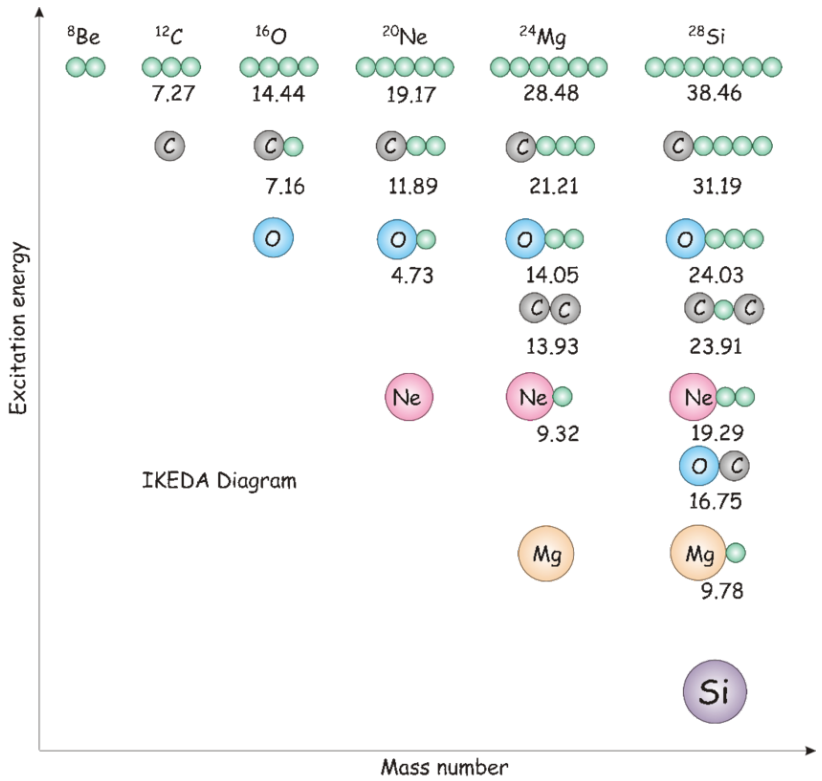
Near Threshold $2n$ Clustering ?

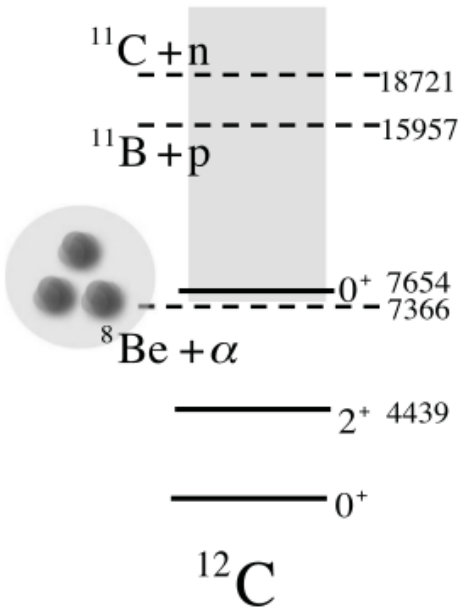
Aldric REVEL

CEA, Saclay, France

2^{nd} Rencontre PhyNuBe
March 27^{th}, 2023

Ikeda conjecture (K. Ikeda *et al.*, Prog. Theor. Phys. Supp., Ext. Num., 464, 1968)



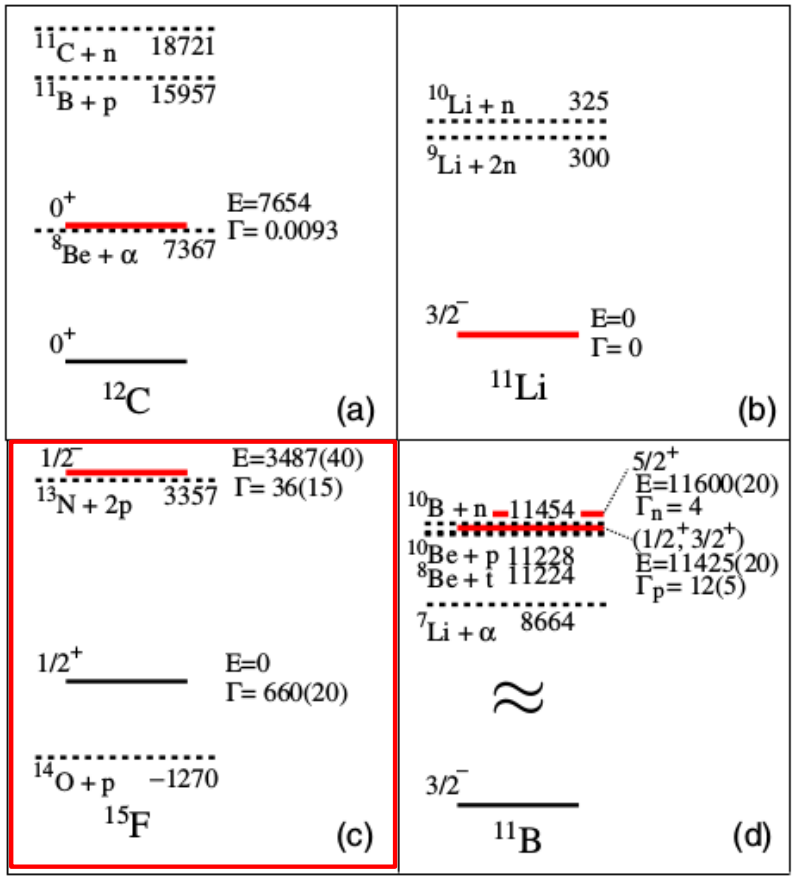


J. Okolowicz et al. Prog. Theor. Phys. Supp., 196 (2012)

→ Nα-cluster states expected in the vicinity of their Nα decay threshold
→ Hoyle State (3α cluster)

→ Can we generalize this Ikeda conjecture to other cluster configurations ?

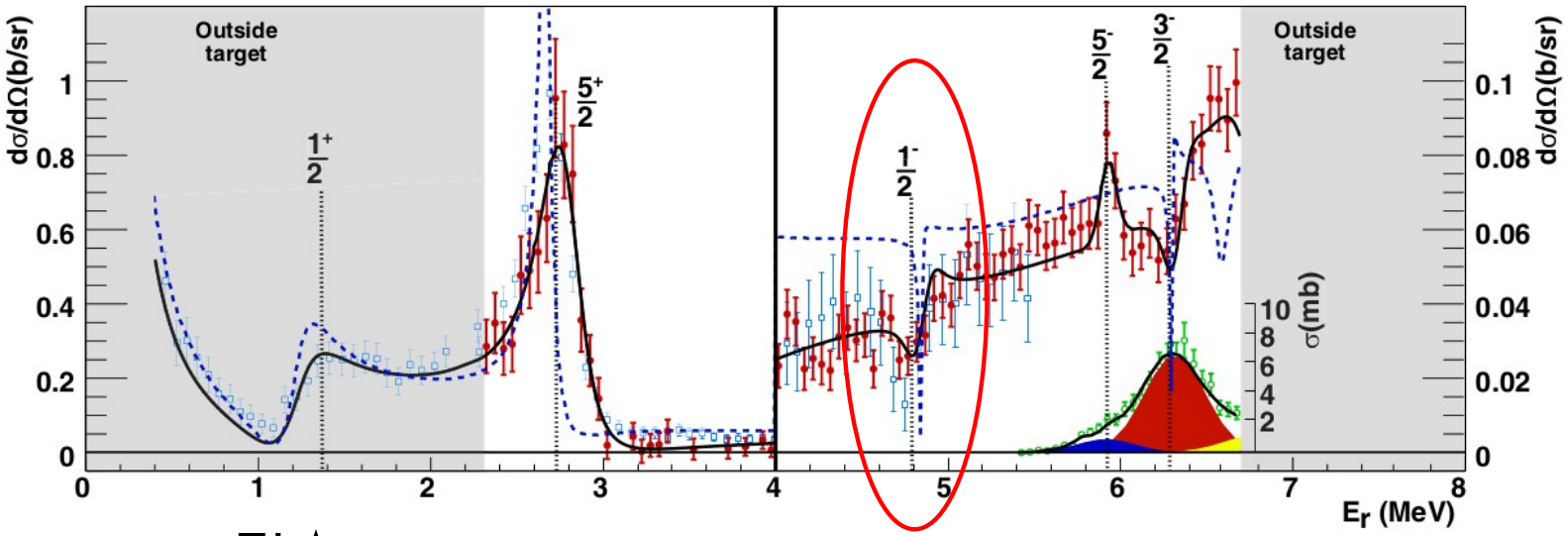
Generalization of Ikeda conjecture

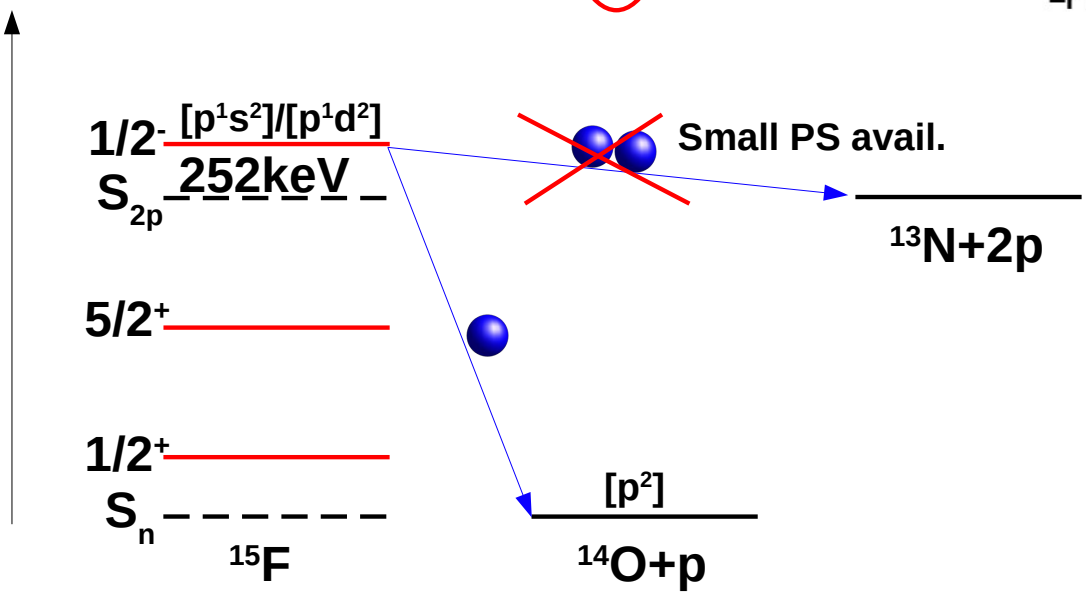


J. Okolowicz *et al*, Phys. Rev. Lett. 124, 042502 (2020)

^{15}F $\rightarrow$ narrow resonance just above S_{2p}

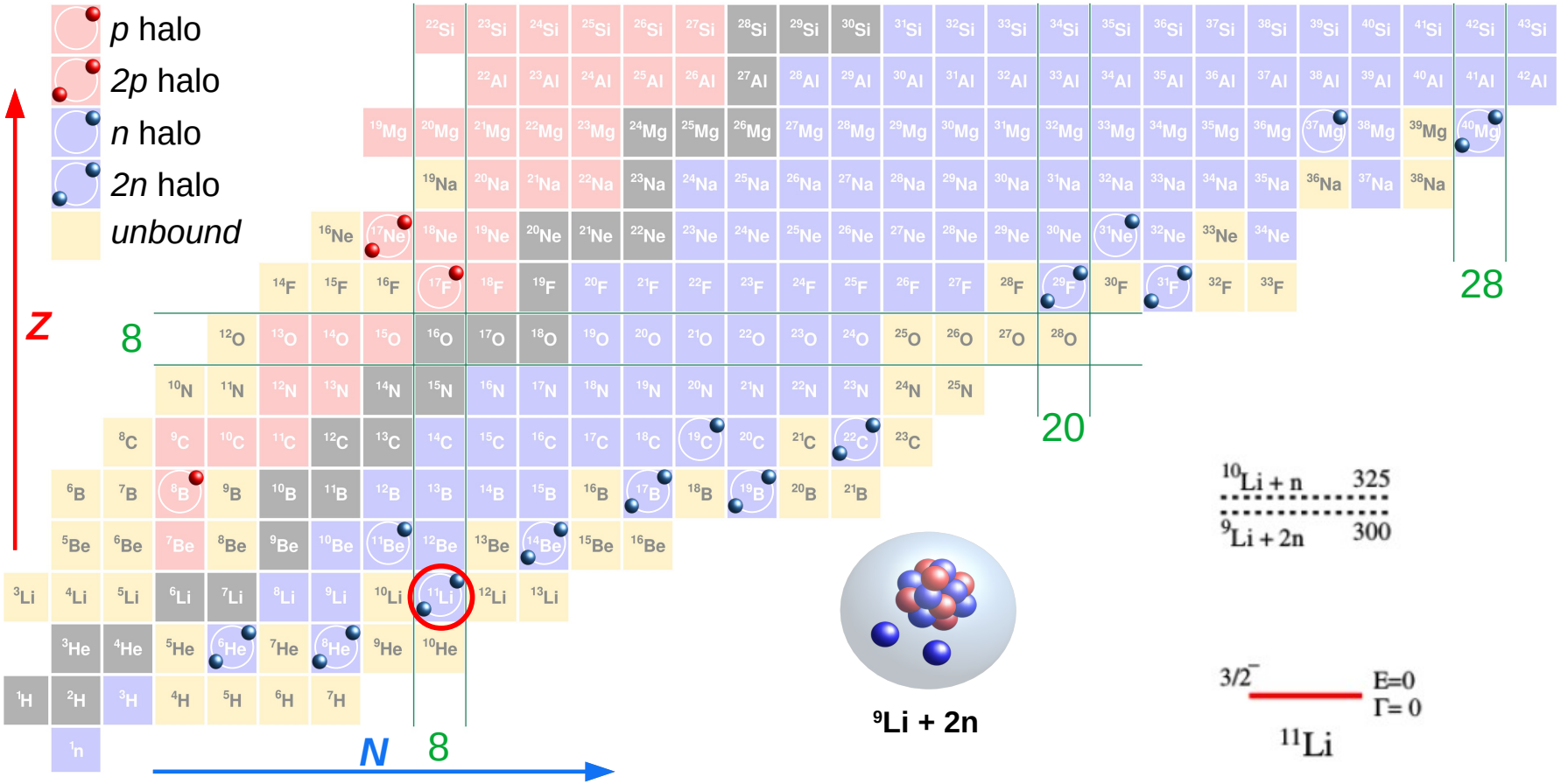
The case of ^{15}F (V. Girard-Alcindor *et al.*, Phys. Rev. C 105, L051301, 2022)





→ Very narrow resonance (Γ=30(15) keV) due to proximity to S_{2p}

Generalization of Ikeda conjecture to $2n$ clustering ?



^{9}Li + 2n

^{10}Li + n 325

^{9}Li + 2n 300

3/2$^-$ E=0 Γ= 0

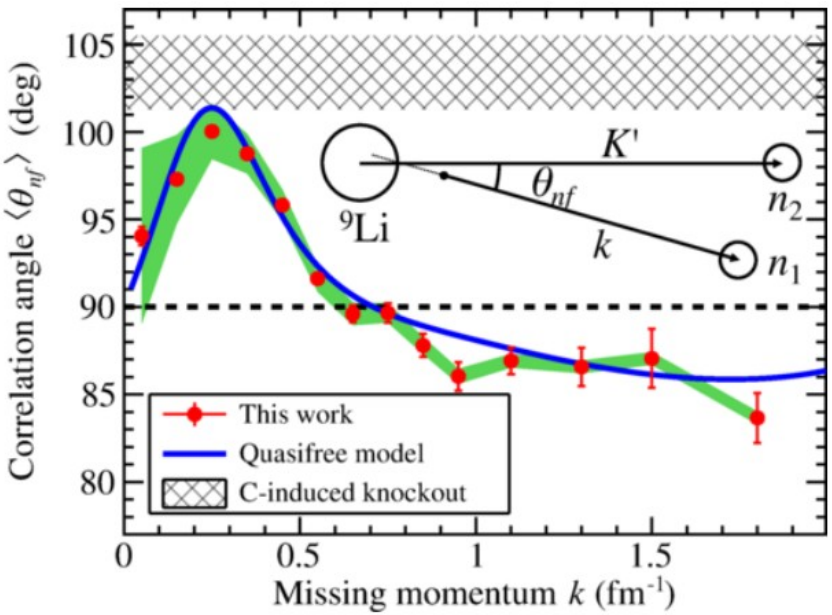
^{11}Li

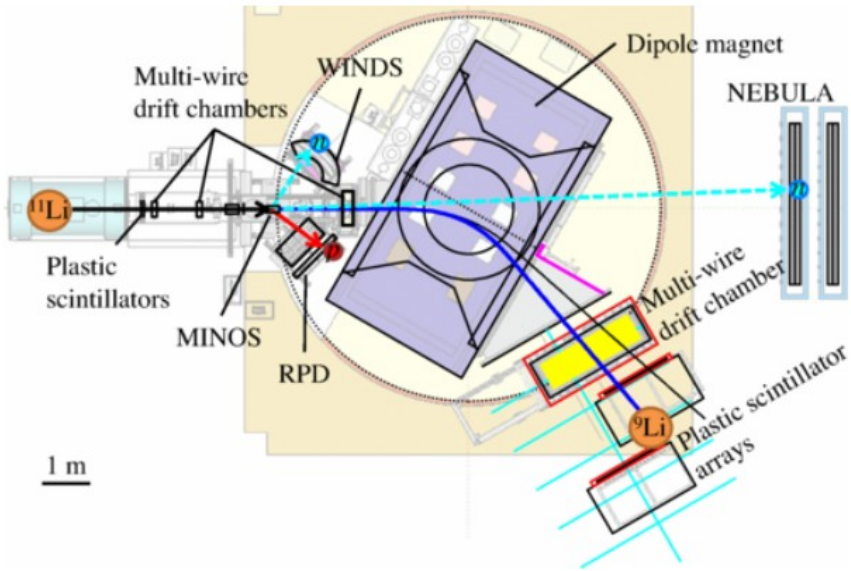
Halo nuclei

core+xN valence nucleons
weak binding
low-orbital angular momentum orbits

The 2*n*-halo ^{11}Li nucleus

Y. Kubota *et al*, Phys. Rev. Lett.. 125, 252501 (2020)





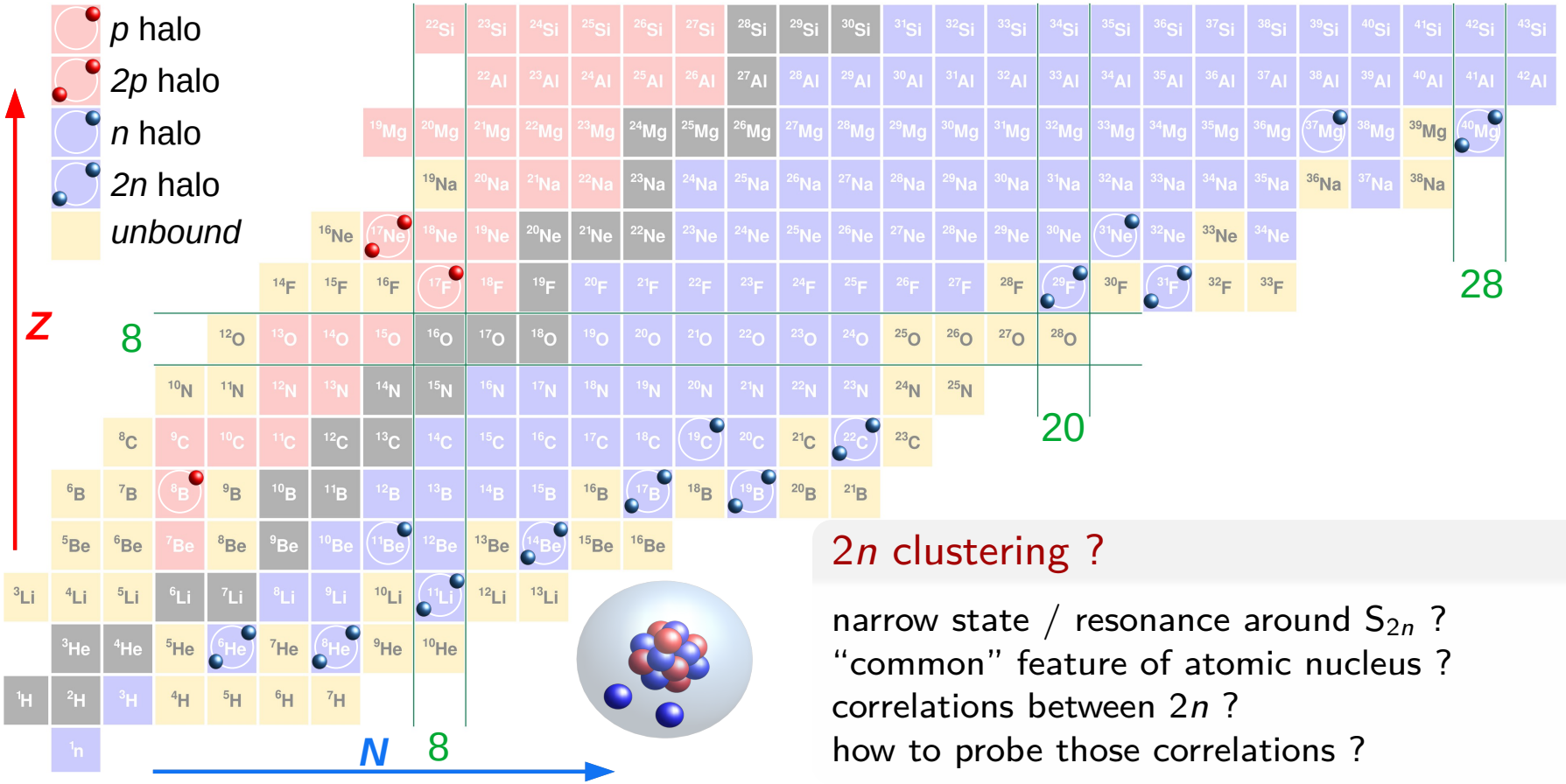
→ ^{11}Li viewed as a ^{9}Li core + 2*n*-halo

→ Investigated using (p,pn) reaction

→ Correlation angle of the 2*n* measured as a function of the missing momentum

→ Reaction calculation reveals a localization of the dineutron at around 3.6 fm

Generalization of Ikeda conjecture to $2n$ clustering ?

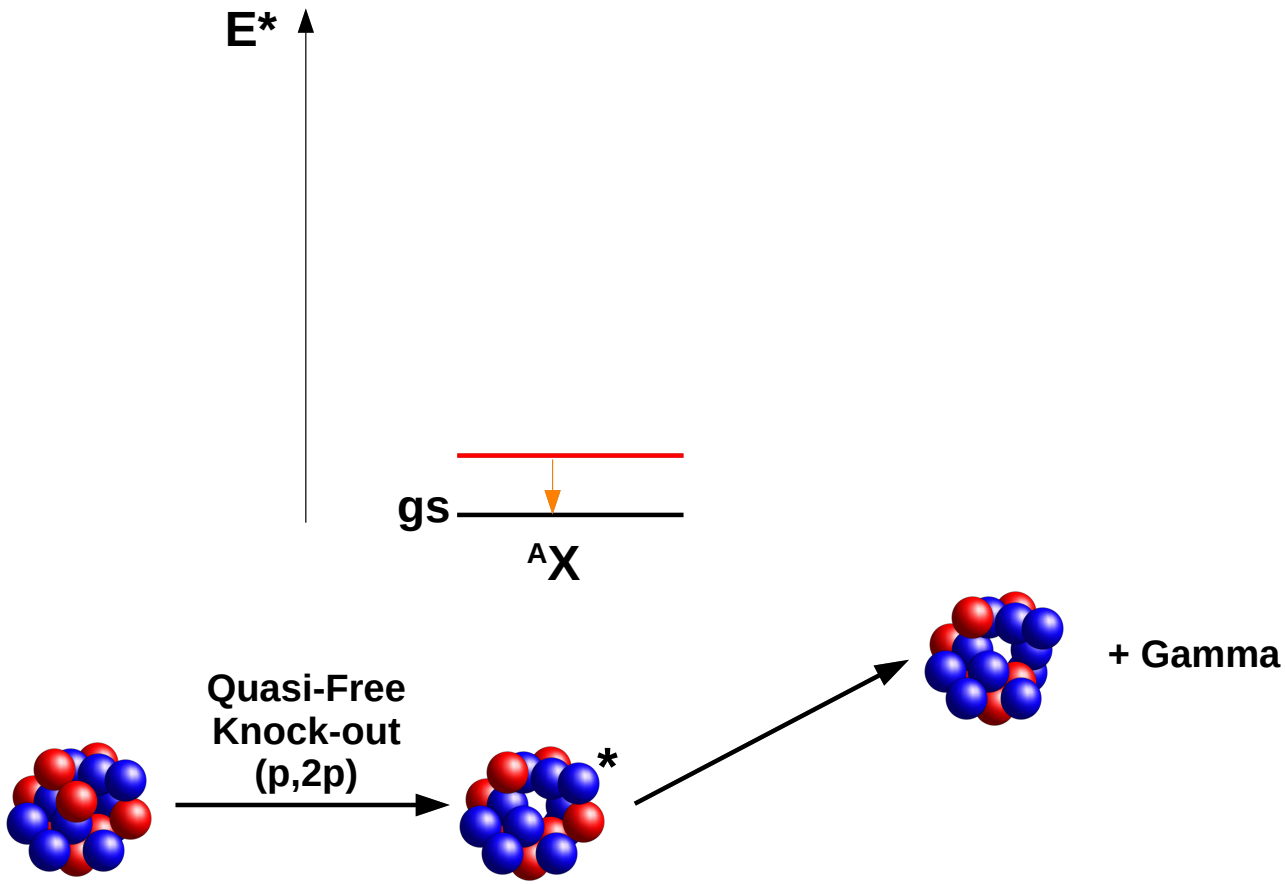


$2n$ clustering ?

narrow state / resonance around S_{2n} ?
"common" feature of atomic nucleus ?
correlations between $2n$?
how to probe those correlations ?

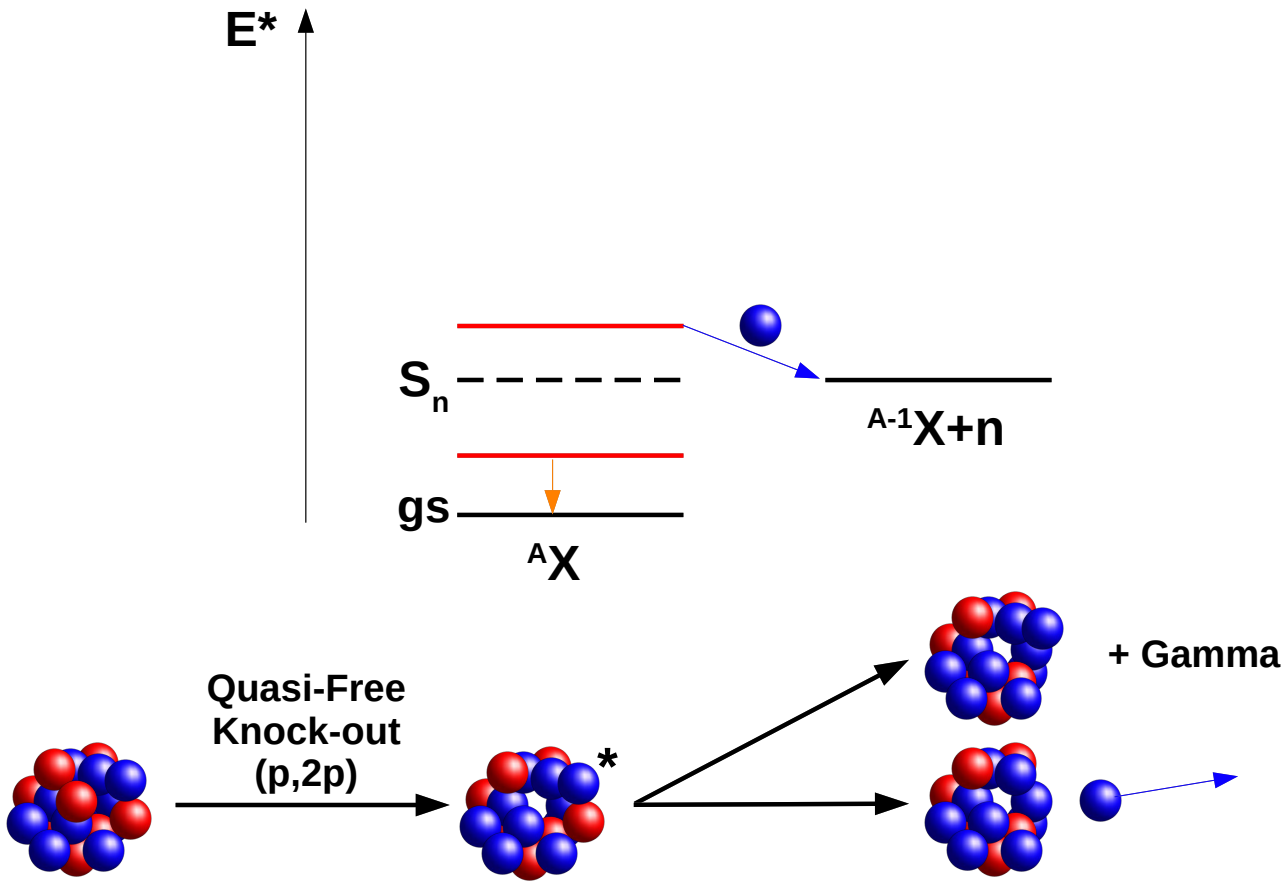
→ Analogously to ^{15}F case

Investigating x*n*-unbound resonances experimentally



Populate excited states up to high excitation energies
Sudden approximation → neutron configuration remains unperturbed

Investigating x*n*-unbound resonances experimentally



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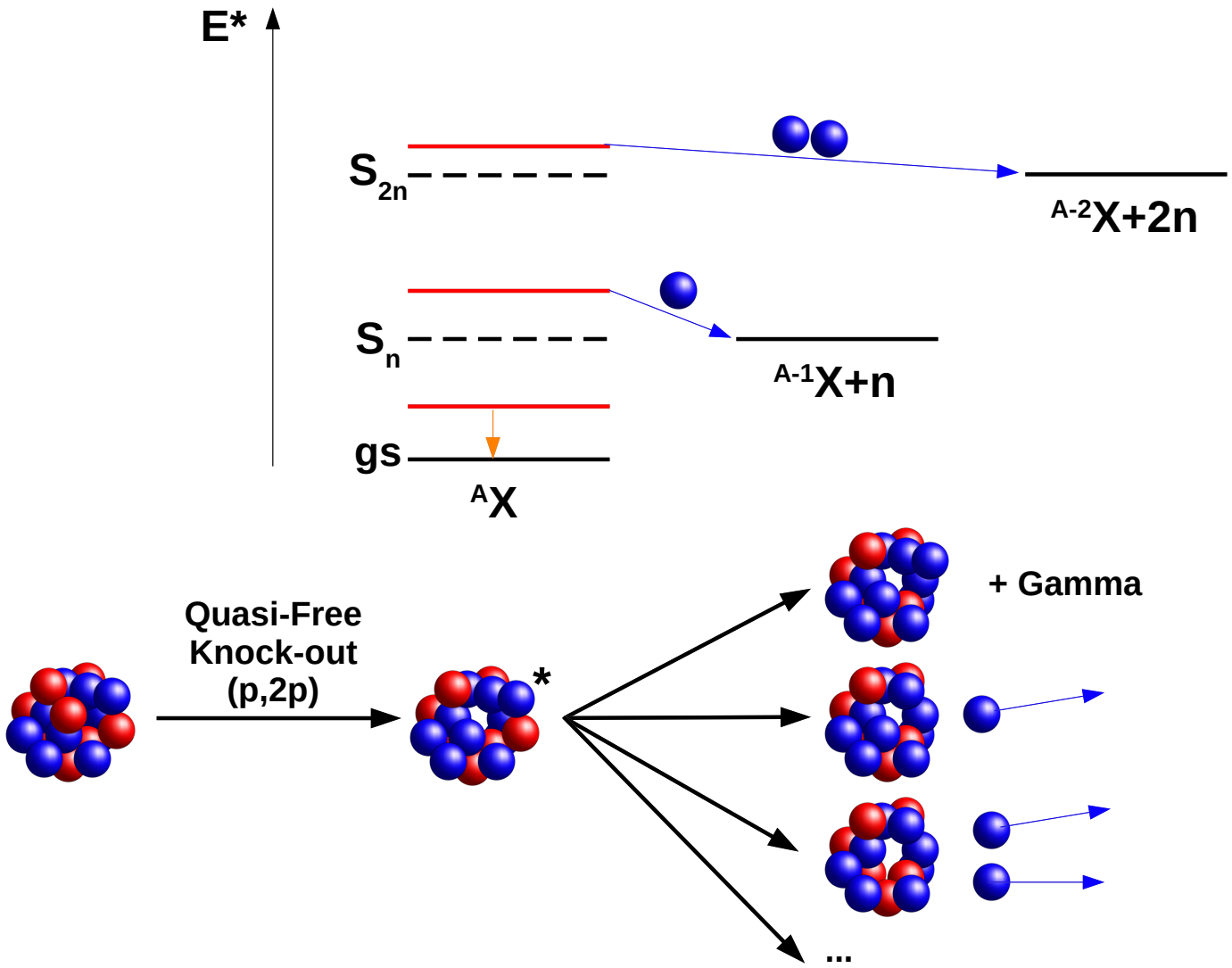

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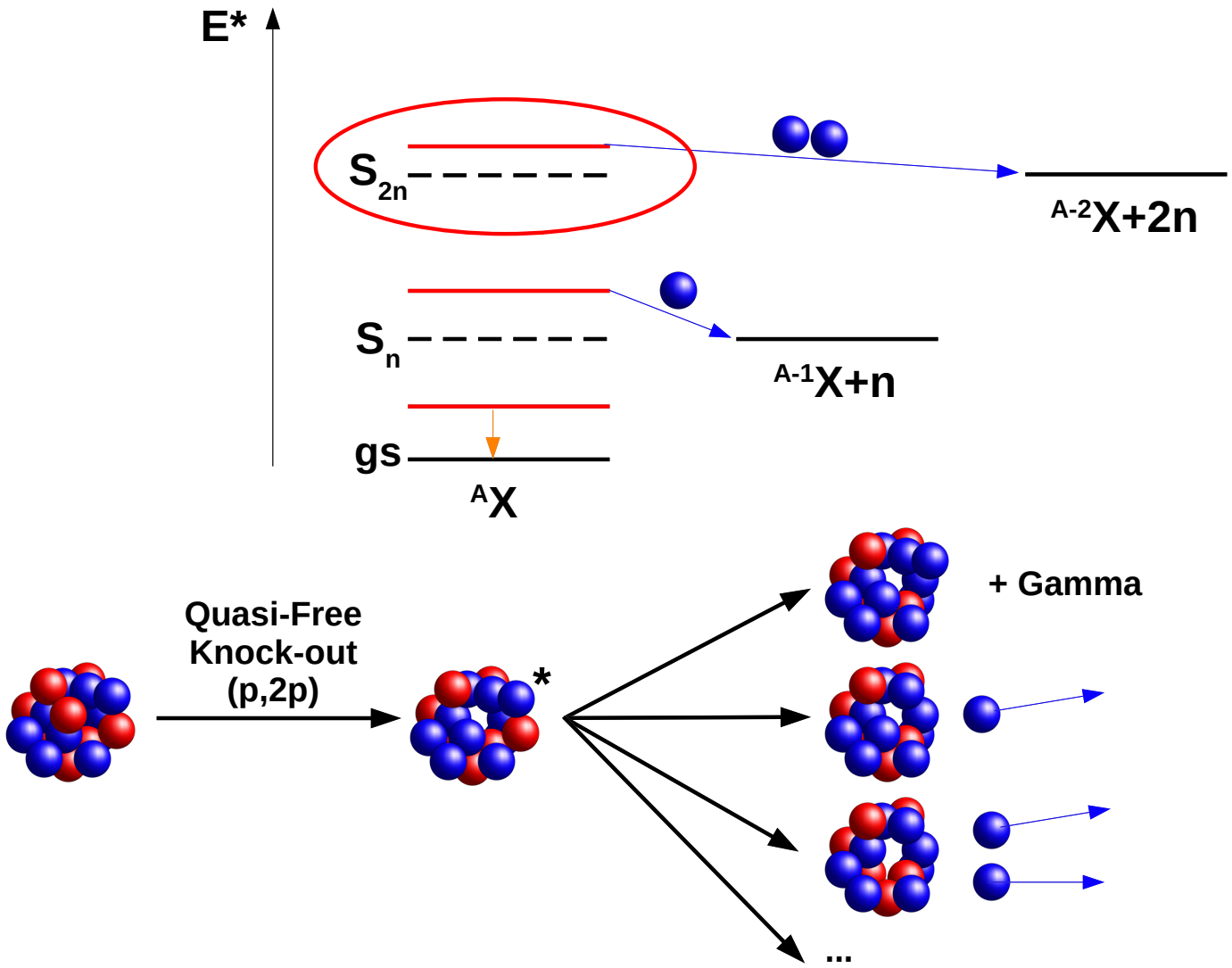


Populate excited states up to high excitation energies
Sudden approximation → neutron configuration remains unperturbed

Invariant-mass method

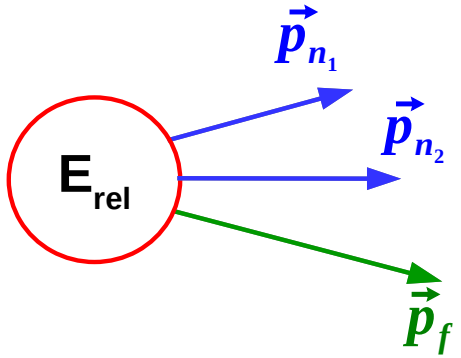
For N-body unbound system :

$$E_{rel} = M_{inv} - \sum_{i=1}^{N} m_i$$

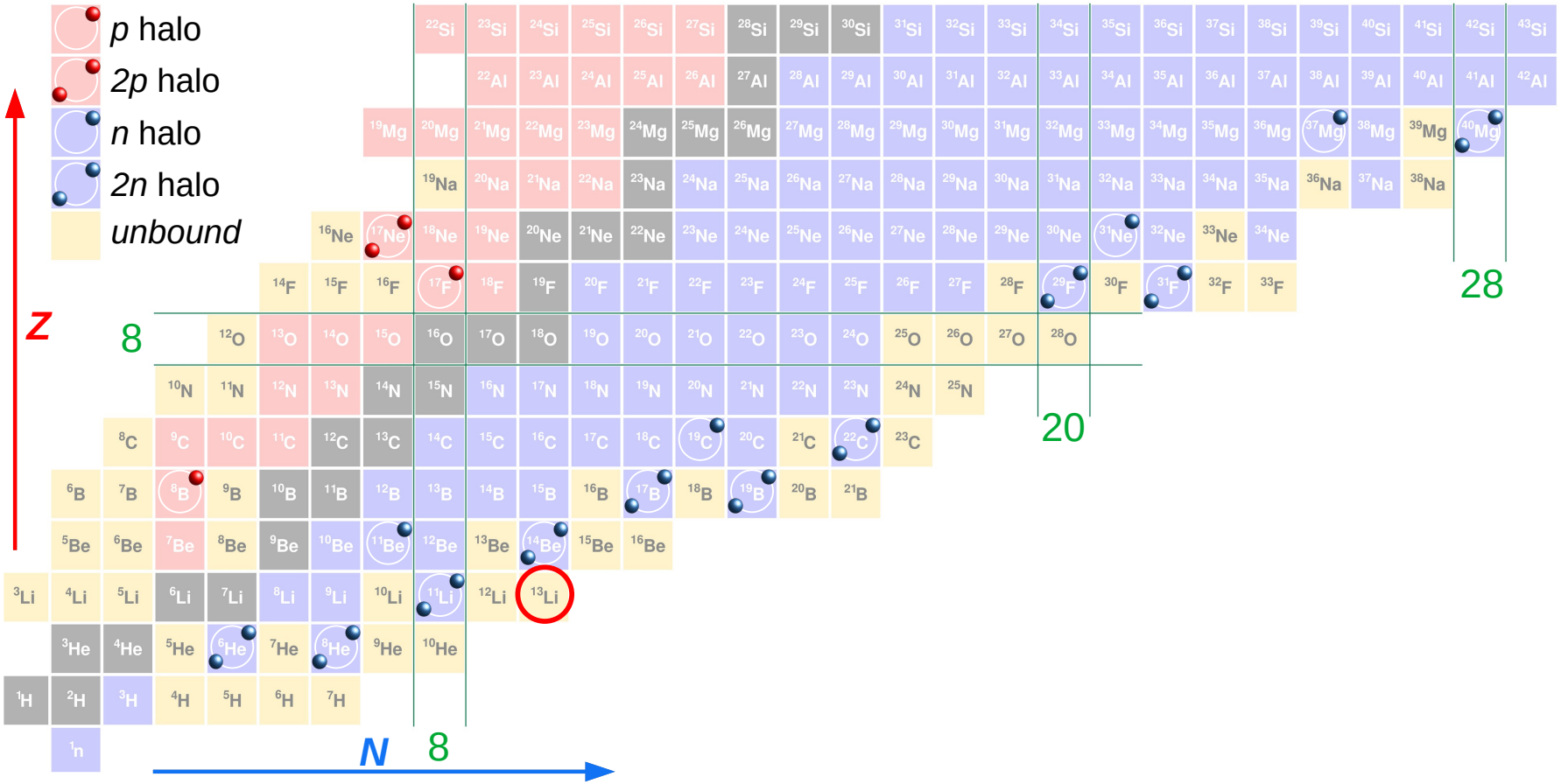
$$M_{inv} = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_i\right)^2}$$

Experimental requirements :

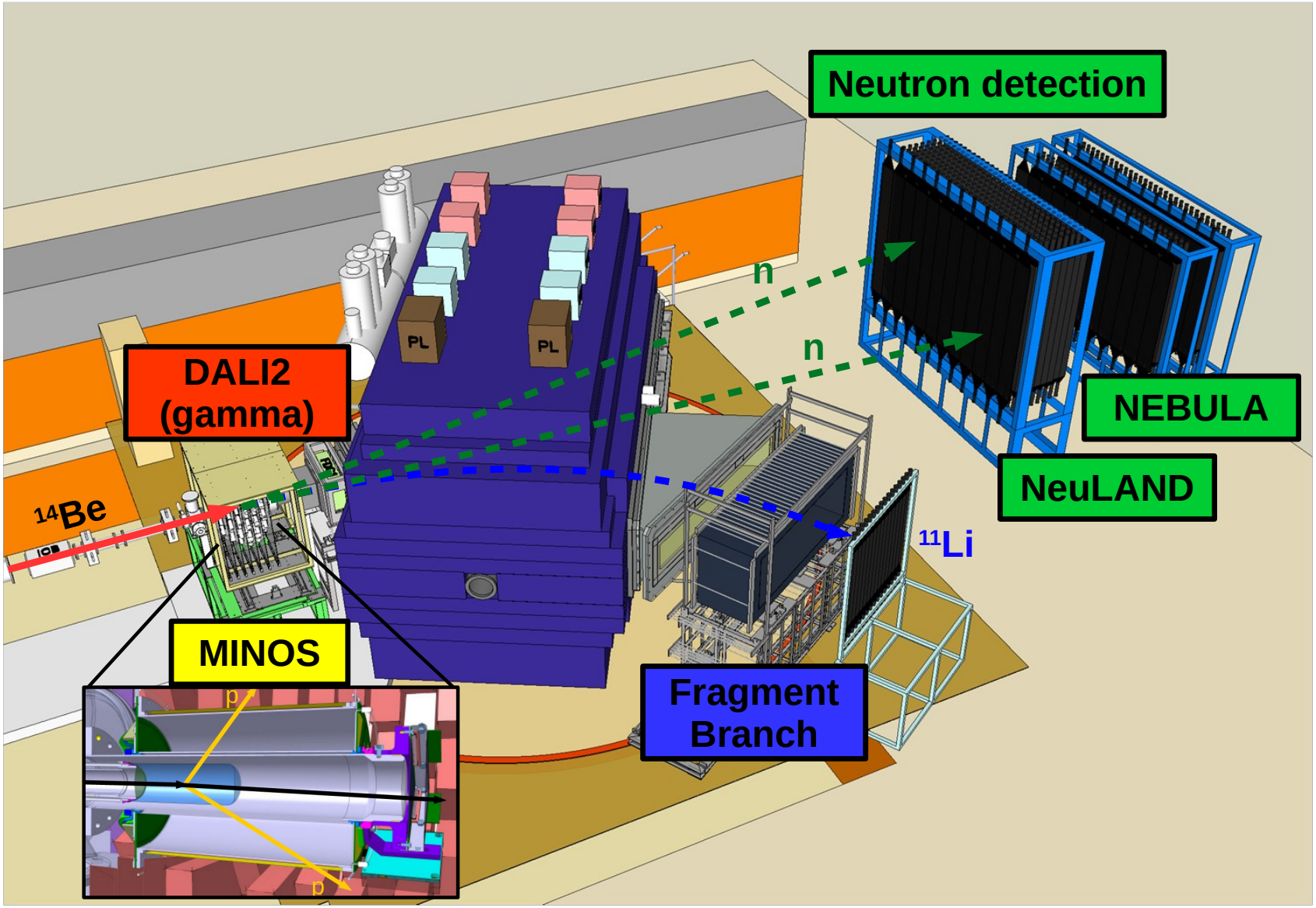
- Momenta of the decay products ($^{A-x}\mathrm{X} + x n$)
- Gamma-ray coincidence
- High-resolution
- High-statistics



2*n*-unbound ^{13}Li



Typical experimental setup (e.g. SAMURAI+MINOS+NEULAND)

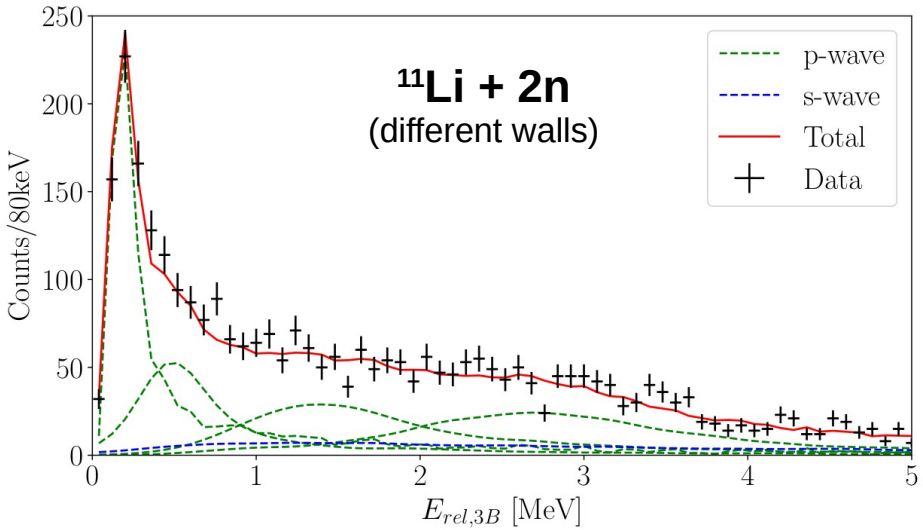


^{13}Li $\rightarrow$ ^{11}Li+n+n relative energy (P. André PhD Thesis, CEA, 2022)

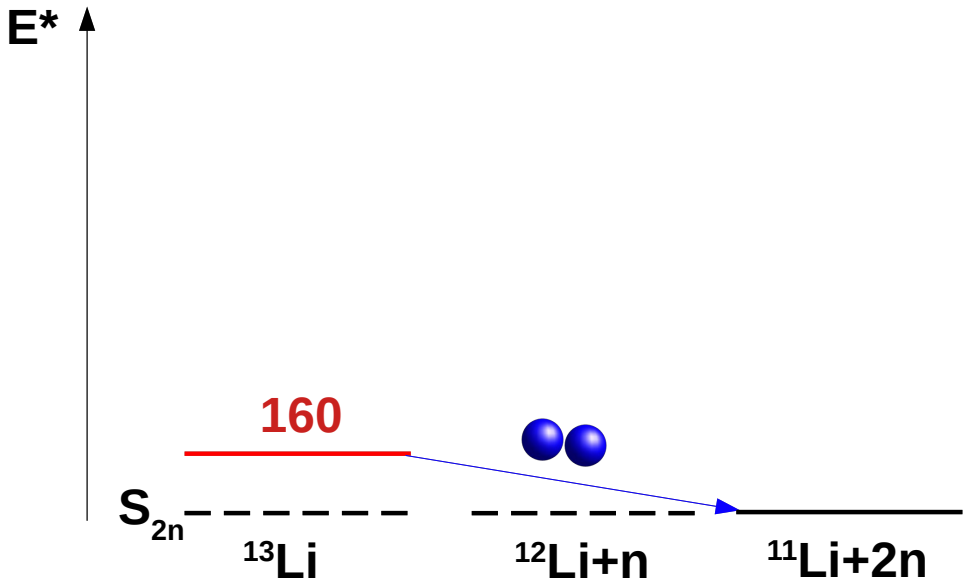
p-wave	E_{res} [MeV]	Γ_{res} [MeV]
1 [1]	0.16(1)	0.16(4)
2	0.45(6)	0.26(11)
3 [2]	1.47(31)	1.7(7)
4	2.8(2)	1.7(7)

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

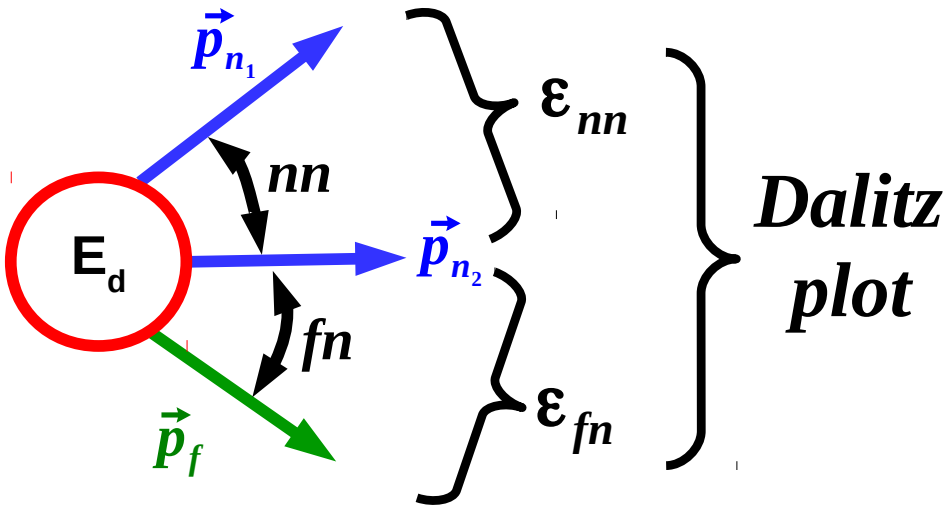
[2] Yu. Aksyutina *et al.*, Phys. Lett. B **666** (2008)



- ^{14}Be(p,2p)^{13}Li
- Resonances compatible with previous results
- Low-energy, rather narrow resonance identified as the g.s.
- Info on 2n resonance configuration from the decay pattern ?



Decay of three-Body unbound system



What is required experimentally ?

- Measurement of full kinematic of the decay ($\vec{p}_{n_1}$, $\vec{p}_{n_2}$, $\vec{p}_f$)
- Invariant-mass method
- Clear identification of $2n$-resonance
- Decay mechanism
- High stastistic
- High resolution

Decay of three-Body unbound system

Direct decay

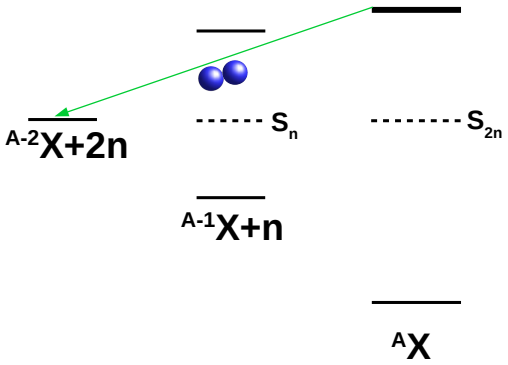
- Phase-Space modified by *n*-*n* correlations

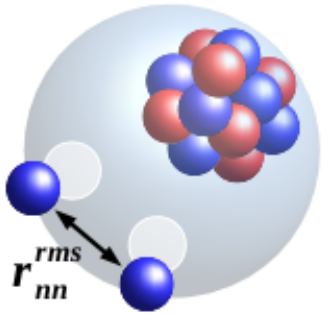
Lednicky Model

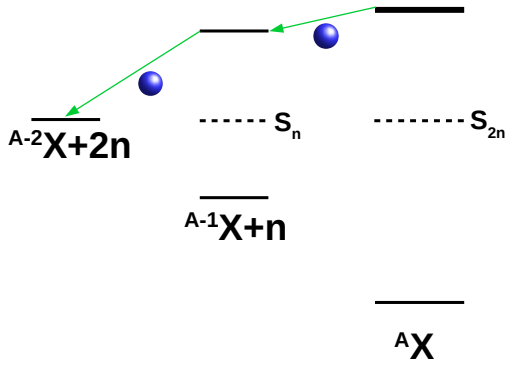
- Simple model to describe FSI in exp. data

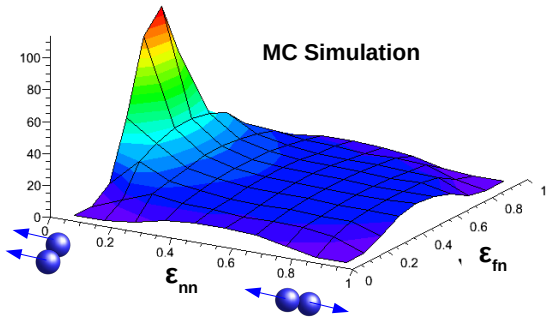
Sequential decay

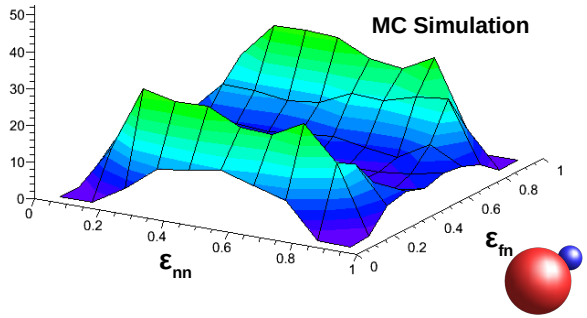
- core+*n* correlations







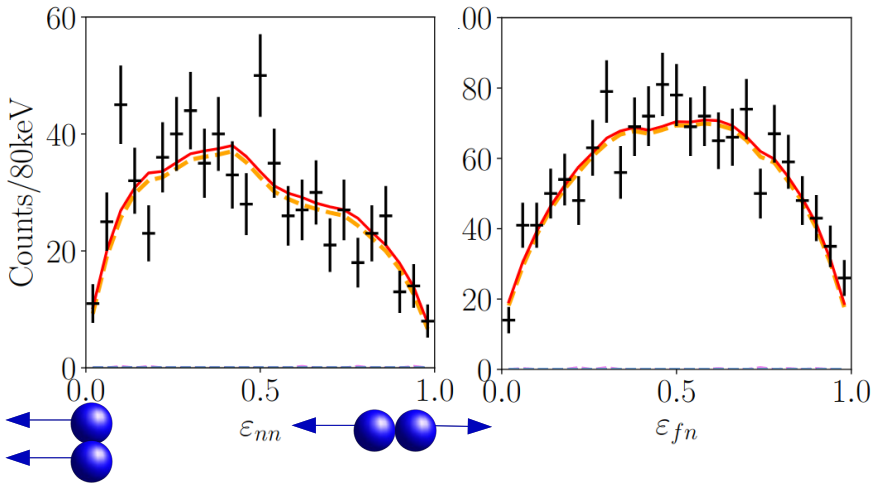


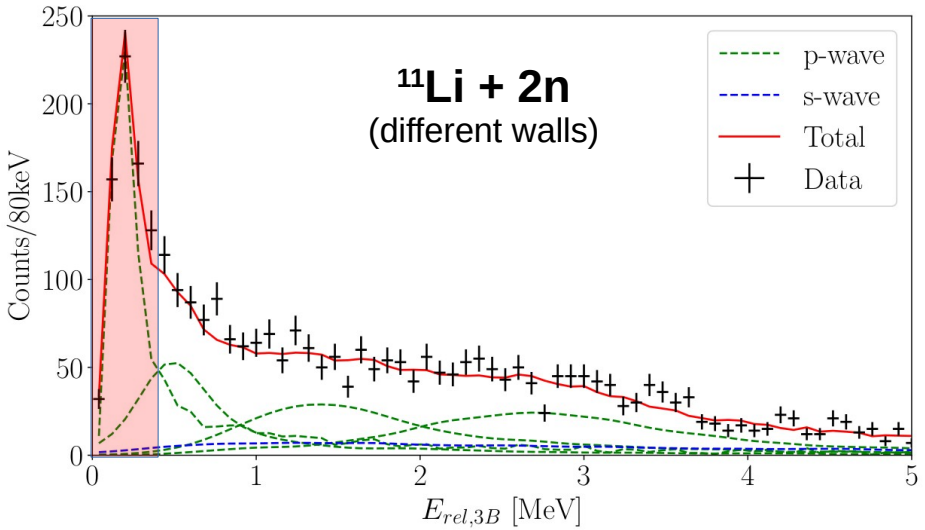


- $\varepsilon_{nn} \approx 0 \rightarrow$ relative *n*-*n* distance r_{nn}

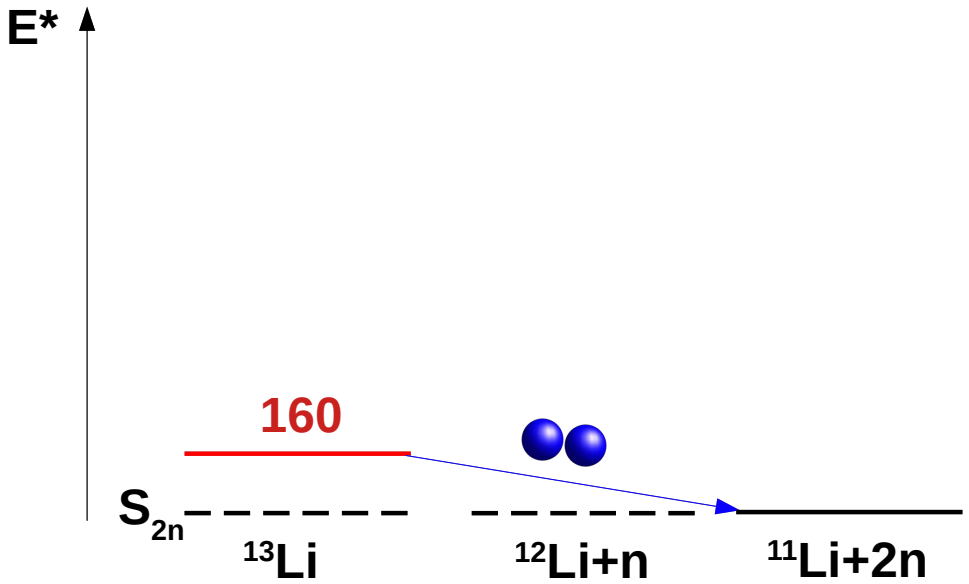
R. Lednicky, Sov. J. Nucl. Phys. 35 (1982)

^{13}Li $\rightarrow$ ^{11}Li+n+n 3B-correlations (P. André PhD Thesis, CEA, 2022)

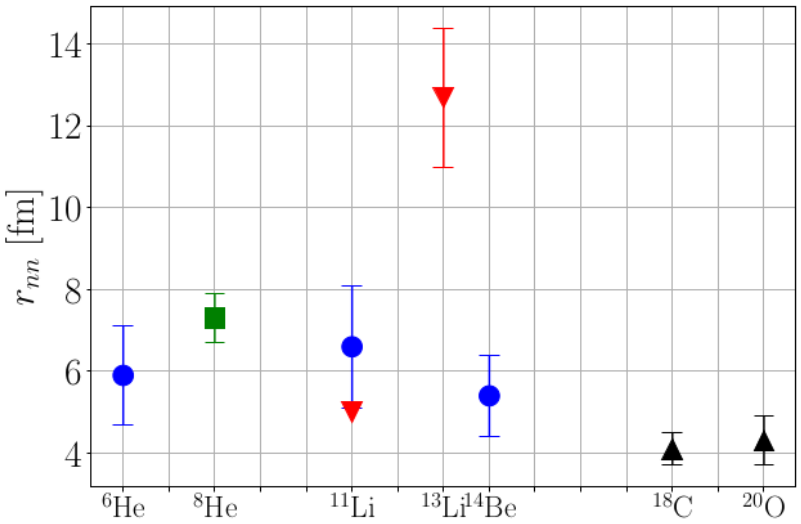


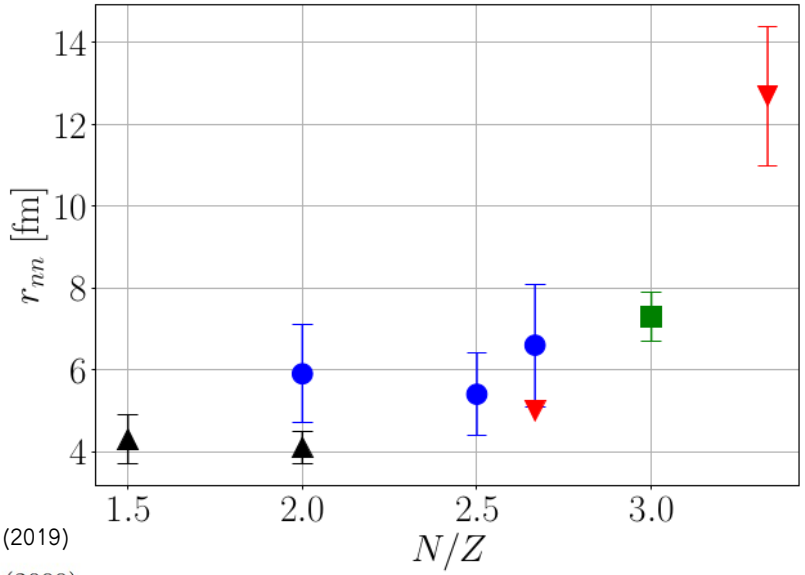


- Gate on ground-state
- $\epsilon_{nn} \rightarrow$ dineutron configuration
- 100% direct decay
- r_{nn} = 12.7 fm



r_{nn}^{Led} systematic (P. André PhD Thesis, CEA, 2022)

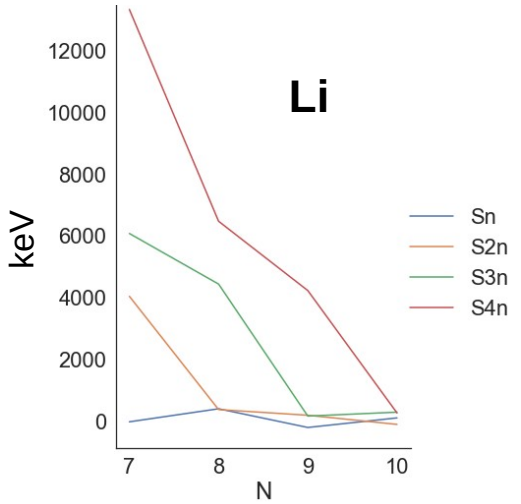




B. Laurent *et al.*,Journal Phys. G 46 (2019)

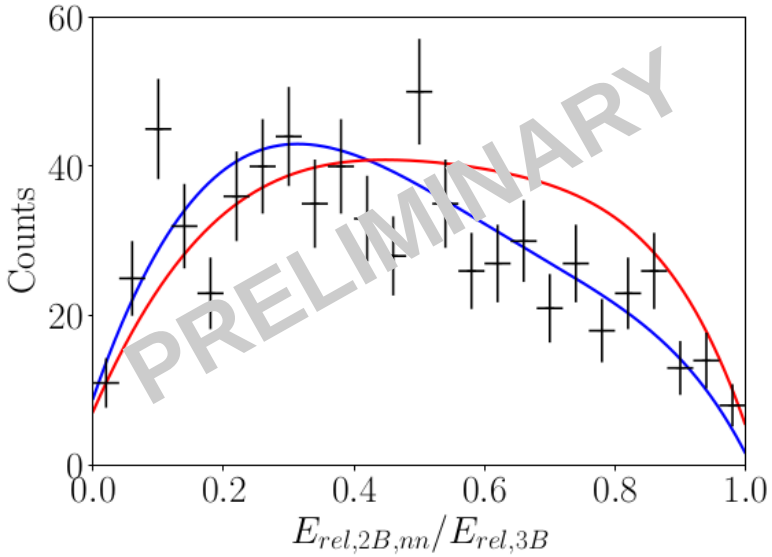
▲ A. Revel *et al.*, PRL **120** (2018) ● F.M. Marqués *et al.*, PLB **476** (2000)

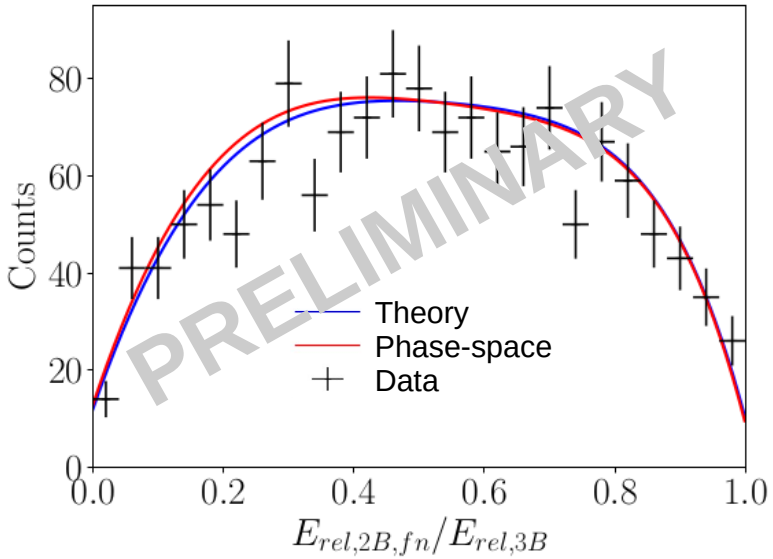
▼ This work — Independent neutrons in liquid-drop model



- Comparison with values obtained within the same framework ("Lednicky" Model)
- ^{13}Li unbound
- $^{13}\mathrm{Li} \rightarrow {}^{9}\mathrm{Li} + 4n$?
- Call for microscopic calculations

Comparison with three-body calculation for ^{13}Li g.s.

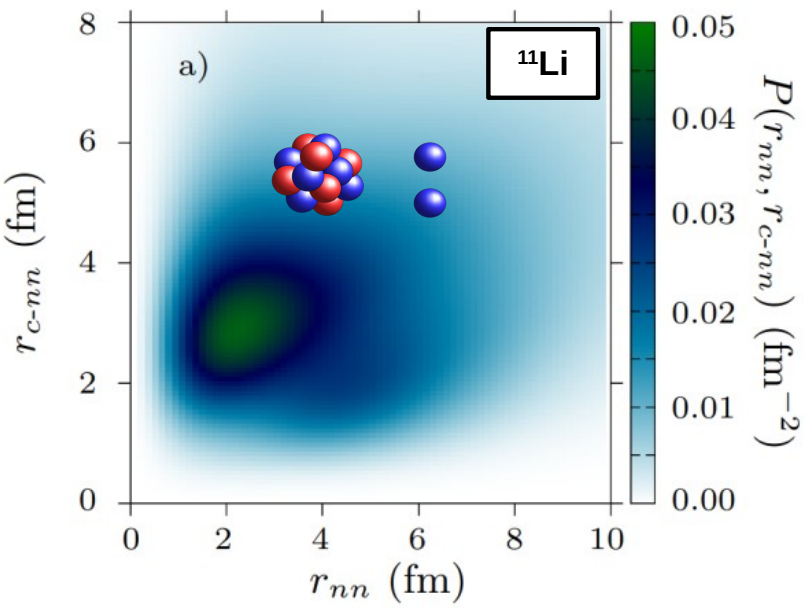


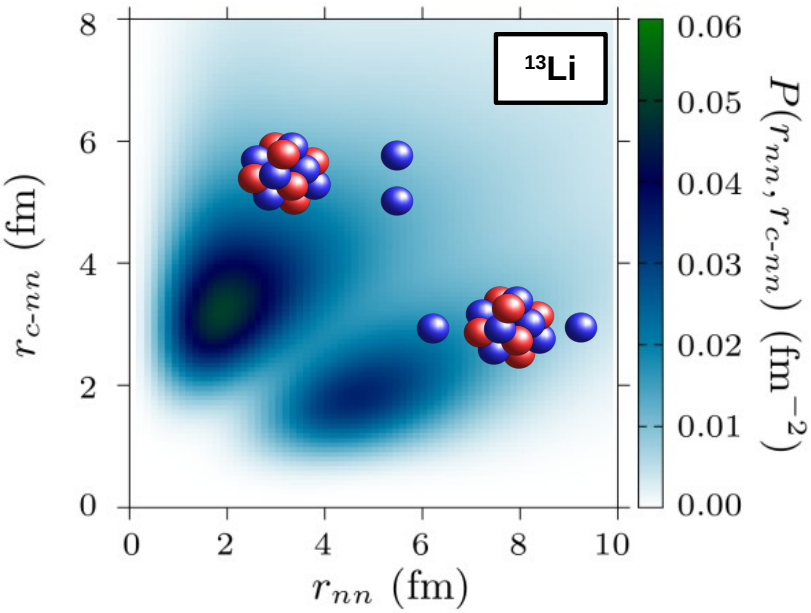


- Time evolution of three-body wave-functions
- Partial relative energies for the ground-state
- Good reproduction of the experimental data

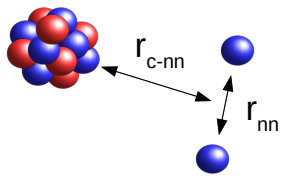
Courtesy of J. Casal, Uni. de Sevilla

Comparison of three-body calculation for $^{11-13}$Li g.s.



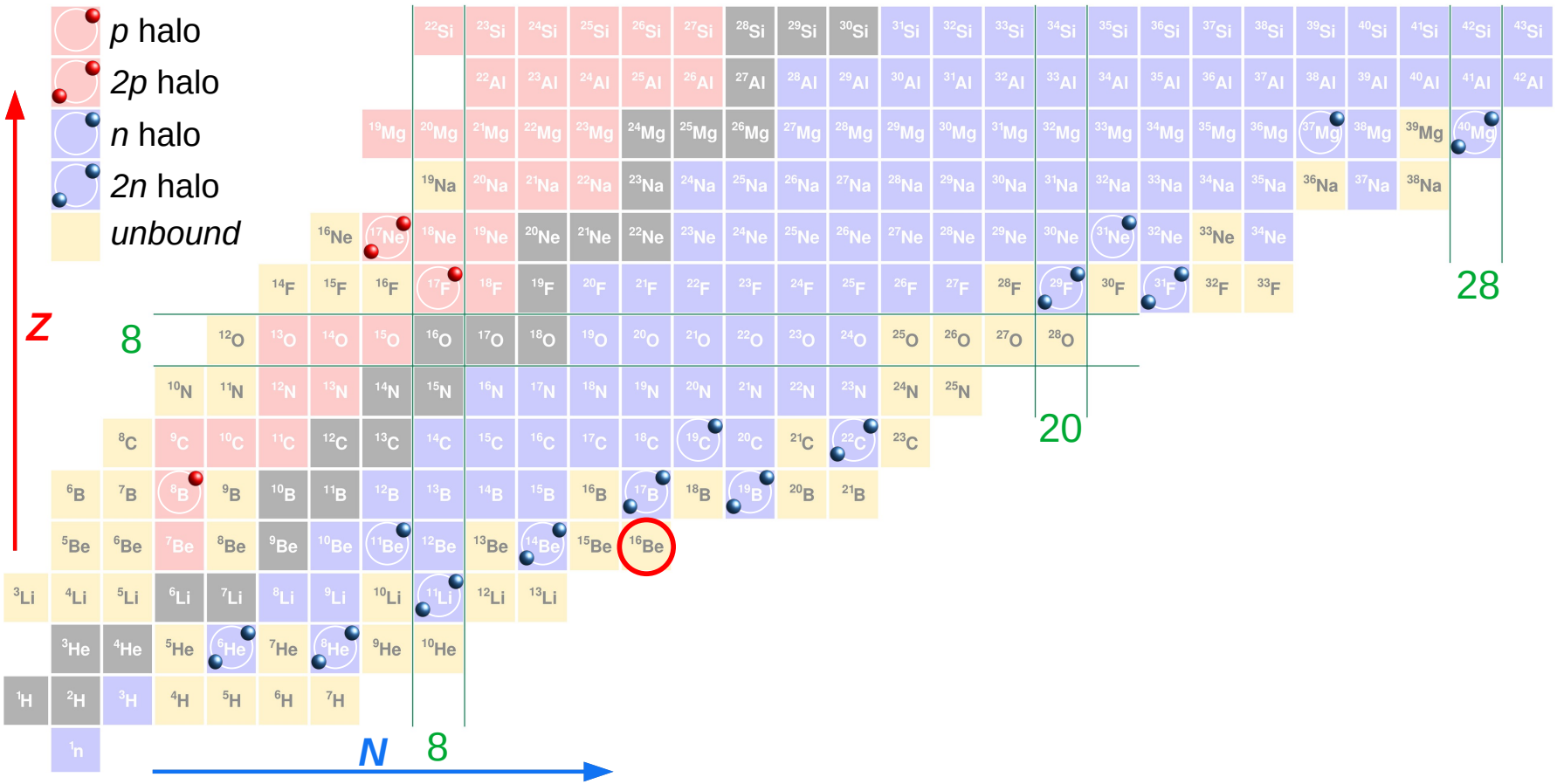


- Time evolution of three-body wave-functions
- Partial relative energies for the ground-state
- Good reproduction of the experimental data
- Dineutron configuration still present in ^{13}Li



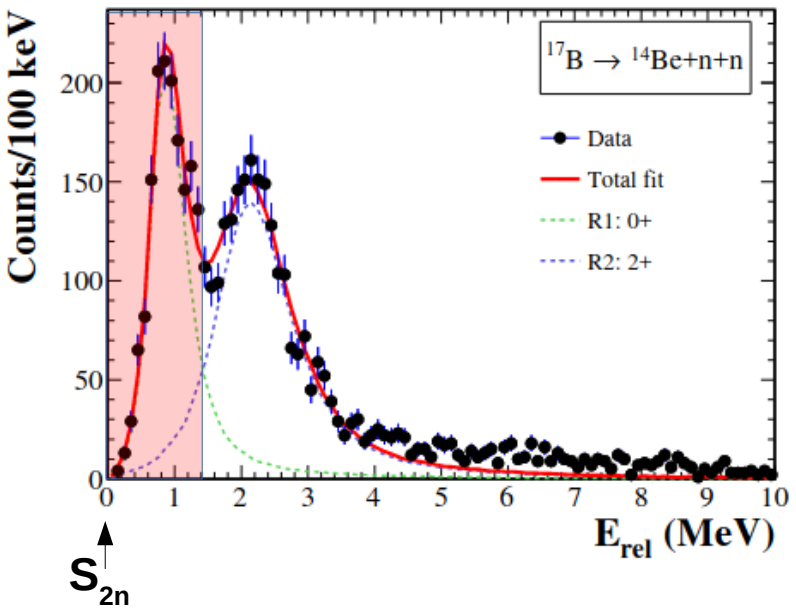
Courtesy of J. Casal, Uni. de Sevilla

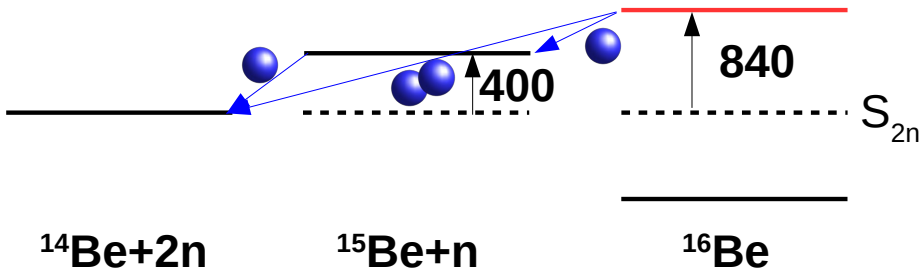
2*n*-unbound ^{16}Be

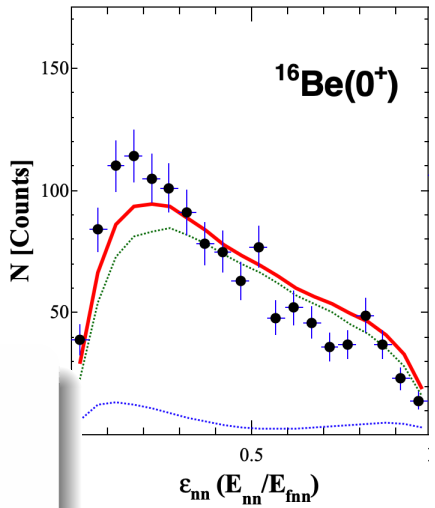


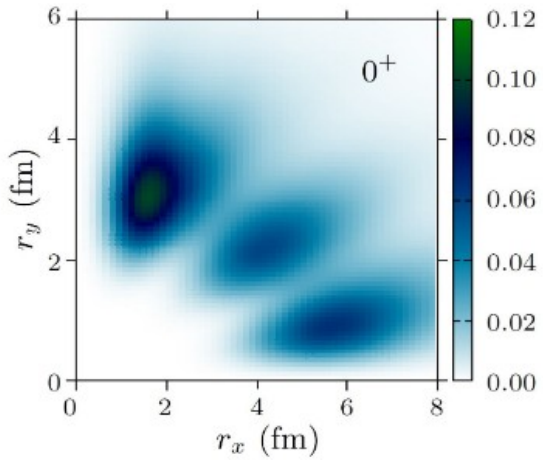
^{16}Be→ ^{14}Be+n+n

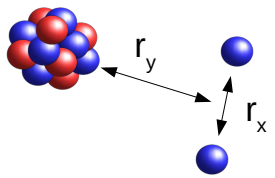
B. Mondeagudo-Godoy, *Private Communication*





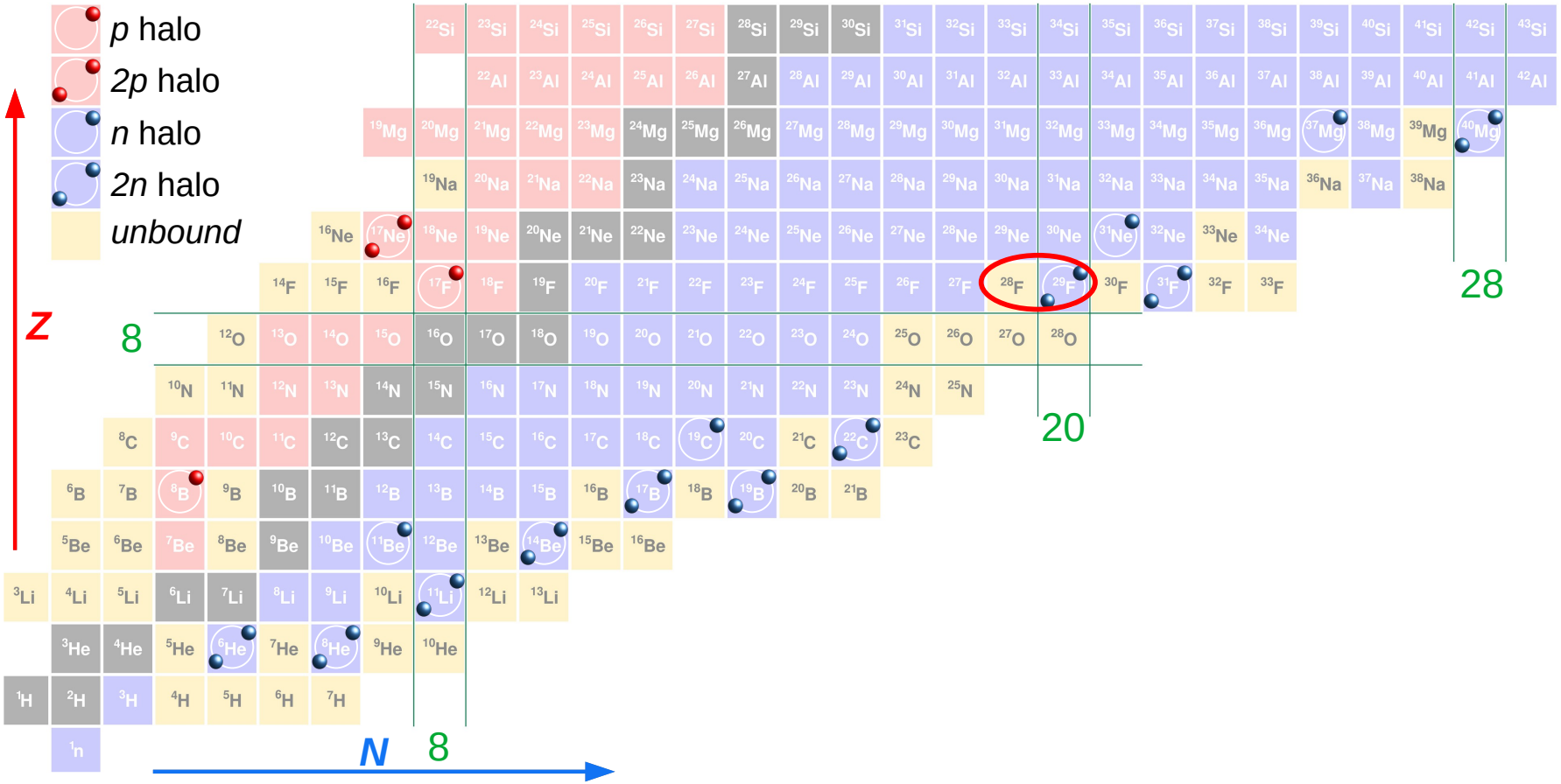






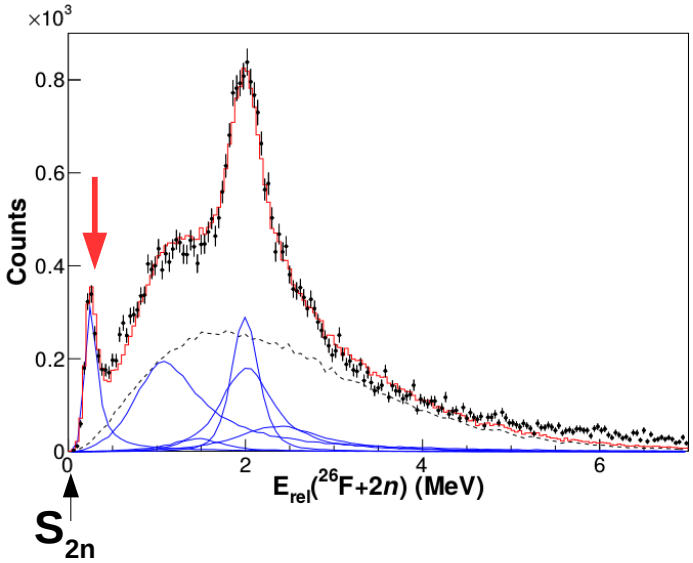
- Two well resolved resonances
- ≈840keV ground-state
- Signal observed at low ε_{nn}
- Direct decay although intermediate resonance available
- 3-body model suggests dineutron configuration dominates

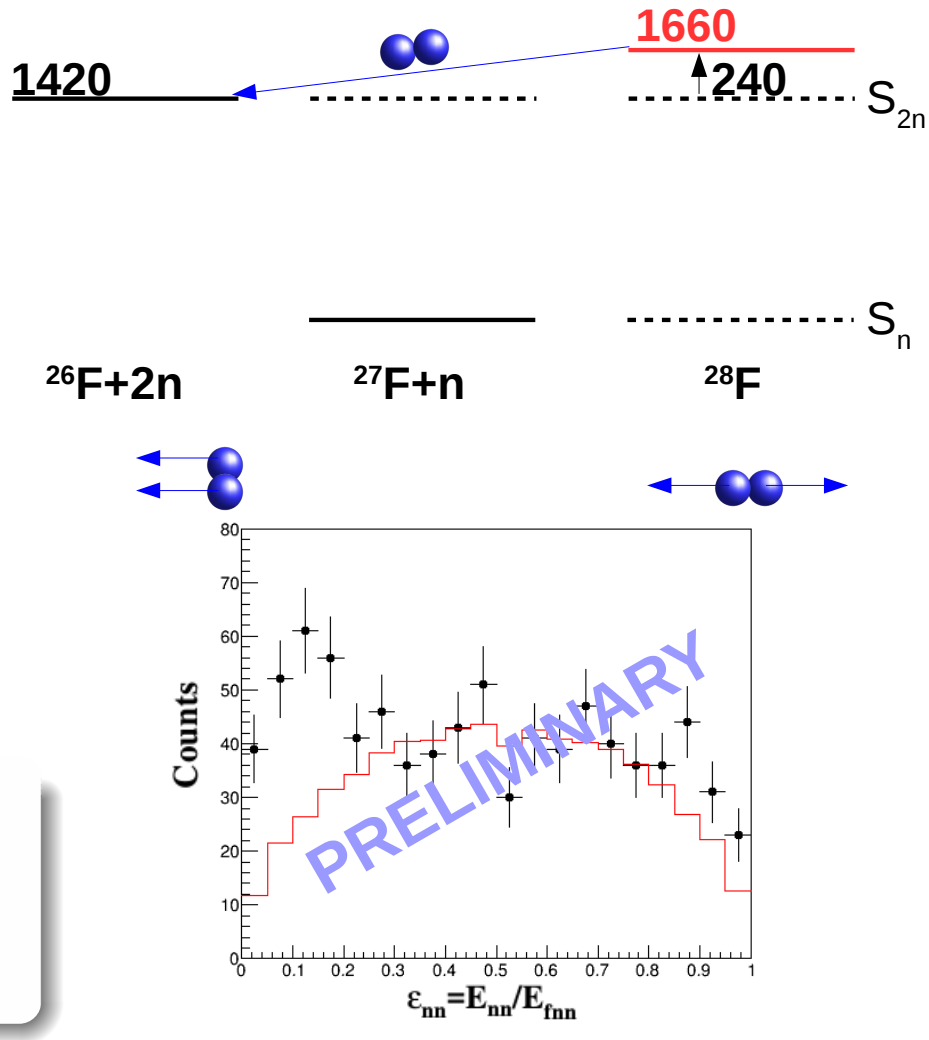
Neutron-rich fluorine isotopes : ^{28,29}F



$^{28}\mathrm{F} \rightarrow {}^{26}\mathrm{F} + n + n$

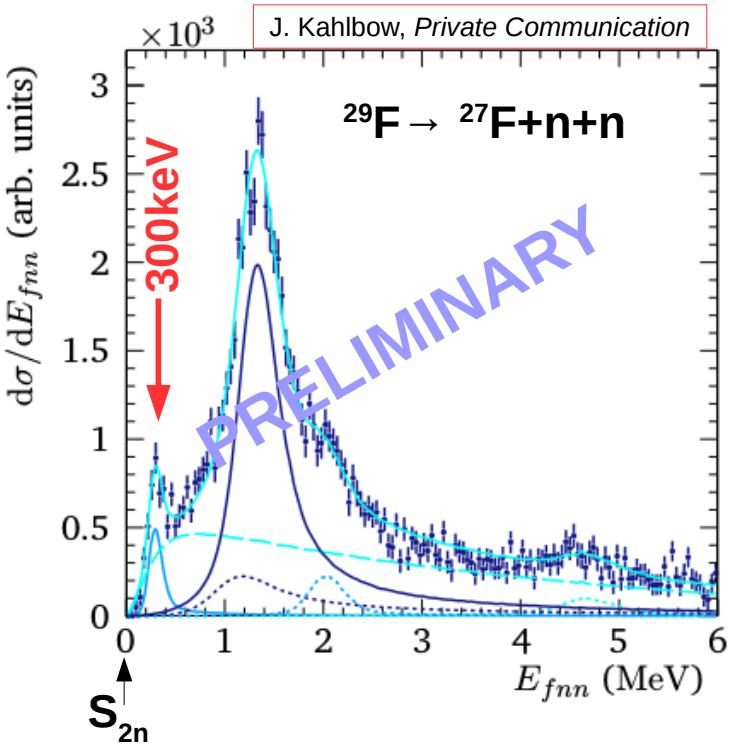
AR *et al*, Phys. Rev. Lett, 124, 152502 (2020)

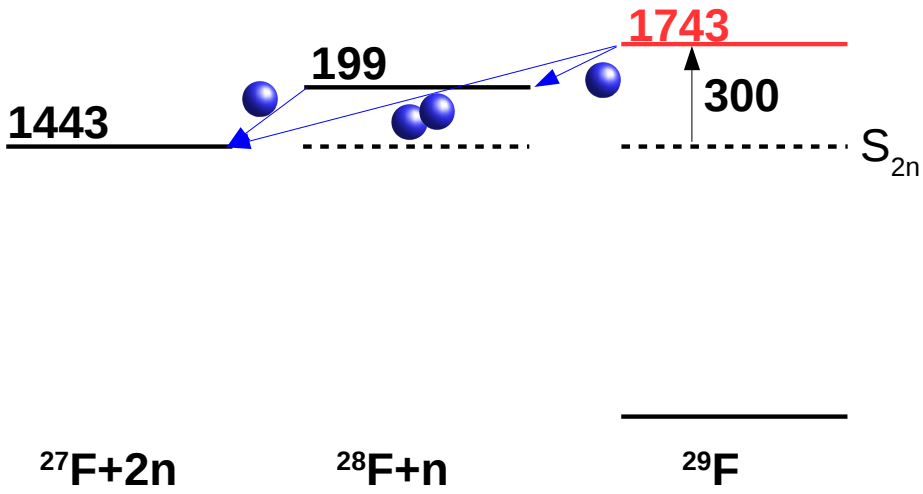




- Several well resolved resonances
- ≈240keV low-lying resonance
- Signal observed at low ε_{nn}

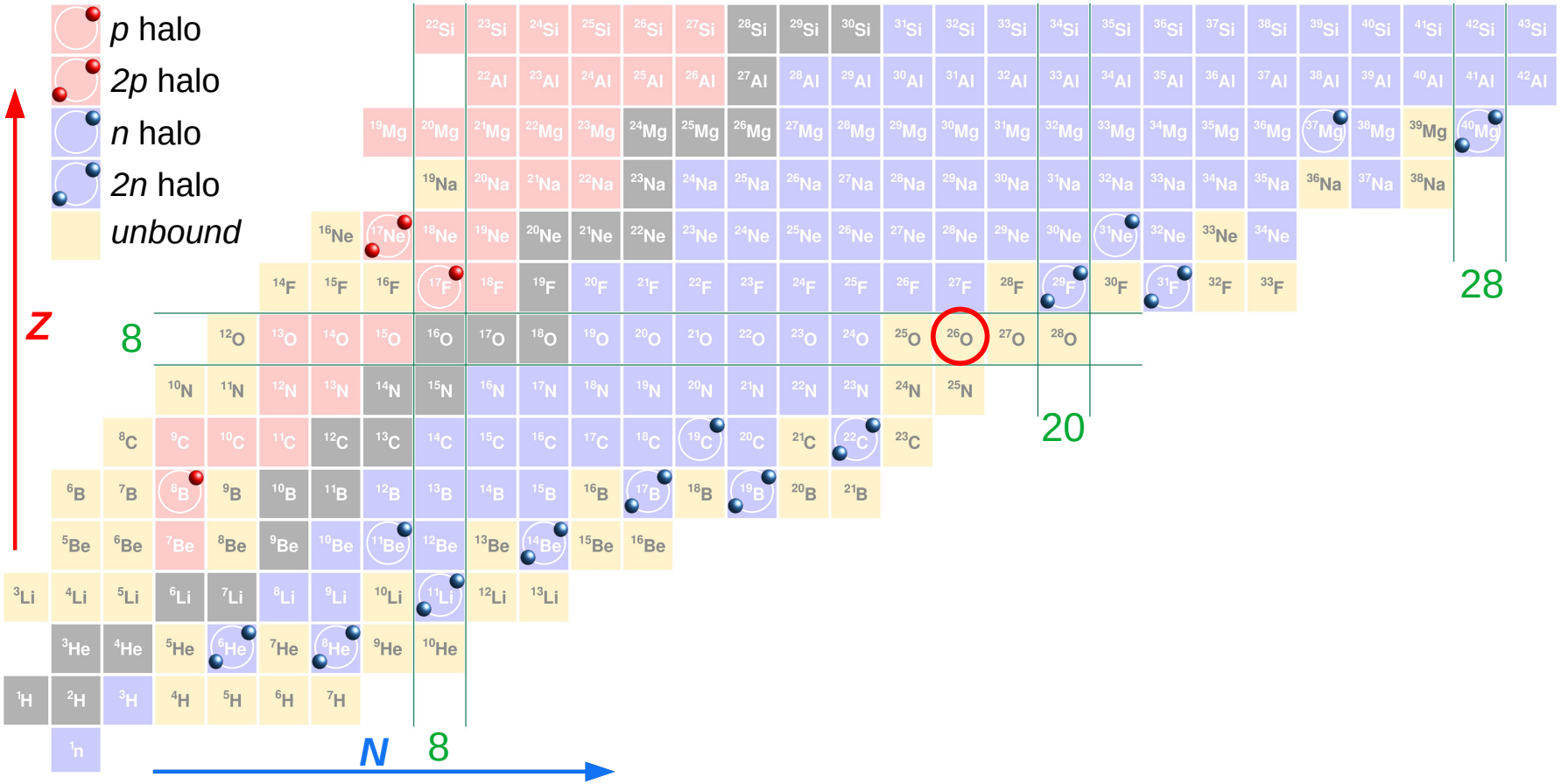
$^{29}F \rightarrow {}^{27}F + n + n$





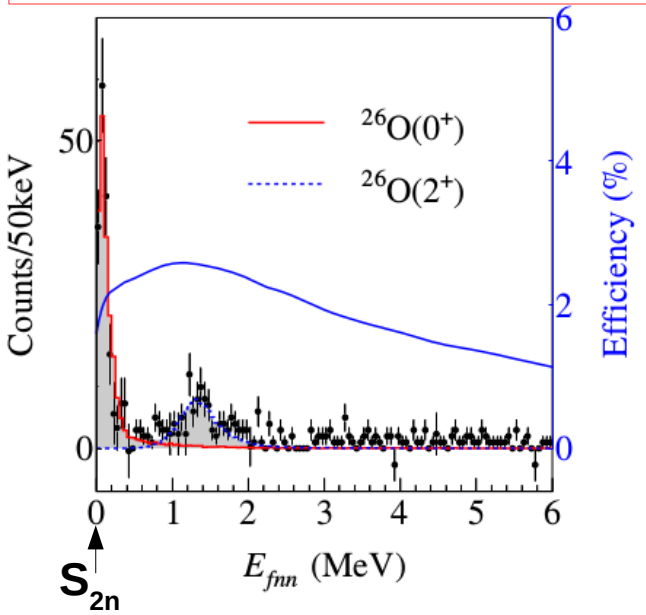
- Several well resolved resonances
- ≈300keV low-lying resonance
- $^{27}F+n$ intermediate resonance
- Statistics too low for 3-Body correlations study

2*n*-unbound ^{26}O : unbound only by 18 keV !!



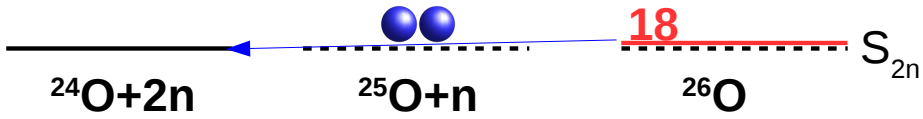
$^{26}O \rightarrow {}^{24}O + n + n$

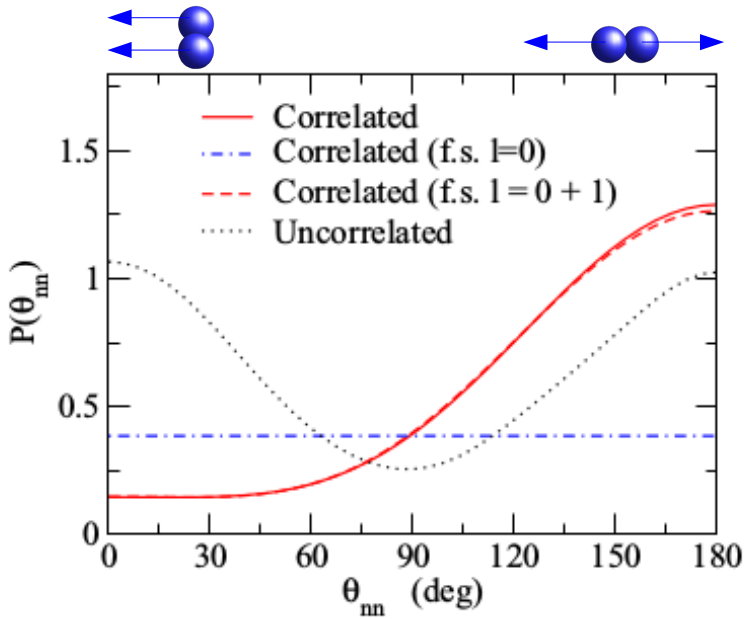
Y. Kondo *et al*, Phys. Rev. Lett., 116, 102503 (2016)



- 18keV low-lying resonance
- ~~$^{24}O + n$ intermediate resonance~~
- Predicted "cigar" configuration
- Very challenging because 3-Body are sharing only 18keV!!

749



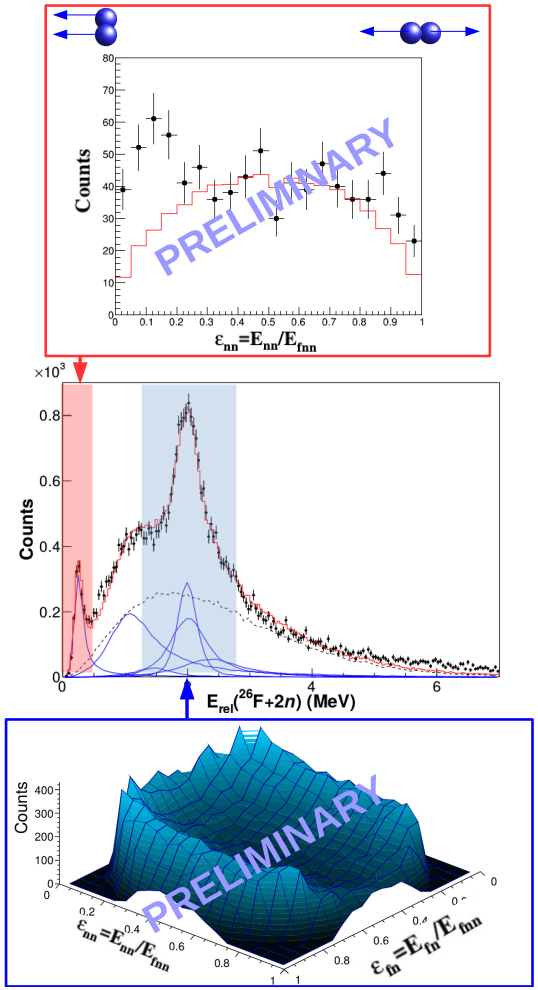


K. Hagino, H. Sagawa, Phys. Rev. C, 89, 014331 (2014)

Conclusion

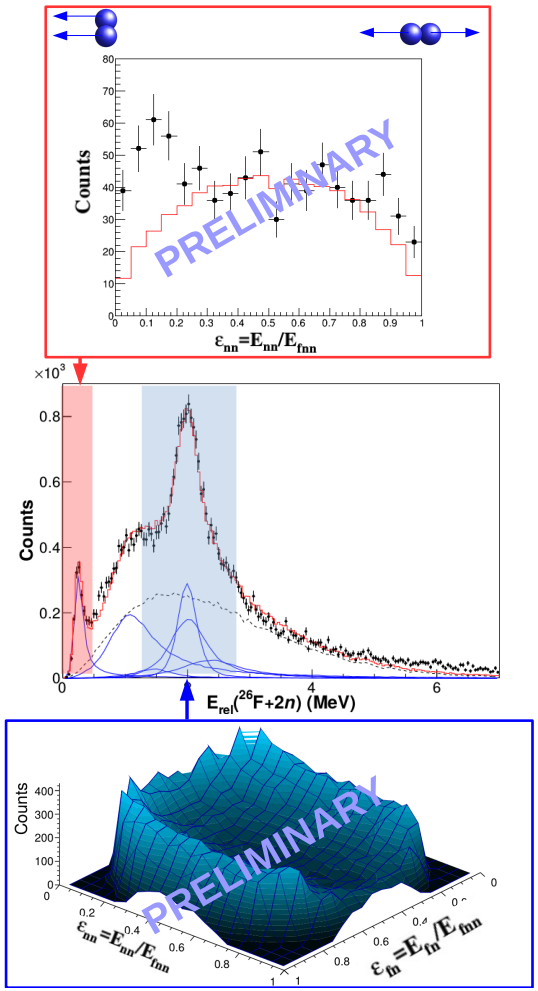
- New era of high-statistics(+)/high-resolution(+) *xn*-decay experiments
  - (+) Beam intensities
  - (+)/(+) Thick LH2 target (MINOS/COCOTIER)
  - (+) Increased *n* detector volume
  - (+) High-granularity *n* detectors

- Study of 3-Body correlations for given resonance
  - → Distinguish Direct/Sequential decays
  - → Identification of intermediate resonances
  - → *n*-*n* correlations challenging for low-energy resonances



Conclusion

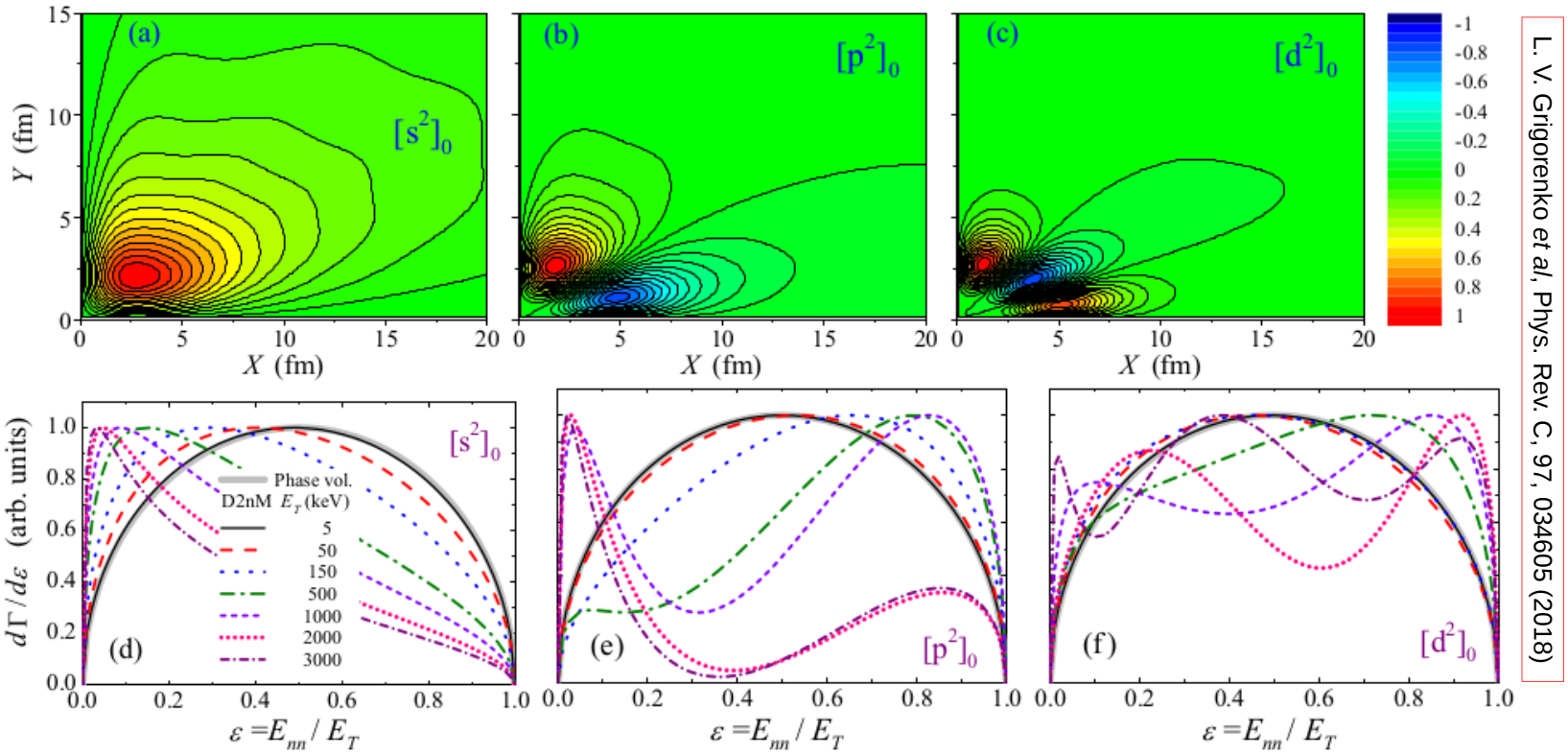
- Clear observation of x*n*-unbound resonances
  - → Seems common feature in proximity to S_{2n}
  - → ^{11}Li, ^{13}Li, ^{14}Be, ^{16}Be, ^{26}O, ^{28}F, ^{29}F ...
- Ongoing experimental/theoretical efforts
- Why such phenonena arise in certain nuclei and not in other ?
  - → Achieve understanding to predict in other nuclei
  - → May have strong implication for astrophysical processes
- What about 4*n* resonances ?
  - → 5-body correlations studies are now within reach (^{28}O)



Thank you for your attention !

Backup slides

Three-Body model

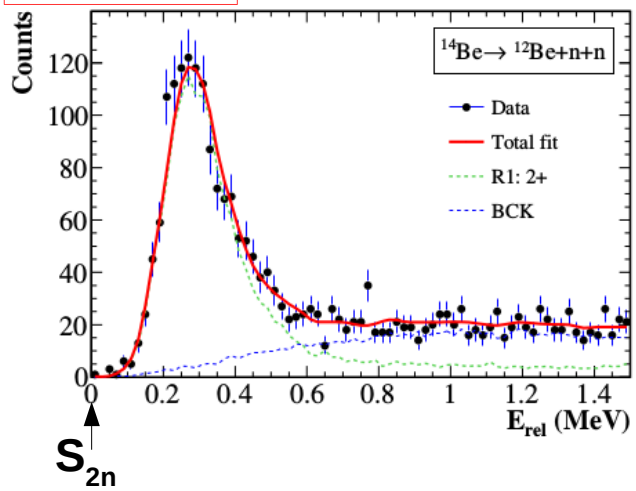


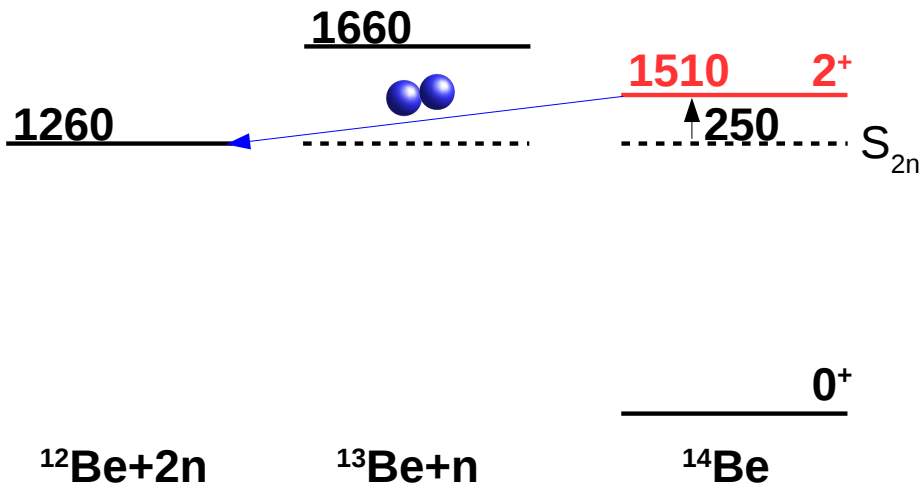
L. V. Grigorenko *et al*, Phys. Rev. C, 97, 034605 (2018)

- Experimentally, we observe similar signal ($[s^2]_0$)
- Why not $[p^2]_0$? $[d^2]_0$?

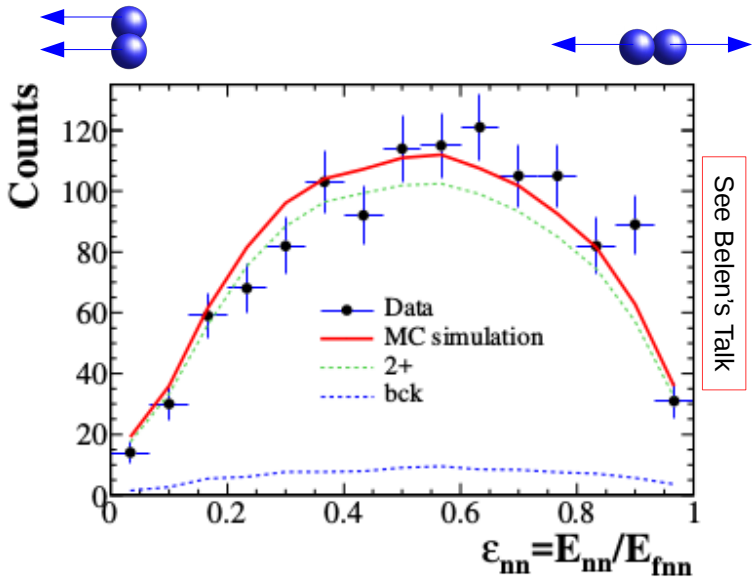
$^{14}Be \rightarrow {}^{12}Be + n + n$

See Belen's Talk



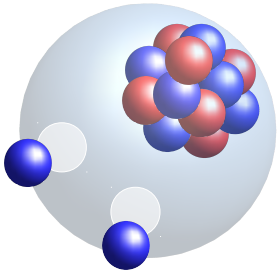


- 250keV low-lying resonance
- ~~$^{12}Be + n$ intermediate resonance~~
- Phase-Space direct decay

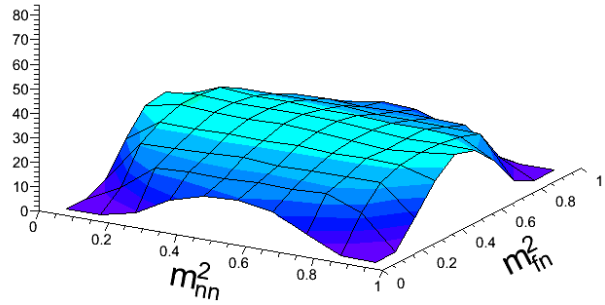


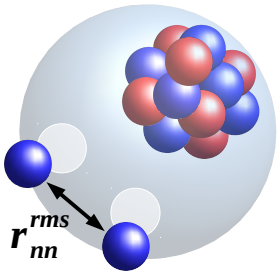
See Belen's Talk

Dalitz plots & correlations (MC Simulations)

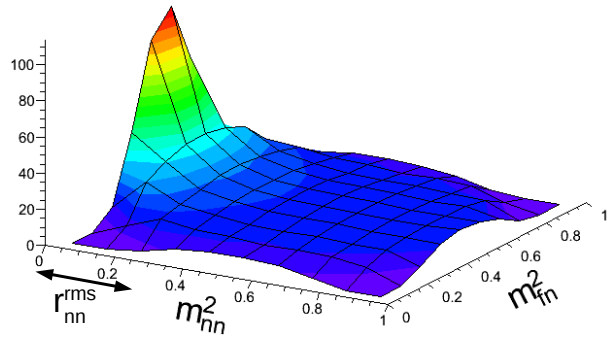


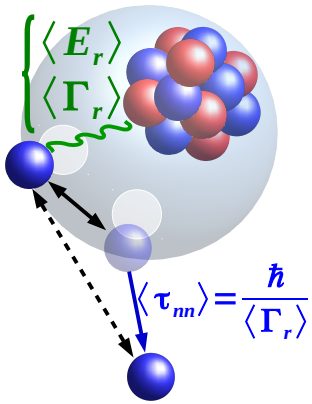
Phase space
(no correlations)





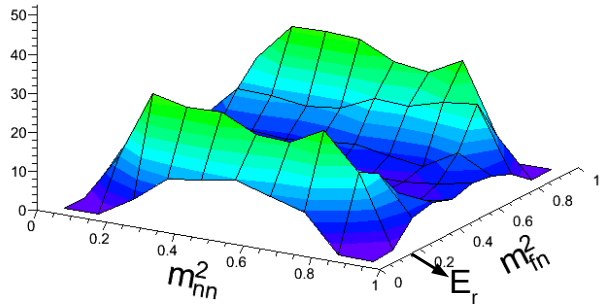
Direct decay :
Phase space $\otimes$ n-n FSI [1]





Sequential decay :

Phase space $\otimes$ { f-n resonance
n-n FSI[1]



[1] Lednicky&Lyuboshits, SJNP 35 (1982) 770