RECENT INSIGHTS FROM THE NO-CORE SHELL MODEL: FROM LIGHT NUCLEI TO COLD ATOMS

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Fundamental Physics, Chalmers, Sweden

Main research funding by:
Vetenskapsrådet
European Research Council erc

TRIUMF workshop, Vancouver, Feb. 21 - 23, 2013

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Outline

- Cold atoms in deformed traps
- Ab initio NCSM towards the driplines
- NNLO (POUNDerS) in the NCSM

From "QCD" to Nuclei

Nuclear Structure

Many-body Methods

ab initio no-core shell model
- A-body HO model space (m scheme)
- Full-space N_{max} energy cutoff

Renormalization Scheme

Renormalized for truncated model space
- SRG flow in HO or momentum space
- Lee-Suzuki transformation

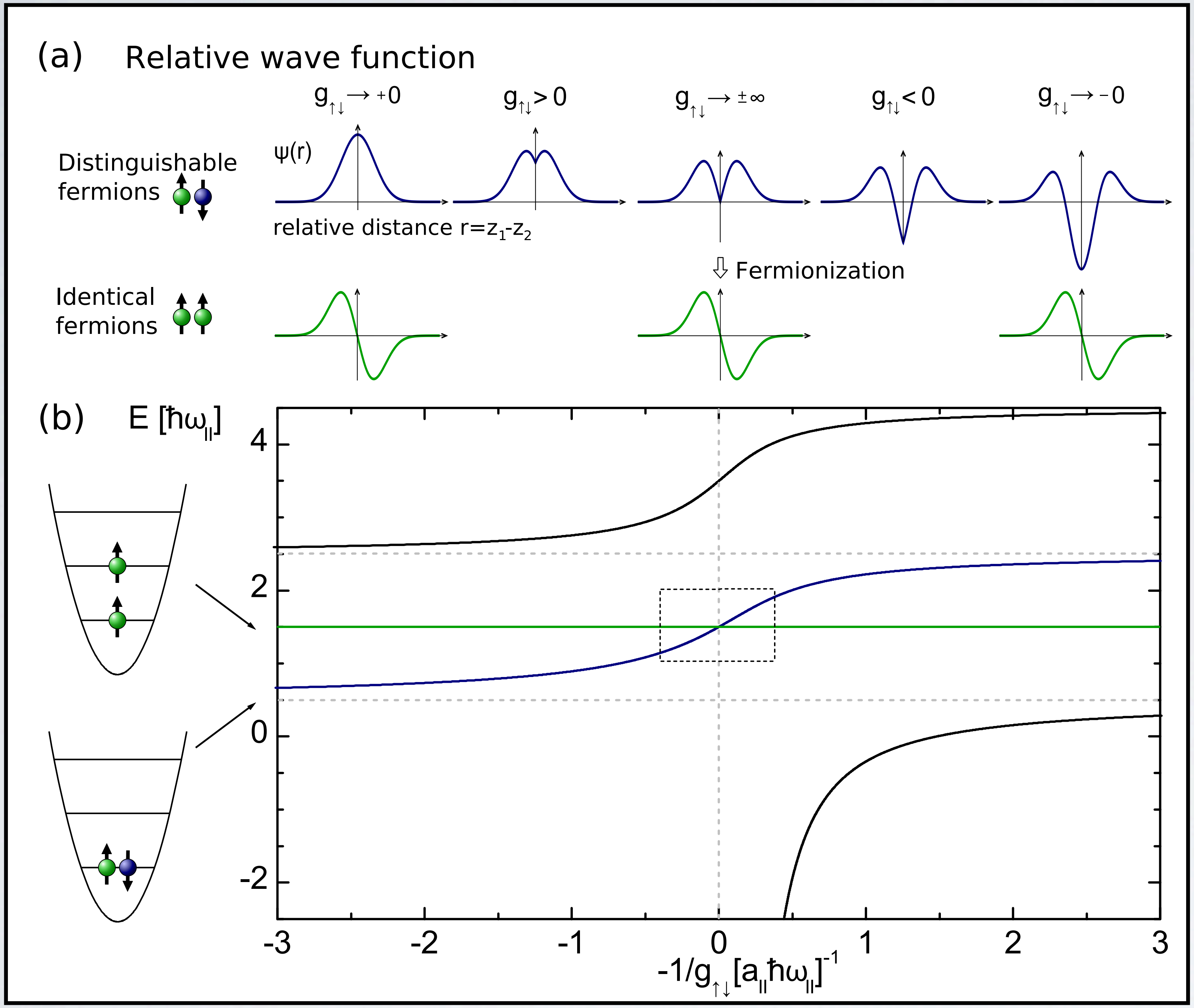
Realistic, effective nuclear interaction

Realistic nuclear interaction
- fits scattering data
- chiral EFT interaction

Low-energy QCD

Cold Atoms In Deformed Traps

Busch model



From: G. Zürn et al., Phys. Rev. Lett. 108, 075303 (2012).

- Zero-range interaction
- Parabolic trapping potential
- Energy spectrum given by the Busch formula

$$\frac{\Gamma(-E/2+1/4)}{\Gamma(-E/2+3/4)} = -\frac{2}{g}$$

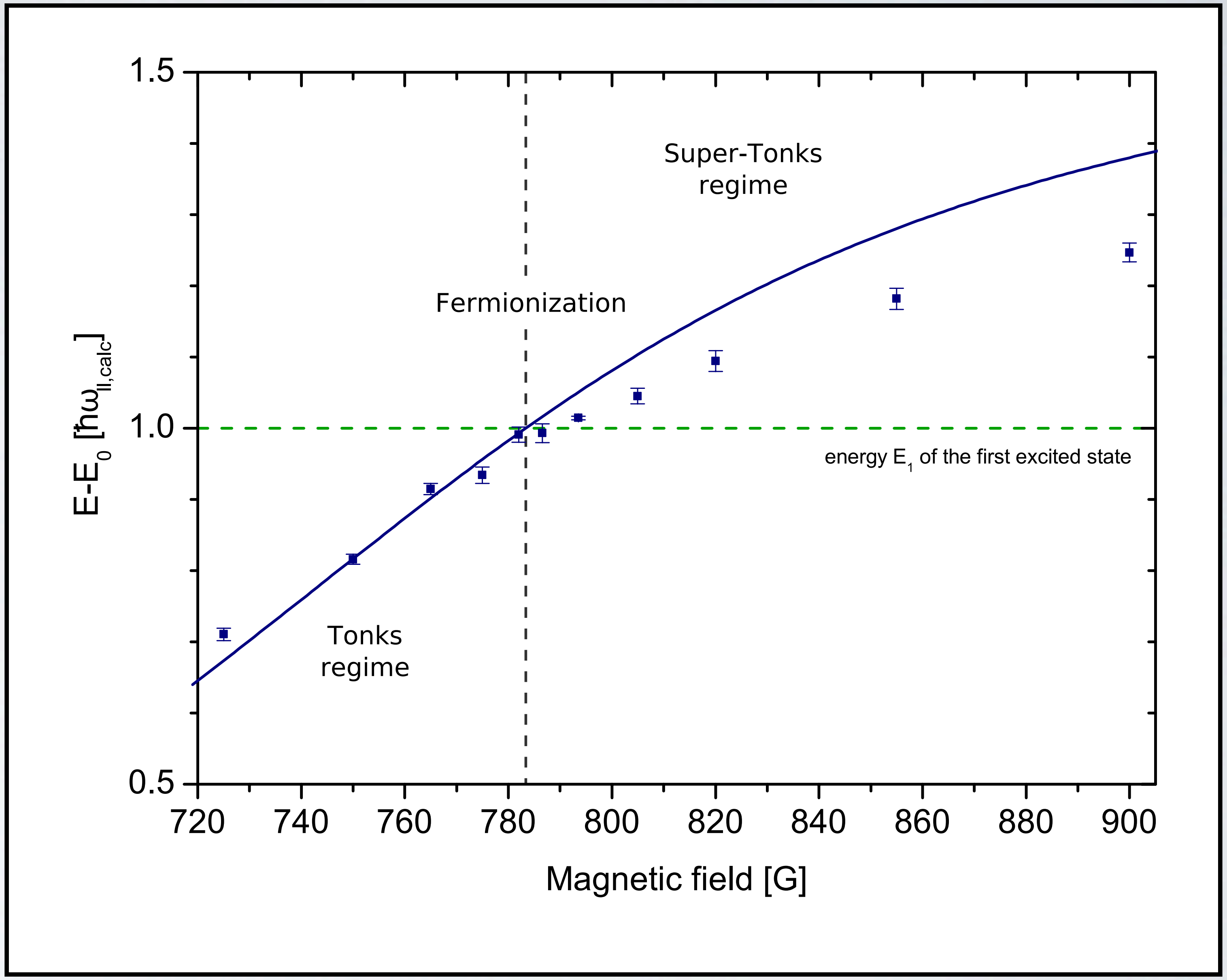
- Analytical expressions for wave functions

T. Busch et al., Foundations of Physics, Vol . 28, No. 4, 1998.

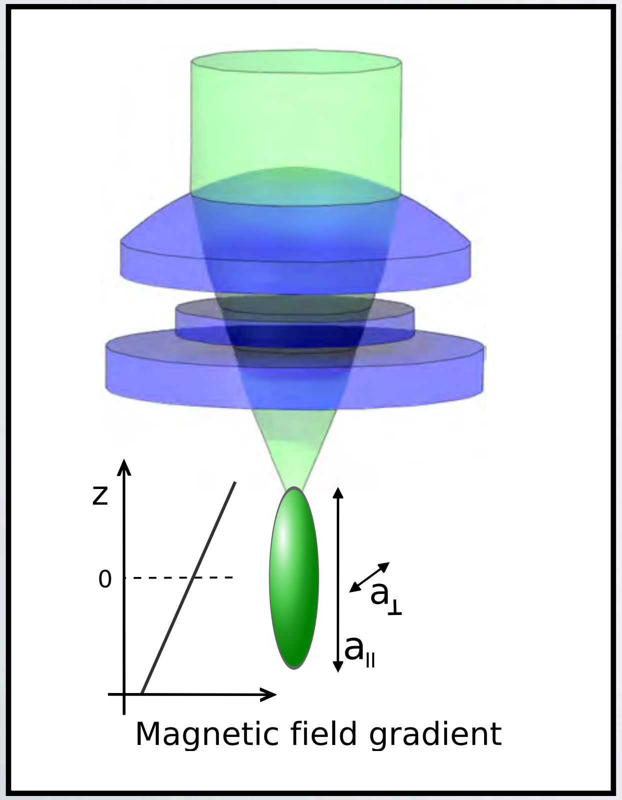
Foundations of Physics, Vol . 28, No. 4, 1998

Heidelberg Experiment

- 1d system with repulsively interacting bosonic gases (Tonks-Girardeau regime)
- Two-component fermionic systems using hyperfine states of ^{6}Li
- 1:10 asymmetric opto-magnetic trap.



From: G. Zürn et al., Phys. Rev. Lett. 108, 075303 (2012).



Model and energy spectrum

- Studied 1+2, 1+3, 1+4 systems

- Hamiltonian

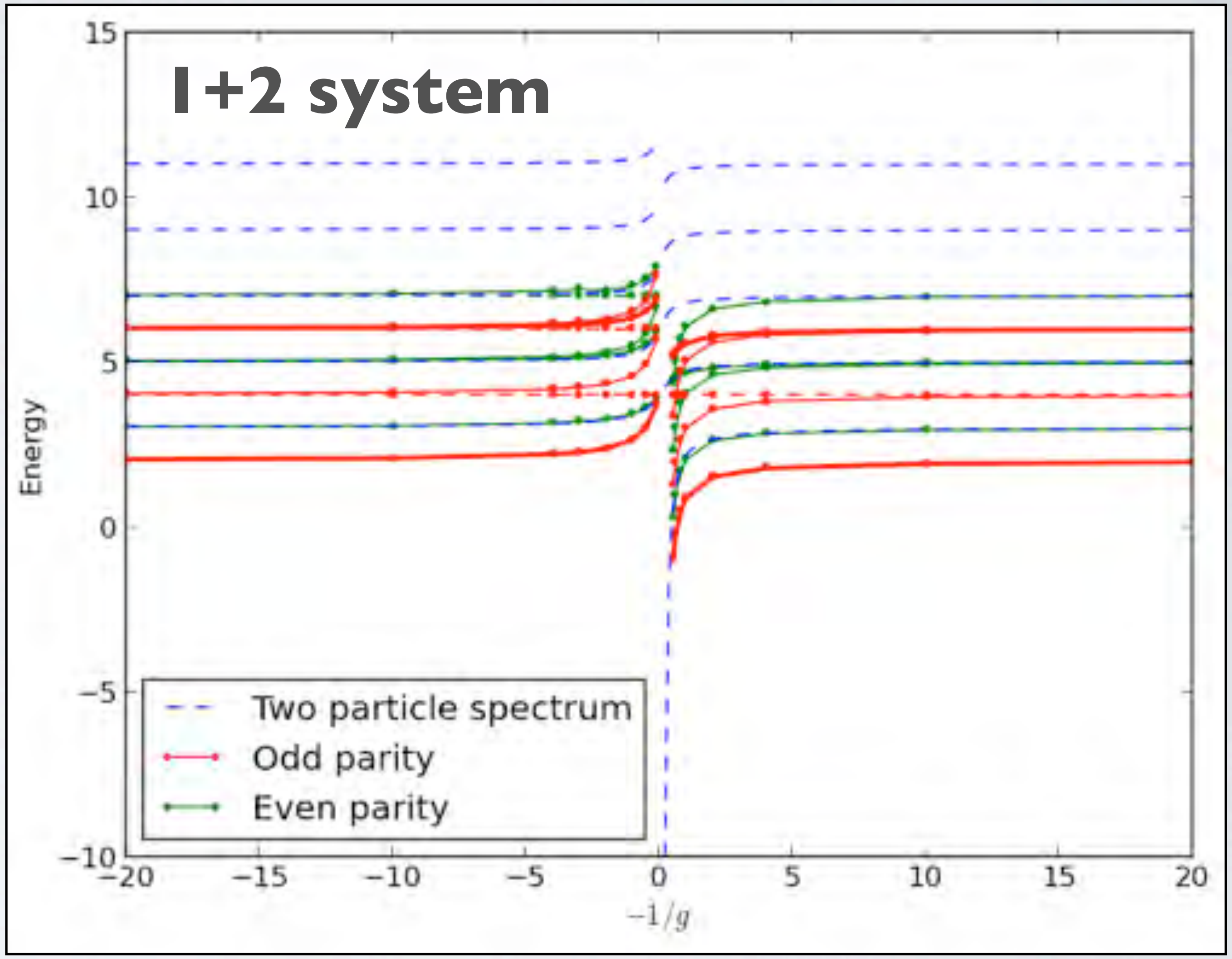
$$H = \sum_{i_\sigma} \left(\frac{p^2}{2} + \frac{1}{2} x_{i_\sigma}^2 \right) + g \sum_{i_\sigma, j_{\tilde{\sigma}}} \delta(x_{i_\sigma} - x_{j_{\tilde{\sigma}}})$$

with $\sigma = \pm, \tilde{\sigma} = -\sigma$

- Coupling strength

$$g \propto \frac{a_{3d}}{1 - C a_{3d}/a_\perp}$$

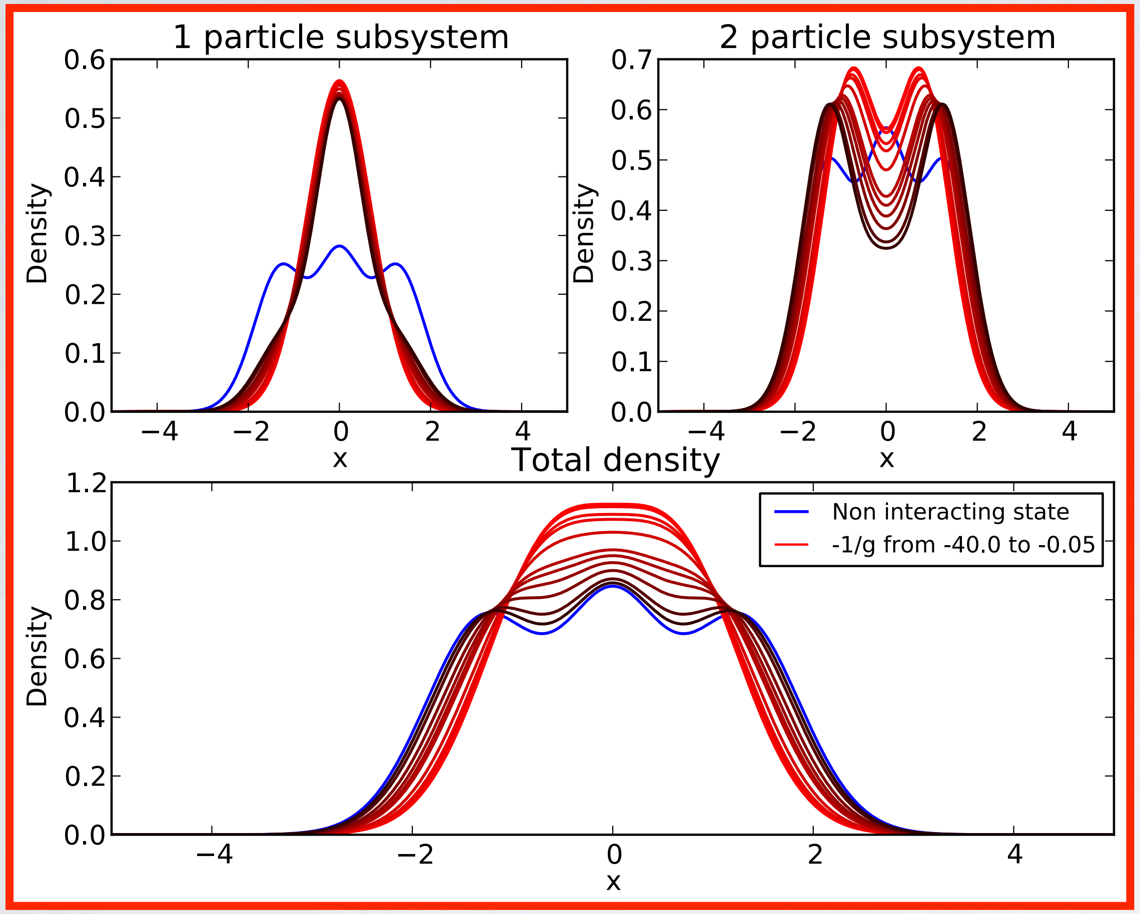
- LS-transformation using exact Busch model solution



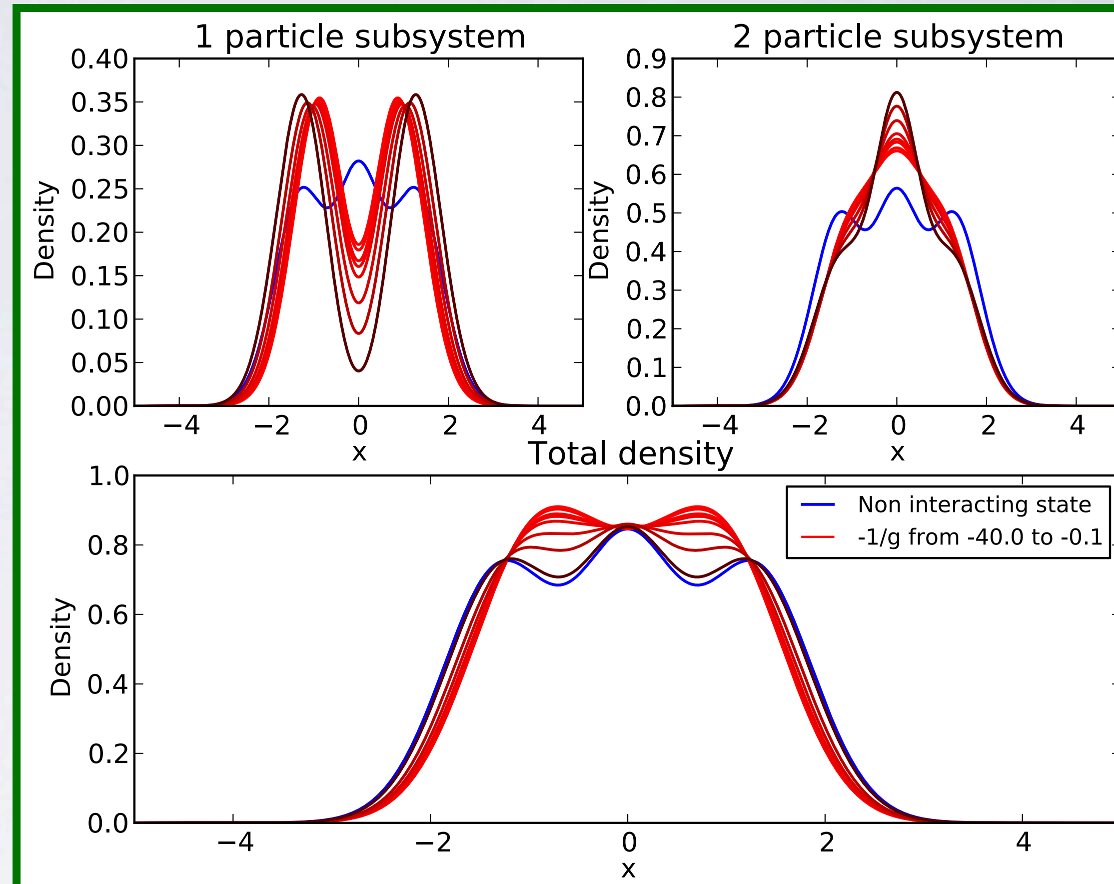
← Repulsive Attractive →

Densities

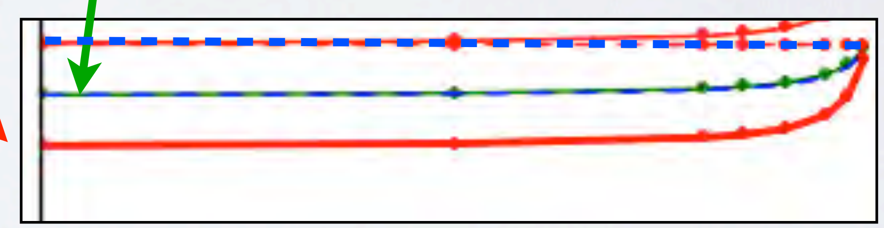
Ground state



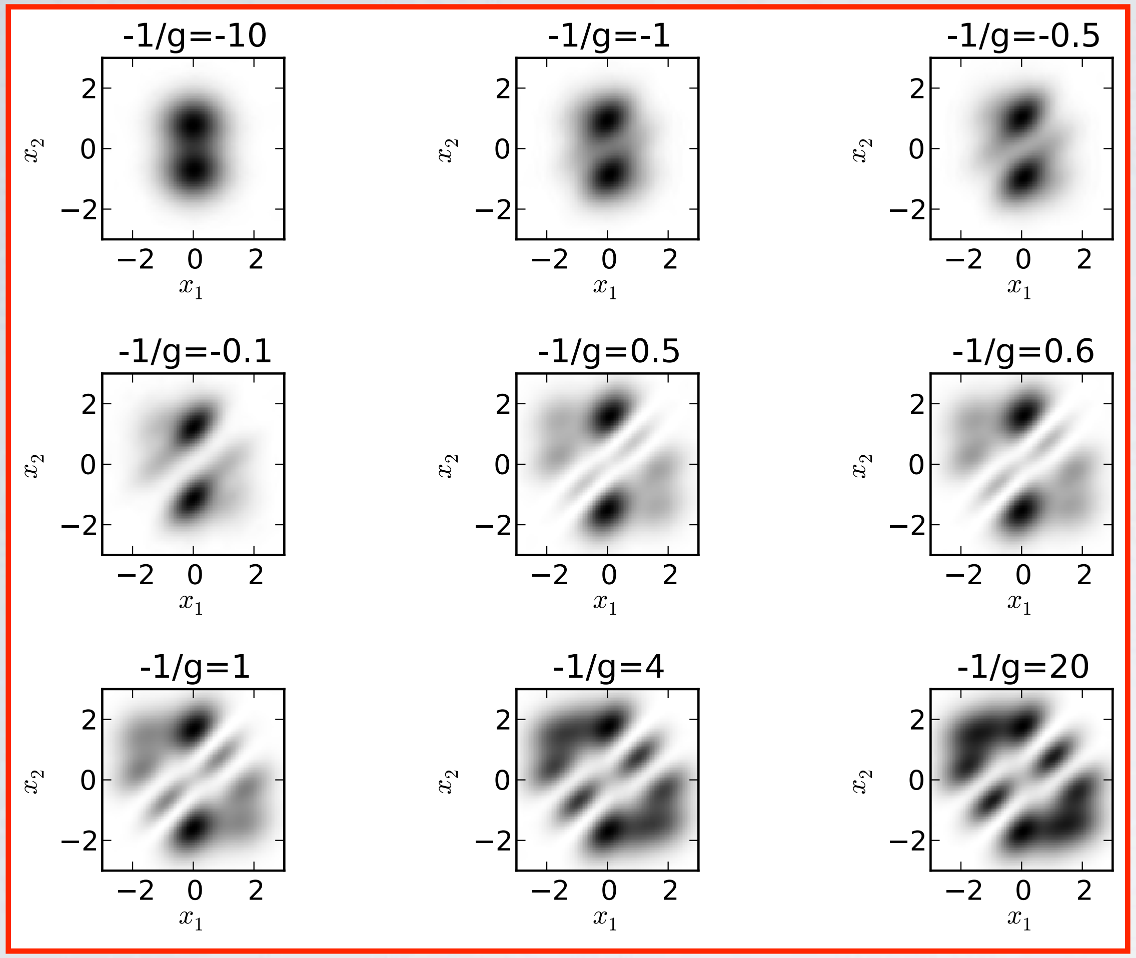
1st excited state

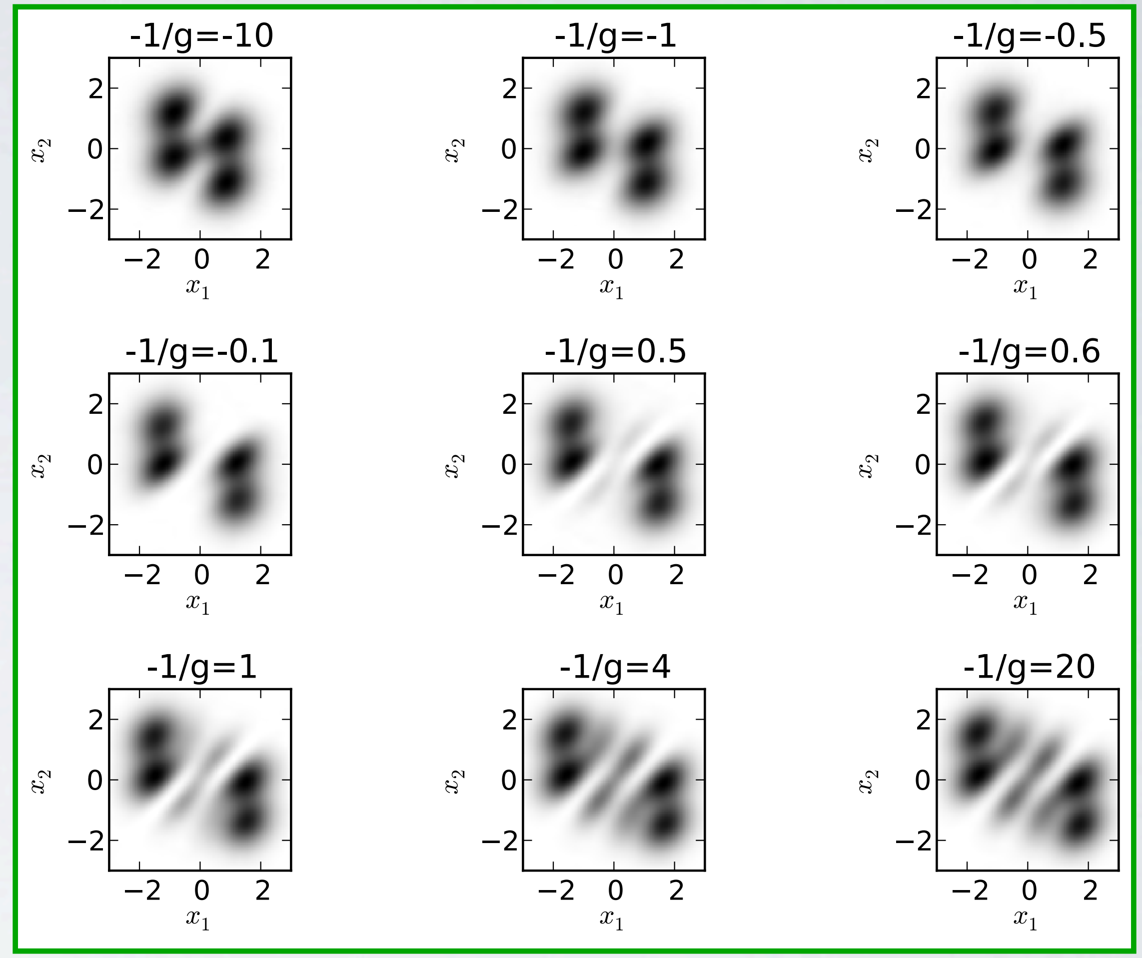


- Repulsive interaction
- From **weak** to **strong**
- **Non-interacting** state corresponds to the three-fermion ground state in HO trap
- At $-1/g \rightarrow 0$, these are degenerate



Densities and correlation densities





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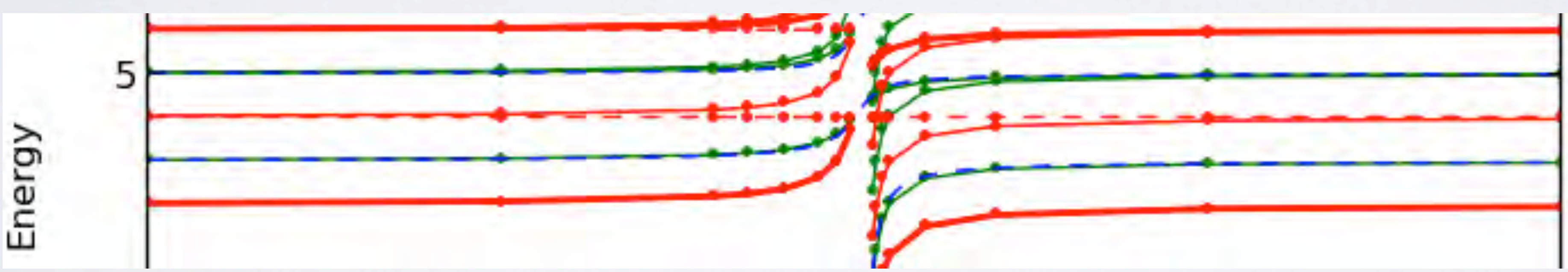
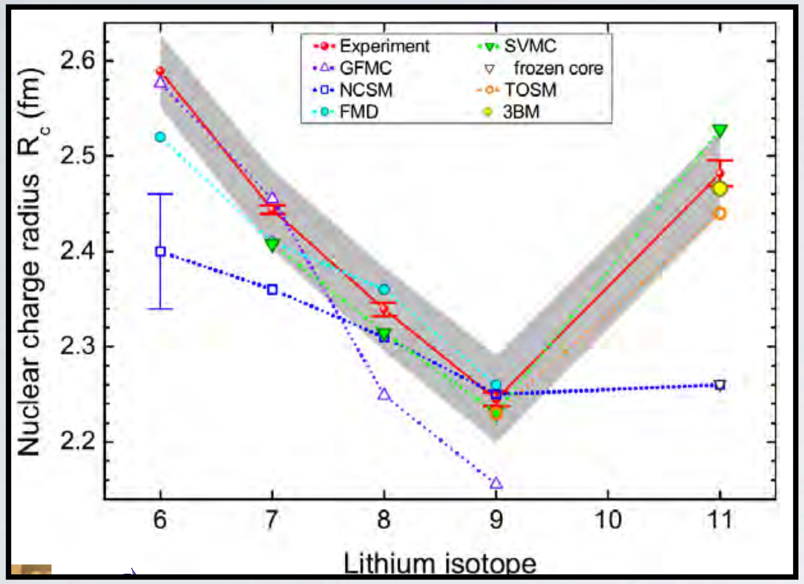
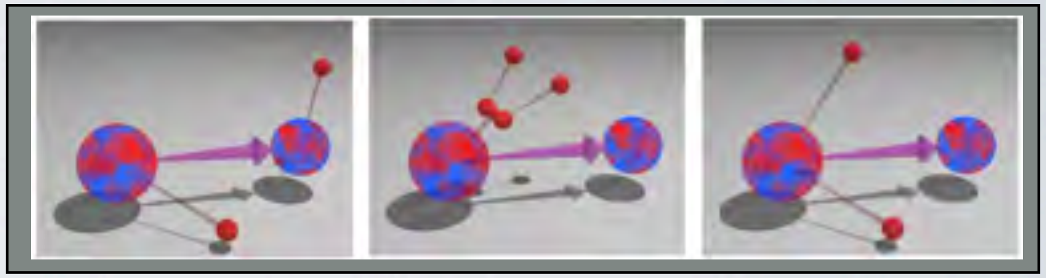


Ab Initio Towards The Driplines

Extremes of the (light) nuclear landscape

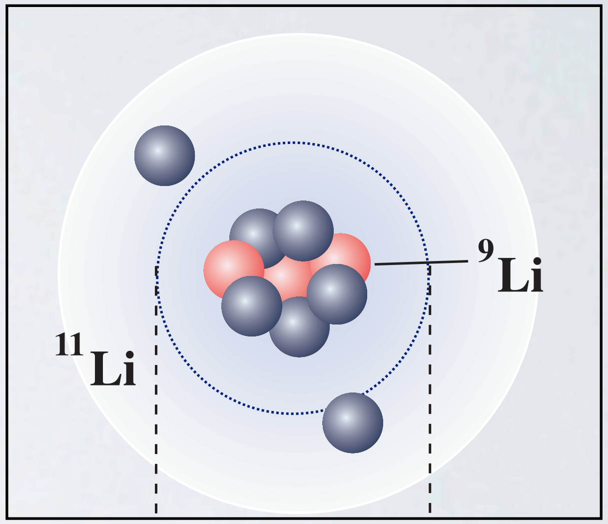
Observables: anomalous trends



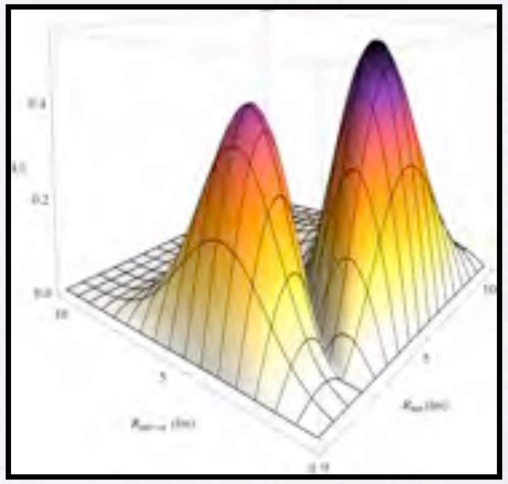


Exotic decay modes

^{17}Ne 109.2 ms
^{17}F 64.8 s
^{18}F 109.7 m
^{13}O 8.58 ms
^{14}O 70.59 s
^{15}O 2.03 m
^{16}O stable
^{17}O stable
^{18}O stable
^{19}O 27.1 s
^{12}N 11 ms
^{13}N 9.96 m
^{14}N stable
^{15}N stable
^{16}N 7.13 s
^{17}N 4.17 s
^{18}N 0.63 s
^{19}N 329 ms
^{9}C 126.5 ms
^{10}C 19.3 s
^{11}C 20.38 m
^{12}C stable
^{13}C stable
^{14}C 5730 a
^{15}C 2.45 s
^{16}C 0.747 s
^{17}C 193 ms
^{18}C 92 ms
^{19}C 49 ms
^{8}B 770 ms
^{10}B stable
^{11}B stable
^{12}B
^{13}B 17.33 ms
^{14}B 13.8 ms
^{15}B 10.4 ms
^{17}B 5.1 ms
^{7}Be 53.29 d
^{9}Be stable
^{10}Be 1.6 10^6 a
^{11}Be
^{12}Be 23.6 ms
^{14}Be 4.35 ms
^{6}Li stable
^{7}Li stable
^{8}Li 840 ms
^{9}Li 179 ms
^{11}Li 8.5 ms
^{3}He stable
^{4}He stable
^{6}He 808 ms
^{8}He 119 ms
^{1}H stable
^{2}H stable
^{3}H 12.3 y
n 10.25 m



Halo states, Borromean systems



Clusterization

C. Forssén, TRIUMF, Feb. 23, 2013

^{6}He Ground-State Properties

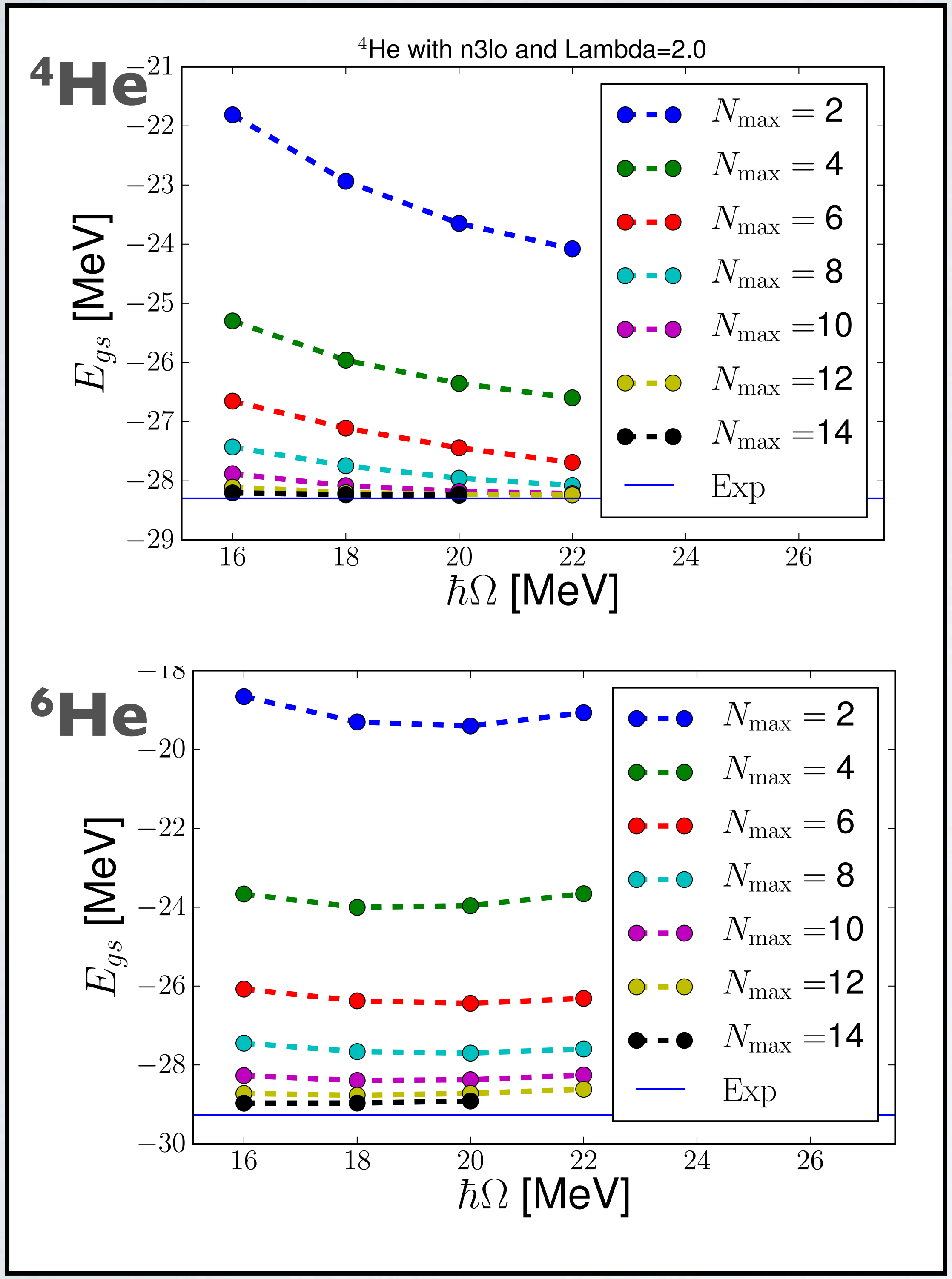
6-He references

- P. Mueller et al., Phys. Rev. Lett. **99** (2007) 252501.
- M. Brodeur et al. Phys. Rev. Lett. **108** (2012) 052504
- S. Bacca. et al. Phys. Rev. C**86**, (2012) 034321

- ❖ Very accurate charge-radius measurements using laser spectroscopy.
- ❖ Very accurate mass measurement with a Penning trap mass spectrometer.
- ❖ Several ab initio calculations
- ❖ Most recently by S. Bacca et al
  - using EIHH and V_{lowk} NN potential based on I-N^{3}LO.
  - Study of Vlowk cutoff-dependence and observable correlations.

NCSM example: Energy convergence

N^3LO, SRG (NN only, Λ = 2.0 fm^{-1})



HO basis cutoff scales

$$\Lambda_{\mathrm{UV}} = \sqrt{2(N+3/2)}\hbar/b$$

$$L_{\mathrm{IR}} = L_2 = \sqrt{2(N+3/2+2)}b$$

Extrapolations from finite HO basis

- R.J. Furnstahl et al., Phys. Rev. C 86(2012)031301R
- S. Coon et al., Phys. Rev. C 86(2012)054002
- R.J. Furnstahl et al., arXiv:1302.3815 (2013)

Previous work with $N_{\max}$ / ħΩ extrapolation

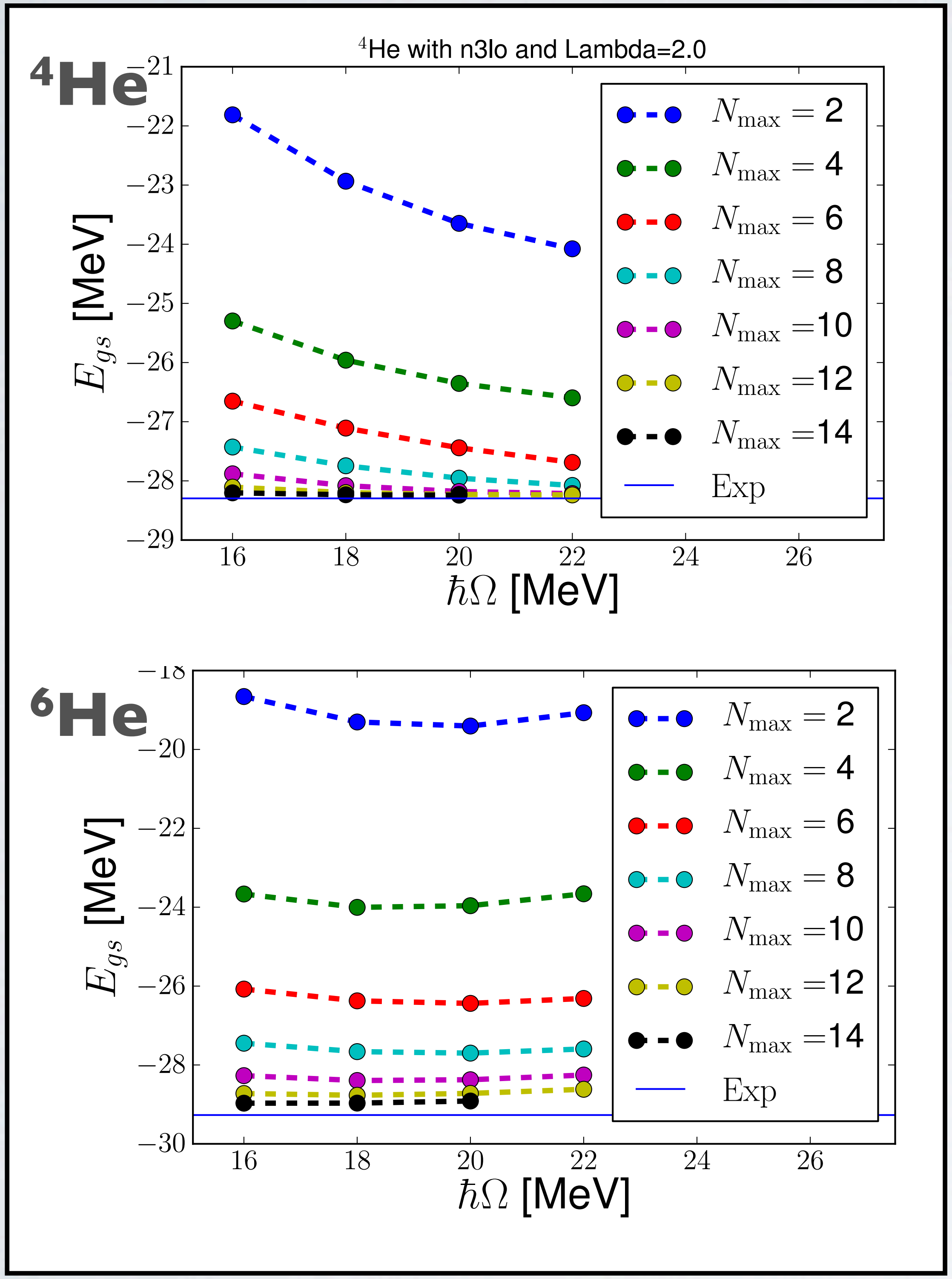
- C. Forssén et al., Phys. Rev. C 77(2008)024301
- P. Maris et al., Phys. Rev. C 79 (2009)014308

Correction to the energy due to finite HO space

$$E_L = E_\infty + \Delta E_L$$

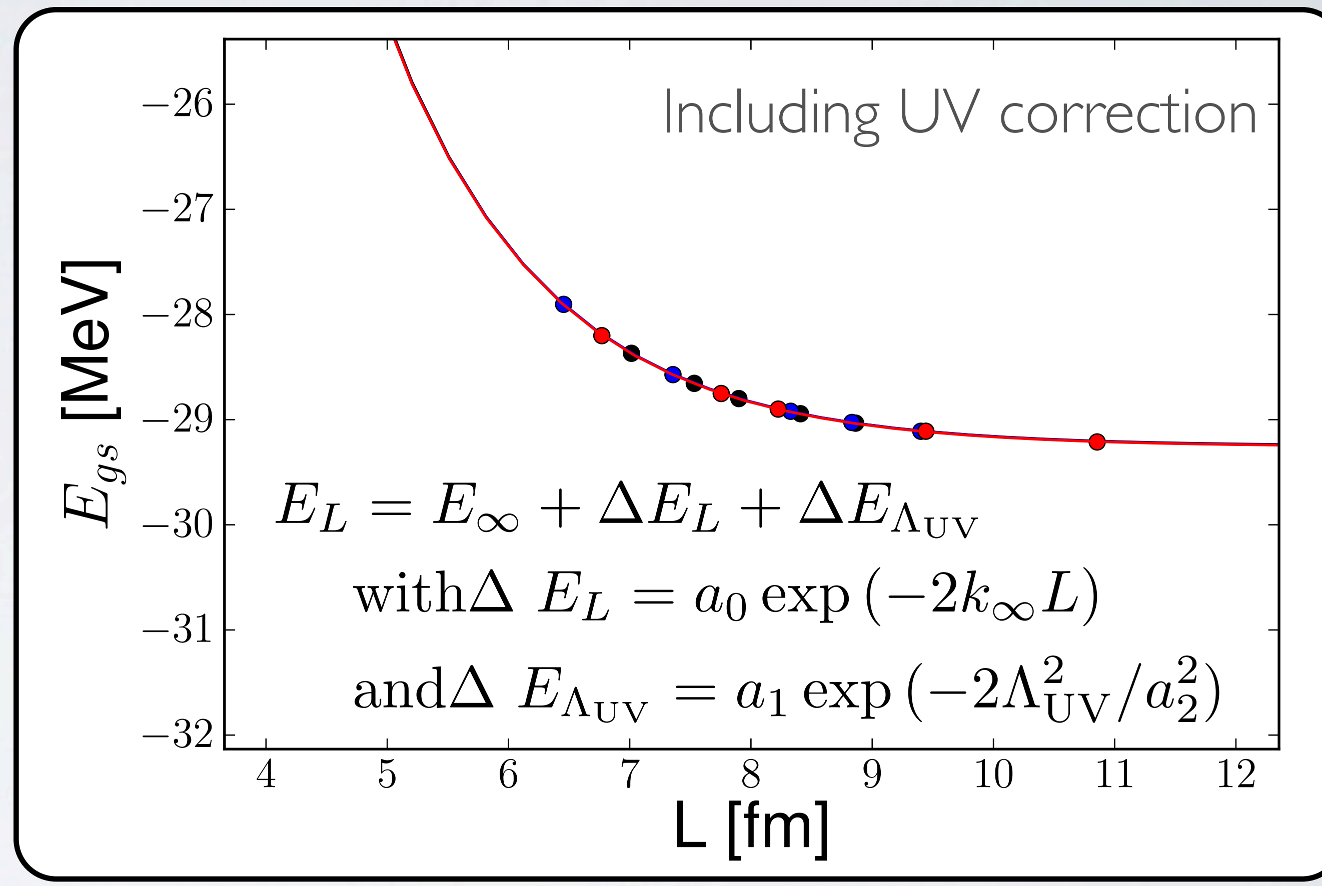
$$\text{with} \Delta\ E_L = a_0 \exp(-2k_\infty L)$$

NCSM example: Energy convergence



Binding energies

N^3LO, SRG (NN only, $\Lambda = 2.0\ \mathrm{fm}^{-1}$)

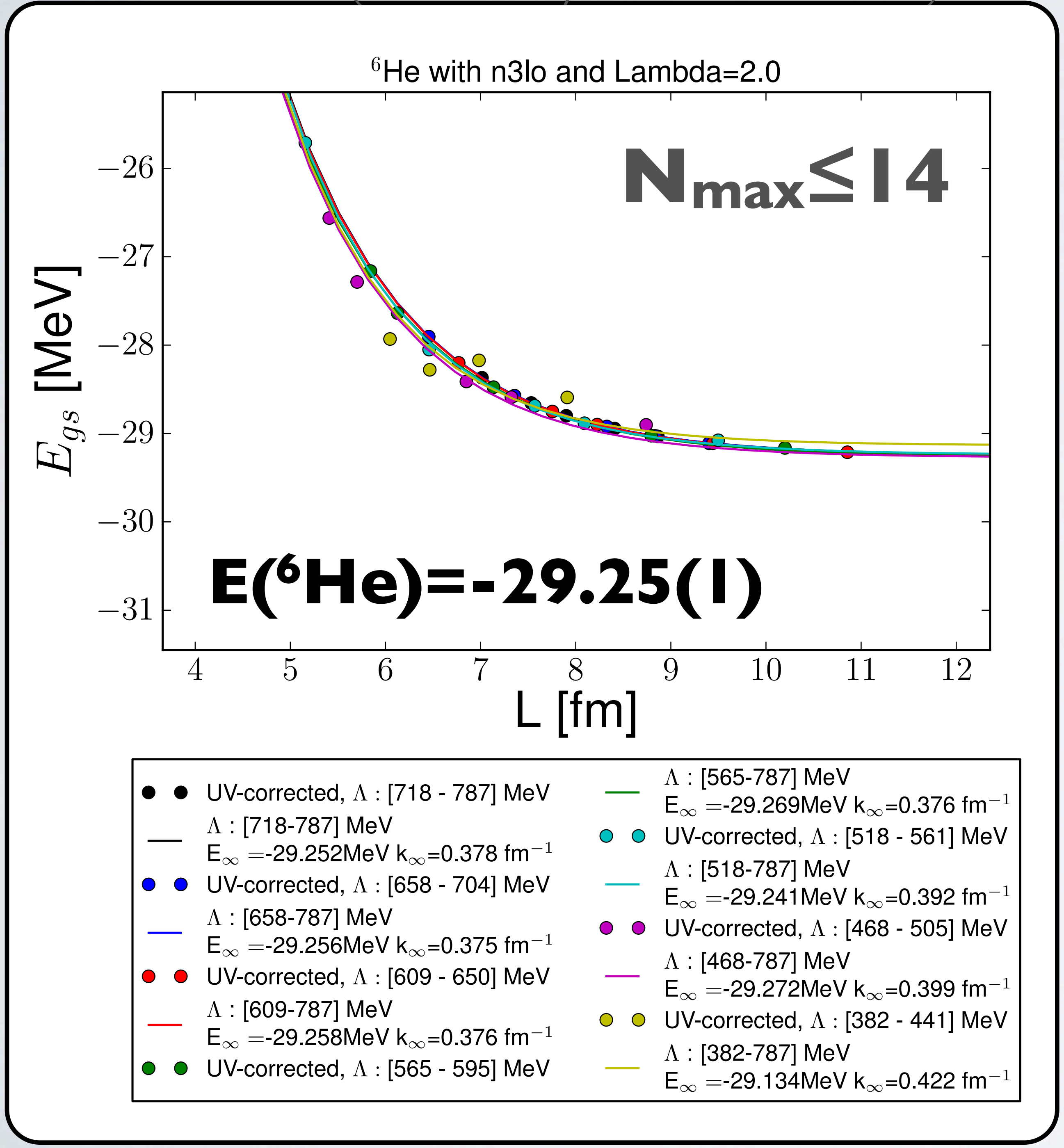


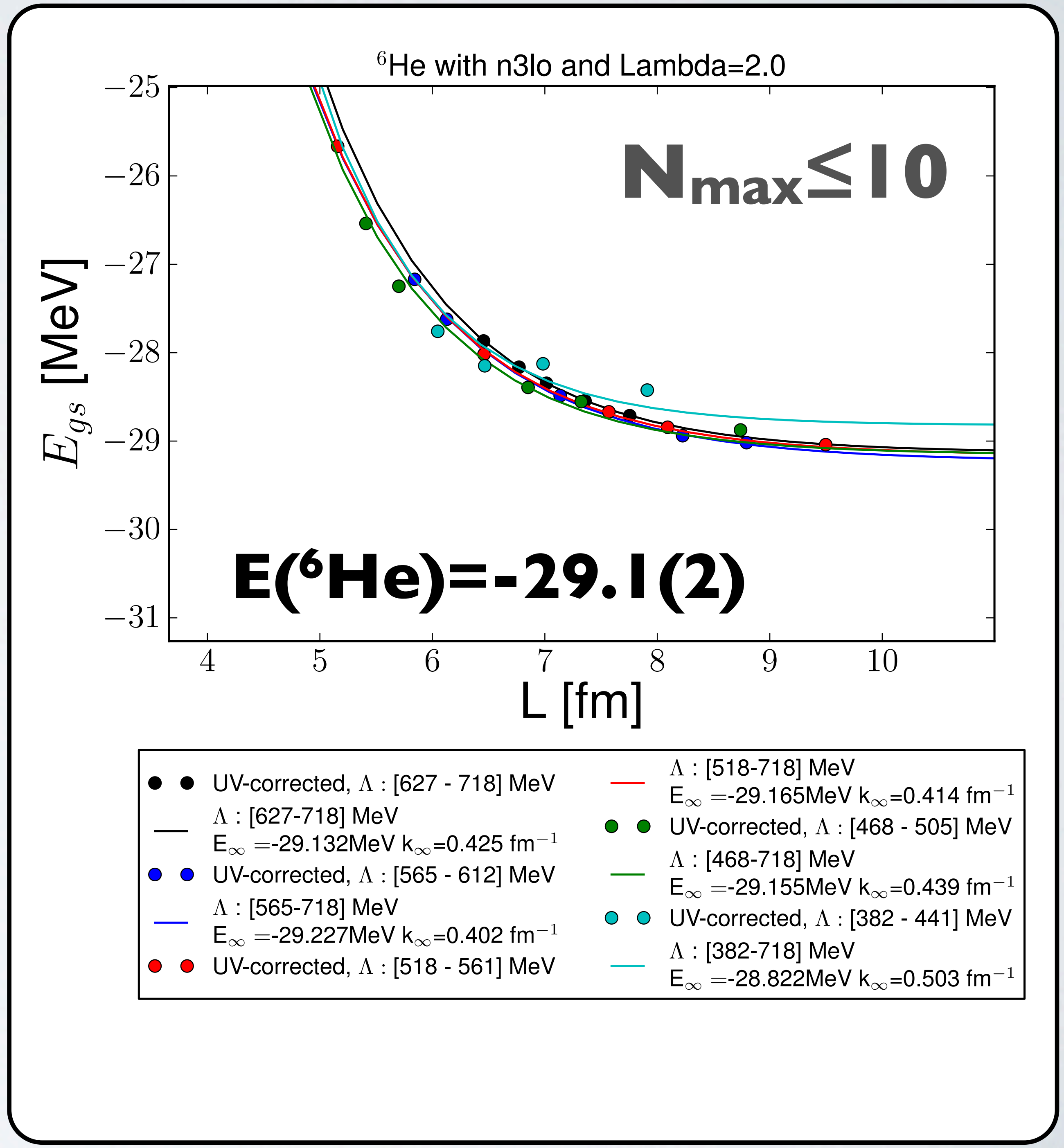
E(^{6}He)	-29.25(1) MeV
S_{2n}	1.01(1) MeV

C. Forssén, TRIUMF, Feb. 23, 2013

NCSM example: Energy convergence

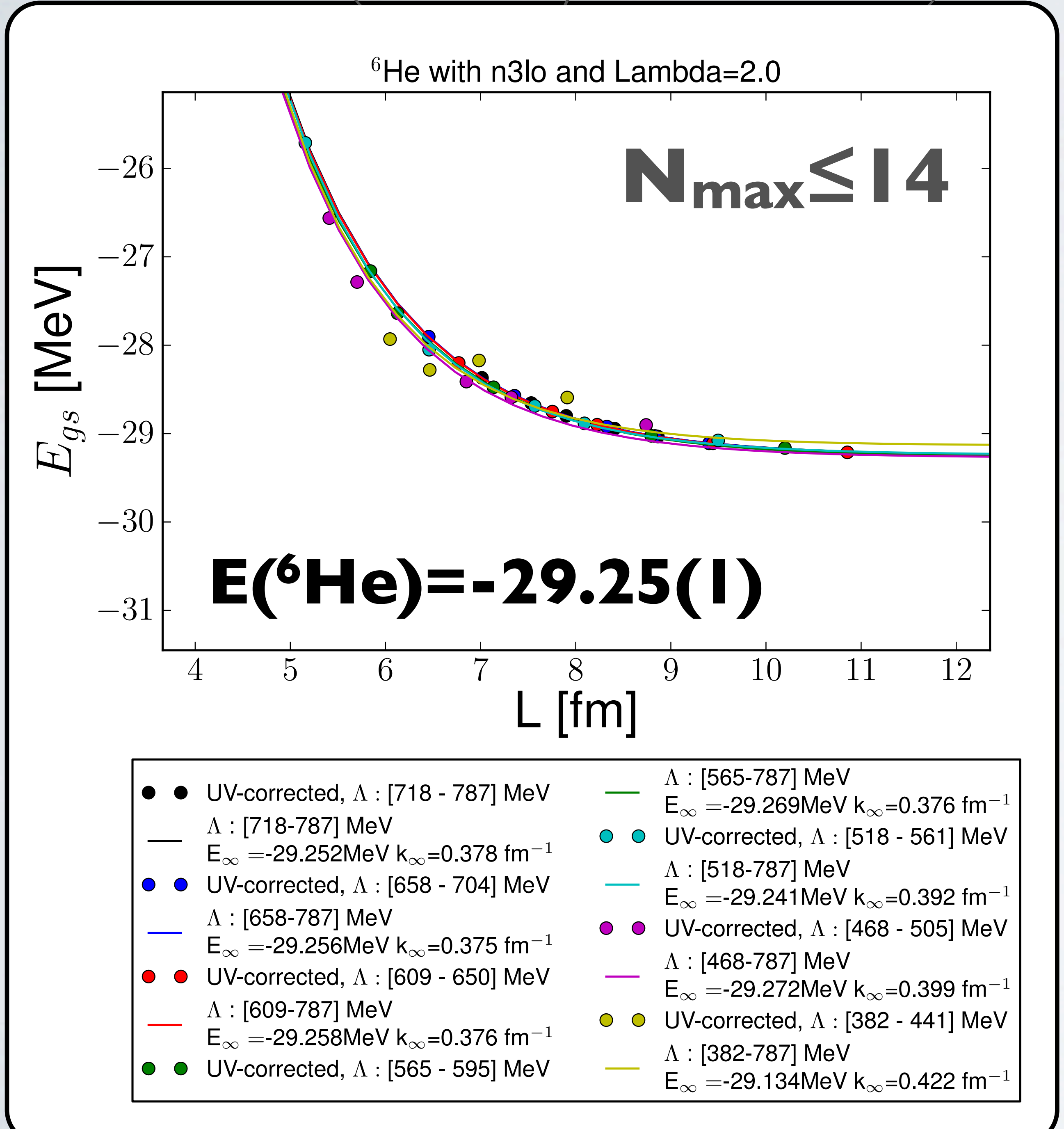
N^{3}LO, SRG (NN only, Λ = 2.0 fm^{-1})

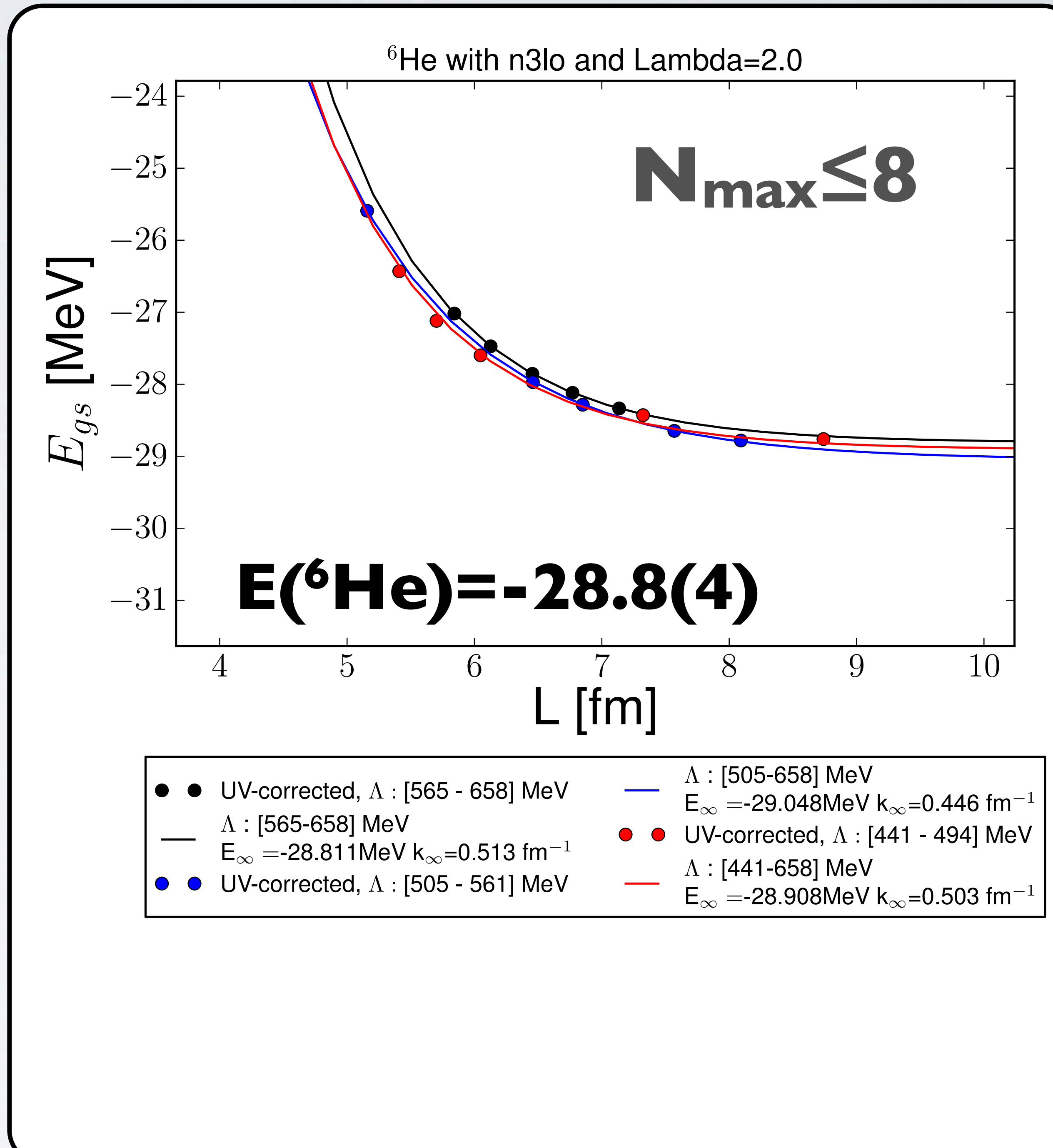




NCSM example: Energy convergence

N^{3}LO, SRG (NN only, Λ = 2.0 fm^{-1})





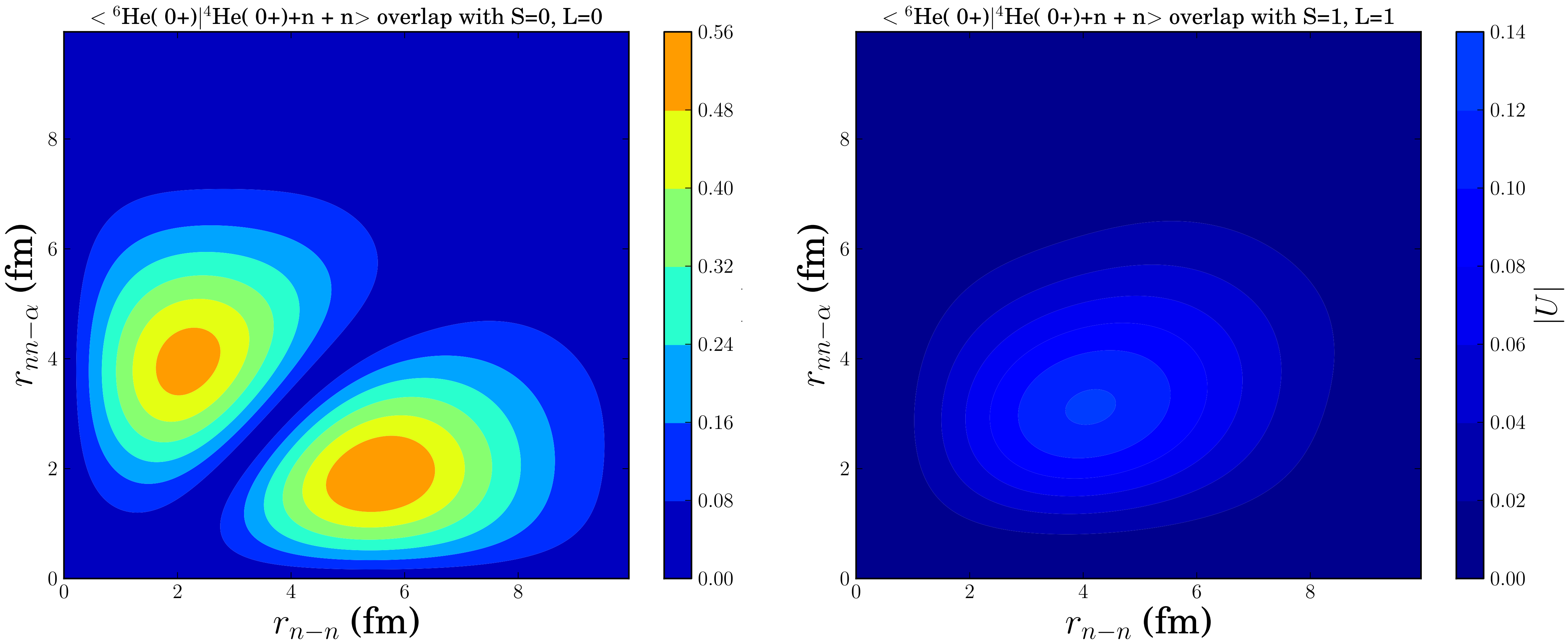
Ab initio < ^{6}He | ^{4}He+n+n > overlap

<^{6}He (0^+) | ^{4}He (0^+)+n+n>

N^{3}LO, SRG
NN only, Λ = 2.0 fm^{-1},
N_{max}=14, HO=20 MeV

L=S=0

L=S=1

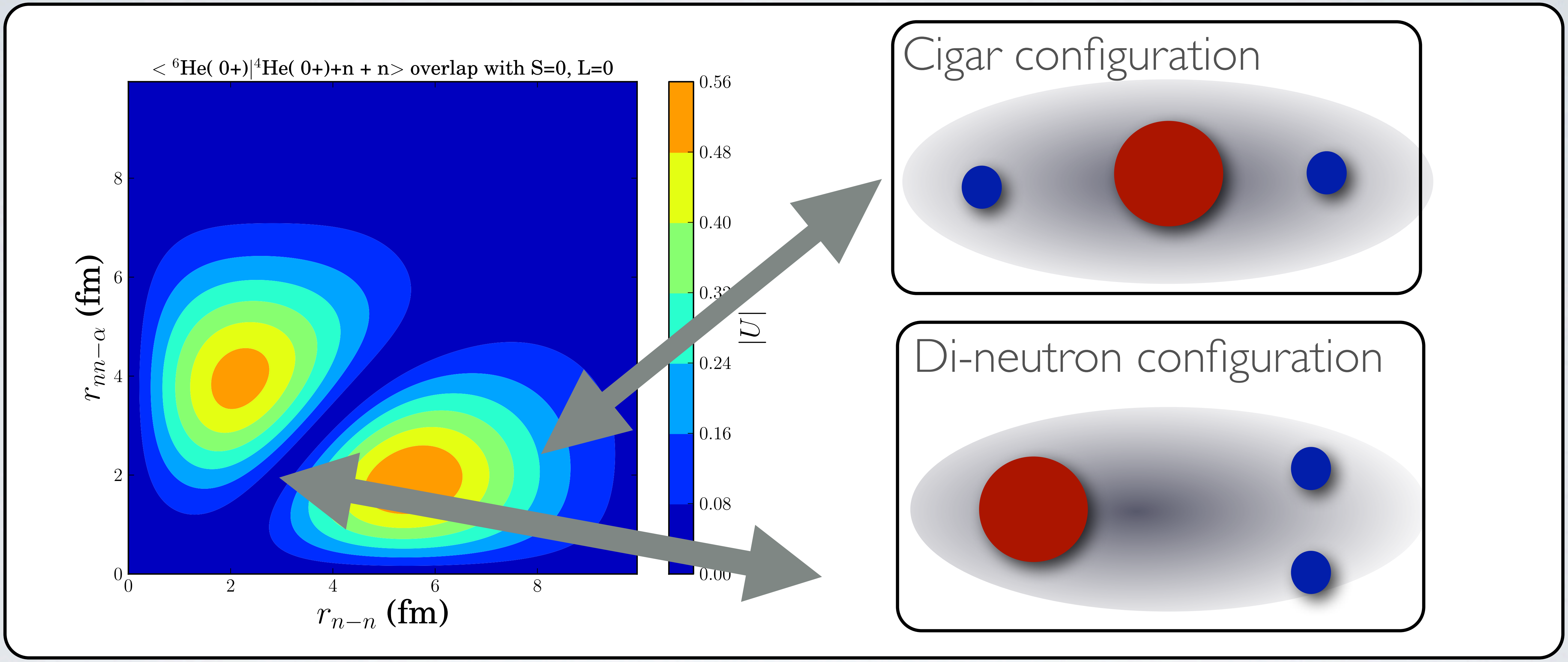


$$u^{AJT}_{(A-2)I_1T_1;LS}(x,y) = \sum_{ij} R_i(x) R_j(y)_{\mathrm{SD}} \langle (A)JT ||| a_i^\dagger a_j^\dagger ||| (A-2) I_1 T_1 \rangle_{\mathrm{SD}}$$

Ab initio < ^{6}He | ^{4}He+n+n > overlap

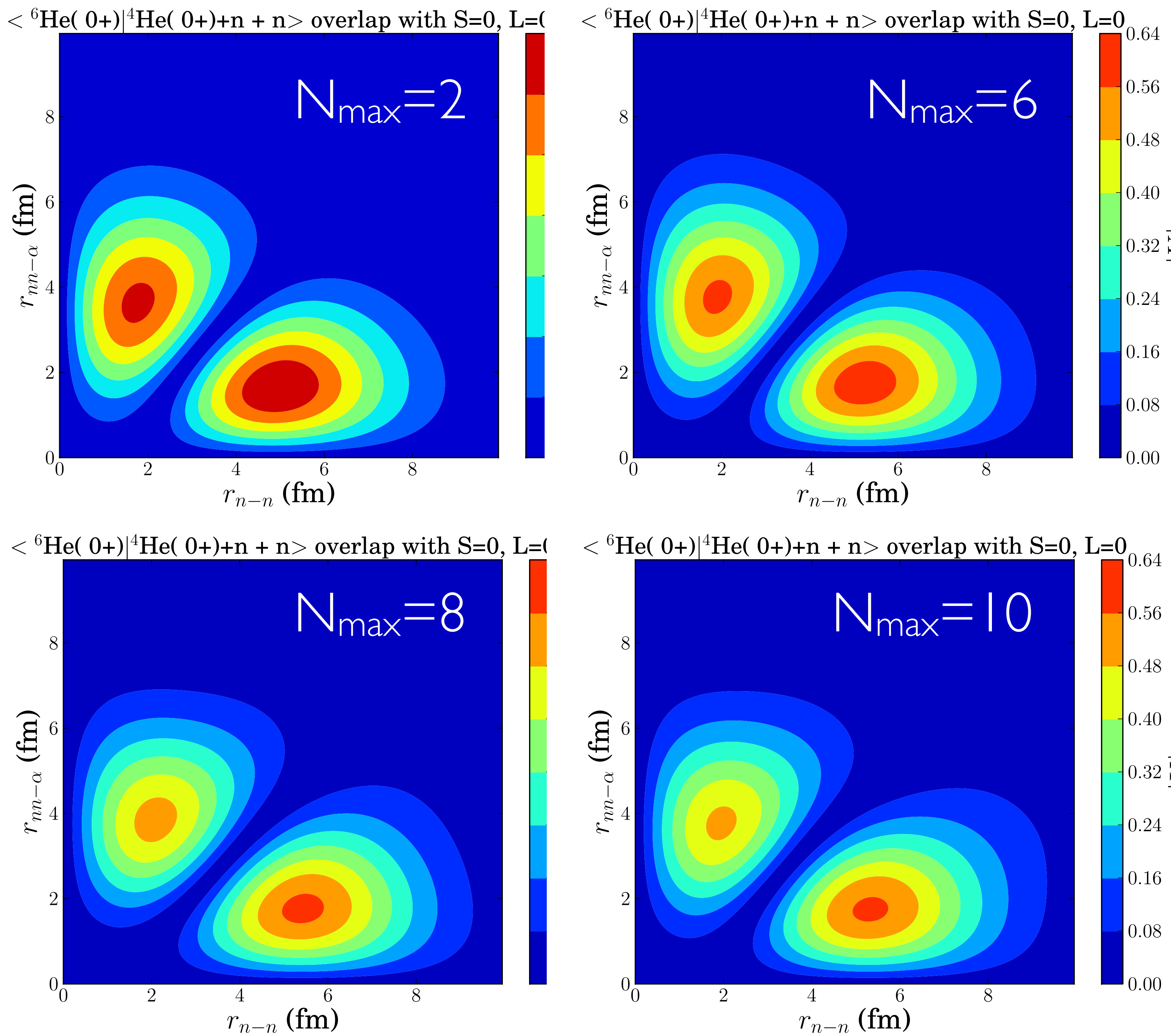
N^{3}LO, SRG
NN only, Λ = 2.0 fm^{-1},
N_{max}=14, HO=20 MeV

<^{6}He (0^+) | ^{4}He (0^+)+n+n>



$< {}^{6}He \mid {}^{4}He+n+n >$ overlap: N_{max} dependence

$<{}^{6}He\ (0^{+}) \mid {}^{4}He\ (0^{+})+n+n>$



N^3LO, SRG

NN only, Λ = 2.0 fm^{-1},

N_{max}=14, HO=20 MeV

Conclusion:
This is a Pauli focusing effect

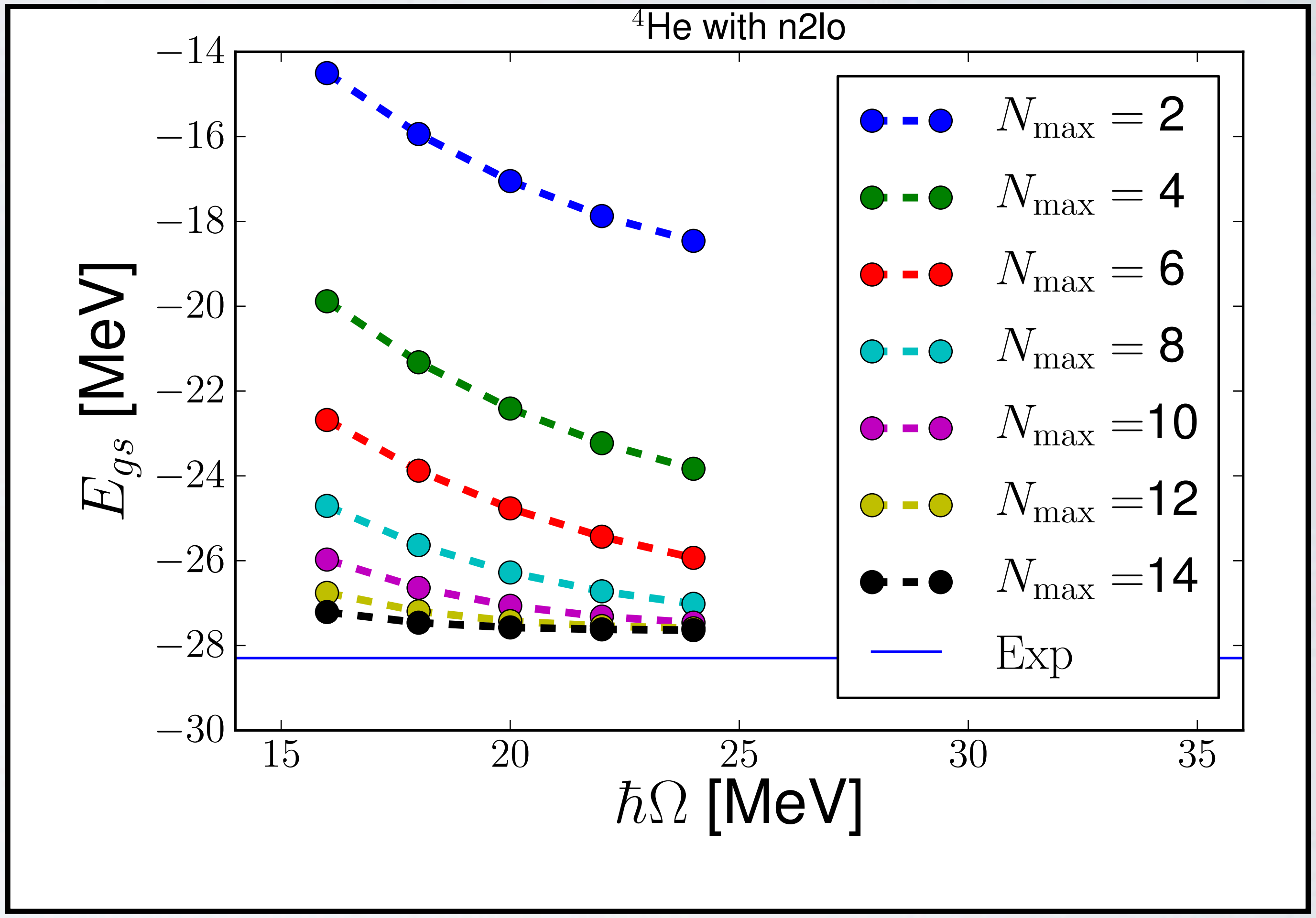
NNLO (POUNDerS) in the NCSM

NNLO (POUNDerS) in NCSM

- NNLO (POUNDerS) **optimized** to NN phase shifts (see A. Ekström's talk)
- It is **soft**:
  we will show bare interaction results in NCSM up to A~10.
- Study effects on the **structure** of light nuclei
- Technical **developments** of shell model code ⇒

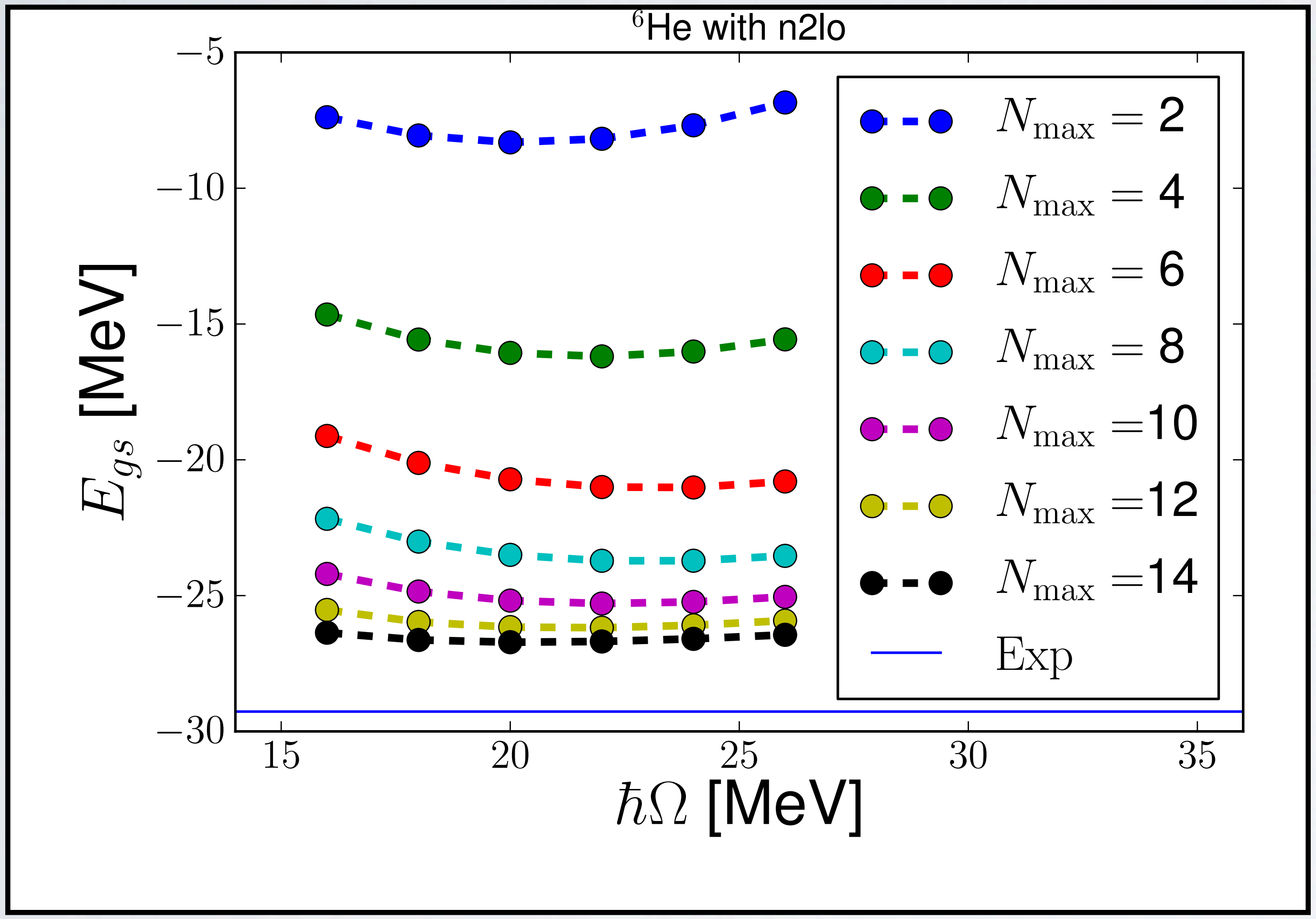
  d~1.7 x 10^9 - one Lanczos iteration in 35 min on **one** node.

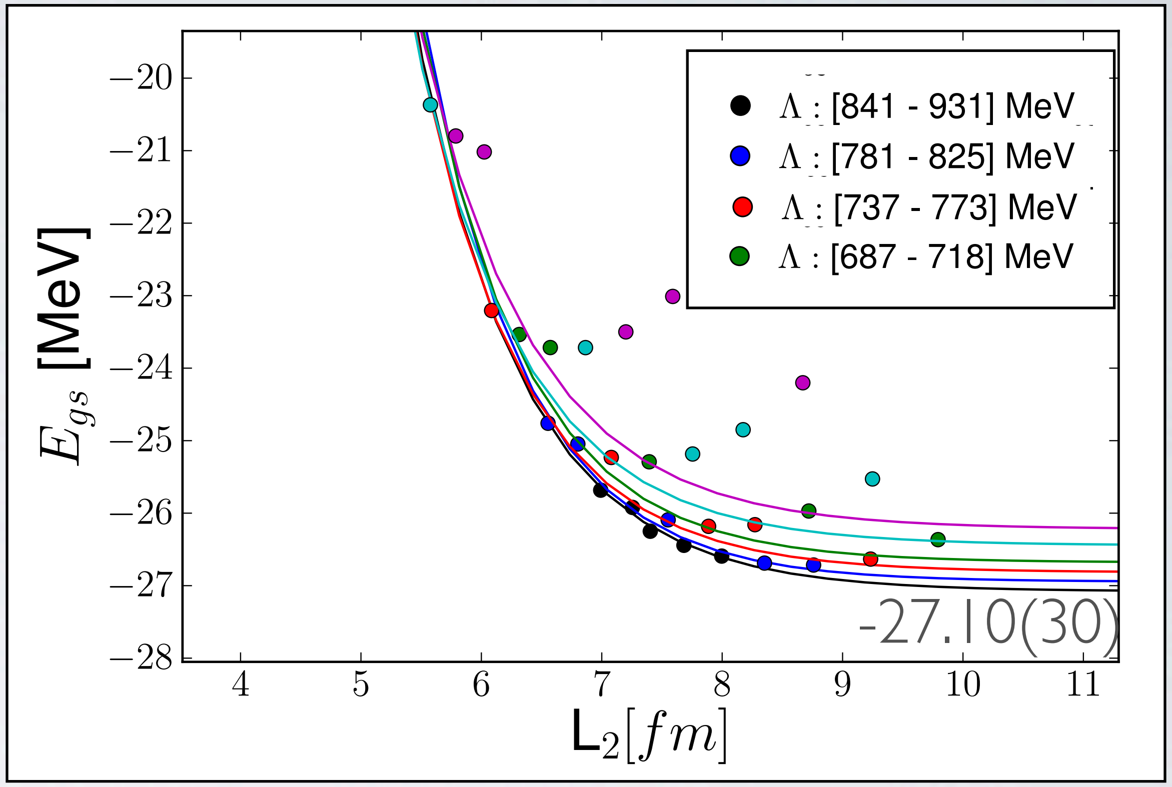
^{4}He with NNLO (POUNDerS) -bare

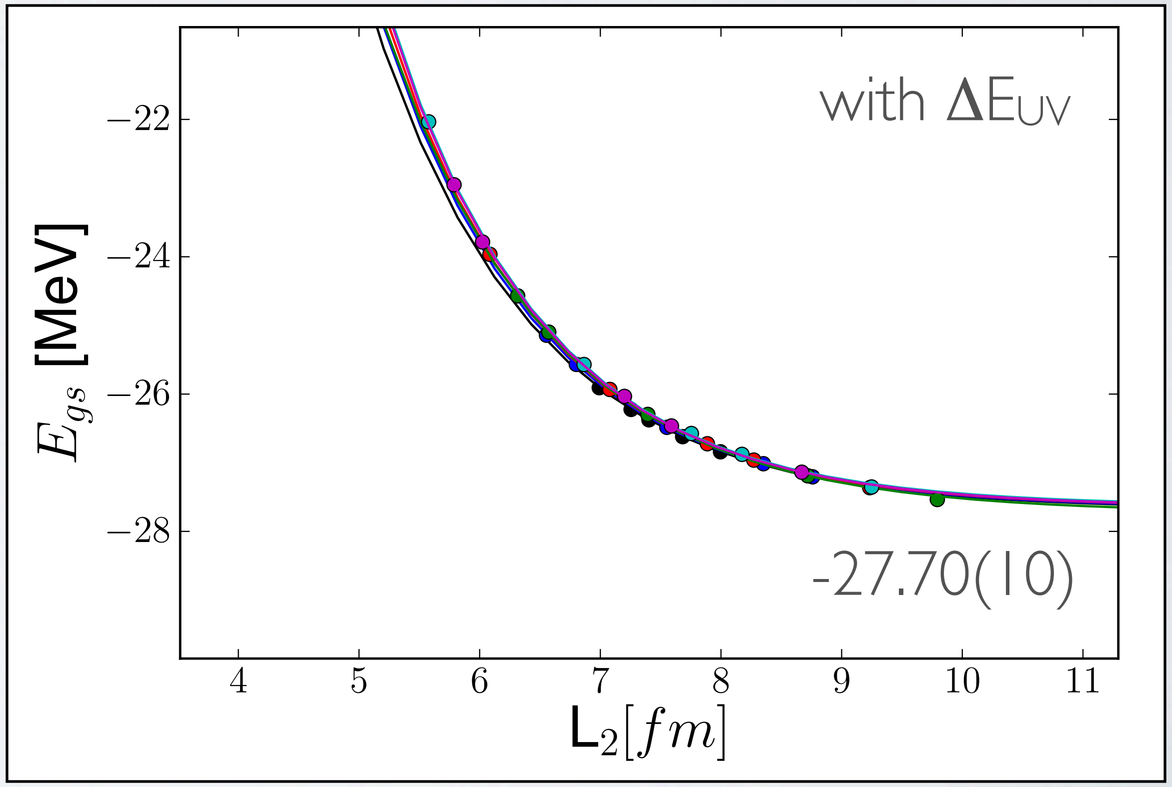


A=6 energy

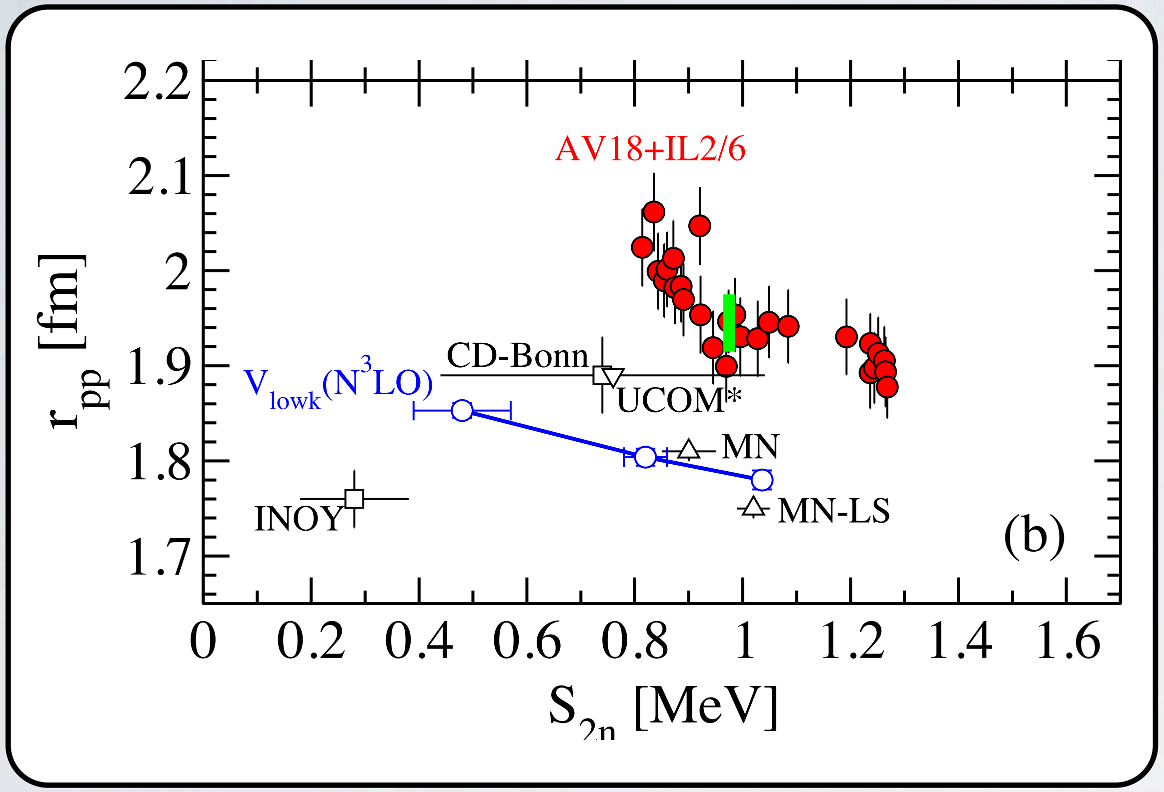
^{6}He with NNLO (POUNDerS) -bare

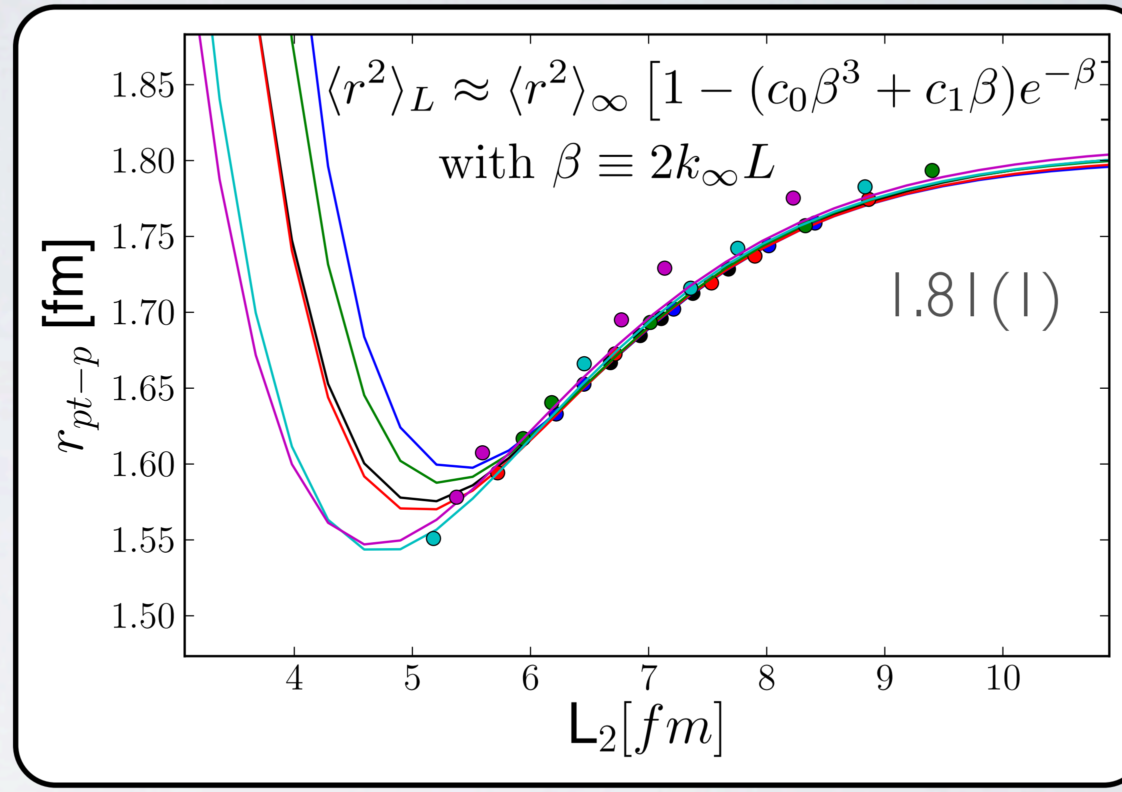






A=6 radii and S_{2n}

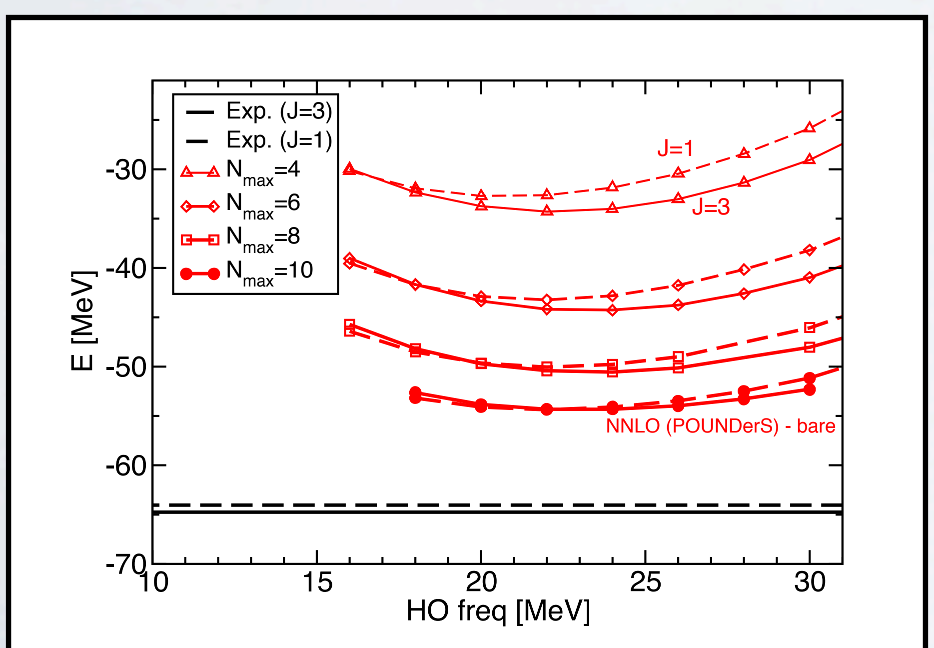


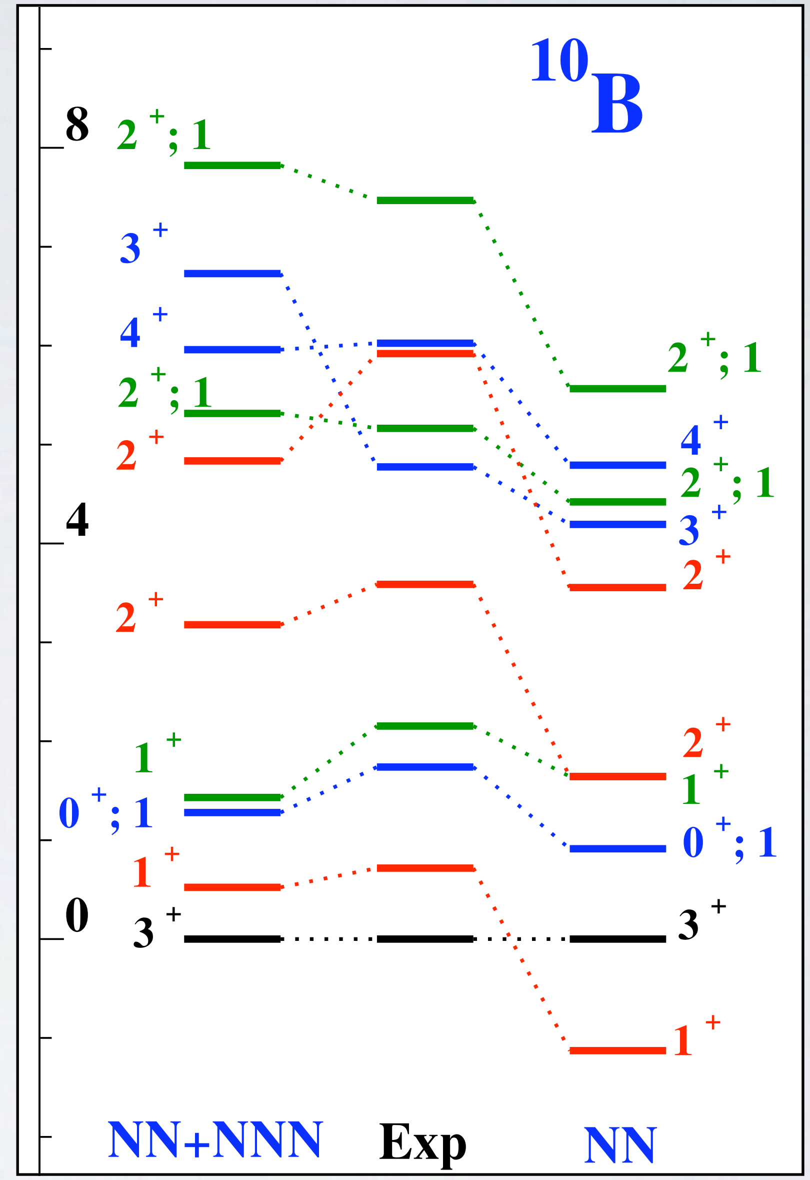


	$r_{pt-p}(^6He)$ [fm]	$S_{2n}(^6He)$ [fm]
Exp.	1.938(23)	0.97
NCSM (SRG Λ = 2.0 fm^{-1}): N3LO (EM)	1.83(1)	1.01(4)
HH (S. Bacca) (LS+V_{lowk}, 2.0 fm^{-1}): N3LO (EM)	1.804(9)	~0.8
NCSM (bare): NNLO (POUNDerS)	1.81(1)	0.1(1)

^{10}B ground state

- Realistic NN interactions predict the incorrect ground-state spin of ^{10}B
- It has been shown that NNN terms in the Hamiltonian are needed to remedy this situation.
- With the NNLO (POUNDerS) NN interaction we find a very small gap between the 3^+, 1^+ levels.

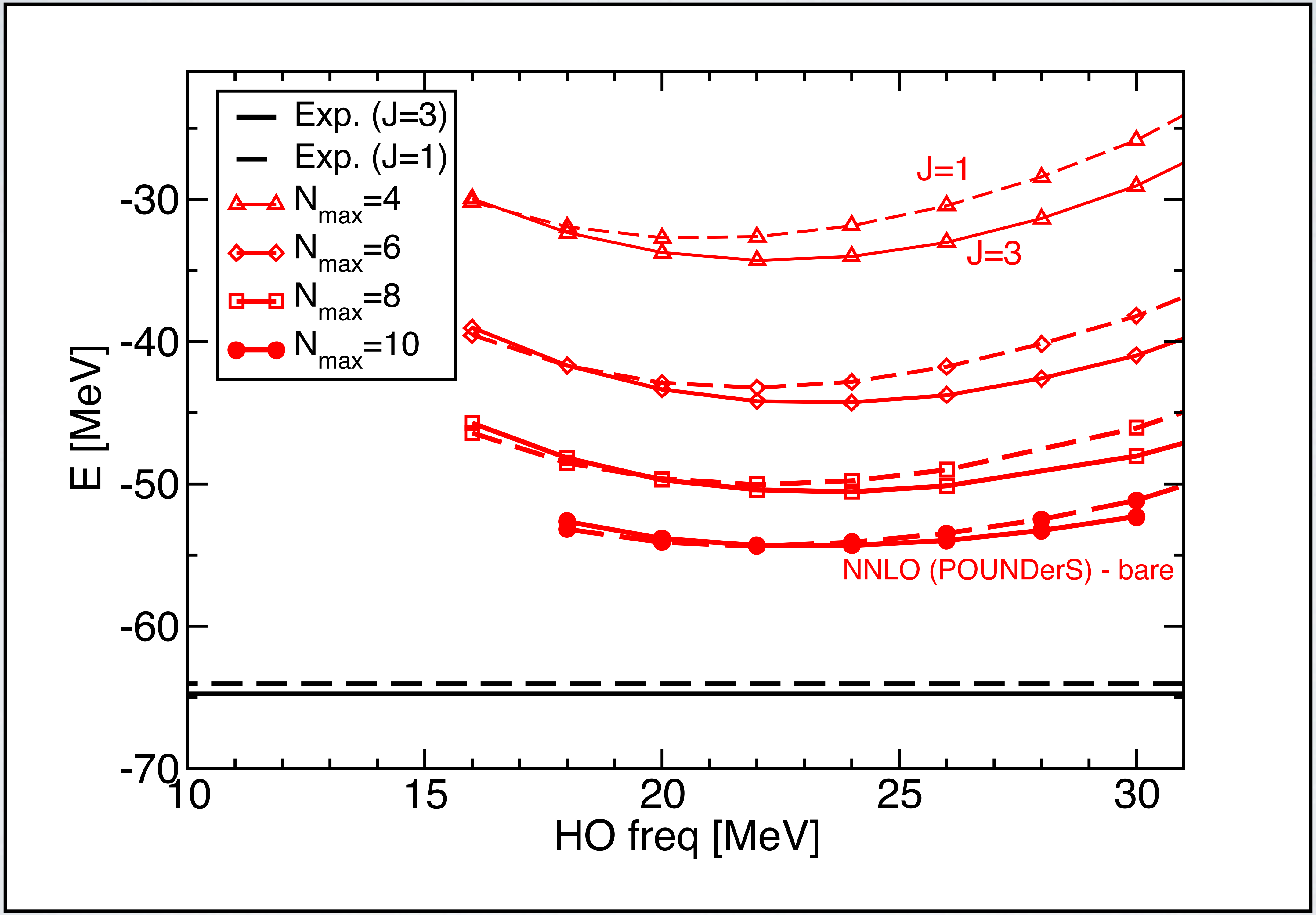




From: P. Navrátil et al., Phys. Rev. Lett. 99(2007)042501.

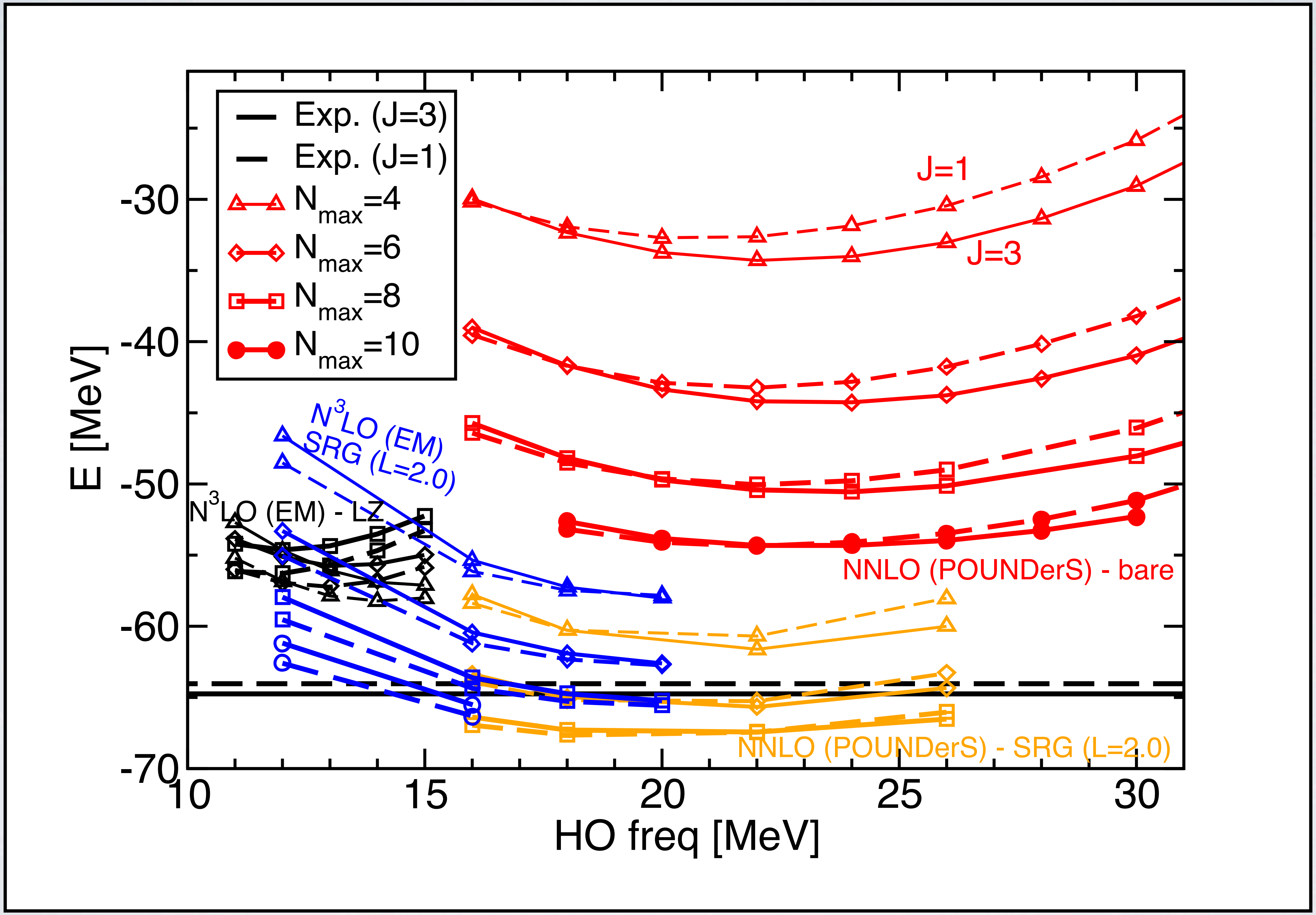
^{10}B ground state

^{10}B with NNLO (POUNDerS) -bare



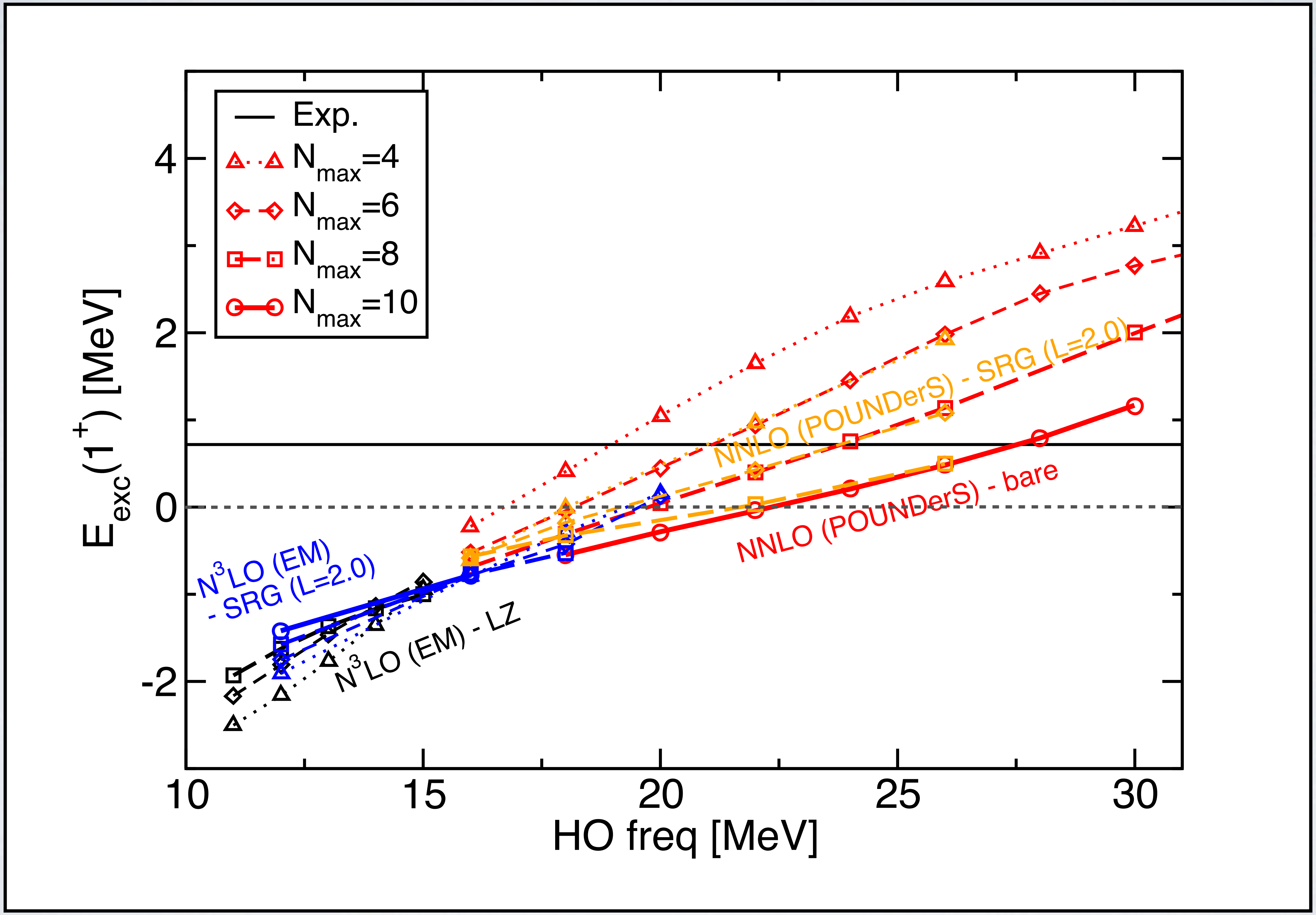
^{10}B ground state

^{10}B with NNLO (POUNDerS) -bare



^{10}B ground state assignment

^{10}B with NNLO (POUNDerS) -bare



Technical developments

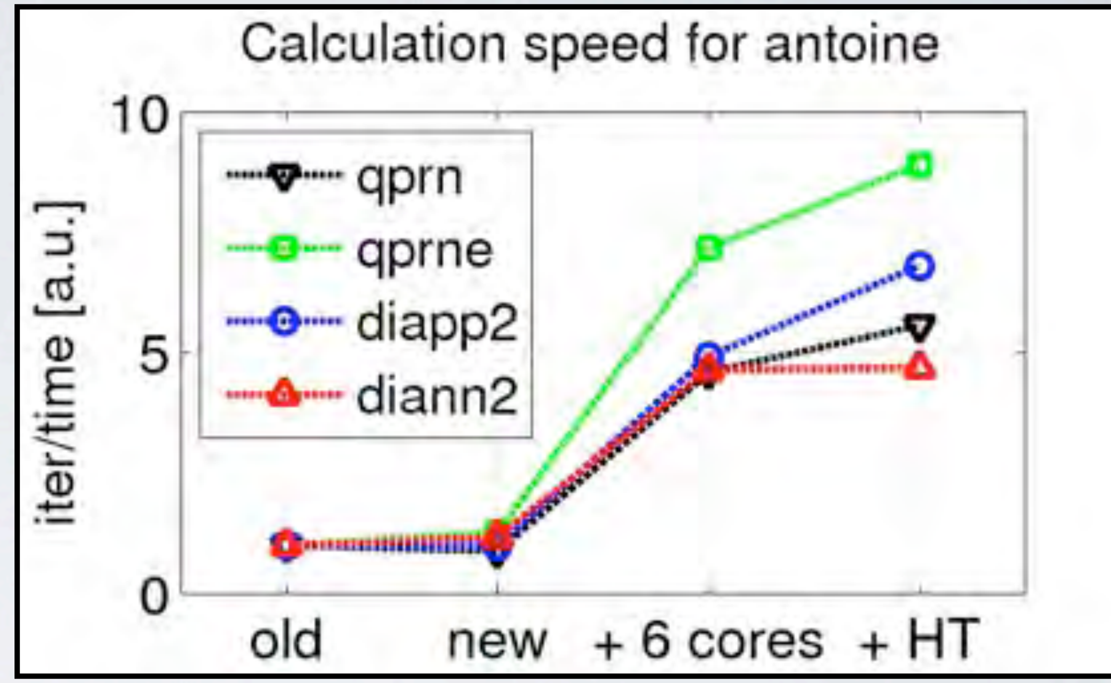
- Antoine employs the (smaller) p/n **subspaces**:
  MB state $i = q_p + r_n$

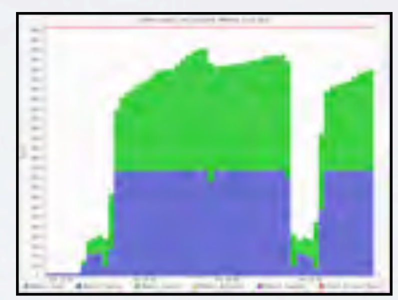
- MB matrix generated **on-the-fly**.
  MatVec operations the largest bottleneck.

- New version: **pANTOINE**
  $M * x = y$, split into subsets
  $(M_1 + M_2 + ...) * x = y$

- Shared memory / **multithread**
  Close to theoretical max of Miter / s on multicore.

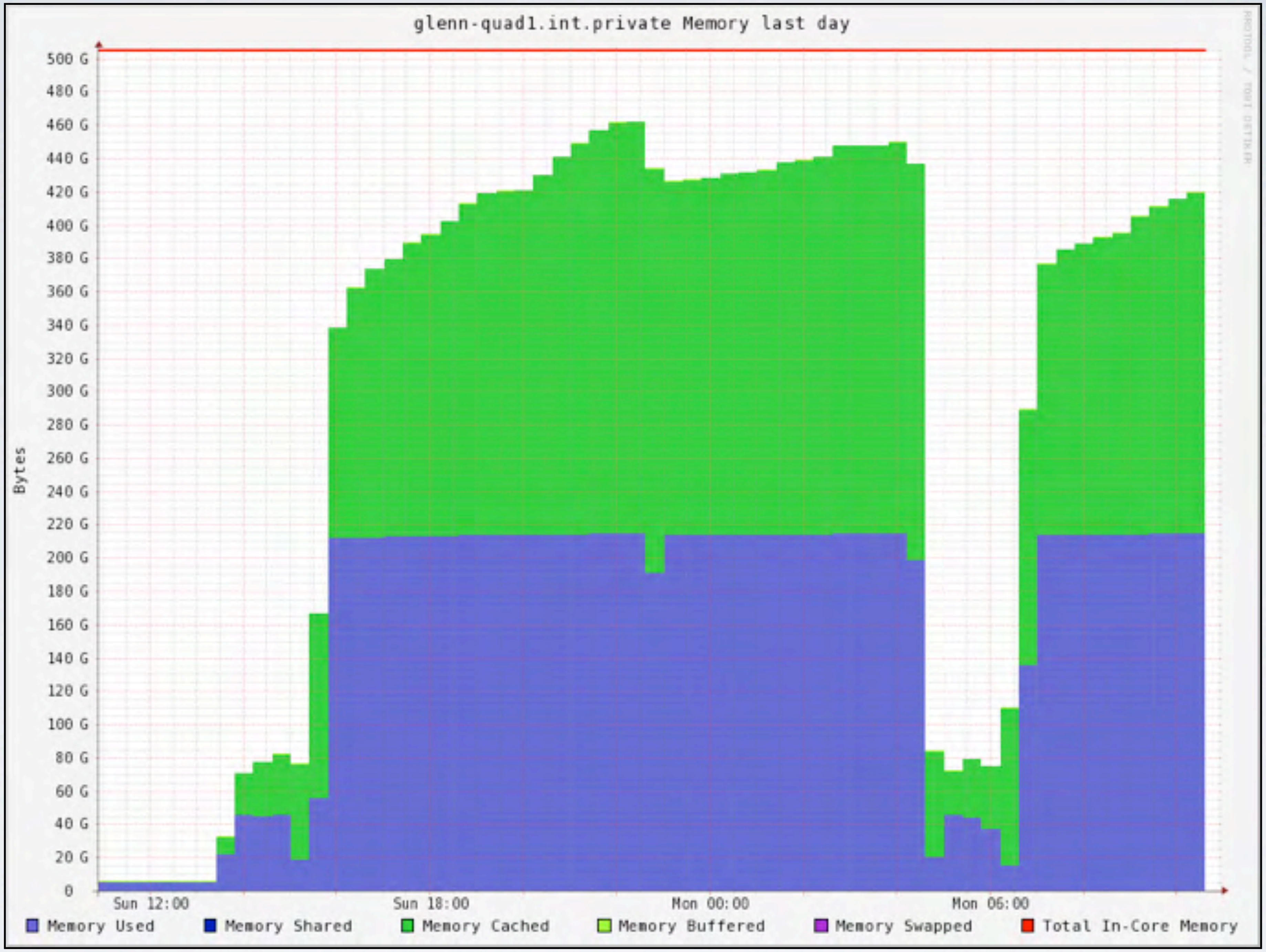
- Timing: qprn used in average 31.8 of 32 cores on Glenn no. 5





Glenn no. 5
Opteron 6220 (4 sockets, 32 cores, 512 GB)

Technical developments



N_{max}=10 for ^{10}B ⇒ d ~ 1.7 × 10^9

Ground state obtained in seven hours on **one** node.

Conclusion and Outlook

- Effective interactions for cold atoms in deformed traps
- Introduction of UV and IR scales; optimization of run sequence
  - BUT still need several large N_{max} computations
  - Technical development - pAntoine
- Microscopic description of clustering
  - Calculate core swelling: r_{pp}
  - Study projection on HH basis
- First results from NNLO (POUNDerS) in the NCSM
  - Soft - bare interaction used
  - $^{10}B(1^+,3^+)$ states almost degenerate