Neutron-rich helium isotopes: complex made simple

Michigan State University (MSU),
Facility for Rare Isotope Beams (FRIB)

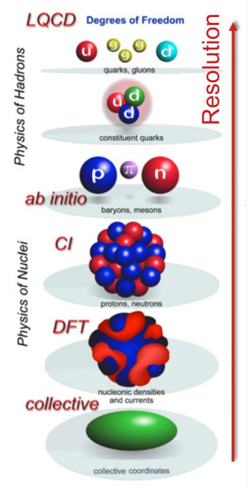
Kévin Fossez, J. Rotureau, W. Nazarewicz

October 23, 2018

NTSE - 2018

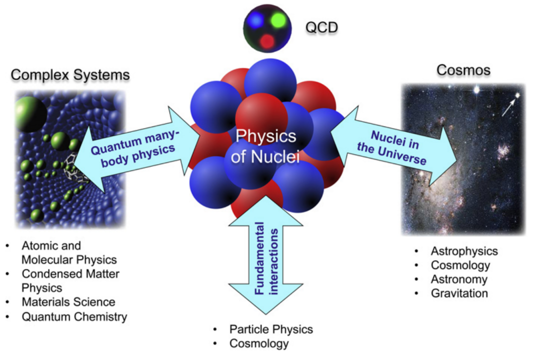
Work supported by:
DOE: DE-SC0013365 (Michigan State University)
DOE: DE-SC0017887 (Michigan State University)
DOE: DE-SC0008511 (NUCLEI SciDAC-4 collaboration)
NSF: PHY-1403906

The nuclear problem



- A multi-scale problem.
- At least two kinds of particles involved.
- A residual, but still strong, interaction.
- Emergent properties.

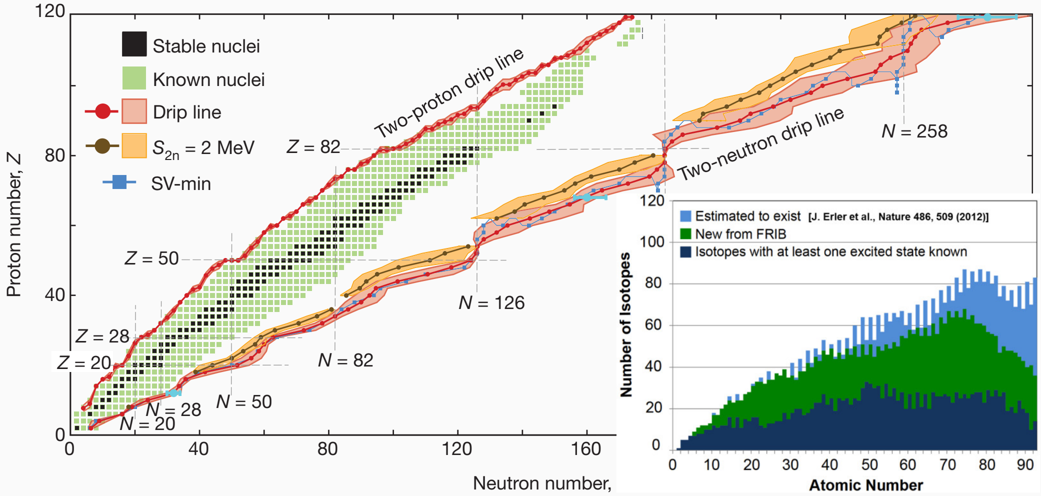
In the middle of the quantum ladder.



From W. Nazarewicz, J. Phys. G **43**, 044002 (2016)

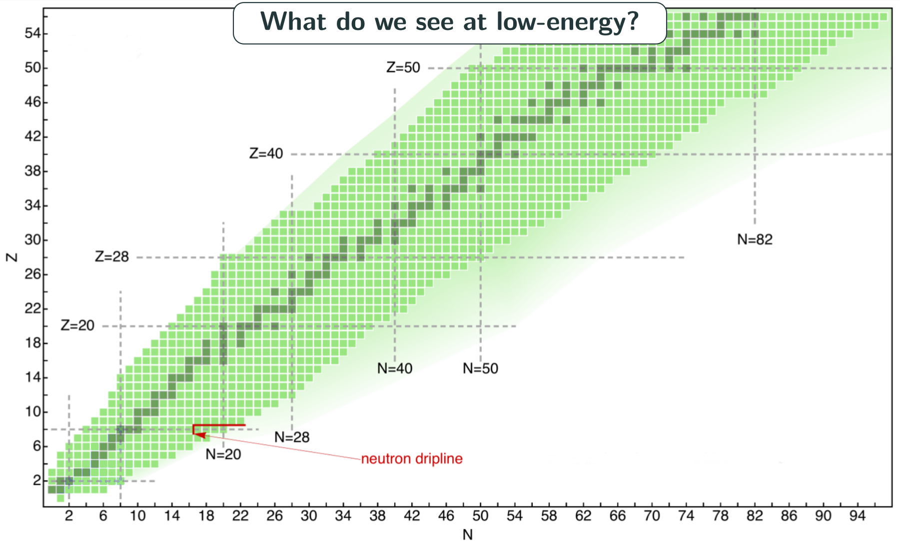
A fundamental problem!

Exploration of the drip lines



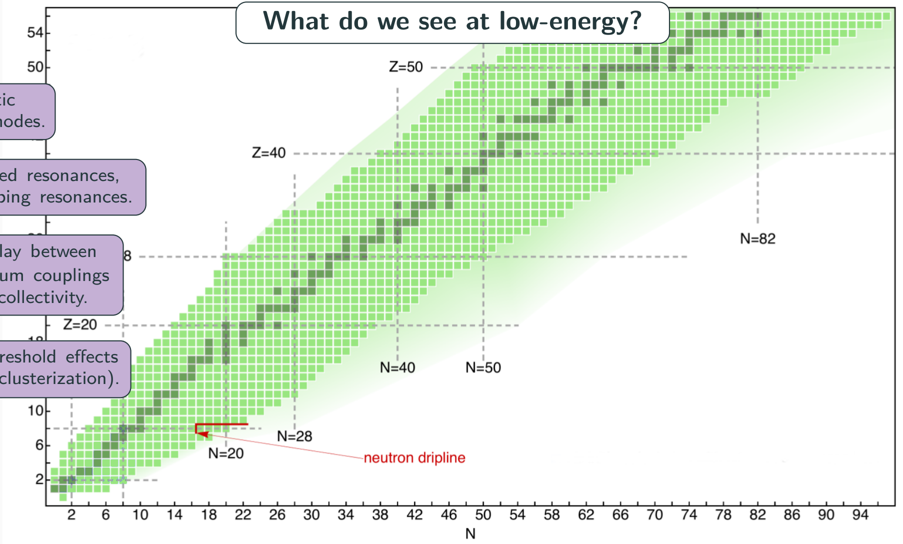
J. Erler *et al.*, Nature **486**, 509 (2012). Right figure stolen from A. Gade's talk.

Low-energy nuclear physics: emergence of a new paradigm



Adapted from H. Hergert's Segre map.

Low-energy nuclear physics: emergence of a new paradigm



Exotic decay modes.

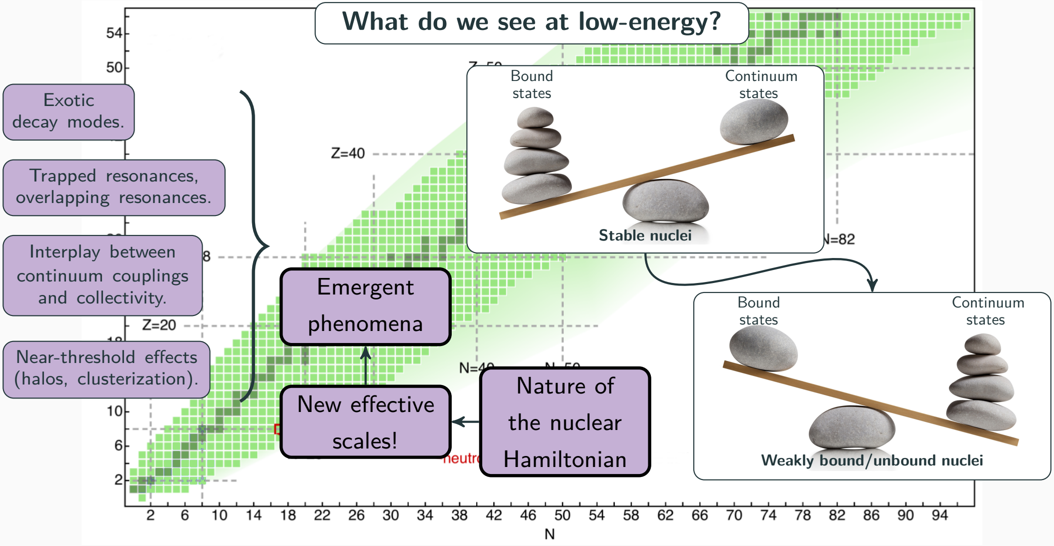
Trapped resonances, overlapping resonances.

Interplay between continuum couplings and collectivity.

Near-threshold effects (halos, clusterization).

Adapted from H. Hergert's Segre map.

Low-energy nuclear physics: emergence of a new paradigm

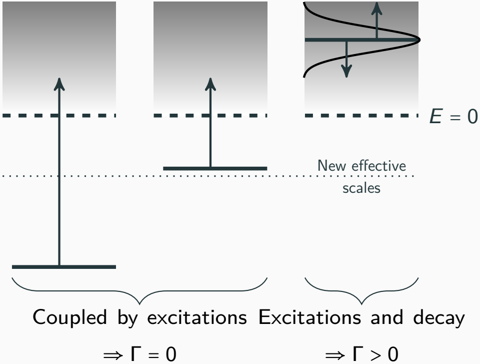


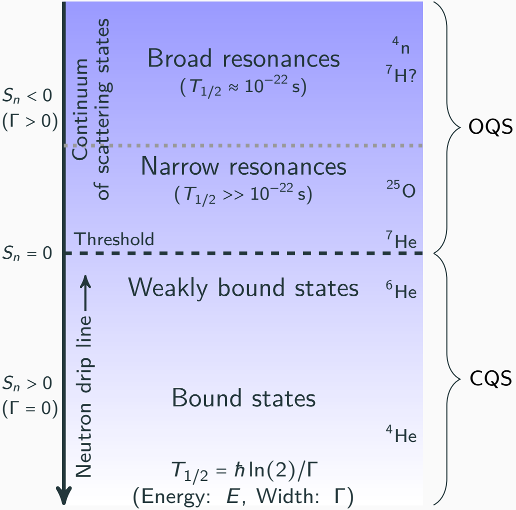
Adapted from H. Hergert's Segre map.

Continuum couplings: a general problem

Physics close to the threshold:

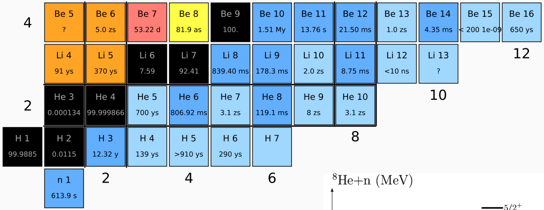
- The Hamiltonian couples bound states with continuum states.





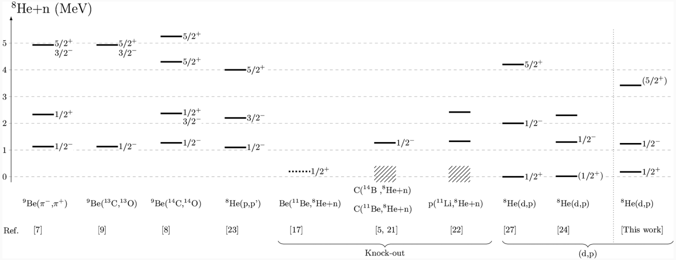
Neutron-rich helium isotopes as open quantum systems

Few-body, emergent effective scales, continuum couplings, exotic states...



- Two- and four-body halos (^{6,8}He).
- Broad resonances ($1/2^-$ in ^{5,7}He).
- Many th. results, high experimental interest.

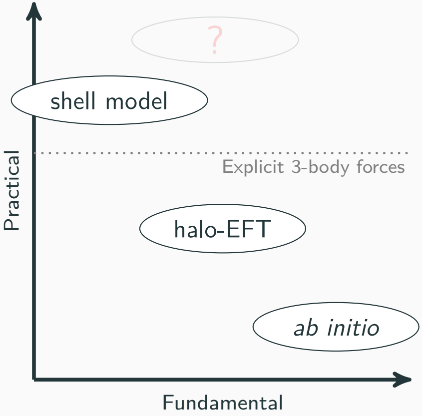
- Uncertain case of ^{9}He.
- Very little known on ^{10}He.



T. Al Kalanee *et al.*, Phys. Rev. C **88**, 034301 (2013)

What are the options to describe ^{9,10}He?

Practical *vs.* fundamental:



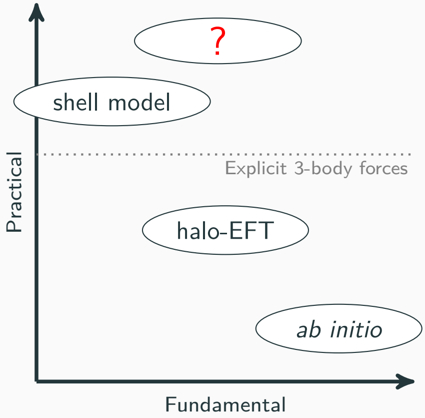
What do we want to describe and with which precision? Is our description accurate? (UQ)

- **Shell model** approaches with continuum give very decent results, but they suffer from systematic uncertainties (CSM, GSM).
- **Halo effective field theories** require three-body forces at LO in ^{6}He, not so practical.
- ***Ab initio*** methods are limited by the quality of their input (forces) and computational cost.

Adding continuum couplings increases the computational cost dramatically.

What are the options to describe ^{9,10}He?

Practical *vs.* fundamental:



What do we want to describe and with which precision? Is our description accurate? (UQ)

- **Shell model** approaches with continuum give very decent results, but they suffer from systematic uncertainties (CSM, GSM).
- **Halo effective field theories** require three-body forces at LO in ^{6}He, not so practical.
- ***Ab initio*** methods are limited by the quality of their input (forces) and computational cost.

Adding continuum couplings increases the computational cost dramatically.

^{9,10}He: complex made simple

Problem:

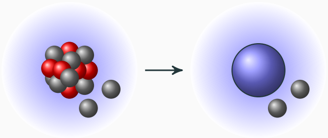
- Experimentalists need about 100 keV precision on energy spectra of exotic nuclei.

Strategy:

- Decrease systematic uncertainties in an effective approach by doing a parameter reduction.

1) ^{4}He is a good core.

→ Fit Woods-Saxon potential on $n - {}^4$He phase-shifts.



2) In the valence space: N-N → n-n ($T = 1$ only).

3) n-n → n—n (dilute, weak binding).

→ Dominant central term in the channel ($S = 0, L = 0$) (halo EFT).

4) Simple, but not too simple.

→ Three Gaussian functions for n-n.

→ Fixed ranges from FHT interaction.

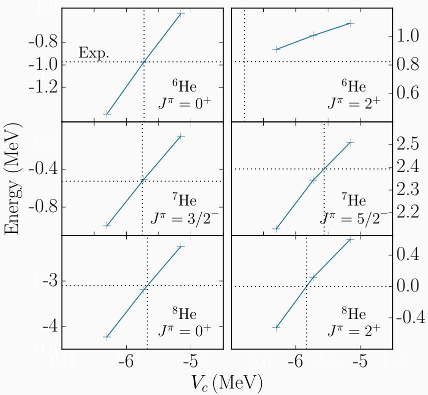
→ L even channels in n-n.

H. Furutani *et al.*, Prog. Theor. Phys. **62**, 981 (1979), Y. Jaganathen *et al.*, Phys. Rev. C **96**, 054316 (2017)

^{9,10}He: complex made simple

How precise can this approach be?

- Only one prefactor V_c in the interaction to fit on $^{6-8}$He.



- One obtains a series of values of V_c.
- $V_c^{(\mathrm{opt})}$ (mean), σ (standard deviation).
- The uncertainty on the energy coming from the interaction is given by:

$$\Delta E = \frac{1}{2}\left|E(V_c^{(\mathrm{opt})} + \sigma) - E(V_c^{(\mathrm{opt})} - \sigma)\right|.$$

→ Energies predicted within tens of keV precision!

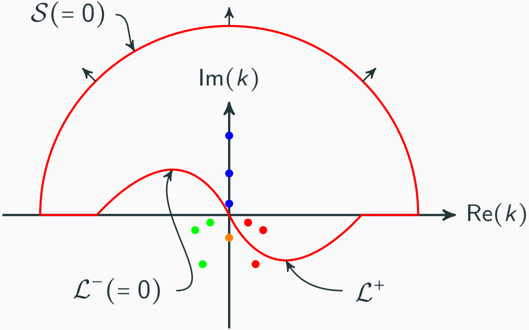
Widths are highly correlated to energies and do not provide additional constraints.

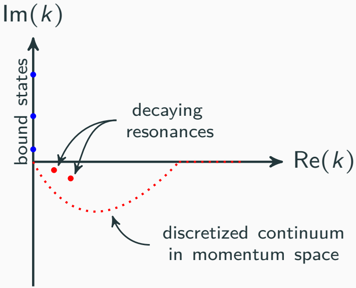
Space: s, p Berggren shells (≈ 35 per lj), d HO shells (6 per lj). Total ≈ 120 shells.

Basis expansion for continuum couplings

The Berggren basis:

- Single particle basis including bound states, decaying resonances and scattering states.



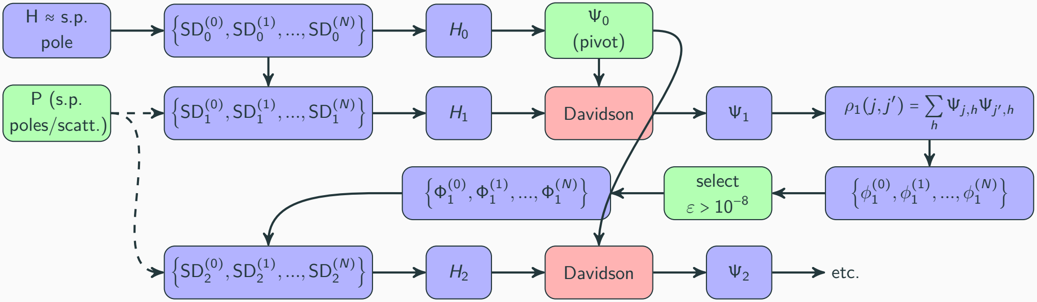


$$\sum_{n\in(b,d)} |u_\ell(k_n)\rangle\langle\tilde{u}_\ell(k_n)| + \int_{\mathcal{L}^+} dk\, |u_\ell(k)\rangle\langle\tilde{u}_\ell(k)| = \hat{\mathbb{1}}_{\ell,j}.$$

T. Berggren, Nucl. Phys. A **109**, 265 (1968),

Many-body method

Density matrix renormalization group for open quantum systems (Gamow-DMRG).



Reference space: s.p. poles of the S-matrix. Medium: continuum states.

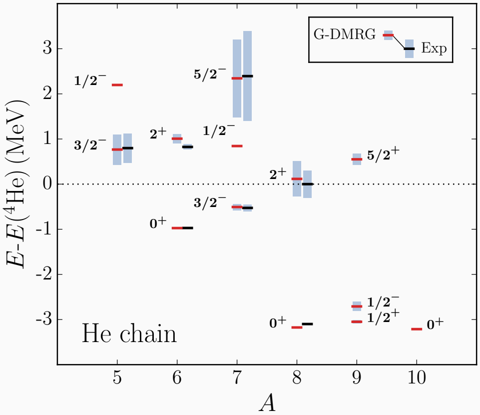
Can handle much larger spaces than standard diagonalization.

$\rightarrow \approx 1000$ cores vs. ≈ 20 cores for dim $= 10^8$ (dense).

(G-DMRG + natural orbits!)

J. Rotureau *et al.*, Phys. Rev. Lett. **97**, 110603 (2006), J. Rotureau *et al.*, Phys. Rev. C **79**, 014304 (2009)

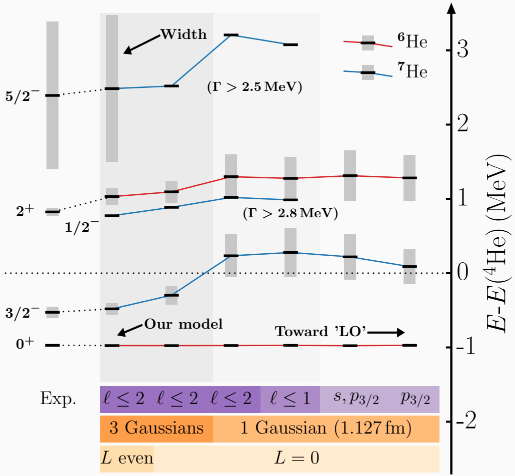
Predictions:



- Broad $1/2^-$ state in ^{7}He.
- Parity inversion in ^{9}He.
- Overall ^{9}He spectrum consistent with exp. results based on (d,p) reactions.
- Similar partial wave occupations in the g.s. of ^{8,9,10}He except for $s_{1/2}$.
- Possible two-neutron decay in ^{10}He including uncertainties.

→ Similar energy patterns between ^{8,9,10}He and ^{26,27,28}O.

Can we learn something useful for halo EFT?

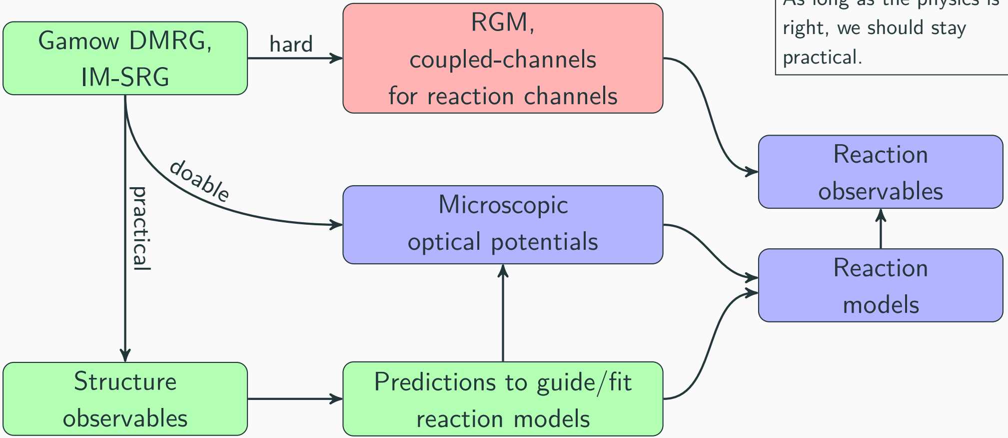


A crude connection with halo EFT:

- At LO, halo EFT has one central two-body contact term in the channel $(S = 0, L = 0)$, regularized by a Gaussian function whose range is adjusted with V_c in the $s_{1/2}$ (or $s_{1/2}$ and $p_{3/2}$) model space.
- We have fixed-range Gaussian functions and a fixed Woods-Saxon core.

→ Changing the range of the medium-range Gaussian function in our model by ±20% and readjusting V_c using the g.s. of ^{6}He yields identical results ('LO').

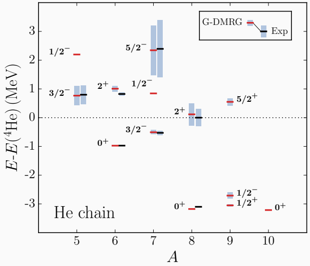
From nuclear structure to reactions



As long as the physics is right, we should stay practical.

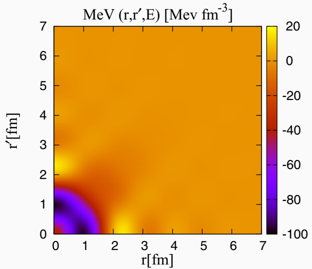
From nuclear structure to reactions

Structure (under control):



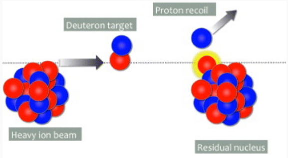
(present work)

Microscopic optical potentials:



(à la J. Rotureau *et al.*)

Reactions (inclusive formalism):



(G. Potel *et al.*)

Figure for (d, p) reaction from K. L. Jones, Physica Scripta **2013**, T152 (2013)
J. Rotureau *et al.*, Phys. Rev. C **95**, 024315 (2017)

Conclusion

The spectra of $^{8-10}$He can be precisely described in a ^{4}He-plus-valence neutron picture.
→ Phenomenology guided by effective scale arguments.

- **Achievements:**

→ Largest ever continuum space for predictions on $^{9-10}$He spectra using Gamow-DMRG.
→ Prediction of energies within tens of keV.

- **Open questions:**

→ Can halo EFT be done differently?
→ What is the structure of ^{10}He?
→ Can this approach be applied to other neutron-rich isotopes (different core)?

We developed an effective approach that provides a reliable alternative to *ab initio* methods for energies and widths.

Thank you for your attention!

arxiv/1806.02936

Michigan State University:

- H. Hergert.
- S. Bogner.
- S. König.

References (th.)

***Ab initio* (without continuum):**

- B. S. Pudliner *et al.*, Phys. Rev. C **56**, 1720 (1997).
- E. Caurier *et al.*, Phys. Rev. C **73**, 021302(R) (2006).
- K. M. Nollett *et al.*, Phys. Rev. Lett. **99**, 022502 (2007).
- A. F. Lisetskiy *et al.*, Phys. Rev. C **78**, 044302 (2008).
- K. M. Nollett, Phys. Rev. C **86**, 044330 (2012).

***Ab initio* (with continuum to some extent):**

- G. Hagen *et al.*, Phys. Lett. B **656**, 169 (2007).
- G. Papadimitriou *et al.*, Phys. Rev. C **88**, 044318 (2013).
- S. Baroni *et al.*, Phys. Rev. Lett. **110**, 022505 (2013).
- S. Baroni *et al.*, Phys. Rev. C **87**, 034326 (2013).
- M. Vorabbi *et al.*, Phys. Rev. C **97**, 034314 (2018).

Shell model with continuum:

- N. Michel *et al.*, Revista Mexicana De Fisica **5 Suplemento 2**, 74 (2004).
- A. Volya *et al.*, Phys. Rev. Lett. **94**, 052501 (2005).
- J. Rotureau *et al.*, Phys. Rev. Lett. **97**, 110603 (2006).
- G. Papadimitriou *et al.*, Phys. Rev. C **84**, 051304(R) (2011).
- Y. Jaganathen *et al.*, Phys. Rev. C **96**, 054316 (2017).

Halo effective field theory (halo-EFT):

- C. A. Bertulani *et al.*, Nucl. Phys. A **712**, 37 (2002).
- P. F. Bedaque *et al.*, Phys. Lett. B **569**, 159 (2003).
- J. Rotureau *et al.*, Few-Body Syst. **54**, 725 (2013).
- C. Ji *et al.*, Phys. Rev. C **90**, 044004 (2014).

(NC)GSM vs DMRG