Ab Initio Spectroscopy of Open-Shell Medium-Mass Nuclei: Merging NCSM and In-Medium SRG

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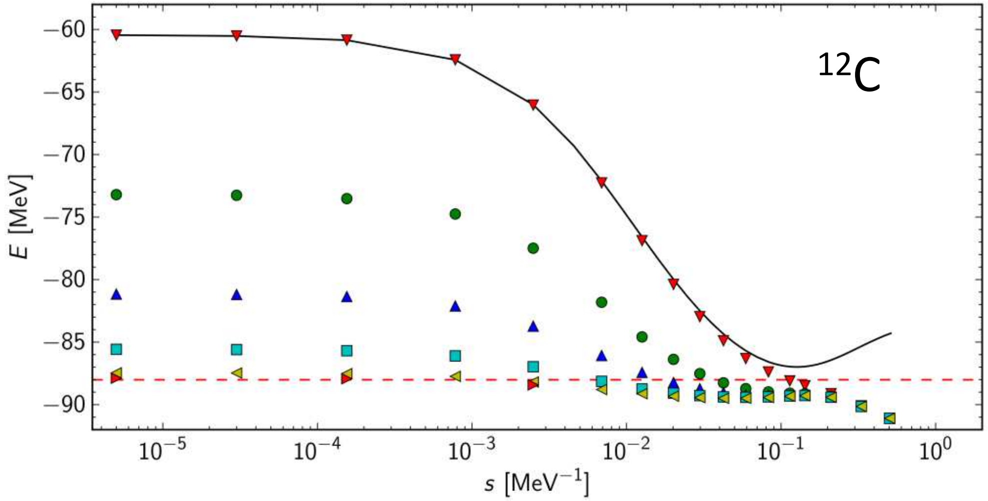

No-Core Shell Model (NCSM)

Barrett, Vary, Navratil, ...

one of the most powerful
exact ab initio methods
for the p- and lower sd-shell

- construct Hamilton matrix using **basis of HO Slater determinants** truncated w.r.t. HO excitation quanta N_max
- solve **large-scale eigenvalue problem** for a few smallest eigenvalues
- range of applicability limited by **factorial growth** of basis with N_max & A

In-Medium Similarity Renormalization Group

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Tsukiyama, Bogner, Schwenk, Hergert,..

use flow equation for
normal-ordered Hamiltonian to decouple
the **reference state** from its excitations

- flow equation for Hamiltonian: $\frac{\mathrm{d}}{\mathrm{d}s} H(s) = [\eta(s), H(s)]$ flow parameter *s*
- *H* in multi-reference normal order w.r.t. to a given reference state $|\Psi\rangle$

  [Kutzelnigg, Mukherjee]

$$H(s) = E(s) + \sum f^{\circ}_{\circ}(s) \tilde{a}^{\circ}_{\circ} + \tfrac{1}{4} \sum \Gamma^{\circ\circ}_{\circ\circ}(s) \tilde{a}^{\circ\circ}_{\circ\circ} + \xcancel{\tfrac{1}{36} \sum W^{\circ\circ\circ}_{\circ\circ\circ}(s) \tilde{a}^{\circ\circ\circ}_{\circ\circ\circ}}$$

- note: $\langle\Psi|H(s)|\Psi\rangle = E(s)$
- choose generator $\eta(s)$ to decouple the reference state from its excitations

Why should we merge…

NCSM + **IM-SRG**

NCSM

- ~~limited to light nuclei~~
- ~~factorial growth of model space~~
- ~~computationally demanding~~
- ~~difficult to obtain model-space convergence~~

+ exact method
+ easy access to excited states
+ spectroscopy for free
+ no limitation to even nuclei

IM-SRG

+ easy access to heavy nuclei
+ soft computational scaling with *A*
+ computationally very efficient
+ decoupling in *A*-body space

- ~~not exact method~~
- ~~only for ground state~~
- ~~spectroscopy not straight-forward~~
- ~~spherical formulation limits to even nuclei~~

How should we merge…

NCSM
define
reference state

- diagonalize Hamiltonian in small model space
- ground state defines reference state

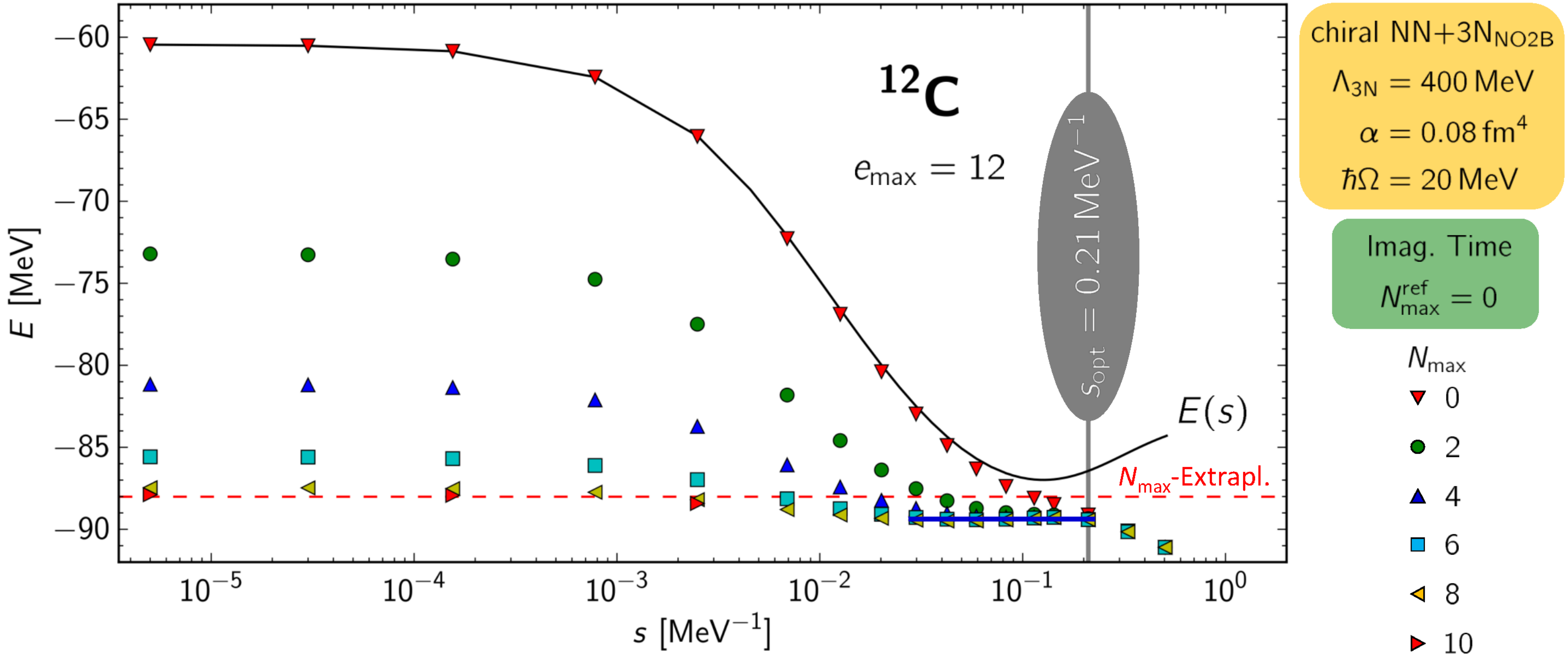
IM-SRG
evolve
operators

- evolve Hamiltonian and other operators
- pre-diagonalization in *A*-body space

NCSM
extract
observables

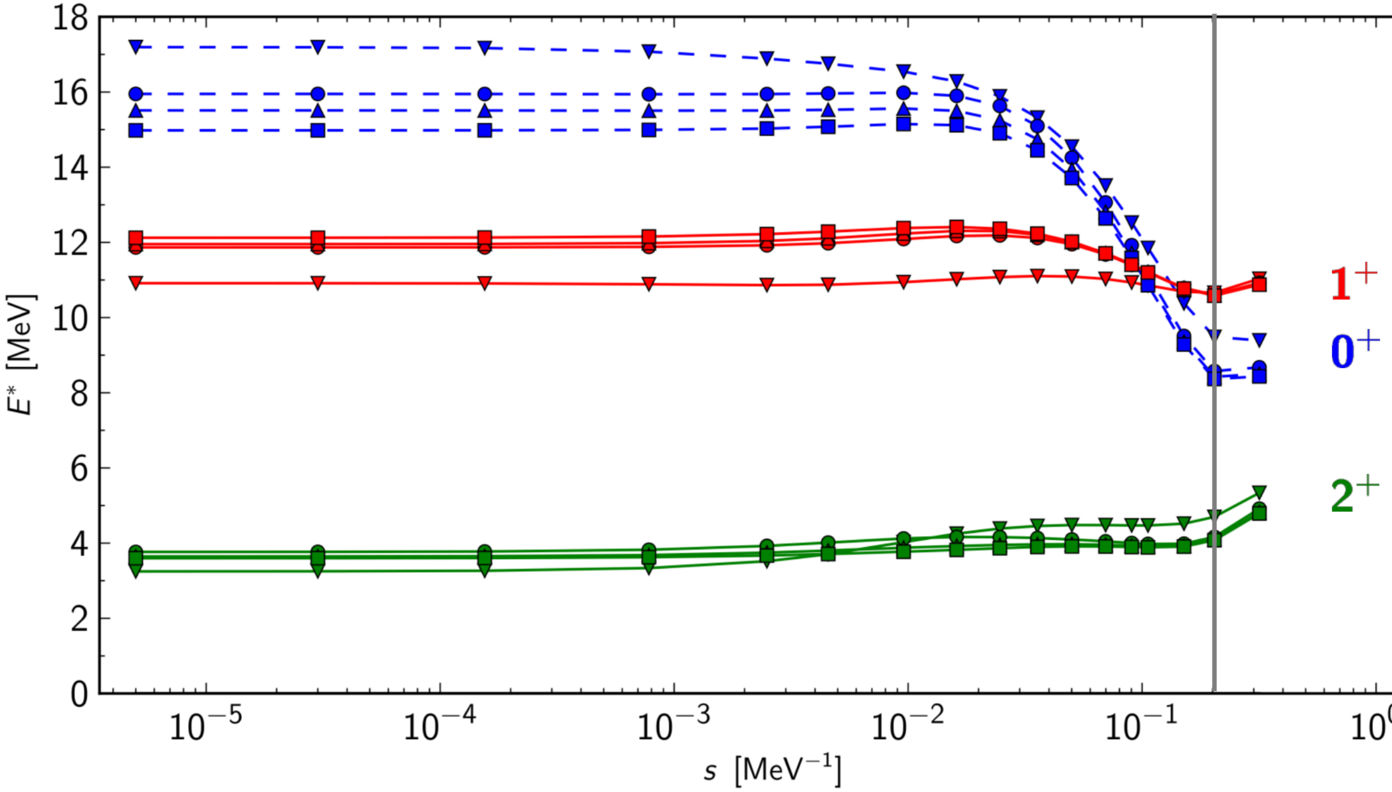
- diagonalize IM-SRG evolved Hamiltonian
- obtain eigenstates and extract observables

Ground-State Energy



- $E(s)$ has a minimum and does not stabilize
- drastically enhanced model-space convergence for NCSM+IM-SRG
- induced many-body contribution 1.5 MeV less than 2 %

Excitation Energies



chiral NN+$3N_{NO2B}$
$\Lambda_{3N} = 400\,\text{MeV}$
$\alpha = 0.08\,\text{fm}^4$
$\hbar\Omega = 20\,\text{MeV}$

Imag. Time
$N_{max}^{ref} = 0$

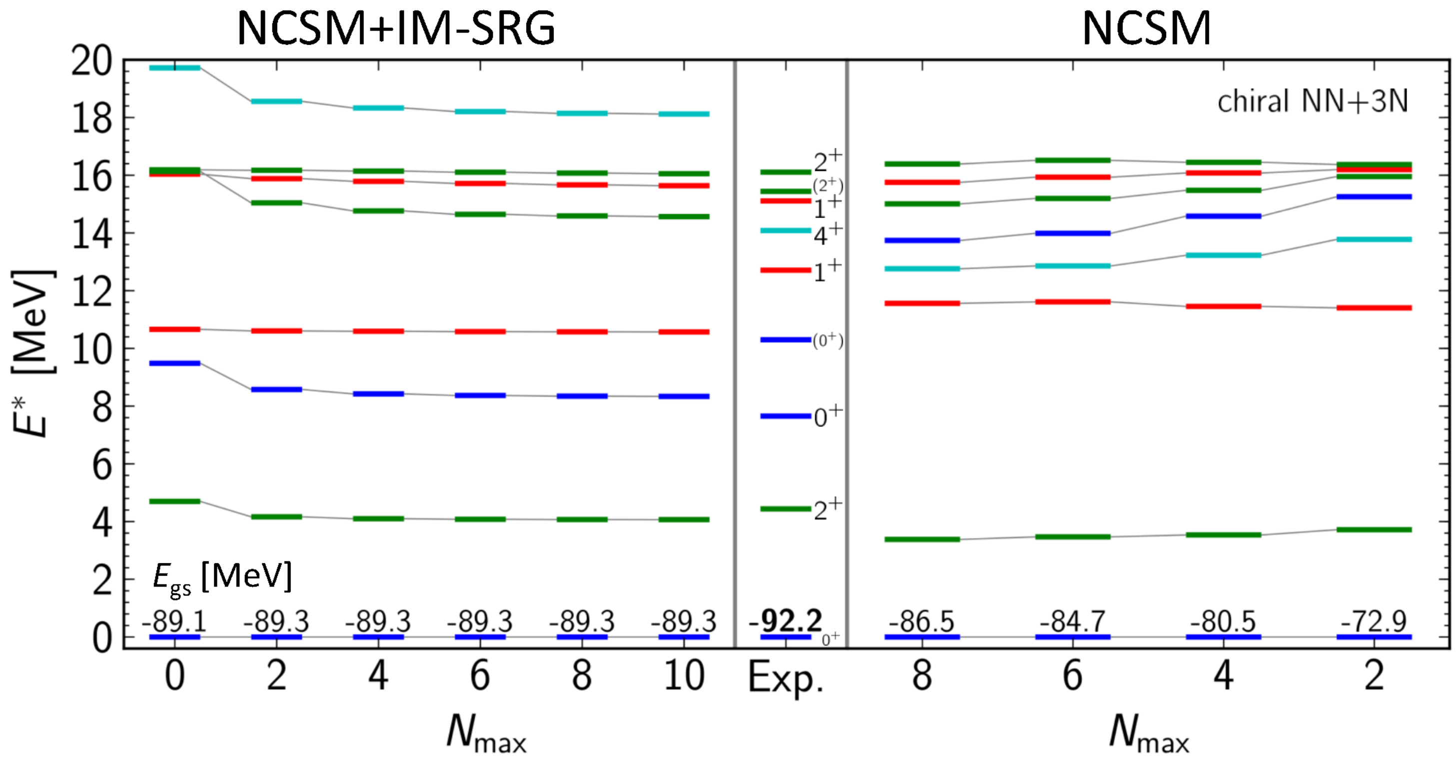
^{12}**C**
$e_{max} = 12$
$\lambda_{Hcm} = 1$

N_{max}
▽ 0
○ 2
△ 4
□ 6

- E^* of 2^+ less dependent on flow parameter
- E^* converges **monotonically from above** for evolved Hamiltonian
  → variational principle for excitation energies!
- **Hoyle state**? → very sensitive to flow parameter
  → needs further investigation

analyze E^* as function of N_{max} at s_{opt}

Spectra



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$\lambda_{\text{Hcm}} = 1$

$s_{\text{opt}} = 0.20$

- difference between NCSM+IM-SRG and NCSM: **induced many-body** and **NO2B**
- NCSM+IM-SRG: ground-state energy perfectly converged and in good agreement with experiment
- NCSM: ground-state energy not converged yet

Summary and Outlook

- ✓ introduced novel many-body technique NCSM+IM-SRG
- ✓ extremely enhanced N_{max} convergence
- ✓ $N_{\mathrm{max}} \leq 4$ sufficient to extract converged ground-state energies
- ✓ NCSM+IM-SRG: variational principle valid for excitation energies since ground-state energy is converged

- ○ variation of several parameters: generator, $\hbar\Omega$, …
- ○ consistent evolution radius and electromagnetic operators
- ○ detailed analysis of the Hoyle state in ^{12}C
- ○ extend applicability of NCSM+IM-SRG to odd nuclei

  → particle-attached or particle-removed formalism

Thank You For Your Attention

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