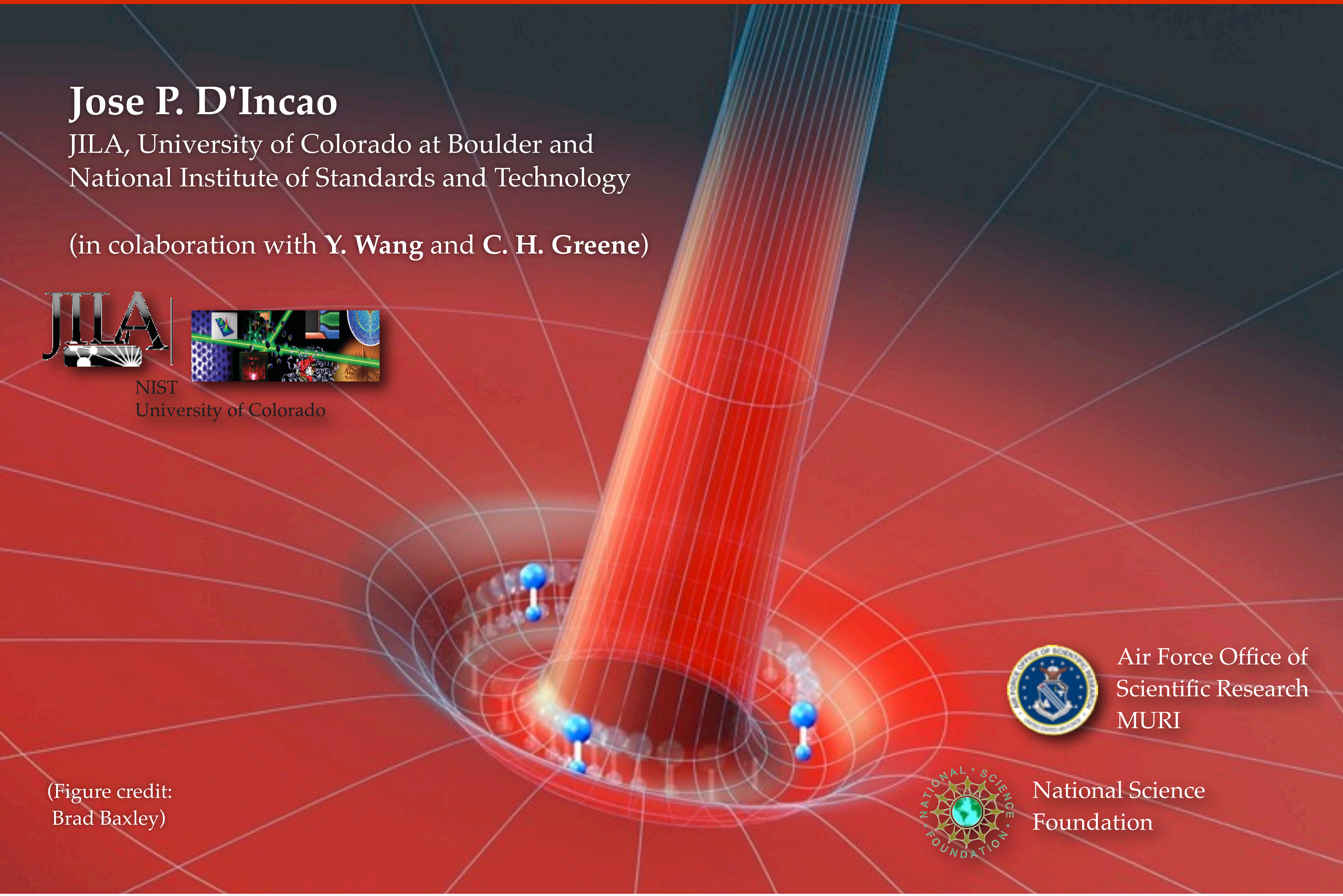
The Persistence of Attraction: the Dipolar Efimov Effect



Jose P. D'Incao
JILA, University of Colorado at Boulder and
National Institute of Standards and Technology

(in colaboration with **Y. Wang** and **C. H. Greene**)

NIST
University of Colorado

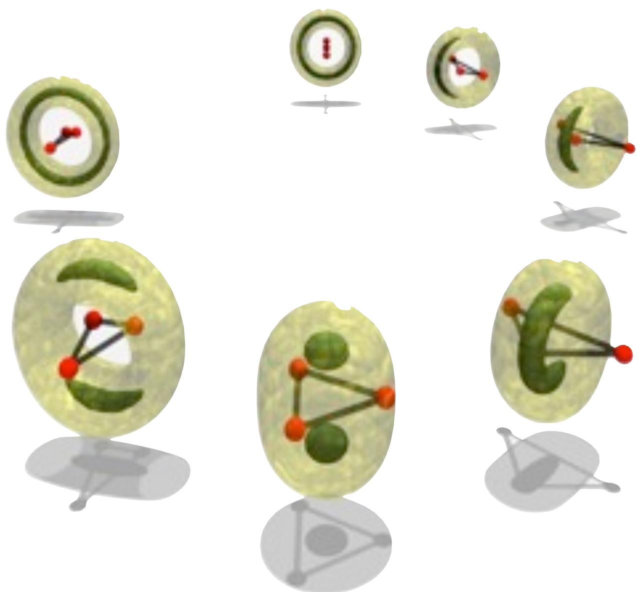
Air Force Office of
Scientific Research
MURI

National Science
Foundation

(Figure credit:
Brad Baxley)

Overview

Universal Few-Body Physics

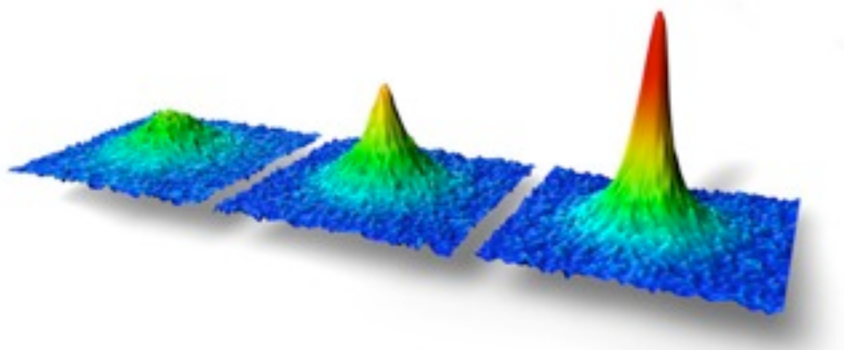


From the theoretical side:

- Signatures of Efimov Physics,
- Four- and More-bodies universal states,
- New families of universal states,

Ultracold Quantum Gases

($<$*pe*V)



From the experimental side:

- clean and accurate experiments
- **CONTROL** of interactions (*B*-field)
- can explore the universal regime (low T and strong interactions)

Overview

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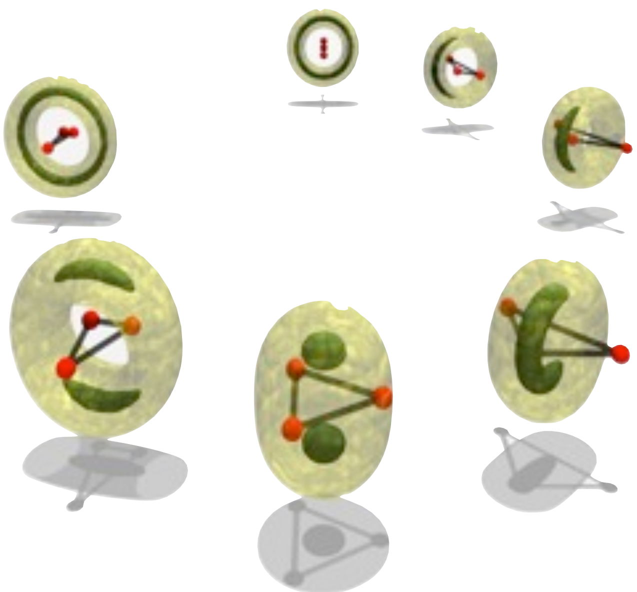
Universal Few-Body Physics



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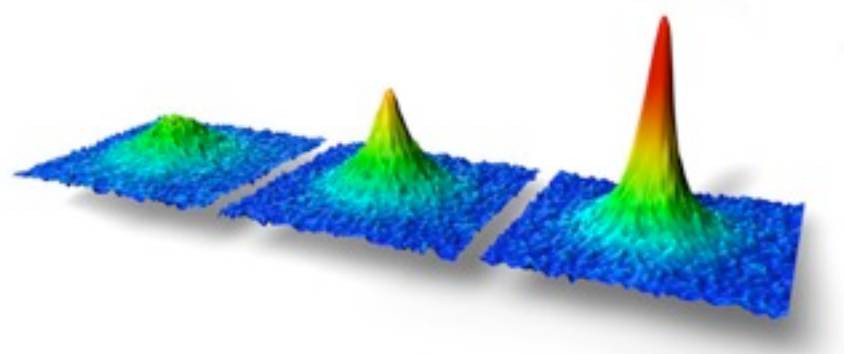


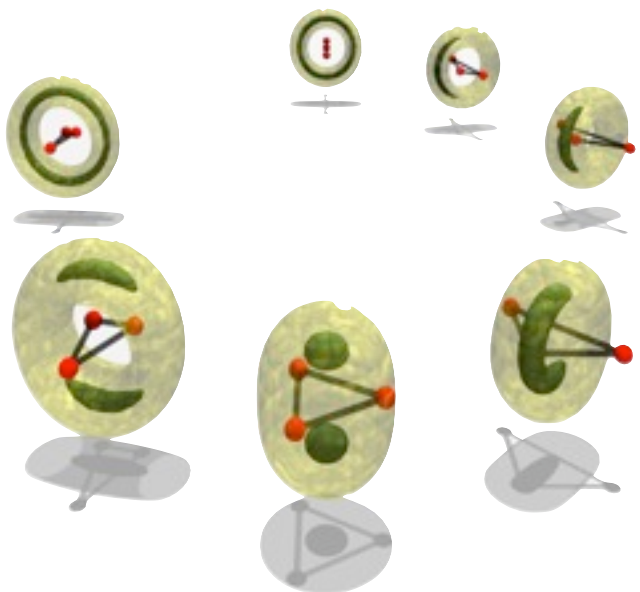
From the experimental side:

- ☑ clean and accurate experiments
- ☑ **CONTROL** of interactions (*B*-field)
- ☑ can explore the universal regime (low T and strong interactions)

→ Allows for the use of simple models !!!

Overview

Universal Few-Body Physics



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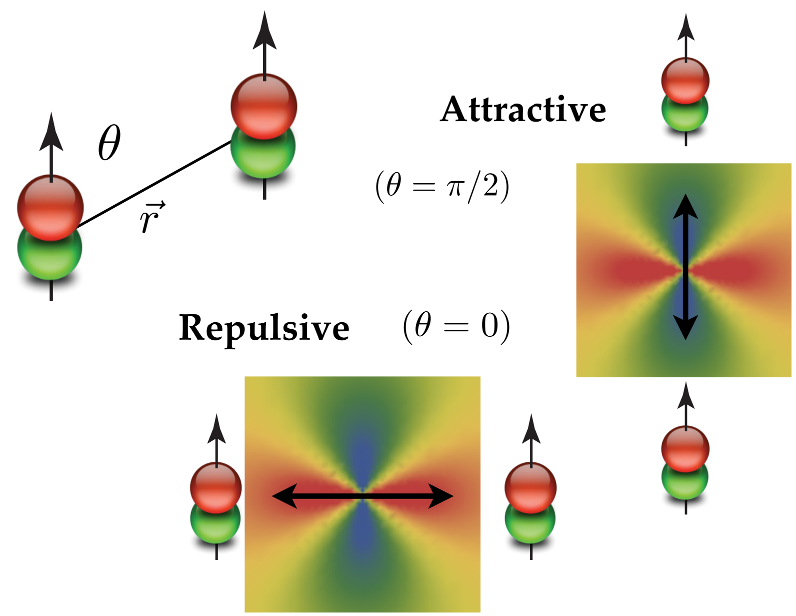
Ultracold Dipolar Quantum Gases



- ☑ **CONTROL** of interactions (E-field)
- ☑ new phases, quantum computing, etc ...
- ☑ long range anisotropic interactions

- ☑ **The Efimov effect persist !!!**
- ☑ **Dipolar interaction is extremely beneficial !!!**
- ☑ **Possible *new* few-body physics !!!**

Few-body physics in Ultracold Gases
(Why do Experiments care about it?)

Atomic/Molecular Losses

(three-body recombination, ...)

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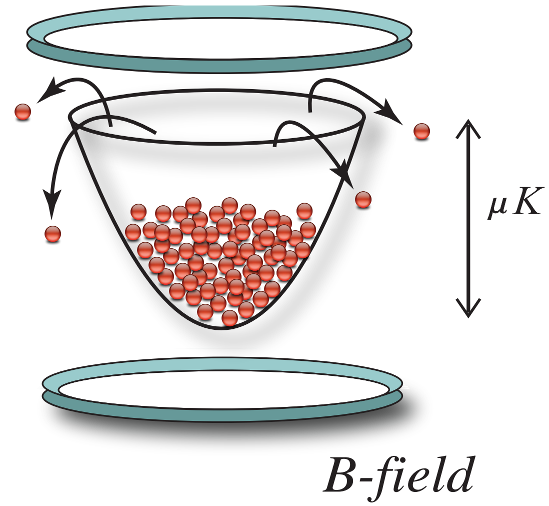
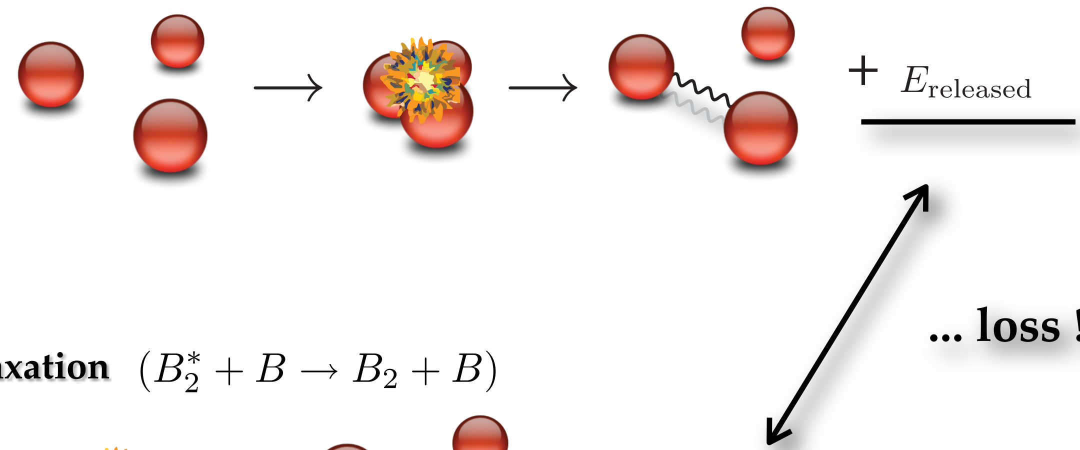
Atomic/Molecular Losses → **Stability and Lifetime of condensates !!!**

(three-body recombination, ...)

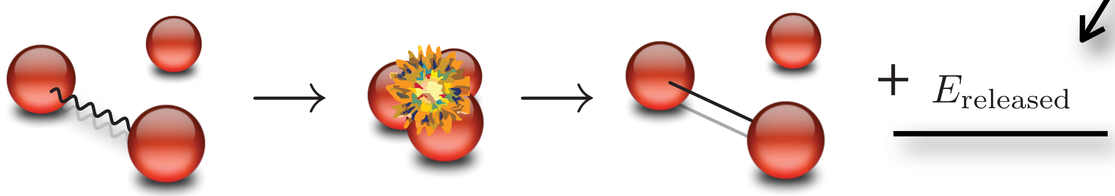


Three-body Recombination $(B + B + B \rightarrow B_2^* + B)$



... loss !!!

Vibrational Relaxation $(B_2^* + B \rightarrow B_2 + B)$



Few-body Physics in Ultracold Gases

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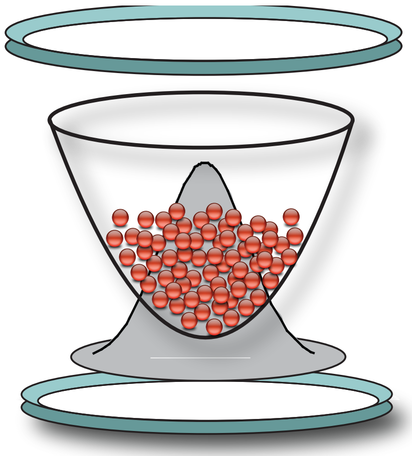
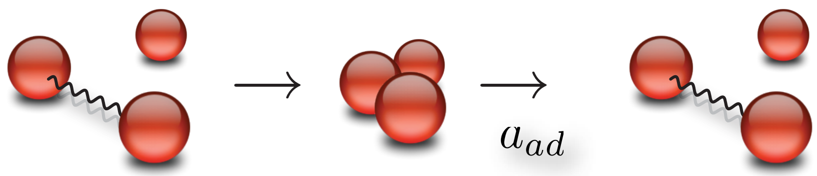
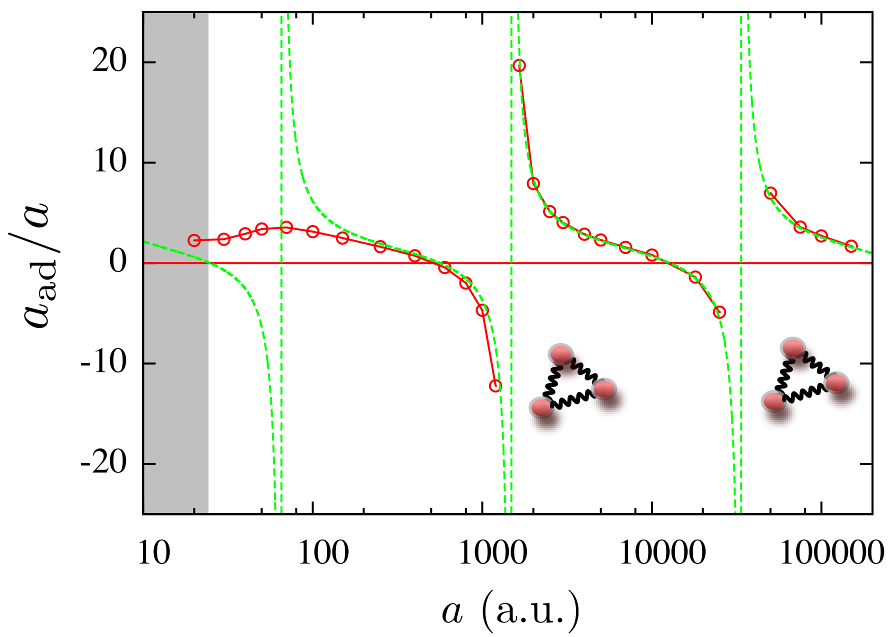
Elastic parameters → **Control of few-body correlations !!!**

(strength of interactions, equation of state, ...)



Atom-dimer scattering $(B_2^* + B \rightarrow B_2^* + B)$

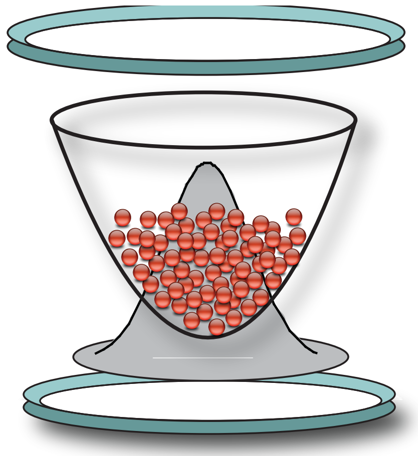




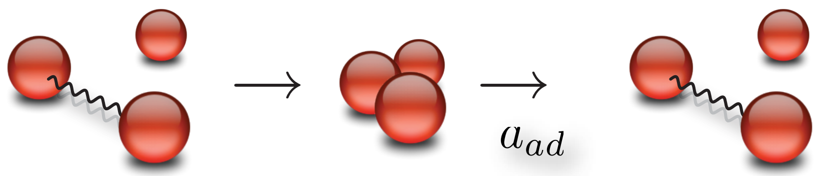
Elastic parameters

(strength of interactions, equation of state, ...)

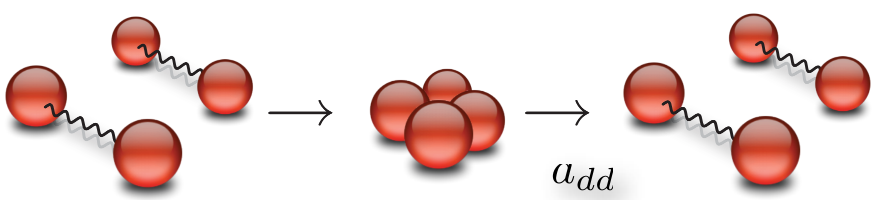
$\longrightarrow$ **Control of few-body correlations !!!**

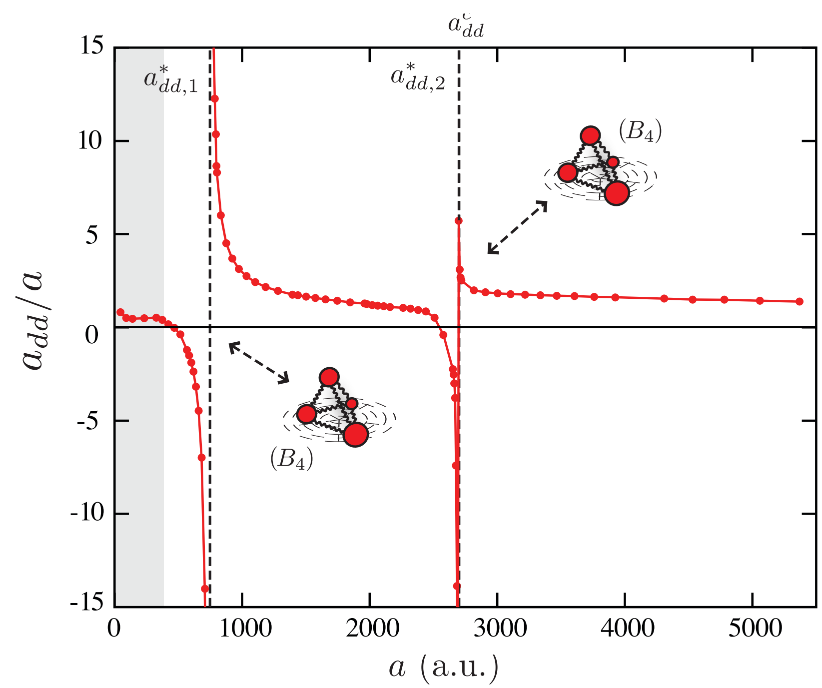


Atom-dimer scattering $(B_2^* + B \rightarrow B_2^* + B)$



Dimer-dimer scattering $(B_2^* + B_2^* \rightarrow B_2^* + B_2^*)$





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Few-body Physics in Ultracold Gases

Efimov Physics

appearance of an *attractive* or *repulsive* three-body effective interaction ... in the strongly interacting regime $(|a| \gg r_0)$

- Control of the few-body interactions
- Scattering length dependence on 3-body collision rates
- Loses = Probe of universal states

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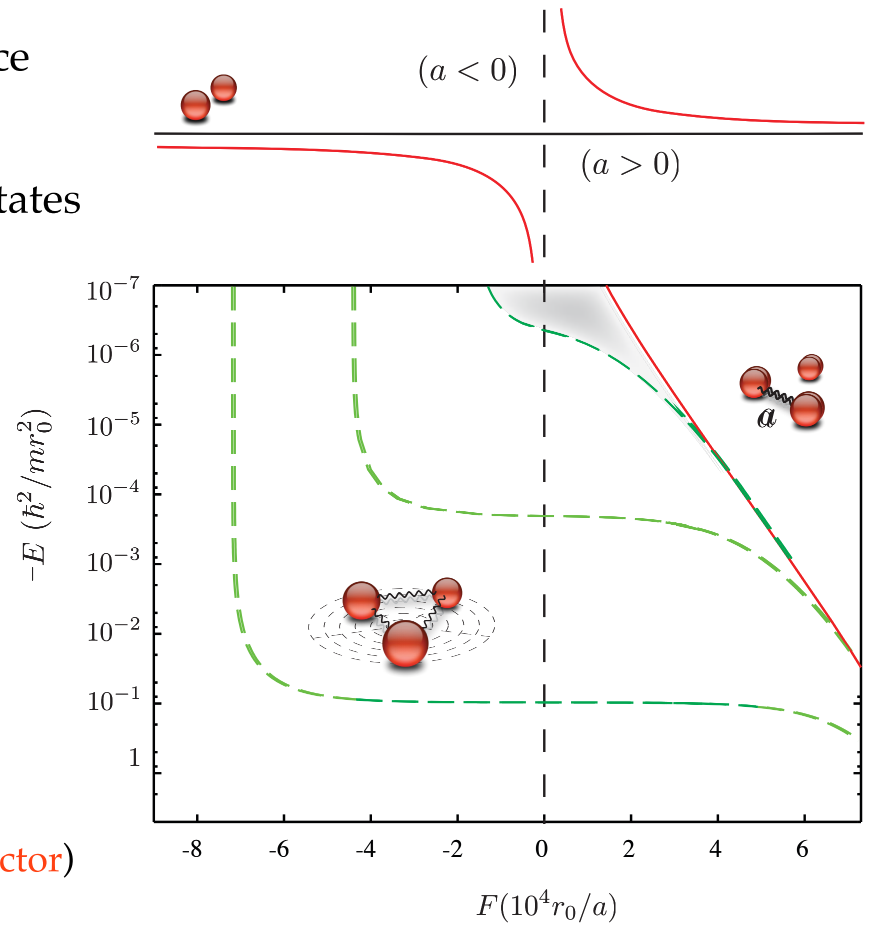
In ultracold gases *a* is a tunable parameter, which allows to the exploration of the full **Efimov energy spectrum**



$$E_n = \frac{E_0}{[e^{\pi/s_0}]^{2n}}, \quad n =, 1, 2, 3, \ldots$$

$$a_n = [e^{\pi/s_0}]^n a_0 \qquad e^{\pi/s_0} \approx 22.7 \quad \text{(geometric factor)}$$

Universal Four-boson States

Universal Four-boson States

- Universal properties of the properties of the four-body system with large scattering lengths, Hammer & Platter, *EPJA* **32**, 113 (2007)
- Signatures of universal four-body phenomena and its relation to the Efimov effect
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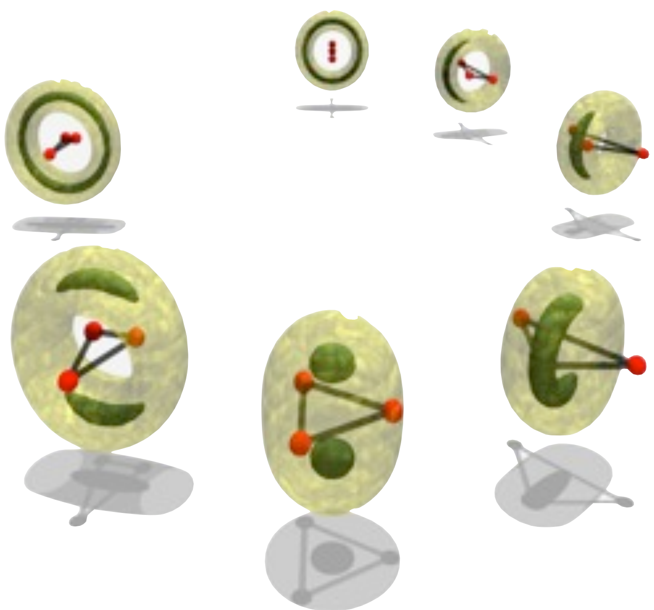

- Two four-boson states for each Efimov trimer [... see also Deltuva, *FBS* **50**, 391 (2011)]

$$E_{4b}^{(n,m)} = c_m E_{3b}^{(n)} \qquad m = 1,2$$
$$n = 1,2,...,\infty$$
$$(c_1 \approx 4.58,\ \ c_2 \approx 1.01)$$

Universal Four-boson States

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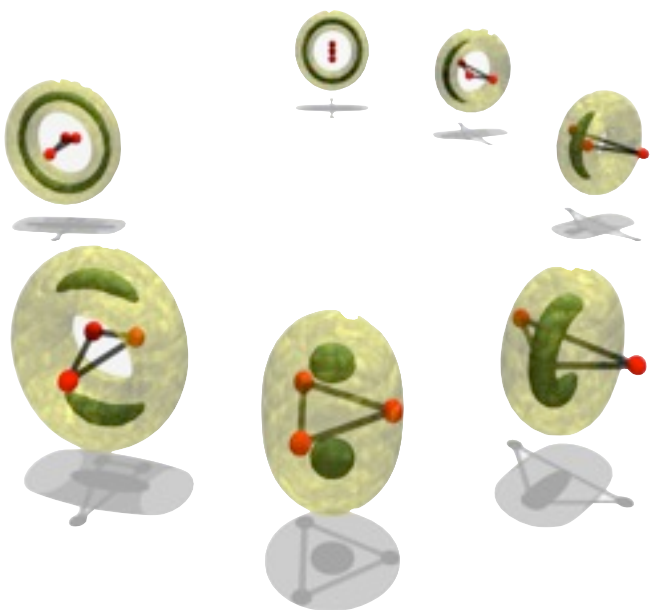

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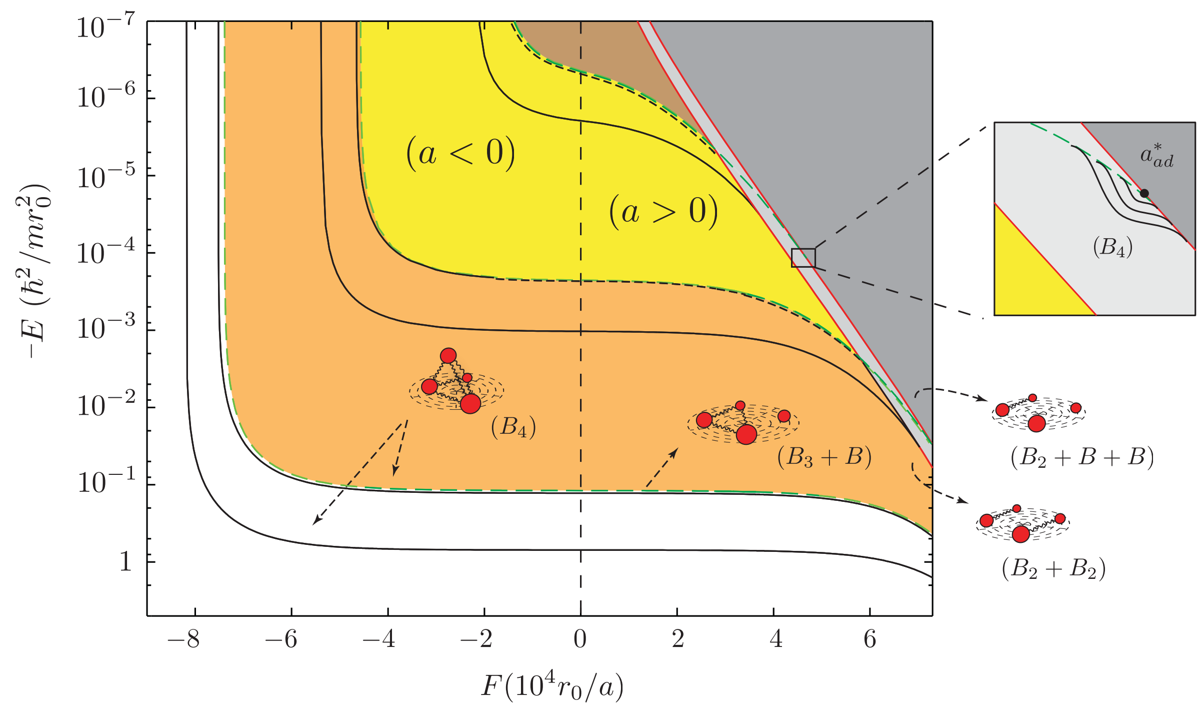

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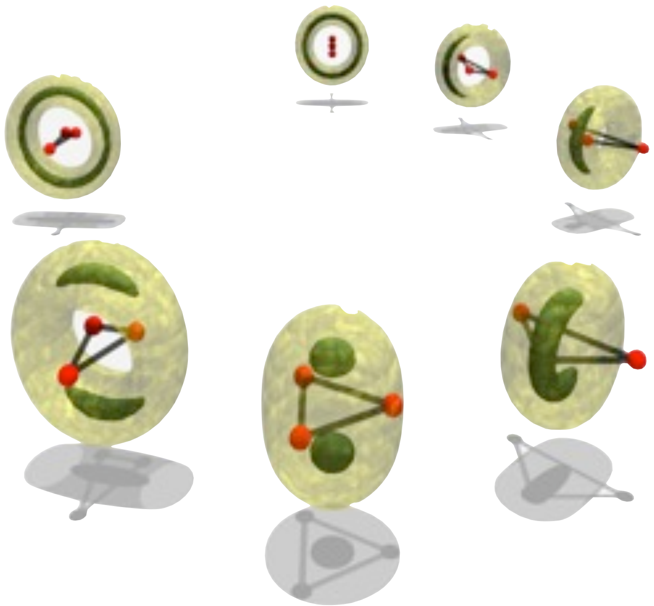
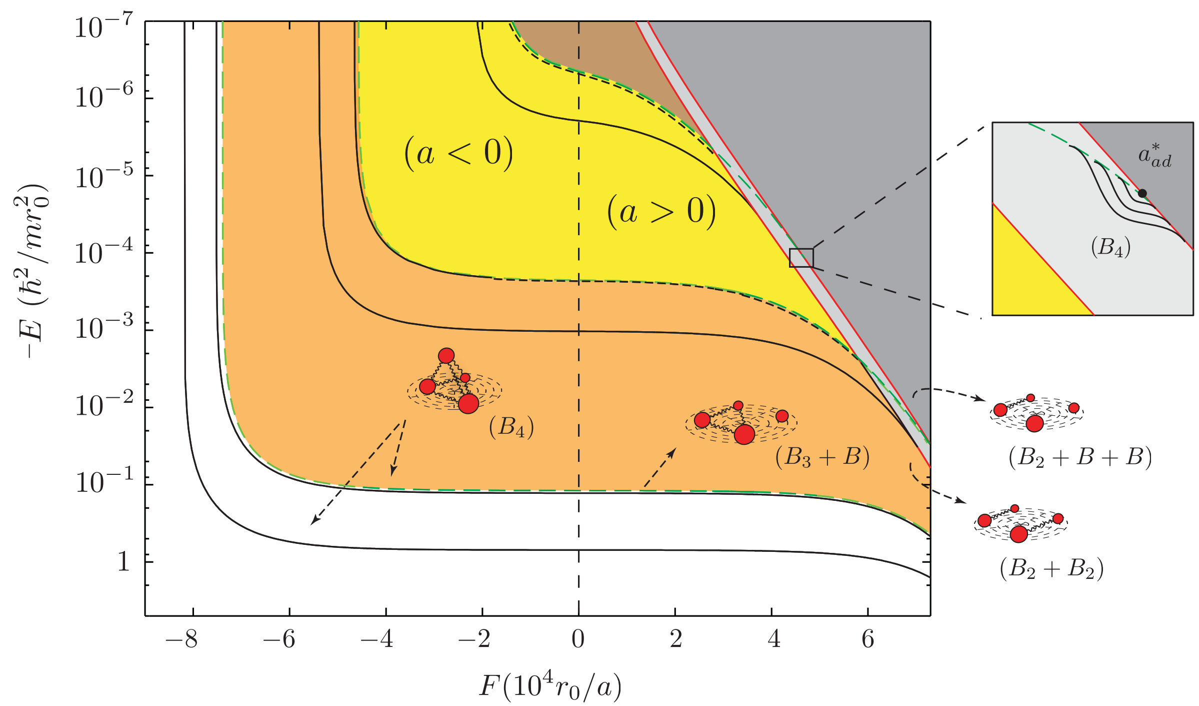


Controversy : (Four-body parameter ?)

- **[Yes?]** Yamashita, Tomio, Delfino, & Frederico, *EPL* **75**, 555 (2006); Hadizadeh, Yamashita, Tomio, Delfino, & Frederico, PRL 107, 135304 (2011)



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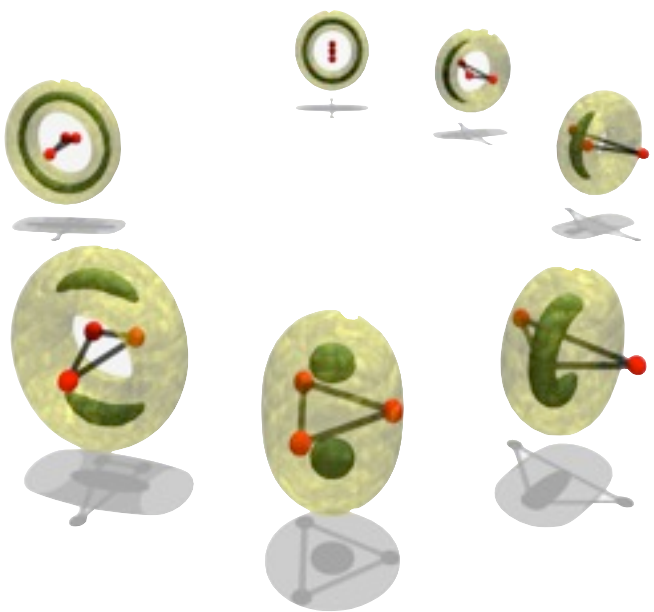
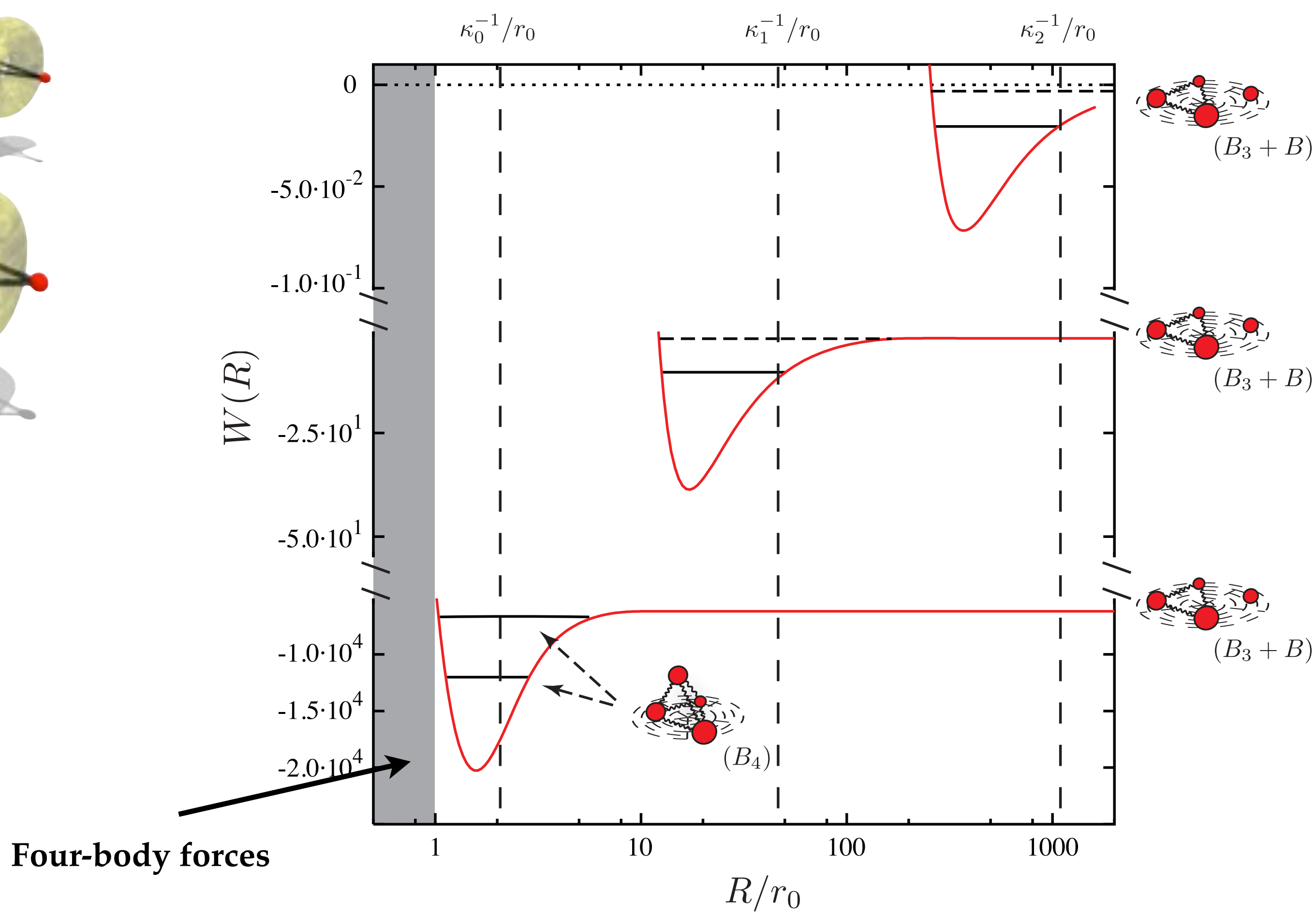


Four-bosons hypersherical potentials at $|a| \to \infty$



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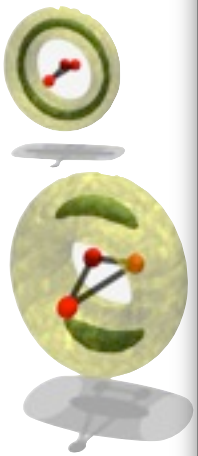
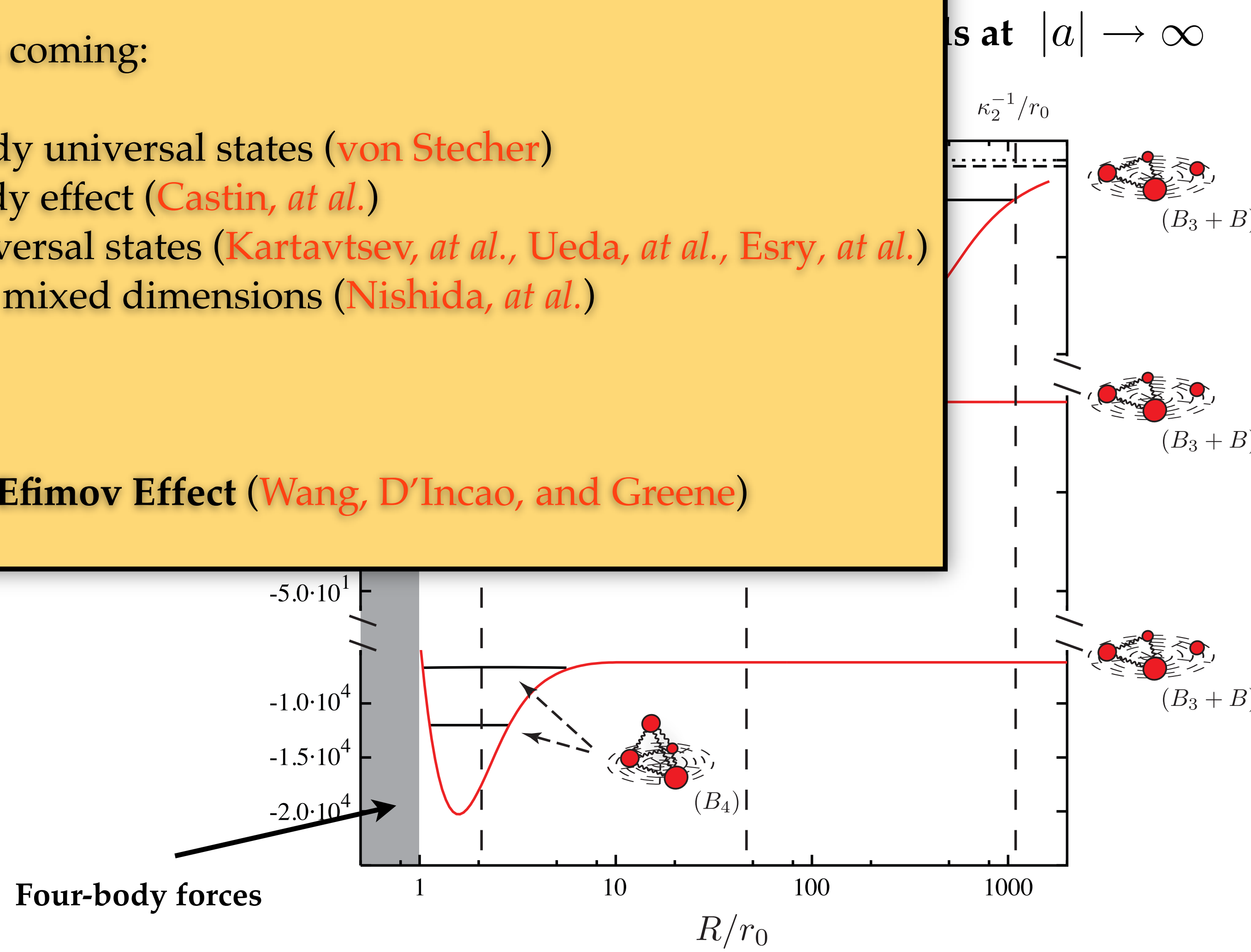


... and much more is coming:

- five- and six-body universal states (von Stecher)
- Efimov four-body effect (Castin, *at al.*)
- Three-body Universal states (Kartavtsev, *at al.*, Ueda, *at al.*, Esry, *at al.*)
- Efimov effect in mixed dimensions (Nishida, *at al.*)

... and of course:

Dipolar Efimov Effect (Wang, D'Incao, and Greene)



The arrival of dipolar gases

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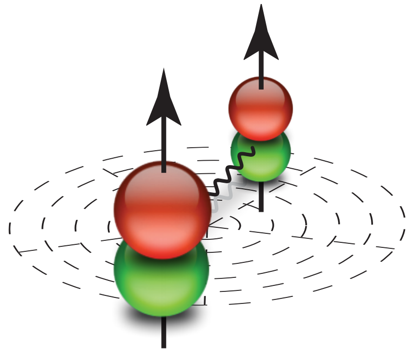
University of Colorado

Ultracold Dipolar Few-body Physics



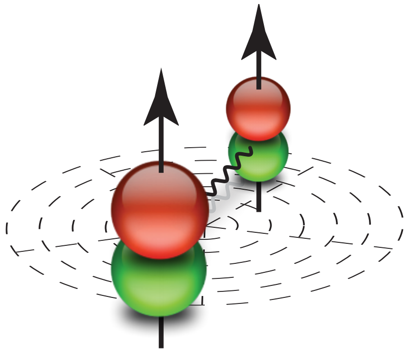
<u>Ultracold Dipolar gases</u>

Atomic (magnetic) dipoles: weak interactions !!!

Molecular (electric) dipoles: strong interactions !!!

(challenging experiments)

Ultracold Dipolar Few-body Physics



SCIENCE VOL 327 12 FEBRUARY 2010

Science AAAS

Quantum-State Controlled Chemical Reactions of Ultracold Potassium-Rubidium Molecules

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JILA, NIST and University of Colorado, Department of Physics, University of Colorado, Boulder, CO 80309, USA.
Institute, NIST and University of Maryland, Gaithersburg, MD 20899, USA.

... also : Innsbruck, Yale, Heidelberg, Hanover, ...

	$d_\ell^{\max}$	$kd_\ell^{\max}$ $(T = 100\text{nK})$
RbK	$\approx 6 \times 10^3 a_0$	2.4
RbCs	$\approx 5 \times 10^4 a_0$	23
LiCs	$\approx 6 \times 10^5 a_0$	238
SrO	$\approx 1.1 \times 10^6 a_0$	467
IK	$\approx 2.8 \times 10^6 a_0$	1100

Ultracold Dipolar Few-body Physics

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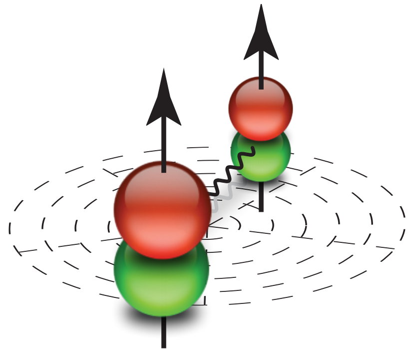

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“Universal” dipolar molecules:
RbK, LiNa, LiK,LiRb, LiCs
(unit probability of reactive collisions)

... reaction dynamics (ultracold controllable chemistry), ...

“Non-universal” dipolar molecules:
RbCs, NaK, NaRb, NaCs, KCs
(no reactive collisions)

..., dipolar quantum phases, ...

[see: Idziaszek and Julienne PRL 104, 113202 (2010); Zuchwski and Hutson, arXiv:1003.1418]

Dipolar Few-body Physics
(... what changes ?)

Ultracold Dipolar Few-body Physics

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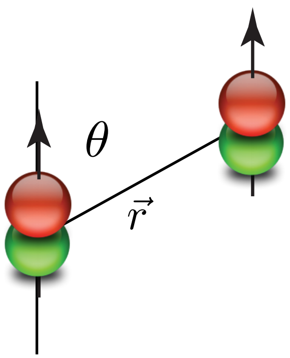
University of Colorado

Ultracold Dipolar Few-body Physics

Dipole-Dipole Interaction:



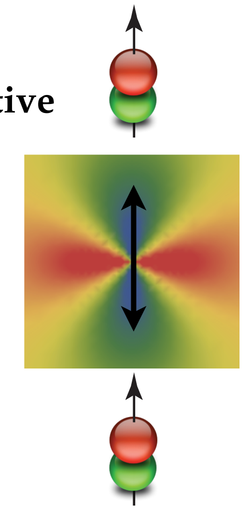
$$v_{dip}(\vec{r}) = \frac{d_\ell}{m}\frac{1-3\cos^2\theta}{r^3}$$

d_ℓ : dipole length

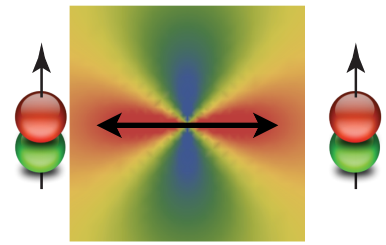
(experimentally controllable parameter)

(anisotropic and long-ranged interactions)

Attractive $(\theta = \pi/2)$

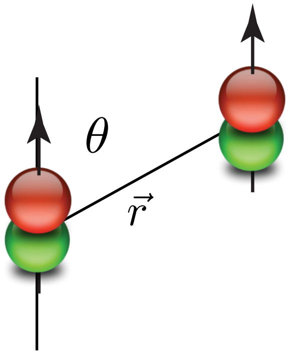


Repulsive $(\theta = 0)$



Ultracold Dipolar Few-body Physics

Dipole-Dipole Interaction:



$$v_{dip}(\vec{r}) = \frac{d_\ell}{m}\frac{1-3\cos^2\theta}{r^3}$$

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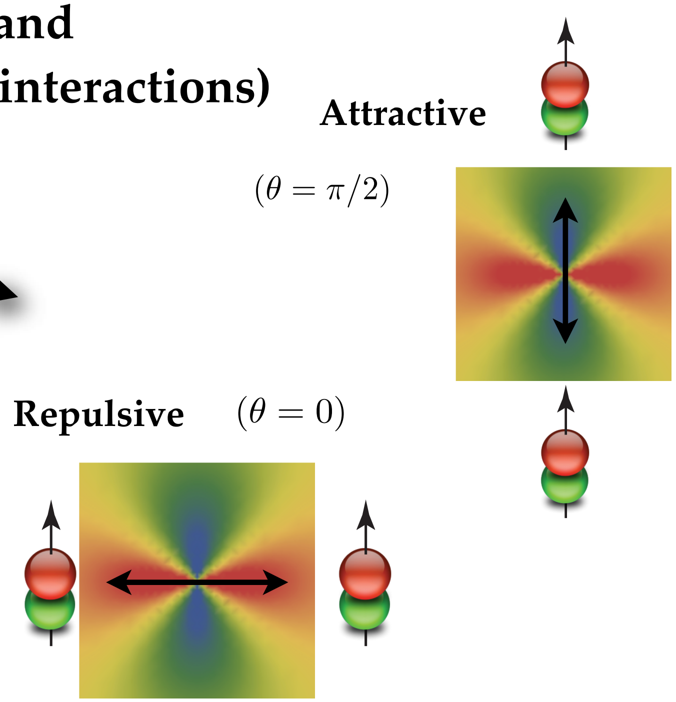
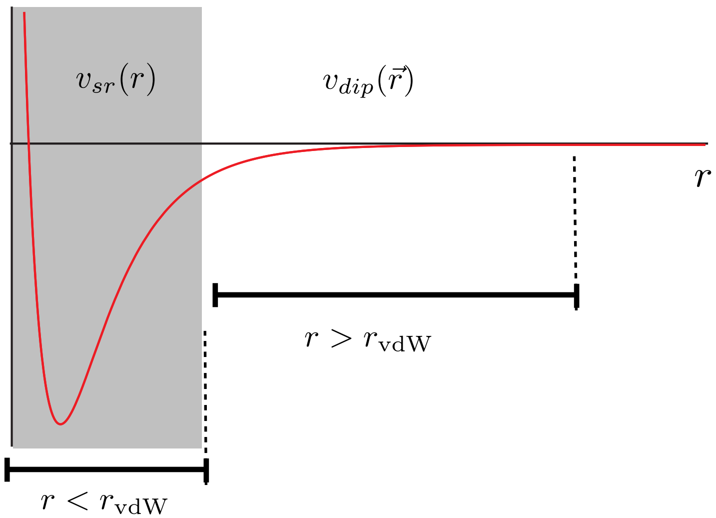
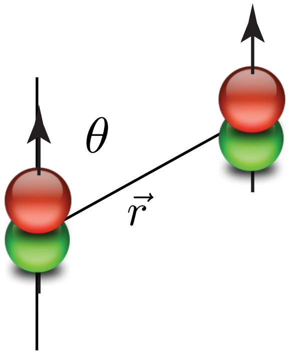
(**anisotropic** and **long-ranged** interactions)



Dipole-Dipole Model Interaction



Dipole-Dipole Interaction:



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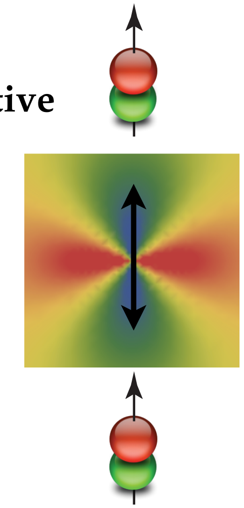
(**anisotropic** and **long-ranged** **interactions)**

Attractive

$(\theta = \pi/2)$



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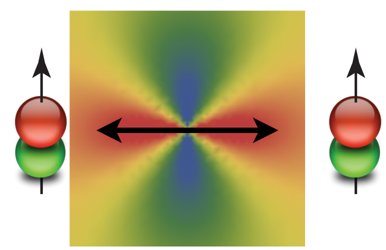
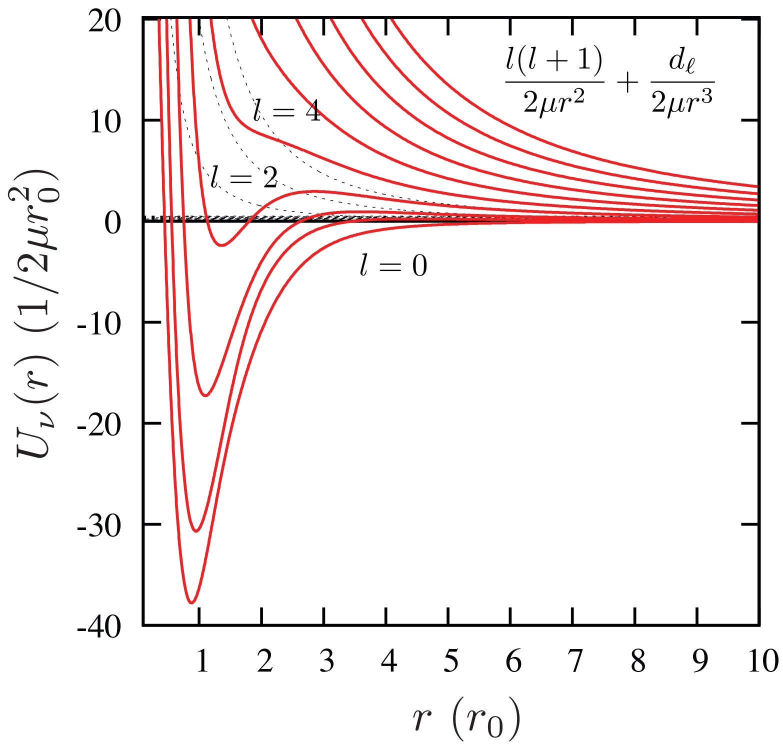


Bosons (m=0)



phase-shift : $\delta_l \propto k\ (\forall l)$

(**not** k^{2l+1})

Scattering length matrix:

$$a_{ll'} = -\frac{K_{ll'}}{k} \neq 0 \quad (k \to 0)$$

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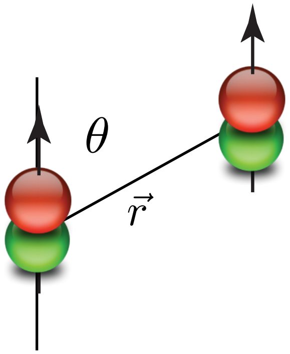
University of Colorado

Dipole-Dipole Interaction:



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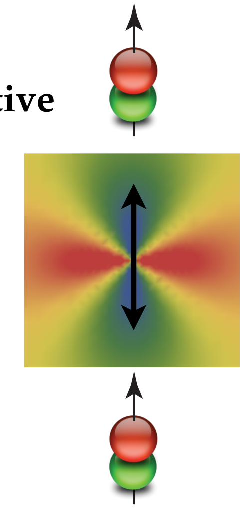

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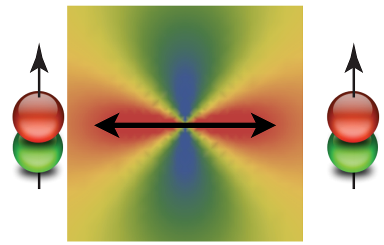
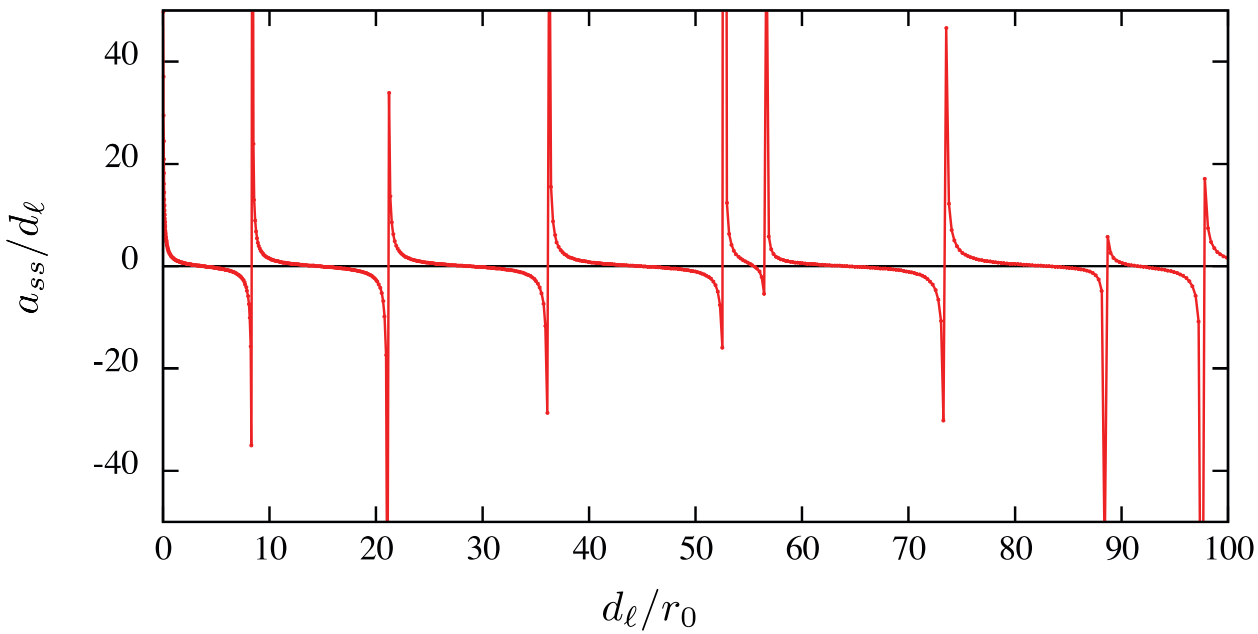


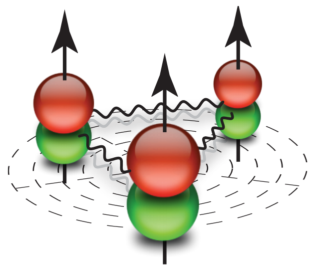


$a_{ss}/d_\ell \gg 1 \quad (d_\ell \gg r_0)$

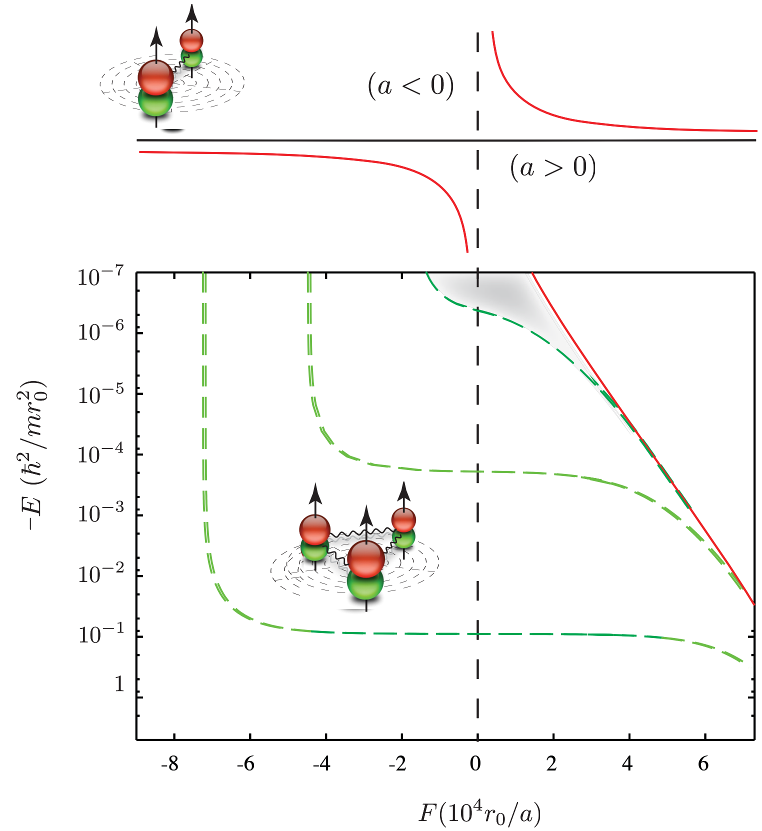
- **control of interactions ...**
- **new phases of the matter ...**
- **losses (?)**

How about Few-body Physics ?

Three-body Dipolar Physics



?



Efimov Physics for dipoles ?

non-dipolar	dipolar
large *s*-wave scattering length	*l* is not conserved (multiple partial waves contributes)
ZRM offers an analytical solution	ZRM for dipoles (?) (no effective-range)
Identical Bosons: J=0	J is also **not** conserved !!!

Strong Losses: **Tichnor & Rittenhouse PRL (2010)**
[pertubative treatment]

Toolkit for Exploring Few-body Physics ...

Toolkit for Exploring Few-body Physics ...

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NIST
University of Colorado

For N particles ...

$$\hat{H} = -\frac{1}{2\mu}\nabla_T^2 + \sum_{i<j} V(r_{ij})$$

... angles + set of non-compact coordinates $r_{ij} \rightarrow [0, \infty]$

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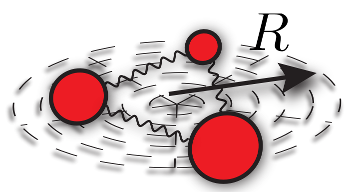
... the hyperspherical way !!!

$$\hat{H} = -\frac{1}{2\mu}\frac{d^2}{d^2R} + \frac{\Lambda^2(\Omega)}{2\mu R^2} + V(R,\Omega)$$



hyperradius R : overall size (collective motion)

$R \rightarrow [0, \infty]$

hyperangles $\{\Omega\}$**:** internal motion

$\{\Omega\} \rightarrow [0, \propto \pi]$

Toolkit for Exploring Few-body Physics ...

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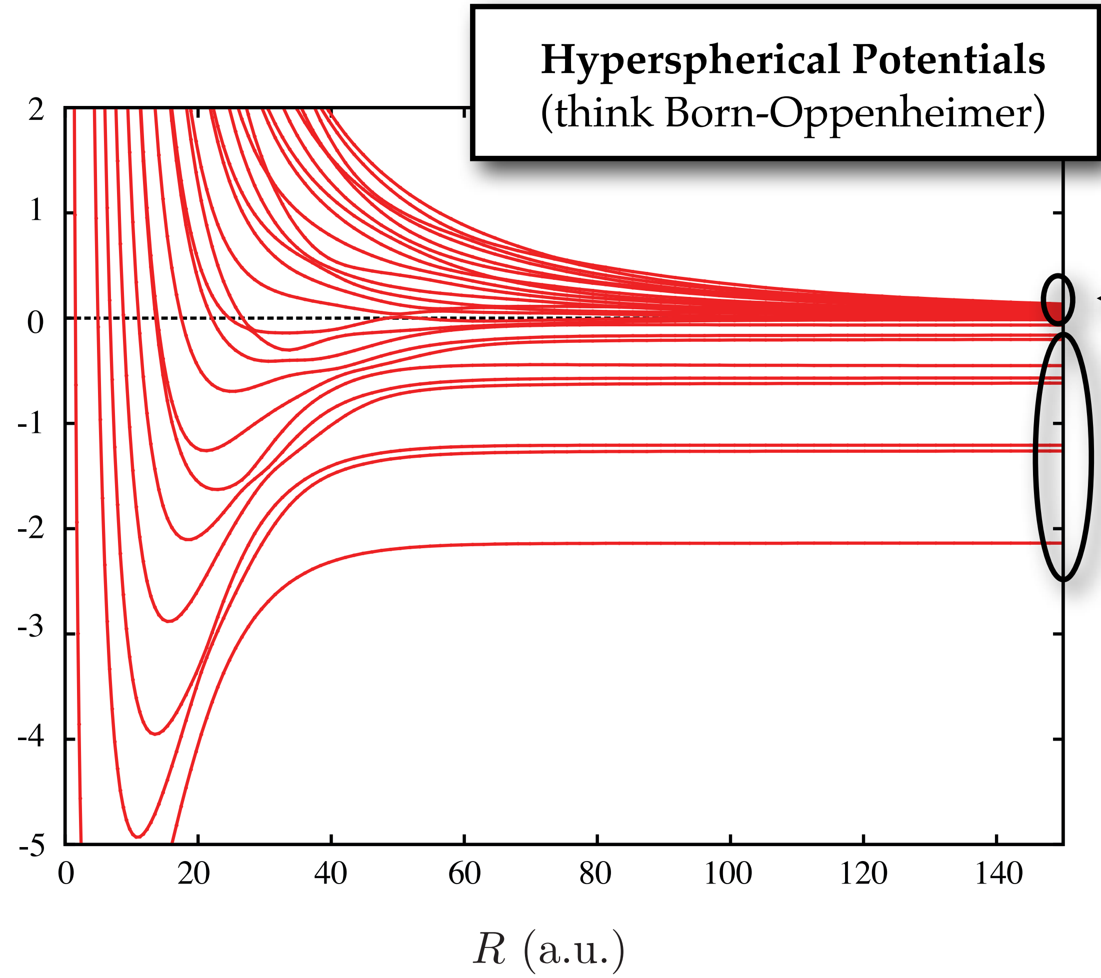
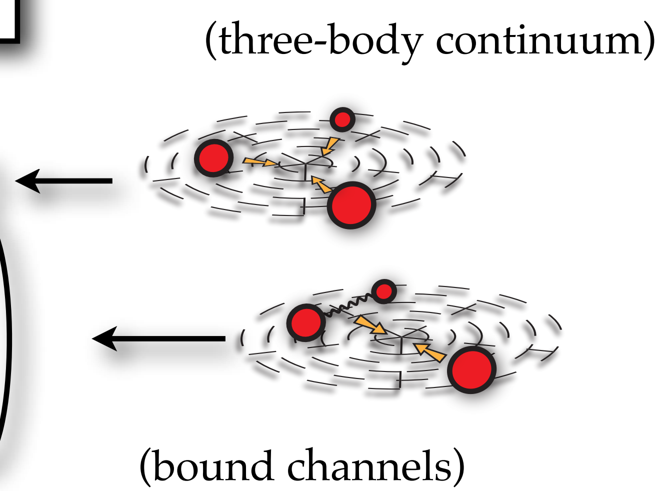


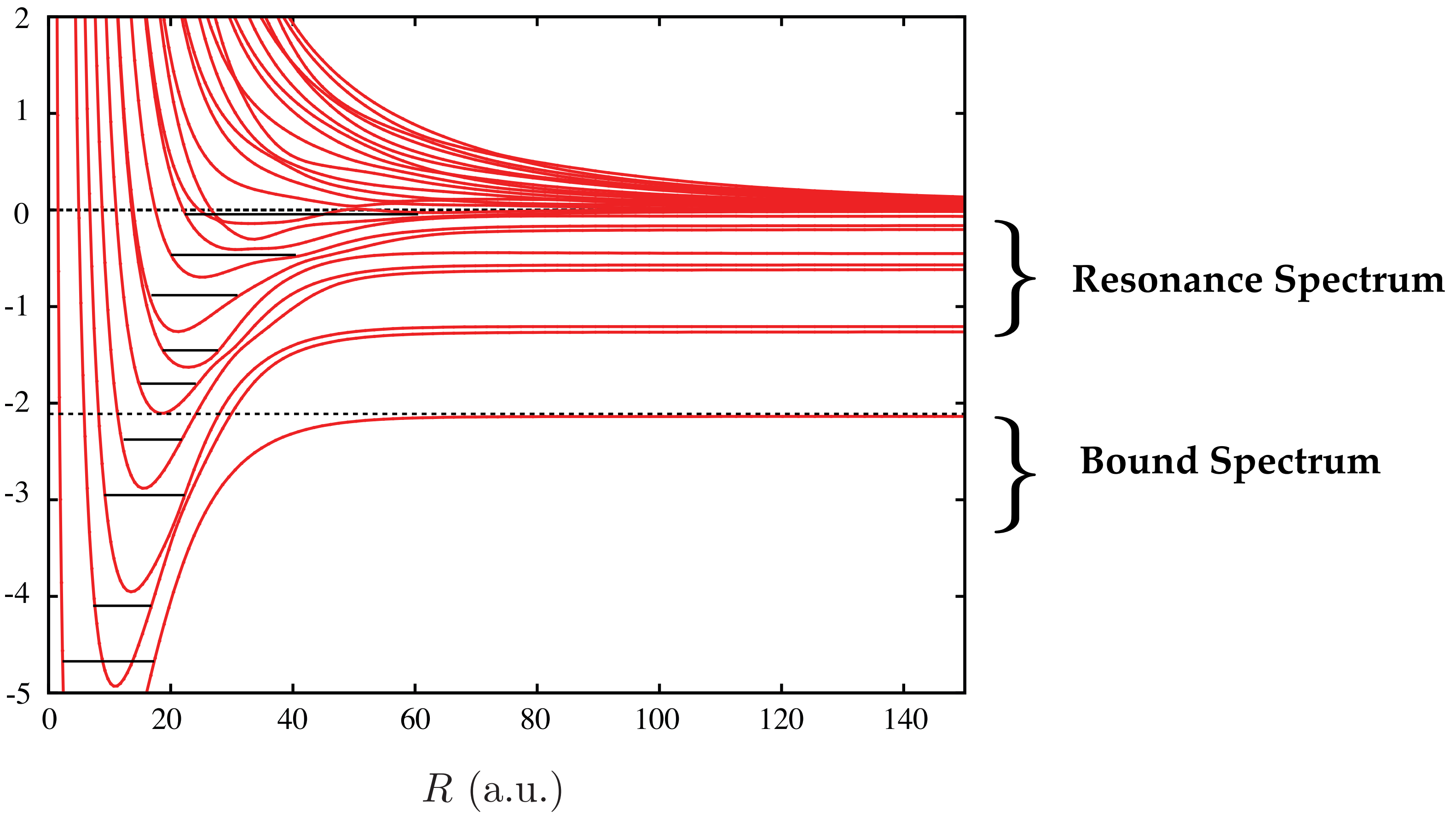


... fixing R, solving Ω

Bound and Scattering Properties

$$\left[-\frac{1}{2\mu}\frac{d^2}{dR^2}+U_\nu(R)-E\right]F_\nu(R)+\sum_{\nu'}W_{\nu\nu'}(R)F_{\nu'}(R)=0$$

(Hyperradial Schrodinger Equation)



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Bound and Scattering Properties

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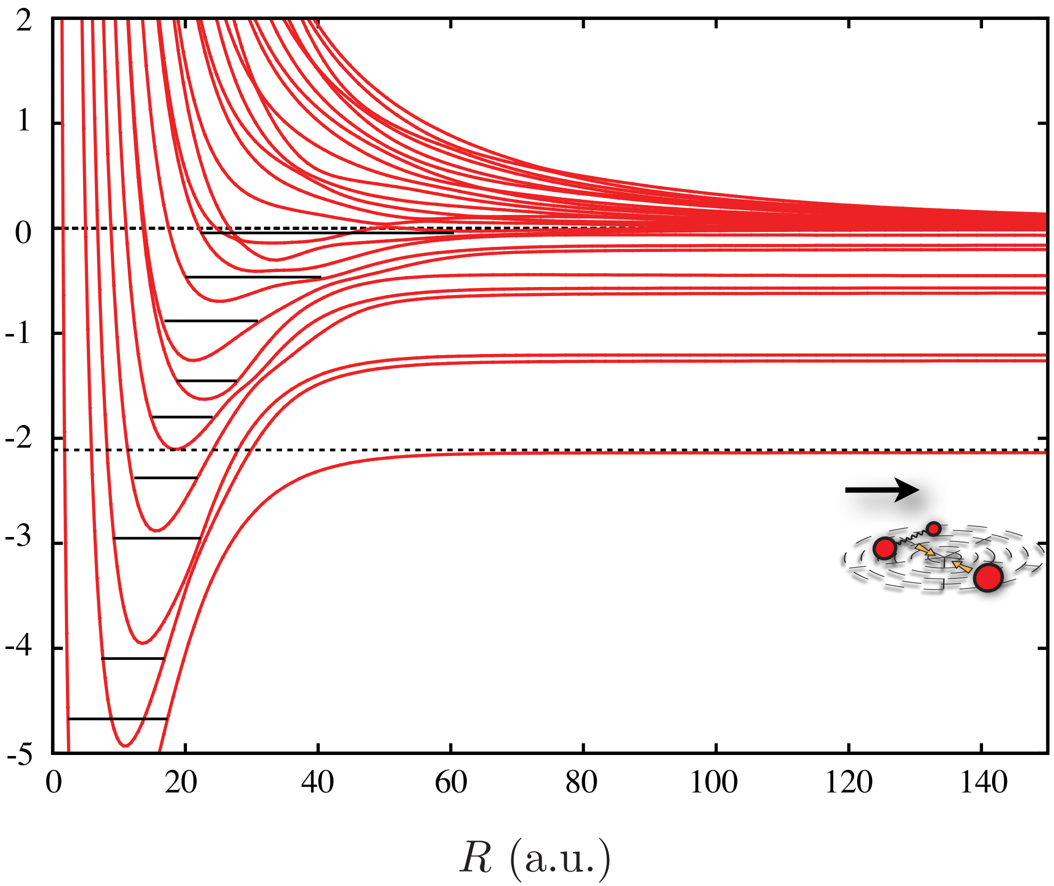

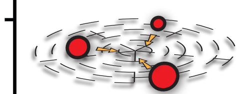

Ultracold Few-body Collisions

$W_{\nu\nu'}(R)$: non-adiabatic couplings
(drive inelastic transitions)

Typical length & energy scales:

- Van der Waals length: $r_0 \approx 100a_0$
- Temperature: $T \approx 100\text{nK}$

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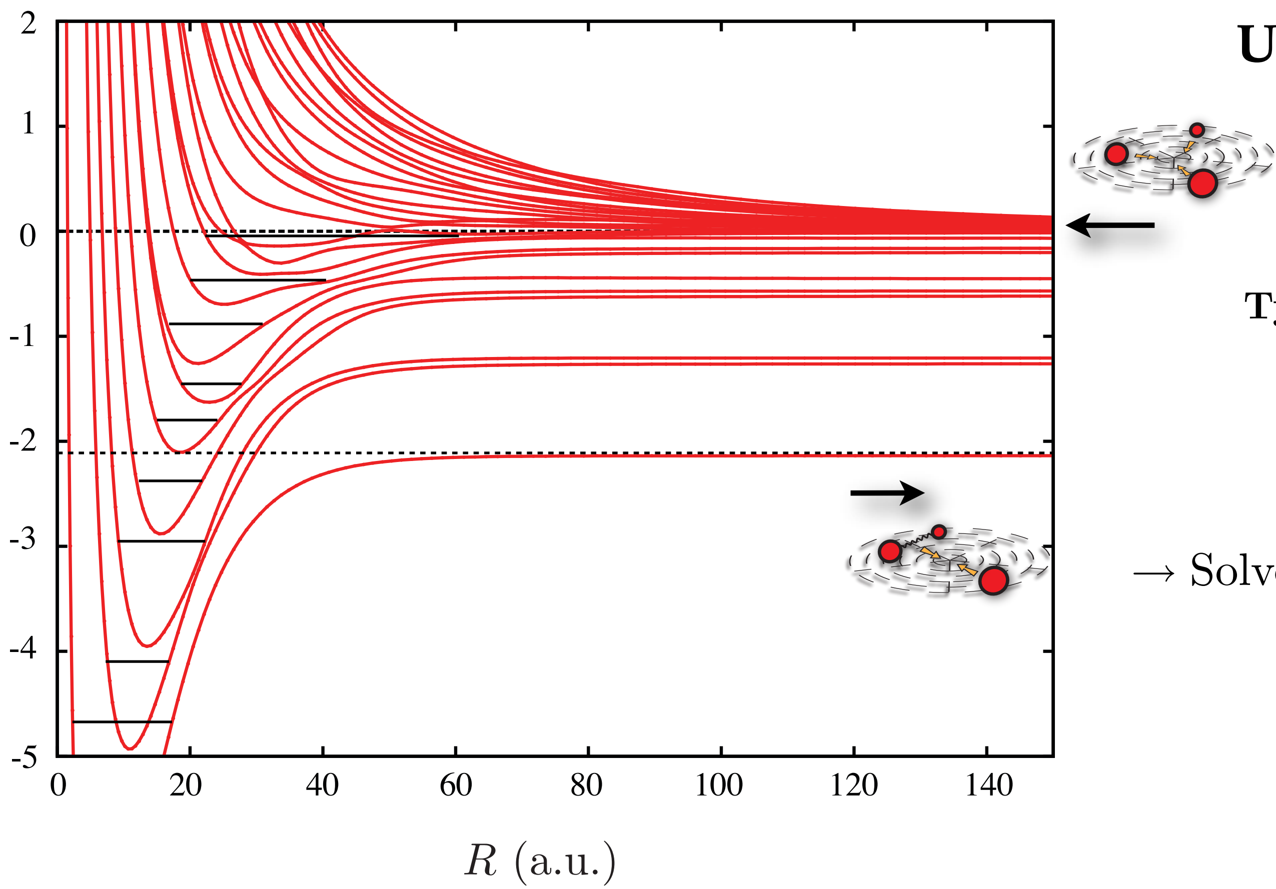

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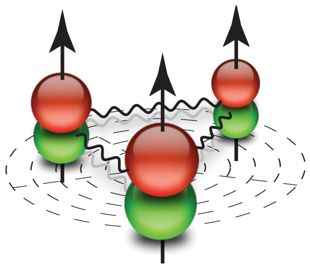
$\rightarrow$ Solve Schrödinger equation for $R \approx 10^6 a_0$
(0.05mm!!!)

Hyperspherical representation for dipoles ...



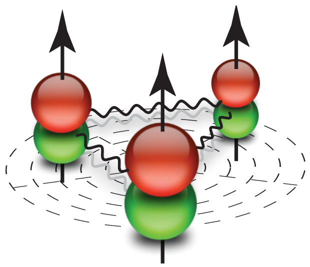
$$\Psi_M(R,\Omega) = \sum_\nu F_\nu^M(R)\Phi_\nu^M(R;\Omega)$$

$$\Phi_\nu^M(R;\Omega) = \sum_J \sum_K \phi_{\nu K}^J(R;\theta,\varphi) D_{KM}^J(\alpha,\beta,\gamma)$$

(J is **not** conserved)

$$\sum_{J'K'} \Bigg[\left\langle JMK \mid \frac{\hat{\Lambda}(\Omega)}{2\mu R^2} \mid J'MK' \right\rangle \delta_{JJ'} + \left\langle JMK \mid \sum_{i>j} v_{dip}(\vec{r}_{ij}) \mid J'MK' \right\rangle - U_\nu(R) \Bigg] \phi_{\nu K'}^{J'}(R;\theta,\varphi) = 0$$

Hypersperical representation for dipoles ...



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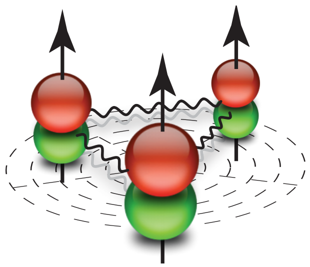
$$\begin{aligned} \langle J'K'M'|v_{dd}(\vec{r}_{ij})|JKM\rangle \quad = \quad & \frac{d_\ell}{\mu_{2b} r_{ij}^3}(-1)^{K+M}\delta_{MM'}\sqrt{(2J+1)(2J'+1)} \times \\ & \left[\delta_{KK'} \begin{pmatrix} J & 2 & J' \\ K & 0 & -K' \end{pmatrix} \begin{pmatrix} J & 2 & J' \\ M & 2 & -M' \end{pmatrix} \right. \\ & -\delta_{K-2,K'} \frac{3}{\sqrt{6}} \begin{pmatrix} J & 2 & J' \\ -K & 2 & K' \end{pmatrix} \begin{pmatrix} J & 2 & J' \\ -M & 0 & M' \end{pmatrix} \left(\frac{r_{ij}^x - i\, r_{ij}^y}{2} \right)^2 \\ & \left. -\ \delta_{K+2,K'} \frac{3}{\sqrt{6}} \begin{pmatrix} J & 2 & J' \\ K & 2 & -K' \end{pmatrix} \begin{pmatrix} J & 2 & J' \\ M & 0 & -M' \end{pmatrix} \left(\frac{r_{ij}^x + i\, r_{ij}^y}{2} \right)^2 \right] \end{aligned}$$

Hyperspherical representation for dipoles ...



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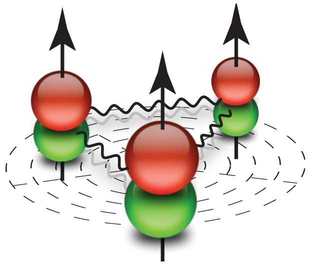
$U_\nu(R)$: Adiabatic Potentials

$P_\nu(R)$ and $Q_{\nu\nu'}(R)$: nonadiabatic couplings

Hyperspherical representation for dipoles ...



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$$\sum_{J'K'} \left[\left\langle JMK \mid \frac{\hat{\Lambda}(\Omega)}{2\mu R^2} \mid J'MK' \right\rangle \delta_{JJ'} \right.$$

$$\left. + \left\langle JMK \mid \sum_{i>j} v_{dip}(\vec{r}_{ij}) \mid J'MK' \right\rangle - U_\nu(R) \right] \phi_{\nu K'}^{J'}(R;\theta,\varphi) = 0$$

$U_\nu(R)$: Adiabatic Potentials

$P_\nu(R)$ and $Q_{\nu\nu'}(R)$: nonadiabatic couplings

$J_{\max} = 14$

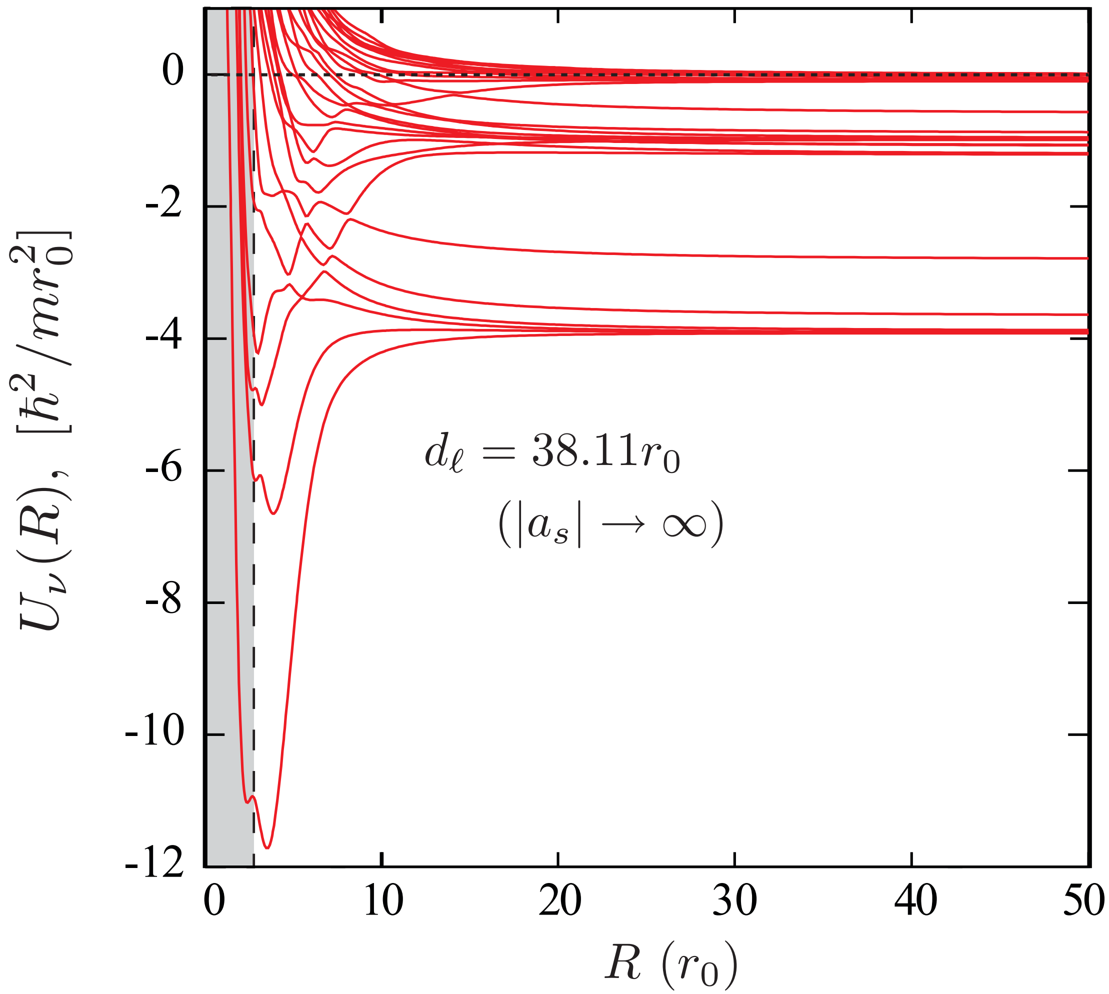
50x50 system of 2D-PDE !!!

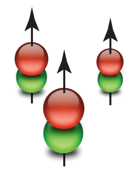
(very challenging !!!)

Dipolar Efimov Effect

Three-dipoles effective potentials

Wang, D'Incao, Greene, *PRL* **106**, 233201 (2011)





Three-dipoles continuum ...

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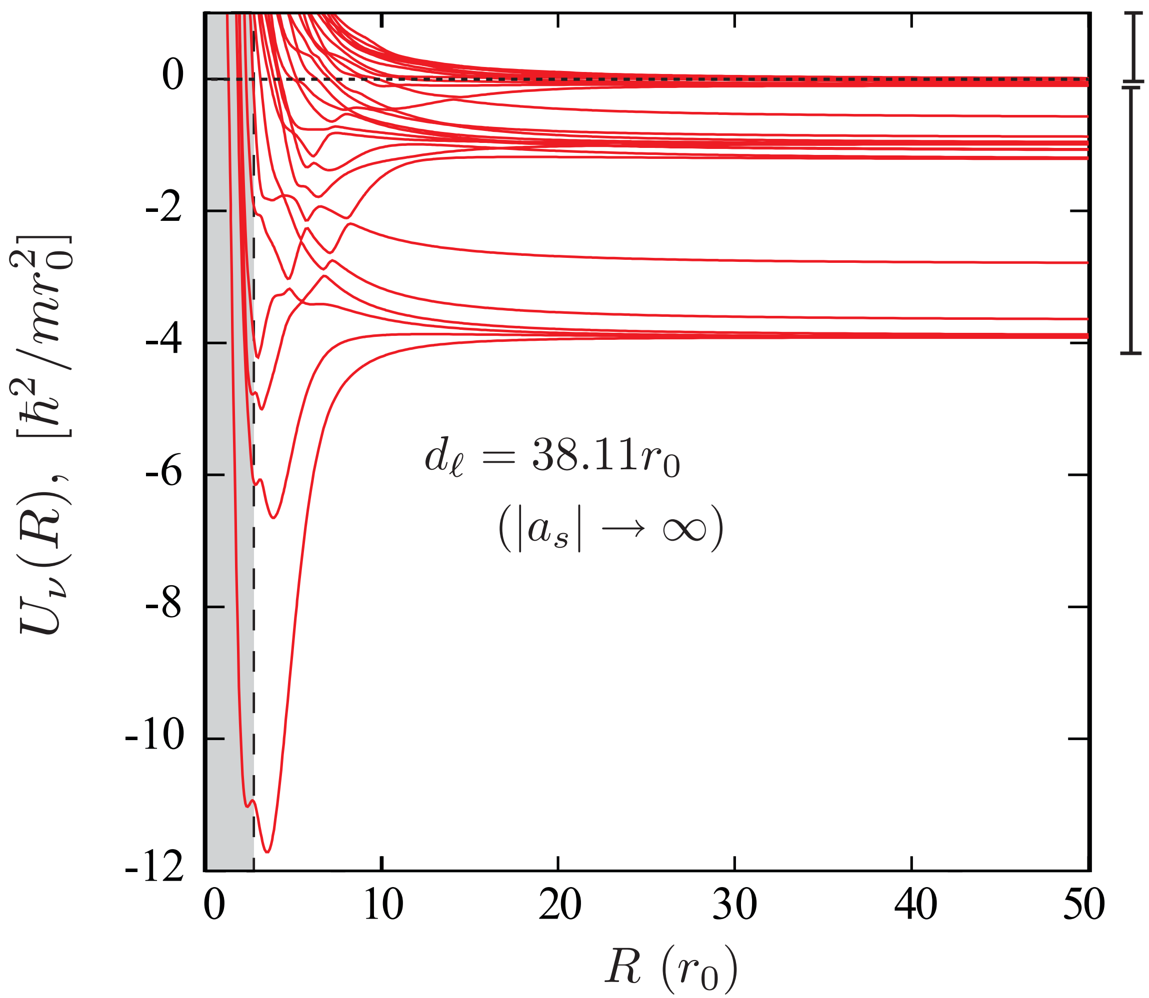
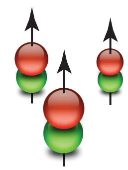
Wang, D'Incao, Greene, *PRL* **106**, 233201 (2011)





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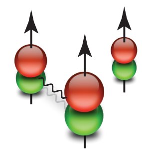
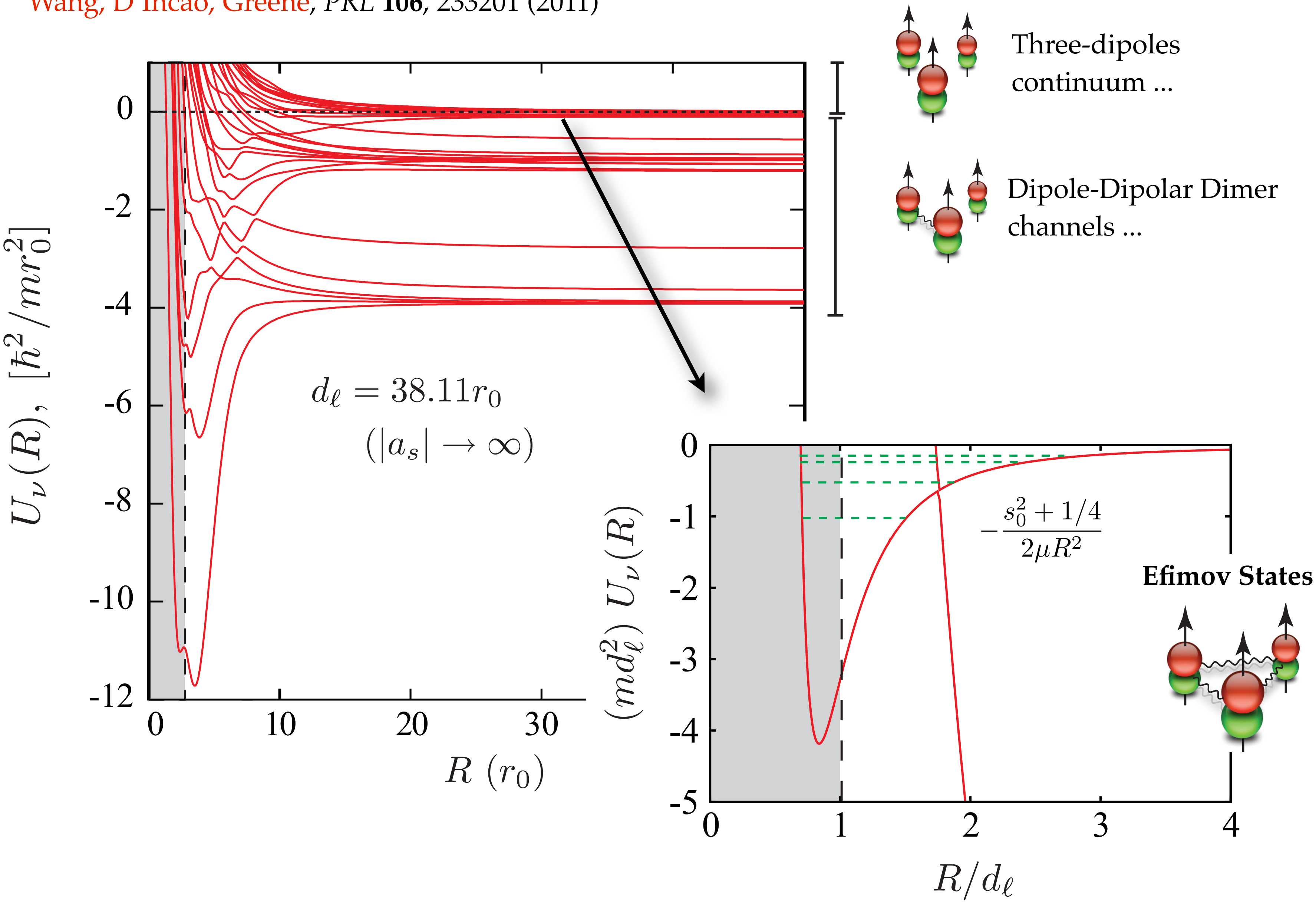


Dipole-Dipolar Dimer channels ...

Three-dipoles effective potentials

Wang, D'Incao, Greene, *PRL* **106**, 233201 (2011)



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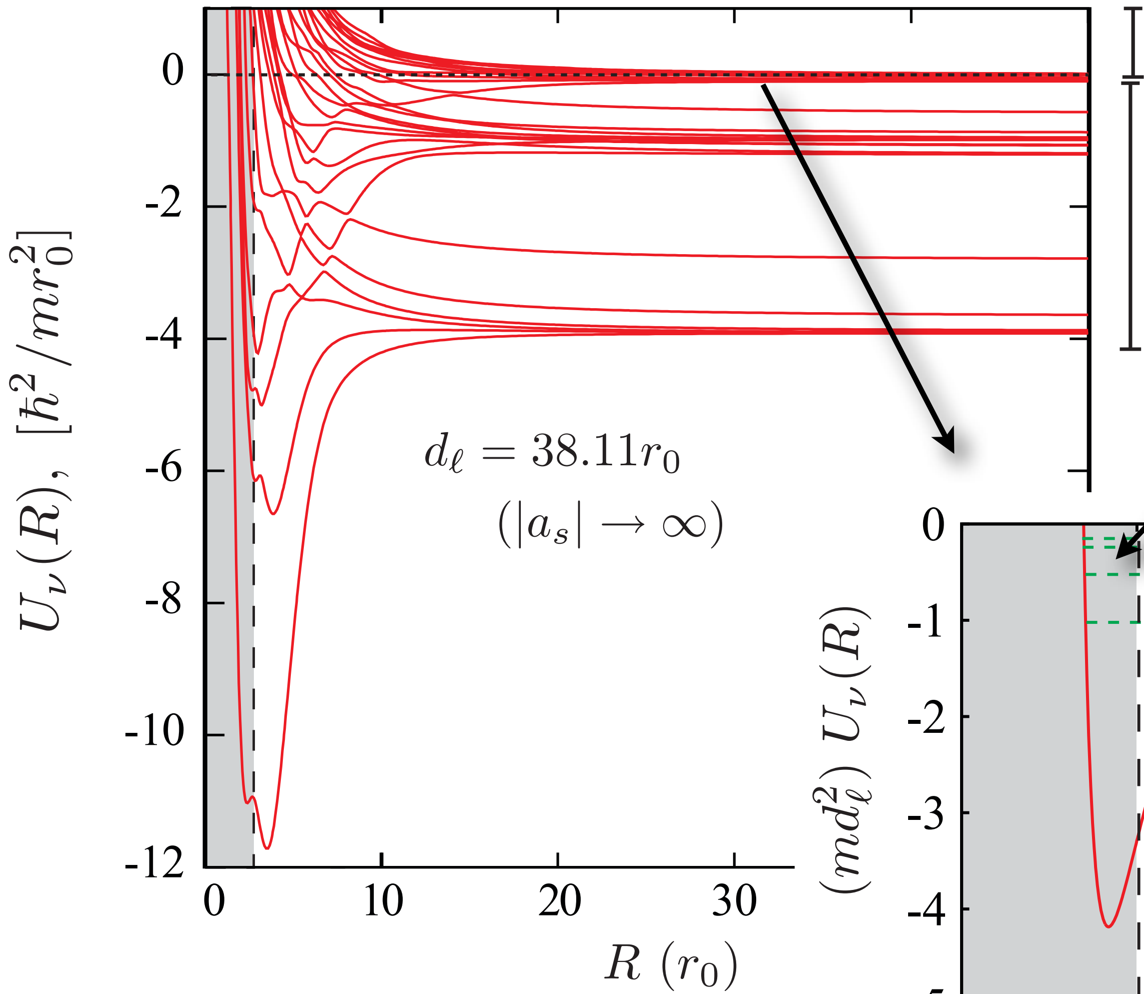

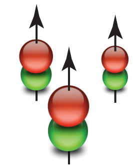

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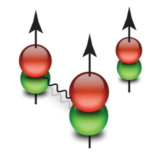
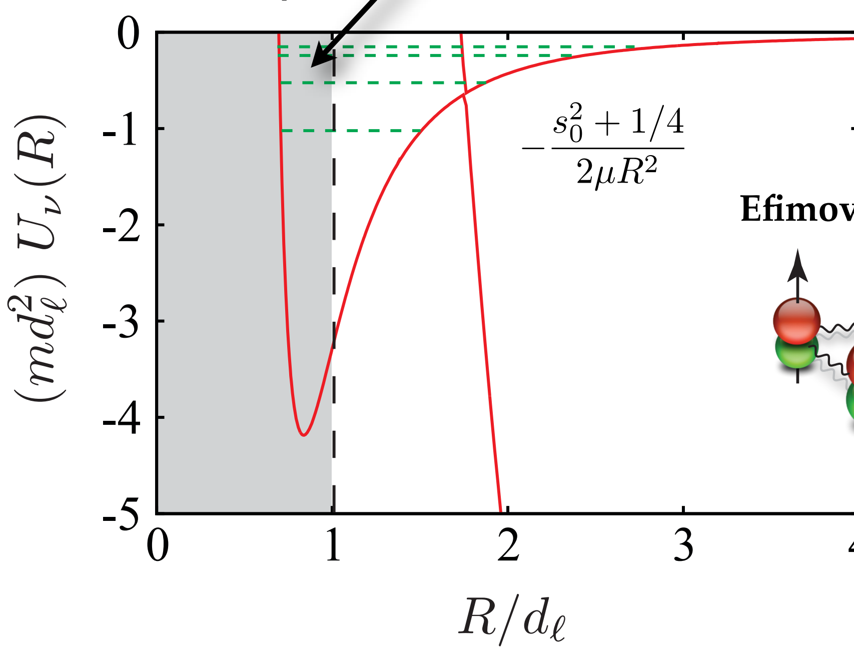


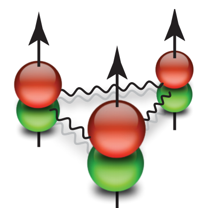
Dipole-Dipolar Dimer channels ...

The Efimov effect persist !!!

(difference: repulsion for $R < d_\ell$**)**



Efimov States



Thursday, October 13, 2011

So what ?

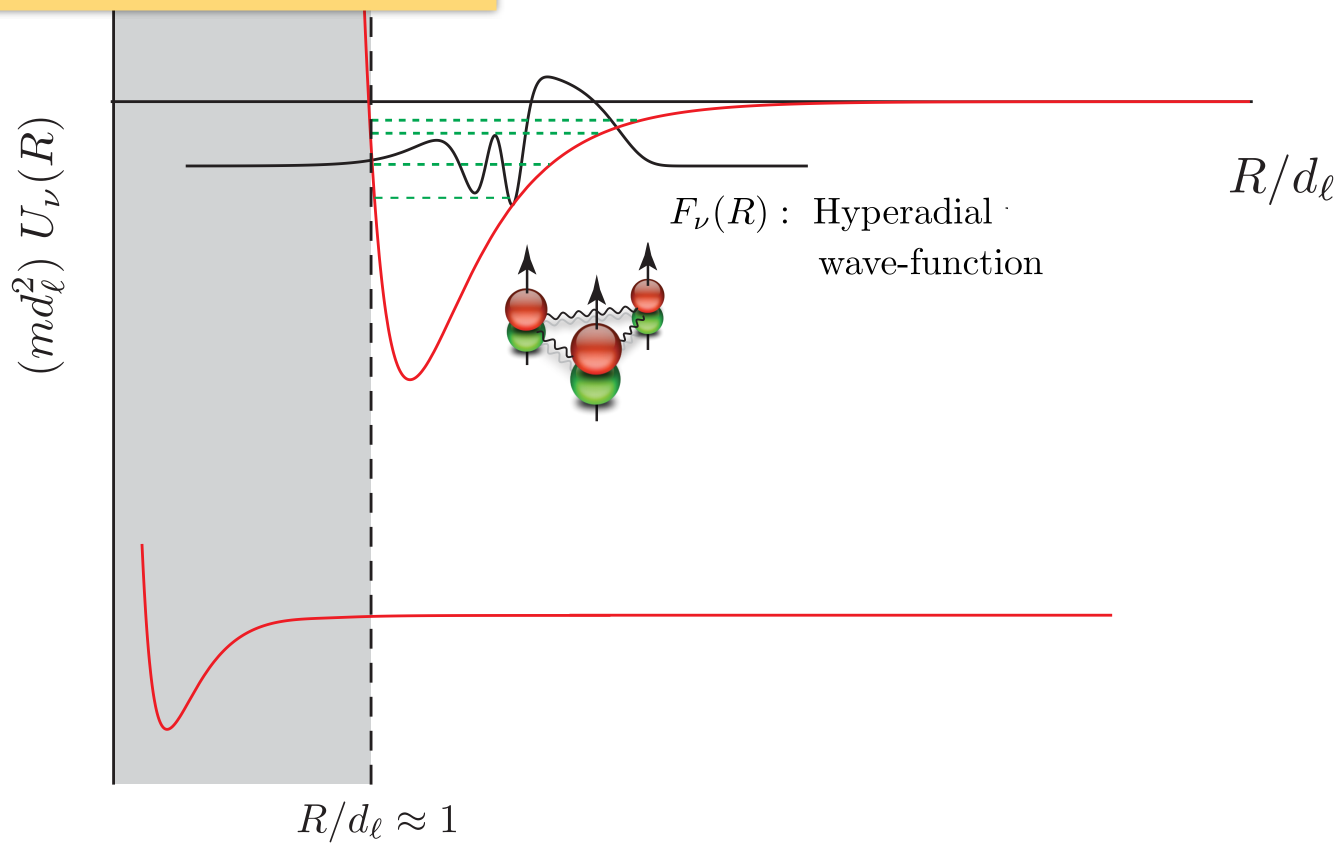
Dipolar Efimov Effect

Dipolar Efimov Effect

Three-dipoles effective potentials

(schematic representation)

The barrier <u>prevents</u> two dipoles to be at distances smaller than d_ℓ !!!



Three-dipoles effective potentials

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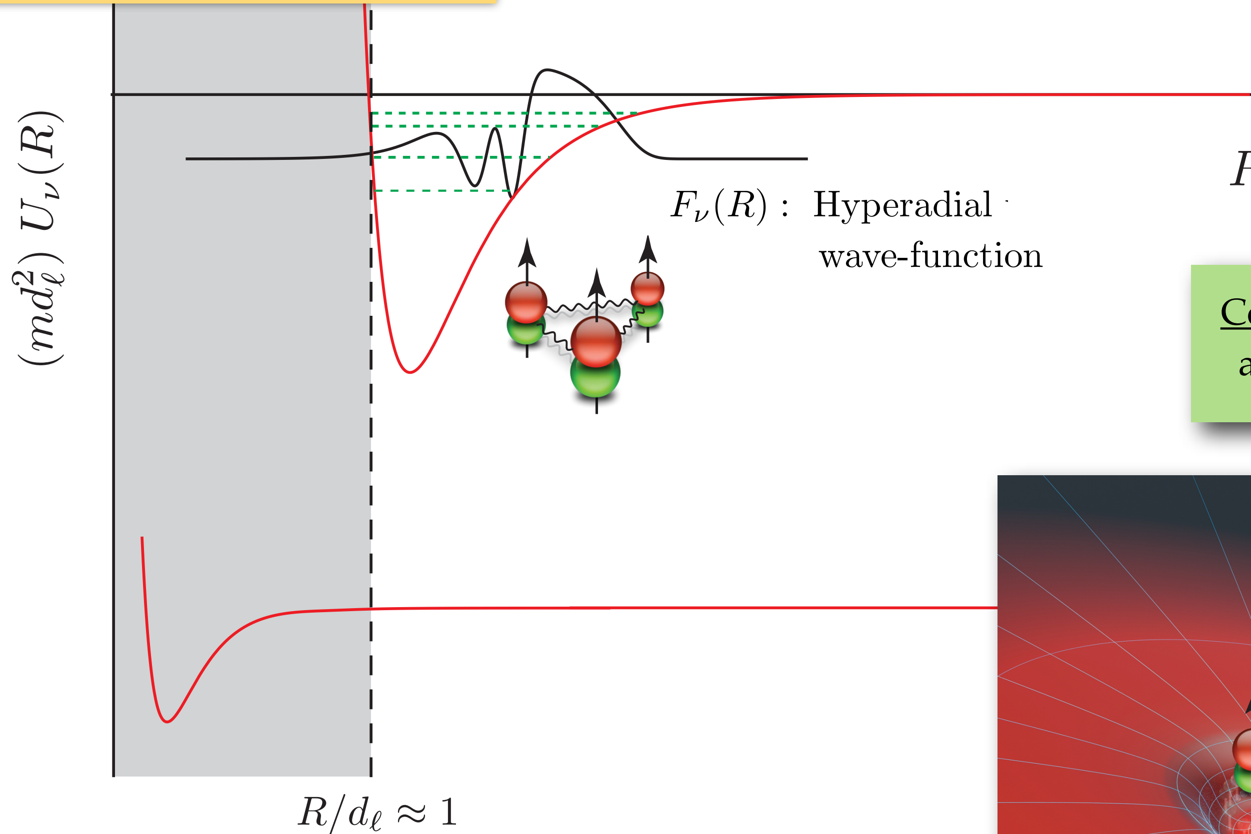
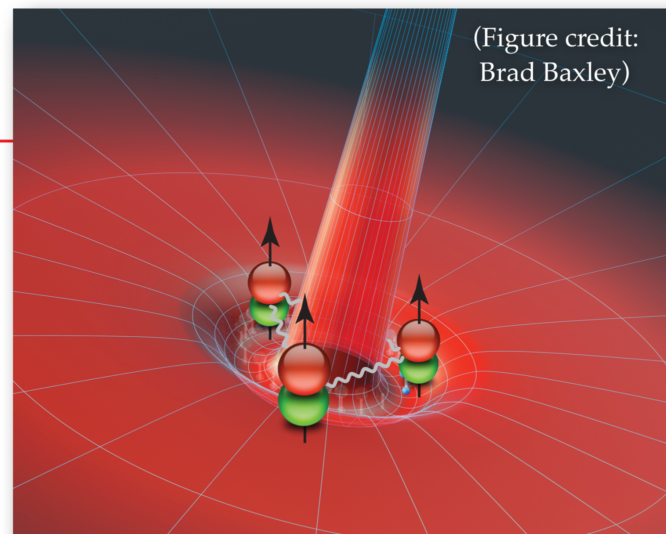


<u>Consequence #1:</u> Energies, geometry, ... are universal !!! (depend only on d_ℓ)

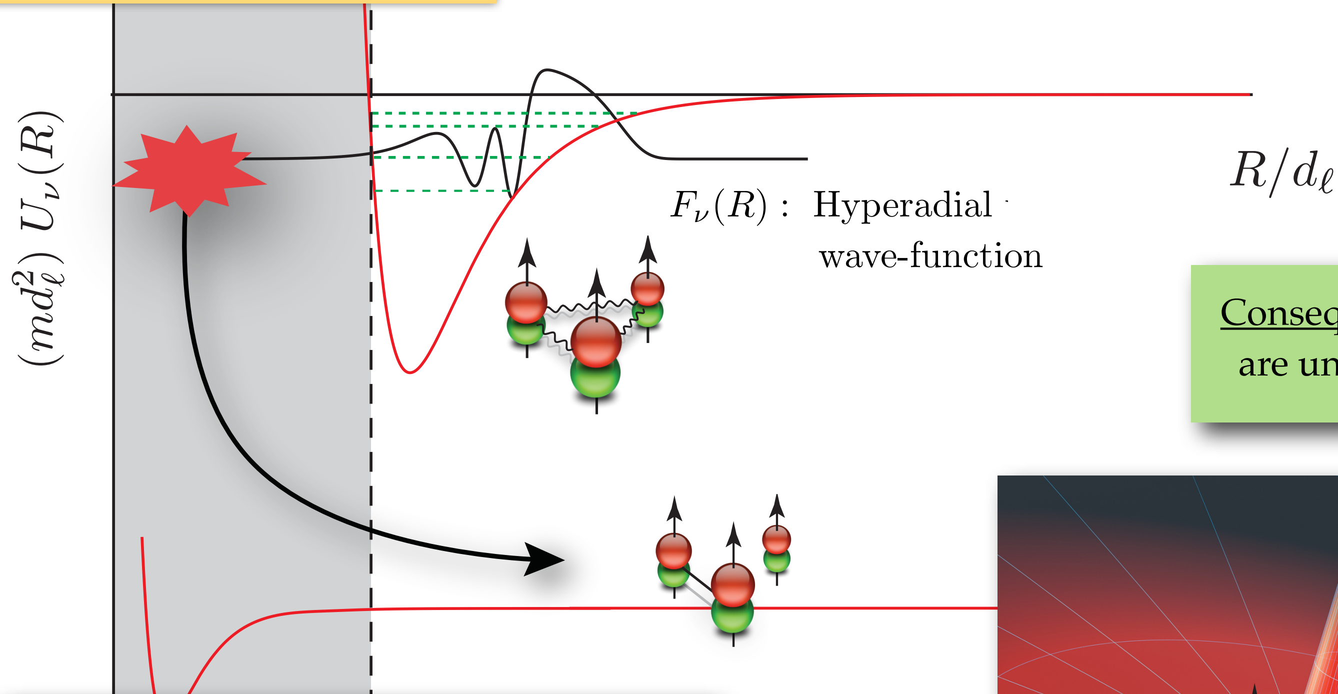

(Figure credit: Brad Baxley)

Dipolar Efimov Effect

Three-dipoles effective potentials

(schematic representation)

The barrier prevents two dipoles to be at distances smaller than d_ℓ !!!



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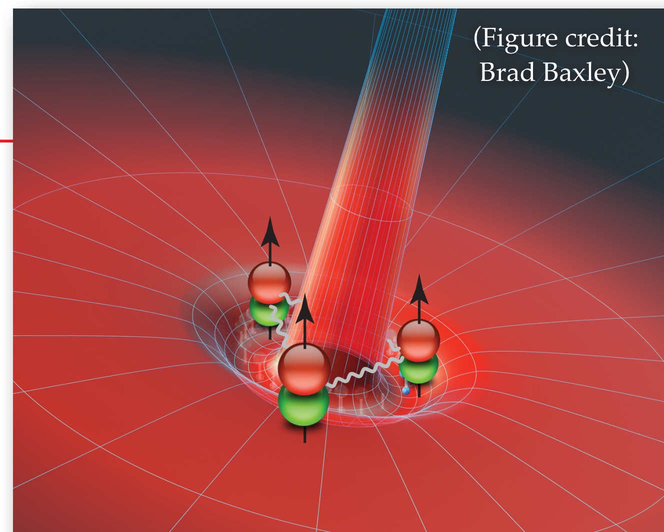


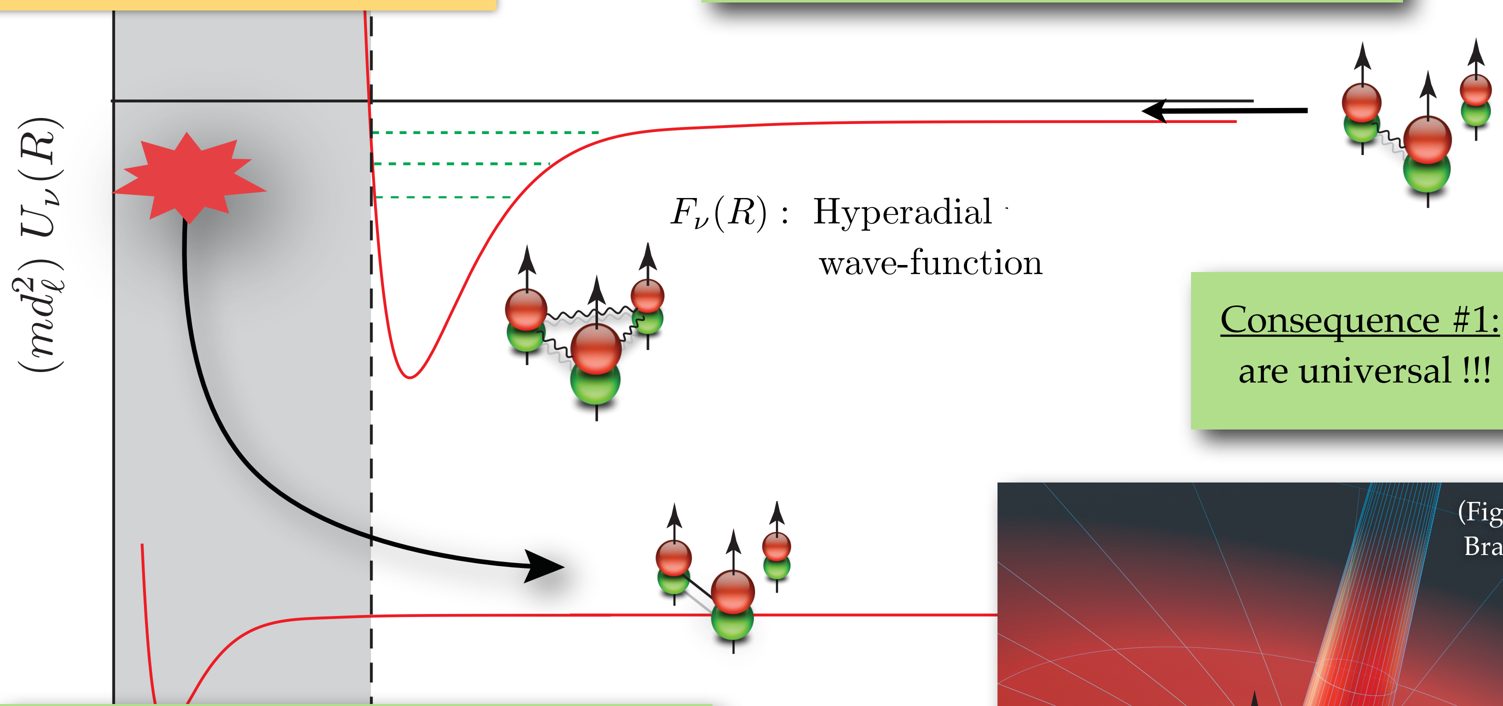
Consequence #2: suppression of decay !!! (long-lived states !!!)

Three-dipoles effective potentials

(schematic representation)

The barrier prevents two dipoles to be at distances smaller than d_ℓ !!!

Consequence #3: universal collisional properties (resonances)



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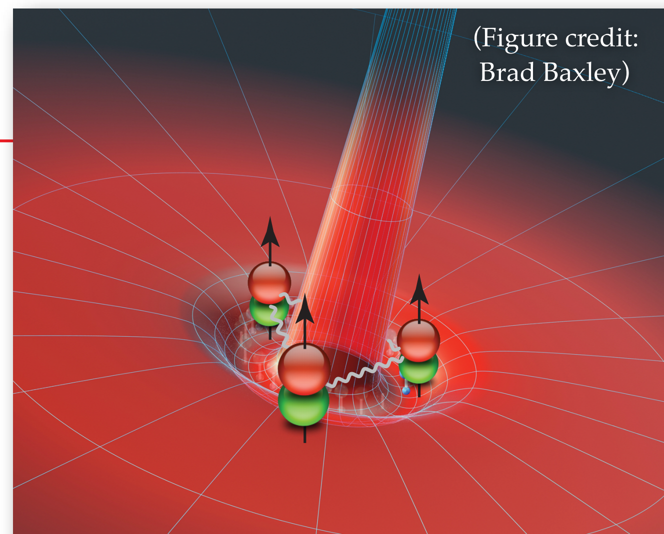
(Figure credit: Brad Baxley)

Dipolar Efimov Effect

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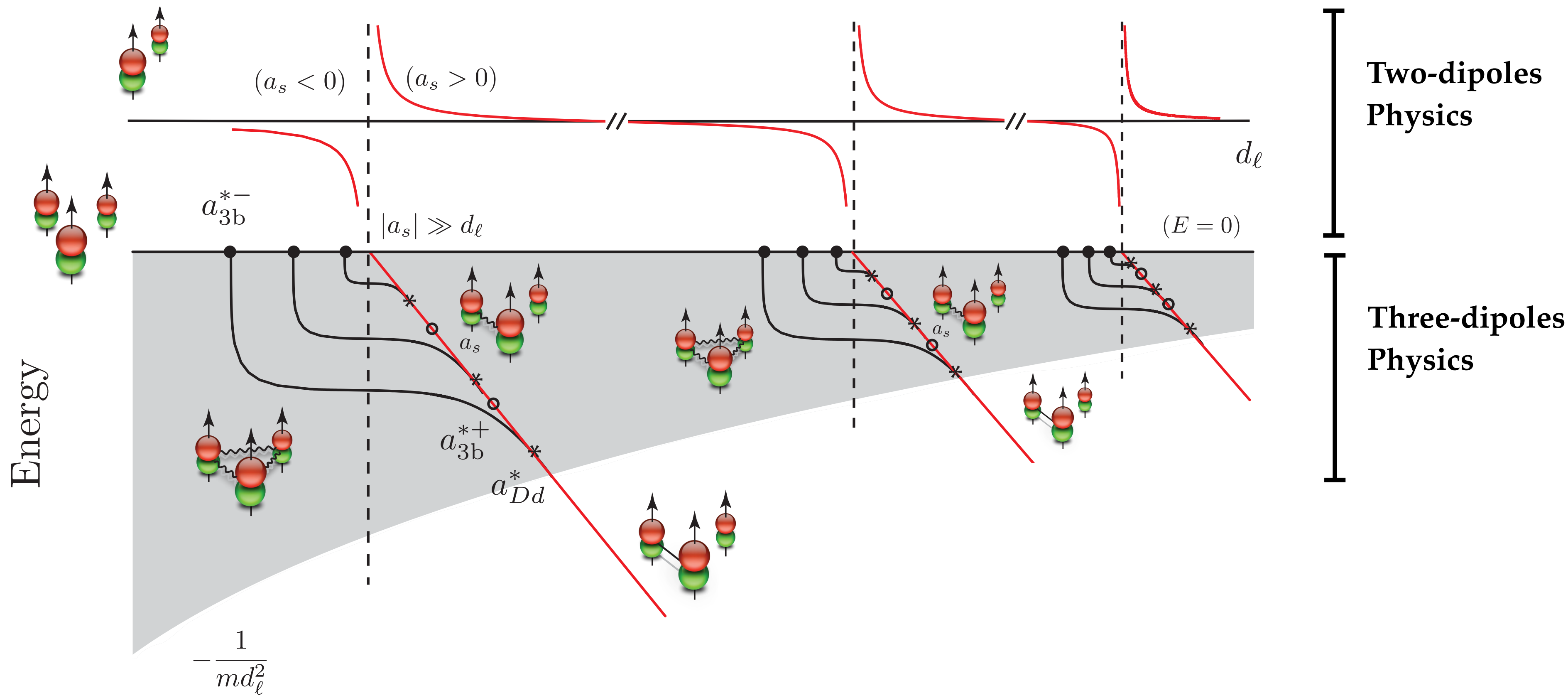
Dipolar Efimov Spectrum

(schematic representation)



a^{*-}_{3b} : resonances in three-dipoles recombination

a^{*+}_{3b} : interference in three-dipoles recombination

a^{*}_{Dd} : resonances in dipole-dipolar dimer collisions

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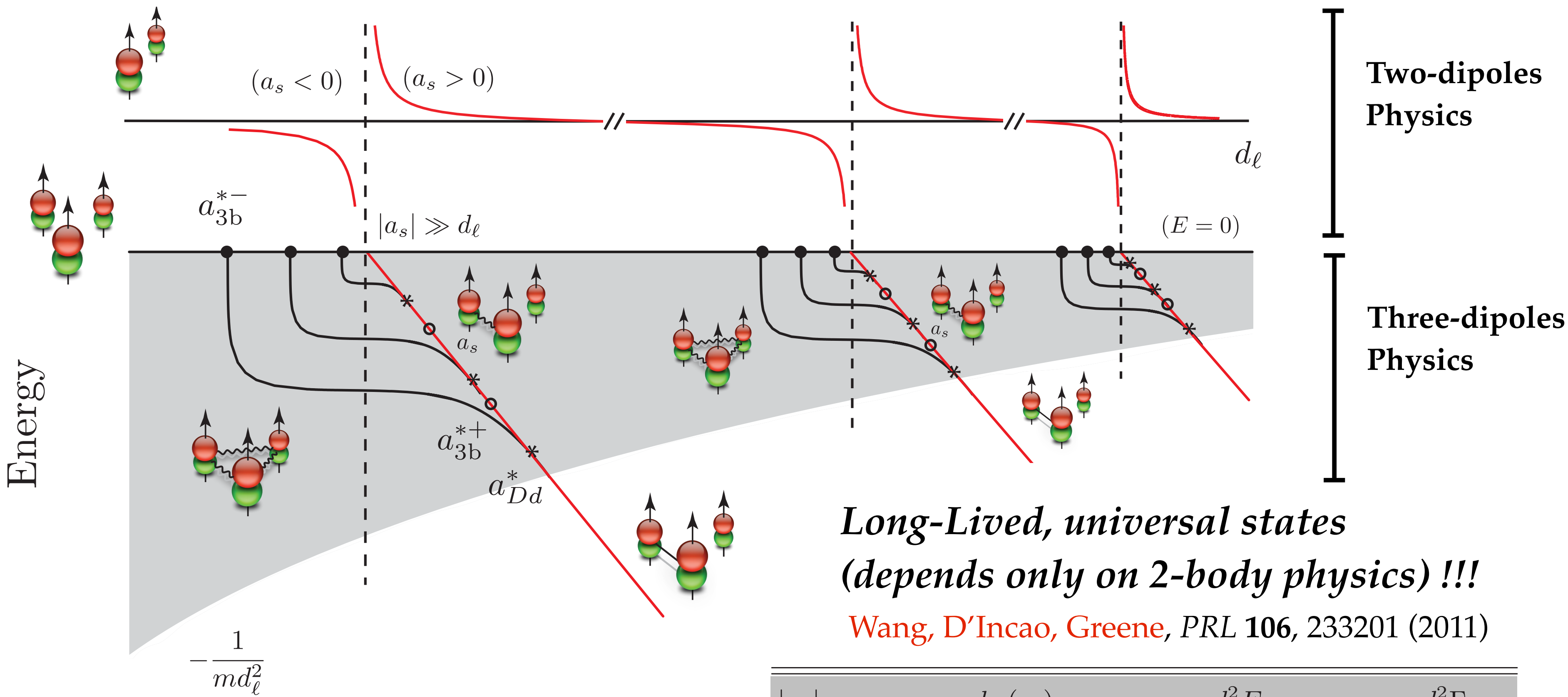
Dipolar Efimov Spectrum

(schematic representation)



Long-Lived, universal states (depends only on 2-body physics) !!!

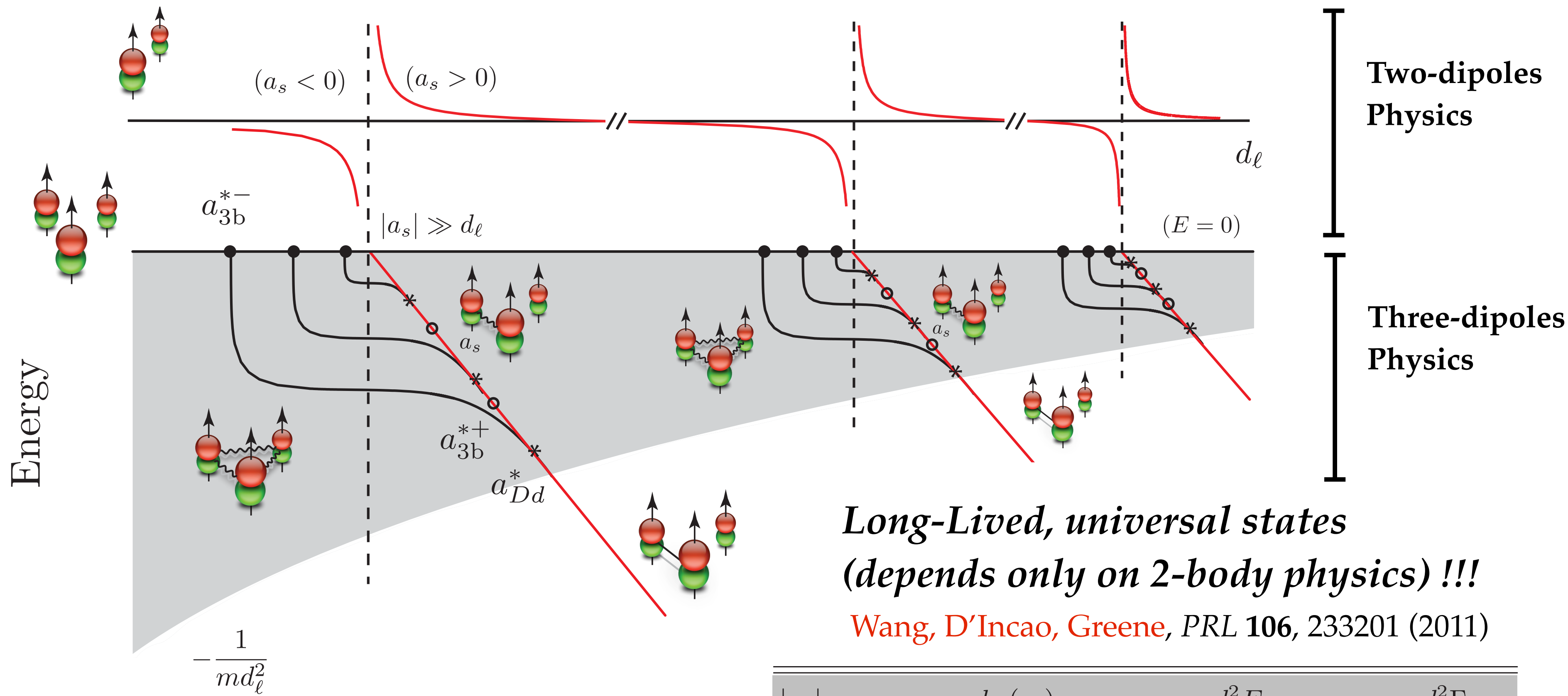
Wang, D'Incao, Greene, *PRL* **106**, 233201 (2011)

$\lvert a_s\rvert \to \infty$	$d_\ell\ (r_0)$	$md_\ell^2 E_0$	$md_\ell^2 \Gamma$
	14.534	3.06×10^{-2}	5.2×10^{-3}
	25.498	3.03×10^{-2}	6.6×10^{-3}
	38.110	2.95×10^{-2}	3.2×10^{-3}
(3-body)	$a^{*-}_{3b}/d_\ell \approx -8.1$	$a^{*+}_{3b}/d_\ell \approx 1.8$	$a^{*}_{Dd}/d_\ell \approx 8.6$
(4-body)	$a^{*-}_{4b,1}/d_\ell \approx -3.5$	$a^{*-}_{4b,2}/d_\ell \approx -7.3$	
	$a^{*}_{dd,1}/d_\ell \approx 20.$	$a^{*}_{dd,2}/d_\ell \approx 57.$	$a^{c}_{Dd}/d_\ell \approx 58.$

Dipolar Efimov Effect

Dipolar Efimov Spectrum

(schematic representation)



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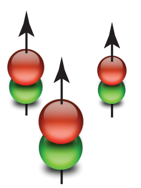
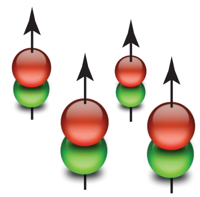
☑ **Three-dipoles resonances**



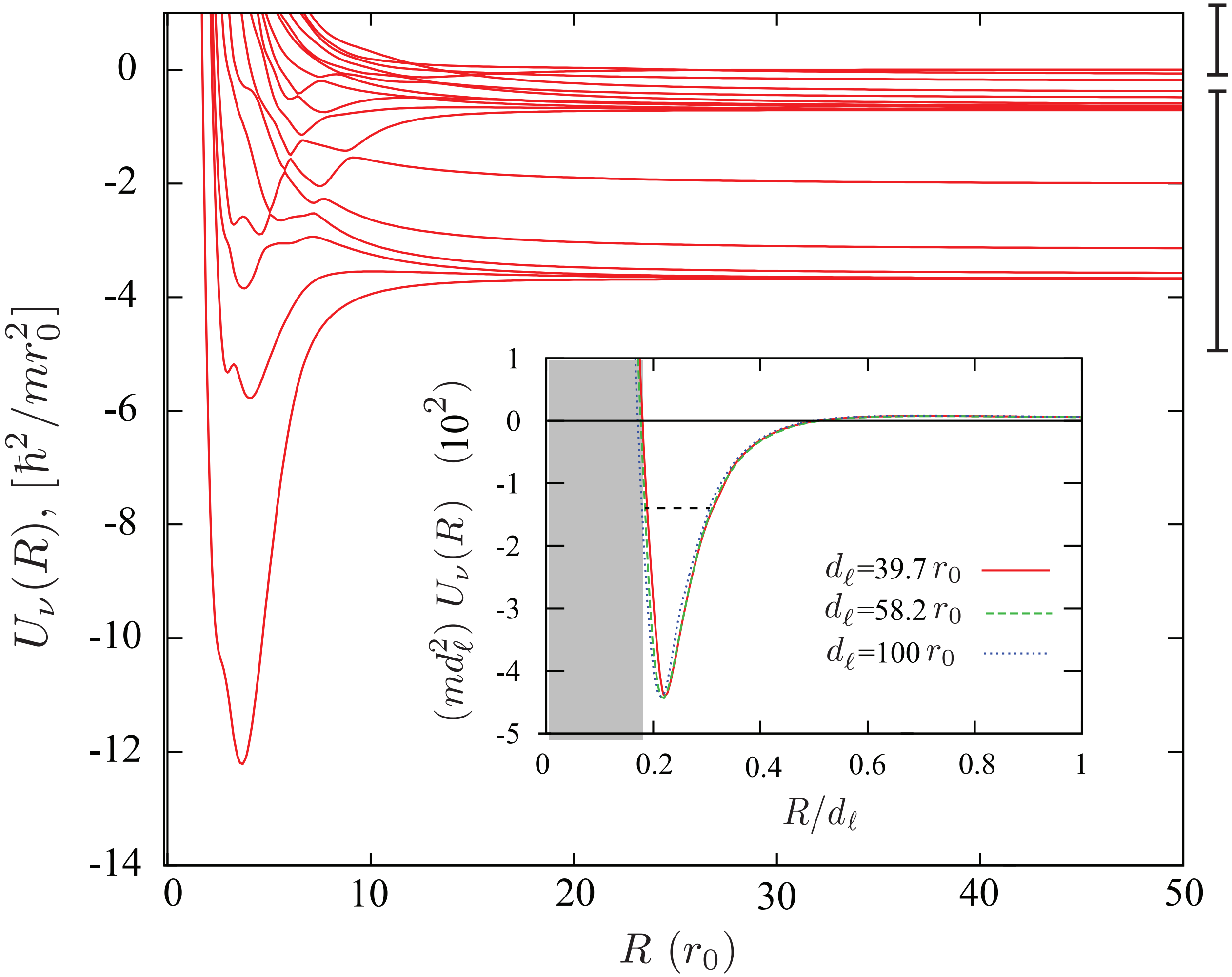
☑ **Four-dipoles resonances**

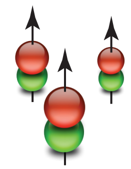


Fermionic Dipoles - a new class of few-body states !?

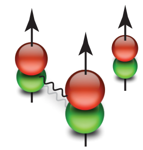
Three-fermionic dipoles effective potentials

- **“Universal three-body physics for fermionic dipoles”**, Wang, D’Incao, Greene, arXiv:1106.6133 (2011)





Three-dipoles continuum ...

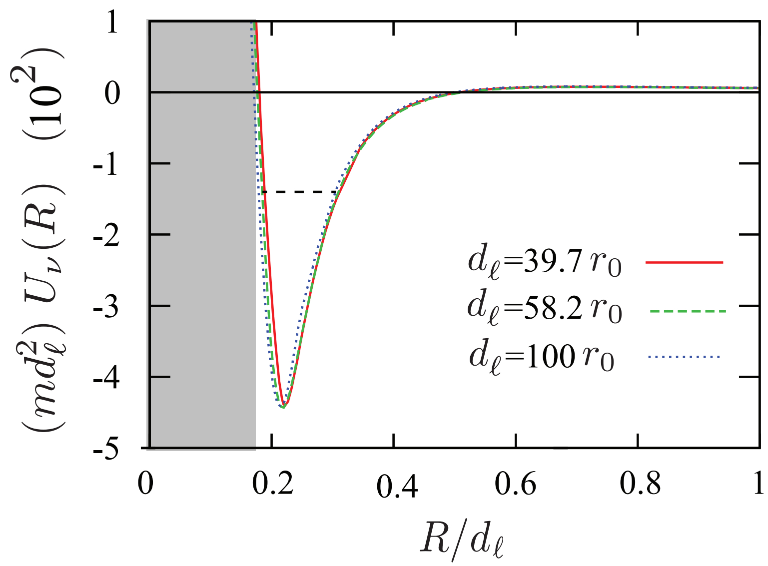


Dipole-Dipolar Dimer channels ...

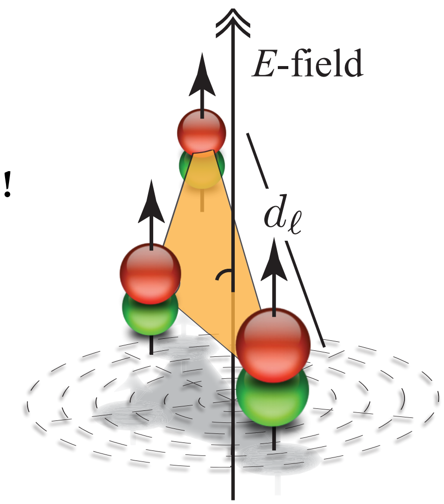
Repulsion for $R < d_\ell$!!!

Three-fermionic dipoles effective potentials

- **"Universal three-body physics for fermionic dipoles",** Wang, D'Incao, Greene, arXiv:1106.6133 (2011)



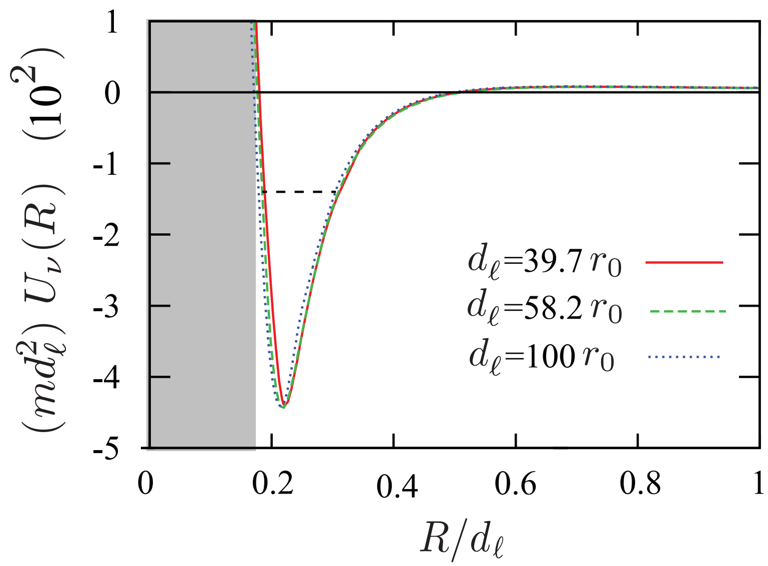
Single Universal State !!!



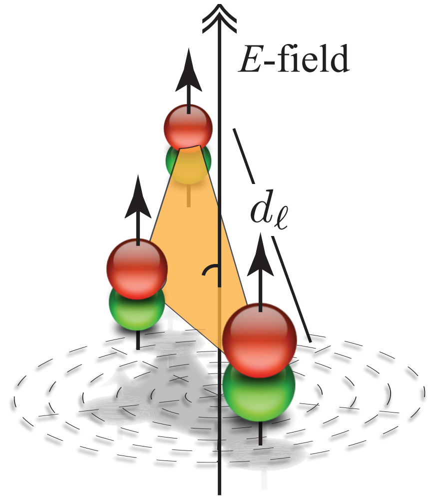
Fermionic Dipoles - a new class of few-body states !?

Three-fermionic dipoles effective potentials

- **"Universal three-body physics for fermionic dipoles"**, Wang, D'Incao, Greene, arXiv:1106.6133 (2011)

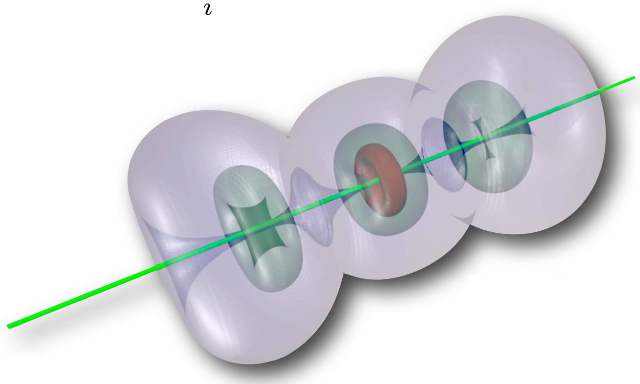


Single Universal State !!!



Probability Density:

$$\rho(\vec{r}) = \frac{1}{3}\langle\Psi|\sum_i \delta(\vec{r}-\vec{r}_i)|\Psi\rangle$$



Thursday, October 13, 2011

JILA NIST University of Colorado

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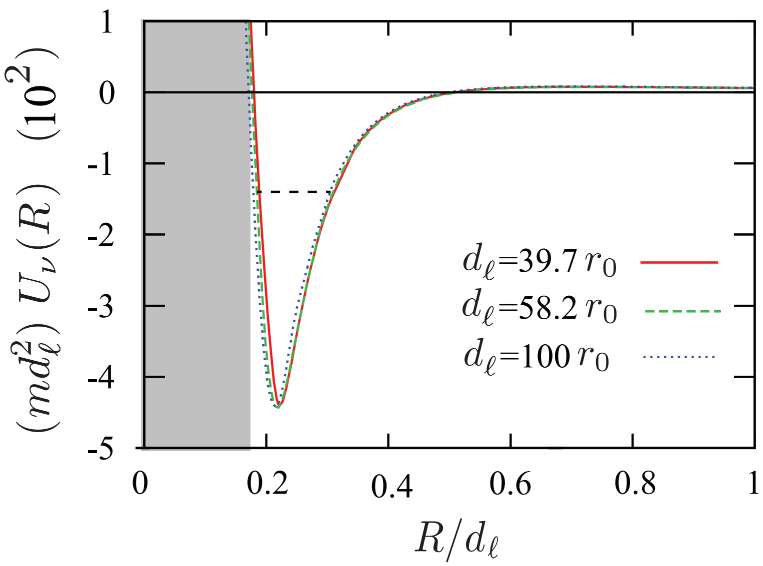

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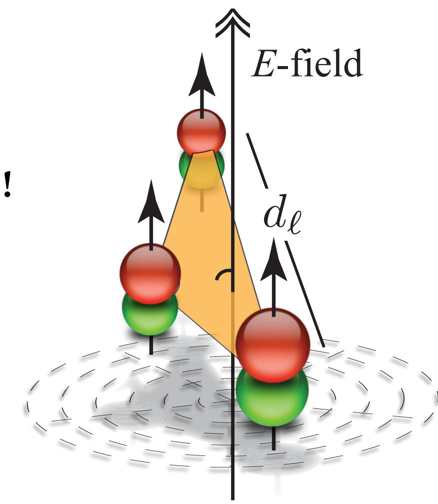

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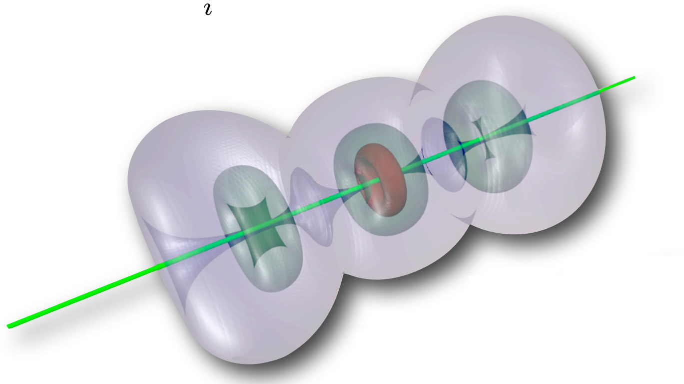

Long-Lived, universal states !!!

$E_{2d} \to 0$	$d_\ell\ (r_0)$	$md_\ell^2 E_{3d}$	$md_\ell^2\Gamma$
	39.7	171	42
	58.2	135	43
	100	139	17
$\Theta \approx 16^\circ$	$b_l \approx 0.26 d_\ell$	$b_s \approx 0.14 d_\ell$	$\Delta \approx 15^\circ$

Summary

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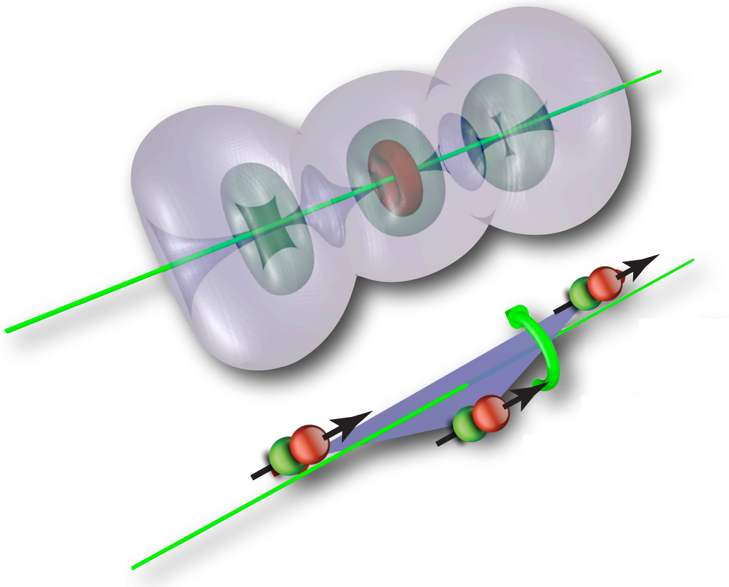

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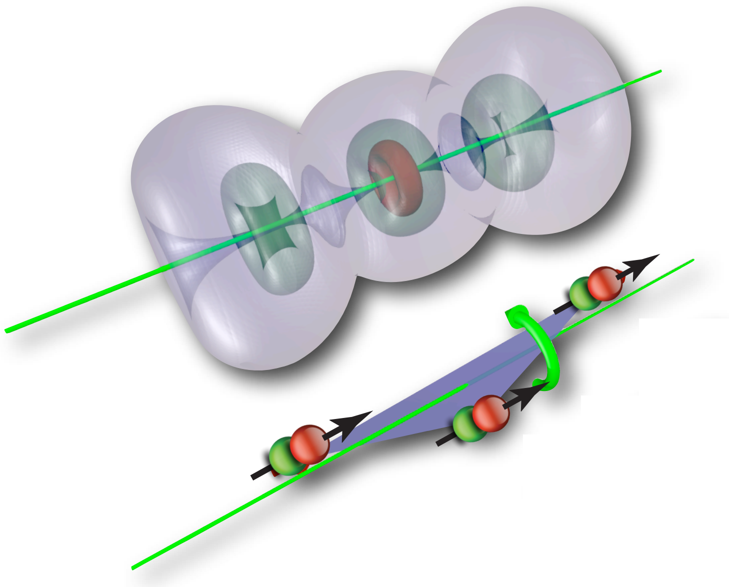

- Both the theoretical and experimental advances in ultracold quantum gases make these systems ideal candidates to explore universal few-body physics

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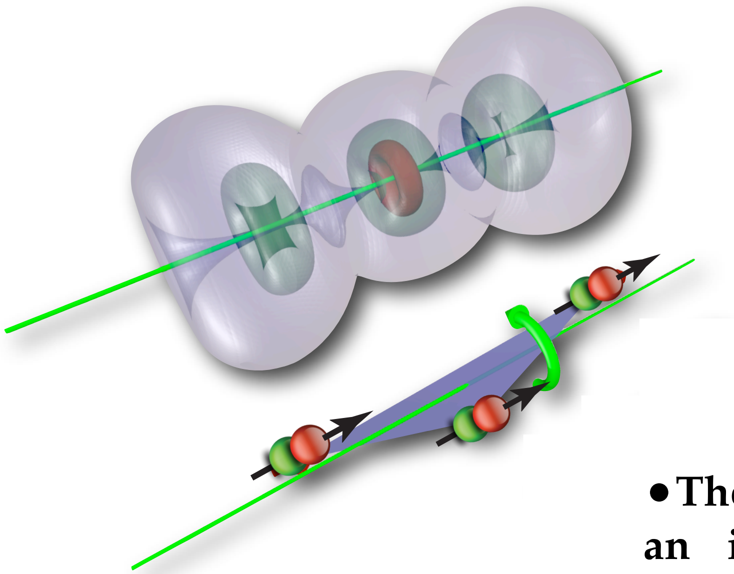

- Both the theoretical and experimental advances in ultracold quantum gases make these systems ideal candidates to explore universal few-body physics

- The persistence of the Efimov effect for dipolar systems represents an important landmark for the characterization of universal properties as well as the expected stability of ultracold dipolar gases.

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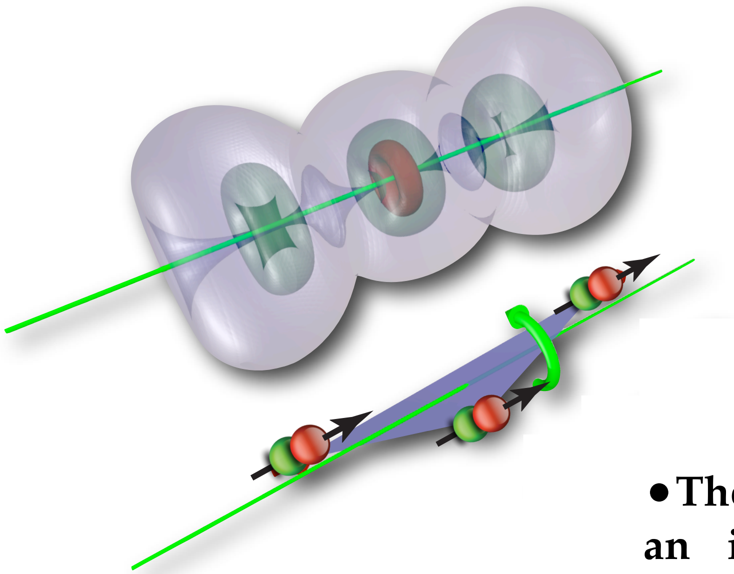

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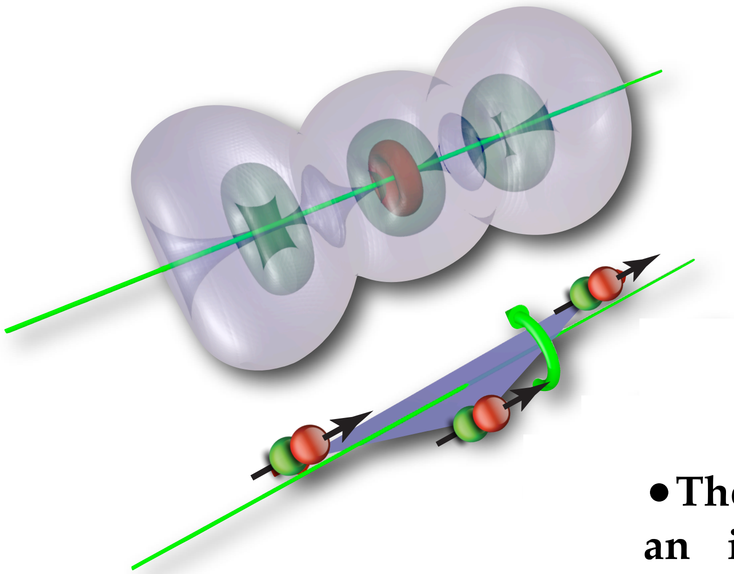

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• The effect of dipolar interaction might be responsible for the origin of a NEW class of universal few-body states

• Future experiments in ultracold dipolar gases are expected to offer a much better scenario to probe few-body universal states.