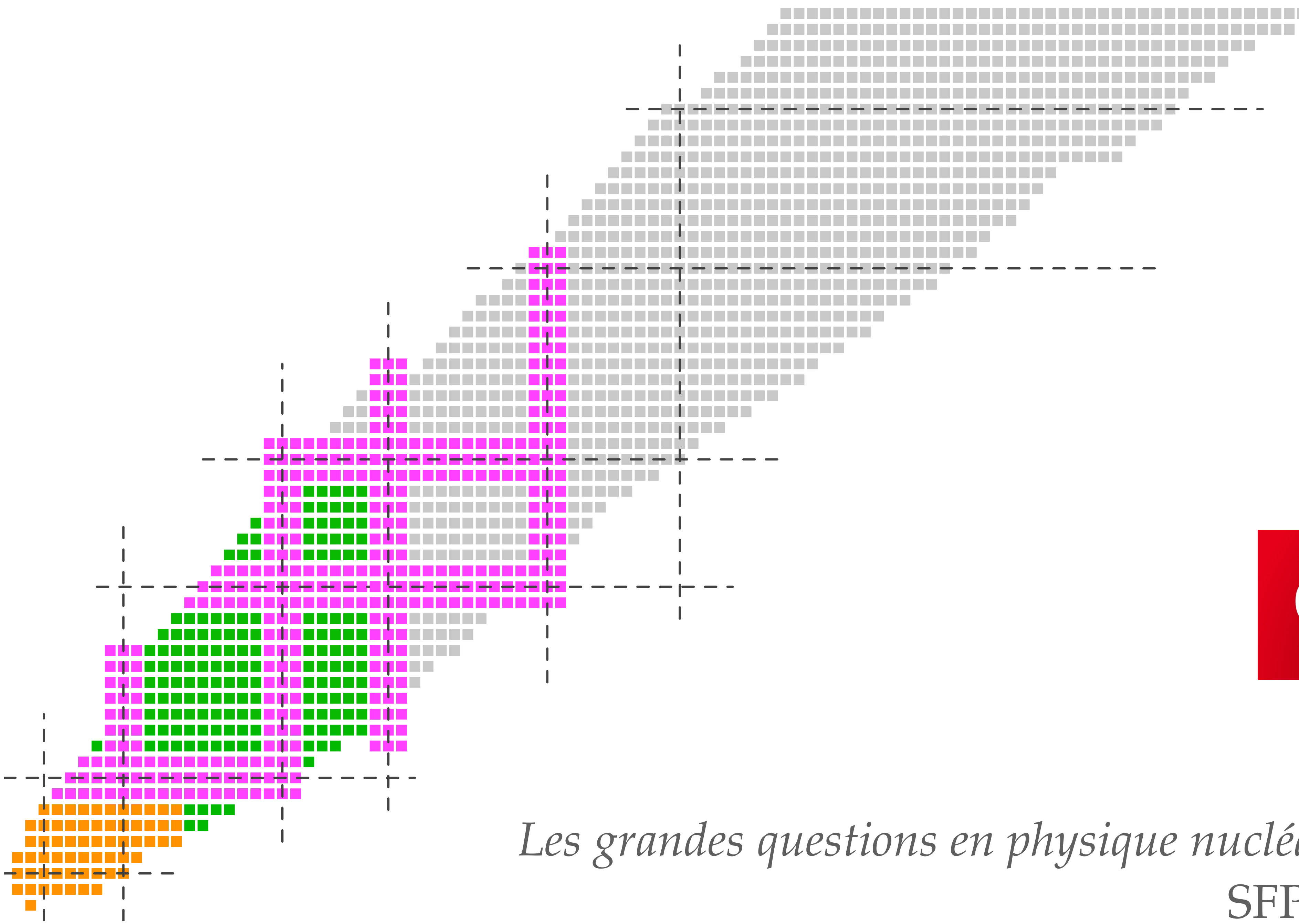
Plusieurs baryons : émergence de la phénoménologie du noyau à partir de la QCD, avec quelles limitations ?



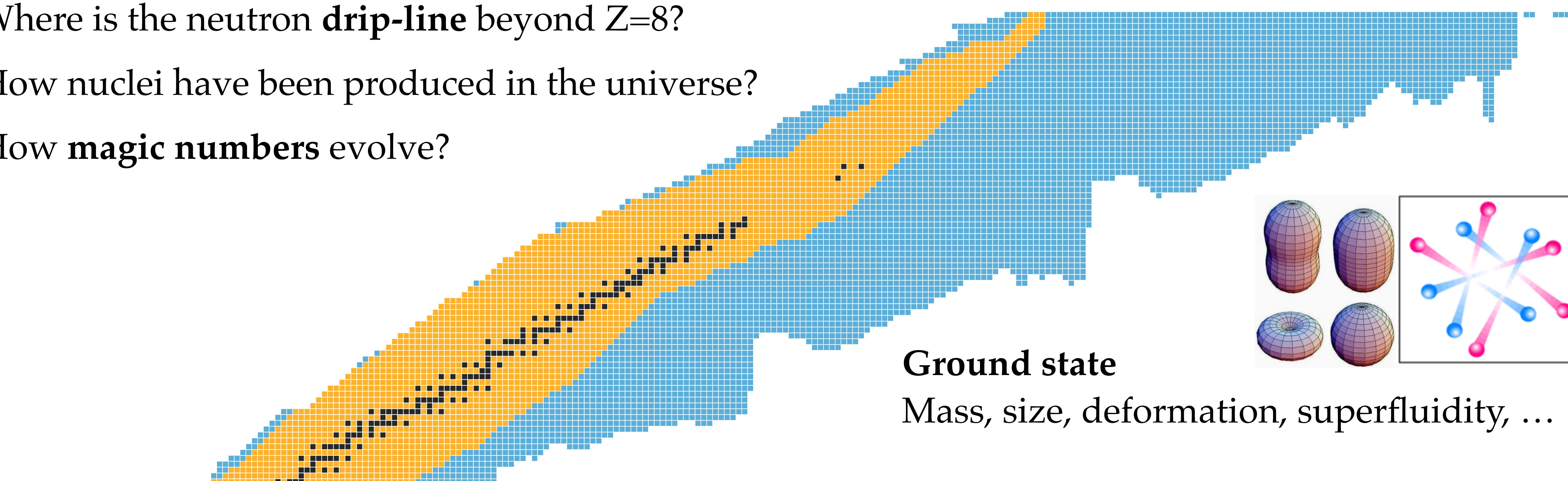
Vittorio Somà
CEA Saclay

Les grandes questions en physique nucléaire fondamentale
SFP-BTPN meeting
Paris, 22 June 2016

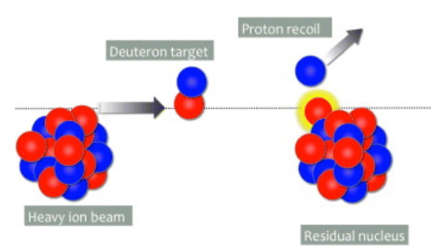
Diversity of nuclear phenomena

- **How many** bound nuclei exist? (~6000-7000?)
- **Heaviest** possible element? Enhanced stability near Z=120?
- Where is the neutron **drip-line** beyond Z=8?
- How nuclei have been produced in the universe?
- How **magic numbers** evolve?

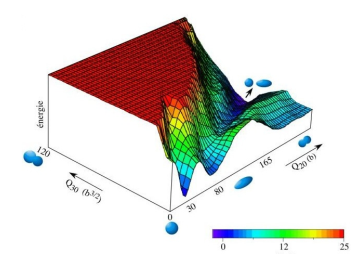
[figure from B. Bally]
[calculations from S. Hilaire *et al.*]



Ground state
Mass, size, deformation, superfluidity, …

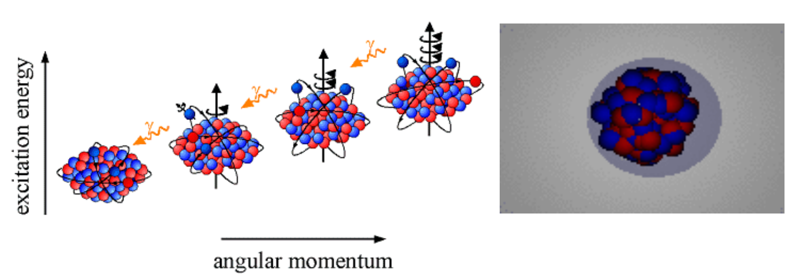


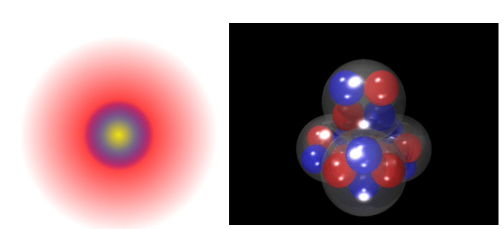
Reaction processes
Fusion, transfer, knockout, …



Radioactive decays
β, 2β, α, p, 2p, fission, …

Spectroscopy
Excitation modes

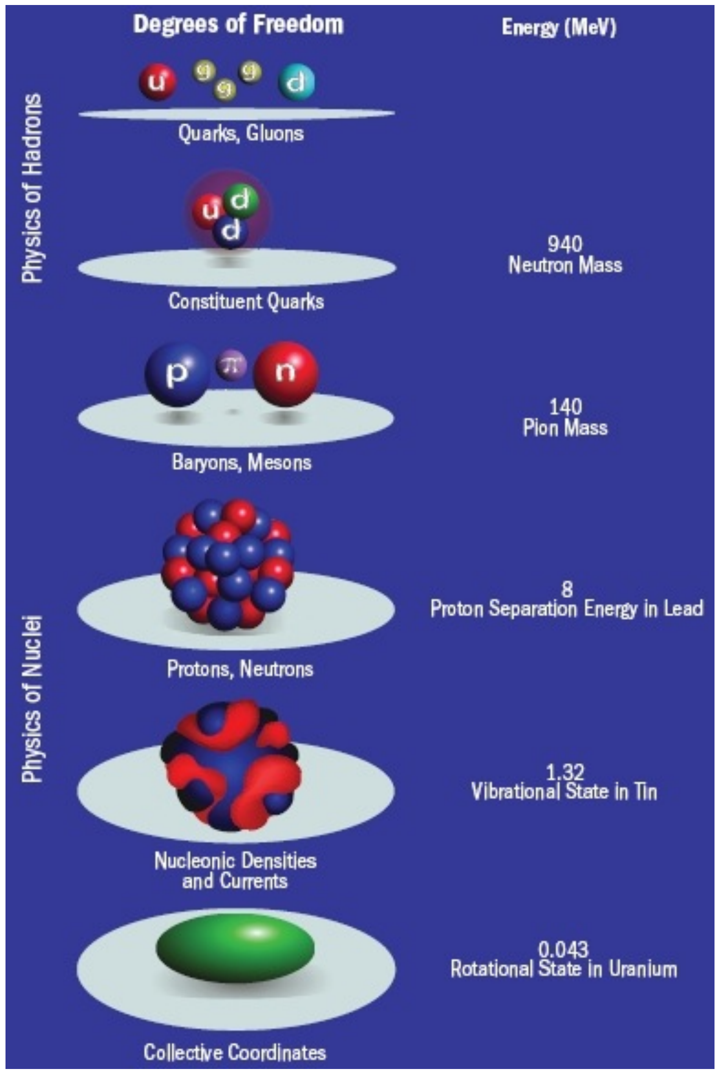




Exotic structures
Clusters, halos, …

Ab initio *A*-body problem

More reductionist / elementary / "fundamental" description



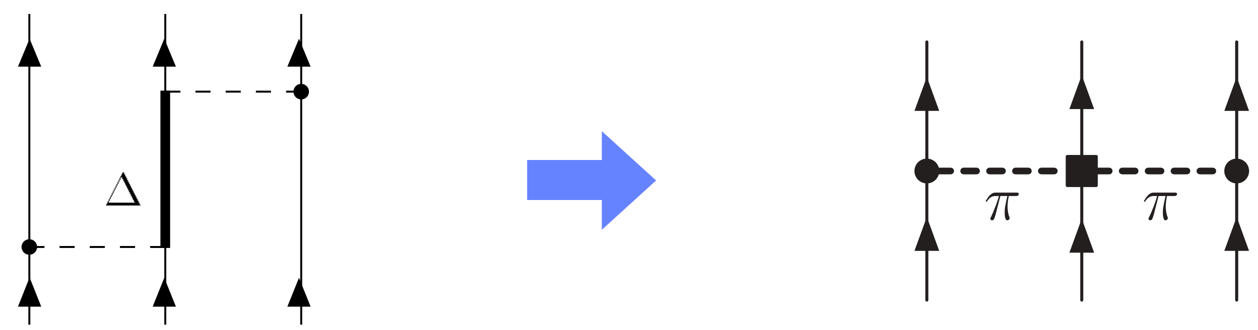
Emergent phenomena amenable to effective descriptions

- Nucleus viewed as effective **structure-less nucleons**
  - Possibly + Δs (+ hyperons)
- Interacting via
  - Low energies → Pions + contact interactions ➟ ***Pionful** EFT*
  - Very low energies → Contact interactions ➟ ***Pionless** EFT*
- **Effective field theory** (EFT)
  - Systematic construction of *A*N interactions (*A*=2, 3, …)
  - Symmetries of underlying theory built in
  - Coupling constants fixed by QCD (ideally) or data

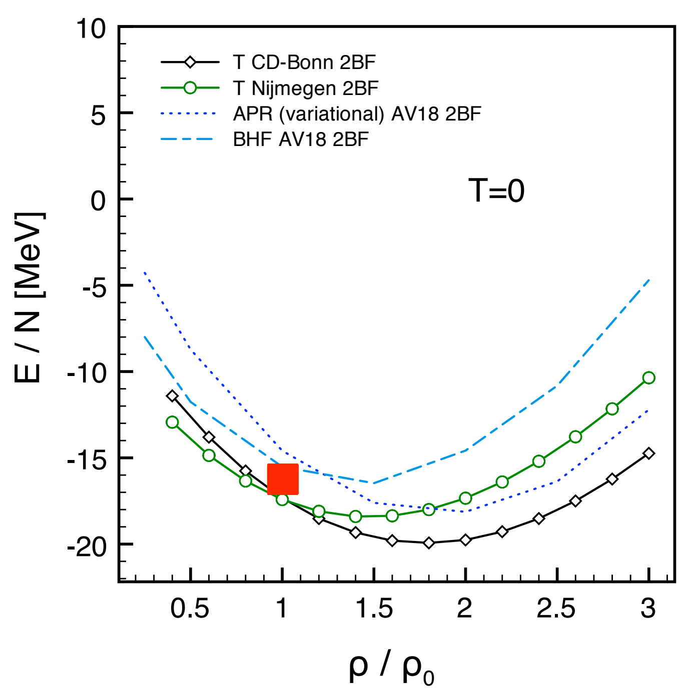
- **Implement** in *A*-body sector → "ab initio" nuclear *A*-body problem
- **Solve** in *A*-body sector → emerging nuclear phenomena (= low-energy observables)
- **Benefits**: systematic improvement, assessment of errors, controlled extrapolations

Three-nucleon forces

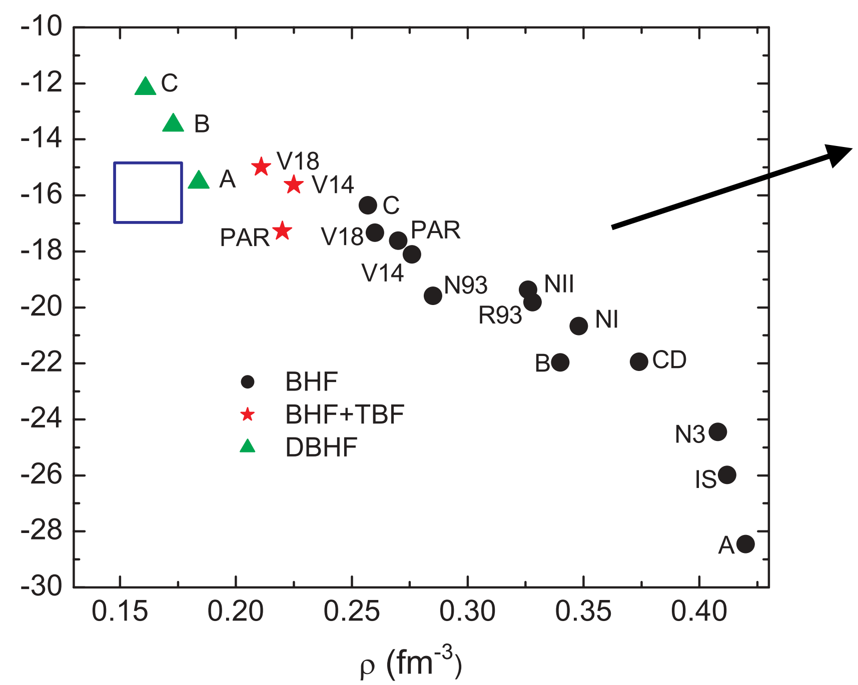
- **Fundamental reason**: nucleons are composite particles, NN is an ***effective*** interaction
  - More complicated processes, e.g. involving nucleon excitations, can not be described as NN



- **Practical reason**: 2N-only interactions fail to reproduce properties of many-nucleon systems
  - E.g. saturation point of infinite nuclear matter



[Somà & Bożek 2009]

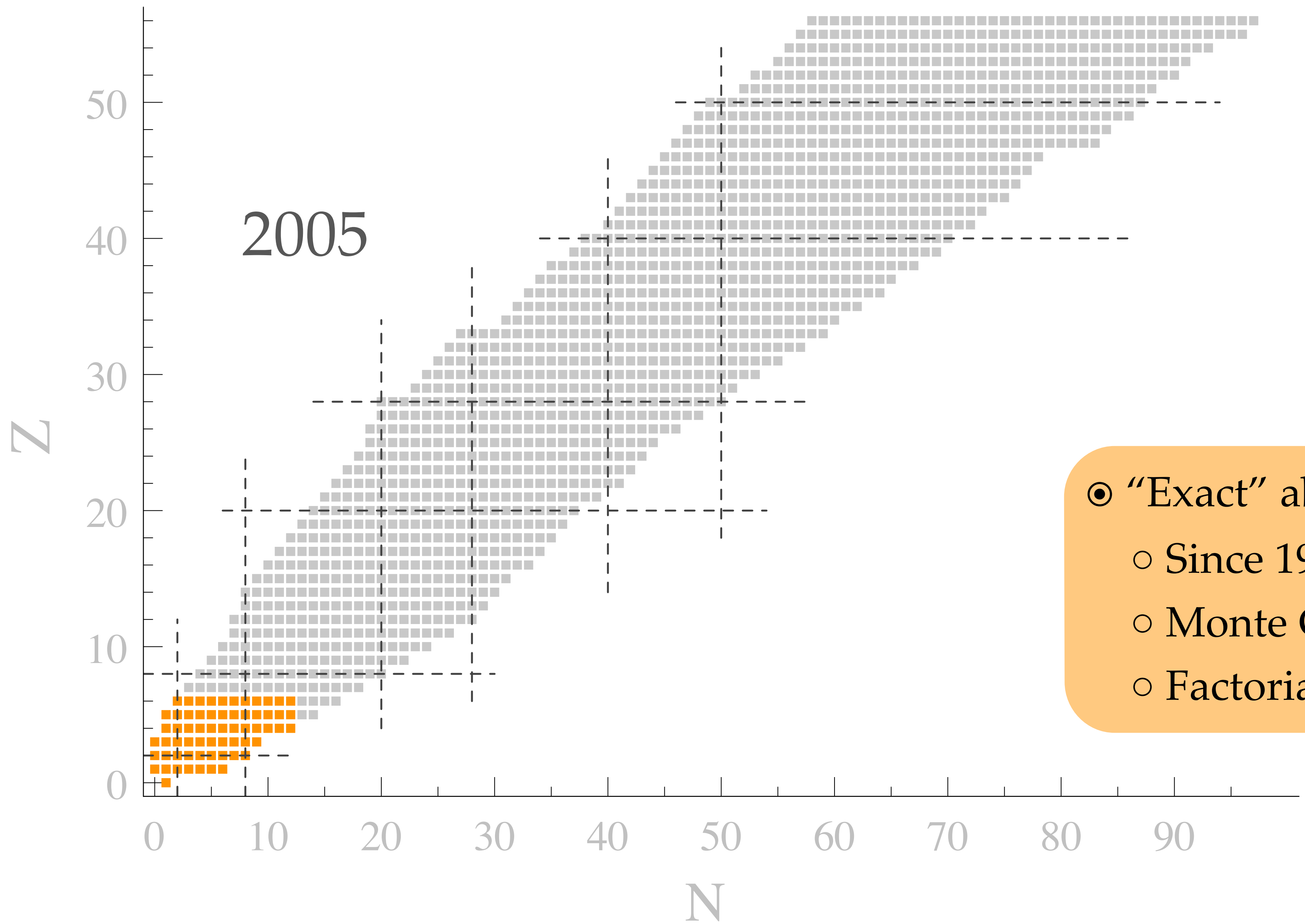


[Li *et al.* 2006]

Coester band

“trade **off-shell** features with **three-body** forces”

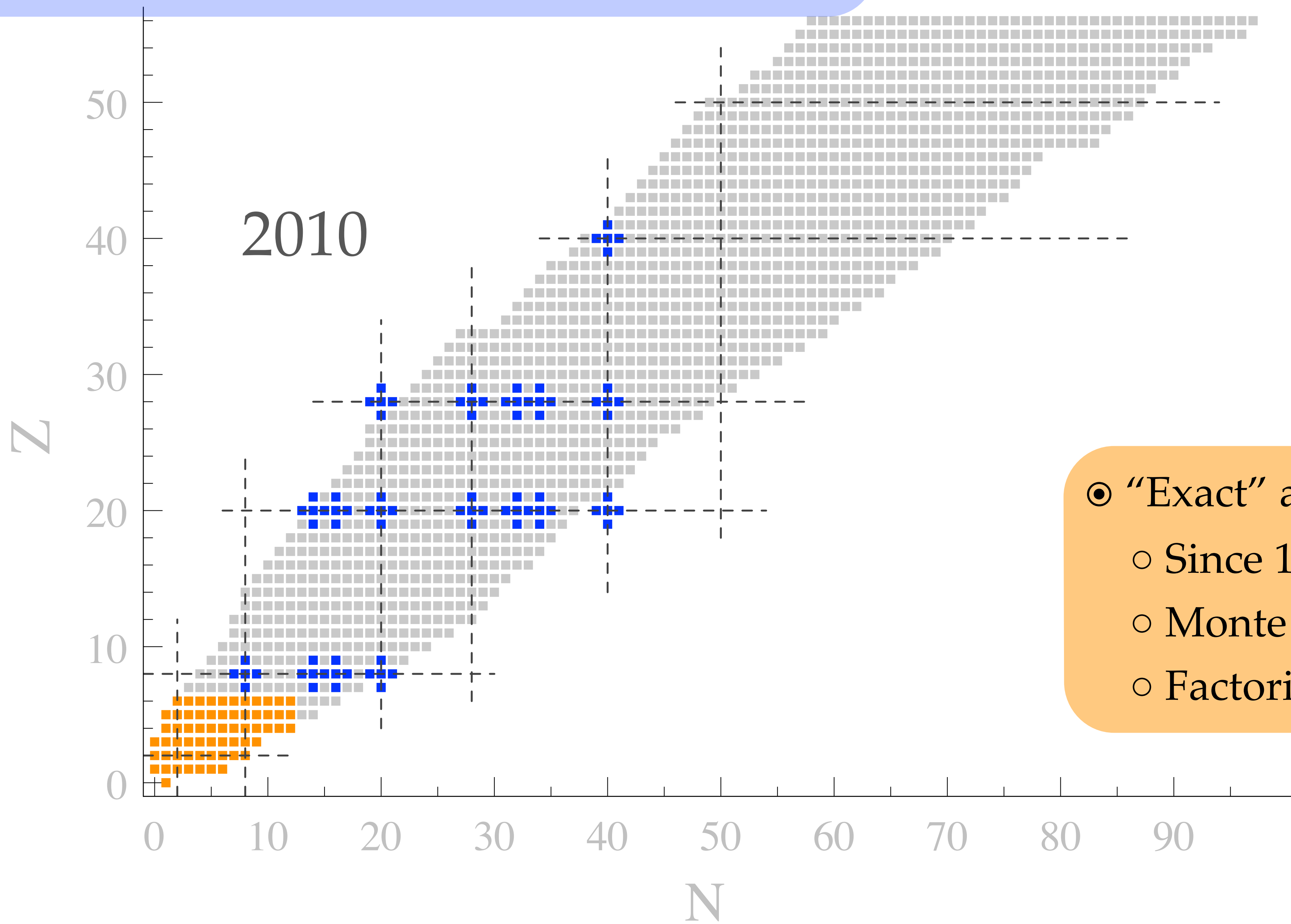
Evolution of ab initio nuclear chart



- ⦿ "Exact" ab initio approaches
  - ○ Since 1980's
  - ○ Monte Carlo, CI, …
  - ○ Factorial scaling

Evolution of ab initio nuclear chart

- ⊙ Ab initio approaches for closed-shell nuclei
  - ○ Since 2000's
  - ○ SCGF, CC, IMSRG
  - ○ Polynomial scaling



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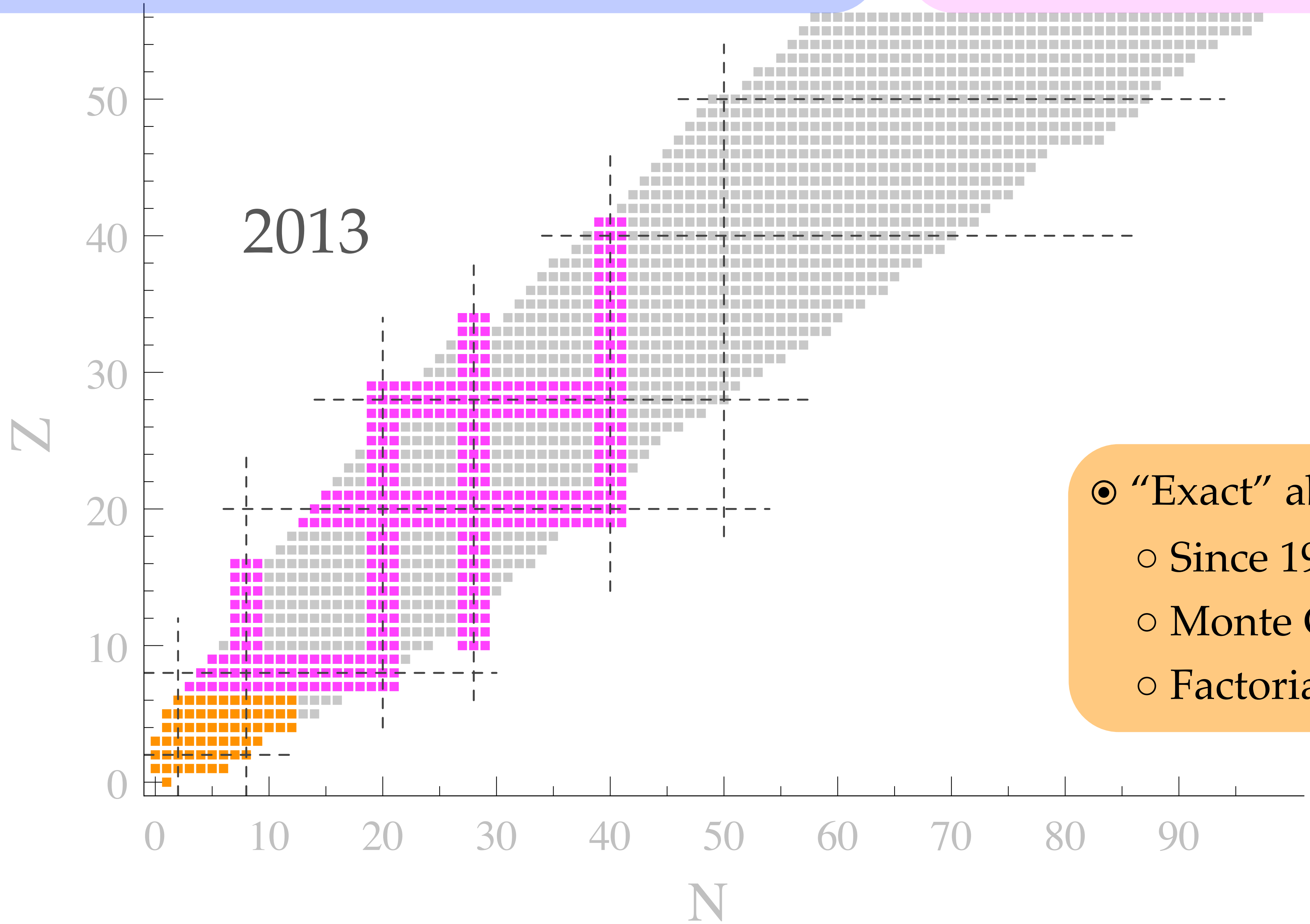

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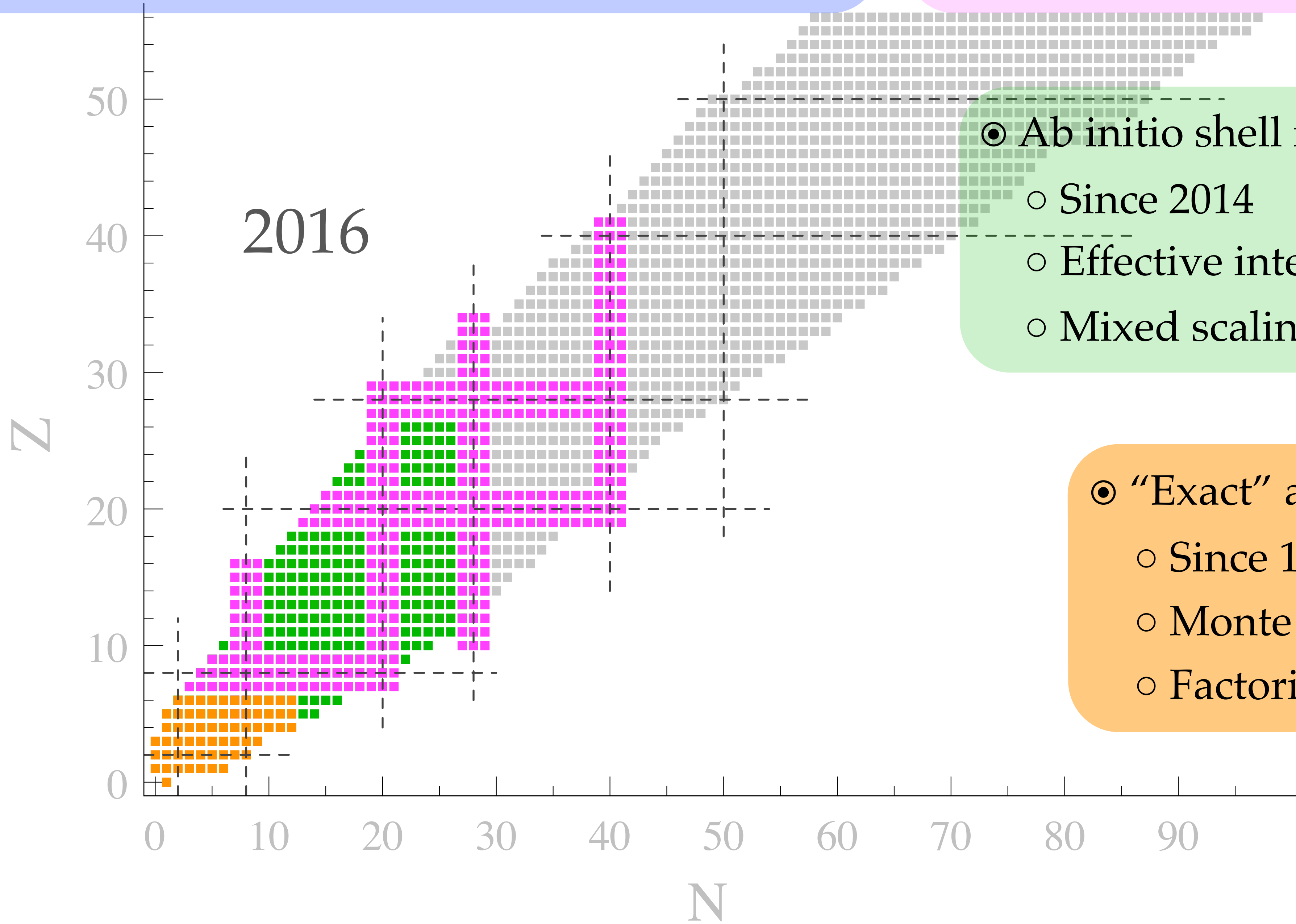
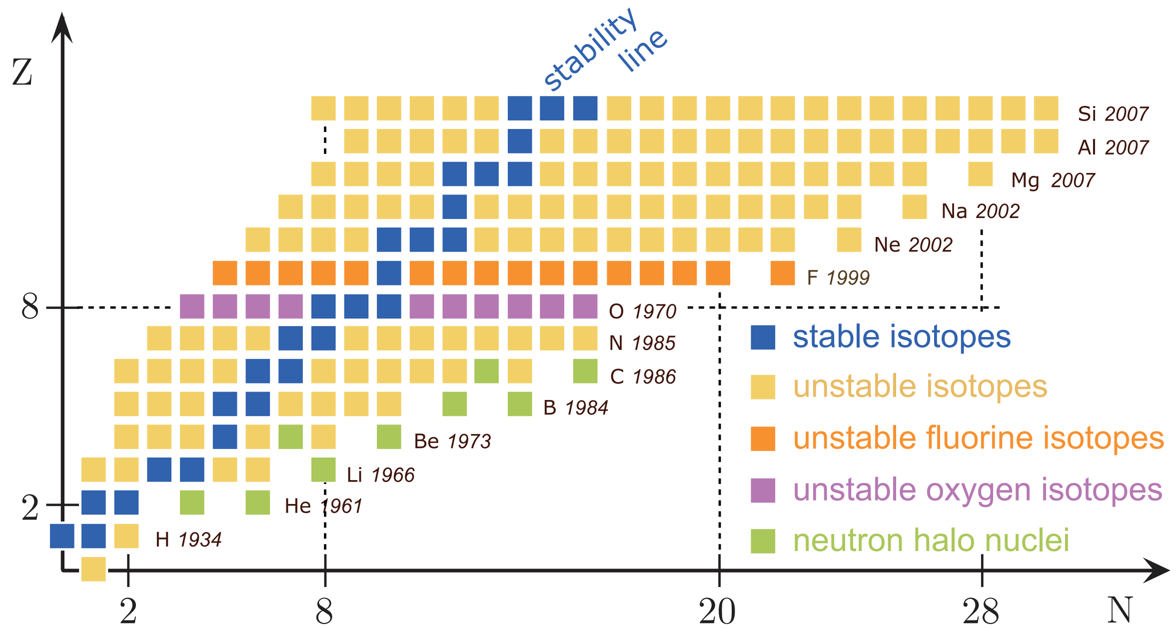


- Ab initio shell model
  - Since 2014
  - Effective interaction via CC/IMSRG
  - Mixed scaling

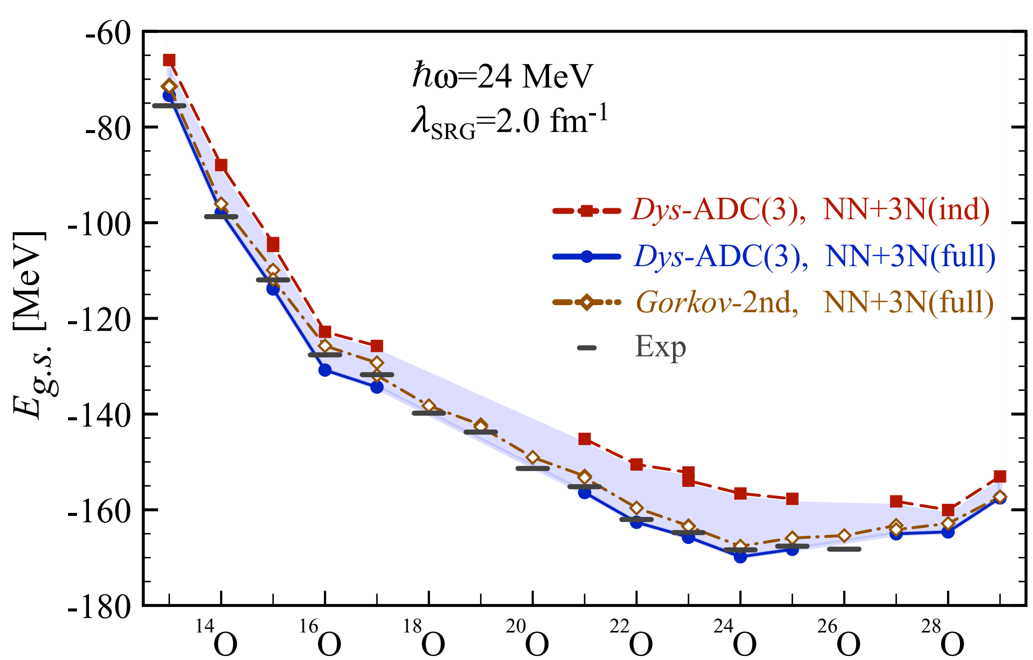
- "Exact" ab initio approaches
  - Since 1980's
  - Monte Carlo, CI, …
  - Factorial scaling

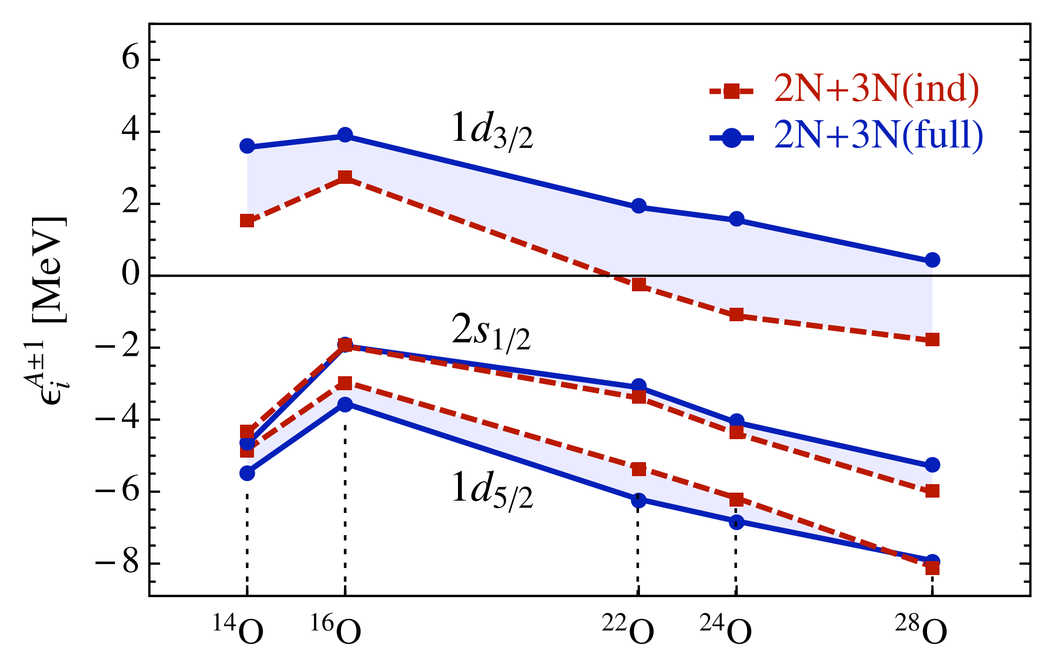
Oxygen anomaly



- Neutron drip line experimentally known only up to Z=8
- O drip line strikingly close to stability

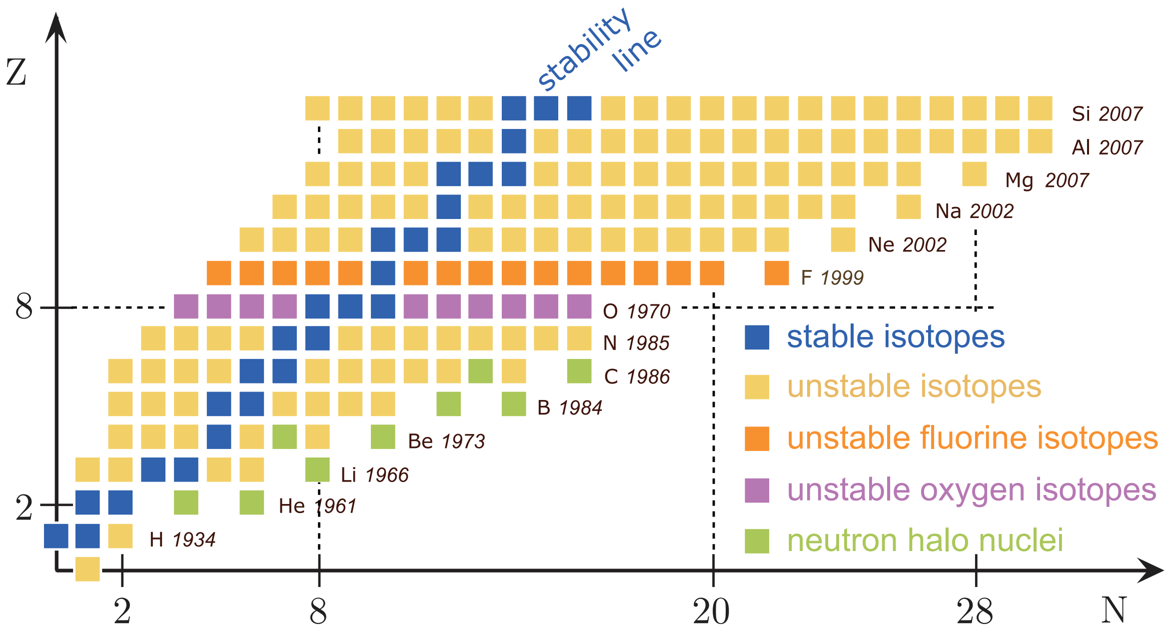
SCGF correctly reproduces drip line at ^{24}O → essential role of three-body forces





[Cipollone *et al.* 2013]

Oxygen anomaly



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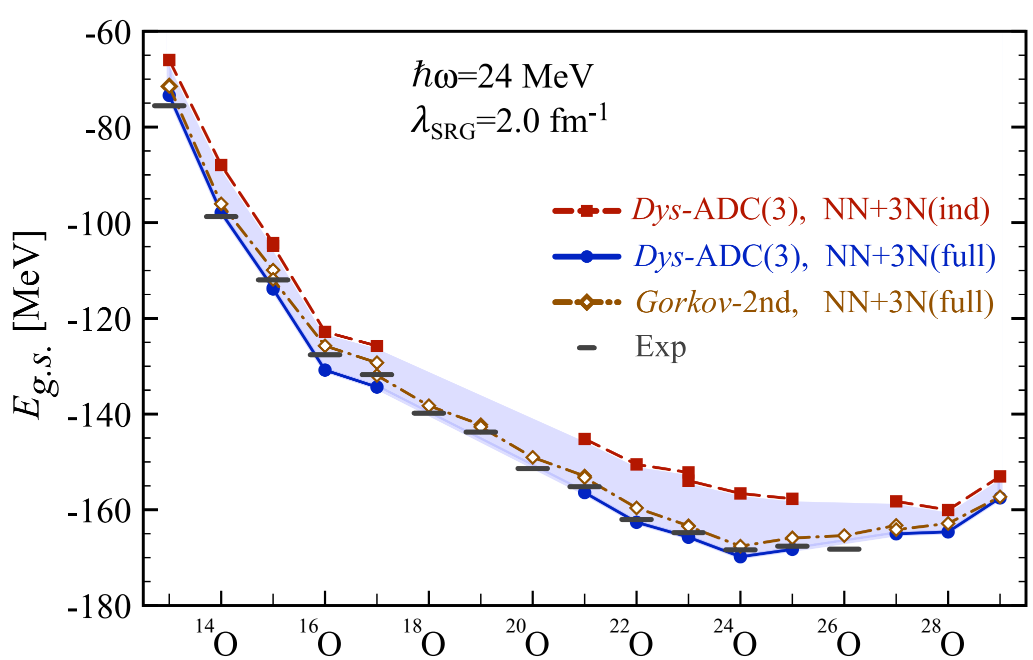
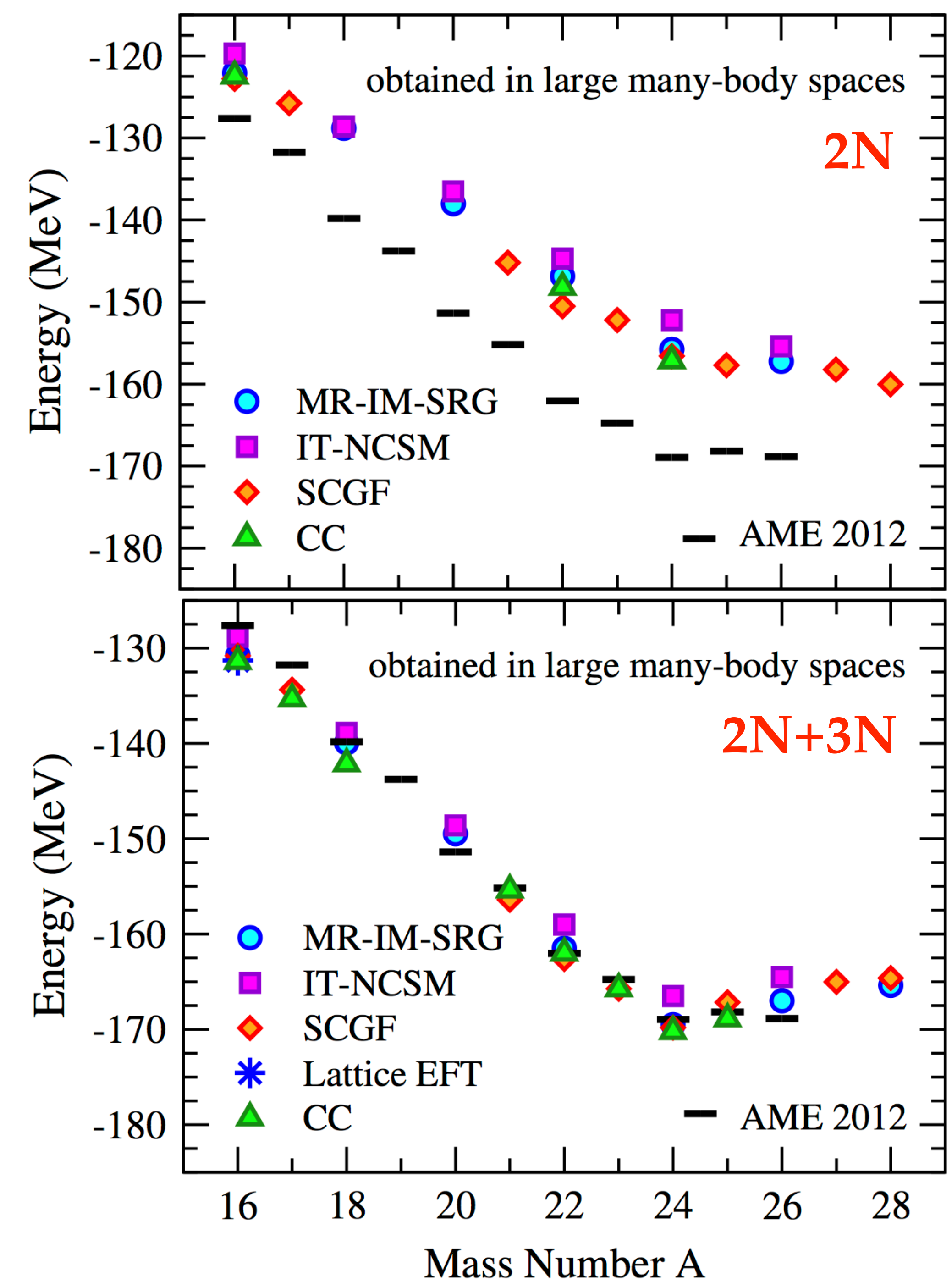


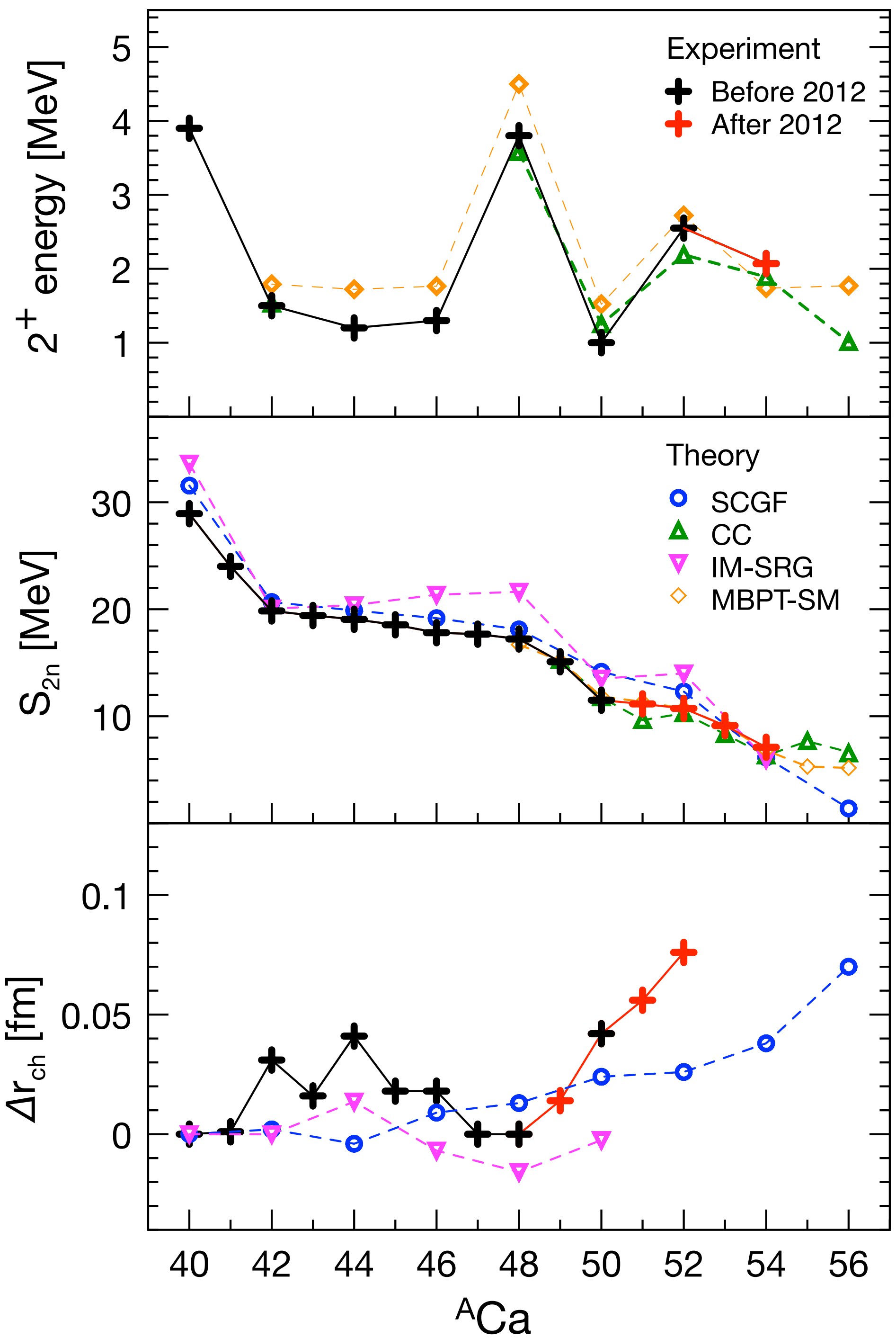
O drip line as ab initio benchmark



[Hebeler *et al.* 2015]

Emergence of magic numbers

- Traditional magic numbers disappear and / or new magic numbers appear in neutron-rich nuclei
- "Magic" features emerge to different extents from underlying 2N+3N interactions



- Magic character assessed from **several observables**, e.g.
  - First 2+ excitation energy
  - Two-neutron separation energy $S_{2n} \equiv E_0^{Z,N} - E_0^{Z,N-2}$
  - Charge radii isotopic shifts

→ Trend correctly reproduced (less for radii)

→ Successful **predictions** for N=32, 34

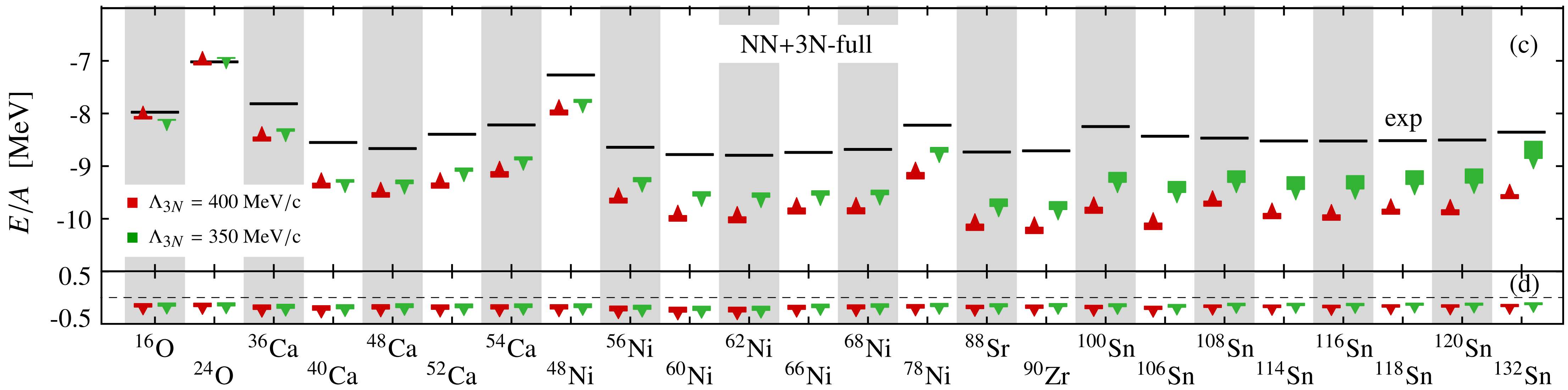
→ **3N forces** again crucial

→ Drip line prediction depends on interaction

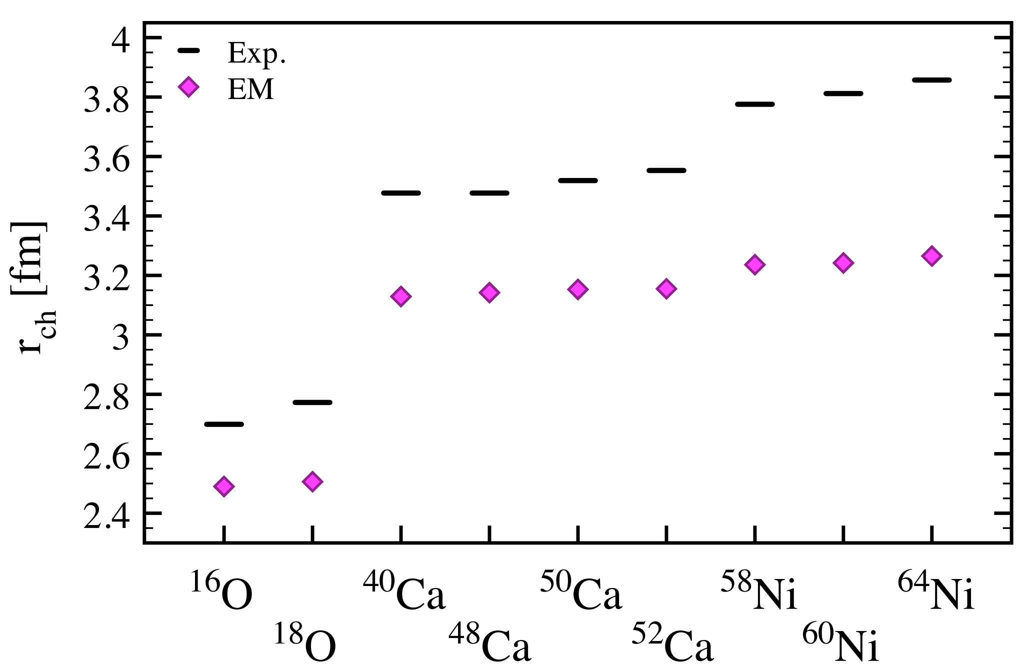
- All **relative quantities**: what about absolute ones?

Towards heavier systems

⊙ **Overbinding,** overestimation of major shell gaps and too small radii when increasing A



[Binder *et al.* 2014]



[Somà *et al.* in preparation]

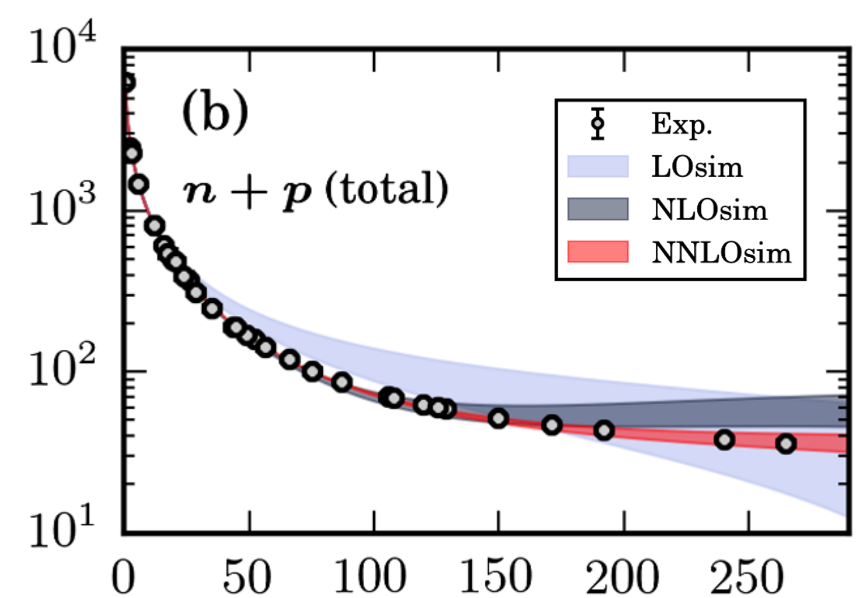
⊙ **Several things still missing or to be improved…**

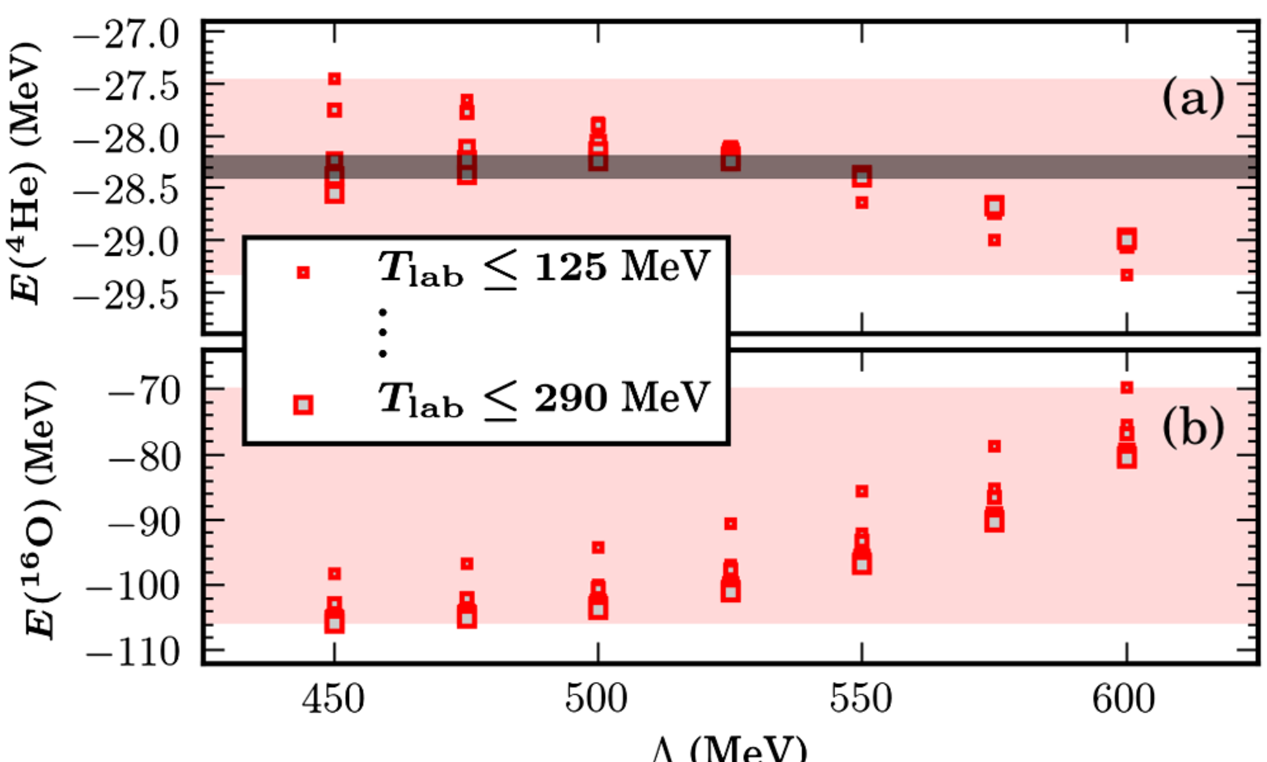
- ○ N^{3}LO 3NF contributions missing
- ○ Induced many-body forces from SRG under control?
- ○ Local vs non-local regulators?
- ○ Thorough assessment of all theoretical uncertainties
- ○ Correct power counting?

Propagating the uncertainty from 2N+3N to A-body

- **NNLO 2N+3N interaction** from chiral EFT (in Weinberg power counting)
- **Fitting protocol**
  - Simultaneous optimisation of all parameters (LEC)
  - Conventional fit on on πN and NN scattering + properties of ^{2}H, ^{3}H, ^{3}He
- **Systematic uncertainty on 2N+3N**
  - Different maximum energies for NN phase shifts fits (T_{lab})
  - Different cutoff energies in regularisation procedure (Λ)

Total cross section





[Carlsson *et al.* 2016]

→ **Large propagated uncertainty**

→ ^{4}**He** covers experiment, ^{16}**O** doesn't

→ Next order??

→ Signals breakdown?

→ **RG invariance?**

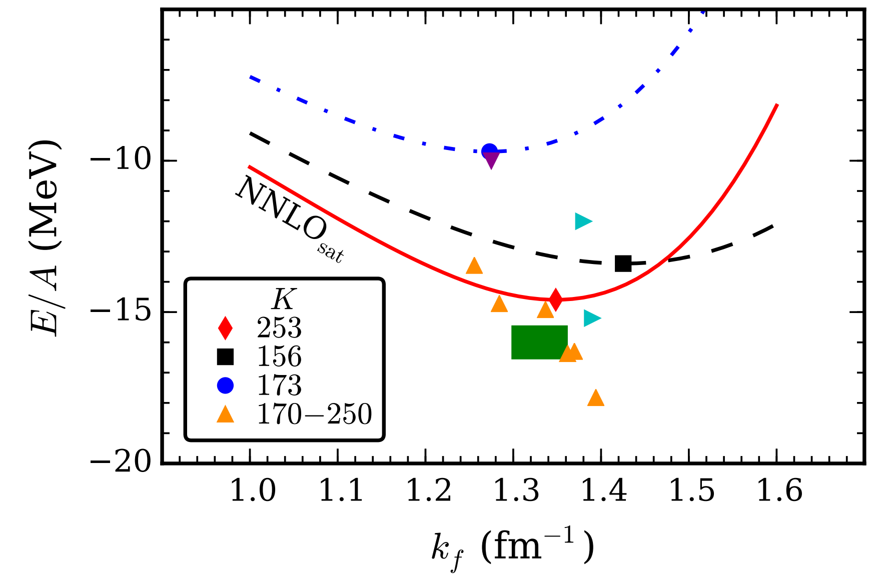
NNLO$_{sat}$: changing the strategy

⊙ New Hamiltonian with **data from light nuclei** in fit of low-energy constants

[Ekström *et al.* 2015]

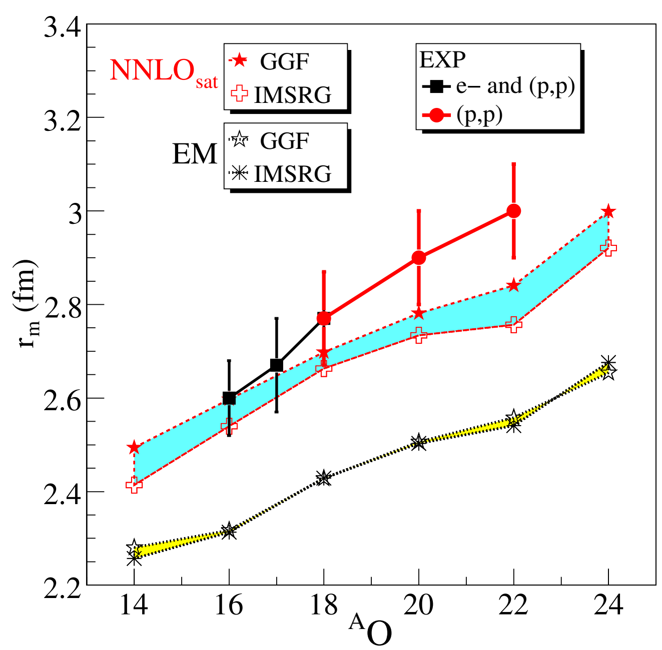
TABLE I. Binding energies (in MeV) and charge radii (in fm) for ^{3}H, ^{3,4}He, ^{14}C, and ^{16,22,23,24,25}O employed in the optimization of NNLO$_{sat}$.

	$E_{g.s.}$	Expt. [69]	r_{ch}	Expt. [65,66]
^{3}H	8.52	8.482	1.78	1.7591(363)
^{3}He	7.76	7.718	1.99	1.9661(30)
^{4}He	28.43	28.296	1.70	1.6755(28)
^{14}C	103.6	105.285	2.48	2.5025(87)
^{16}O	124.4	127.619	2.71	2.6991(52)
^{22}O	160.8	162.028(57)		
^{24}O	168.1	168.96(12)		
^{25}O	167.4	168.18(10)		



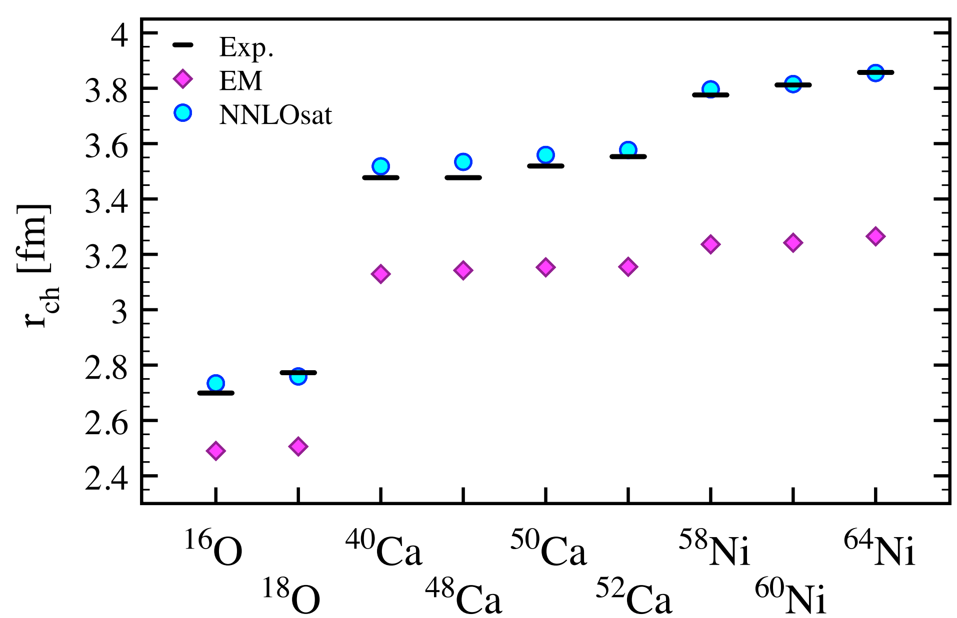
⊙ Some important deficiencies corrected → Systematic improvement? Error estimates?

Matter radii



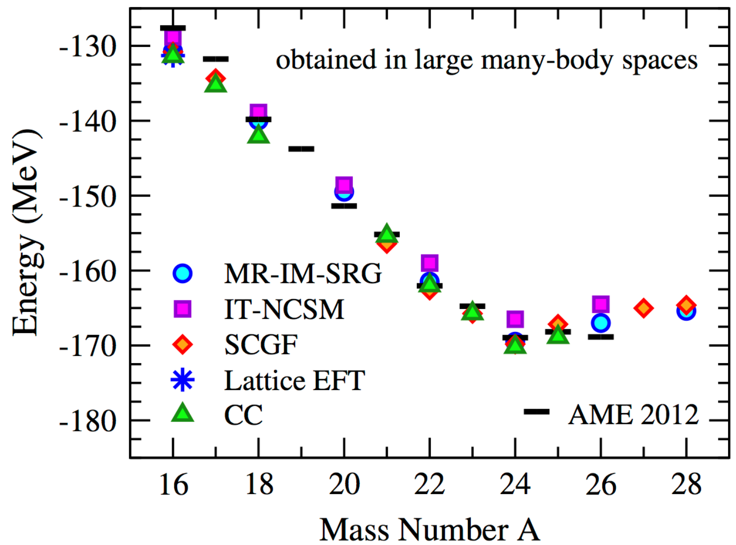
[Lapoux *et al.* submitted]

Charge radii

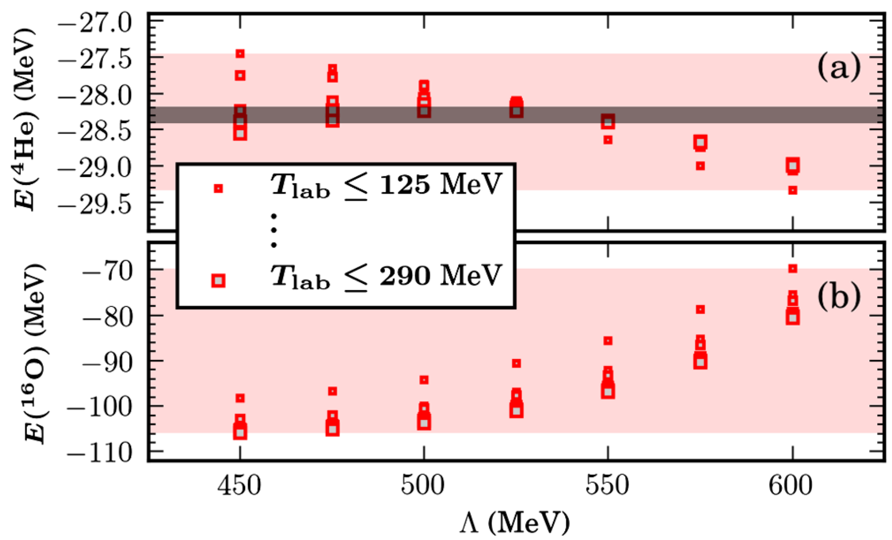


[Somà *et al.* in preparation]

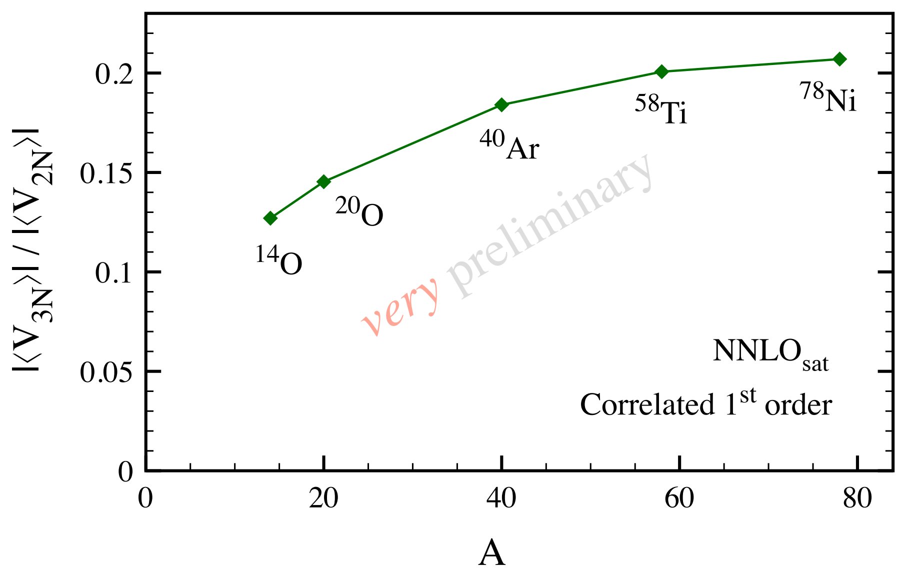
Conclusions & challenges



- **Many-body techniques**
  - Great progress in last 10 years
  - Many-body uncertainties under control
  - Bottleneck for A>100 is treatment of 3N forces



- **2N, 3N, … forces**
  - Chiral EFT: great promises, not yet fully exploited
  - Uncertainty propagation is / will be crucial
  - $NNLO_{sat}$: filter or change of strategy?



- **Validity of "conventional" ab initio strategy**
  - When does it become inefficient?
  - New EFT based on different degrees of freedom?