Towards a predictive description of direct nuclear reactions

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Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments,
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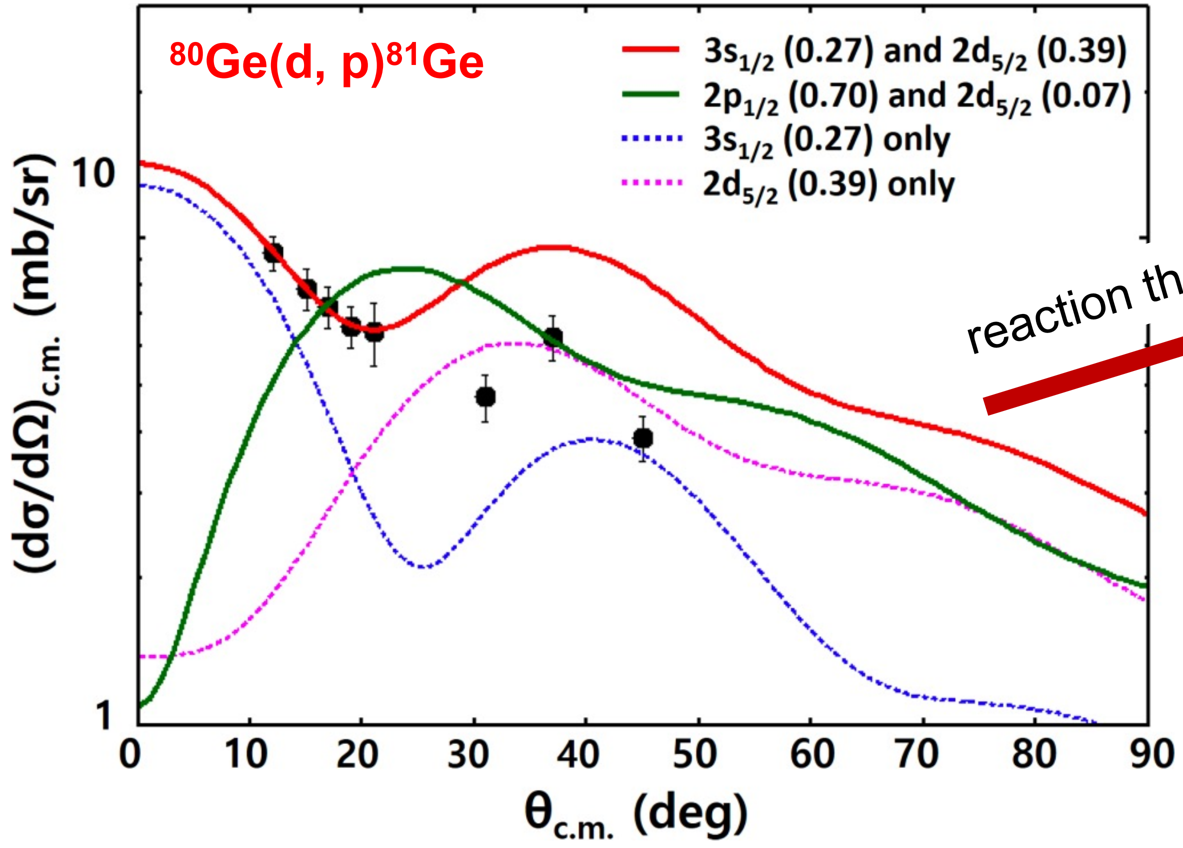
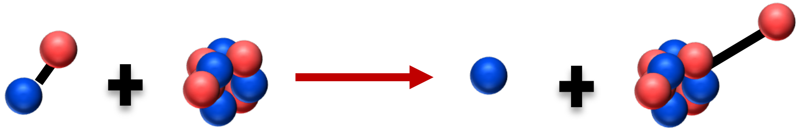
Example: deuteron-induced reactions particularly useful extracting nuclear properties, neutron capture reaction rates



reaction theory



E_x(keV)	J^π	S_{nlj}
679	$\frac{1}{2}^+$	$S_{3s\frac{1}{2}} = 0.27 \pm 0.11$
711	$\frac{5}{2}^+$	$S_{2d\frac{5}{2}} = 0.39 \pm 0.17$

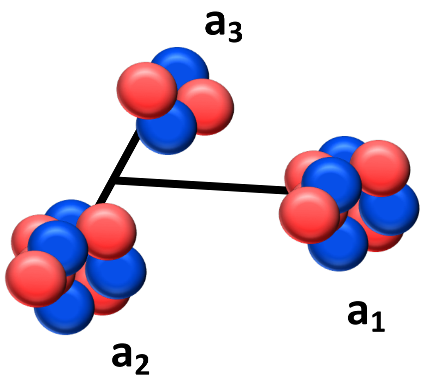
^{81}Ge energy levels

S. Ahn, PRC**100**, 044613 (2019)

An accurate reaction theory is needed to credibly structure properties

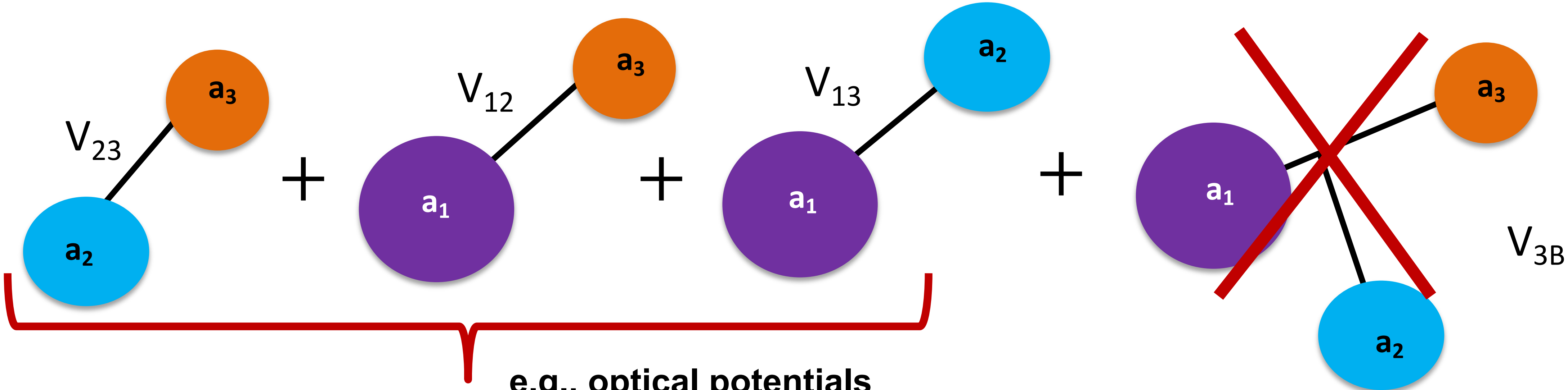
Many problem reduced onto the three-particle space by identifying relevant degrees of freedom

$$H_A \left|\Psi_A\right\rangle = E \left|\Psi_A\right\rangle$$



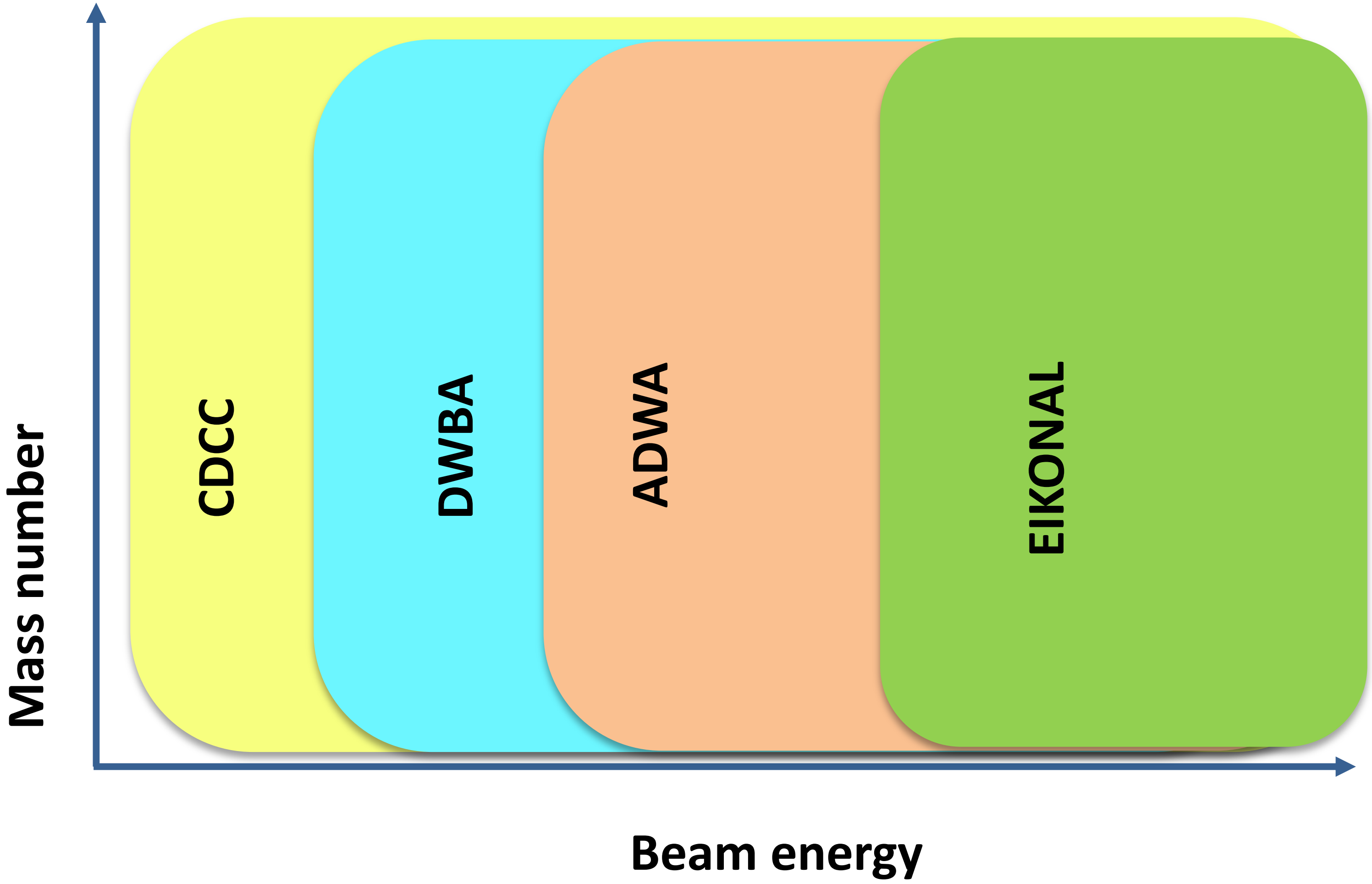
$$H_3 \left|\Psi_3\right\rangle = E \left|\Psi_3\right\rangle$$

Excitations of the cores allowed

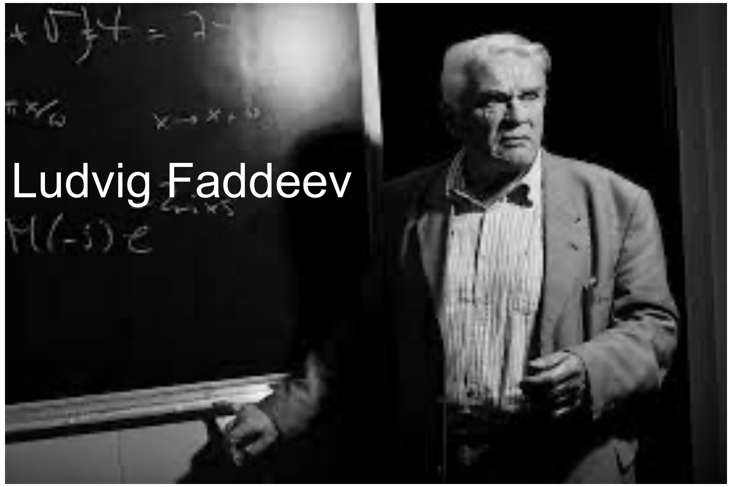


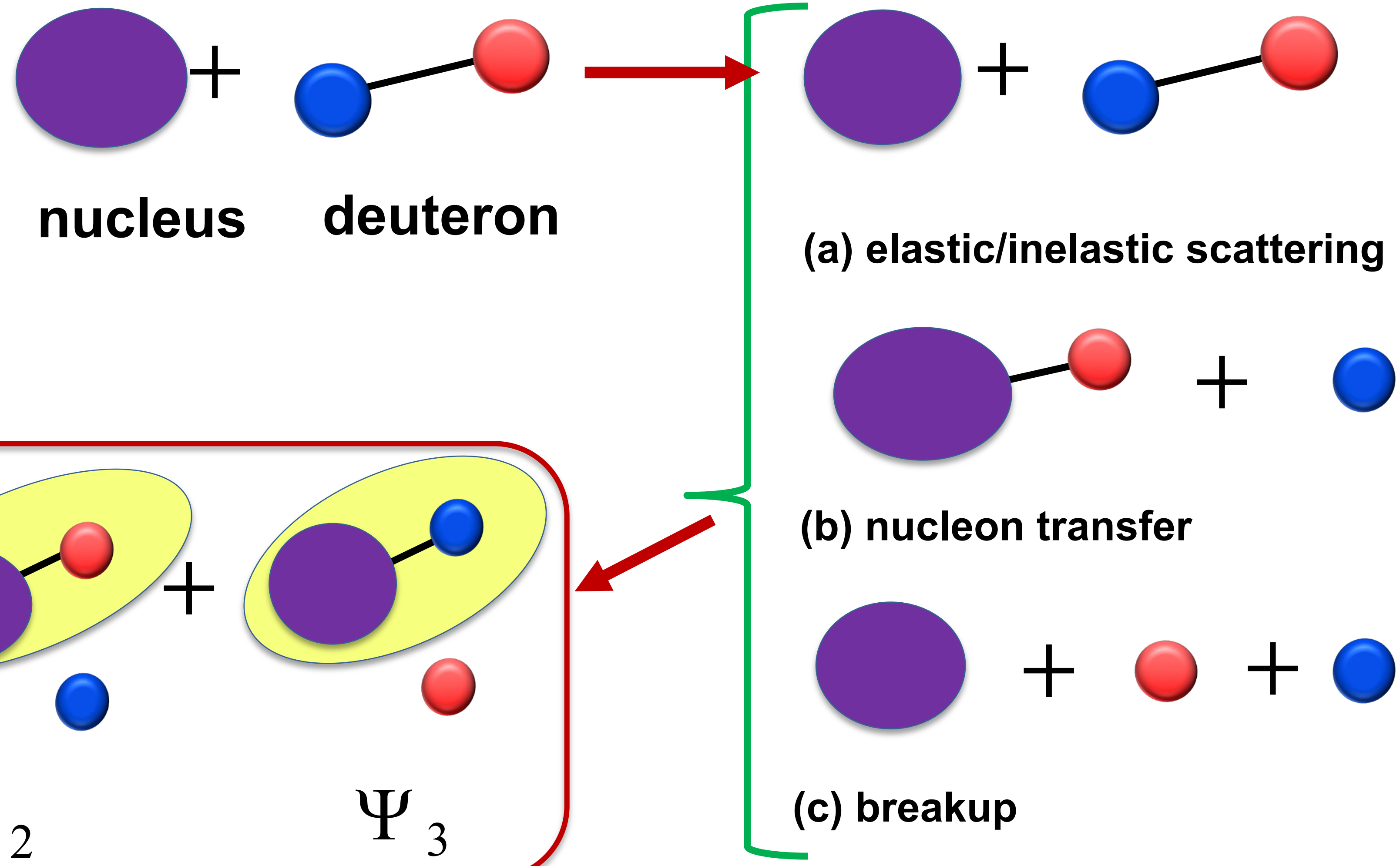
e.g., optical potentials

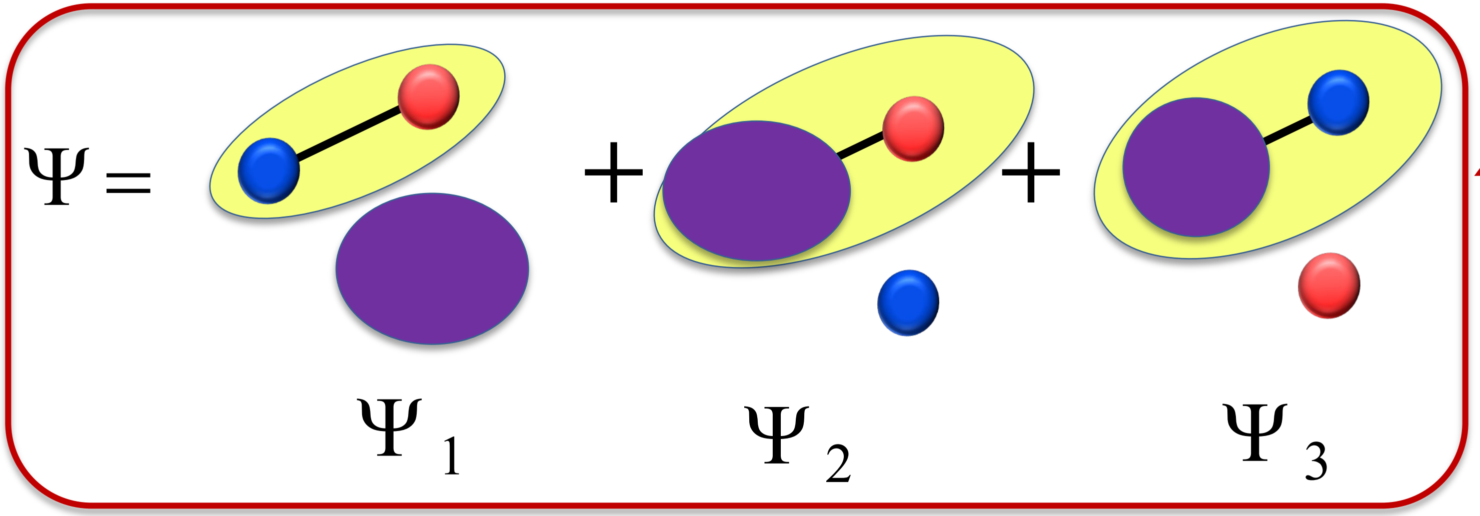
A variety of approximate techniques with a varying degrees of complexity



Exact and complete solution of three-body problem provided by Faddeev formalism

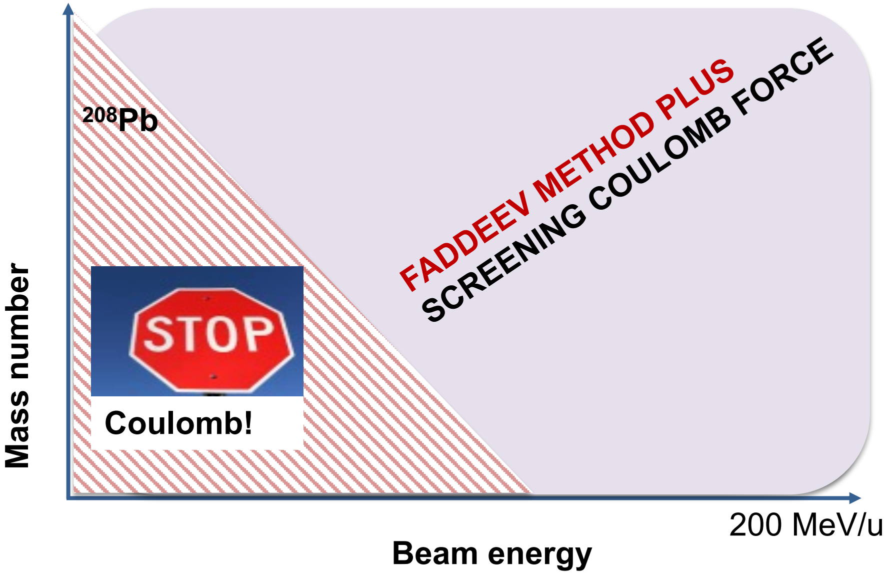




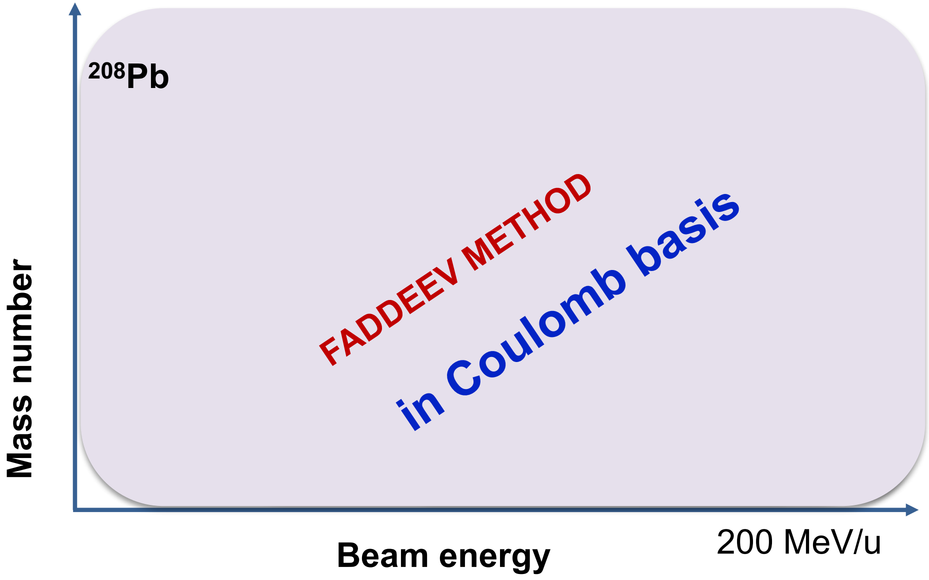


Provides exact treatment of three-body reactions

We solve the AGS formulation in a basis of momentum eigenstates and Coulomb scattering states (charged clusters <= 2)



COUL-AGS

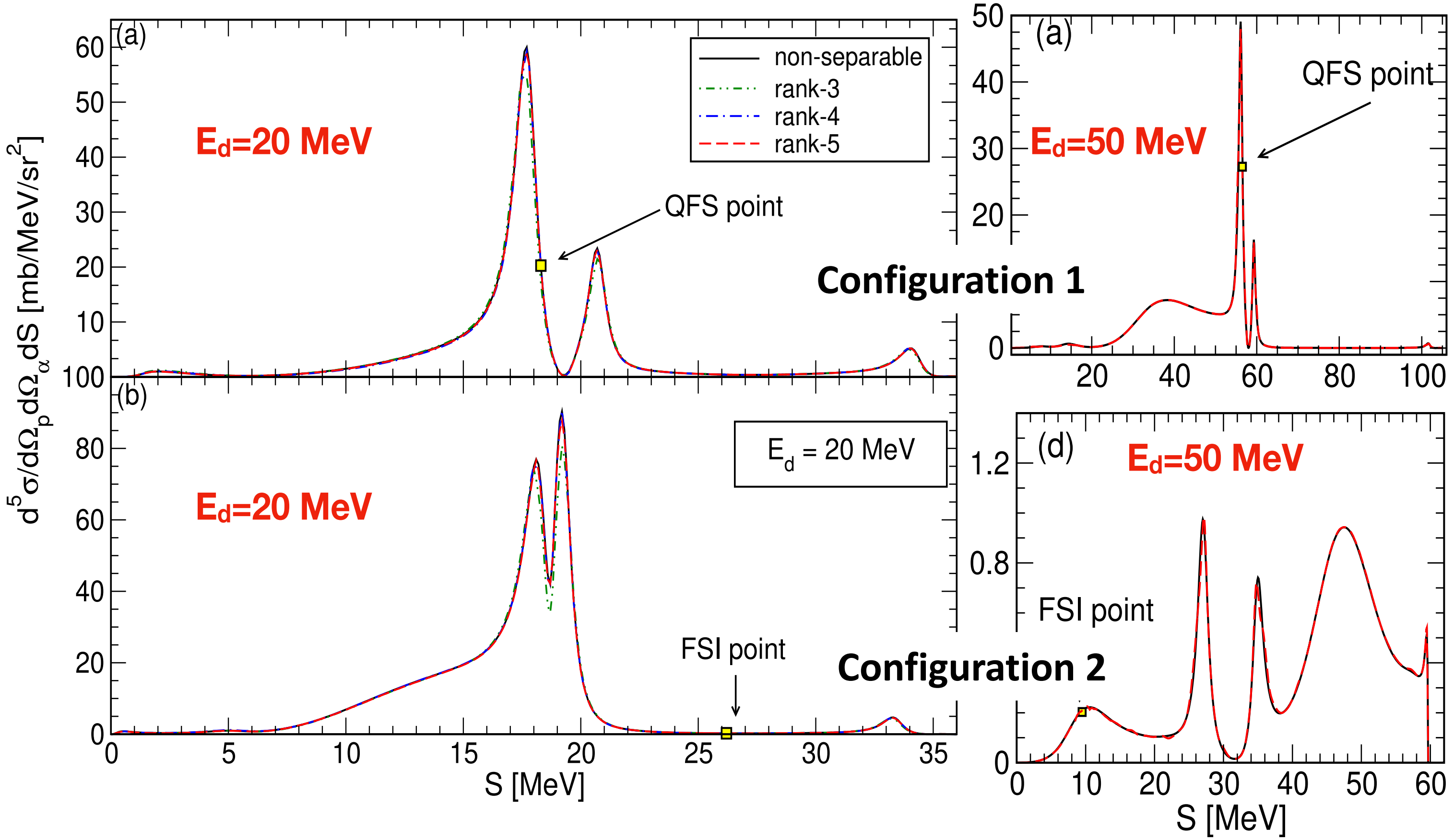


Faddeev method with exact treatment of Coulomb potential:

- ✓ Separable representation of pairwise potentials
- ✓ Treatment of complex singular integrals momentum space

Binary and ternary observables computed simultaneously and consistently

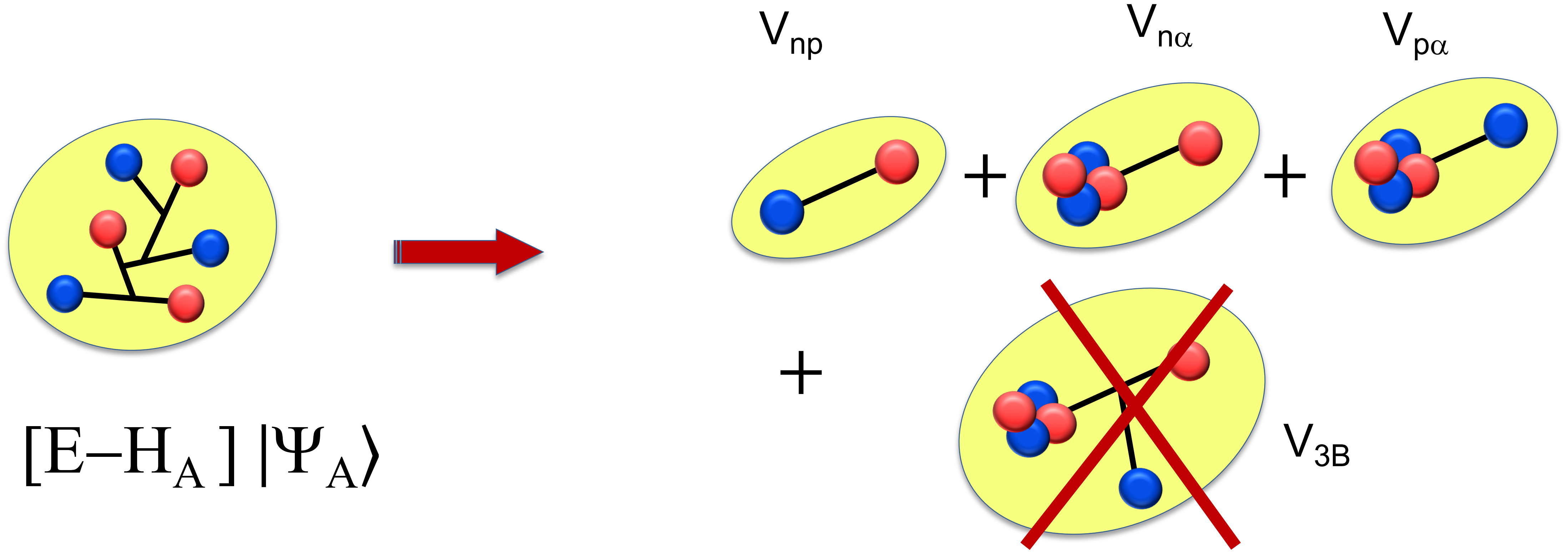
d+α cross sections



- **Elastic and inelastic scattering**
- **Transfer cross sections**
- **Breakup:** Five-fold differential cross sections for a variety A-p-n configurations

Hlophe et. al, Phys. Rev. C 100 (2019)

Grounding the few-body problem on microscopic theory

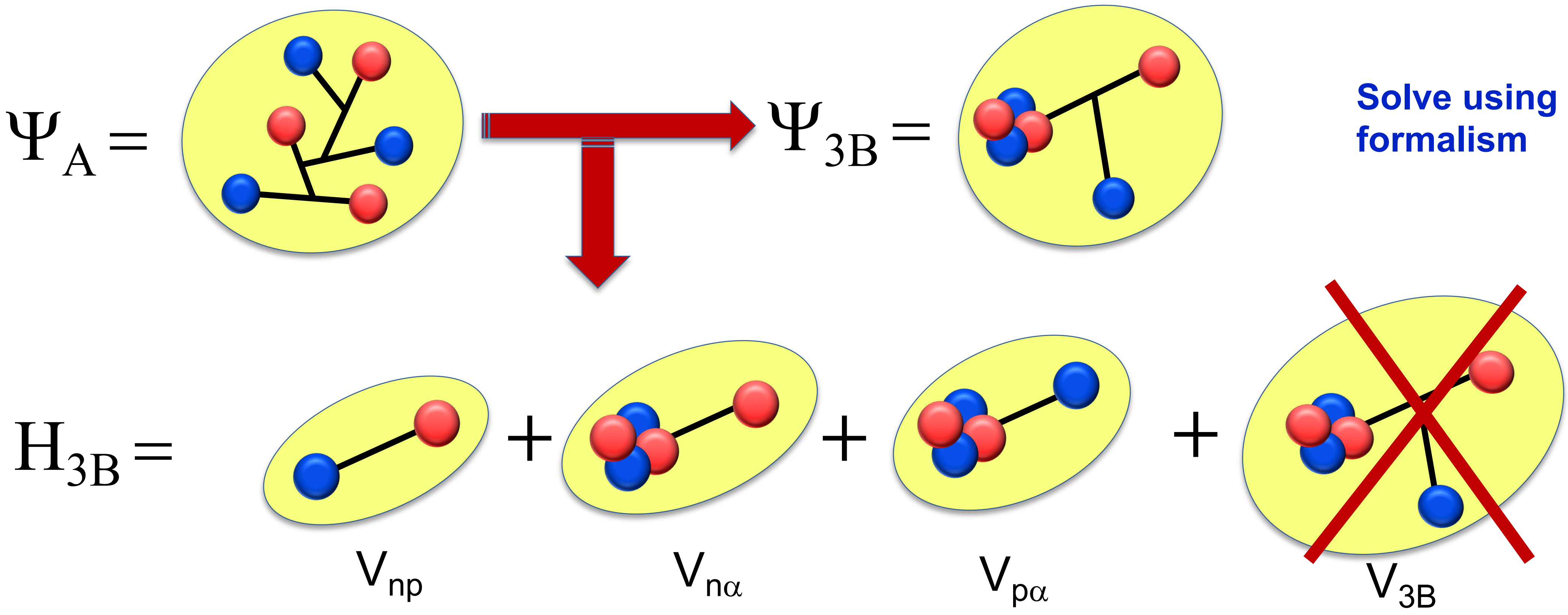


$$[E - H_A]\,|\Psi_A\rangle$$

$$[E - H_{3B}]\,|\Psi_{3B}\rangle$$

Internal cluster dynamics can be recovered by using ab initio nucleon-nucleus potentials

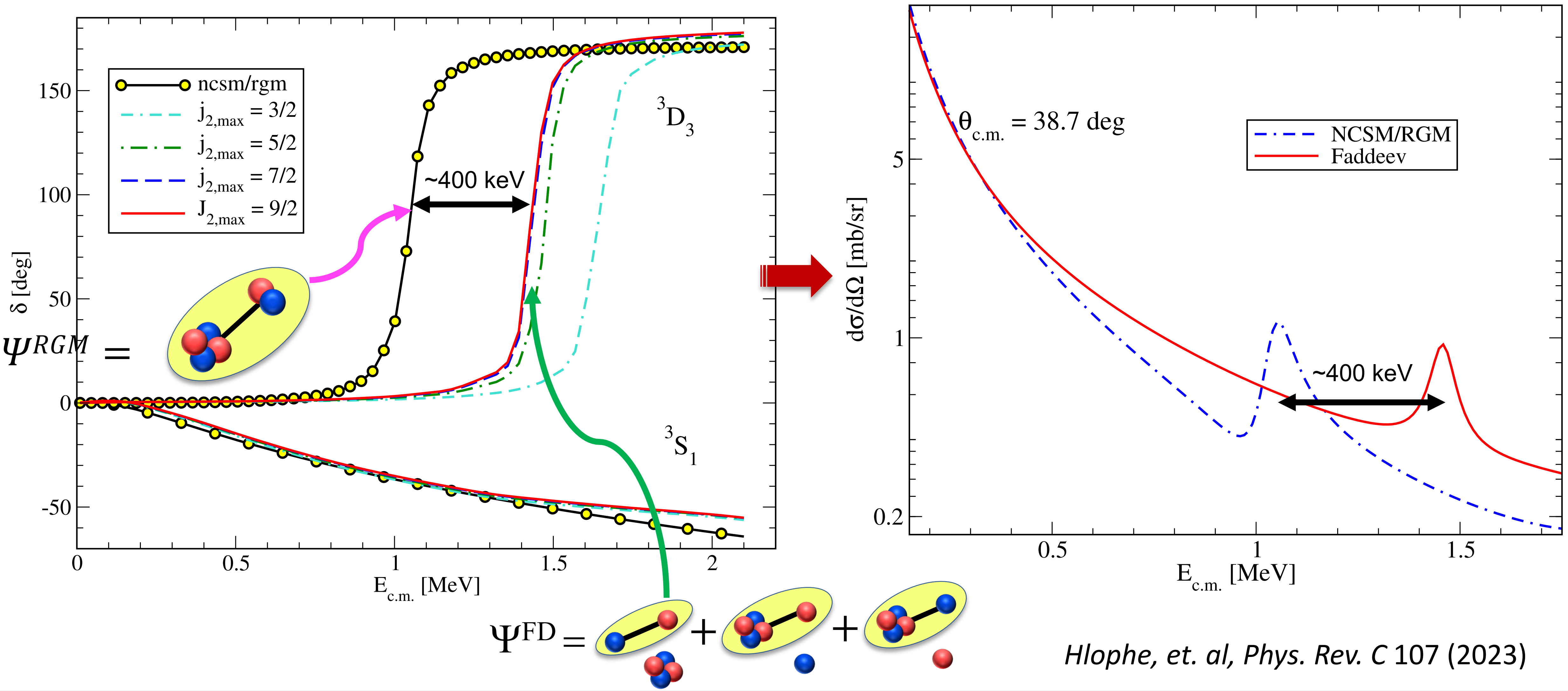
Exact and complete solution of three-body problem provided by Faddeev formalism



Solve using Faddeev formalism

Internal cluster dynamics can be recovered by using ab initio nucleon-nucleus potentials

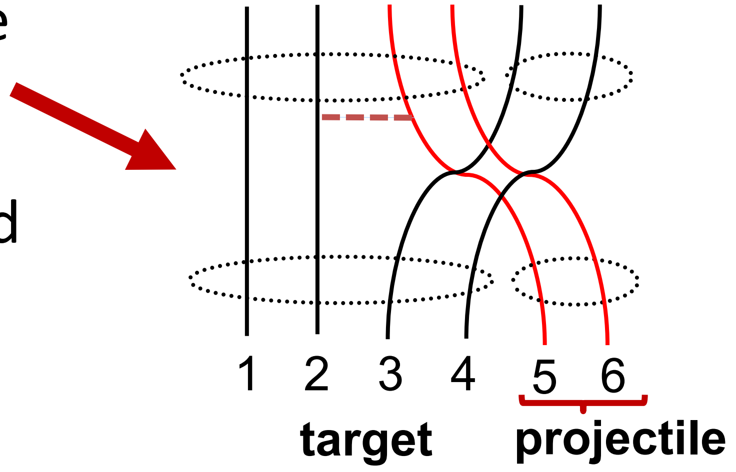
Similarly, the omission of such three-body interaction terms also shifts the position of the 3⁺ d-α resonance by ~400 keV



Hlophe, et. al, Phys. Rev. C 107 (2023)

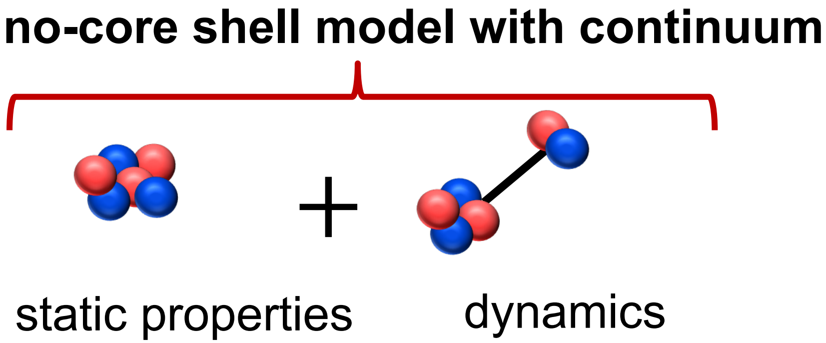
Conclusion and outlook

- The irreducible effective three-body force arising from antisymmentrization of (A+n+p)-body system has sizeable effects on d+A observables



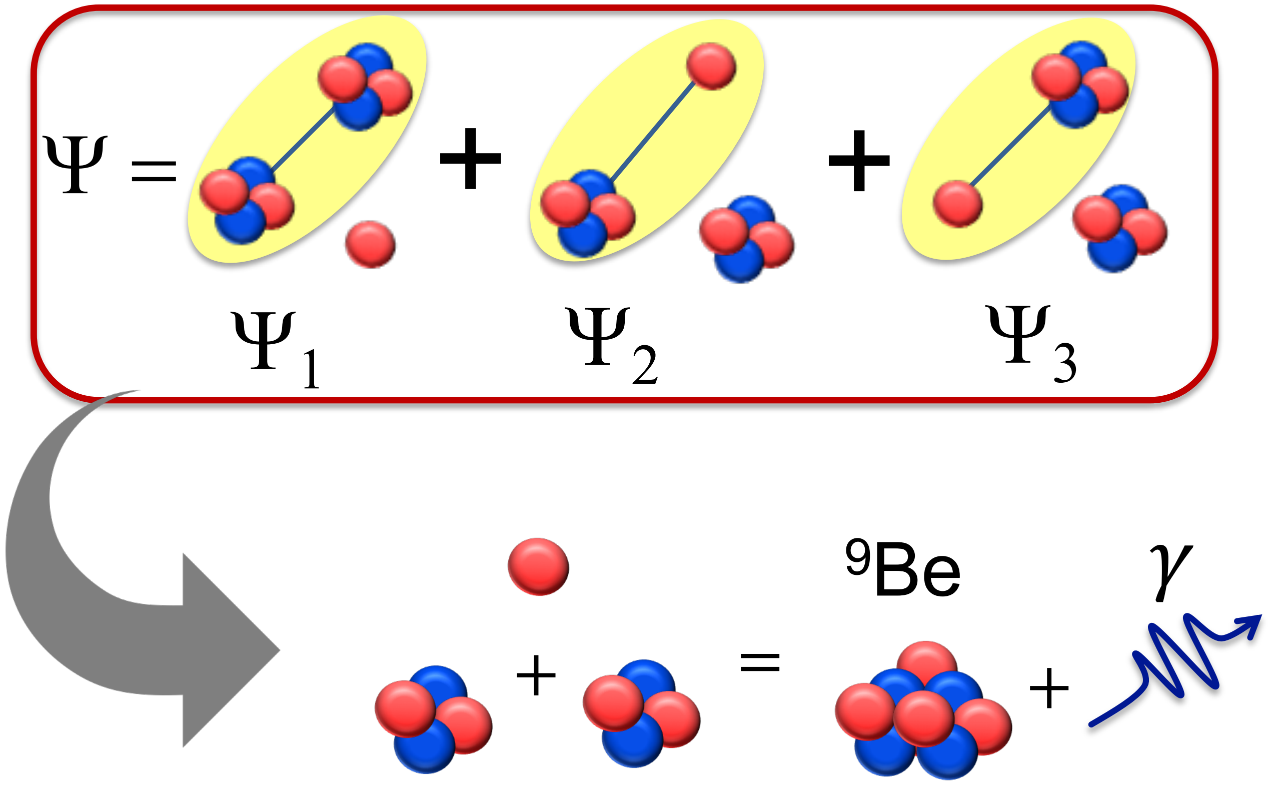
- Performing similar studies for a variety of d+A systems and higher beam energies to establish energy dependence
- Lays groundwork to derive a scheme to represent such terms using n/p-A interactions and thus improve the three-body calculations
- Use NCSMC instead of NCSM/RGM to assess effect of core excitations

$\psi^{NCSMC} =$



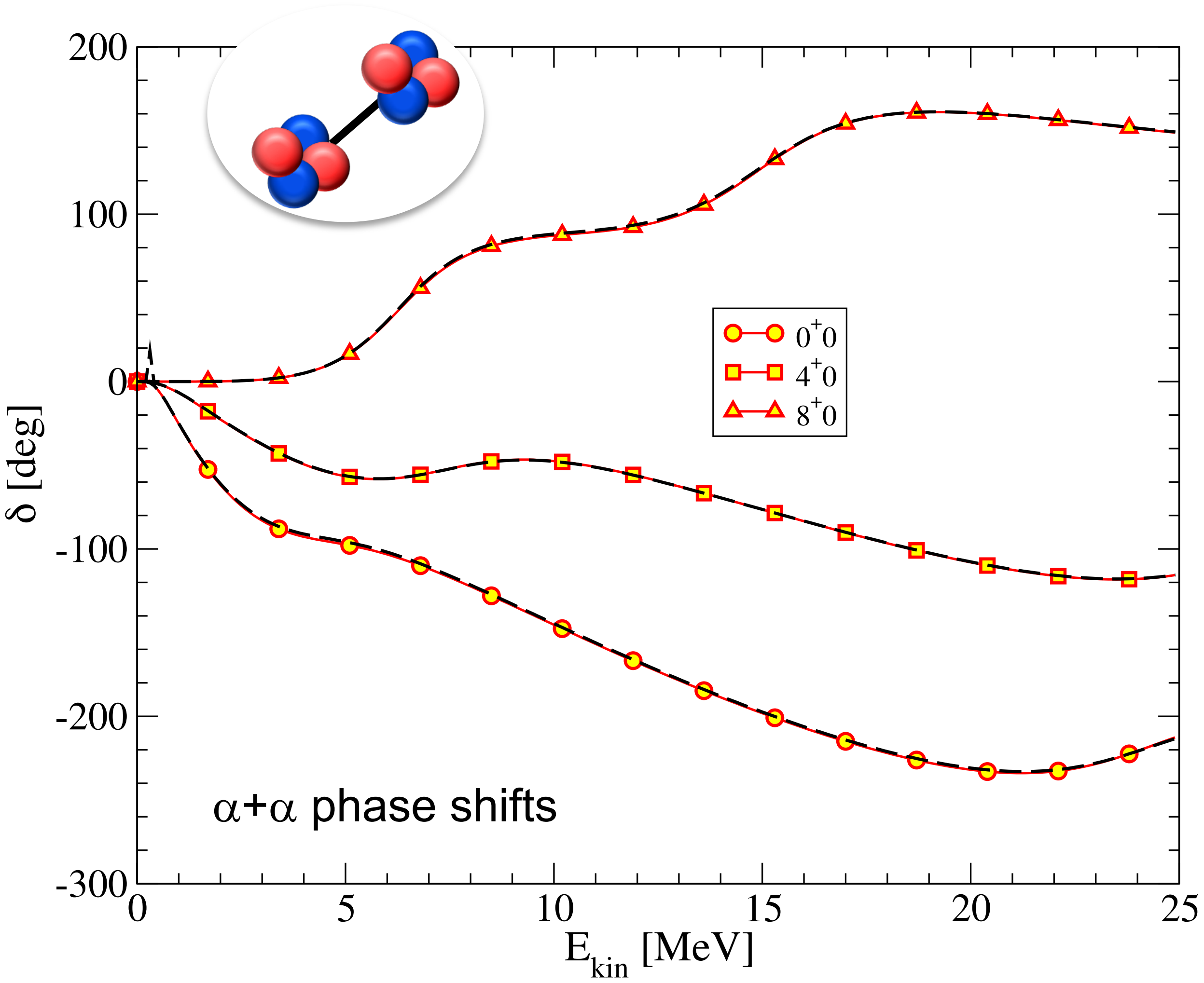
Hlophe, et. al, Phys. Rev. C 107 (2023)

Predictive microscopic theory for ternary reactions



- Compute three-body interactions from NCSMC
- Solve Faddeev equations to compute reaction rate with proper inclusion of irreducible three-body force
- Use predicted rates in r-process nucleosynthesis to predict abundances

More recent advances allow for extension to heavier projectiles, e.g., α particle

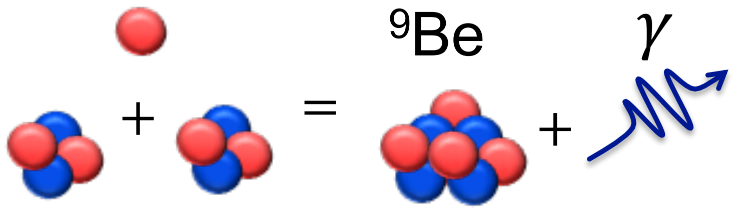


Momenutm space NCSM/RGM

vs

Microscopic r-matrix NCSM/RGM

Next: α+α+n capture cross sections



Outlook

Leveraging exact description of few-body dynamics and ab initio theory to advance the description of nuclear reactions

Faddeev framework: elastic and inelastic, scattering, transfer, breakup, capture

Application to deuteron-induced reactions: nucleon transfer, breakup

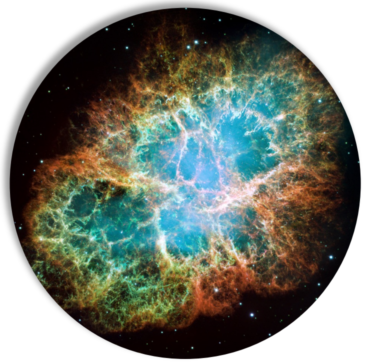
Microscopic theory to improve three-body model

Few-body universality with focus on $^{17}B(t,p)^{19}B^*$

Extension of Faddeev method to four-body continuum

Advance ab initio reaction theory for ternary reactions $\alpha(\alpha n,\gamma)^9Be$ reaction

FRIB

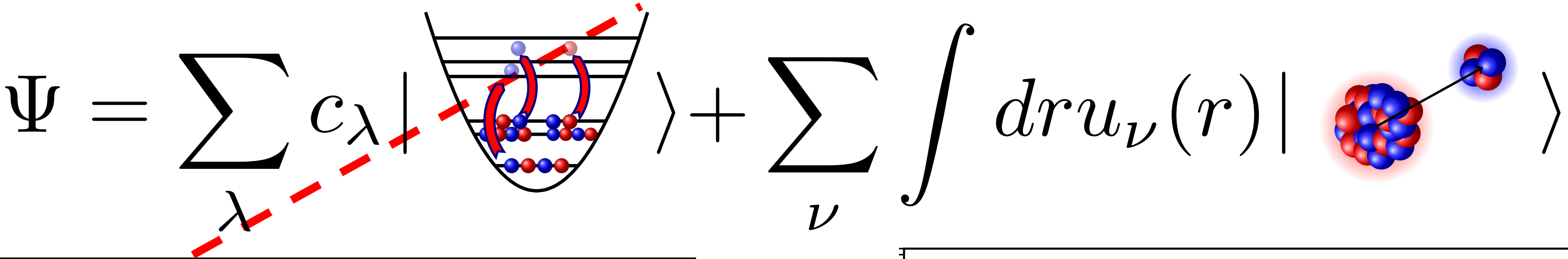


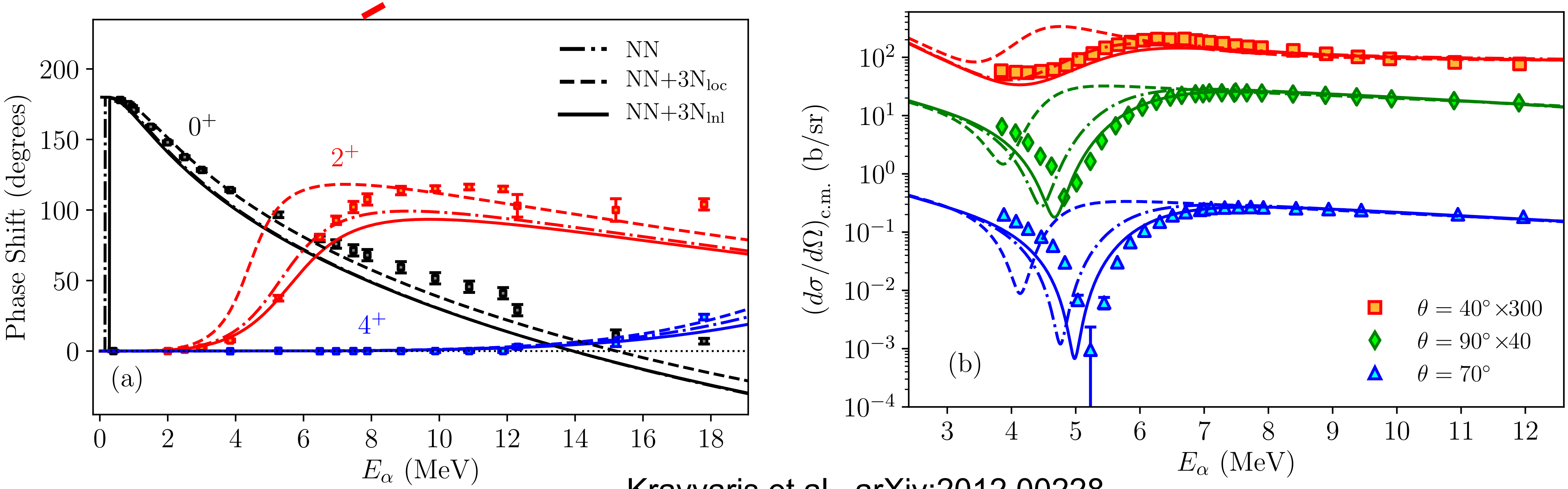
Perspectives on few-body cluster structures in exotic nuclei, Fossez et. al., arXiv:2211.06281

Thank you!

Acknowledgements: K. Kravvaris, S. Quaglioni

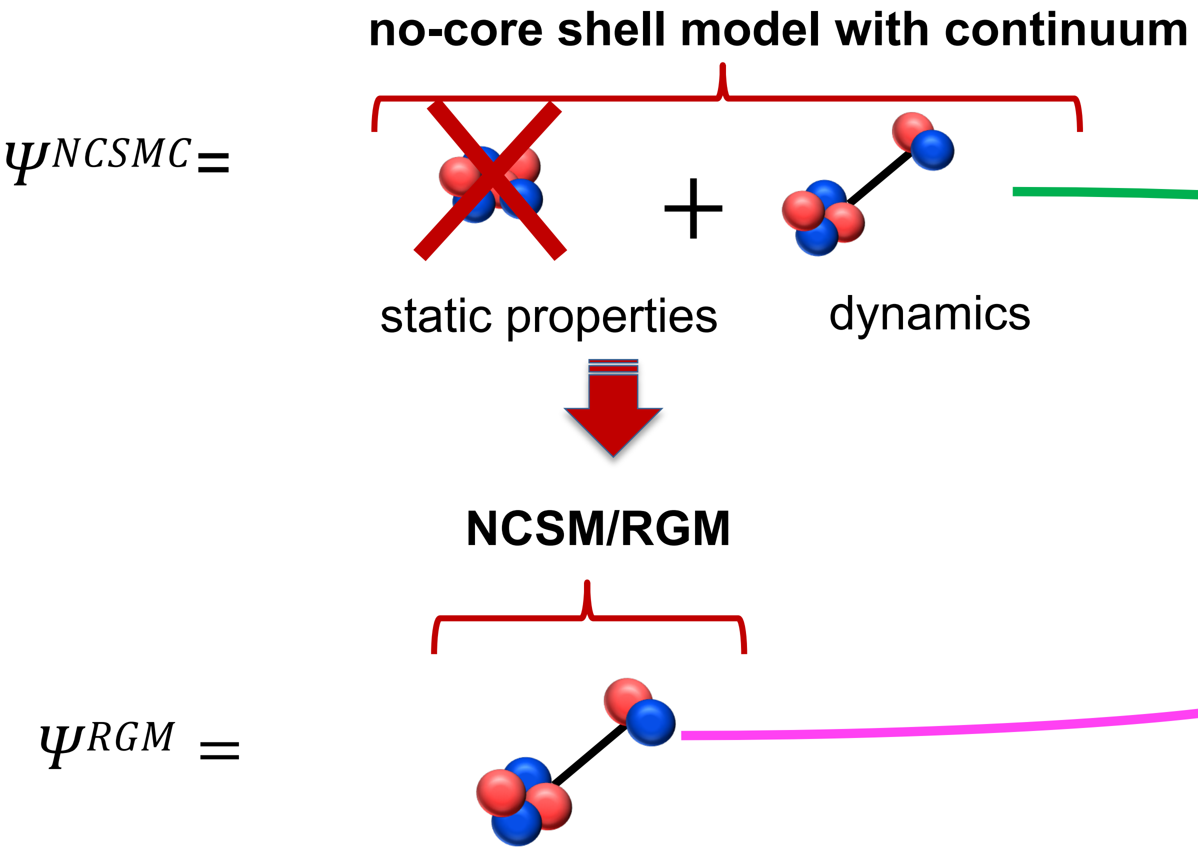
More recent advances allow for extension to heavier projectiles, e.g., α particle

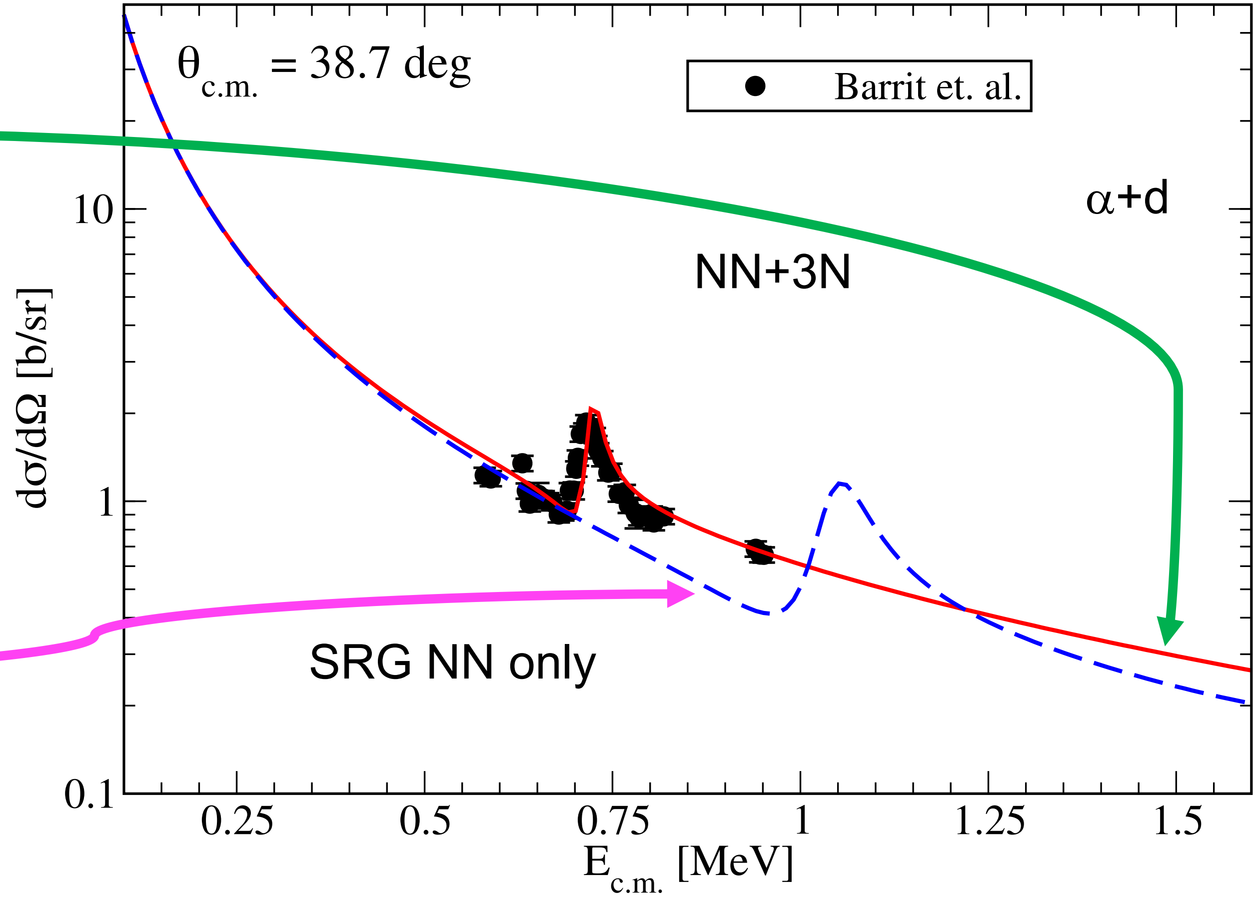




Kravvaris et al., arXiv:2012.00228

We adopt ab initio reaction theory based on the no-core shell model (NCSM) combined with the resonating group method (RGM)





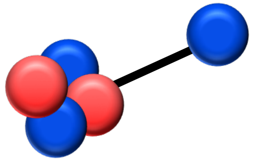
As a first step, we adopt the simpler NCSM/RGM for the present study, and only include the ^{4}He g.s.

NCSM/RGM is used to compute momentum space n/p-α potentials

- Use NSCM/RGM formalism to generate nucleon-nucleus (N-A) potentials
- Ansatz for (A+a)-body scattering wavefunction

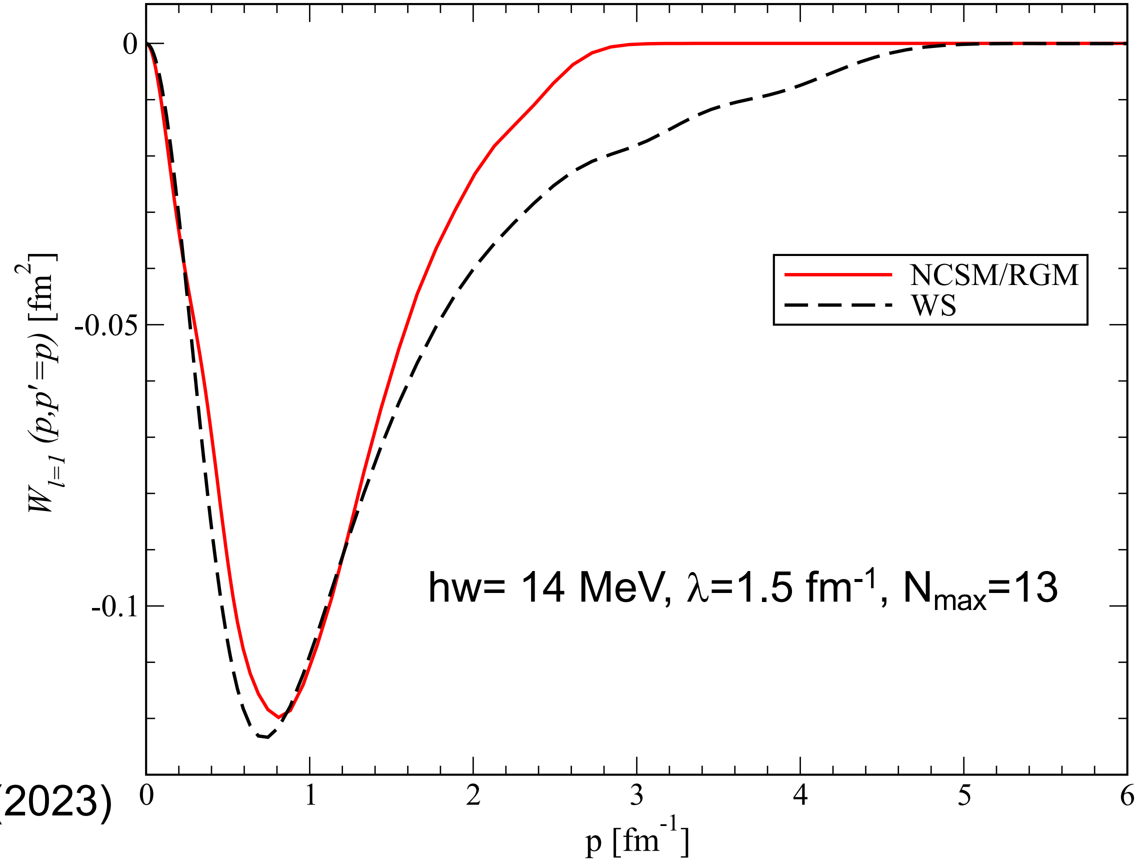
$$\left|\Psi^{J^\pi T}_{\nu_0;\,p_0}\right\rangle = \sum_\nu \int dp p^2\, \tilde{g}^{J^\pi T}_{\nu\nu_0}(p,p_0)\, \mathcal{A}\left|\Phi^{J^\pi T}_{\nu p}\right\rangle$$

Eigenstates of nuclei A and a are computed with NCSM



- Potentials generated directly in momentum space
- The n-p, n-α, p-α potentials are consistently derived from same NN interaction (N3LO)

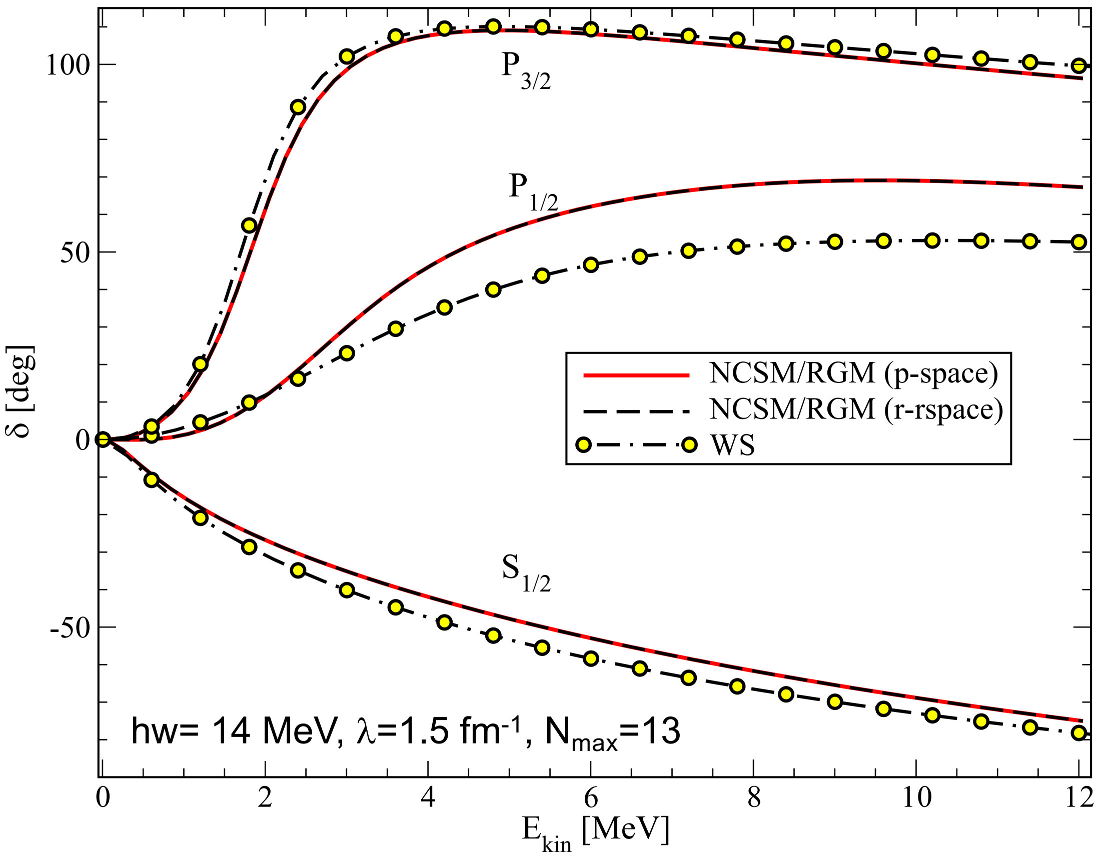
- NCSM/RGM yields real, non-local energy-independent potentials $W_{\nu'\nu}(p', p)$



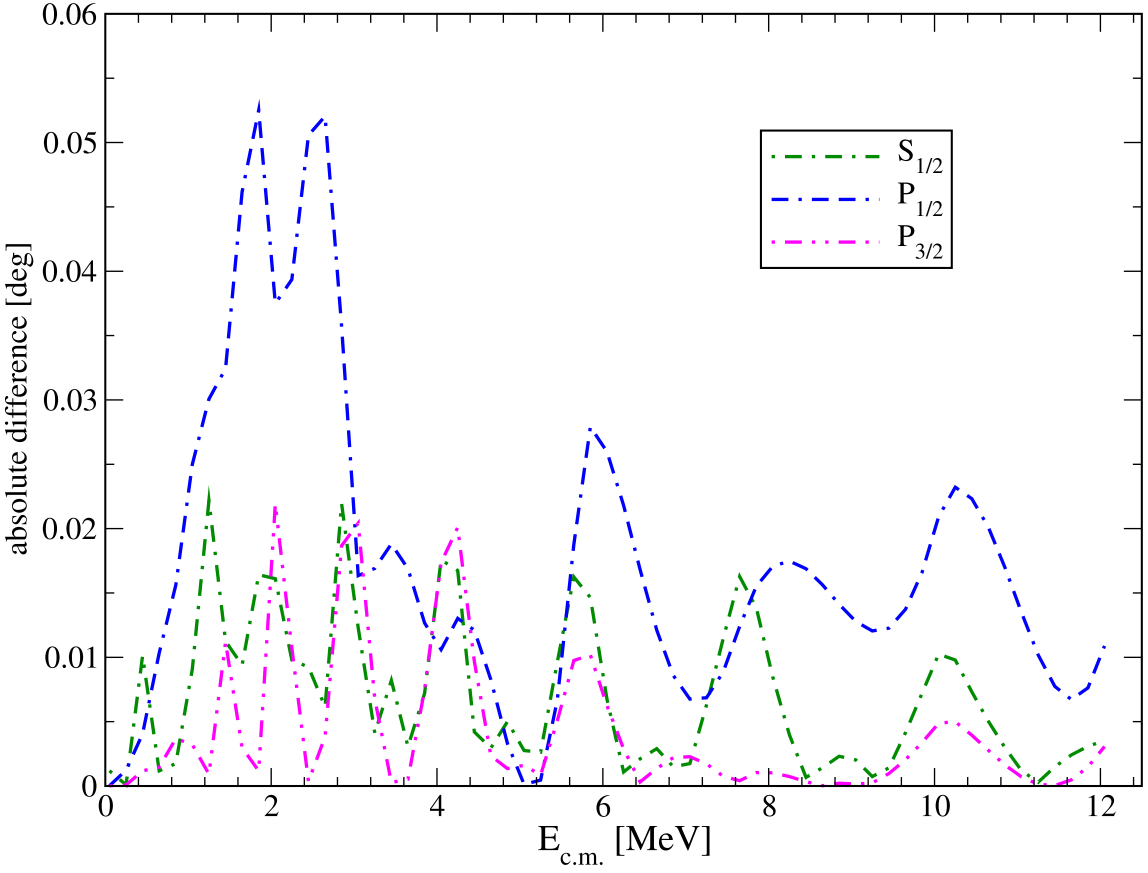
Hlophe et al., PRC**107**, 014315 (2023)

Momentum space NCSM/RGM gives the same n+α scattering phase shifts as coordinate space calculations

n+α phase shifts

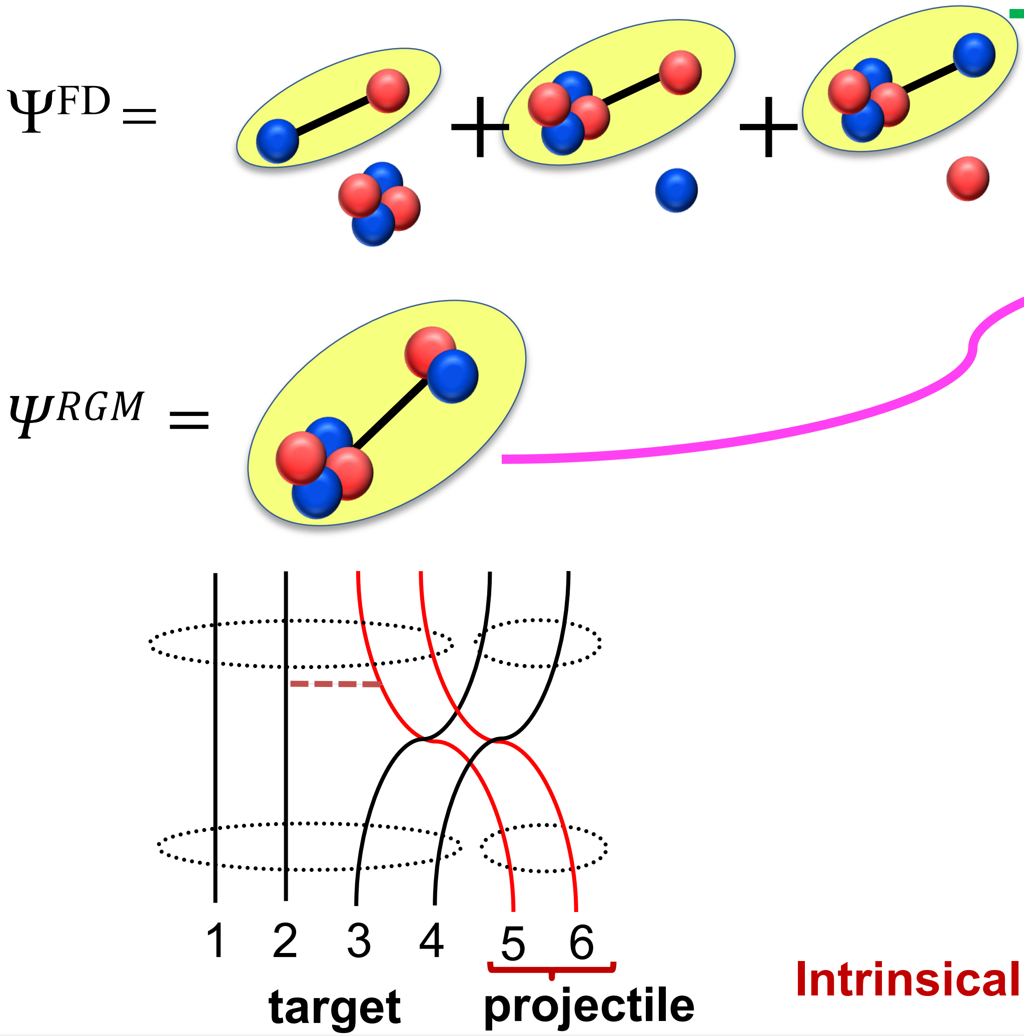


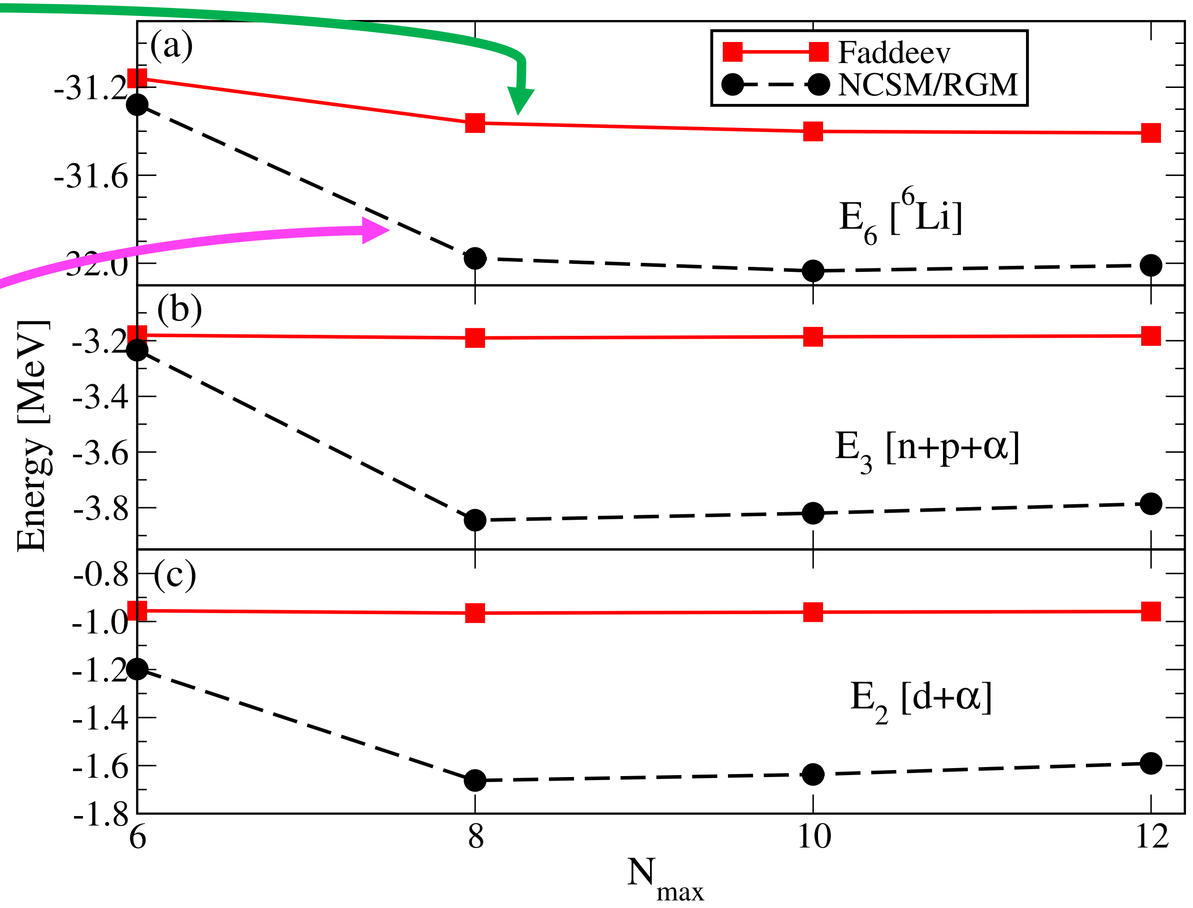
absolute difference



Hlophe et al., PRC**107**, 014315 (2023)

The omission of 'exchange' three-body interaction terms causes ~600 keV underbinding for the ^{6}Li ground state





Intrinsically three-body terms not captured in pairwise potentials!

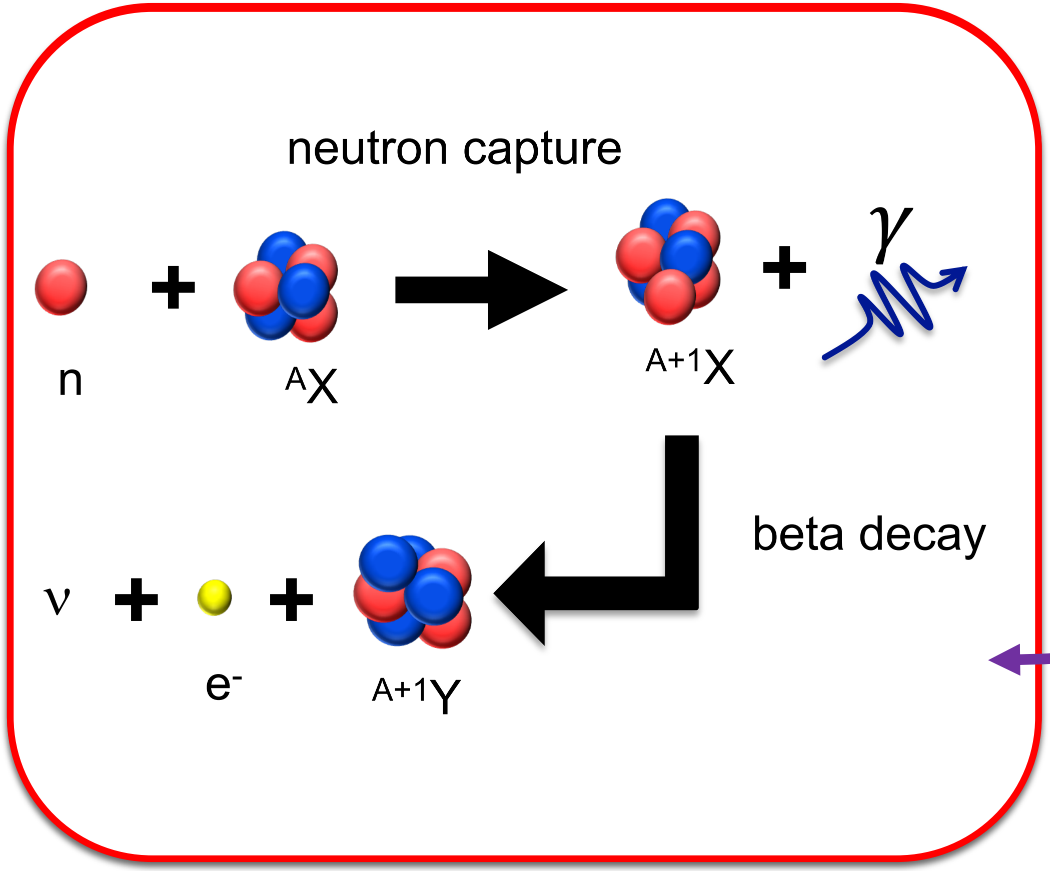
Faddeev

N_{max}	5	7	9	11	13
$E(^6Li)$ [MeV]	-30.610	-31.160	-31.363	-31.401	-31.408

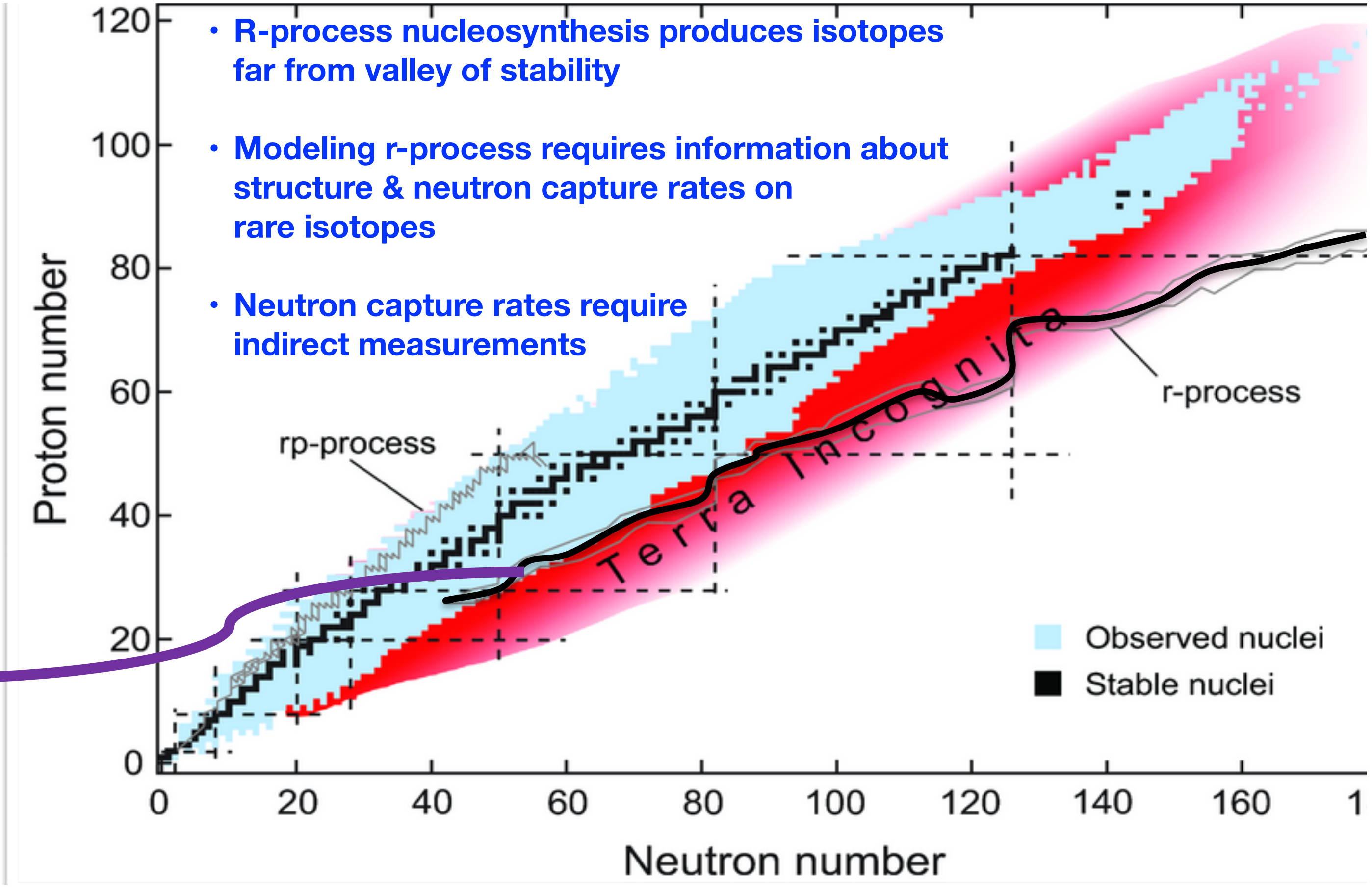
N_{max}	5	7	9	11	13
$E_3(^6Li)$ [MeV]	-3.334	-3.180	-3.190	-3.186	-3.183

N_{max}	5	7	9	11	13
$E(^4He)$ [MeV]	-27.276	-27.983	-28.173	-28.214	-28.224

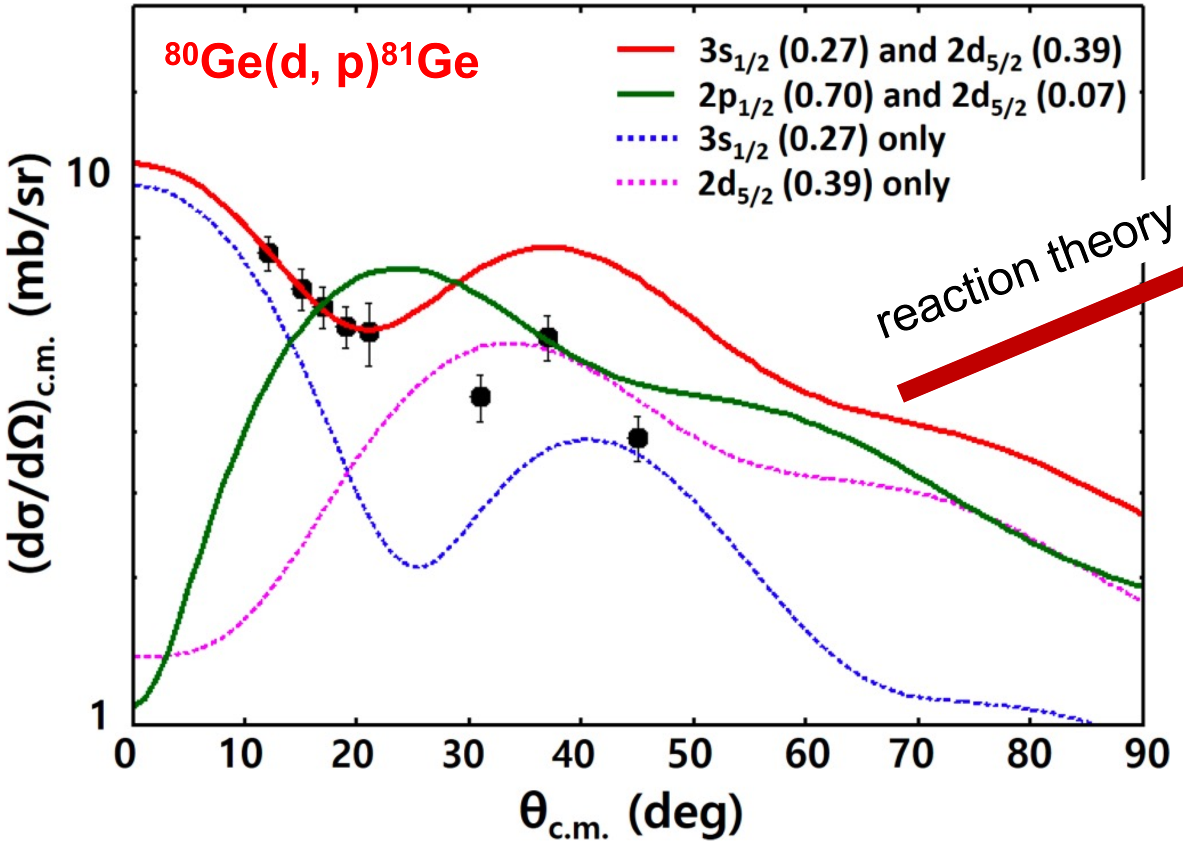
Astrophysics: r-process abundances simulated using nuclear properties as input, e.g., neutron capture rates



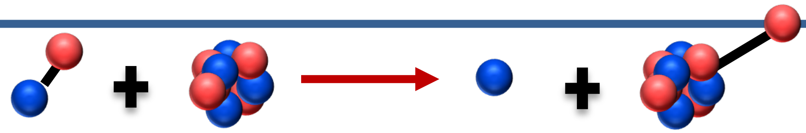
- R-process nucleosynthesis produces isotopes far from valley of stability
- Modeling r-process requires information about structure & neutron capture rates on rare isotopes
- Neutron capture rates require indirect measurements



Example: deuteron-induced reactions particularly useful extracting nuclear properties, neutron capture reaction rates



reaction theory



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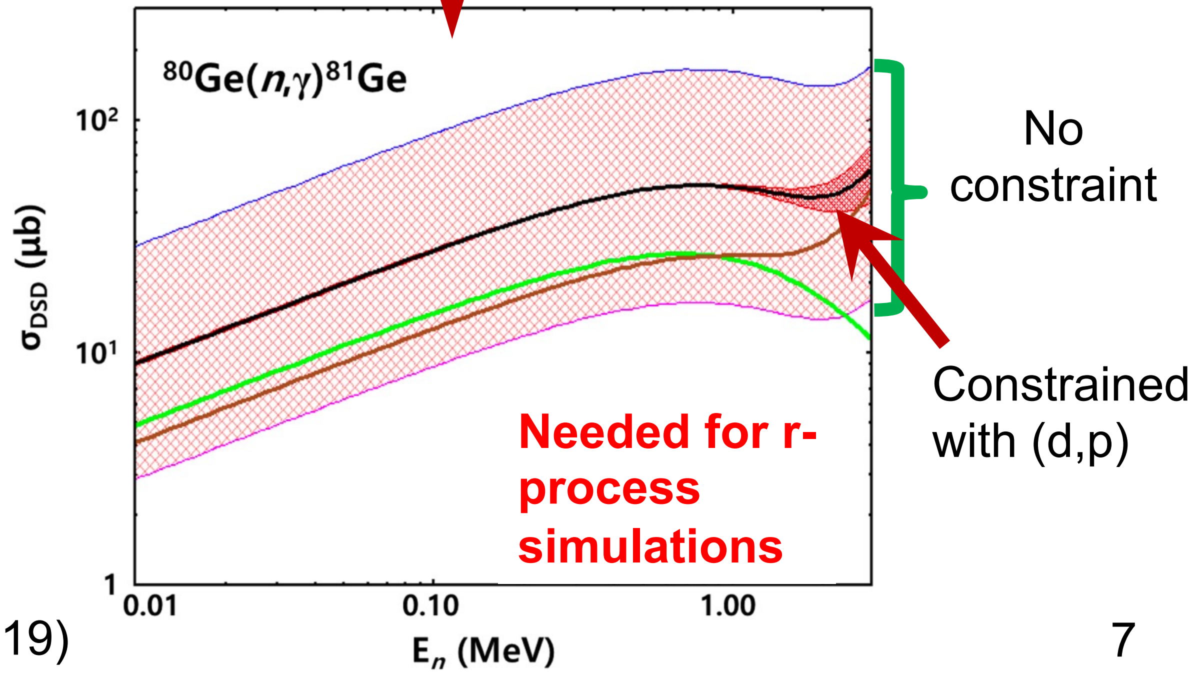
^{81}Ge energy levels



S. Ahn, PRC**100**, 044613 (2019)

An accurate reaction theory is needed to credibly constrain (n,γ) reaction

NCSM/RGM

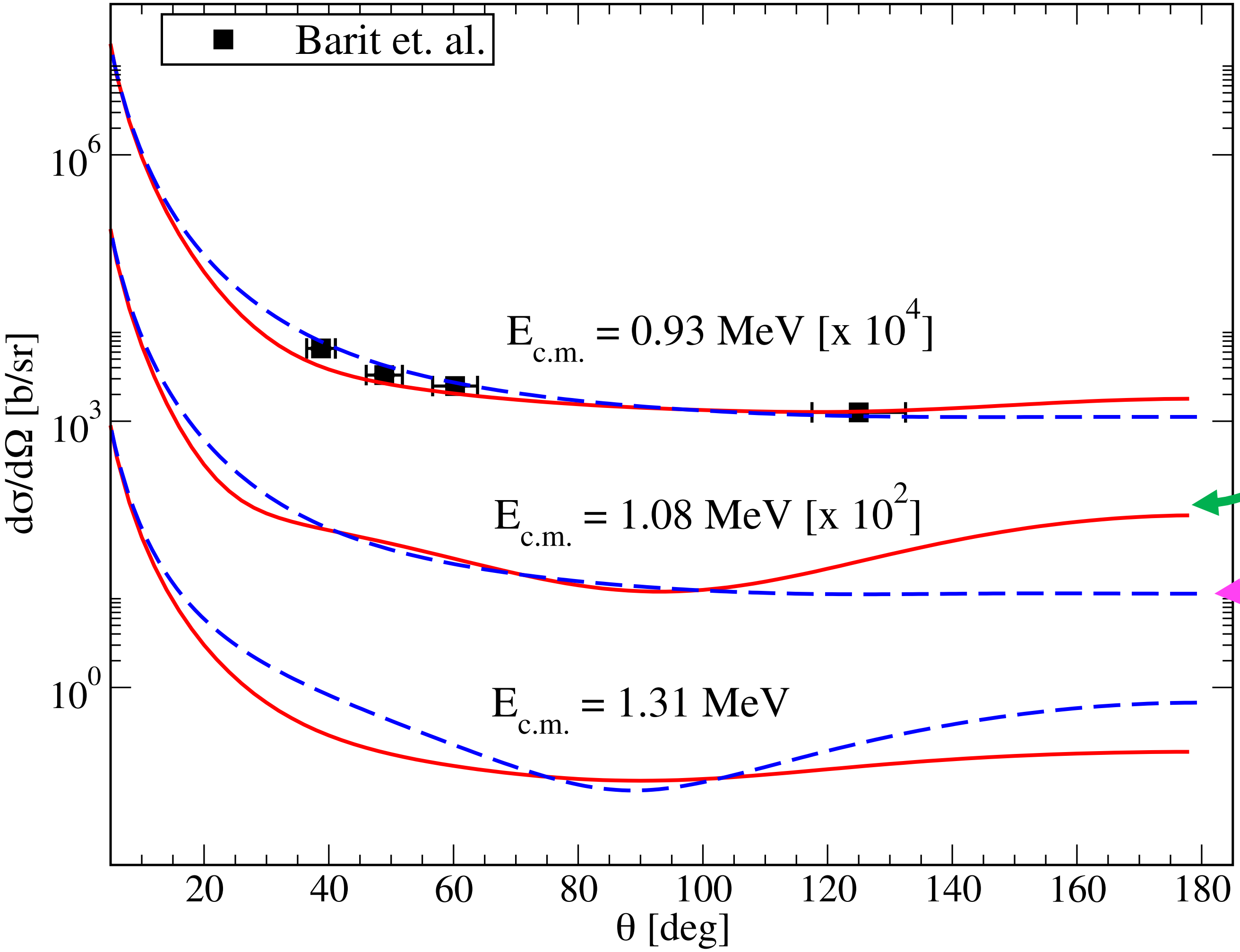
N_{max}	6	8	10	12
$E(^4He)$ [MeV]	-27.983	-28.173	-28.214	-28.224

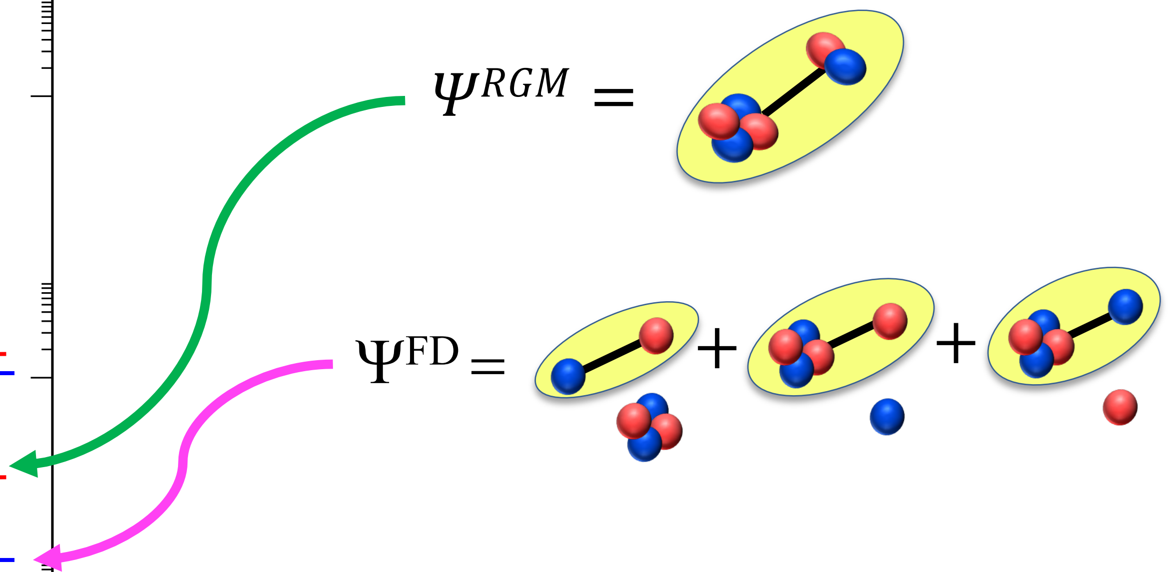
N_{max}	6	8	10	12
$E(^2H)$ [MeV]	-2.098	-2.143	-2.183	-2.195

N_{max}	7	9	11	13
$E_2(d\text{-}\alpha)$ [MeV]	-1.198	-1.662	-1.637	-1.591

N_{max}	7	9	11	13
$E_3(n\text{-}p\text{-}\alpha)$ [MeV]	-3.234	-3.845	-3.820	3.786
N_{max}	7	9	11	13
$E(^6Li)$ [MeV]	-31.279	-31.978	-32.035	-32.009

The shift in the 3+ resonance leads to a change in shape for the angular differential cross section





Shape of differential cross section differ appreciably for the two approaches

Three-body model for d+α problem is revisited using potentials derived from ab initio reaction theory

Use NSCM/RGM formalism to generate nucleon-nucleus (N-A) potentials

- Start from (A+1)-body Hamiltonian
- NN interactions from χ-EFT and SRG evolved to improve convergence
- Expand wavefunction in basis

$$\Psi = \sum_{\nu} \int dr u_{\nu}(r) | \quad \rangle$$

Eigenstates of nucleus A computed with NCSM

- The n-p, n-α, p-α potentials are consistently derived from same NN interaction → ambiguity of phenomenological fits is avoided

n-α phase shifts