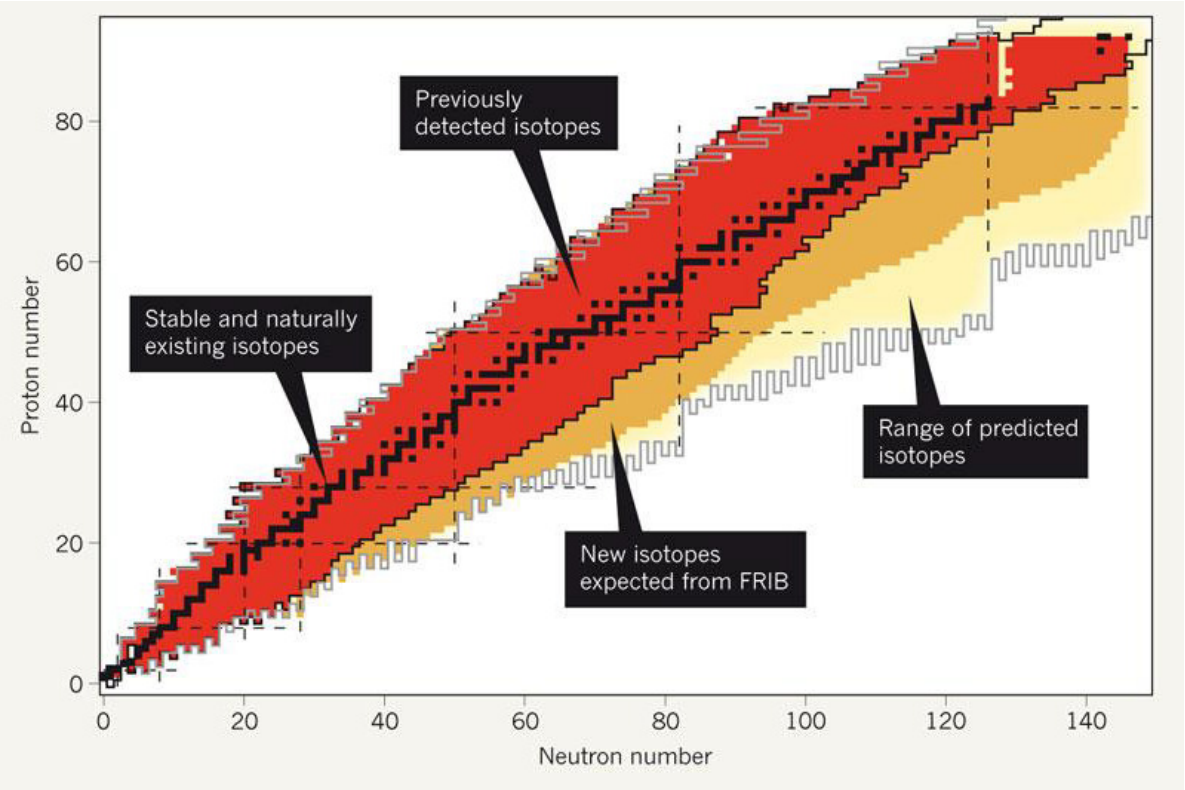
Selected recent developments in reaction theory

Chloë Hebborn

December, 12 2023

Exciting time to be a nuclear physicist !



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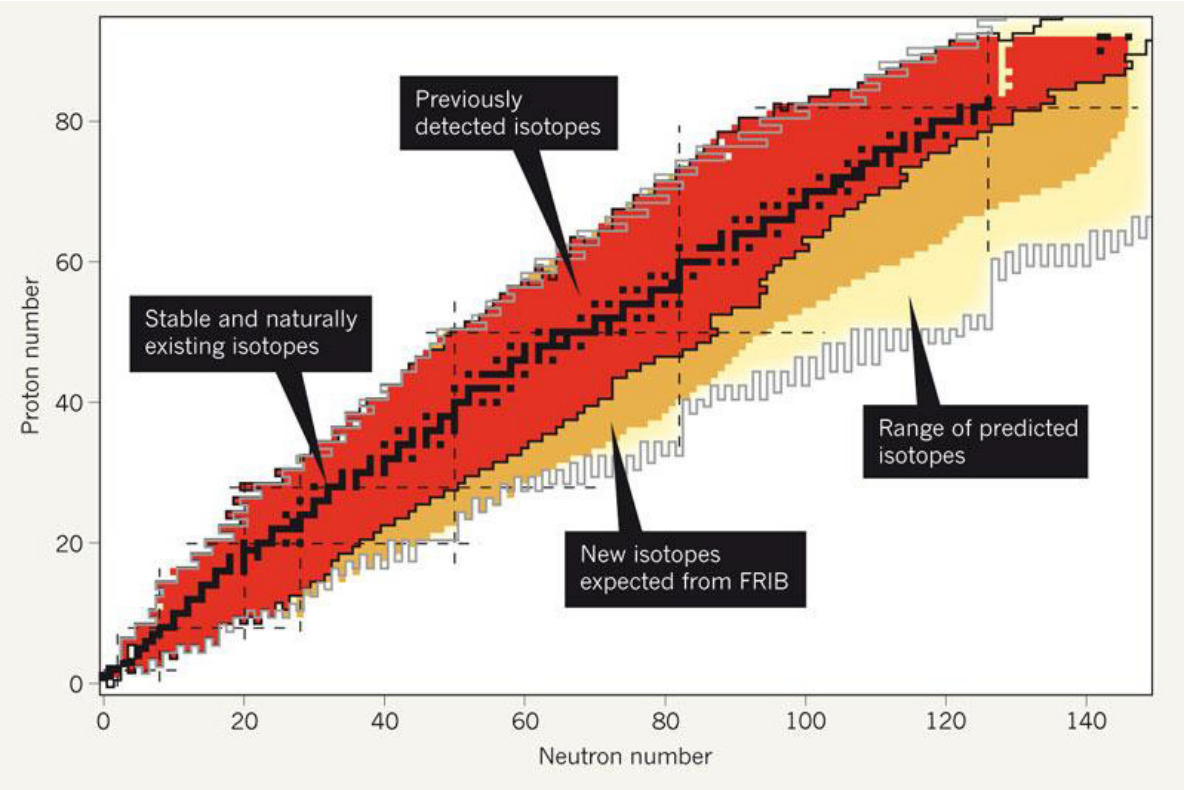

FRIB

nuclear structure
nuclear astrophysics
fundamental symmetries
benefits of nuclear science to the nation and humankind

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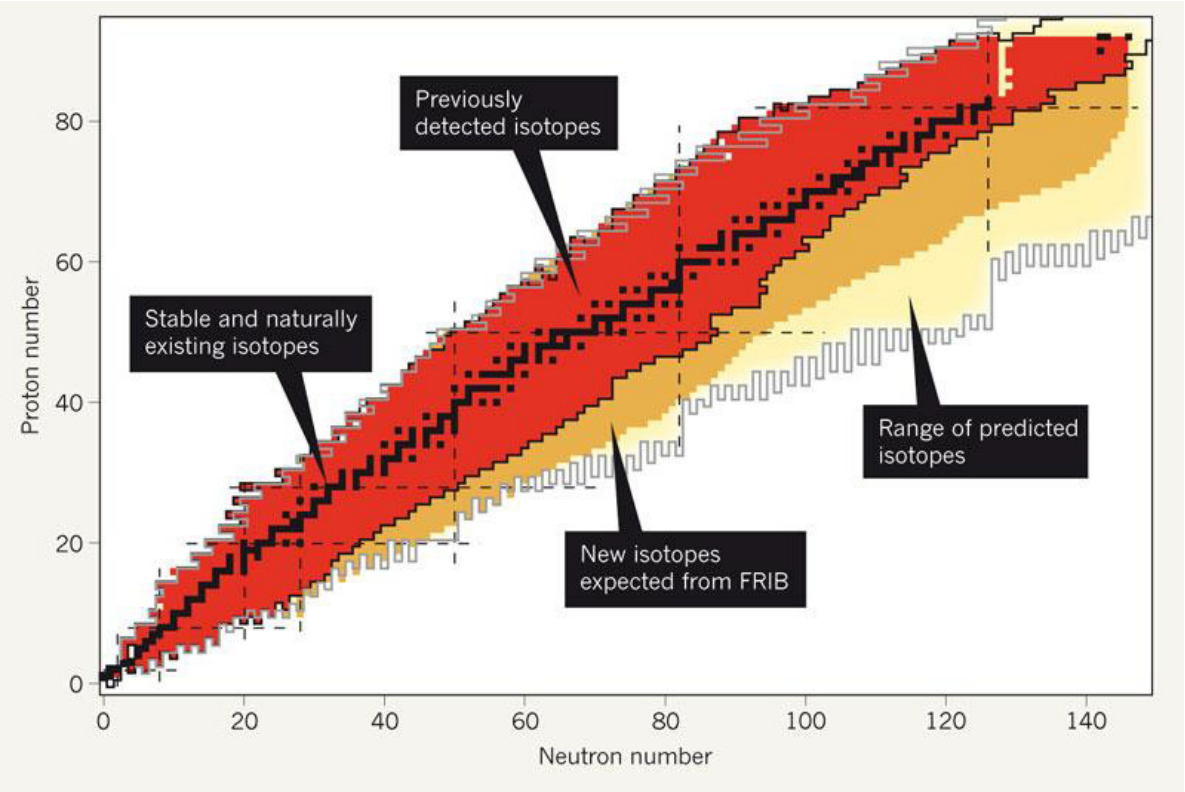

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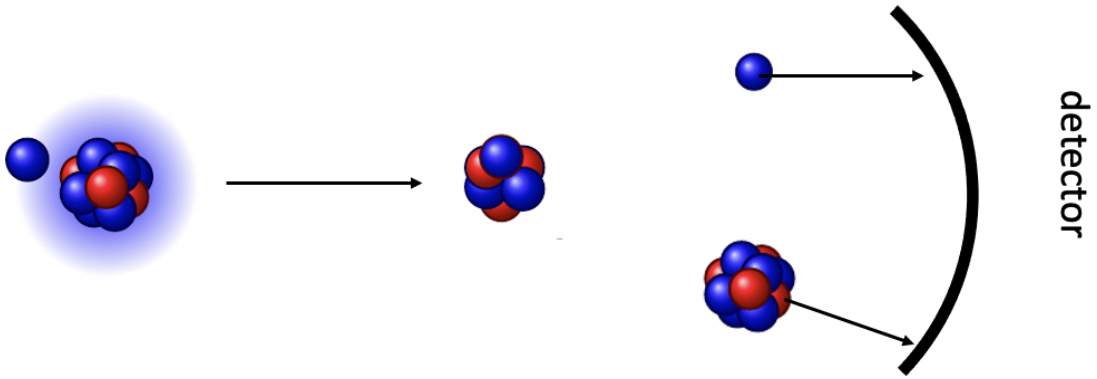
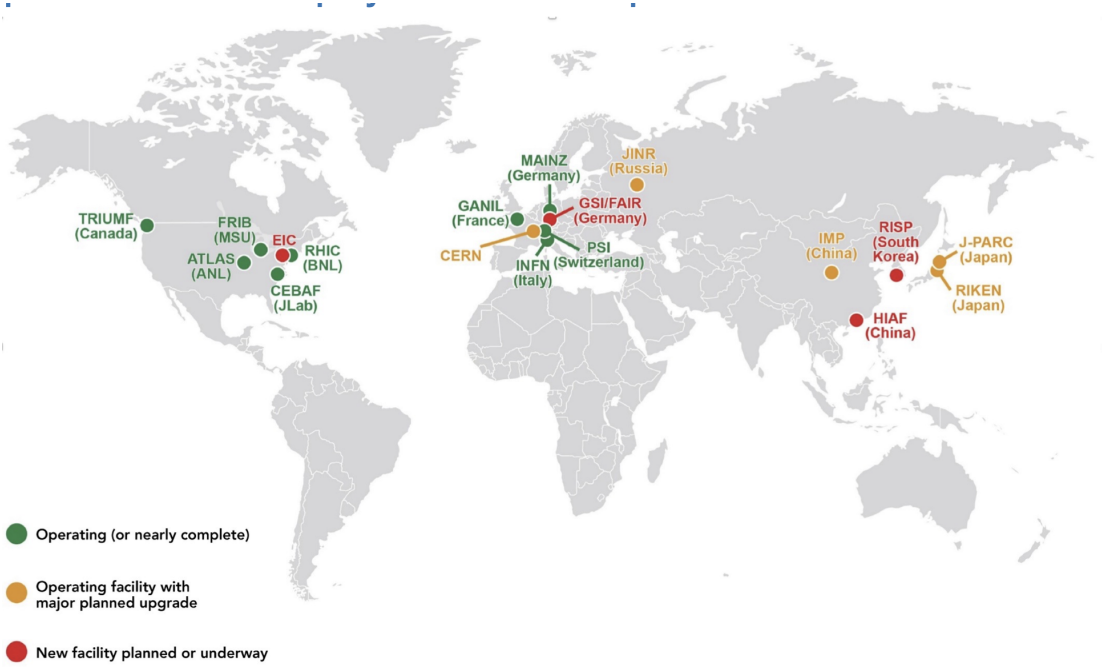
Accurate predictions are needed to support the analysis of experiments and for reactions not accessible experimentally





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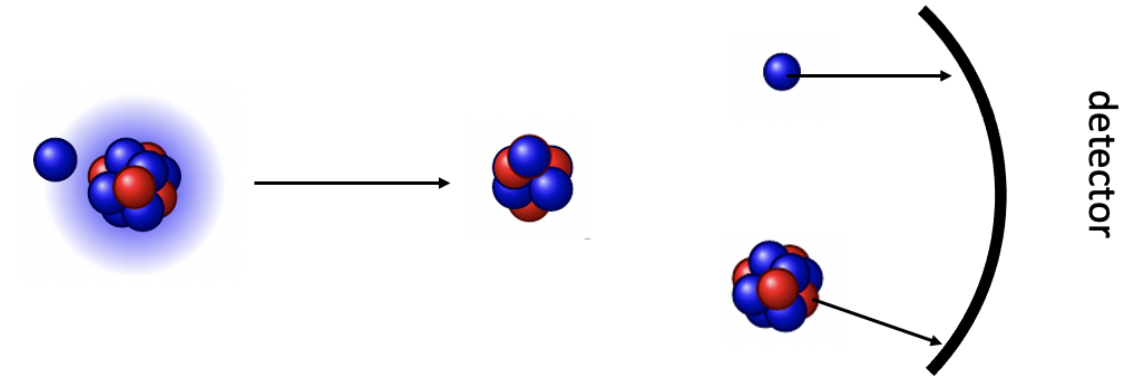
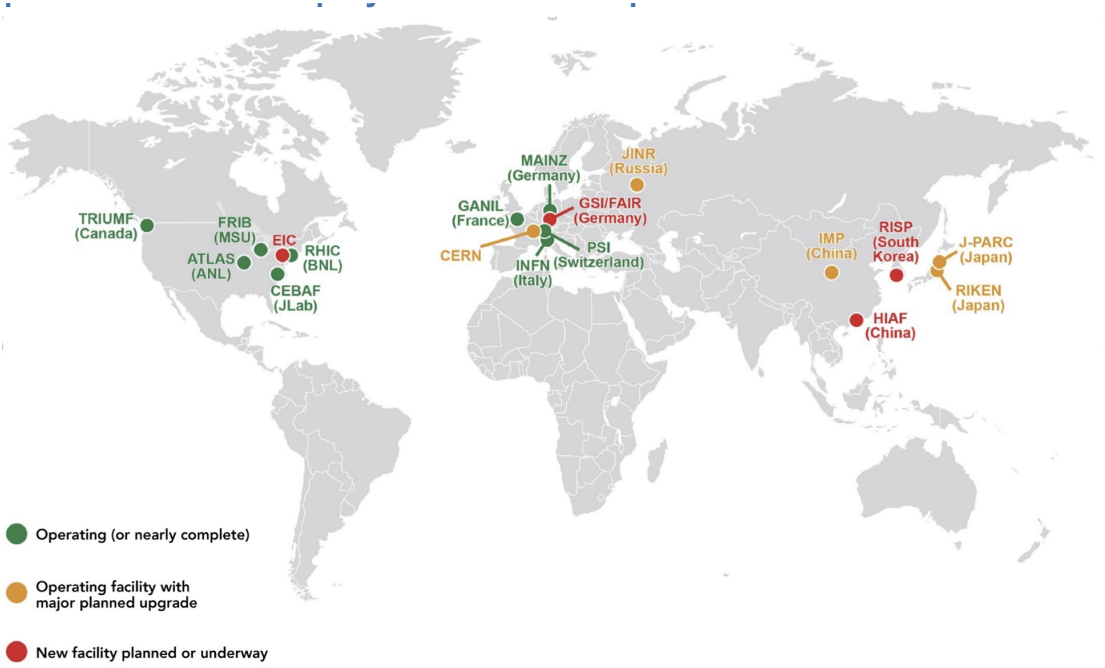
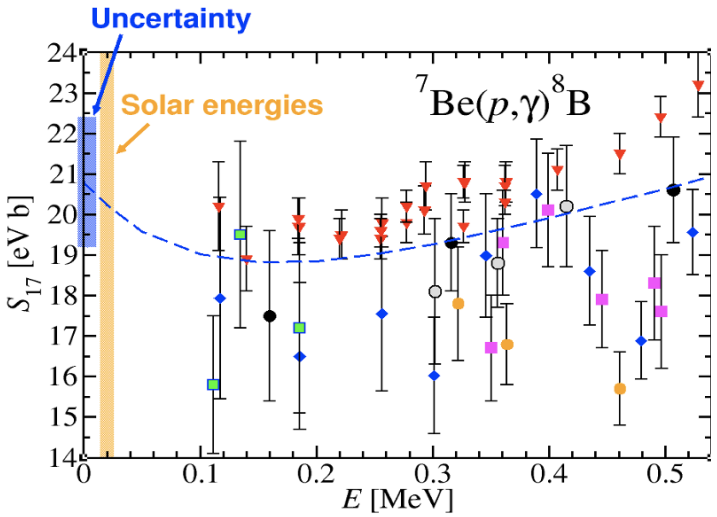
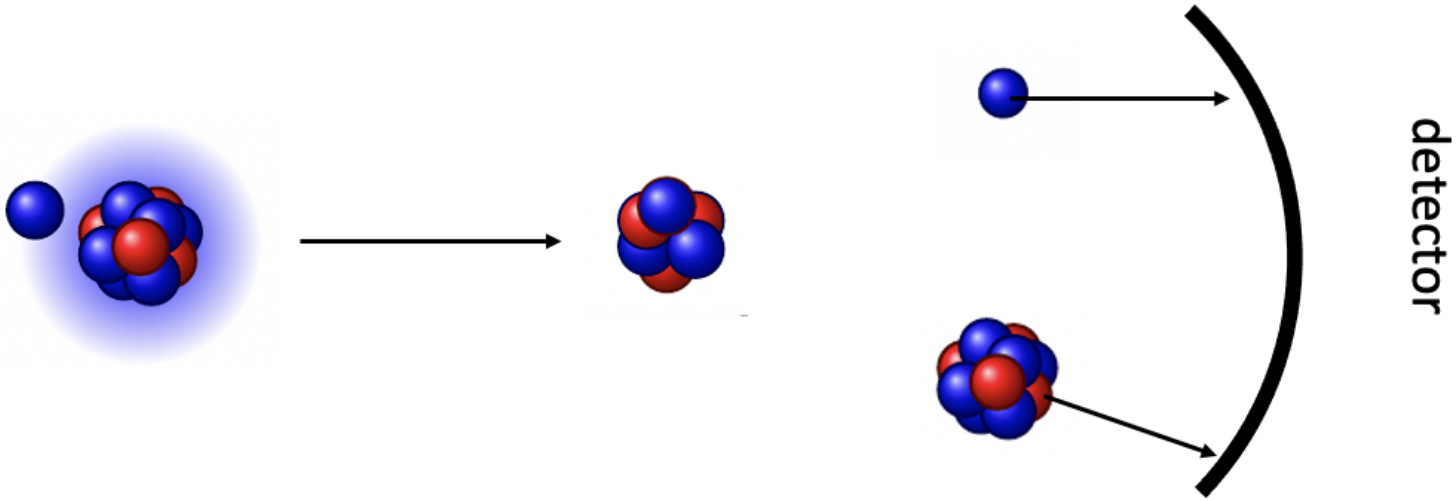






Three main challenges in any models



To make accurate predictions :

1) Choose dofs & use an accurate model

2) Interactions grounded in the underlying theory

3) Have an estimate of model & input uncertainties

Ideally, we want to describe all reactions from nucleon's degrees of freedom, with interactions derived from QCD

1) No core shell model with continuum [Phys. Scr. **91**, 053002 (2016)]
(cf Dean's talk for NLEFT)

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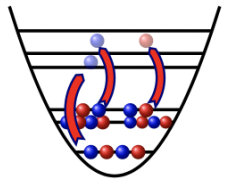
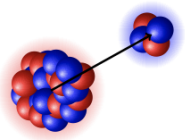


Discrete structure information input



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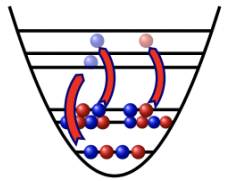

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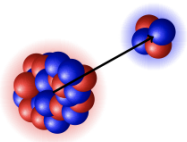
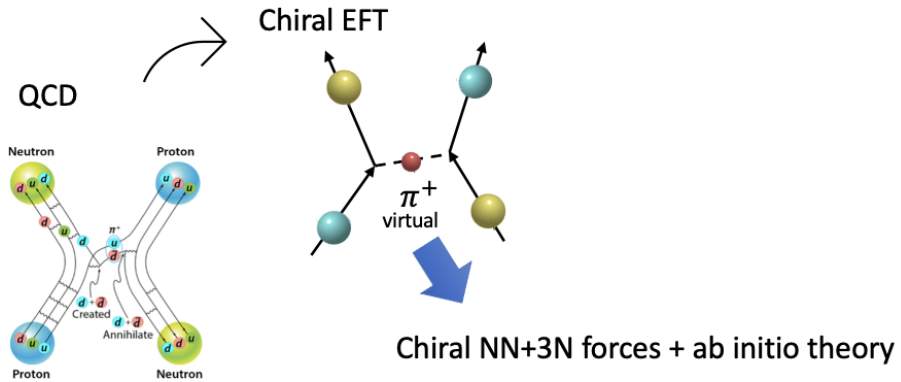


Continuous dynamical input (clustering/reactions)

2) Use of chiral-EFT interactions



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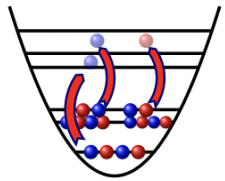

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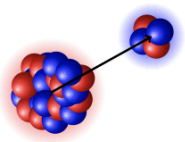

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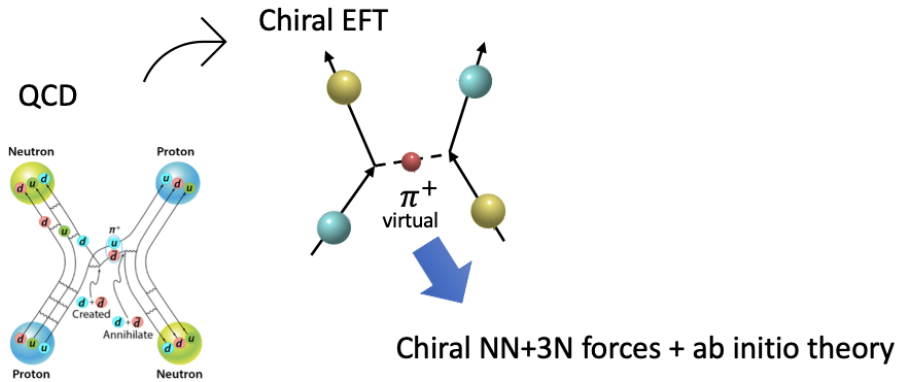
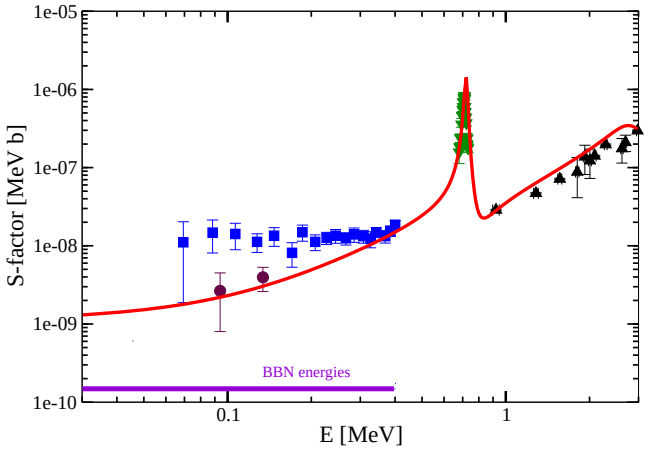
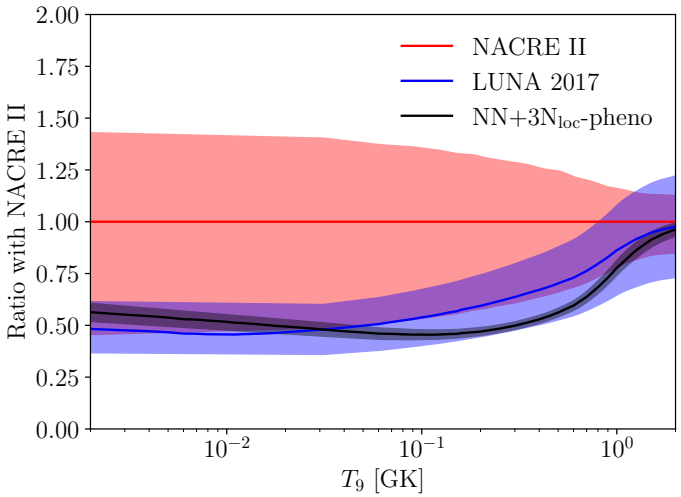


3) Vary the interactions and truncation of model spaces

Recent predictions constrain astrophysical reactions relevant for the BBN & the p-p chain

$\alpha(d,\gamma)^6$Li





[Hebborn *et al.* PRL 129 042503 (2022)]

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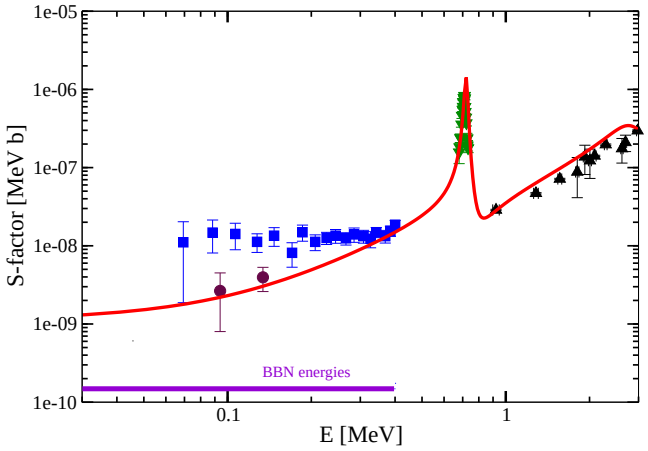

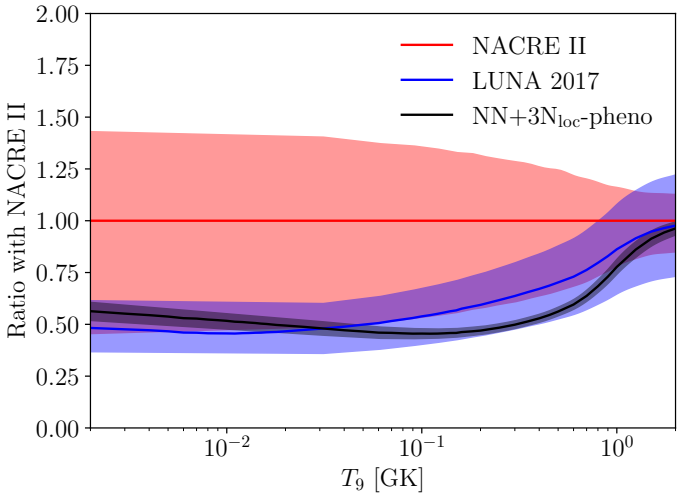

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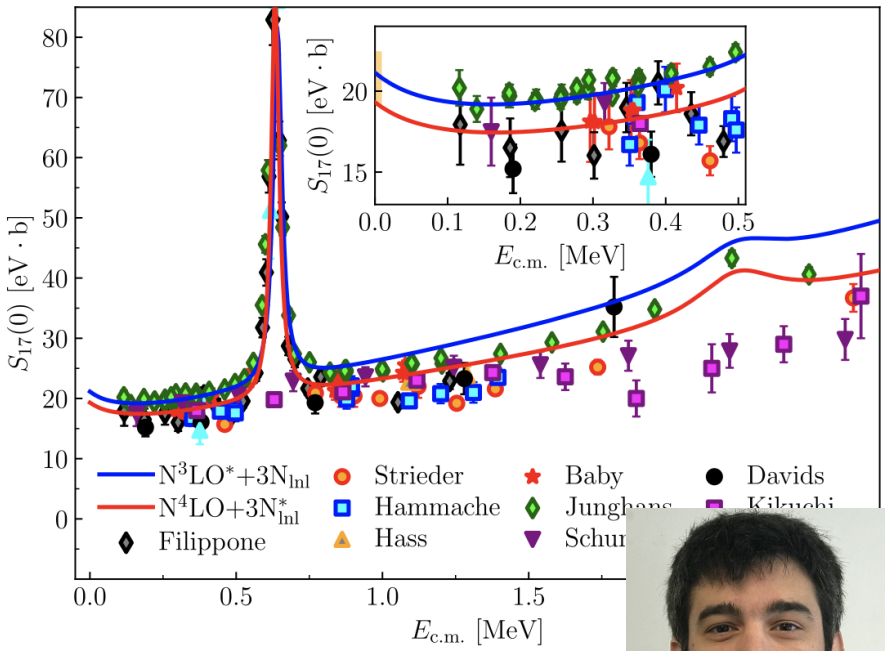
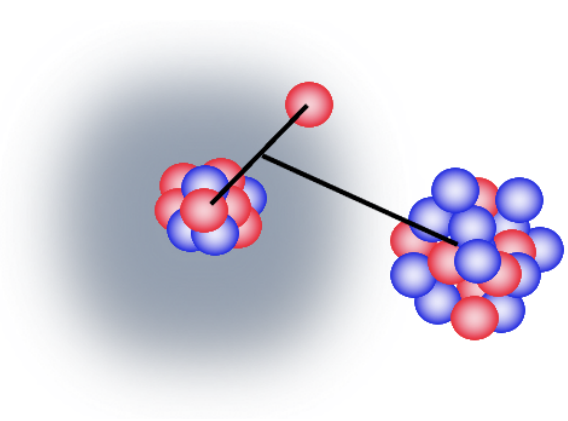
^{7}Be$(p,\gamma)^8$B



[Kravvaris *et al.* PLB 845 138156 (2023)]

For reactions involving heavier nuclei, one needs to make approximations

light nuclei & low E



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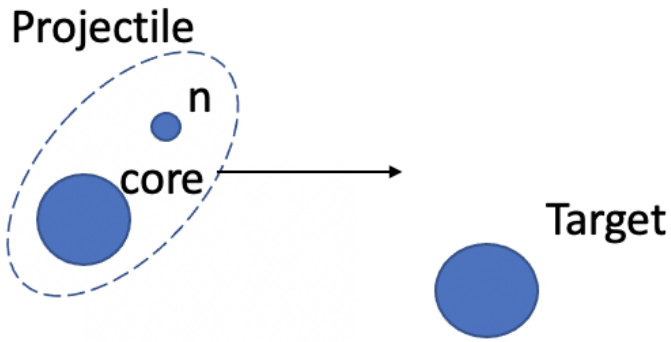

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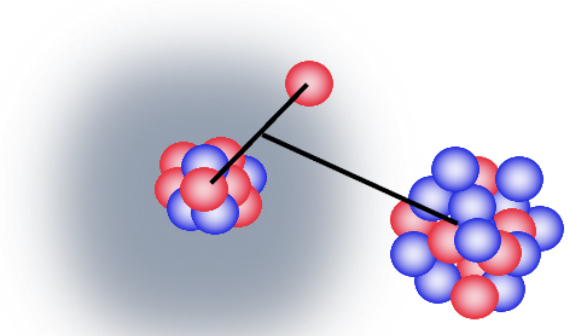

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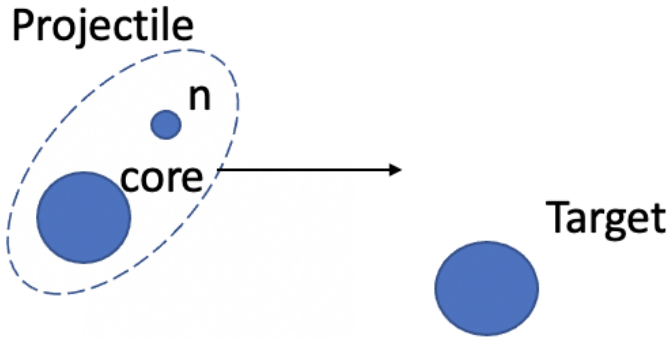

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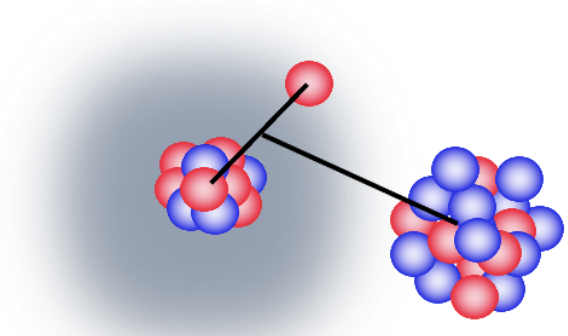

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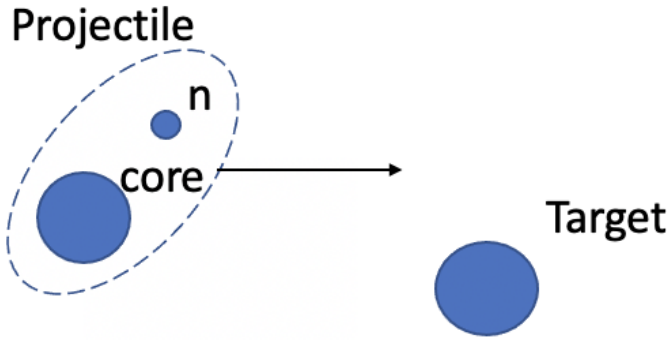

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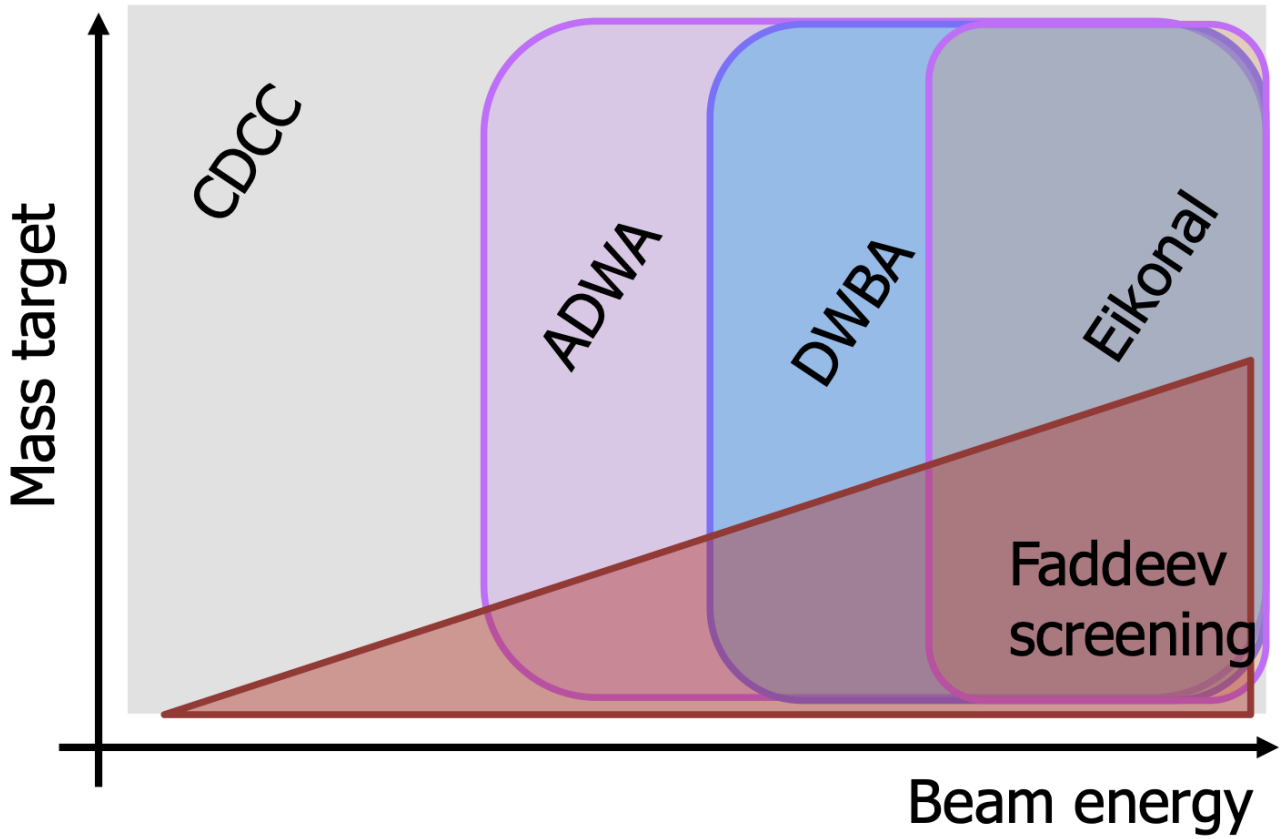

Faddeev : need for screening of the Coulomb interaction limits A & E

[Figure courtesy of F. Nunes]

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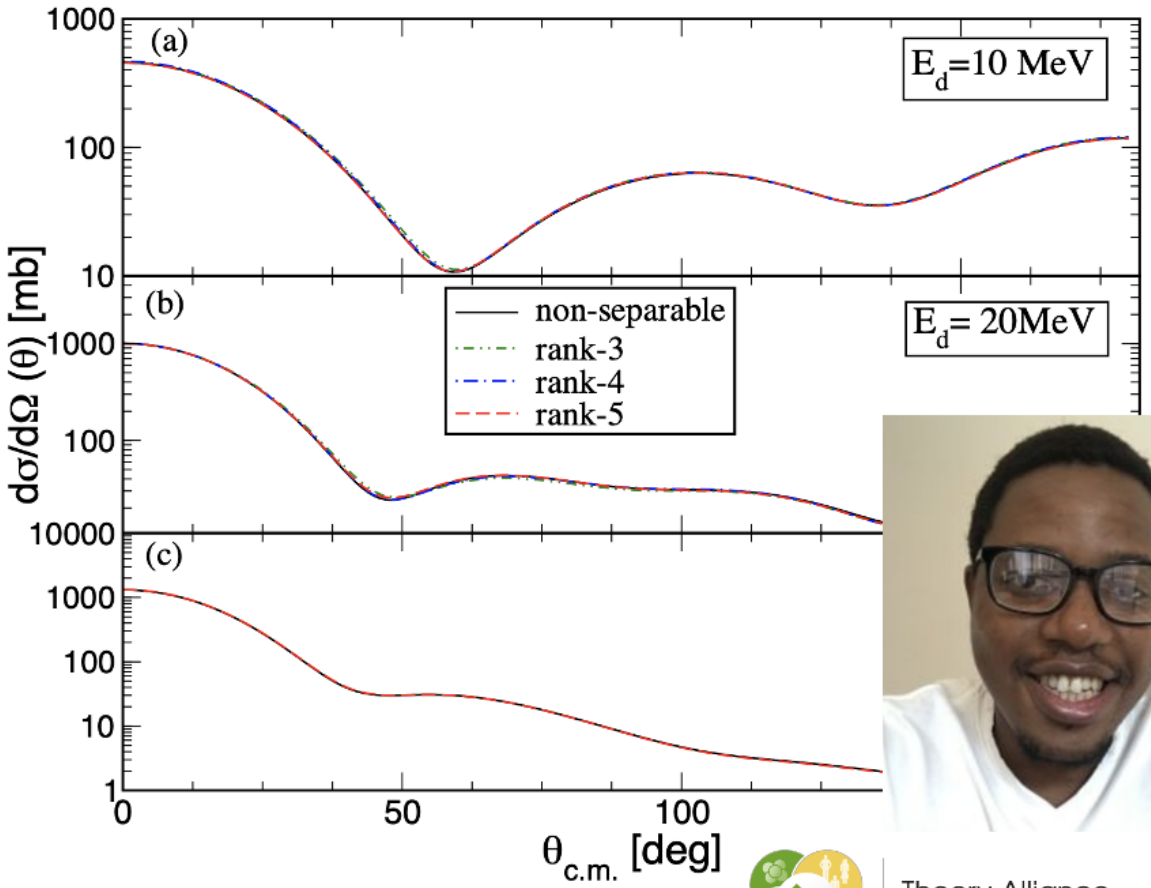
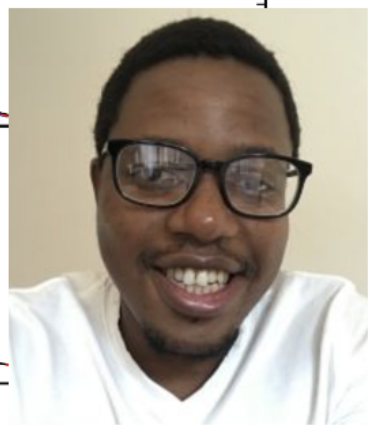
Recent effort by Linda Hlophe at LANL : Faddeev without screening

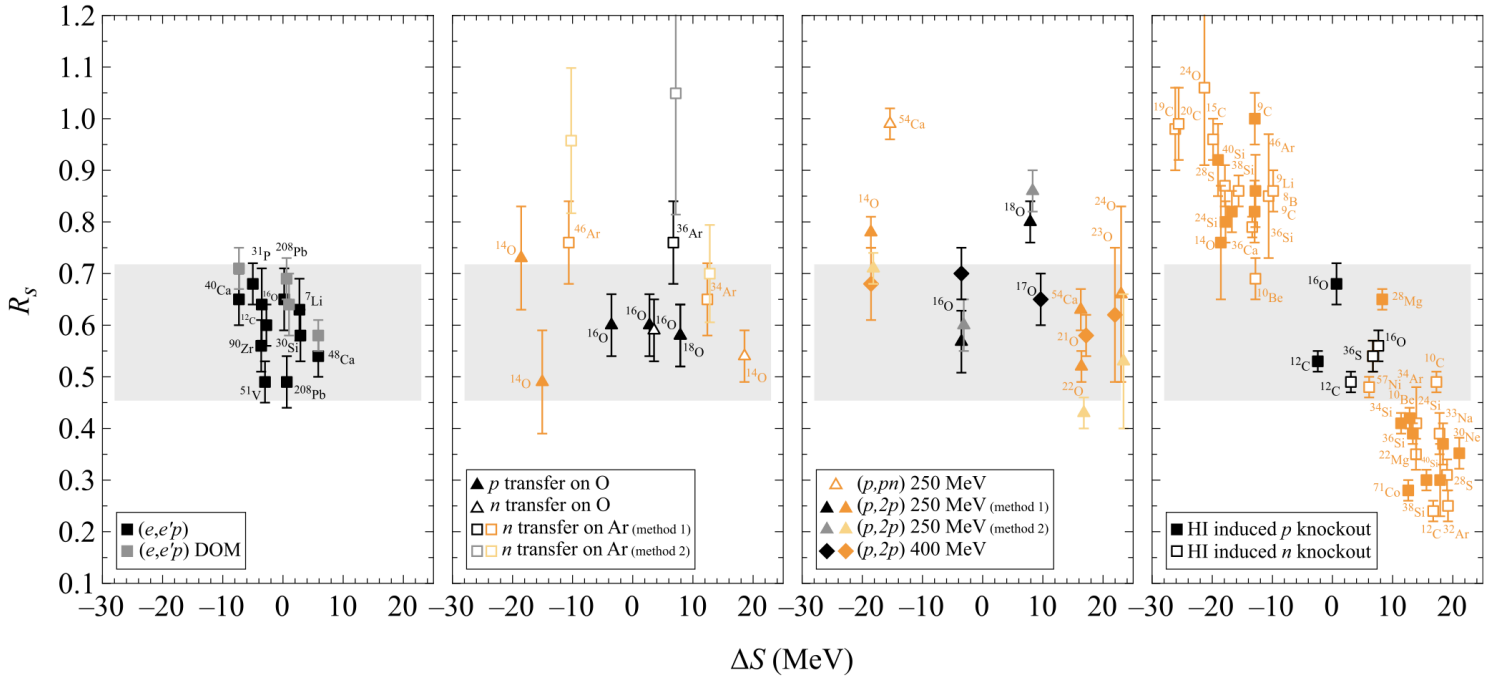
[PRC 100, 034609 (2019)]





Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

There have also been recent efforts to improve the eikonal treatment of breakup reactions



[Aumann *et al.* PPNP 118 103847 (2021)]

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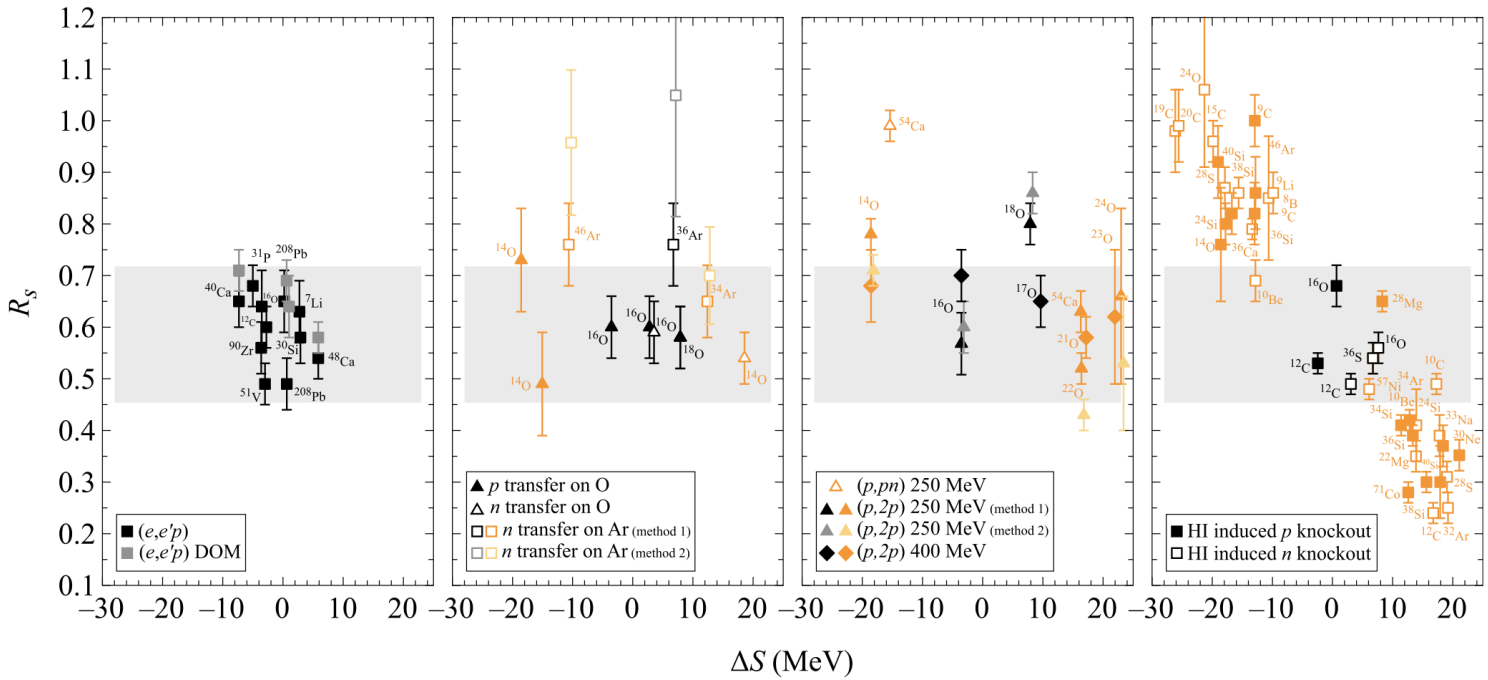

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Improvement to the reaction dynamics, sensitivity analysis & non-locality

[CH, Capel PRC 96 054607(2017) ; PRC 98 04461 (2018) ; PRC 100 054607 (2019) ; PRC 103, 064614 (2021) ; arXiv :2311.10830 ; CH, Baye, PRC 101, 054609 (2020) ; CH, Nunes, PRC 104, 034624 (2021)]

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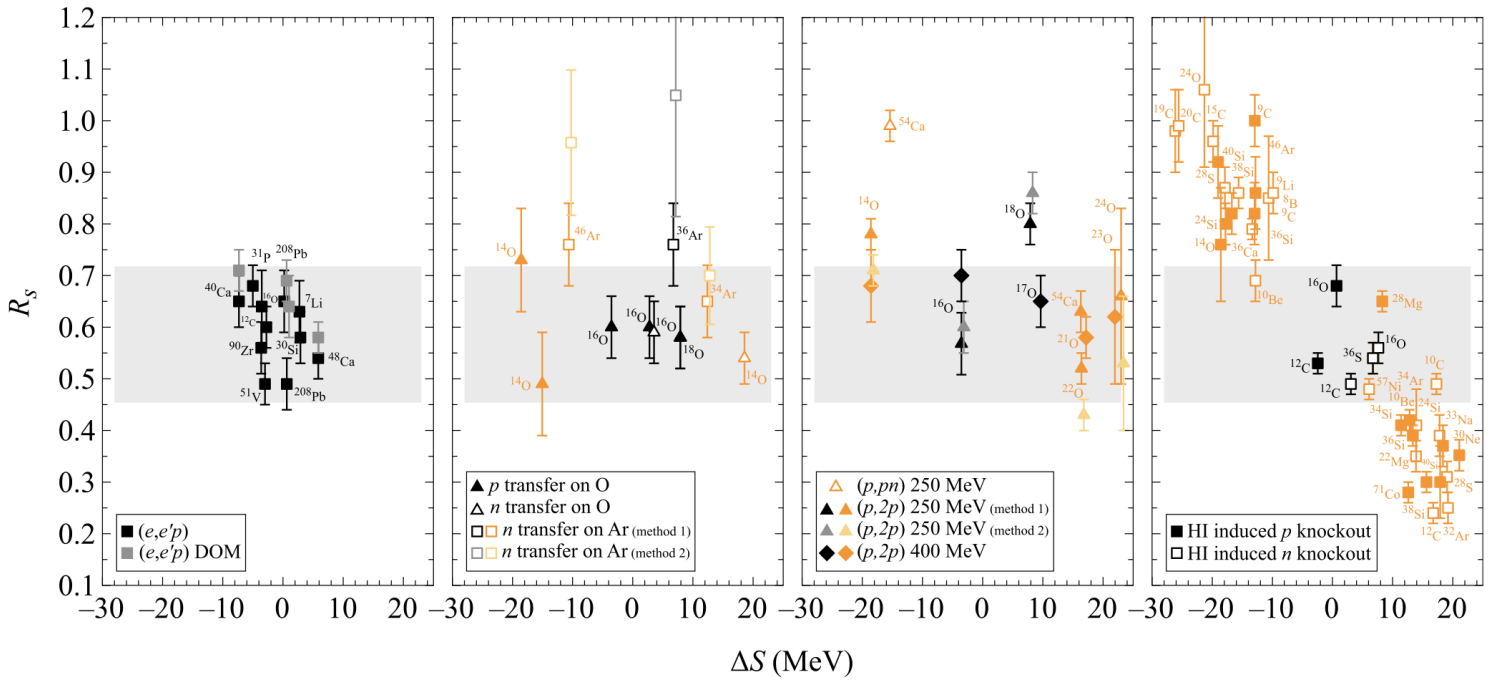

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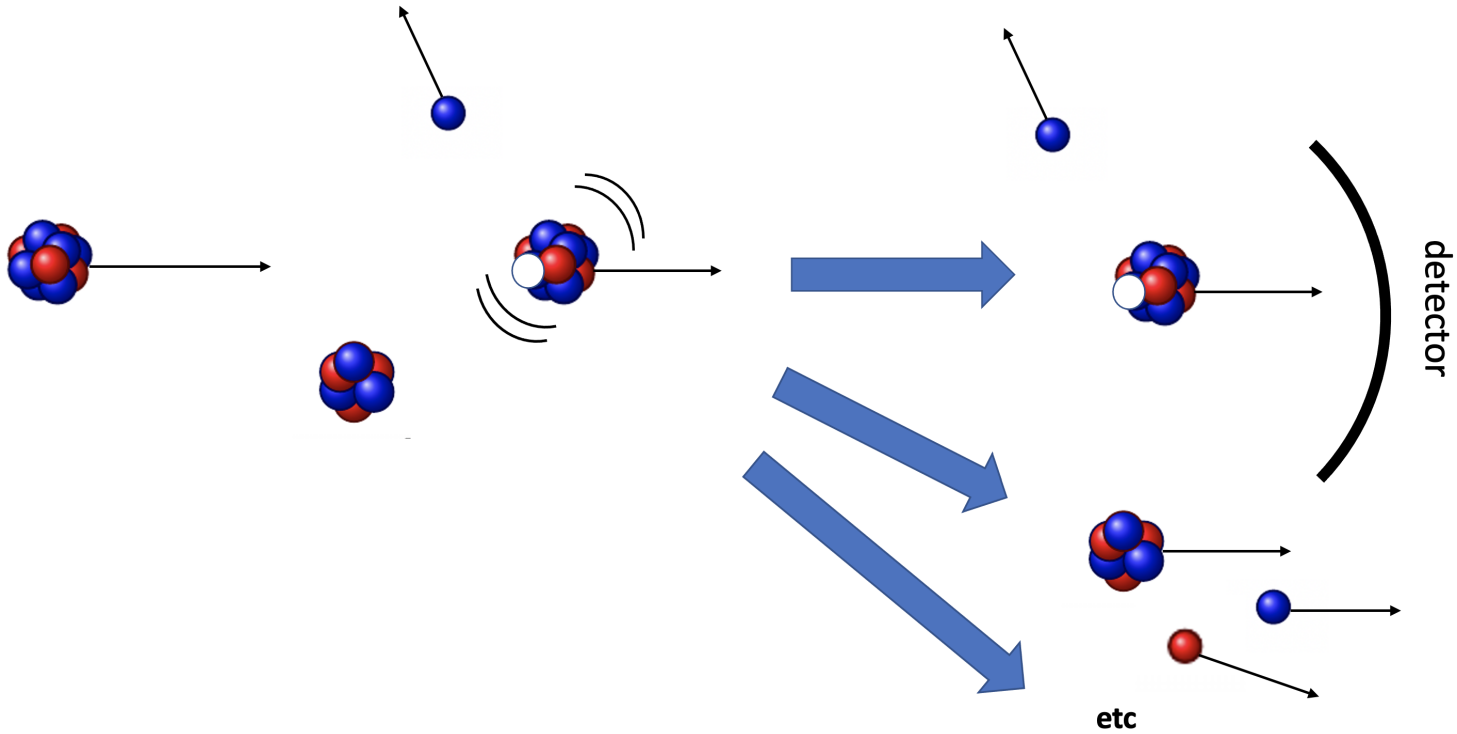
→ Going in the right direction, but not satisfactory... so what's next ?

Going beyond the core-spectator approximation with the Green's function knockout formalism

Goal : include dissipative processes due to the hole propagation in the many-body systems with dispersive potentials

→ structure & reaction treated consistently [PRC 107 014607 (2023)]



ongoing... with Potel, Pruitt & Escher at LLNL

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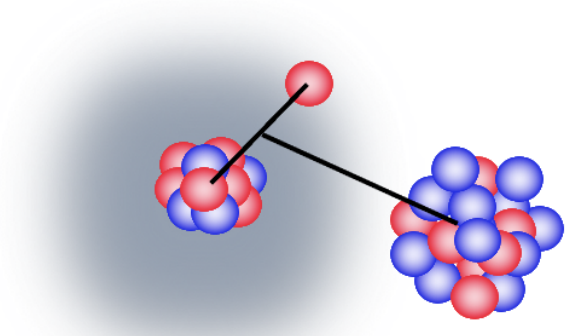

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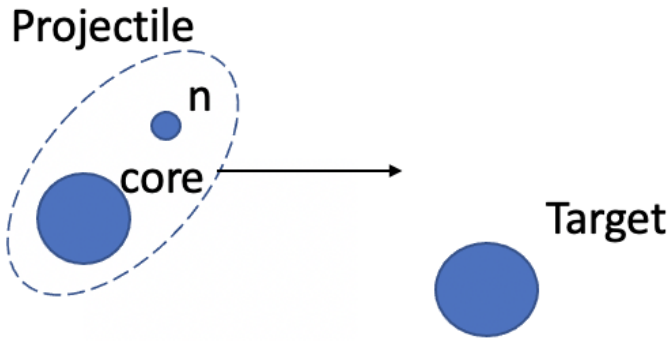

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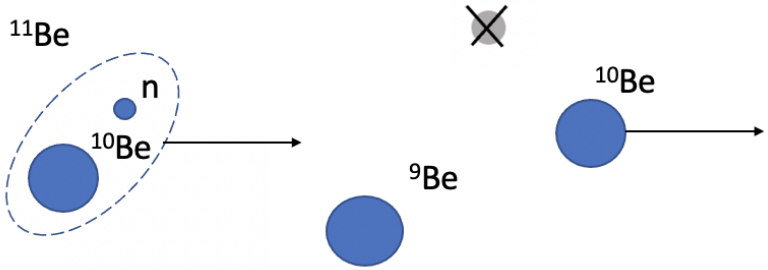
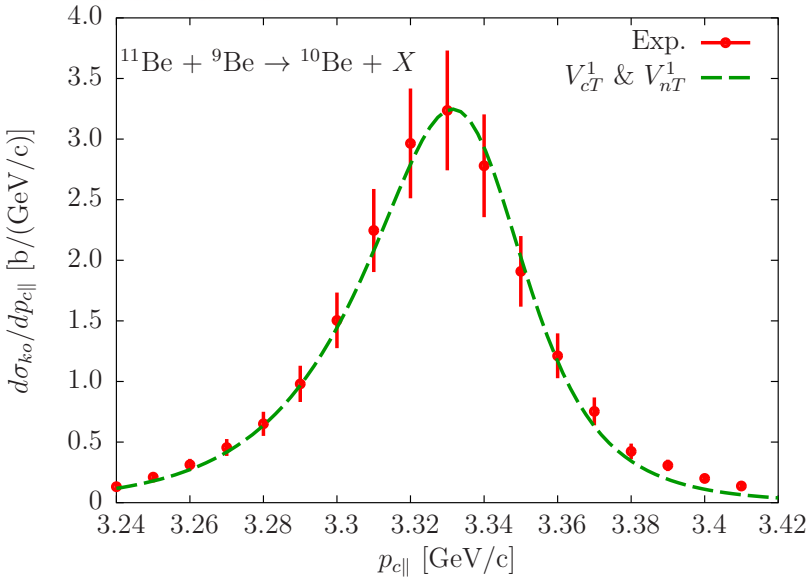
Combining EFTs, *ab initio* predictions and few-body models lead to accurate knockout cross sections

Halo-EFT of ^{11}Be using NCSMC prediction for ANC [PRL **117**, 242501 (2017)]





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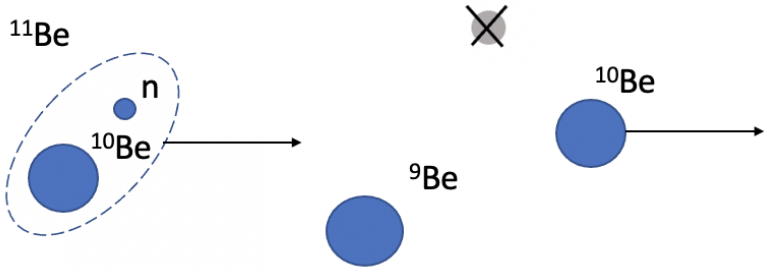

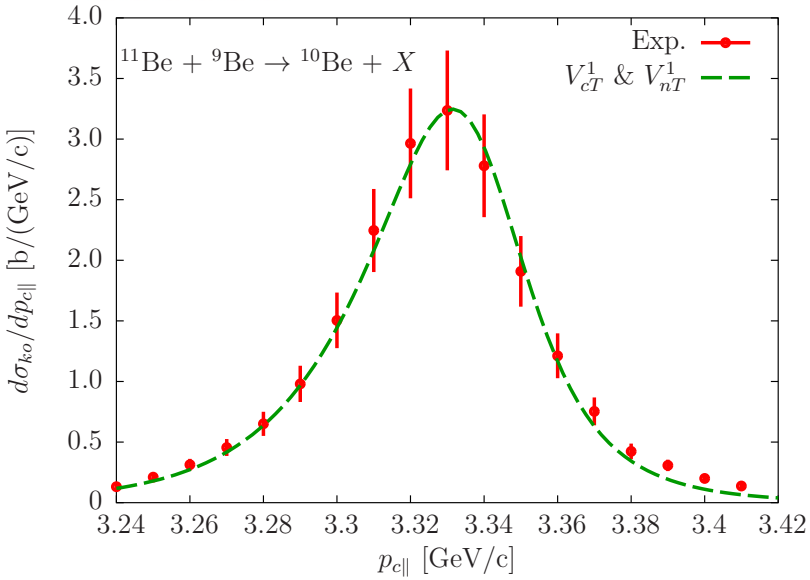

Similar plan for Coulomb breakup of ^{37}Mg (PAC2)

see Aldric's talk

[Exp. : Aumann *et al.* PRL 84, 35 (2000)] [Th. : Hebborn and Capel, PRC 104, 024616 (2021) ; PRC 100, 054607 (2019)]

Similar idea can be used to interpret reactions $(^6\mathrm{Li}, d)$ data extracting ANCs used to constrain astrophysical rates

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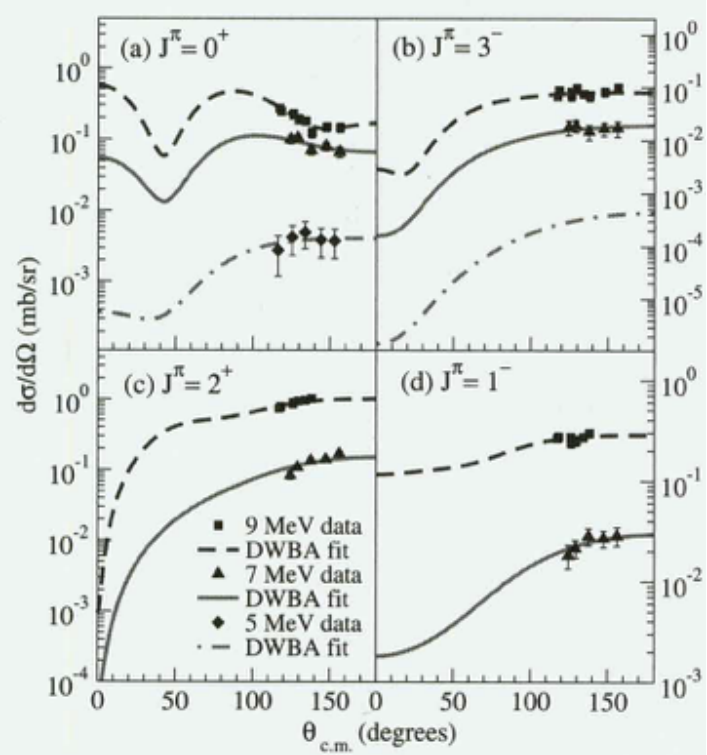

[Avila *et al.* PRL **114**, 071101 (2015)]

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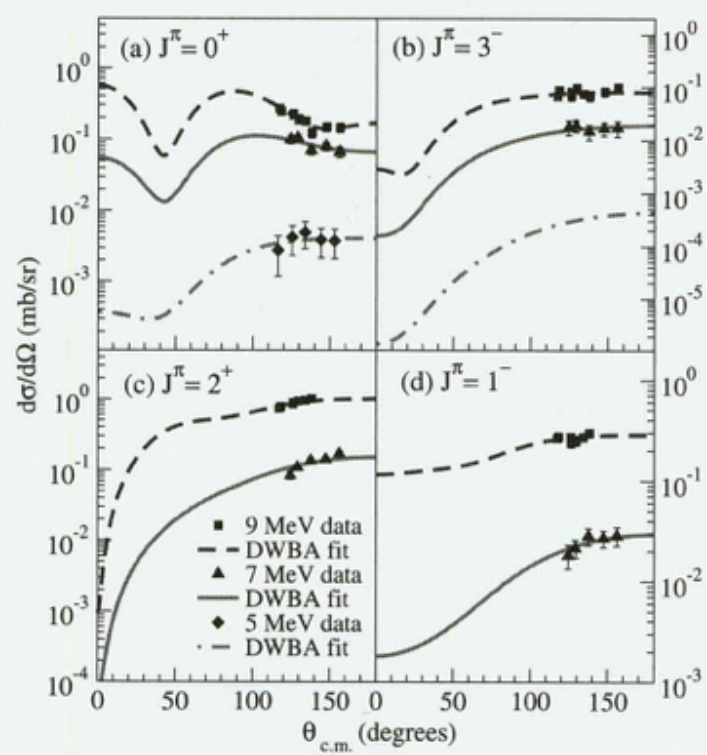

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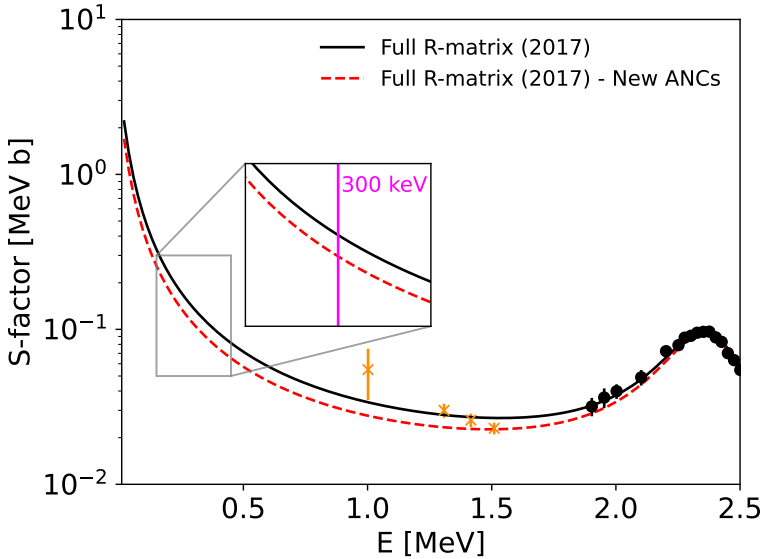
Ab initio $(C_{\alpha-d})^2 \rightarrow$ 21% reduction of the S-factor at stellar energies !

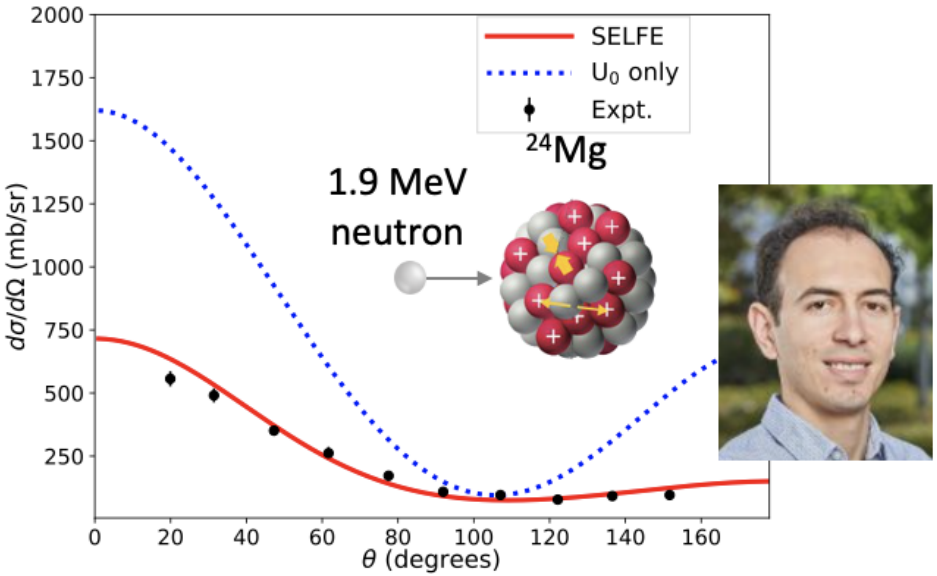


[Hebborn, Avila, Kravvaris, Potel & Quaglioni arXiv :2307.05636]

To reach a more unified treatment of structure & reactions, recent efforts to derive microscopic optical potentials

Shell model optical potentials

Grigor Sargsyan, FRIB-TA fellow



Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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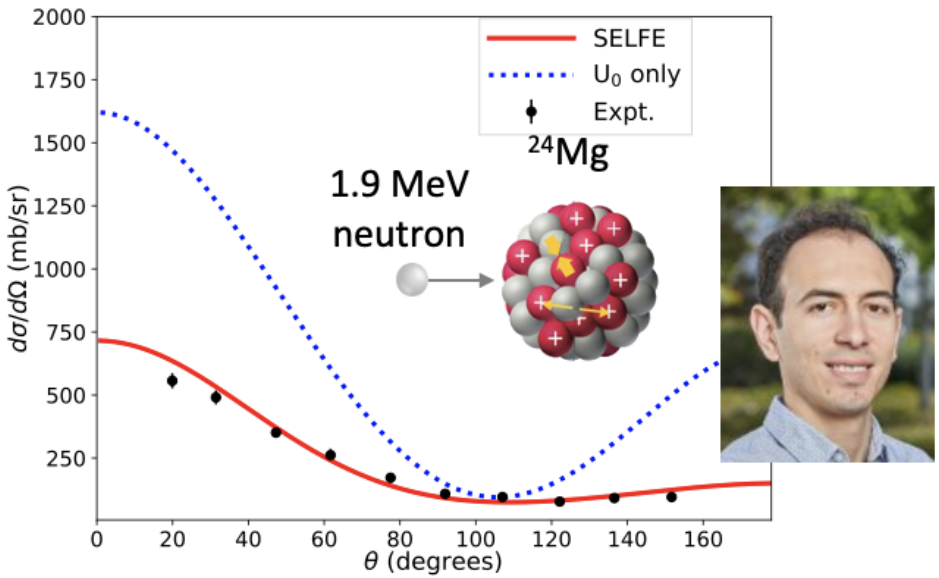
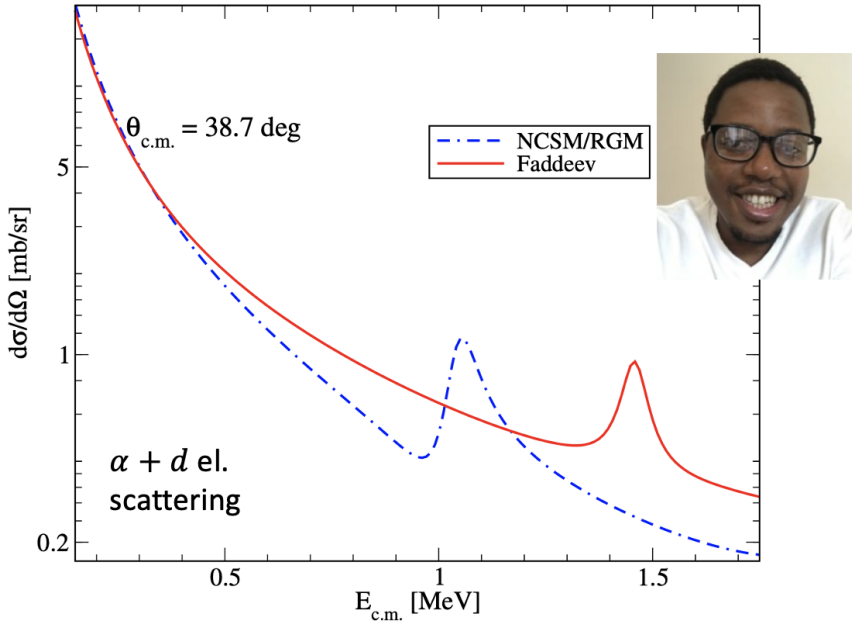


Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

Importance of 3b force

Linda Hlophe, LANL FRIB-TA fellow



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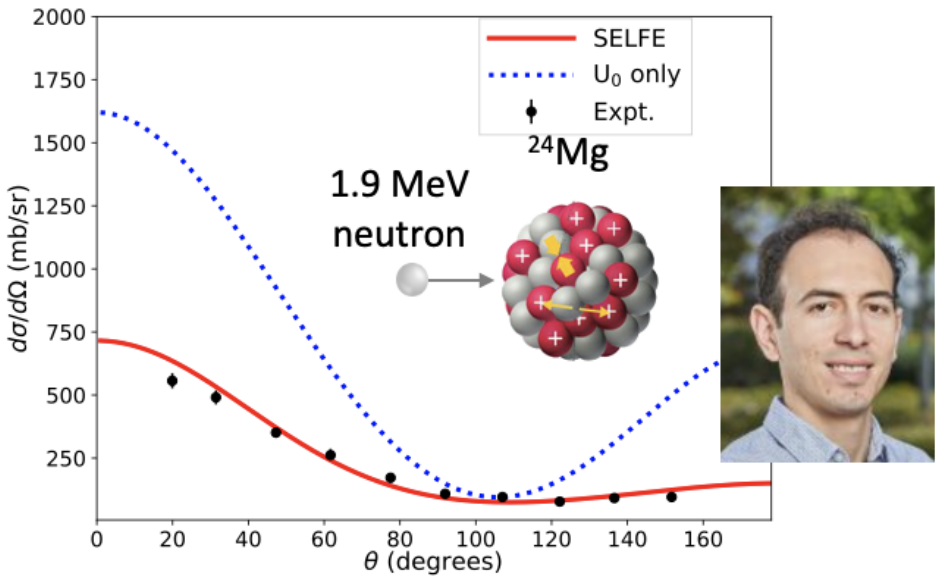

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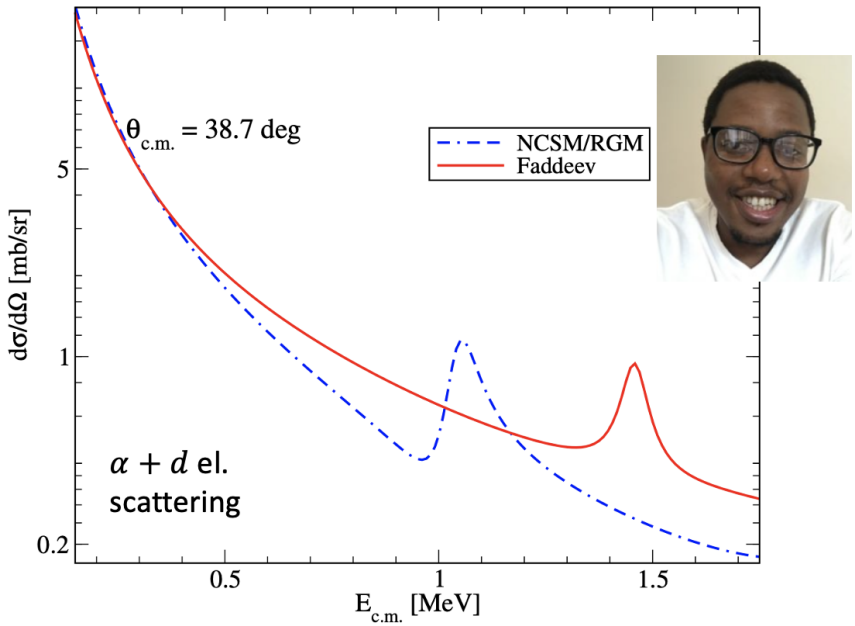

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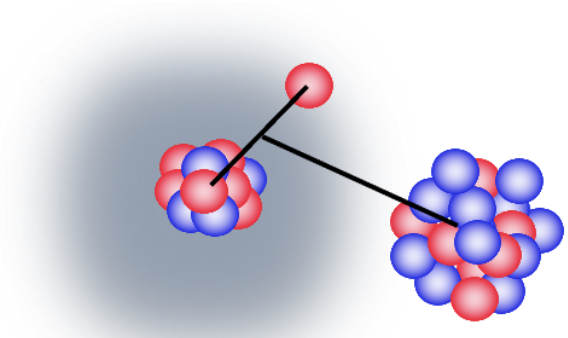
\+ ongoing efforts to derive optical potentials from the NCSMC...

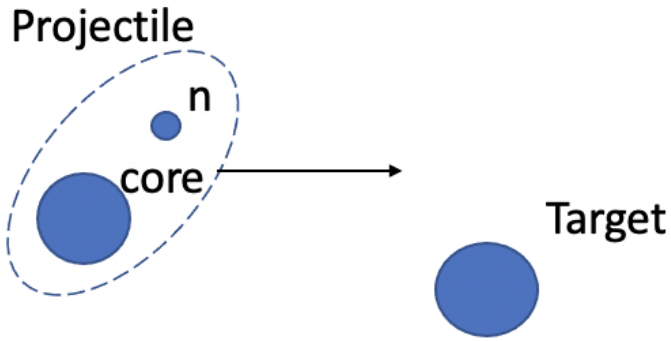
FRIB-TA program → whitepaper on optical potentials + website
[Hebborn *et al.* JPG 50 060501 (2023)]

For reactions involving heavier nuclei, one needs to make approximations

light nuclei & low E



heavier nuclei & higher E



To make accurate reaction predictions :

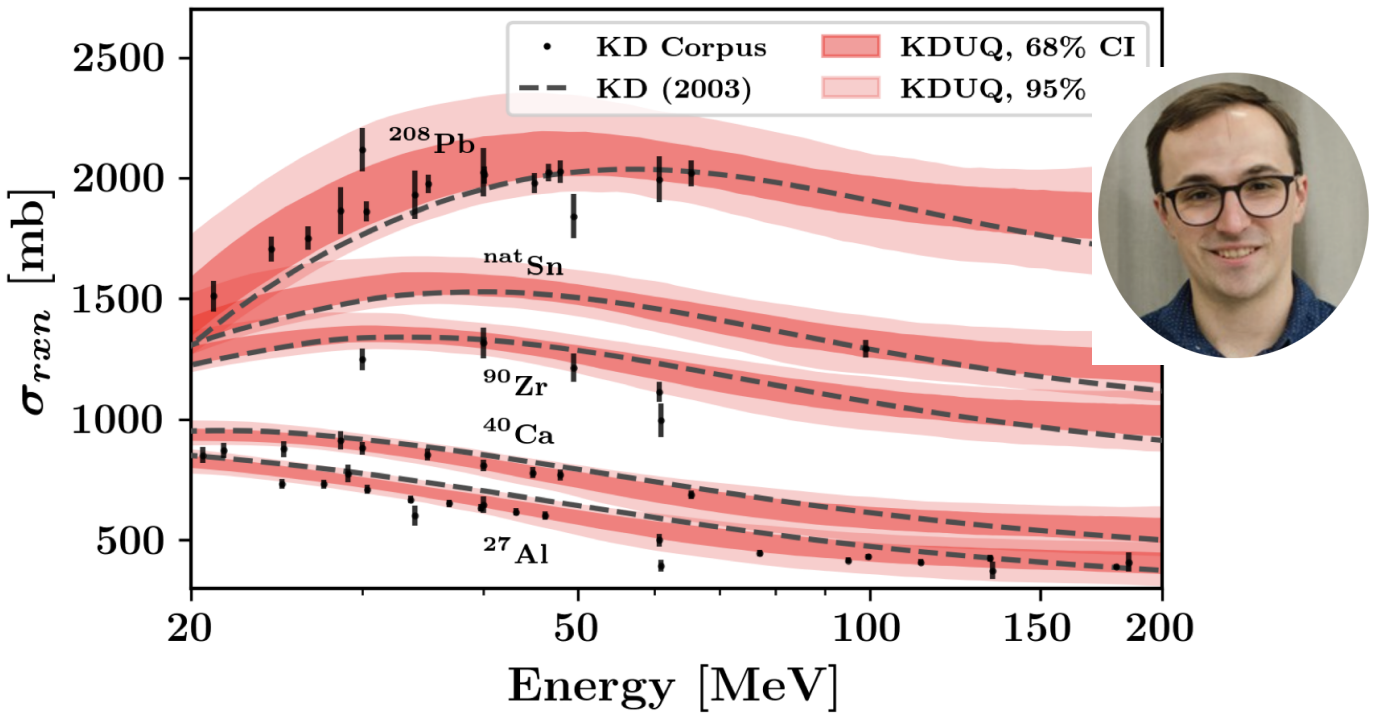
1) Choose dofs & use an accurate model

2) Interactions grounded in the underlying theory

3) **Have an estimate of model & input uncertainties**

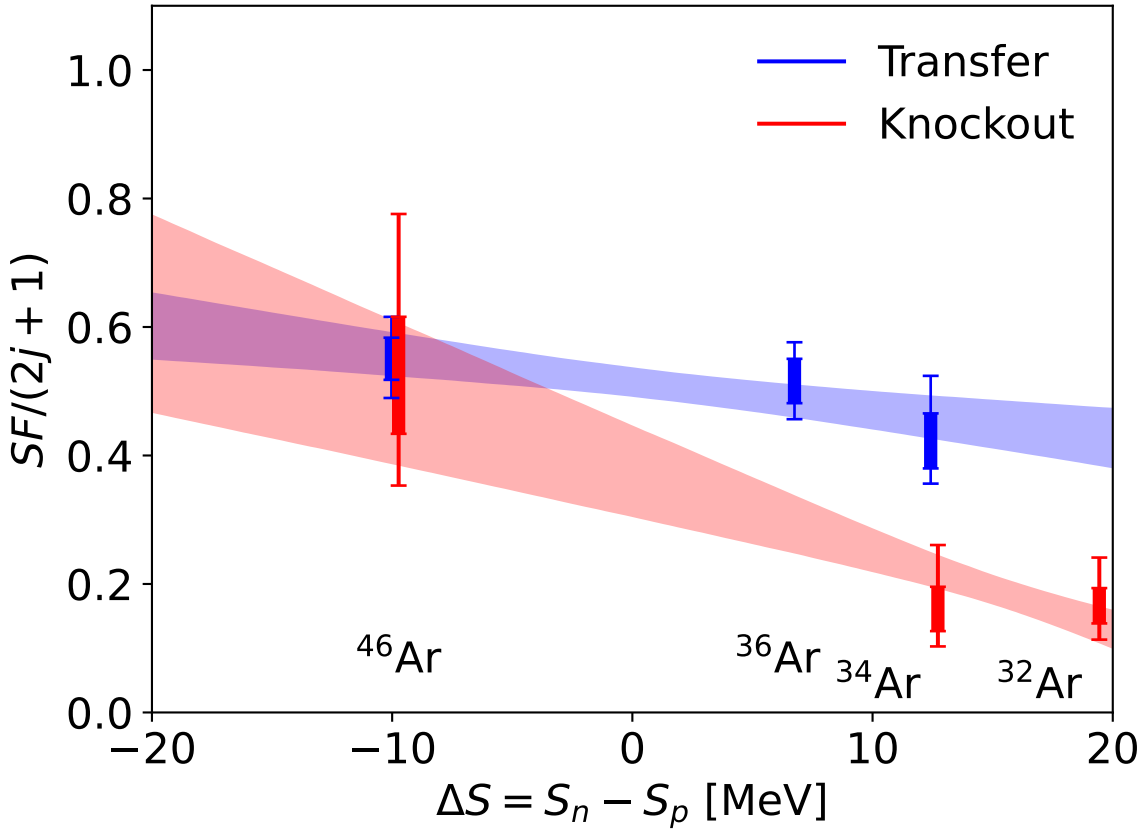
Impressive recent effort to quantify uncertainties for global parametrization of optical potential at LLNL

Global fit using Bayesian statistics by Cole Pruitt



[Pruitt *et al.* PRC 107, 014602 (2023) including python scripts !]

Using *consistent* s-p description, we quantify the uncertainties due to optical potentials in knockout & (p,d) reactions



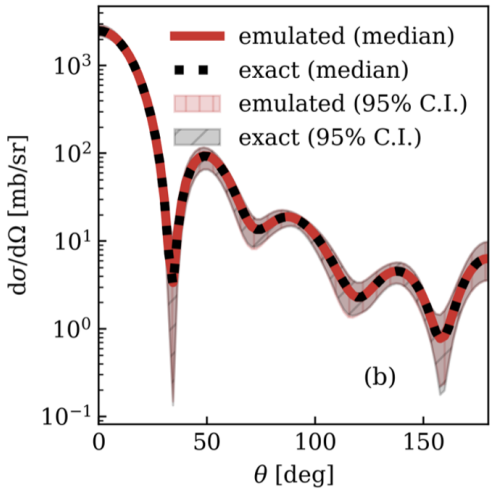
No discrepancy for $\Delta S \ll 0$ and likely model deficiencies for $\Delta S \gg 0$!

[C. Hebborn, F. Nunes, A. E. Lovell, PRL 131, 212503 (2023)]

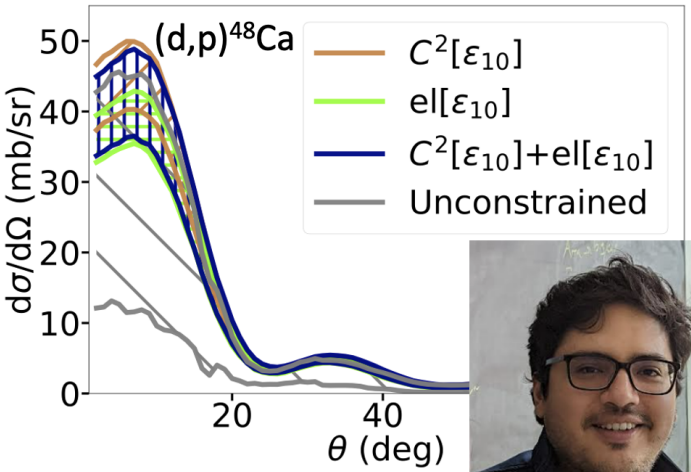
possible follow up with O. Sorlin *et al.*

At MSU, large effort pushing for a systematic quantification of uncertainties

Emulator for reaction study
[Drischler *et al.* PLB, 13677 (2021)]
https://github.com/bandframework/rose/]

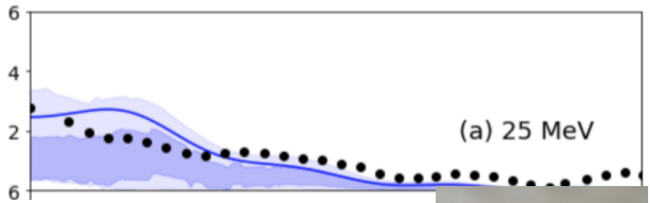


Complete quantification of uncertainties
& exploring exp. conditions to reduce them
[PRC 108 024601 (2023); PRC 100 064615 (2019]



M. Catacora Rios
(PhD student at MSU)

Propagating KDUQ into charge exchange
(in prep. with Remco and Filomena)



(p,n)48Ca, by A. Smith
(PhD student at MSU)

Pablo & Filomena

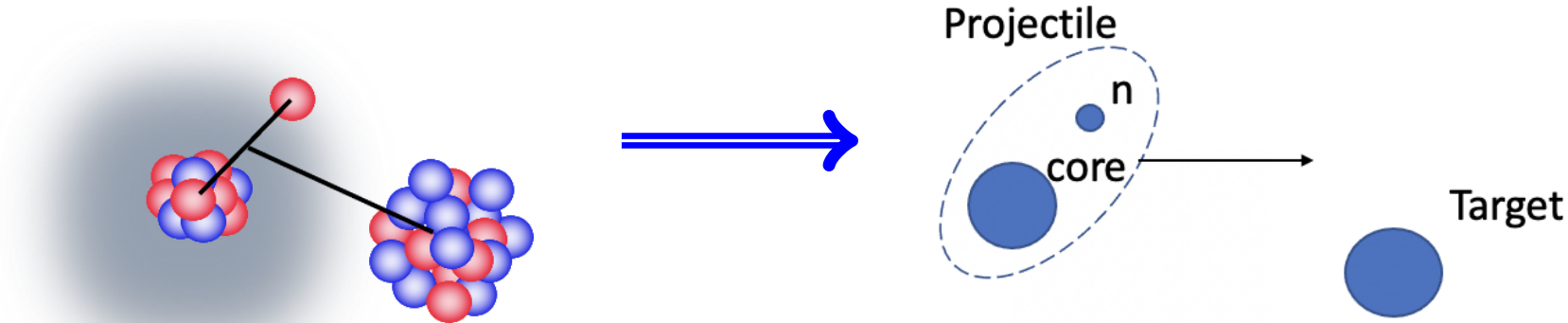
+ many other efforts not listed

BAND
Bayesian Analysis of Nuclear Dynamics

There are still challenges to improve our description of reactions

light nuclei & low E

heavier nuclei & higher E



To make accurate reaction predictions :

1) Choose dofs & use an accurate model
   Interest in improving eikonal description & moving to 4-body reactions

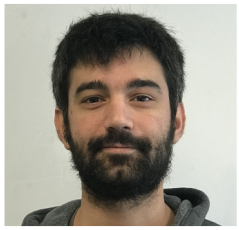
2) Interactions grounded in the underlying theory
   Halo-EFT & microscopic optical potentials

3) Have an estimate of model & input uncertainties
   Bayesian analysis of reactions

Thanks to my collaborators...

Lawrence Livermore National Laboratory

Sofia Quaglioni


Kostas Kravvaris

Gregory Potel

Jutta Escher

Cole Pruitt

JG|U

Pierre Capel

Los Alamos NATIONAL LABORATORY

Amy Lovell

Argonne NATIONAL LABORATORY

Melina Avila

TRIUMF

Petr Navratil

Peter Gysbers

IJCLab Irène Joliot-Curie

Guillaume Hupin

the few-body reaction group at MSU

Filomena Nunes

Chloë Hebborn

Pablo Giuliani

Grigor Sargsyan

Cate Beckman

Manuel Catacora Rios

Andy Smith

Daniel Shiu

& you for your attention !