Theory Alliance
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Lawrence Livermore National Laboratory

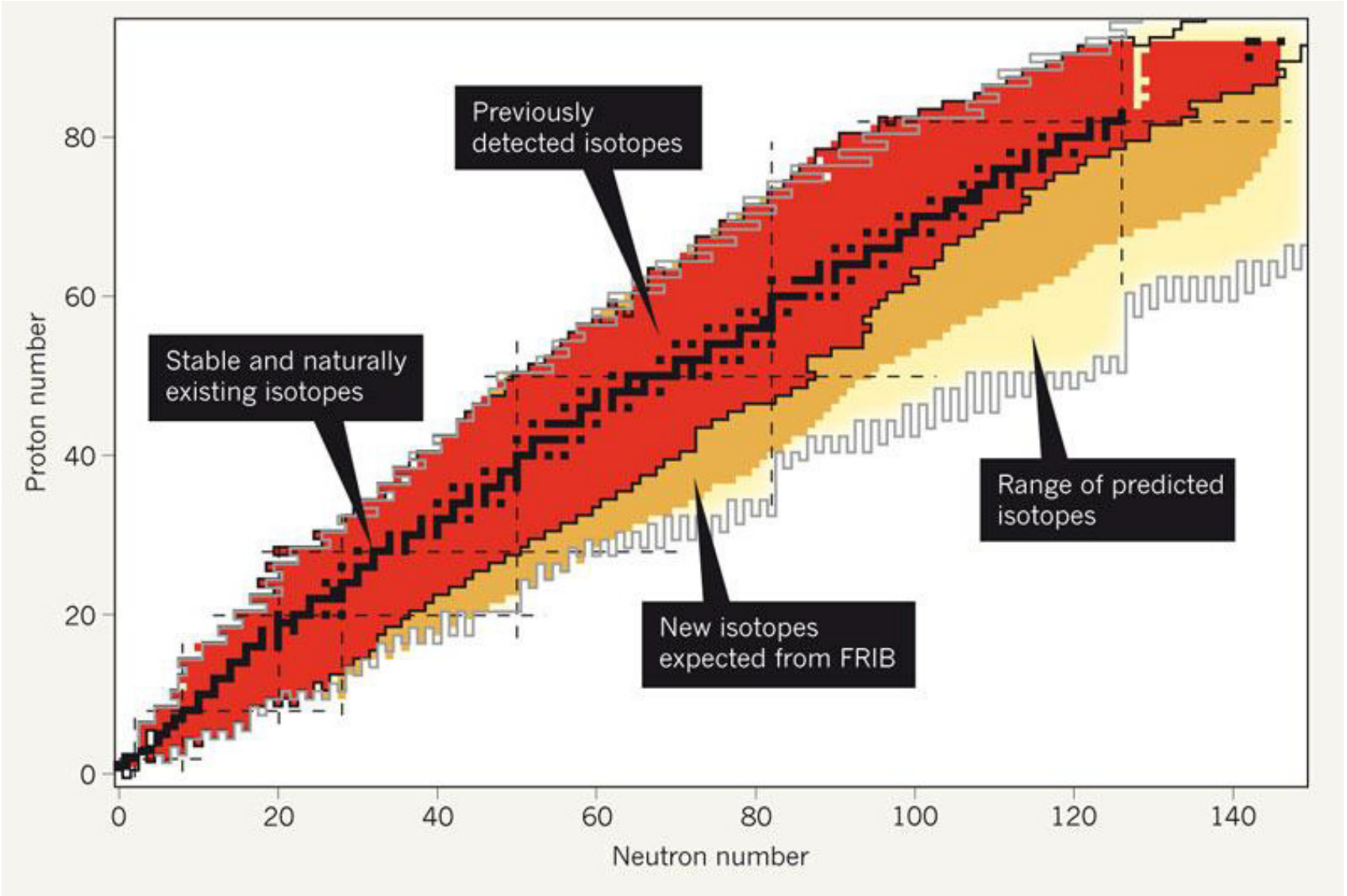
MICHIGAN STATE UNIVERSITY

One-neutron knockout reactions of halo nuclei and as a probe for neutron skin

Chloë Hebborn

August, 31 2022

It is a very exciting time to be a nuclear physicist !



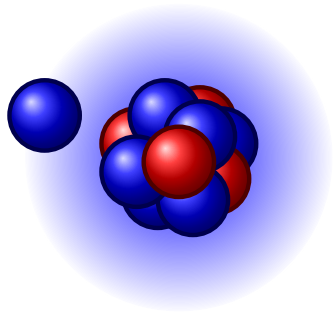
[Nature 477, 15, 2011]

Unstable nuclei exhibit exotic feature and are fascinating !

Halo nuclei exhibit a very large matter radius

Compact core + one loosely-bound neutrons

Ex : $^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + n$



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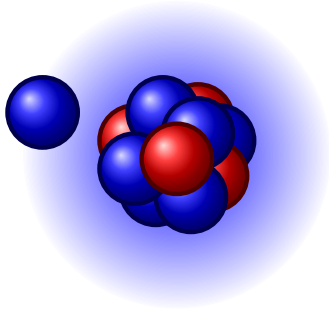
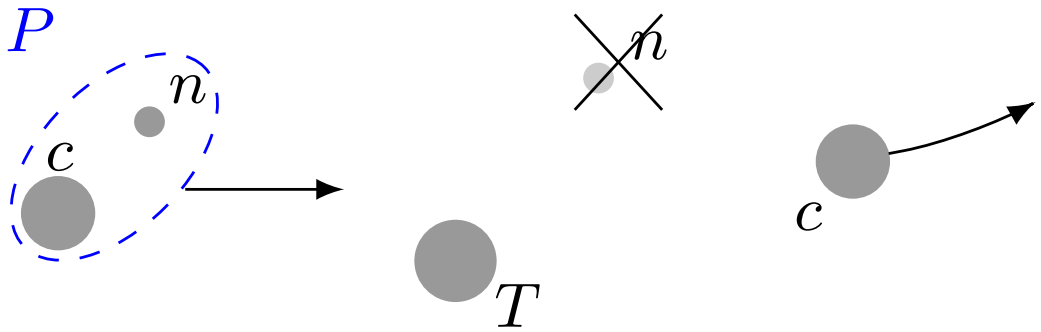


→ Studied through **reaction processes**

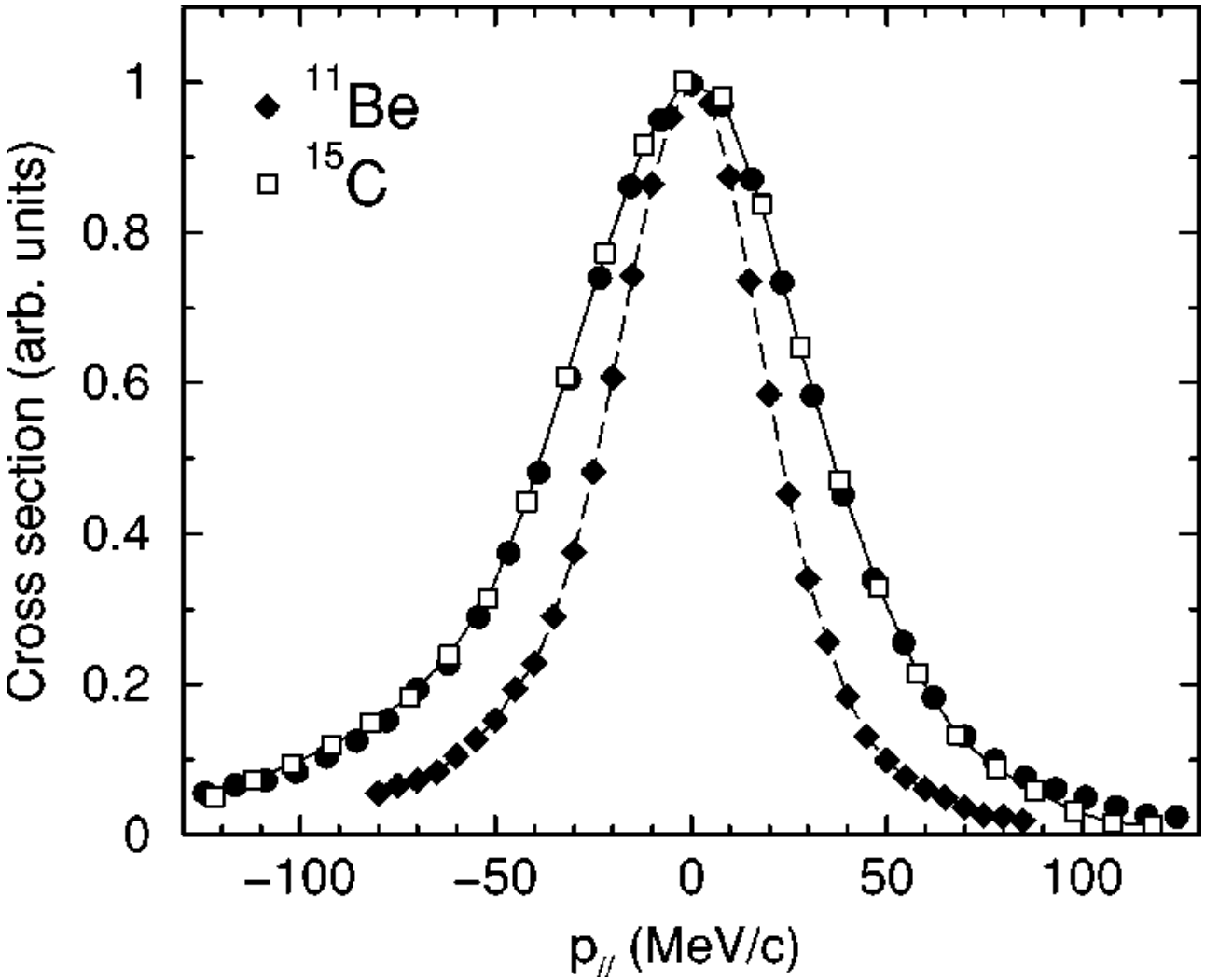
One-neutron knockout :

$P(\equiv c + n) + T \rightarrow c + X$



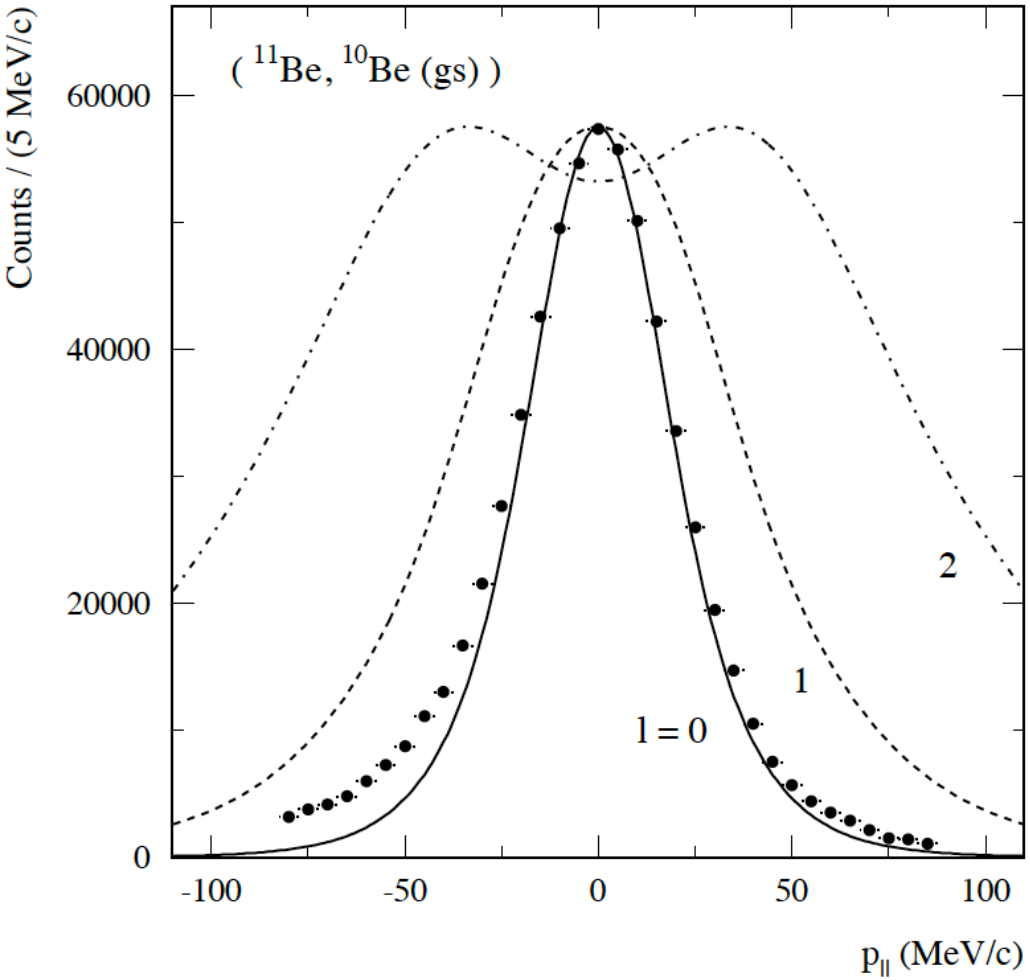
⇒ high statistics since the neutron is not detected in coincidence !

Knockout cross sections carry information about the nucleus size

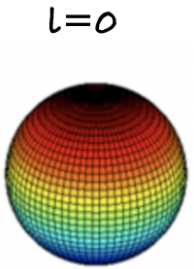


[J. A. Tostevin *et al.*, PRC **66**, 024607 (2002)]

Knockout reactions are also a powerful spectroscopic tool



[Aumann *et al.* PRL **84**, 35 (2000).]



$5/2^+$ 1.274 $d5/2$

^{10}Be+n

$\epsilon = 0$

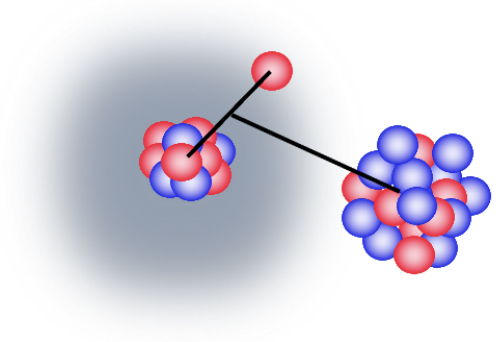
$1/2^-$ -0.184 $0p1/2$

$1/2^+$ -0.501 $1s1/2$

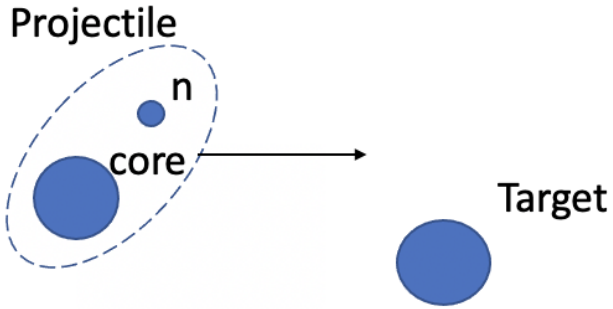
^{11}Be spectrum

→ Parity inversion !

For reactions at high energies and with projectile and target nuclei, simplifications are needed



$\Rightarrow$



$$\sigma_{th} = \sum_i SF_i \times \sigma_{ko}^{sp,i}$$

with SF_i the occupancy of a s.p. orbital i

$\sigma_{ko}^{sp,i}$ s.p. knockout cross section = diffractive breakup σ + stripping σ

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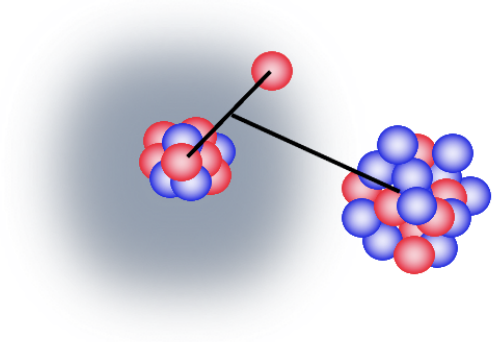

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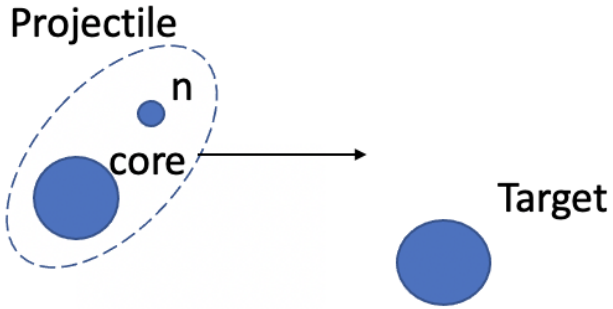

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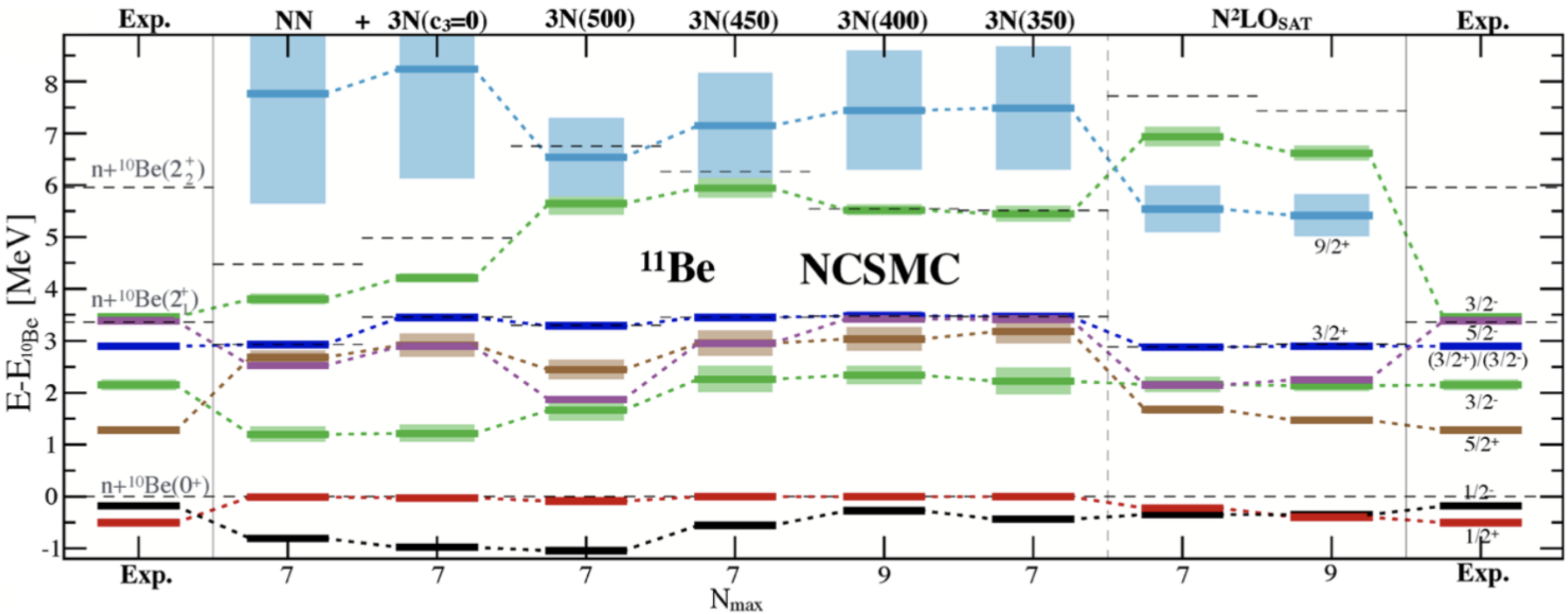
To compute reaction cross section, we need

- $P-T$ interactions : phenomenologicaloptical potentials
- **Build an effective interaction for the c-n interaction...**

Accurate *ab initio* description for halo nuclei exists, how do use them to predict knockout observables ?

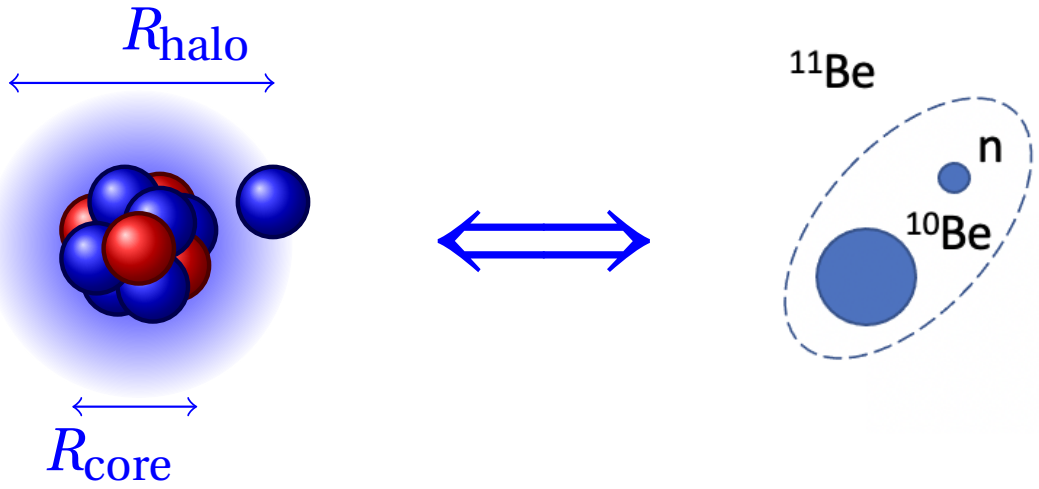


[Calci *et al.* PRL **117**, 242501 (2016)]

Halo-EFT bridges *ab initio* theory and reactions involving halo nuclei

EFT description of ^{11}Be : uses separation of scale $R_{\rm core} \ll R_{\rm halo}$

[Hammer *et al.* JPG **44**, 103002 (2017)]



→ There is no free lunch... there are some unknown EFT coefficients

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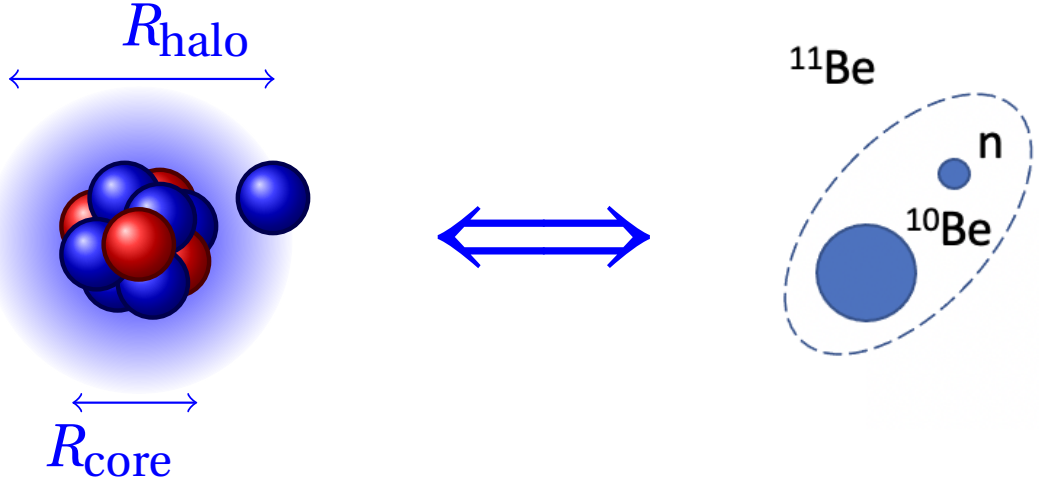

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→ NLO : exp. binding energies and *ab initio* predictions for ANCs

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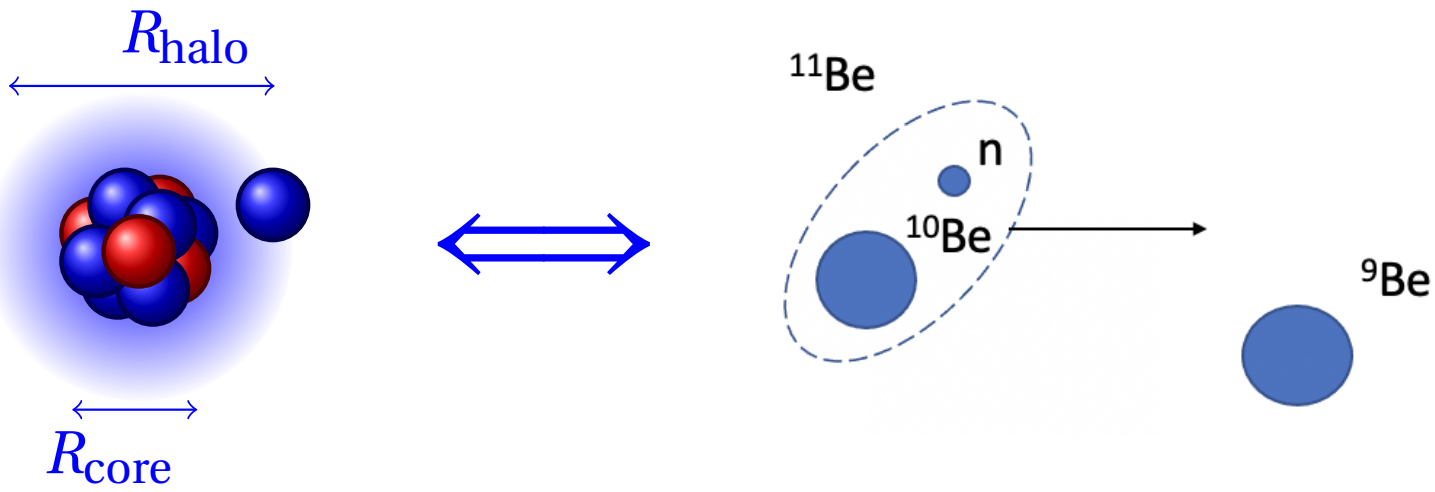

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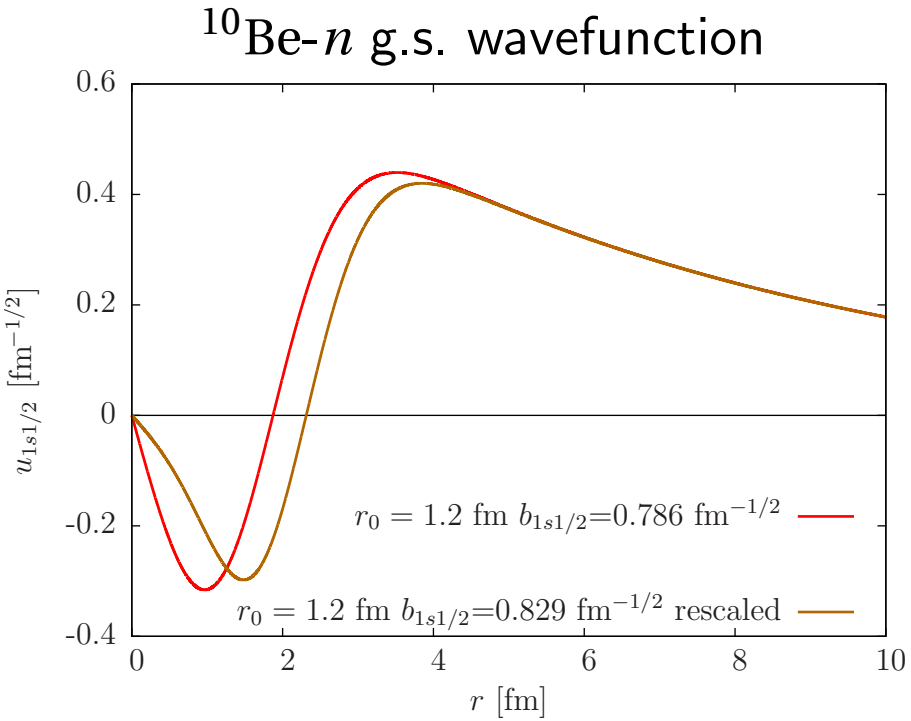
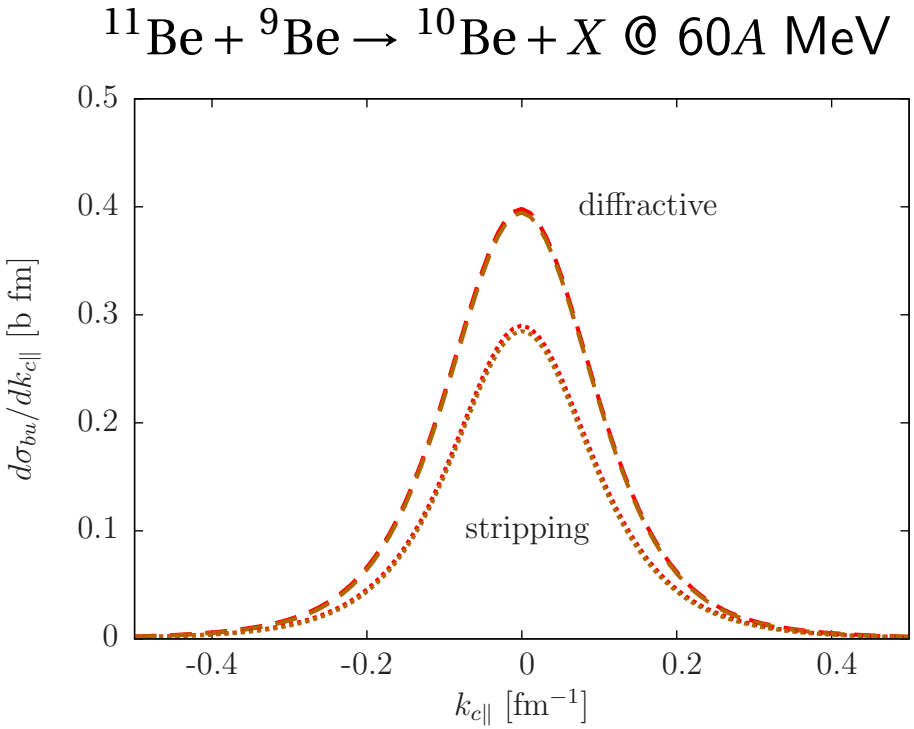
NLO description of ^{11}Be is enough for knockout reactions





[Hebborn and Capel, PRC **100**, 054607 (2019)]

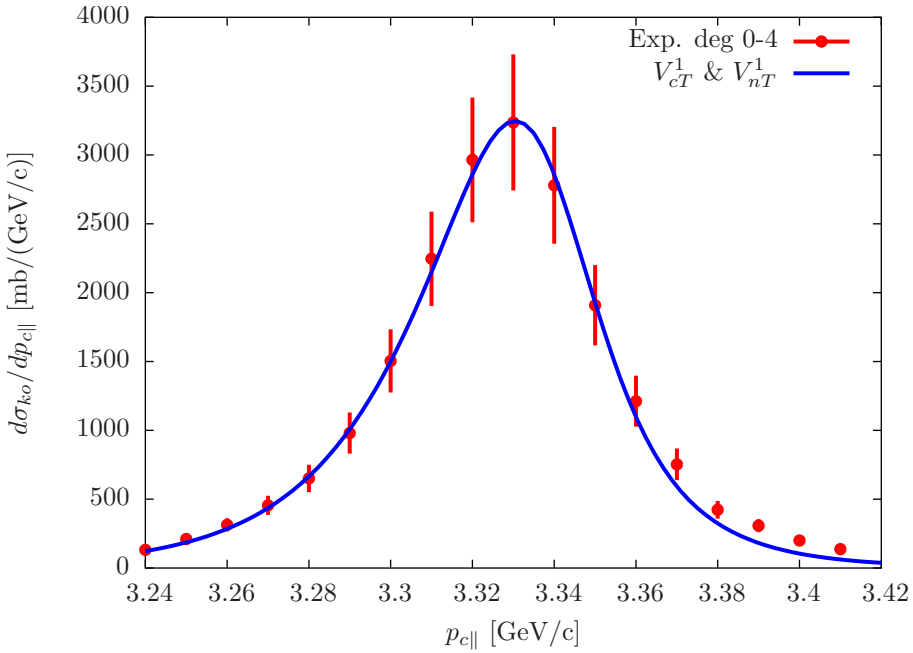
Reference calculation : ANC=0.786 fm$^{-1/2}$ [Calci *et al.* PRL **117**, 242501 (2016)]

Same ANC but different interior : same cross sections

Universality (peripherality) of knockout reactions off halo nuclei

Combining EFTs, *ab initio* predictions and few-body models lead to accurate knockout cross sections

$^{11}\mathrm{Be} + {}^{9}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + X$ at $60A$ MeV



[Exp. : Aumann *et al.* PRL **84**, 35 (2000) ; Th : Hebborn and Capel, PRC **104**, 024616 (2021)]

ANCs of NCSMC (^{11}Be) → validation of the *ab initio* prediction !

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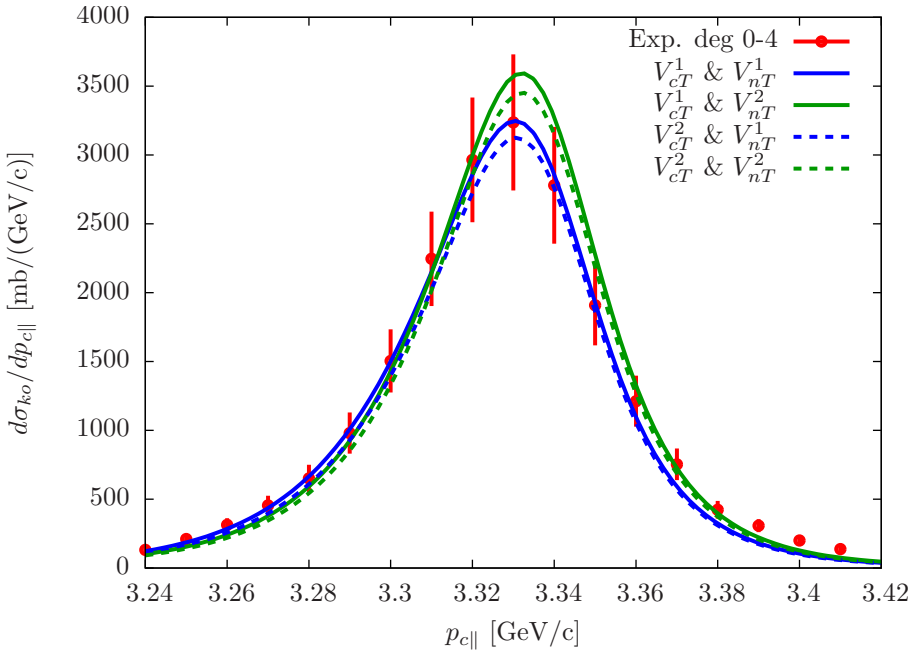

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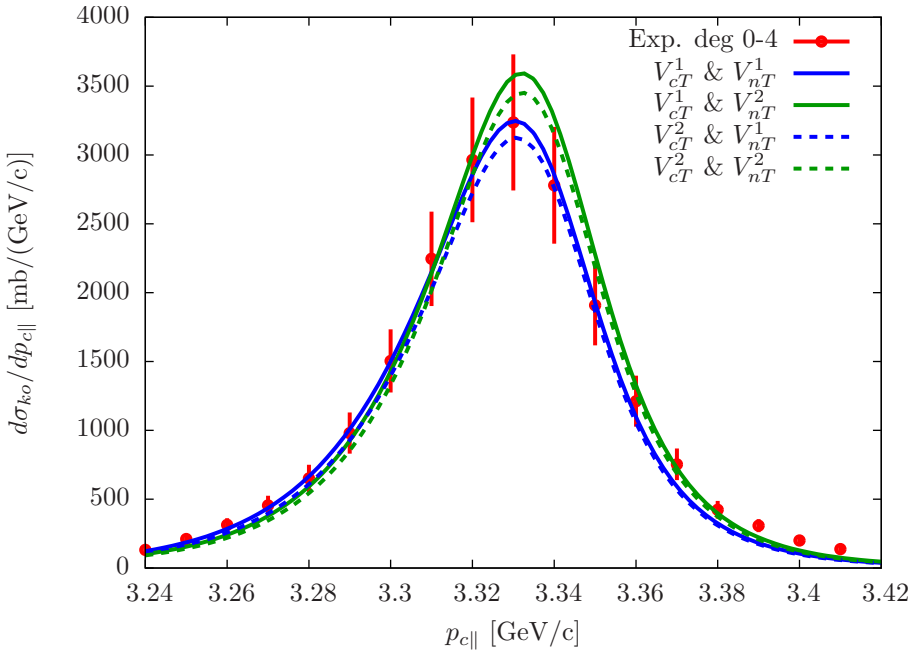

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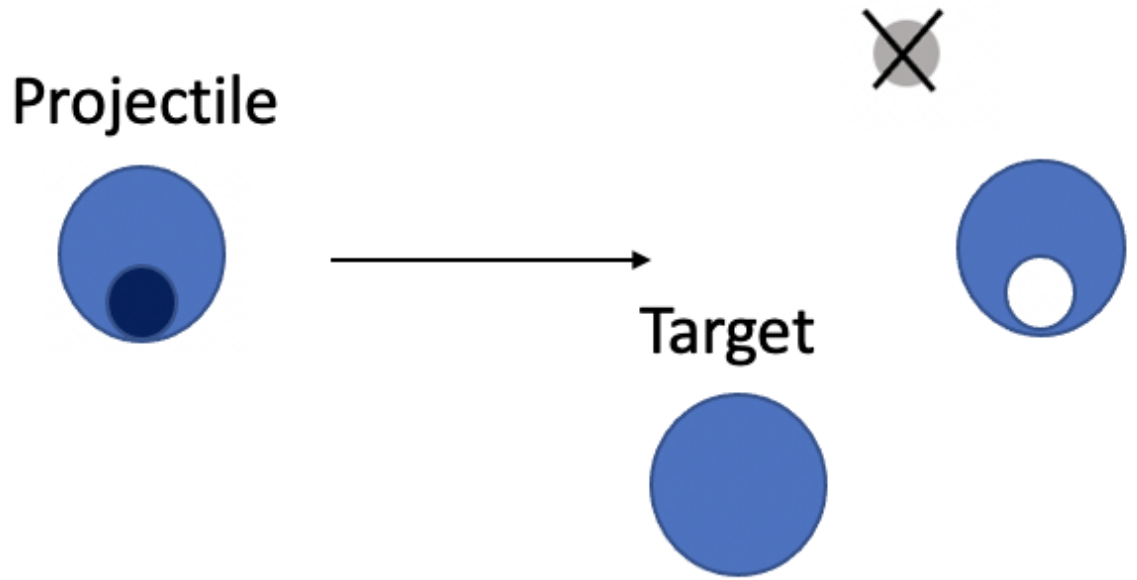
Ab initio ANCs predict knockout and transfer data ! !

[PRC **98**, 034610 (2018) ; PRC **98**, 054602 (2018) ; PRC **100**, 044615 (2019)]

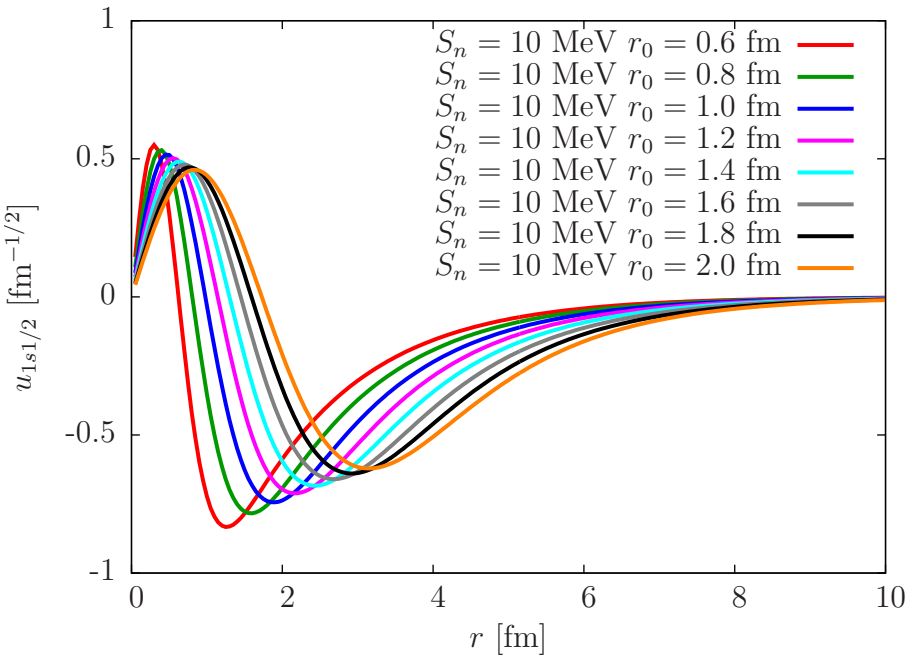
What about knockout on more bound projectiles ?

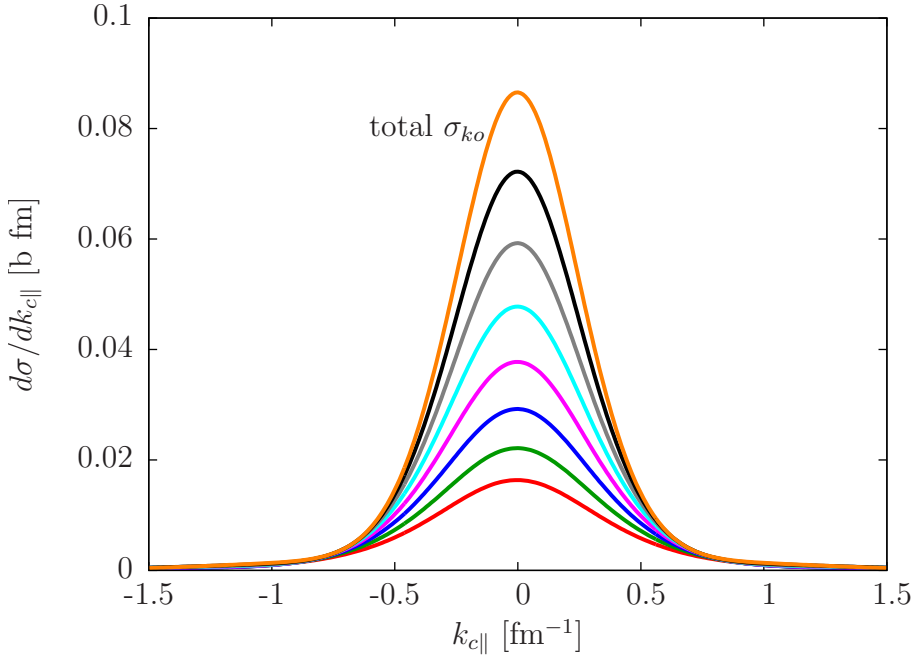
No more separation of scale when the nucleus is more bound



Are knockout of deeply bound nucleon still peripheral ?

Knockout of deeply-bound nucleon are not strictly peripheral





- Larger r_0 → larger ANC → larger σ_{ko}

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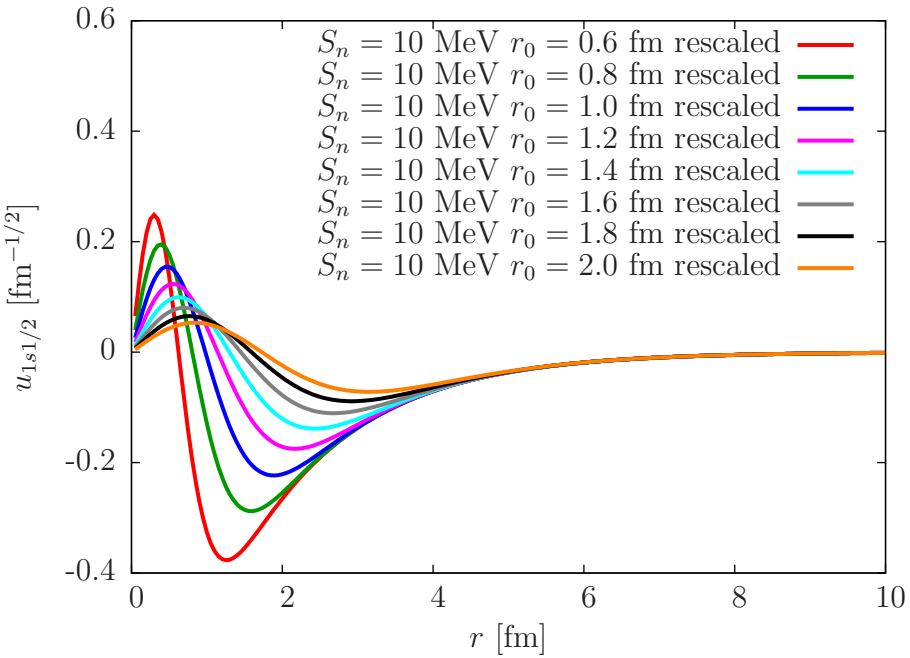

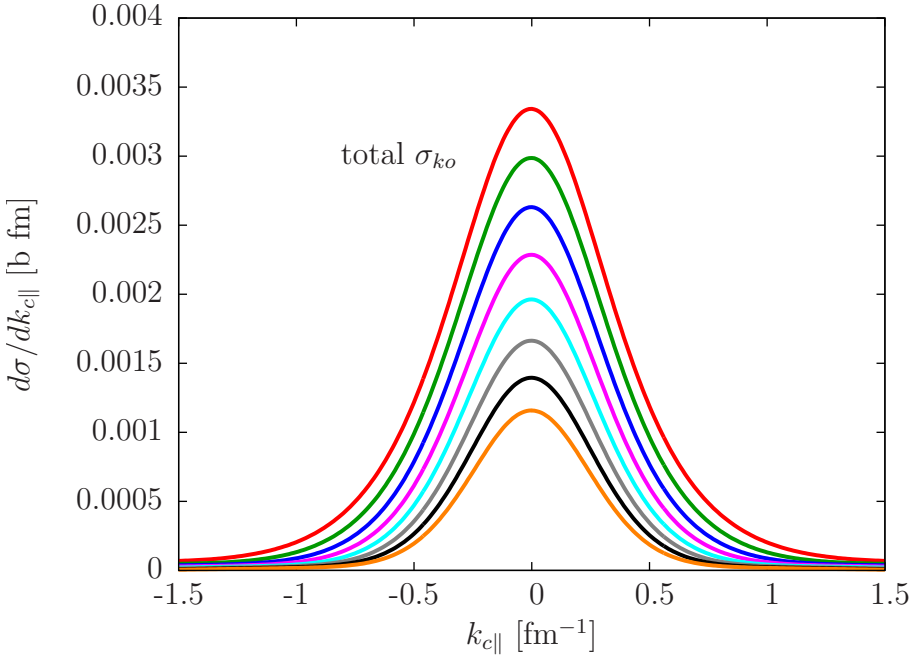

- Larger r_0 → larger ANC → larger σ_{ko}
- Rescale with the ANC → same asymptotics but SF=0.2–0.01
  ⇒ σ_{ko} **is sensitive to the inner part of the wavefunction**
  ⇒ σ_{ko} **depends non-linearly on SF**

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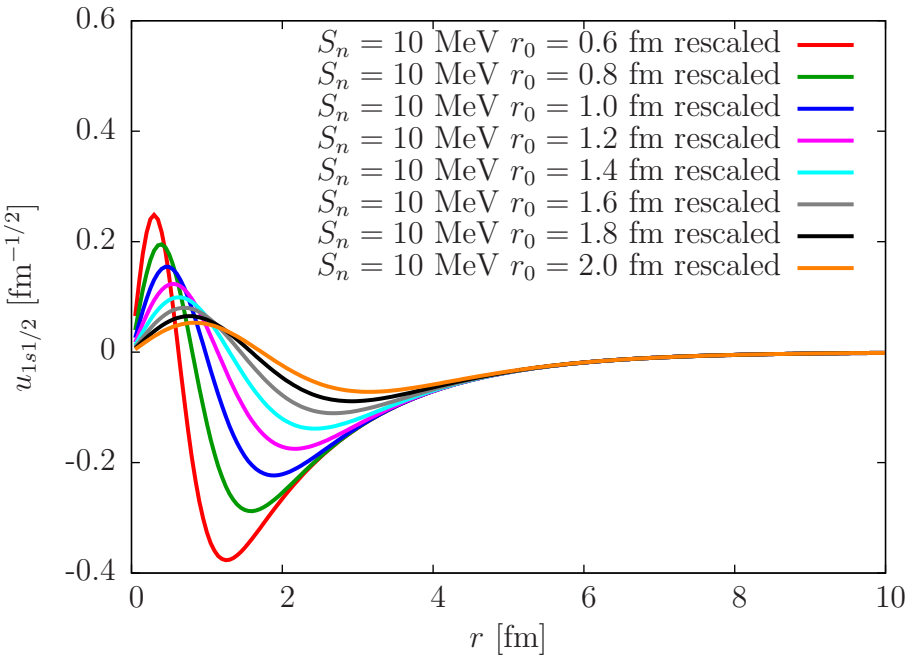

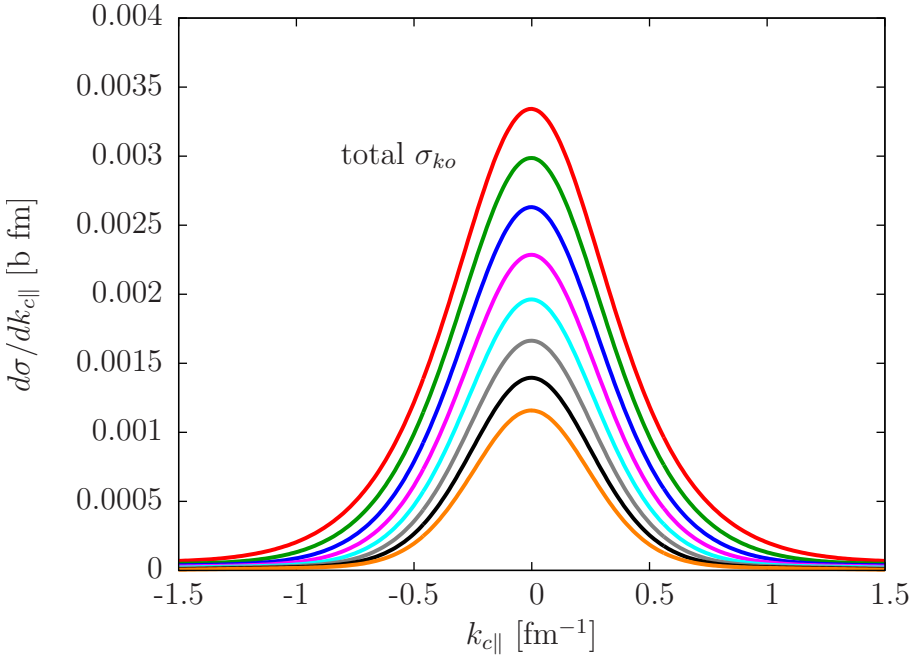

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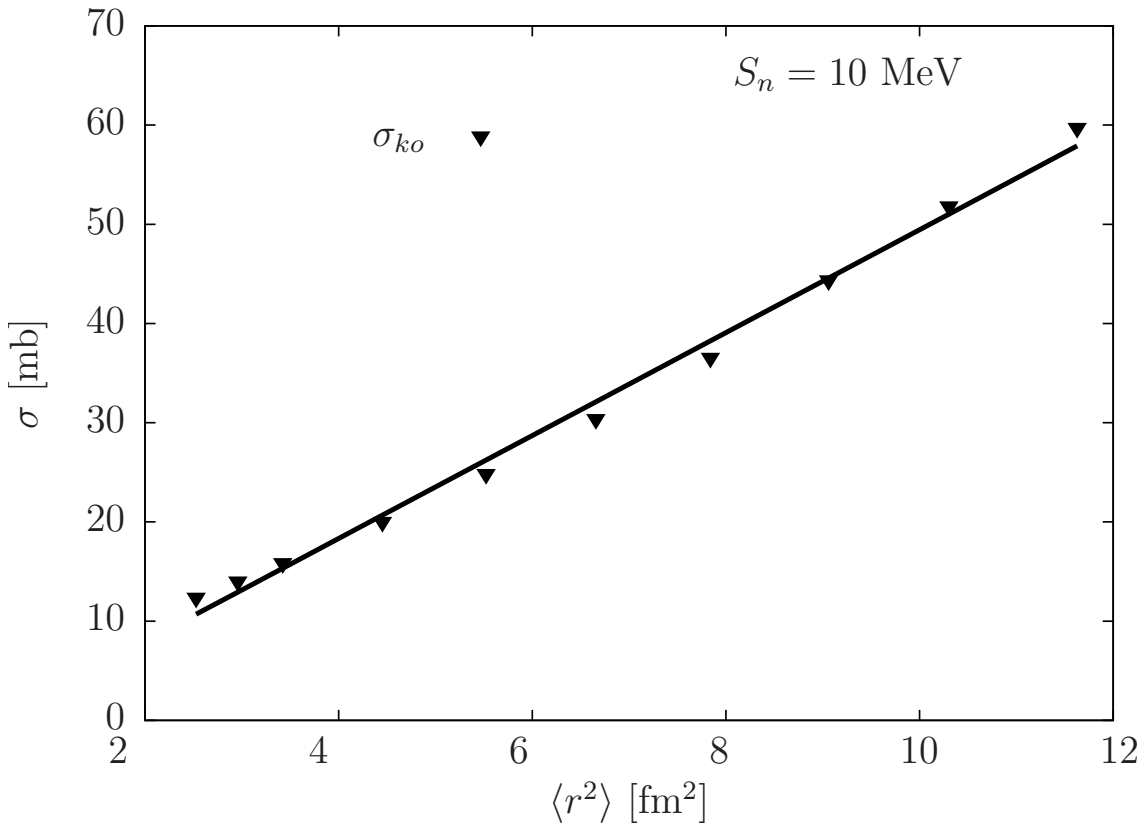
What nuclear observable σ_{ko} are sensitive to ?

One can predict knockout cross sections using $\langle r^2 \rangle$



Approximate $\sigma_{ko} \sim \langle r^2 \rangle$ (also demonstrated analytically)

[Hebborn and Capel, in preparation] [Gade *et al.* PRC 044306 (2008)]

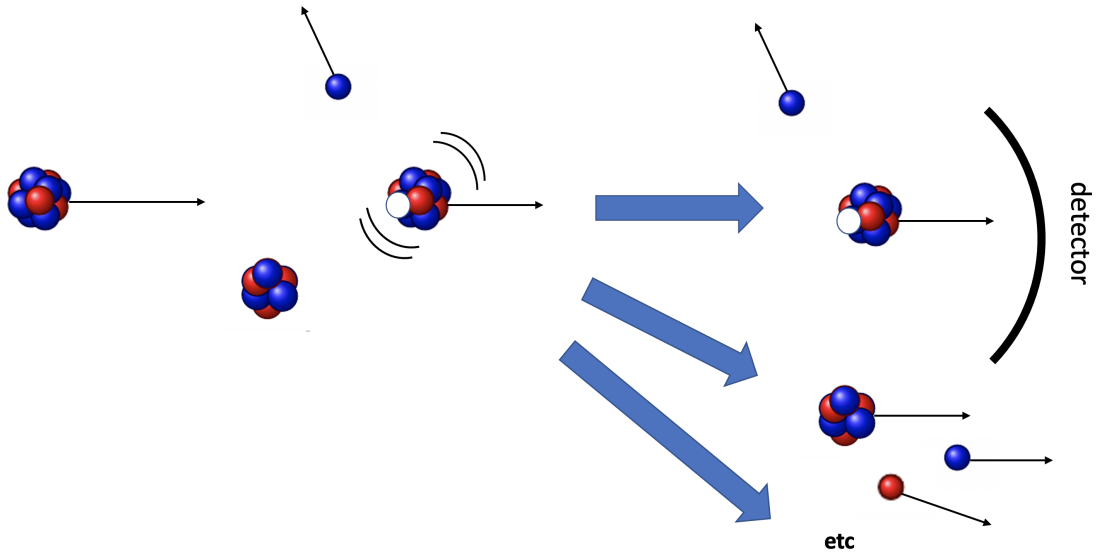
One-neutron knockout data to infer neutron skin thickness...

[Aumann *et al.* PRL **119**, 262501 (2017)]

To infer accurate neutron skin thickness, multistep reactions effects need to be included in the reaction theory

Importance of core particle decay for knockout of deeply-bound nucleon

[Louchart *et al.* PRC **83**, 011601(R) (2011)]



Green's function knockout formalism : [Hebborn and Potel, arXiv : 2206.09948]

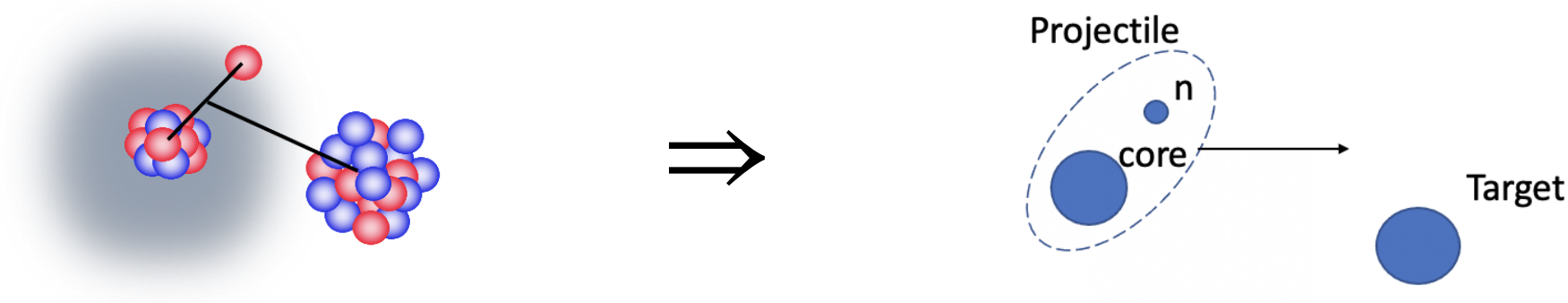
Many-body hole-core dynamics included via dispersive optical potentials

→ applicable to N-removal & -addition, e.g. knockout, (p,d), (d,p)

Summary and prospects

Knockout reactions are very powerful spectroscopic tools !

Halo nuclei : Halo-EFT bridges *ab initio* structure and reaction theory



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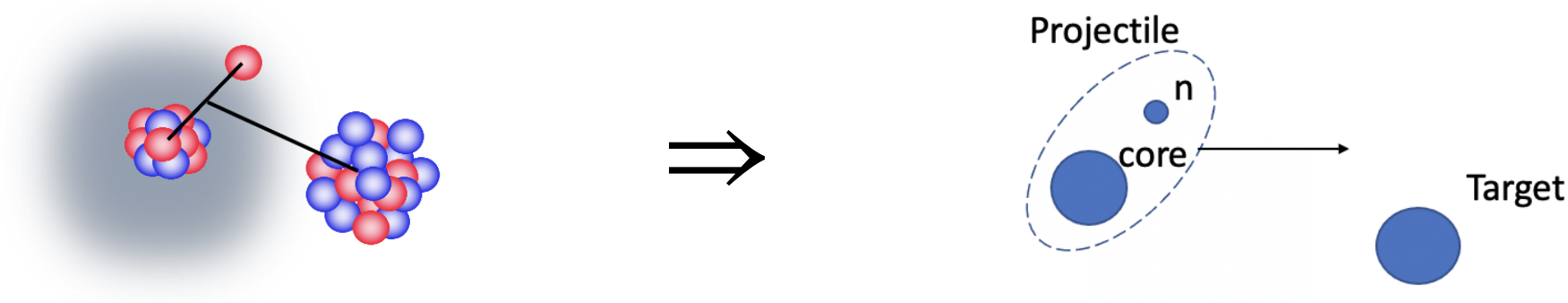

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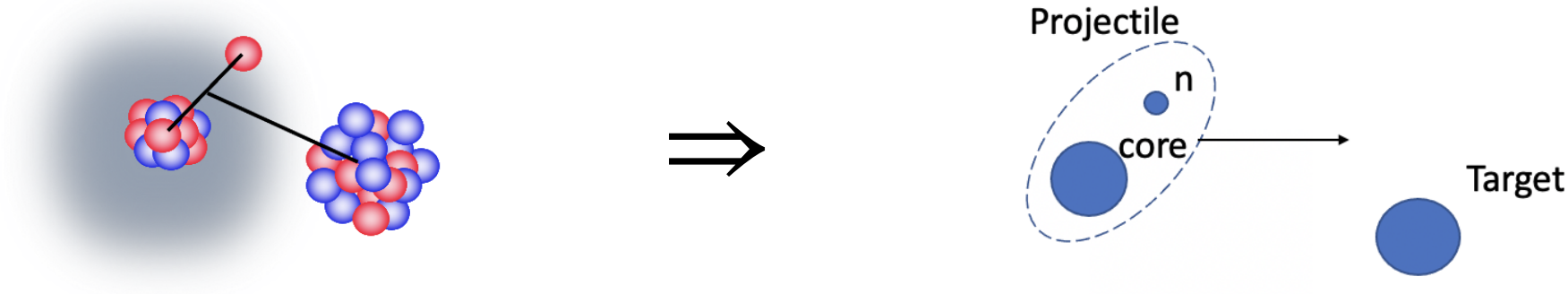

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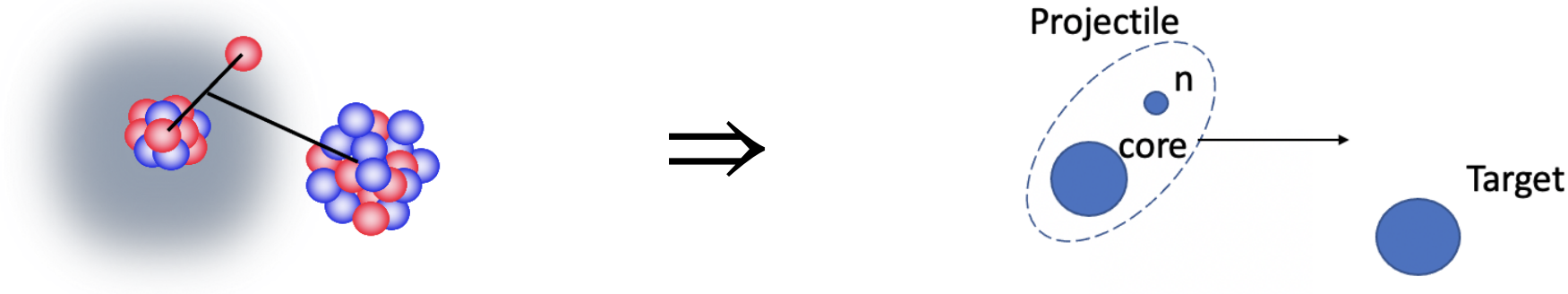

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Prospects : UQ due to the optical potentials

with T. Whitehead (MSU), A. Lovell (LANL) and F. Nunes (MSU)

Inclusion of multistep reactions in the eikonal theory

with G. Potel (LLNL)