Pionless EFT

- -

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2024: still talking about contact theories

QCD

Pionless EFT

χEFT

…

Cluster EFT

Realistic ab initio interactions

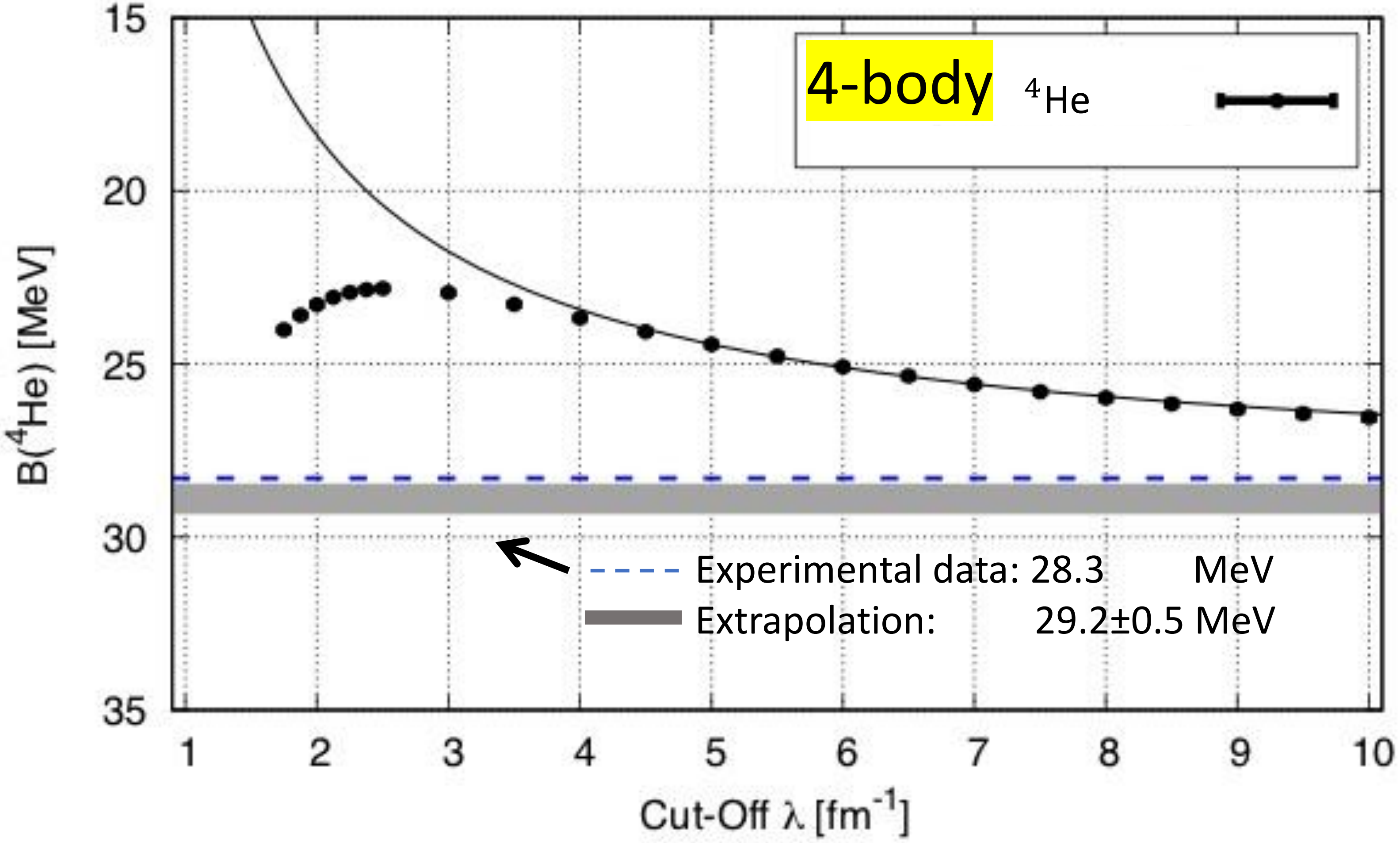
Which theory is best for my system?

How to connect different theories?

Why pionless EFT ?

- It has *clear* momentum limitations
- “Simple”
- Connected with universality
- Most of the conclusions I will do here can be translated in other EFTs

Good 2-, 3-body, and 4 body …



L. C., N. Barnea, and A. Gal Phys. Rev. Lett. 121, 102502

2-body

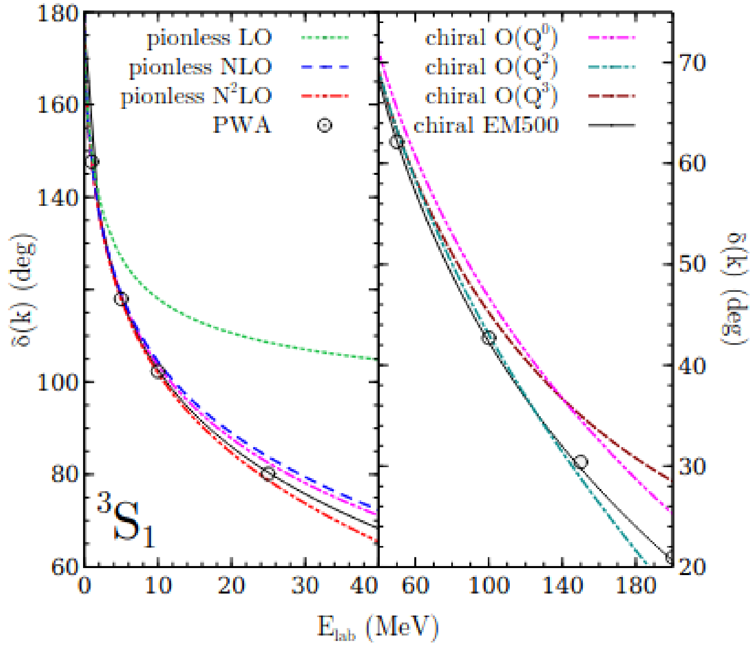
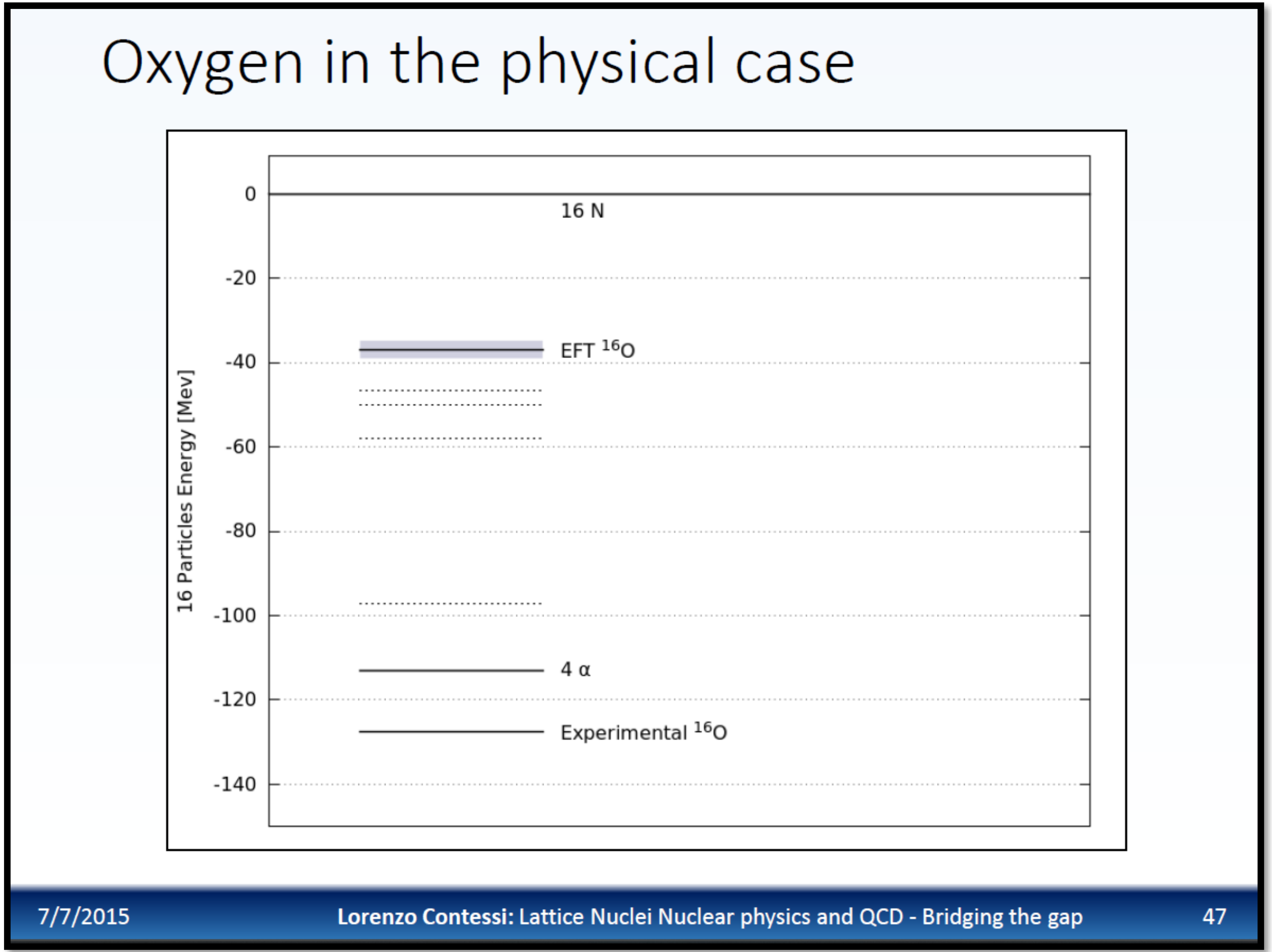
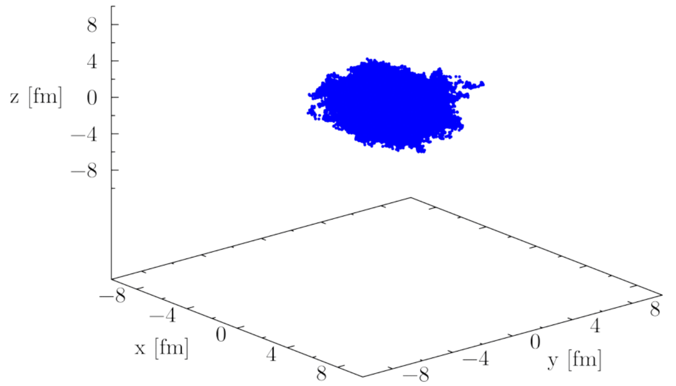


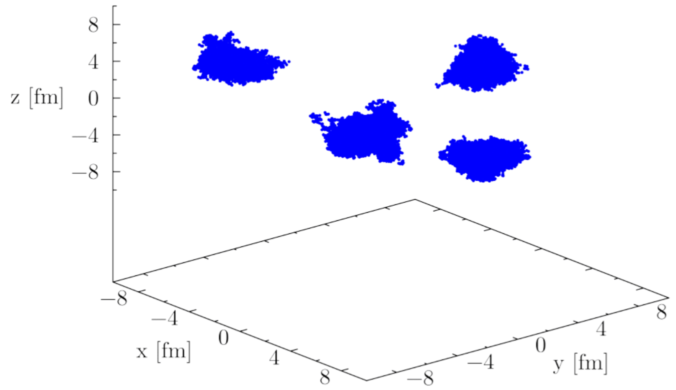
Figure 7 The *NN* scattering phase shift δ as a function of the nucleon laboratory energy $E_{\rm lab}$ in the $^3S_1$ partial wave for Pionless EFT and Chiral EFT at various orders (Long and Yang, 2012a) (results kindly provided by C.-J. Yang), and the chiral potential "EM500" (Entem and Machleidt, 2003). For comparison we show the partial-wave analysis (PWA) of Navarro Pérez *et al.* (2013), with error bars smaller than the symbols.

My first talk here (ECT* - 2015)





$\lambda = 2\ \mathrm{fm}^{-1}$



$\lambda = 8\ \mathrm{fm}^{-1}$

Stetcu, B. R. Barrett, U. van Kolck, Phys.Lett.B653:358-362 (2007)
W. G. Dawkins, J. Carlson, U. van Kolck, A. Gezerlis (2020)
M. Schäfer, L. Contessi, J. Kirscher, J. Mareš PLB 816 (2021)

5He 6He

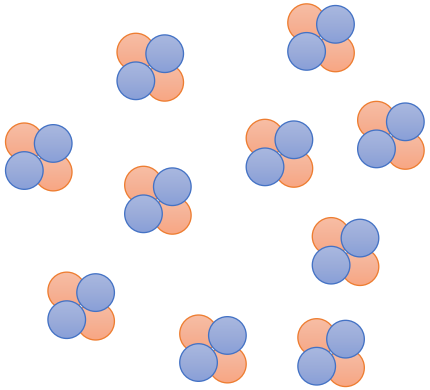
J. Kirscher, H. W. Grießhammer, D. Shukla, H. M. Hofmann: arXiv:0909.5606

Breaks in $\alpha + n$ and $\alpha + n + n$

40Ca

QMC calculation suggests the breaking in:

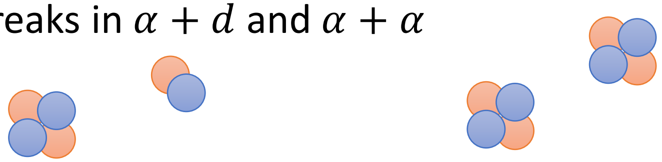
Breaks in $\alpha + \alpha + \alpha +$ …

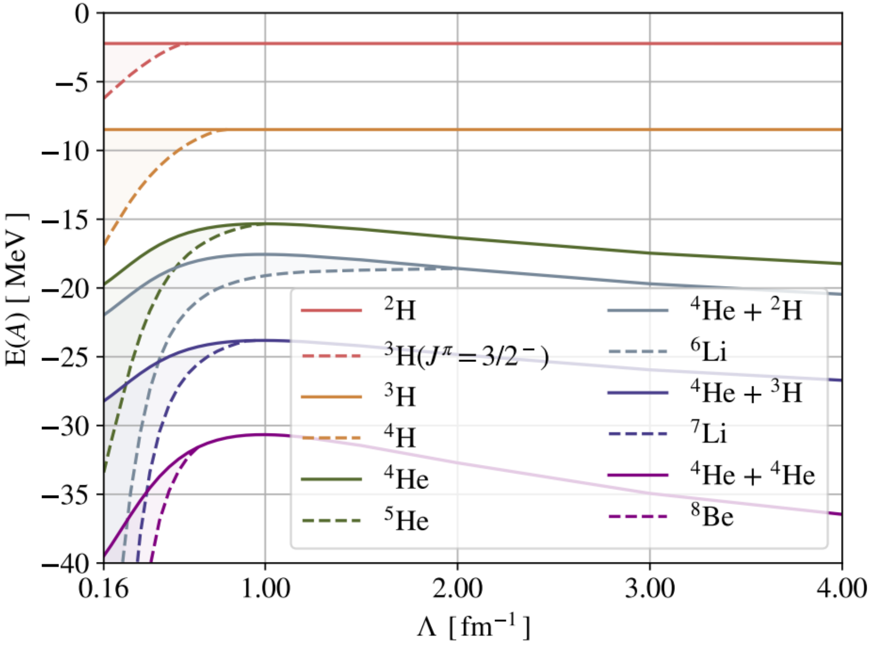


7Li 8Be

W. G. Dawkins (2020)
Our calculations in SU(4) symmetry

Breaks in $\alpha + d$ and $\alpha + \alpha$

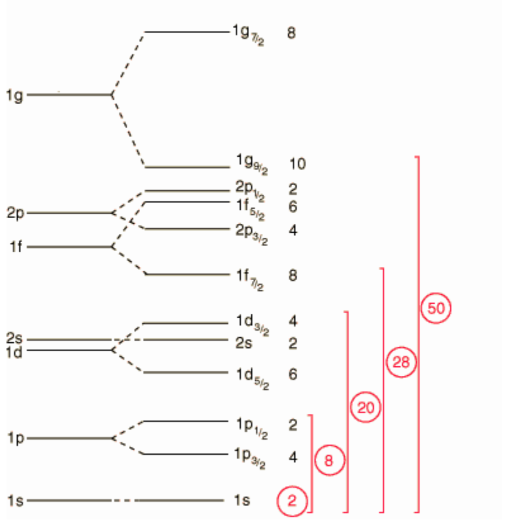




P-wave systems

In a shell model representation

Relation between shell model and magic numbers

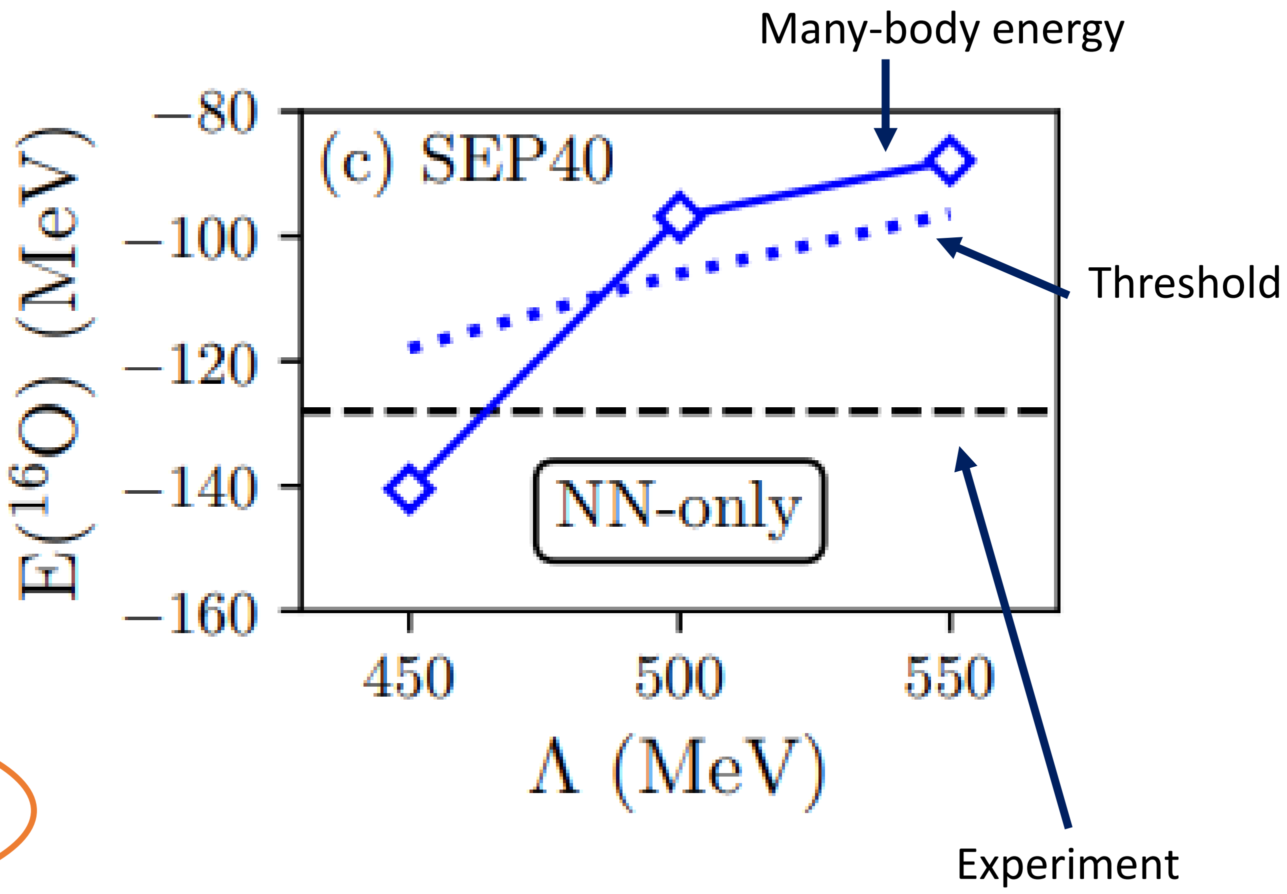


Will they ever bind?
Why are they bound?

Instability problem in modified Weimberg powercounting

C.-J. Yang, A. Ekström, C. Forssén, G. Hagen, G. Rupak, and U. van Kolck (2023)

The energy of **Oxygen** and **Calcium** is larger than the relative threshold (4α and 10α)

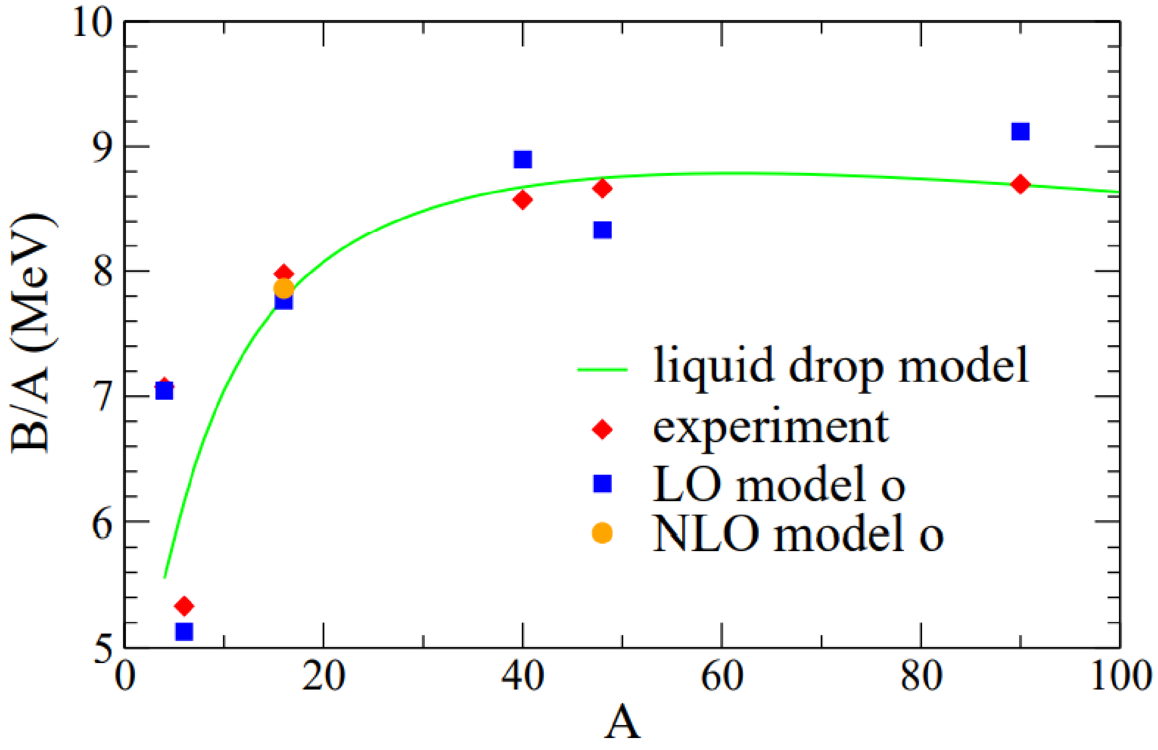


In the chiral case:

- A 3B force solves the issue

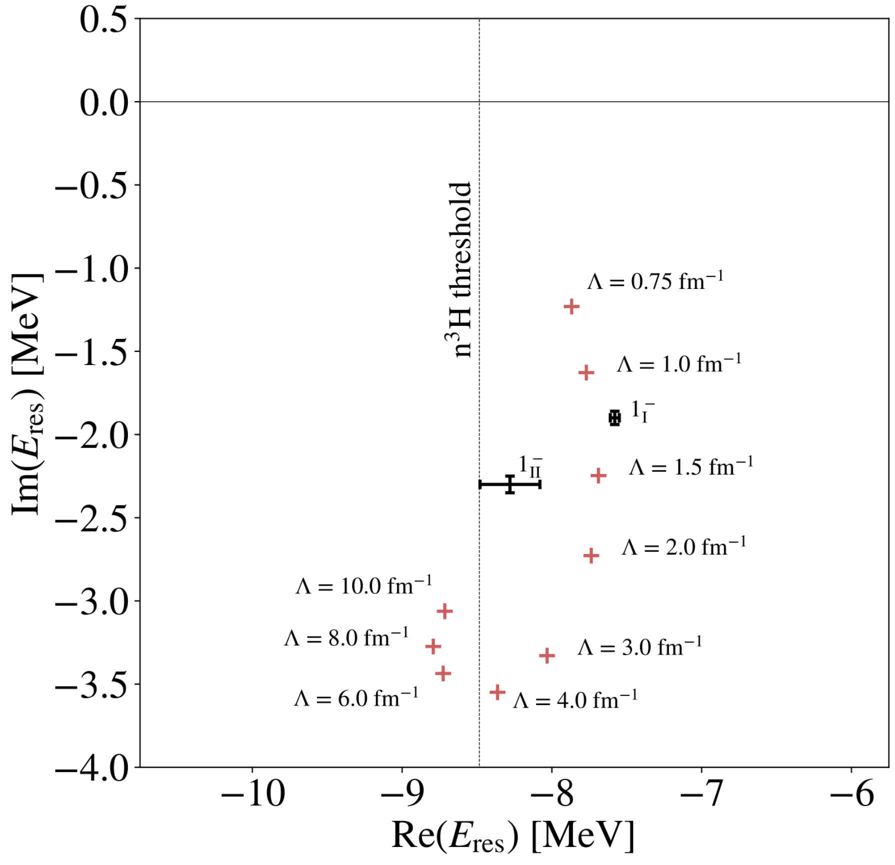
In our case:
Can a subleading order do the job as well?

Finite range Pionless-like interactions
Do not have instability problem



R. Schiavilla, L. Girlanda , A. Gnech, A. Kievsky, A. Lovato, L.E. Marcucci, M. Piarulli, and M. Viviani (2021)

It is possible to have P-shell poles (resonance) with pionless at LO

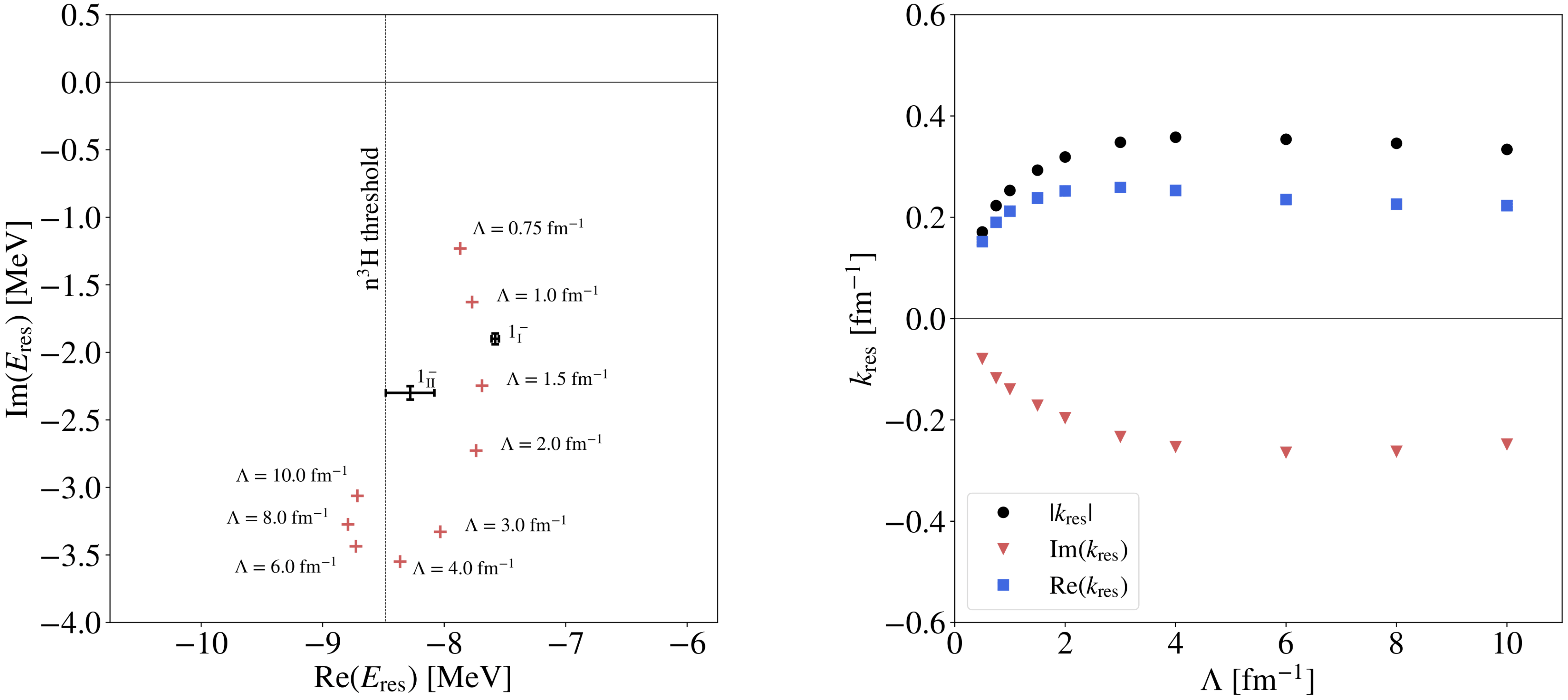


L.C., M. Schäfer, J. Kirscher, R. Lazauskas, J. Carbonel (2023)

Results (4H Resonance position)

L.C., M. Schäfer, J. Kirscher,
R. Lazauskas, J. Carbonel (2023)

The reseonance energy is calculated directly using FY



Momentum of the resonance with respect to the Triton-neutron threshold

Contact EFT LO

- Performs good in few body sector
- Bad in many-nucleon systems (not stable)

Contact powercounting breaking

Subleading order stabilize the systems

GOTO NLO

How to do it?

Contact EFT LO

- Performs good in few body sector
- Bad in many-nucleon systems (not stable)

Contact powercounting breaking

Subleading order stabilize the systems

GOTO NLO

How to do it?

Possible solutions

[**IF** a near threshold (unstable) state exist]

Perturbatively move the pole in the stable region

Is this possible (?) surely hard and troublesome

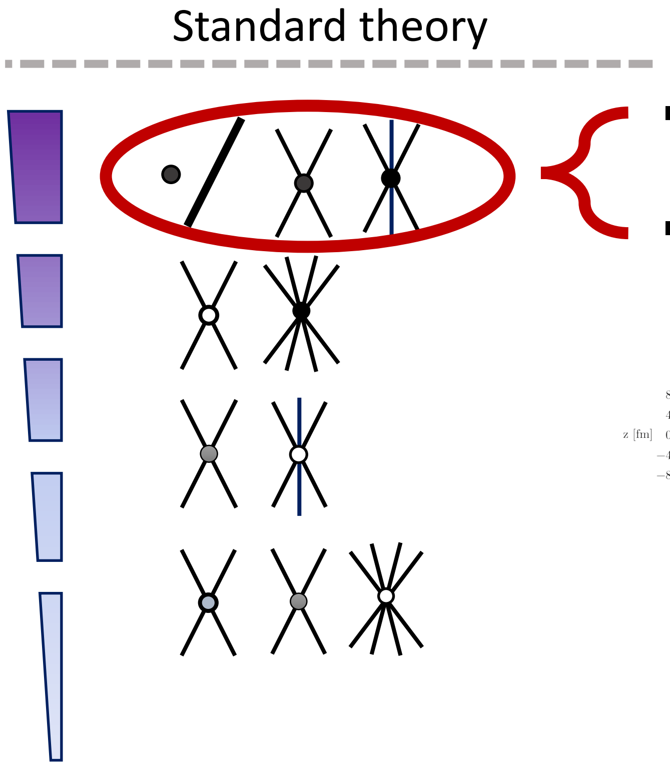
C.-J. Yang (2024)

Find an alternative way
to deal with the theory

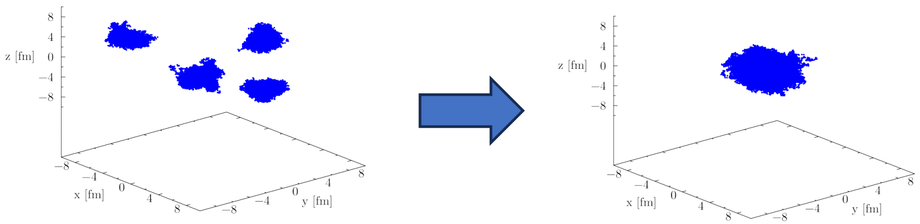
Improved action

Premise: using a “**pure**” LO EFT for many-body calculations is -- challenging—

- arbitrariness on the fitting procedure
- renormalization procedure (if the regulator is not explicitly removed)



- Not satisfying
- Hard to compute



Example: the contact LO can be fitted on

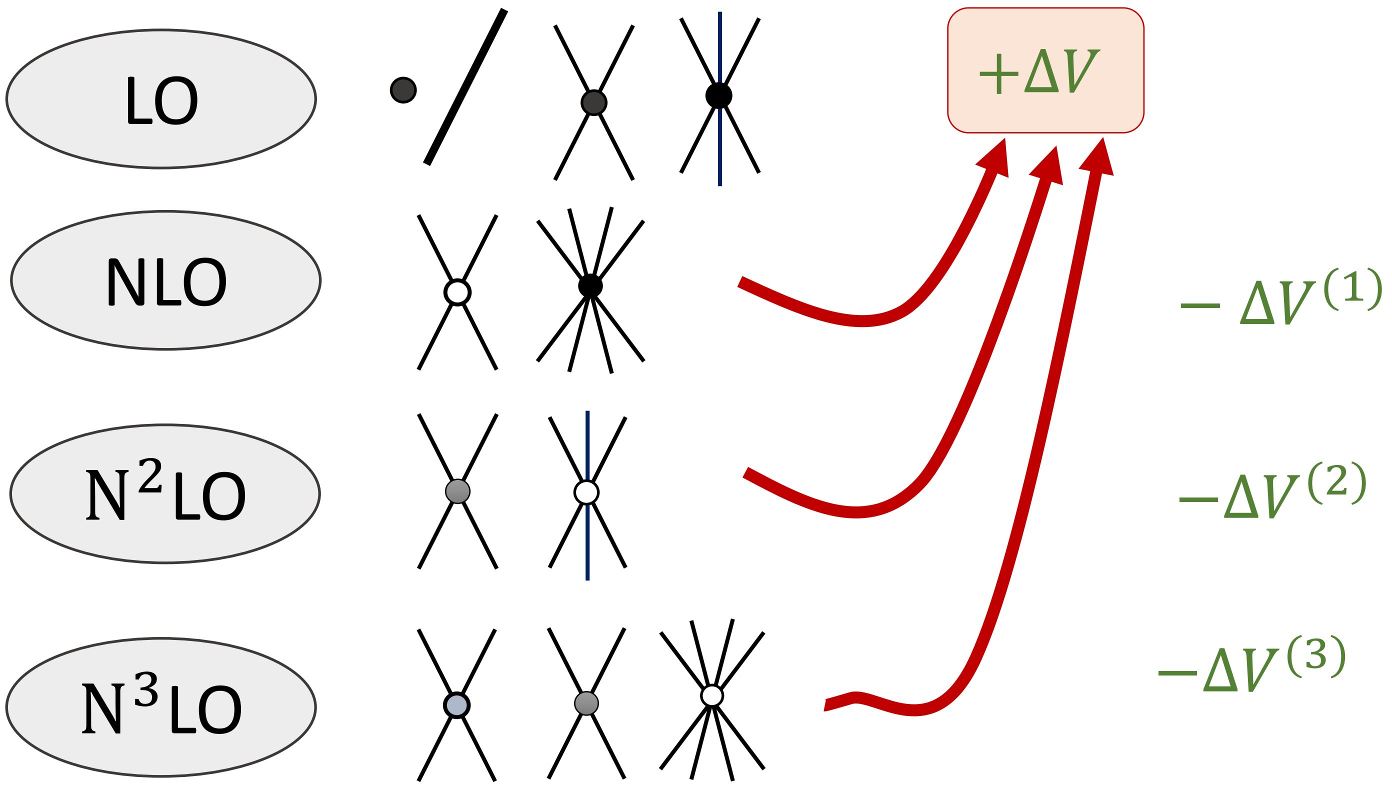
- binding energy
- Scattering parameters

Example: impossibility of using infinite cutoffs

Can we exploit this arbitrariness?

Improved action

Nuc. Phys. B K. Symanzik (1983)
Phys. Rev. A L.C., M. Schäfer, U. van Kolck (2024)
Phys. Lett. B L.C., M. Pavòn Valderrama, U. van Kolck (2024)
L.C., M. Schäfer, A. Gnech, A. Lovato, U. van Kolck (in preparation)



We can use this arbitrariness to change the LO to our advantage

1) Add a subleading modification to LO

2) Remove the improvement order by order

Improved action: two body

How much I can change the LO before the NLO can not correct it perturbatively?

In our study we use
p-n scattering as an example

Toy model:

$$T = \frac{4\pi}{m}\frac{1}{k\cot(\delta) - ik} \rightarrow k\,cot(\delta) = -\frac{1}{\boldsymbol{a_0}} + \frac{1}{2}\boldsymbol{r_0}\,k^2 + \boldsymbol{\omega_4}\,k^4 + \boldsymbol{\omega_6}\,k^6 \;//$$

-- using a energy dependent approach --

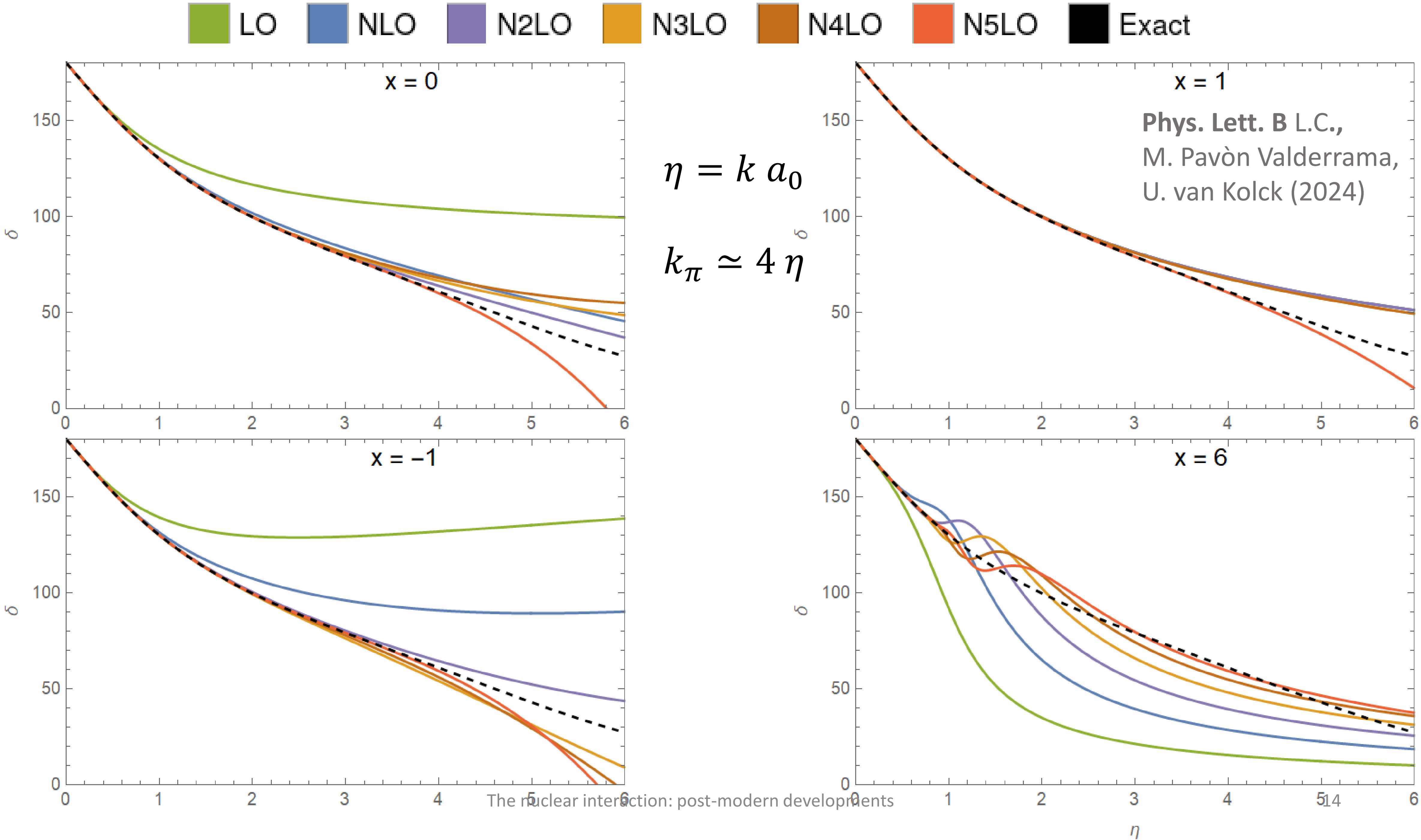
LO $\rightarrow k\,cot(\delta) = -\frac{1}{a_0} + (x\,r_0)\frac{1}{2}k^2$

NLO $\rightarrow$ **correct perturbatively** $(1-x)r_0$

$\mathbf{N^2LO} \rightarrow$ ω_4

…

See also (in spirit)
S. Beck, B. Bazak, N. Barnea 2019
S. Beane and R. Farrell 2021



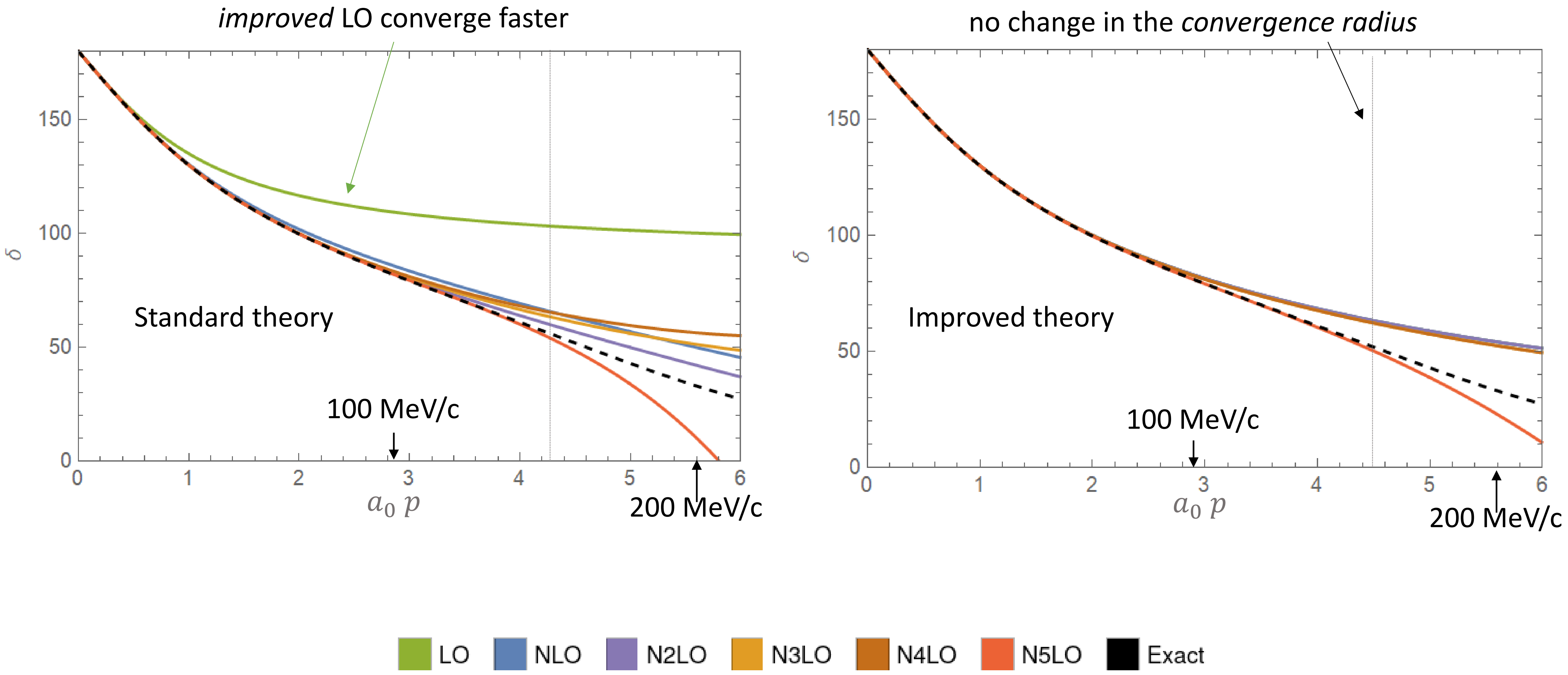
$$\eta = k\, a_0$$

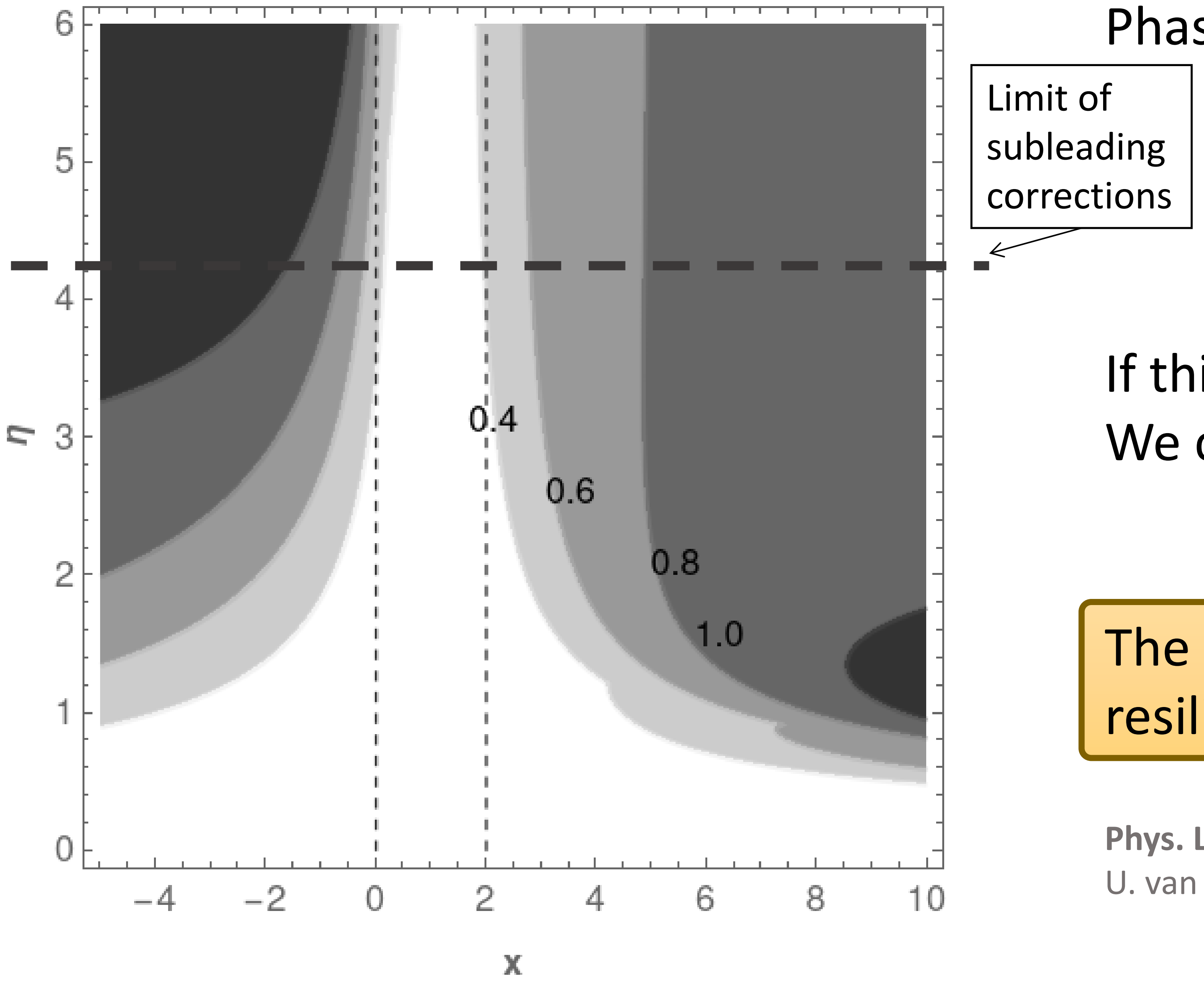
$$k_\pi \simeq 4\,\eta$$

Phys. Lett. B L.C., M. Pavòn Valderrama, U. van Kolck (2024)

Phase shifts of n-p (deuteron channel):

Phys. Lett. B L.C.,
M. Pavòn Valderrama,
U. van Kolck (2024)





Phase shift convergence

$$\frac{\delta_{NLO}}{\delta_{LO}}$$

If this is approaching 1:
We cannot correct the artifact

The theory is surprisingly resilient to resummation.

Phys. Lett. B L.C., M. Pavòn Valderrama, U. van Kolck (2024)

Improved action: Few-body (atoms)

Hamiltonian that reproduces the scattering length a_0

$$V(r_{ij}) = \delta(\Lambda, r_{ij}) = \mathrm{C}_0(\Lambda, \mathrm{a}_0)\exp\left(-\frac{1}{4}\frac{r_{ij}^2}{\mathrm{R}_0^2}\right)$$

This is an **example** you can chose any other potential !

Induces spurious scattering parameters ($\bar{a}, \bar{r}, \bar{\omega}_4, \bar{\omega}_6$, ...)

$\bar{a} = a_0$ (fitted)

$\bar{r} \propto R_0$

$$\bar{r} = x\, r_0$$

R_0 controls the amount of resummation

$$x \propto \frac{R_0}{r_0}$$

$$\bar{\omega}_4 = \bar{\omega}_4(\mathrm{R}_0) \overset{\mathrm{R}_0 \to 0}{\rightarrow} 0$$

$$\bar{\omega}_6 = \bar{\omega}_6(\mathrm{R}_0) \overset{\mathrm{R}_0 \to 0}{\rightarrow} 0$$

$\bar{\omega}_N$ are artifacts of the model

Improved action: Few-body (atoms)

Phys. Rev. A L.C., M. Schäfer, U. van Kolck (2024)

Hamiltonian that reproduces the scattering length a_0

$$V^{(0)}(r_{ij}) = \delta(\mathrm{R}_0, r_{ij}) = \mathrm{C}_0(\mathrm{R}_0, \mathrm{a}_0)\exp\left(-\frac{1}{4}\frac{r_{ij}^2}{\mathrm{R}_0^2}\right)$$

$$\Delta V = \mathrm{C}_0(\mathrm{R}_0, a_0)\,\delta_{R_0} - \mathrm{C}_0(\Lambda, \mathrm{a}_0)\,\delta_\Lambda$$

Induces spurious scattering parameters $(\bar{a}, \bar{r}, \bar{\omega}_4, \bar{\omega}_6, \ldots)$

$\bar{a} = a_0$ (fitted)

$\bar{r} \propto R_0 = x\, r_0$

$$\bar{\omega}_4 = \bar{\omega}_4(\mathrm{R}_0) \overset{\mathrm{R}_0\to 0}{\to} 0$$

$$\bar{\omega}_6 = \bar{\omega}_6(\mathrm{R}_0) \overset{\mathrm{R}_0\to 0}{\to} 0$$

For simplicity I show results where also the thee-body has a fixed range

$R_3 = R_0$

NLO

Restores $\bar{r} \to r_0$

Still has a **cutoff dependence**
(we do not want further contaminations):

$$V_{NLO} = \left(C_0^{(1)} + C_2^{(1)}\ \nabla_{ij}^2\right)\exp\left(-\frac{1}{4}r_{ij}^2\,\Lambda^2\right)$$

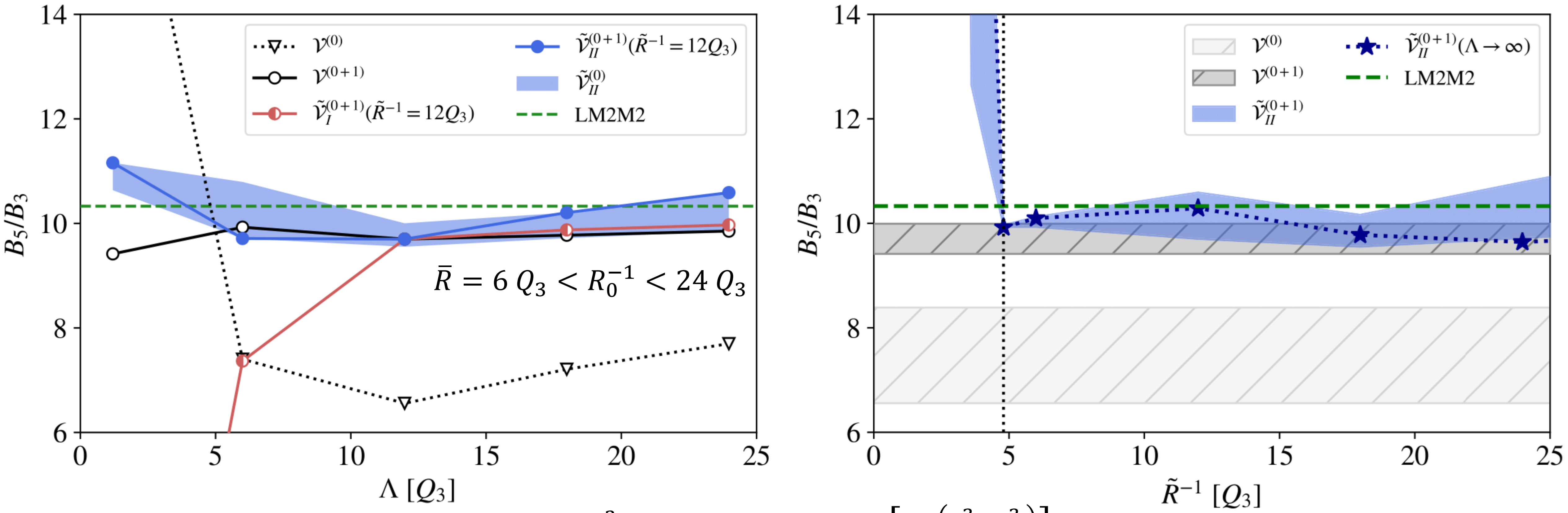
$C_0^{(1)}(\mathrm{R}_0, \Lambda)$, $C_2^{(1)}(\mathrm{R}_0, \Lambda)$ are used to fit a_0 and r_0

5 bosons (NLO)

$\bar{\boldsymbol{R}} = \mathrm{R}_0$ is the parameter that controls the resummation

$\boldsymbol{\Lambda}$ is the theory cutoff that should go to "infinity"

Phys. Rev. A L.C., M. Schäfer, U. van Kolck (2024)



$$H^{LO} = -\frac{\hbar^2}{2m}\sum_i \nabla^2 + \sum_{ij} C_0^*(\bar{R}^{-1})\, e^{-\frac{r_{ij}^2}{4\bar{R}^2}} + \sum_{ijk} D_0^*(\bar{R}^{-1}) \sum_{cyc}\left[e^{-\frac{\left(r_{ij}^2+r_{ik}^2\right)}{4\bar{R}^2}}\right]$$

$$Q_3 = \sqrt{\frac{2}{3} m\, B_3}$$

Going nuclear

$$H^{LO} = -\frac{\hbar^2}{2m}\sum_i \nabla^2 + \sum_{ij} C_s{}^{(0)}(x)\, e^{-\frac{r_{ij}^2}{4\,x\,R_s^2}} P_s + \sum_{ij} C_t{}^{(0)}(x)\, e^{-\frac{r_{ij}^2}{4\,x\,R_t^2}} P_t + \sum_{ijk} D^{(0)}(y,x) \sum_{cyc} \left[e^{-\frac{\left(r_{ij}^2 + r_{ik}^2\right)}{4\,yR_3}} \right]$$

R_t and R_s reproduce effective ranges for $x = 1$
R_3 reproduce *at best* $E(\,^4\mathrm{He})$ for $\mathrm{y} = 1$

For $x = y = 1$ NLO is small*

- 4-Body force is not zero
- Coulomb and isospin breaking apply

Fixing R_3 on $\mathrm{E}(\,^4\mathrm{He})$ can be dangerous: interestingly $R_3 \sim \left(\frac{R_s}{2}\right) \sim \left(\frac{R_t}{2}\right)$

R. Schiavilla, L. Girlanda, et al. 2021

$$H^{NLO} = \mathrm{Counterterms}(\lambda, \{R\}) +$$
$$\sum_{ij} C_s{}^{(1)}(x,\lambda)\, e^{-\frac{\lambda^2 r_{ij}^2}{4\,x}} P_s + \sum_{ij} C_t{}^{(1)}(x,\lambda)\, e^{-\frac{\lambda^2 r_{ij}^2}{4\,x\,R_t^2}} P_t + \sum_{ijk} E^{(1)}(y,x,\lambda) \sum_{cyc} \left[e^{-\frac{\lambda^2\left(r_{ij}^2 + r_{ik}^2\right)}{4}} \right]$$

Improving the nuclear LO

$$H^{LO} = -\frac{\hbar^2}{2m}\sum_i \nabla^2 + \sum_{ij} C_s{}^{(0)}(x)\, e^{-\frac{r_{ij}^2}{4\,x\,R_s^2}} P_s + \sum_{ij} C_t{}^{(0)}(x)\, e^{-\frac{r_{ij}^2}{4\,x\,R_t^2}} P_t + \sum_{ijk} D^{(0)}(y,x) \sum_{cyc}\left[e^{-\frac{\left(r_{ij}^2+r_{ik}^2\right)}{4\,yR_3}}\right]$$

R_t and R_s fitted to reproduce the effective ranges for $x = 1$
R_3 is fitted to reproduce *at best* $E(\,^4\mathrm{He})$ for y $= 1$

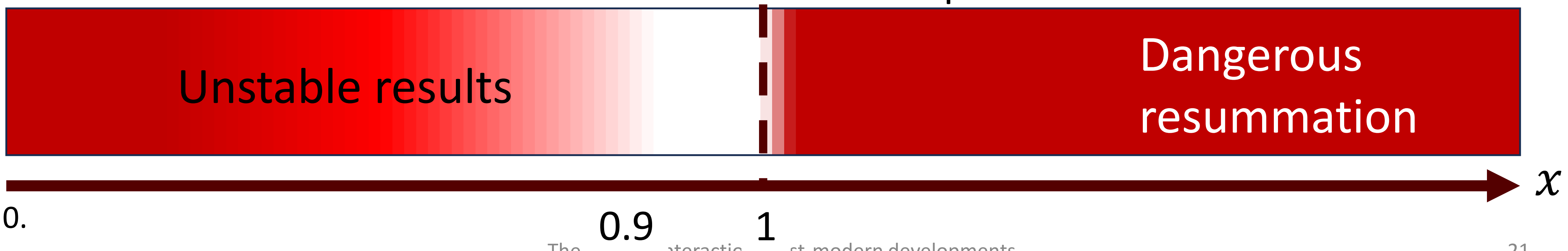
For $x = y = 1$ NLO is small*

- 4-Body force is not zero
- Coulomb and isospin breaking apply

Fixing R_3 on $\mathrm{E}(\,^4\mathrm{He})$ can be dangerous:
interestingly $R_3 \sim \left(\frac{R_s}{2}\right) \sim \left(\frac{R_t}{2}\right)$

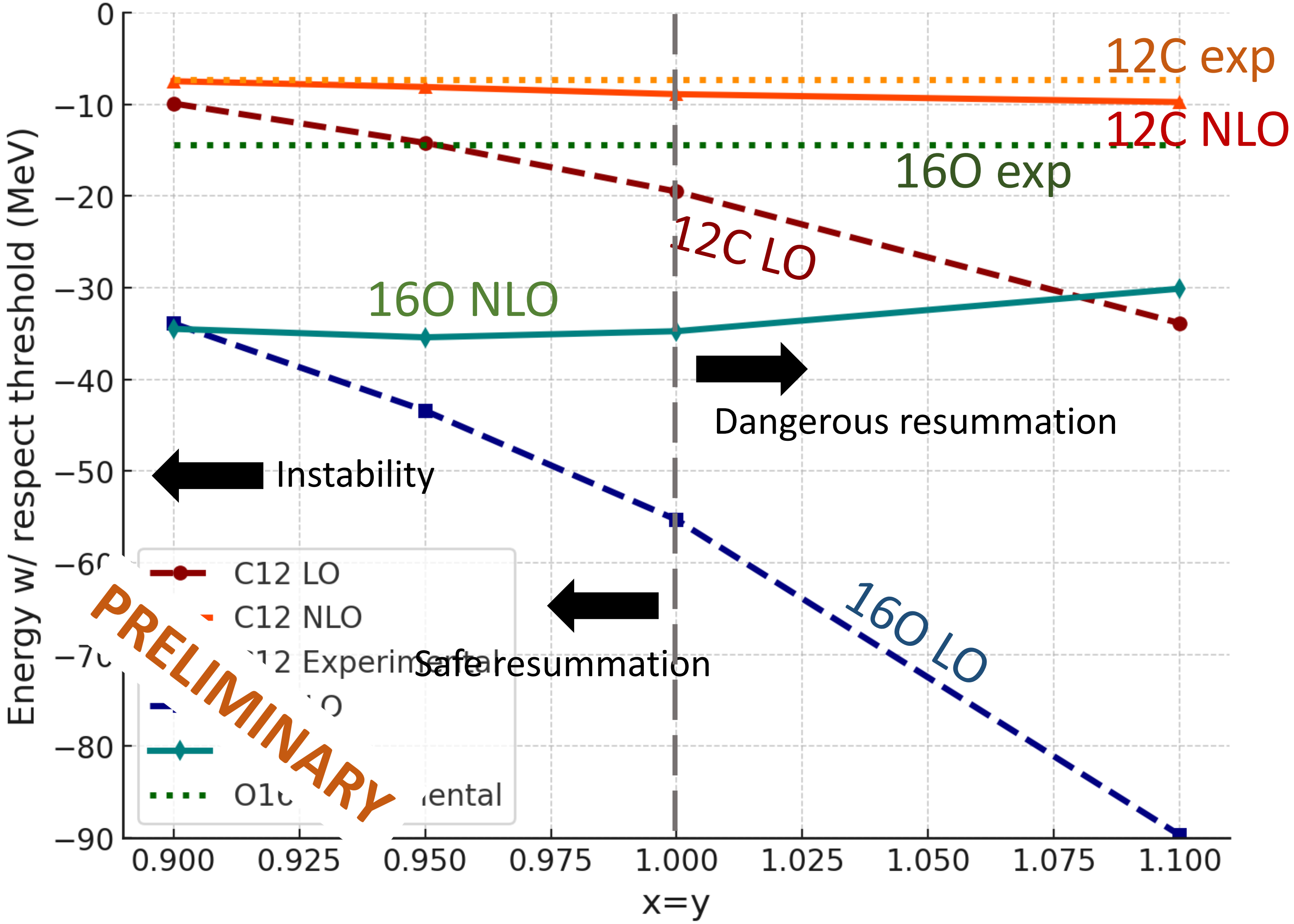
R. Schiavilla, L. Girlanda, et al. 2021

Based on 6He results we expect



Improved action: Nucleons

L.C., M. Schäfer, A. Gnech, A. Lovato, U. van Kolck
(in preparation)



The results are **preliminary** but **encouraging**.

stabilize Oxygen and Carbon

NLO stabilize the result for different improvement

Warning:
NLO cutoff $4\ fm^{-1}$ (small)
No cutoff study done (YET)

Take aways

Resumming subleading orders:

Is a **flexible** way to fiddle the theory

Is limited: the improvement should a perturbation

If done correctly (for what we check):

Renormalizability is preserved

Convergence radius is preserved

Help the calculations (softening is just an example)

The price:

Lose **cutoff control** of the improved order

Lose **order-by-order improvement** for the improved order

Thinks to think about

Arbitrary resumed potential ΔV

⇩

Connection between EFT and **realistic interactions**

Applicable to other EFTs

Other kind of resummations?
(one-body potentials)

[if already good behaved]
add entire orders non-perturbatively?

What about cases that are not "Hamiltonian" renormalizable*?

THANK YOU FOR YOUR ATTENTION

* For example for an unnaturally large effective range?

(almost) three questions

- Study the powercounting …
- How to treat subleading contributions …
- Collaboration between theory and mnay-body calculations

- How to connect different EFTs?
  And what do we expect from this “connection”?

- Can we translate what we know for many-body friendly DoF? (? alphas ?)

THANKS TO YOU AND ALL MY COLLABORATORS!

QMC solvers
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G. Hupin [b]
V. Somá [c]

Few-body and hypernuclei
N. Barnea [d]
A. Gal [d]
M. Schäfer [e]
J. Mareš [e]
A. di Donna [a]

Effective theories
U. van Kolck [b,l]
J. Kirscher [f]
M. Pavòn Valderrama [g]

Neutron systems and density formalism
M. Urban [b]

Few-body
R. Lazauskas [h]
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