# Three-nucleon forces at neutron-rich extremes

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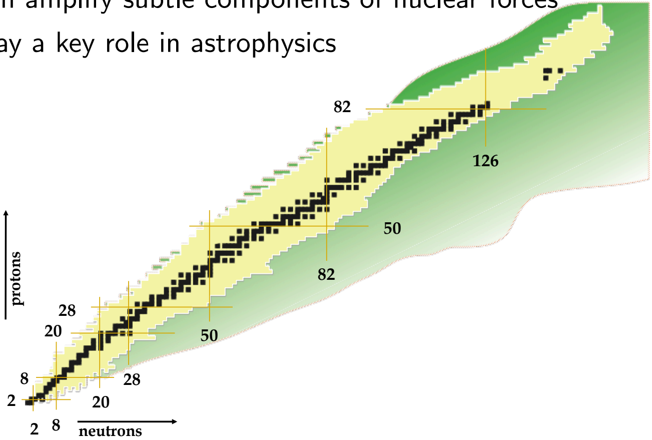
# Physics motivation

## Neutron-rich nuclei

- exhibit new shell structures
- can amplify subtle components of nuclear forces
- play a key role in astrophysics



# Microscopic calculations of medium-mass nuclei

Valence-shell calculations based on nuclear forces

- Use chiral Effective Field Theory interactions, includes naturally NN, 3N and higher-body forces
- Perform a renormalization group evolution to $V_{low\ k}$ interaction to enhance convergence of the MBPT calculation
- Apply Many-Body Perturbation Theory (MBPT) to obtain interactions to be used in Shell-Model (SM) calculations

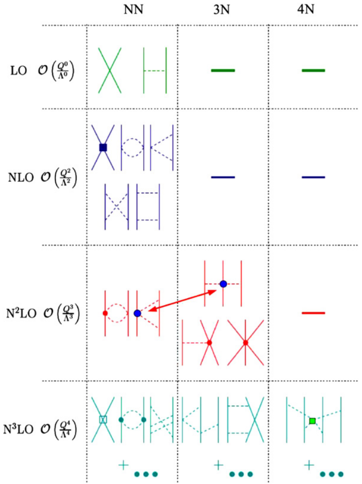
⇒ All parameters in the valence-shell Hamiltonian calculated from microscopic interactions (no fits!)

⇒ Test nuclear forces for stable and exotic nuclei

⇒ Goal: reliable predictions for neutron-rich extremes with controlled uncertainties

# NN+3N forces in chiral EFT

Systematic expansion for nuclear forces




- NN force couplings fitted to NN, $\pi$N data
- 3N force couplings: $c_i$'s consistent with NN; $c_D$,$c_E$ fitted to few-body data: $^3$H binding energy, $^4$He charge radius
- Chiral EFT potentials for NN up to N$^3$LO and 3N up to N$^2$LO
- But: N$^3$LO 3N $\sim 1/3$ of N$^2$LO 3N $\rightarrow$ T. Krüger's talk

Tews *et al.*, *PRL* **110** 032504 (2013).

# Shell-Model interactions

- Results with NN+3N forces included to 3rd order in MBPT
- In addition to standard *sd* and *pf* shell
  - O isotopes: $sdf_{7/2}p_{3/2}$ valence space
  - Ca isotopes: $pfg_{9/2}$ valence space
- Full diagonalizations using ANTOINE

  Caurier *et al.*, *RMP* **77** 427 (2005).

- MBPT with enlarged valence space to explicitly include orbits non-perturbatively
- Open problem for valence space beyond one major shell: center-of-mass factorization

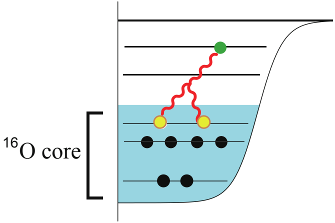
  difficulty that $< H_{cm} >$ is not real indicator

  Hagen *et al.*, *PRL* **103** 062503 (2009).

# 3N forces for valence-shell Hamiltonians

- Contribution to valence neutron interactions

Effective one body




$$\langle a|V_{3N,1b}|a\rangle = \frac{1}{2}\sum_{\alpha,\beta\in core}\langle\alpha\beta a|V_{3N}|\alpha\beta a\rangle$$

$\Rightarrow$ (Effective) single-particle energies (SPE)

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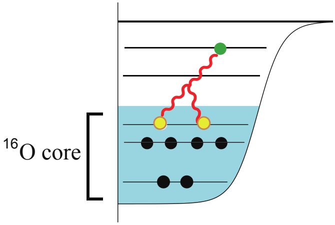
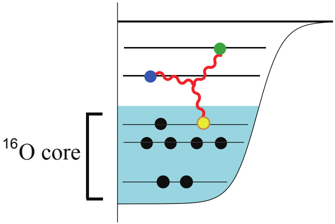



$$\langle a|V_{3N,1b}|a\rangle = \frac{1}{2}\sum_{\alpha,\beta\in core}\langle\alpha\beta a|V_{3N}|\alpha\beta a\rangle$$

⇒ (Effective) single-particle energies (SPE)

Effective two body




$$\langle ab|V_{3N,2b}|a'b'\rangle = \sum_{\alpha\in core}\langle\alpha ab|V_{3N}|\alpha a'b'\rangle$$

⇒ (Effective) two-body matrix elements (TBME)

# 3N forces for valence-shell Hamiltonians

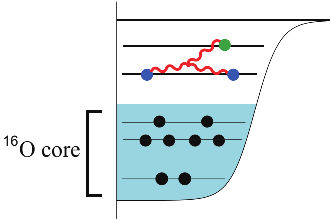
When going to neutron-rich extremes must include

- Residual three body

Friman, Schwenk, arXiv:1101.4858.

  - Estimated to be suppressed $N_v/N_c$

$$\Delta E \sim \frac{N_v}{N_c} E_{2-body}^{normal-ordered}$$

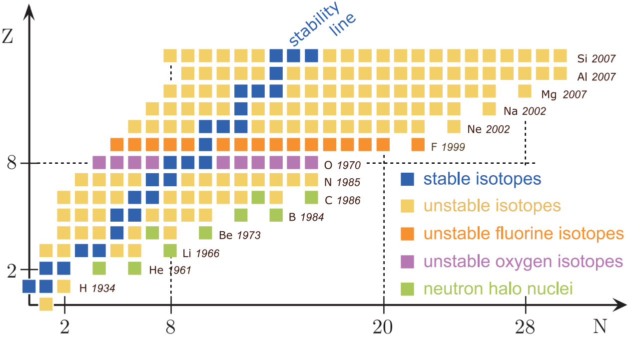



  - Becomes important for most neutron-rich isotopes
  - Included perturbatively using wave function from ANTOINE

$$\Delta E_{3N,res} = \langle \Psi_{NN+3N,2b} | V_{3N} | \Psi_{NN+3N,2b} \rangle$$

# The oxygen anomaly

Where is the neutron dripline?



# The oxygen anomaly

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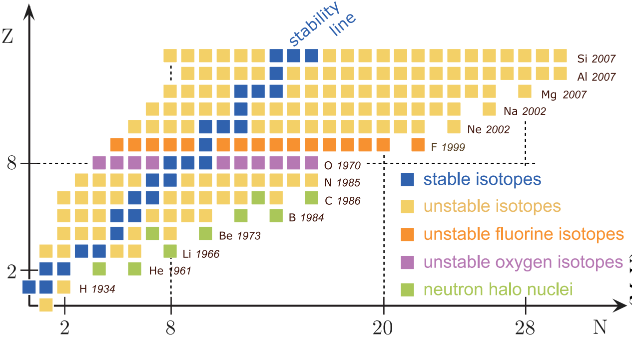
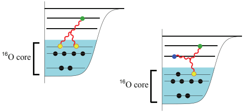
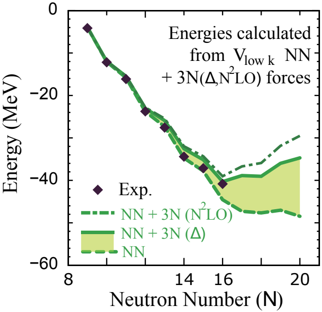


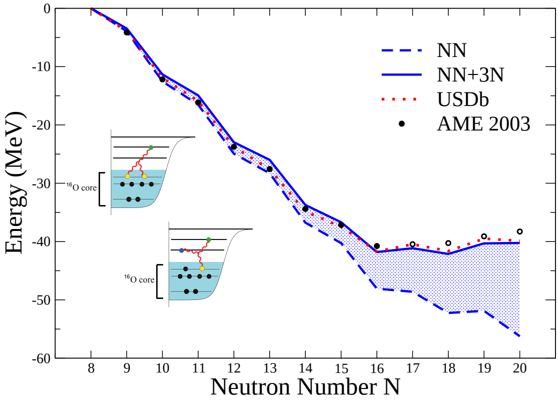




- NN forces too attractive
- Inclusion of normal-ordered 3N force leads to repulsion
  
  ⇒Correct prediction of dripline

Otsuka *et al.*, *PRL* **105** 032501 (2010).

# Neutron-rich oxygen isotopes

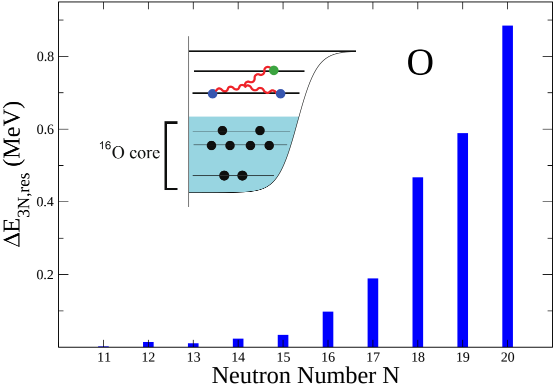



- NN predicts dripline at $^{28}$O
- normal-ordered 3N forces lead to repulsion
- phenomenological USDb in good agreement
- 3N effect confirmed in other calculations

  Hagen *et al.*, *PRL* **108** 242501 (2012).,

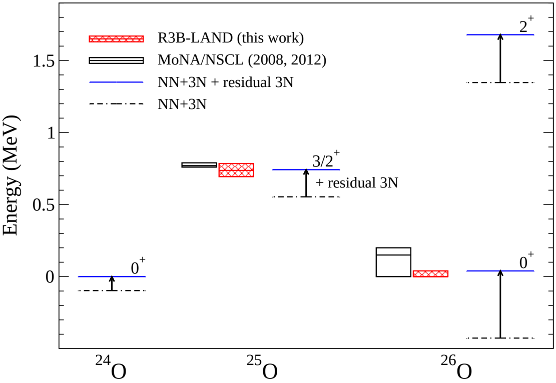
  Hergert *et al.*, in prep.

# Neutron-rich oxygen isotopes - residual three body




- Residual three-body contribution is repulsive, small compared to normal-ordered 3N
- Increases with neutron number as expected
- Effect is marginal for $11 \leq N \leq 15$

# Theory vs. experiment - arXiv:1209.0156



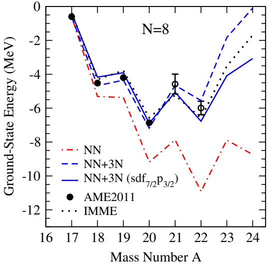

Hoffman *et al.*, *PRL* **100** 152502 (2008);
Lunderberg *et al.*, *PRL* **108** 142503 (2012).

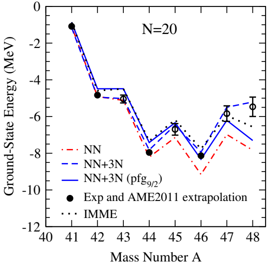
- Recent measurements for $^{25,26}$O at MSU and at GSI
- Residual contributions relevant for a direct comparison
- Very good agreement with resonances in $^{25,26}$O
- continuum not included, expected contribution about 200 keV to $^{25,26}$O

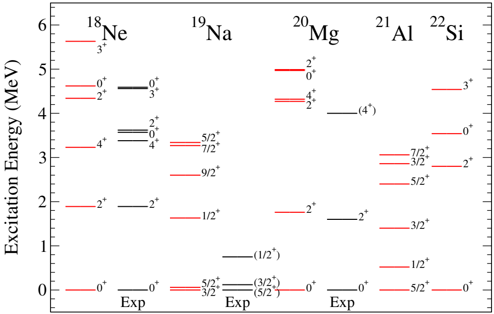
Hagen *et al.*, *PRL* **108** 242501 (2012).

# 3N forces and proton-rich nuclei

first results with 3N forces of N=8, 20 Holt *et al.*, *PRL* **110** 022502 (2013).



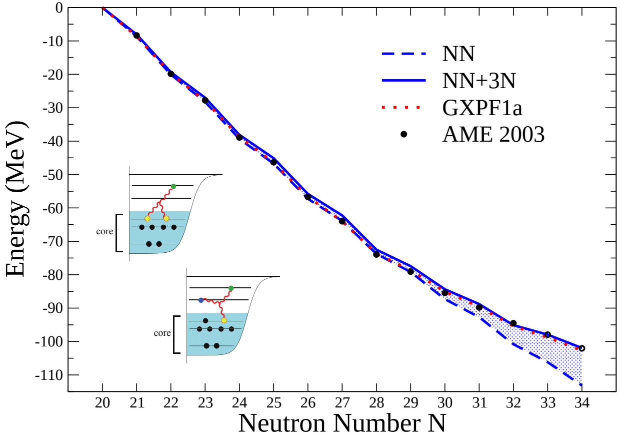




prediction for $^{20}$Mg agrees with new state observed at GSI Mukha, private comm.

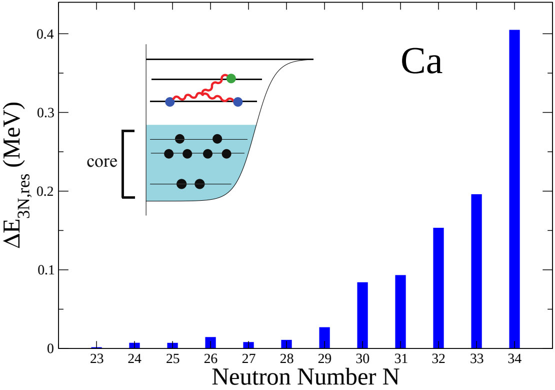
first results away from semi-magic chains

# Neutron-rich calcium isotopes



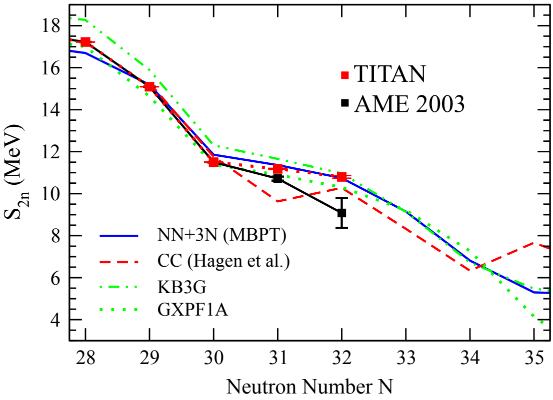

- NN forces too attractive for $N > 28$
- normal-ordered 3N forces lead to repulsion

# Neutron-rich calcium isotopes - residual three body




- Residual three-body contribution is smaller than in O, expected from $N_v/N_c$
- Effect is marginal for $23 \leq N \leq 29$

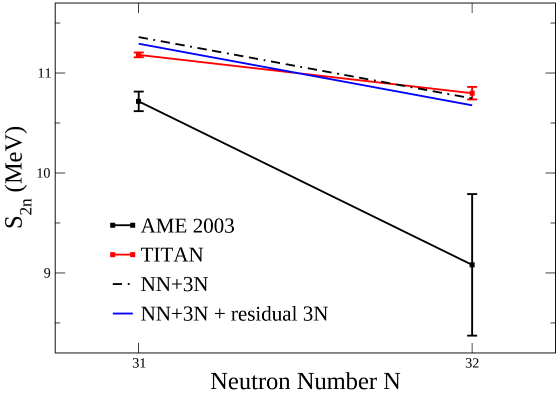
# Two-neutron separation energies of Ca isotopes




Gallant *et al.*, *PRL* **109** 032506 (2012).

- New mass measurement at TITAN
- Significant deviations for $^{51,52}$Ca from AME 2003
- NN+3N comparable with KB3G/GXPF1a
- Effect of residual three body?

# Two-neutron separation energies of $^{51,52}$Ca




Gallant *et al.*, *PRL* **109** 032506 (2012).

- TITAN $S_{2n}$ deviate by 0.5 MeV and 1.7 MeV for $^{51,52}$Ca from AME 2003
- NN+3N in very good agreement
- residual three-body contribution is a minor correction to $S_{2n}$ for $^{51,52}$Ca

# Summary

Microscopic calculation of medium-mass nuclei based on chiral EFT (NN+3N forces) with inclusion of residual three-body contribution for the first time

Contribution of residual three body small compared to the normal-ordered 3N $E_{2-\text{body}}^{\text{normal}-\text{ordered}}$, but increases with neutron number in the Shell Model up to 0.4 MeV in $^{26}$O

Very good agreement with neutron-rich oxygen isotopes $^{25,26}$O

First results away from semi-magic chains

# Thank you for your attention!