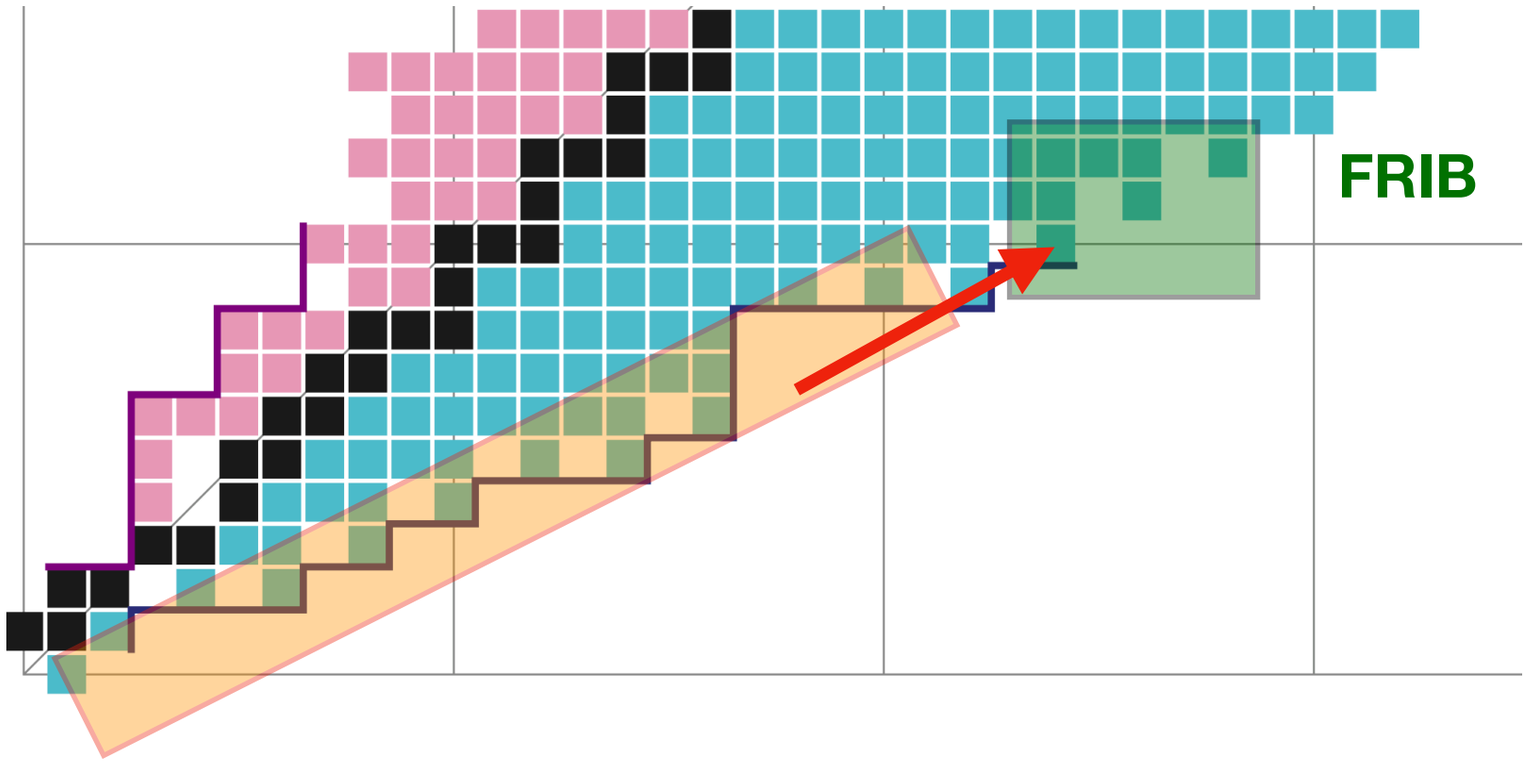
Study of Deformed p-wave Halos at FRIB

Belen Monteagudo

FRIBTA Topical Program (05/22/23)

This material is based upon work supported by the National Science Foundation under Grant No. PHYS-2209138

Neutron Dripline Physics at FRIB



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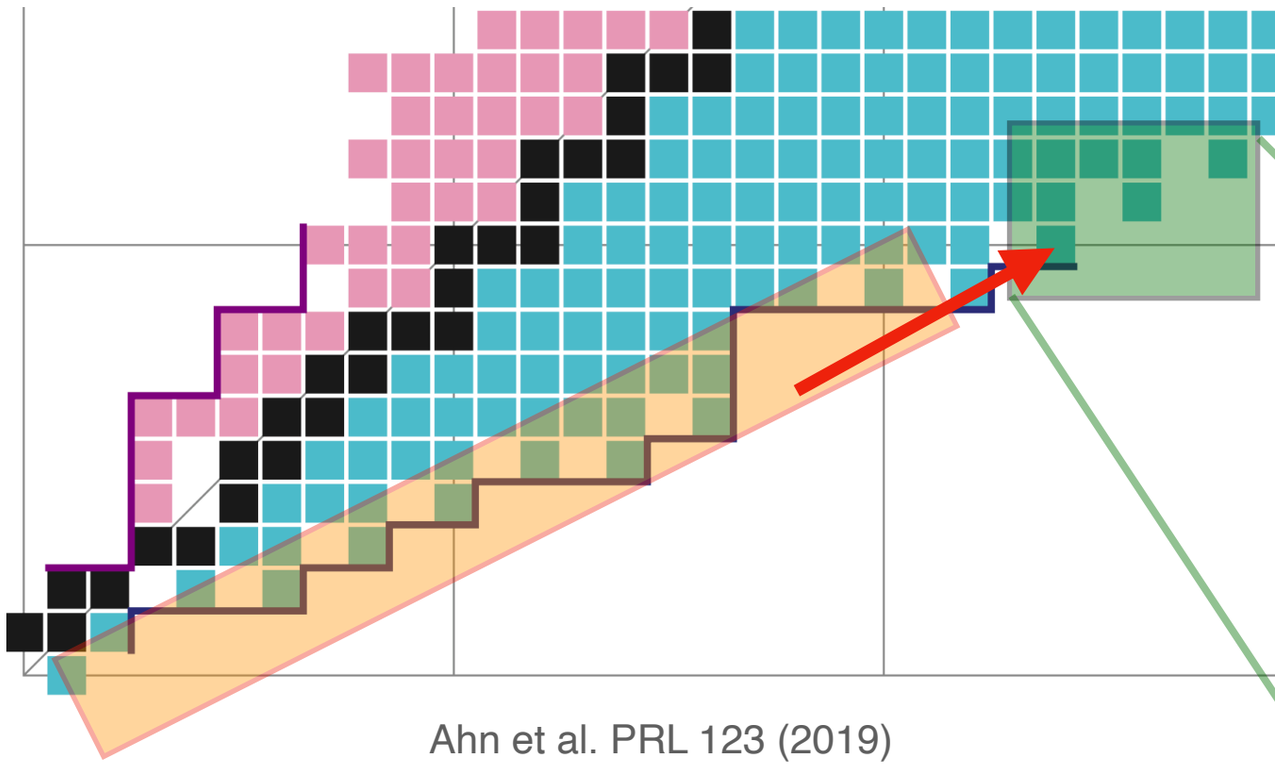
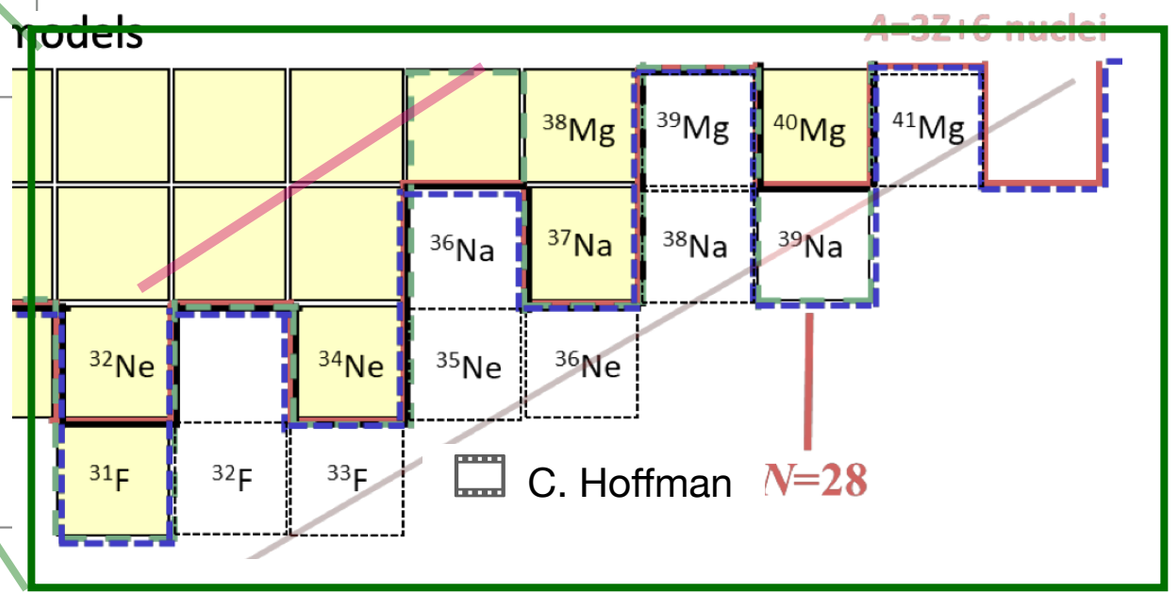
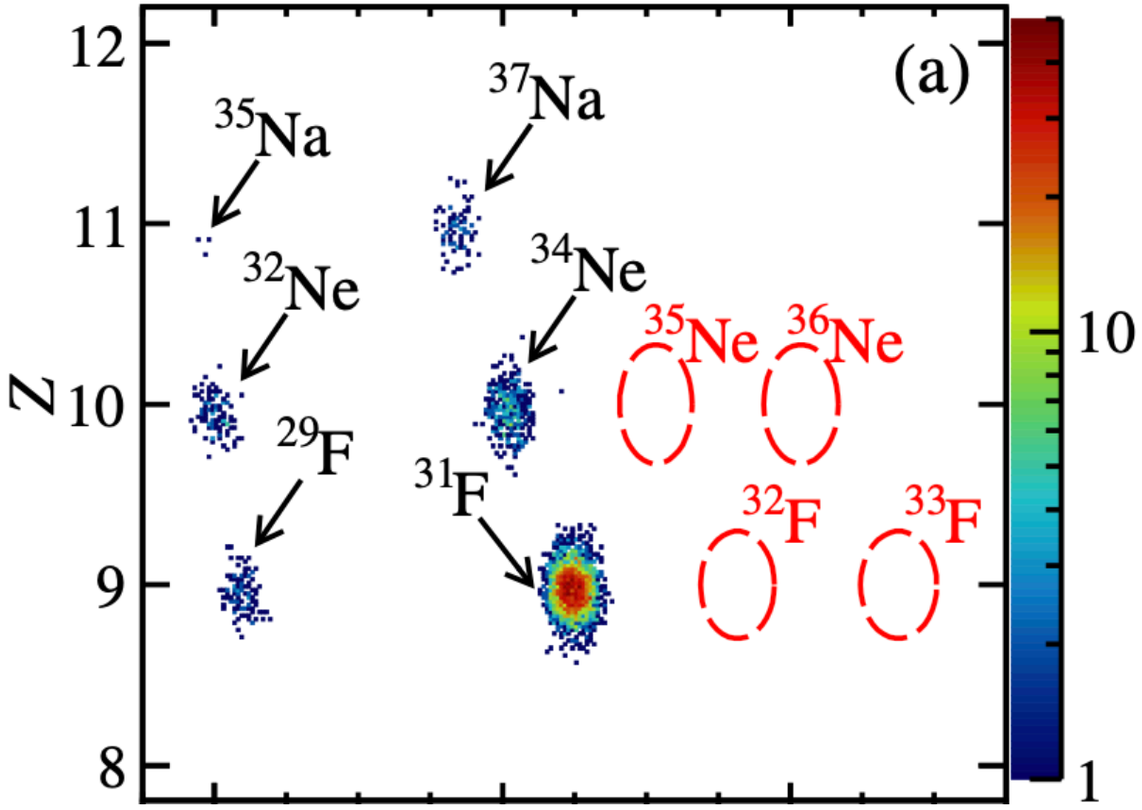


Ahn et al. PRL 123 (2019)

Region between N=20 and N=28





Dripline Nuclei between N=20 and N=28

F: 31F

Ne: 34Ne

Na: 39Na

Mg: 42,44Mg?

Al: 43Al?

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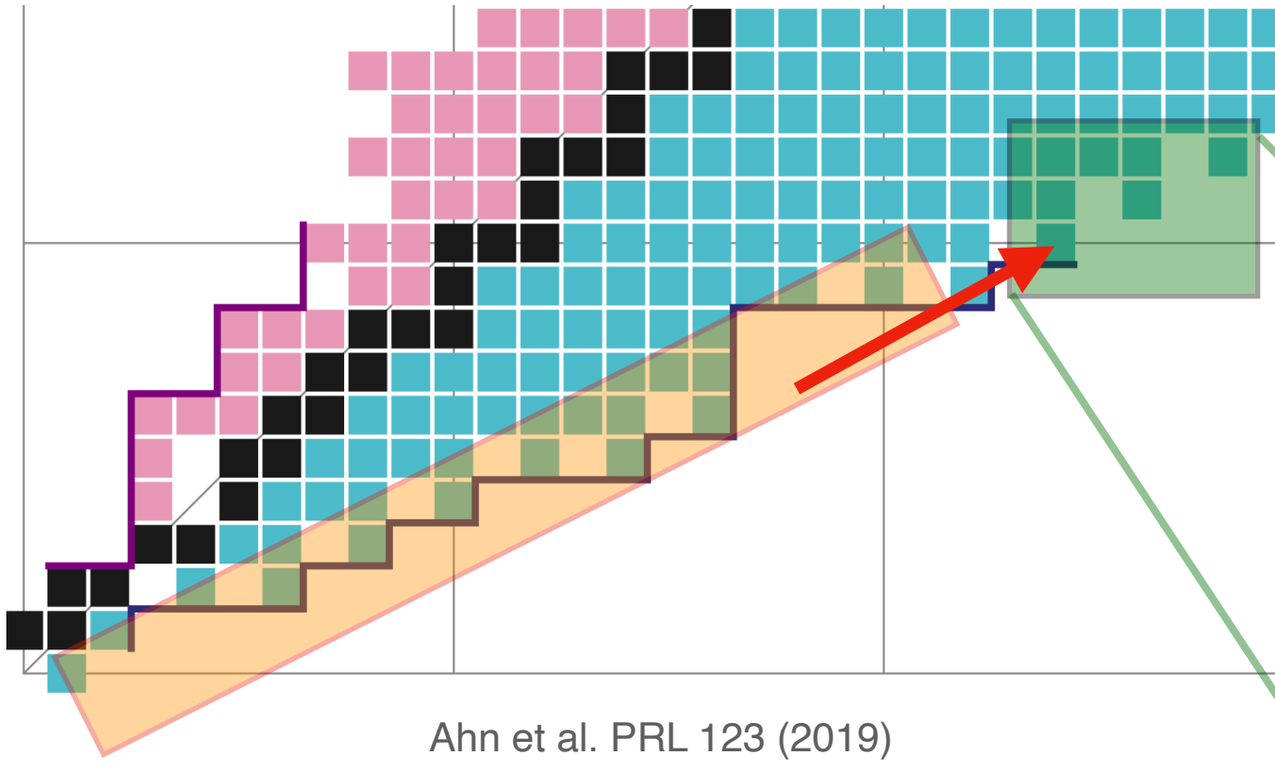

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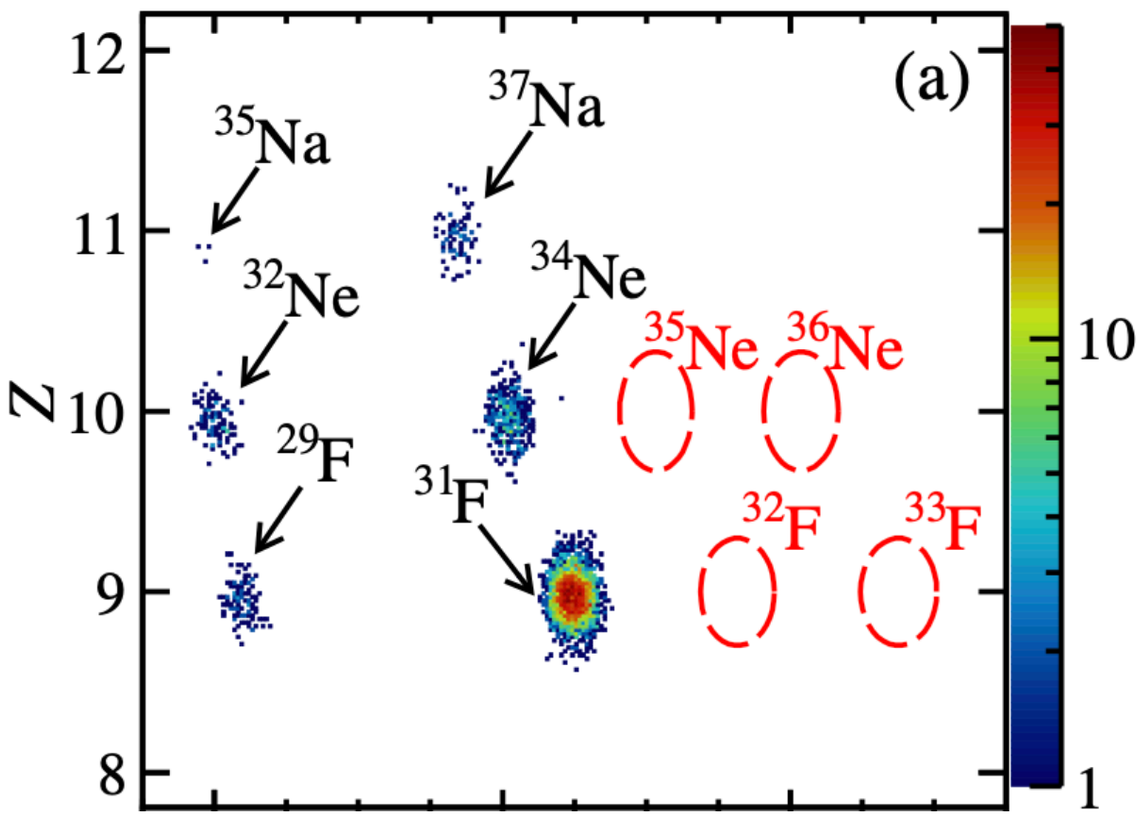

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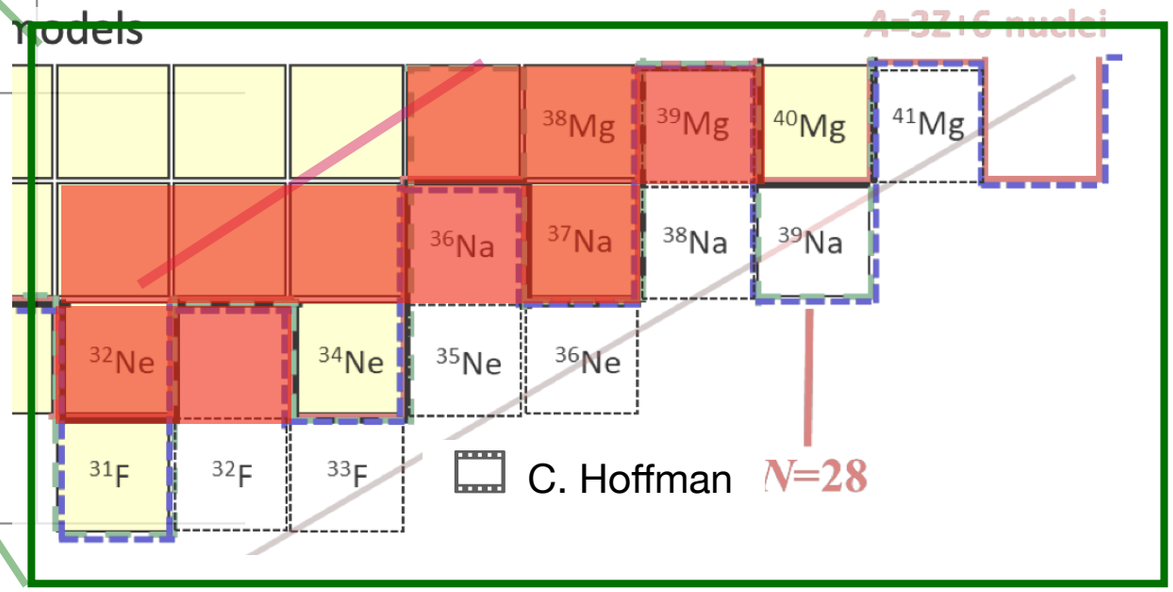

PAC3

Dripline Nuclei between N=20 and N=28

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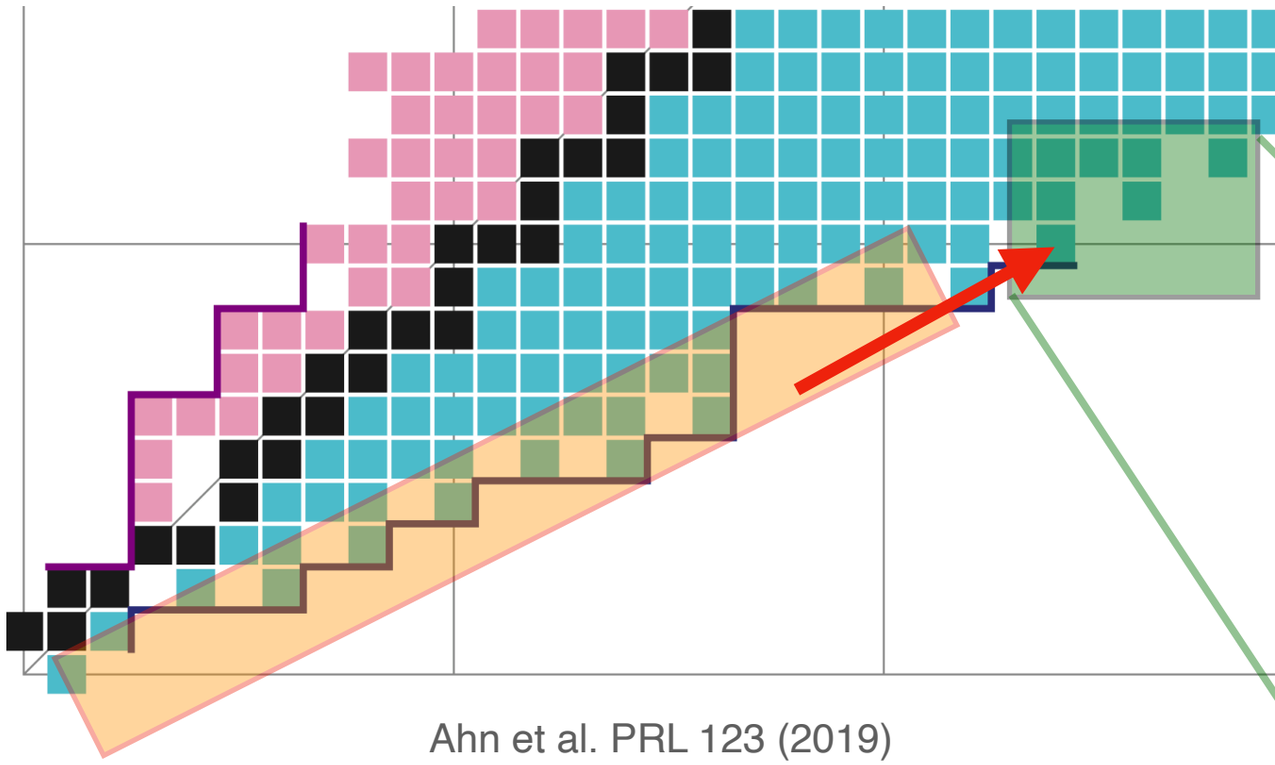

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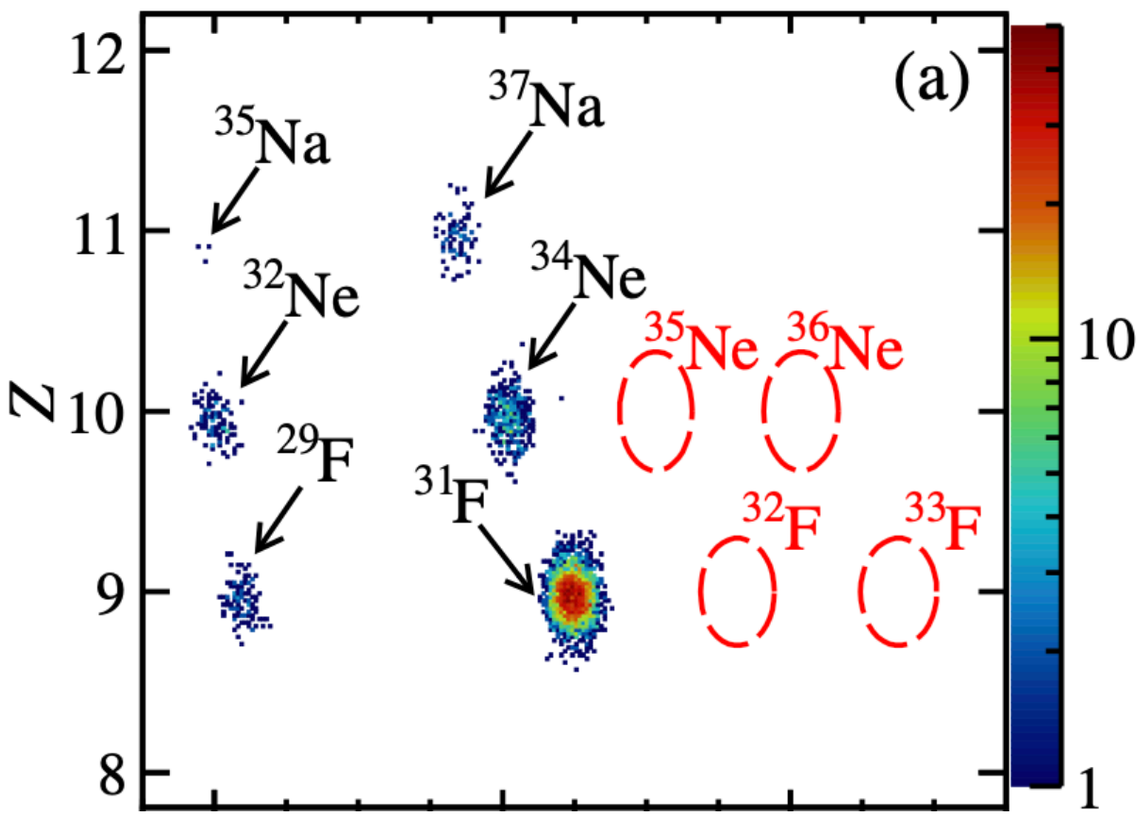

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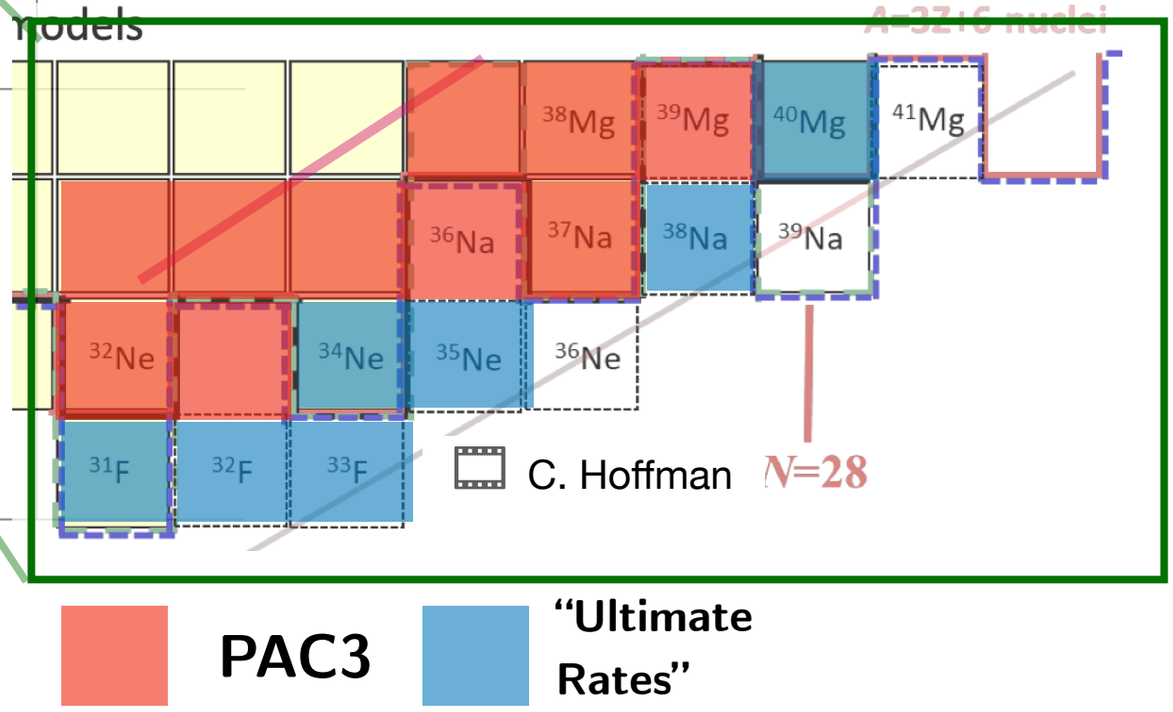

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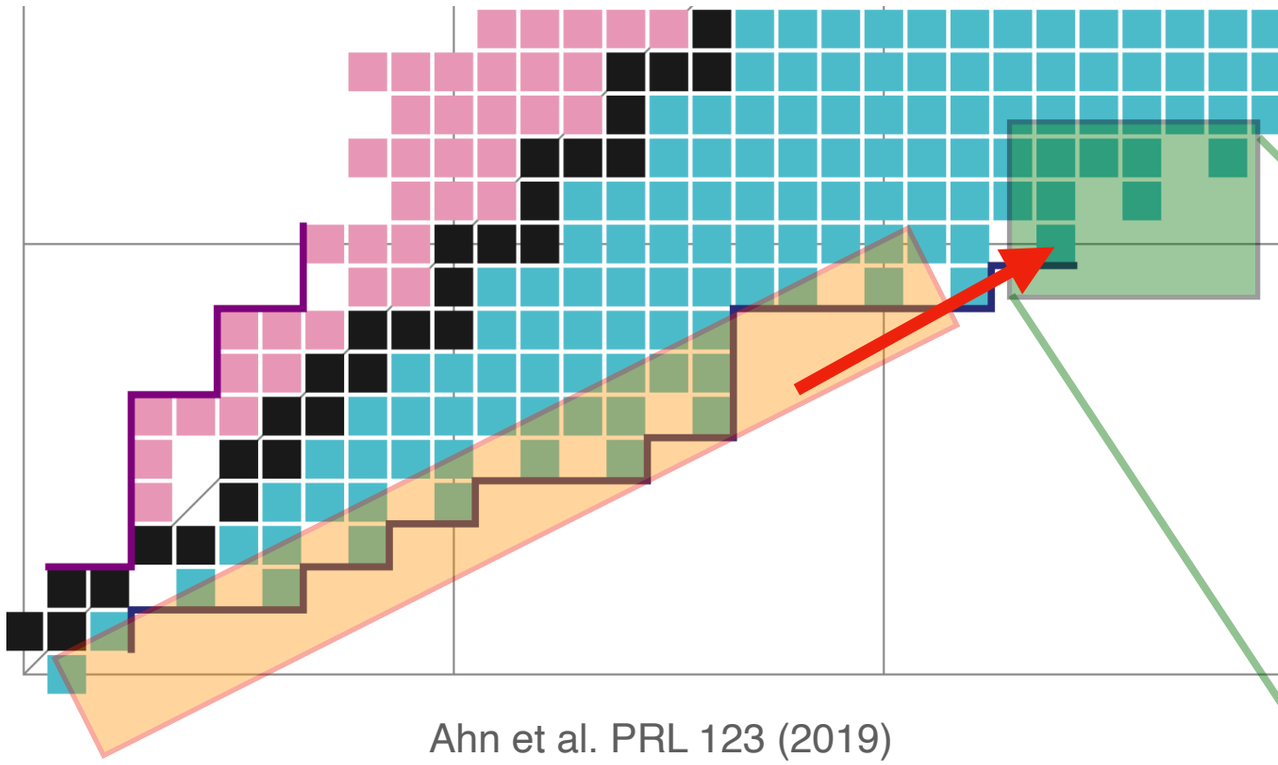

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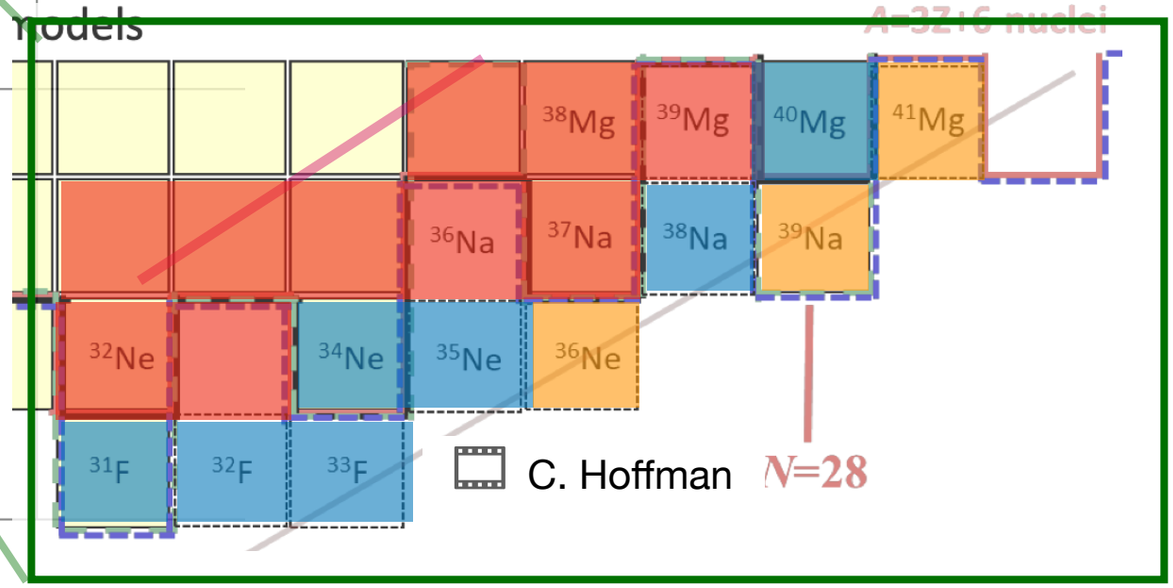
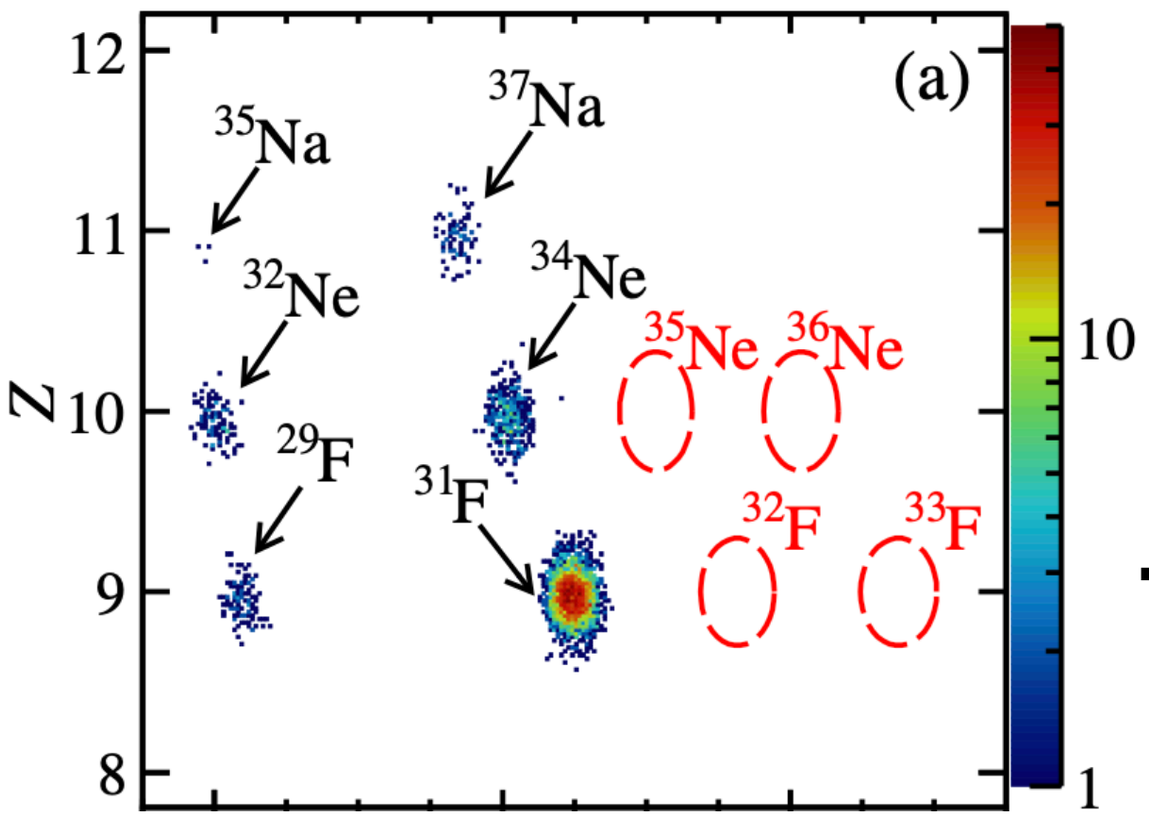


PAC3 | "Ultimate Rates" | Upgrade?



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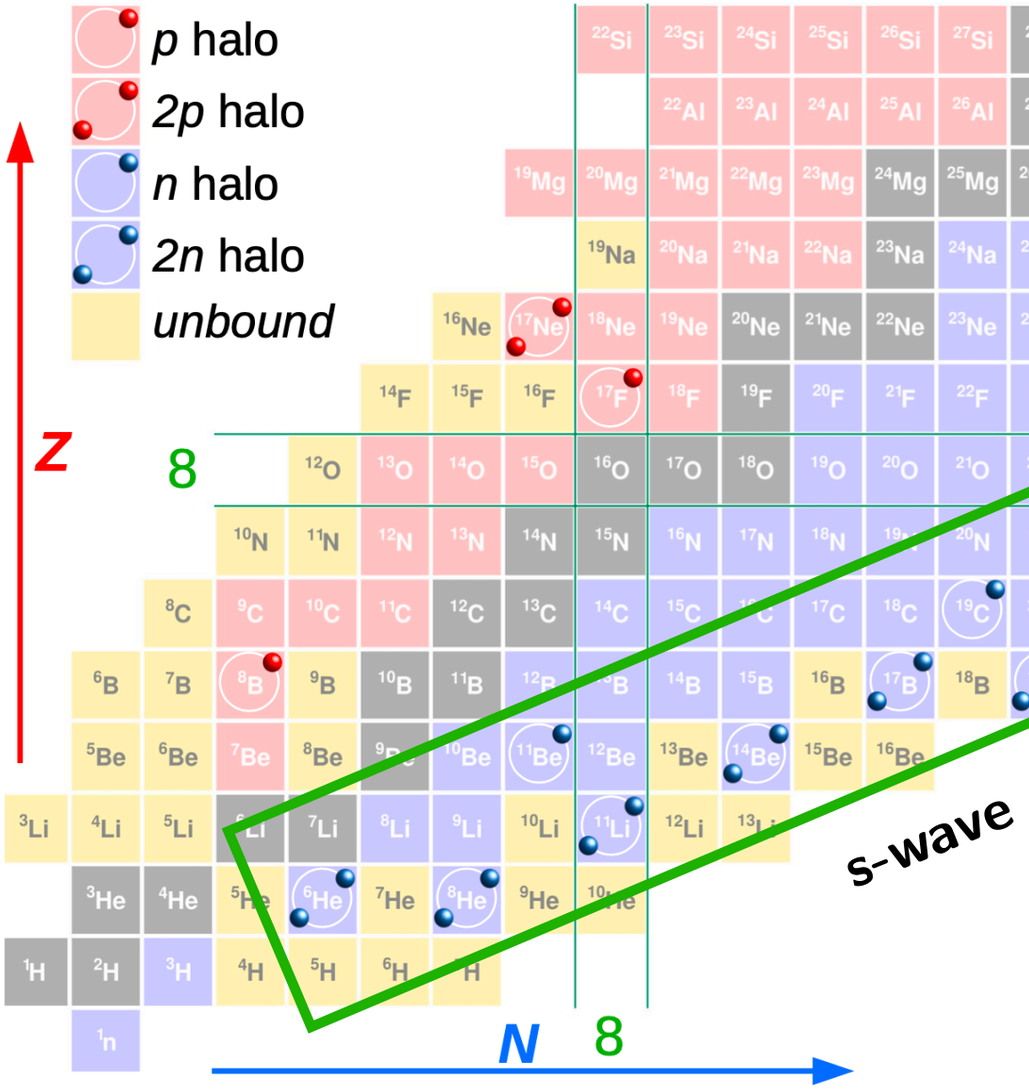


One- and Two neutron halos

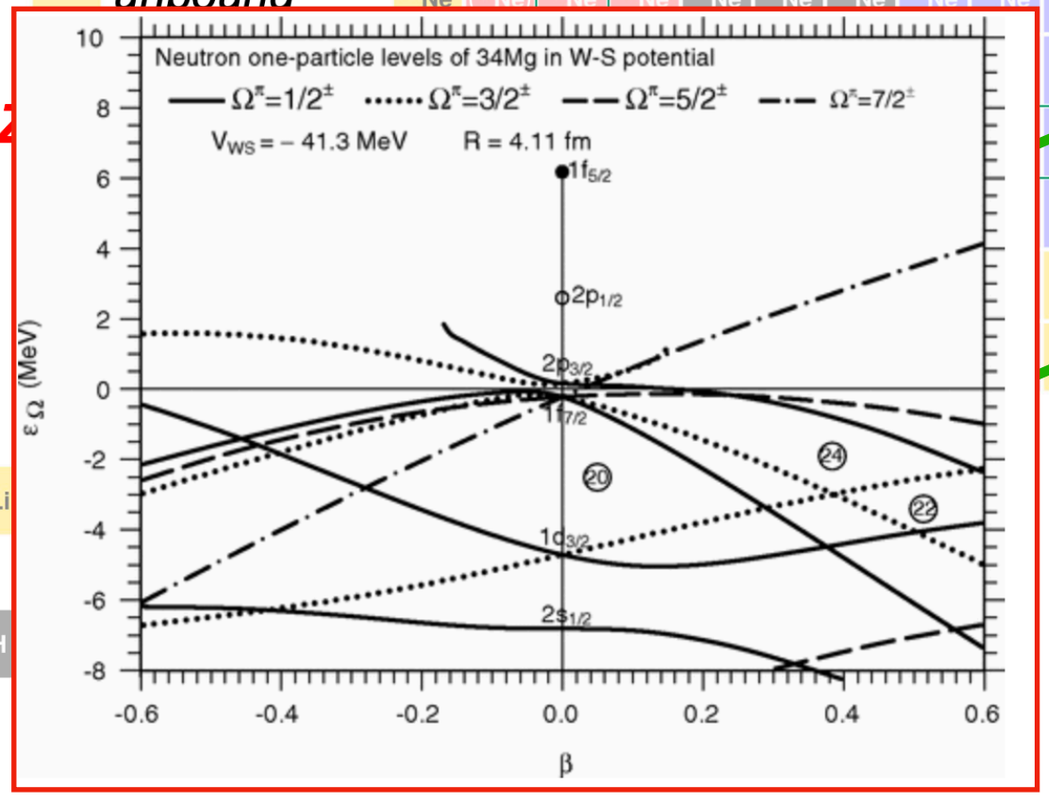
Z<8

(a) Weak binding energy, Sn<1 MeV

(b) Low l-value for valence neutron (l=**0**,1)

Where to Find Neutron Halos?

p halo
2p halo
n halo
2n halo
unbound



Hamamoto, PRC 85 (2012)

p-wave

28

20

One- and Two neutron halos

Z<8

(a) Weak binding energy, Sn<1 MeV

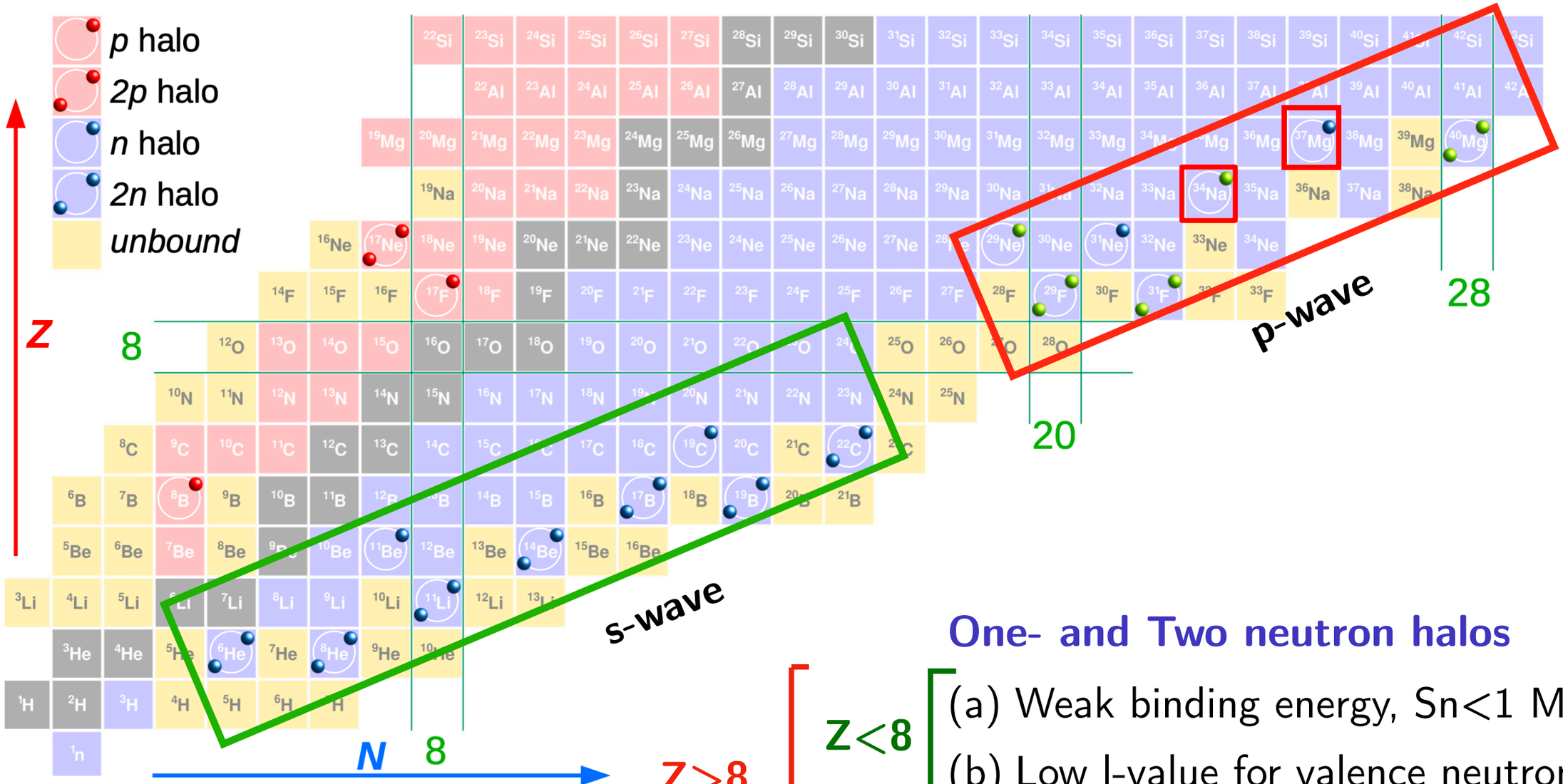
(b) Low l-value for valence neutron (l=0,1)

Near degeneracy of 1f7/2 and 2p3/2 levels

⇒ Deformation (Jahn Teller effect)

⇒ p enhanced ⇒ Halo formation

Where to Find Neutron Halos?



One- and Two neutron halos

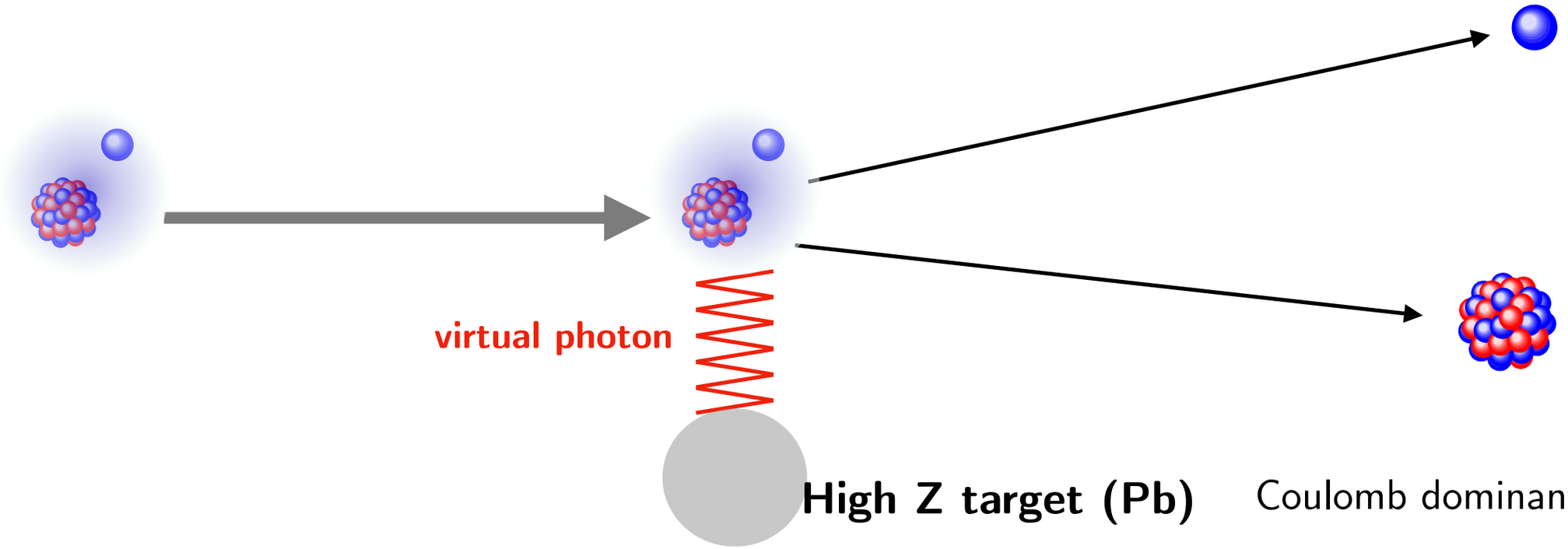
Z<8

- (a) Weak binding energy, Sn<1 MeV
- (b) Low l-value for valence neutron (l=0,**1**)
- (c) Deformation & Shell Evolution

Investigate interplay between deformation, shell evolution and halo formation at FRIB

- Are halos a characteristic feature of dripline nuclei towards medium masses?
  Deformed s-wave halos around N=50 shell gap: Cr & Fe?

Direct Breakup of 1n

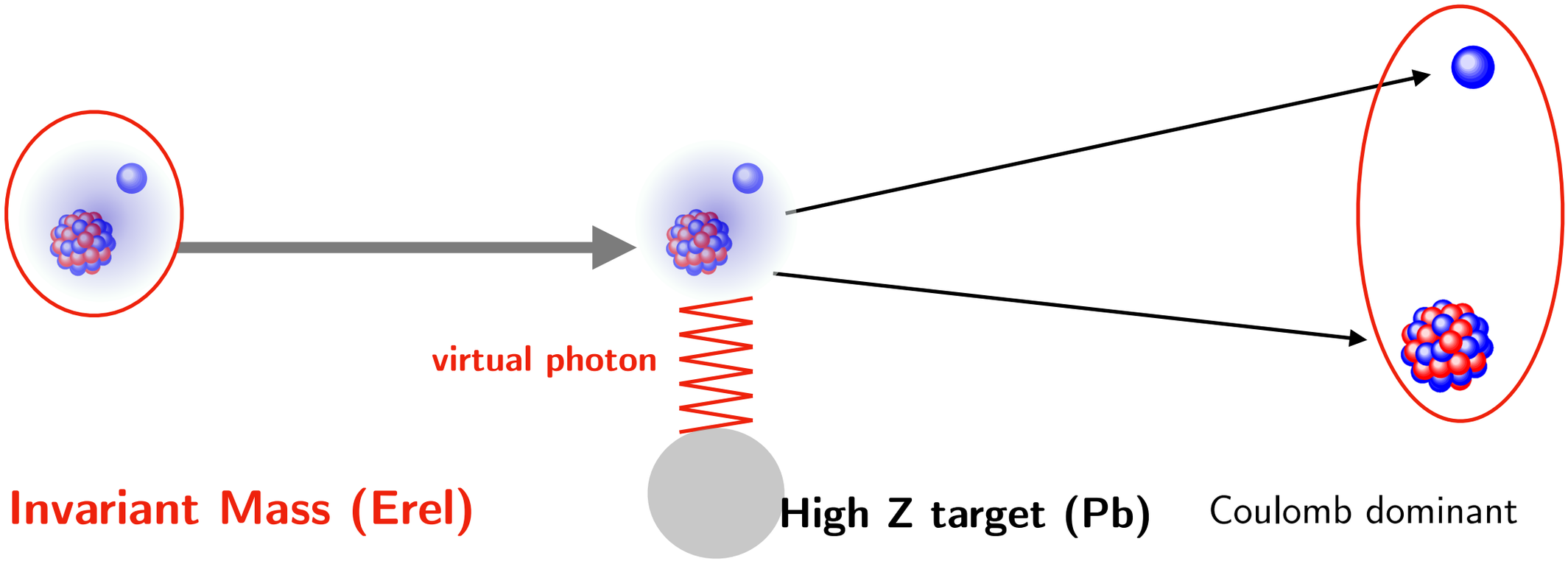


High Z target (Pb) Coulomb dominant

Nuclear target (C) Nuclear dominant

Coulomb Breakup of Halo Nuclei

Direct Breakup of 1n



Invariant Mass (Erel)

+

Cross Sections (σ)

High Z target (Pb)	Coulomb dominant
Nuclear target (C)	Nuclear dominant

Coulomb Breakup of Halo Nuclei: Sweeper + MoNA setup

Beam energies

Limited by Sweeper setup (100-200 MeV/nuc)

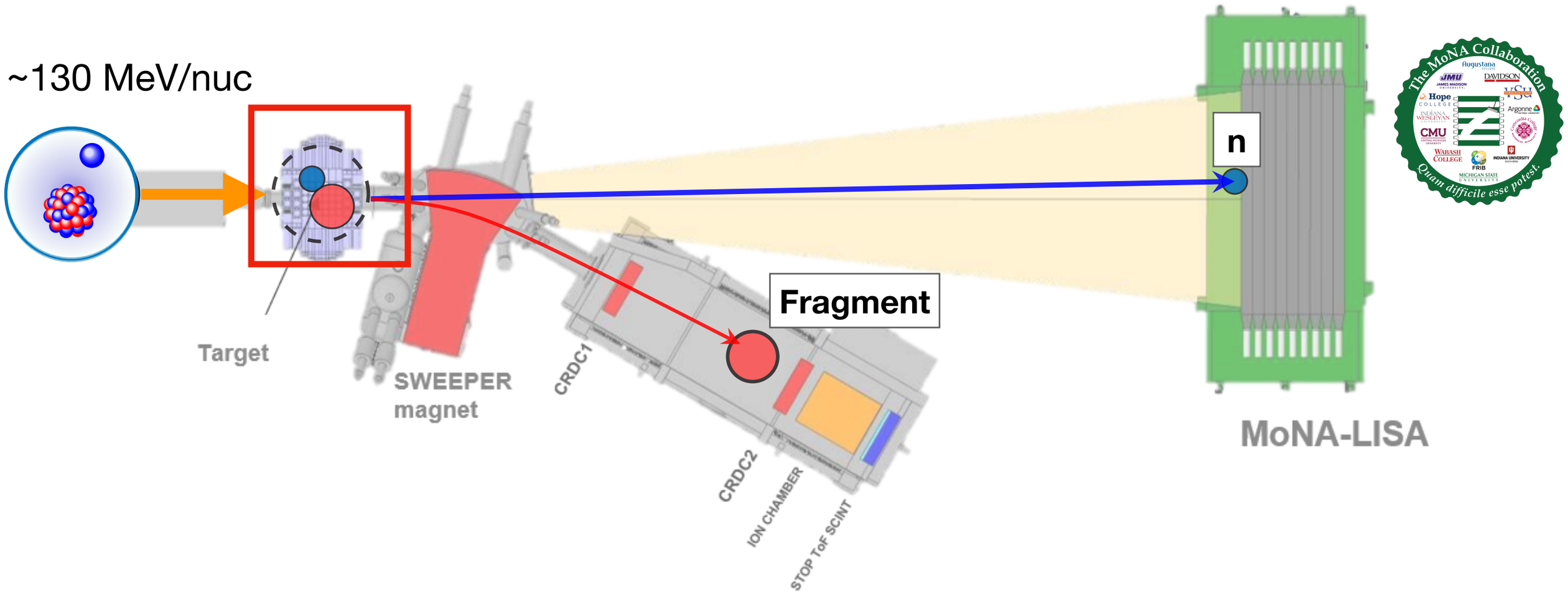
Beam intensities

>30-200 pps

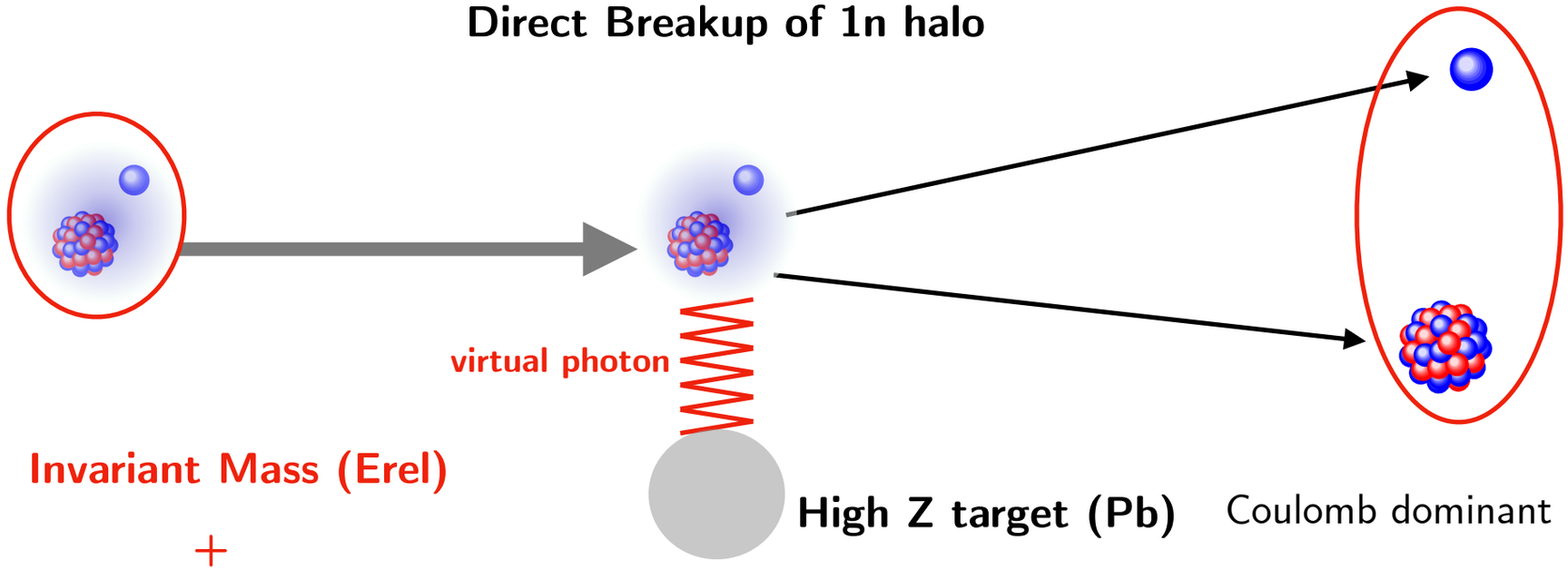
S2

- Sweeper Upgrade
- MoNA-LISA
- CAESAR
- Beam Tracking

INVARIANT MASS SPECTROSCOPY



Coulomb Breakup of Halo Nuclei: Observables



- Breakup Cross Section Distribution
- E1 Strength Distribution

$$\frac{d\sigma}{dE_{rel}} \xrightarrow{\text{Equivalent Photon Method}} \frac{dB(E_1)}{dE_{rel}}$$

Integrated CD cross-section

$$\sigma$$

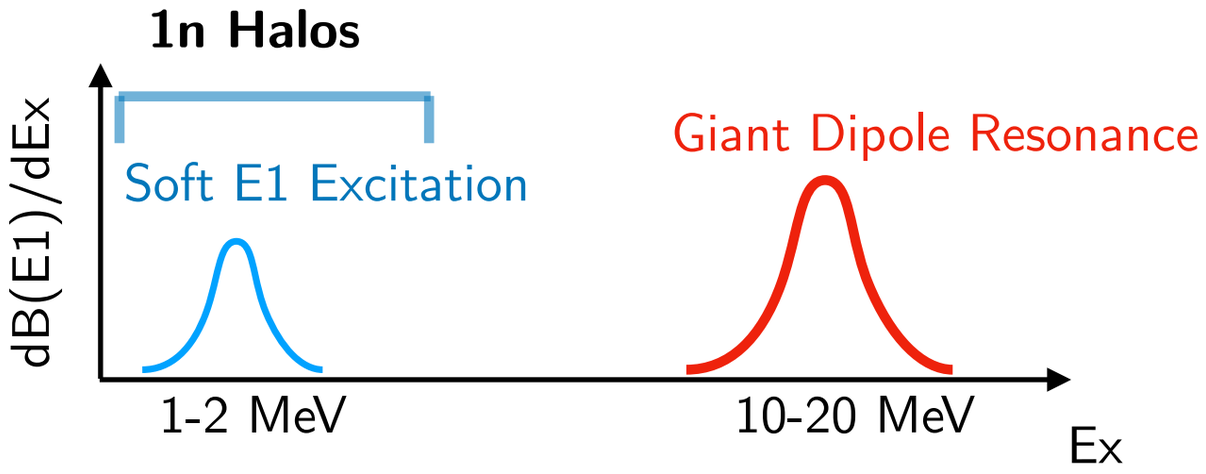
Integrated B(E1) strength

$$B(E1)$$

- Angular distribution of the fragment-neutron system in the center of mass $\frac{d\sigma}{d\Omega}$
- Parallel Fragment Momentum $\frac{d\sigma}{p_{//}}$

Coulomb Breakup of Halo Nuclei: What to expect

Experimental expectations from a 1n halo breakup...



- Large B(E1) strength at low energies, $B(E_1) > 1\ e^2fm^2$
- Large Cross-Section, $\sigma > 0.5\ b$
- Narrow momentum distributions (s or p)
- Forward peaked angular distributions

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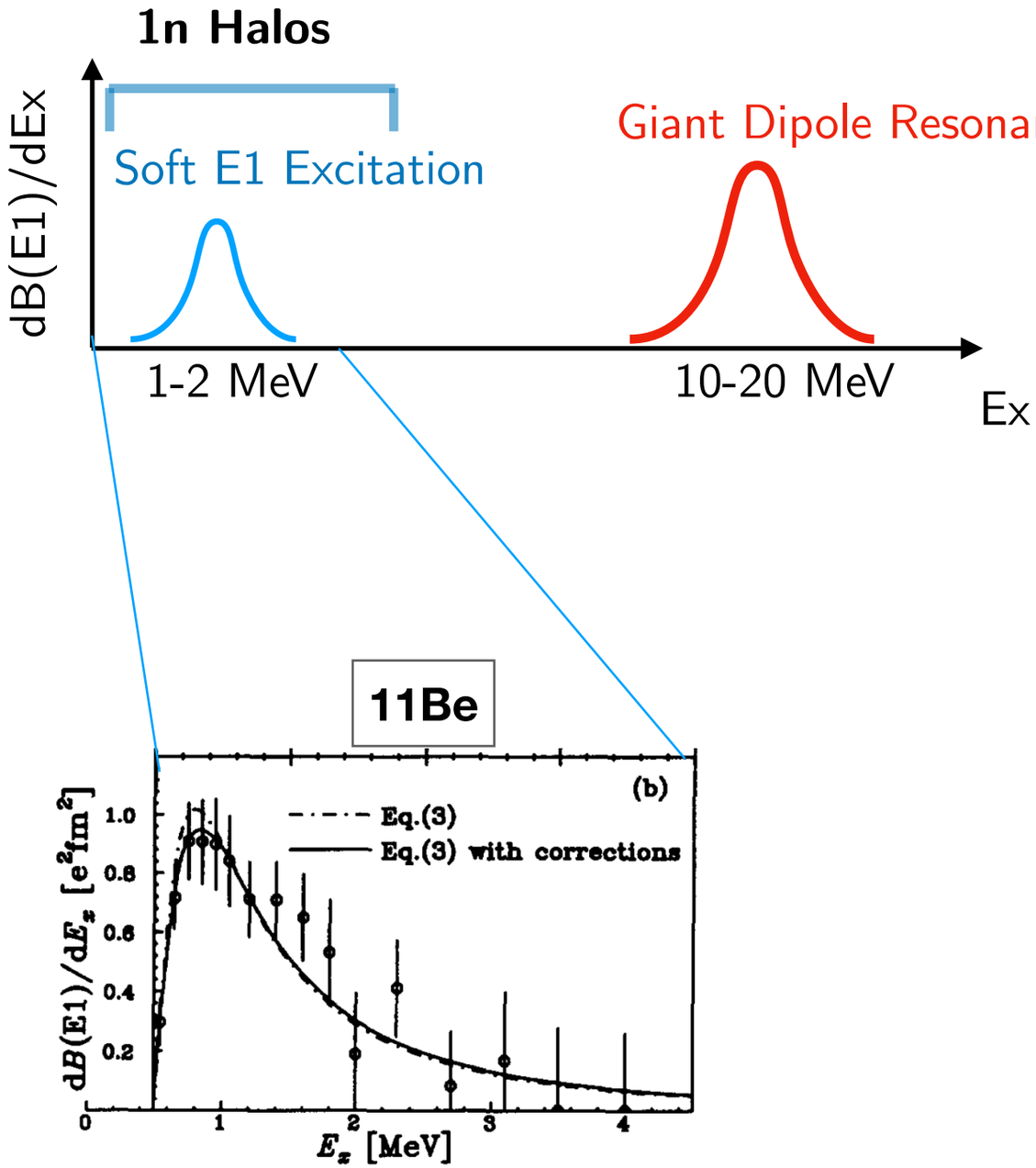

Nakamura, PLB (1994)

$B(E1) = 1.3 \pm 0.3\ e^2fm^2$

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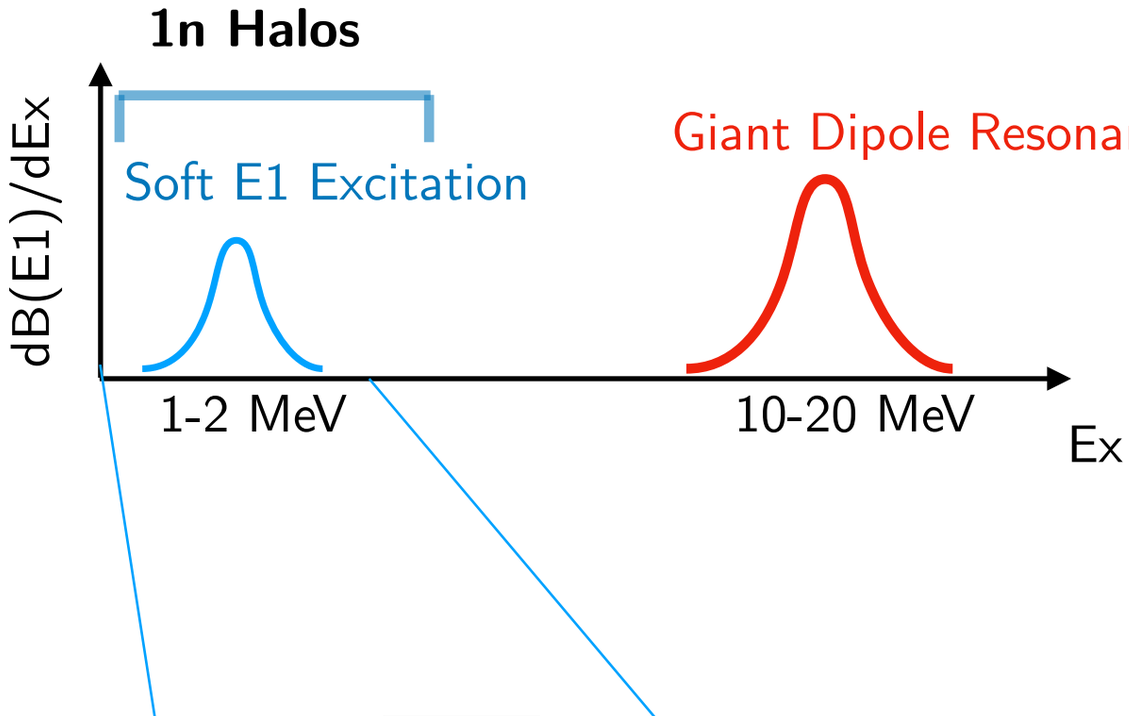

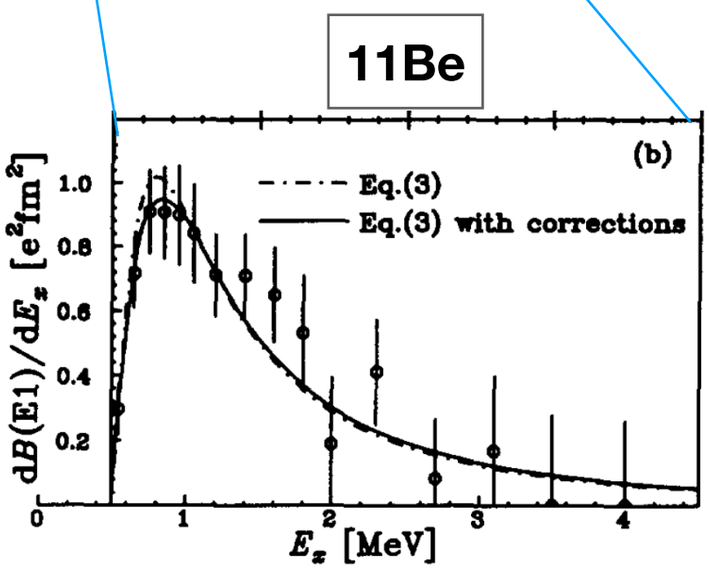

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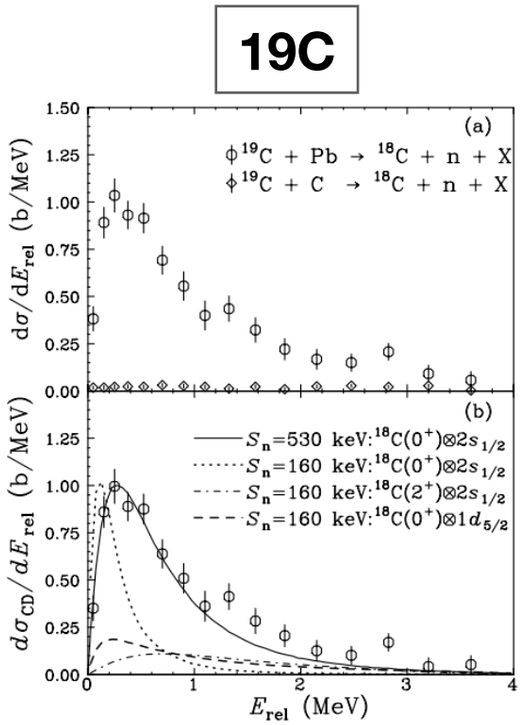

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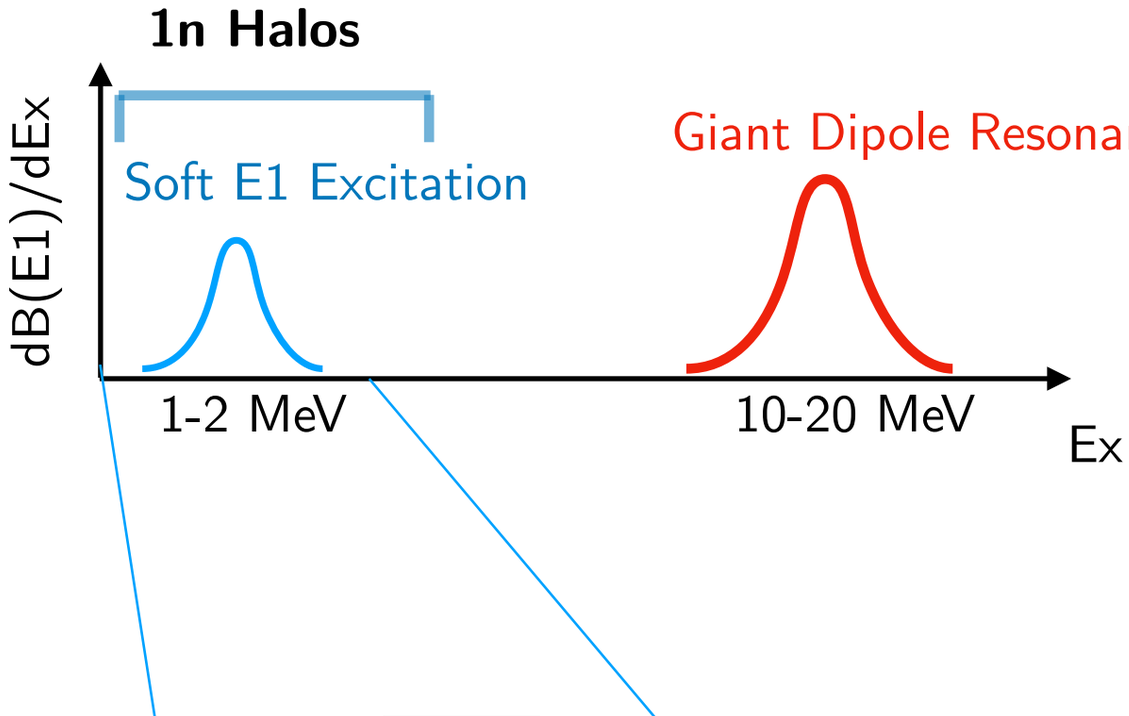

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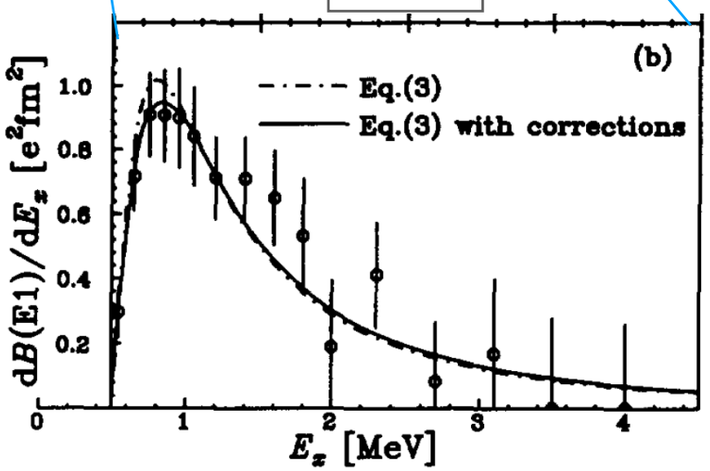
11Be



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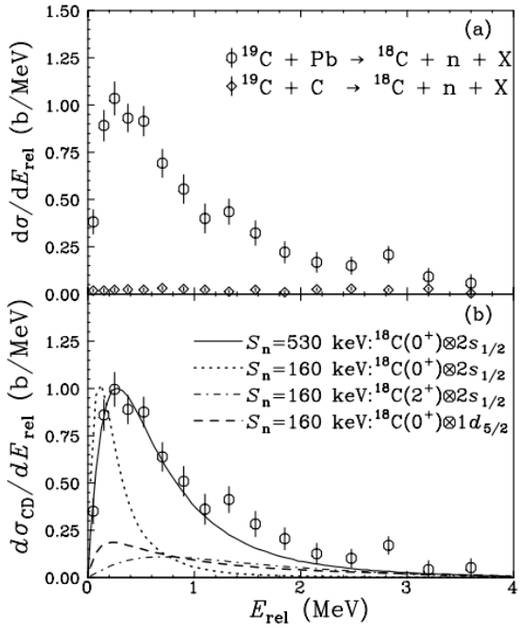
19C



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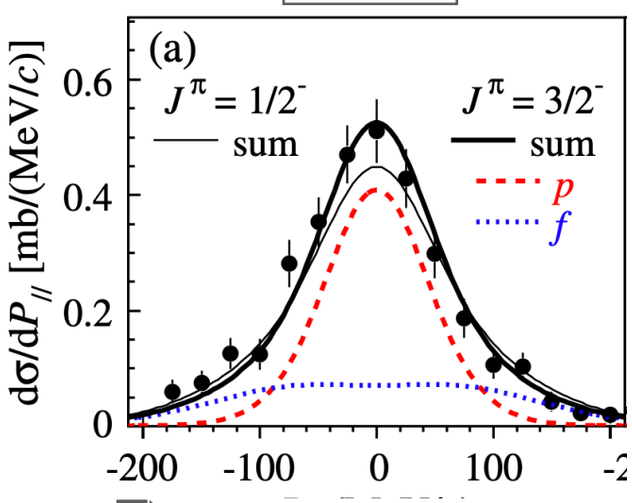
37Mg



Kobayashi, PRL (2014)

Characterizing Neutron Halos for Z>8

- The halo character is easily revealed by the data, but the full interpretation and characterization of the halo structure needs theory input

The shape of dsigma/dErel & dB(E1)/dErel distributions and their integrated value are sensitive to the characteristics of the halo:

- **Neutron configuration** (l value) and C2S
- **Neutron Separation Energy** (Sn)
- and... **deformation?**

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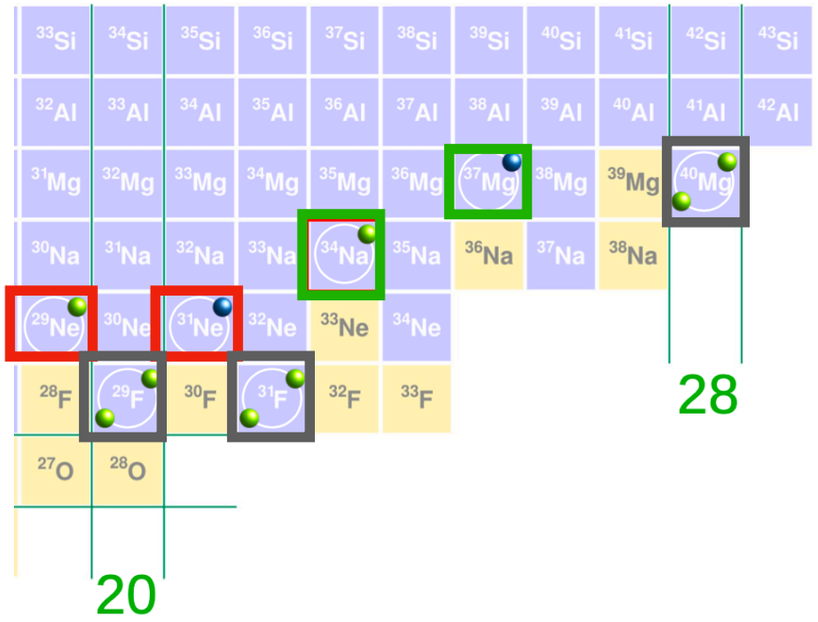

- Predicted and observed halos Z>8?

RIKEN (1n): 29Ne, 31Ne

PAC2 (1n): 34Na, 37Mg

FRIB? (2n): 29F, 31F, 40Mg

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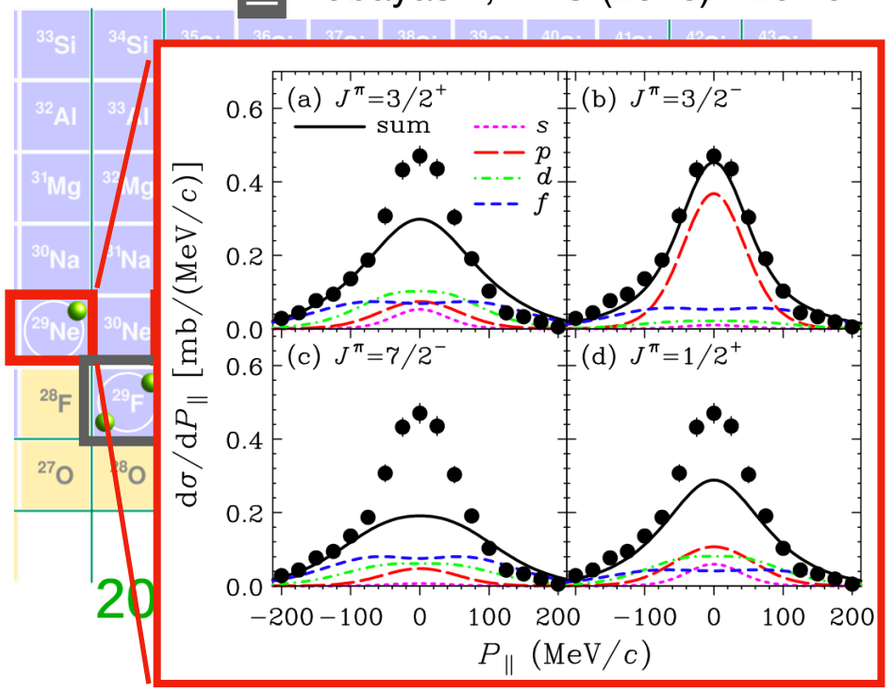
Kobayashi, PRC (2016) - 29Ne



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- Configuration Mixing
- Sn measured with large uncertainty
- Ground State spin-parity is sometimes not well known

PAC2: 34Na, possible p-wave halo

34Na (N=23)

Spokesperson: B. Monteagudo

Dripline: 39Na

- In Island of Inversion? Deformation?
- Low Sn=0.17(50) MeV Gaudefroy, PRL **109** (2012)
- Ground state spin and parity is unknown (2-?)

Predominant p3/2 valence neutron configuration?

Does it follow example of N=21 (31Ne) and N=25 (37Mg) near dripline nuclei?

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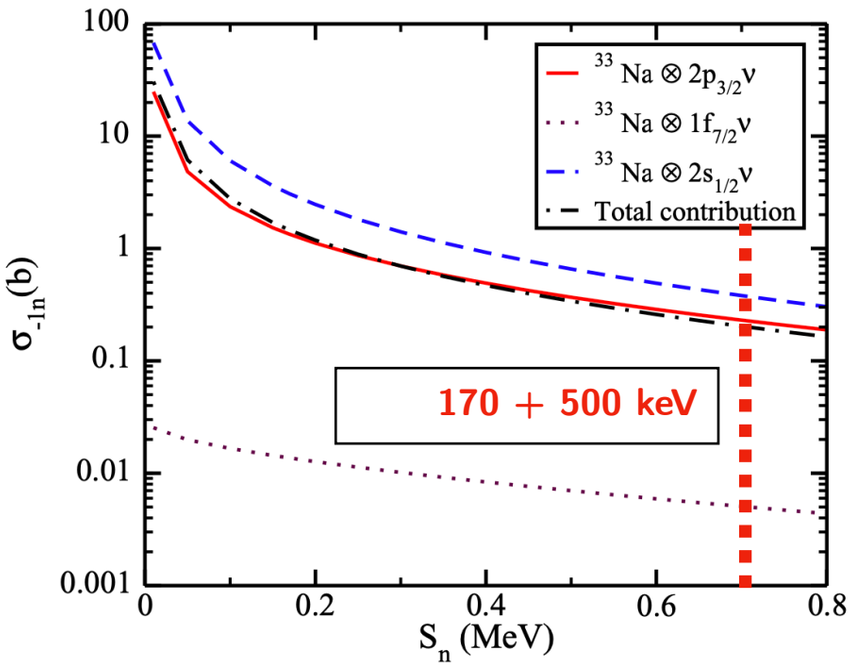
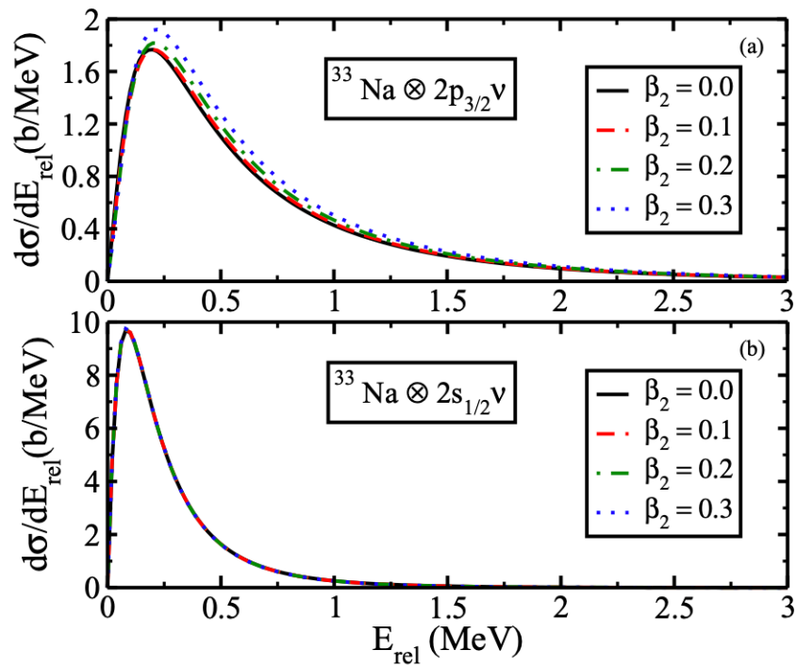
Singh, PRC (2016)





PAC2: 37Mg, Heaviest p-wave halo

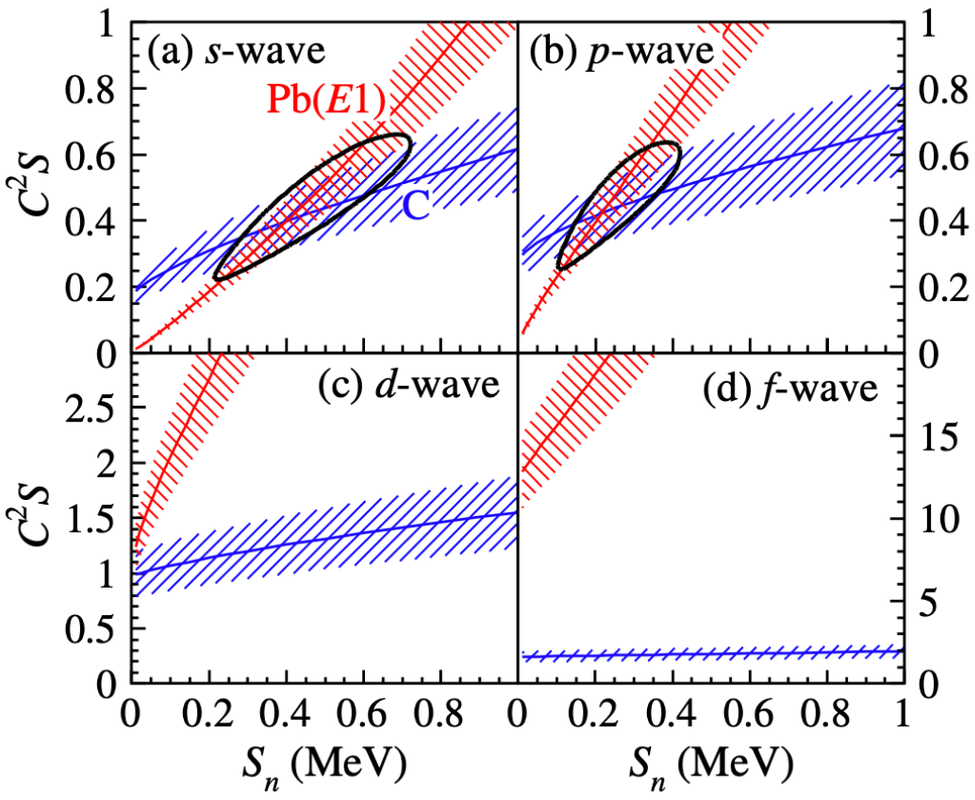
37Mg (N=25)

Spokesperson: A. Revel

Dripline: 42,44Mg?

- **Heaviest p-wave halo nucleus observed to date**
- **Inclusive Cross Sections:** Kobayashi, PRL (2014)
  - *Deduced* Sn=0.22(12)(9) MeV
  - *Deduced* $p_{3/2}$ neutron (C2S= 0.42). Consistent with deformation
  - Ground state assignment J=3/2- or J=1/2-

Kobayashi, PRL (2014)



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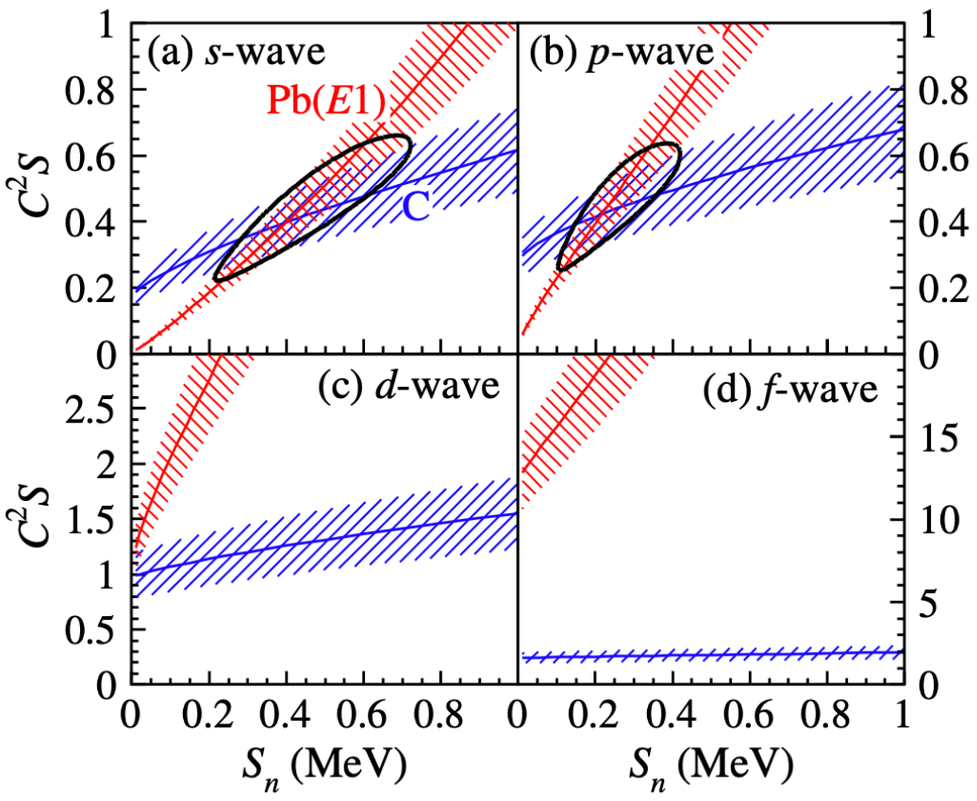


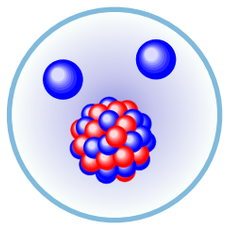
NO THEORY for exclusive measurements

Two Neutron Halo Structures

The Matryoshka case

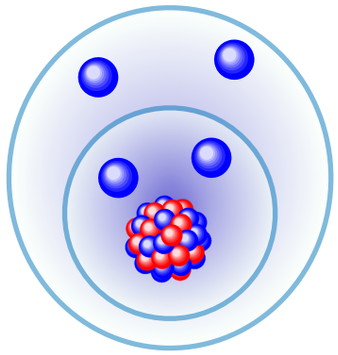
S2n = 0.5 MeV

17B



18B
(Unbound)

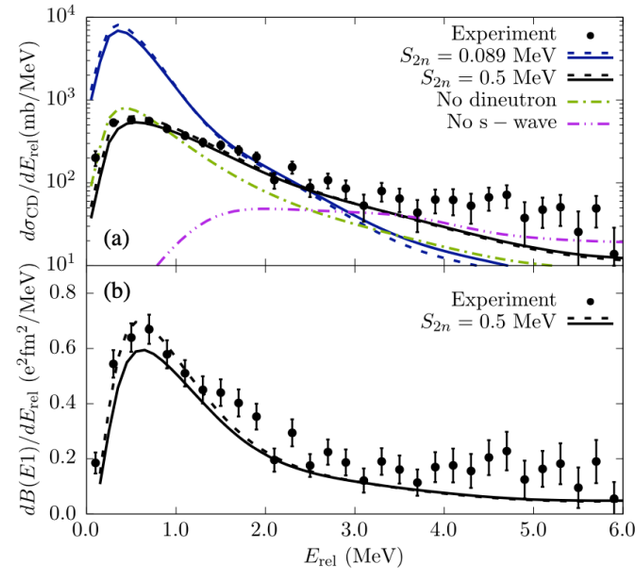
19B

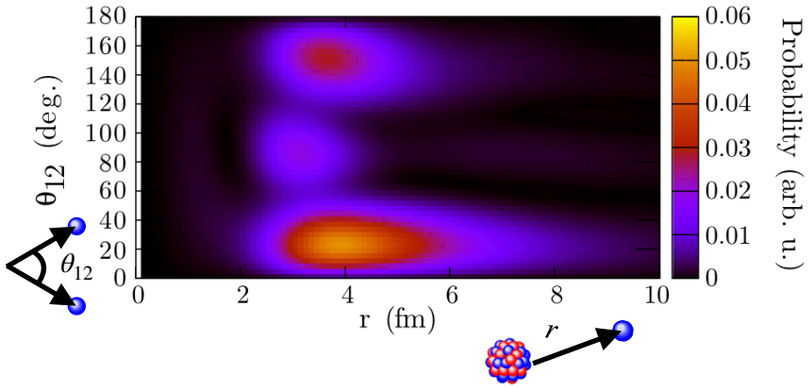


15B+4n ?

17B+2n ?

Cook, PRL 124 (2020) - 19B





Two Neutron Halo Structures

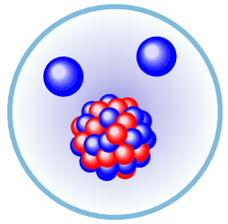
Other 2-neutron halo: **40Mg**, 42Mg?

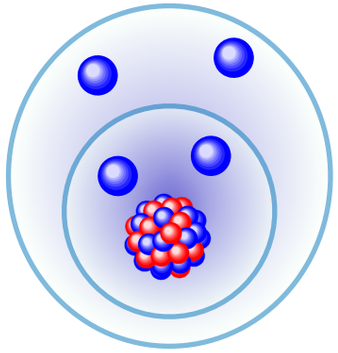
?

29F

30F
(Unbound)

31F





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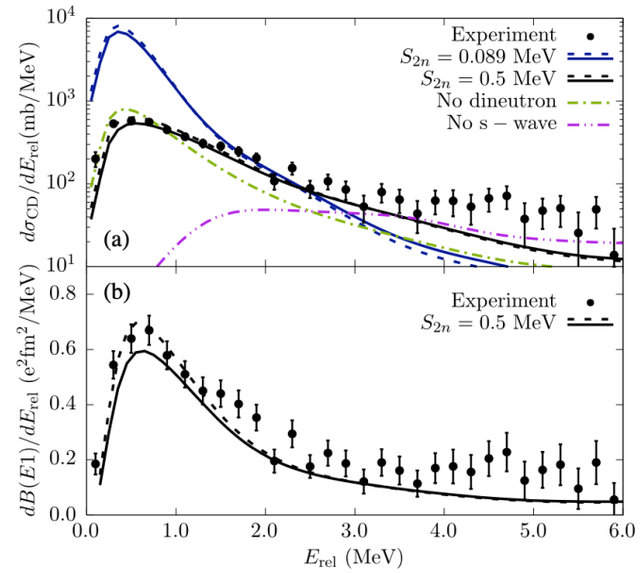
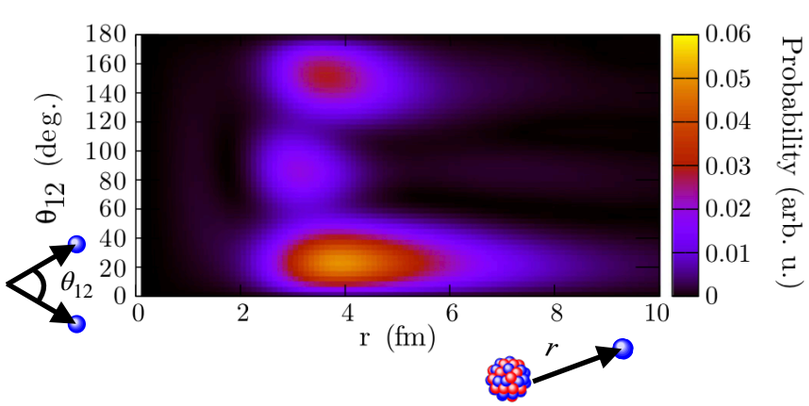
Cook, PRL 124 (2020) - 19B





Two Neutron Halo Structures

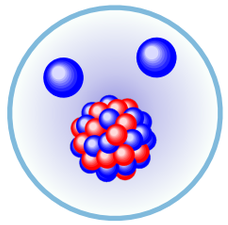
?

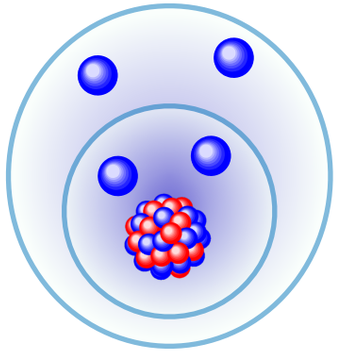
Other 2-neutron halo: **40Mg**, 42Mg?

29F

30F
(Unbound)

31F





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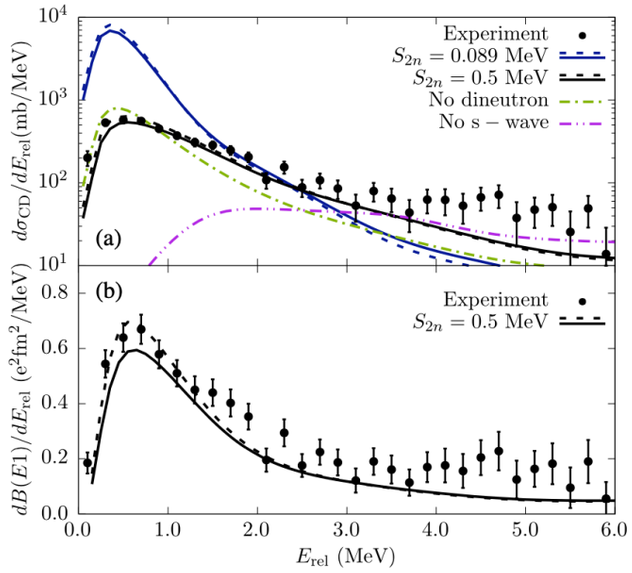
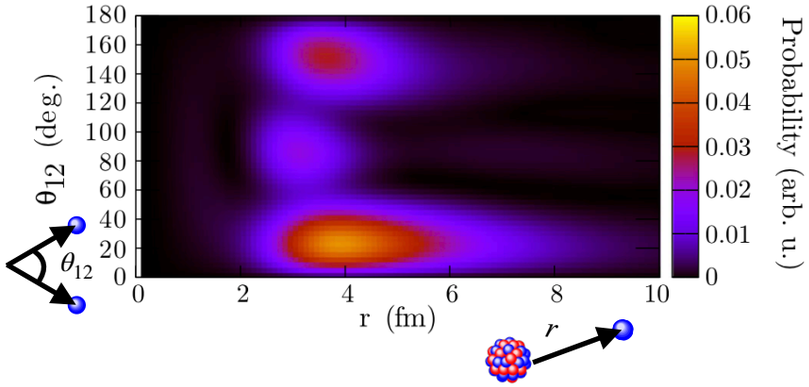
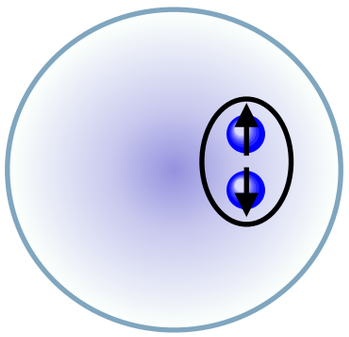




2 Neutron halo structure

Core + 2n (3body)

- "Dineutron" configuration? 11Li Kubota, PRL (2022)
- Dineutron formation on surface of neutron stars?
- FSI needs to be taken into account



Spatially compact neutron pair on surface of nucleus

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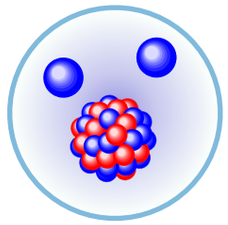

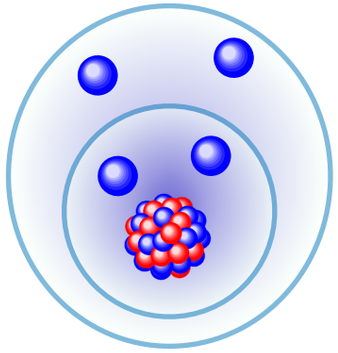

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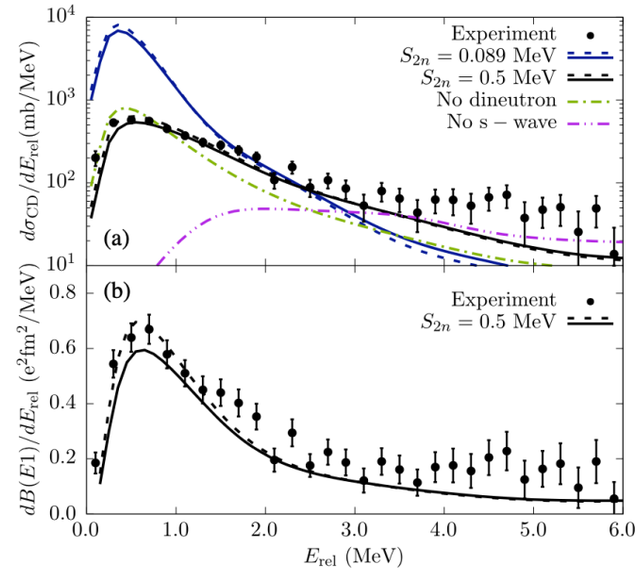

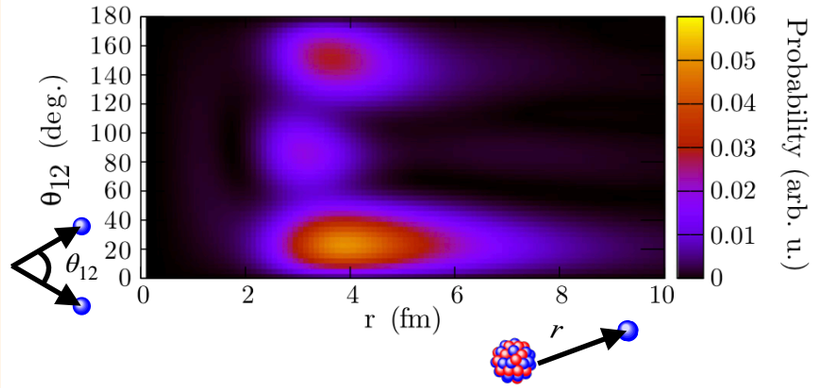

2 Neutron halo structure

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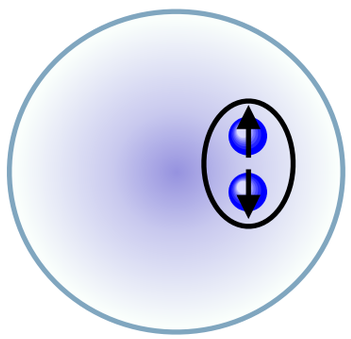
- FSI needs to be taken into account Matsuo, PRC (2006)



Spatially compact neutron pair on surface of nucleus

OR Core + 4n (skin)

- A more complex structure than a 3body.

Two Neutron Halo Structures: FRIB

?

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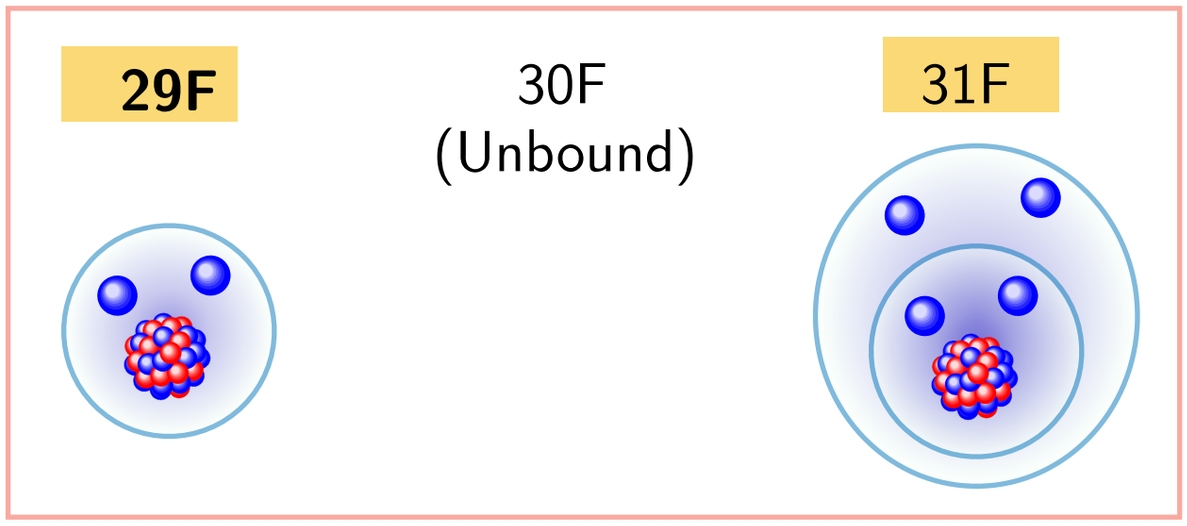

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FRIB RATES

- Exclusive measurement for 29F in future 3-5 years
- Inclusive measurement for 31F?

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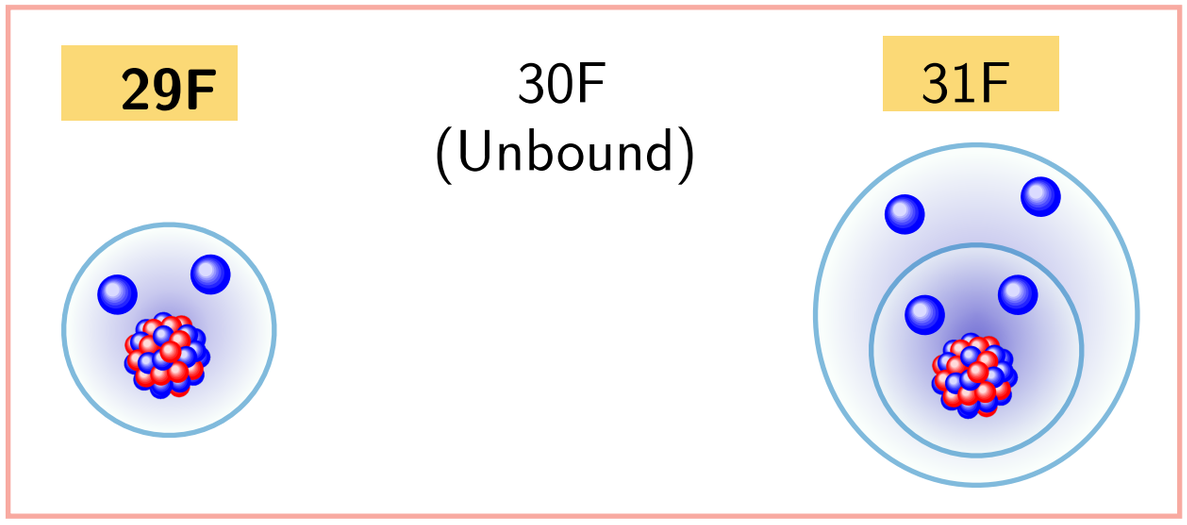

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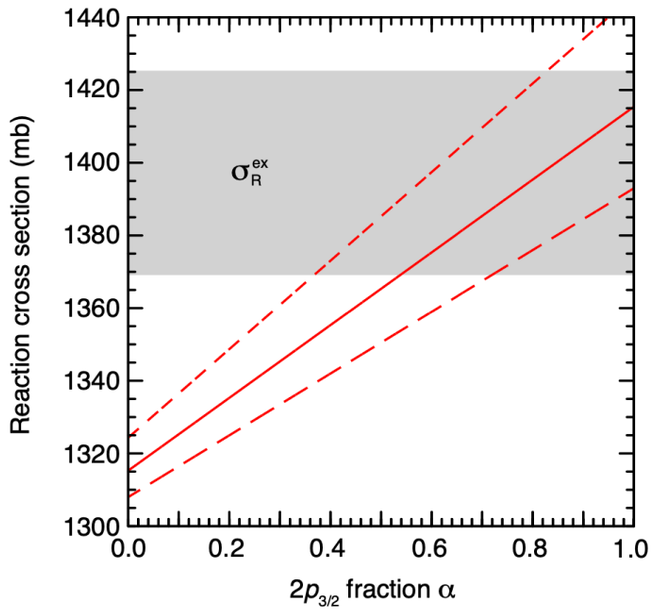
29F: Inclusive Cross Sections

- Important p-wave contribution
- Halo radius (rms): 6.6 fm



Bagchi, PRL (2020)

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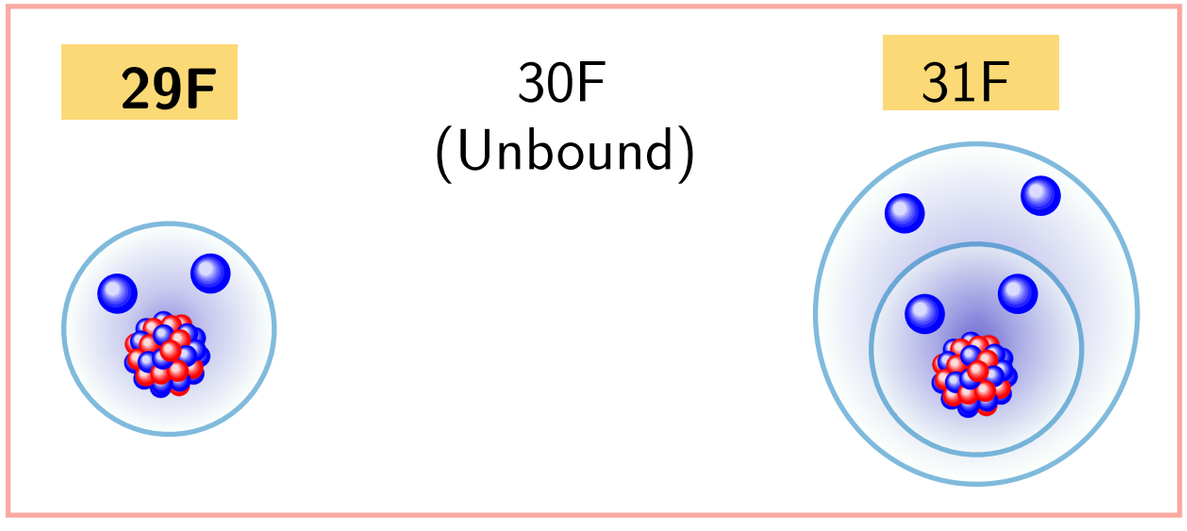

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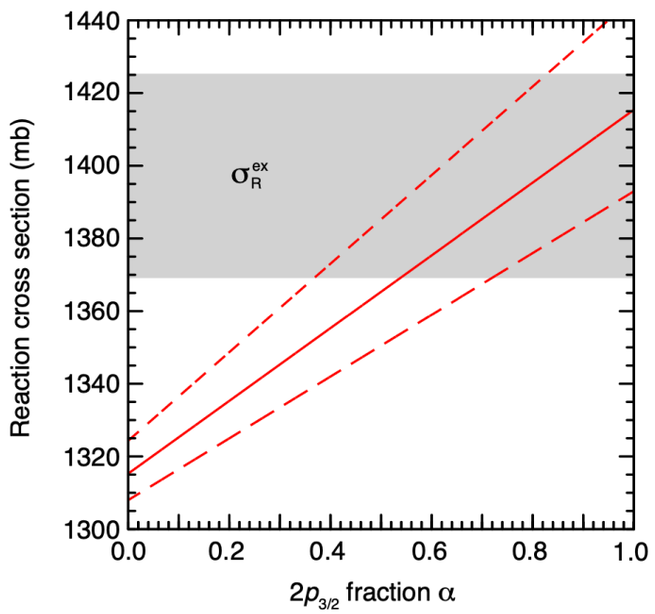
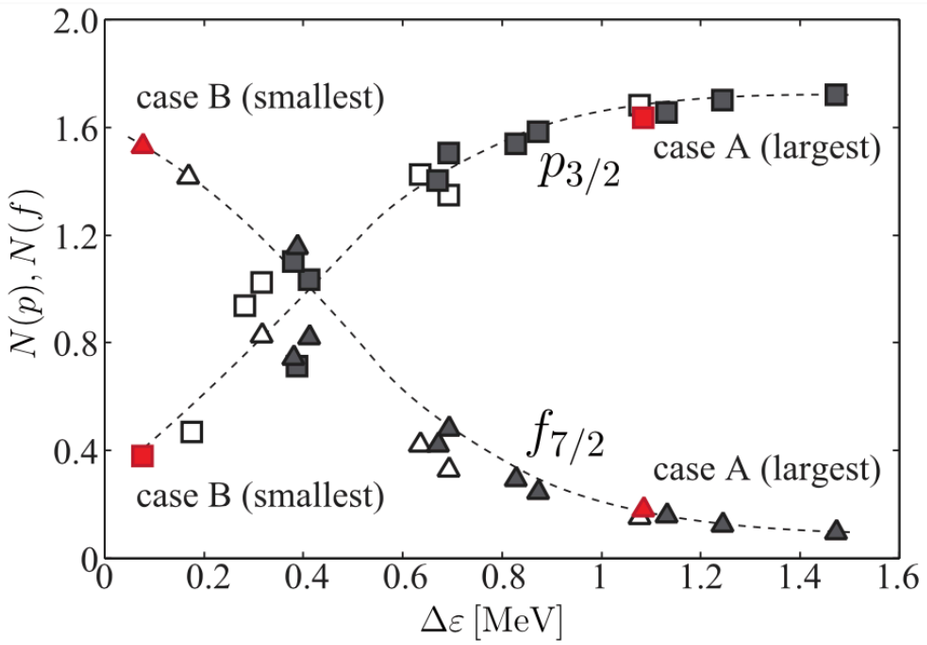


Bagchi, PRL (2020)

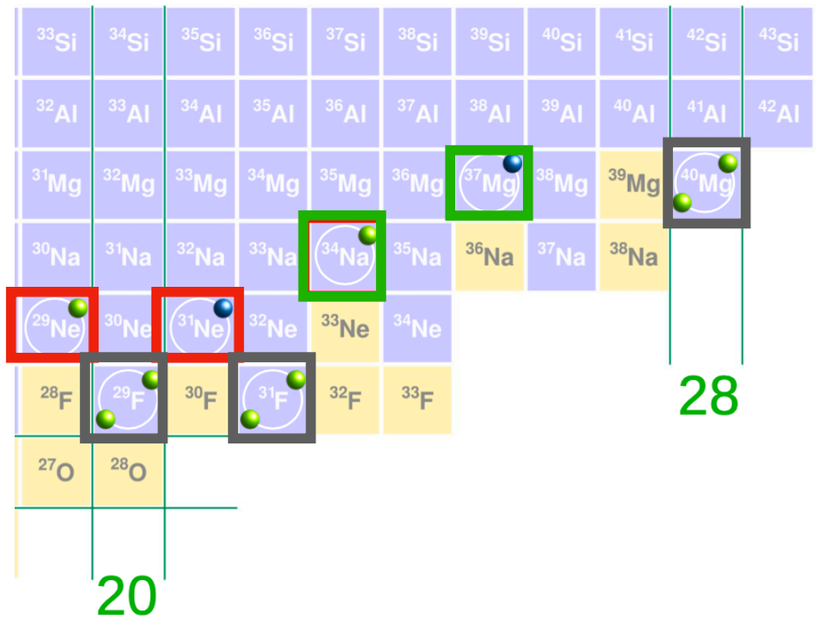
31F: No Information

- 2n halo or Anti-halo effect?



Masui, PRC (2020)

Conclusions & Open Questions

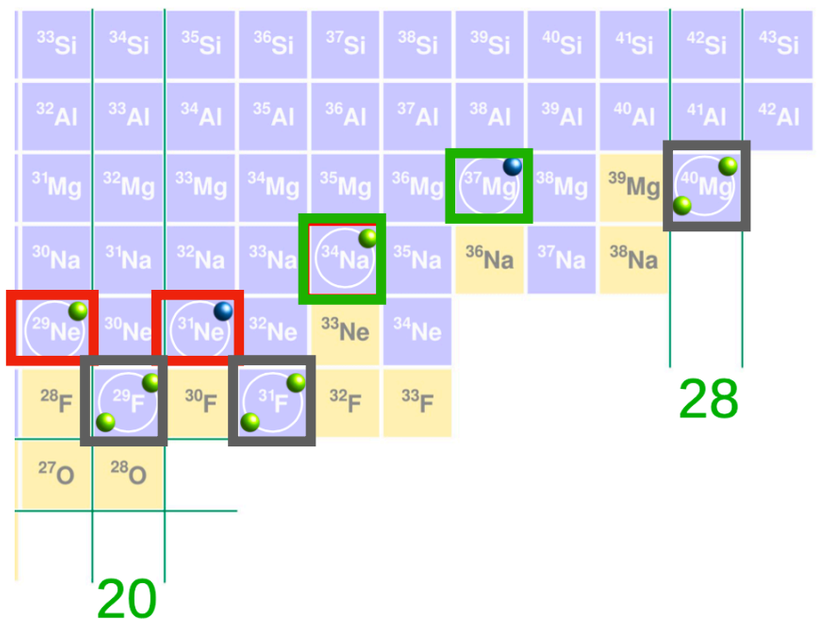


FRIB: Start program to identify and characterize halo nuclei beyond the sd shell

Halo nuclei around N=20 & N=28

- Important p-wave component, indicative of shell evolution and deformation
- Characterization of halo structure via **Coulomb Breakup reactions**
- Exclusive measurement: Sweeper+MoNA
- Observables: **Erel, Cross Sections,** Angular Distribution, Fragment Parallel Momentum?

Conclusions & Open Questions



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Where to look?

- One neutron halos:
  - **PAC2 experiments: 37Mg, 34Na.**
  - Other candidates? 37Na?
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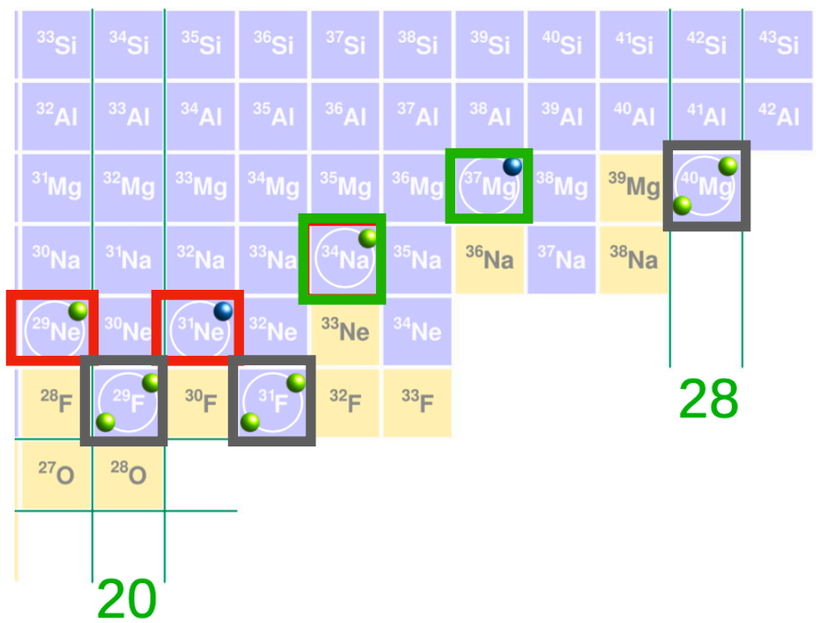
Conclusions & Open Questions



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  - **29F**, 31F? 40Mg?

Fully characterization of halo structure needs theory

- Complimentary experiments focused on structure are needed: knockout, gamma spectroscopy, etc.
- **Theory is essential**
  - dB(E1)/dErel depends on Sn and l value
  - Can we extract information about the **deformation**?
  - Can halos give us insight about structural changes in the region?
  - How can we investigate the 3body (or skin) **structure of 2n halos** from Coulomb breakup? Dineutron? Anti halo effect?

BACK-UP

Halo structures: FSI

FSI impact on cross-sections?

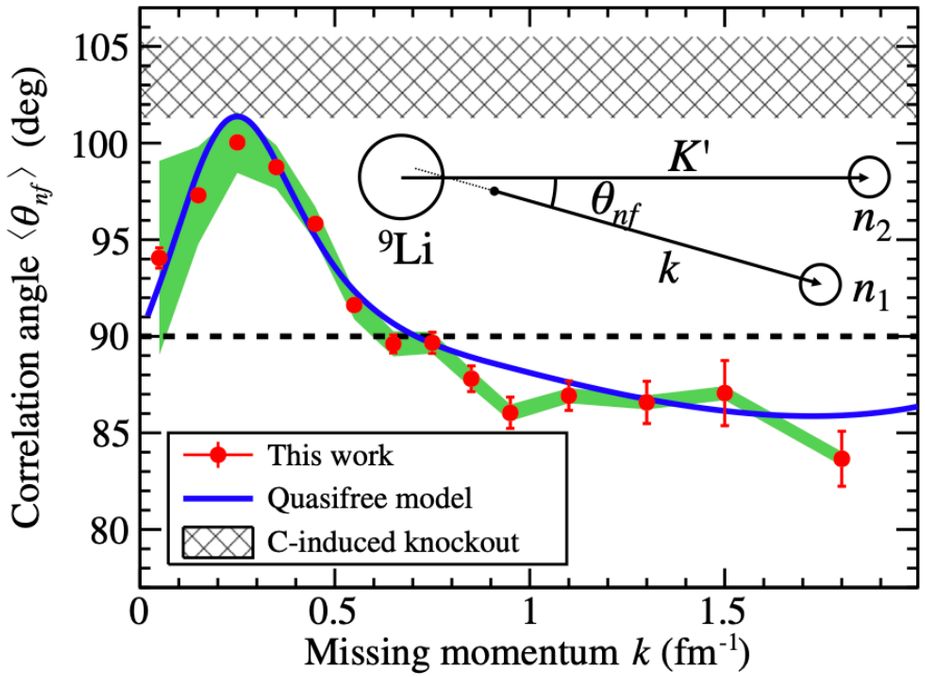
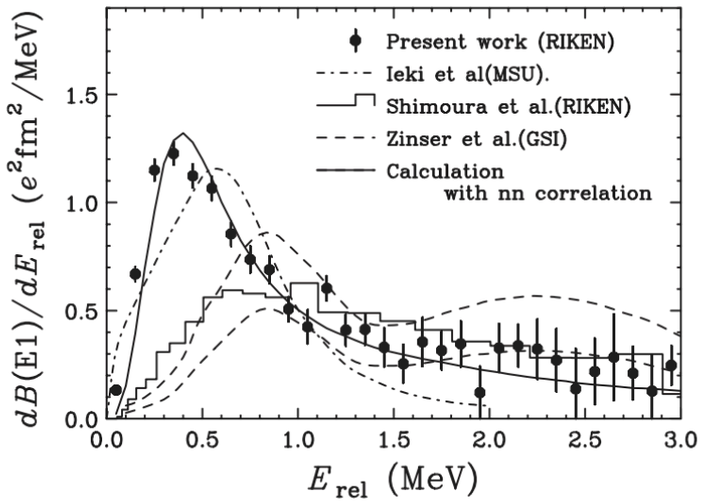


FIG. 4. Mean values of the correlation angle $\langle\theta_{nf}\rangle$ in momentum space. Red points show the data in this study. Error bars and the green line show the statistical and systematic uncertainty, respectively. The blue curve shows the quasifree model calculation. Black hatched area shows the average correlation angle obtained in a previous study [24]. Black dashed line shows the expected $\langle\theta_{nf}\rangle$ value for the two uncorrelated neutrons. Inset shows a schematic diagram of the correlation angle θ_{nf} in ^{11}Li. Black dot on the line between ^{9}Li and n_1 represents the center of mass of ^{11}Li.



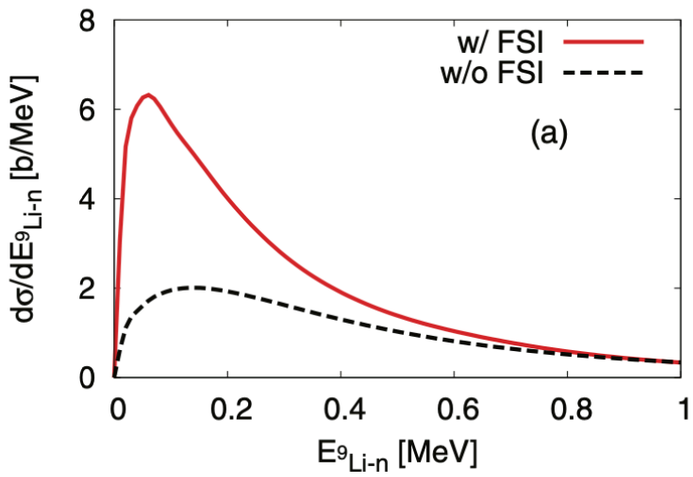


Figure 1.5: (Left) $B(E1)$ distribution from ^{11}Li + Pb at 70 MeV/nucleon. Taken from Ref. [40]. (Right) Calculated cross section of ^{9}Li + n system. The red solid and the black dashed curves show calculated cross sections with the final-state interaction (FSI) and those without the FSI, respectively. Taken from Ref. [23].

Spatial distribution better with **quasi-free reactions** (more transparent)