From nuclei to stars

Theoretical course

NPAC 2019 / 2020

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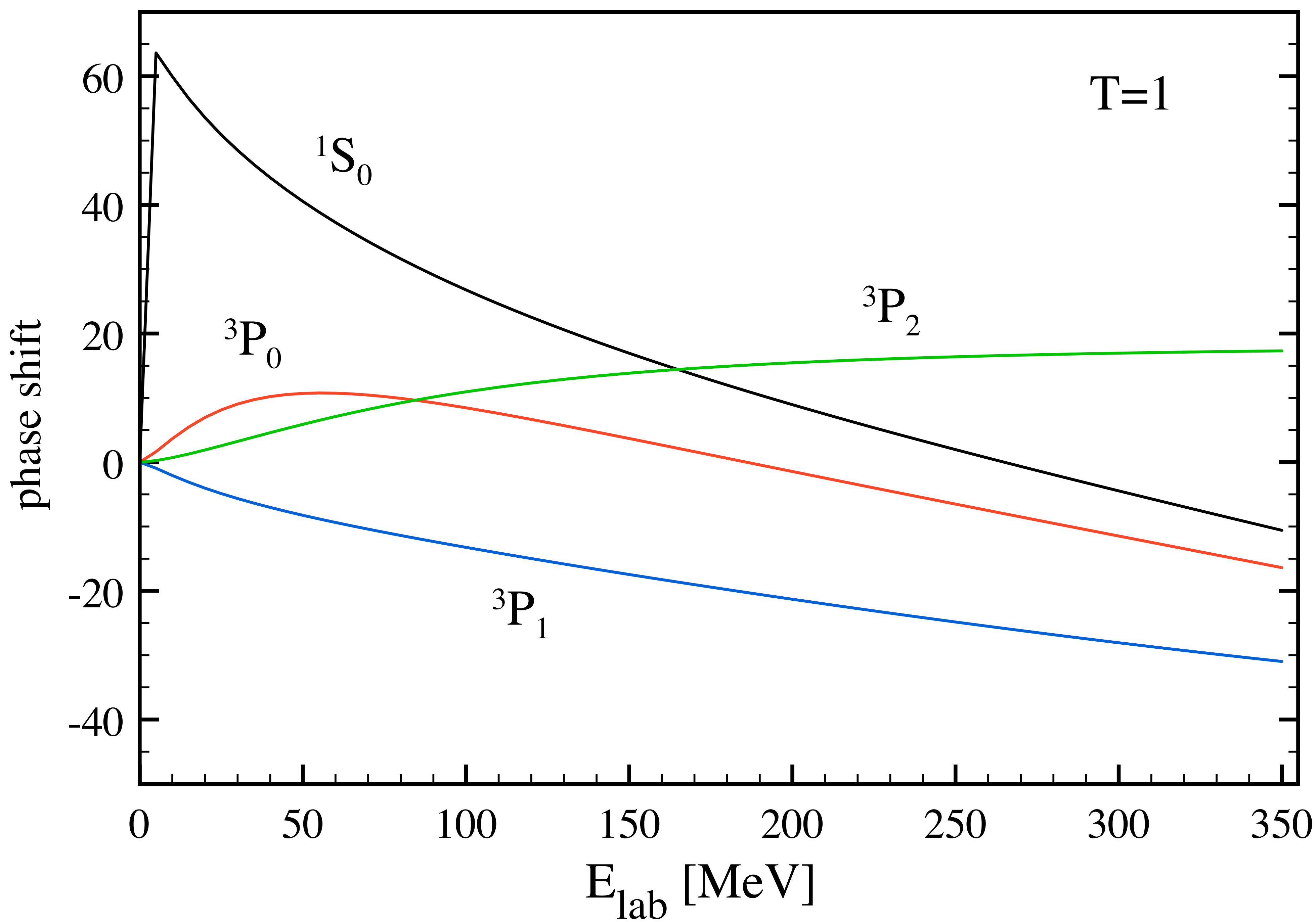
Chapter 2: NN interaction

Nucleon-nucleon phase shifts

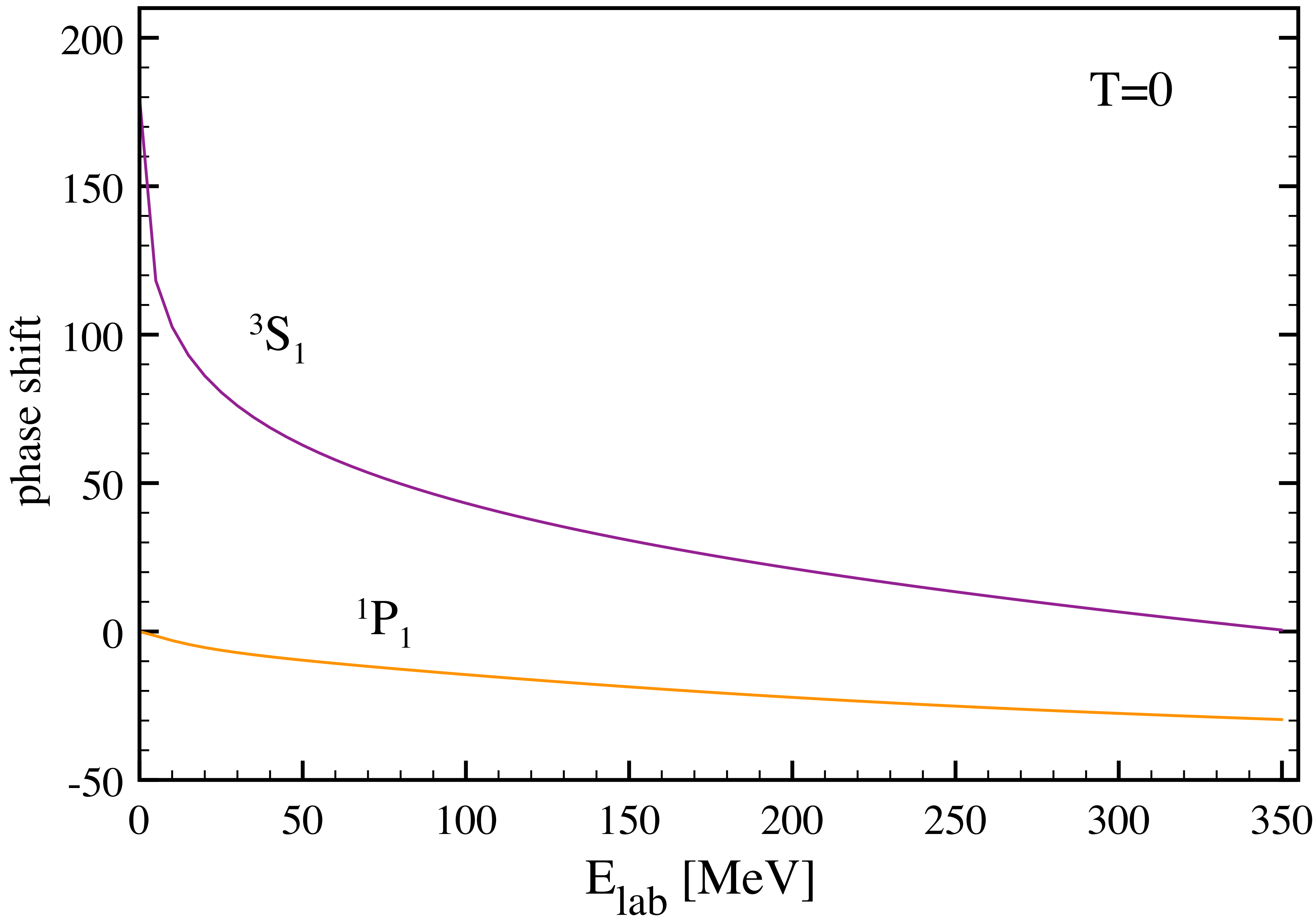
⊙ **Nucleon-nucleon scattering**

○ Example of phase shifts



Nucleon-nucleon phase shifts

- **Nucleon-nucleon scattering**
  - Example of phase shifts



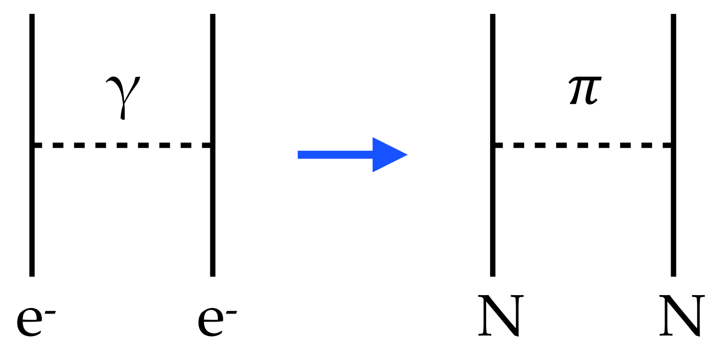
Yukawa potential

What was known:
- ○ Coulomb interaction between charged particles (infinite range)
- ○ Nuclear interaction is short range ~ 2 fm

➪ **Idea: nuclear force mediated by massive spin-0 boson** (the "mesotron" → later, pion)

[Yukawa, Proca]

1935



Yukawa potential

$$V(r) \propto \frac{e^{-mr}}{r}$$

m ~ 100 MeV ← r ~ 2 fm

Range ~ Compton wavelength of exchanged boson ~ 1/m

⦿ One-pion exchange describes long-range attraction between nucleons

- ○ Generate tensor and $\tau \cdot \tau$ structures
- ○ Works so well that, as of today, it is part of most sophisticated potential models!

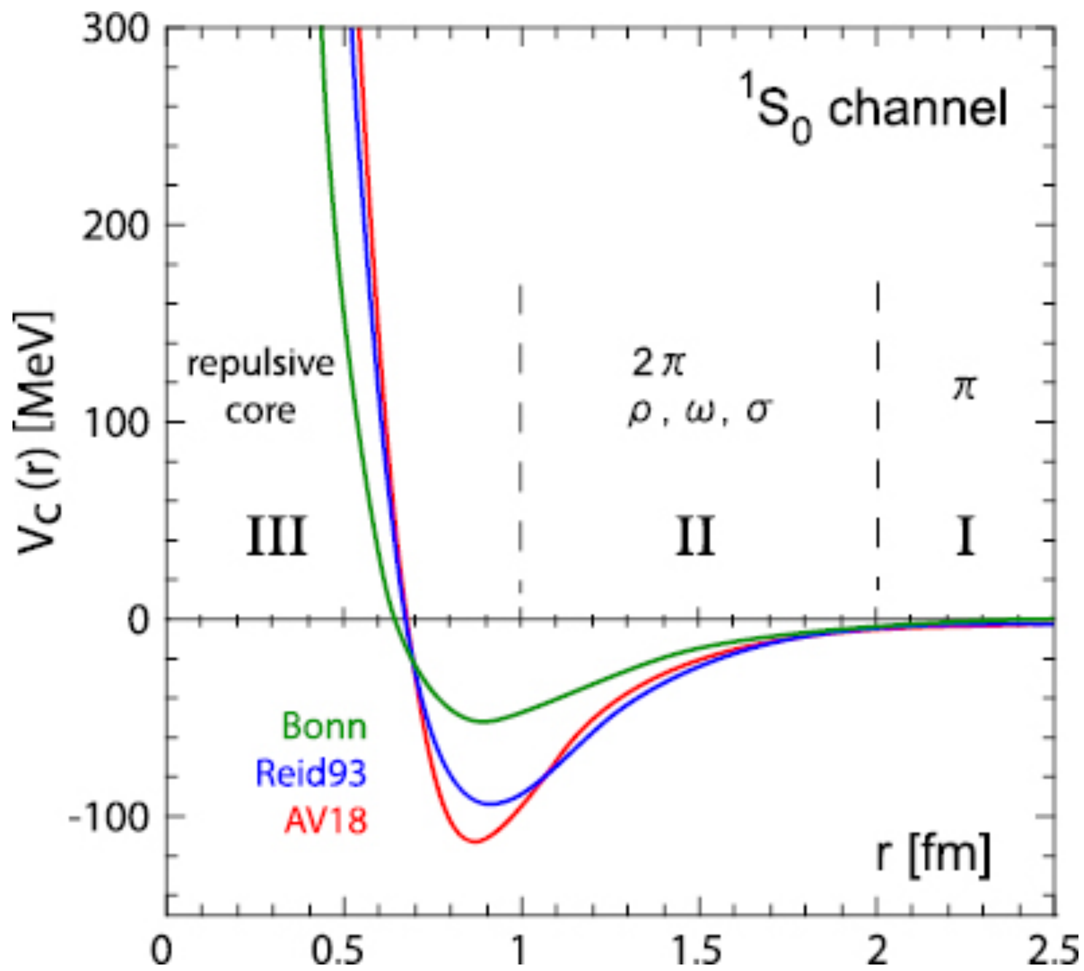
⦿ However, not the full story. Short-range part?

- ○ 1950's: Multi-pion exchange: disaster
- ○ 1960's: More mesons discovered → multi-pion resonances ≈ exchange of heavier mesons

One-boson-exchange potentials

- Meson with larger masses (ρ , ω, σ) can model ranges smaller than $1/m_\pi$
  - Different spin/isospin structures generated
  - Parts sometimes phenomenological (or the whole, e.g. Av18)

1970's



- Experimental side: more and more precise *NN* data
- Theoretical side: more sophisticated potentials $\rightarrow$ $\chi^2 \approx 2$ in the 1980's, $\chi^2 \approx 1$ in the 1990's

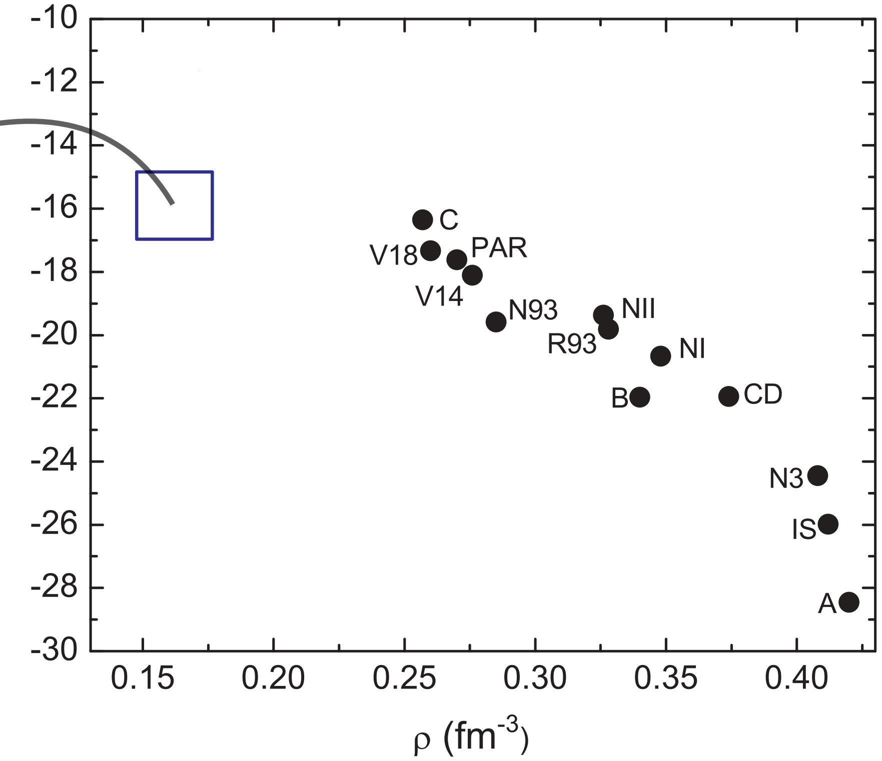
Three-nucleon forces

⦿ Calculations with accurate (χ^2= 1) OBE potentials show deficiencies in systems with A>2

- ○ Lightest nuclei do not match experiment
- ○ Saturation point of nuclear matter is not reproduced

Three-nucleon forces must be considered

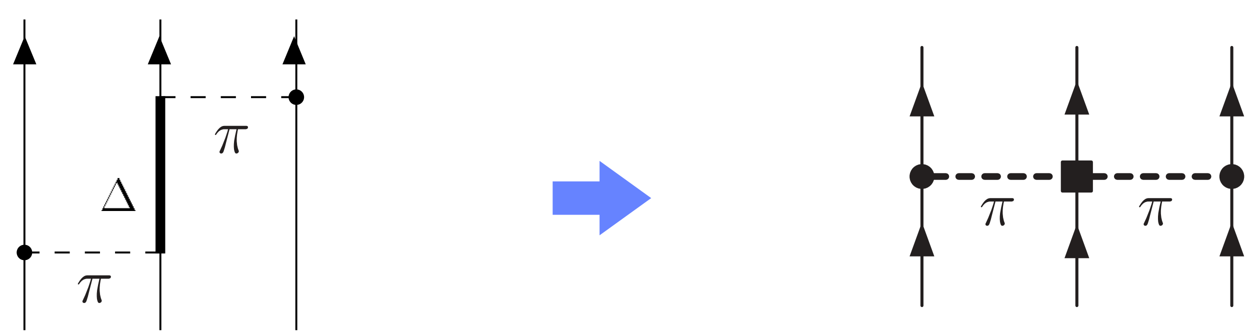
1980's



[Li *et al.* 2006]

➪ **Fundamental reason**: nucleons are composite particles, but we treat them as structureless

- ○ Certain processes, e.g. involving nucleon excitations, can not be described as 2-body

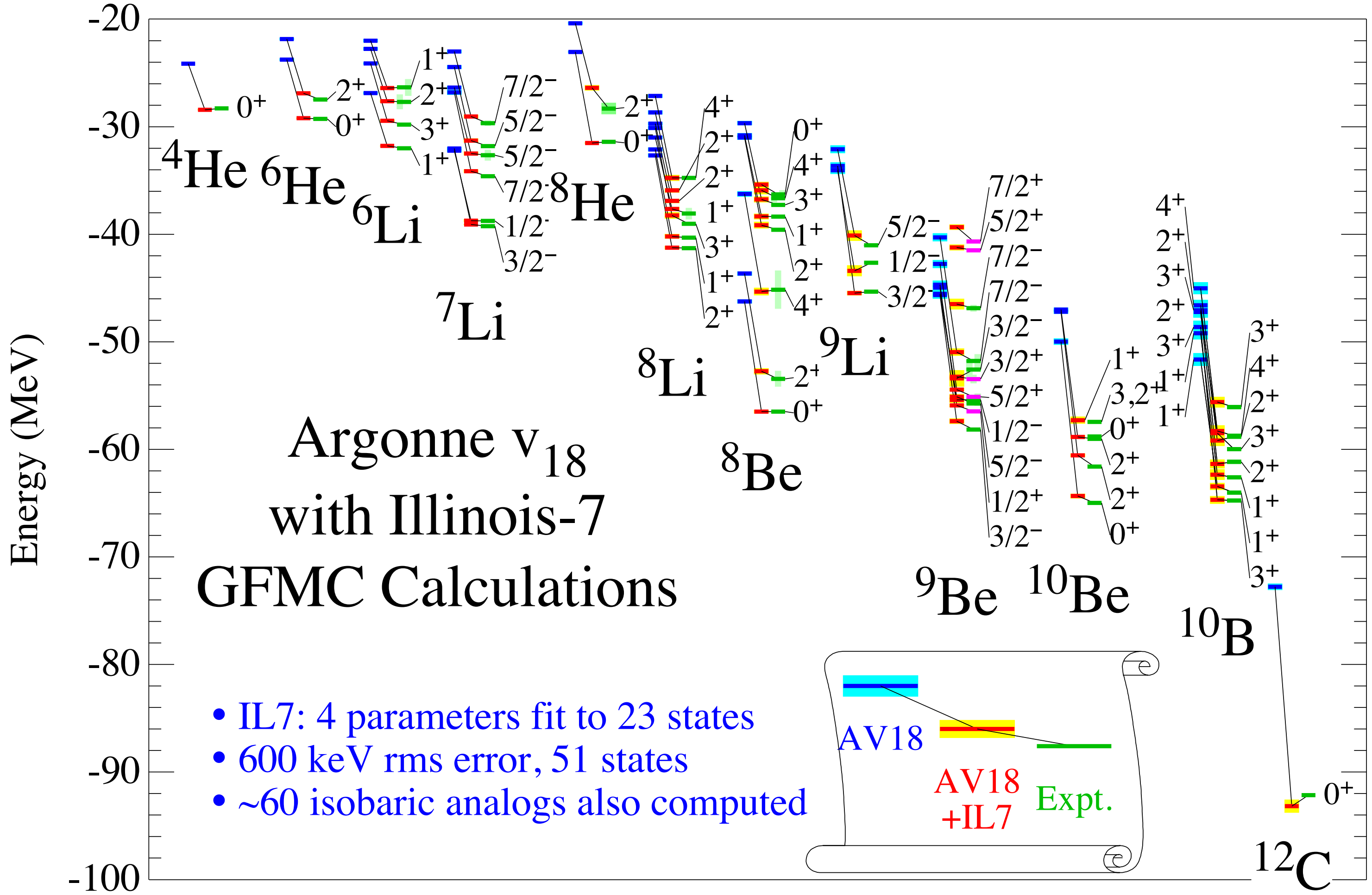


[Fujita, Miyazawa]

- ○ Three-nucleon forces are added mostly phenomenologically to OBE potentials

First ab initio calculations

- ⦿ **1990's: Green function Monte Carlo approach**
  - ○ MC techniques to sample many-body wave function in coordinate, isospin and spin space
- ⦿ **2000's: No-core shell model approach**
  - ○ Diagonalisation of the Hamiltonian in a finite-dimensional space



[Pieper & Wiringa 2001]

Nuclei simulated from scratch!

Closed the gap between elementary nucleon-nucleon interactions and properties of nuclei

✗ Computational effort increases exponentially / factorially with nucleon number

Resolution scale of nucleon-nucleon interactions

- Two main problems with OBE potentials

1. Substantial part remains phenomenological (in particular 3N sector)

2. Strong repulsive short-range component (“hard core”)

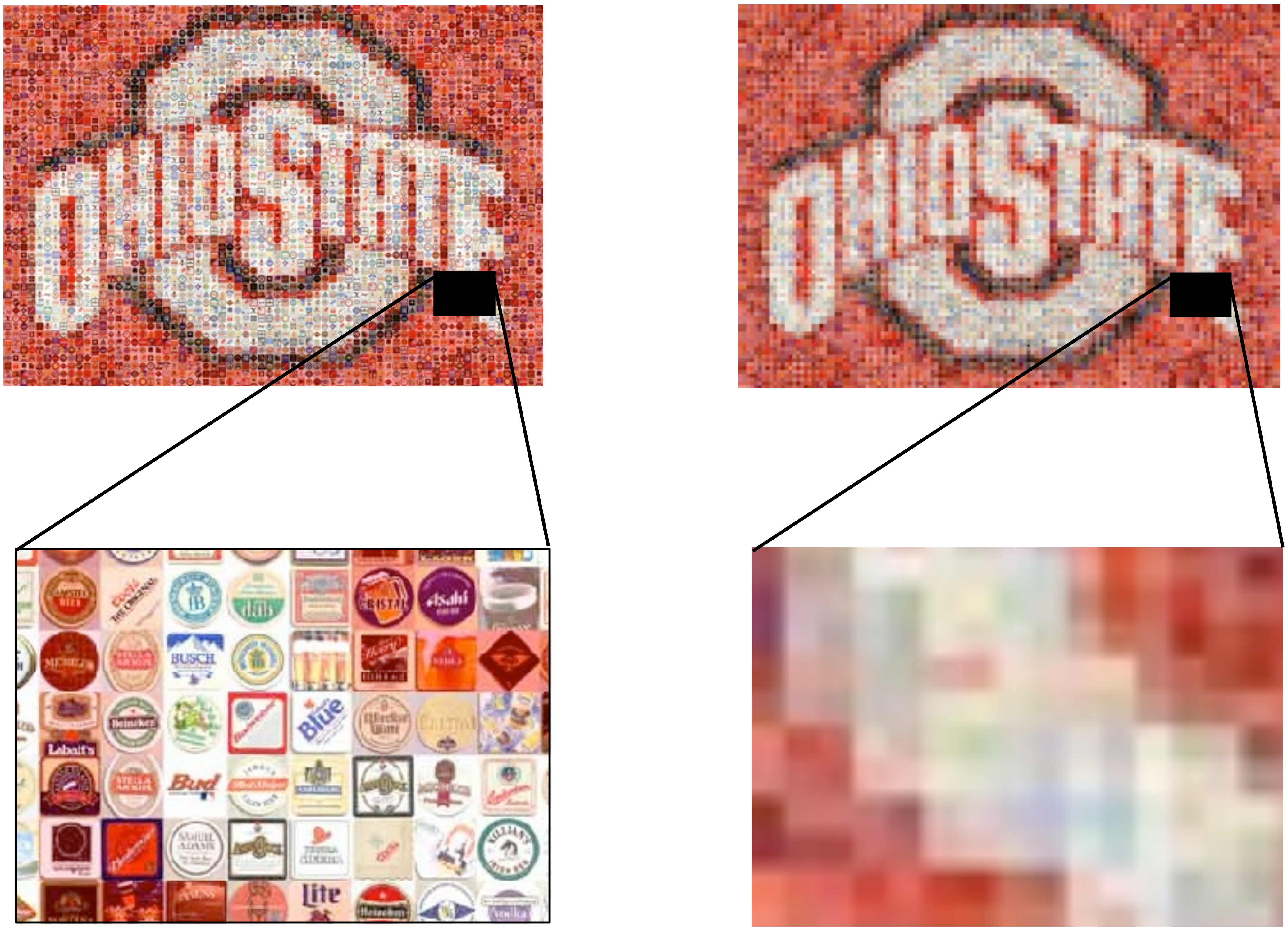
Hard core $\leftrightarrow$ Strong coupling between low and high momenta $\leftrightarrow$ High resolution

Do we really need such high resolution to compute properties of nuclei?

ρ , ω, σ masses > 700 MeV spatial distances < 0.5 fm cf. nucleon radius ~ 0.8 fm	$\leftrightarrow$	pion mass ~ 140 MeV av. nucleon momenta ~ 200 MeV	$\leftrightarrow$	observables ~ 0.1-10 MeV

➪ For many of the observables we are interested in, the answer is **NO**

Resolution scale of nucleon-nucleon interactions



[figures from K. Hebeler]

Effective field theory

⦿ The principles

[Weinberg, van Kolck, ..]

1990's

1. Use separation of scales to define d.o.f. & expansion parameter

   Typical momentum at play ← $\frac{Q}{M}$ → High energy scale (not included explicitly)

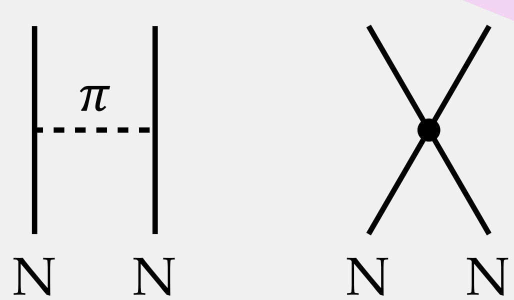
2. Write all possible terms allowed by symmetries of underlying theory (QCD)
3. Order by size all possible terms → **systematic** expansion (= "power counting")
4. Truncate at a given order and adjust coupling constants (use underlying theory or data)

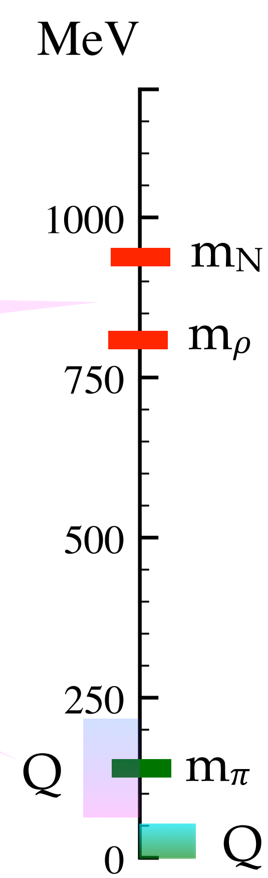
Chiral EFT

➪ Expand around Q ~ m_π

High-energy via contact interactions

Keep pion dynamic explicit

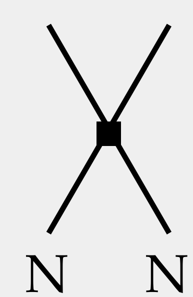




Pionless EFT

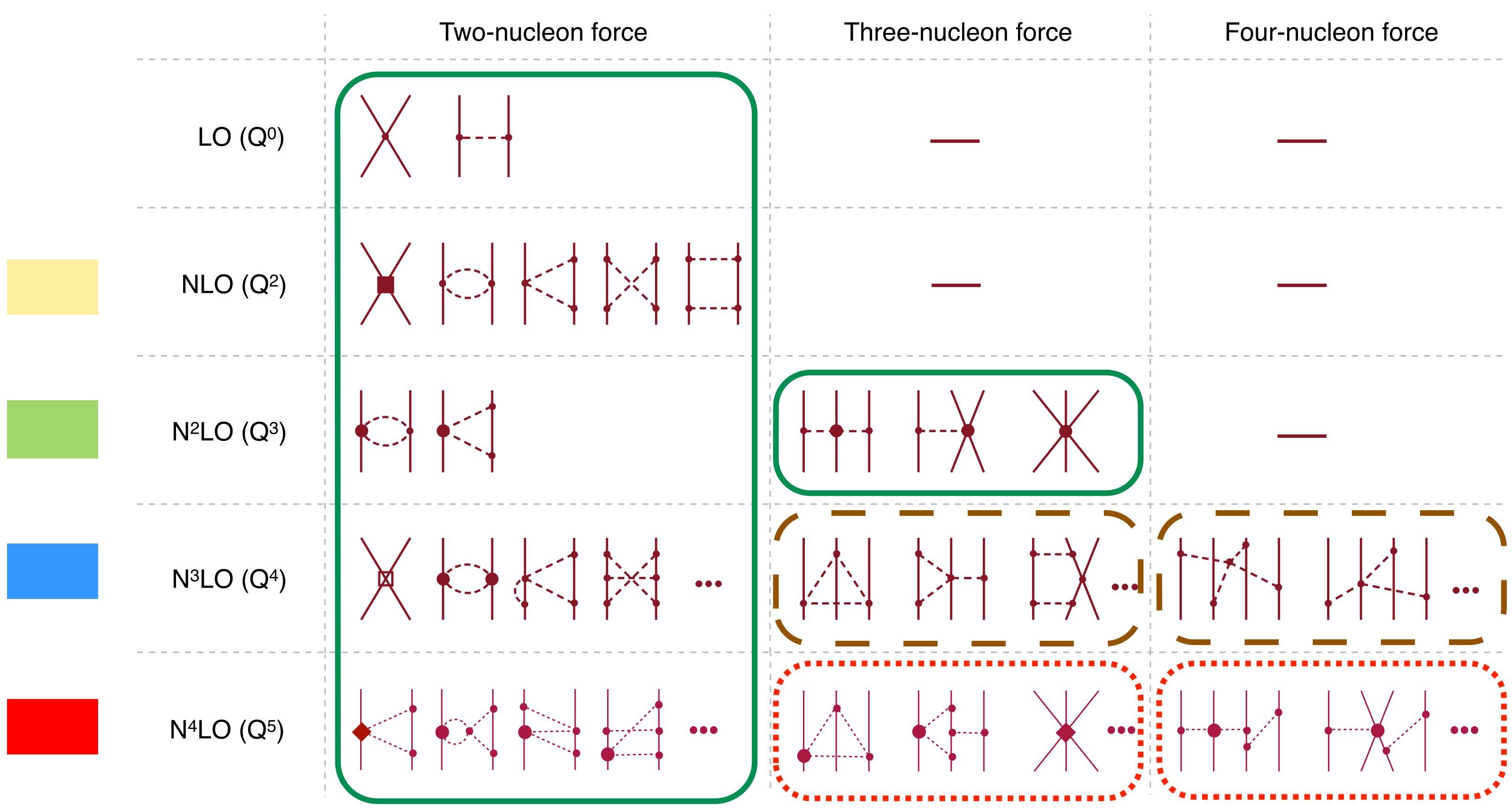
➪ Expand around Q ~ 0

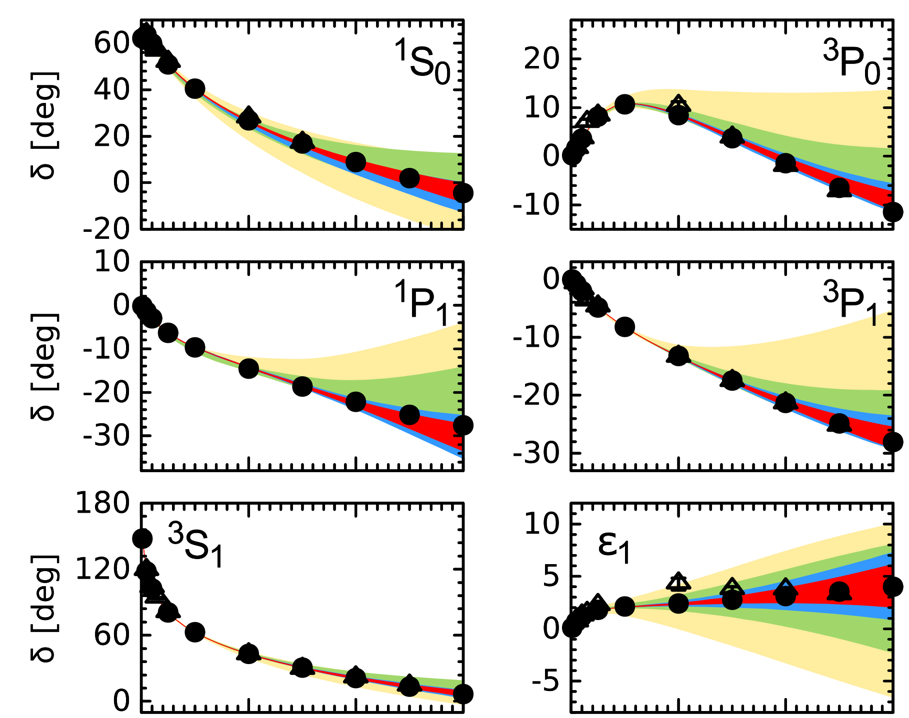
Integrate out pions too
→ only contact terms



Chiral effective field theory

- **Systematic** framework to construct AN interactions (A=2, 3, …)
- A **theoretical error** can be assigned to each order in the expansion





[Meißner 2016]

- Is the chiral expansion **converging** quickly enough?
- Goal: apply to the many-nucleon system (and propagate the theoretical error!)