EFFECTIVE FIELD THEORY for FEW-NUCLEON SYSTEMS

FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Bira van Kolck

cnrs

THE UNIVERSITY OF ARIZONA

Outline

- Effective field theories
- Pionless EFT
- Light nuclei
- Not-so-light nuclei
- Where is QCD?
- Conclusion

Effective Field Theories

Weinberg '90'91
Ordóñez + vK '92
...

a systematic description of the Standard Model
and its extensions in processes with typical momentum

$$Q \lesssim M_{QCD} \sim 1\ \mathrm{GeV}$$

"Folk Theorem" Weinberg '79

The quantum field theory generated by the most general Lagrangian with some assumed symmetries will produce the most general S matrix incorporating quantum mechanics, Lorentz invariance, unitarity, cluster decomposition and those symmetries, with no further physical content.

phenomenology
(experiment vs models)

- effective degrees of freedom
- symmetries

more generally: $M_{QCD} \rightarrow M_{hi}$ breakdown scale

Crucial elements

Gell-Mann, Low '54
...
Wilson '70
...

renormalization loops $\overset{\Lambda}{\longleftrightarrow}$ bare parameters

power counting what remains $\begin{cases} Q \sim M_{\mathrm{lo}} & \text{low-energy scales} \\ \text{finite parameters} \end{cases}$

"NATURALNESS" 't Hooft '79 Veltman '80

estimated with $\Lambda \to M_{\mathrm{hi}}$

pert th: naturalness → NDA
nonpert th: not

$$\Rightarrow \quad S^{(\bar{\nu})}(Q \sim M_{\mathrm{lo}} \ll M_{\mathrm{hi}}) - 1 \propto \sum_{\nu=0}^{\bar{\nu}} \left[\frac{Q}{M_{\mathrm{hi}}}\right]^{\nu} F^{(\nu)}\left(\frac{Q}{M_{\mathrm{lo}}}\right) \times \left\{1 + \mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{\mathrm{hi}}^{\bar{\nu}+1}}, \frac{Q^{\bar{\nu}+1}}{M_{\mathrm{hi}}^{\bar{\nu}}\Lambda}\right)\right\}$$

S Matrix at $\mathrm{N}^{\bar{\nu}}\mathrm{LO}$

SYSTEMATIC EXPANSION

CALCULABLE FUNCTIONS

CONTROLLED UNCERTAINTY

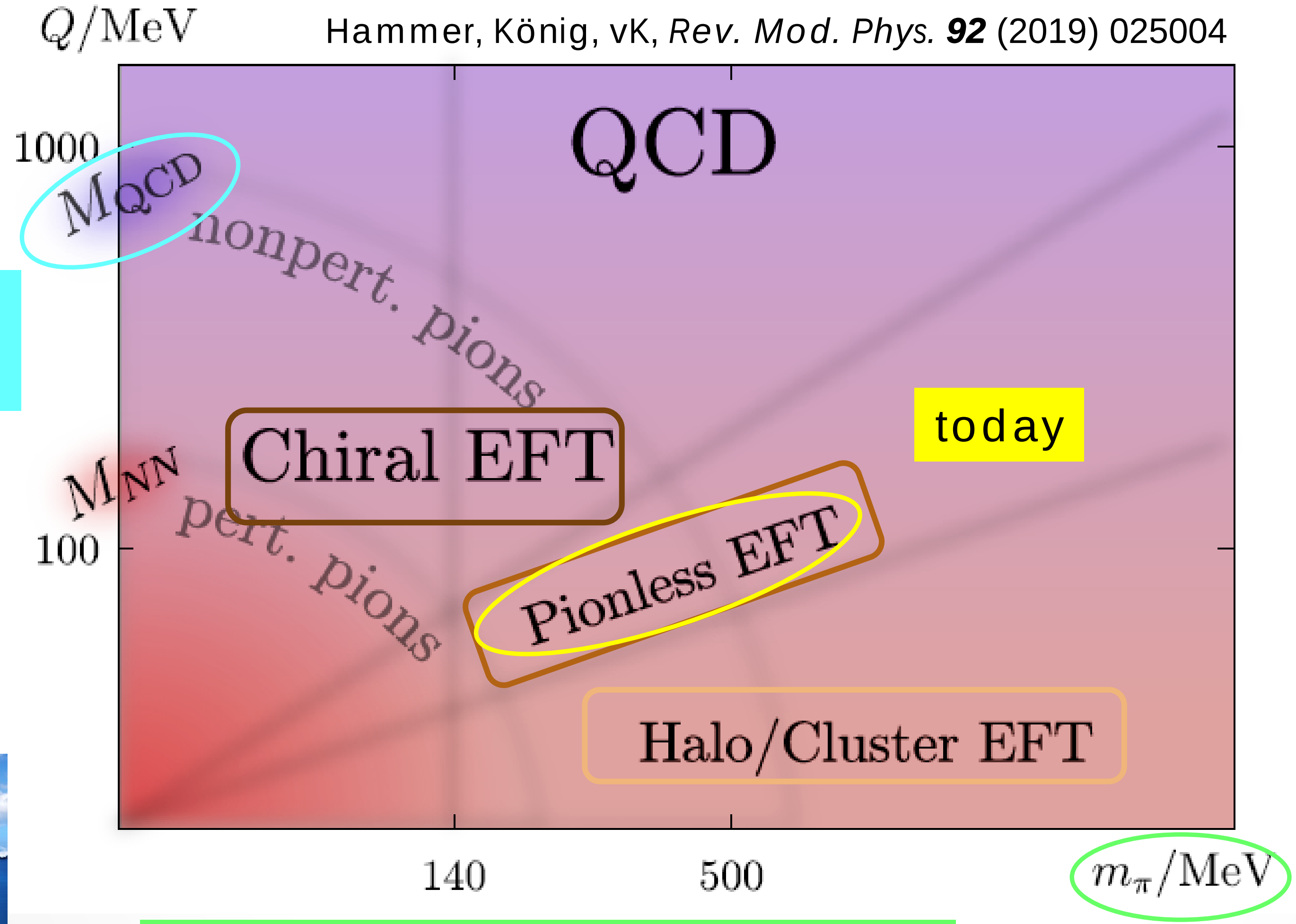
MODEL INDEPENDENCE

$\Lambda \gtrsim M_{\mathrm{hi}}$

Nuclear Effective Field Theories

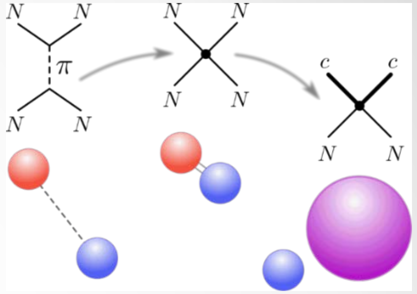
typical momentum

chiral-symmetric QCD scale



chiral-symmetry breaking scale

pion mass



$M_{\rm lo} \sim m_\pi, m_\Delta - m_N, \ldots$

- nucleons, pions, Deltas, …
- softly broken χ symmetry

$M_{\rm lo} \sim \sqrt{2m_N B_t/3}, \ldots$

- nucleons
- softly broken isospin

$M_{\rm lo} \sim \sqrt{\mu_{Nc}\left(B_{Nc} - B_c\right)}, \ldots$

- nucleons, alpha particles, …
- no flavor symmetry

Nuclear effective field theory: status and perspectives

H.-W. Hammer*

Institut für Kernphysik,
Technische Universität Darmstadt,
64289 Darmstadt,
Germany
ExtreMe Matter Institute EMMI,
GSI Helmholtzzentrum für Schwerionenforschung GmbH,
64291 Darmstadt,
Germany

Sebastian König†

Institut für Kernphysik,
Technische Universität Darmstadt,
64289 Darmstadt,
Germany
ExtreMe Matter Institute EMMI,
GSI Helmholtzzentrum für Schwerionenforschung GmbH,
64291 Darmstadt,
Germany
Department of Physics,
The Ohio State University,
Columbus, Ohio 43210,
USA
Department of Physics,
North Carolina State University,
Raleigh, NC 27695,
USA

U. van Kolck‡

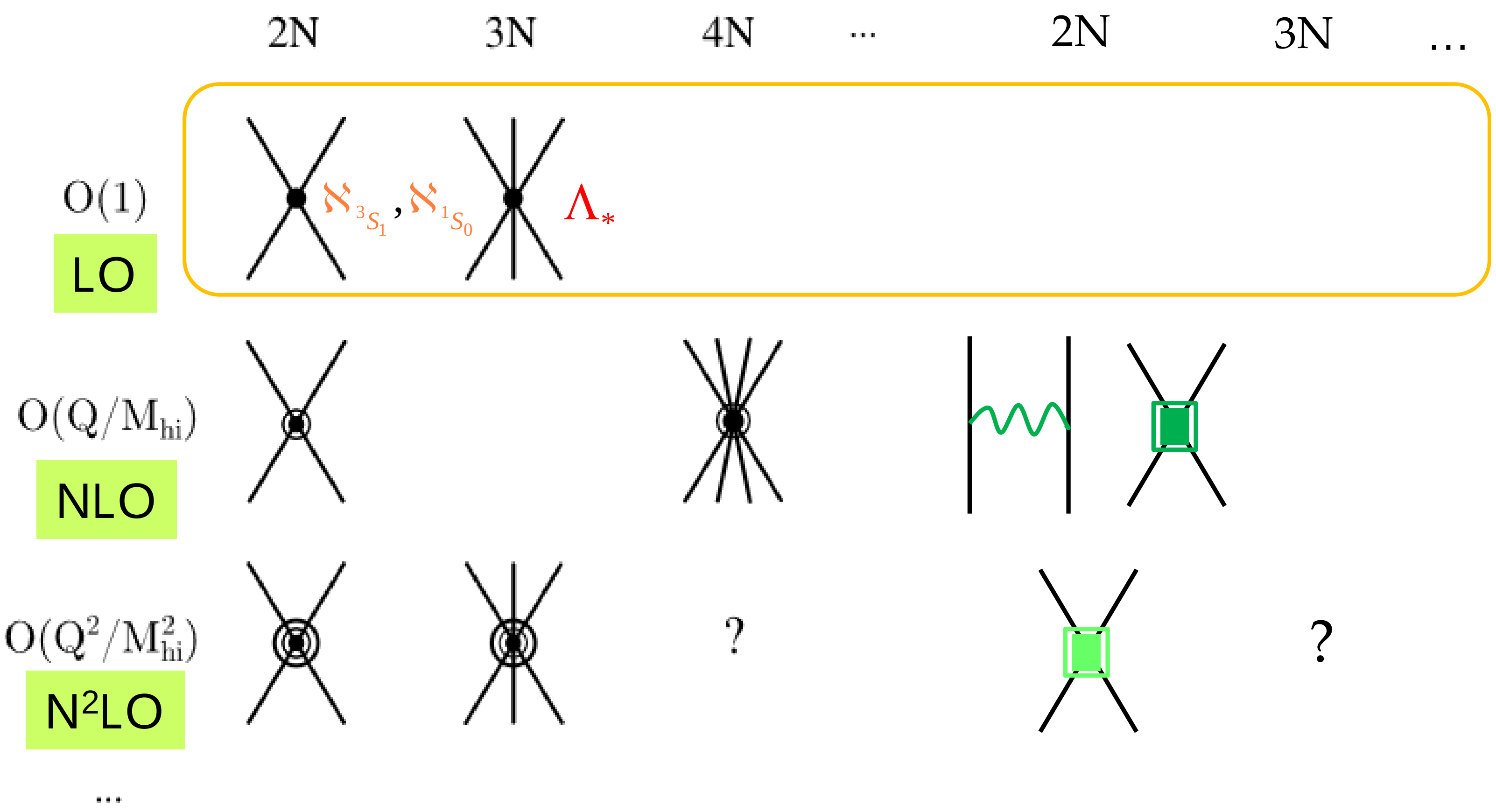
Institut de Physique Nucléaire,
CNRS/IN2P3, Université Paris-Sud,
Université Paris-Saclay, 91406 Orsay,
France
Department of Physics,
University of Arizona,
Tucson, AZ 85721,
USA

(Dated: July 1, 2019)

The nuclear physics landscape has been redesigned as a sequence of effective field theories (EFTs) connected to the Standard Model through symmetries and lattice simulations of Quantum Chromodynamics (QCD). EFTs in this sequence are expansions around different low-energy limits of QCD, each with its own characteristics, scales, and ranges of applicability regarding energy and number of nucleons. We review each of the three main nuclear EFTs—Chiral, Pionless, Halo/Cluster—highlighting their similarities, differences, and connections. In doing so, we survey the structural properties and reactions of nuclei that have been derived from the *ab initio* solution of the few- and many-body problem built upon EFT input.

Pionless EFT

interactions isospin-symmetric isospin-violating



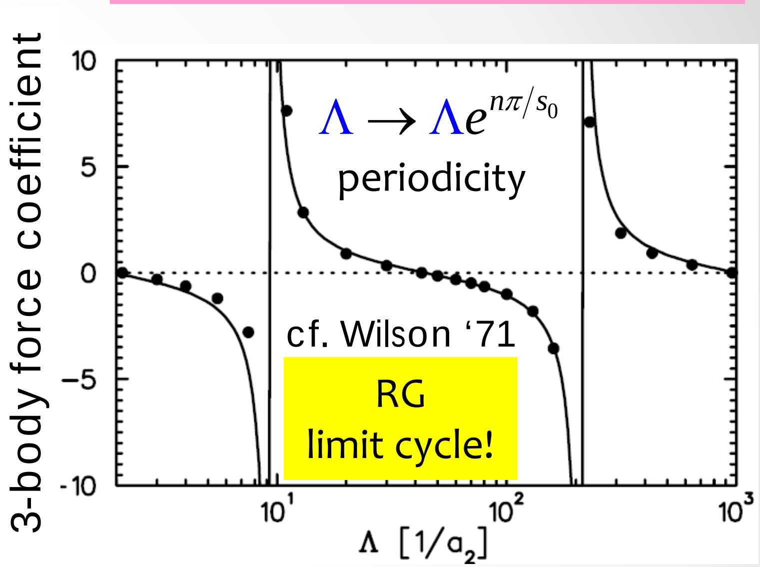
vK '97'99
Kaplan, Savage, Wise '98
...

Bedaque, Hammer, vK '99'00
...

Bazak, Kirscher, König, Pavón, Barnea, vK '19
...

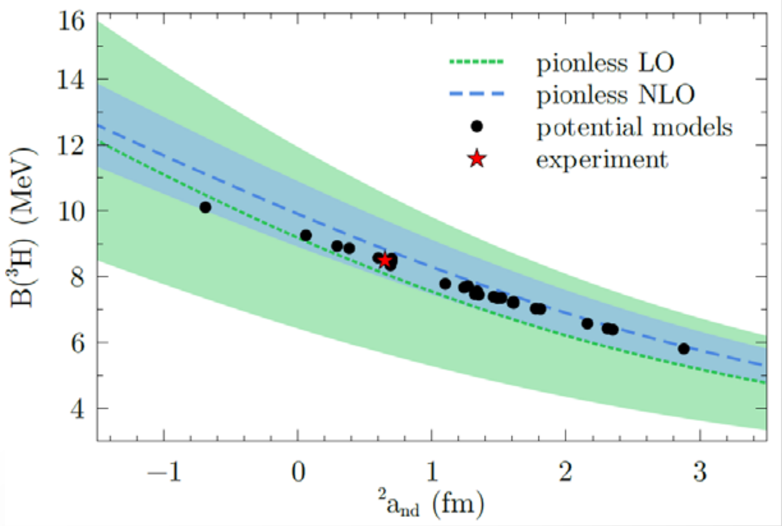
König, Grießhammer, Hammer, vK '16
...

discrete scale invariance!



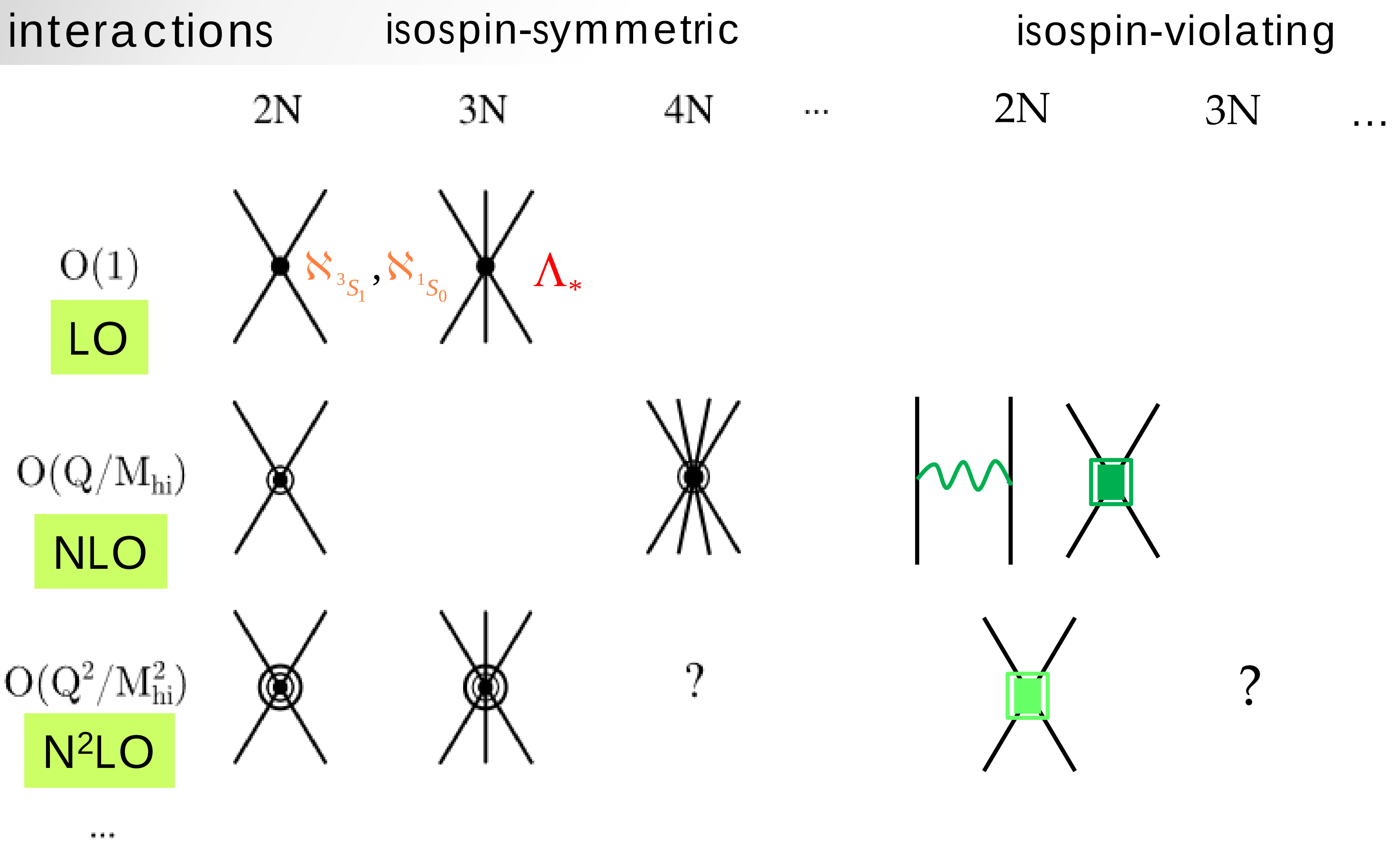
Bedaque, Hammer, vK, *Phys. Rev. Lett.* 82 (1999) 463

position of the cycle:
one parameter Λ_*
→ correlations, e.g.



Hammer, König, vK, *Rev. Mod. Phys.* 92 (2020) 025004

Pionless EFT



vK '97'99
Kaplan, Savage,
Wise '98
...

Bedaque,
Hammer,
vK '99'00
...

Bazak, Kirscher,
König, Pavón,
Barnea, vK '19
...

König,
Grießhammer,
Hammer, vK '16
...

discrete scale invariance!

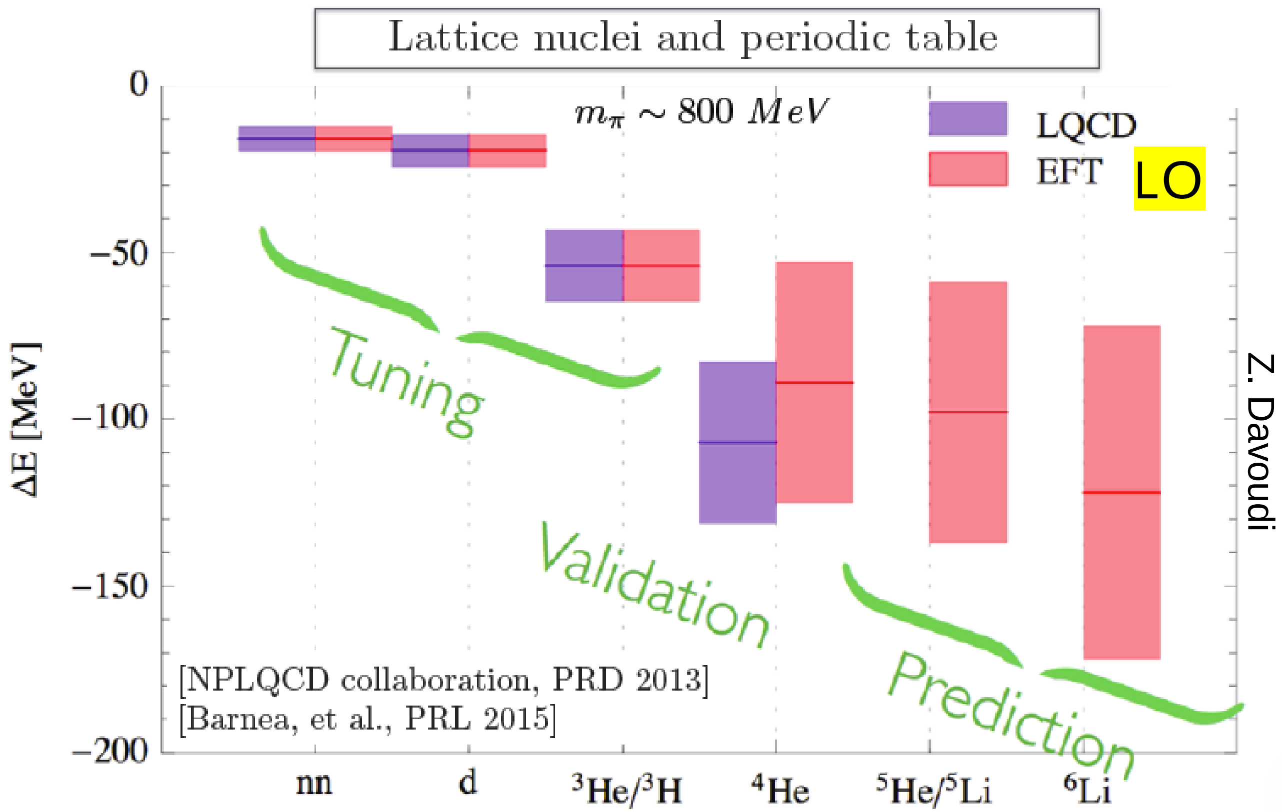
distorted-wave perturbation theory

Unphysical quark masses

three parameters at LO: $\Lambda_*, \aleph_{^3S_1}, \aleph_{^1S_0}$

Barnea, Contessi, Gazit, Pederiva + vK '15
Kirscher, Barnea, Gazit, Pederiva + vK '15
Contessi, Lovato, Pederiva, Roggero, Kirscher + vK '17
Bansal *et al.* '18

Matching to QCD



Proof of principle for extending QCD to larger nuclei

For NPLQCD input (however…),
qualitatively similar to physical pion mass,
just more bound by a factor ~5

see Parreño's talk

Physical quark masses (near two-body unitarity)

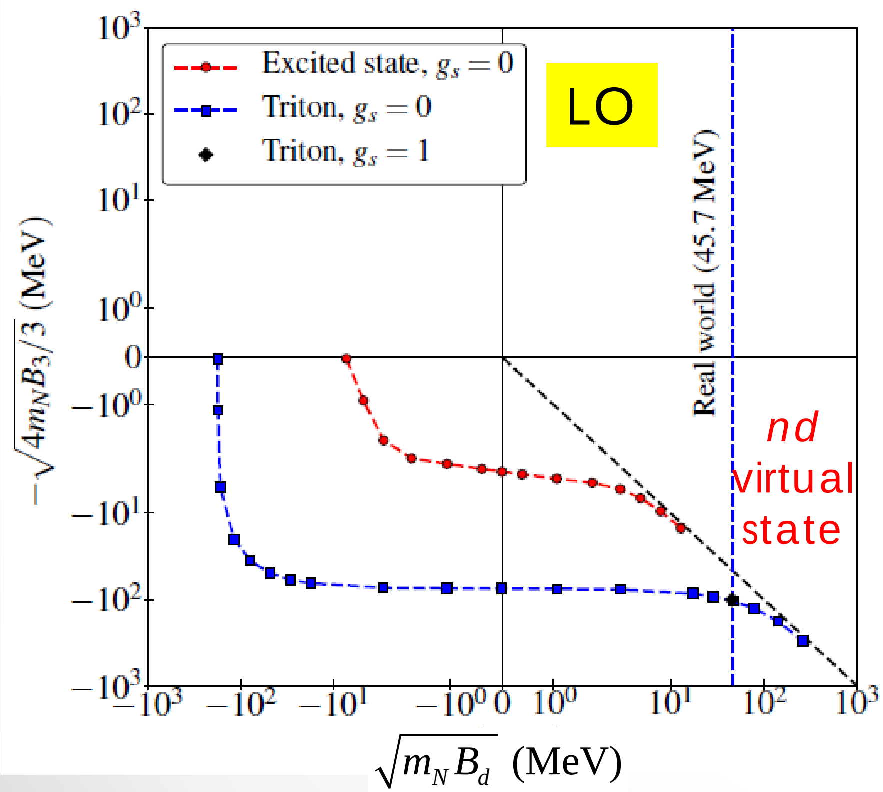
one parameter at LO: Λ_*

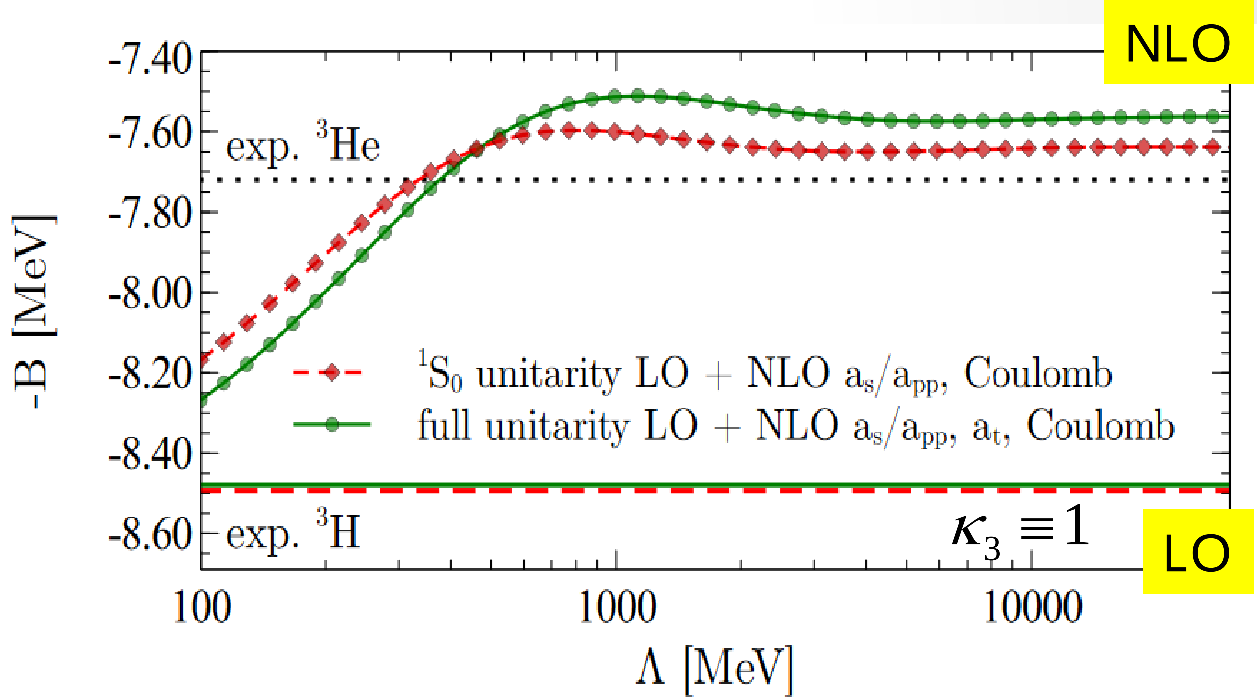
discrete scale invariance

- geometric towers of states (Efimov ’71, Hammer + Platter ’07, …)
- ground states: $$\frac{B_A^{(0)}(\Lambda_*)}{A} = \kappa_A^{(0)} \frac{B_3(\Lambda_*)}{3}$$

universal numbers for four-component fermions

$A = 3$





Rupak, Vaghani, Higa, vK, *Phys. Lett. B* **791** (2019) 414

König, Grießhammer, Hammer, vK, *Phys. Rev. Lett.* **118** (2017) 202501

König, Grießhammer, Hammer + vK ’17
…

Physical quark masses (near two-body unitarity)

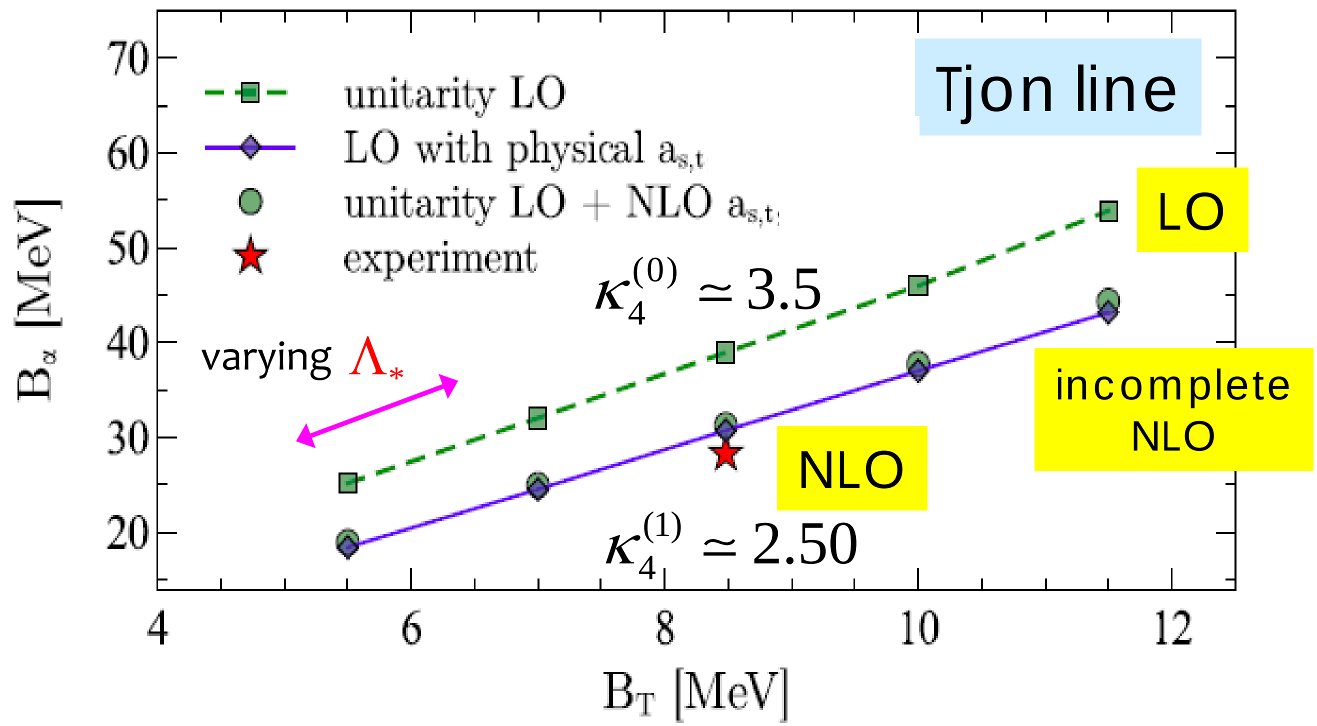
one parameter at LO: Λ_*

discrete scale invariance

- geometric towers of states (Efimov ’71, Hammer + Platter ’07, …)
- ground states: $\dfrac{B_A^{(0)}(\Lambda_*)}{A} = \kappa_A^{(0)} \dfrac{B_3(\Lambda_*)}{3}$

universal numbers for four-component fermions

$A = 4$



alpha-particle first excited state

$$\frac{B_{\alpha^*}^{(0)}(\Lambda_*)}{B_t(\Lambda_*)} \simeq 1.002 \quad \text{vs} \quad \frac{B_{\alpha^*}^{(\exp)}}{B_t^{(\exp)}} \simeq 0.96$$

Emergence of
light nuclear structure
from
two-body unitarity

König, Grießhammer, Hammer, vK, *Phys. Rev. Lett.* **118** (2017) 202501

Bosons at two-body unitarity

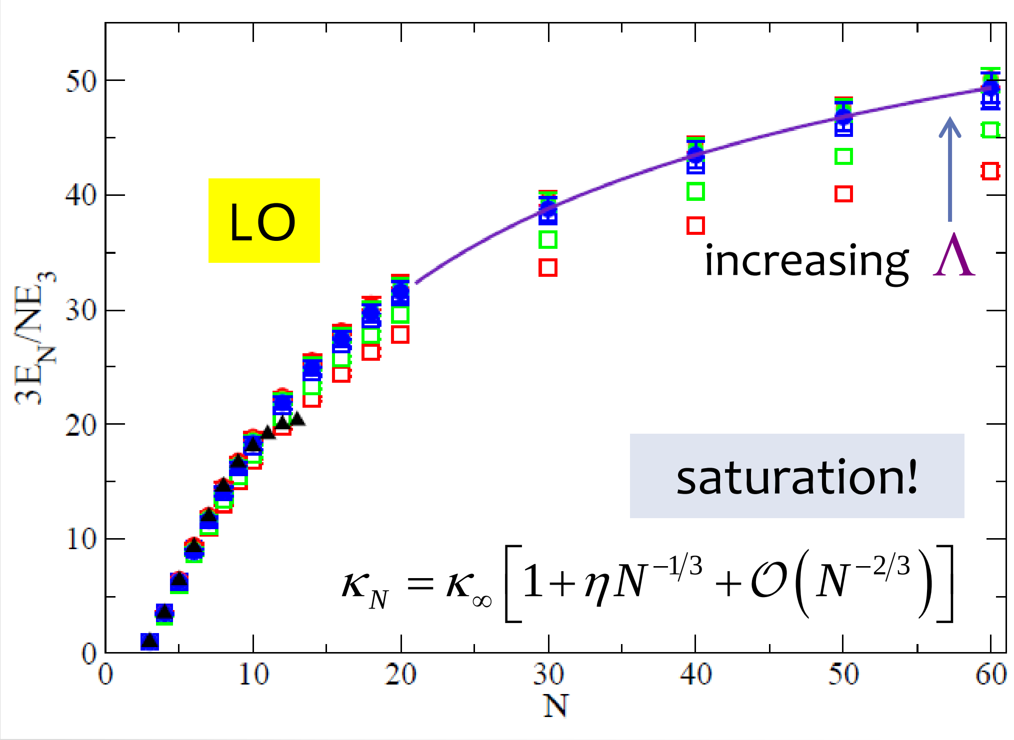
v Stecher '10
Nicholson '12
Gandolfi, Carlson, Vitiello + vK '17
...

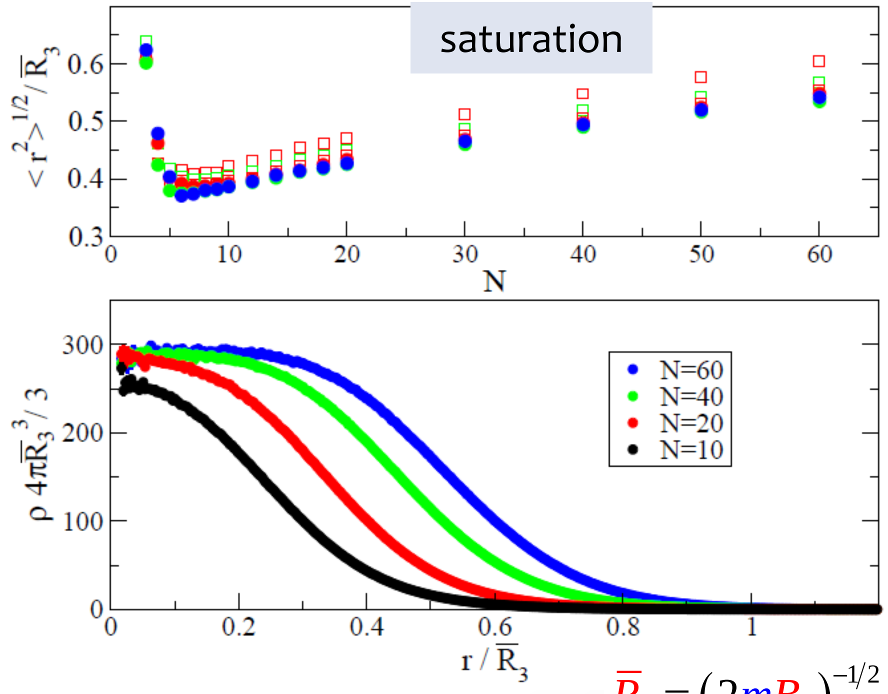
one parameter at LO: Λ_*

discrete scale invariance

- geometric towers of states (Efimov '71, Hammer + Platter '07, ...)
- ground states: $$\frac{B_A^{(0)}(\Lambda_*)}{A} = \kappa_A^{(0)} \frac{B_3(\Lambda_*)}{3}$$

universal numbers for *bosons*





$\overline{R}_3 \equiv \left(2mB_3\right)^{-1/2}$

Emergence of *quantum liquid* from two-body unitarity

Gandolfi, Carlson, Vitiello, vK, *Phys. Rev. Lett.* 119 (2017) 223002

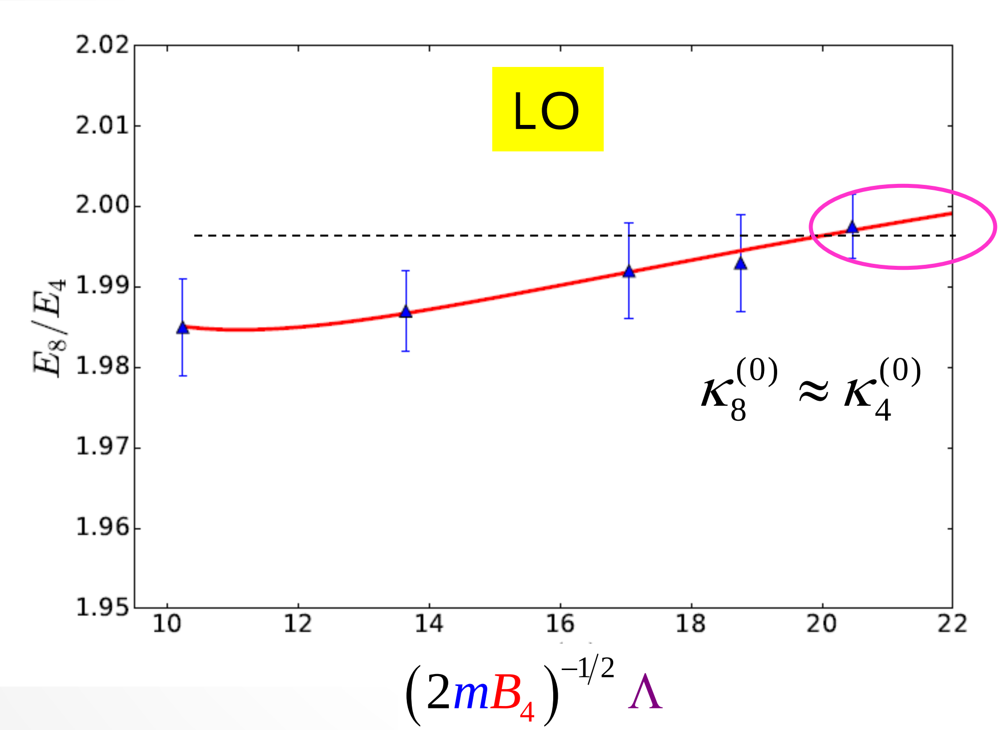
Physical quark masses (near two-body unitarity)

one parameter at LO: Λ_*

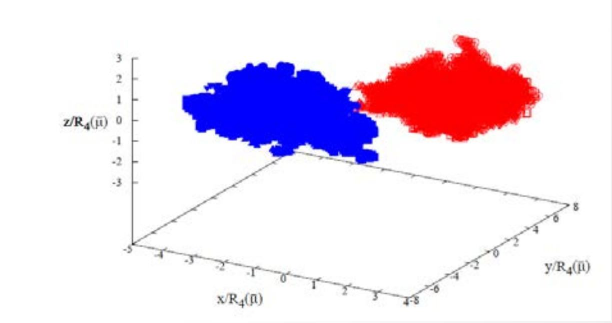
discrete scale invariance
- geometric towers of states (Efimov ’71, Hammer + Platter ’07, ...)
- ground states: $\dfrac{B_A^{(0)}(\Lambda_*)}{A} = \kappa_A^{(0)} \dfrac{B_3(\Lambda_*)}{3}$

universal numbers for four-component fermions

$A = 8$



consistent with ^{8}Be

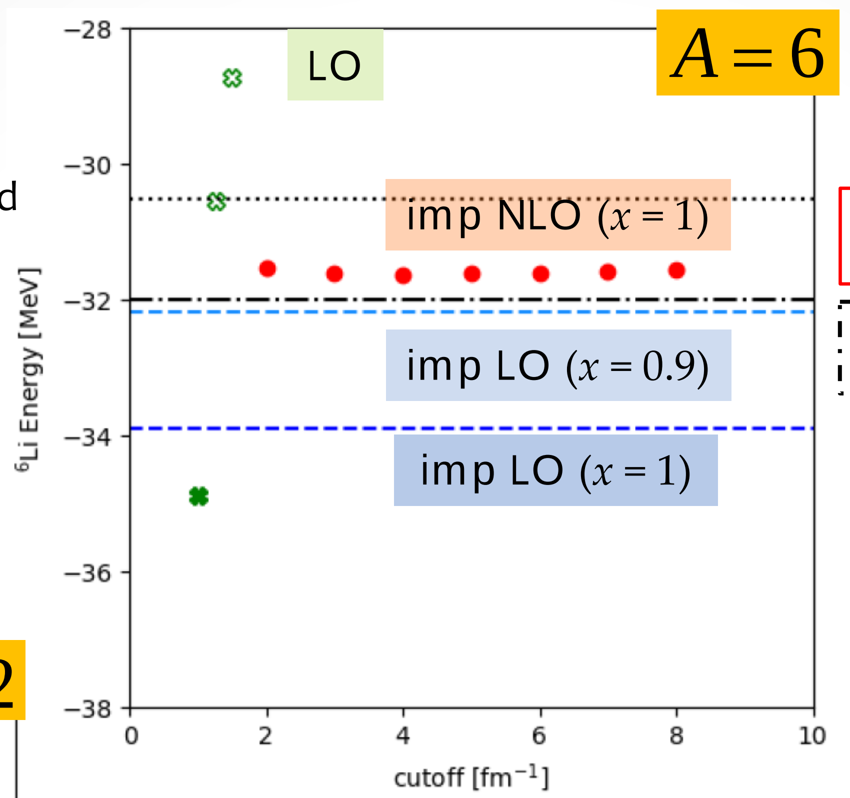


Emergence of *nuclear clustering* from two-body unitarity

Dawkins, Carlson, vK, Gezerlis, *Phys. Rev. Lett.* **124** (2020) 143402

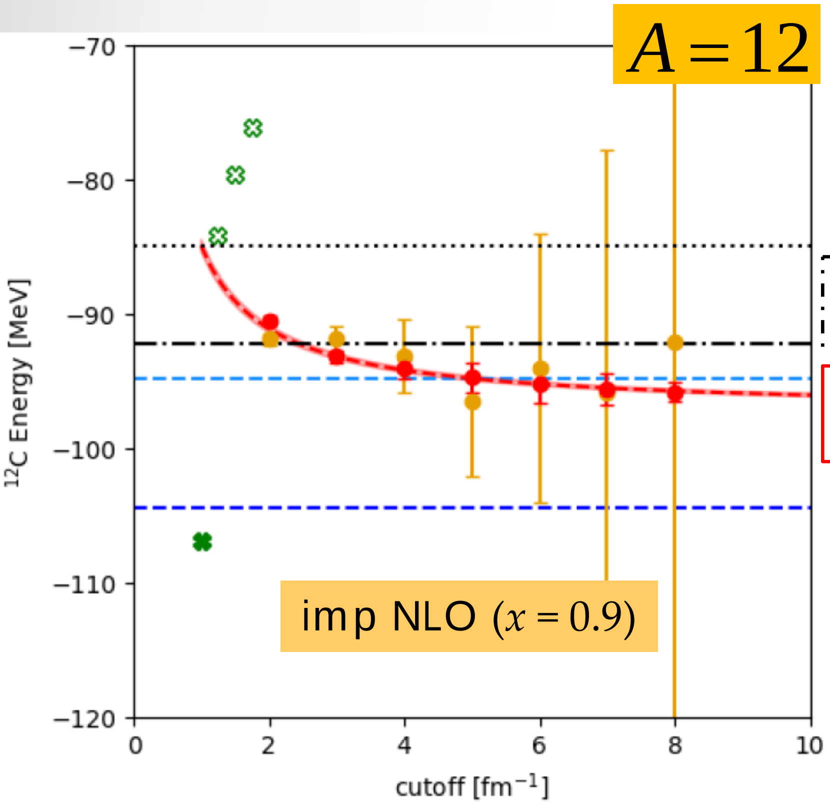
Contessi, Schäfer, Gnech, Lovato, vK,
arXiv:2505.09299

uncertainty
from residual
cutoff dependence
at NLO



$$E_6^{(1)} = -\left(31.57 \pm 0.02 \pm 0.3\right)\ \text{MeV}$$

$$E_6^{(\text{exp})} = -31.994\ \text{MeV}$$

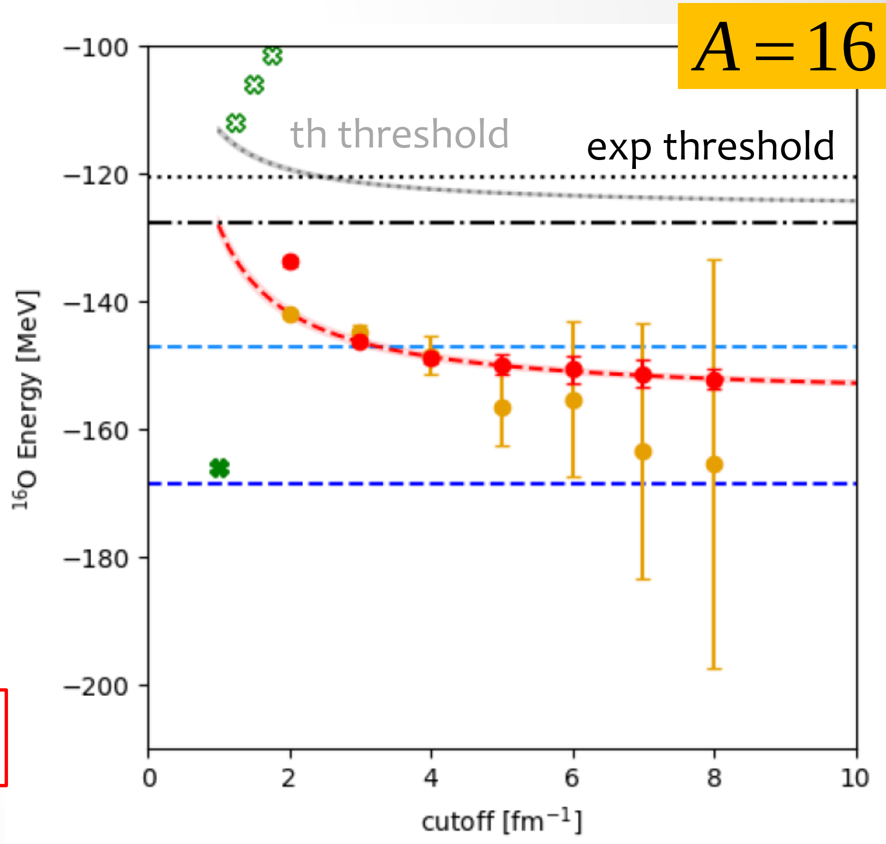


$$E_{12}^{(\text{exp})} = -92.162\ \text{MeV}$$

$$E_{12}^{(1)} = -\left(97.3 \pm 0.1 \pm 5\right)\ \text{MeV}$$

$$E_{16}^{(\text{exp})} = -127.619\ \text{MeV}$$

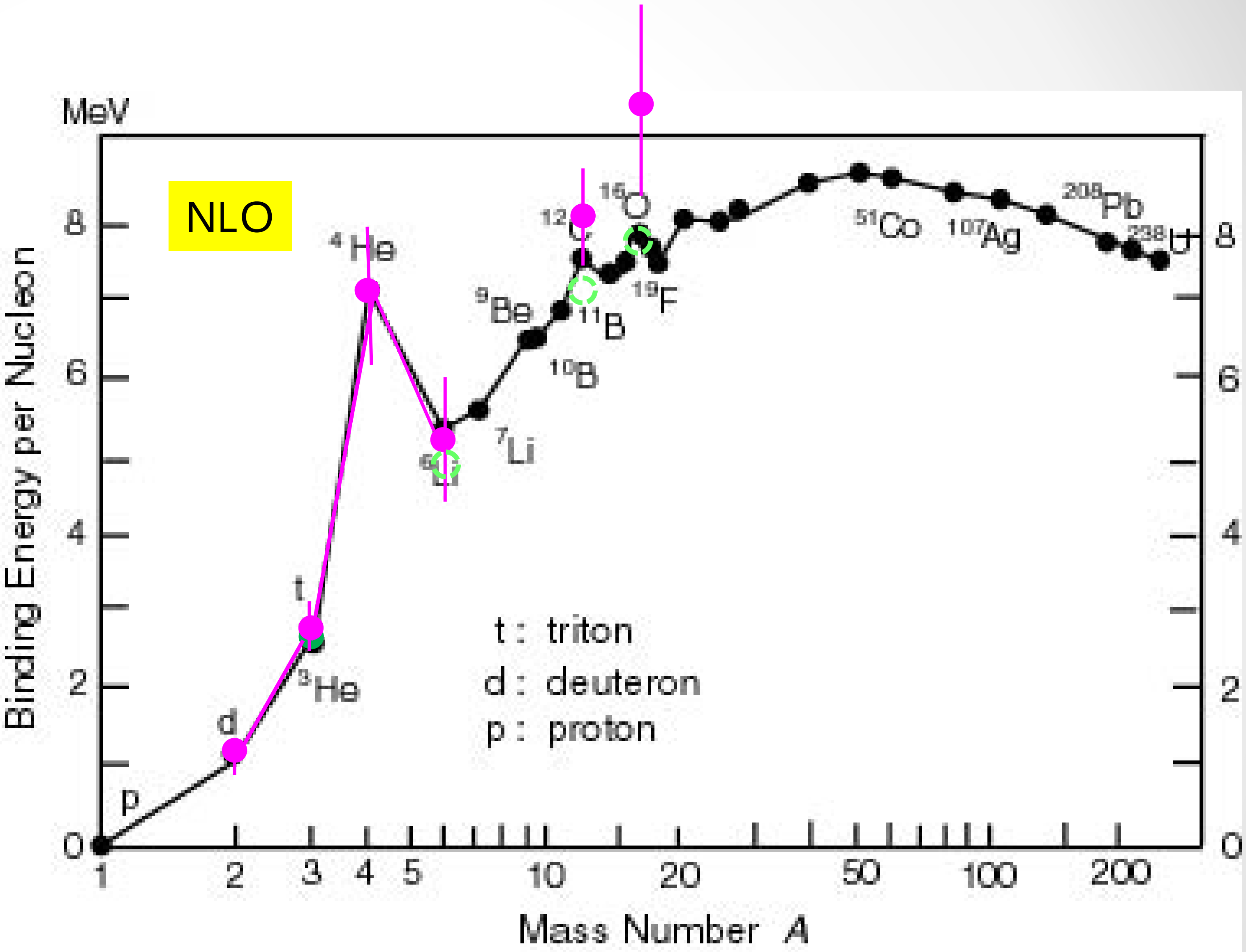
$$E_{16}^{(1)} = -\left(155.6 \pm 0.3 \pm 20\right)\ \text{MeV}$$



Summary

$$\frac{3B_A^{(1)}(\Lambda_*,\ldots)}{AB_3(\Lambda_*)} \equiv \kappa_A^{(1)}(\ldots)$$

A	$\kappa_A^{(1)}$	$\kappa_A^{(\mathrm{exp})}$
4	2.50	2.50
6	1.86	1.89
12	2.9	2.72
16	3.5	2.81



https://ne.phys.kyushu-u.ac.jp/seminar/MicroWorld3_E/3Part3_E/3P34_E/nuclear_fusion_E.htm

www.environmental-finance.com/

nuclear structure from one essential, three-body parameter!?

External probes

→ Electroweak form factors

Chen, Rupak, Savage '99
Phillips, Rupak, Savage '00
...

→ Radiative capture/fusion

Chen, Rupak, Savage '99
Kong, Ravndal '99
...

→ Photo/electrodisintegration

Christlmeier, Grießhammer '08
Ryezawa *et al.* '08
...

→ Compton scattering

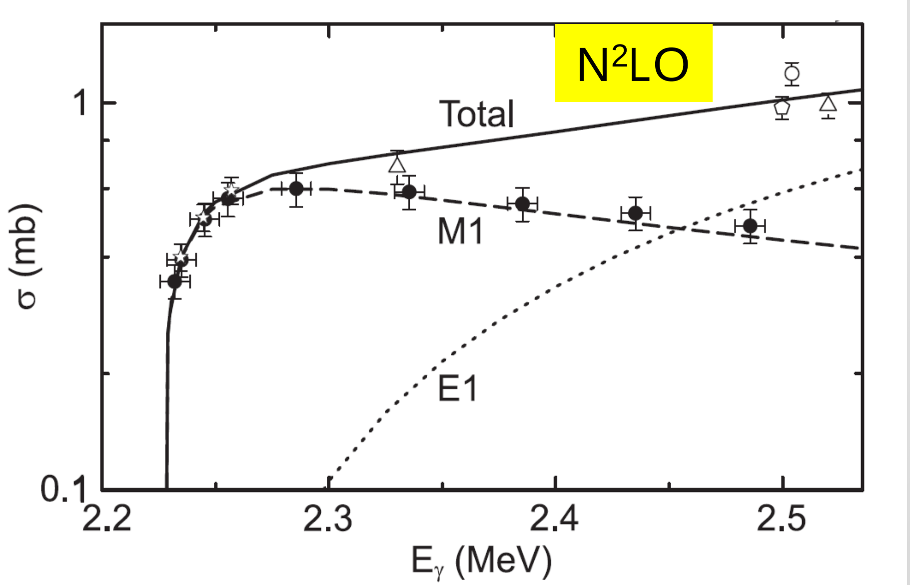
Grießhammer, Rupak '02
...

→ Neutrino scattering

Butler, Chen '00
...

→ *etc.*

Example
Deuteron electrodisintegration

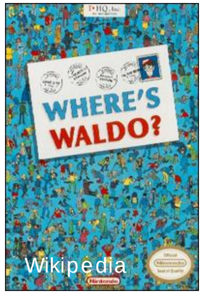


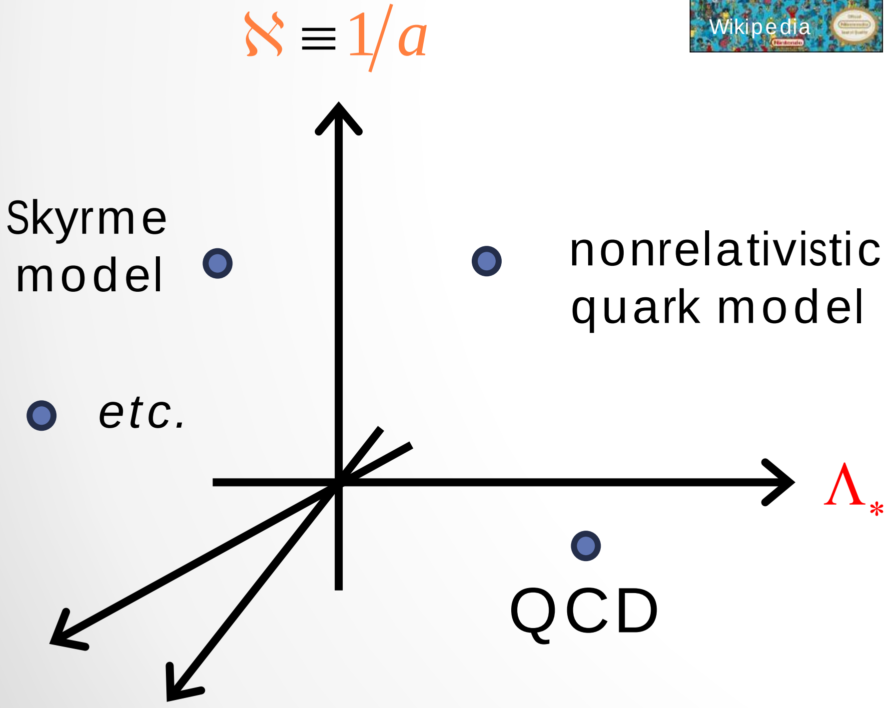
Ryezayeva *et al.*, *Phys. Rev. Lett.* **100** (2008) 172501

Universality but no chiral symmetry…

Where is QCD?

space of
EFT coefficients





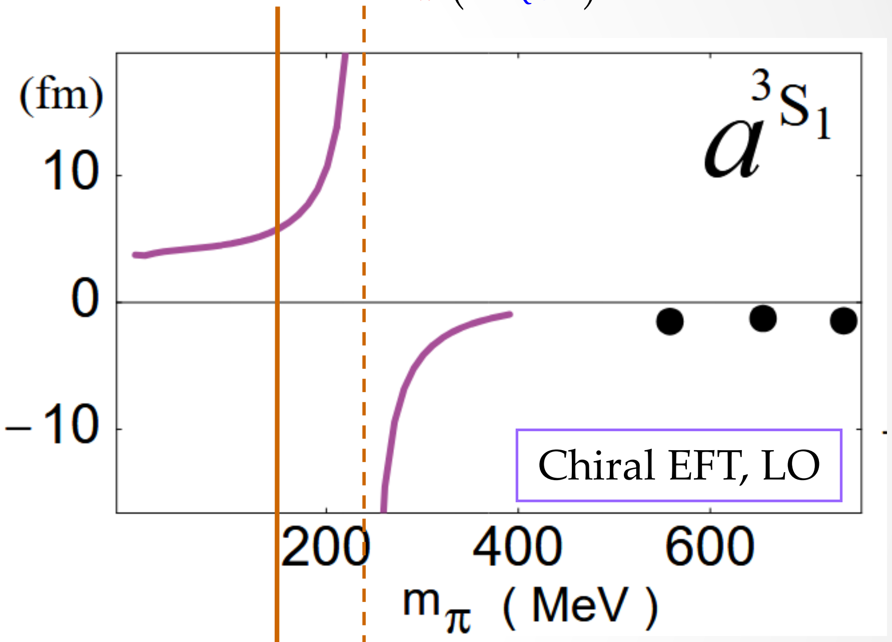
Unitarity: how?

Beane, Bedaque, Savage + vK '02
Beane + Savage '03
Epelbaum + Meißner '03
…

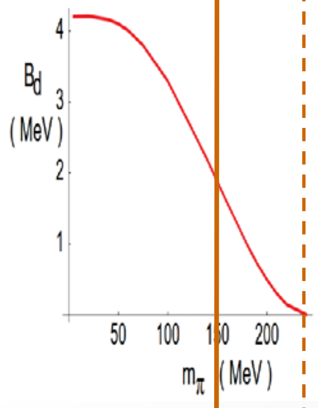
real world
$m_\pi \simeq 140$ MeV

unitarity limit $|a| \to \infty$
$m_\pi^*(M_{QCD})$

A conjecture



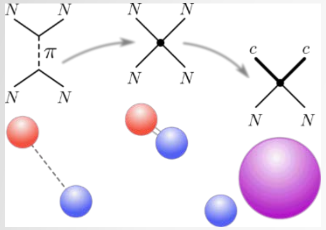
deuteron
binding
energy



analogous to
Feshbach
resonance
$B \to m_\pi$

Beane, Bedaque, Savage, vK, Nucl. *Phys.* A **700** (2002) 377

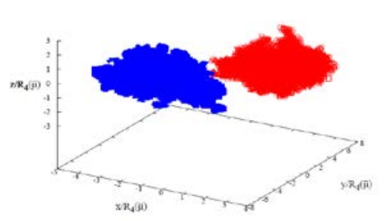
Conclusion



Several **nuclear EFTs** of QCD have been formulated

Systems at unitarity are **discrete-scale invariant** and depend on essentially *one* (**three-body!**) parameter

Bosons saturate and form a **quantum liquid**



Multi-component fermions tend to **cluster**

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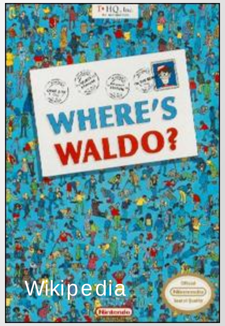
Light-medium **binding energies** are within ~15% of experiment at NLO

More observables? Heavier nuclei? Higher orders?



Origin of two-body unitarity in QCD?