Alpha clustering and nuclear forces

Report on recent activities

Kévin Fossez
FRIB Theory Fellow
ANL & FRIB, MSU

Low-Energy
Community Meeting

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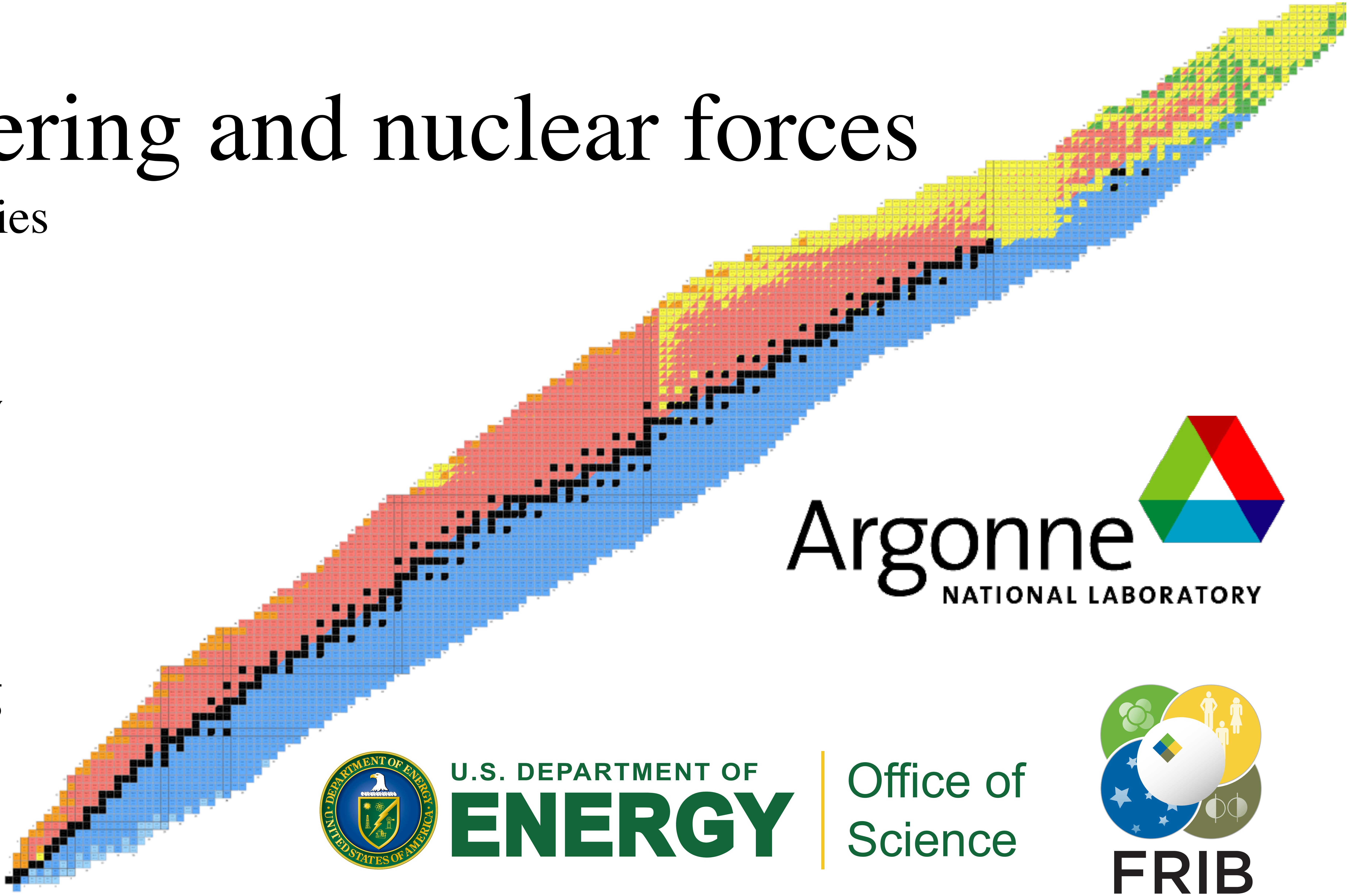
2020

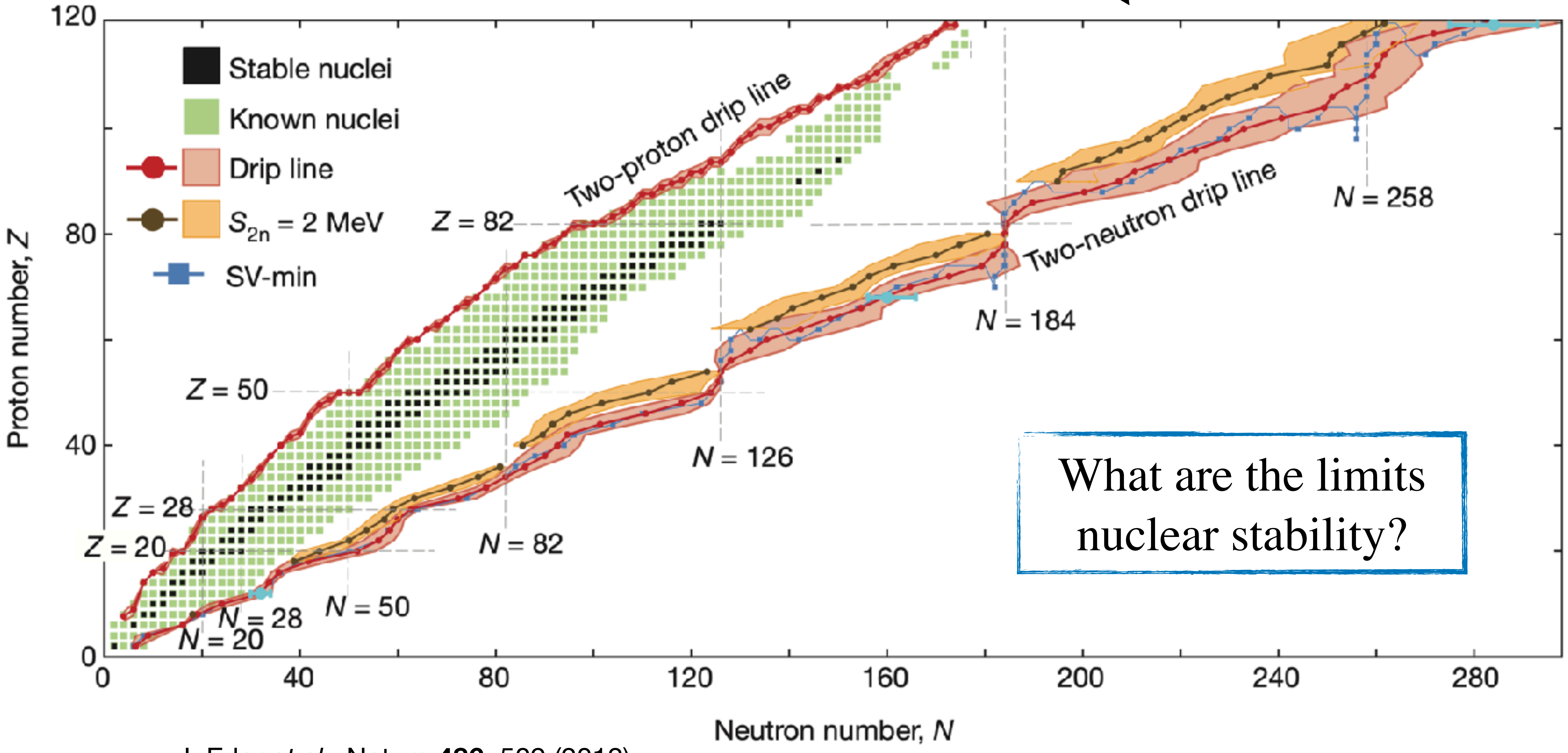


DOE: DE-SC0013617 (Office of Nuclear Physics, FRIB Theory Alliance)

Science Focus

How does subatomic matter organize itself and what phenomena emerge?

Long Range Plan for Nuclear Science (2015)



J. Erler *et al.*, Nature **486**, 509 (2012)

What are the limits nuclear stability?

How do nuclear properties emerge?

- Shell structure
- Deformation
- Rotational bands
- Clustering

- Halos
- Exotic decay modes
- Resonances

Not just describe, understand…

Scientific program: overview

Goal: Exploration of the drip lines in the FRIB era. Obtain an accurate description of light and medium-mass exotic nuclei.

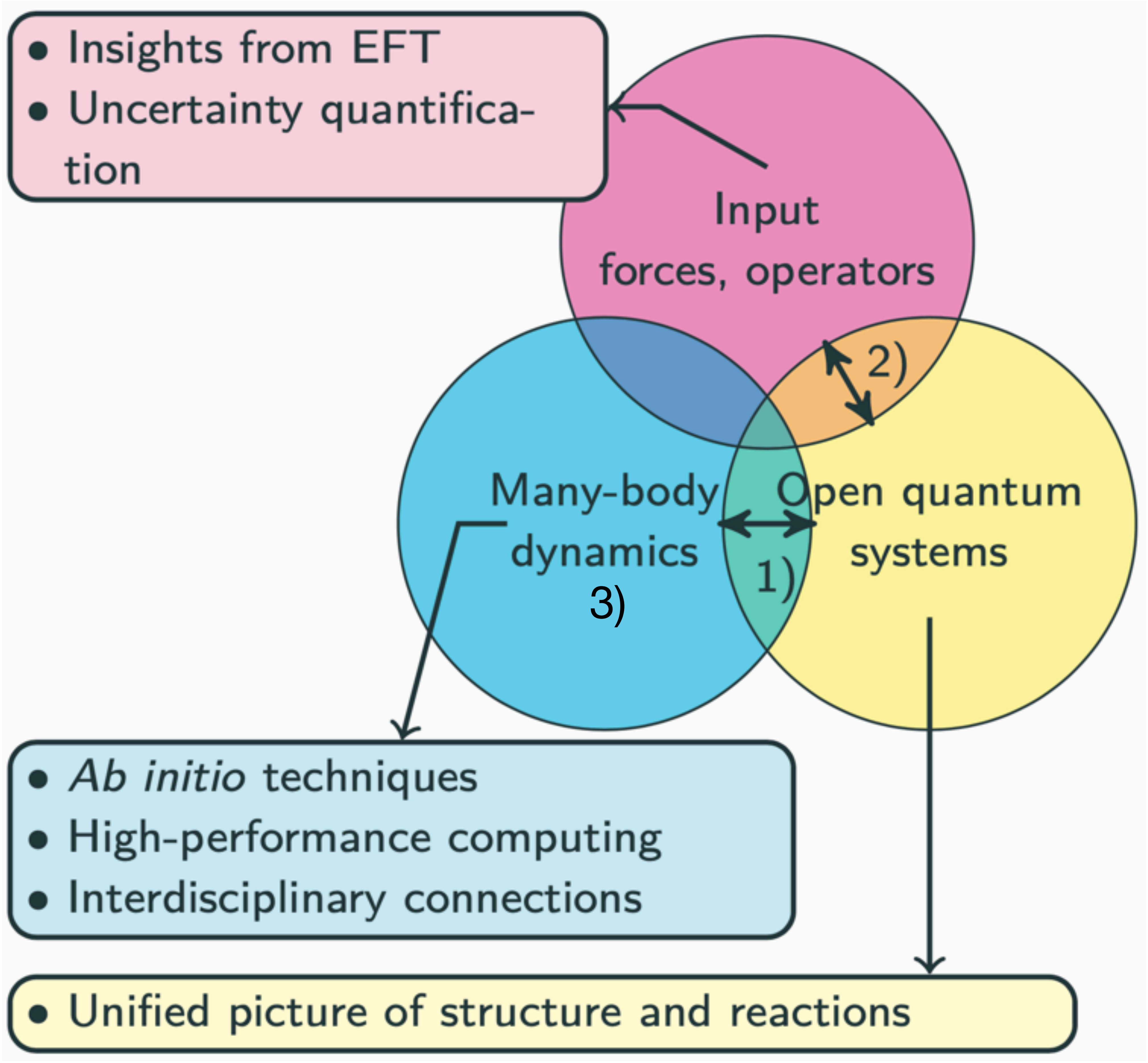
1) Extension of the ab initio IM-SRG method to continuum couplings. — Predictive power

2) Development of an effective field theory for the shell model. — Precision

3) Optimization of the DMRG algorithm to treat larger model spaces.

★ Interdisciplinary developments:
- Eigenvector continuation.
- Bayesian uncertainty quantification.
- Quantum computing.

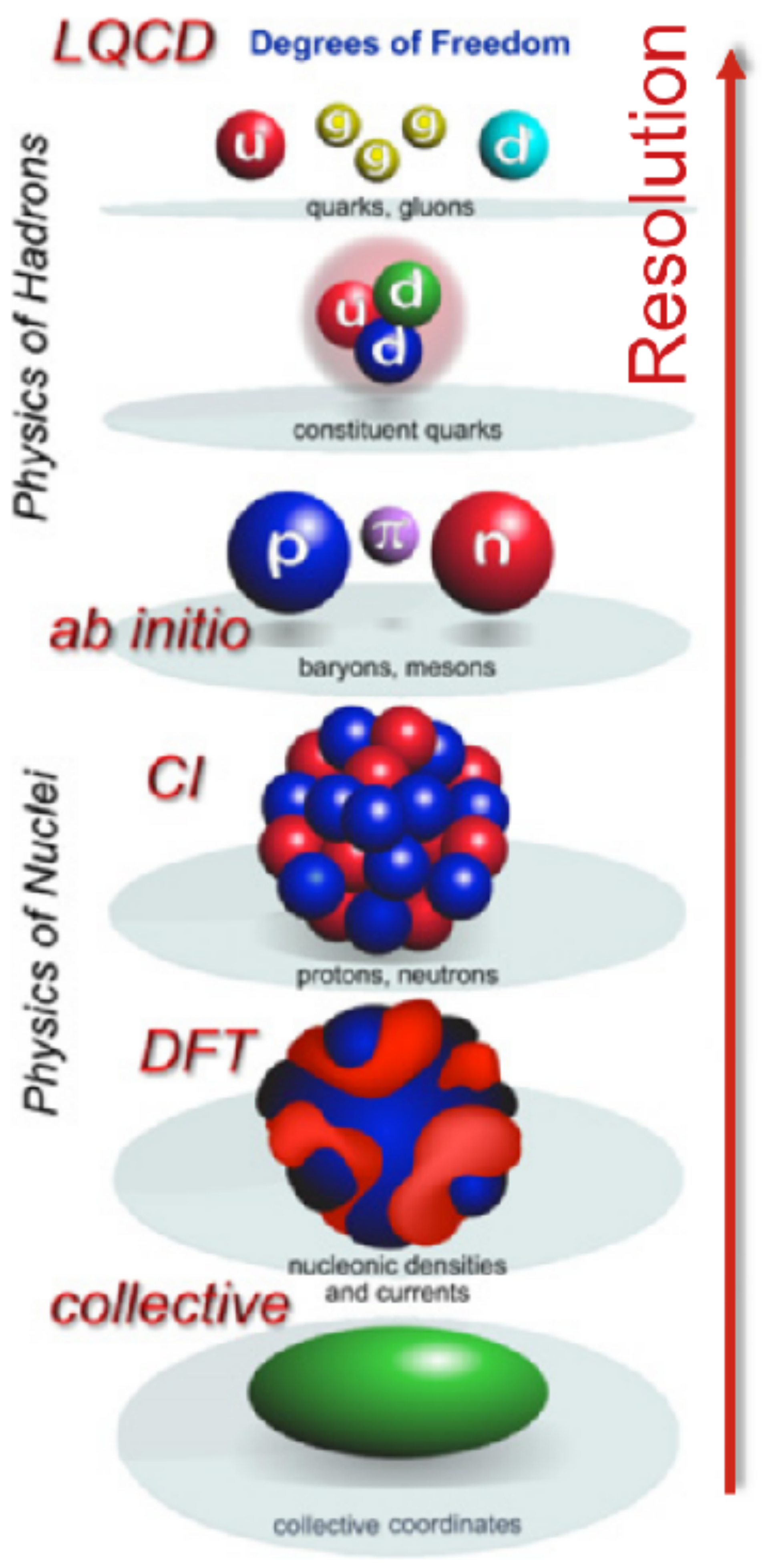
Leverage novel techniques & technologies



Adapted from J. Phys. G **43** 044002 (2016)

Meanwhile…

Connecting ab initio with the shell model



EFT:
- Scale separation
- Active degrees of freedom
- Symmetries of the Hamiltonian
- Power counting

Pionless EFT for the valence interaction.

L. Huth *et al.*, Phys. Rev. C **98**, 044301 (2018)

(Try to) Generalize halo EFT:

C. A. Bertulani *et al.*, Nucl. Phys. A **712**, 37 (2002)
R. Higa, Few-Body Syst. **50**, 251 (2011)
E. Ryberg *et al.*, Phys. Rev. C **89**, 014325 (2014)
C. Ji *et al.*, Phys. Rev. C **90**, 044004 (2014)
J. Rotureau *et al.*, Few-Body Syst. **54**, 725 (2013)

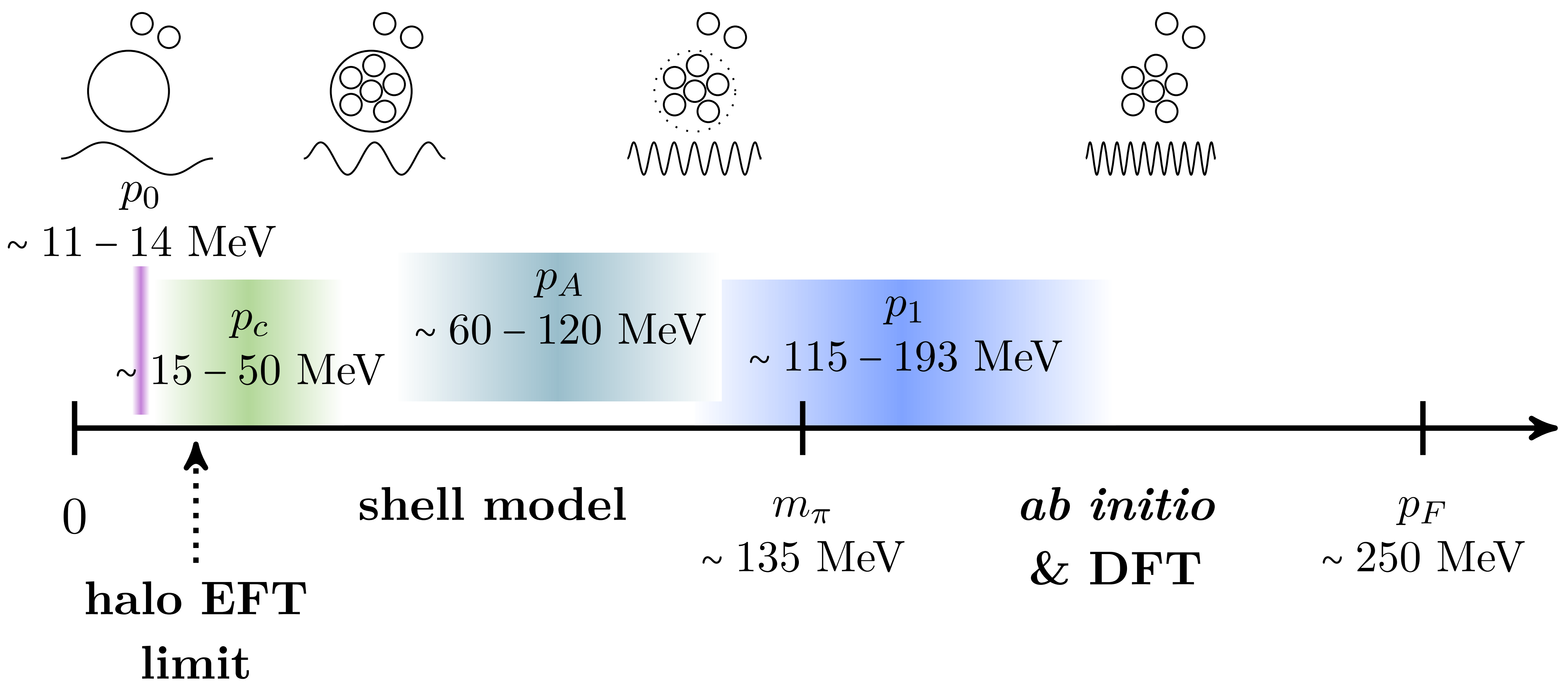
Formalism & implementation:
~80% complete.

- When is an effective core a good core?

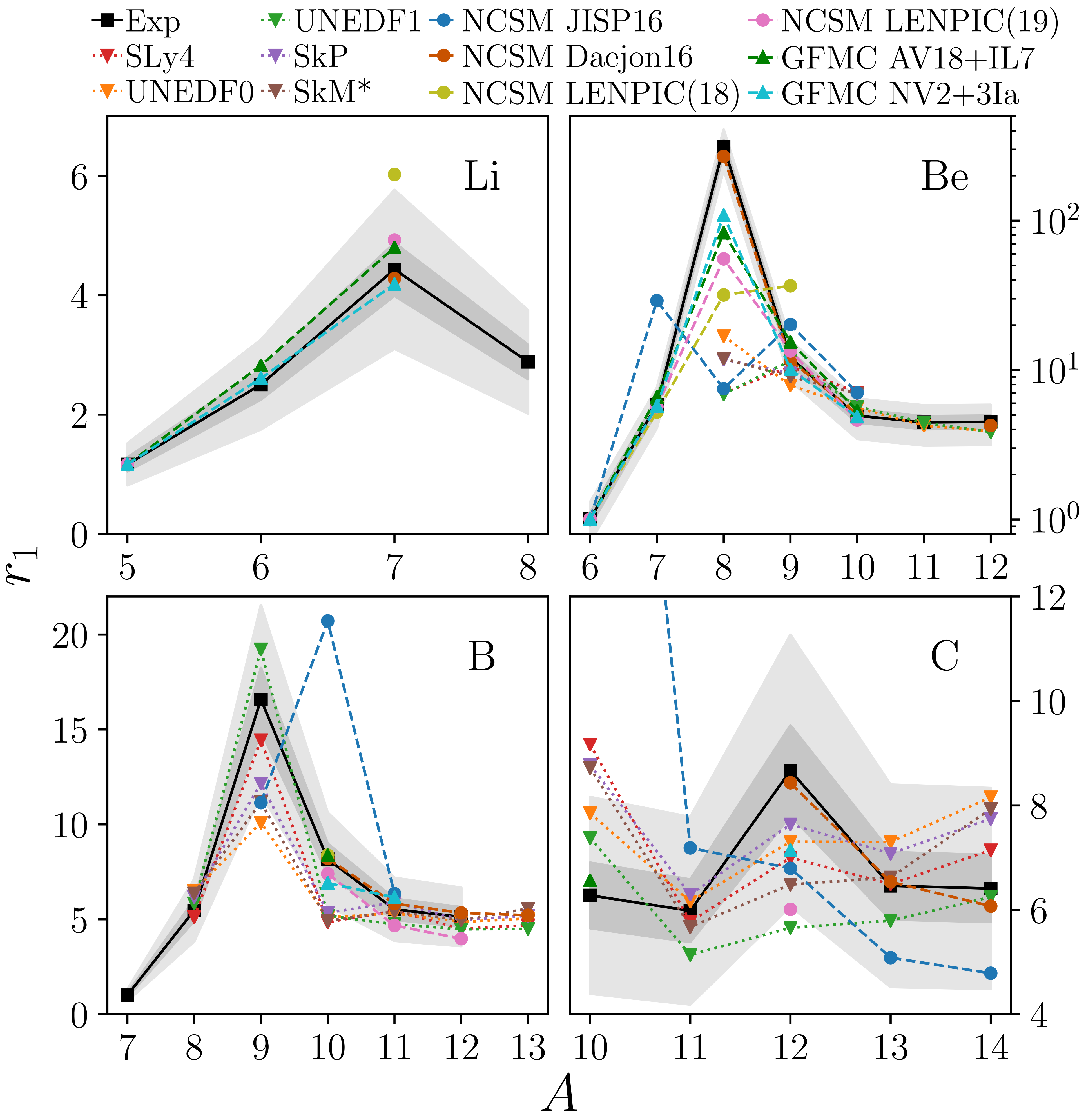
$$\alpha(A, A_c) = \frac{\bar{E}_{\textbf{remove one valence nucleon}}}{\bar{E}_{\textbf{remove one core nucleon}}}$$

In practice, good core for $\alpha(A, A_c) < 0.3$.

- **If a core is just a cluster, can we quantify the degree of clustering ($A \approx (A - \alpha) + \alpha$)?**



Alpha clustering from binding energies



Gray: 10% and 30% relative error bands (Exp).

- Simple, sensitive measure of alpha clustering in light nuclei.

$$r_1(A) = \frac{E(A) - E_\alpha}{Q_\alpha(A)} \approx \frac{E_{\textbf{remove valence nucleons one-by-one}}}{E_{\textbf{remove an alpha}}}$$

- Justified from perturbation theory for two interacting clusters.

  Crude, unnormalized approximation for $|\langle A|(A-\alpha)+\alpha\rangle|^2$.

Impact: First systematic test of nuclear forces on alpha clustering!

- Alpha clustering underestimated in ^{8}Be and ^{12}C (even by the best).
- Critical role of three-body forces in alpha clustering.
- Important implications in medium-mass nuclei (see next slide).

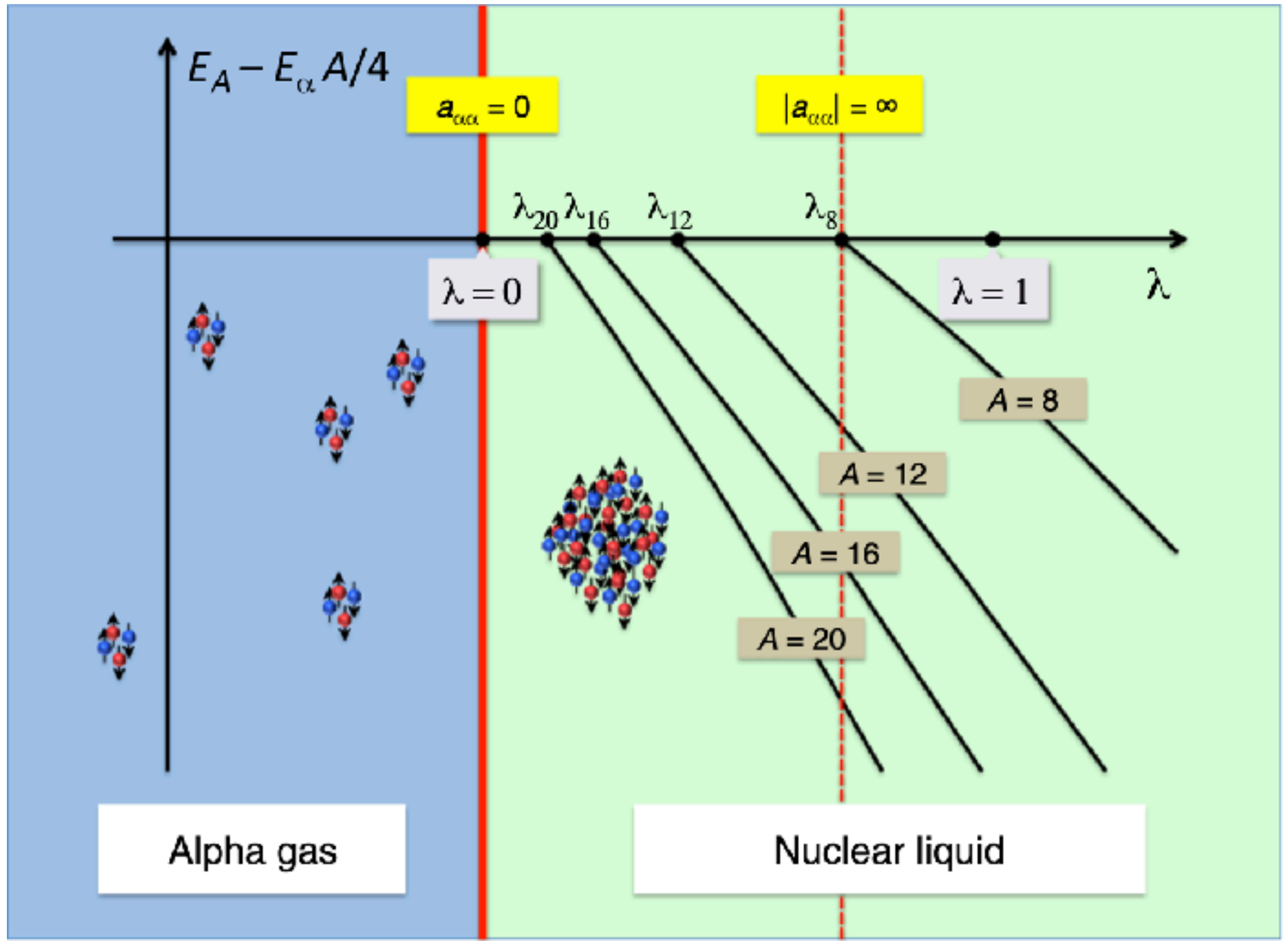
Collaboration with R. Holt (ANL/Caltech) on the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction.

K. Fossez, submitted (2020)

Alpha clustering from binding energies

Why underestimating alpha clustering is a big problem for future ab initio studies?

J. -P. Ebran *et al*., Nature **487**, 341 (2012)
M. Girod *et al*., Phys. Rev. Lett. **111** 132503 (2013)
J. -P. Ebran *et al*., Phys. Rev. C **89** 031303(R) (2014)
L. M. Satarov *et al*., Phys. Rev. C **101**, 024913 (2020)



S. Elhatisari *et al*., Phys. Rev. Lett. **117**, 132501 (2016)

Nuclear matter near a phase transition, controlled by the strength and locality of the interaction.

In medium-mass and heavy nuclei, this is dominated by the Wigner SU(4) symmetric part of the interaction.

It also controls the ground state of the alpha particle.

S. Elhatisari *et al*., Nature **528**, 111 (2015)
Bing-Nan Lu *et al*., Phys. Lett. B **797**, 134863 (2019)

Wrong α-clustering → wrong Wigner SU(4) → wrong binding.

Nuclear forces must capture alpha clustering properly to be valid beyond light nuclei.

K. Fossez, submitted (2020)

Alpha clustering from binding energies

How precise should you be on binding energies?

Input: $\{E(A_i)\}$ ⟶ Model ⟶ Output: $\{r_1^{\exp}(A_i) \pm 10\,\%\}$

Back propagate uncertainties

Nucleus	E_{exp}	$\mu(E)$	$\sigma(E)$	Nucleus	E_{exp}	$\mu(E)$	$\sigma(E)$
^{5}He	-27.56	-27.44	114	^{12}Be	-68.65	-68.65	181
^{6}He	-29.27	-29.27	96	^{8}B	-37.74	-37.75	215
^{7}He	-28.86	-28.86	137	^{9}B	-56.31	-56.32	152
^{8}He	-31.4	-31.39	141	^{10}B	-64.75	-64.77	8
^{5}Li	-26.33	-26.33	143	^{11}B	-76.2	-76.22	20
^{6}Li	-31.99	-32.00	3	^{12}B	-79.57	-79.58	169
^{7}Li	-39.25	-39.25	4	^{13}B	-84.45	-84.44	216
^{8}Li	-41.28	-41.28	136	^{14}B	-85.42	-85.42	217
^{9}Li	-45.34	-45.34	207	^{8}C	-24.81	-24.82	219
^{6}Be	-26.92	-26.91	138	^{9}C	-39.04	-39.04	210
^{7}Be	-37.6	-37.61	2	^{10}C	-60.32	-60.31	165
^{8}Be	-56.5	-56.49	141	^{11}C	-73.44	-73.45	15
^{9}Be	-58.16	-58.21	124	^{12}C	-92.16	-92.16	159
^{10}Be	-64.98	-64.99	120	^{13}C	-97.11	-97.17	146
^{11}Be	-65.48	-65.47	176	^{14}C	-105.3	-105.3	144

$$r_1(A) = \frac{E(A) - E_\alpha}{Q_\alpha(A)}$$

Easy way to check or adjust an interaction:

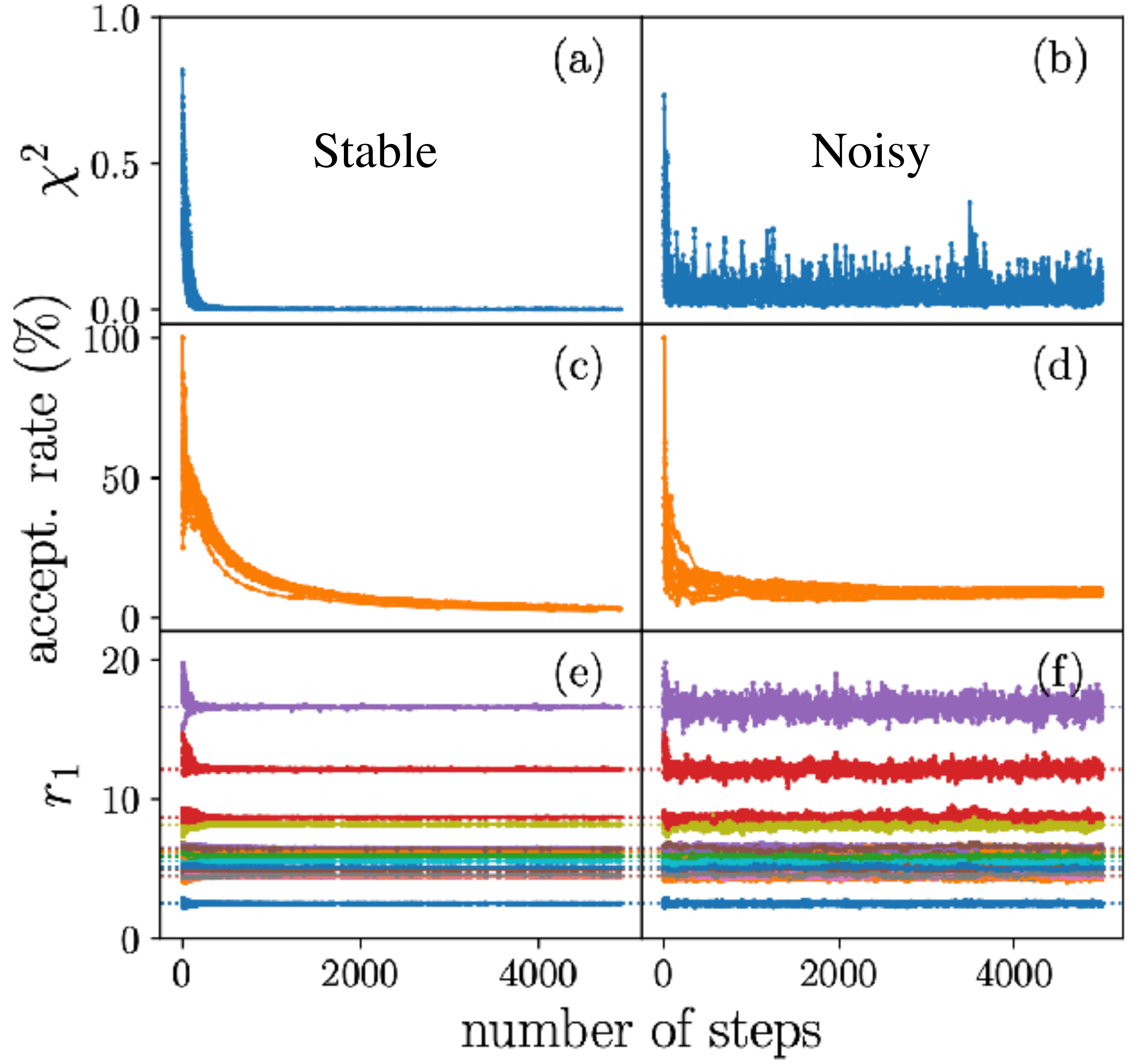
^{6,7}Li, ^{7}Be, ^{10,11}B, ^{11}C

Measure ANCs
$|\langle A | (A-\alpha) + \alpha \rangle|^2$
at ATLAS

Bayesian inference of uncertainties using a Markov chain Monte Carlo algorithm.

"machine learning"

K. Fossez, submitted (2020)



Thank you for your attention!

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