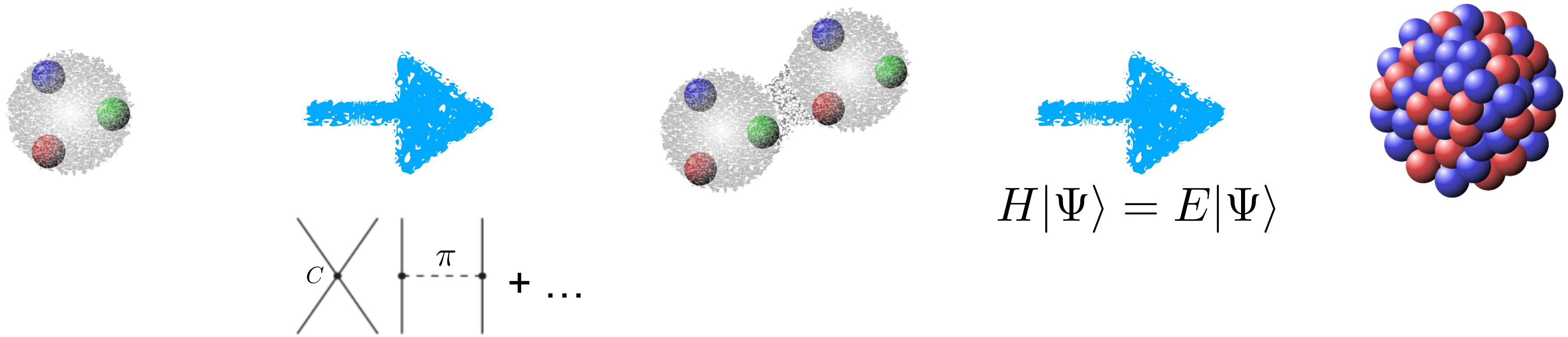
Heavy-mass frontier in nuclear ab initio calculations



Takayuki Miyagi

SFB workshop, Darmstadt (October 6, 2022)

Collaborators

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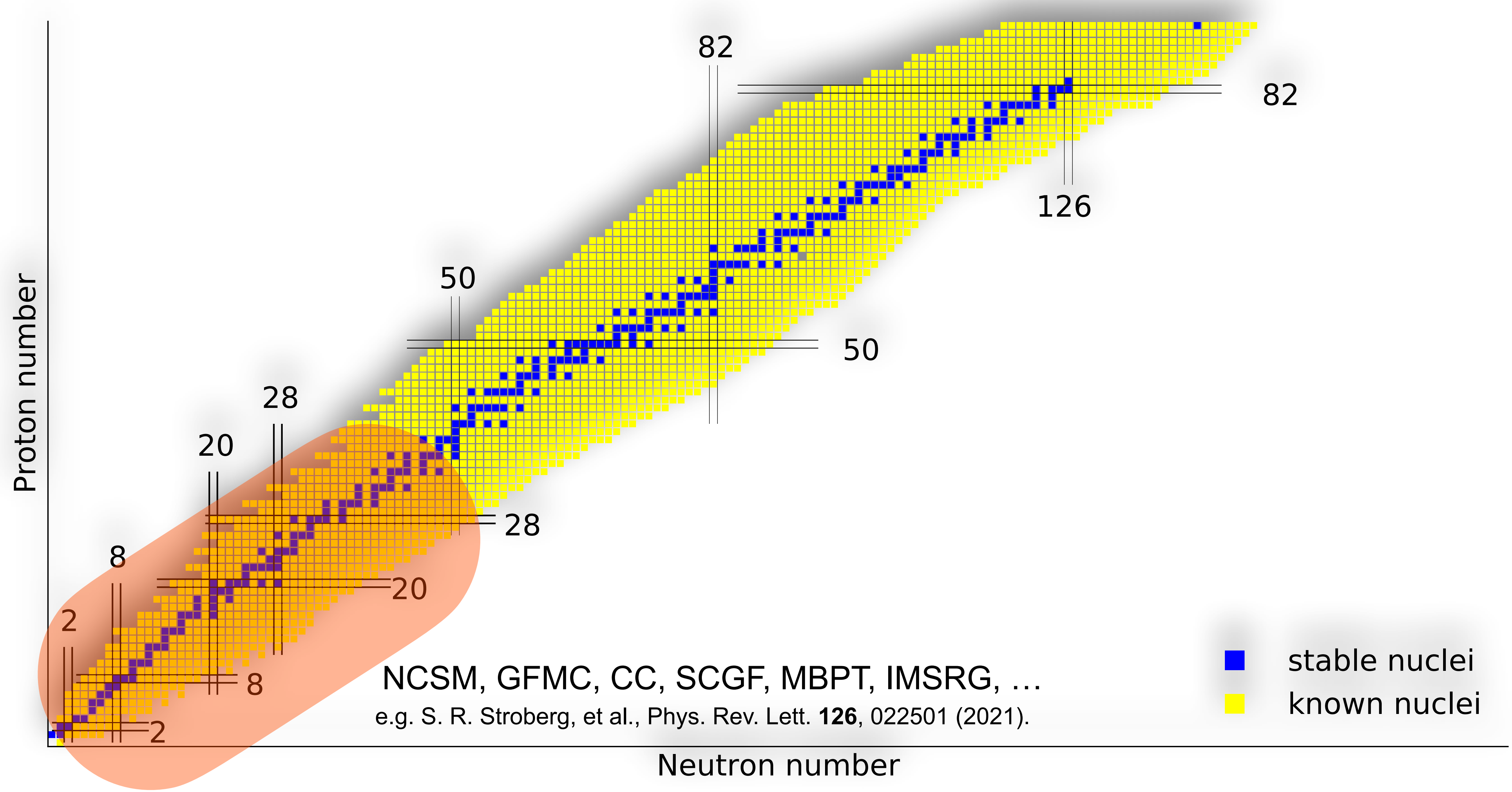
Yusuke Tsunoda (University of Tsukuba)

New 3N matrix element storage
TM et al., Phys. Rev. C 105, 014302 (2022).

Application to ^{208}Pb
B. Hu et al., Nat. Phys. (2022).

Large valence-space diagonalization

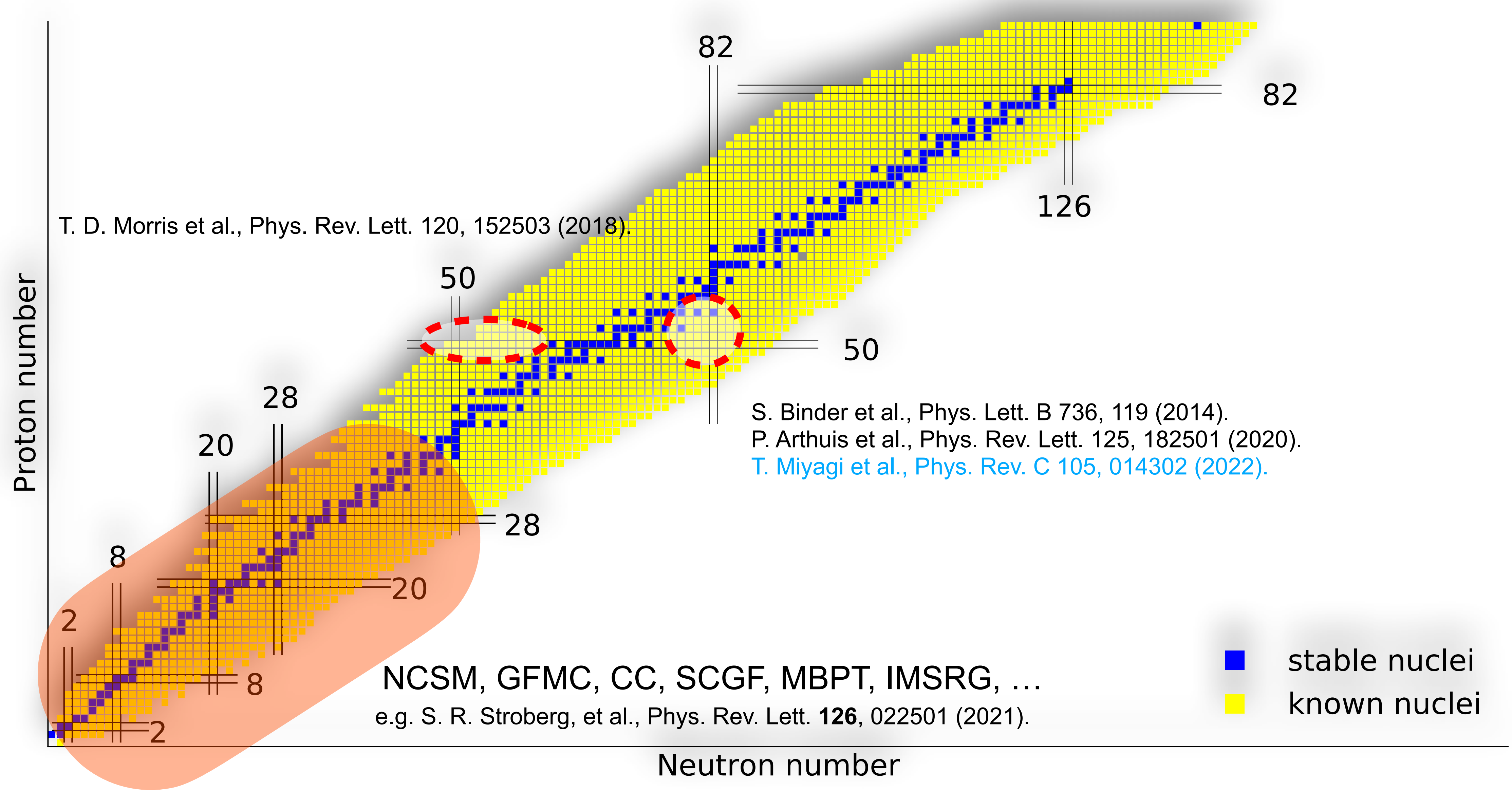
Heavy-mass frontier in ab initio methods



NCSM, GFMC, CC, SCGF, MBPT, IMSRG, …

e.g. S. R. Stroberg, et al., Phys. Rev. Lett. **126**, 022501 (2021).

Heavy-mass frontier in ab initio methods



T. D. Morris et al., Phys. Rev. Lett. 120, 152503 (2018).

S. Binder et al., Phys. Lett. B 736, 119 (2014).
P. Arthuis et al., Phys. Rev. Lett. 125, 182501 (2020).
T. Miyagi et al., Phys. Rev. C 105, 014302 (2022).

NCSM, GFMC, CC, SCGF, MBPT, IMSRG, …
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Nuclear ab initio calculation

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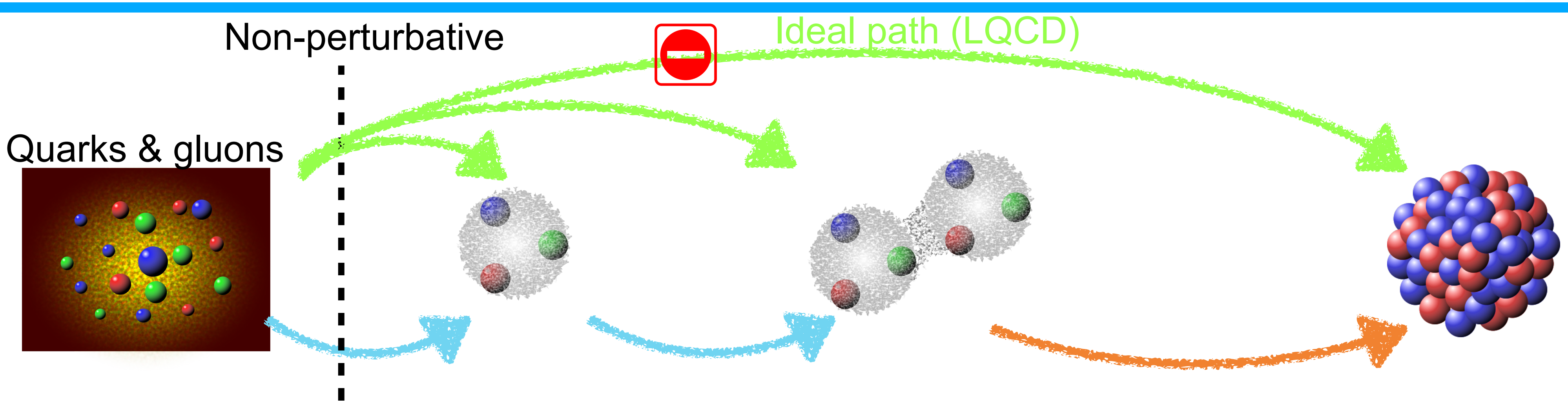
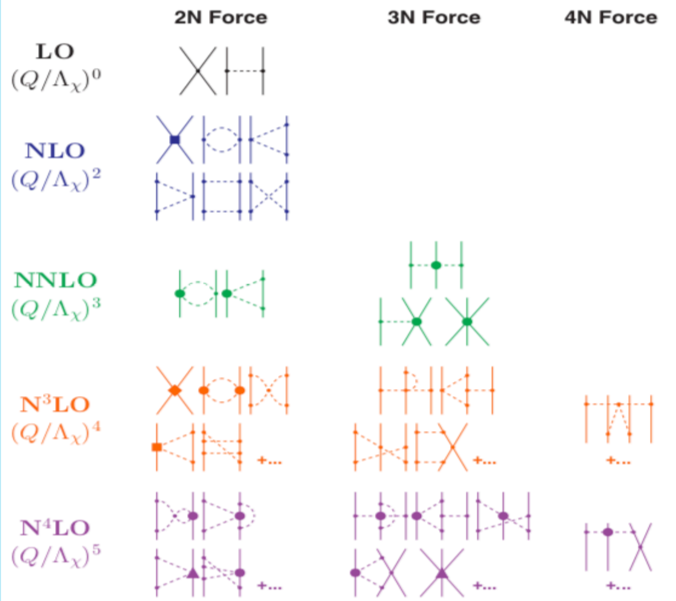


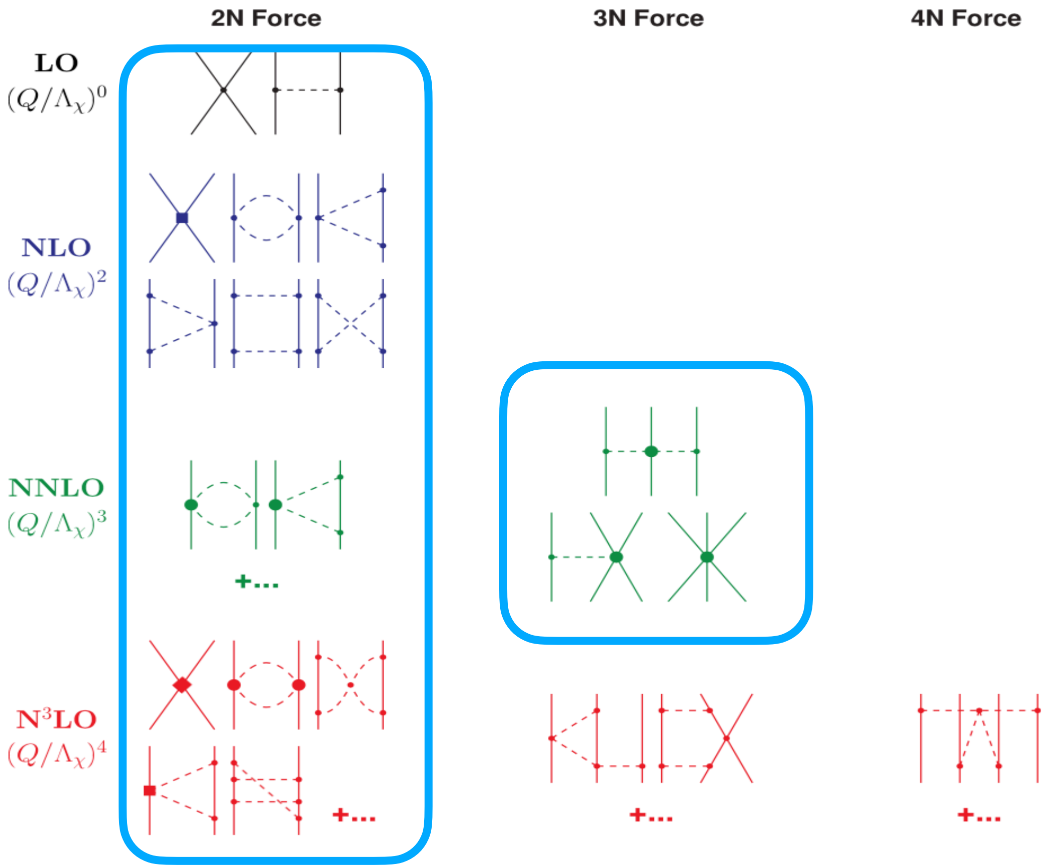


Nuclear many-body problem

- Green’s function Monte Carlo
- No-core shell model
- Nuclear lattice effective field theory
- Self-consistent Green’s function
- Coupled-cluster
- In-medium similarity renormalization group
- Many-body perturbation theory

Nuclear interaction from chiral EFT

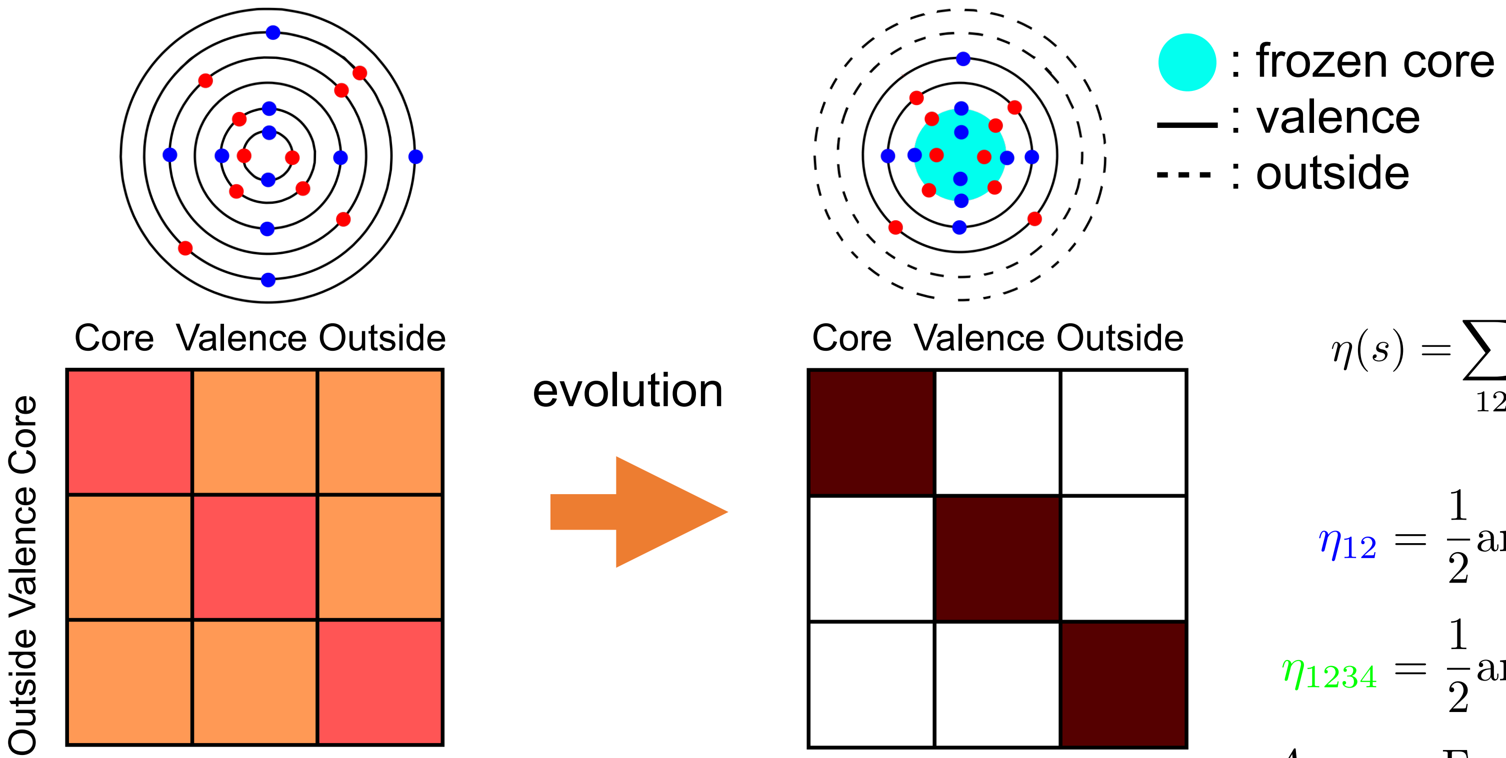
- Lagrangian construction
  - ✦ Chiral symmetry
  - ✦ Power counting
- Systematic expansion
  - ✦ Unknown LECs
  - ✦ Many-body interactions
  - ✦ Estimation of truncation error



Weinberg, van Kolck, Kaiser, Epelbaum, Glöckle, Meißner, Entem, Machleidt, …

H. Hergert, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tsukiyama, Phys. Rep. **621**, 165 (2016).
S. R. Stroberg, H. Hergert, S. K. Bogner, and J. D. Holt, Annu. Rev. Nucl. Part. Sci. **69**, 307 (2019).

Valence-space in-medium similarity renormalization group



Similarity transformation

$$H \qquad H(s) = e^{\Omega(s)} H e^{-\Omega(s)}$$

$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4}\sum_{1234} \Gamma_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

s: flow parameter

$$\frac{d\Omega}{ds} = \eta(s) - \frac{1}{2}[\Omega(s), \eta(s)] + \cdots$$

$$\eta(s) = \sum_{12} \eta_{12}(s)\{a_1^\dagger a_2\} + \sum_{1234} \eta_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

$$\eta_{12} = \frac{1}{2}\arctan\left(\frac{2f_{12}}{f_{11} - f_{22} + \Gamma_{1212} + \Delta}\right)$$

$$\eta_{1234} = \frac{1}{2}\arctan\left(\frac{2\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234} + \Delta}\right)$$

$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

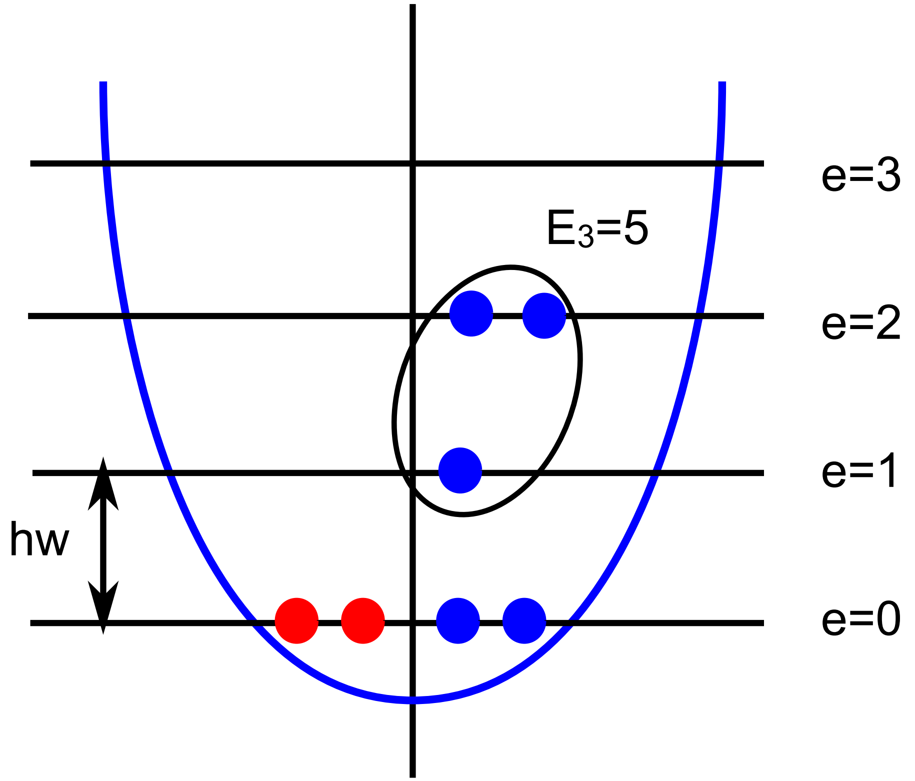
f_{12}, Γ_{1234} : matrix element we want to suppress

Model-space convergence

- NN+3N Hamiltonian (harmonic oscillator basis)

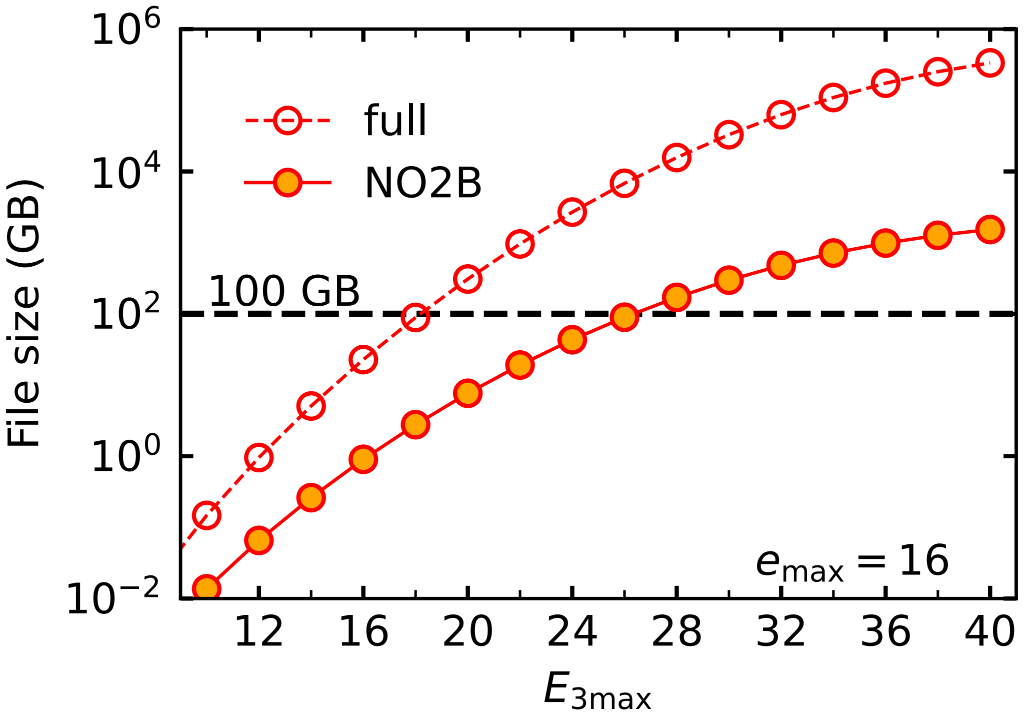
- Parameters:
  - ✦ hw
  - ✦ e_{max}=max(2n+l)*
  - ✦ E_{3max}=max(e_1+e_2+e_3).

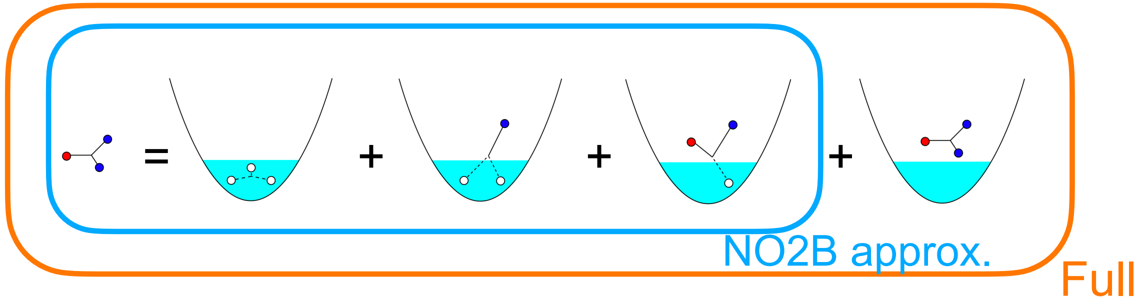
- As e_{max} and E_{3max} increases, the observable should not depend on all the parameters.



*Equivalent to (number of major shells)+1

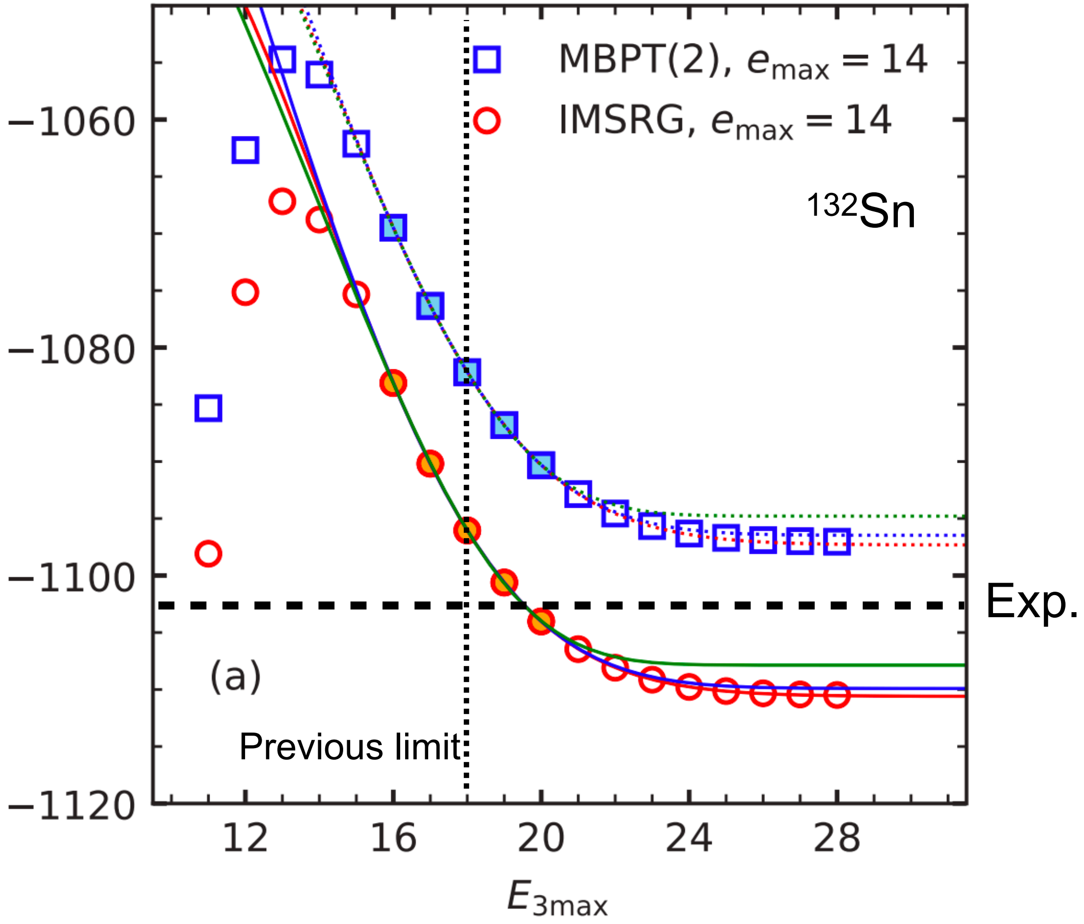
E_{3max} convergence in heavy nuclei





NO2B approximation error ~ a few %
[S. Binder et al., Phys. Rev. C 87, 021303 (2013).]

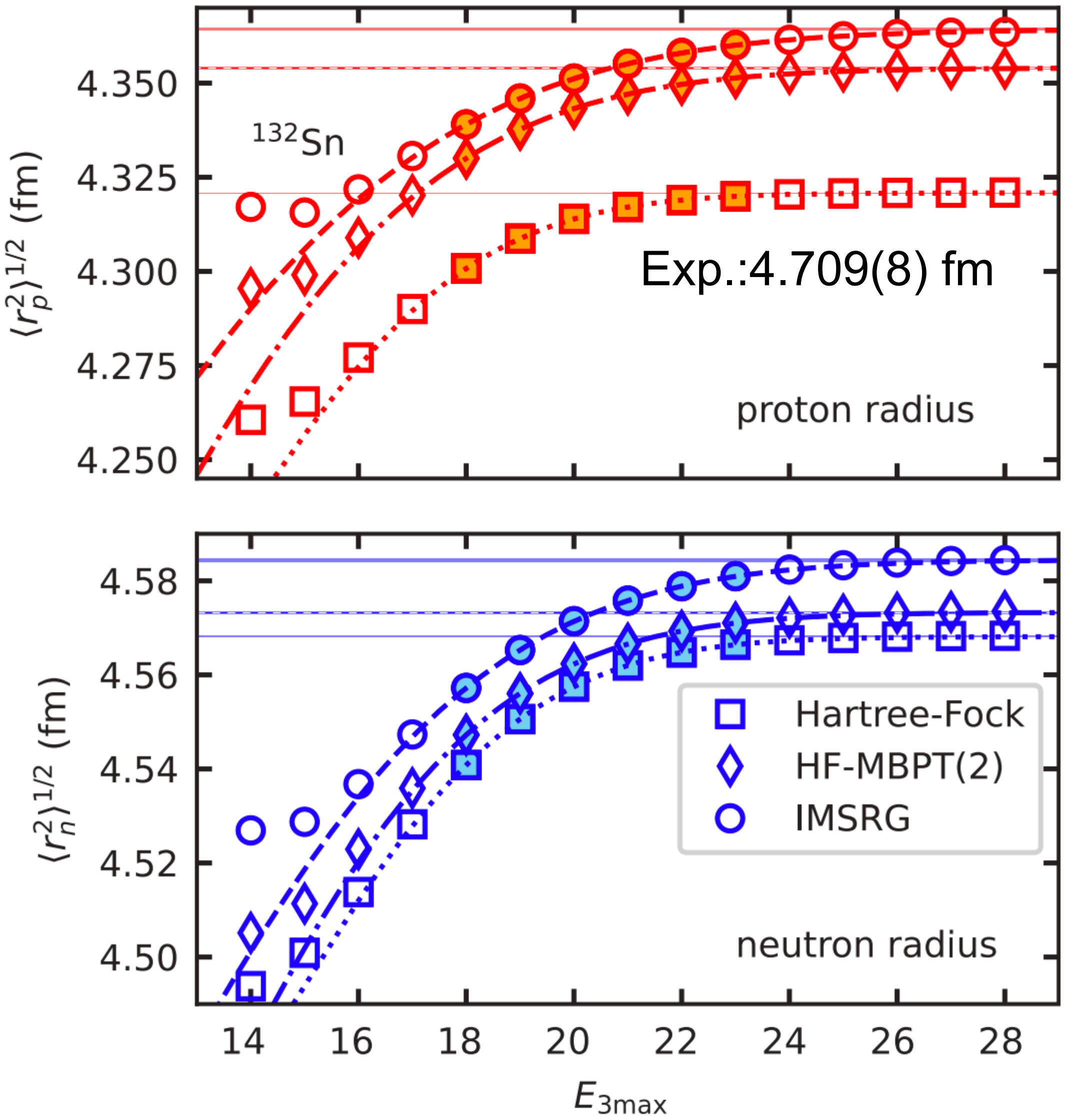
TM, S. R. Stroberg, P. Navrátil, K. Hebeler, and J. D. Holt, Phys. Rev. C 105, 014302 (2022).

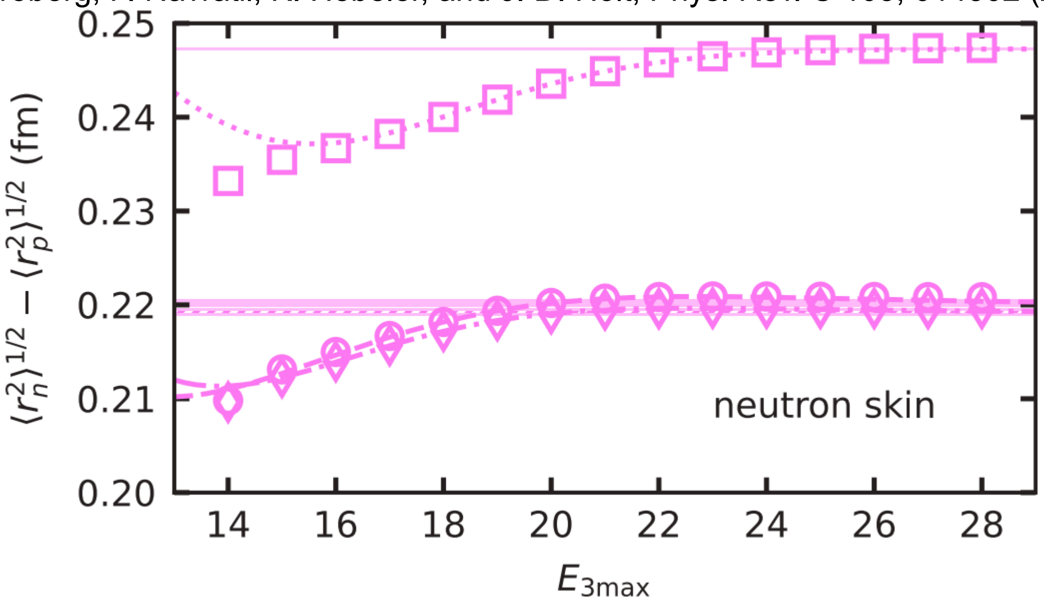


Asymptotic form: $E \approx A\gamma_{\frac{2}{n}}\left[\left(\frac{E_{3\max}-\mu}{\sigma}\right)^{n}\right]+E_{\infty}$

Radii

TM, S. R. Stroberg, P. Navrátil, K. Hebeler, and J. D. Holt, Phys. Rev. C 105, 014302 (2022).

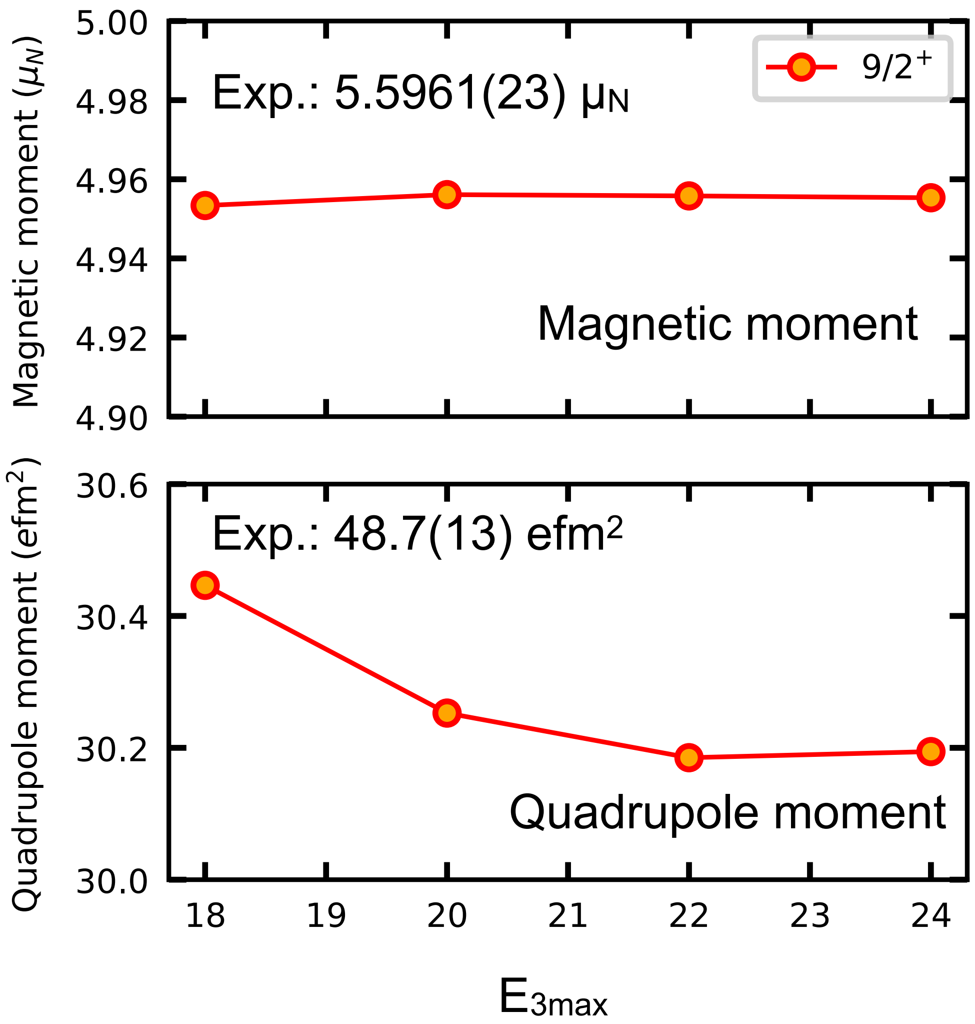


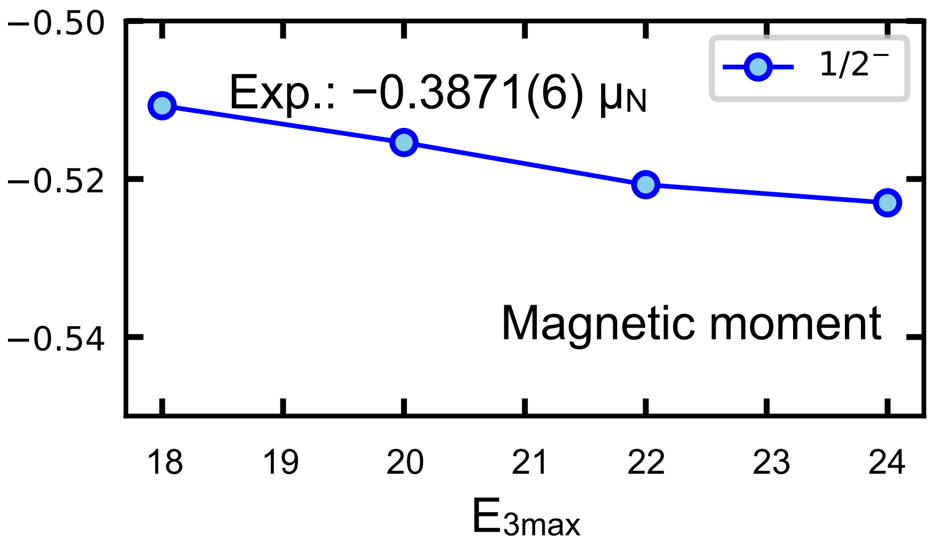


Asymptotic form: $\langle r^2\rangle \approx A\gamma_{\frac{2}{n}}\left[\left(\frac{E_{3\max}-\mu}{\sigma}\right)^n\right] + \langle r^2\rangle_\infty$

EM observables

^{129}In, VS-IMSRG, 1.8/2.0 (EM), e_{max}=12





Convergence is OK.

Disagreement with the experiment

- Nuclear Hamiltonian
- Many-body approximation
- Higher order EM current

Experimental data: A. R. Vernon et al, Nature 607, 260 (2022).

Light tin isotopes

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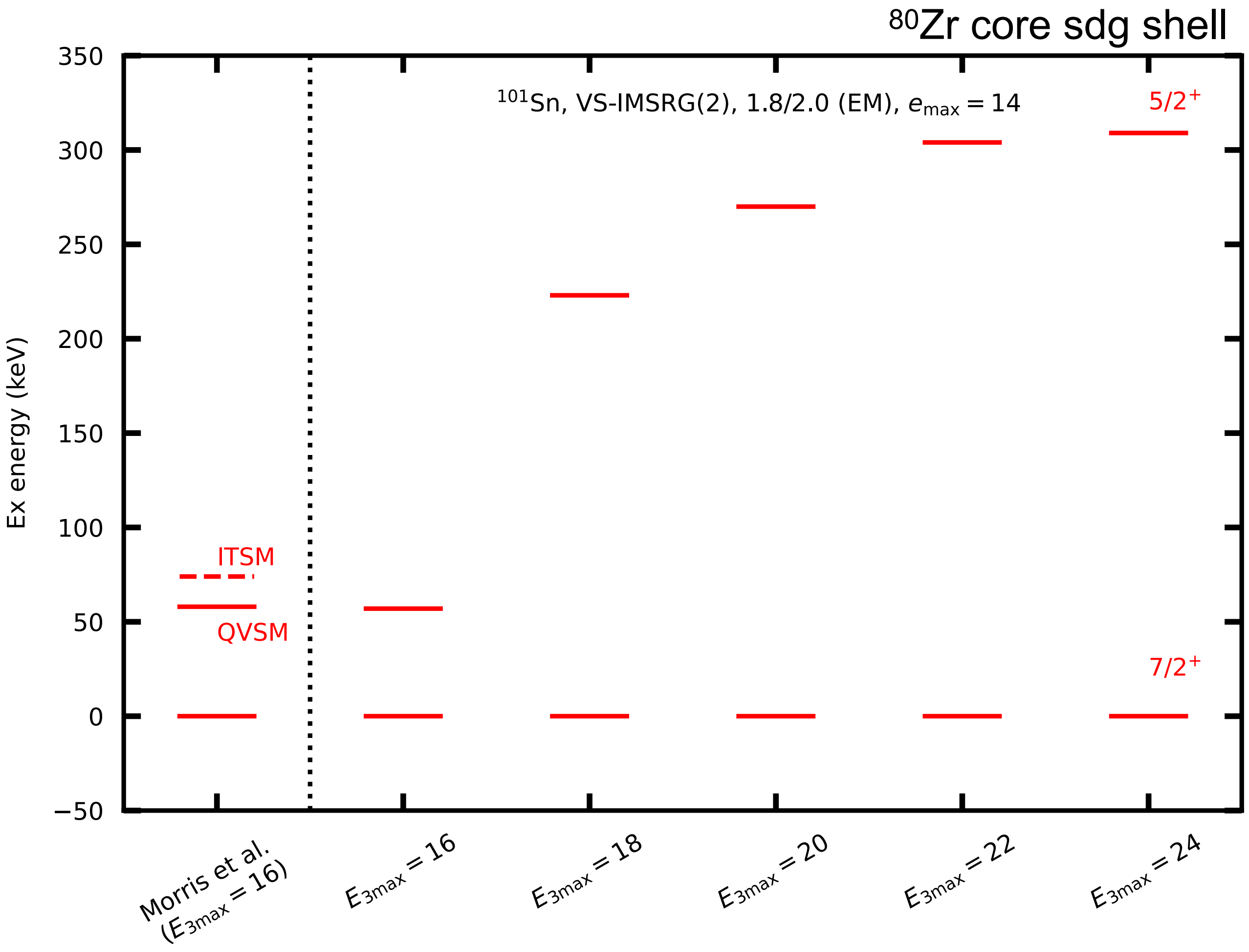
- Near degenerate single-particle structure
- Valence-space IMSRG approach
- The valence-space dimension > ~ 10^{13}
  - ✦ Exact diagonalization is impossible
- Quasi-particle vacuum shell model (QVSM)

  N. Shimizu et al., Phys. Rev. C 103, 014312 (2021).
- Error of QVSM is the order of 10 keV



T. D. Morris et al., Phys. Rev. Lett. 120, 152503 (2018).

Light tin isotopes

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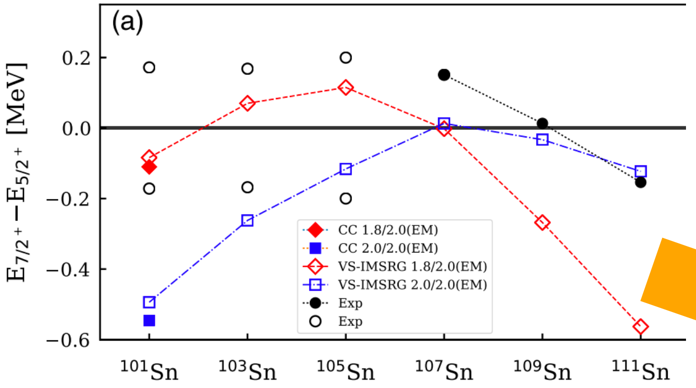
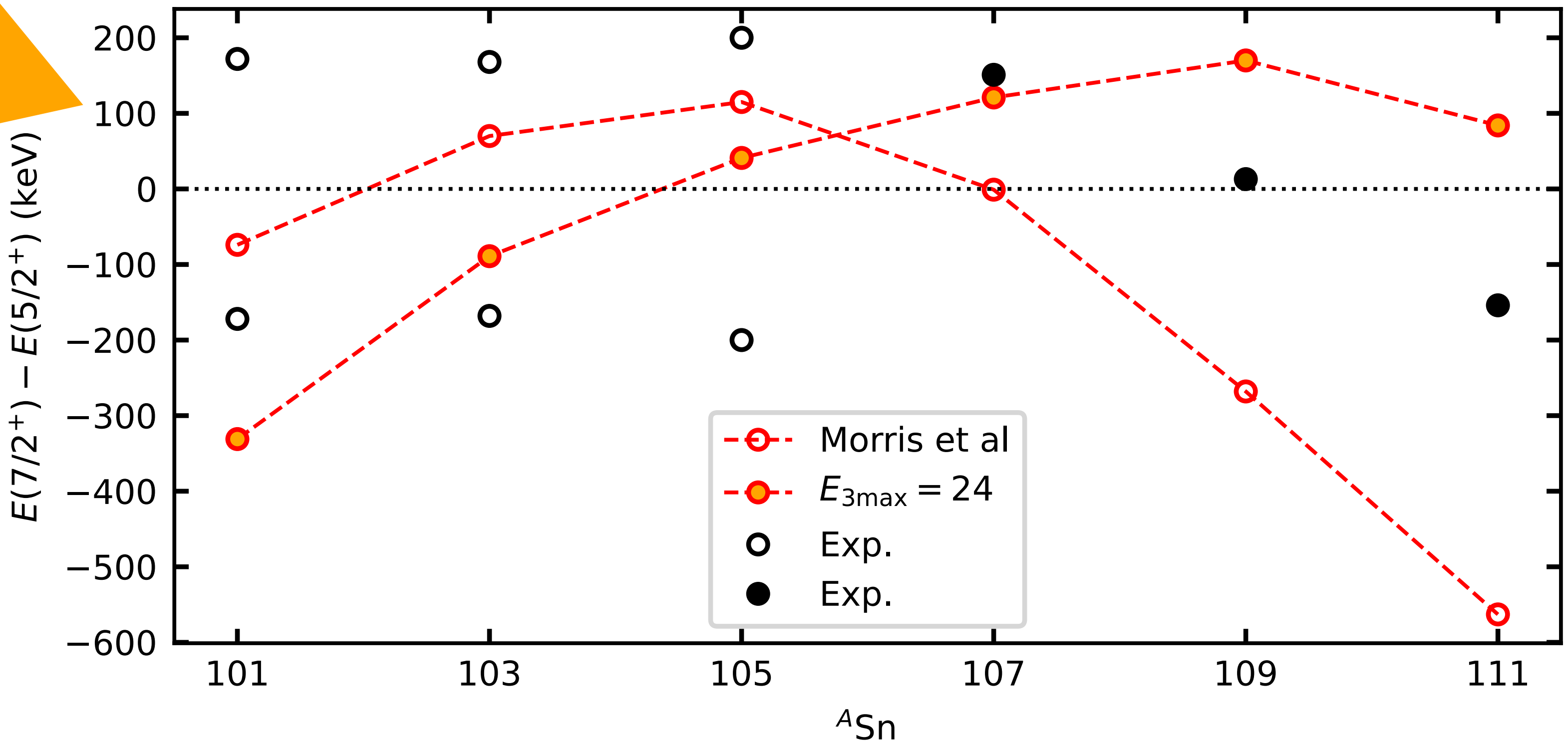


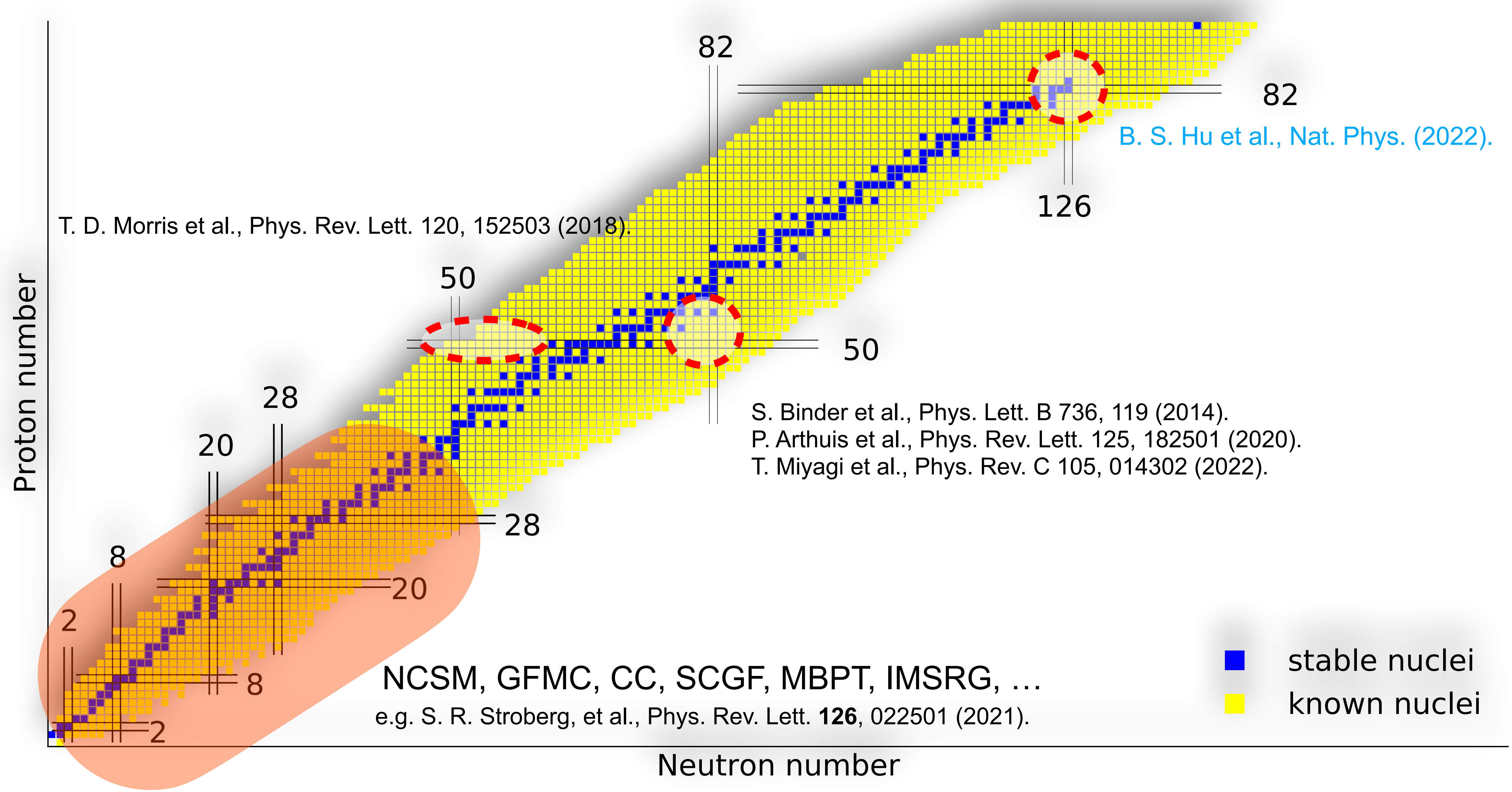
Update

QVSM by N. Shimizu and Y. Tsunoda

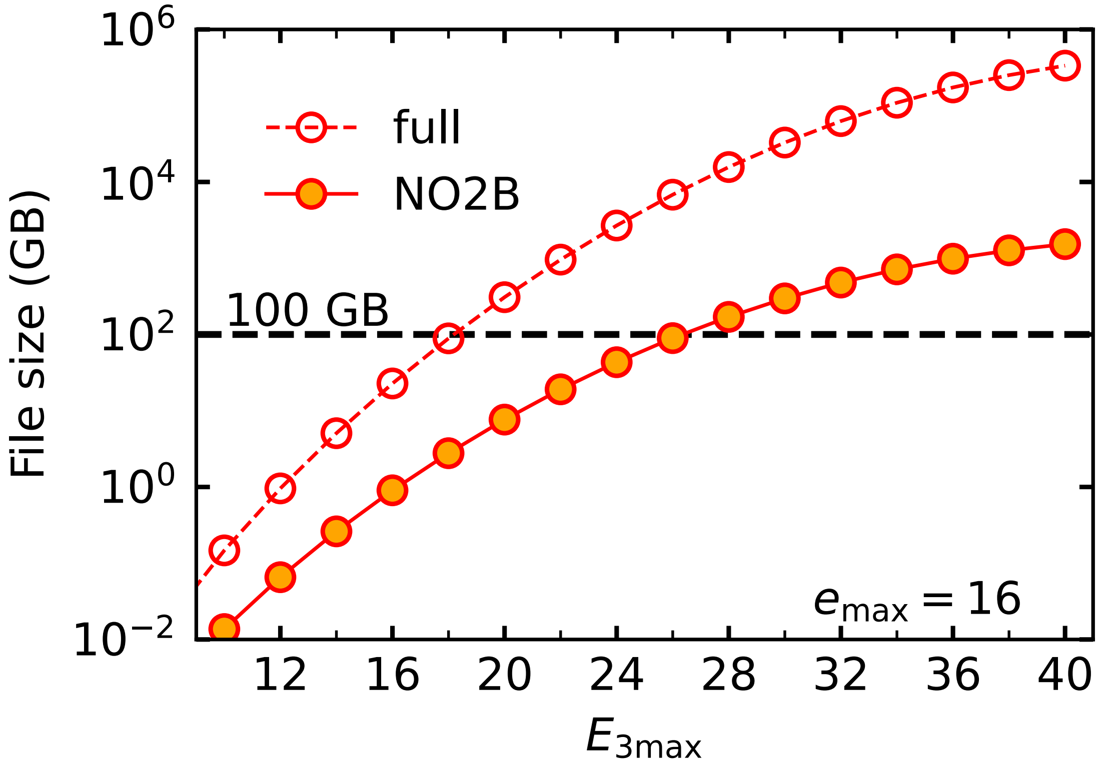


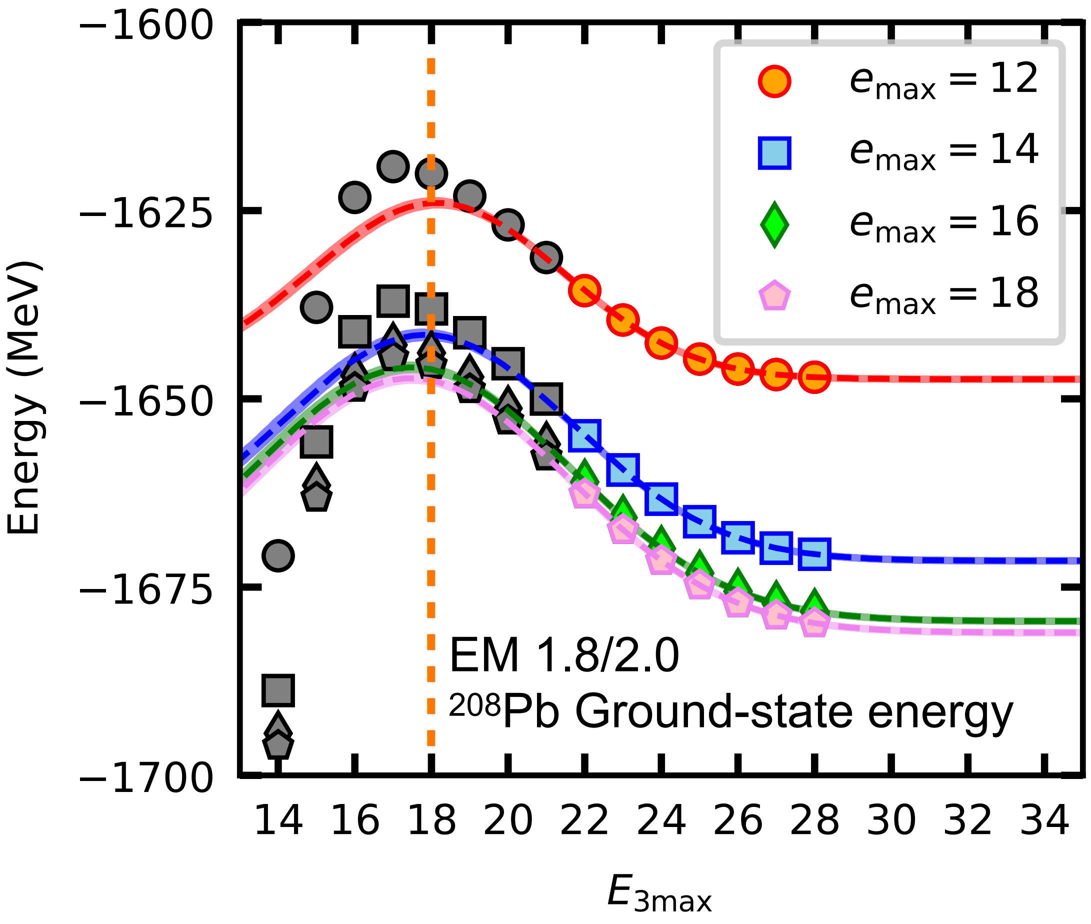
Still difficult to draw a conclusion, but large E_{3max} calculations are needed.

Towards ^{208}Pb



^{208}Pb with the new 3N storage scheme

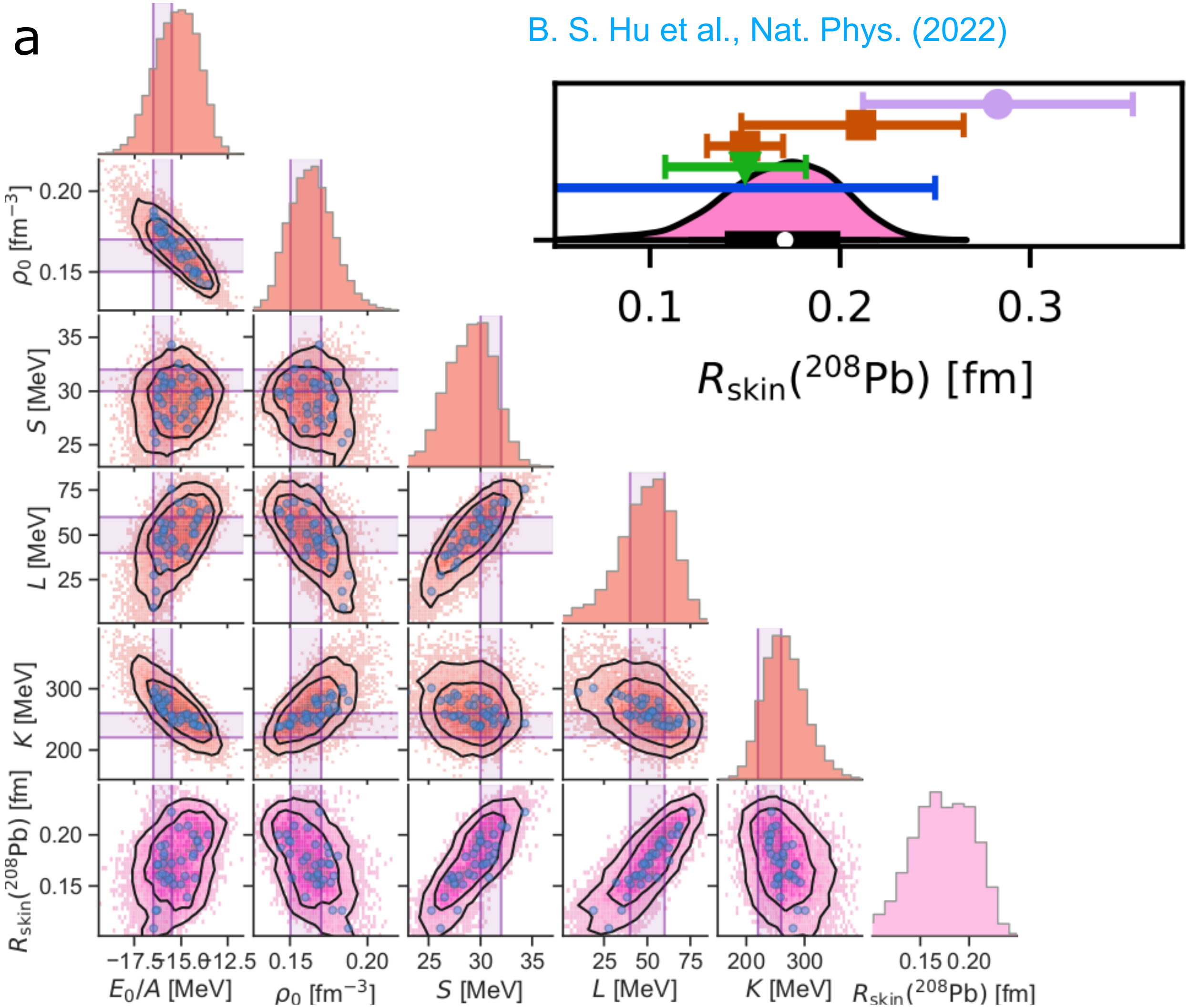




Neutron skin of ^{208}Pb and EoS parameters

- ^{208}Pb can connect Finite and infinite systems
  - ✦ Neutron skin and nuclear EoS parameter
- Delta-full EFT up to N^{2}LO
- 34 NI interactions consistent with few-body and ^{16}O data
- Posterior predictive distribution
  - ✦ Calibrated by ^{48}Ca data
  - ✦ 0.14 < Rskin(^{208}Pb) < 0.20

B. S. Hu et al., Nat. Phys. (2022)



See Christian Forssen’s talk.

Summary & outlook

- Newly introduced 3N storage scheme [TM et al., Phys. Rev. C 105, 014302 (2022).].
- A > 100 region is becoming accessible.
- Neutron skin prediction for ^{208}Pb [B. S. Hu et al., Nat. Phys. (2022)].

- Many possible applications:
  - ✦ Energies, radii, EM moments and transitions for A > 100 systems.
  - ✦ 0vbb-decay NMEs [A. Belley et al., Phys. Rev. Lett. 126, 042502 (2021)]
  - ✦ ….