# Recent progress and future perspectives in the theory of direct reactions and exotic nuclei

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# Thank you for your input!

- Alexandra Gade
- Augusto Macchiavelli
- Antonio Moro
- Filomena Nunes
- Nigel Orr
- Ian Thompson

**How did visible matter come into being and how does it evolve?**

**How does subatomic matter organize itself and what phenomena emerge?**

**Are the fundamental interactions that are basic to the structure of matter fully understood?**

**How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?**

**Reactions are one of the most diverse probes in nuclear physics**

**Reactions will continue to be an integral part of science programs addressing these big questions**

**Reliable reaction theory is an essential ingredient to extract most of the desired information**

U.S. National Research Council decadal survey
“Nuclear Physics: Exploring the Heart of Matter”
http://www.nap.edu/catalog/13438

# Probing the structure of nuclei near the driplines

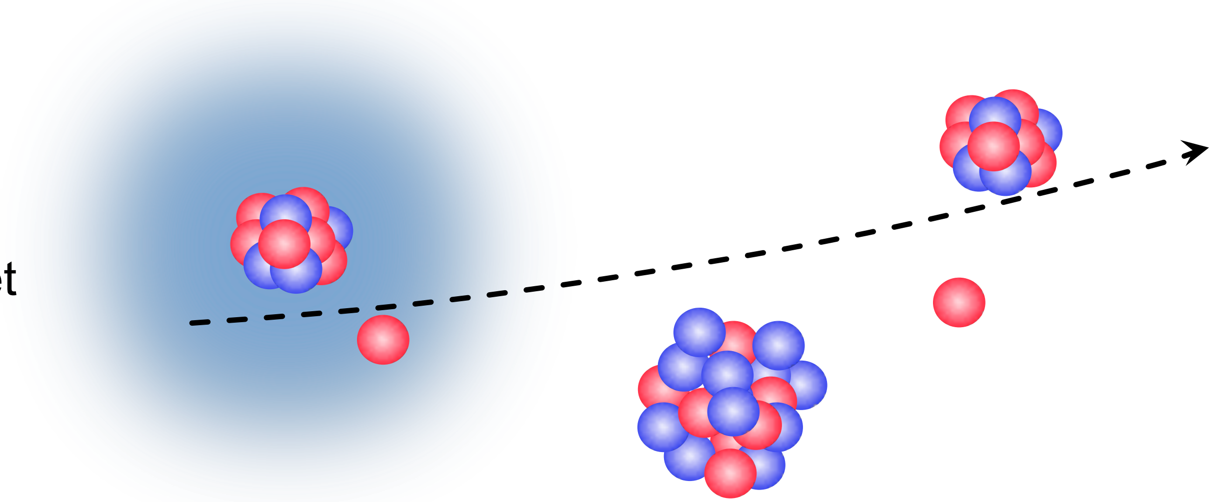
## Direct Reactions …

- Nuclei make 'glancing contact' and separate immediately
- Only few degrees of freedom modified in the process, retain recollection of initial state
- Dominance of single-particle properties over dynamical effects

## … with exotic nuclei

- Weakly bound, short-lived, unstable nuclei (inverse kinematics)
- Halo structures

**e.g.:** collision of a halo nucleus with a target



# A wide array of reaction data …

1) **Elastic Scattering**: projectile and target remain in their ground state

2) **Inelastic Scattering:** projectile and/or target left in excited state

3) **Elastic/Inelastic Breakup Reactions**: projectile breaks into 2 or more fragments leaving target in ground (elastic)/excited (inelastic) state
   - **Knockout Reactions:** removal of one or more projectile nucleons

4) **Transfer Reactions:** transfer of one or more nucleons between projectile and target (bound/unbound final state)

5) **Charge-Exchange Reactions:** projectile/target mass numbers remain the same, but atomic numbers change. Can be 'elastic' or 'inelastic'.

6) **Capture/Decay Processes**: $\gamma$-emission of final-state nucleus

7) **Fusion Reactions:** nuclei stick together (usually not thought as direct)

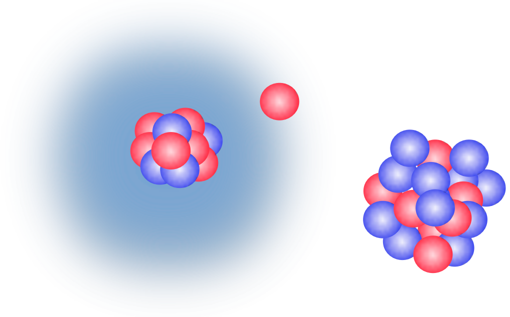
# … allows to probe a variety of properties

- Single-particle behavior (transfer, inelastic, breakup)
- Collective behavior (inelastic)
- Halos (transfer, breakup, knockout)
- Reactions important for astrophysics, national security
  - Direct measurements
  - Indirect measurements: e.g., (d,N) transfer to unbound state as a means to (p,$\gamma$) and (n,$\gamma$) cross sections on unstable nuclei

**Need theory to interpret reaction data and extract desired properties**

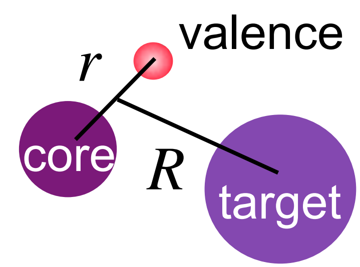
# Our problem: quantum mechanical scattering. The 'fundamental' and the 'pragmatic' solution

## Microscopic Theory



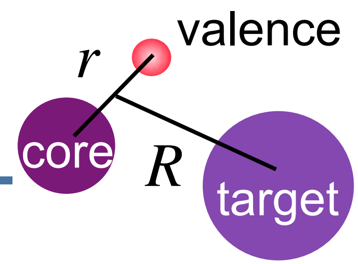
- A nucleon degrees of freedom
- 'Realistic'/effective nucleon-nucleon (NN) and three-nucleon (3N) forces
- Pauli principle treated exactly
- Extremely difficult to solve
  - **'Realistic' NN(+3N) int.:** 'Exact' for A = 3,4; ab initio up to A~12
  - **Effective NN int.**: applications up to A~20

## Few-Body Model



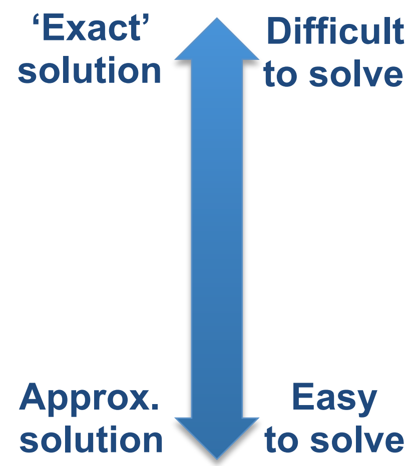

- Few (3 or 4) relevant 'cluster' d.o.f.
- Structure of clusters is neglected
- Phenomenological (optical) potential between core, valence and target
- Pauli principle approximated
- 'Easier' to solve, more widely applicable

# Few-body models




## Some of the challenges:

- Accurate solution of few-body scattering problem
  - Faddeev, Alt-Grassberger-Sandhas (AGS) equations
  - Hyperspherical Adiabatic (HA) expansion method
  - Continuum-Discretized Coupled Channels (CDCC)
  - Adiabatic Distorted-Wave Approximation (ADWA)
  - Semi-classical approximations (Eikonal+variants)
  - Distorted-Wave Born Approximation (DWBA)

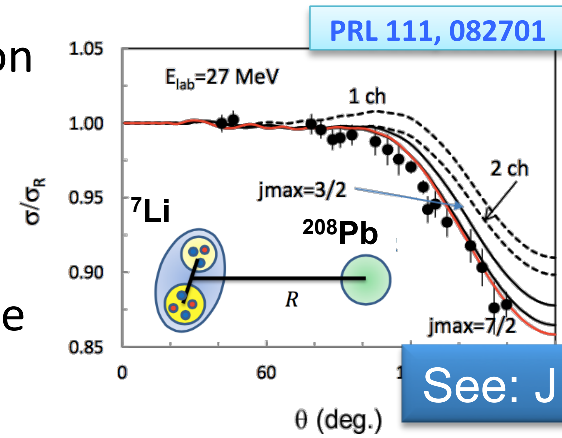


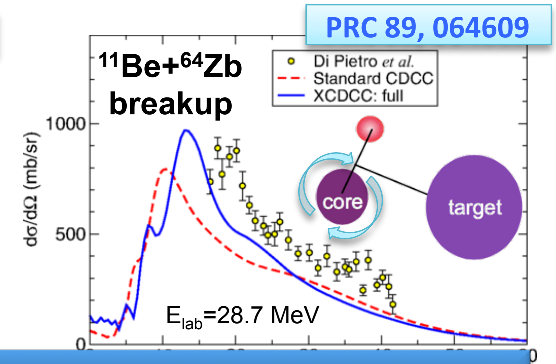

- How to connect back to the many-body problem?
  - More realistic description of projectile
  - More realistic, more accurate inter-cluster interactions

# Some illustrative examples

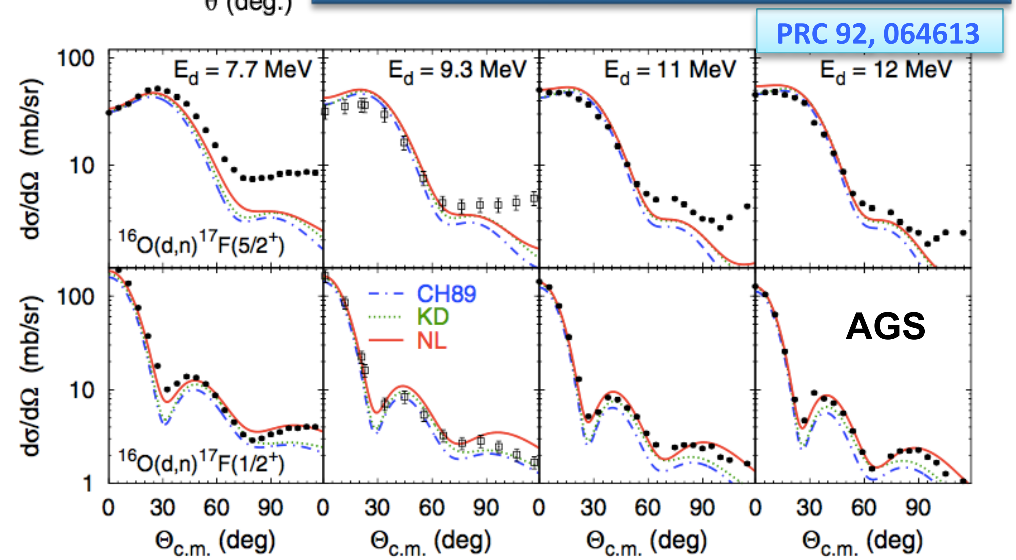
# Few-body models are being extended to arrive at a more realistic description of the projectile …

- CDCC with microscopic description of projectile
  - Core excitations ‘automatic’
  - Elastic, inelastic scattering
- CDCC with deformed valence-core & core-target potentials
  - Elastic scattering & breakup
- Faddeev/AGS with excited states of the core
  - Elastic, inelastic, transfer reactions
- Extension of DWBA to include dynamic core-excitation effects
  - Transfer reactions
- Prospect/Challenge:
  - More microscopic core excitations



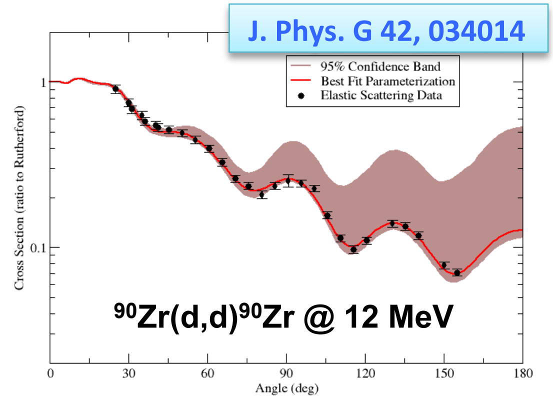

See: J. Lay, M. Gomez-Ramos



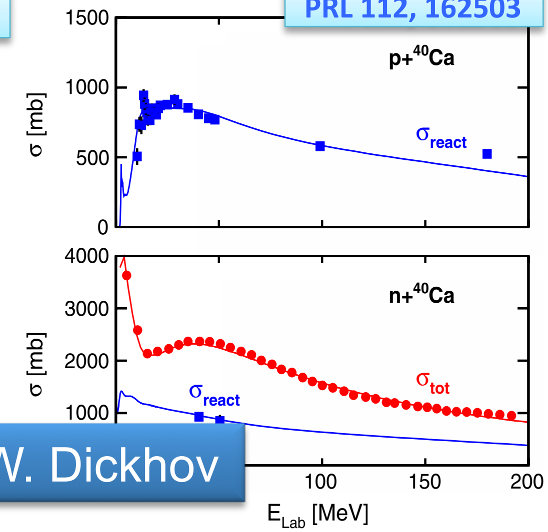
# … and efforts are under way to arrive at quantified, more realistic optical potentials

- Error quantification in few-body reaction models
  - Optical potential largest uncertainty
- Non-local nucleon self-energy links reactions with structure
  - Dispersive optical model (DOM) potentials fitted to available data
- (Non-local) Microscopic optical potentials are being developed from QCD-routed NN+3N forces
  - Many-body perturbation theory
  - Coupled Cluster
- Effect of non-locality of optical potential is being investigated

J. Phys. G 42, 034014

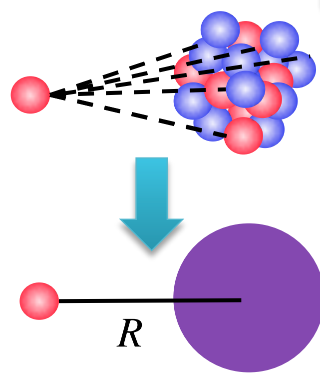



PRL 112, 162503



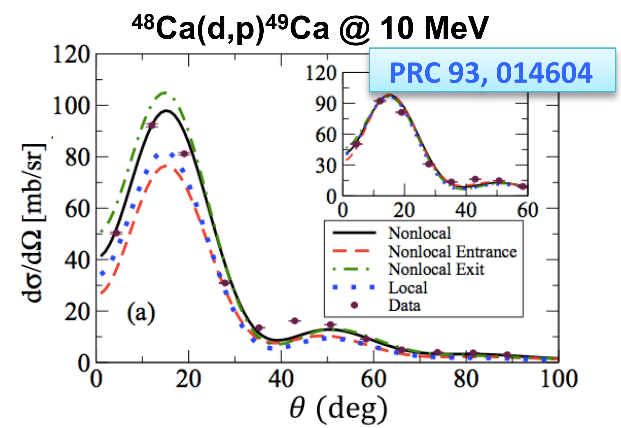

See: W. Dickhov

$U(r_1, r_2, \cdots, r_A)$




$U(R,R',E) + iW(R,R',E)$

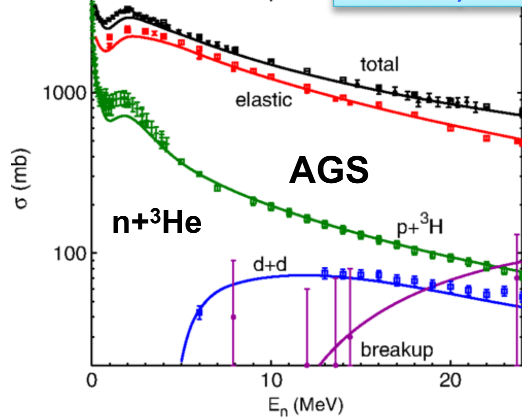
PRC 93, 014604



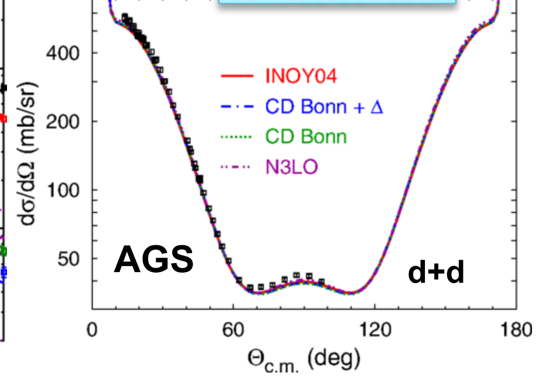
# We are witnessing exciting progress in the solution of the four-body scattering problem

- 'Exact' solution of multichannel four-nucleon system above breakup threshold with AGS
  - Elastic, transfer, charge-exchange, breakup reactions
- Development of four-body CDCC methods
  - $^{6}Li$, $^{6}He$, $^{9}Be$, $^{11}Li$ projectiles
  - With microscopic description of projectile (with core excitations)
  - With three-body approximation of projectile
- Prospects/challenges:
  - AGS for 4-body reactions
  - Core excitations in 4-body CDCC

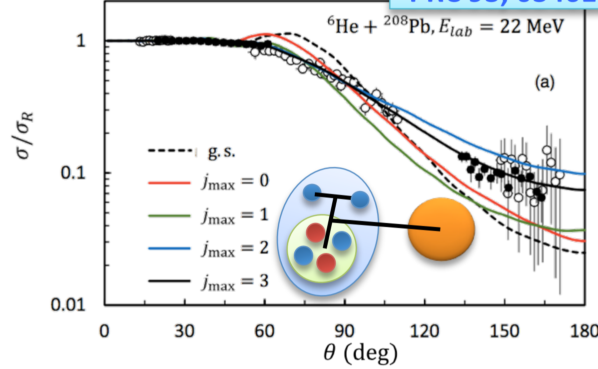
PRL 113, 102502



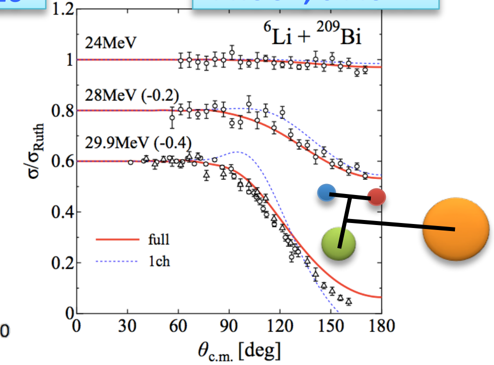

PRC 92 024001




PRC 93, 034616



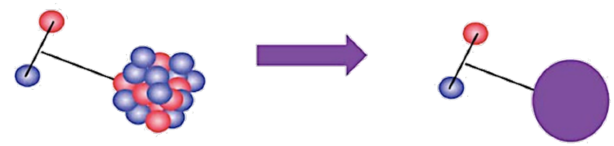

PRC 92, 044611

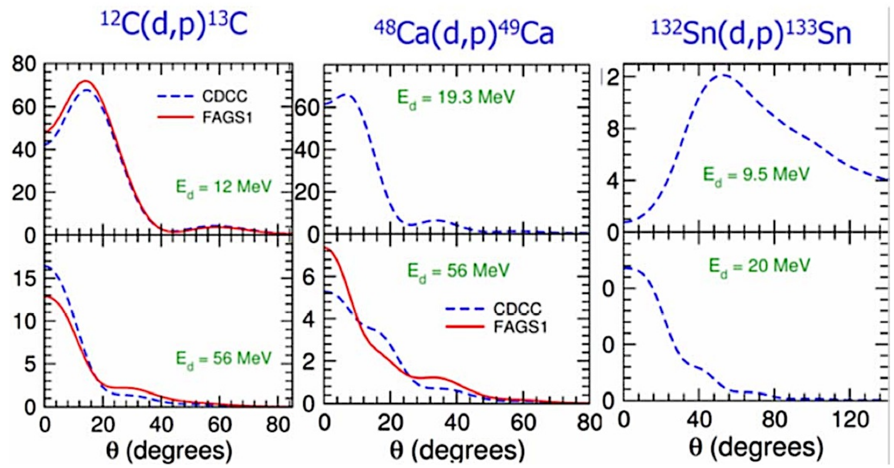


# Faddeev with Coulomb screening and CDCC benchmarked, spurred new formulation

- Emphasis on (d,p) reactions and connection to (n,$\gamma$) reactions
- Revealed shortcomings of Faddeev approach for systems heavier than Calcium …
- … and of CDCC approach for low-energy breakup and higher energy transfer
- Spurred new Faddeev treatment of (d,p) reactions in momentum space
  - Explicit inclusion of target excitations
  - Explicit inclusion of Coulomb interaction
  - PRC **86**, 034001 (formulation);
    PRC **90**, 061602(R) and 014615 (implementation)

**(d,p) reactions as three-body problem**



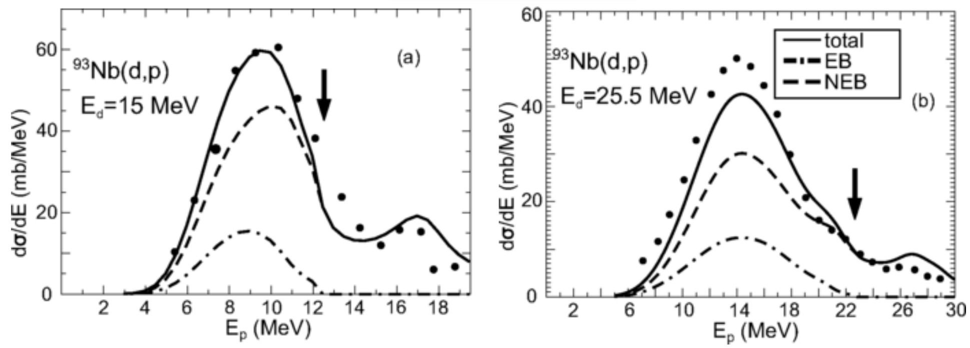



ReactionTheory.org

# DBWA formalisms for inclusive breakup processes revisited and implemented

- Inclusive breakup: projectile breaks up and only one of its remnants is measured
  - e.g.: A(d,p)X, A($^6$Li,$\alpha$)X
  - Sum of elastic and non-elastic breakup cross sections
  - Includes partial fusion of projectile with target
  - Beyond direct reaction, involves compound-nucleus formation
  - (d,p) proposed as 'surrogate' for neutron capture on short-lived target (inverse kinematic)
- Solved long-time controversy & first applications
- Prospects/Challenges:
  - For halos, need to go beyond DWBA

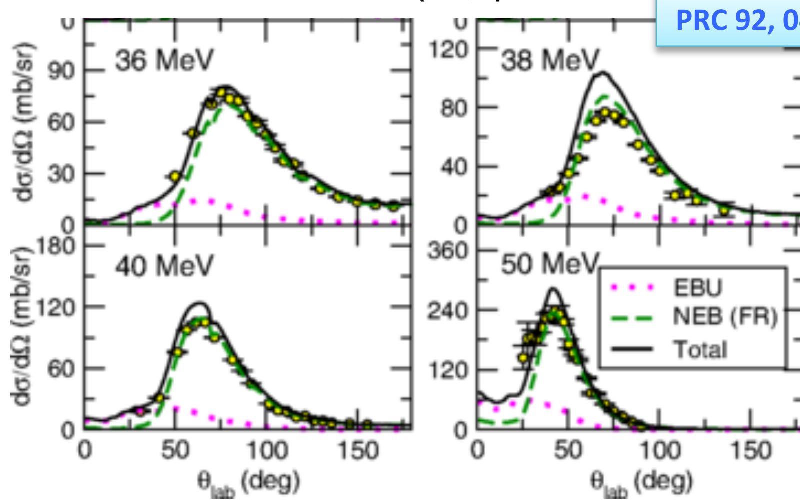
PRC 92, 034611




See: G. Potel

$^{209}$Bi($^6$Li,$\alpha$)X

PRC 92, 044616



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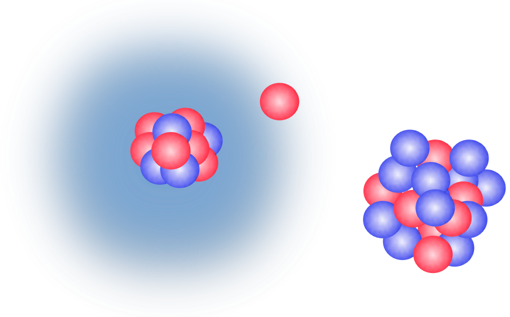

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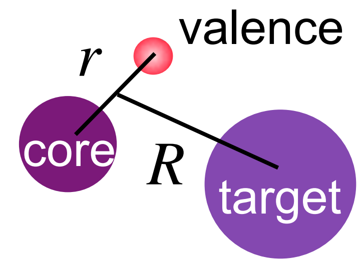


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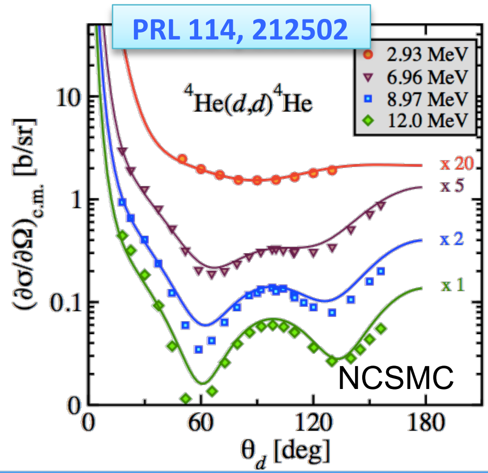
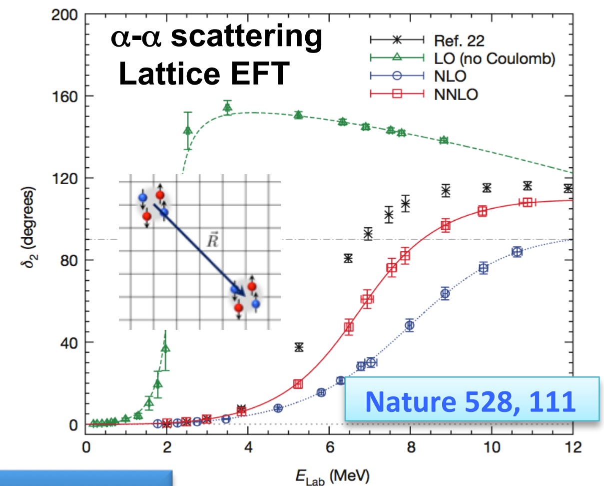
# Some illustrative examples

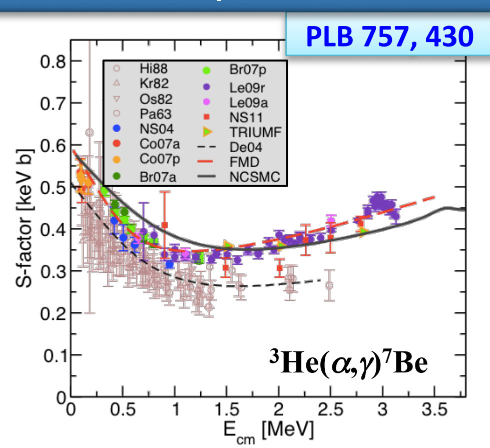
# Ab initio calculations starting to bridge the gap between structure and reactions in light nuclei

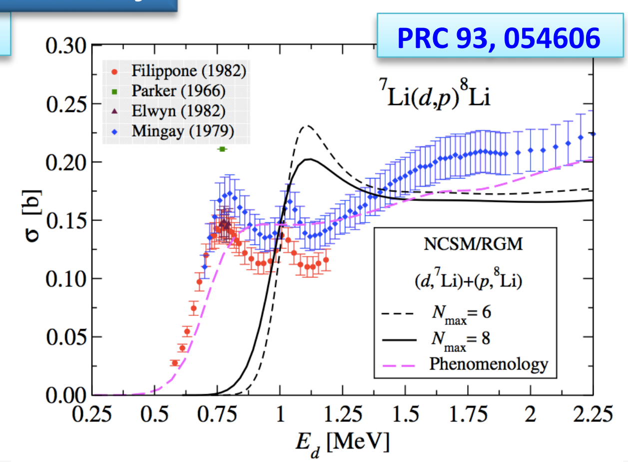
- Unified description of many-body and continuum correlations
- Light-nucleus scattering with NN+3N forces routed in QCD
  - No-Core Shell Model with Continuum (NCSMC)
  - Green' Function Monte Carlo
  - Lattice EFT with Adiabatic Projection Method
- Ab initio calculations of direct capture, transfer reactions on p-shell targets with soft NN interactions
  - $^3$He($\alpha$,$\gamma$)$^7$Be, $^3$H($\alpha$,$\gamma$)$^7$Li
  - $^7$Li(d,p)$^8$Li



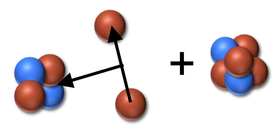

See: G. Hupin & J. Dohet-Eraly

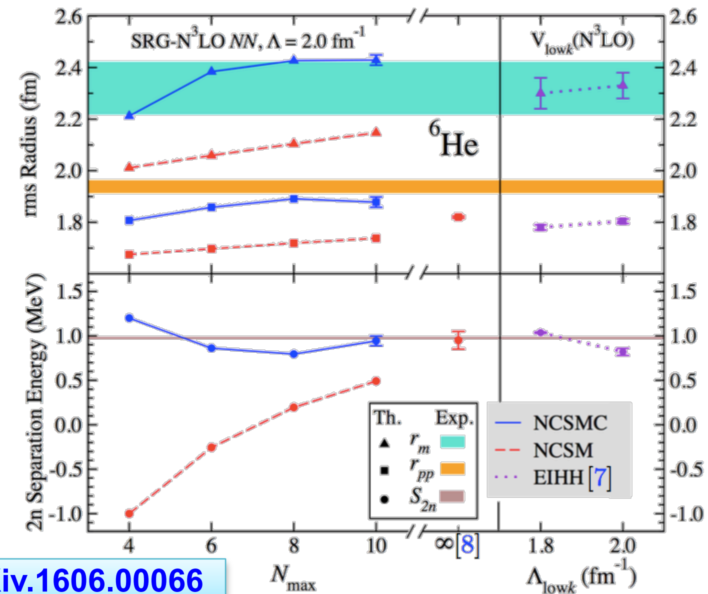


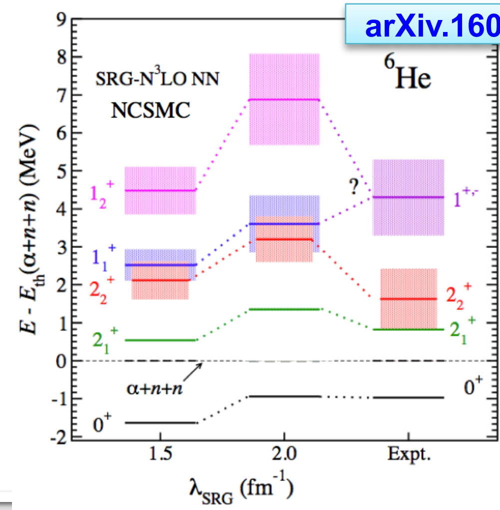
# Ab initio calculations simultaneously addressing many-body correlations and 3-cluster dynamics

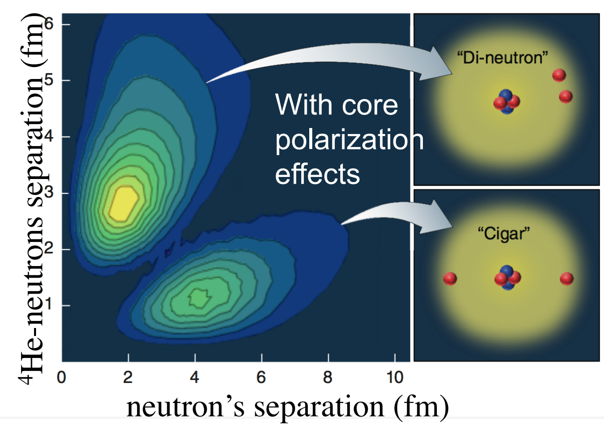
- The no-core shell model with continuum is being extended to the description of core+n+n dynamics
  - Soft realistic NN interactions
  - Implicit inclusion of core excitations
- Largely solved long-standing problem of simultaneously reproducing $^6$He small binding energy and extended radii
- Most advanced description of $^6$He low-lying continuum
- Prospects/Challenges:
  - Inclusion of 3N forces, description of $^{11}$Li, …
  - Direct reactions with ab initio projectiles






arXiv.1606.00066



# Conclusions and Outlook

- Many more developments I could not cover
  - Ratio method (see F. Colomer), two-nucleon decays (see e.g., A. Lovell), size properties of unstable nuclei (see, Horiuchi), advances in charge-exchange reactions, 2-neutron removal reactions (see e.g., Matsumoto), fusion processes (see Simpson) …
- The connection between few-body models and the underlying many-body problem is starting to be forged
- Many-body reaction methods routed in the underlying theory of QCD are emerging, starting to describe the lightest nuclei
- More work is needed:
  - Description of nucleon transfer to states in the continuum
  - Theory for (p,2p), (p,pn) knockout reactions
  - Theory for double charge-exchange reactions
  - Ab initio theory for heavier systems
  - …

**Reaction Theory and experiment need to keep working hand-in-hand**

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