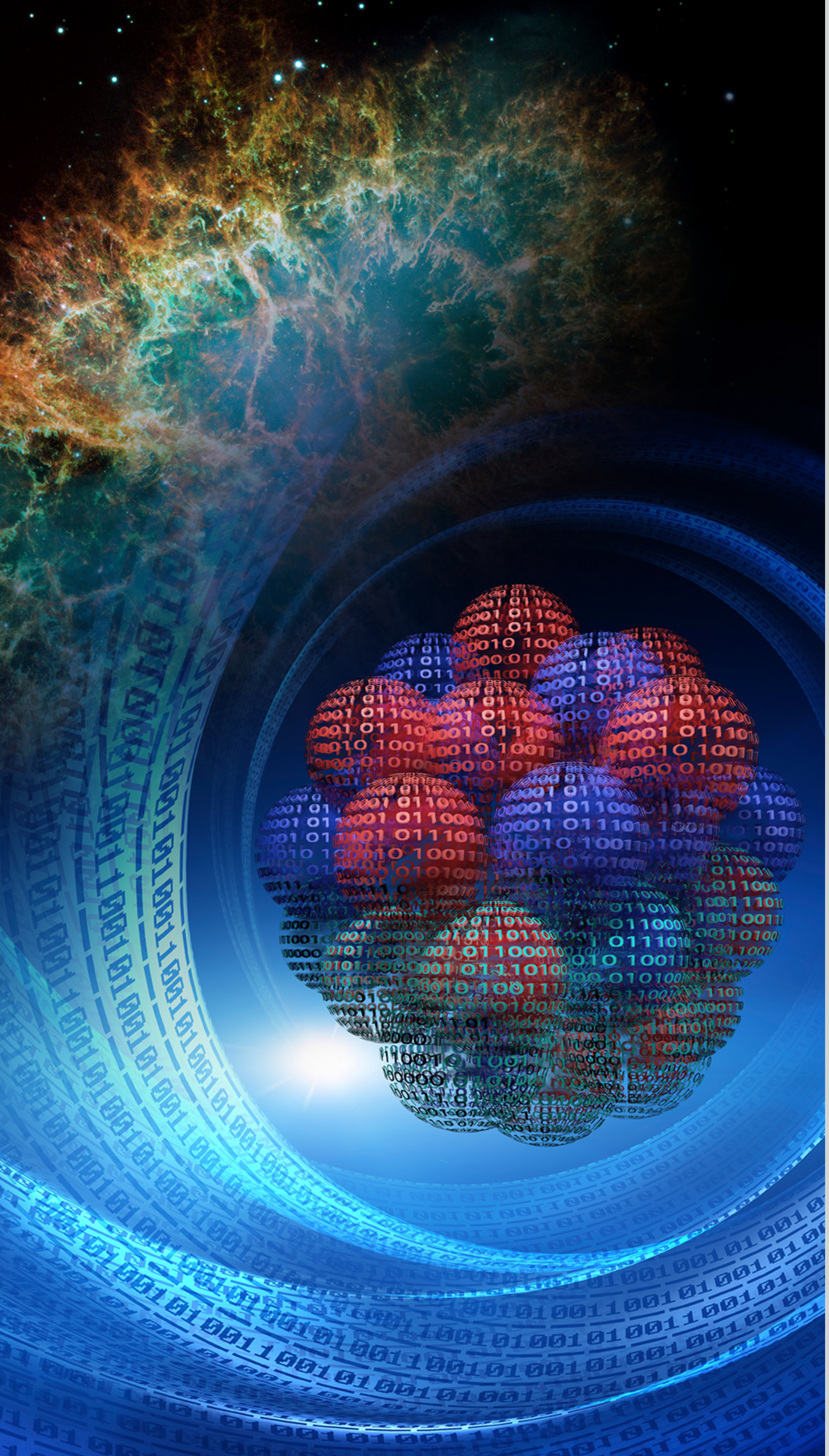


EUROSCHOOL ON EXOTIC BEAMS

Christian Forssén,
Department of Physics, Chalmers

# NUCLEAR THEORY AND PREDICTIVE POWER

## LECTURE 2

# FORCES IN NATURE

| Type | Gauge boson | Spin [hbar] | Range [m] | Strength @ hadronic scales |
|---|---|---|---|---|
| **Gravity** | graviton | 2 | $\infty$ | $10^{-40}$ |
| **Weak** | W,Z | 1 | $10^{-17}$ | $10^{-5}$ |
| **EM** | Photon | 1 | $\infty$ | 1/137 |
| **Strong** | Gluons | 1 | $10^{-15}$ | ~1 |

- Electroweak interactions are perturbative at hadronic scales.
- Strong interactions are really strong. $\Rightarrow$ **Non-perturbativ**e

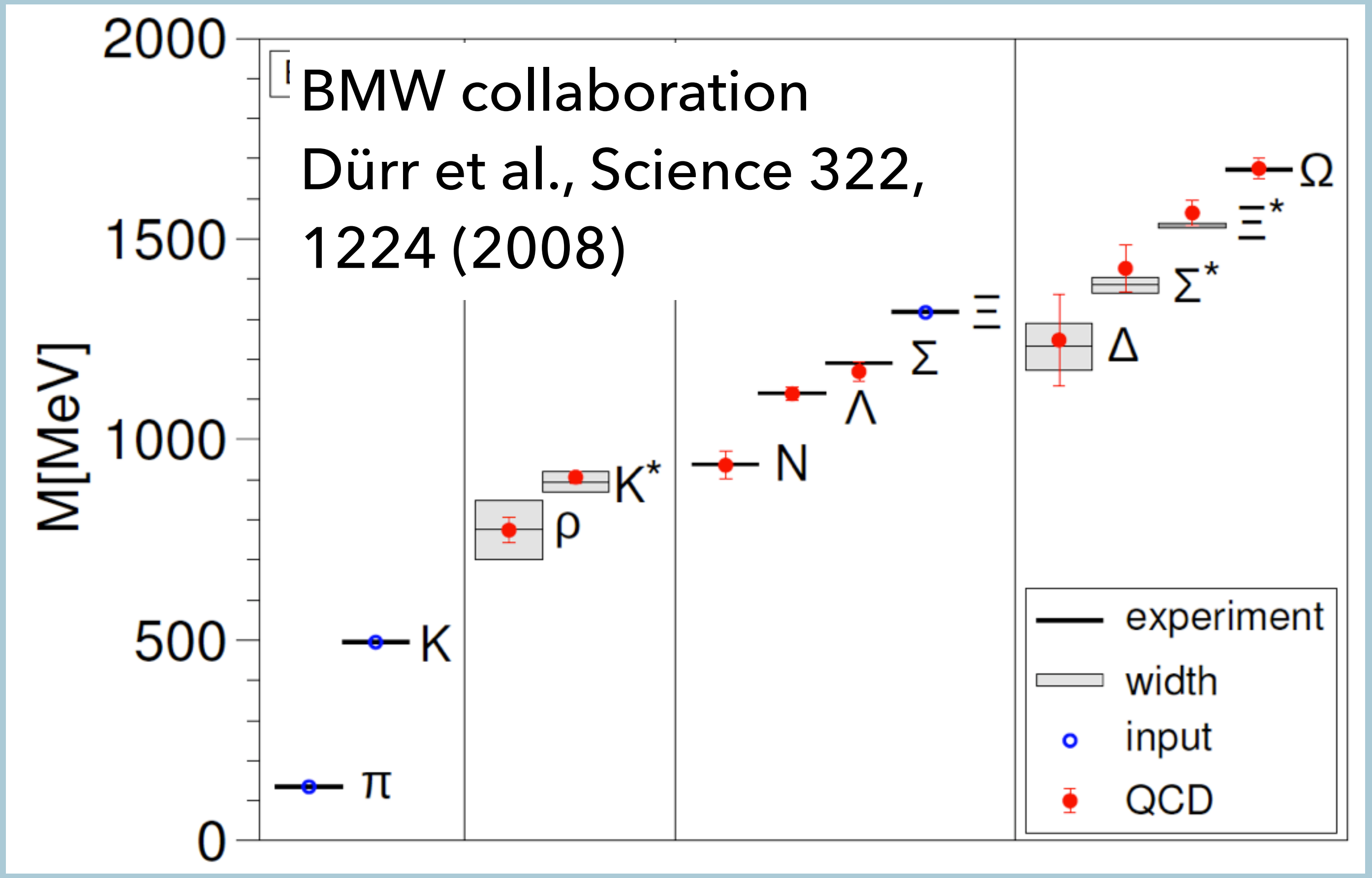
# GRAND CHALLENGE: STRONG QCD

- **The standard model has two open ends:**
  1. Physics beyond the SM
  2. Strong QCD

**1. Quarks and gluons form hadrons**

➡ Exploring the strong color force

➡ Lattice QCD




- **Two facets of strong QCD:**

**2. Nucleons and mesons form nuclei**

➡ Nuclear physics

➡ Exploring the residual color force

# INGREDIENTS FOR BUILDING ATOMIC NUCLEI "FROM QCD"

- A nucleon-nucleon interaction
  - linked to QCD via its symmetries
  - that allows for systematic calculations with a controlled theoretical error

(CHIRAL) EFFECTIVE (FIELD) THEORY

- A nuclear many-body solver
  - using only controlled approximations
  - extending from few- to many-body systems

AB INITIO METHODS

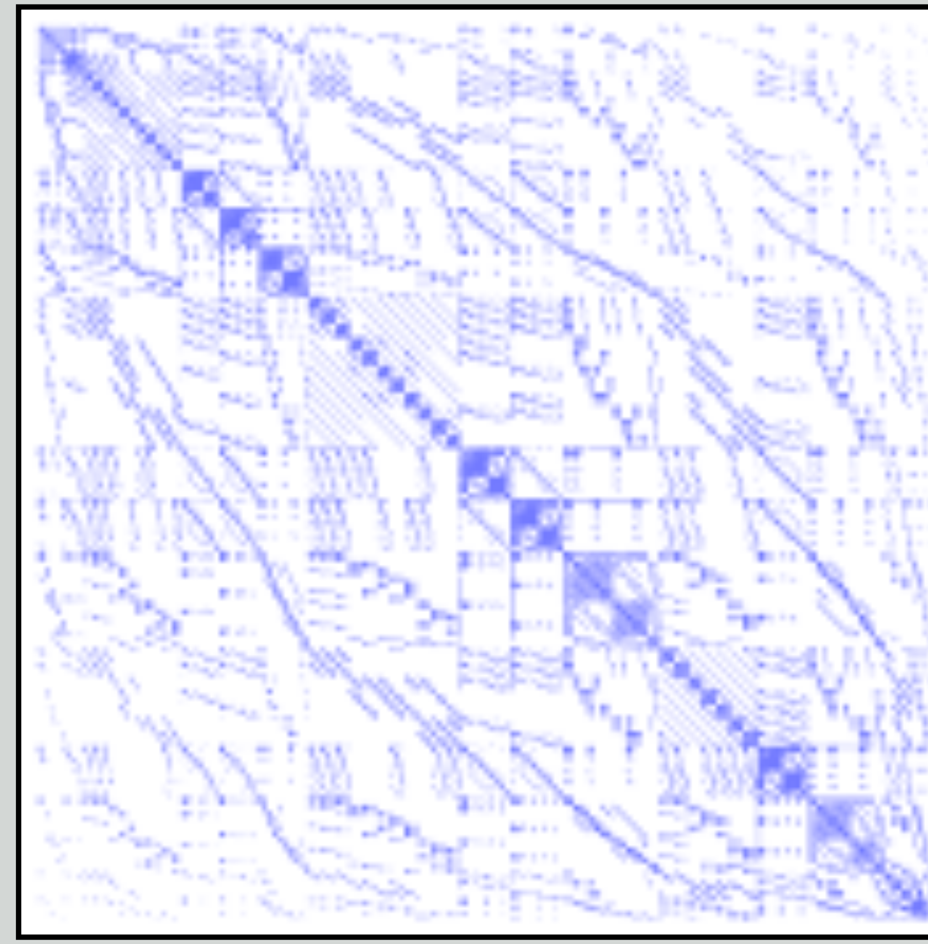
# AB INITIO APPROACHES

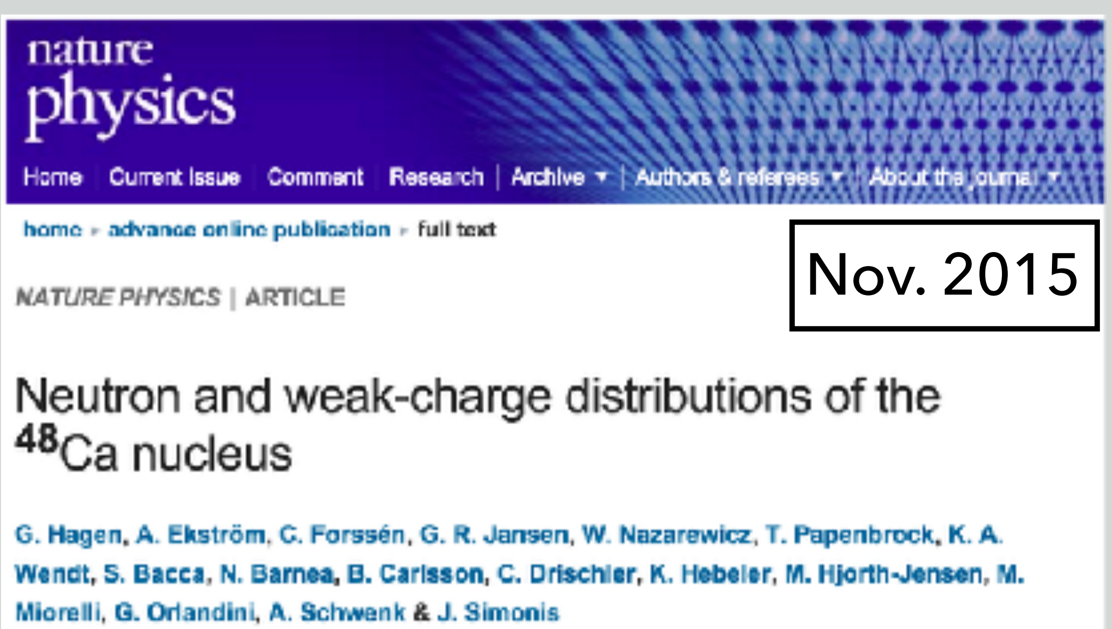
- Consider an A-nucleon system described by a well defined microscopic Hamiltonian
- Ab initio methods solve the relevant QM many-body equations without uncontrolled approximations
- Controlled approximations, e.g. number of channels, are allowed as they can be systematically improved.
- Converged results are considered precise  ab initio results.

# AB INITIO APPROACHES

## TECHNOLOGY EXAMPLE: NCSM LARGE-SCALE MATRIX DIAGONALIZATION

- Current limit: $N_{dim} = 10^{10}$
- Sparse, BUT: $N_{non\text{-}zero}=5\times10^{14}$, equivalent to 6 PB data
- In effect, we perform $2.5\times10^{9}$ multiplications / sec / machine

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Nov. 2015

*NATURE PHYSICS* | ARTICLE

Neutron and weak-charge distributions of the $^{48}$Ca nucleus

G. Hagen, A. Ekström, C. Forssén, G. R. Jansen, W. Nazarewicz, T. Papenbrock, K. A. Wendt, S. Bacca, N. Barnea, B. Carlsson, C. Drischler, K. Hebeler, M. Hjorth-Jensen, M. Miorelli, G. Orlandini, A. Schwenk & J. Simonis


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Archive › Volume 528 › Issue 7580 › Letters › Article

Dec. 2015

*NATURE* | LETTER

日本語要約

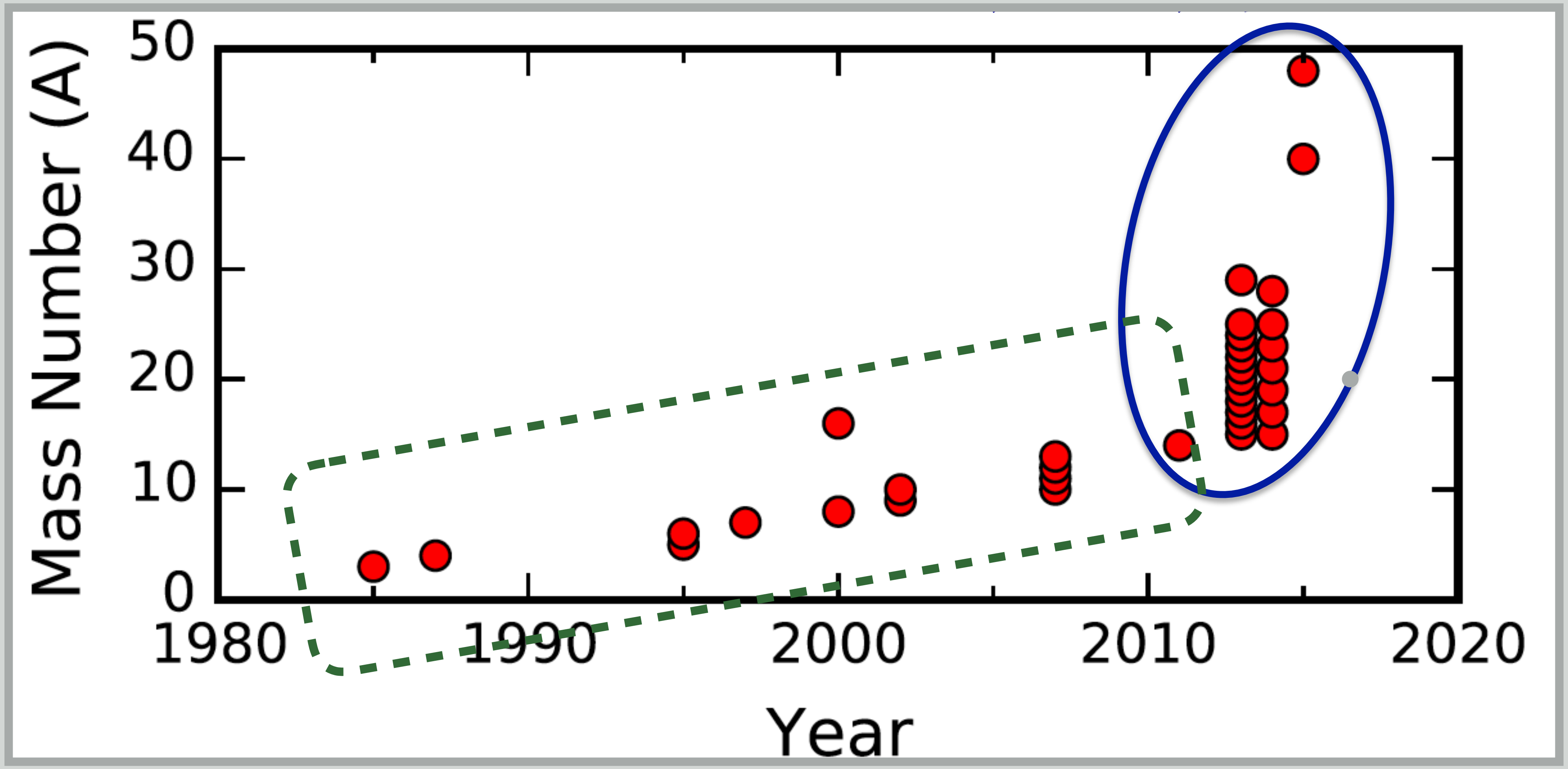
*Ab initio* alpha–alpha scattering

Serdar Elhatisari, Dean Lee, Gautam Rupak, Evgeny Epelbaum, Hermann Krebs, Timo A. Lähde, Thomas Luu & Ulf-G. Meißner

# TREND IN REALISTIC AB INITIO CALCULATIONS

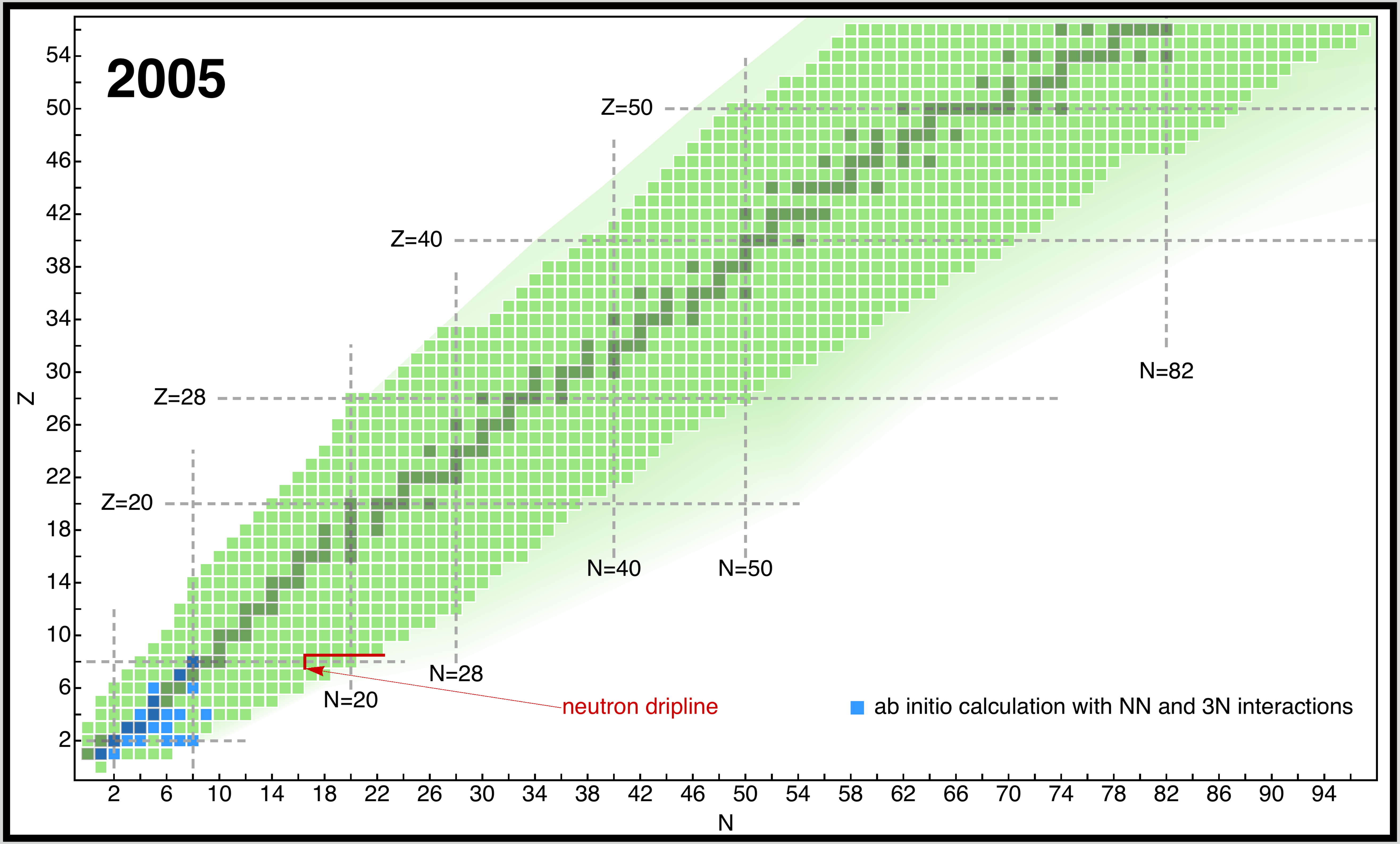
**Explosion of many-body methods**

(From: Green's function Monte Carlo, No-Core Shell Model
To: Coupled clusters, In- Medium SRG, Lattice EFT, Self-Consistent Green's Function, UMOA, …)



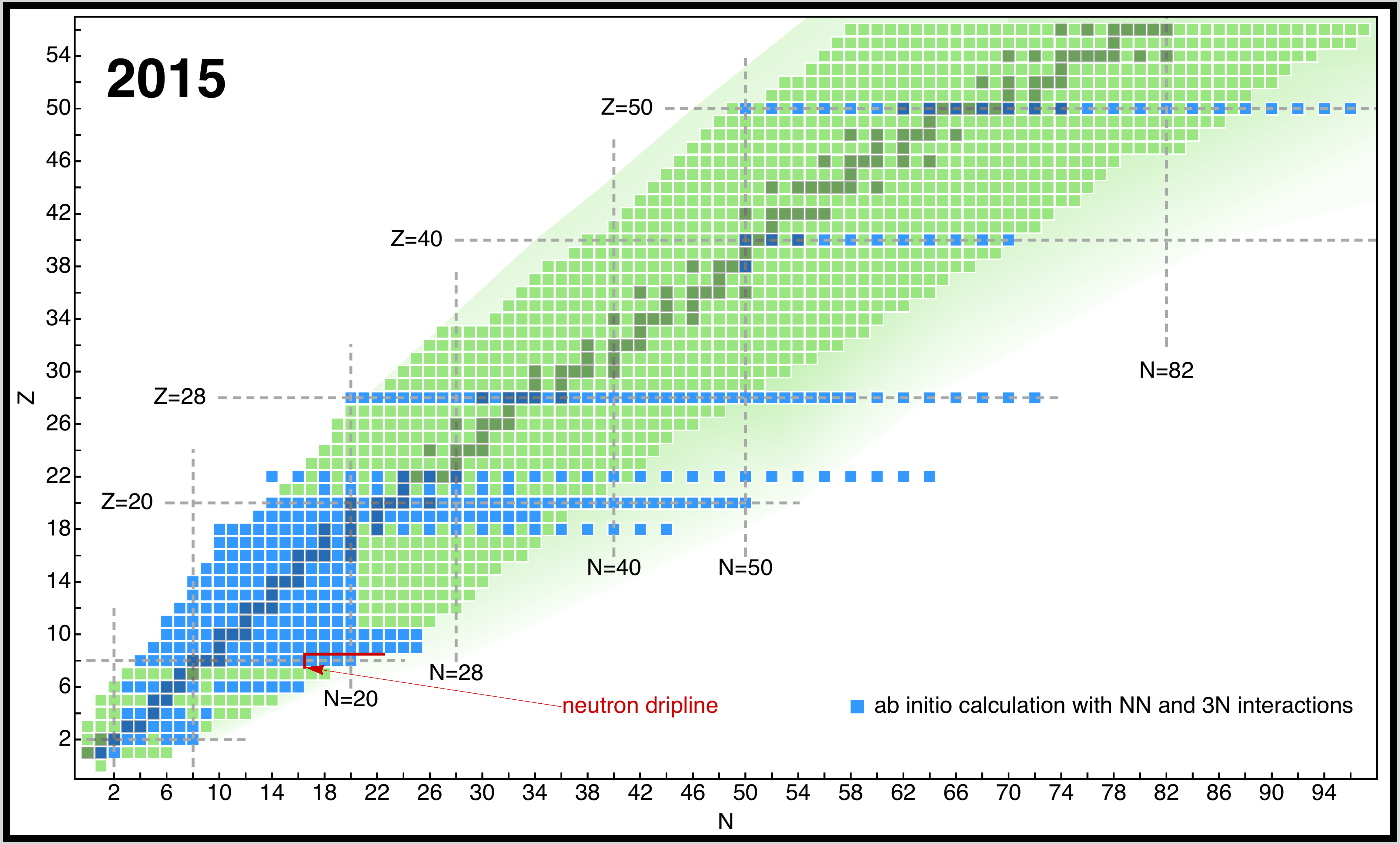

What is the most plausible explanation for the significant increase of reach from ~2010

# REACH OF AB INITIO CALCULATIONS




[Hergert et al, Phys. Rept. 621, 165 (2016)]

# REACH OF AB INITIO CALCULATIONS




[Hergert et al, Phys. Rept. 621, 165 (2016)]

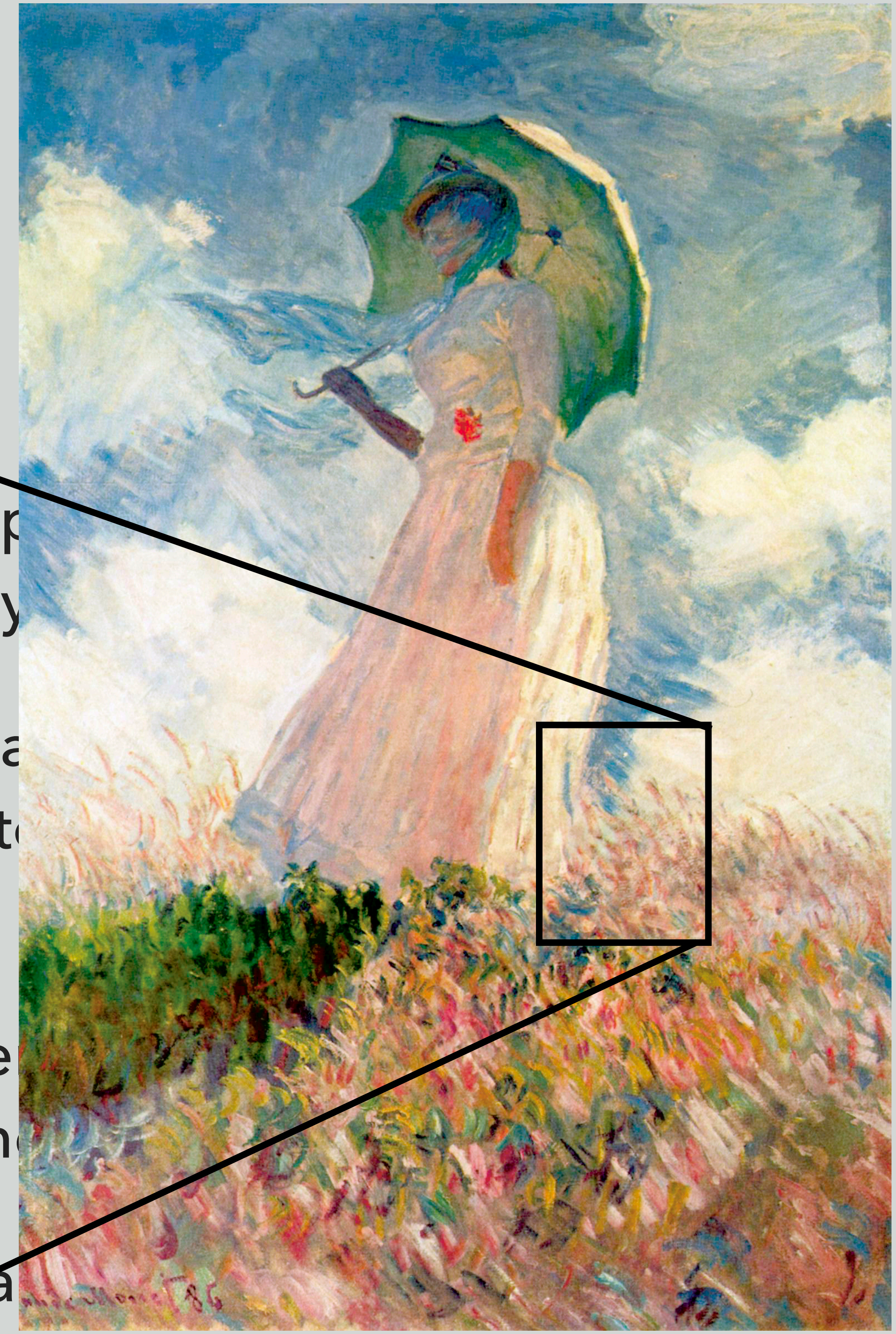
# AB INITIO REFERENCES

- No-core shell model:
  Navrátil, Quaglioni, Stetcu, Barrett, J. Phys. G 36, 083101 (2009); arXiv:0904.0463.
- Greens Function Monte Carlo:
  Pieper & Wiringa: Ann. Rev. Nucl. Part.Sci. 51, 53 (2001); nucl-th/0103005
- Coupled cluster method:
  T. Crawford and H. Schaefer, Rev. Comp. Chem. 14, 33 (2000); I. Shavitt and R. Bartlett, Many-Body Methods in Chemistry and Physics (Cambridge, 2009); Hagen, TP, Hjorth-Jensen & Dean, arXiv:1312.7872.
- Lattice Monte Carlo:
  Dean Lee, Prog. Part. Nucl. Phys. 63 117-154 (2009); arXiv:0804.3501
- In-medium SRG:
  Hergert et al., Phys. Rep. 621, 165 (2016); arXiv:1512.06956
- Self-consistent Green's functions:
  A. Carbone and C. Barbieri, Lecture Notes in Physics, arXiv:1611.03923 (2017)

# EFFECTIVE THEORIES

**Phenomena at low energies (long wavelength) cannot probe details of high-energy (or short-distance) dynamics**

- Ef tic imp di rrectly
- Im cs on a th ined t ET
- Th efficie ex ermin
- Sy nts ca



YOU MAY USE ANY DEGREES OF FREEDOM YOU LIKE TO DESCRIBE A PHYSICAL SYSTEM, BUT IF YOU USE THE WRONG ONES, YOU'LL BE SORRY

**S. Weinberg**

Third law of progress in theoretical physics

# CLASSICAL EXAMPLE OF AN EFFECTIVE THEORY

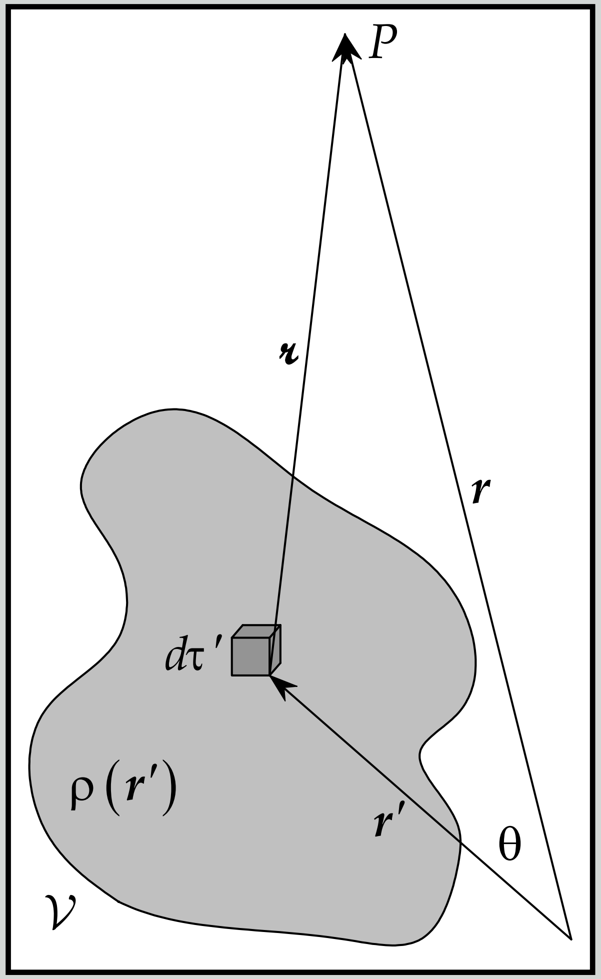
- Multipole expansion of the electric field from a localised charge distribution far away (a≪r).

$$\phi(\vec{r}) \propto \int \frac{\rho(\vec{r}\,')}{\left|\vec{r}-\vec{r}\,'\right|} dV' \quad = \frac{1}{r}\int \rho(\vec{r}\,') dV'$$

$$+\frac{1}{r^2}\int r' \cos\theta' \rho(\vec{r}\,') dV' + \frac{1}{r^3}\int (r')^2 \left(\frac{3}{2}\cos^2\theta' - \frac{1}{2}\right) \rho(\vec{r}\,') dV' + \ldots$$

$$= \frac{1}{r}\left[ q\left(\frac{a}{r}\right)^0 + \tilde{d}\left(\frac{a}{r}\right)^1 + \tilde{Q}\left(\frac{a}{r}\right)^2 + \ldots \right]$$

LO NLO NNLO

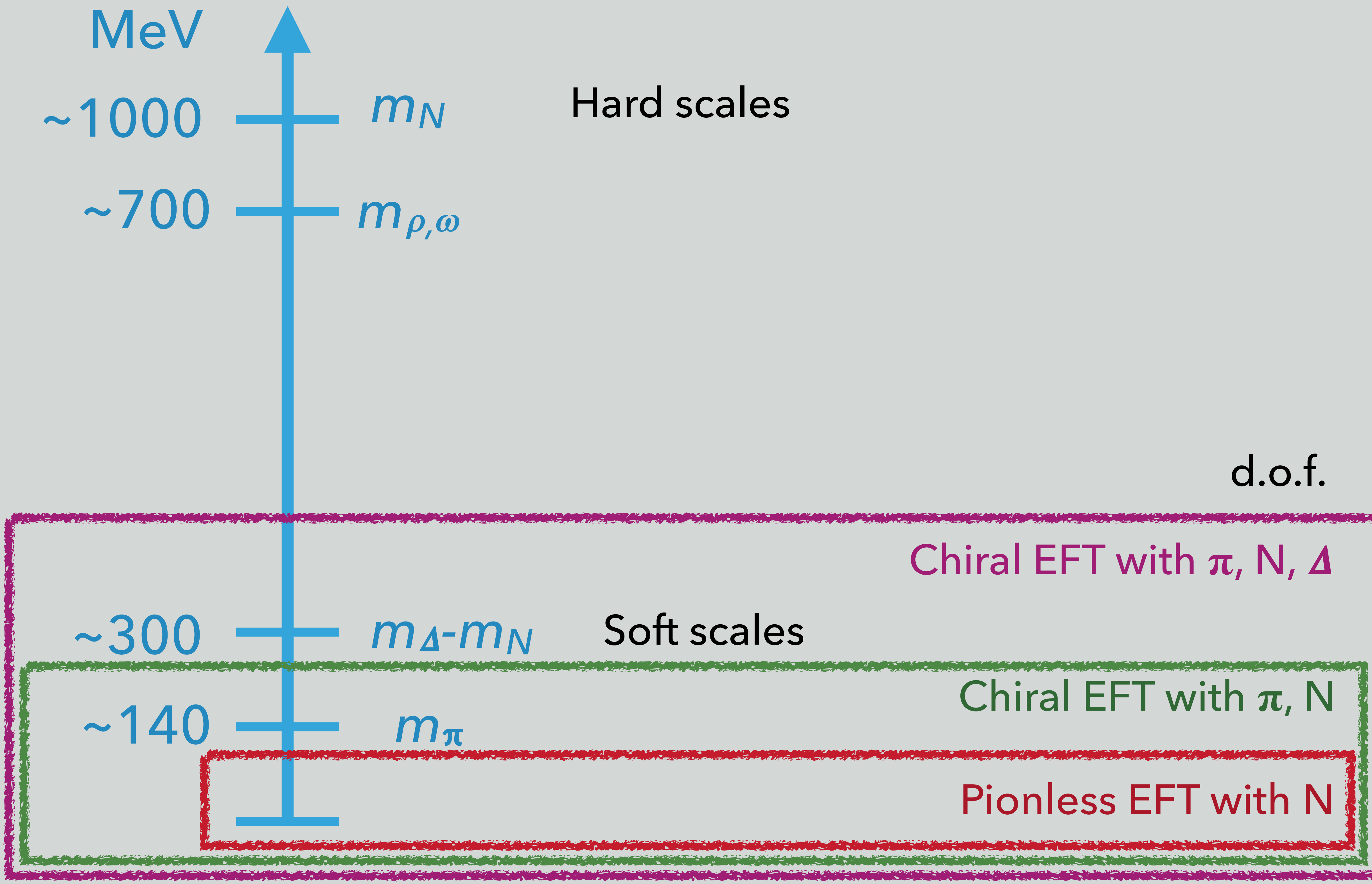



- In this particular example, the underlying physics is known.
- One can also employ effective theories in situation where the short-distance physics is known only through its symmetries.

# EFFECTIVE FIELD THEORY ALGORITHM

- Identify the relevant degrees of freedom
- Identify high- and low-energy scales. Ratios form expansion parameters $Q$
- Identify symmetries of low-energy theory
- Choose the accuracy required. This, together with the size of $Q$, tells you the order, $n$, to which you must calculate.
- Write down all possible local operators, consistent with the symmetries, that have dimensions up to that order (and contribute).
- Derive the behaviour of loops, and calculate them. You should have all operators needed for renormalization up to order $n$.

# Identify relevant degrees of freedom



# CHIRAL PERTURBATION THEORY

Weinberg (79); Gasser & Leutwyler (85); Jenkins & Manohar (91);
Bernard,Kaiser,Kambor & Meissner (92)

- Crucial features of low-energy QCD: confinement and hidden chiral symmetry

- Degrees of freedom: nucleons and pions. Effects of other particles encoded in coupling constants

- Build most general $\mathscr{L}(\boldsymbol{\pi},\mathrm{N})$ consistent with the $SU(2)_V$ x $SU(2)_A$ symmetry of QCD and the pattern of its breaking (i.e. include terms that arise due to $m_q \neq 0$)

- Organize terms as an expansion in $Q = \dfrac{\max(p, m_\pi)}{m_\rho, 4\pi f_\pi}$

# CHIRAL EFFECTIVE (FIELD) THEORY

- build the most general effective Langrangian consistent with (broken) symmetries of QCD.

$$\mathcal{L} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ \ldots\ ,$$

- we organize the NN Lagrangian order-by-order in powers of $Q/\Lambda_\chi$ (only even powers due to parity conservation)

$$\mathcal{L}_{NN} = \mathcal{L}_{NN}^{(0)} + \mathcal{L}_{NN}^{(2)} + \mathcal{L}_{NN}^{(4)} + \mathcal{L}_{NN}^{(6)} + \ldots\ ,$$

- The pion exchange contributions are organized in a similar low-momentum expansion:

$$V_{1\pi} = V_{1\pi}^{(0)} + V_{1\pi}^{(2)} + V_{1\pi}^{(3)} + V_{1\pi}^{(4)} + V_{1\pi}^{(5)} + V_{1\pi}^{(6)} + \ldots$$
$$V_{2\pi} = V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + V_{2\pi}^{(4)} + V_{2\pi}^{(5)} + V_{2\pi}^{(6)} + \ldots$$

# CHIRAL E(F)T AT LEADING ORDER

- One-pion exchange potential (p, p′ are initial and final relative momenta)

$$V_{1\pi}(\vec{p}\,',\vec{p}) = -\frac{g_A^2}{4f_\pi^2}\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\,\frac{\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}}{q^2+m_\pi^2}$$

$$\vec{q} \equiv \vec{p}\,' - \vec{p}$$

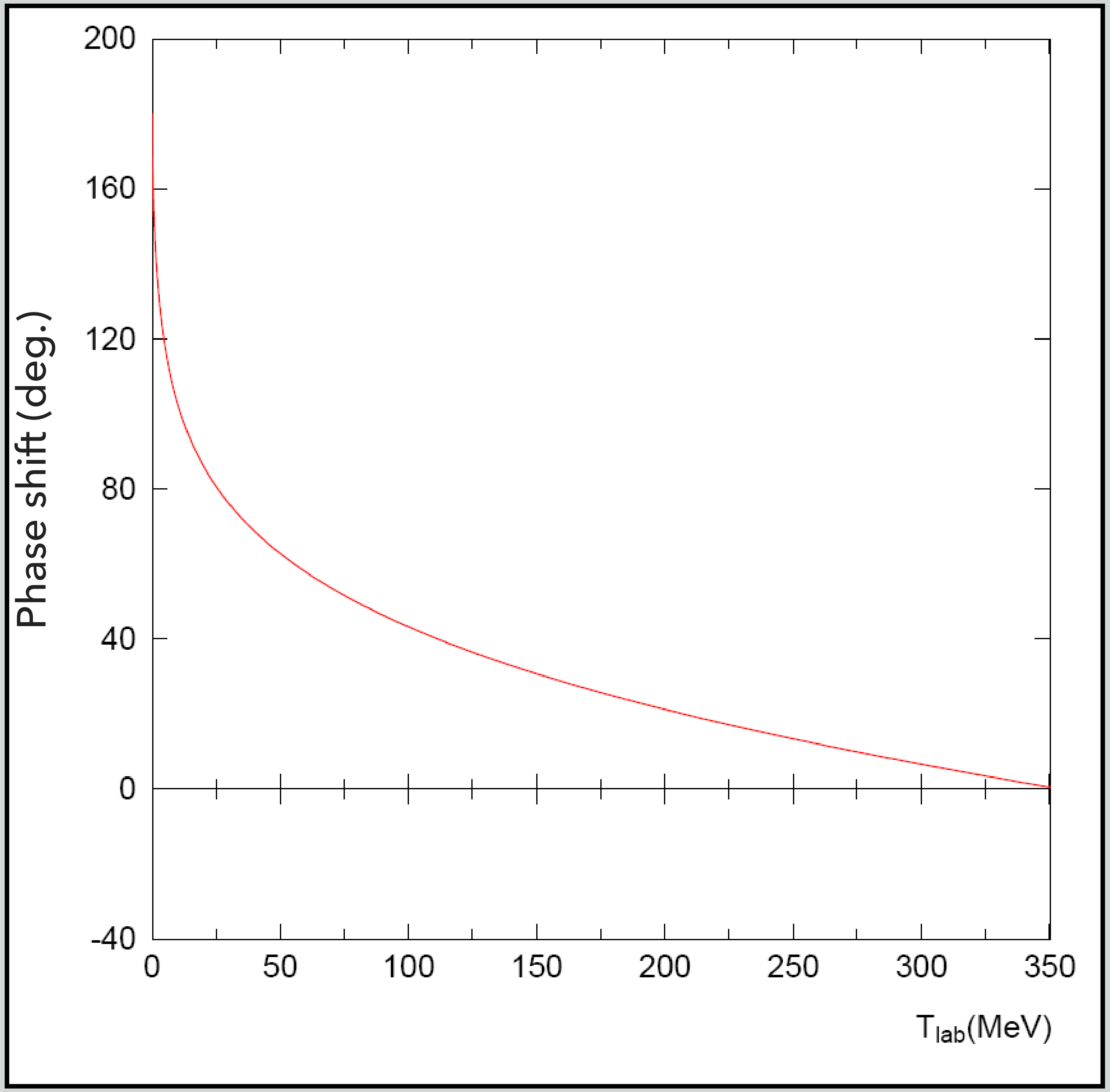
- Leading order contact term (encode unknown short-range physics)

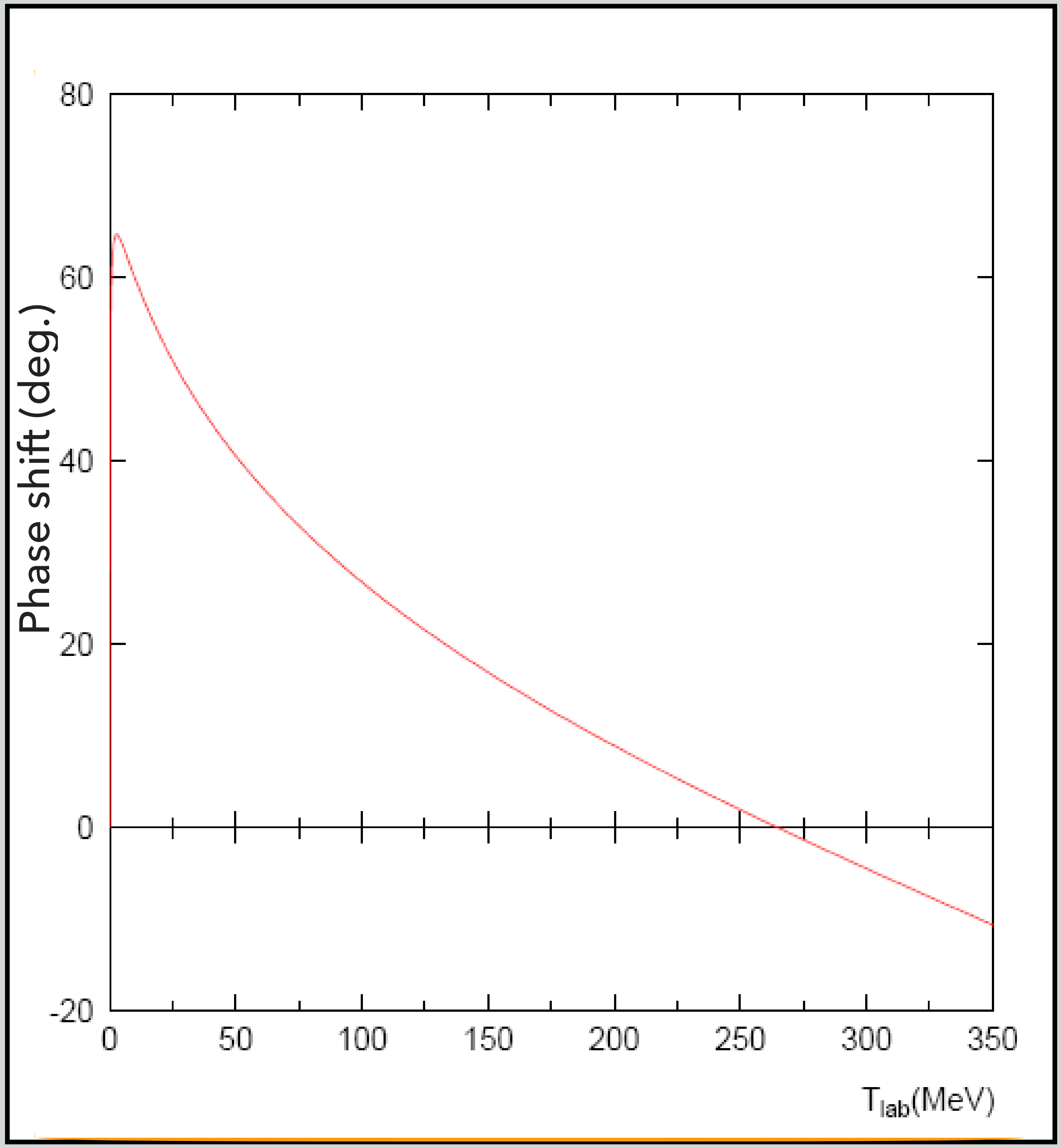
$$V^{(0)}(\vec{p'},\vec{p}) = C_S + C_T\,\vec{\sigma}_1\cdot\vec{\sigma}_2$$

Must determine low-energy constants (LECs) from data

# THE NN SYSTEM

http://nn-online.org/

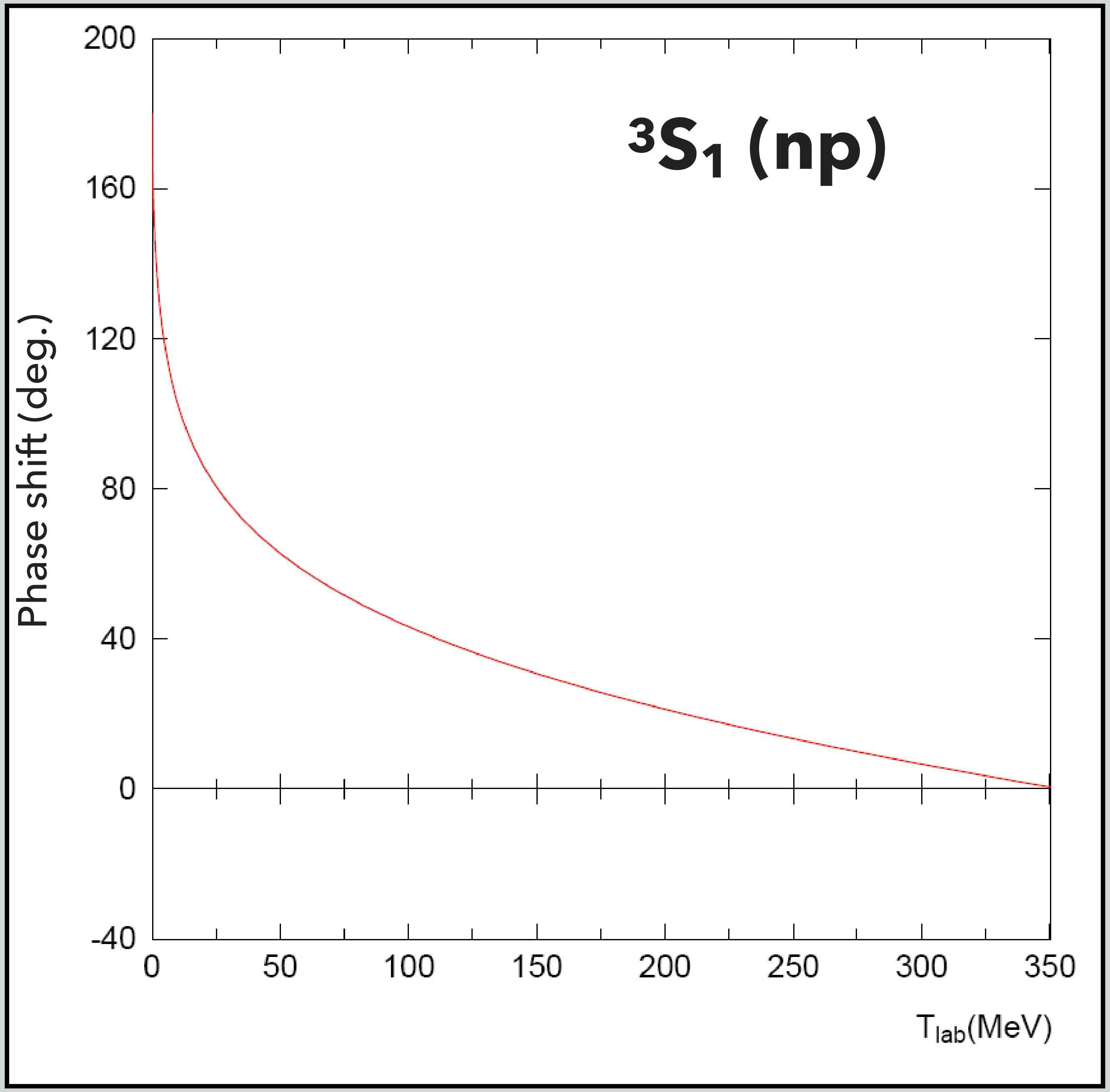



**Which partial wave phase shifts are shown in these plots?**

# THE NN SYSTEM

http://nn-online.org/




Deuteron is a very weakly bound system!

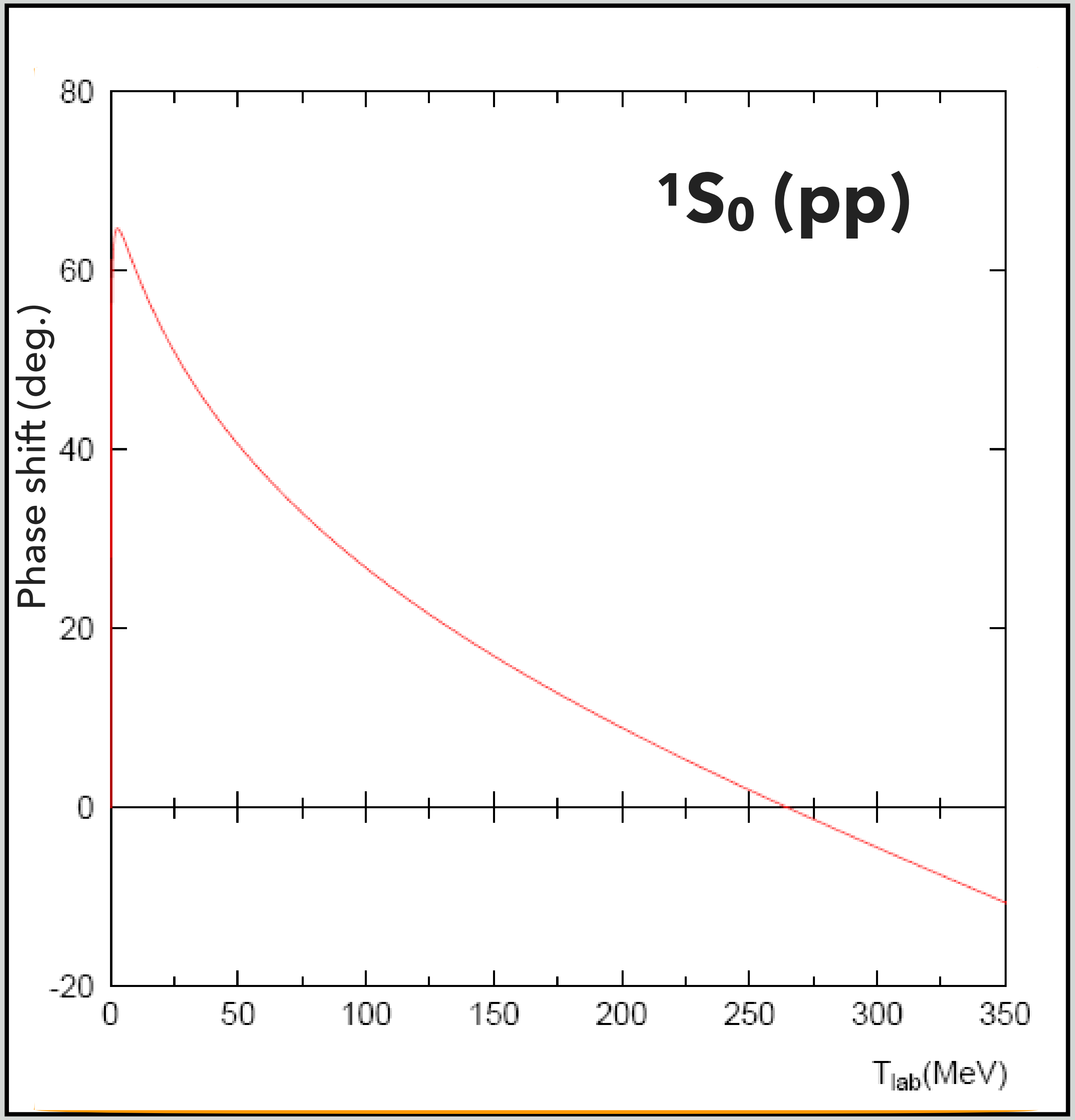
System has one bound state.

Steep decrease from 180 degrees due to large scattering length a = 5.5 fm.

Acts repulsive due to large (positive) scattering length.

# THE NN SYSTEM

http://nn-online.org/




These states (bound and virtual NN state) will not be produced by perturbation theory

Need to iterate the Lippmann-Schwinger equation.

This process also requires treatment of infinities with regularization.

nn/pp systems (barely) fails to exhibit bound state.
Steep rise at E=0 due to large scattering length $a_{pp}$ = -18 fm.
Monotonous decrease due to hard core.

# DETERMINATION OF EFT PARAMETERS

**How do we best determine the low-energy constants of an EFT interaction?**

# TITLE TEXT

A. NN phase shifts

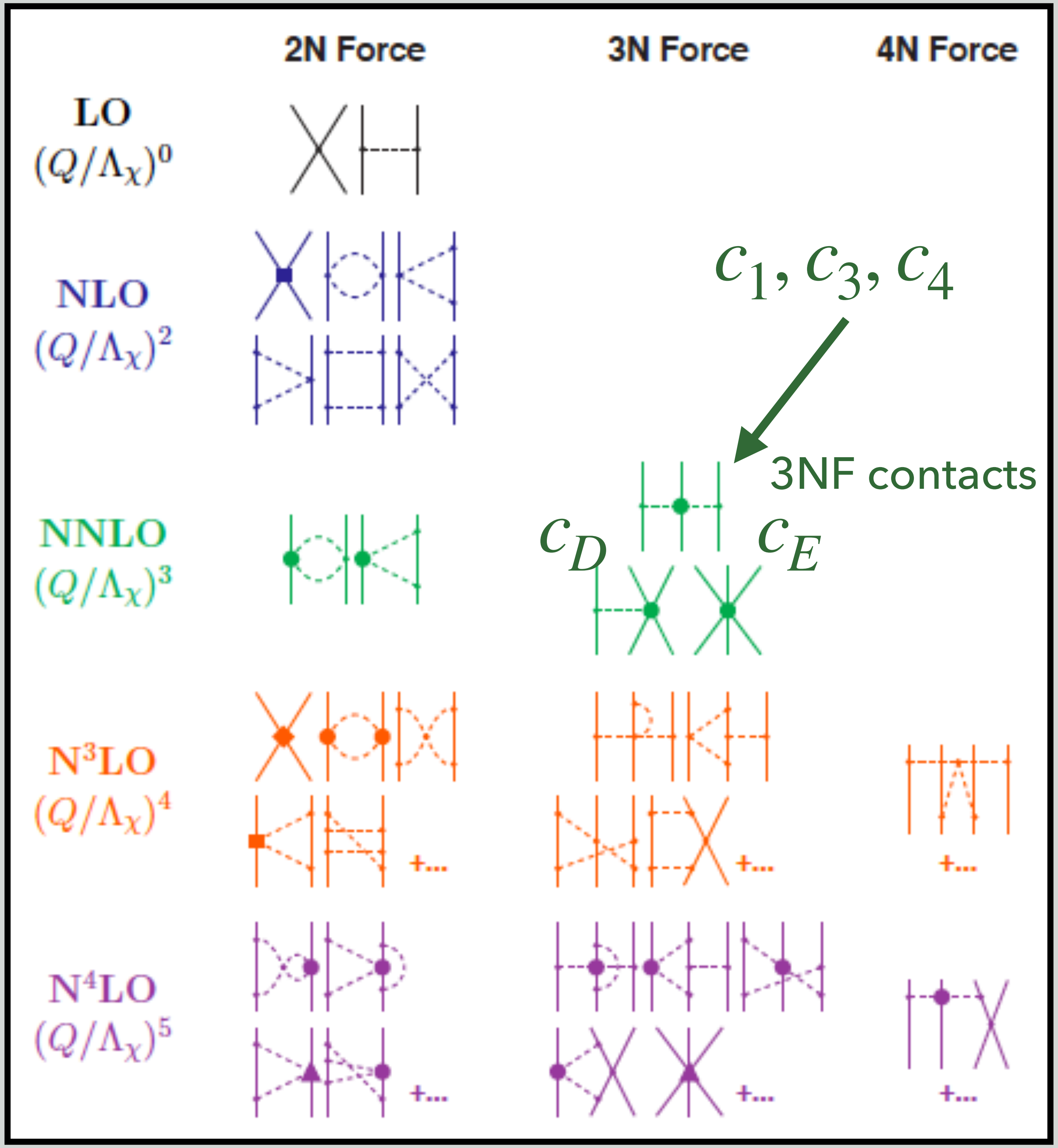
B. NN cross sections

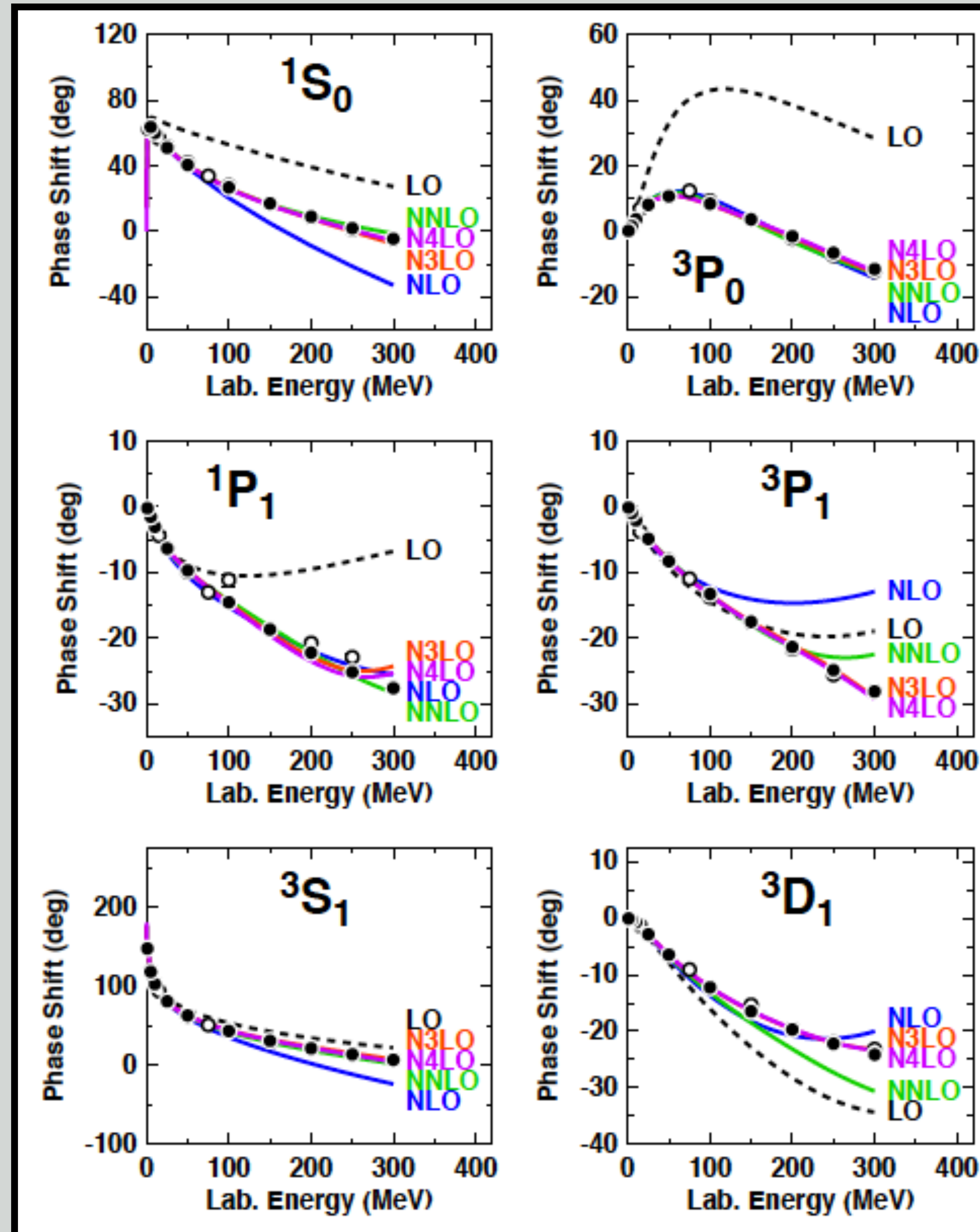
C. Binding energies of light nuclei

D. Nuclear observables all over the nuclear chart

E. Saturation properties of nuclear matter

# CHIRAL E(F)T AND NN PHASE SHIFTS TO N4LO




D. R. Entem, R. Machleidt, Y. Nosyk arXiv:1703.05454 (2017)

# DETERMINATION OF EFT PARAMETERS

**How do we best constrain the three-nucleon force?**

# SOME SUGGESTIONS FOR HOW TO CONSTRAIN THE 3NF

A. Binding energies of 3H and 3He

B. Binding energy of 3H and n+d scattering length

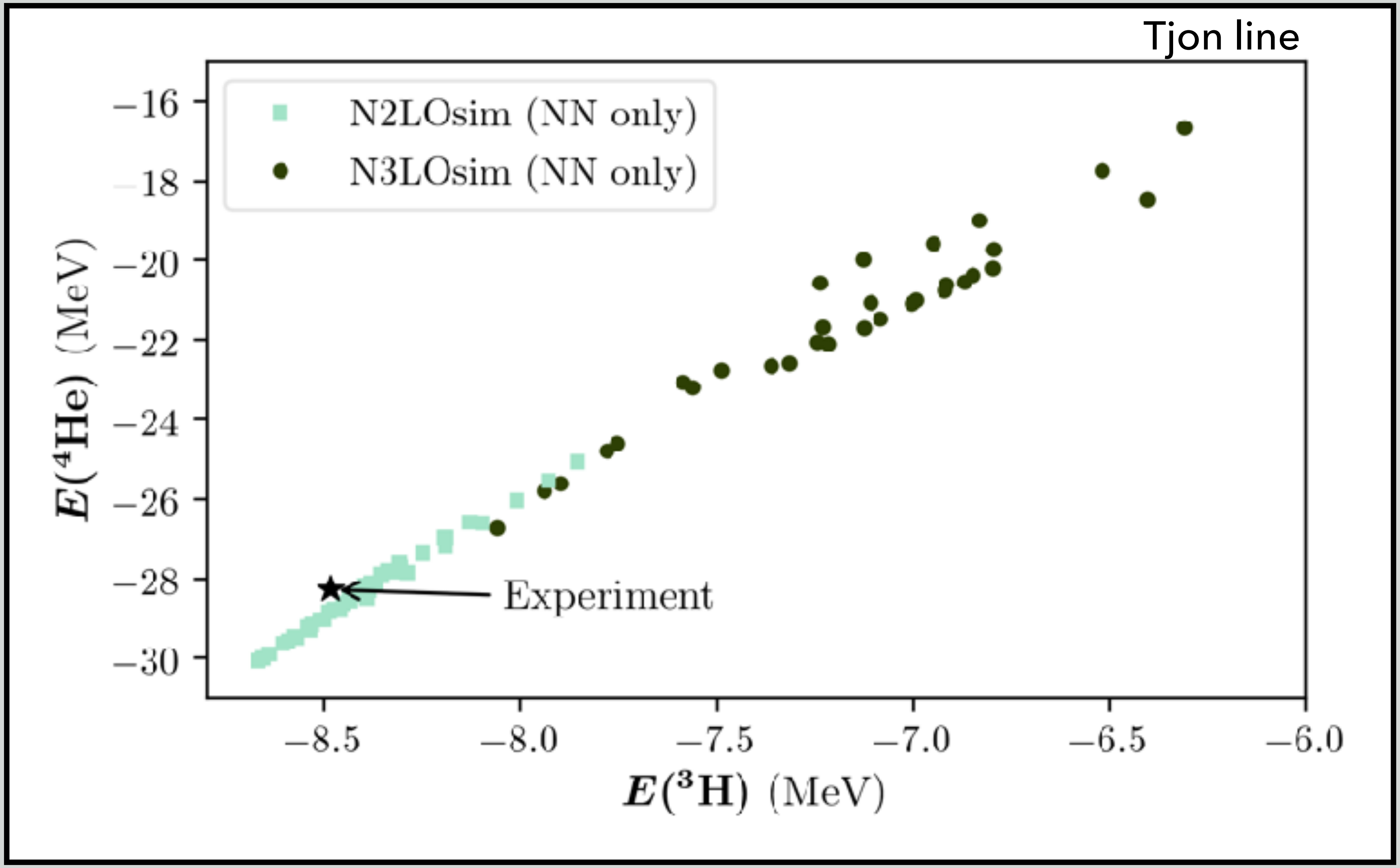
C. Binding energies of 3H and 4He

D. Binding energy of 3H and GT matrix element <3H | GT | 3He>

E. Nuclear observables for nuclei A>3

F. Saturation properties of nuclear matter

# NON-UNIQUENESS OF THREE-NUCLEON FORCE




3NFs play an important but complicated role in nuclear physics

LECs of 3NFs are tuned together with, and depend on, the underlying nucleon-nucleon interaction

# OUTSTANDING ISSUES WITH NUCLEAR EFT

- What is the best leading order?
- Applying naive EFT power counting to potential in other partial waves does not work for $\Lambda$>1 GeV
- Renormalization group invariance
- Regulator artefacts
- Either use perturbation theory to treat corrections beyond LO or be restricted to low cutoffs, where iteration is (somewhat) justified
- Convergence pattern: is it better with an explicit $\Delta(1232)$?
- What is the sub-leading three-body force?
- How reliably can $\pi$N LECs be extracted?

# ACCOMPLISHMENTS OF AB INITIO NUCLEAR STRUCTURE CALCULATIONS

- Demonstration that nuclei can be built from scratch. Validation and benchmarking performed for complementary methods.
- Demonstration that three-nucleon forces must be included in the description of nuclei.
- Have been used to determine low-energy constants of potentials from chiral effective (field) theories.
- Provide a solid basis that other methods can build on and link to
  - UNEDF www.unedf.org, NUCLEI www.computingnuclei.org projects)
  - Effective interactions for shell-model valence spaces
  - Halo effective field theory (degrees of freedom: nucleons + clusters of nucleons)
- Much effort is now going back to the construction of (EFT) interactions.

Based on: A. Ekström et al, Phys. Rev. C **91** (2015) 051301(R)

Rapid Communication

Accurate nuclear radii and binding energies from a chiral interaction

A. Ekström, G. R. Jansen, K. A. Wendt, G. Hagen, T. Papenbrock, B. D. Carlsson, C. Forssén, M. Hjorth-Jensen, P. Navrátil, and W. Nazarewicz

Phys. Rev. C **91**, 051301(R) – Published 1 May 2015

# SELECTED EXAMPLES

and: G. Hagen et al, Nat. Phys. **12** (2015) 186

nature physics

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*NATURE PHYSICS* | ARTICLE

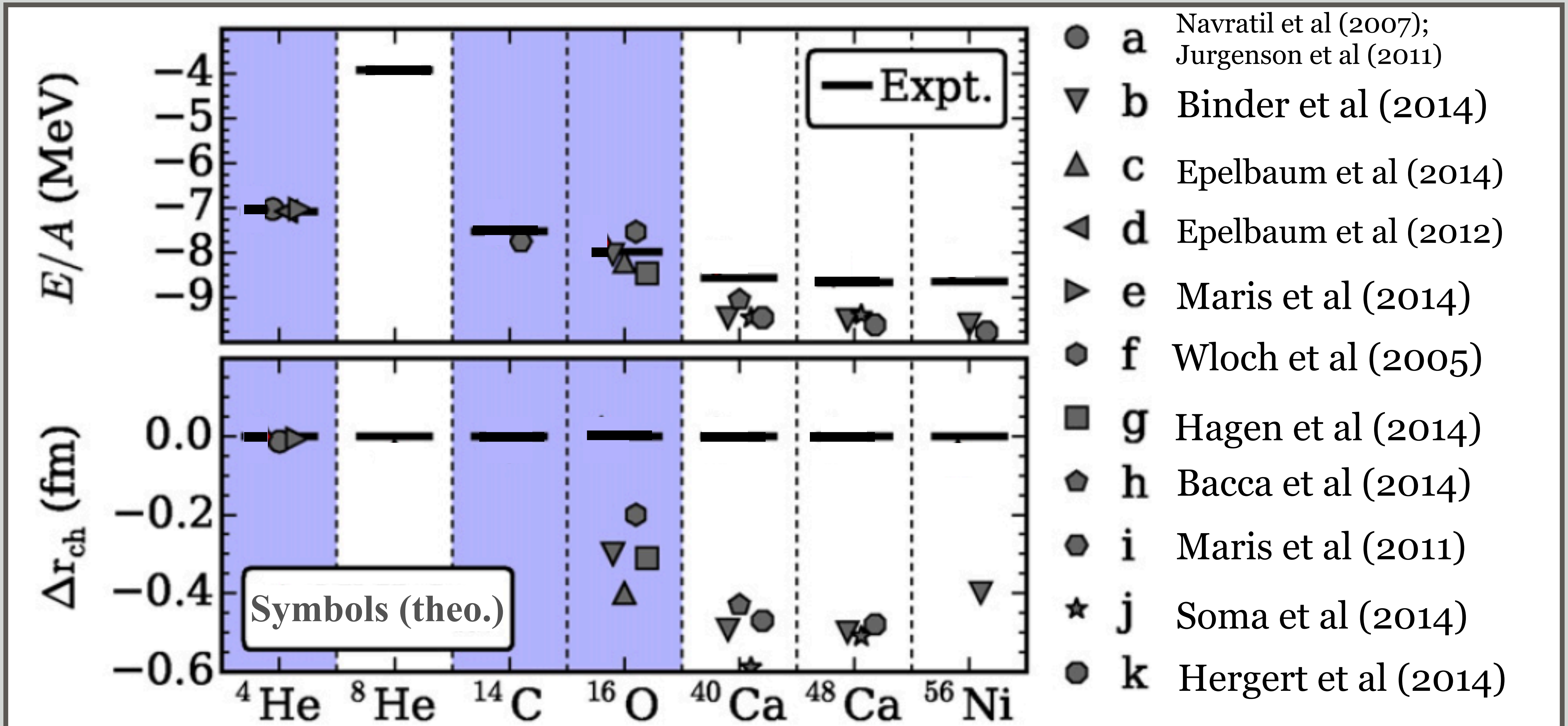
Neutron and weak-charge distributions of the $^{48}$Ca nucleus

G. Hagen, A. Ekström, C. Forssén, G. R. Jansen, W. Nazarewicz, T. Papenbrock, K. A. Wendt, S. Bacca, N. Barnea, B. Carlsson, C. Drischler, K. Hebeler, M. Hjorth-Jensen, M. Miorelli, G. Orlandini, A. Schwenk & J. Simonis

# STATUS OF CHIRAL-FORCE PREDICTIONS

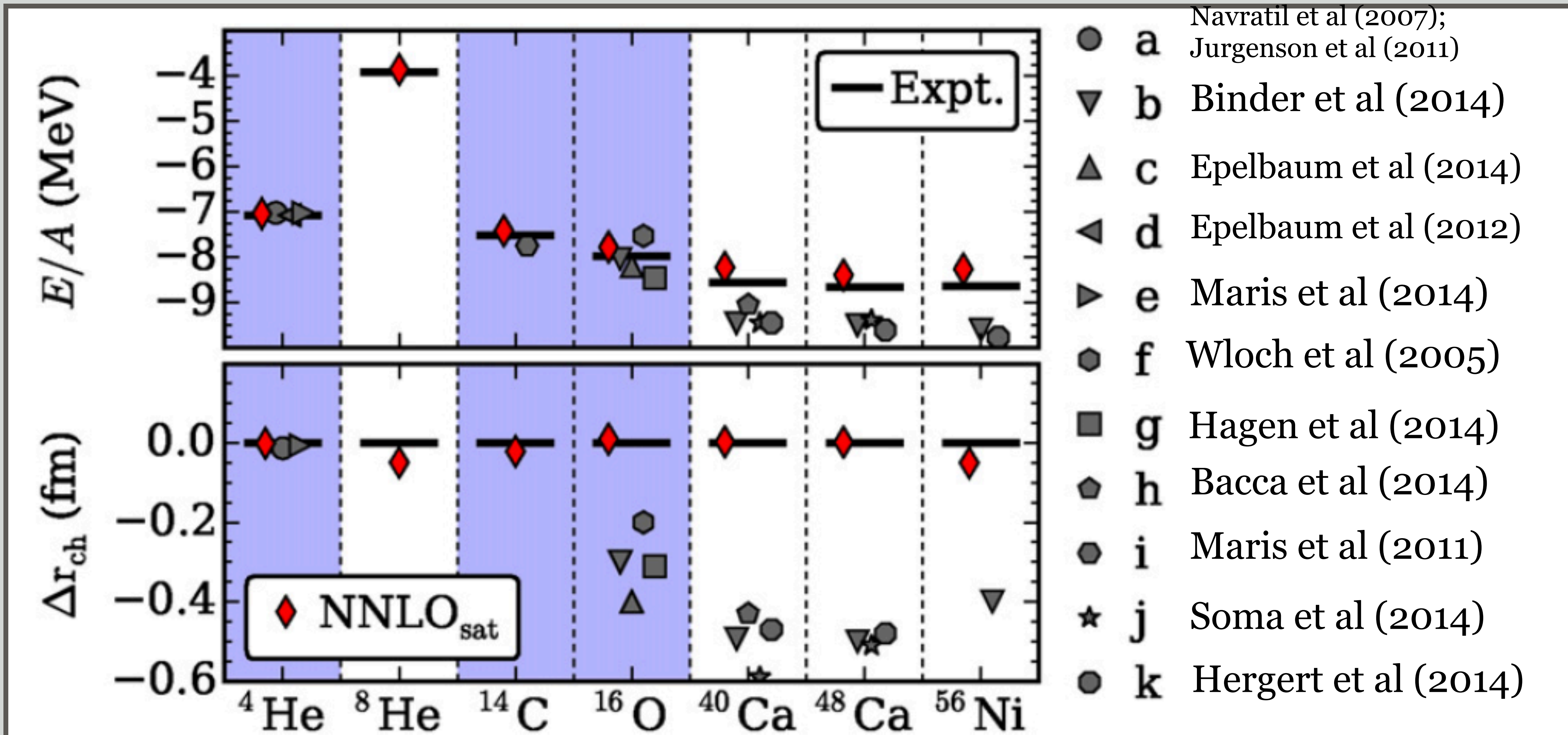
**Ab initio calculations with existing chiral interactions**

- **overbind** medium-mass and heavy nuclei, and
- **underestimate charge radii**.

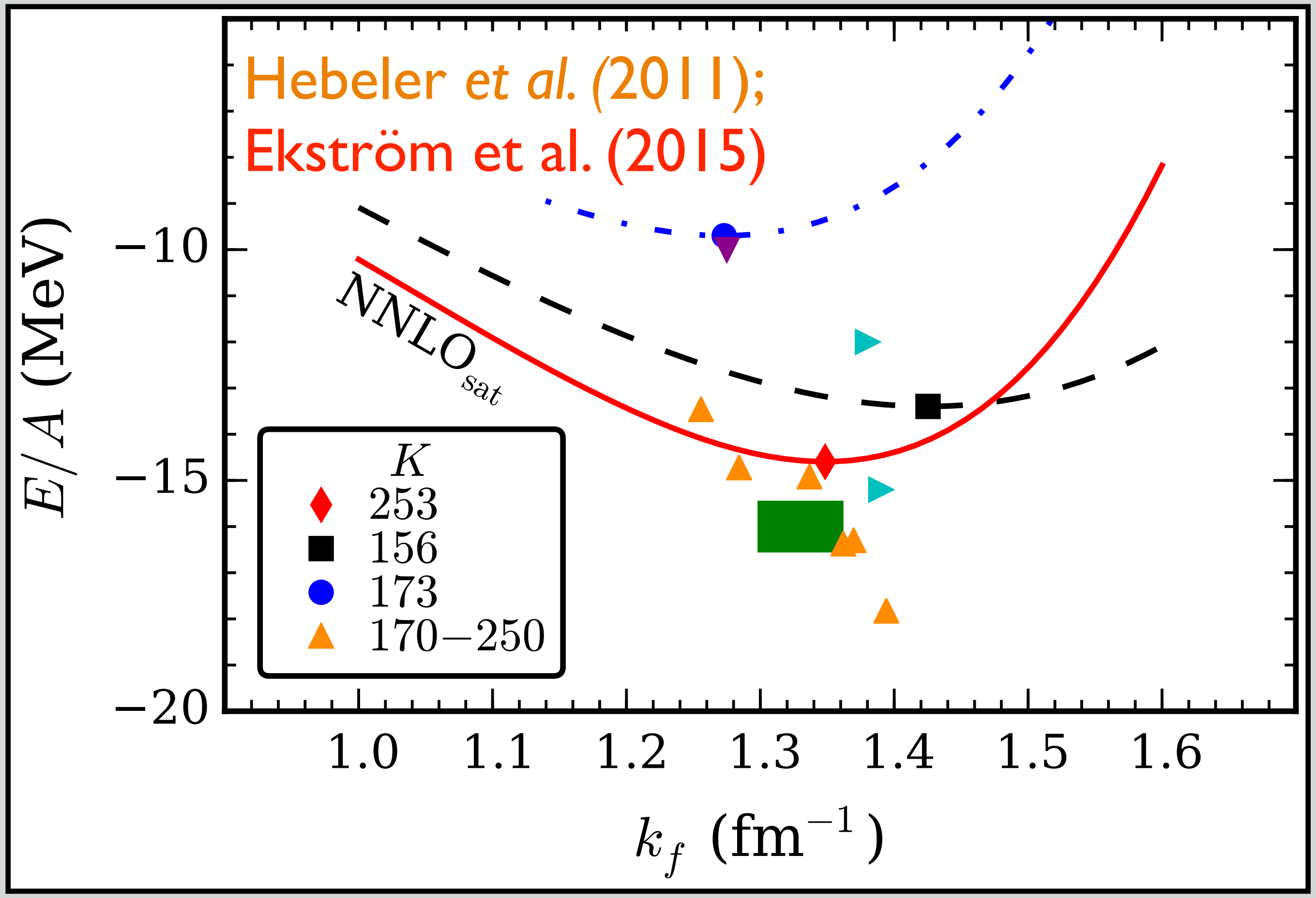


# PRAGMATIC APPROACH

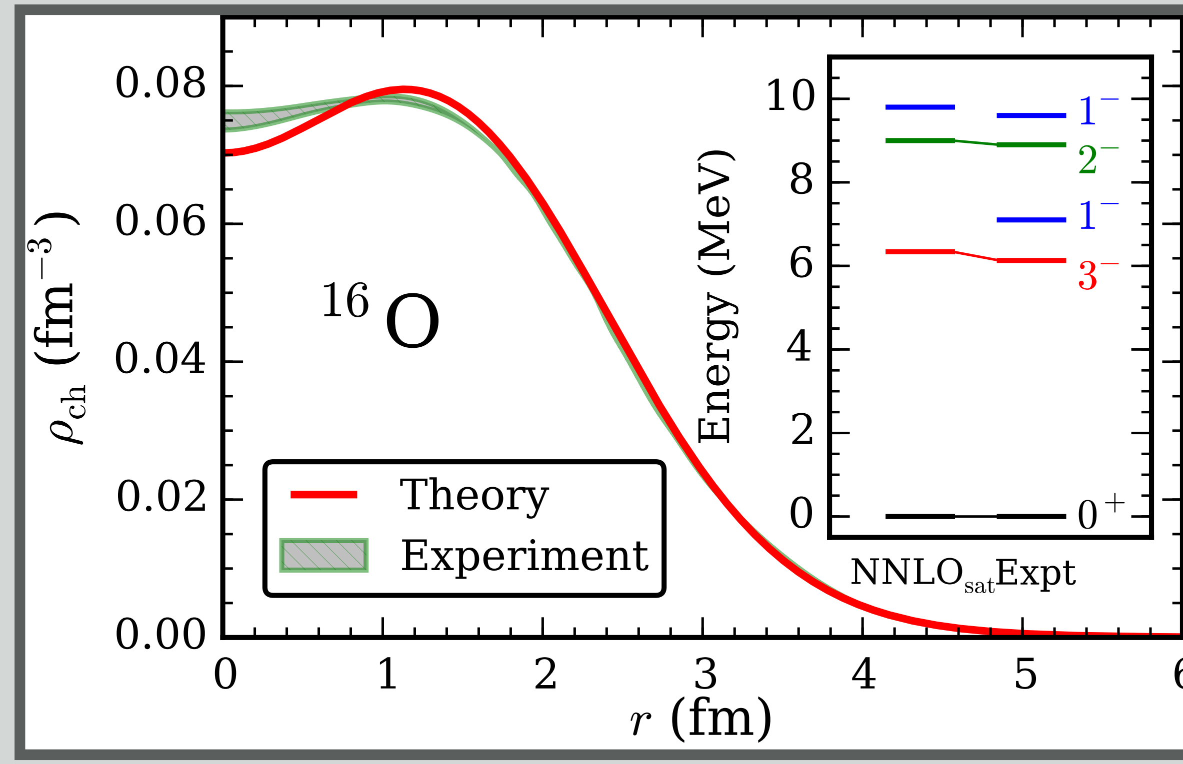
- **Simultaneous optimization** of NN and NNN LECs at NNLO.
- NCSM and CC calculations performed within the optimization.
- Adjusted to **NN scattering data** ($T_{lab}$< 35 MeV) … and to A=2,3,4 nuclei, … and to **BEs of $^{14}$C, $^{16,22,24,25}$O**, and to **radii of $^{14}$C and $^{16}$O**



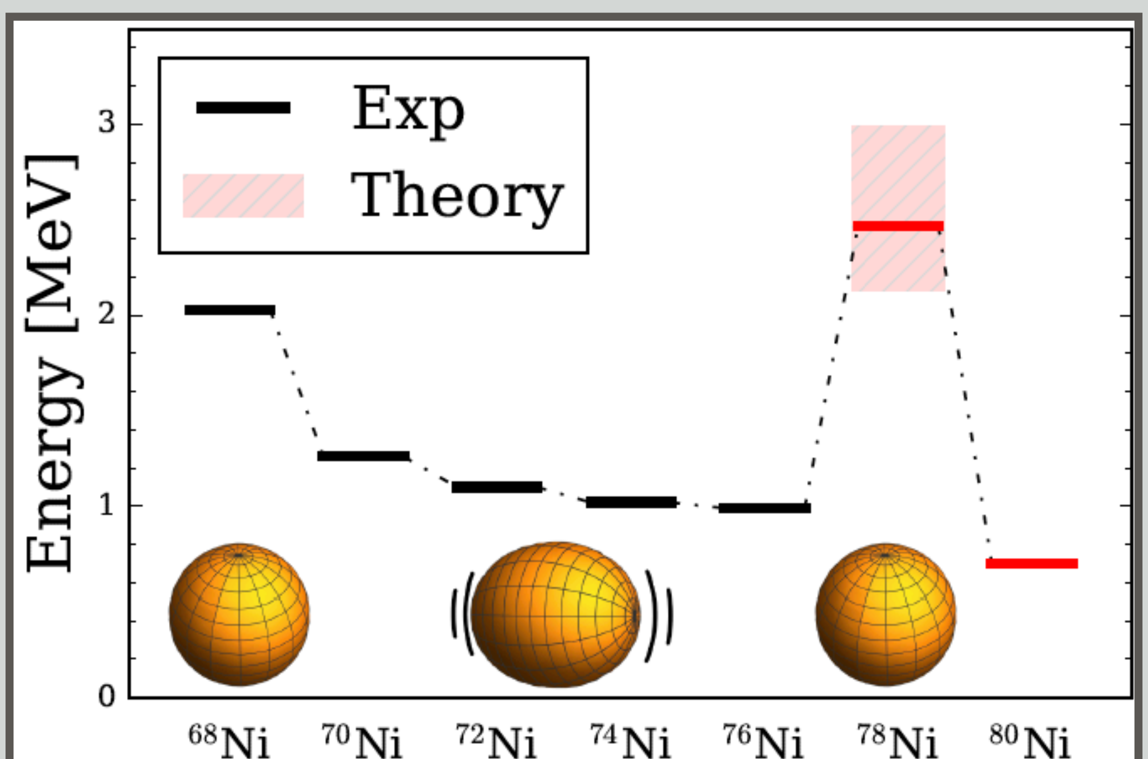
# ACCURATE PREDICTIONS FOR FINITE NUCLEI AND NUCLEAR MATTER




**Accurate saturation**



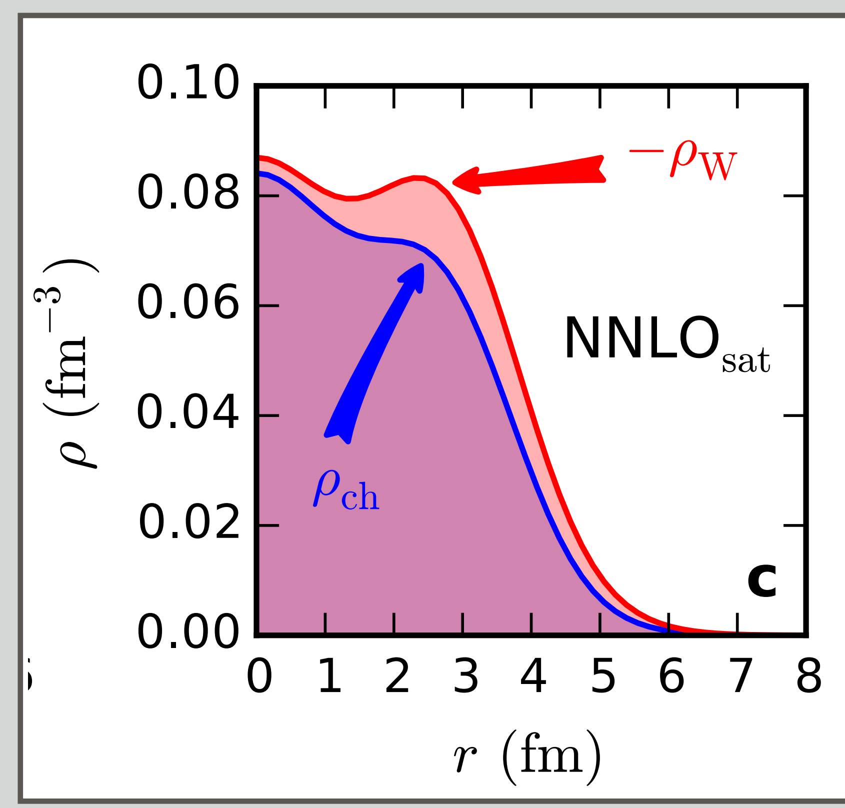

**$^{16}$O charge radius**




**Structure of $^{78}$Ni**

G. Hagen, et al., Phys. Rev. Lett. 117, 172501 (2016).

**Neutron skin of $^{48}$Ca**



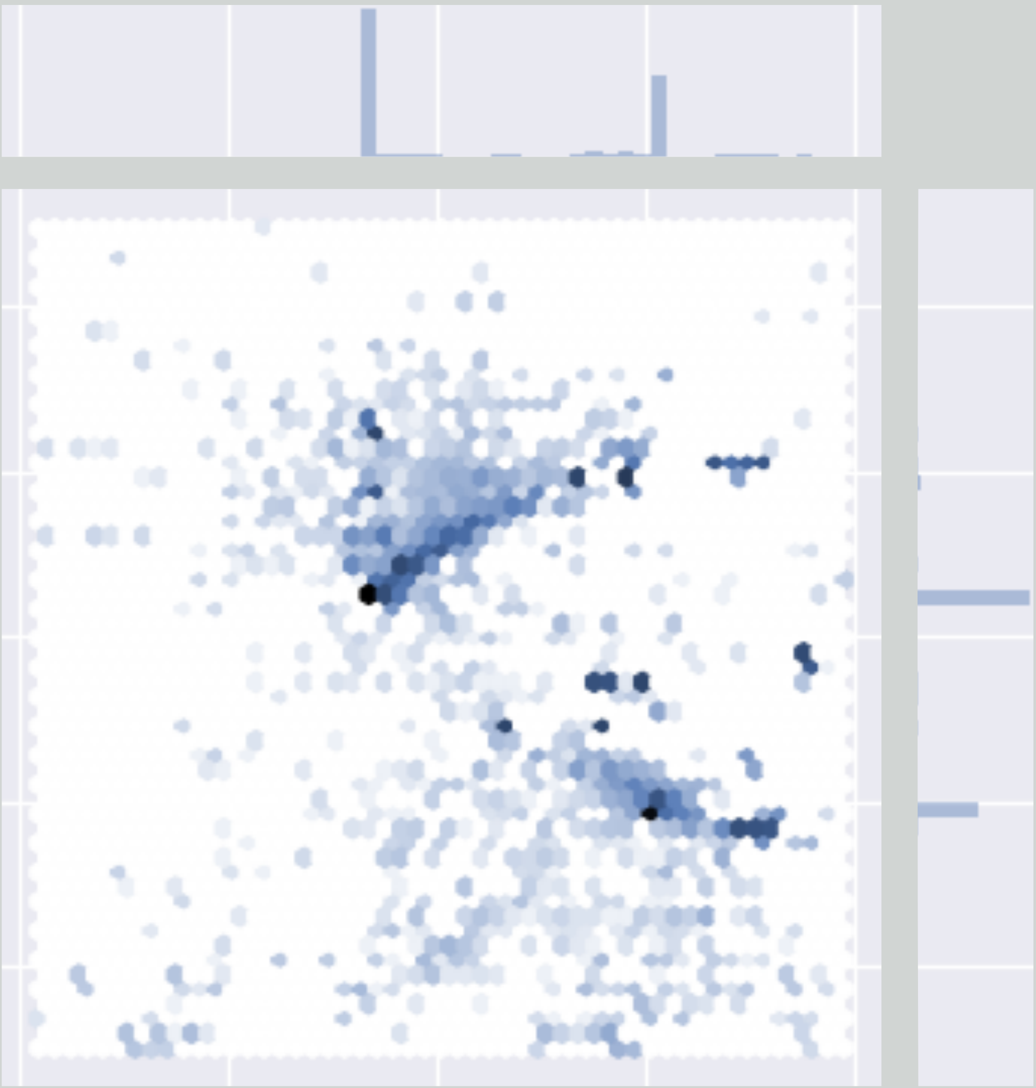
# STILL MISSING

- An extensive and credible program for uncertainty quantification (ongoing work: BUQEYE collaboration; Epelbaum et al; Ekström, Forssén et al).
- Revisit the EFT power counting issues

**To accomplish this we need to employ the ability to quantify systematic theory errors with:**

**- Ab initio methods (method uncertainty controlled)**

**- Effective field theory (quantify importance of physics that was not included)**



# BAYESIAN ANALYSIS OF EFT INTERACTIONS

# THEORISTS ANONYMOUS

1. Admit that you have a problem: your theory has uncertainties
2. Acknowledge the existence of a higher power
3. Seek to understand its impact on our theory
4. Make a searching and fearless inventory of errors
5. Acknowledge your mistakes
6. Make amends for those mistakes
7. Help others who must deal with the same issues

# THE BAYES' WAY

- EFTs are special because they have a convergence pattern:

$$X^n(p) = X_0 \sum_{\nu=0}^{n} c_\nu Q^\nu, \quad Q = \frac{\max(p, m_\pi)}{\Lambda_\chi}$$

- Bayes lets us consistently incorporate EFT details: naturalness of LECs/observable expansion, truncation errors, breakdown scale.

- We can tell if EFTs are working → model checking!

- Can incorporate truncation errors consistently! (treat as nuisance parameters)

**THANK YOU!**