + 2\underline{\mathbf{r}_1 \cdot \mathbf{r}_2}\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r_{c,2n}^2 \rangle$$





The calculated two-neutron probability densities show substantial enhancement of a dineutron correlation.

K.J.Cook et al., Phys. Rev. Lett. 124, 212503 (2020)

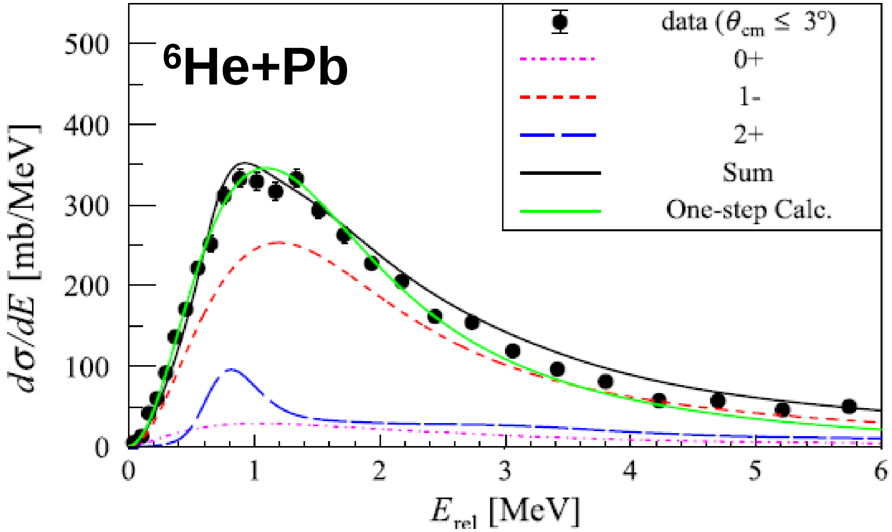
# Coulomb breakup of $^6$He and $r_{\text{n-n}}$

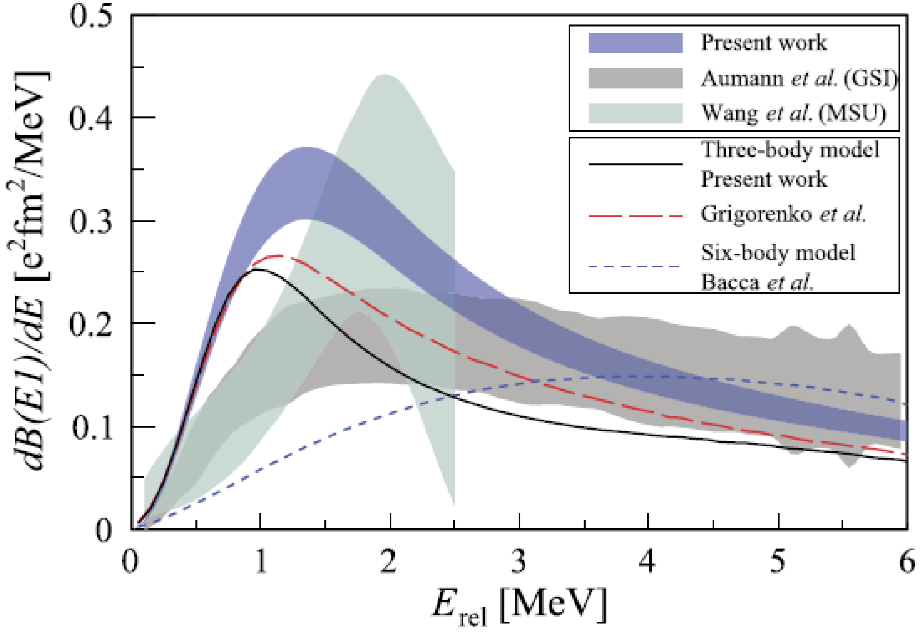
The measured Coulomb breakup cross sections are dominated by low-energy E1 excitation as calculated by CDCC. The summed B(E1) gives an estimate of the root-mean-square distance 3.9(2) fm between the core and 2n.

$$B(E1)=\int_{-\infty}^{+\infty} dE\,\frac{dB(E1)}{dE}=\frac{3}{\pi}\left(\frac{Ze}{A}\right)^2\langle r_{c-2n}^2\rangle$$

With known matter radius information for $^6$He (2.49 fm) and $^4$He (1.46 fm), root-mean-square radius for $r_{\text{n-n}}$ can be determined as 4.1(7) fm, with opening angle of 56(10) degrees.

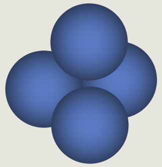
$$\langle r_m^2\rangle=\frac{A_{\mathrm{core}}}{A}\langle r_m^2\rangle_{\mathrm{core}}+\frac{2A_{\mathrm{core}}}{A^2}\langle r_{c-2n}^2\rangle+\frac{1}{2A}\langle r_{nn}^2\rangle$$





Y.L.Sun et al., Phys. Lett. B814, 136072 (2021)

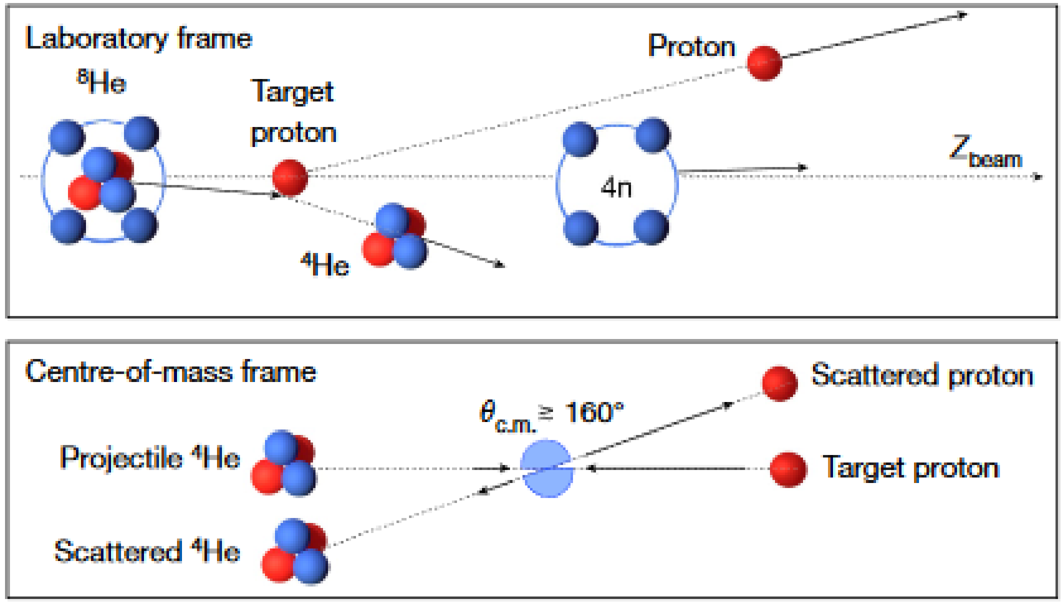
# Element 0 – tetraneutron $^4n$

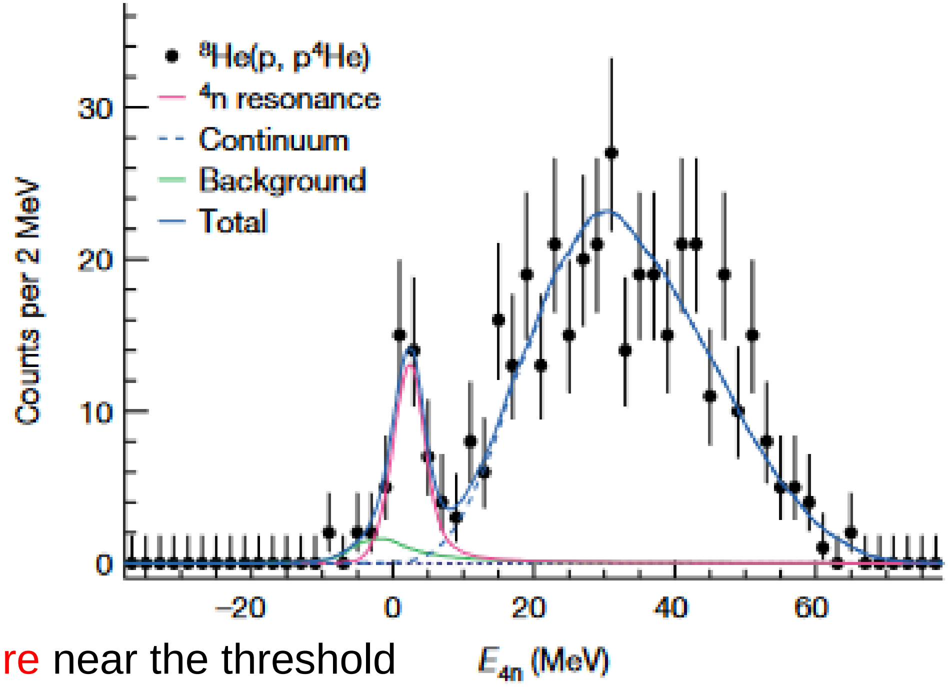


The **possible** existence of a cluster state of four neutrons, tetra-neutron, has been discussed. Current theoretical models with realistic nuclear force do not support the existence of a tetra neutron as a bound state or a sharp resonance with a width significantly smaller than 1 MeV.

0
**Ez**
Element Zero
0

2
**He**

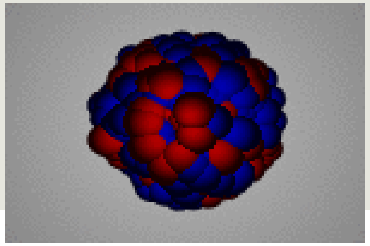




The observation of a **resonance-like** structure near the threshold
… M.Duer et al., Nature 606, 678 (2022)

Emergence of the low-energy peak due to **dineutron-dineutron correlations**
… R.Lazauskas, E.Hiyama, J.Carbonell, PRL 130, 102501 (2023)

# GDR and PDR

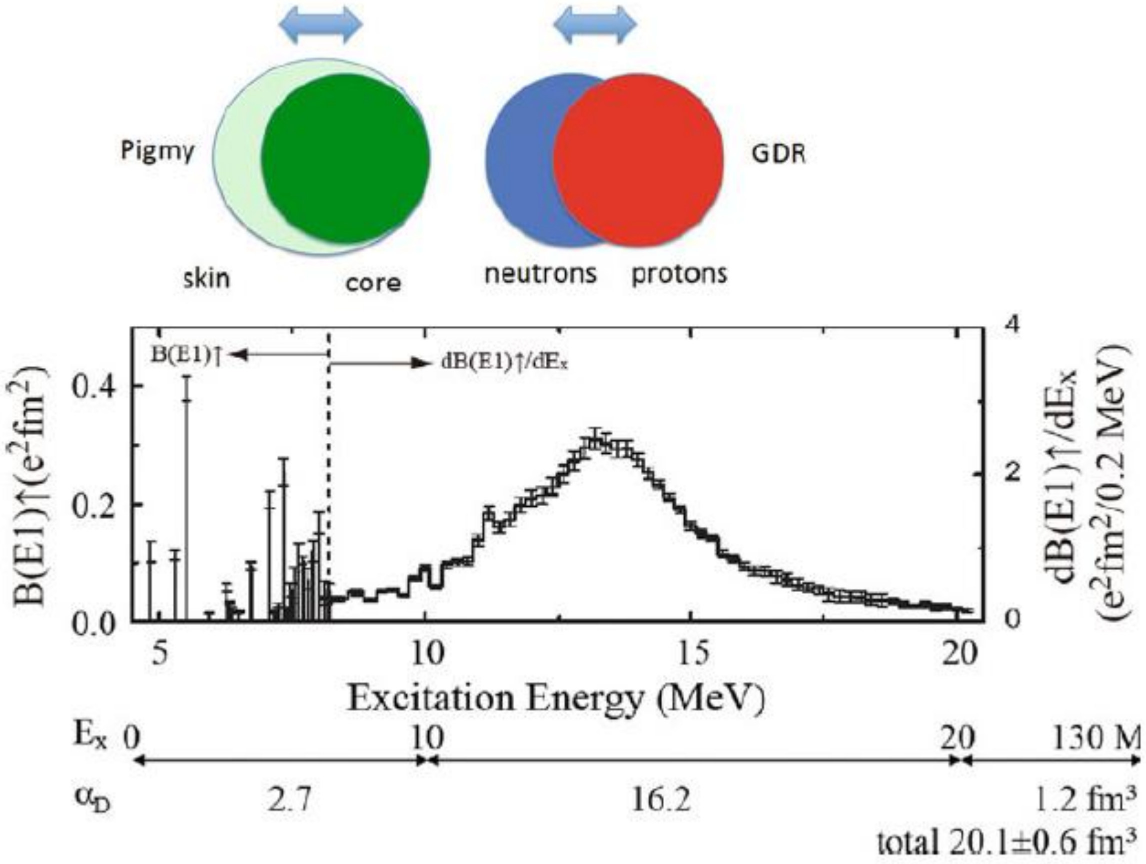


Isovector Giant Dipole Resonance (IVGDR) is nuclear collective mode (E1) in which protons and neutrons oscillate against each other (IV ··· out of phase, Dipole, E1 ··· 1D)

Pigmy Dipole Resonance (PDR) is oscillation between skin and core nuclei.

$$\alpha_D = 2e^2 \sum_n \frac{|\langle n|O(E1)|0\rangle|^2}{\omega_n}$$

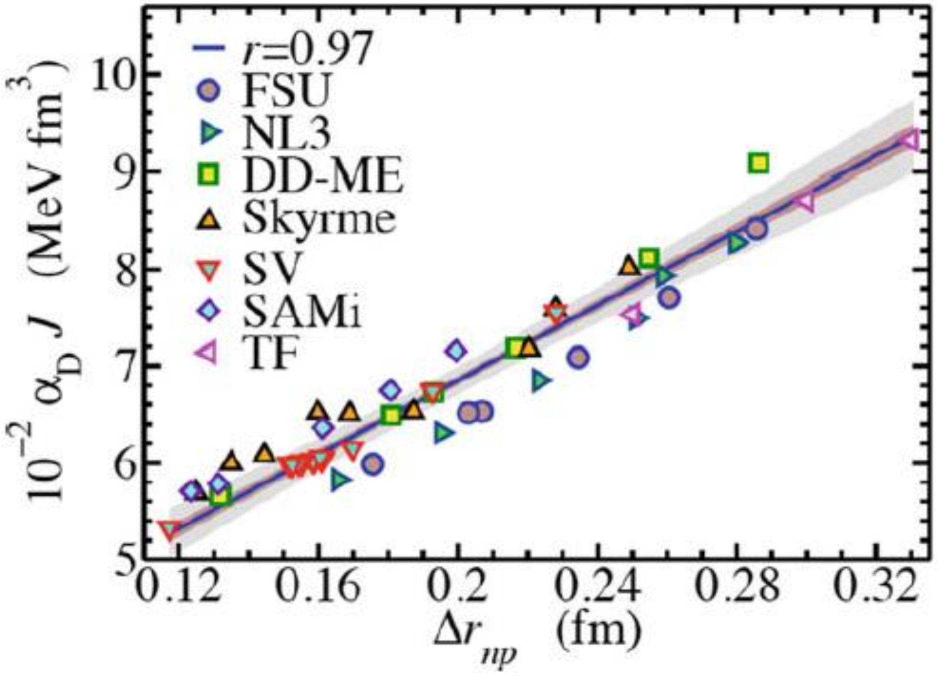
Summed E1 strengths can quantify dipole polarizability $\alpha_D$ which is a measure of the distortion of nuclear density under and external electric field.

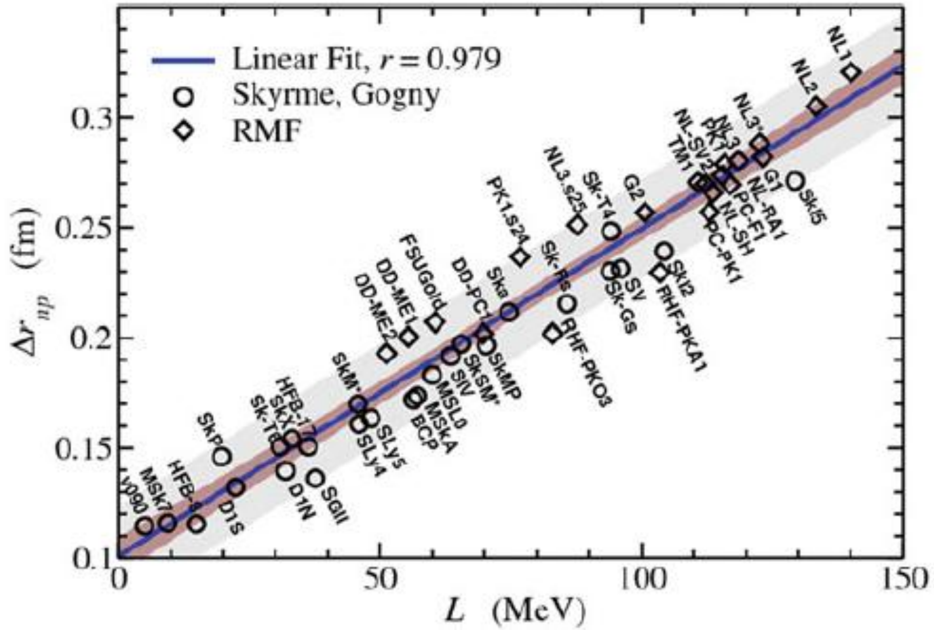


from A.Obertelli and H. Sagawa, Modern Nuclear Physics (Springer)

# Dipole polarizability and neutron skins

Various theories indicate that there is a linear relation between dipole polarizability and neutron skins, which in turn is closely related to the symmetry energy parameter L.





$$\Delta r_{np} = \sqrt{< r^2 >_n} - \sqrt{< r^2 >_p}$$

$$E_{sym}(\rho) \equiv S(\rho) = J + L\frac{(\rho-\rho_0)}{3\rho_0} + \frac{1}{2}K_{sym}\frac{(\rho-\rho_0)^2}{9\rho_0^2}$$

Asym term in SEMF
at normal ρ0

$$J = S(\rho_0) \quad L = 3\rho_0\frac{\partial S(\rho)}{\partial\rho}\bigg|_{\rho=\rho_0}$$

from A.Obertelli and H. Sagawa, Modern Nuclear Physics (Springer)

# Semi-empirical mass formula and neutron stars

Semi-empirical Mass Formula is given by:

$$M(Z,A) = Z \cdot (M_p + m_e) + N \cdot M_n - B(Z,A)c^2$$

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(Z-N)^2}{A} - \Delta$$

*Volume* term; $a_v = 15.3$ MeV
each nucleon feels the effect of the nucleons surrounding

*Surface* term; $a_s = 16.1$ MeV
volume term overestimates the effect at the surface

*Coulomb* term; $a_c = 0.69$ MeV
Repulsive force among the charged particles (protons)

*Asymmetry* term; $a_a = 22.5$ MeV
Nuclei tend to have N = Z

*Pairing* term; $\Delta$ $-12A^{-1/2}$ for even-even nuclei,
$+12A^{-1/2}$ for odd-odd nuclei, 0 for others

Based on Semi-empirical Mass Formula, what would be the minimum radius or mass for neutron stars to make a bound system due to the gravitational attraction $3GM^2/(5R)$?
Apply the SEMF for pure neutron system (Z=0, A=N) and ignore surface, pairing, and Coulomb terms. Very rough estimate can be made for radius by $1.2A^{1/3}$ fm.

Volume + **gravity** = attractive term
Asymmetry = repulsive term

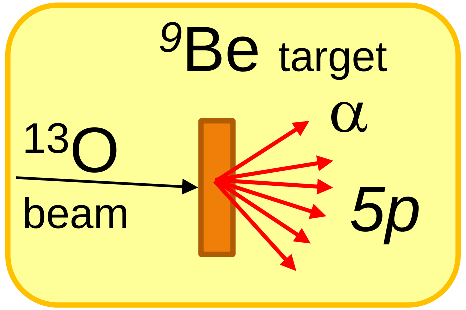
Ans. 4.3 km or $8.1 \times 10^{28}$ kg/$0.04M_{Sun}$

# $^{9}$N: 5 unbound protons plus alpha

$^{9}$N – alpha + 5p

more than one half of it (5p) unbound

Invariant mass with 5p plus alpha detection

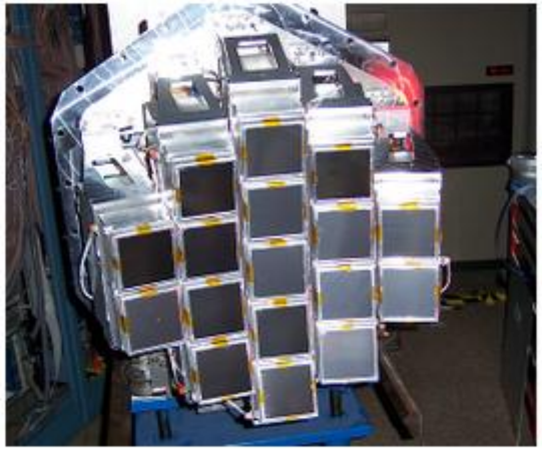

$^{9}$Be target

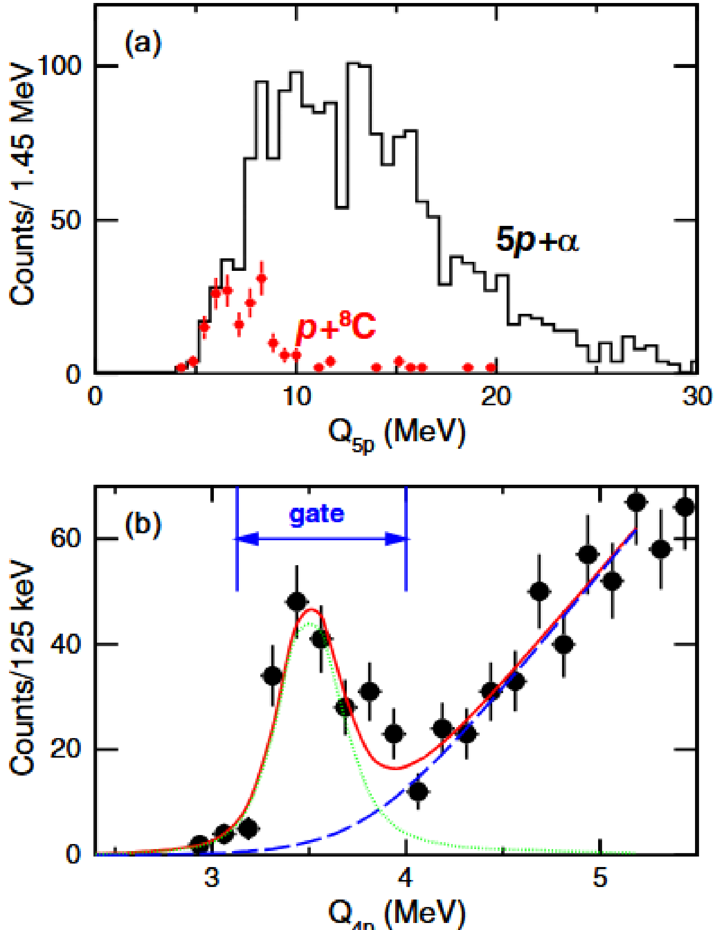
$^{13}$O beam

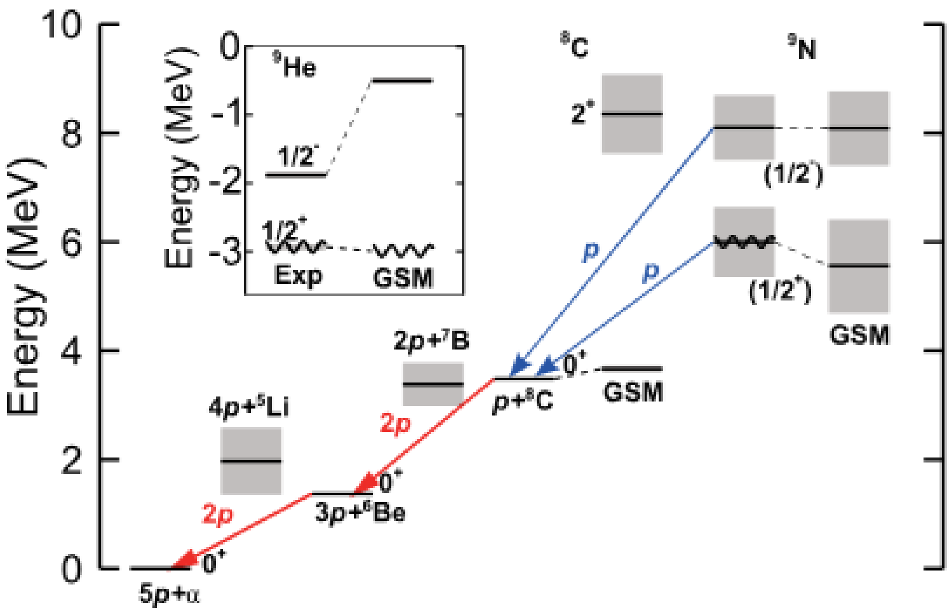
α

5p

from HIRA at MSU





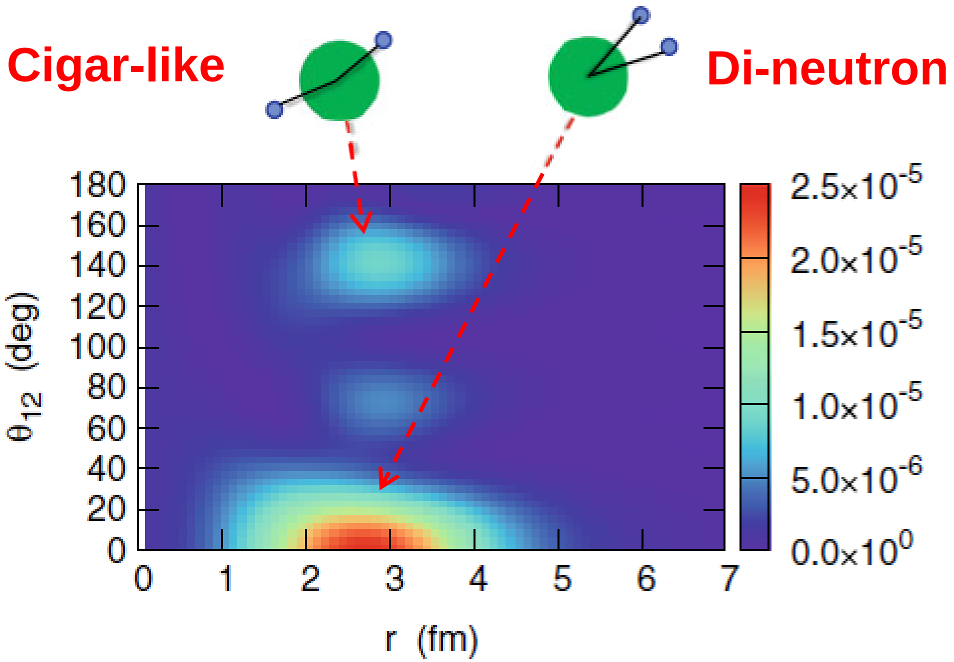


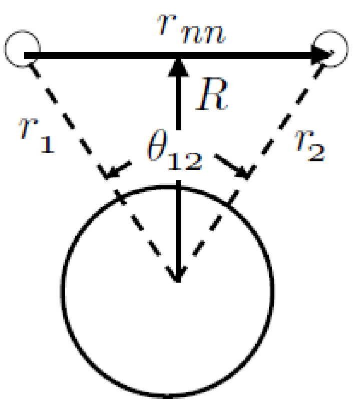
R.J.Charity, et al.,
PRL131, 172501 (2023)

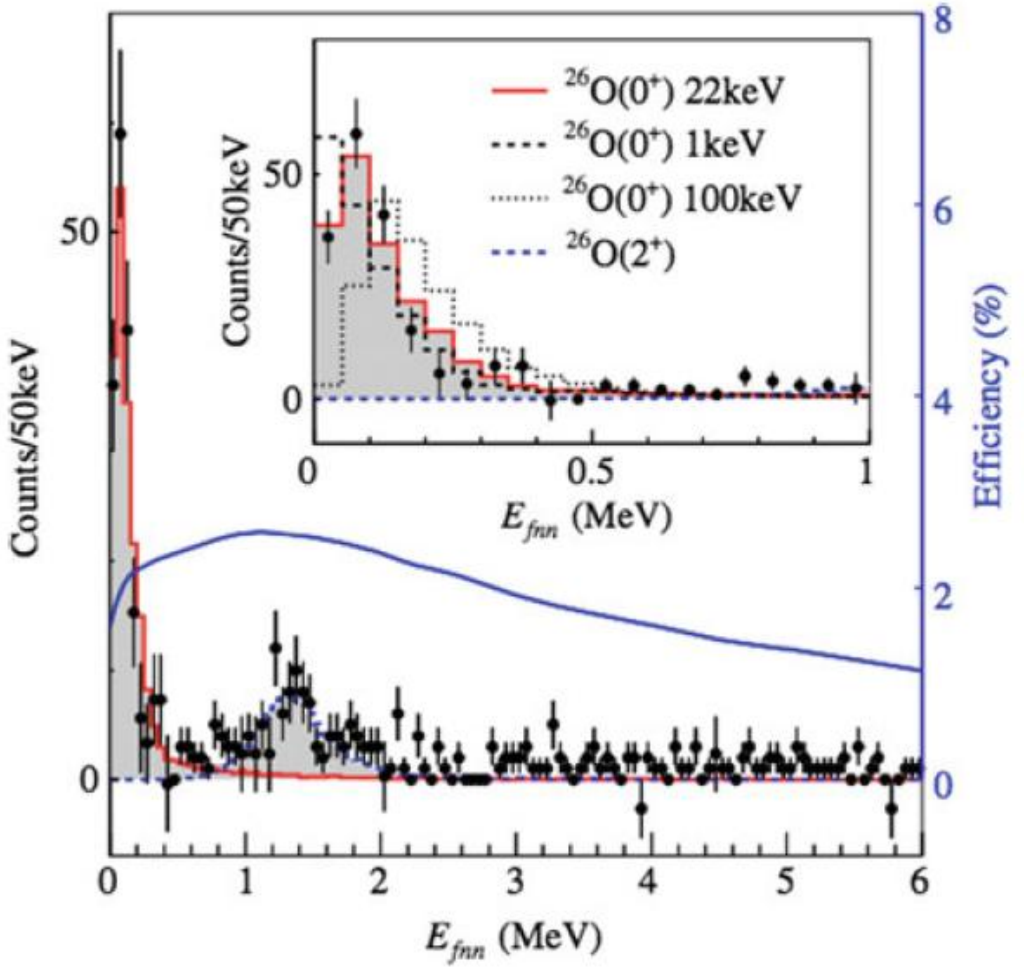
# Two neutron correlations in $^{26}$O

The barely unbound ($S_{2n}$ = 19keV) ground state of $^{26}$O has been observed.

A mixing of different parity single-particle states plays an essential role to induce the localization of di-neutron wave function at small angles. (s & p for $^{11}$Li)







Y.Kondo et al., PRL116, 102503 (2016)

# Today’s menu for experimental nuclear physics I & II

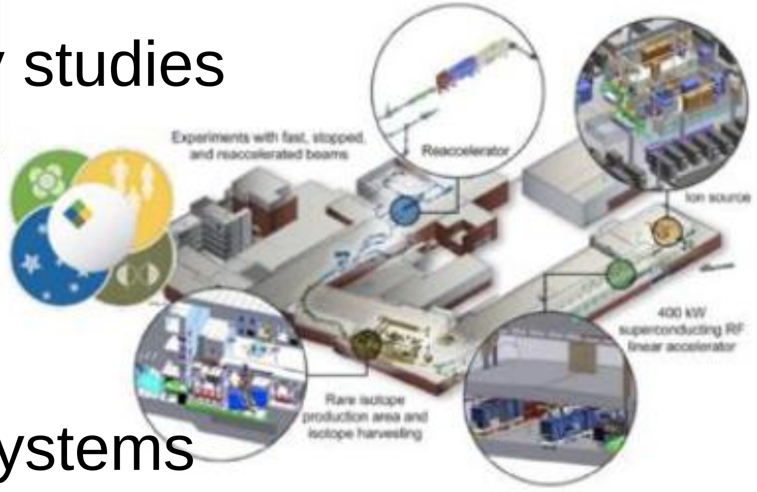
- To understand complex structure of atomic nuclei, various experimental methods need to be combined
- Experiments with rare isotopes pose additional challenges to achieve required precision and sensitivity

Be familiar with representative experimental methodology and approaches
Be aware of recent highlights in our field at FRIB era

This (first) lecture :
- RI-beam production for new isotope search and decay studies
- In-beam Gamma Spectroscopy with fast RI beams

to track structural changes

Next (second) lecture:
- Invariant-mass Spectroscopy to study weakly bound systems



# Thank you for attention and supports in National Nuclear and Particle Physics Summer School 2026

**Any questions: iwasaki@frib.msu.edu**
**any time welcome**

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