IN2P3 Prospectives Théorie 2021

Unitarity Limit & Universality

BIRA VAN KOLCK

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Few-Body

Jaume Carbonell (IJCLab)

Mario Gattobigio (INPHYNI)

Guillaume Hupin (IJCLab)

Rimas Lazauskas (IPHC)

Mario Sánchez Sánchez (CENBG)

Ubirajara van Kolck (IJCLab)

Lorenzo Contessi (CEA-Saclay → IJCLab)

Many-Body

Thomas Duguet (CEA-Saclay)

Marcella Grasso (IJCLab)

Denis Lacroix (IJCLab)

Vittorio Somà (CEA-Saclay)

Michael Urban (IJCLab)

Two-Body Unitarity & Universality

$$T_2(k) \equiv \frac{i\pi}{\mu k}\left(1 - S_2(k)\right) \equiv \frac{2\pi}{\mu k}\left(\cot\delta_2(k) - i\right)^{-1} \simeq \frac{2i\pi}{\mu k}\left(1 + \mathcal{O}\left(\frac{1}{k a_2}, kR\right)\right)$$

S matrix — phase shift — scattering length — finite range

$$\Rightarrow \begin{cases} S_2(k) \simeq -1 \\ \delta_2(k) \simeq \pi/2 \end{cases}$$

$k \equiv \sqrt{2\mu E} \ll 2\mu$ (nonrelativistic)

regardless of short-range details (also atomic physics, *etc.*)

Two-component fermions

Three- or more-component fermions, bosons

(continuum) scale invariance

RG invariance → limit-cycle three-body force with single dimensionful parameter
e.g. three-body ground-state energy $E_{3,0} = -B_{3,0}$

discrete scale invariance

degree of universality

Does the additional symmetry improve our understanding of nuclear structure/reactions?

Neutrons

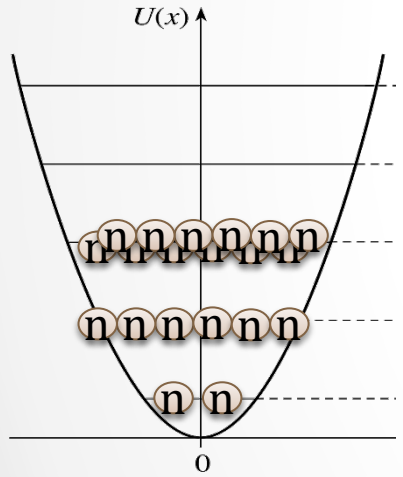
- how close are intermediate-density neutron systems to unitarity?
- what are the implications to neutron-star matter?

scale invariance

no bound states except for external interaction/trap

e.g. $\left.\frac{E_N^{(0)}}{N}\right|_{N\to\infty} = \frac{3k_F^2}{10m}\left(\xi + \mathcal{O}\left(\frac{1}{k_F a_2}, k_F R\right)\right)$ — free gas; ξ: *universal number* Bertsch '99

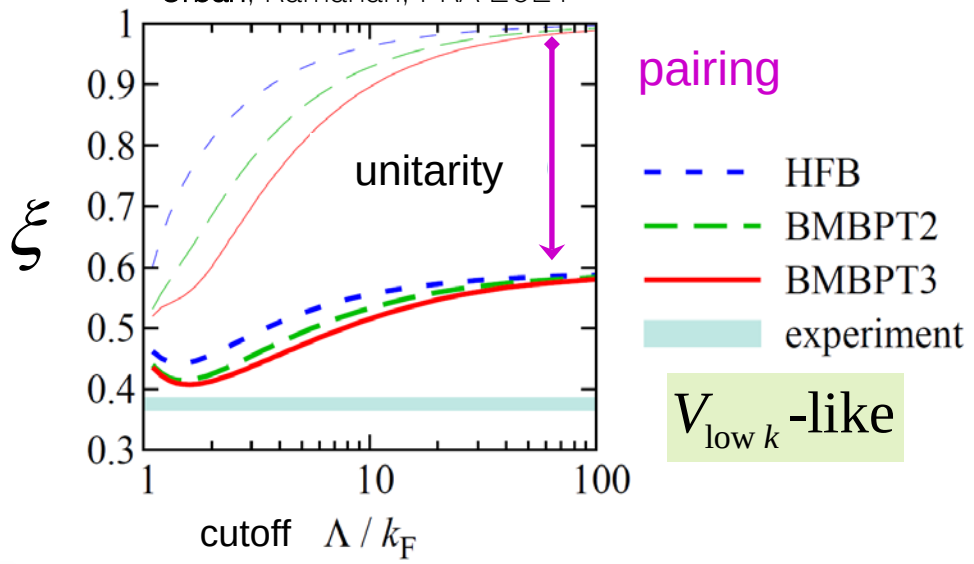
$k_F = (3\pi^2\rho)^{1/3}$



Neutron drops:
gateway to larger systems

EFT + QMC
(**Contessi**, **Somà**)

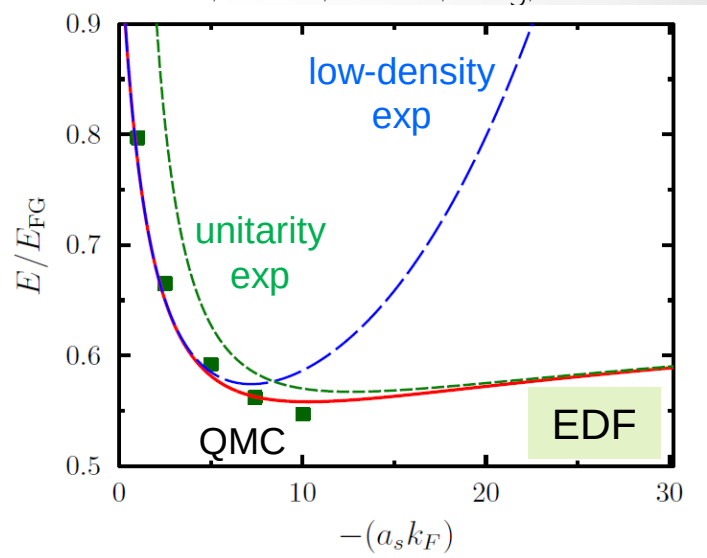
Urban, Ramanan, PRA 2021



$V_{\mathrm{low}\,k}$-like

To be added (**Urban**)
- induced three-body interactions
- higher orders in BMBPT
- nonperturbative resummations

Lacroix, Boulet, Grasso, Yang, PRC 2017



- new energy density functionals with unitarity constraints

(**Grasso**, **Lacroix**)

Bosons

simplest systems with discrete scale invariance

discrete scale invariance

1) Geometric towers of excited states

2) Ground-state correlations

$$\frac{B^{(0)}_{N,0}}{N} = \kappa_N \frac{B^{(0)}_{3,0}}{3}$$

universal numbers

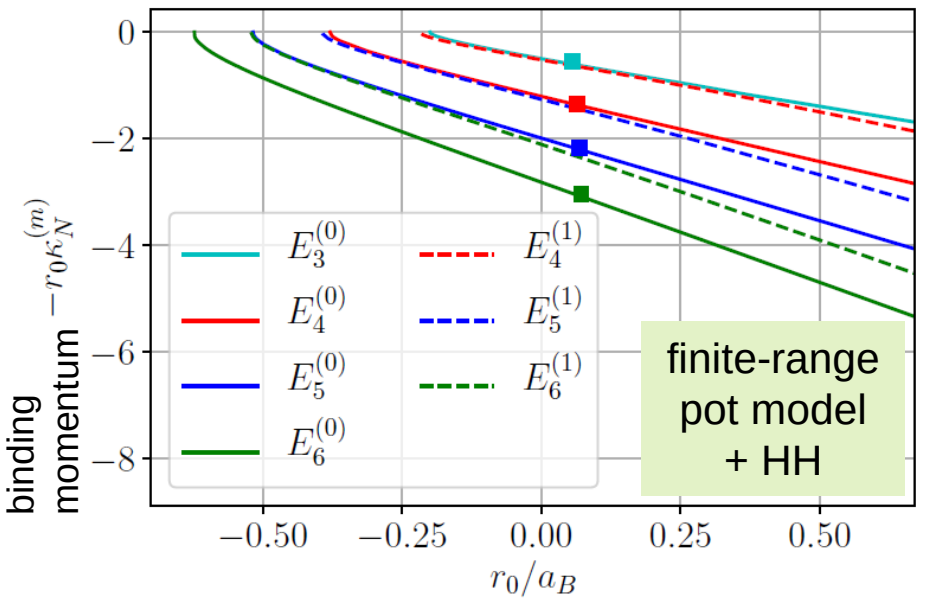
$N = 3$ Efimov '70

$N = 4$ Hammer, Platter '07

$N \geq 5$ von Stecher '10'11
Gattobigio *et al.* '11'12'14'20…

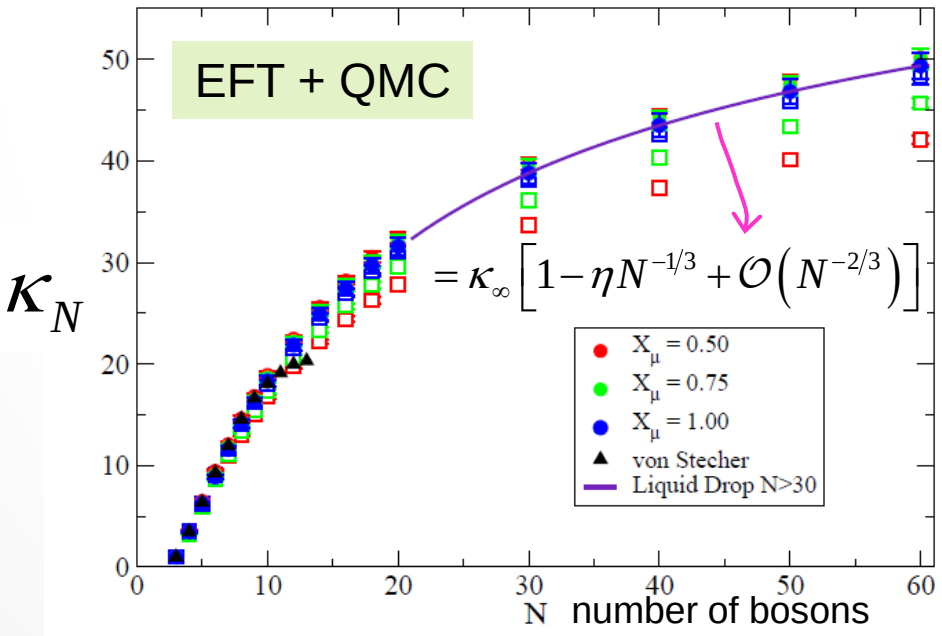
towers multiply

Kievsky, Girlanda, Gattobigio, Viviani, ARNPS 2021



effective range/scattering length

Carlson, Gandolfi, Vitiello, vK, PRL 2017



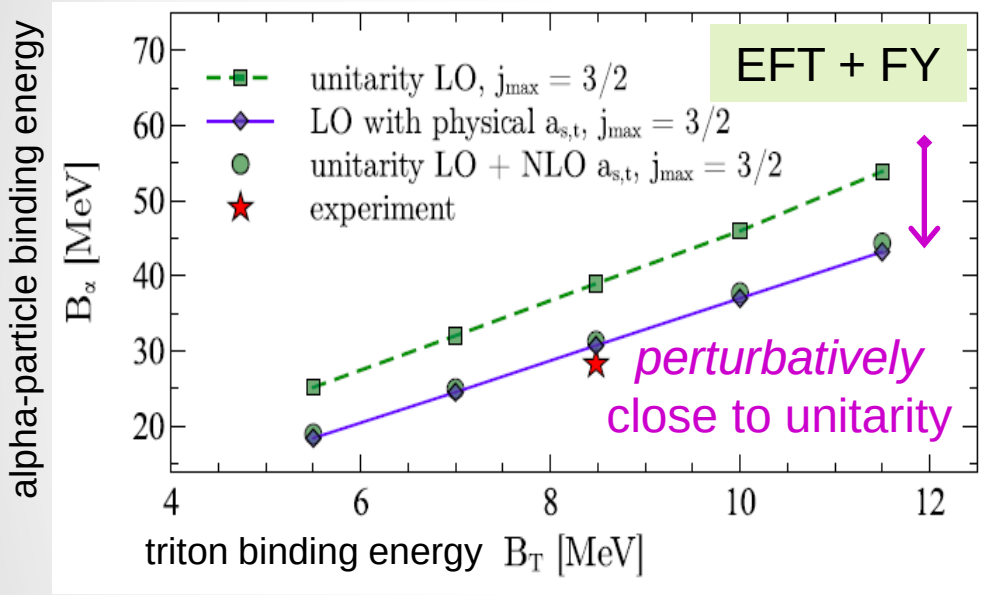
- why do towers multiply?
- what are the corrections to unitarity?
- how close are ^{4}He atomic clusters to unitarity?

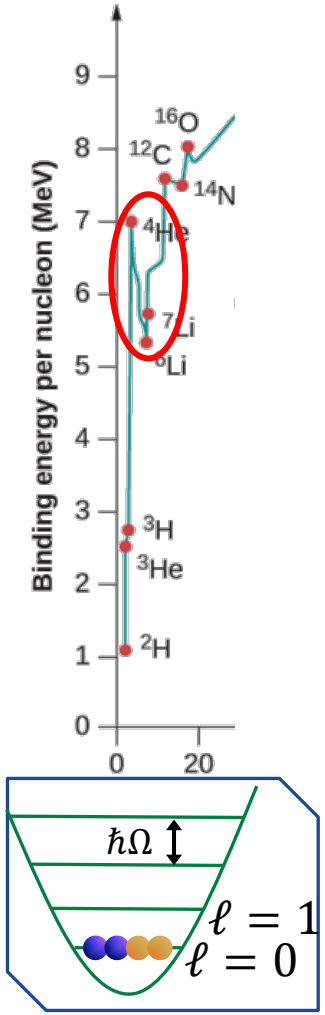
(**Contessi**, **Gattobigio**, **vK**)

Nucleons

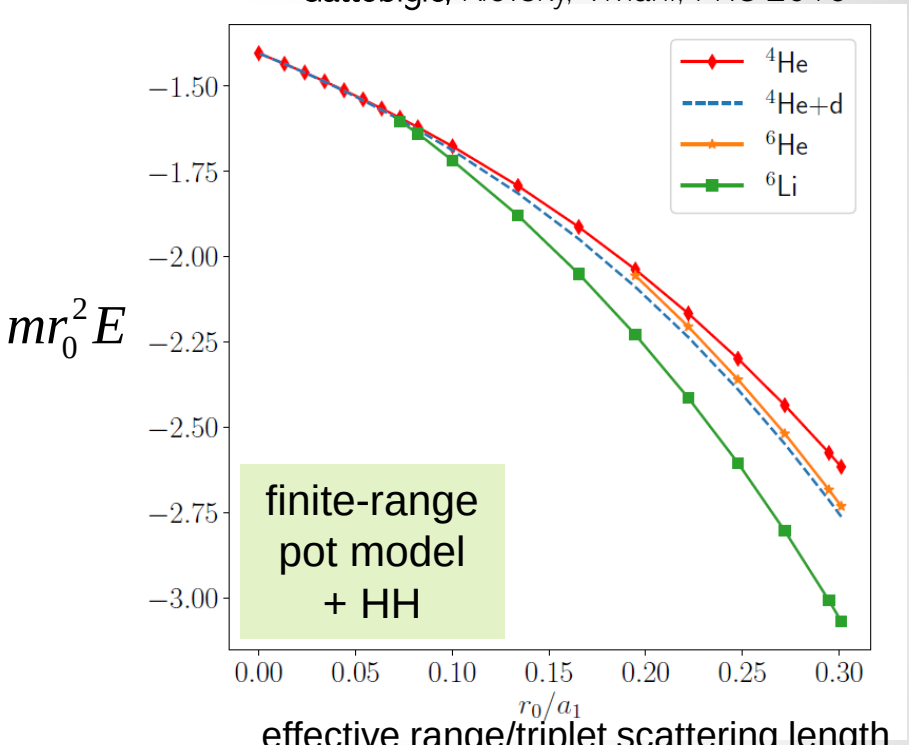
~ bosons + shell effects

König, Grießhammer, Hammer, vK, PRL 2017





Gattobigio, Kievsky, Viviani, PRC 2019



effective range/triplet scattering length

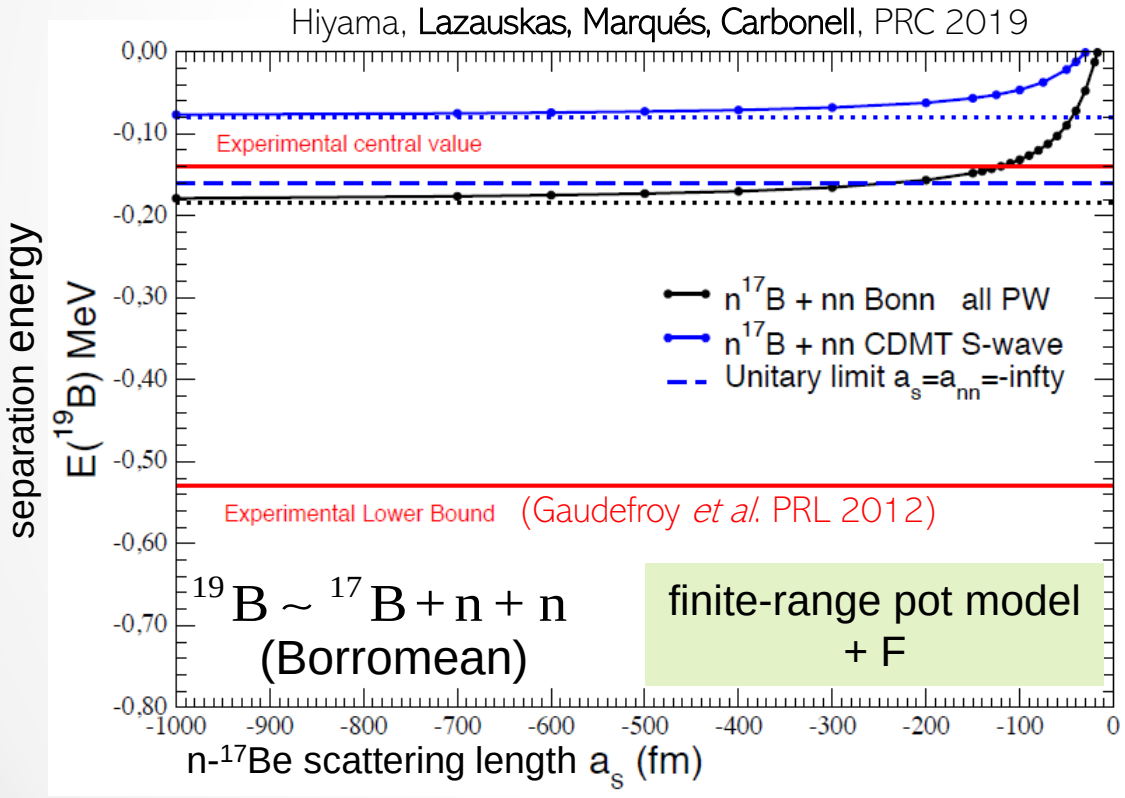
- how does the first-excited unitarity state become a p+^{3}H resonance?
- can we get p,...-shell physics in expansion around unitarity?
  ^{4}He p-wave states, ^{5}He, ^{6}He, ^{6}Li, ..., ^{16}O, ...

(**Contessi, Gattobigio, Hupin, Sánchez Sánchez, vK**)

Halo/Cluster Nuclei

~ boson-fermion or fermion-fermion mixtures

- Is an expansion around unitarity useful also for halo/cluster nuclei?



- more neutrons: ^{20}B, ^{21}B
  (cf. Leblond *et al.* PRL 2018)
- other cores
- multiple cores, *e.g.* ^{8}Be

(**Carbonell, Lazauskas, vK**)

Conclusion

Unitarity and universality simplify description of physical systems

Expansion around unitarity works for light nuclei
and intermediate-density neutron matter

Is it useful also for larger nuclei?
Could the saturation mechanism be similar to that for unitary bosons?
Can it inspire better energy density functionals?