Few- and many-body physics of mass-imbalanced two-components systems

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RIKEN

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2005	PhD in France (Laboratoire Aimé Cotton, Orsay) in ultracold atom theory. Formation of molecules in Bose-Einstein condensates
2005-2008	Postdoctoral researcher at NIST (National Institute of Standards and Technology) Properties of Alkaline-earth atoms for atomic clocks
2008-2012	Postdoctoral researcher at the University of Tokyo. Efimov states in ultracold-atom experiments
2012	Research Scientist at RIKEN Universal few-body and many-body physics

Two-component systems

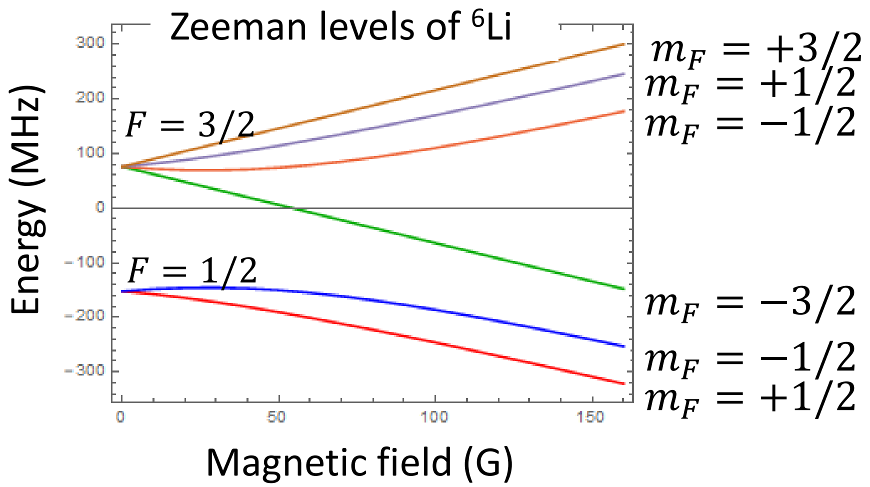
- Identical particles in two different states

Same mass

- Two different kinds of particles

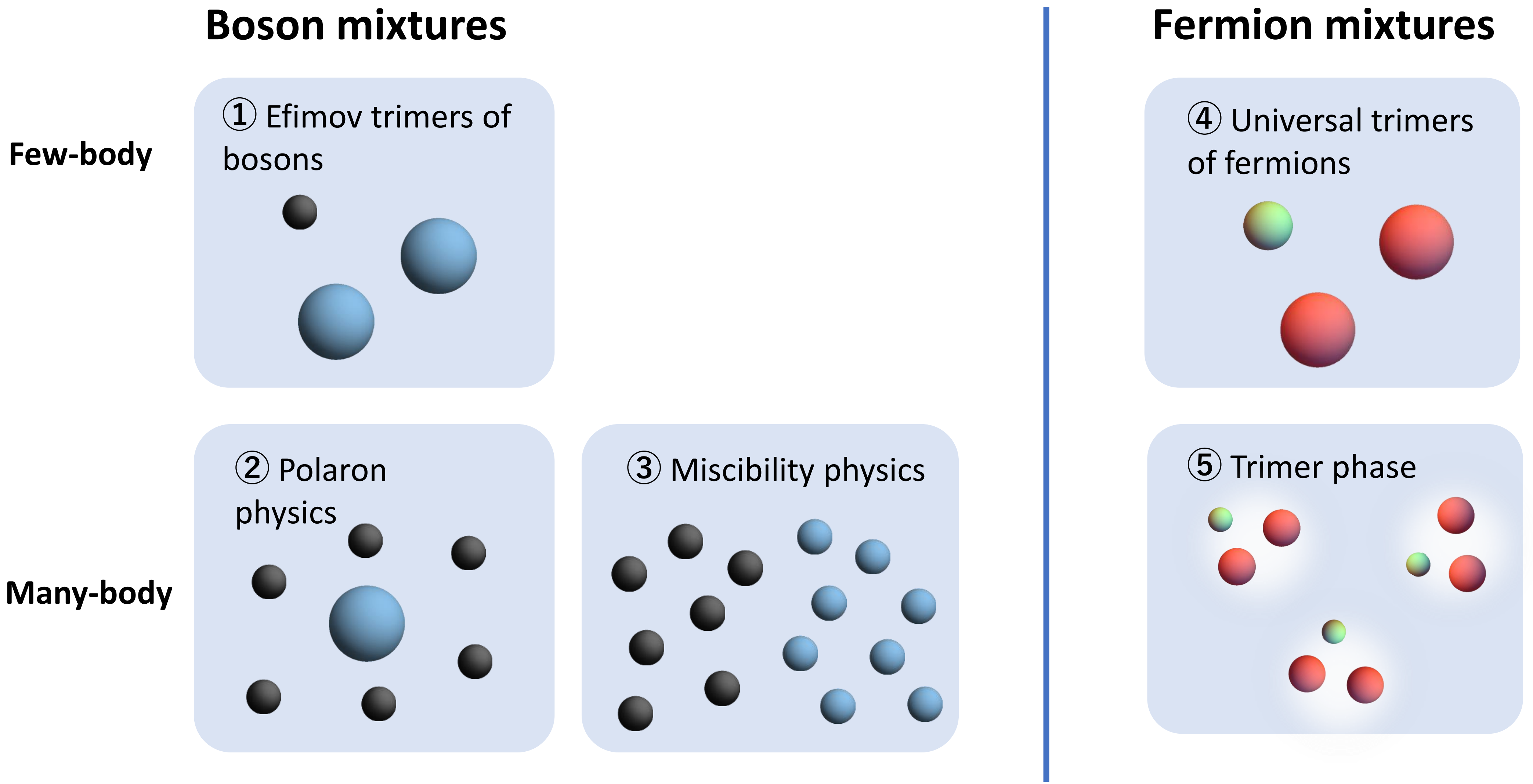
Different masses

Spin ½ particles (e.g. Neutrons)
Atoms in different hyperfine states



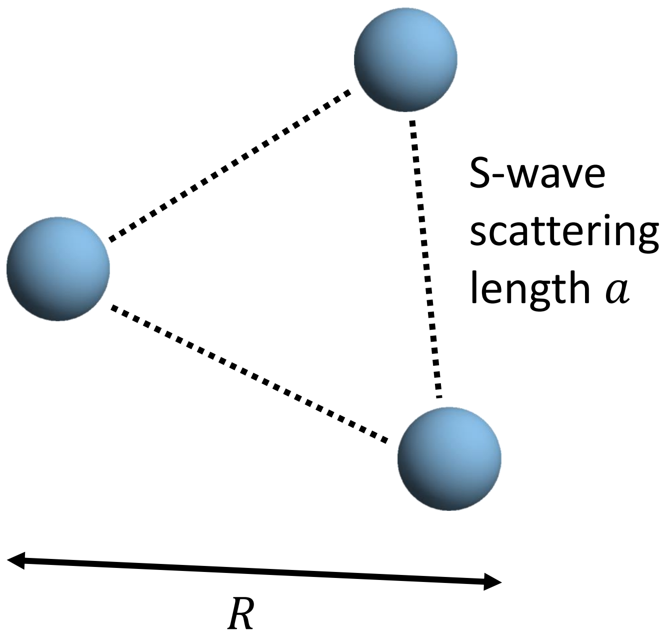
Different species of atoms in a polarised hyperfine state

Two-component systems

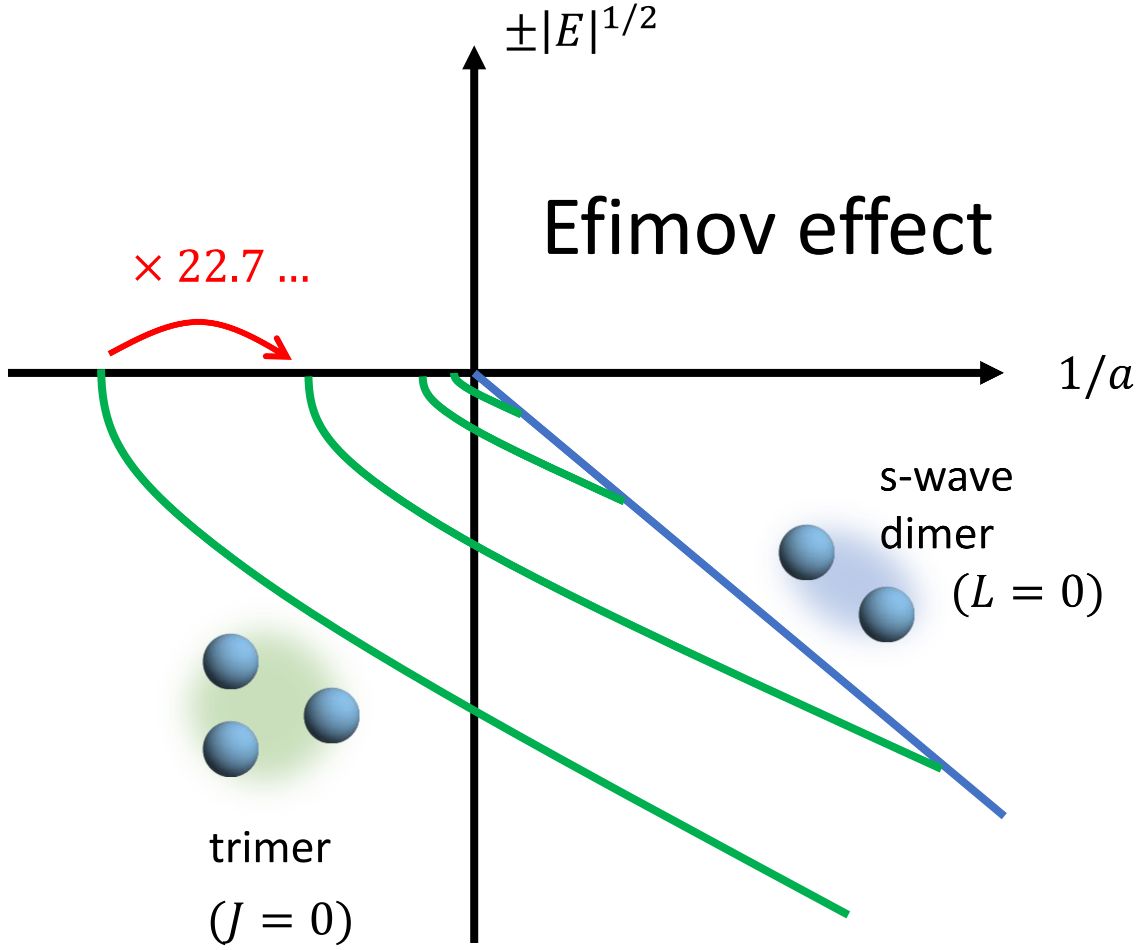


① Efimov trimers of bosons

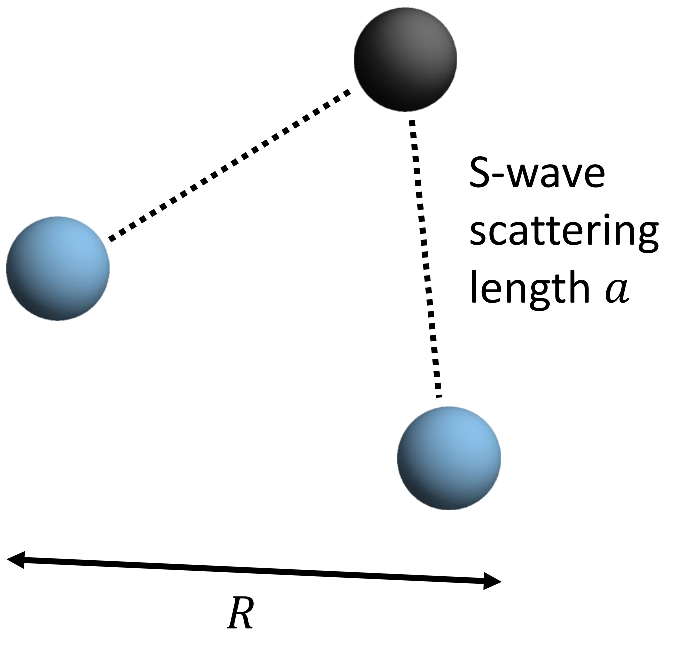
3 identical bosons



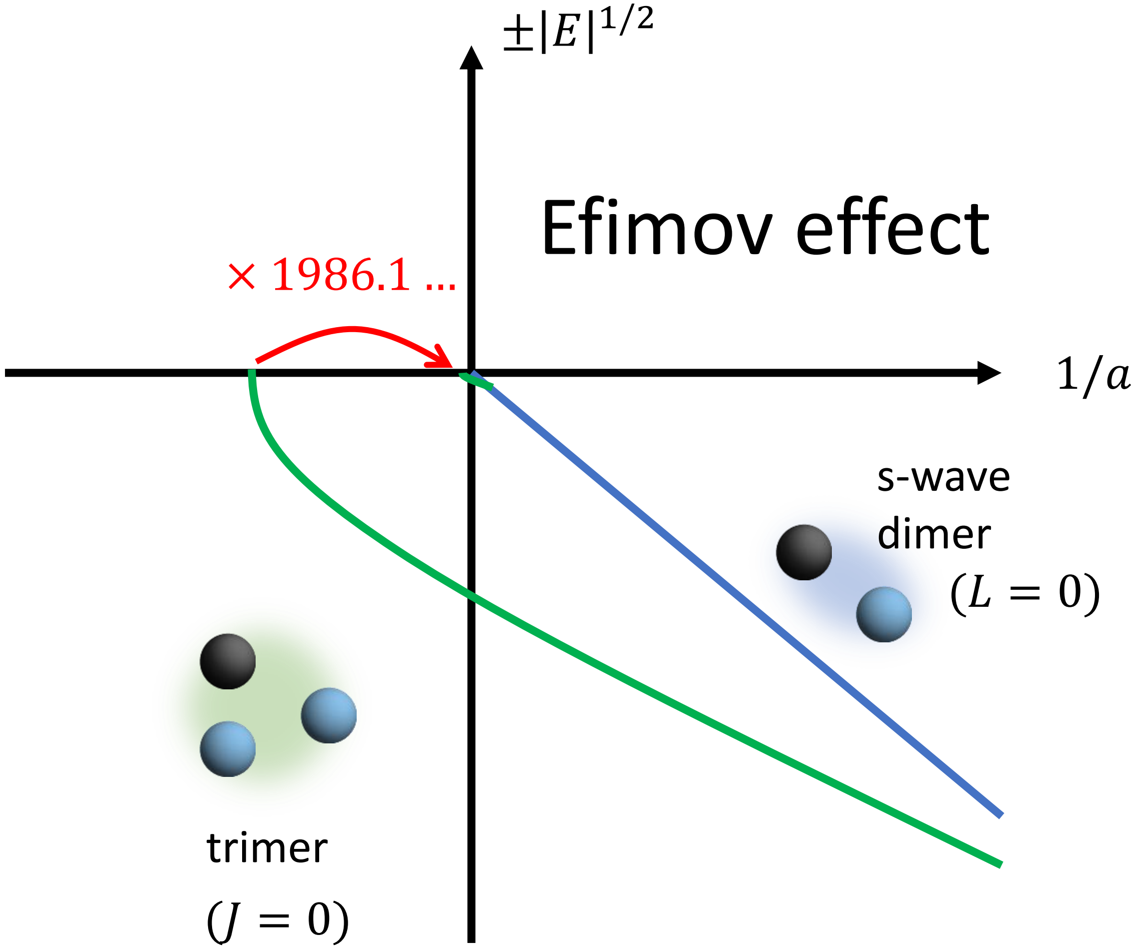
Efimov attraction: $V_{3B}(R) \sim -\frac{1}{R^2}$



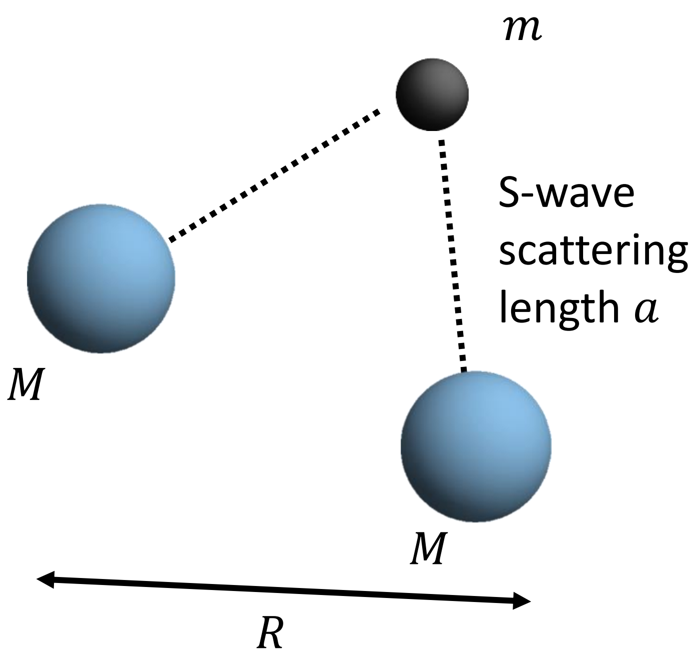
2 identical bosons + 1 particle

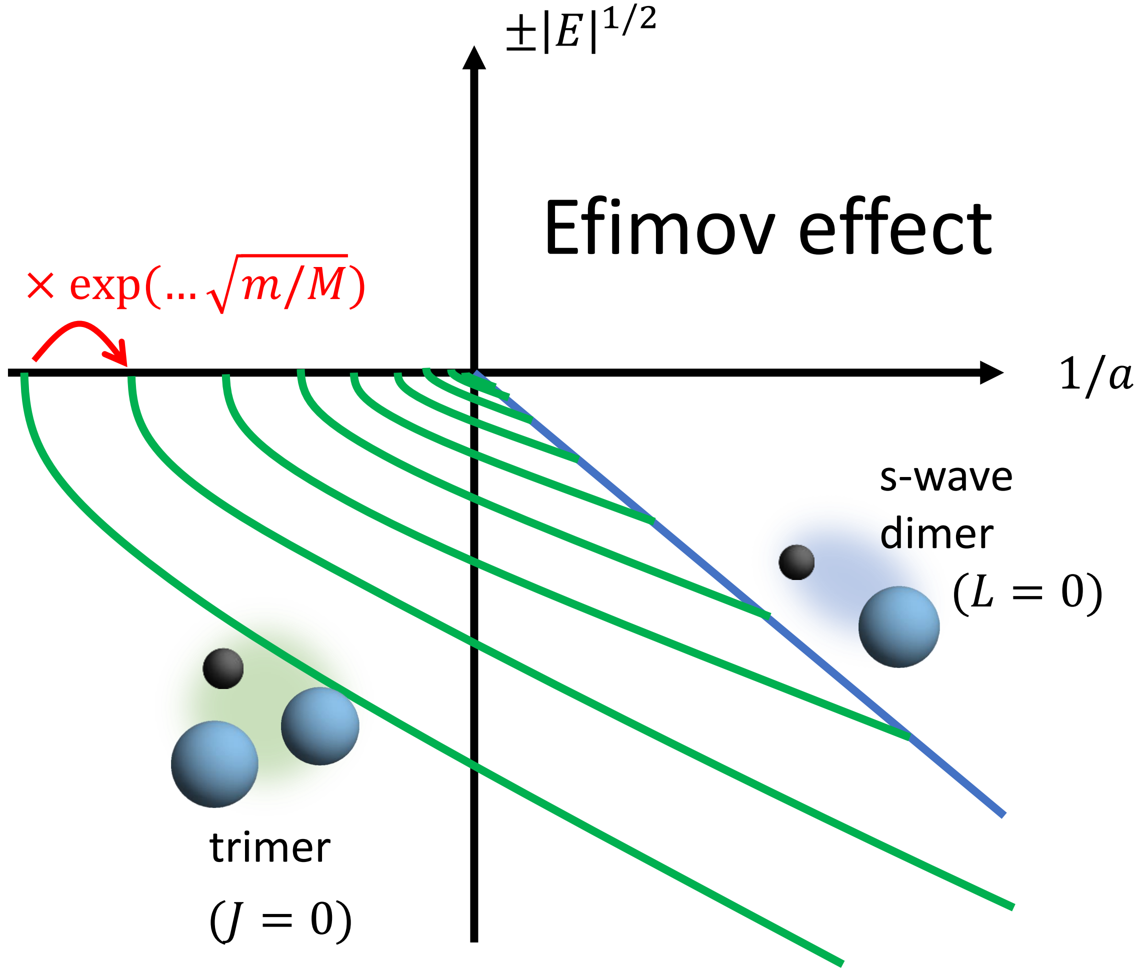


Efimov attraction: $V_{3B}(R) \sim -\frac{0.17}{R^2}$



2 identical bosons + 1 particle





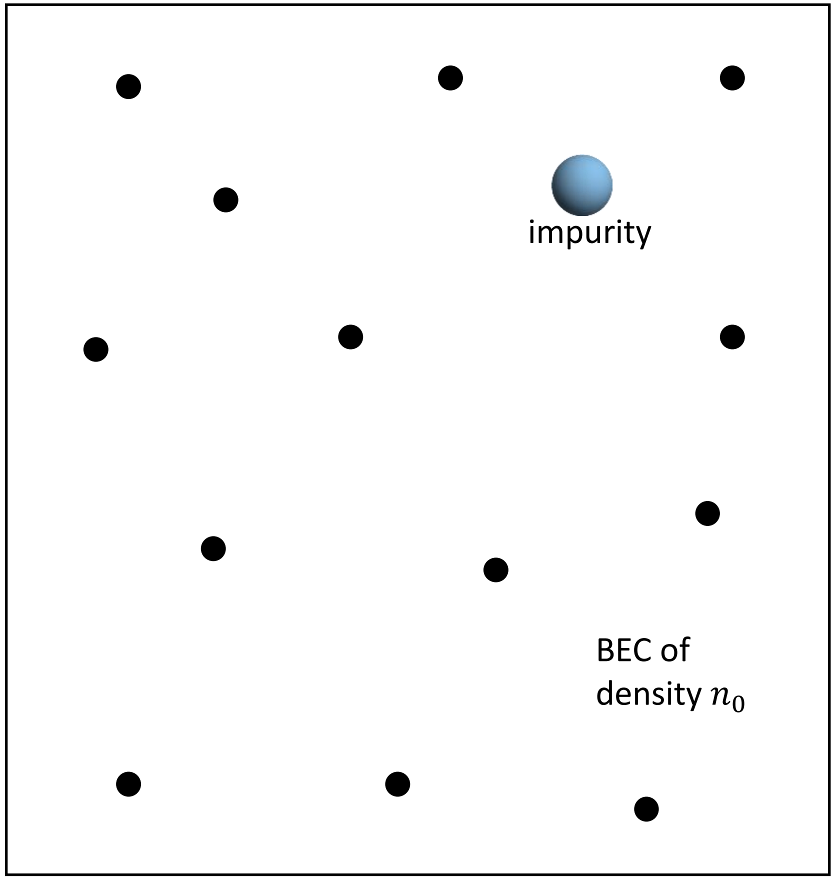
Efimov attraction: $V_{3B}(R) \sim -\frac{M}{m}\frac{0.16}{R^2}$

② Polaron physics

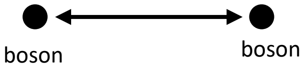
Two impurities in a Bose-Einstein condensate: from Yukawa to Efimov attracted polarons
J. Phys. Soc. Jpn. 87, 043002 (2018)
[arxiv:1607.04507]

Tetramers of two heavy and two light bosons
Few-Body Syst 59, 64 (2018)
[arxiv:1802.06237]

Polaron: particle interacting with a medium



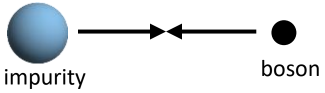
Short-range repulsion



Small scattering length $a_B > 0$

$n_0 a_B^3 \ll 1$

Short-range attraction



Small or large scattering length a

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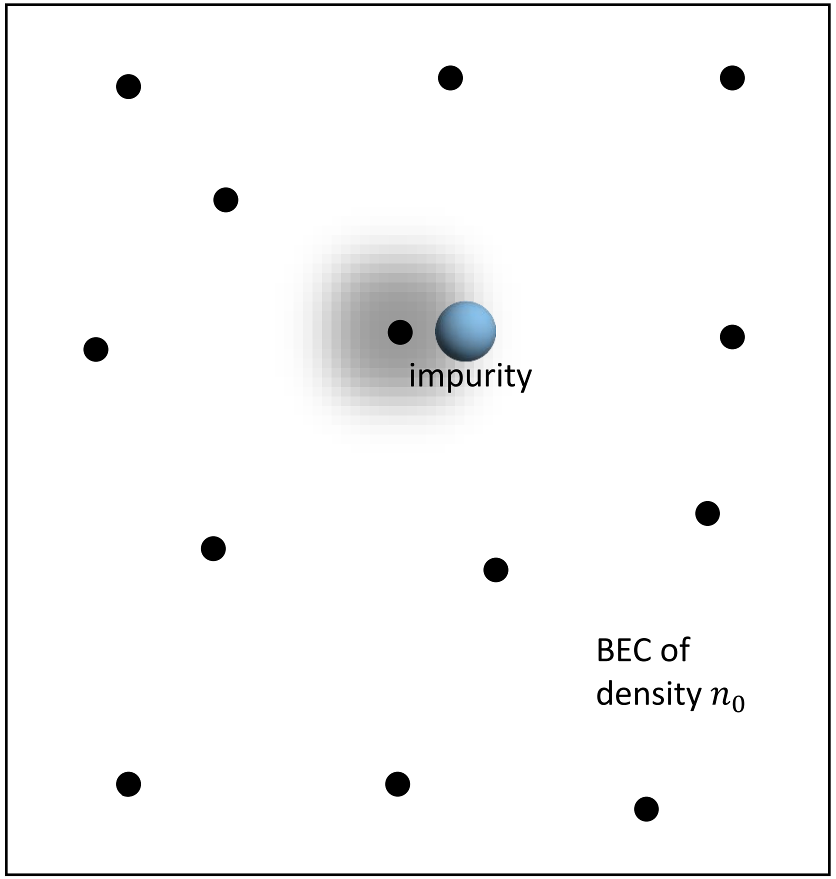

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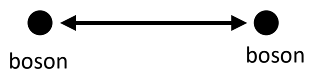

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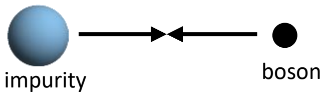

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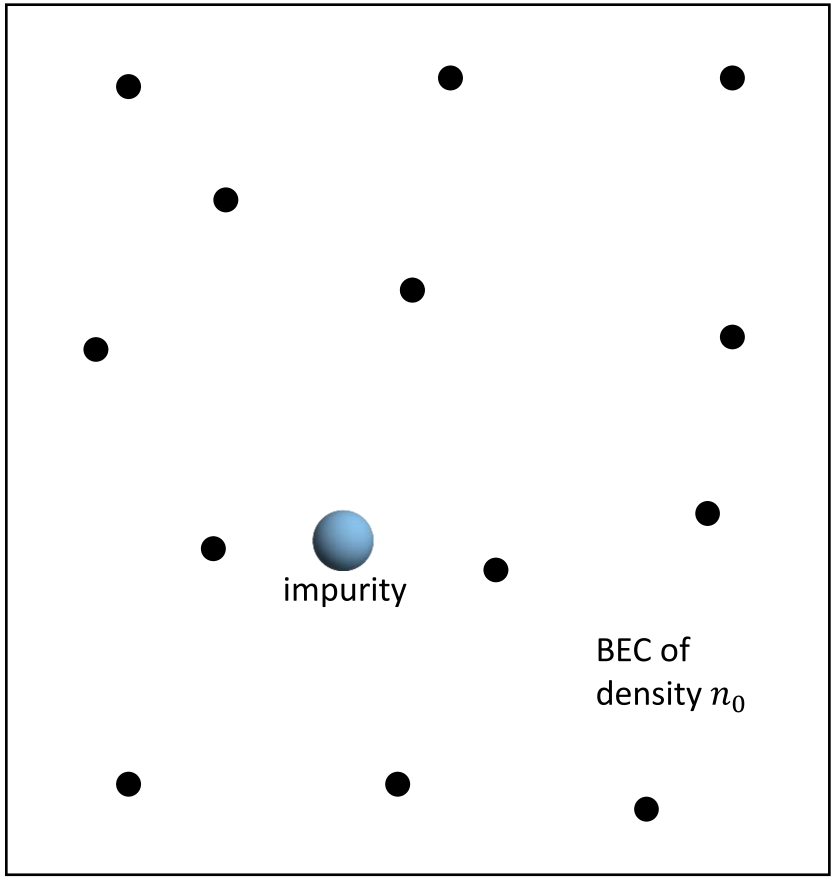
Polaron: particle interacting with a medium



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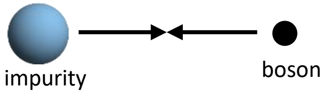

Small or large scattering length a

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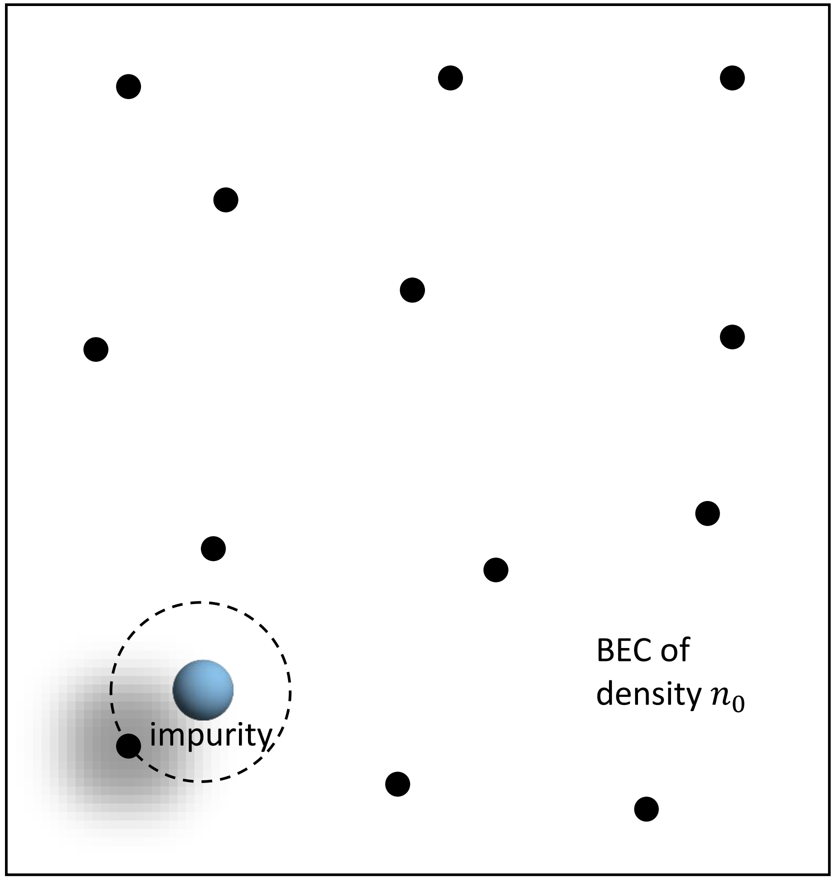

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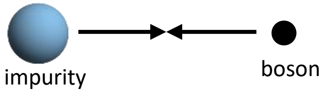
Short-range attraction



Small or large scattering length a

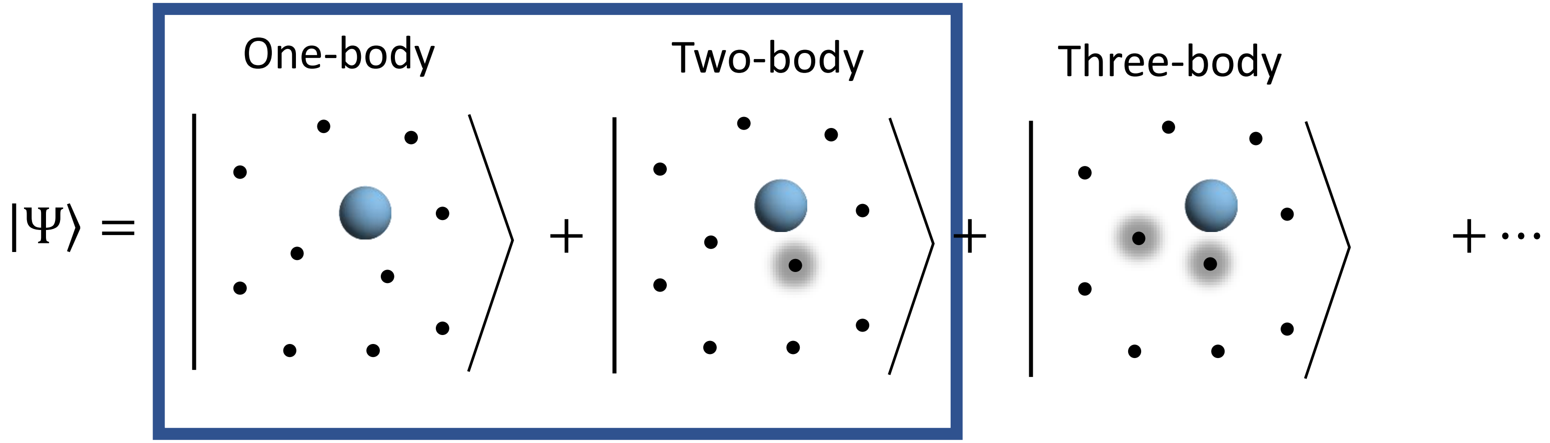
"Bose polaron"

"Artificial nucleon"

How do they interact?
How can they cluster?

One Bose polaron

The polaron problem can be treated as a set of coupled few-body problems
(Truncated basis method)



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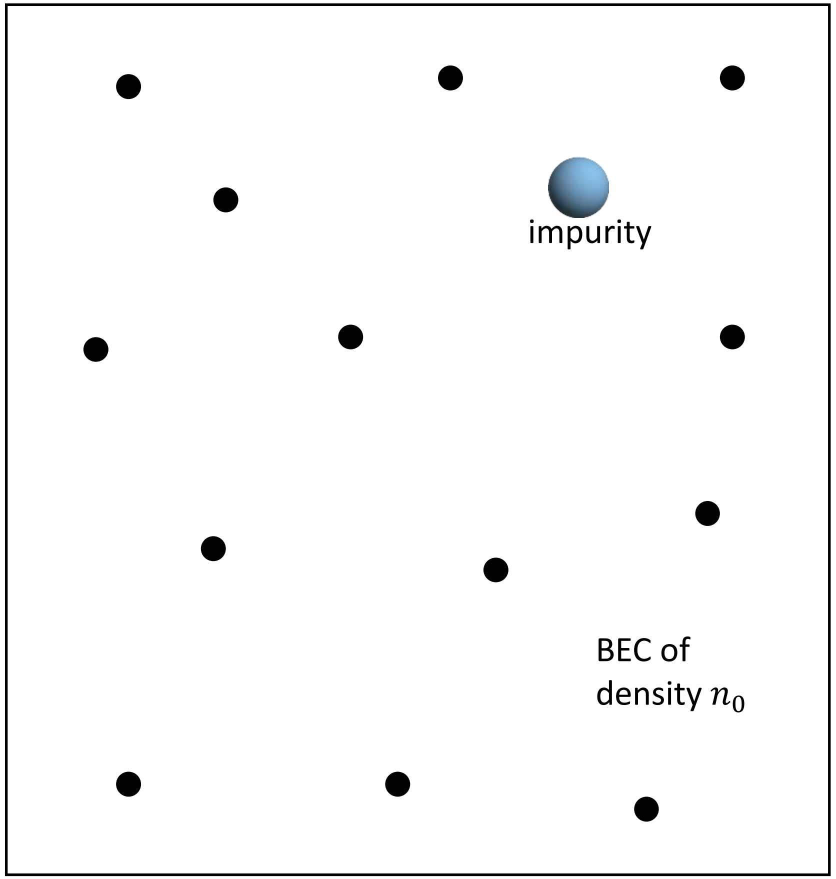

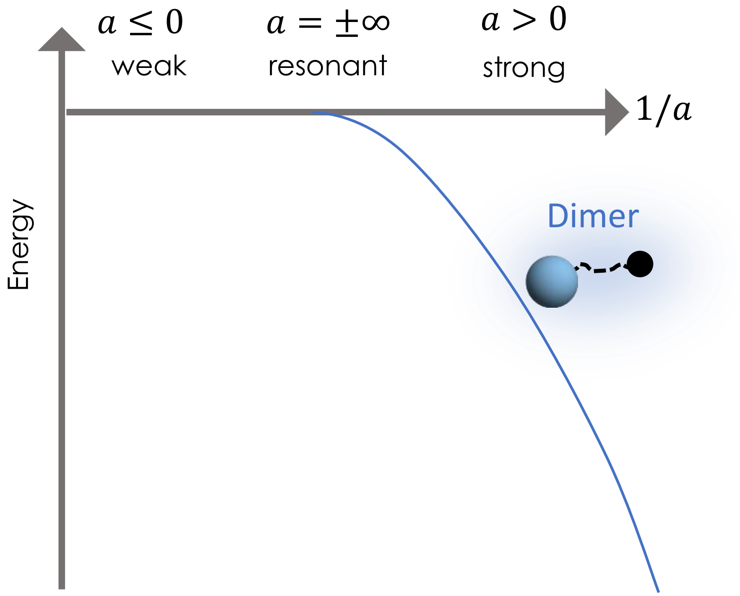

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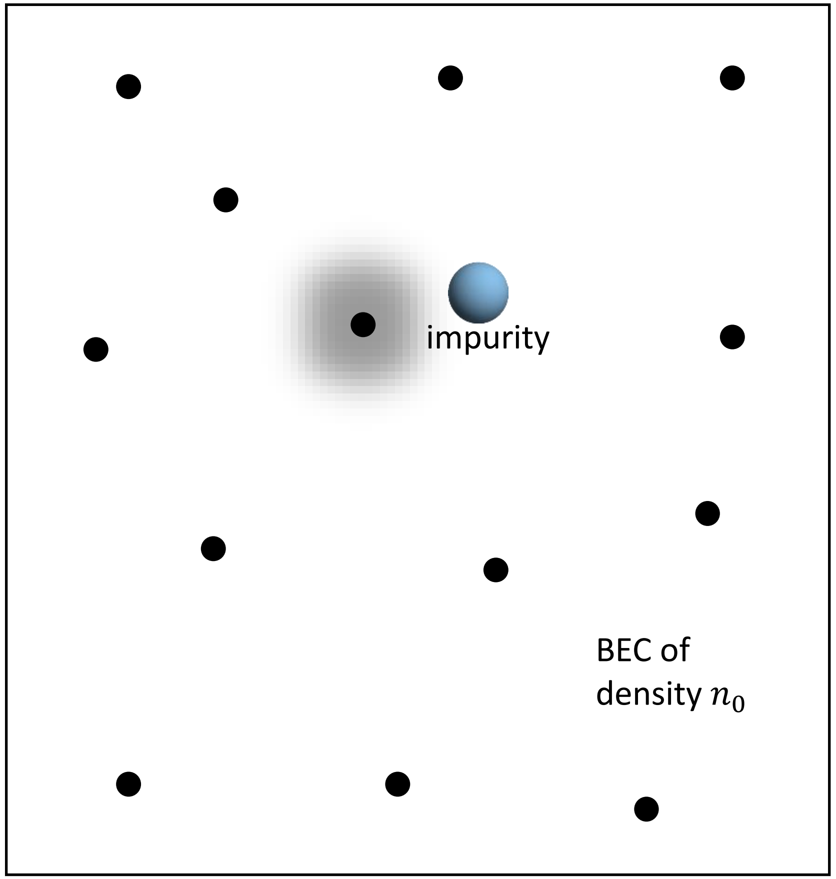

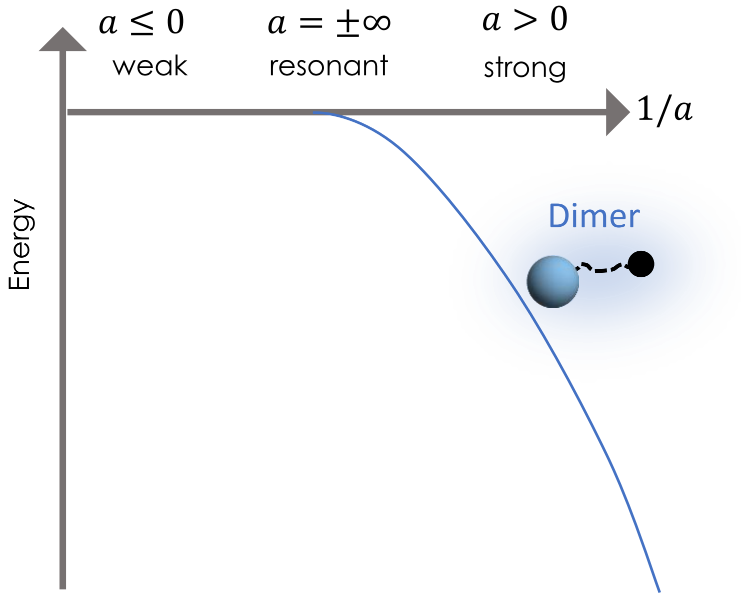

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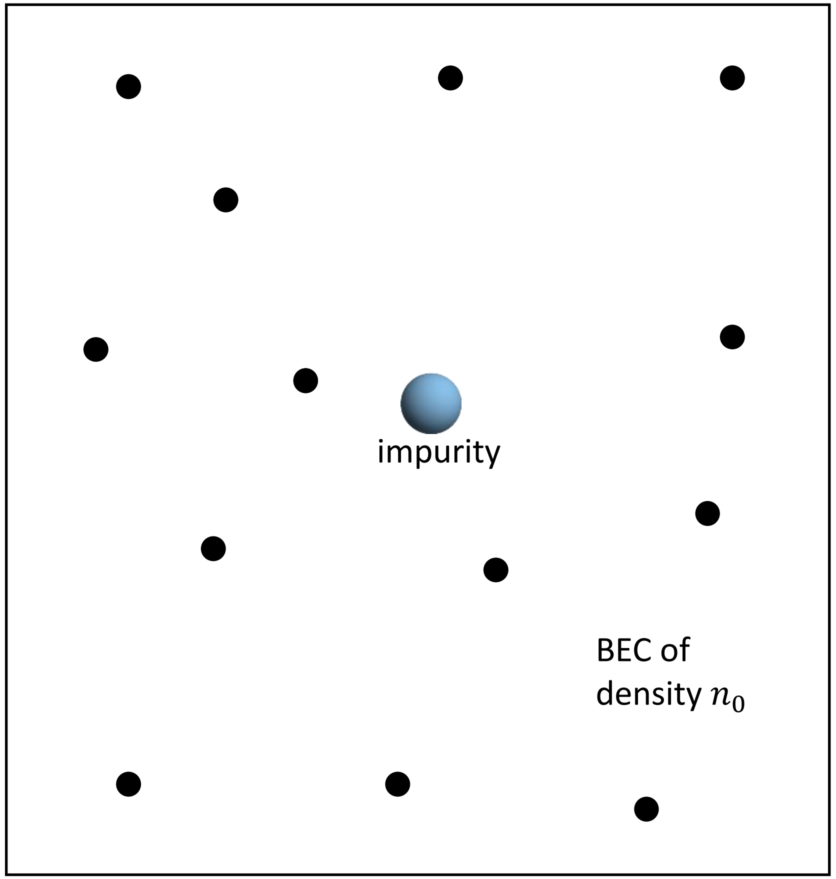

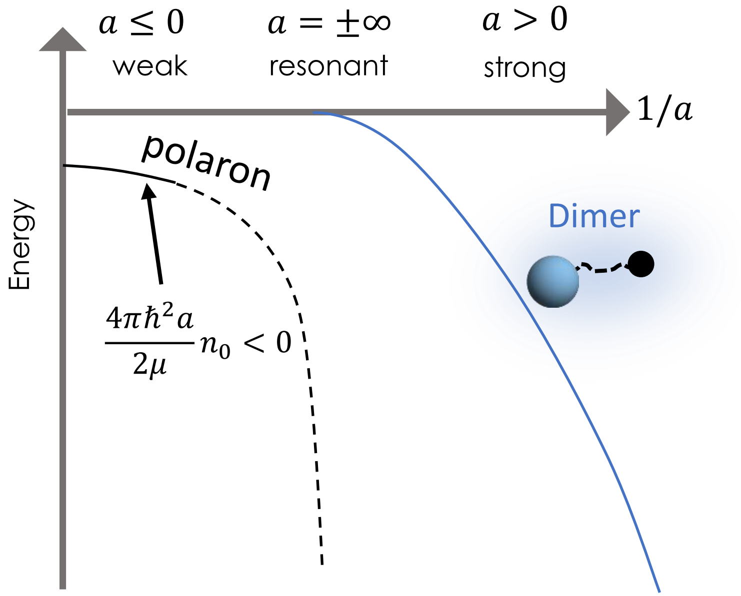

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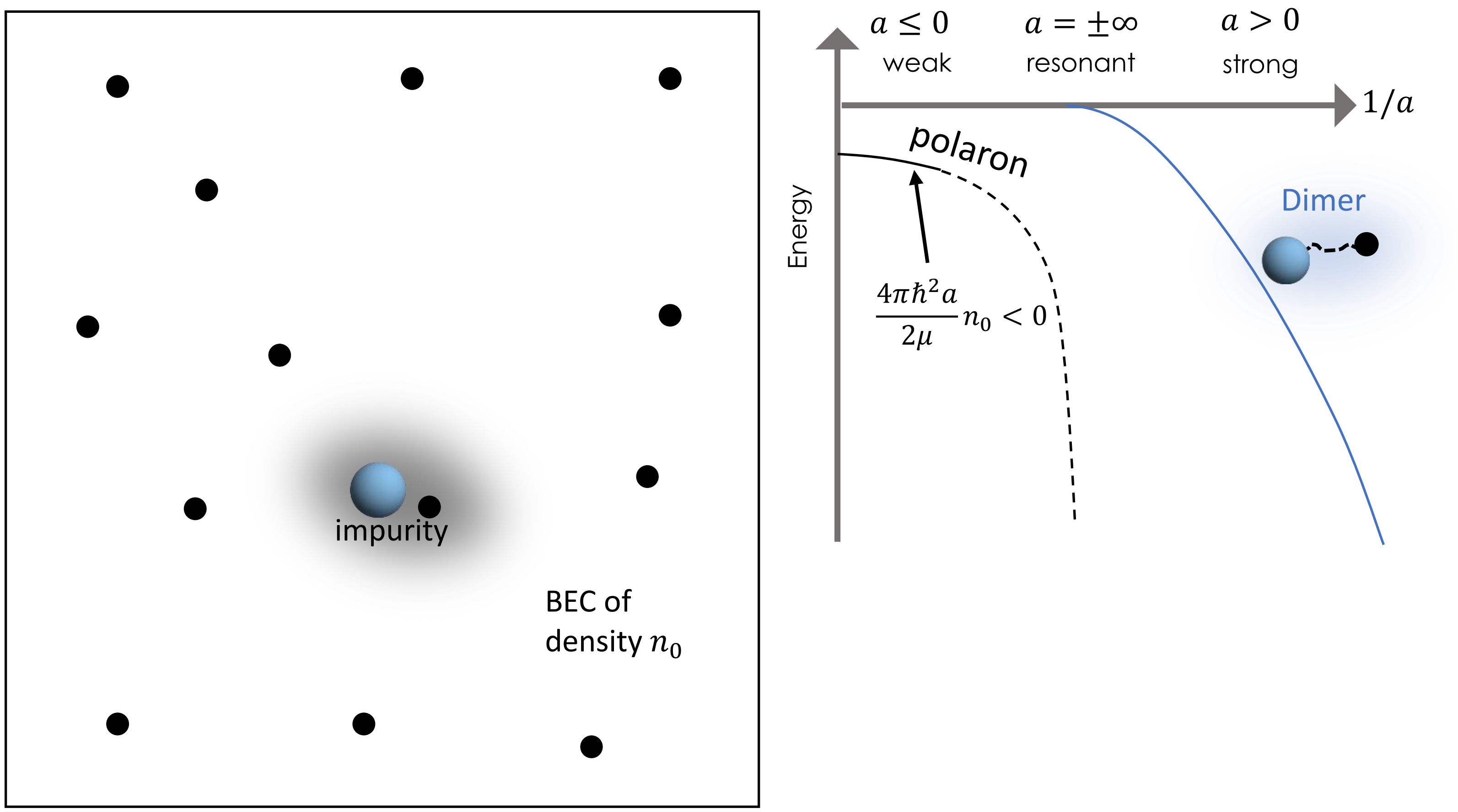
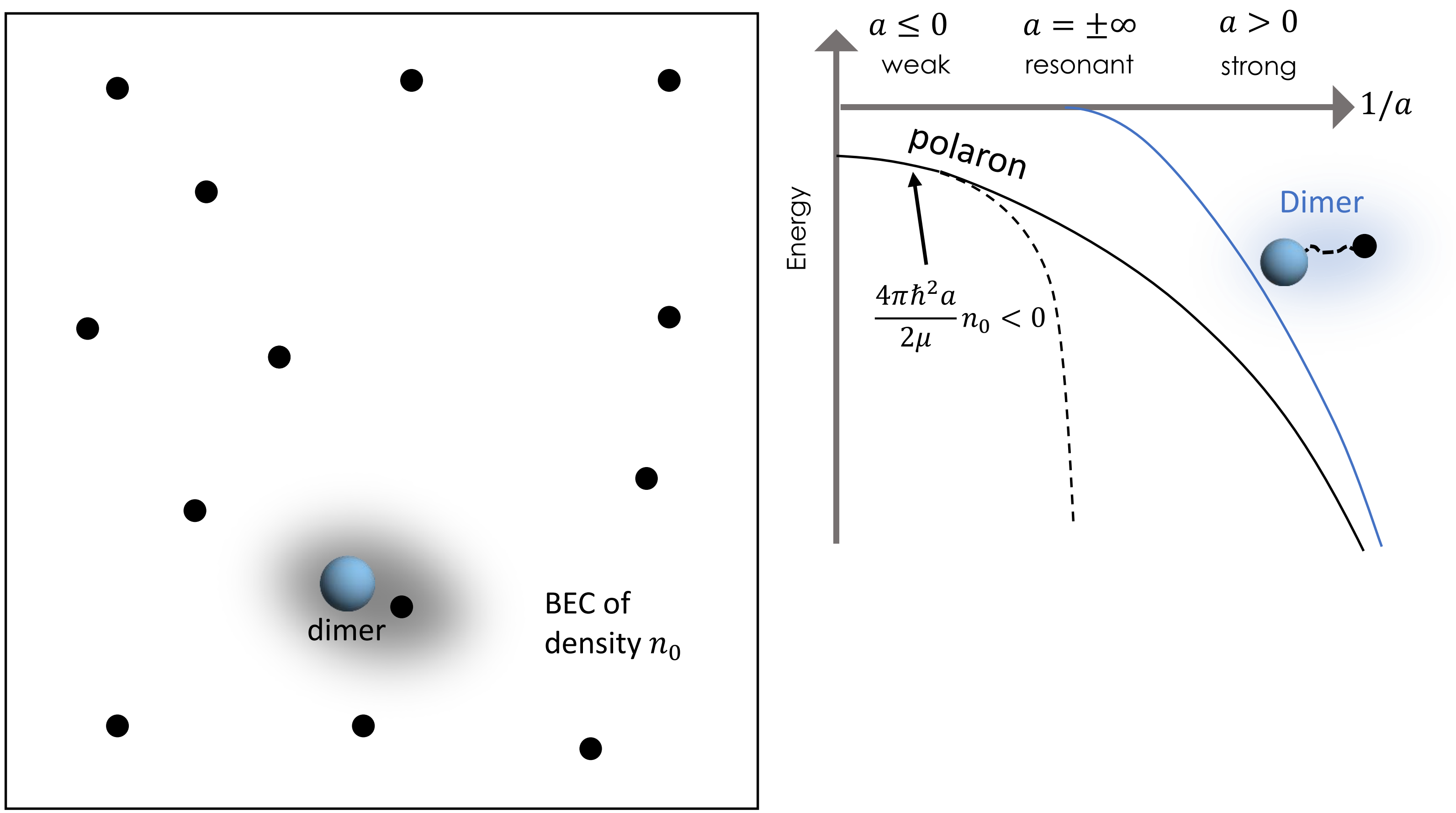
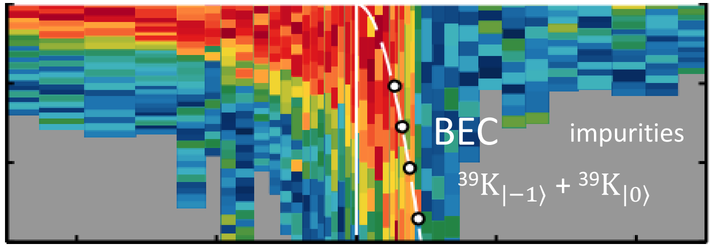


One Bose polaron

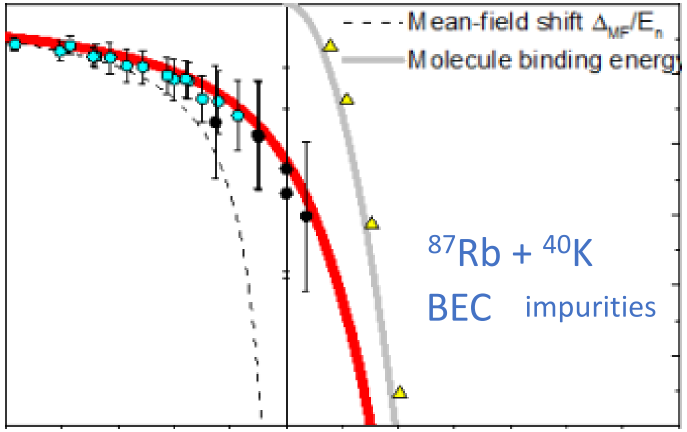


One Bose polaron

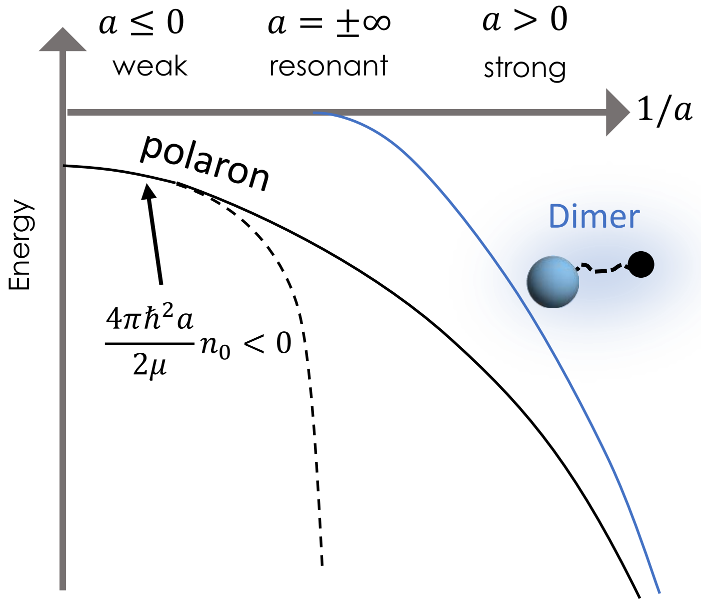
Observation of the Bose polaron



Jørgensen et al, PRL 117, 055302 (2016)

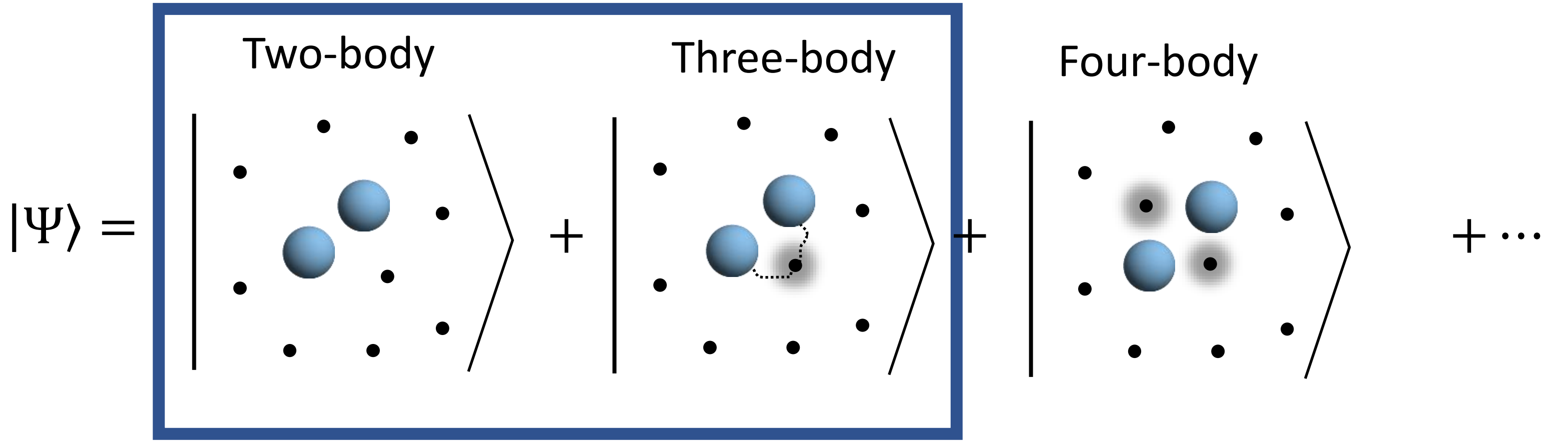


Ming-Guang Hu et al, PRL 117, 055301 (2016)



Two Bose polarons

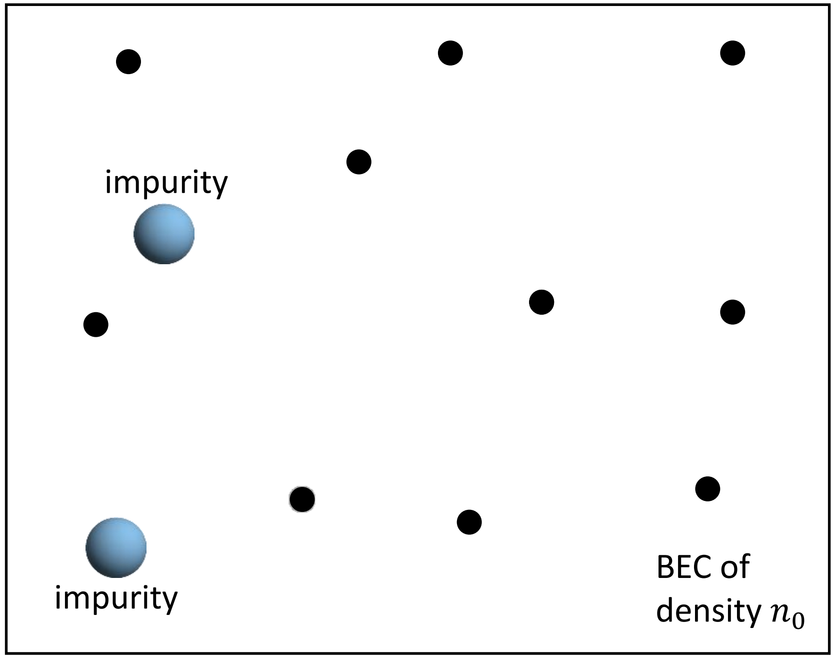
The two-polaron problem can be treated as a set of coupled few-body problems
(Truncated basis method)



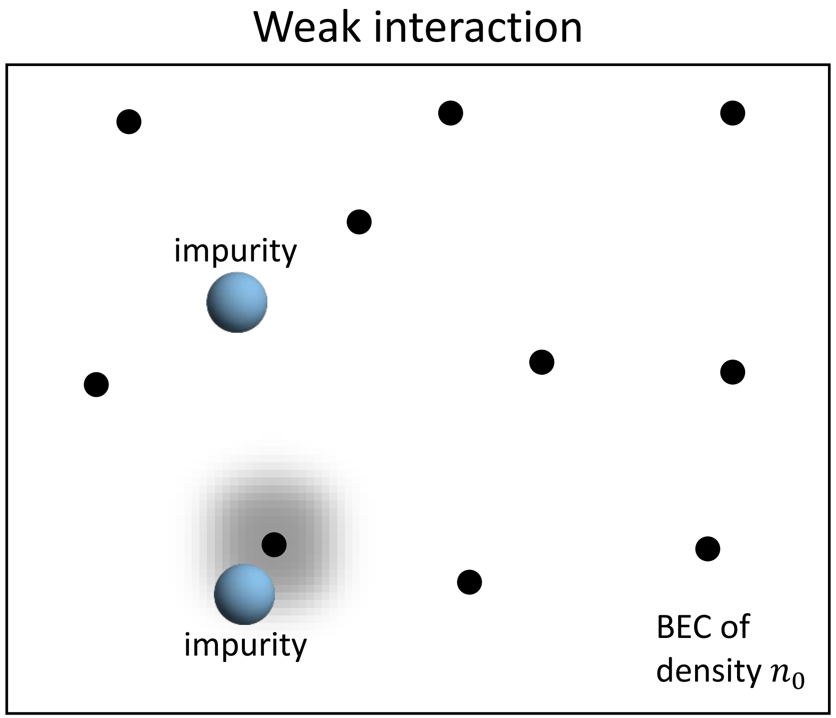
Excitations can mediate an interaction between the two impurities

Two Bose polarons

Weak interaction



Two Bose polarons



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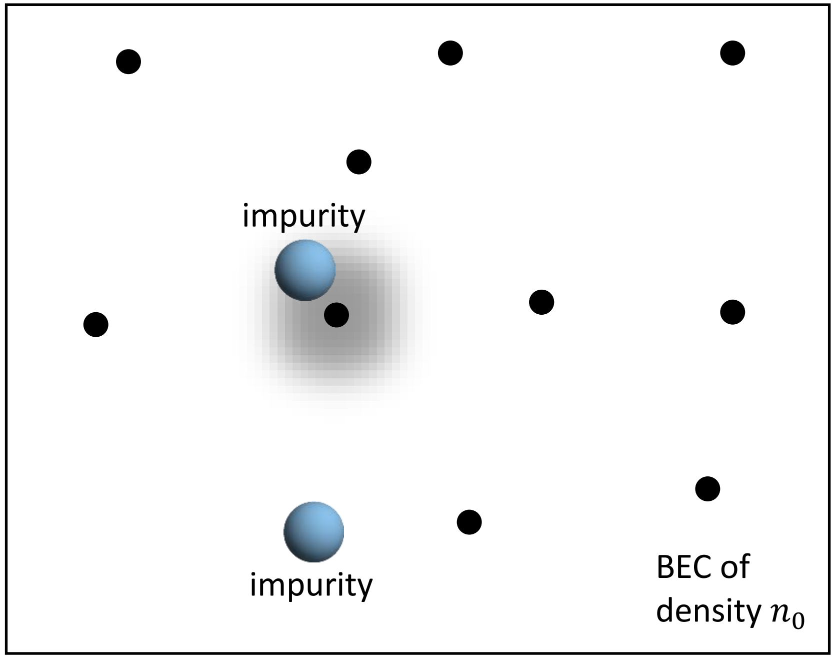
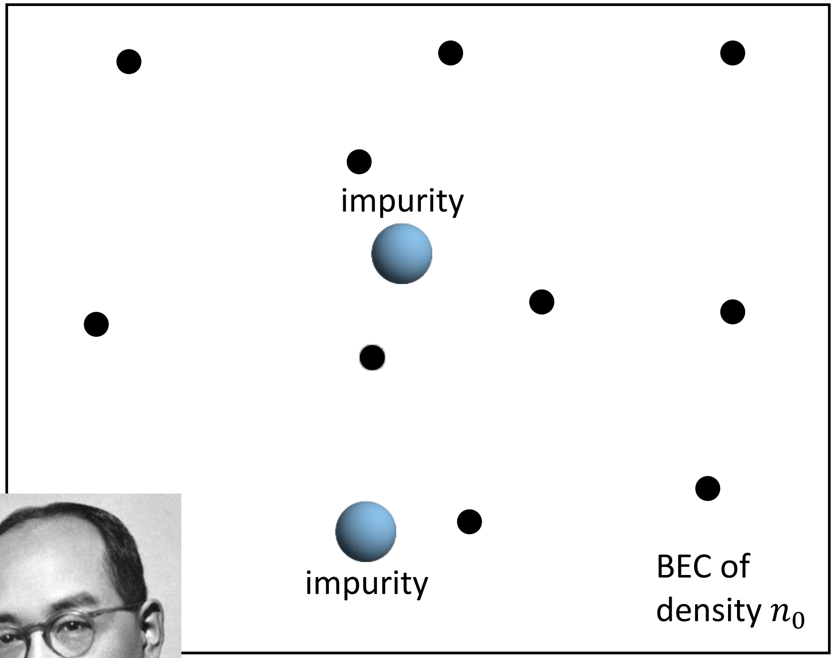
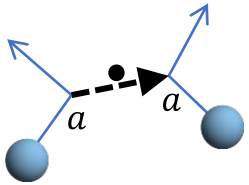
Weak interaction



Two Bose polarons

Weak interaction





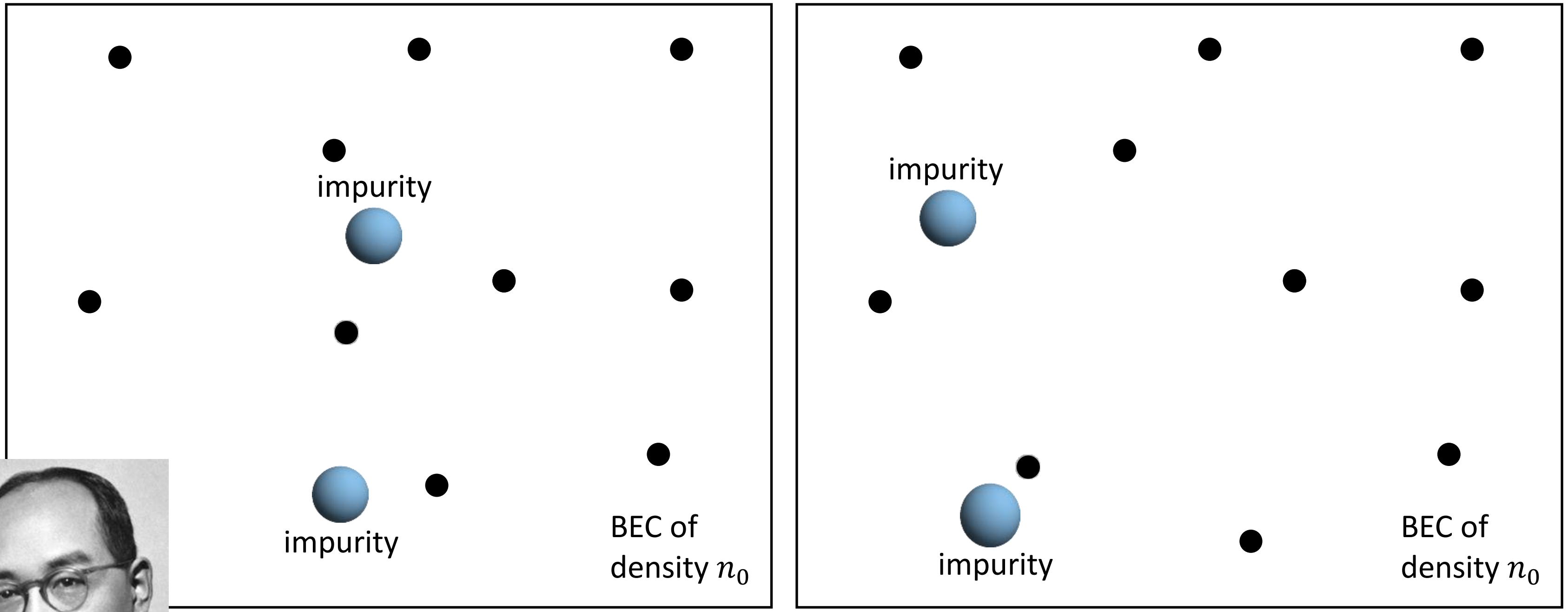
Yukawa potential

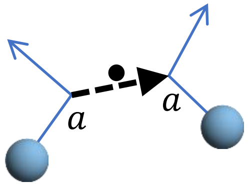
$$V(r) \propto -a^2 n_0 \frac{e^{-\sqrt{2}r/\xi}}{r}$$

$$\xi = (8\pi n_0 a_B)^{-1/2}$$

Two Bose polarons

Weak interaction | Resonant interaction





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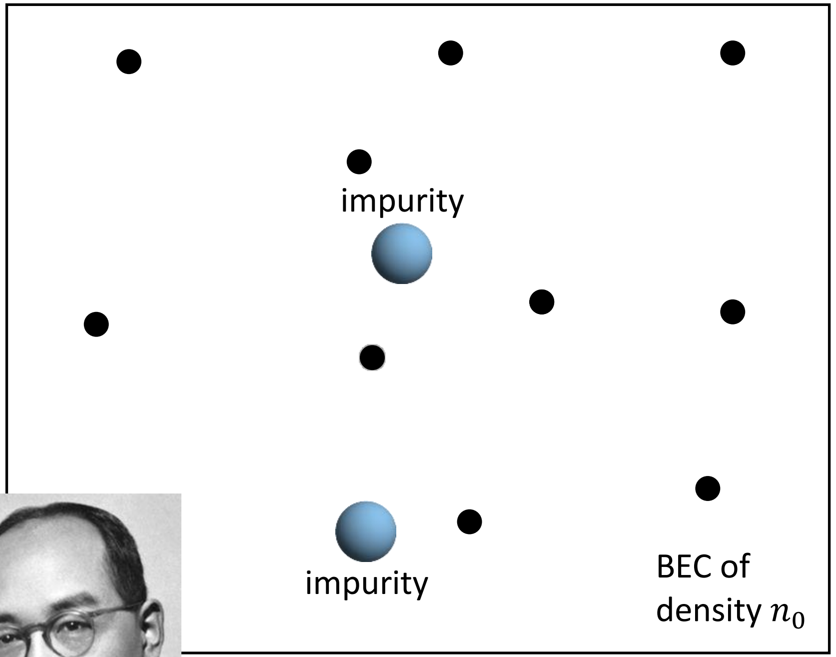
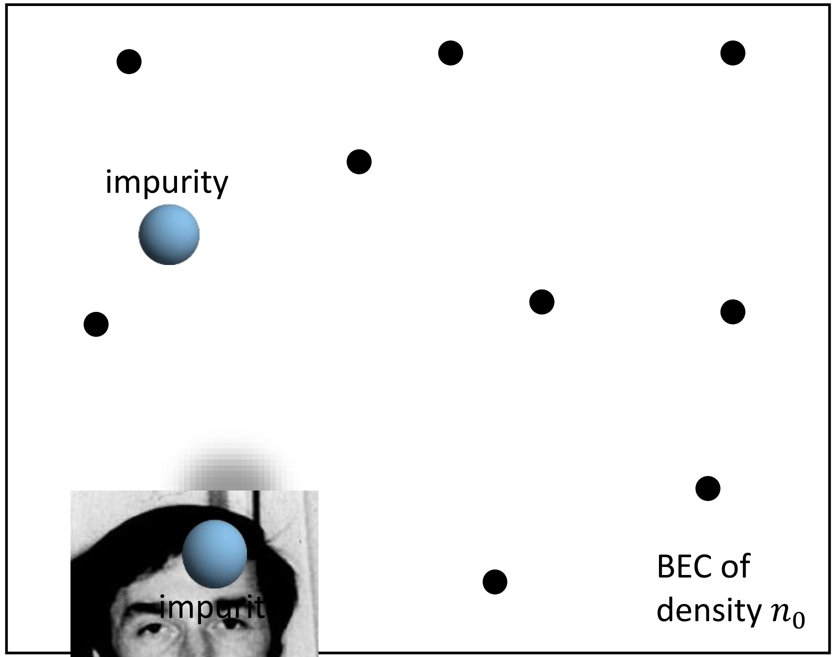
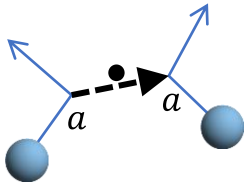
Two Bose polarons

Weak interaction



Resonant interaction





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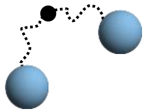

Efimov potential

$$V(r) = -\frac{\hbar^2}{m}\frac{0.16}{r^2}$$

Two Bose polarons

Weak interaction

Yukawa potential

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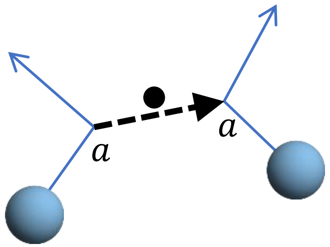

Resonant interaction

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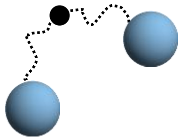


"exchange of virtual bosons"

"exchange of real bosons"

Two Bose polarons

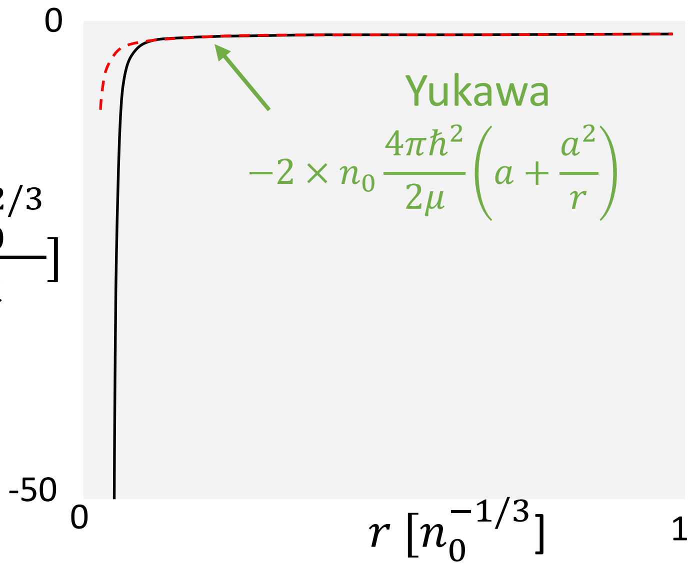
Effective potential (Born-Oppenheimer) between polarons:

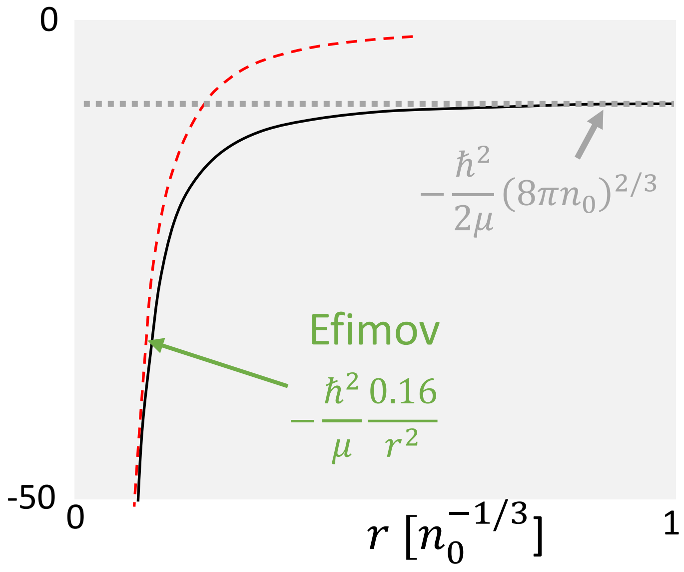
$$V(r) = -\frac{\hbar^2\kappa^2}{2\mu} \qquad \frac{1}{a} - \kappa + \frac{1}{r}e^{-\kappa r} + \frac{8\pi n_0}{\kappa^2} = 0 \qquad (a_B \to 0)$$

For small a $(a = -0.05 n_0^{-1/3})$

At resonance $a = \pm\infty$

$V(r)\ [\frac{\hbar^2 n_0^{2/3}}{2\mu}]$





Two Bose polarons

Calculation of the spectrum at a given mass ratio

Mass of impurities

$$\frac{M}{m} = 19$$

Mass of bosons

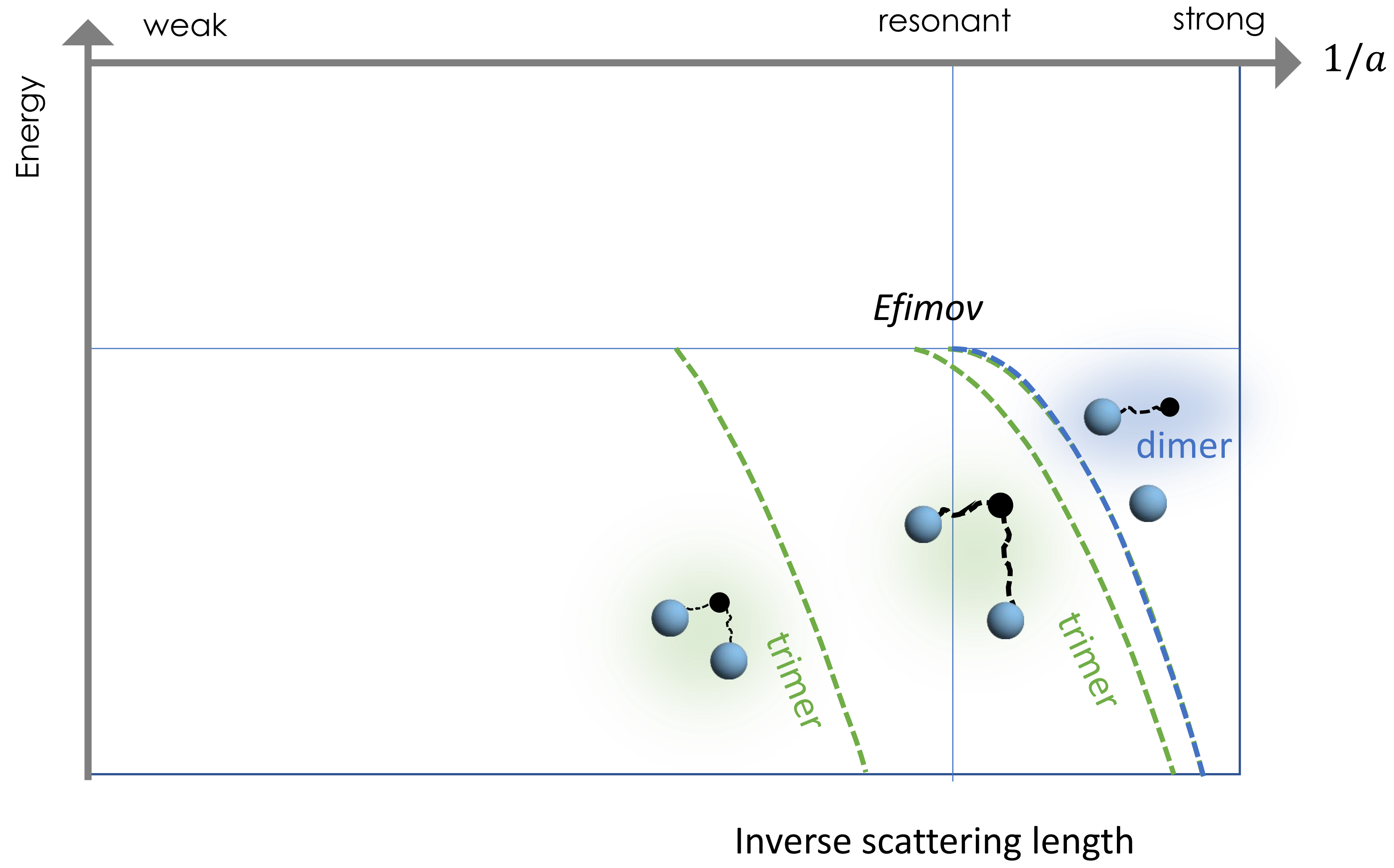
Ex:
impurities: Cesium-133
Bosons: Lithium-7

$$n_0 a_B^3 = 0.00001$$

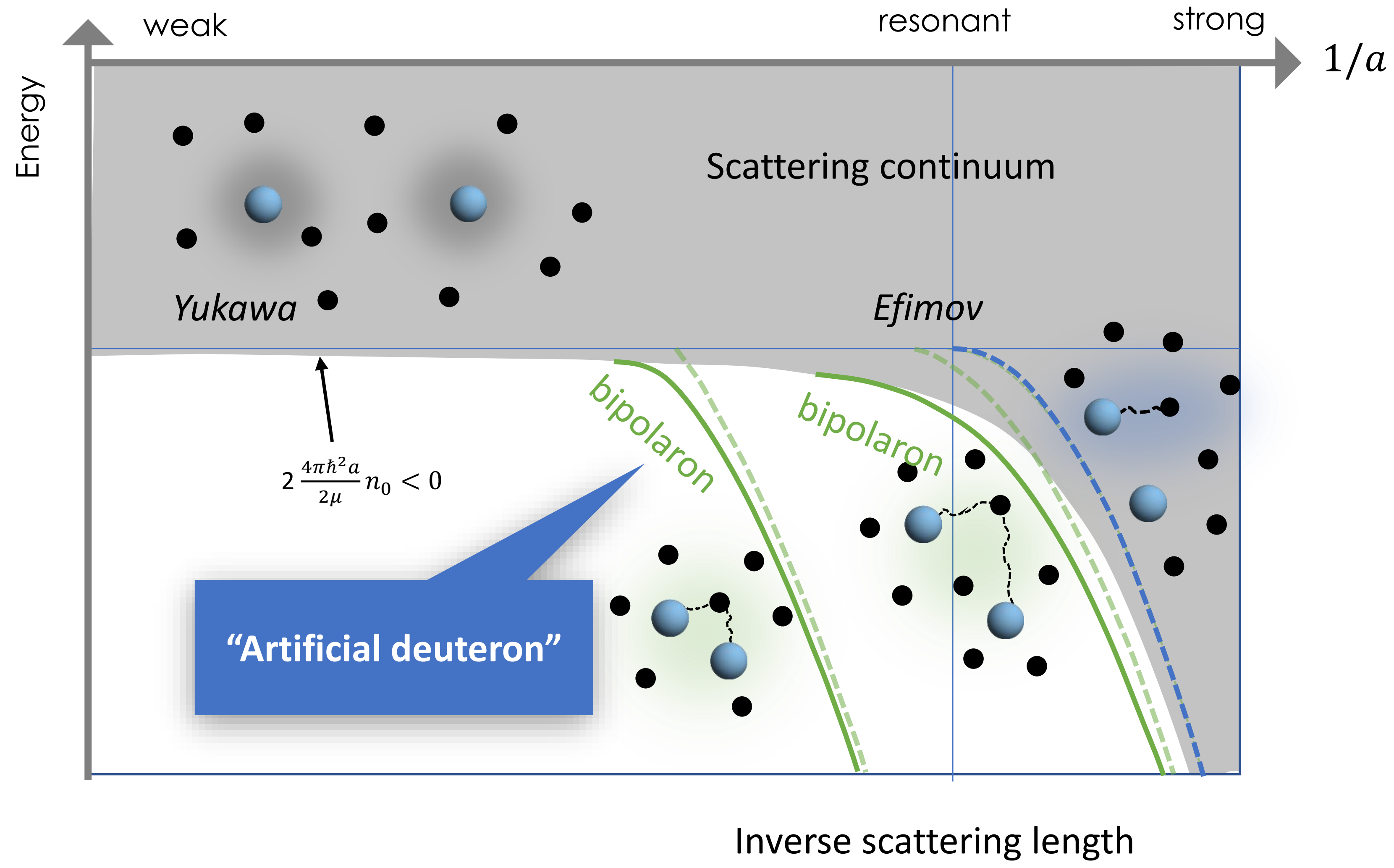
Density of bosons

Scattering length of bosons

Two Bose polarons

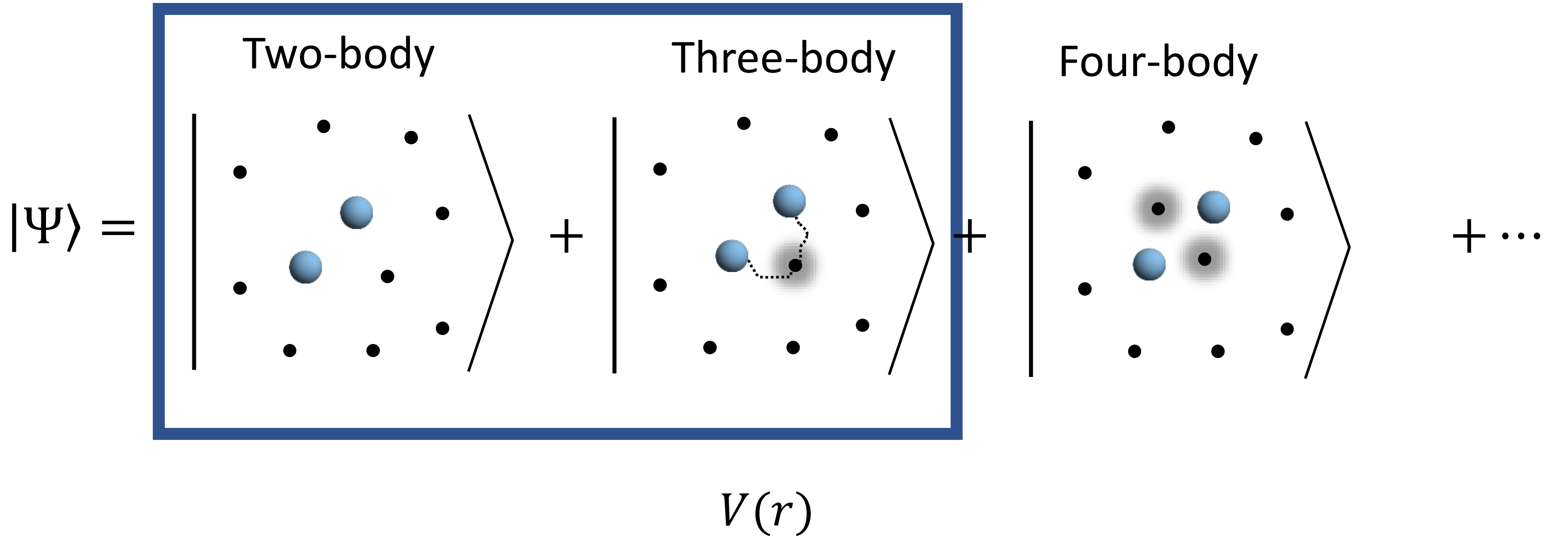


Two Bose polarons



Two Bose polarons

The two-polaron problem can be treated as a set of coupled few-body problems



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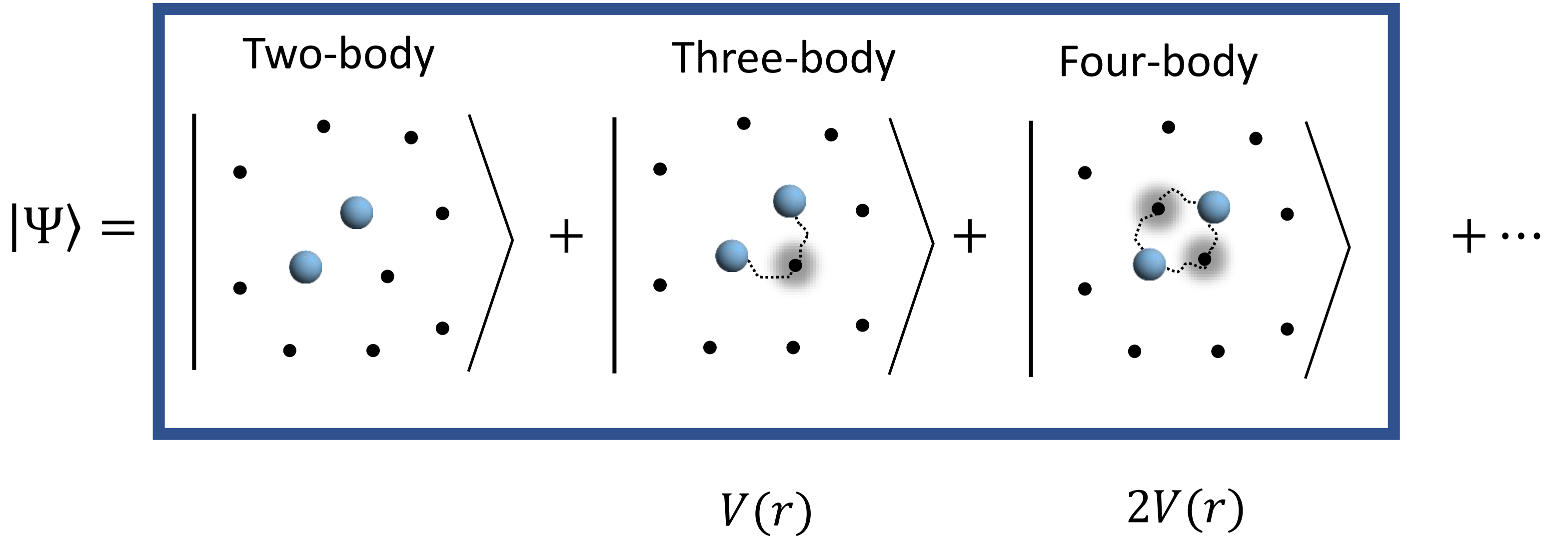

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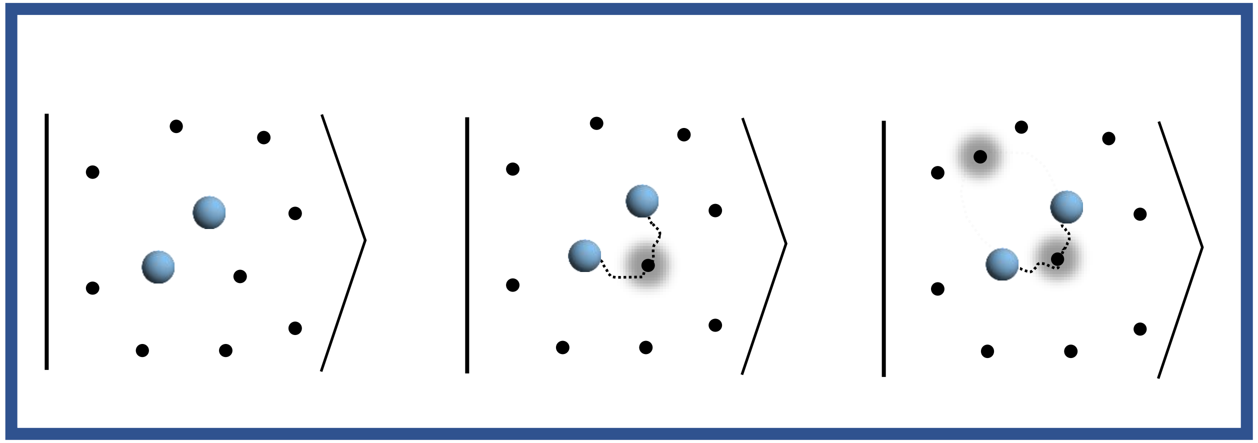
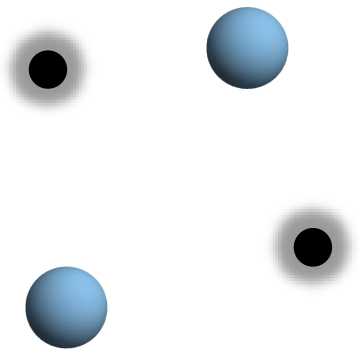


$V(r)$ $V(r)$

FOUR-BODY PROBLEM: 2+2 bosons



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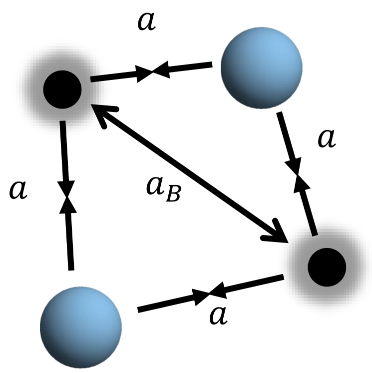


Separable interaction model:

$$V = \frac{4\pi\hbar^2}{2\mu} g|\phi\rangle\langle\phi| \qquad g < 0 \qquad \phi(p) = \begin{cases} 1 \text{ for } p \leq \Lambda \\ 0 \text{ for } p > \Lambda \end{cases}$$

Scattering length $a = \left(g^{-1} + \frac{2}{\pi}\Lambda\right)^{-1}$

Contact interaction limit: $\Lambda \to \infty$

$$V_B = \frac{4\pi\hbar^2}{m} g_B|\phi_B\rangle\langle\phi_B| \qquad g_B > 0 \qquad \phi_B(p) = \begin{cases} 1 \text{ for } p \leq \Lambda_B \\ 0 \text{ for } p > \Lambda_B \end{cases}$$

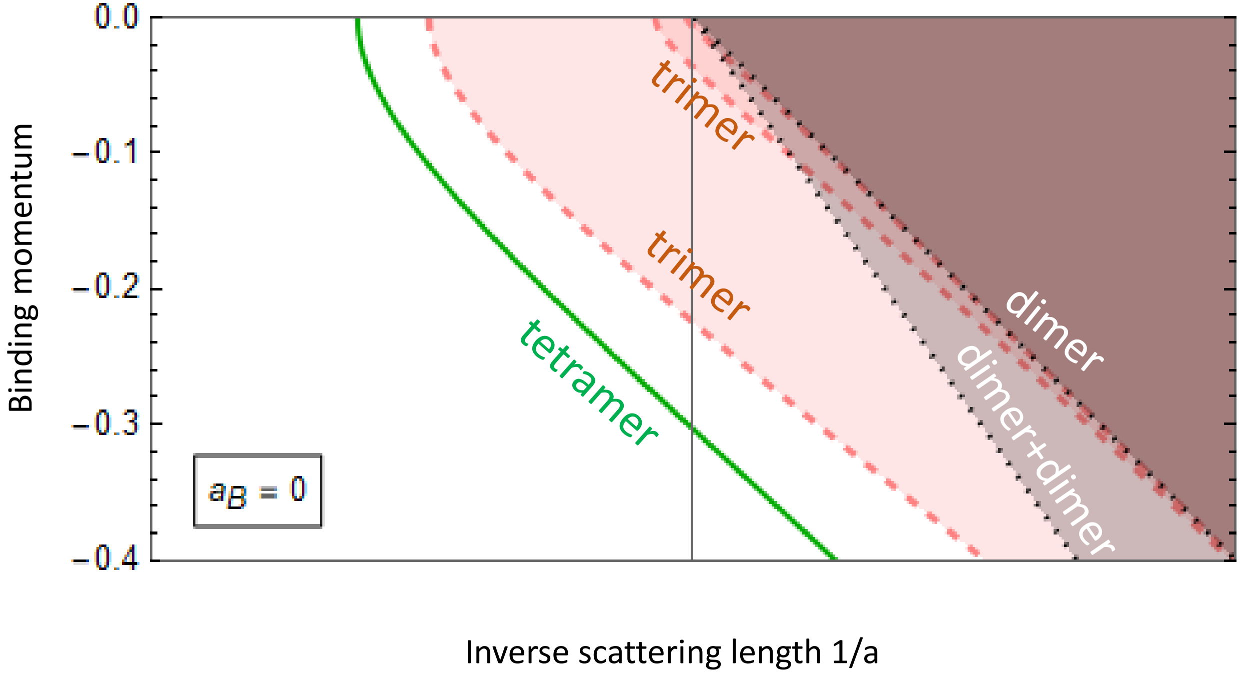
3-body cutoff $\Lambda_3 \sim \ l_{vdW}^{-1}$

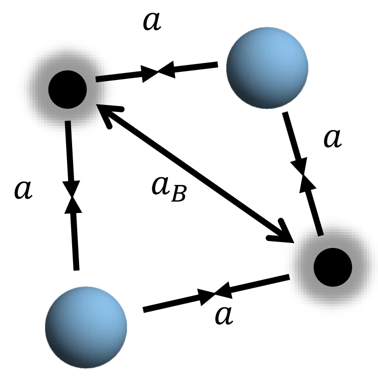
Scattering length $a_B = \left(g_B^{-1} + \frac{2}{\pi}\Lambda_B\right)^{-1}$

Strong repulsion limit: $g_B \to \infty$

FOUR-BODY PROBLEM: 2+2 bosons

Energy spectrum $\frac{M}{m} = 19$ (^{133}Cs in ^{7}Li)





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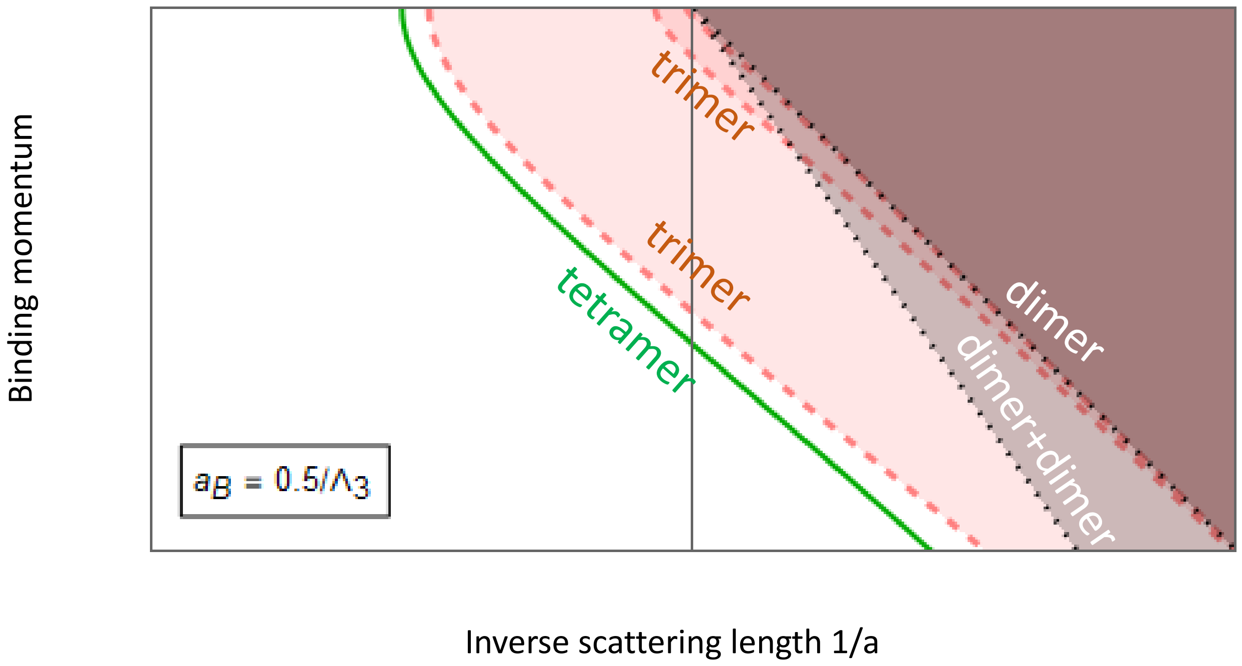

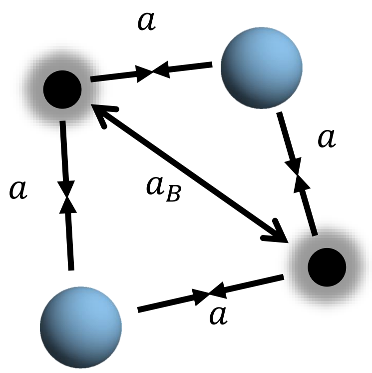

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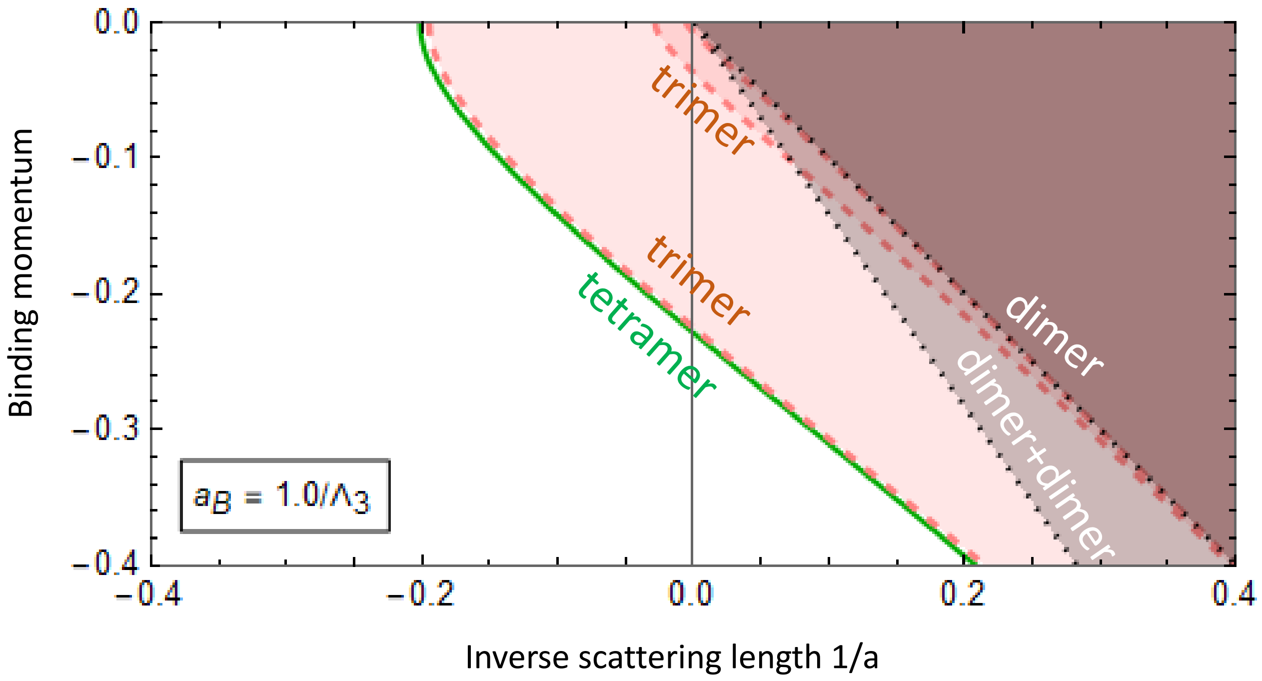
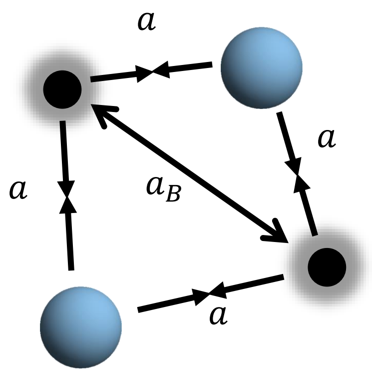
Energy spectrum $\frac{M}{m} = 19$ (^{133}Cs in ^{7}Li)

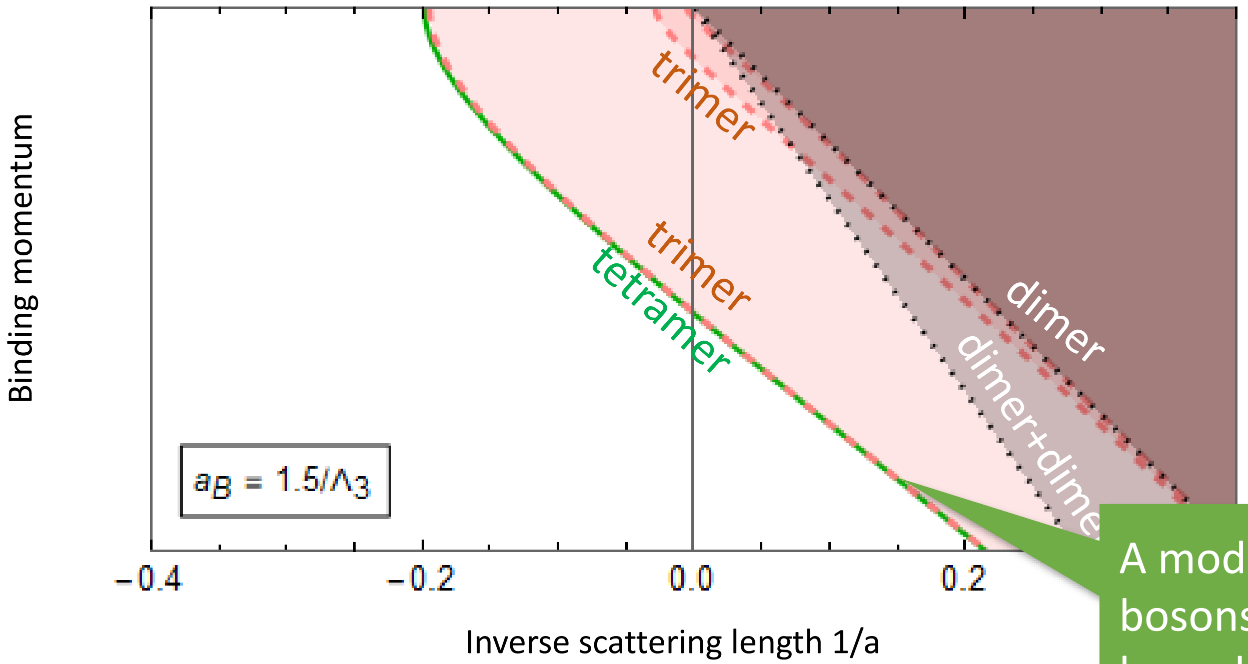


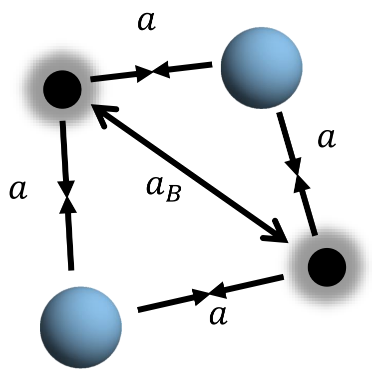


3-body cutoff $\Lambda_3 \sim \; l_{vdW}^{-1}$

FOUR-BODY PROBLEM: 2+2 bosons

Energy spectrum $\frac{M}{m} = 19$ (^{133}Cs in ^{7}Li)





3-body cutoff $\Lambda_3 \sim l_{vdW}^{-1}$

A moderate repulsion between bosons can suppress the four-body bound state

② Polaron physics: summary

- The 3-body Efimov effect in mass imbalanced systems close to unitarity affects the polaron physics. The mediated interaction changes from Yukawa to Efimov type, and leads to bipolarons.
- A simple single-excitation picture captures this physics.

Outlook

- More consistent picture with more excitations?
- More polarons.

③ Miscibility physics

Dmitry Petrov

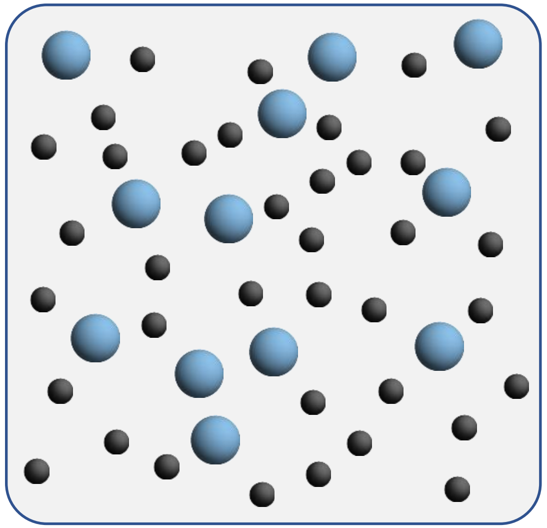
LPTMS, Orsay

Mixed bubbles in Bose-Bose mixtures

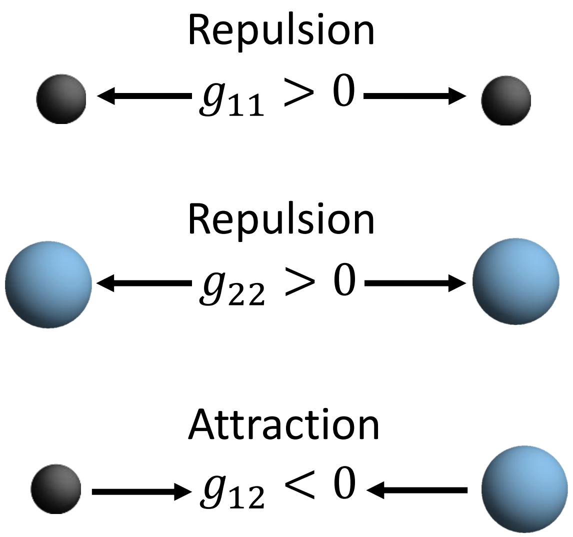
Phys. Rev. Lett. 126, 115301 (2021)

[arXiv:2008.05870]

Mixture of cold atoms: many-body



Mixture



The coupling constants are given by the scattering lengths

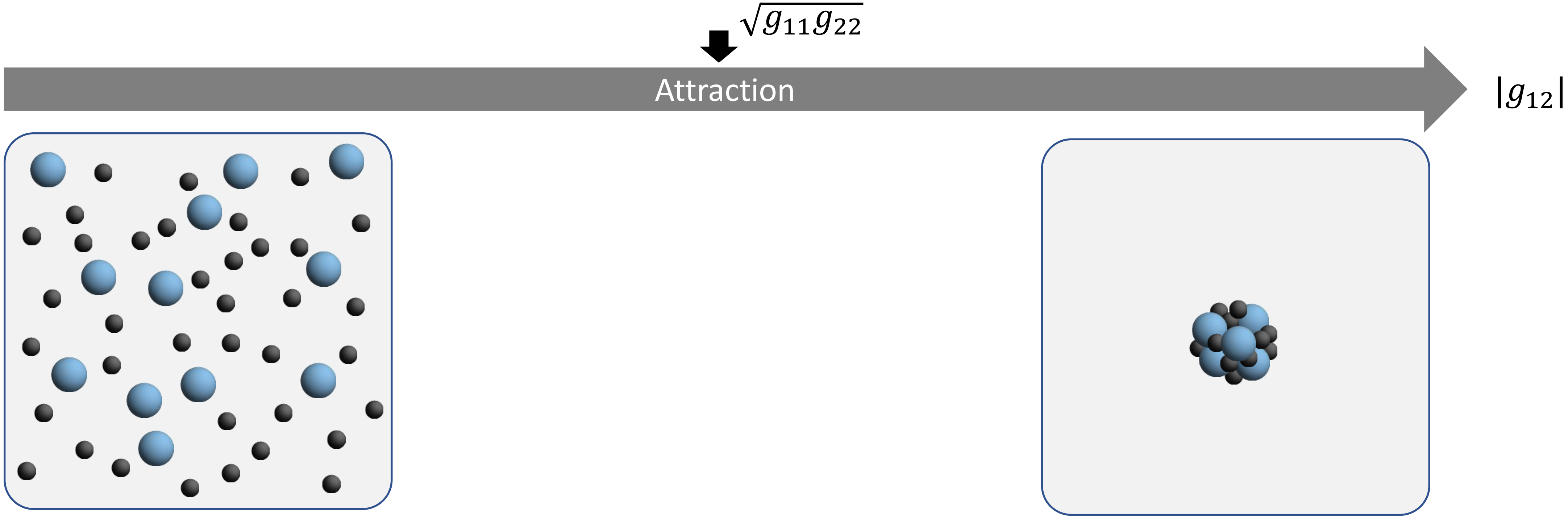
$$g_{ij} = \frac{4\pi\hbar^2 a_{ij}}{m}$$

Weak interactions, far from unitarity!
(no Efimov effect)

Mean-field theory:

$$E/V = \frac{1}{2} g_{11} n_1^2 + \frac{1}{2} g_{22} n_2^2 + g_{12} n_1 n_2$$

Mixture of cold atoms: many-body

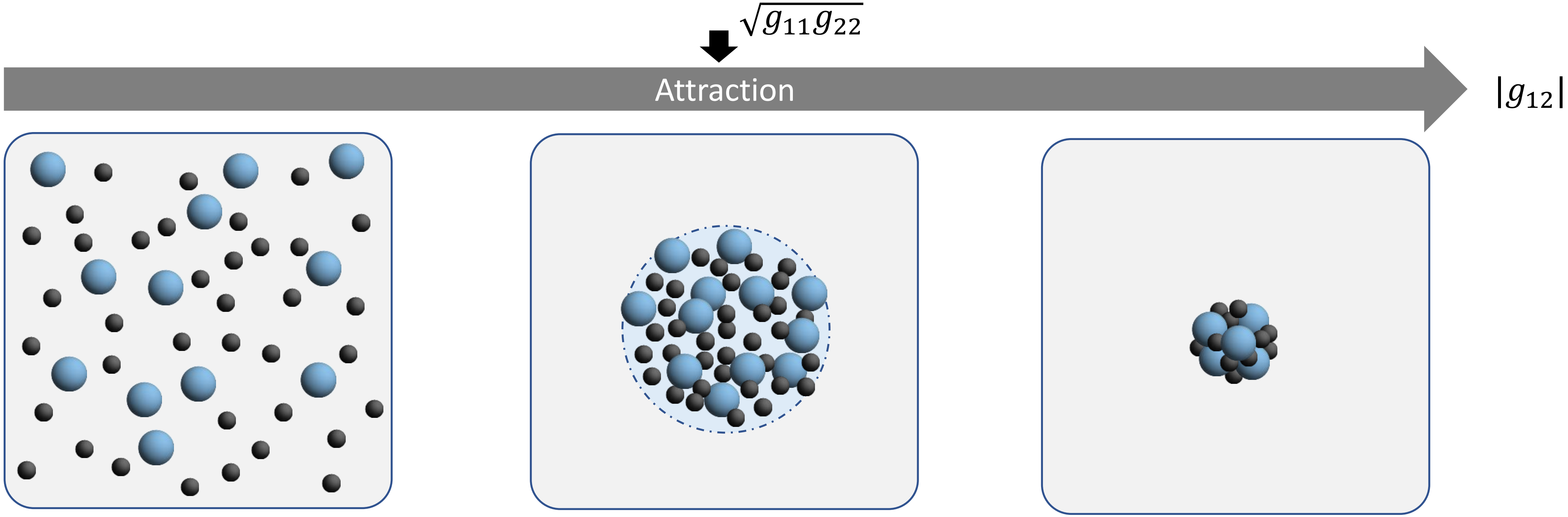


Mixture **Collapsed (solid)**

Mean-field theory:

$$E/V = \frac{1}{2}g_{11}n_1^2 + \frac{1}{2}g_{22}n_2^2 + g_{12}n_1n_2$$

Mixture of cold atoms: many-body

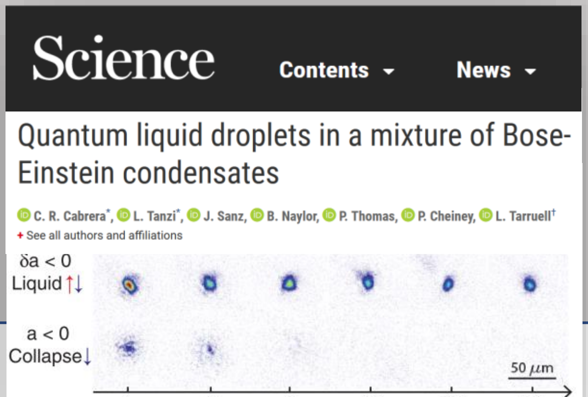


Mixture

Collapsed (solid)

Dmitry Petrov
Prediction (2015)

Observation (2018)


Science Contents News

Quantum liquid droplets in a mixture of Bose-Einstein condensates

C. R. Cabrera*, L. Tanzi*, J. Sanz, B. Naylor, P. Thomas, P. Cheiney, L. Tarruell†
+ See all authors and affiliations

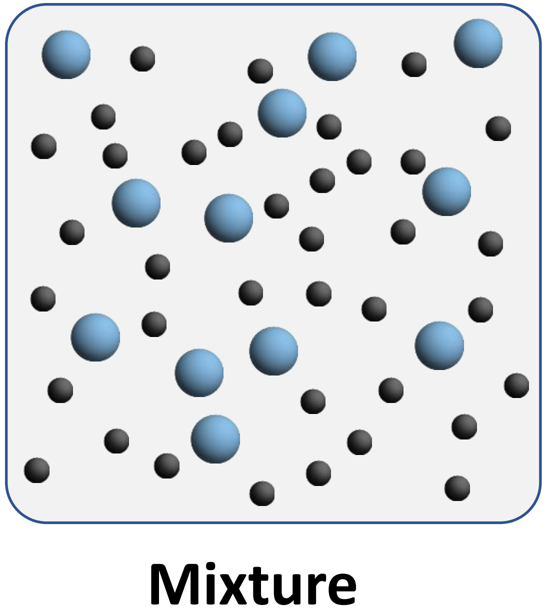
Beyond mean-f

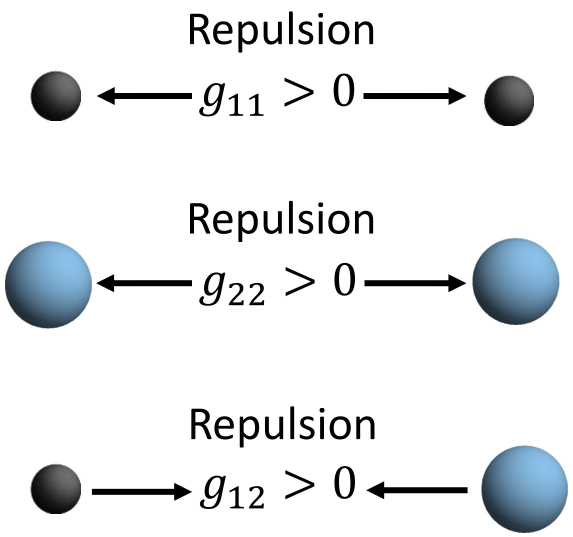
$E/V =$

$\propto n^{5/2}$

(n_1, n_2)

Mixture of cold atoms: repulsive

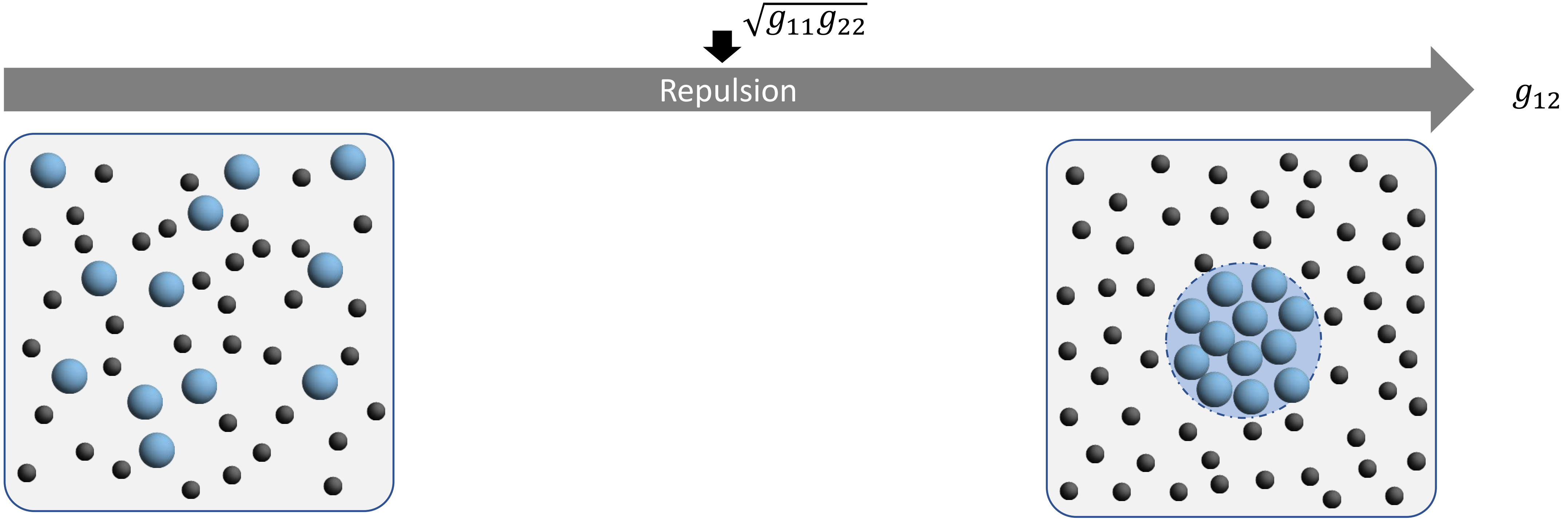




Mean-field theory:

$$E/V = \frac{1}{2} g_{11} n_1^2 + \frac{1}{2} g_{22} n_2^2 + g_{12} n_1 n_2$$

Mixture of cold atoms: repulsive

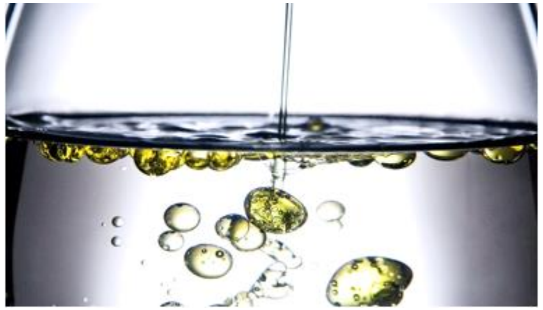


Mixture

Separated

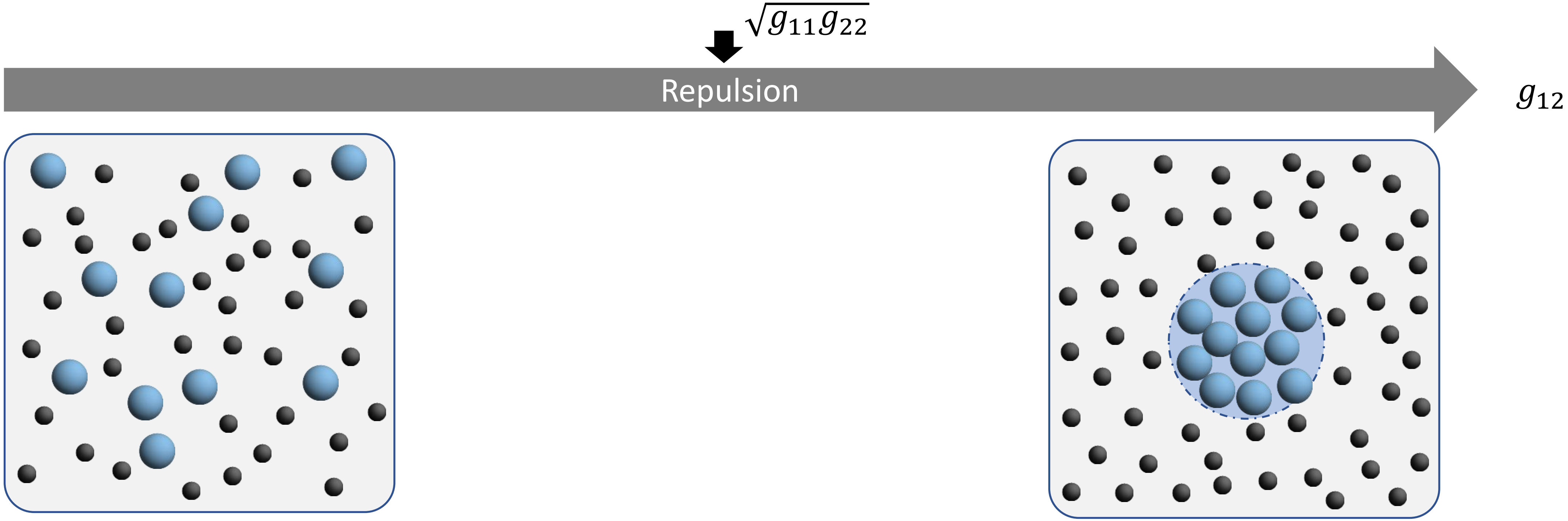
Mean-field theory:

$$E/V = \frac{1}{2} g_{11} n_1^2 + \frac{1}{2} g_{22} n_2^2 + g_{12} n_1 n_2$$



Like oil and water (but gases!)

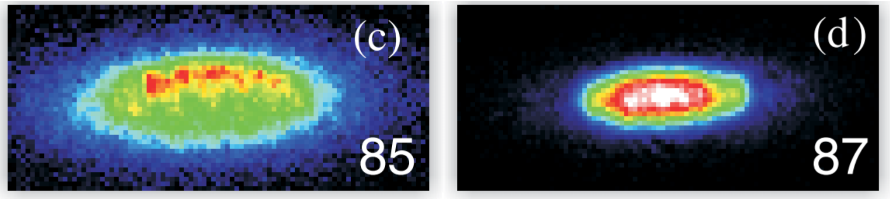
Mixture of cold atoms: repulsive



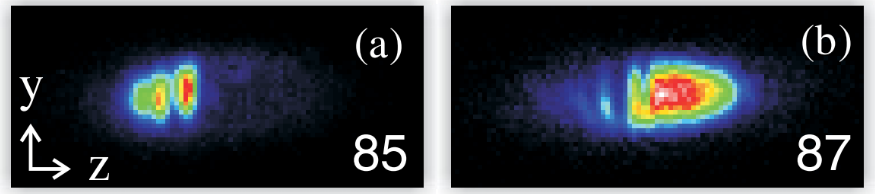
Mixture

Separated

Rubidium atom mixture ($^{85}Rb + ^{87}Rb$)

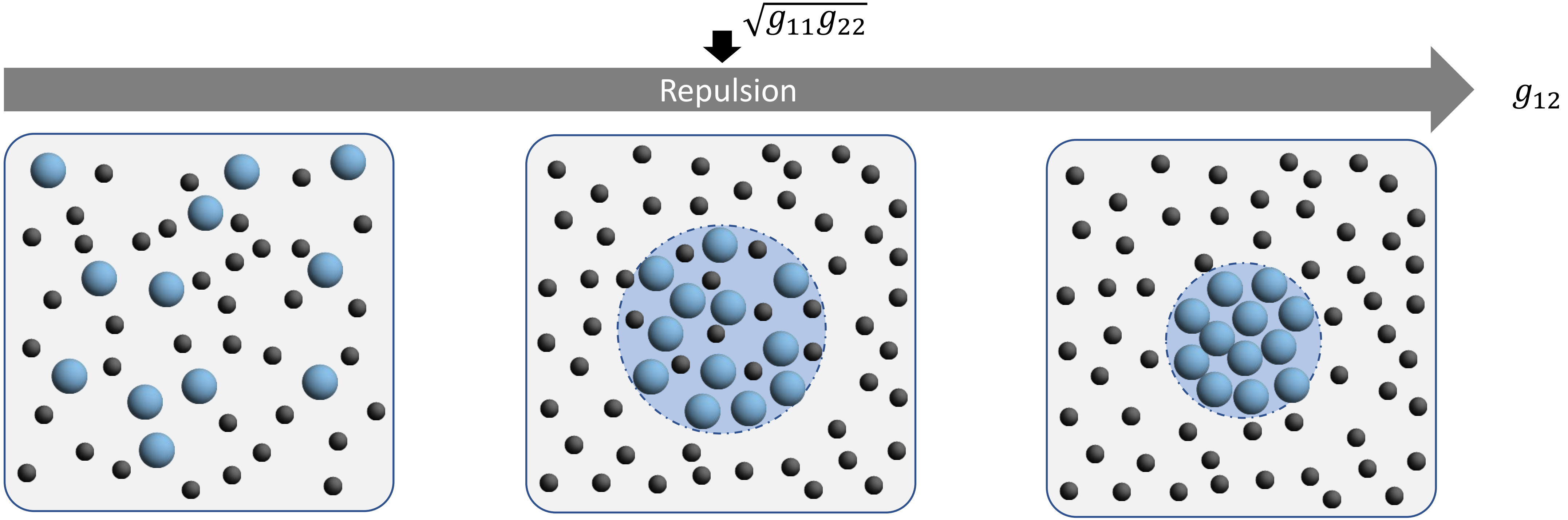


Rubidium atom mixture ($^{85}Rb + ^{87}Rb$)



Papp et al., PRL 101, 040402 (2008)

Mixture of cold atoms: repulsive



Mixed

$g_{12} < \sqrt{g_{11}g_{22}} - \epsilon$

Partially mixed
"mixed bubble"

Separated

$g_{12} > \sqrt{g_{11}g_{22}}$

Beyond mean-field theory:

$$E/V = \frac{1}{2} g_{11} n_1^2 + \frac{1}{2} g_{22} n_2^2 + g_{12} n_1 n_2 + E_{LHY}(n_1, n_2)$$

③ Miscibility physics: Summary

- Close to miscibility/immiscibility threshold of a Bose mixture, quantum fluctuations allow the existence of partially mixed bubbles, bearing some similarity to quantum liquid droplets.
- Compared to the liquid droplet, the mixed bubble may be difficult to observe experimentally.

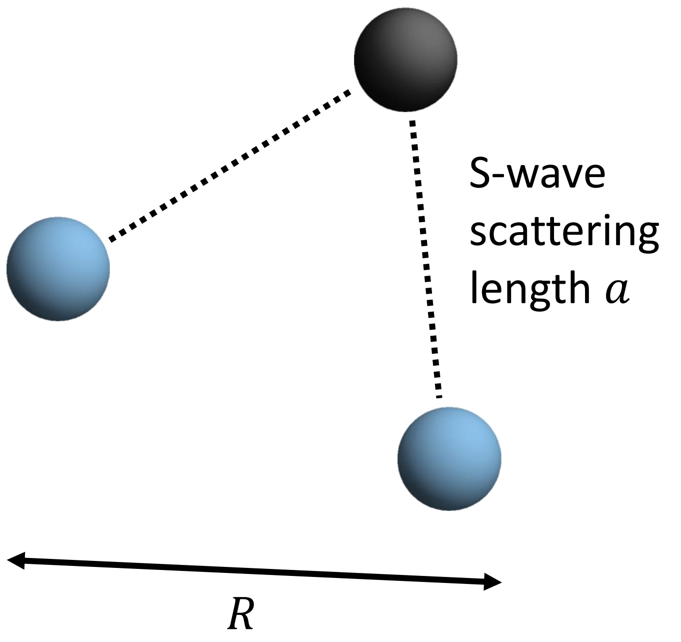
④ Universal trimers of fermions

Ludovic Pricoupenko
Sorbonne Université

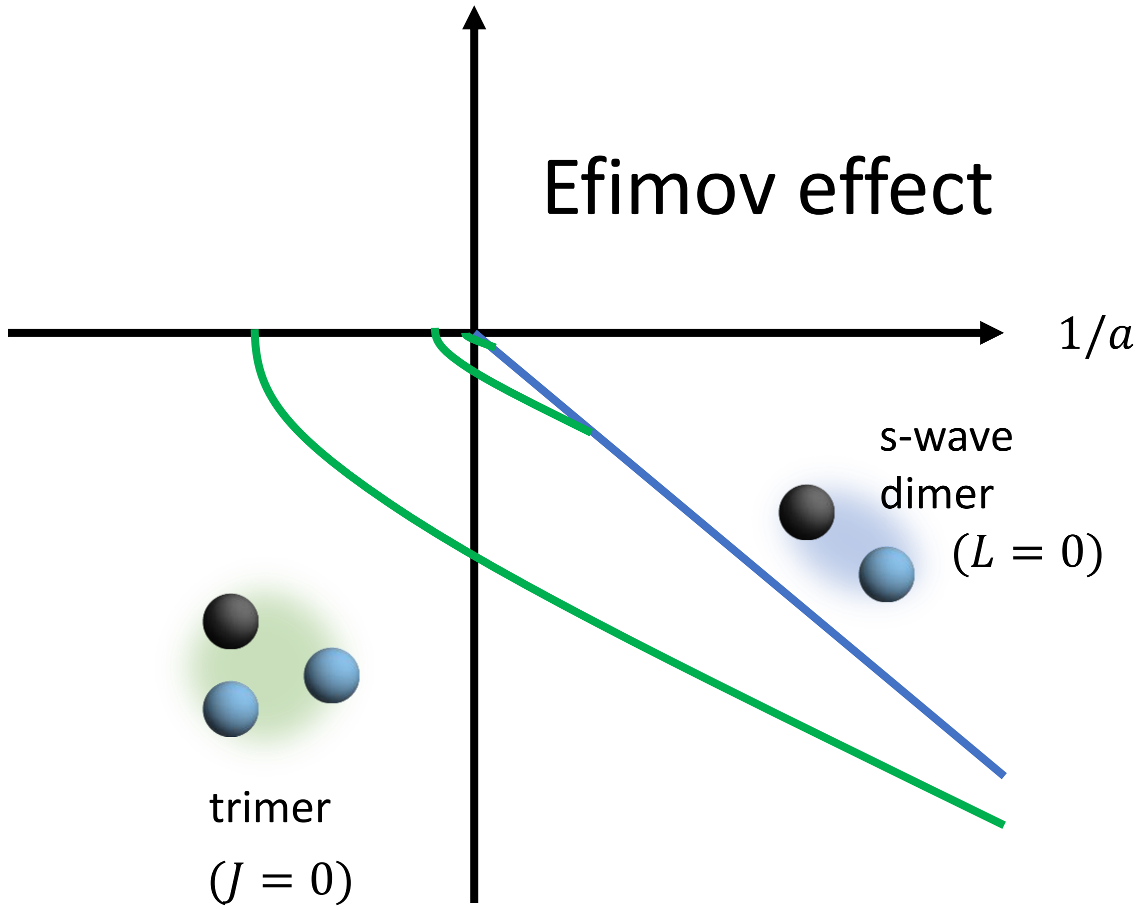
Christiane Schmickler
RIKEN

Shallow Trimers of Two Identical Fermions and One Particle in Resonant Regimes
[arxiv:2112.02983]

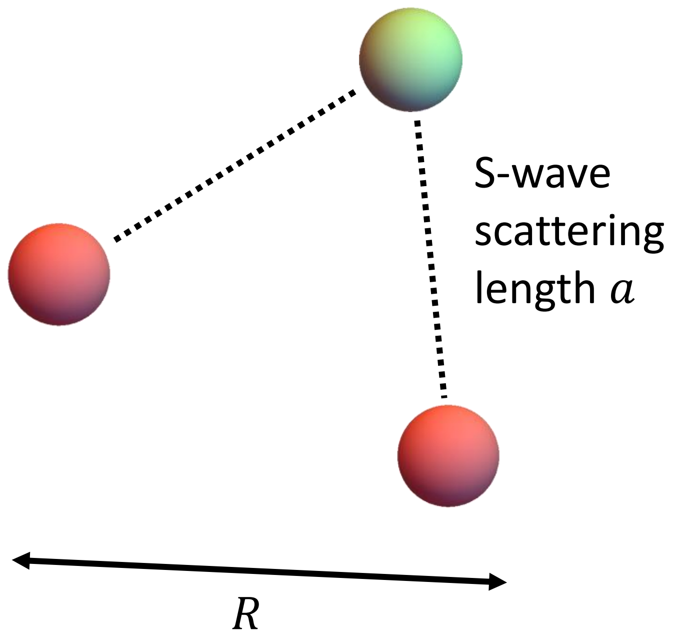
2 identical bosons + 1 particle



Efimov attraction: $V_{3B}(R) \sim -\frac{0.17}{R^2}$

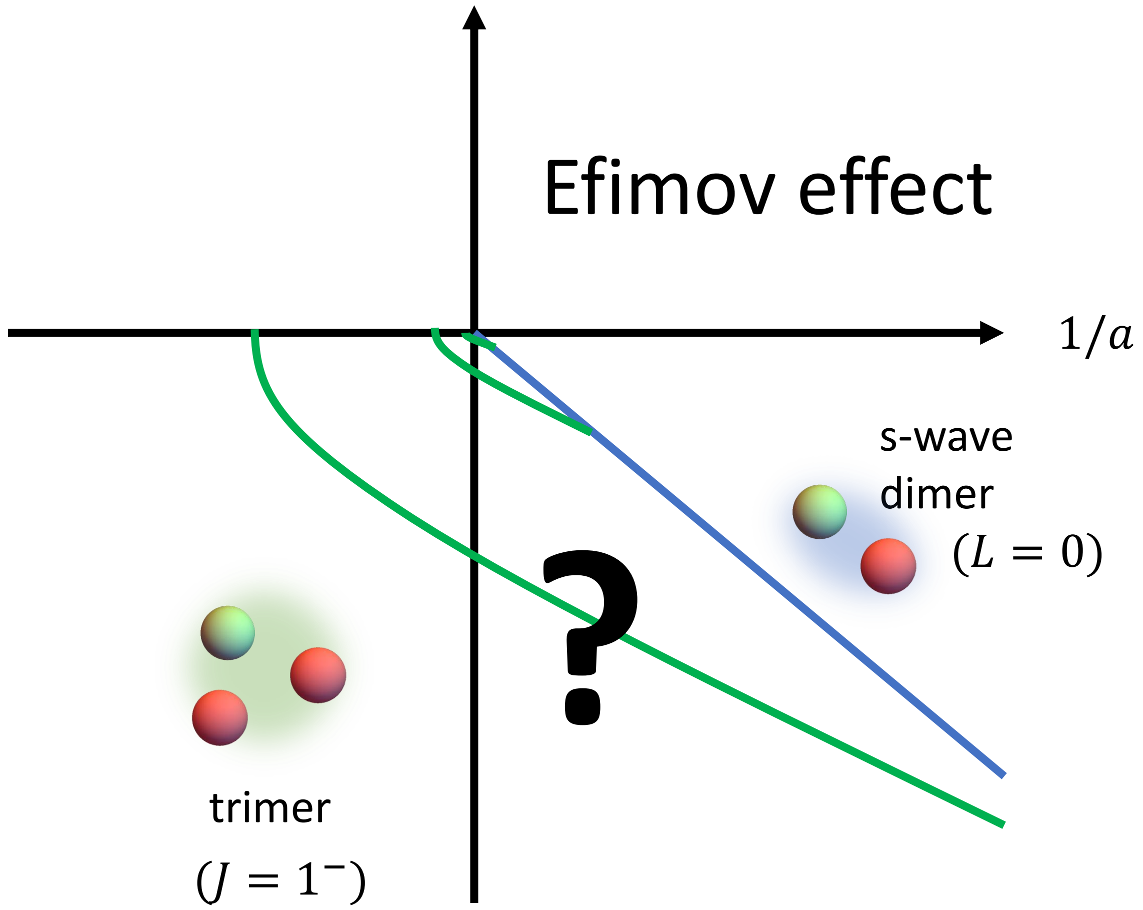


2 identical fermions + 1 particle

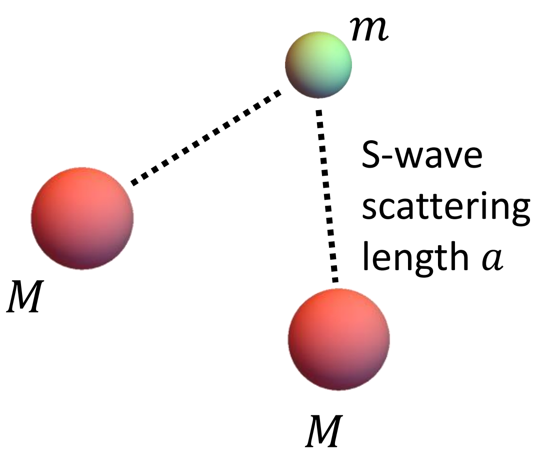


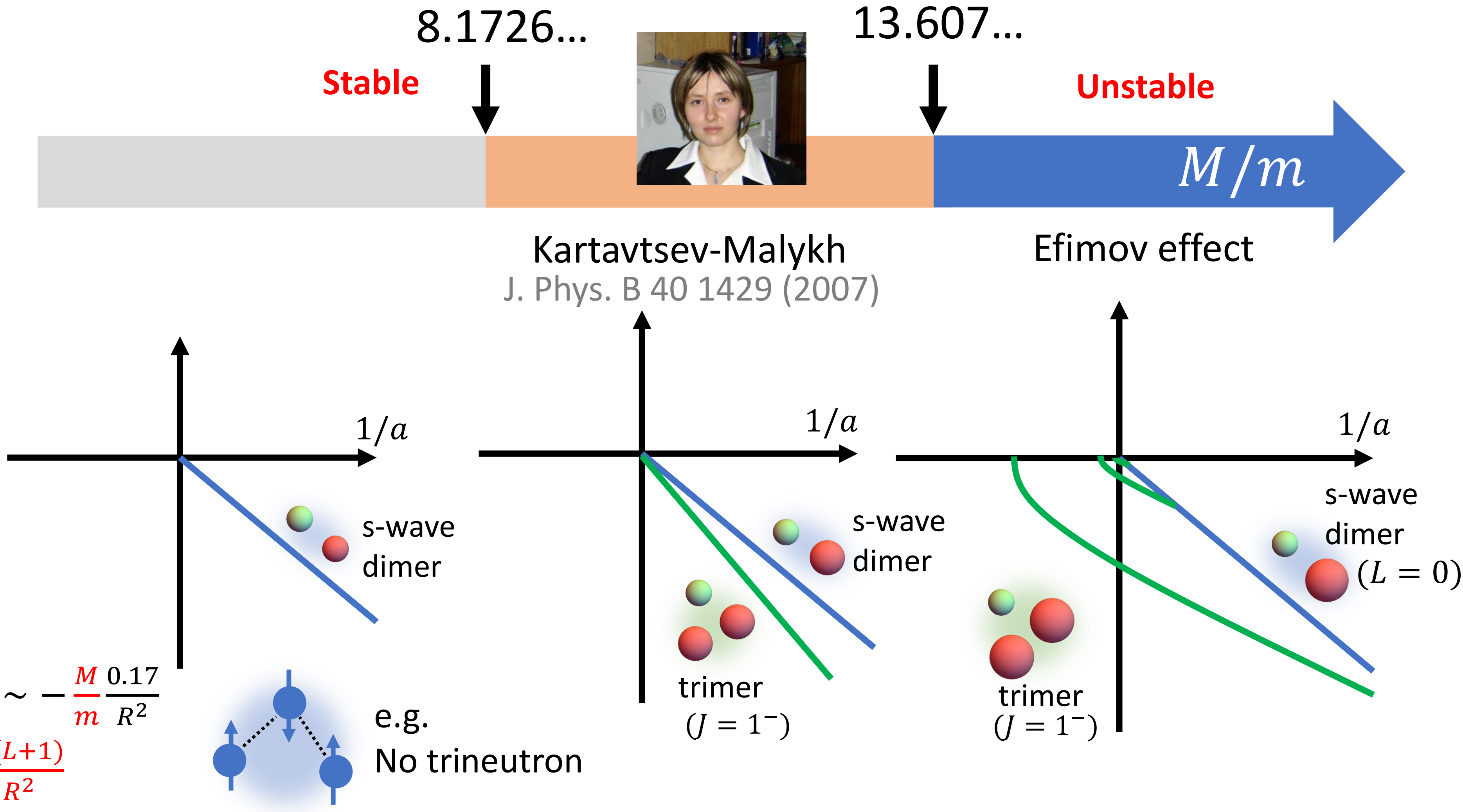
Efimov attraction: $V_{3B}(R) \sim -\frac{0.17}{R^2}$

Centrifugal repulsion: $+\frac{L(L+1)}{R^2}$



2 identical fermions + 1 particle



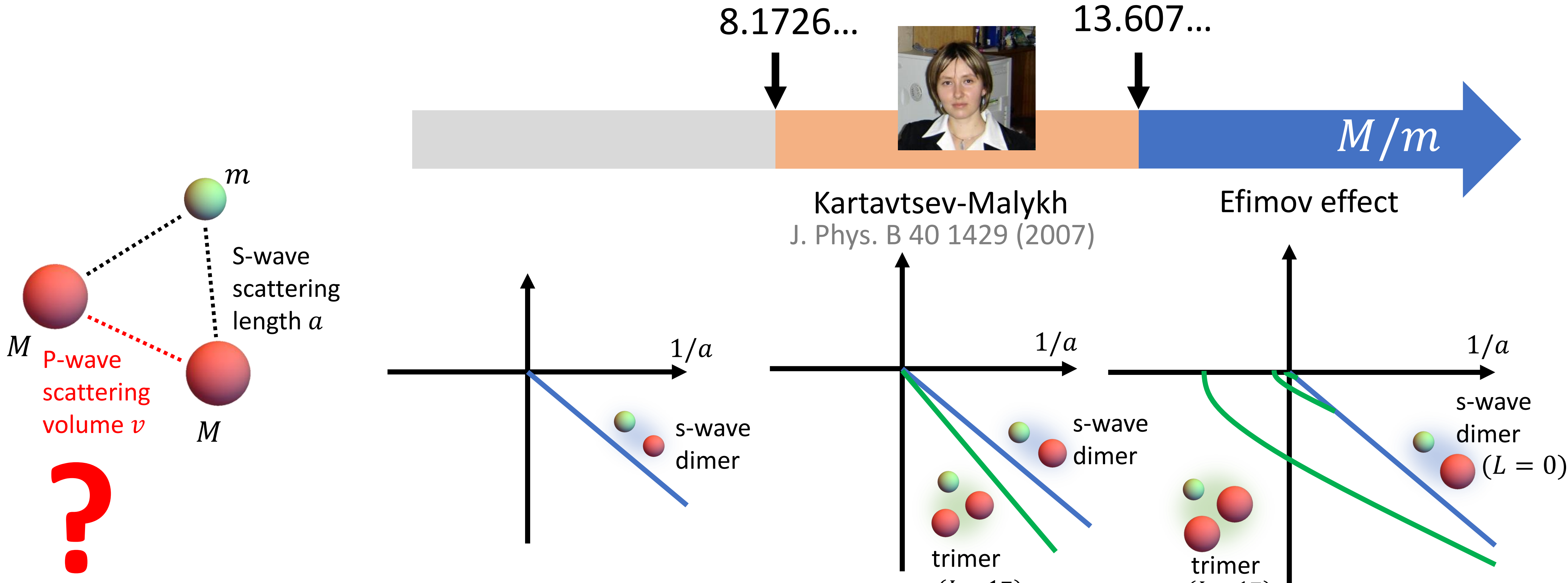


Efimov attraction: $V_{3B}(R) \sim -\frac{M}{m}\frac{0.17}{R^2}$

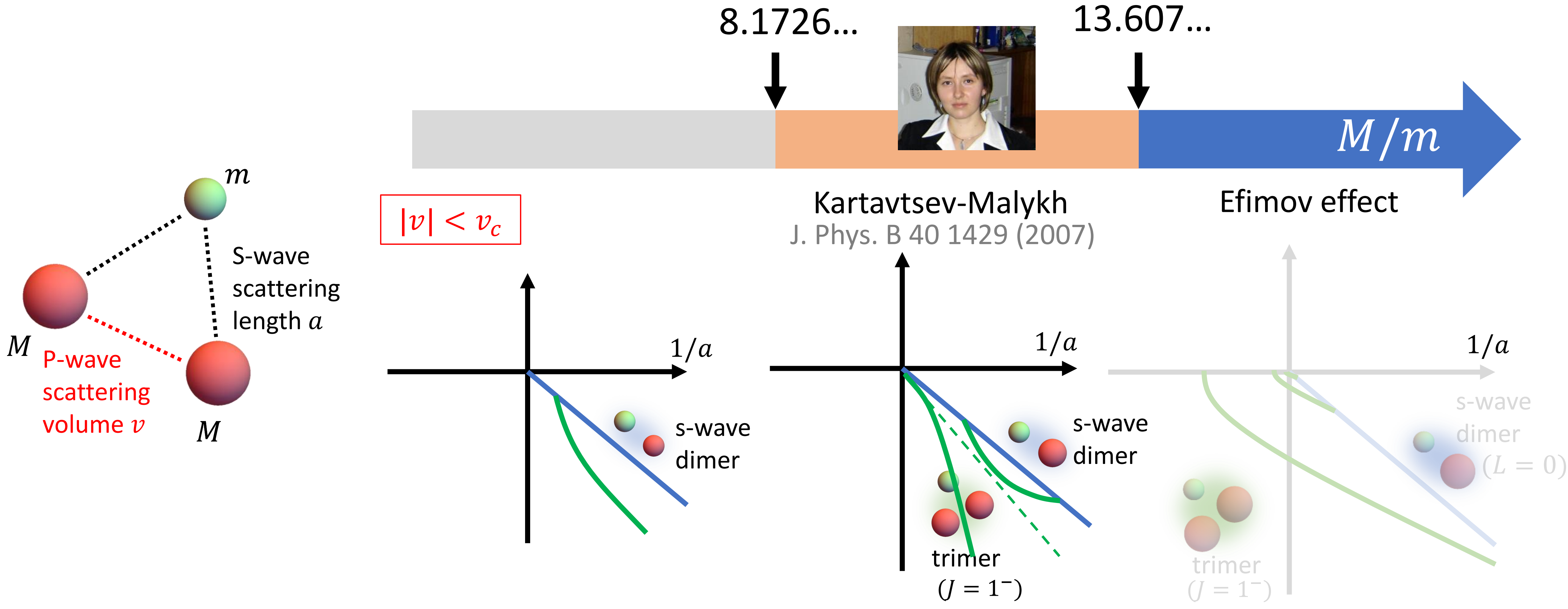
Centrifugal repulsion: $+\frac{L(L+1)}{R^2}$

e.g.
No trineutron

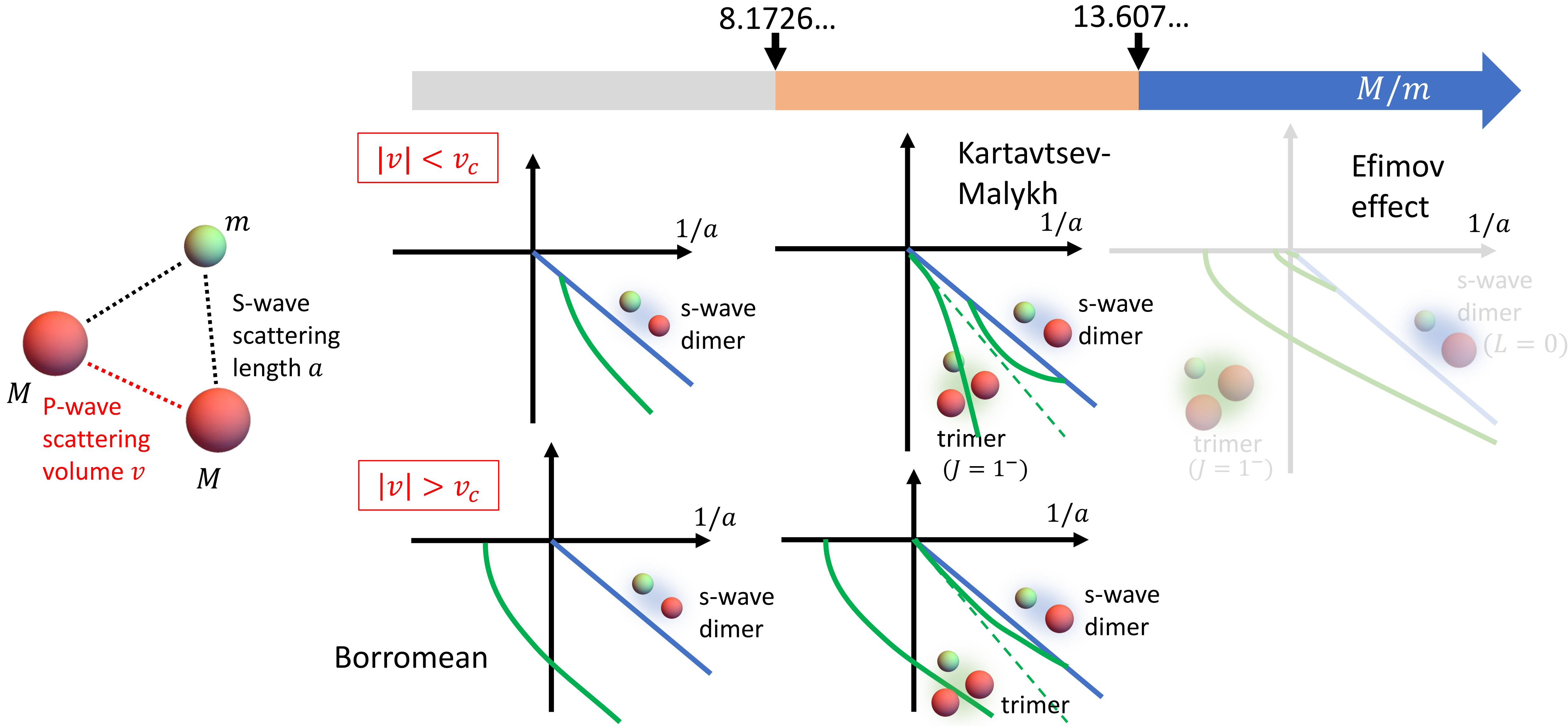
2 identical fermions + 1 particle



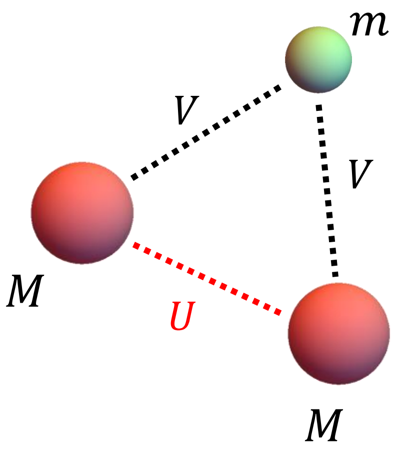
2 identical fermions + 1 particle



2 identical fermions + 1 particle



2 identical fermions + 1 particle



Separable interactions:

S wave: $V = \xi|\chi\rangle\langle\chi|$ With $\langle \boldsymbol{k}|\chi\rangle = \chi(k)$

P wave: $U = \sum_m g_m|\Phi_m\rangle\langle\Phi_m|$ With $\langle \boldsymbol{k}|\Phi_m\rangle = \phi(k)\boldsymbol{k}\cdot\boldsymbol{e}_m$

Form factors:

Cut-off: $\begin{cases} 1 \text{ for } k \le \Lambda \\ 0 \text{ for } k > \Lambda \end{cases}$

Gaussian: $\exp(-k^2/\Lambda^2)$

Yamaguchi: $\left(1 + \frac{k^2}{\Lambda^2}\right)^{-1}$

Yamaguchi-squared: $\left(1 + \frac{k^2}{\Lambda^2}\right)^{-2}$

The model parameters ξ, Λ_0 and g_m, Λ_1 are adjusted to give **the same low-energy parameters**:

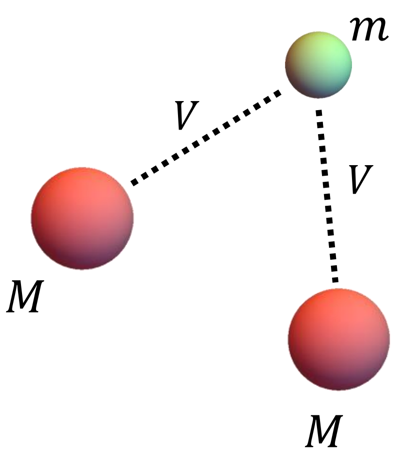
S wave: scat. length a, eff. range $\bar{r}_e$

$k\cot\delta_S = -\frac{1}{a} + \frac{1}{2}r_e k^2 + \cdots$ and $\bar{r}_e = r_e(a \to \infty)$

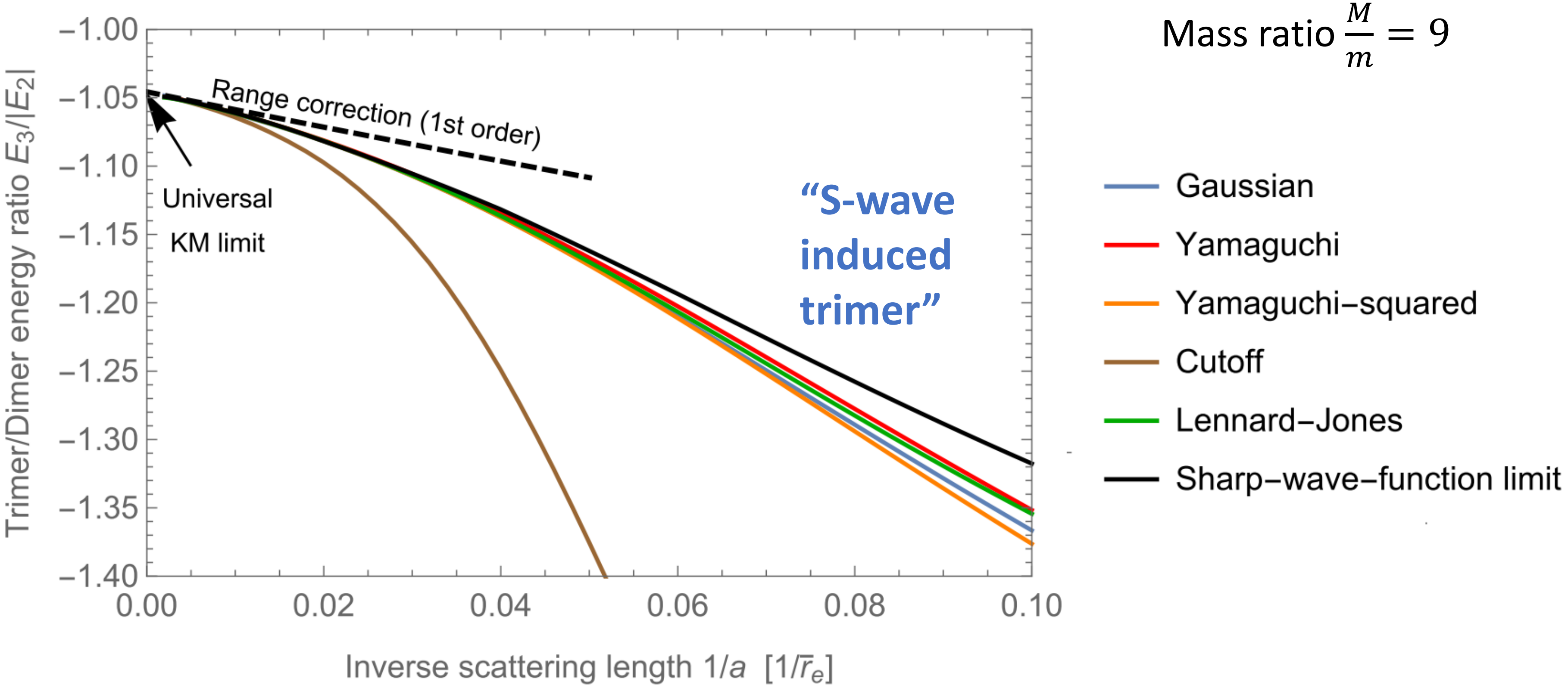
P wave: scat. volume v, width parameter $\bar{\alpha}$

$k\cot\delta_P = -\frac{1}{k^2 v} - \alpha + \cdots$ and $\bar{\alpha} = \alpha(v \to \infty)$

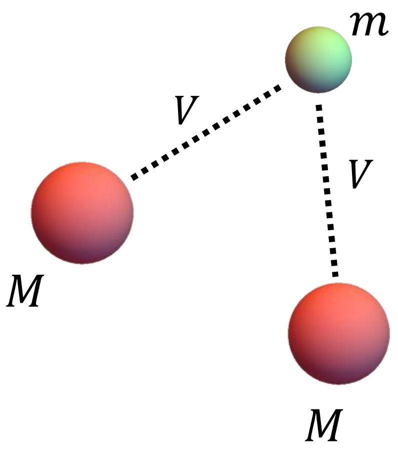
2 identical fermions + 1 particle



Without p-wave interaction:



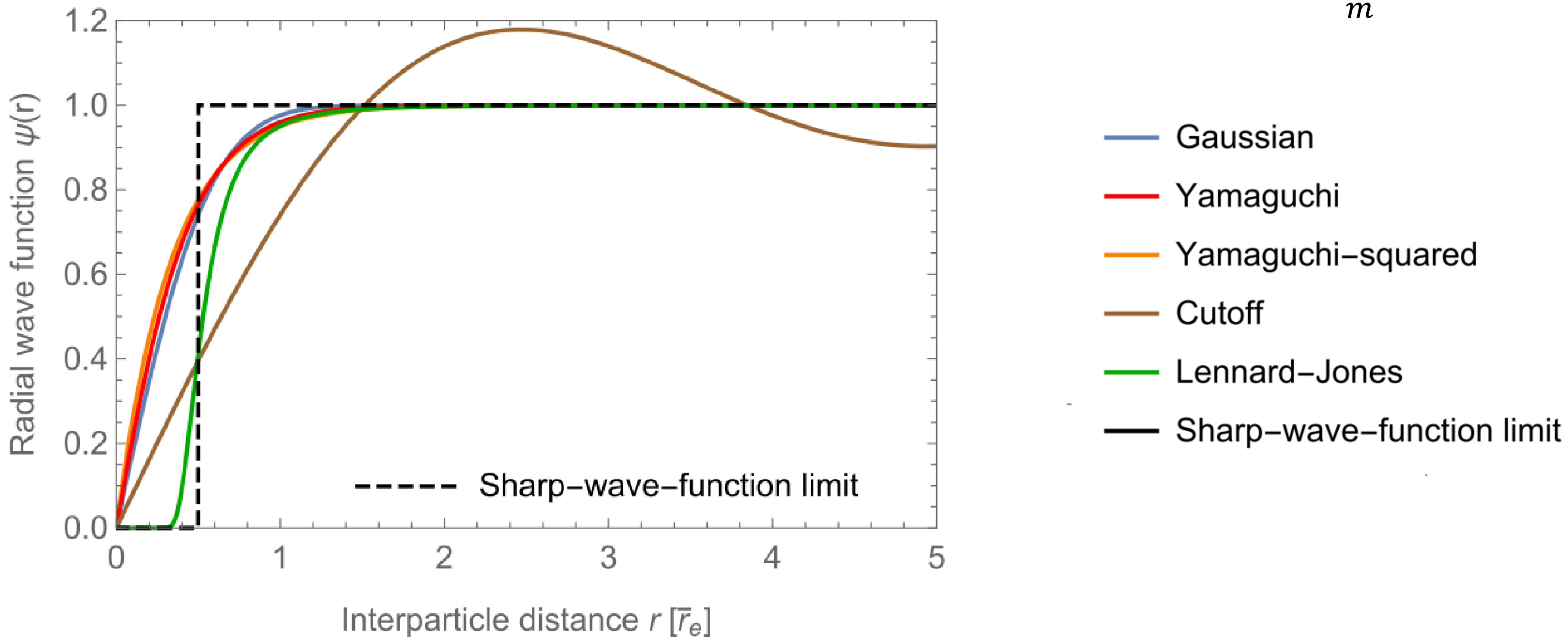
2 identical fermions + 1 particle



Without p-wave interaction:

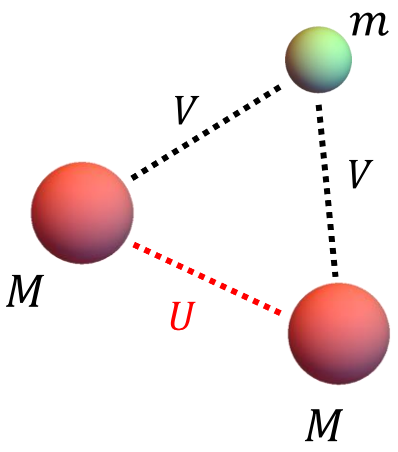
Two-body radial wave function

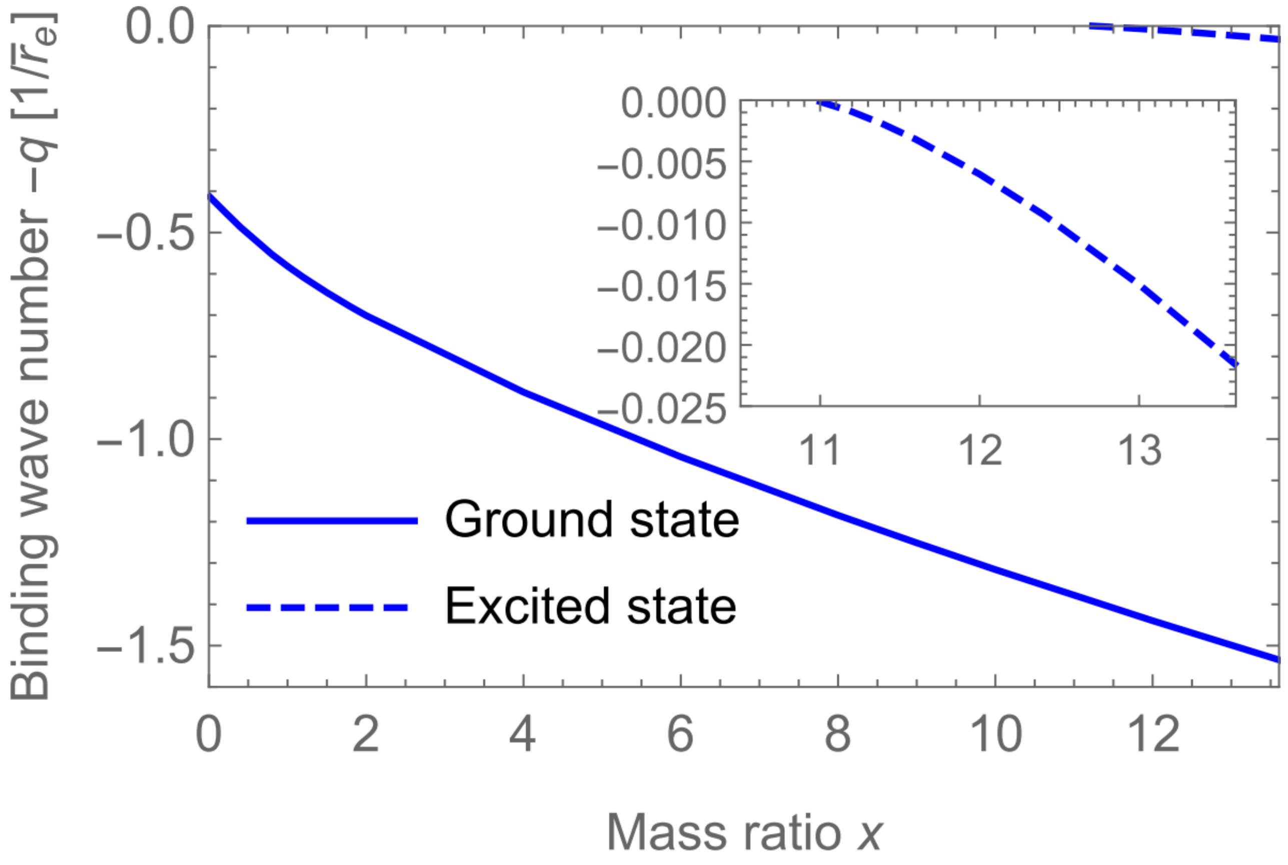
Mass ratio $\frac{M}{m} = 9$



2 identical fermions + 1 particle

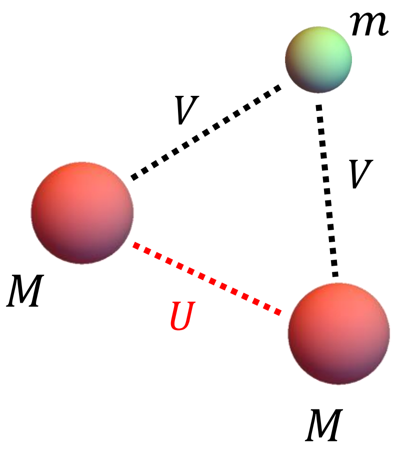
With p-wave interaction: $a = \infty$ and $v = \infty$



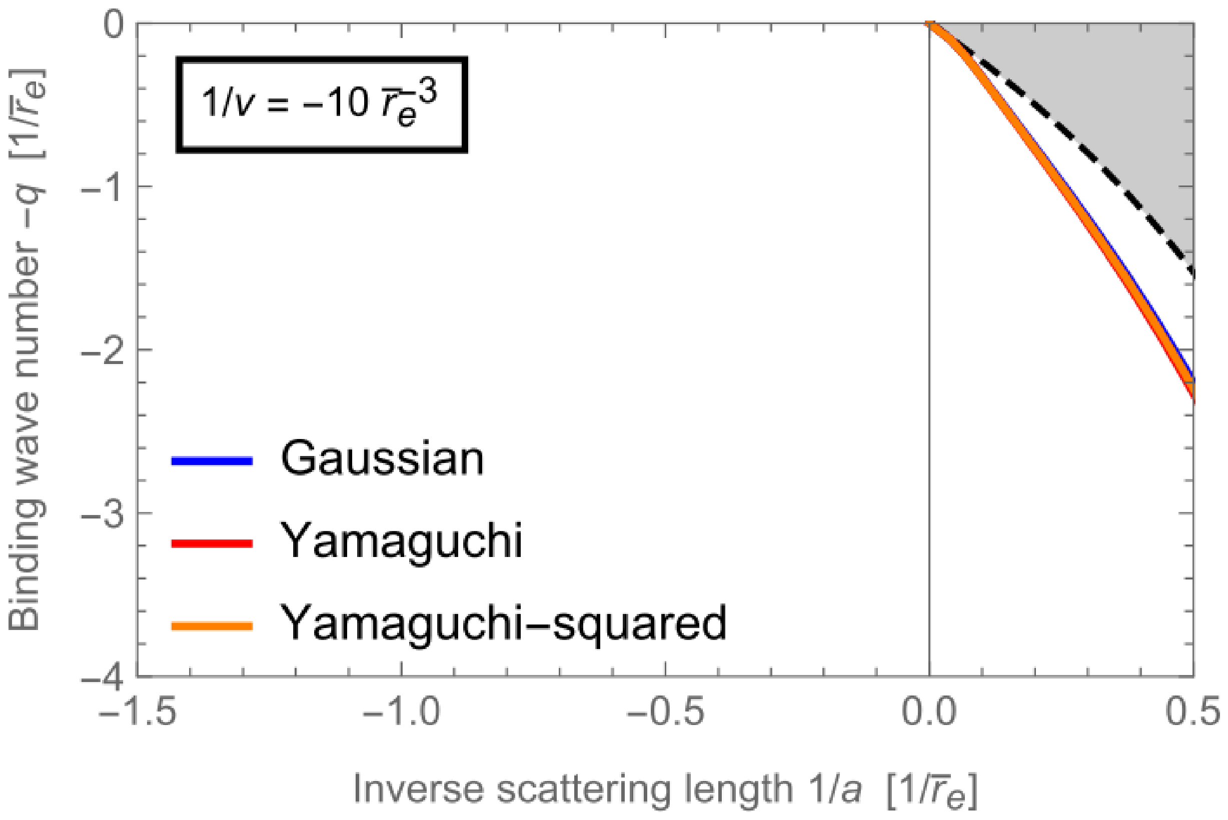


"P-wave induced trimer"

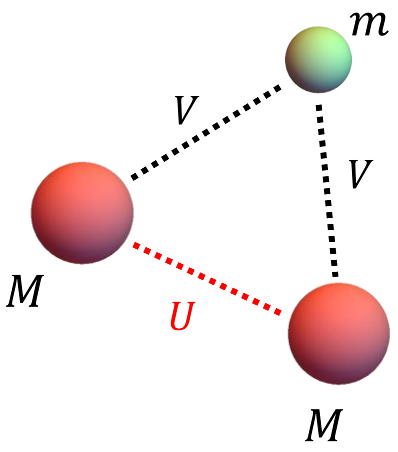
2 identical fermions + 1 particle



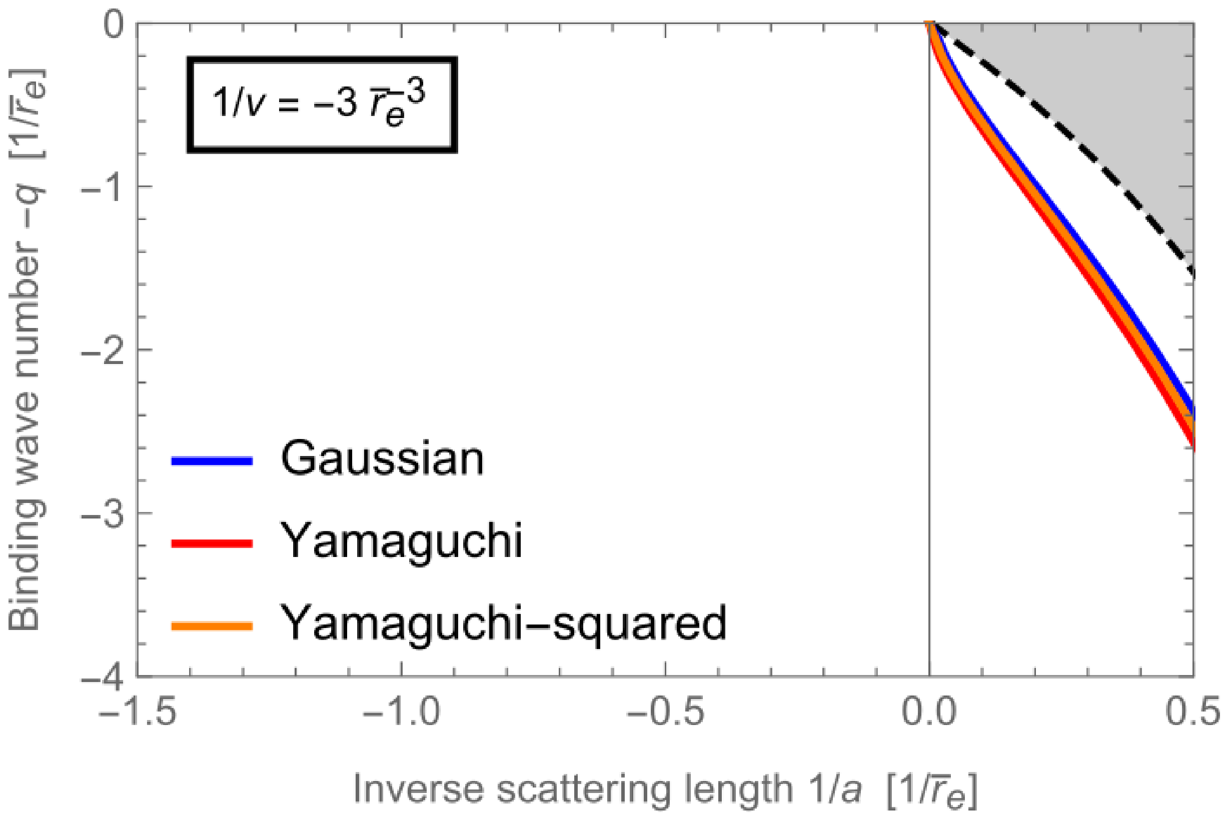
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



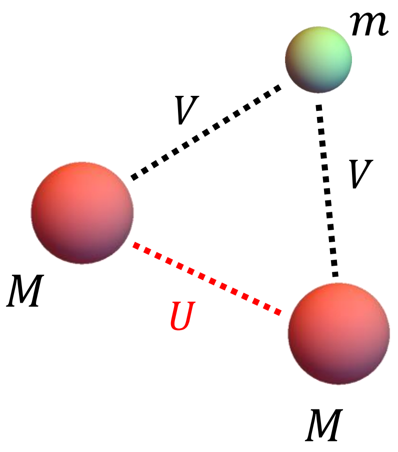
2 identical fermions + 1 particle



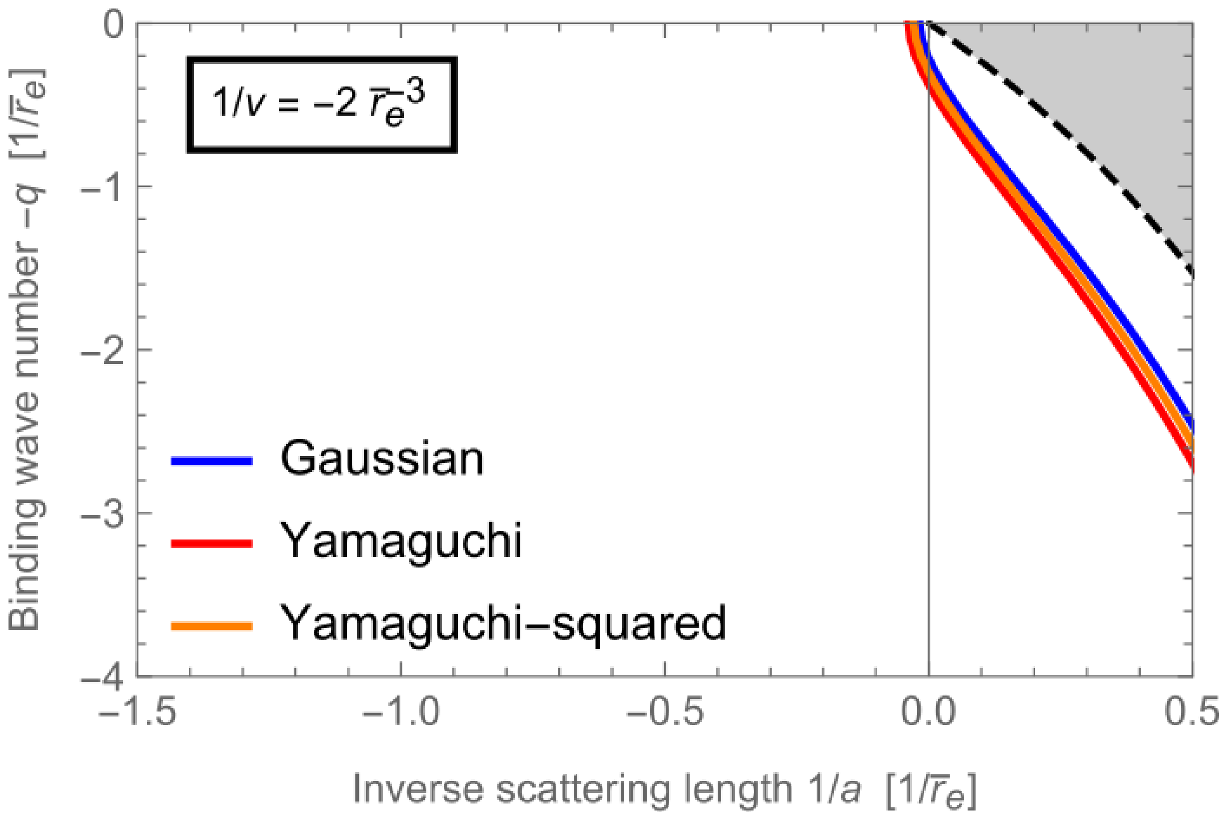
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



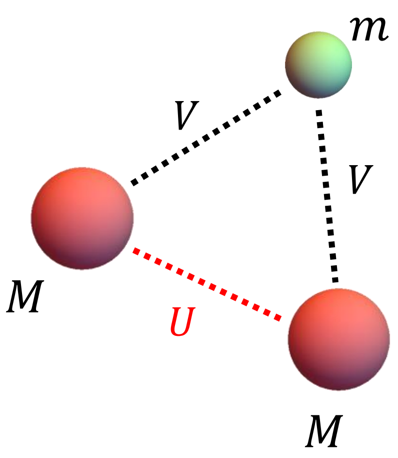
2 identical fermions + 1 particle



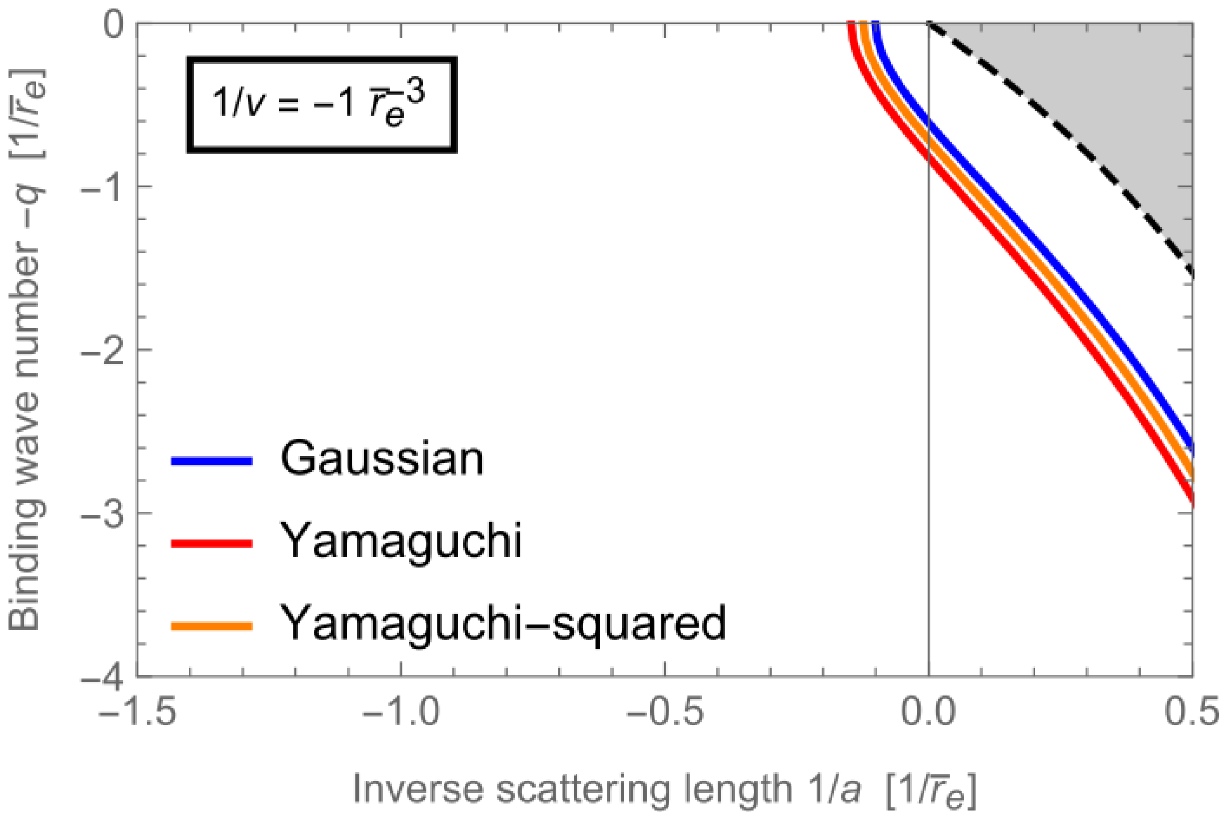
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



2 identical fermions + 1 particle

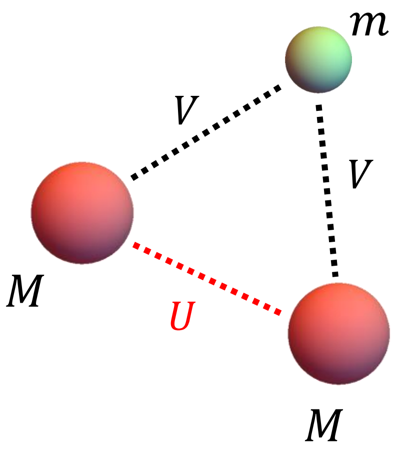


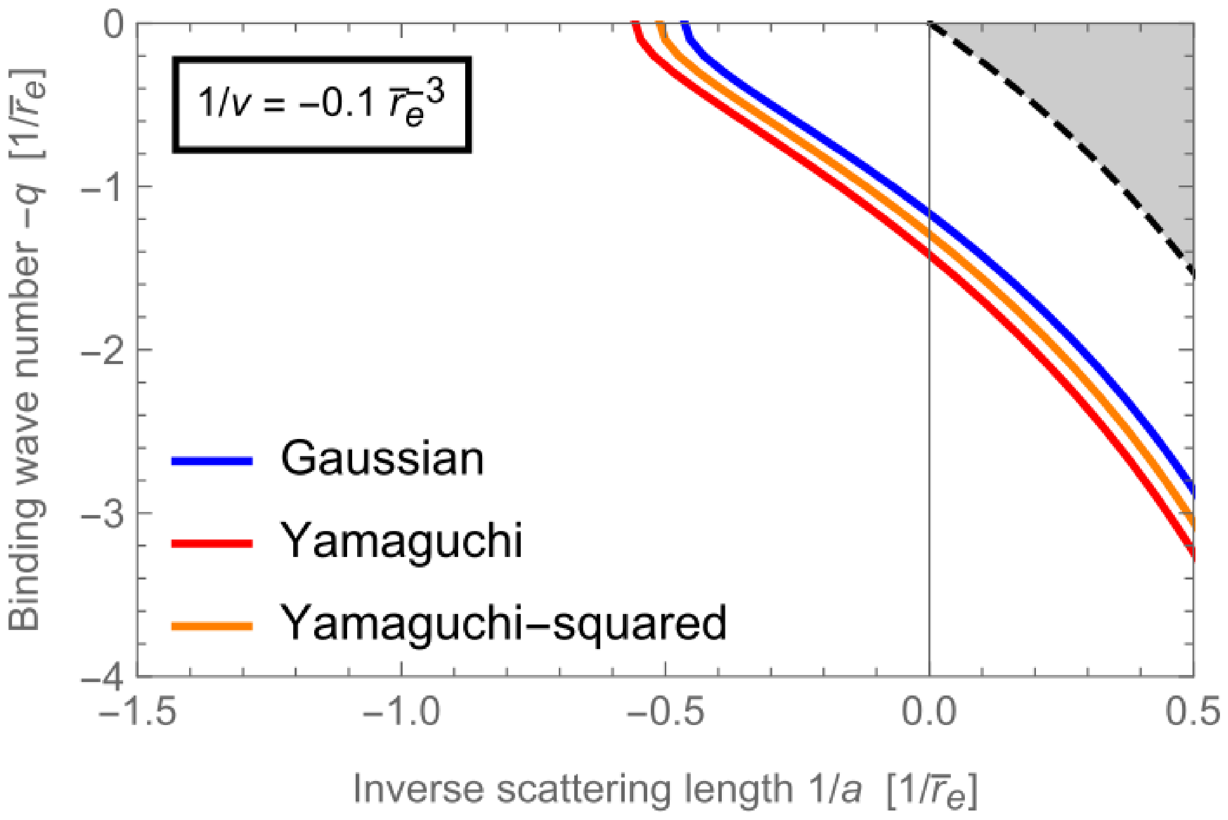
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



2 identical fermions + 1 particle

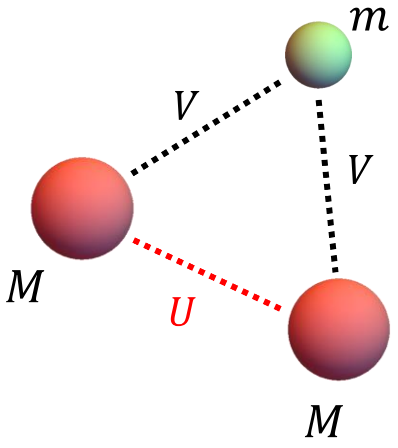
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)

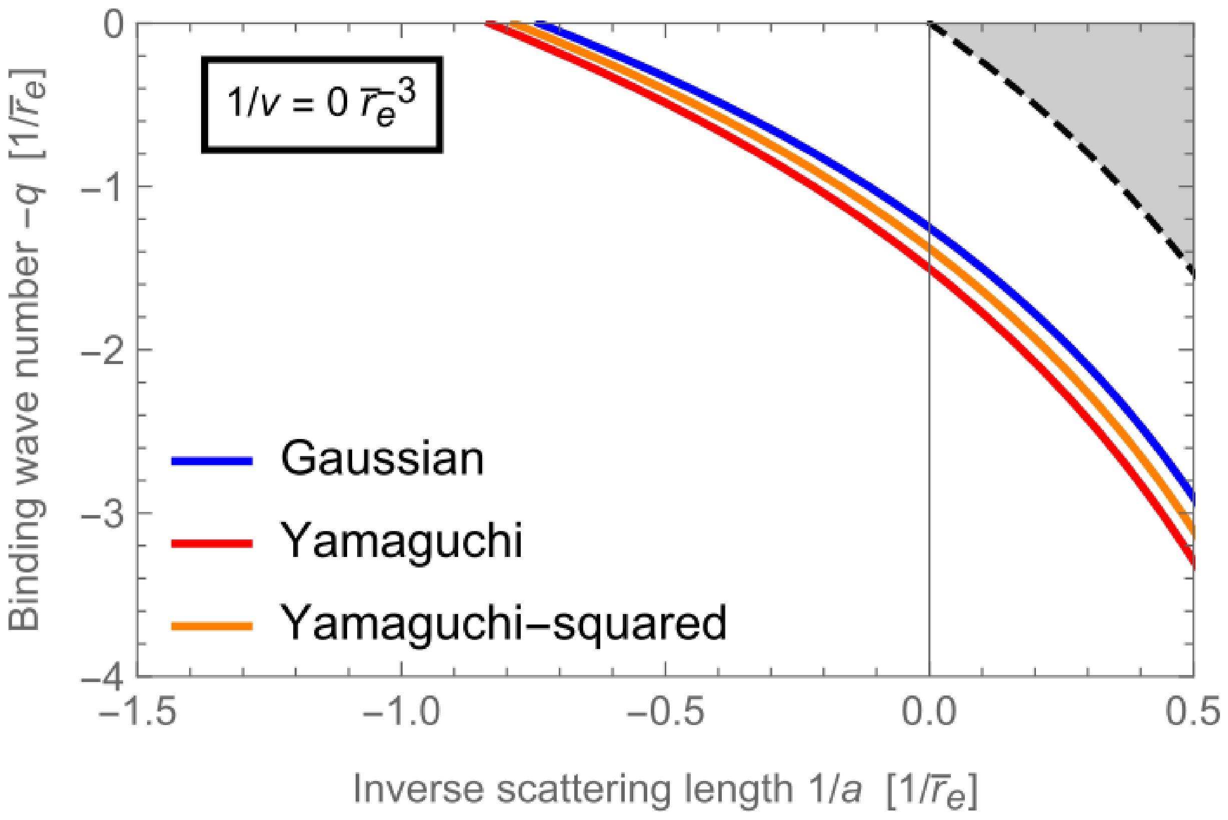




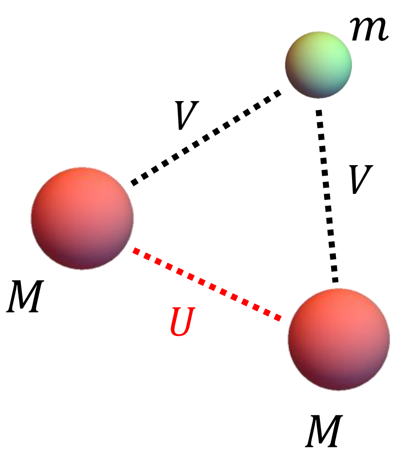
2 identical fermions + 1 particle

With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)





2 identical fermions + 1 particle



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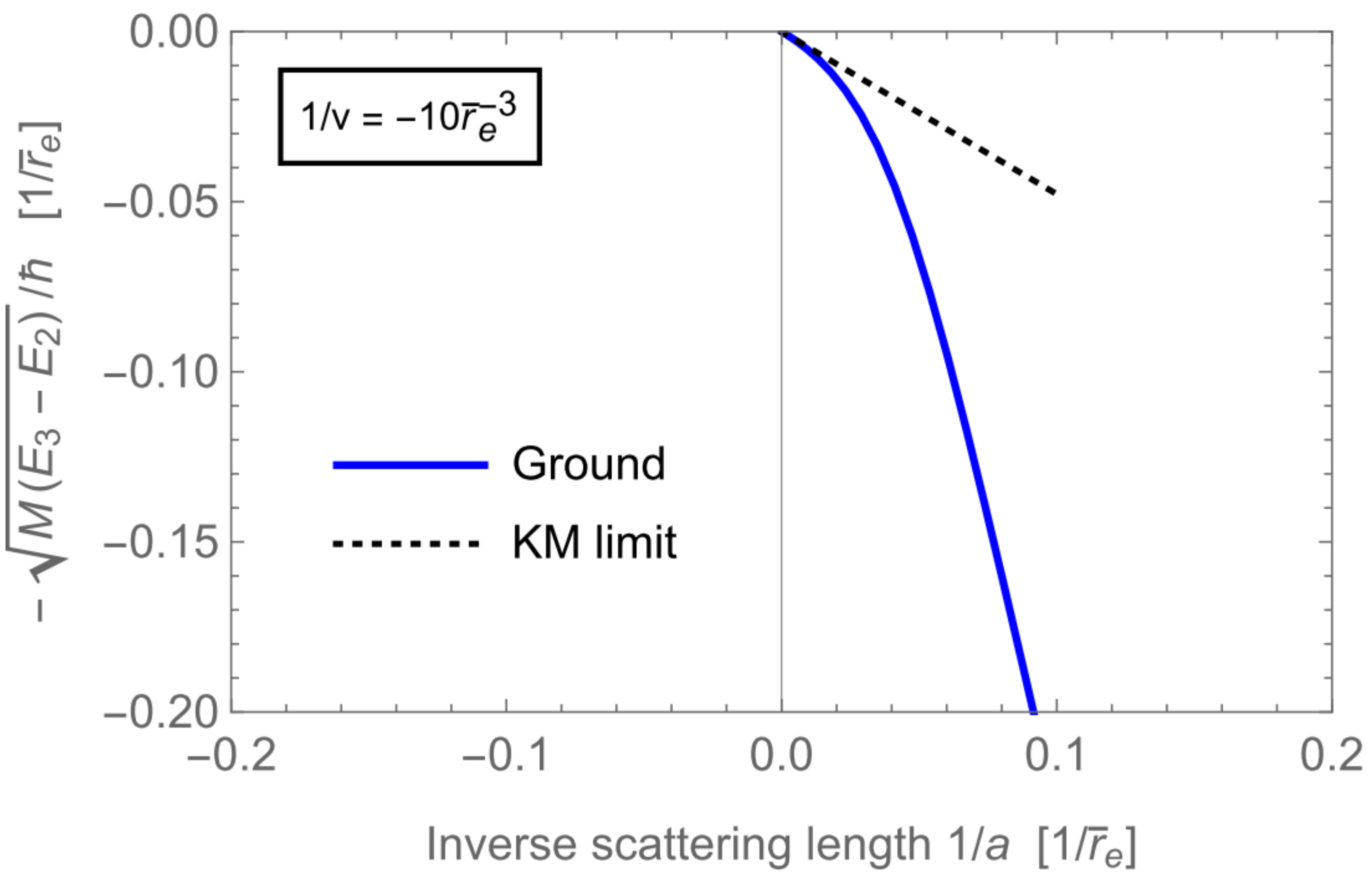
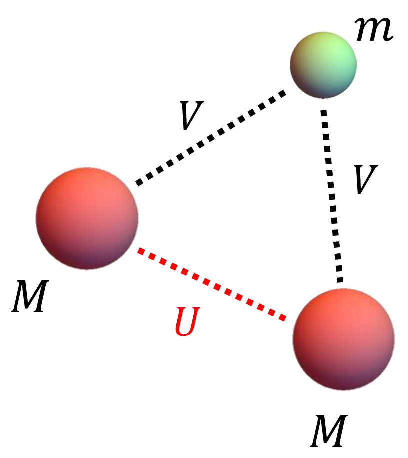
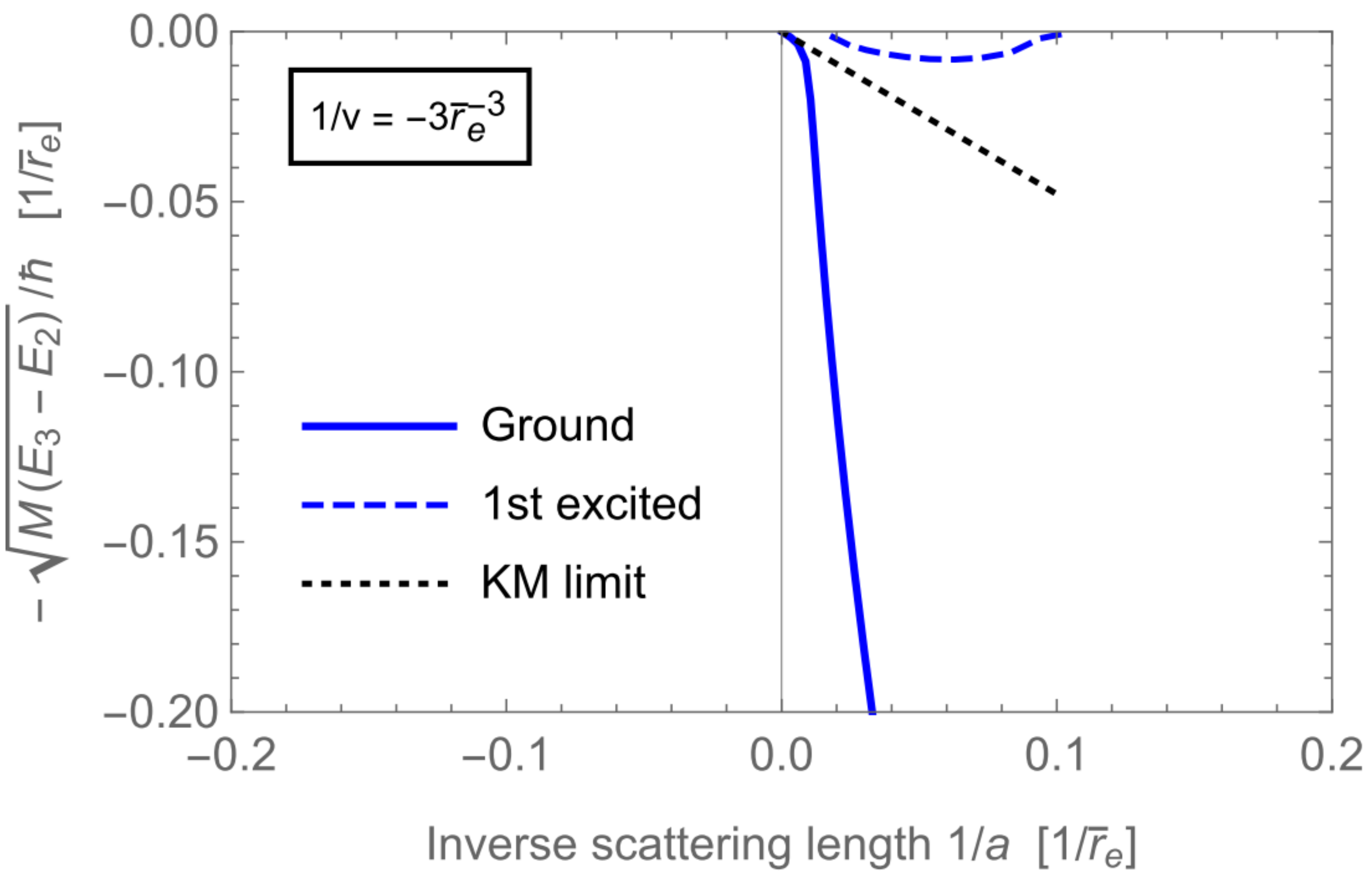


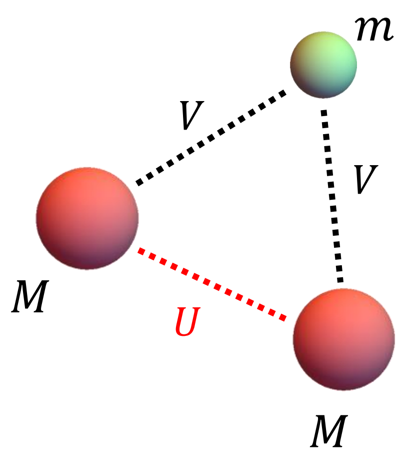
2 identical fermions + 1 particle



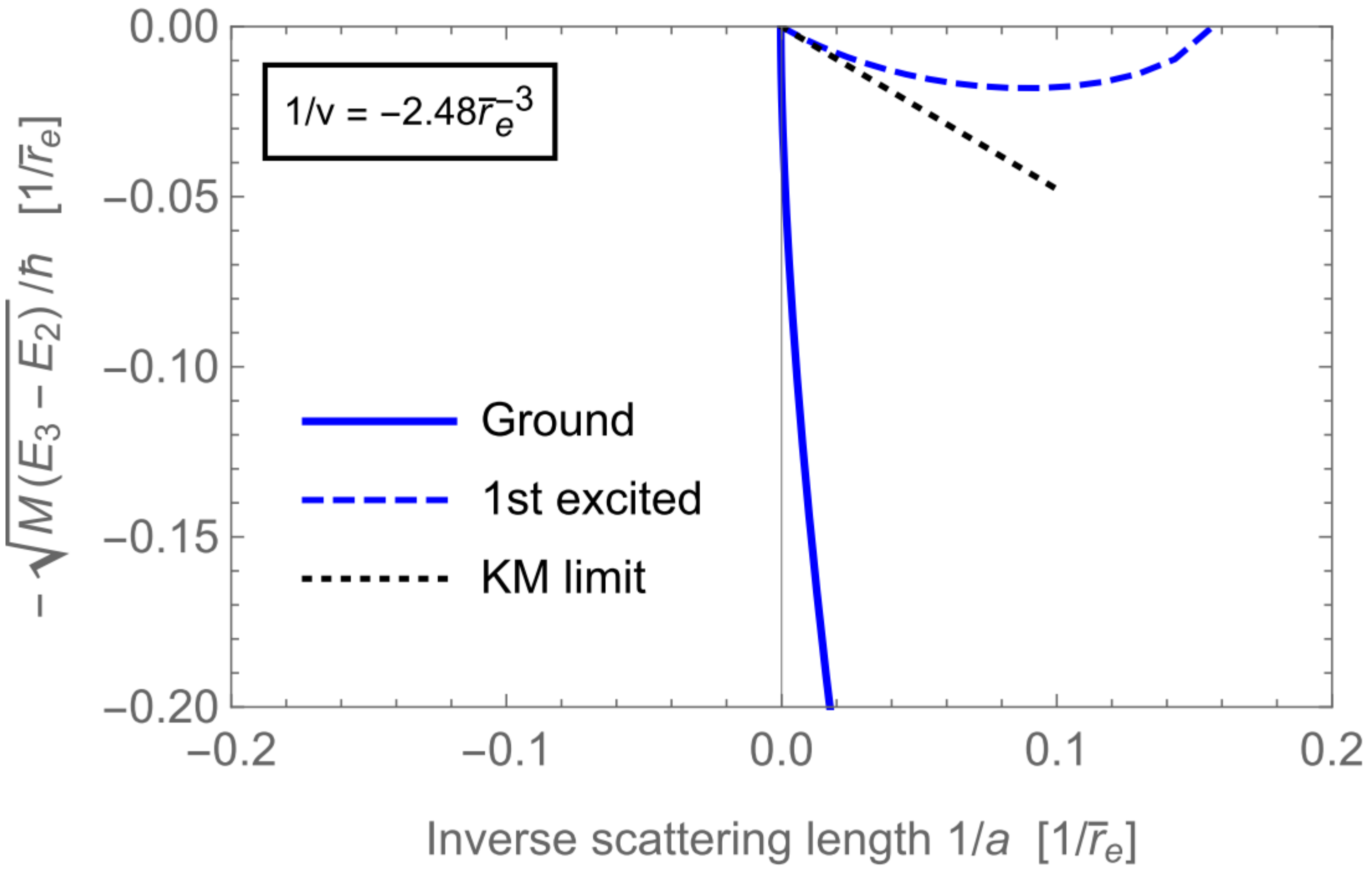
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



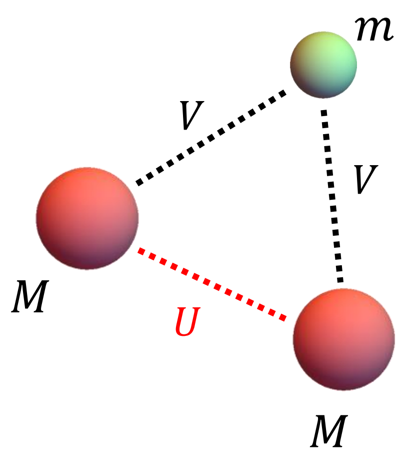
2 identical fermions + 1 particle



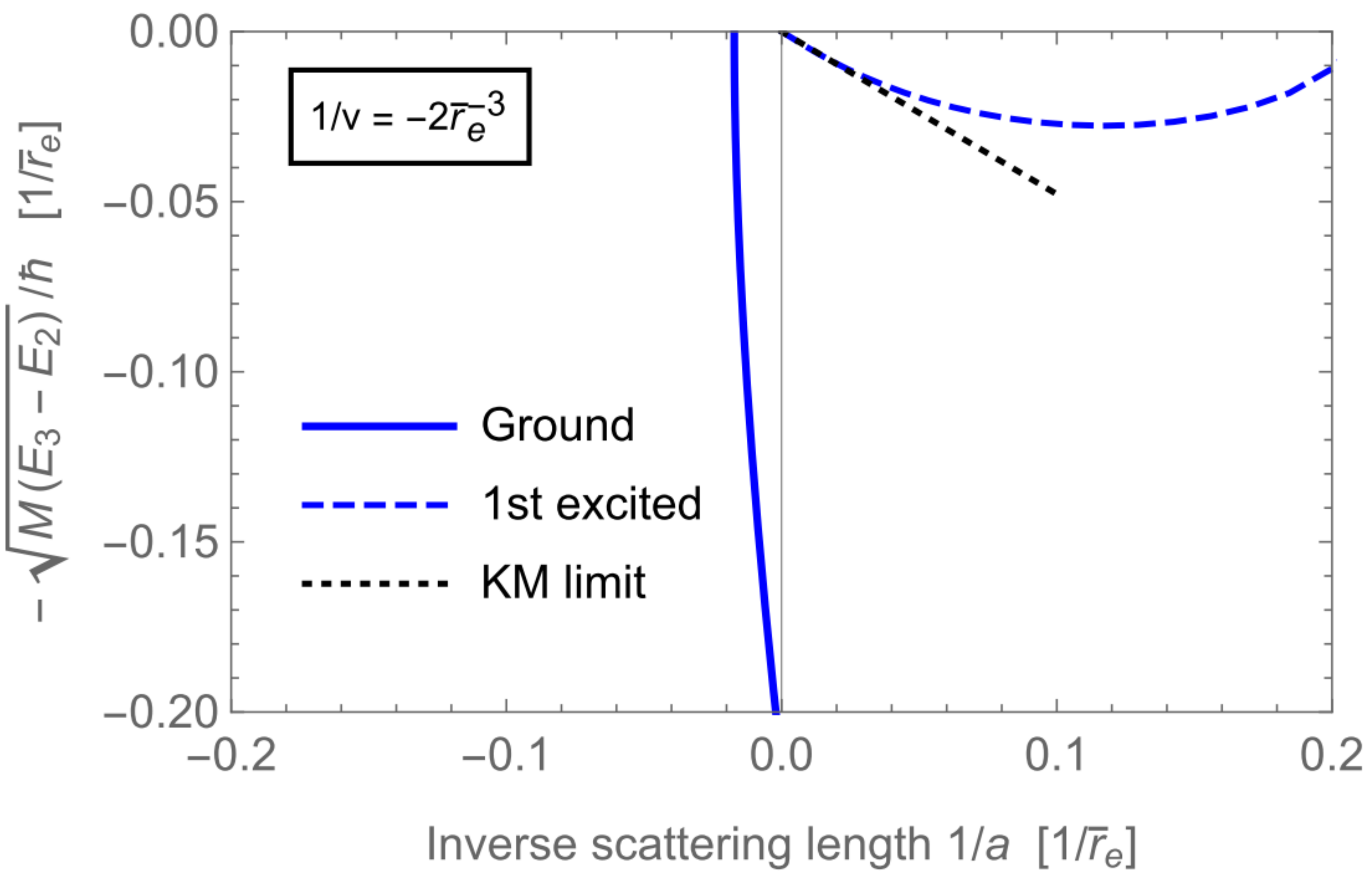
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



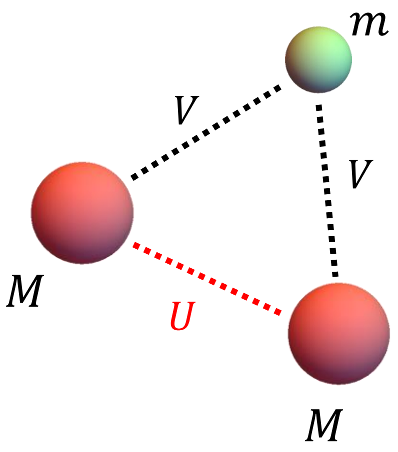
2 identical fermions + 1 particle



With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



2 identical fermions + 1 particle



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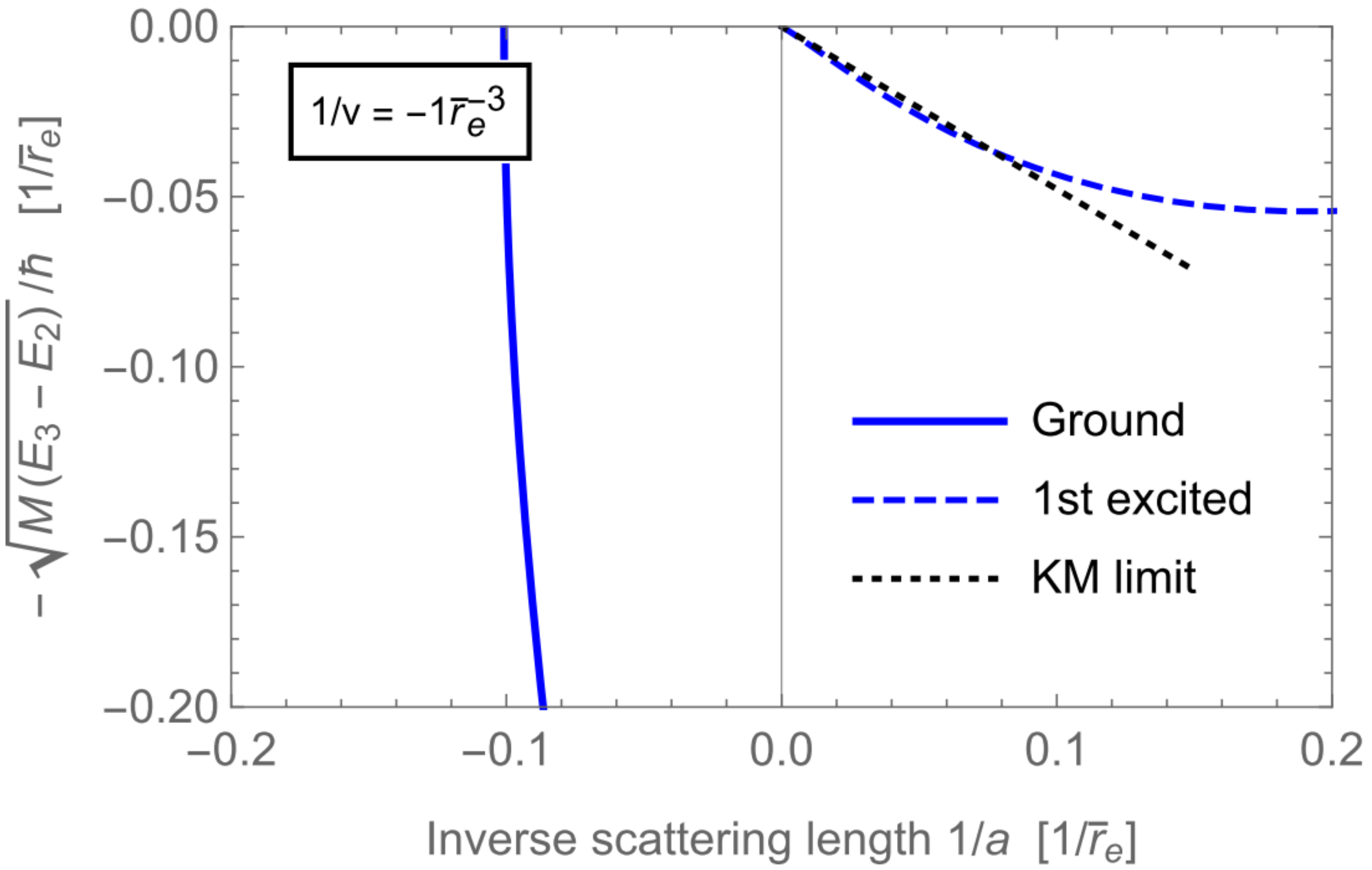

2 identical fermions + 1 particle

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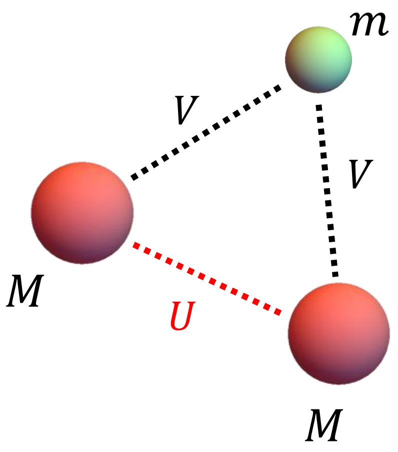
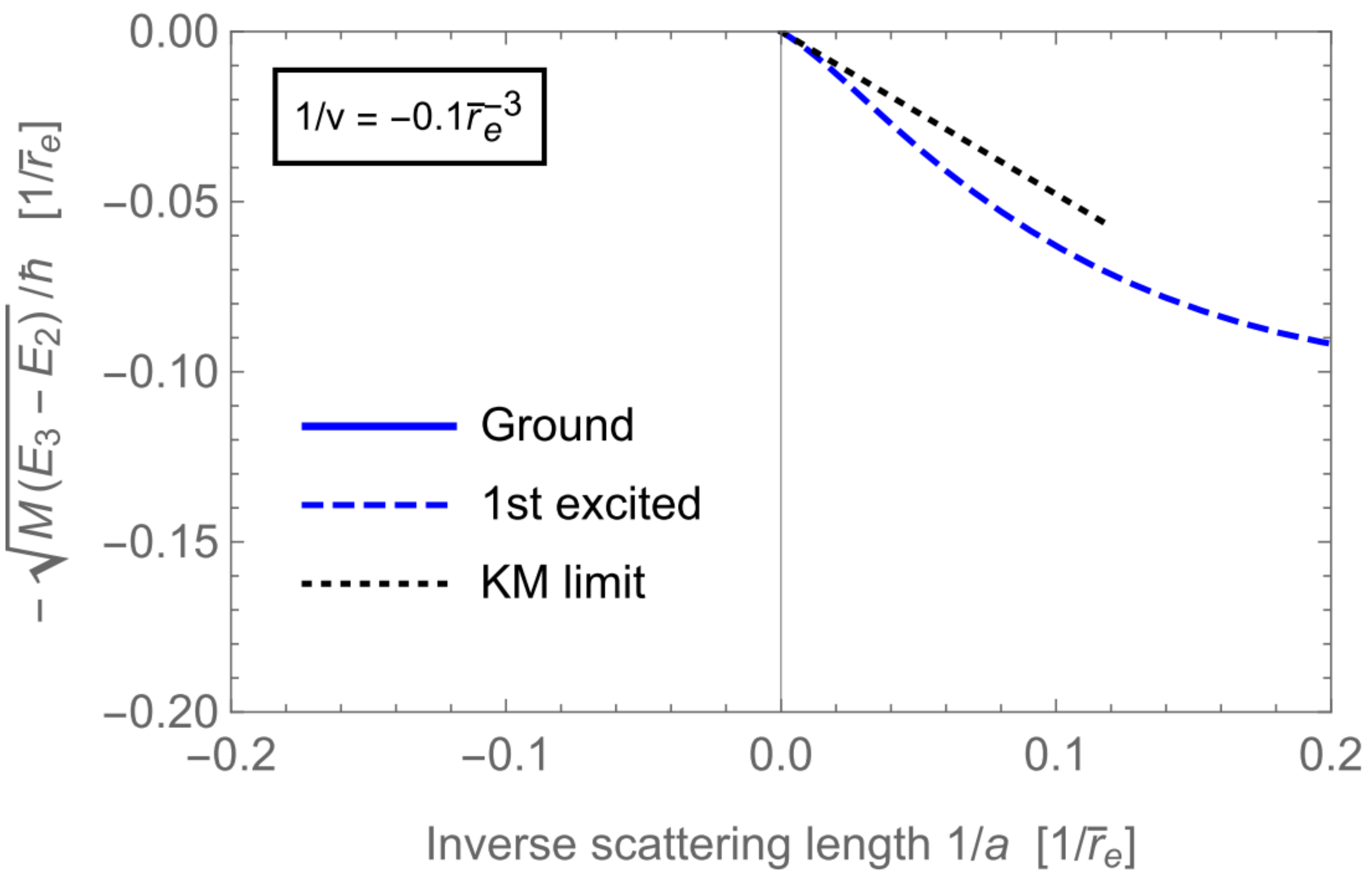
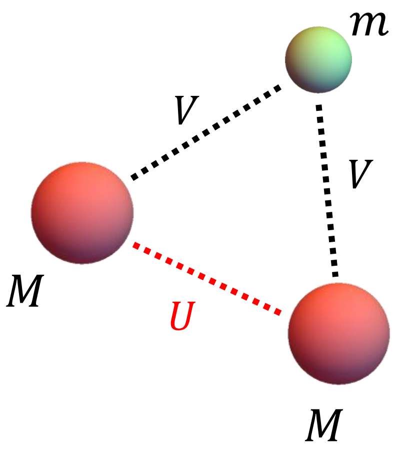
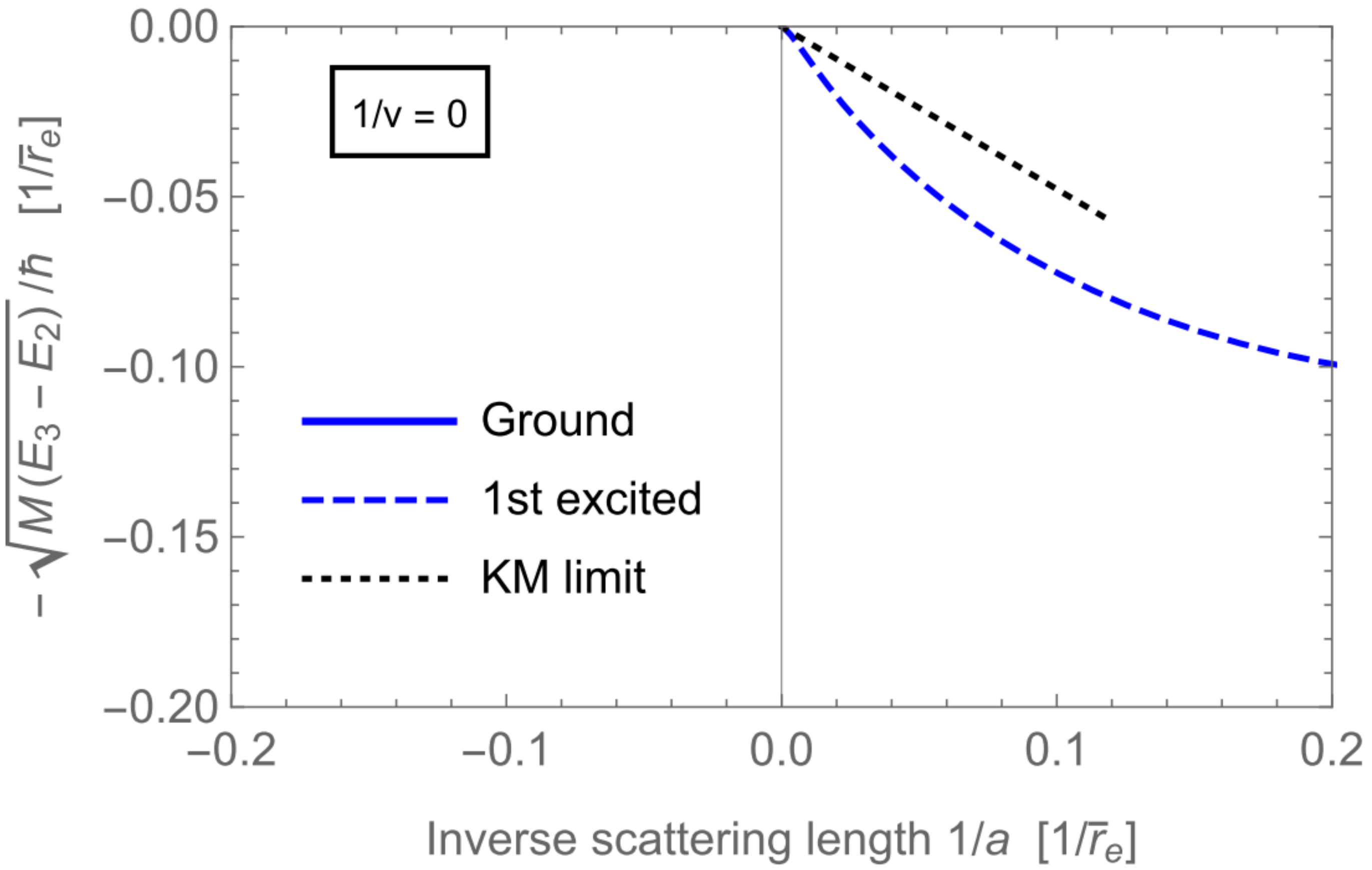




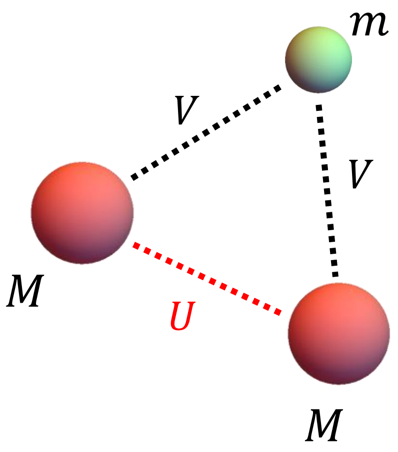
2 identical fermions + 1 particle



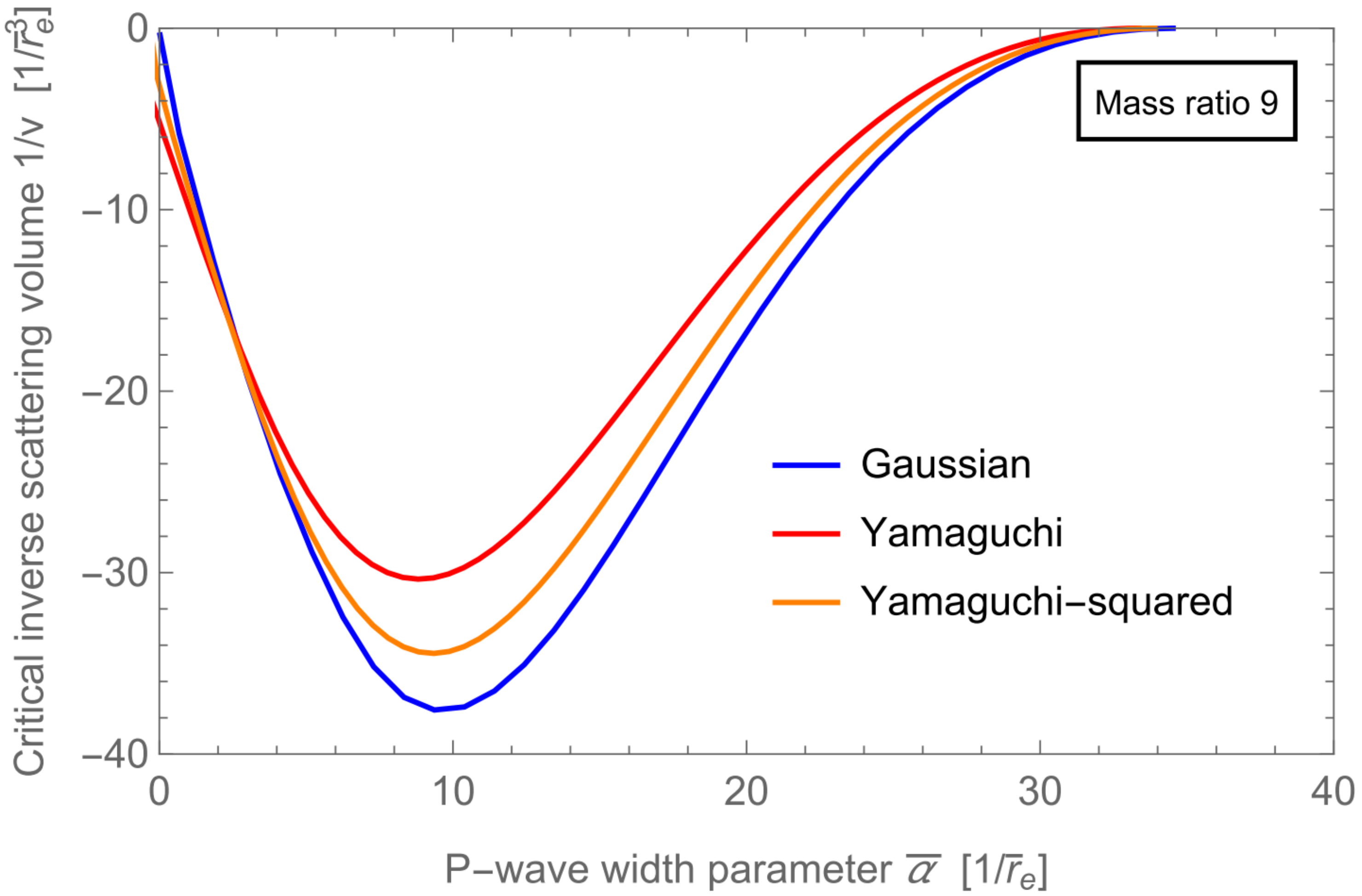
With p-wave interaction: (Mass ratio $\frac{M}{m} = 9$)



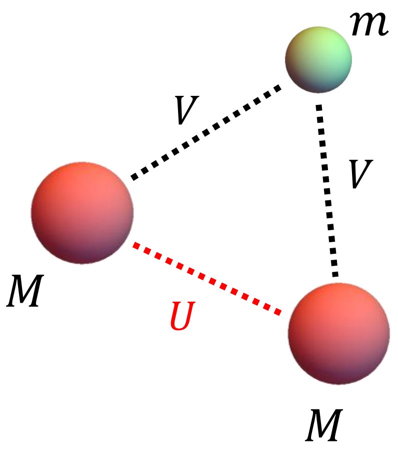
2 identical fermions + 1 particle



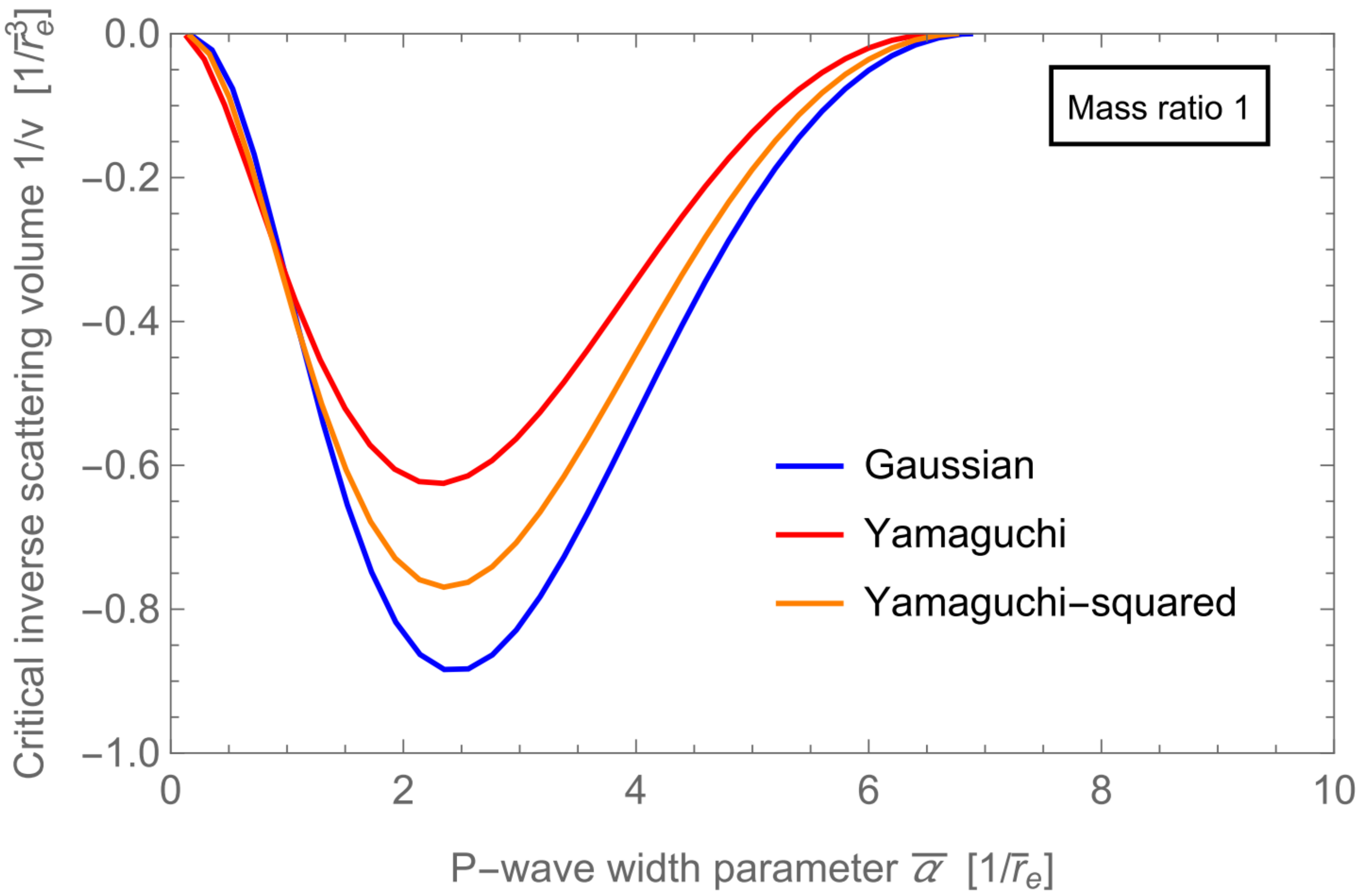
Critical scattering volume for a Borromean state



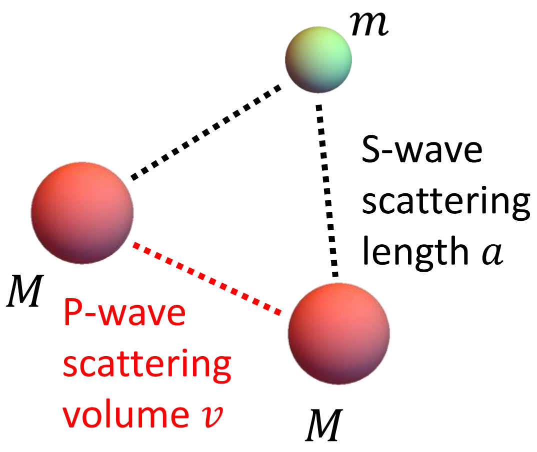
2 identical fermions + 1 particle



Critical scattering volume for a Borromean state



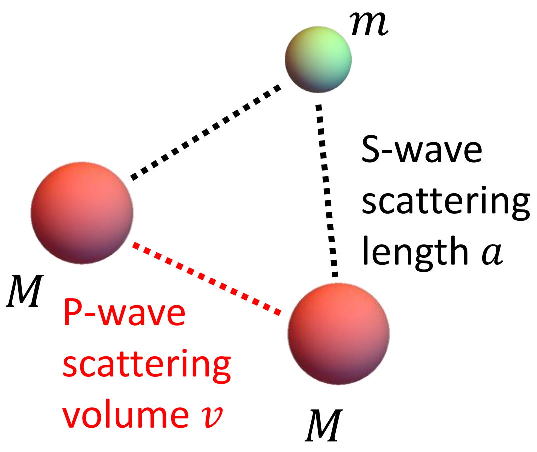
④ Universal trimers of fermions: summary



- In 2 fermions + 1 particle systems with p-wave interactions, the universal trimers predicted by Kartavtsev and Malykh for mass ratios between 8.17 and 13.6 always exist for (very!) large scattering lengths.

- However, the p-wave interaction enriches the spectrum by at least one additional state, which can be Borromean and exist *for any mass ratio*.

④ Universal trimers of fermions: summary



Outlook

- Beyond the separable approximation?
- Van der Waals universality for atoms?
- Coupled-channel interactions?
- Stability against recombination?

⑤ Trimer phase of fermionic mixtures

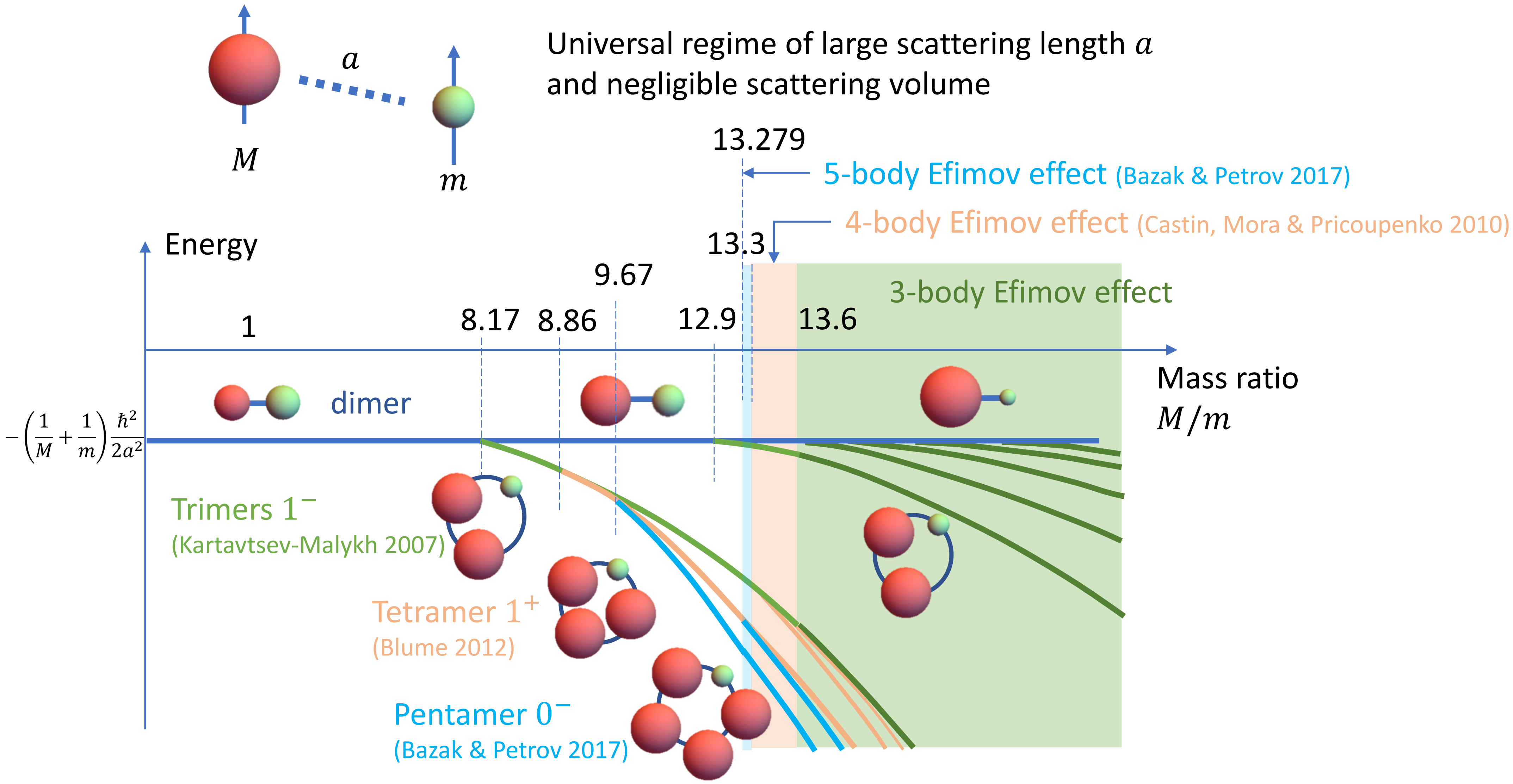
Shimpei Endō
Tohoku University

Antonio M. García-García
Shanghai Jiao Tong University

Scattering of universal fermionic clusters in the resonating group method
J. Phys. B, 49, 3, 034002 (2016) [arxiv:1507.06373v1]

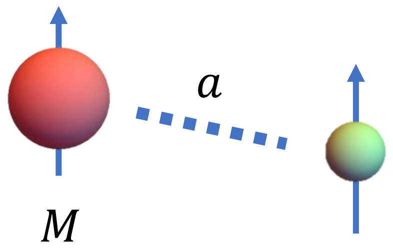
Universal clusters as building blocks of stable quantum matter
Phys. Rev. A 93, 053611 (2016) [arxiv:1507.06309v2]

N+1 fermions



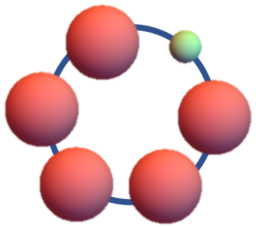
a
M
m
Universal regime of large scattering length a
and negligible scattering volume
13.279
5-body Efimov effect (Bazak & Petrov 2017)
4-body Efimov effect (Castin, Mora & Pricoupenko 2010)
13.3
Energy
9.67
3-body Efimov effect
1
8.17
8.86
12.9
13.6
Mass ratio
M/m
dimer
$-\left(\frac{1}{M}+\frac{1}{m}\right)\frac{\hbar^2}{2a^2}$
Trimers 1^-
(Kartavtsev-Malykh 2007)
Tetramer 1^+
(Blume 2012)
Pentamer 0^-
(Bazak & Petrov 2017)

N+1 fermions



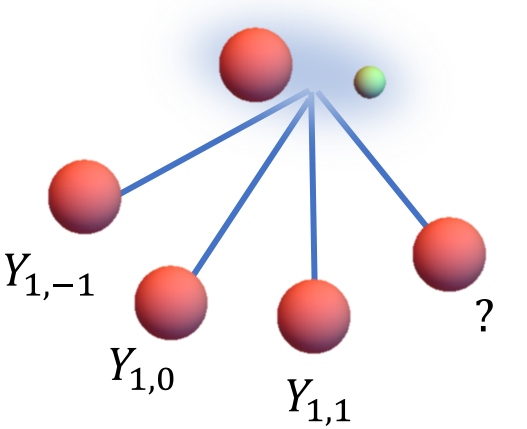
Universal regime of large scattering length a and negligible scattering volume

- Is there a 6-body Efimov effect?
- Is there a universal hexamer?



- What about the large N limit?

Shell-model argument (Bazak & Petrov):



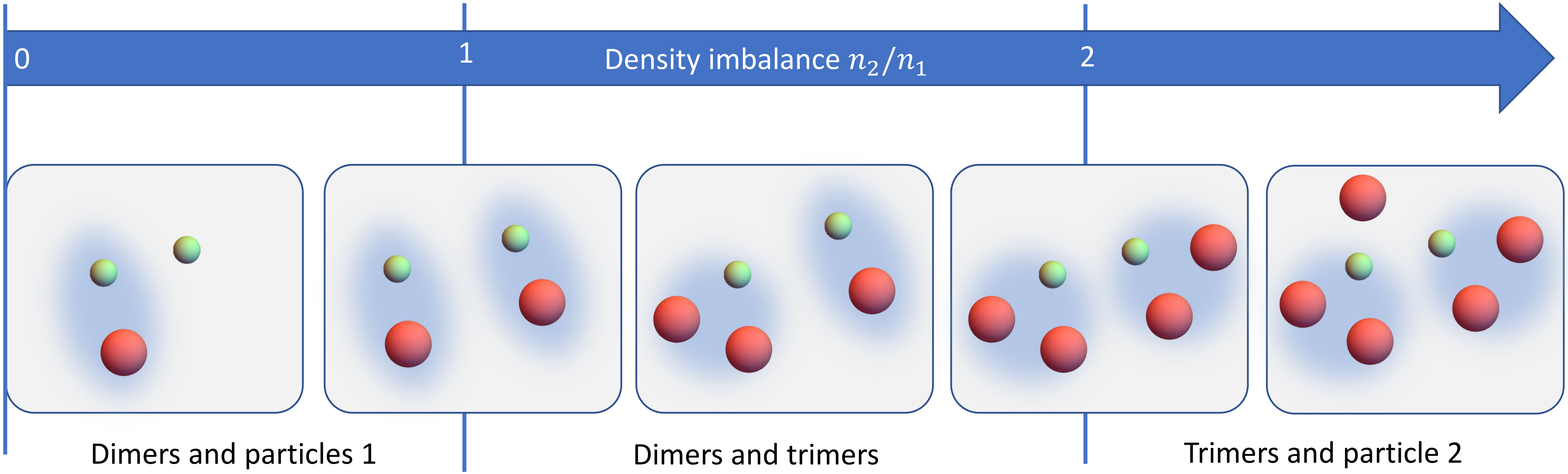
Two-component fermion mixture

$$8.17 < \frac{M}{m} < 8.86 \ldots$$

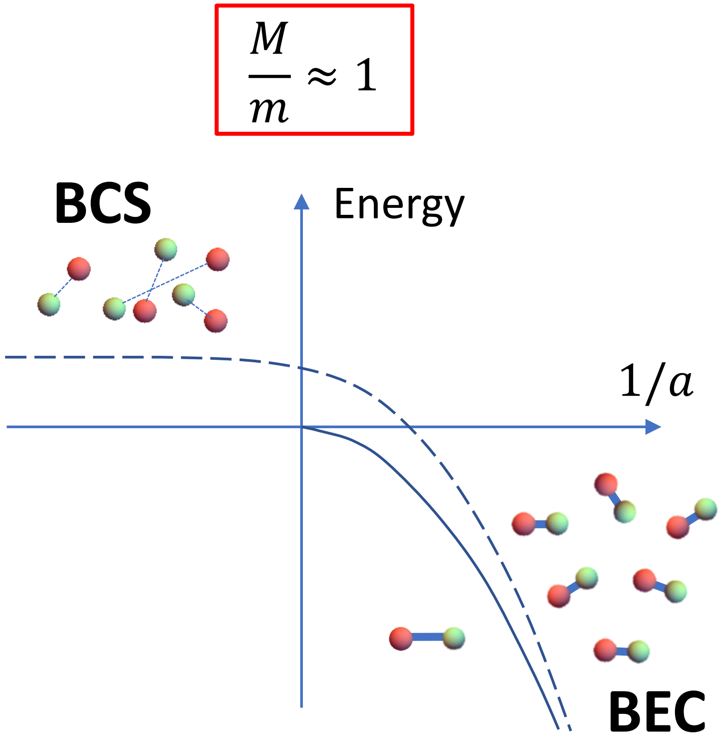
Two dimers are favoured over one trimer

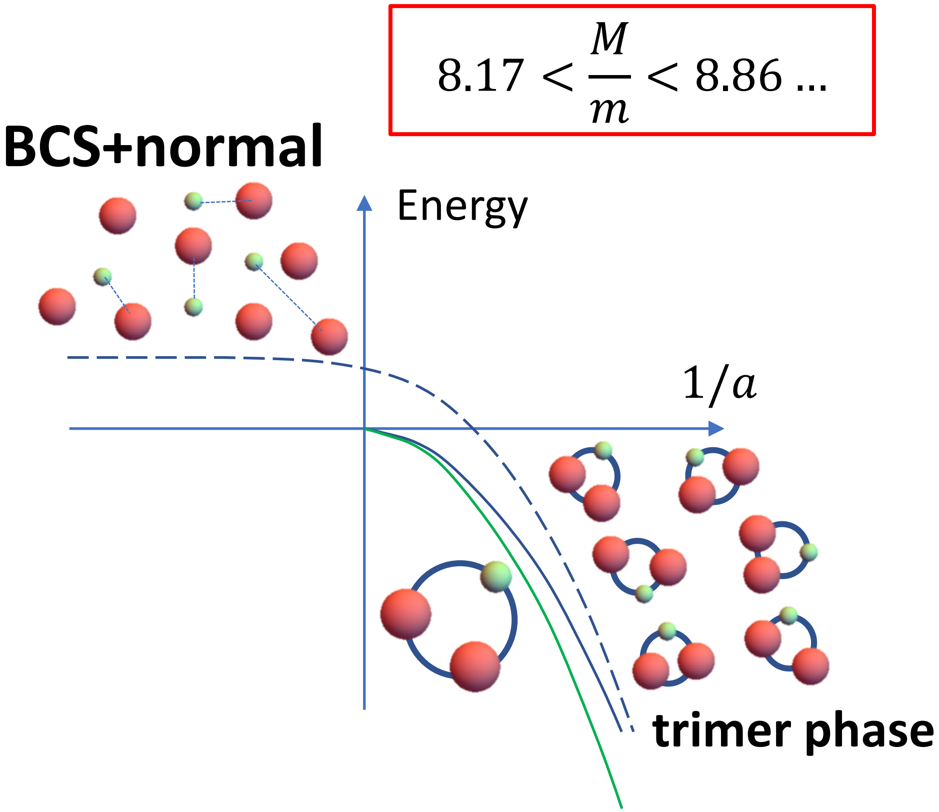
$$|E_2| < |E_3| < 2|E_2|$$

No tetramers, pentamers, etc…



Two-component fermion mixture

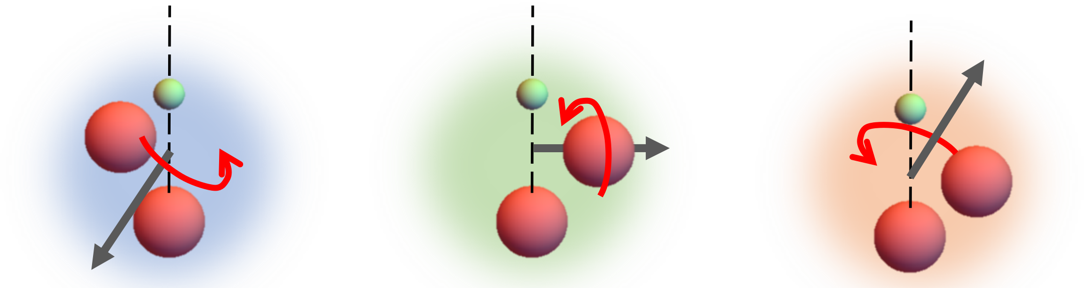




Two-component fermion mixture

The trimers are

- **fermions**
- with **one unit of angular momentum $\boldsymbol{J = 1}$**
- So there are three degenerate rotational states :

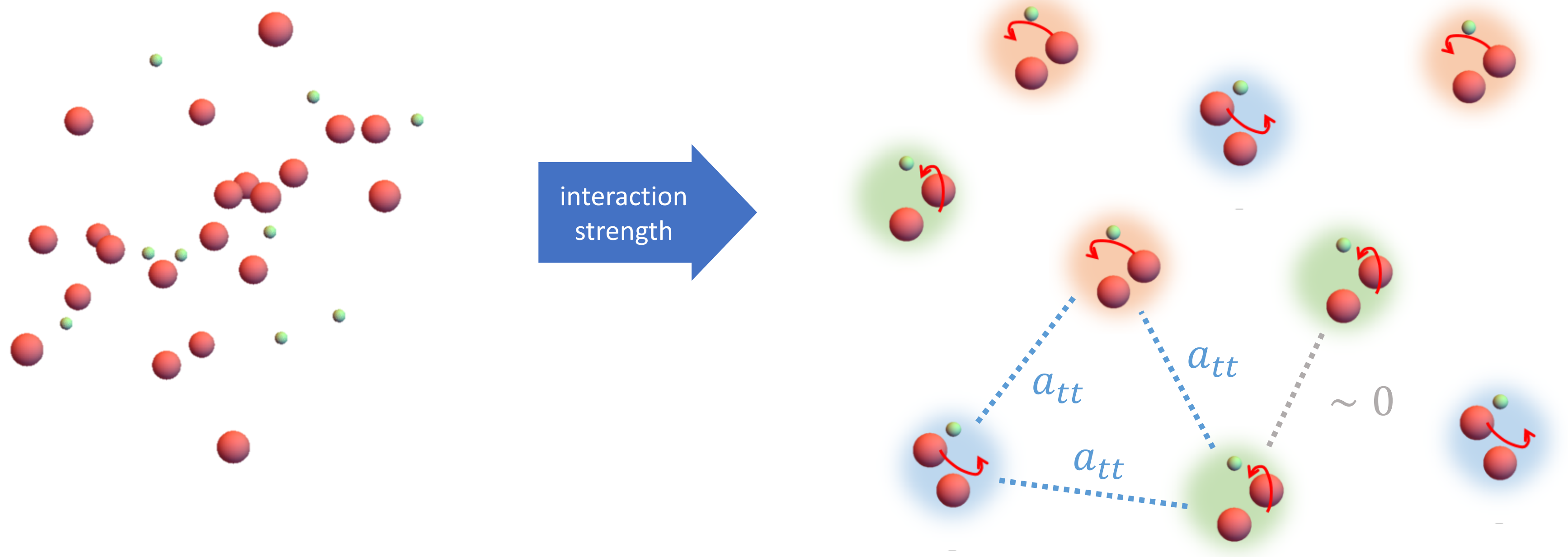


$m = -1$ $m = 0$ $m = +1$

Trimer mixture phase

At low density, the system forms a mixture of trimers

2-component Fermi system **3-component Fermi system**



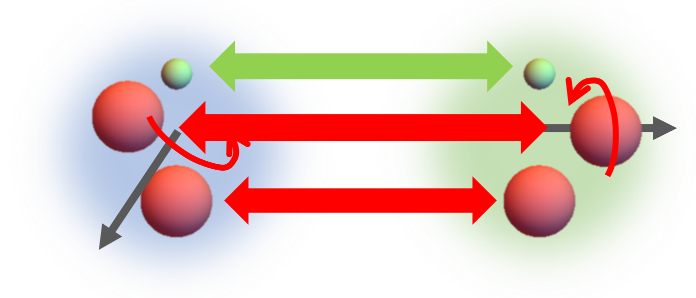
SU(3) symmetry: same scattering length a_{tt} for all pairs

Trimer mixture phase

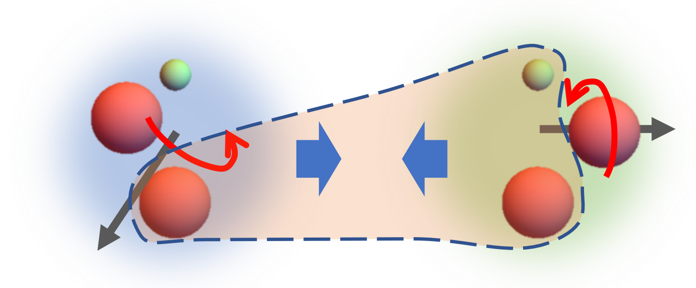
Is the phase superfluid or not?

It depends on whether the trimer-trimer interaction is attractive or not.

No 6-body bound state means the interaction is weak, but is it repulsive or attractive?



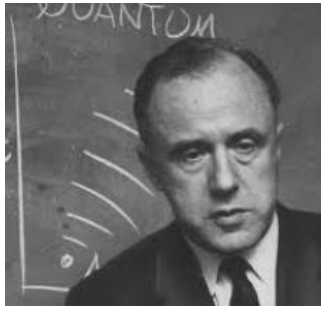
On the one hand, identical fermions tend to repel



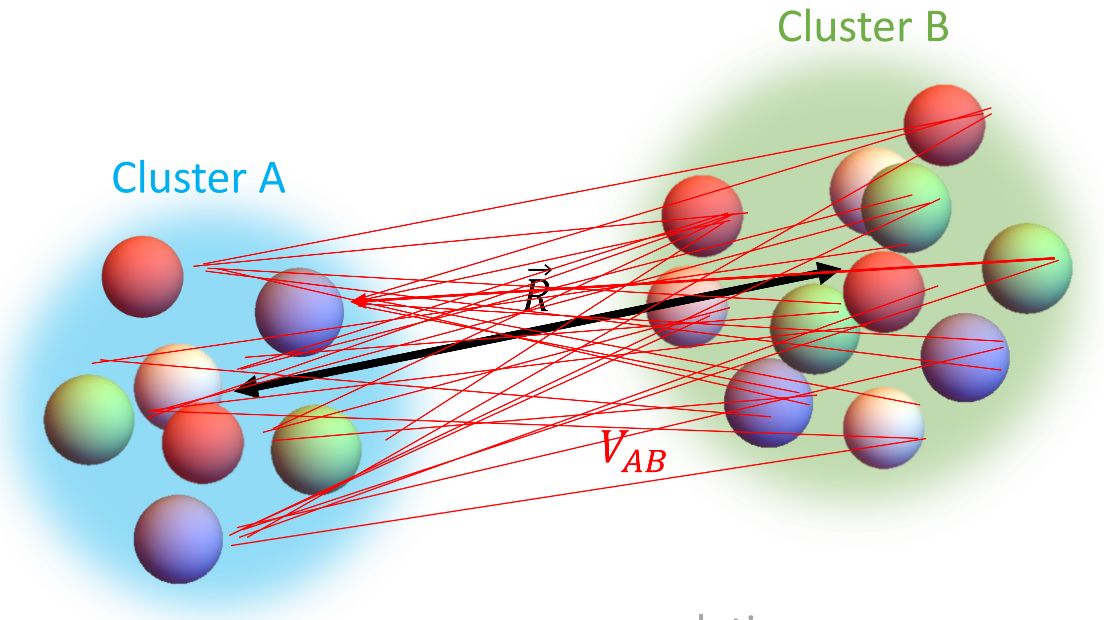
On the one hand, there is 3-body Efimov attraction

How to solve the six-body problem?

The Resonating Group Method (RGM)



John A. Wheeler
"Molecular Viewpoints in Nuclear Structure" (1937)
Physical Review 52, 1083



Anti-symmetrisation — cluster A — cluster B — relative motion — No excitation (rearrangement) during collision

$$\Psi = S\left[\ \phi_A(1,2,\dots,n)\ \phi_B(n+1, n+2, \dots, N)\ \psi\left(\vec{R}\right)\right]$$

Variational principle

$$\Rightarrow \quad K \cdot \left(-\frac{\hbar^2}{2\mu}\vec{\nabla}^2\psi\right) + V \cdot \psi = 0$$

$$K \cdot \varphi = \langle \phi_A \phi_B | S(\phi_A \phi_B \varphi)\rangle \quad \approx \varphi$$

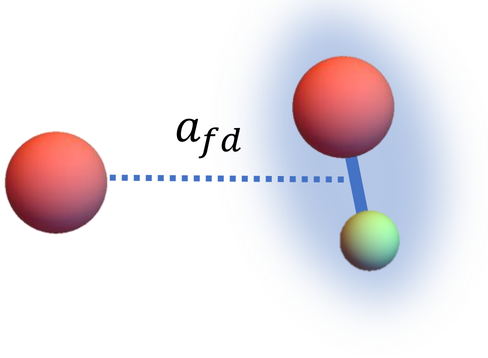
Effective potential (non-local) → Local potential

$$V \cdot \varphi = \langle \phi_A \phi_B | V_{AB} | S(\phi_A \phi_B \varphi)\rangle \qquad V_{\mathrm{loc}}(r) = \int d^3r' V(r, r')$$

The Resonating Group Method

How well does it work for universal fermionic clusters?

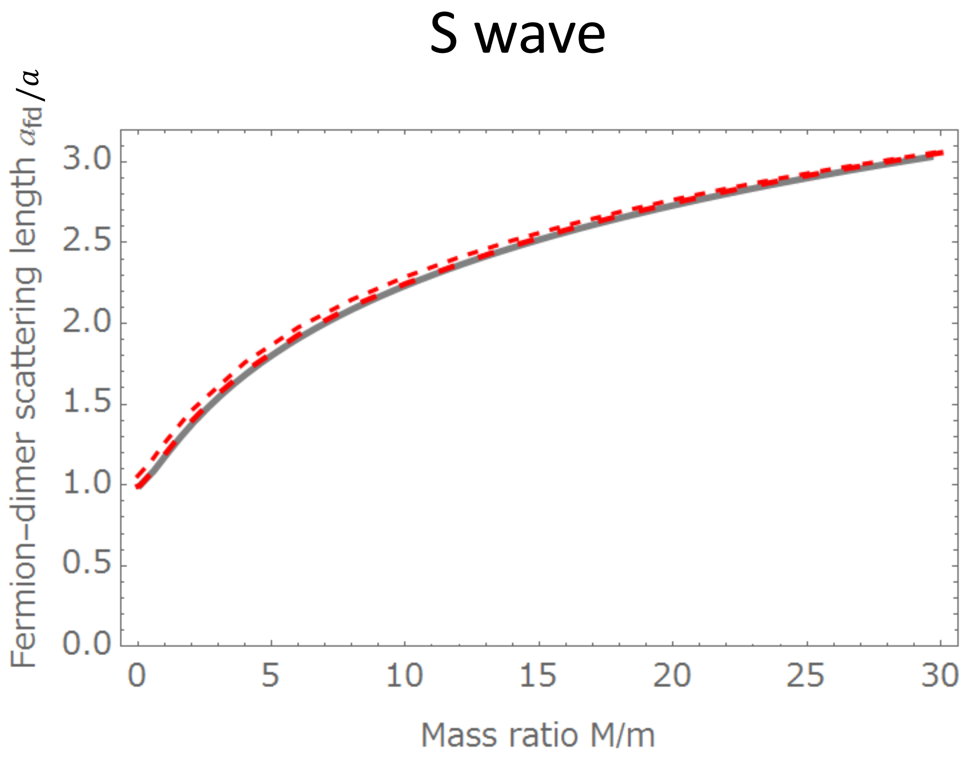
Fermion + dimer scattering



Exact
Petrov et al. PRA **71** 012708 (2005)

RGM

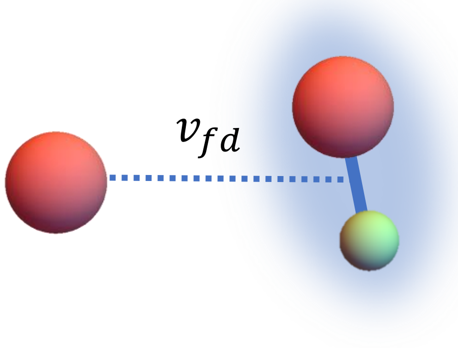
Local RGM

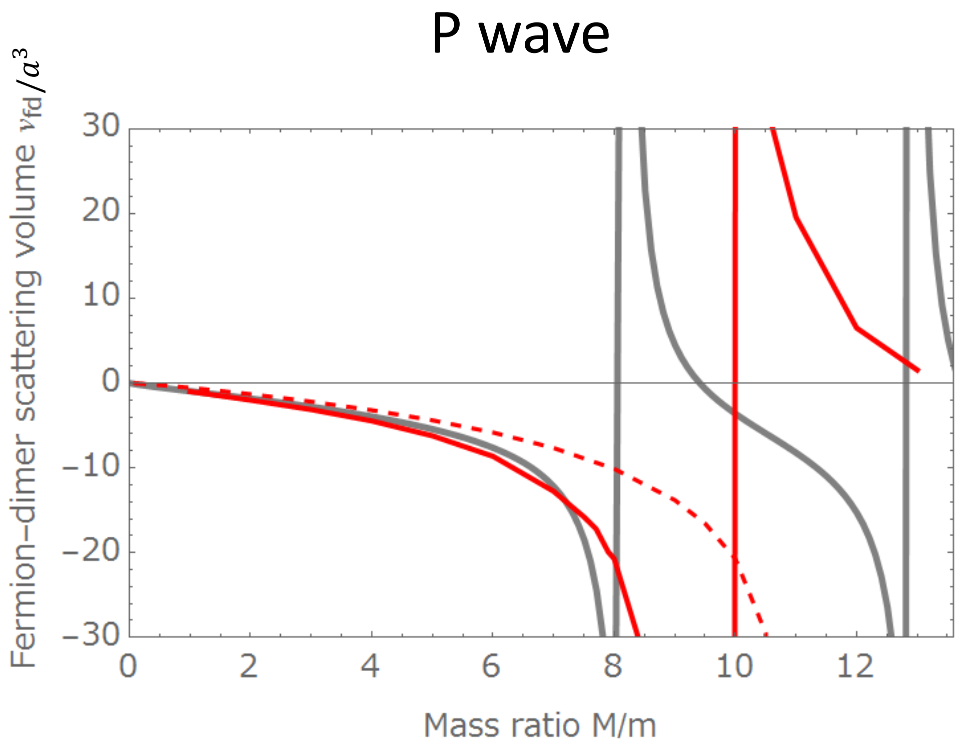


The Resonating Group Method

How well does it work for universal fermionic clusters?

Fermion + dimer scattering





Exact
Endo et al, Few-body Syst. (2011)

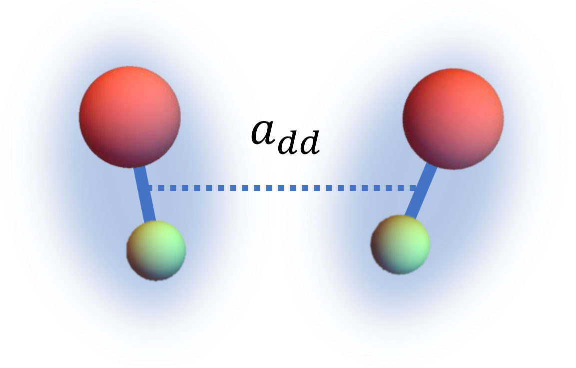
RGM

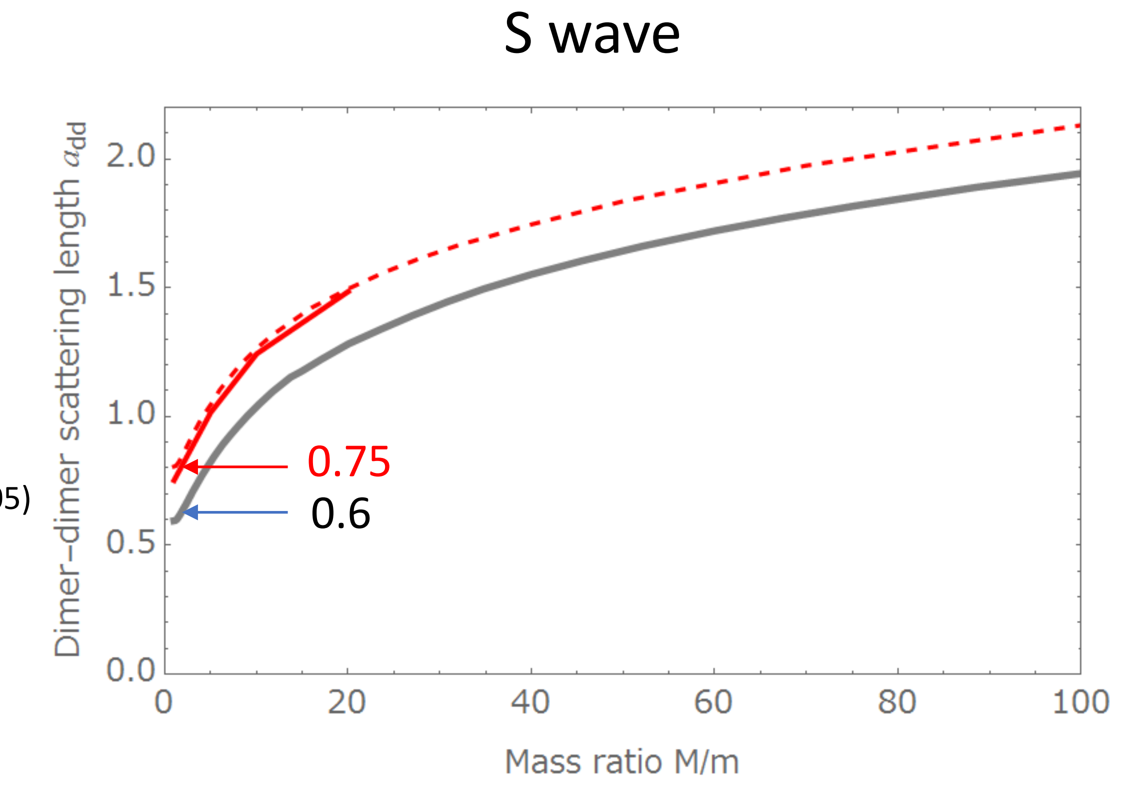
Local RGM

The Resonating Group Method

How well does it work for universal fermionic clusters?

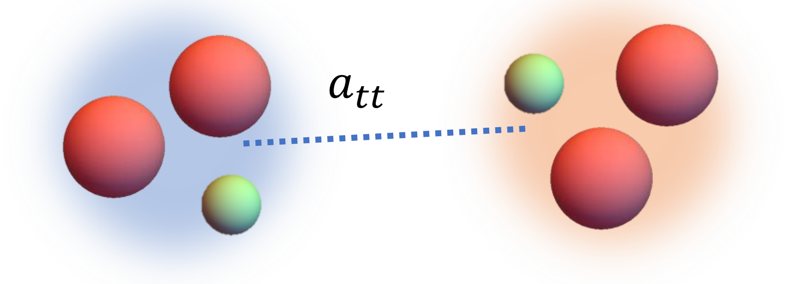
Dimer + dimer scattering





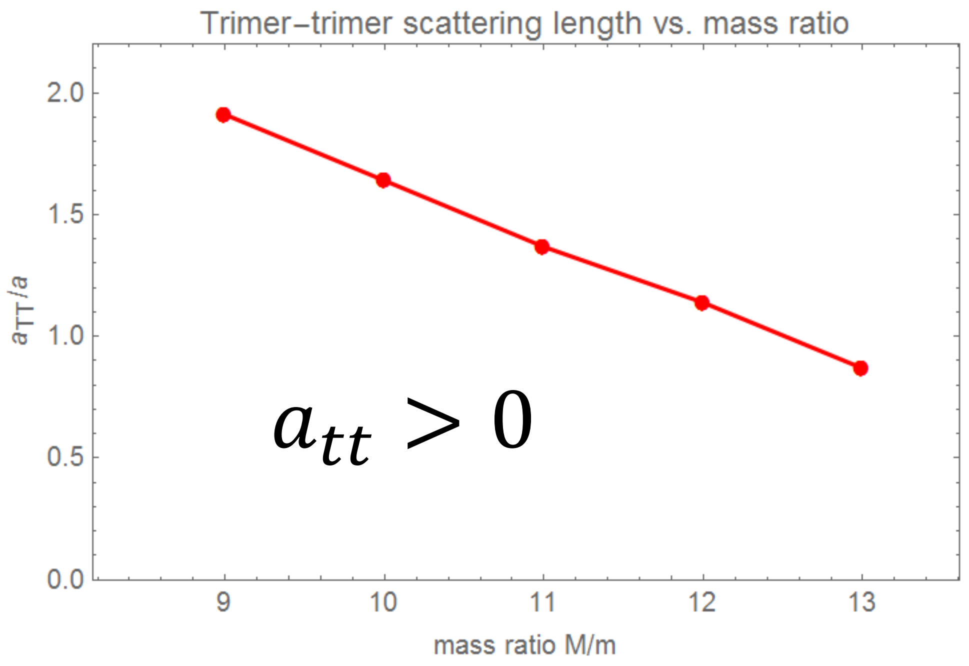
The Resonating Group Method

Trimer + Trimer scattering



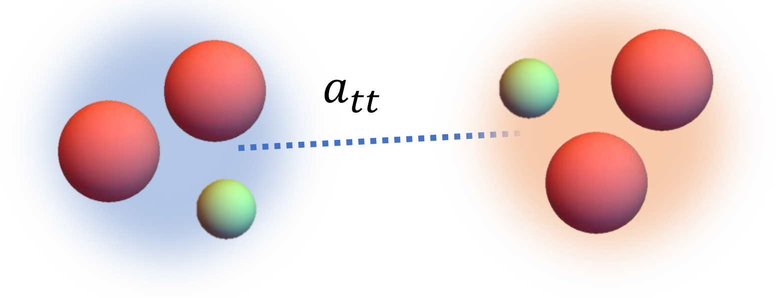
Local potential $\boldsymbol{V}$ given by 9-dimensional integrals, calculated by Monte-Carlo

S wave

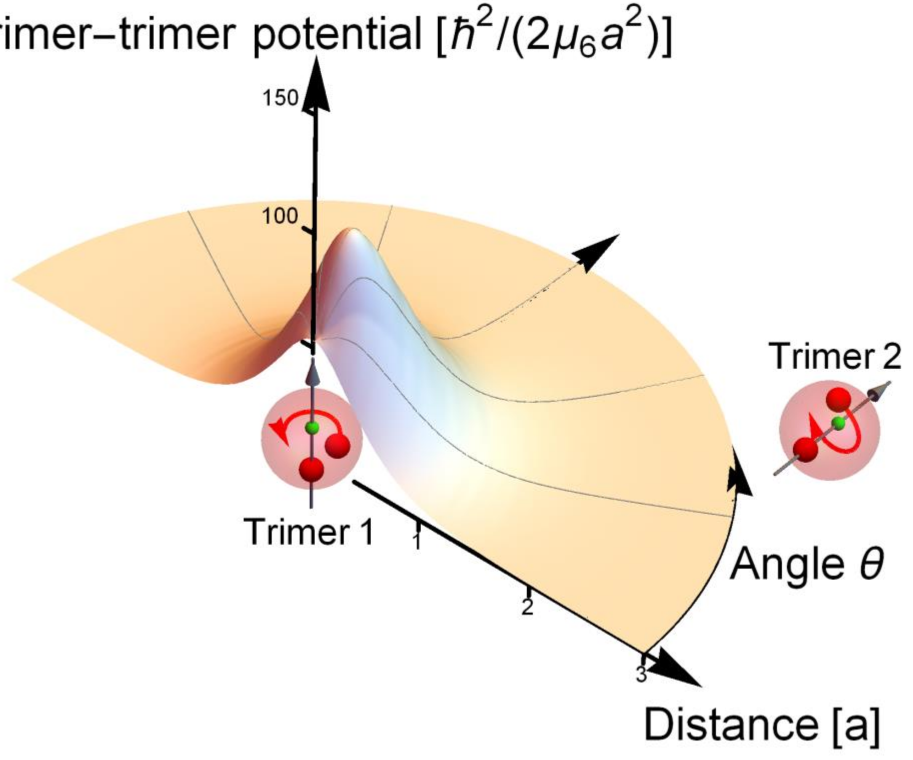


The Resonating Group Method

Trimer + Trimer scattering



(local approximation)



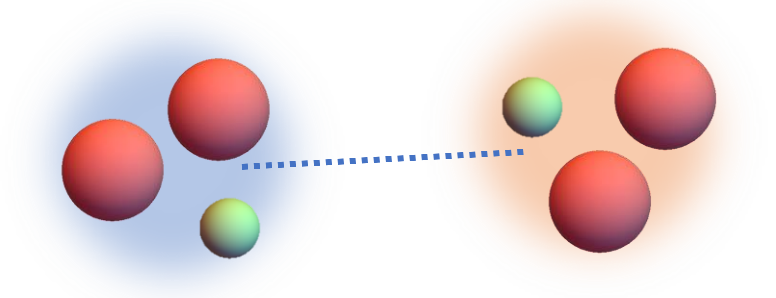
⑤ Trimer phase: Summary

- 2-component mass-imbalanced Fermi systems close to unitarity can turn into a 3-component Fermi system of universal trimers

- The resonating group method predicts a repulsion between universal trimers, implying the existence of a many-body phase that is a non-superfluid SU(3) Fermi gas.

Outlook

- Can we solve this 6-body problem?
- What if we include the p-wave interaction?



General summary

- Two-component boson mixtures near unitarity exhibit the 3-body Efimov effect, which plays a role in many-body settings like the polaron problem. Non-resonant interactions also lead to interesting phenomena like liquid droplets and partially-mixed bubbles.

- Two-component fermion mixtures near unitarity can exhibit a rich spectrum of universal trimers below the Efimov critical mass ratio. The universal trimers may form an SU(3) Fermi gas.