

Universal clustering and the Efimov effect

Pascal Naidon, RIKEN

D01 Emergence mechanism of hierarchical structure of
matter studied by ab-initio calculations

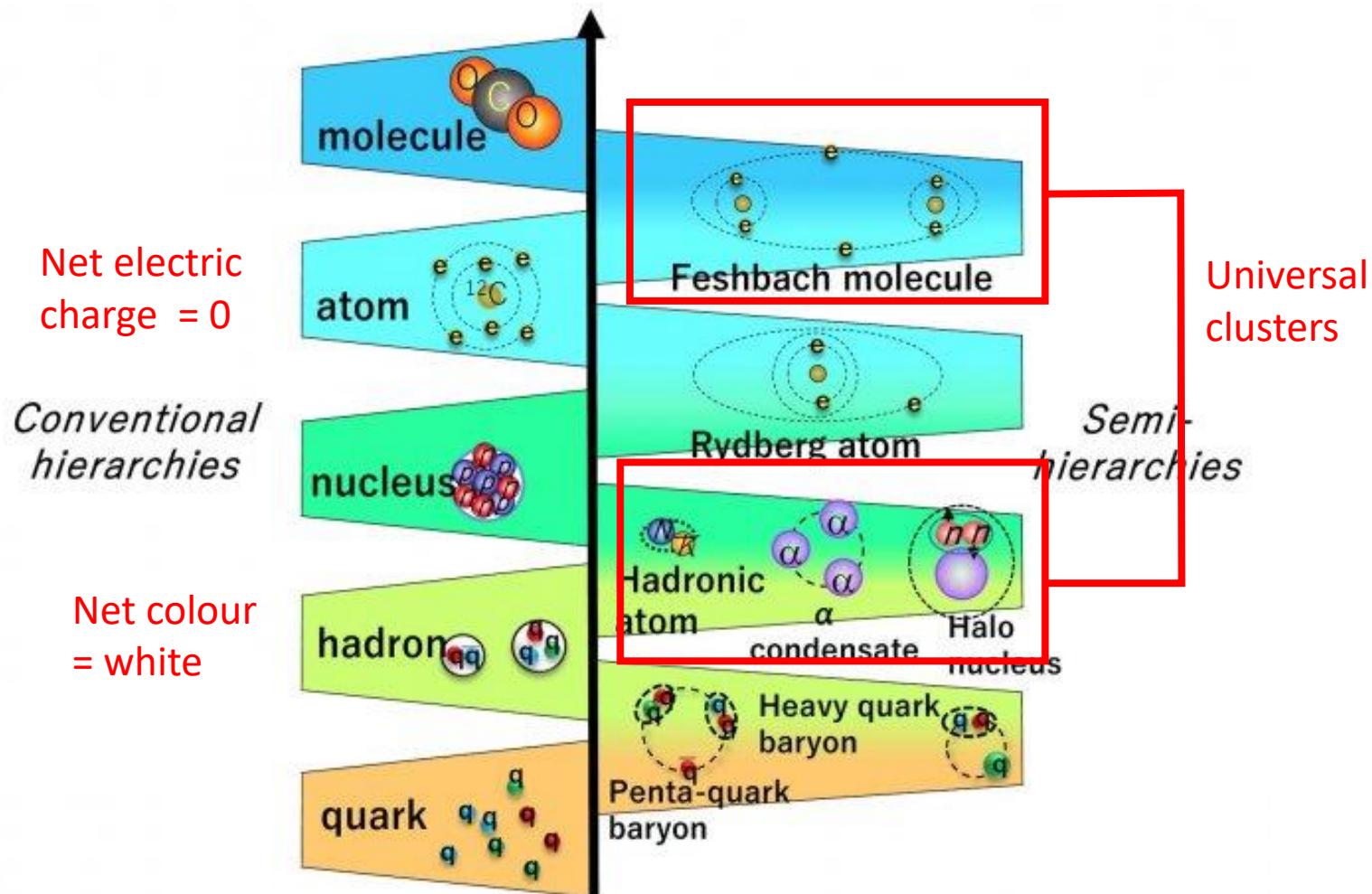
Clustering as a window on the hierarchical structure of quantum systems

Kick-off symposium
Tokyo Institute of Technology, 2018-11-20

Outline

- What are universal clusters and what is the Efimov effect?
- Projects

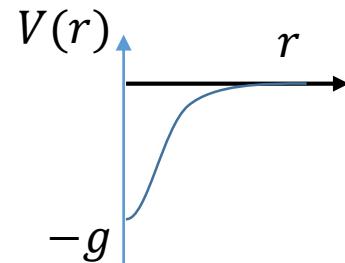
What are universal clusters?



(source: Takashi Nakamura)

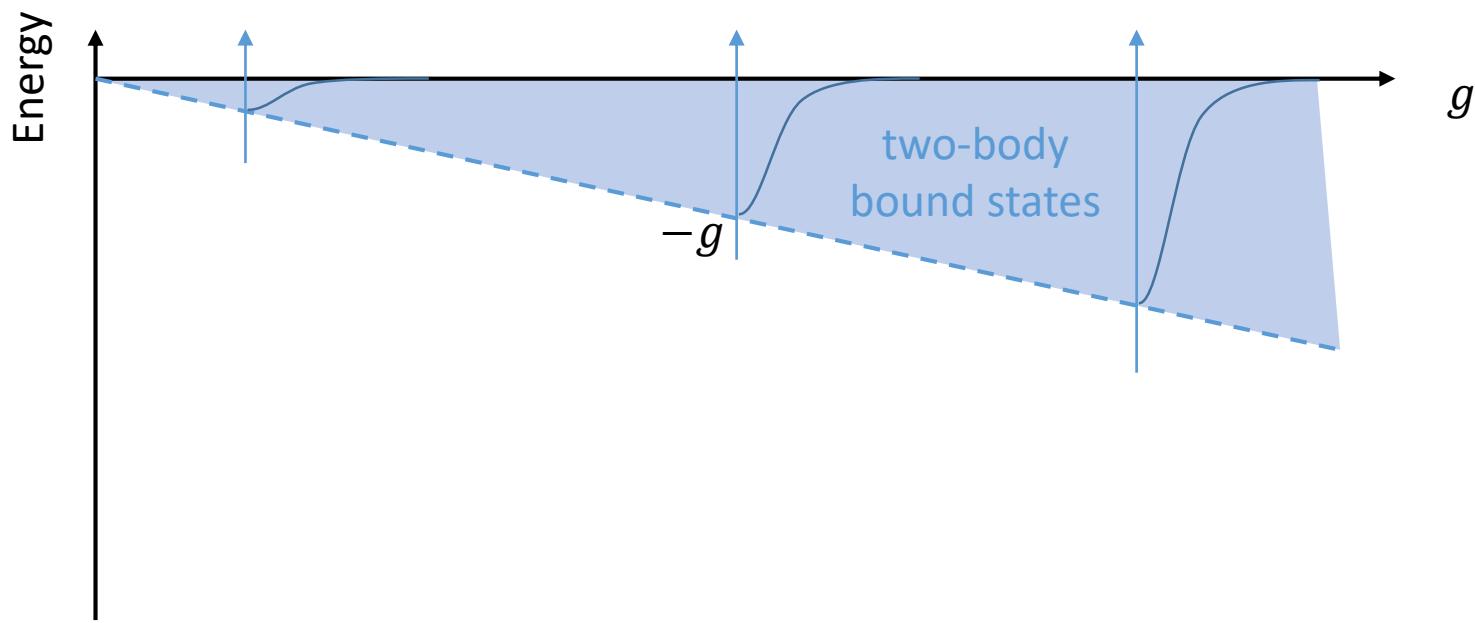
What are universal clusters?

Short-range attractive interaction potential



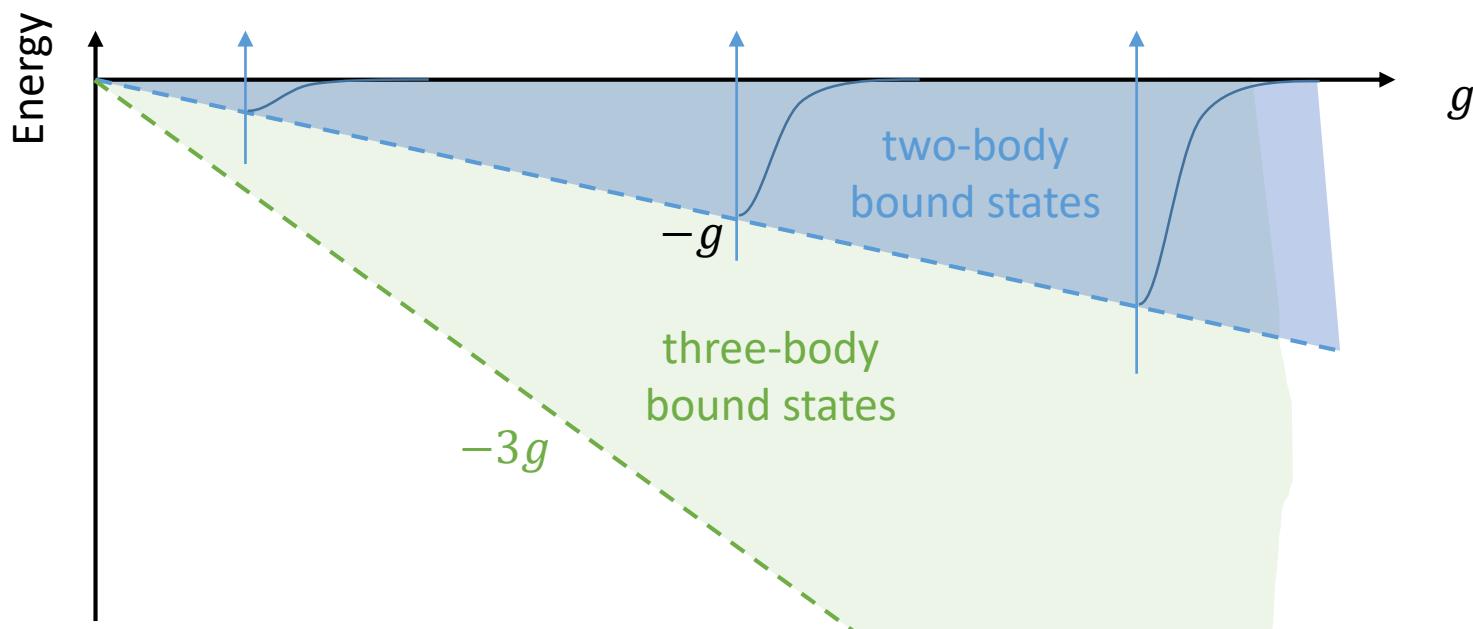
What are universal clusters?

Binding in classical systems



What are universal clusters?

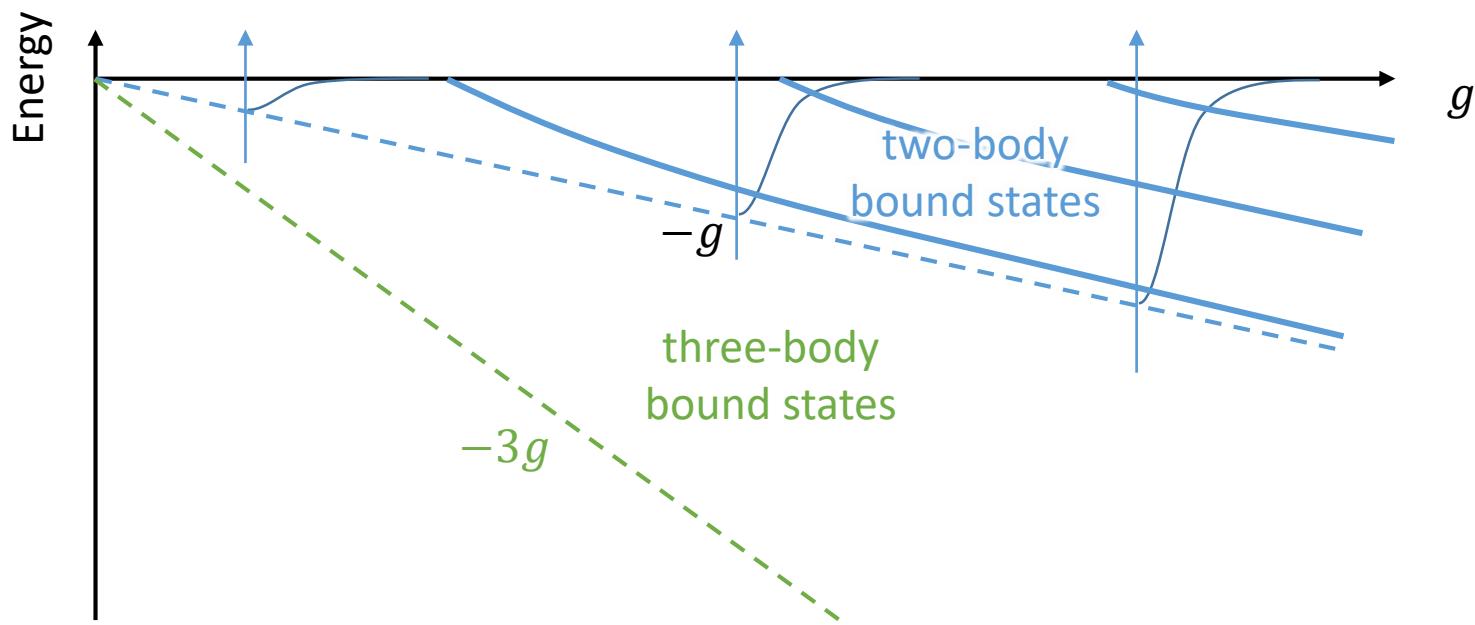
Binding in classical systems



What are universal clusters?

Binding in quantum systems

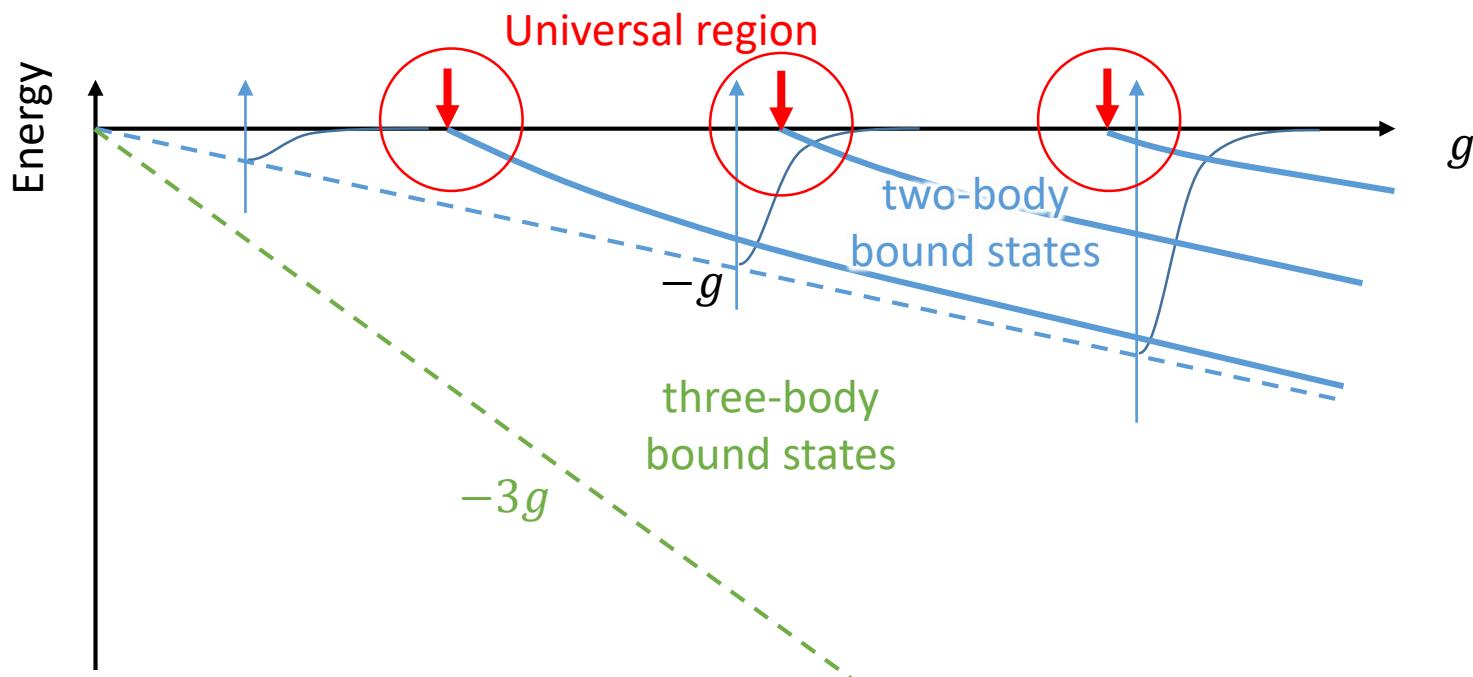
Quantum fluctuations + interactions \Rightarrow critical strength g (zero-point) and quantisation



What are universal clusters?

Binding in quantum systems

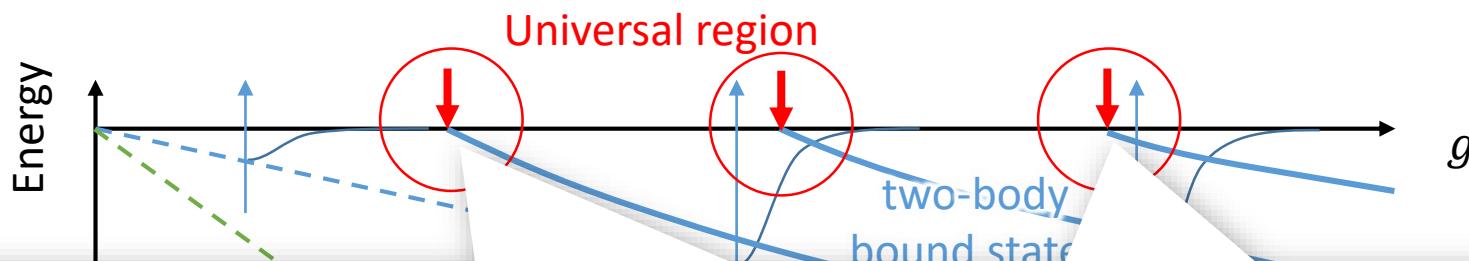
Two-body resonances \Rightarrow unitarity points, universality and scale invariance



What are universal clusters?

Binding in quantum systems

Two-body resonances \Rightarrow unitarity points, universality and scale invariance

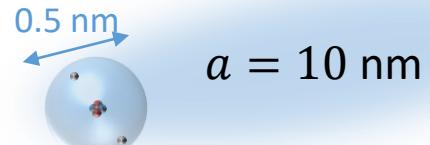


In nature

Deuteron

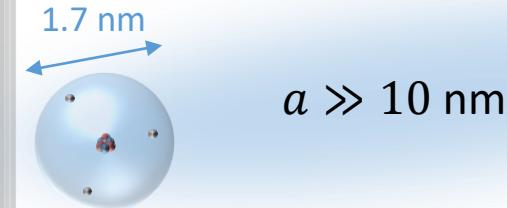


Helium-4 dimer



In the laboratory

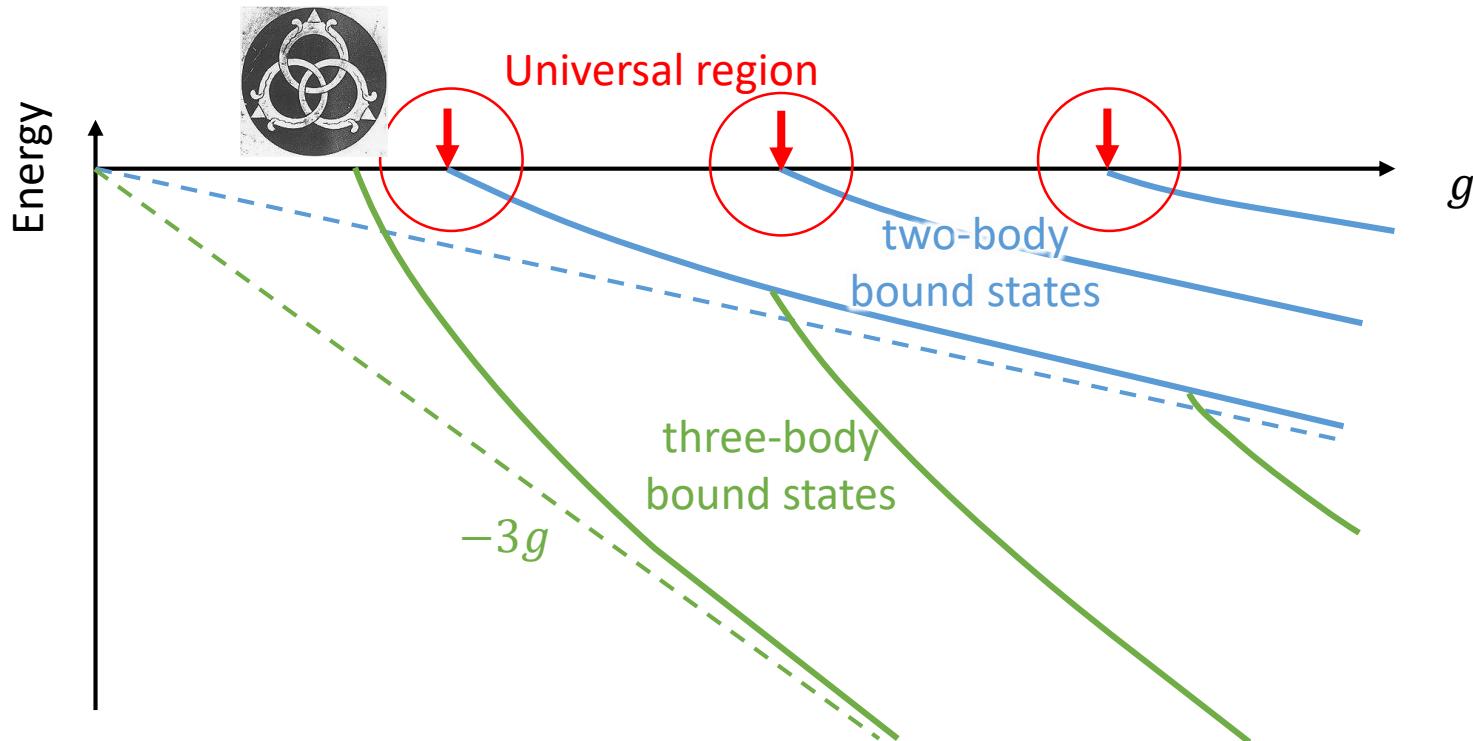
Feshbach dimers from cold atoms



What are universal clusters?

Binding in quantum systems

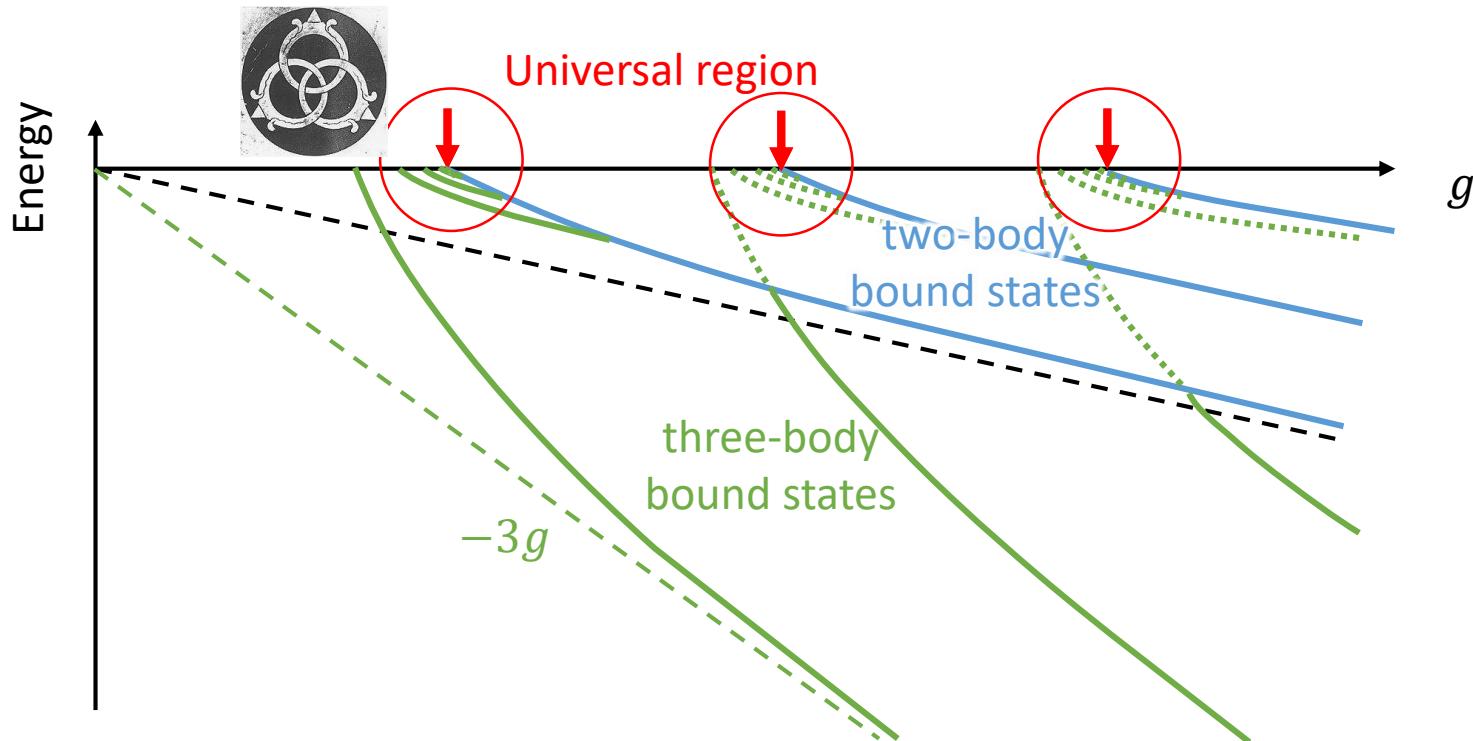
Two-body resonances \Rightarrow unitarity points, universality and scale invariance



What are universal clusters?

Binding in quantum systems

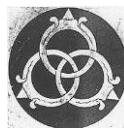
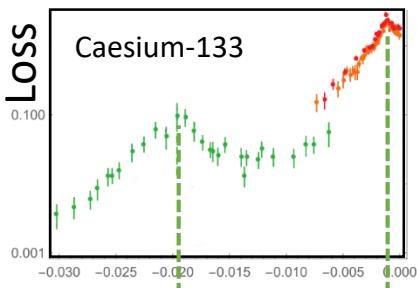
Two-body resonances \Rightarrow unitarity points, universality and scale invariance



The Efimov effect



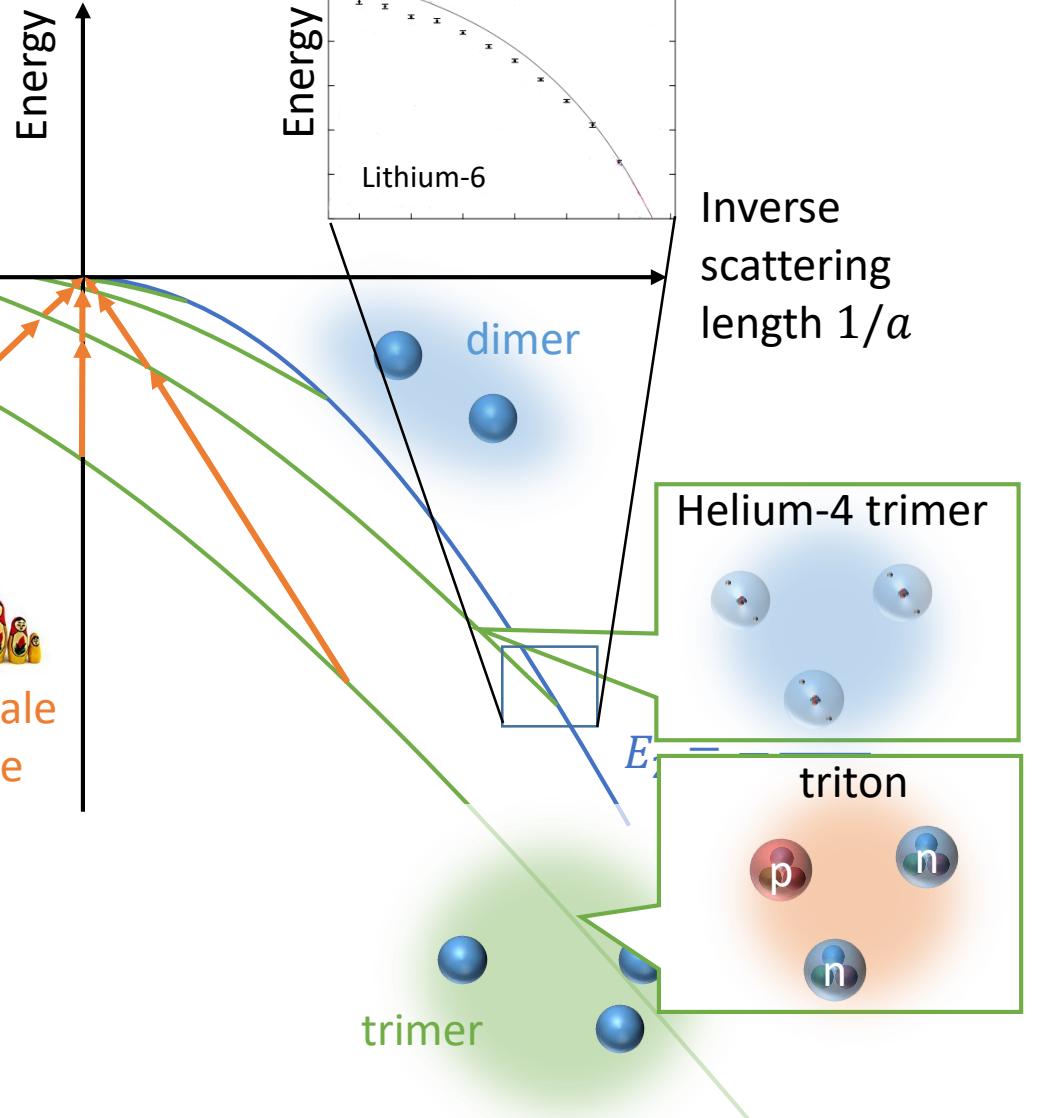
Predicted
in 1970

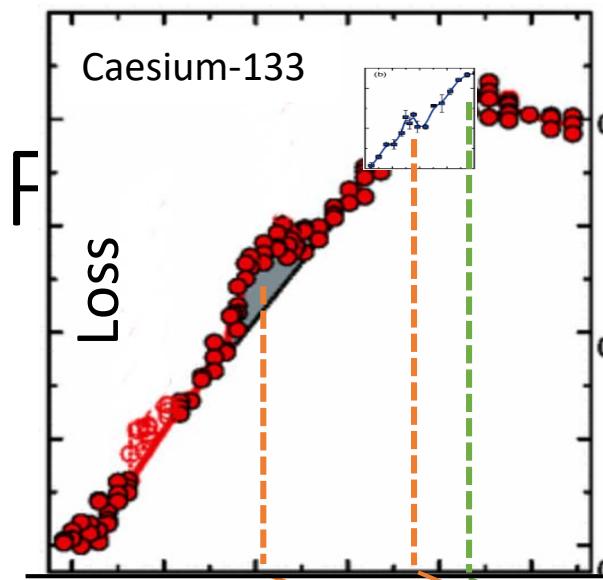


Efimov
attraction

$$\left(-\frac{1}{m} \frac{d^2}{dR^2} - \frac{1}{m} \frac{\alpha}{R^2} - E_3 \right) \psi = 0$$

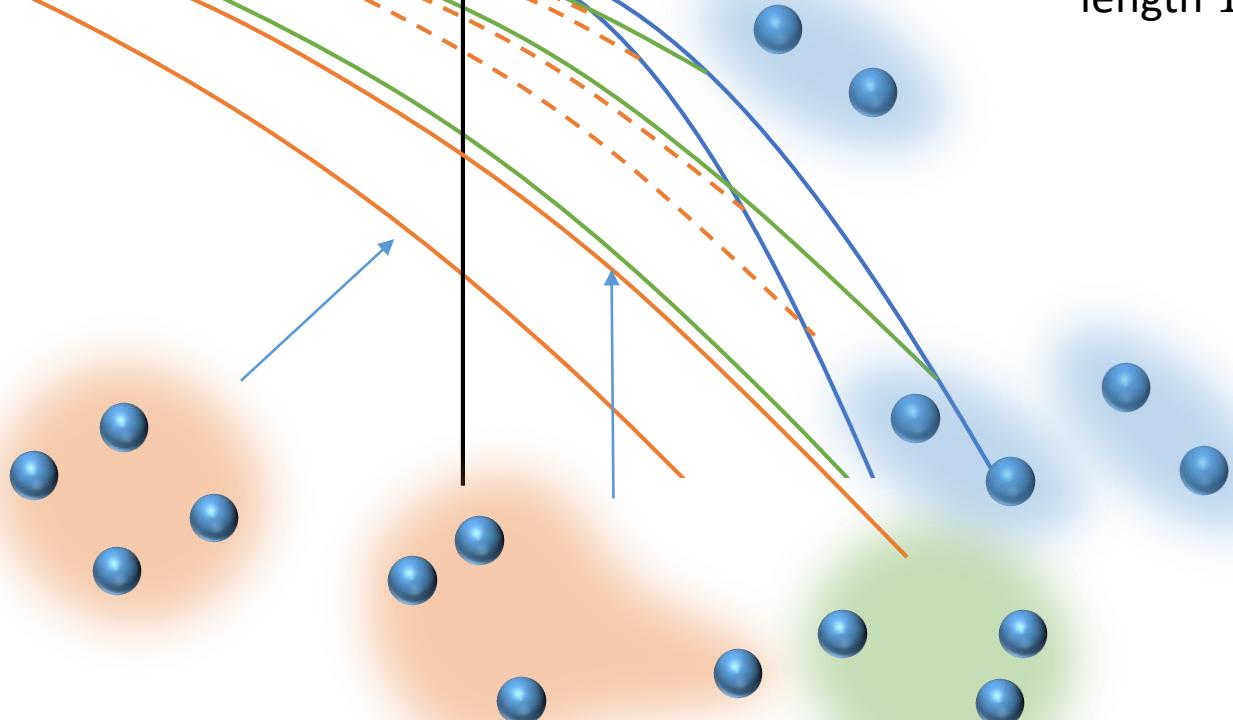
Discrete scale
invariance



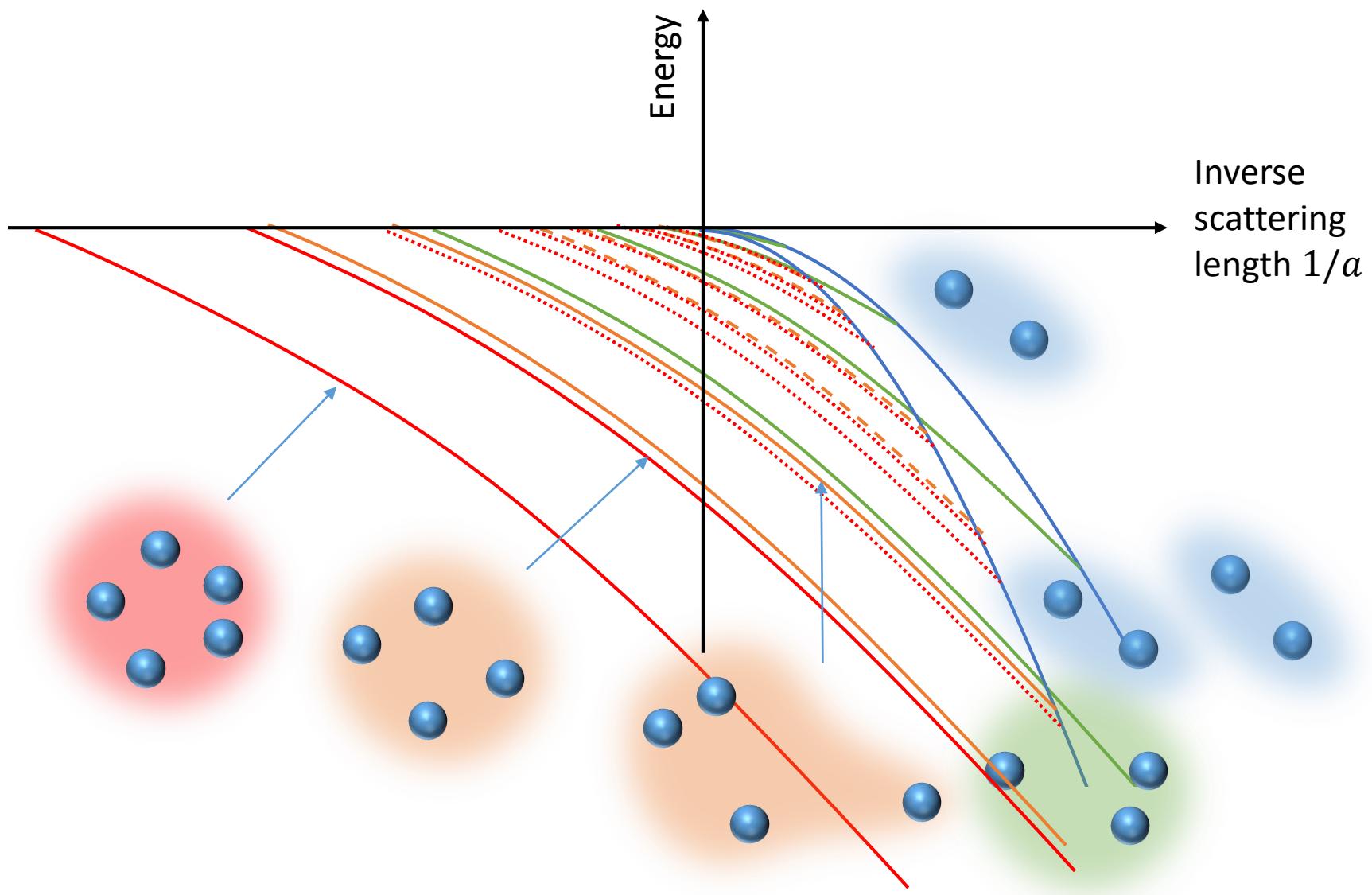


Energy

Inverse
scattering
length $1/a$



Five bosons



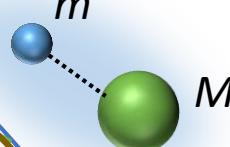
Two different bosons

$$\left(-\frac{1}{m} \frac{d^2}{dR^2} - \frac{1}{M} \frac{1}{R^2} - E_3 \right) \psi = 0$$

unfavoured

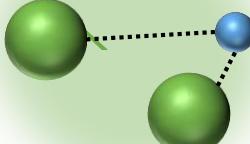
Energy

Inverse
scattering
length $1/a$

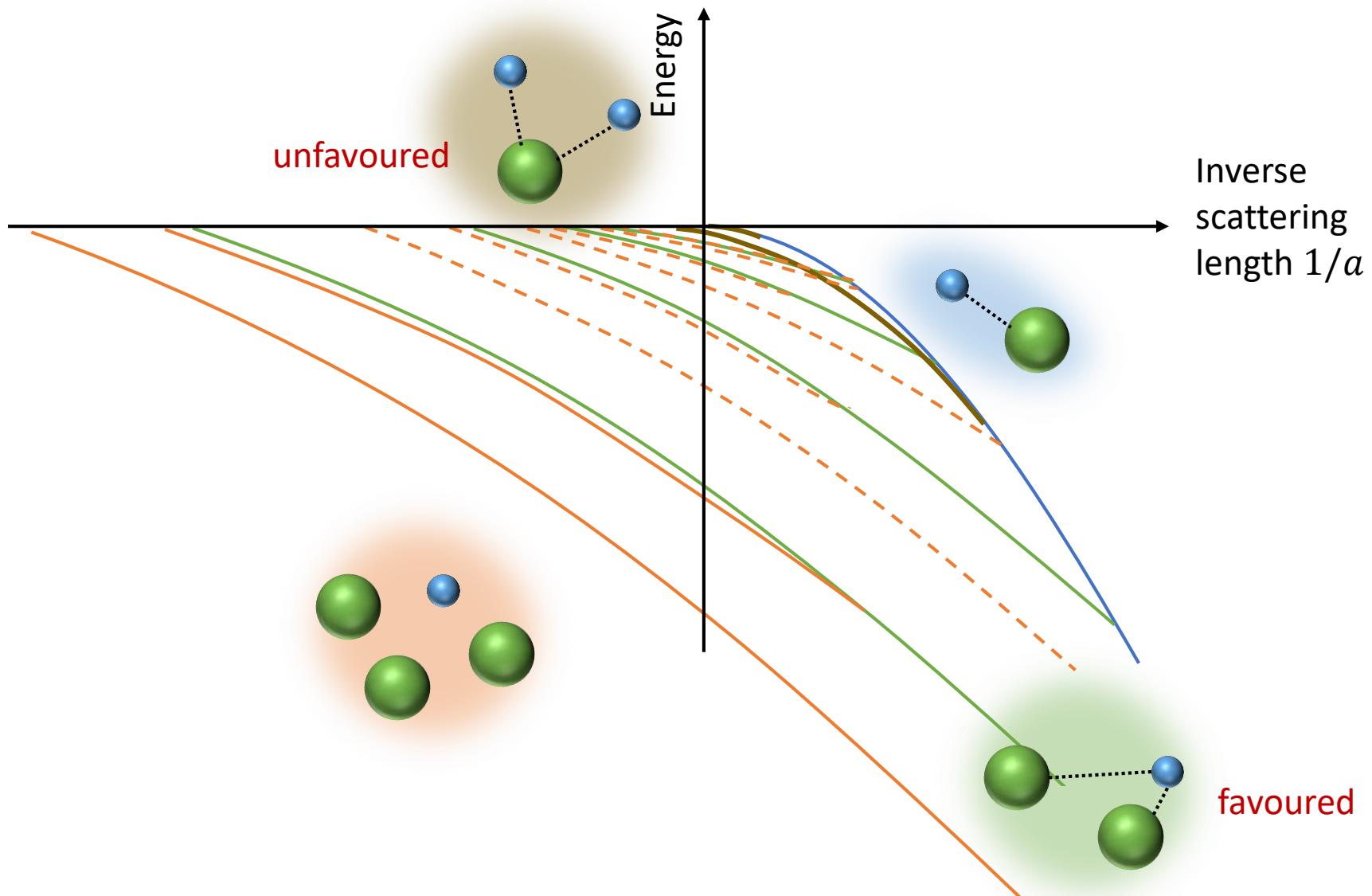


$$\left(-\frac{1}{M} \frac{d^2}{dR^2} - \frac{1}{m} \frac{1}{R^2} - E_3 \right) \psi = 0$$

favoured



Two different bosons



Review papers

IOP Publishing Reports on Progress in Physics
Rep. Prog. Phys. **80** (2017) 056001 (78pp)
<https://doi.org/10.1088/1361-6633/aa50e8>

Review

Efimov physics: a review

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Universal few-body physics and cluster formation

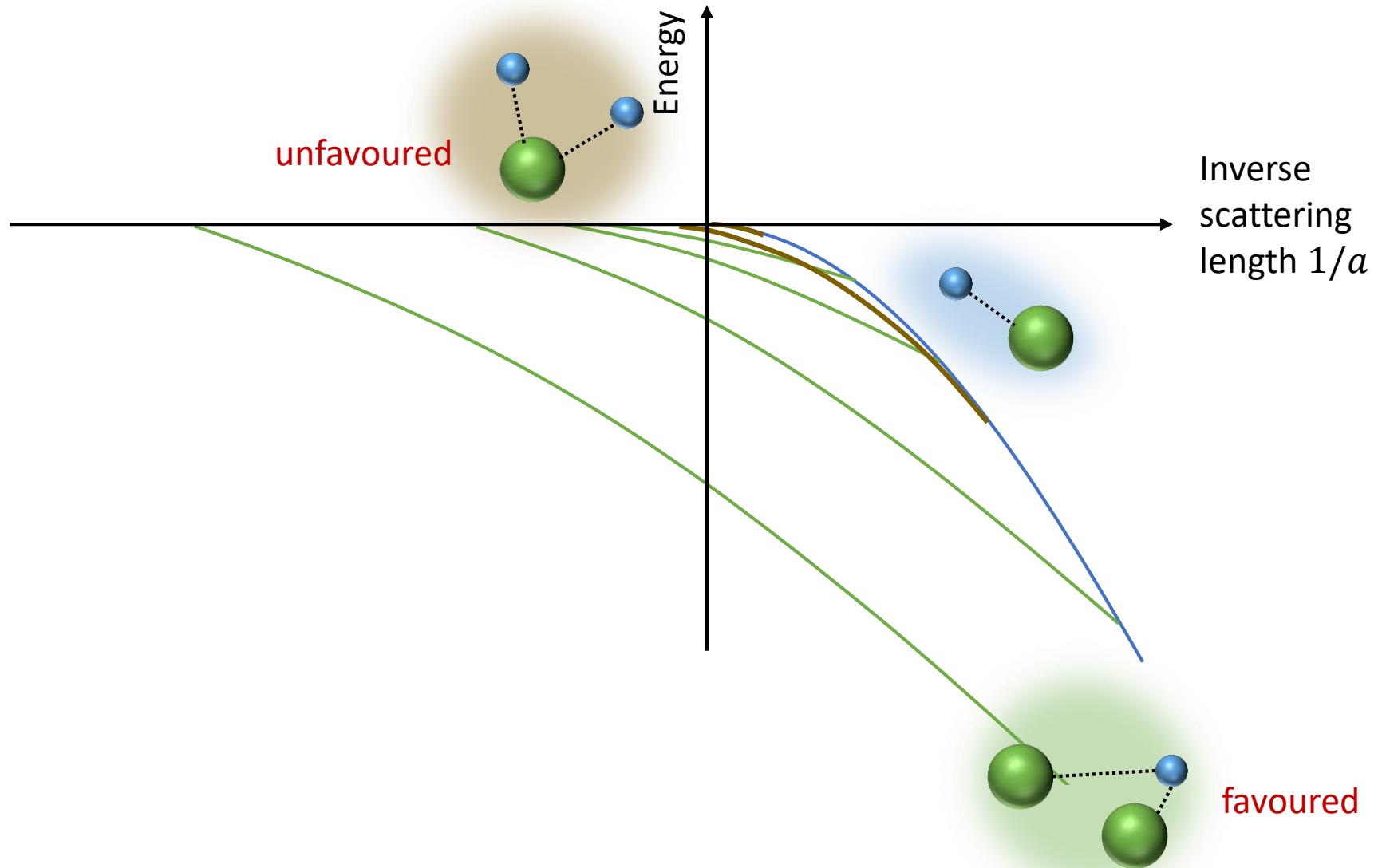
Chris H. Greene, P. Giannakeas, and J. Pérez-Ríos
Rev. Mod. Phys. **89**, 035006 – Published 28 August 2017

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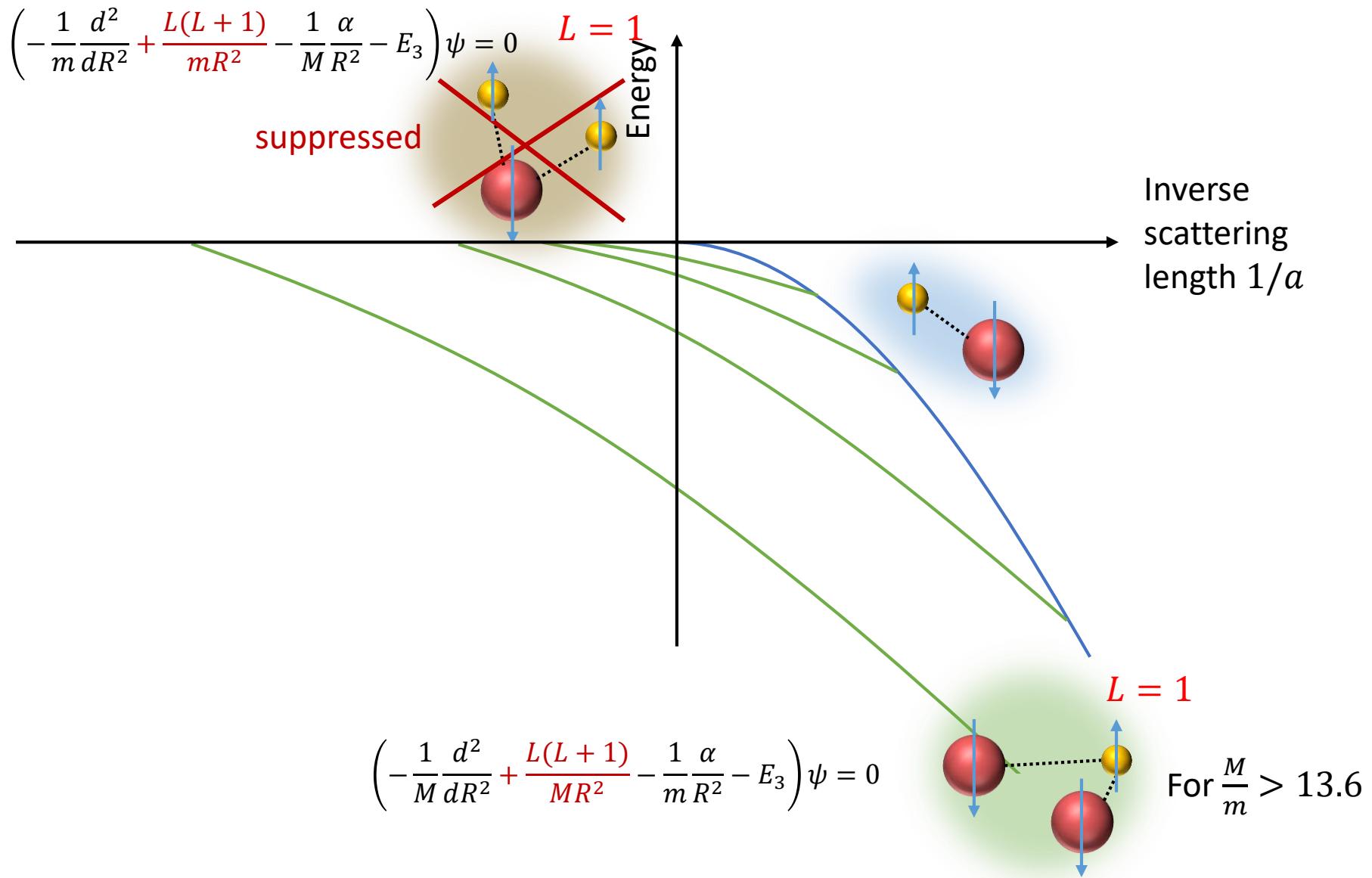
Projects

- Universal clusters with nonzero angular momentum
- Universal clusters in many-body systems

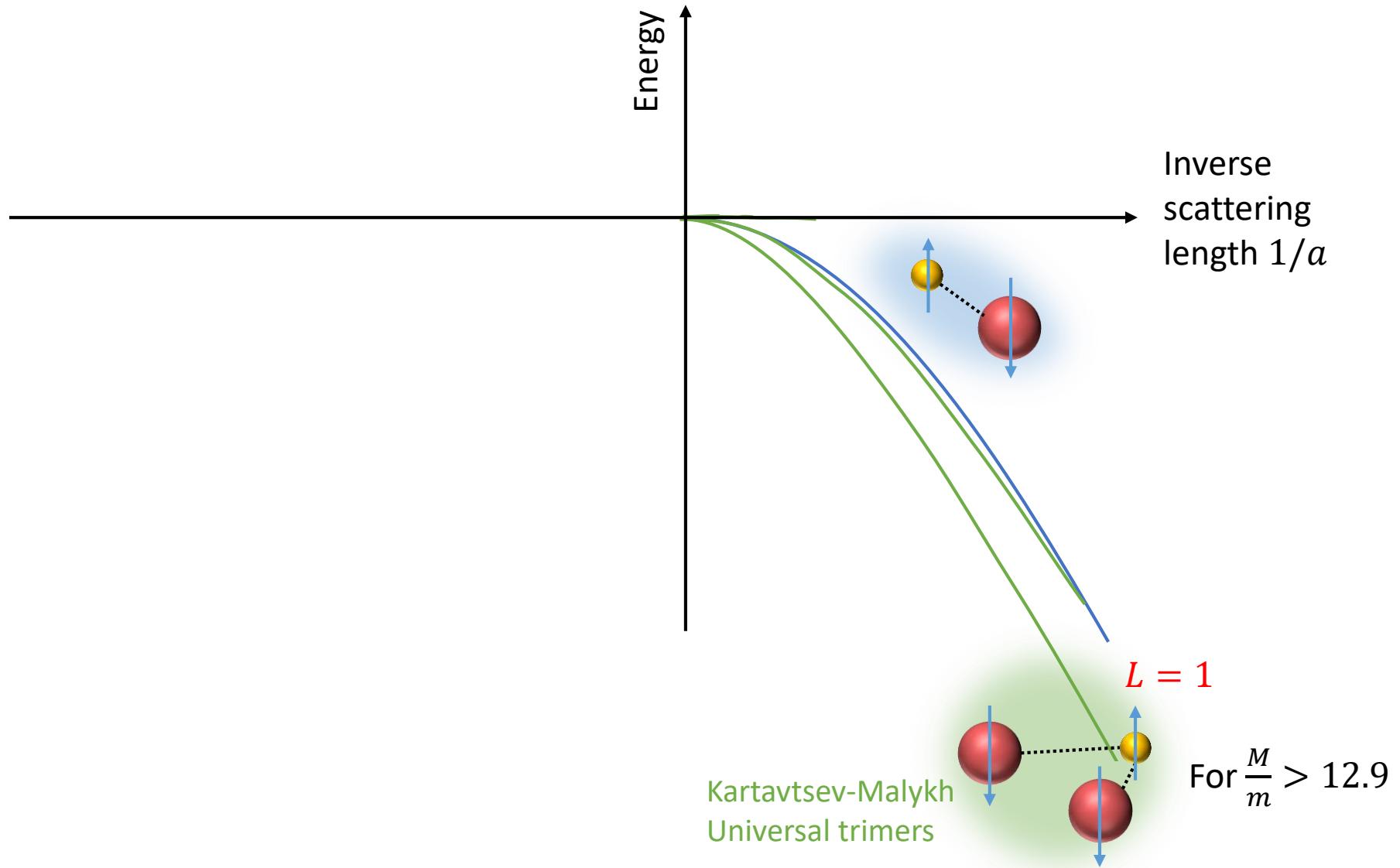
Universal clusters with $L \neq 0$



Universal clusters with $L \neq 0$



Universal clusters with $L \neq 0$

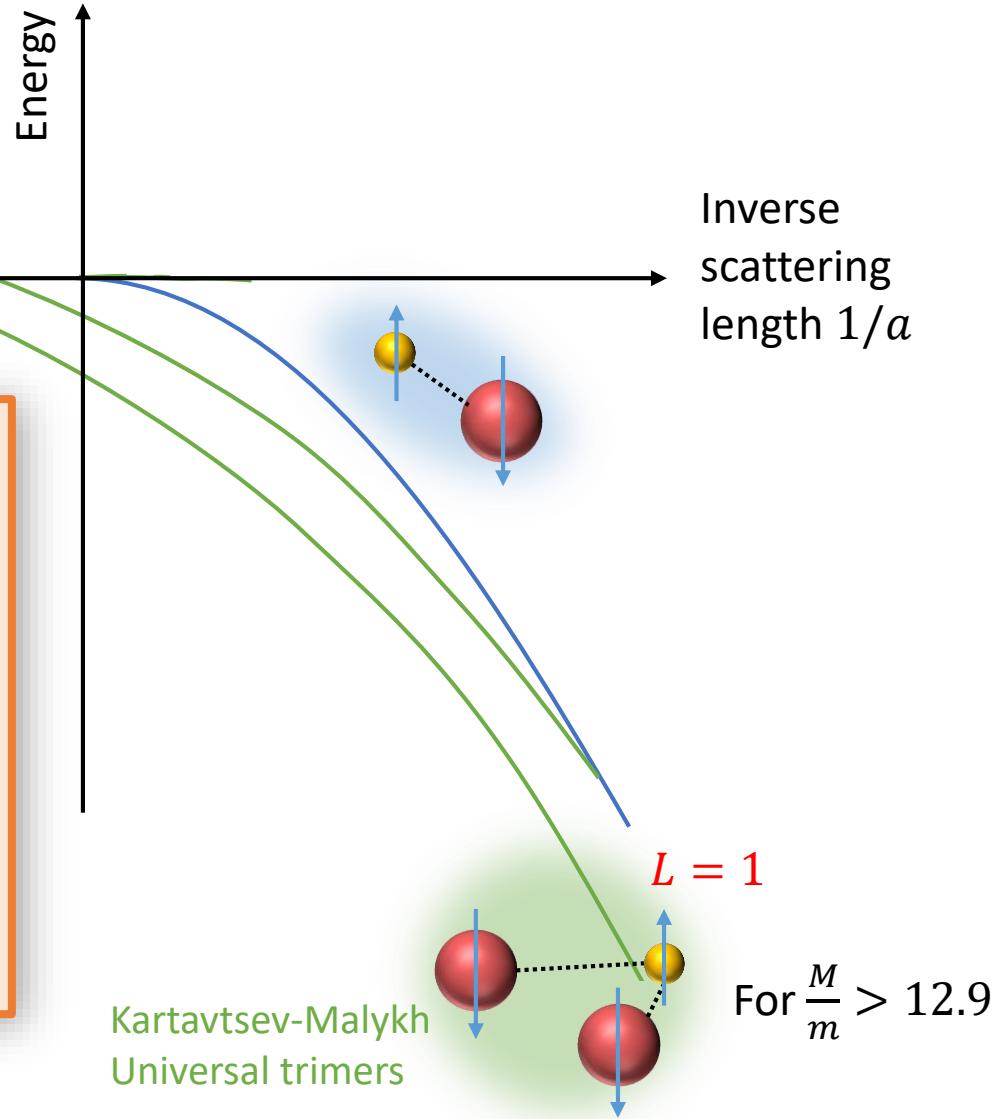
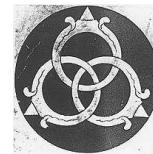


Universal clusters with $L \neq 0$

Zero-range theory: Borromean states are in principle possible!

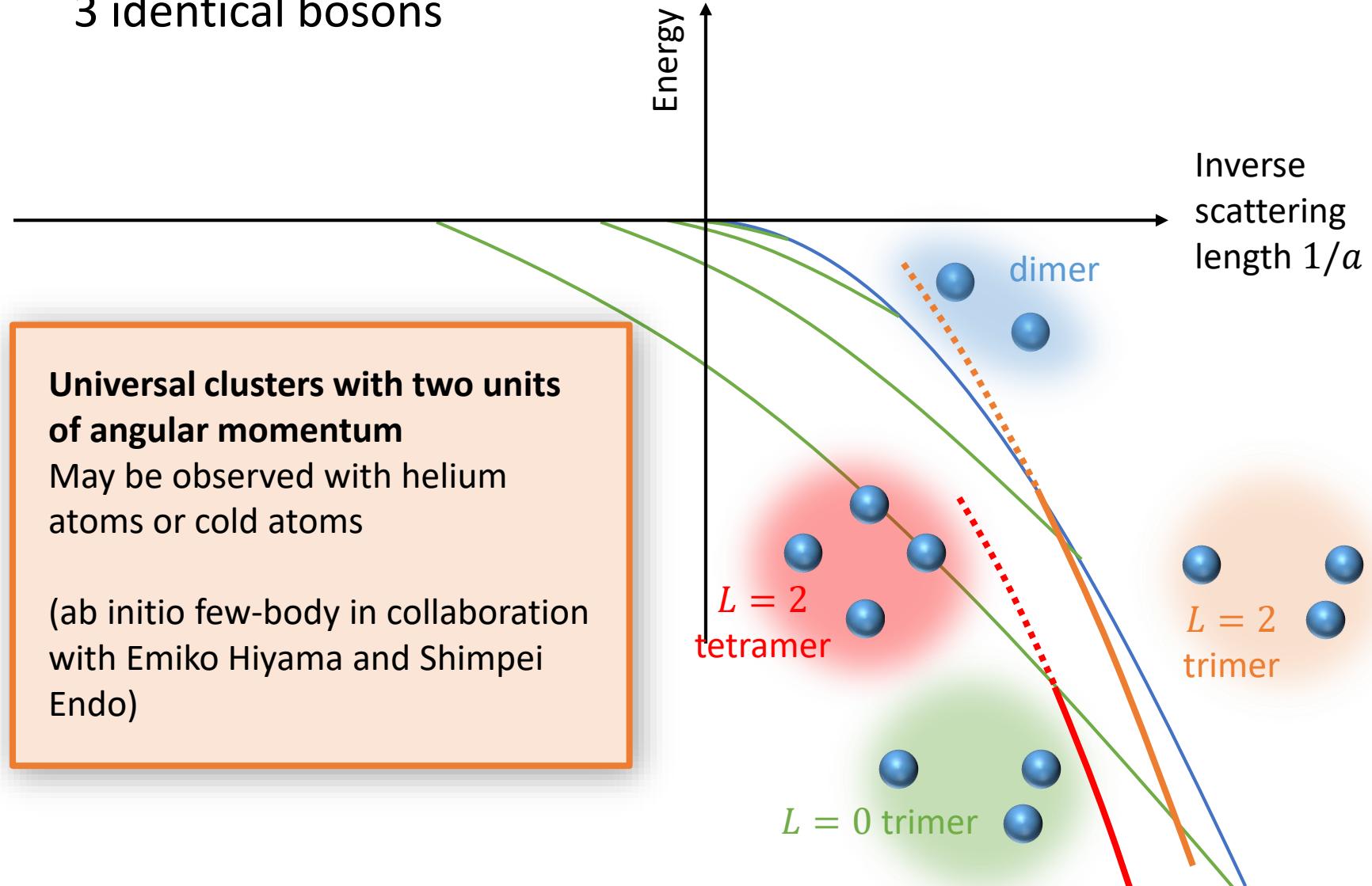
We need to determine which conditions in the **finite-range potentials** leads to this possibility.

(ab initio 3-body in collaboration with Emiko Hiyama)

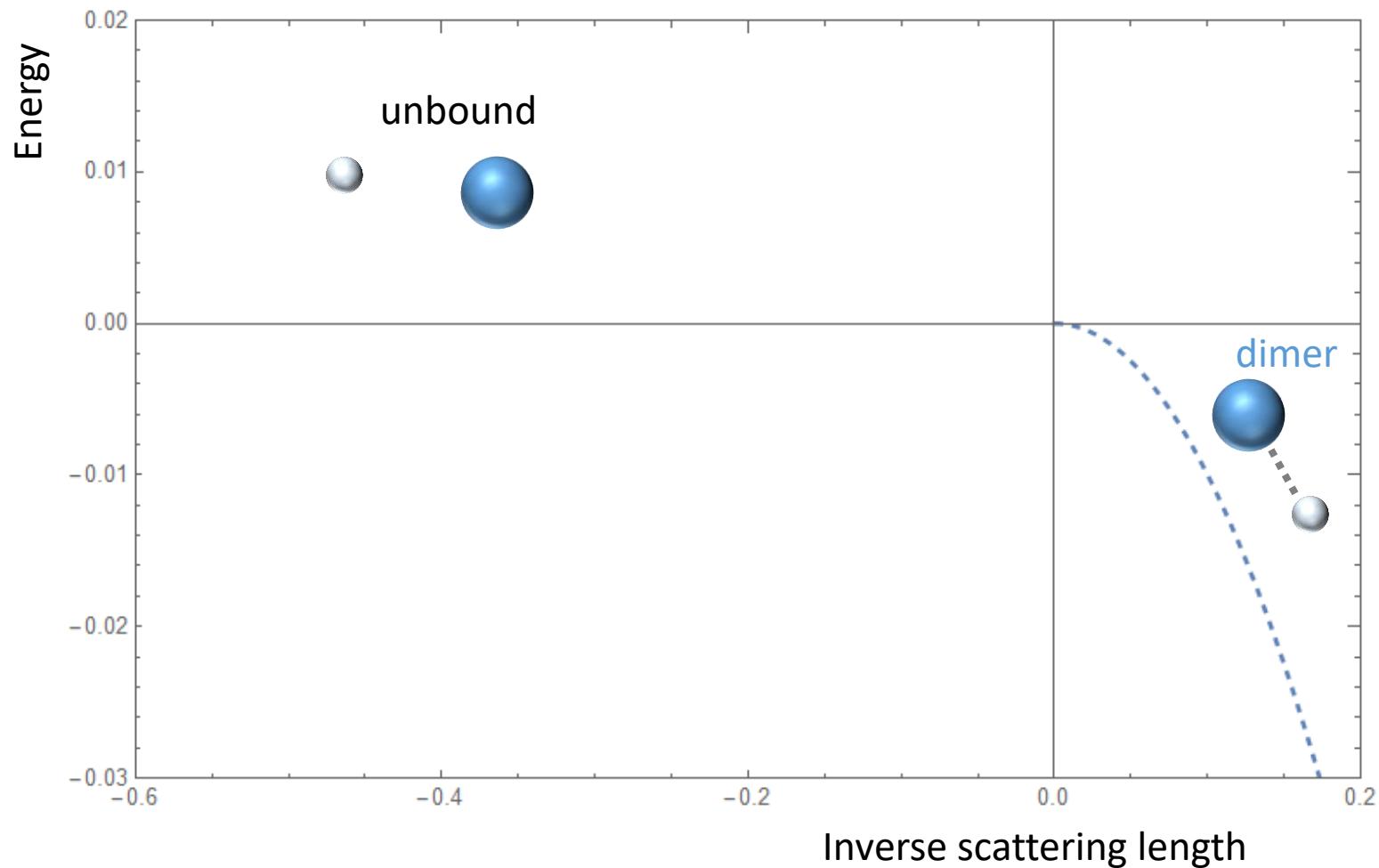


Universal clusters with $L \neq 0$

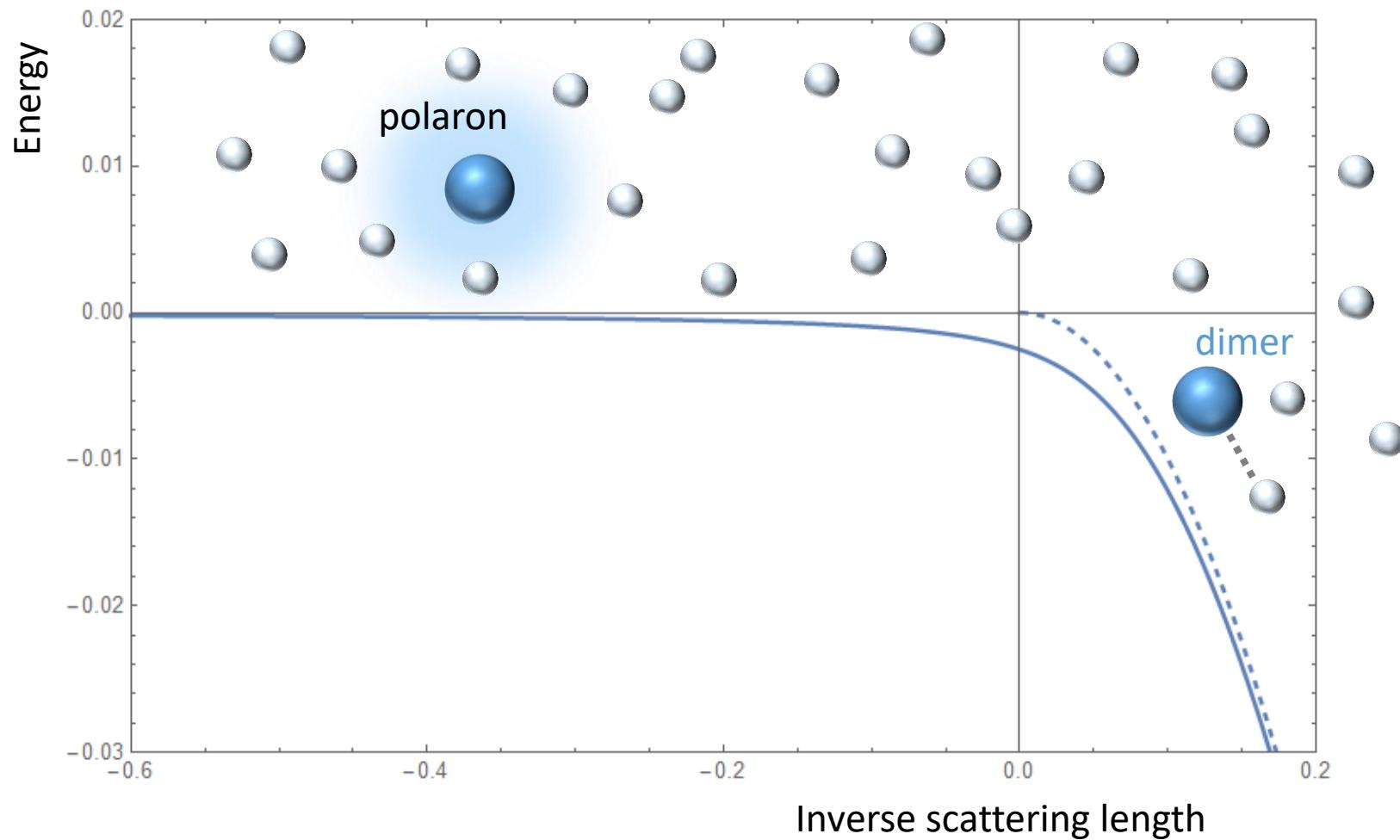
3 identical bosons



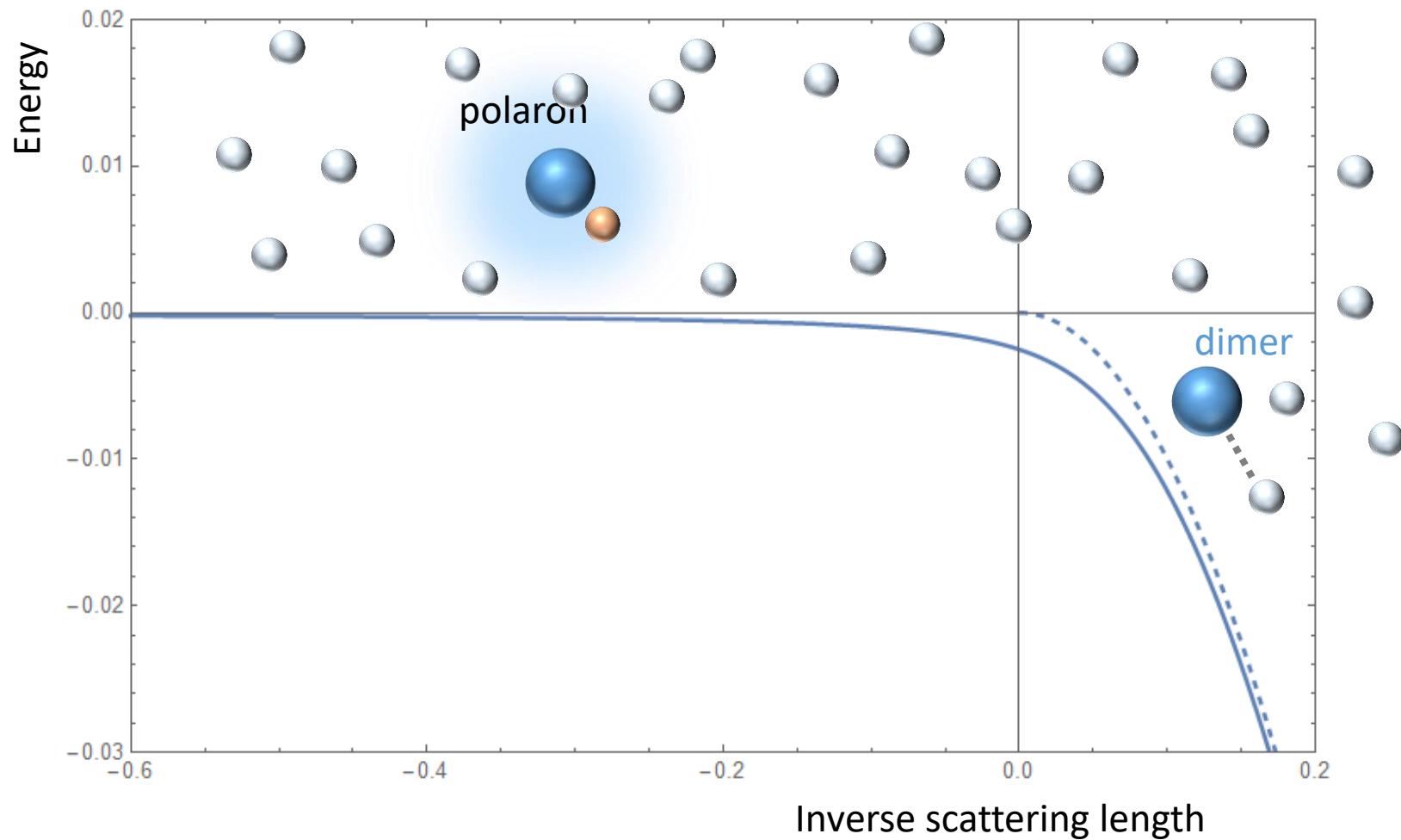
Clusters in many-body systems



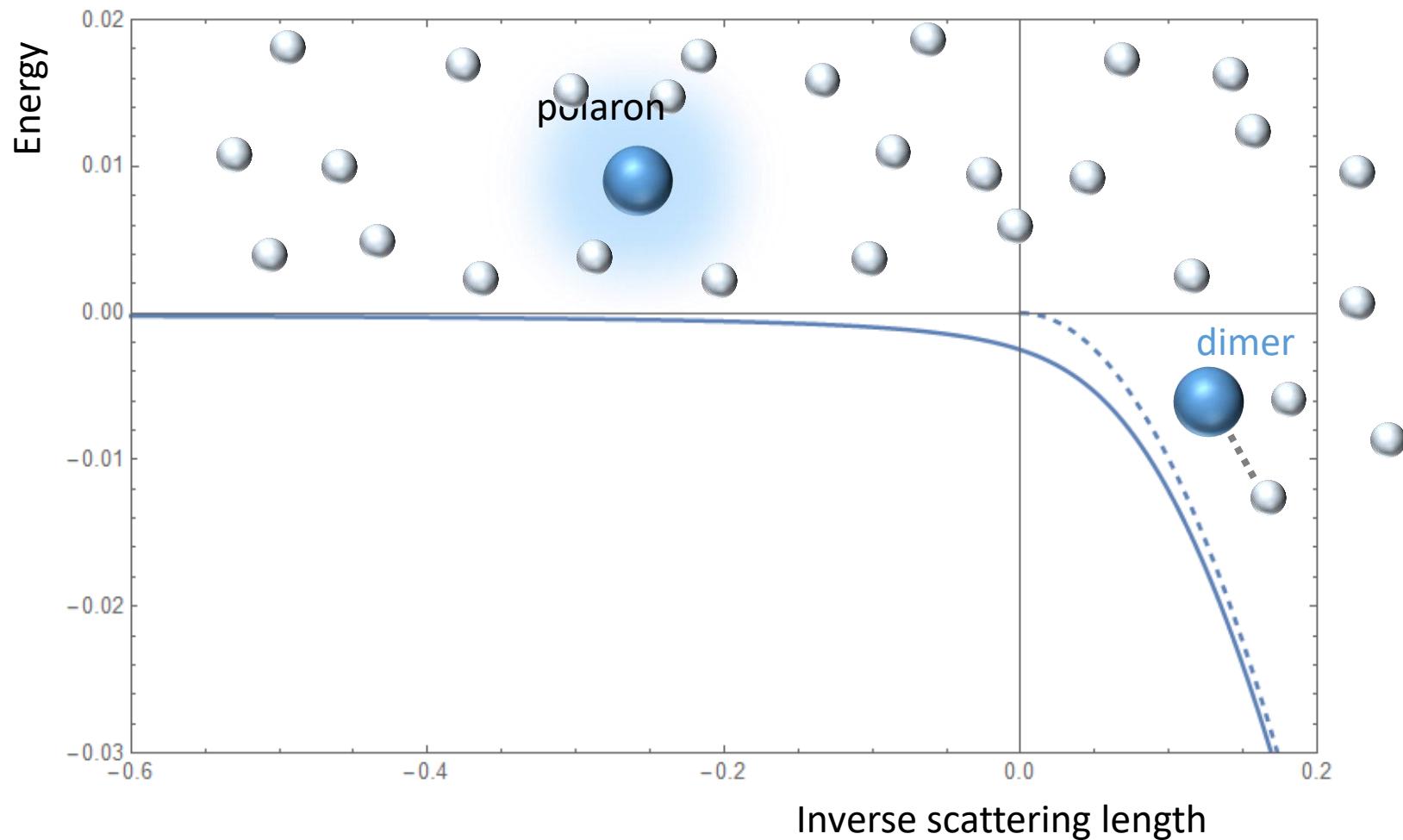
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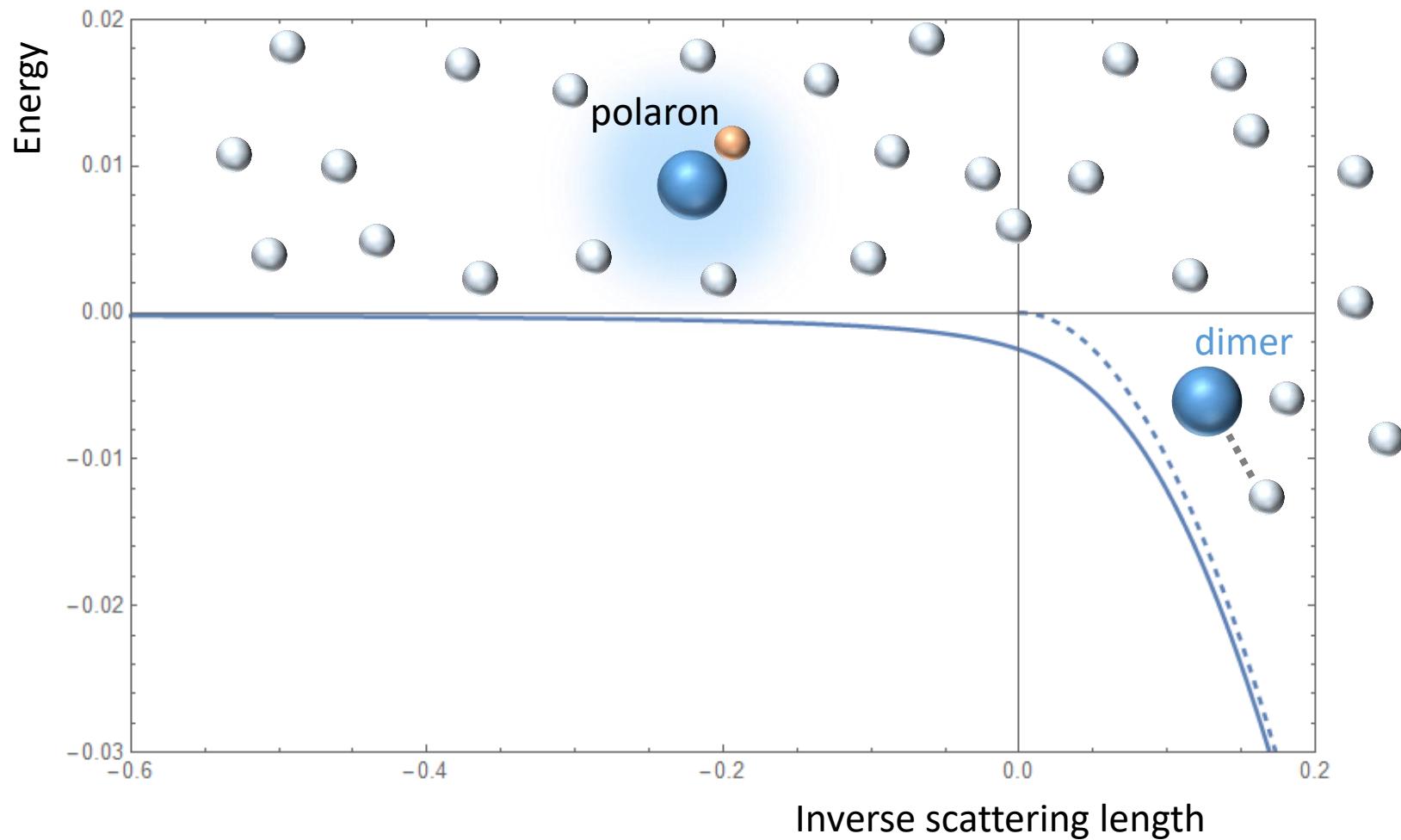
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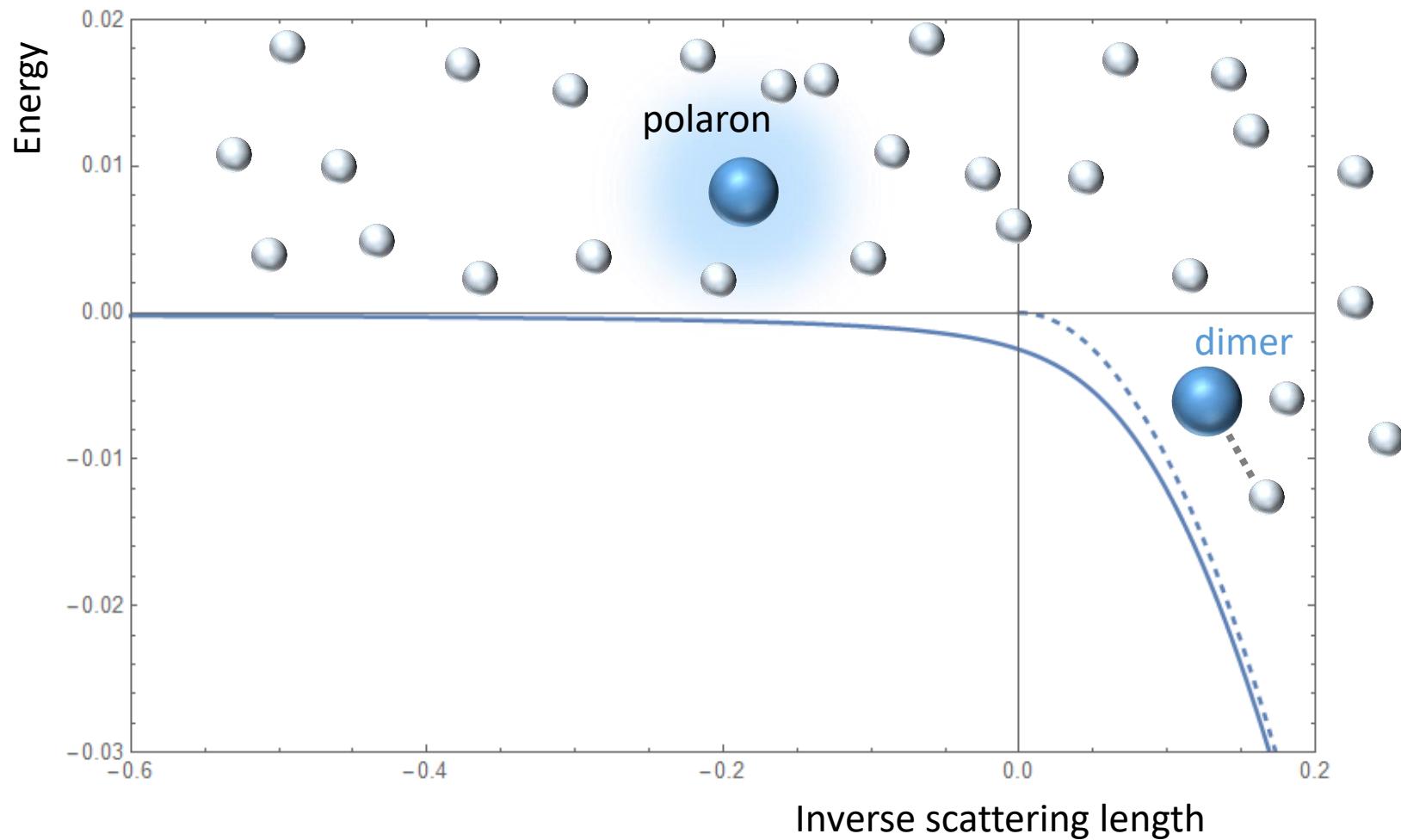
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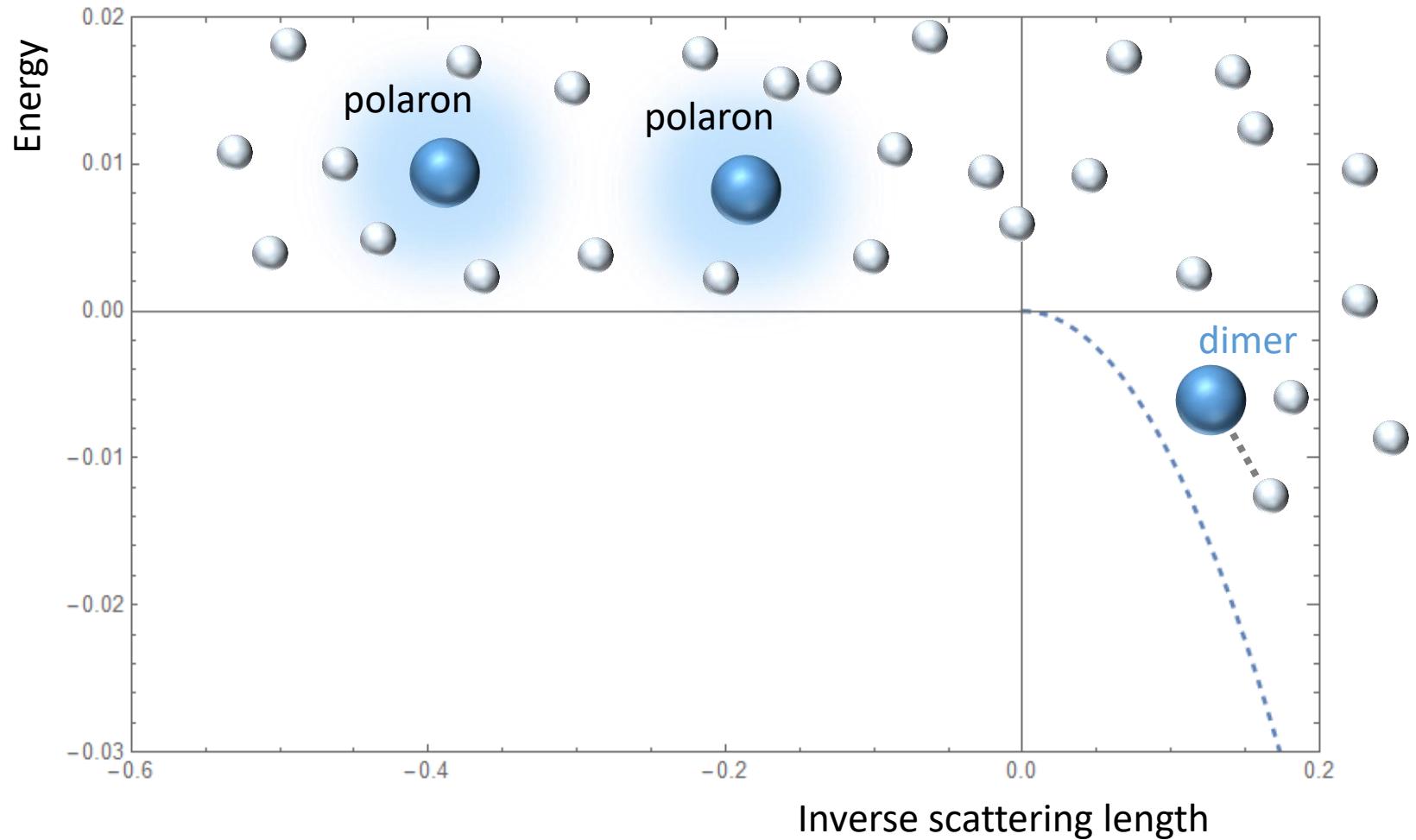
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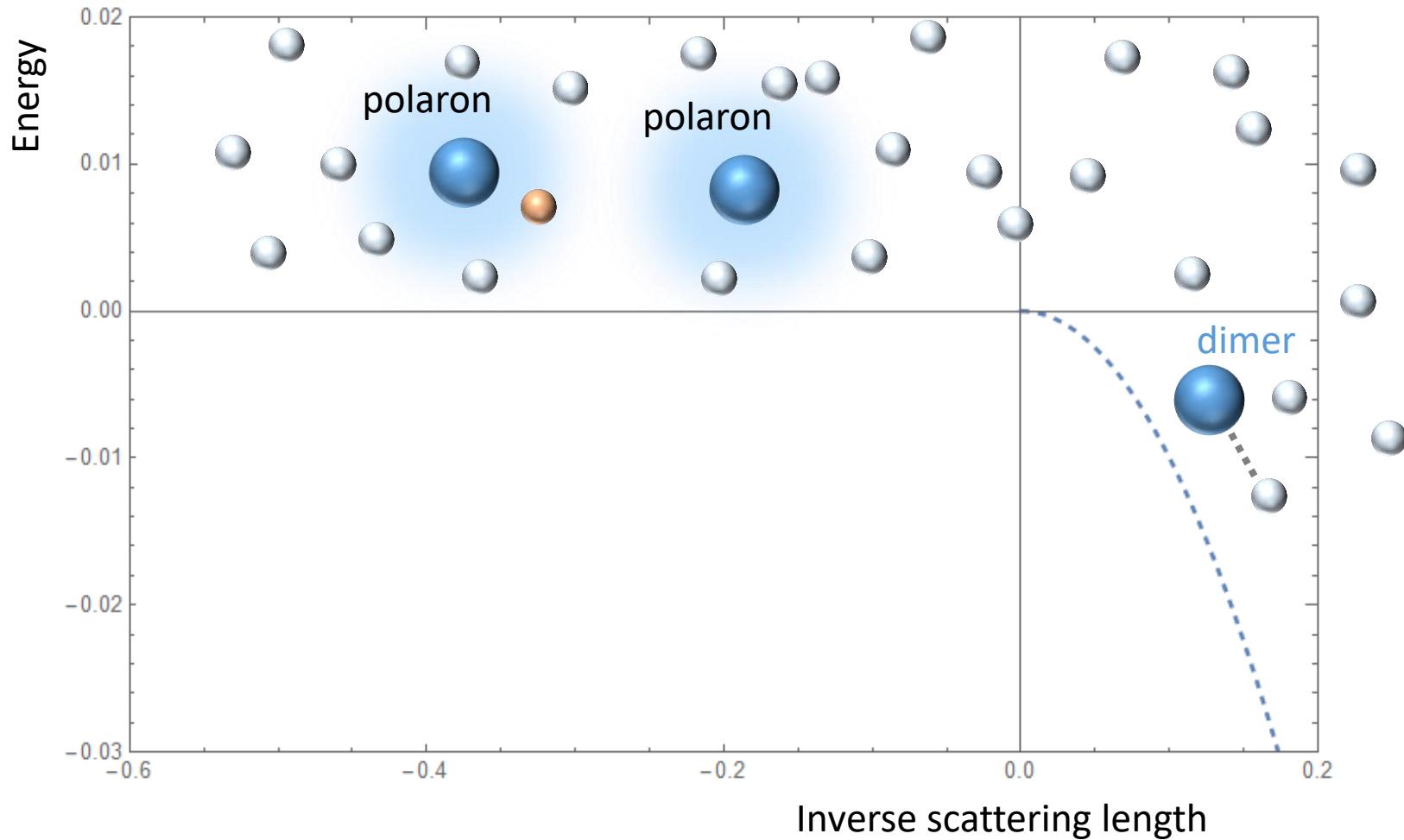
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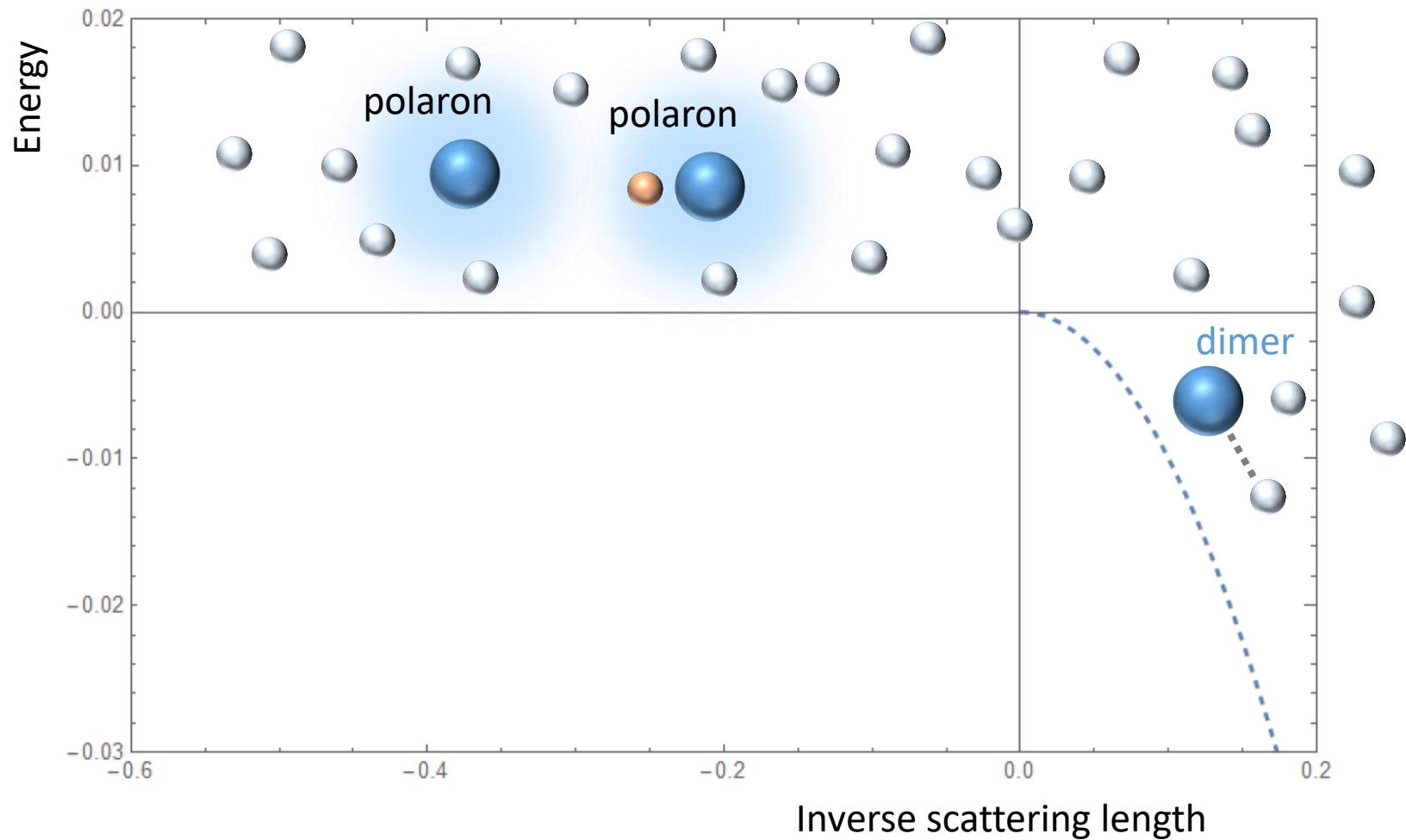
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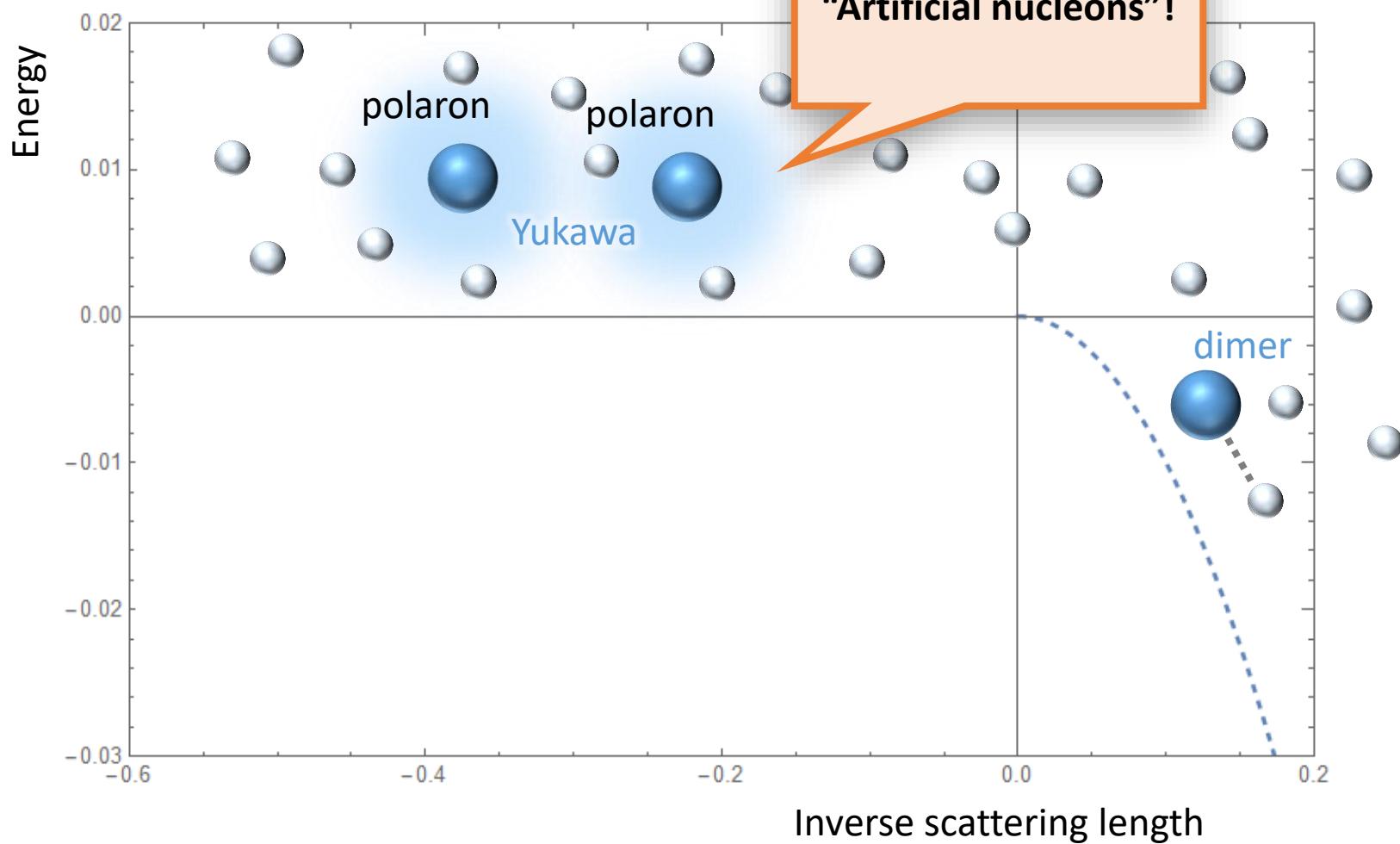
Clusters in many-body systems



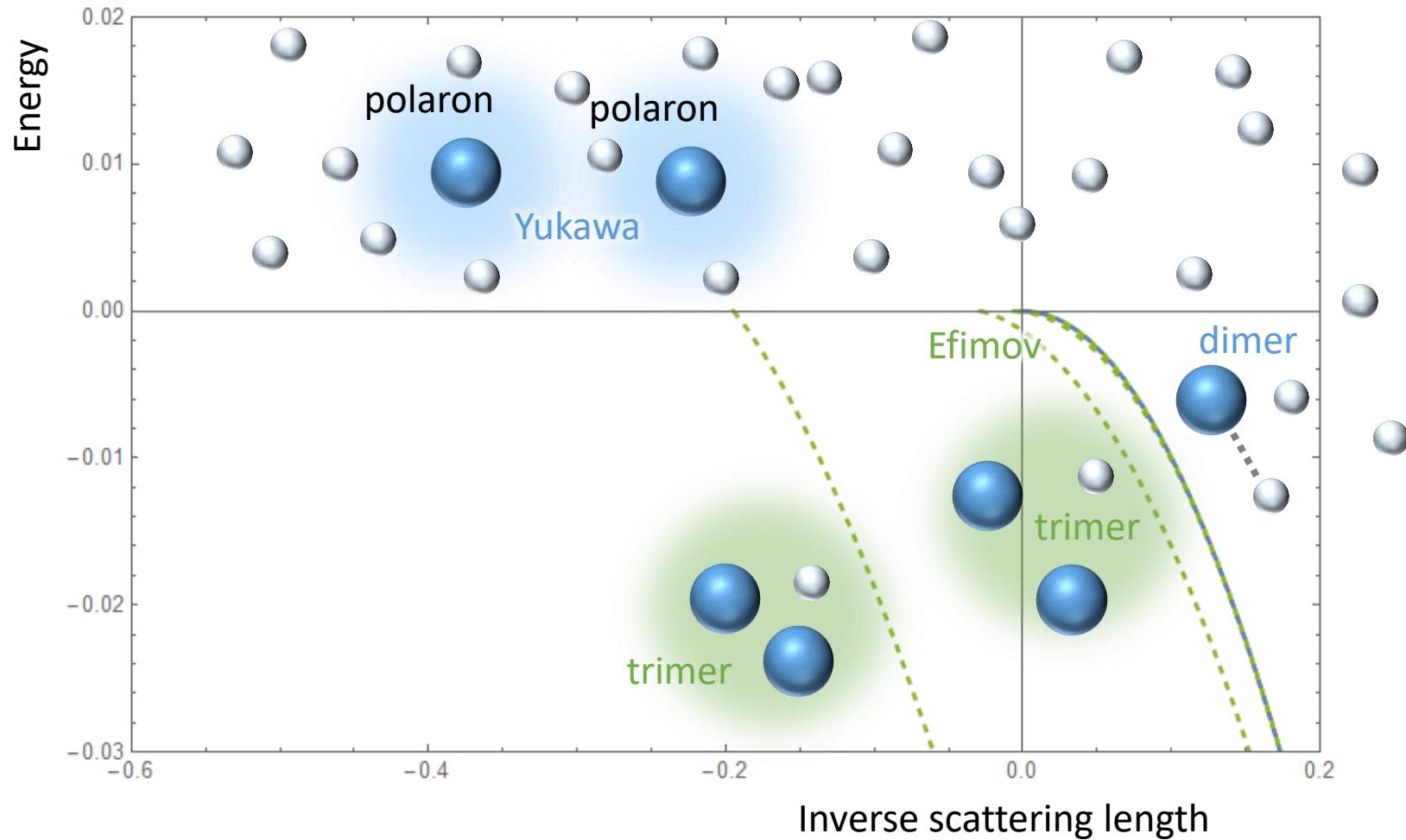
Clusters in many-body systems



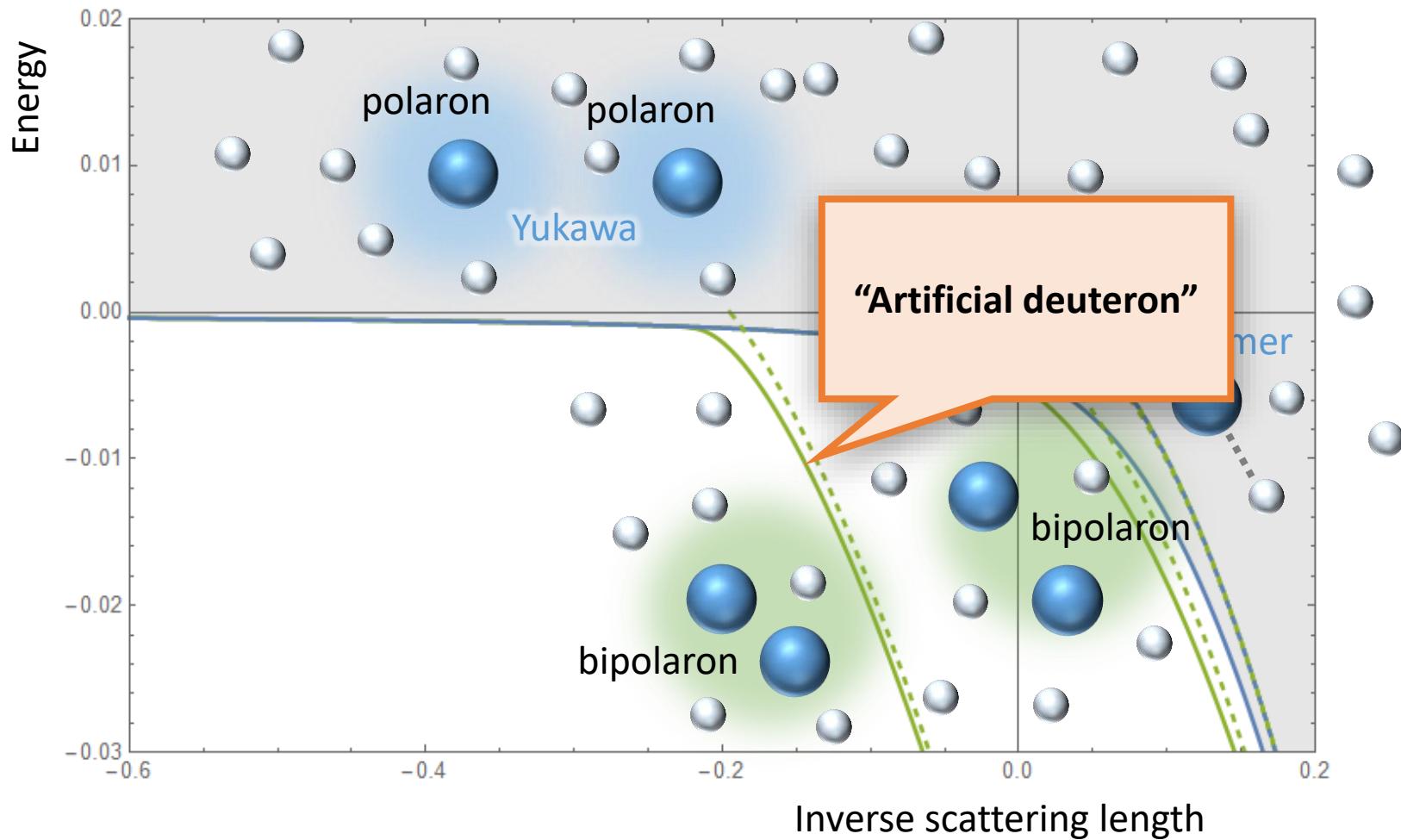
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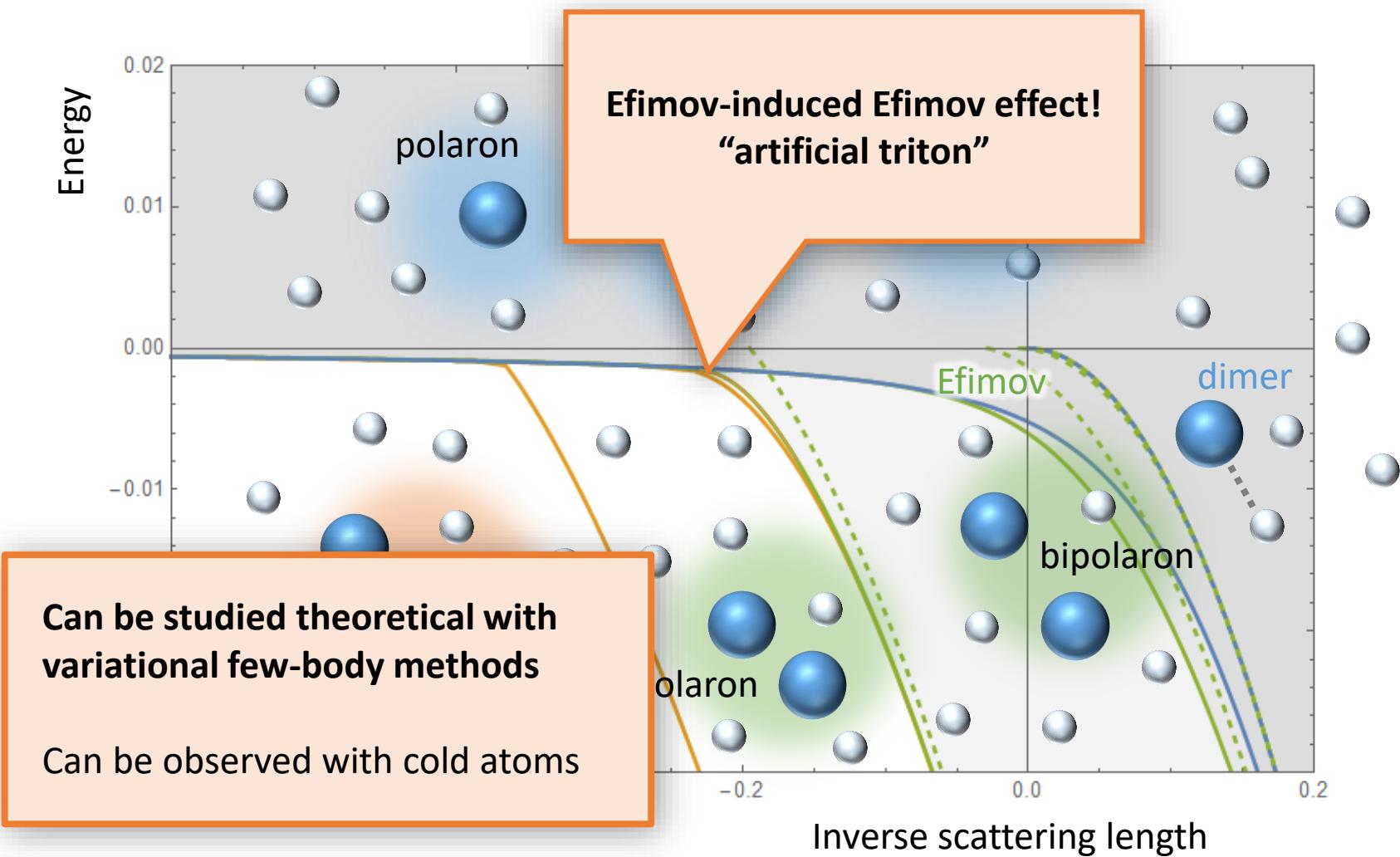
Clusters in many-body systems



Clusters in many-body systems



Clusters in many-body systems



Conclusion

- Weakly bound clusters near the critical binding of two particles form an exotic yet universal class of states, where the Efimov attraction is a central paradigm.
- We want to explore these universal clusters with higher angular momentum and in many-body systems.
- They can be realised experimentally with cold atoms, and help us to understand general clustering mechanisms.