"Three-body Physics in Quenched Unitary Bose gases"

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John Bohn (JILA), Chris H. Greene (Purdue)

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A Few-body Perpective in Ultracold Quantum Gases

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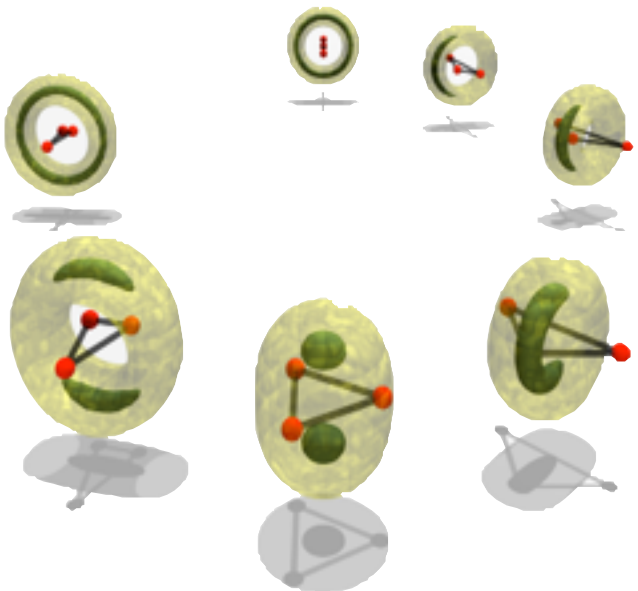
Universal Few-Body Physics

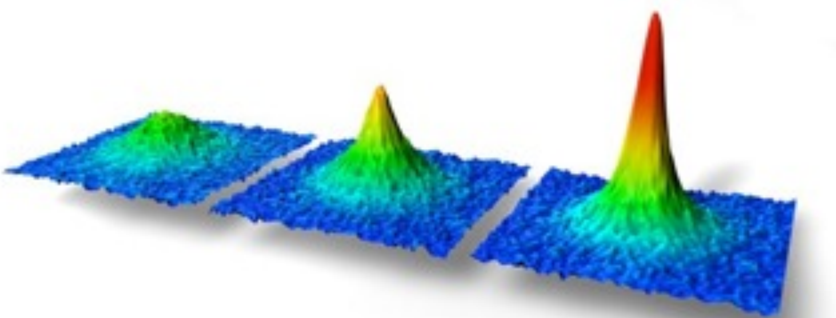


From the theoretical side:

- Signatures of Efimov Physics,
- Four- and More-bodies universal states,
- New families of universal states,
- Approaching a quantitative level (exps.)

Ultracold Quantum Gases

(<*pe*V)



From the experimental side:

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

A Few-body Perpective in Ultracold Quantum Gases

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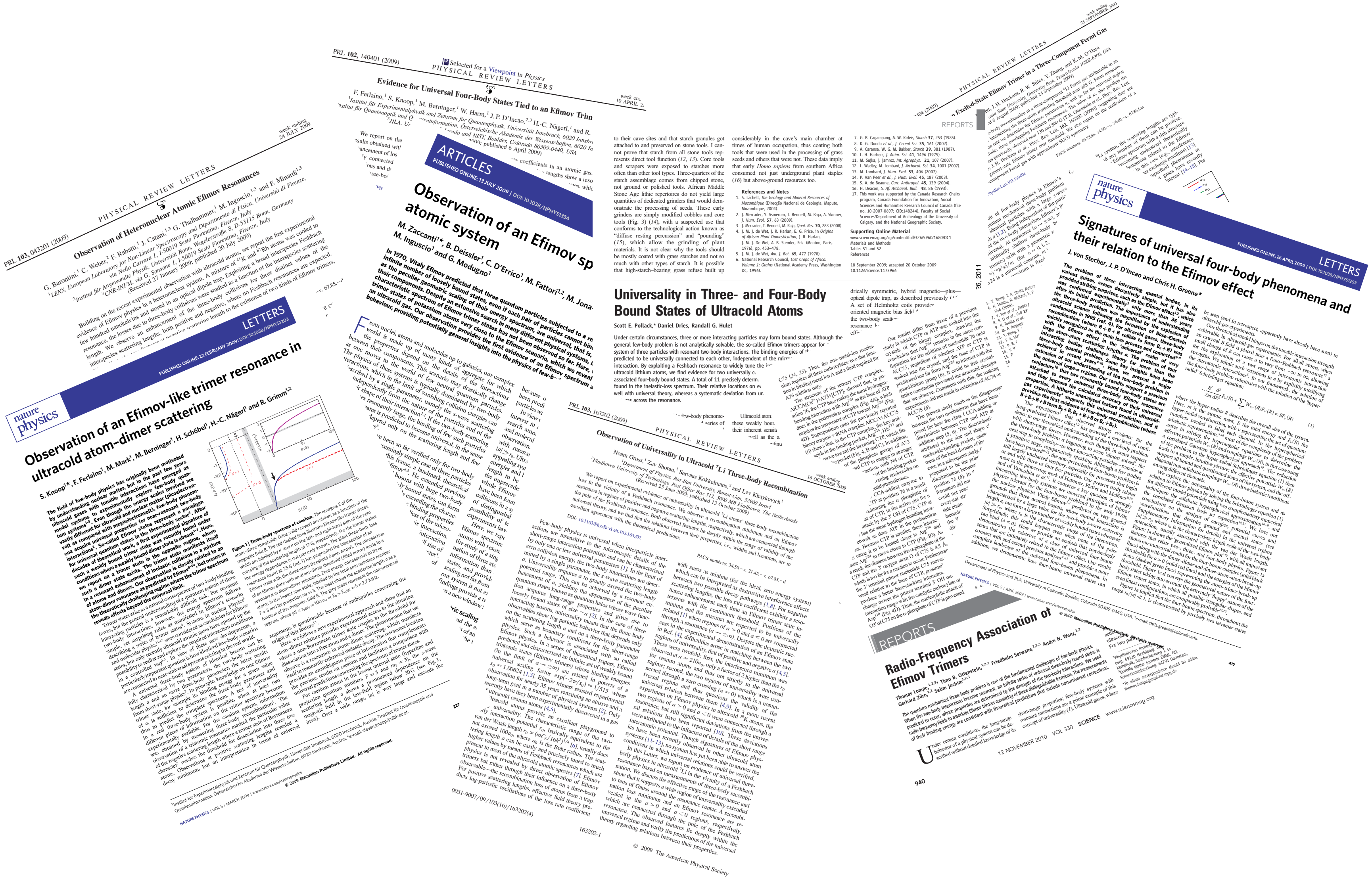
A new research venue ?



Toolkit for Exploring Few-body Physics ...

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For N particles ...

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

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

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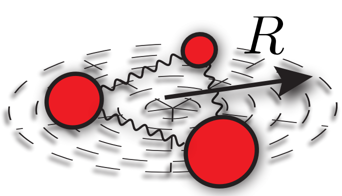
... the hyperspherical way !!!

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



hyperradius R : overall size (collective motion)

$R \rightarrow [0, \infty]$

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

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

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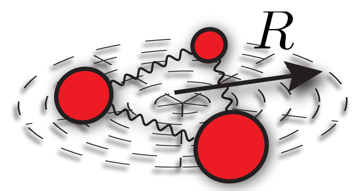

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(**Democratic hyperangles:**
Smith-Whitten, Johnson, Kuppermann, Aquilanti)

- ☑ Fragmentation thresholds
- ☑ Symmetrization is simpler

Toolkit for Exploring Few-body Physics ...

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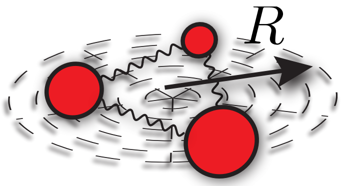

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Adiabatic representation:

$$\Psi(R;\Omega) = \sum_{\nu} F_\nu(R)\Phi_\nu(R;\Omega)$$

$$\left[\frac{\Lambda(\Omega)}{2\mu R^2} + V(R,\Omega)\right]\Phi_\nu(R;\Omega) = U_\nu(R)\Phi_\nu(R;\Omega)$$

(effective potential)

Toolkit for Exploring Few-body Physics ...

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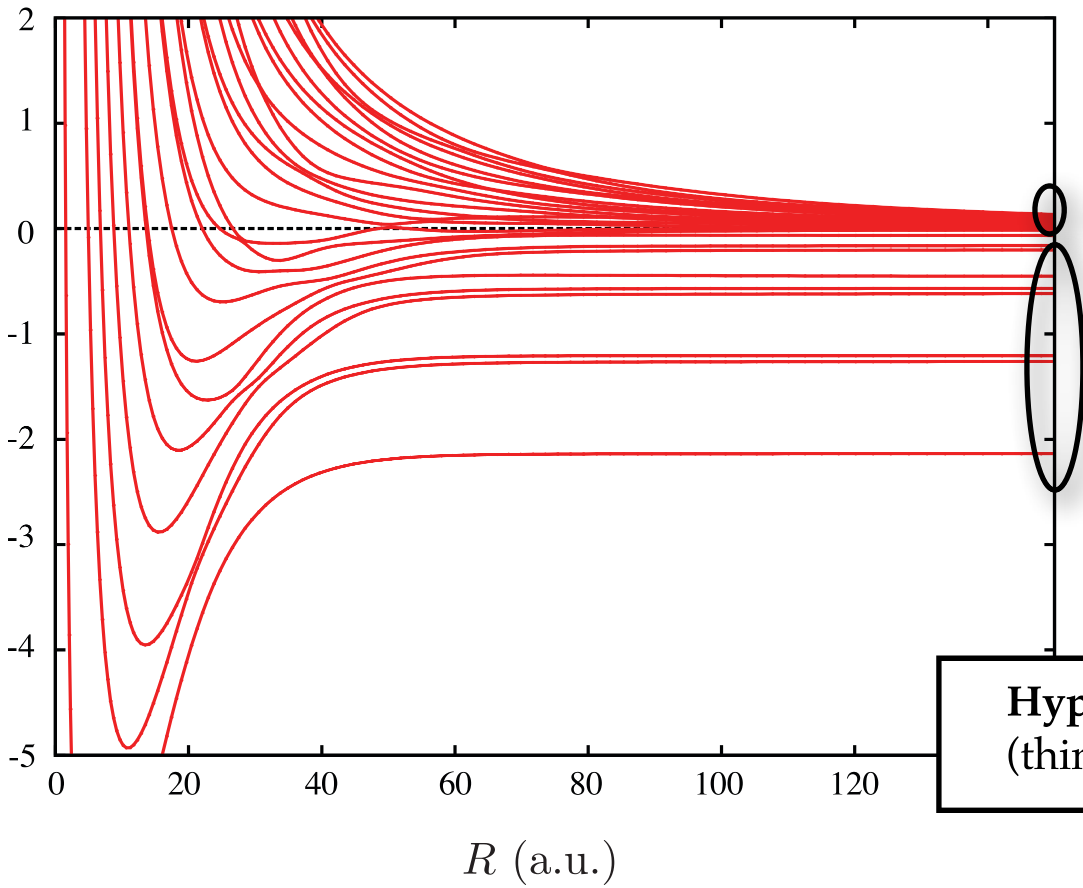
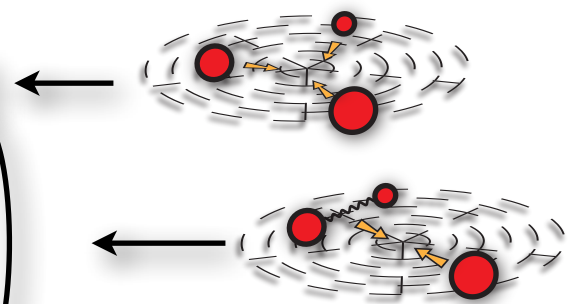


(three-body continuum)



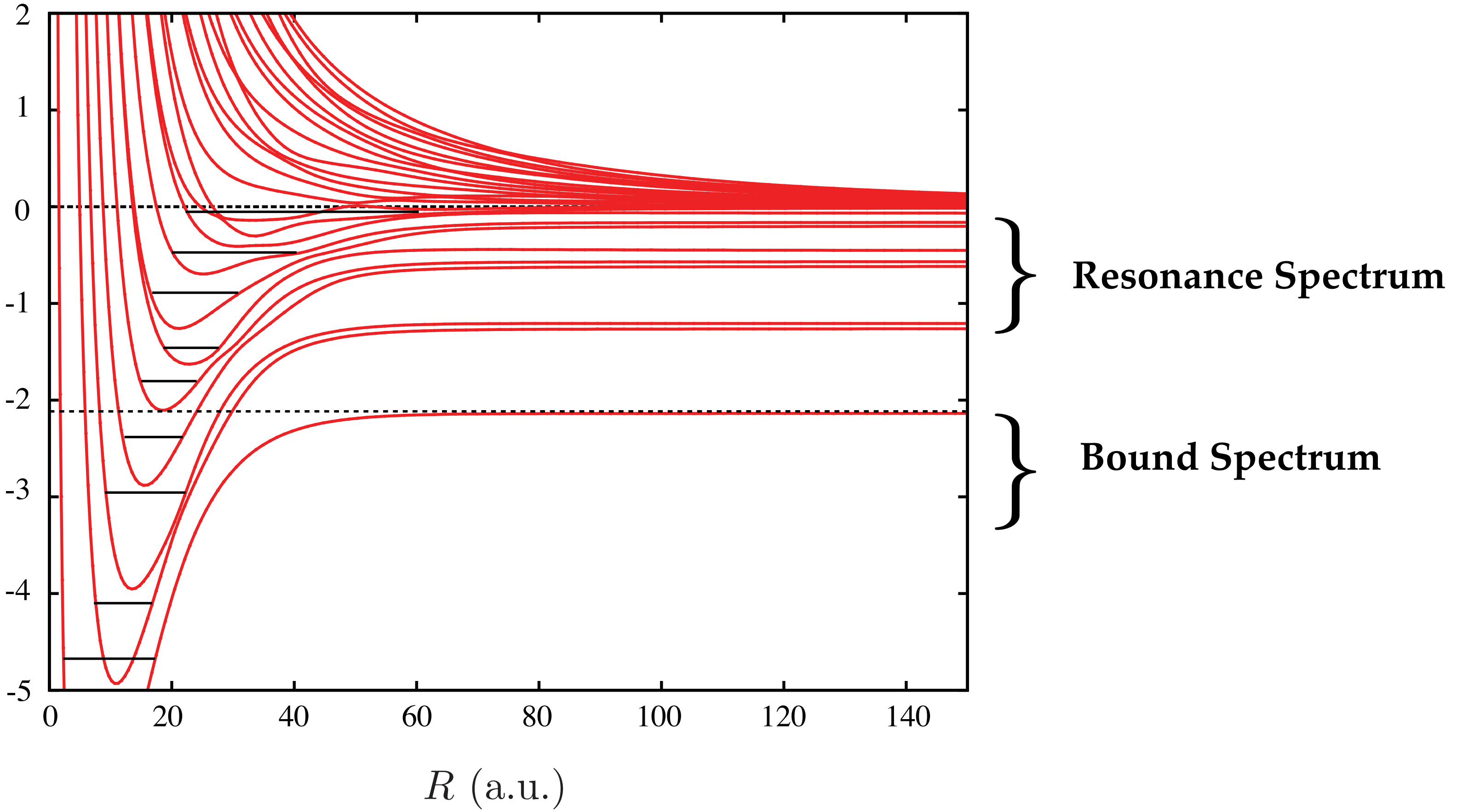
(bound channels)

Hyperspherical Potentials
(think Born-Oppenheimer)

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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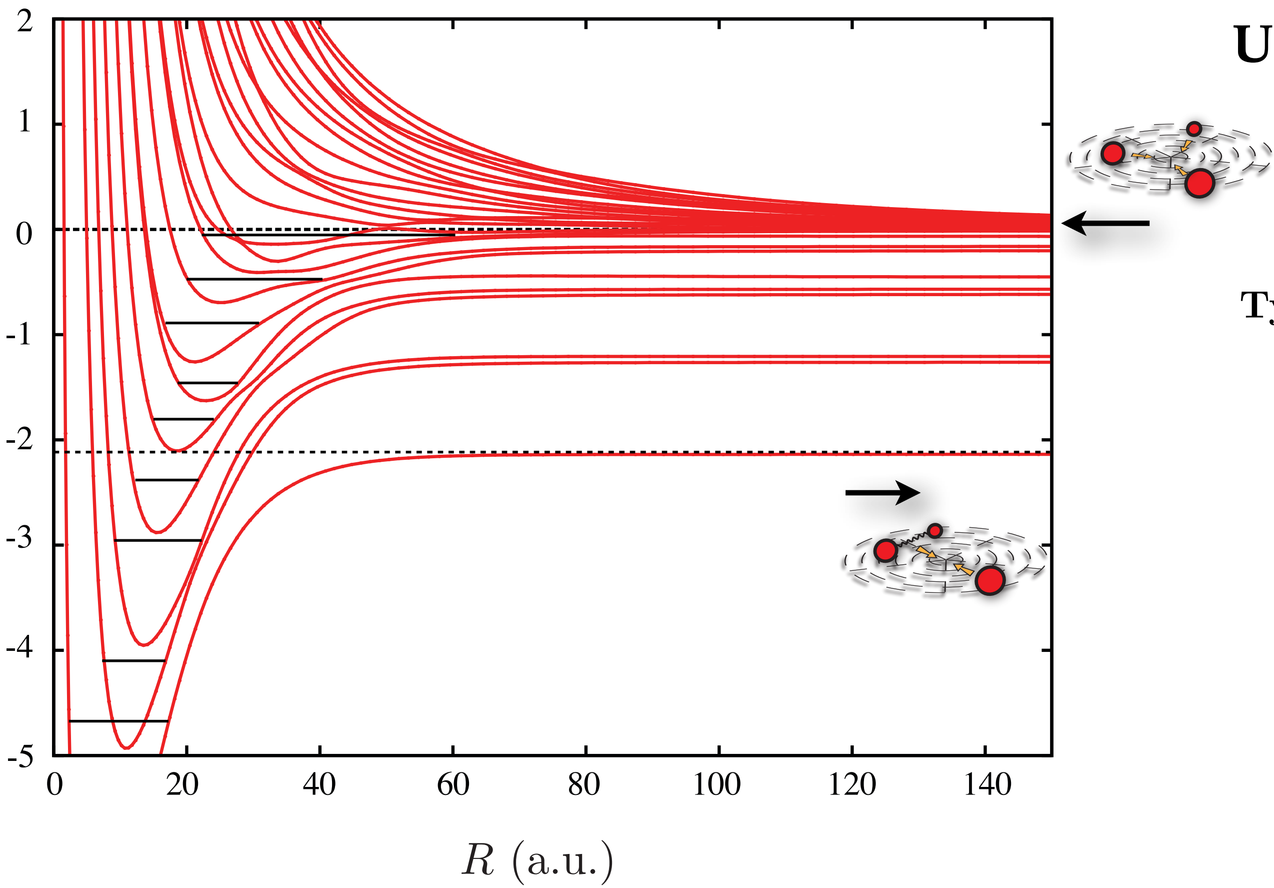

Ultracold Few-body Collisions

$W_{\nu\nu'}(R)$: 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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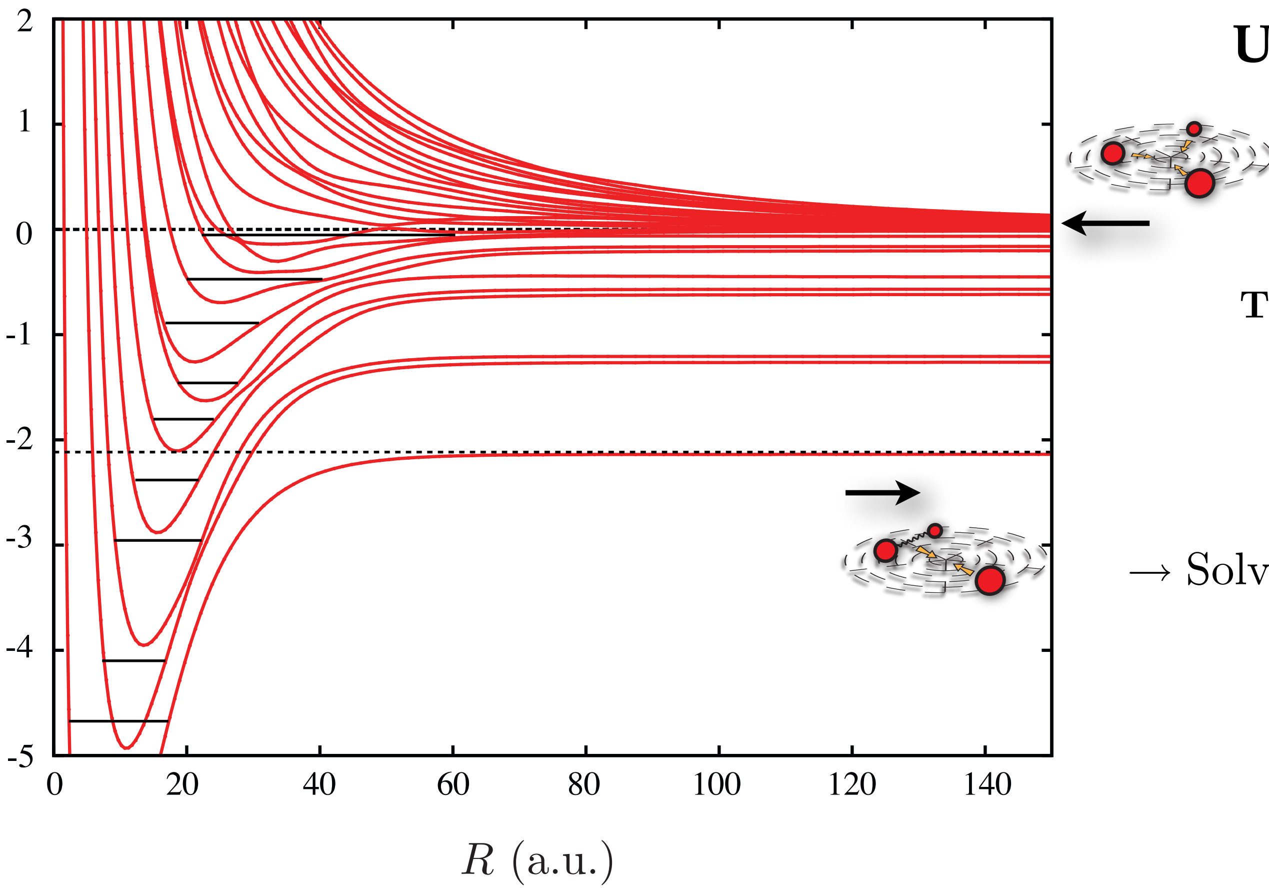

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$\rightarrow$ Solve Schrödinger equation for $R \approx 10^6 a_0$
(0.05mm!!!)

Unitary Quantum gases

$(n|a|^3 \gg 1)$

Unitary Quantum Gases ($n|a|^3 \gg 1$)

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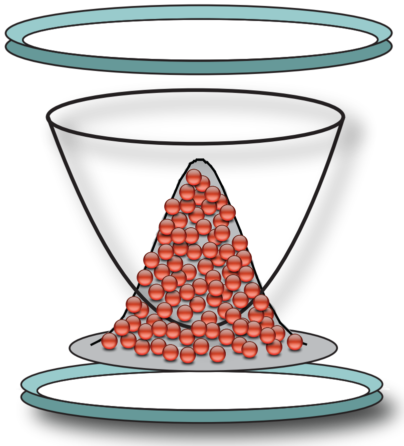
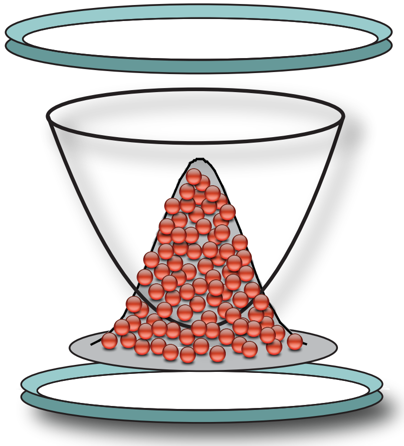
Unitary Bose Gases (fundamental interest)



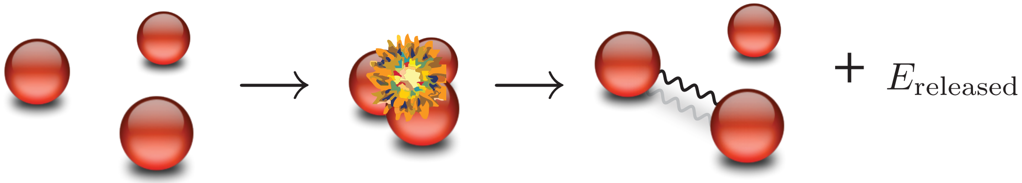
Unitary Fermi Gases: BEC-BCS crossover, Superfluidity …
(Duke, Innsbruck, JILA, MIT, Rice, …)

Stable and Universal state !!!
[see Giorgini, Pitaevskii & Stringari, RMP (2008)]

Unitary Bose Gases (fundamental interest)



Three-Body Losses: (three-body recombination)

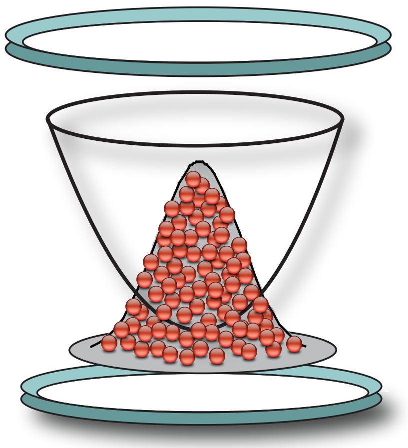


Fermions: $L_3 \propto T a^6$ (0 for $T \to 0$)

Bosons: $L_3 \propto a^4$ (**const.** for $T \to 0$)

Unitary Quantum Gases (n|a|^3>>1)

Unitary Bose Gases (fundamental interest)



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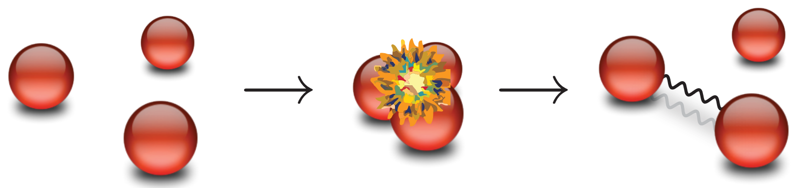

$+ \; E_{\text{released}}$

Fermions: $L_3 \propto T a^6$ (0 for $T \to 0$) $\quad \dfrac{\tau_{\text{loss}}}{\tau_{\text{mb}}} \gg 1$

Bosons: $L_3 \propto a^4$ (**const.** for $T \to 0$) $\quad \dfrac{\tau_{\text{loss}}}{\tau_{\text{mb}}} \ll 1$

[τ_{mb}: timescale for many-body physics]

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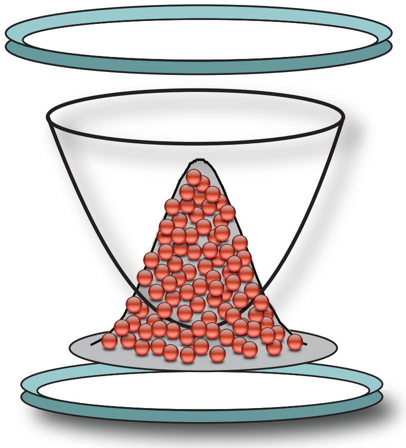

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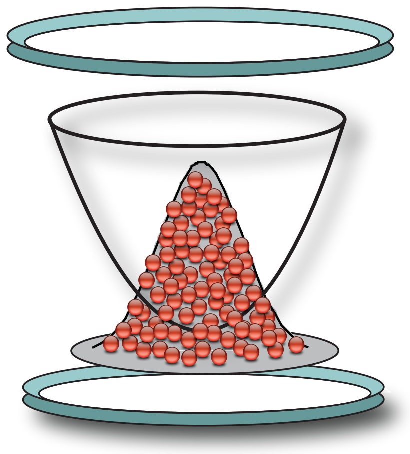

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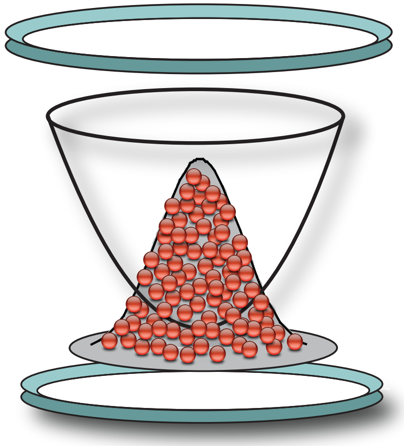
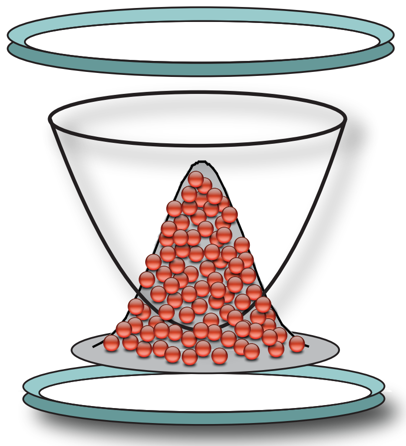


Efimov Physics (~1970, nuclear physics)

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

- ☑ **Repulsive Interactions** (Fermions): Long lifetimes
- ☑ **Attractive interactions** (Bosons)**:** infinite number of weakly bound three-body states (**Efimov effect**)

Unitary Bose Gases (fundamental interest)



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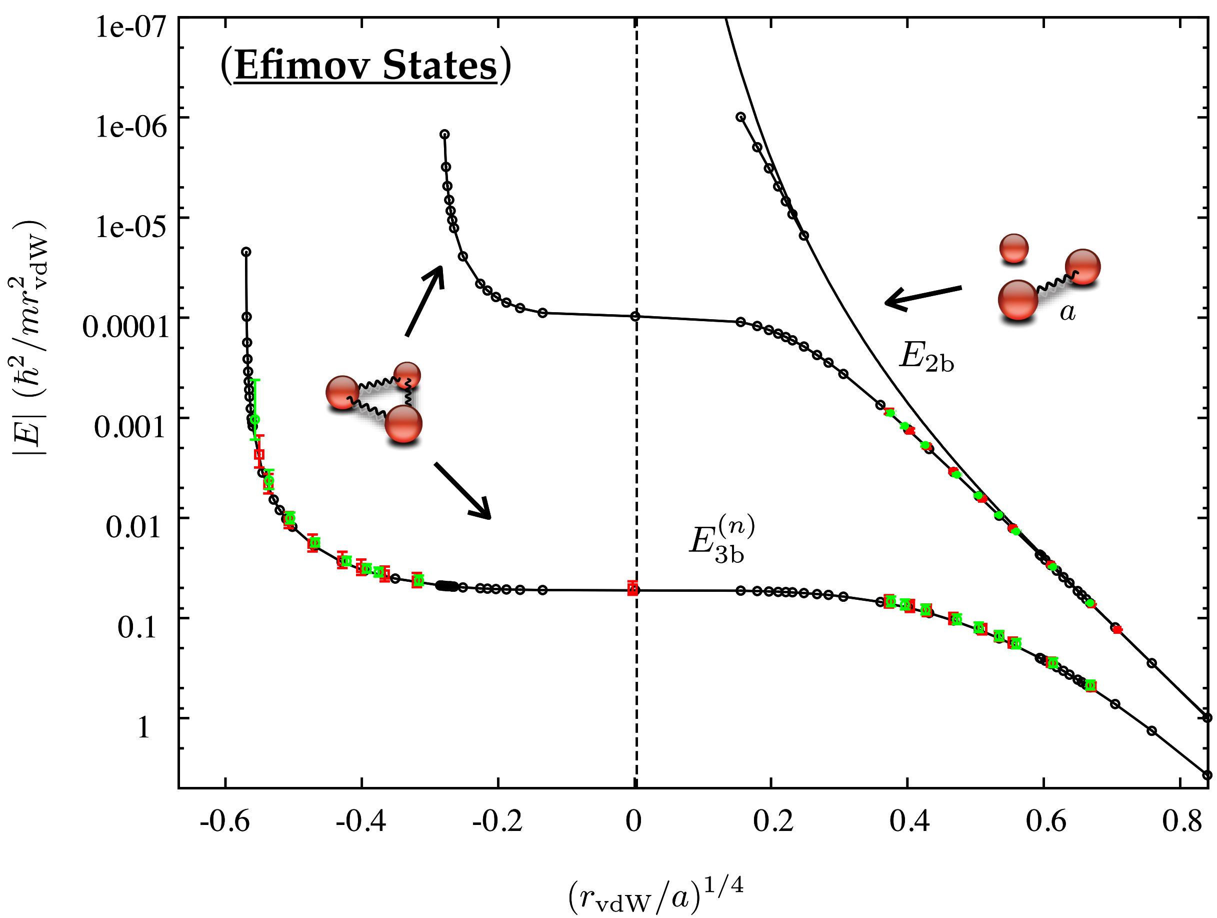

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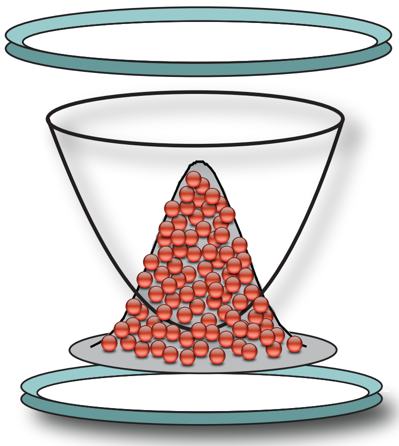

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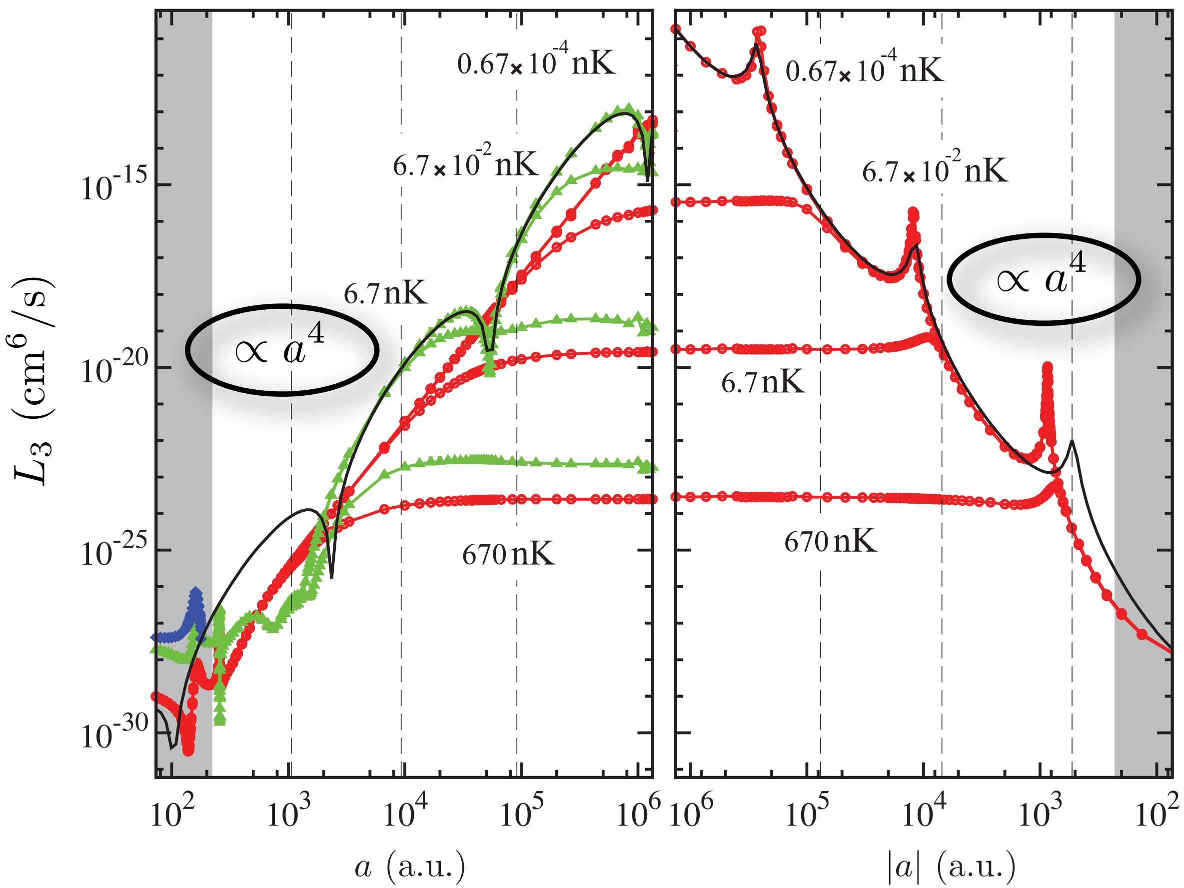

Unitary Quantum Gases (n|a|^3>>1)

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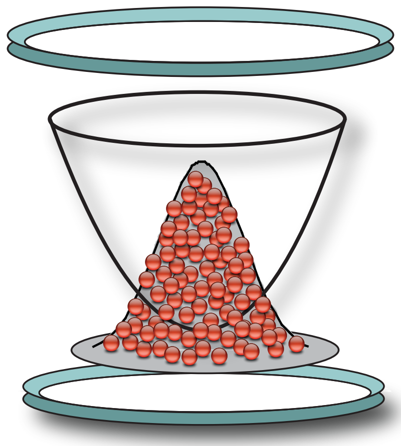
Unitary Bose Gases (fundamental interest)



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

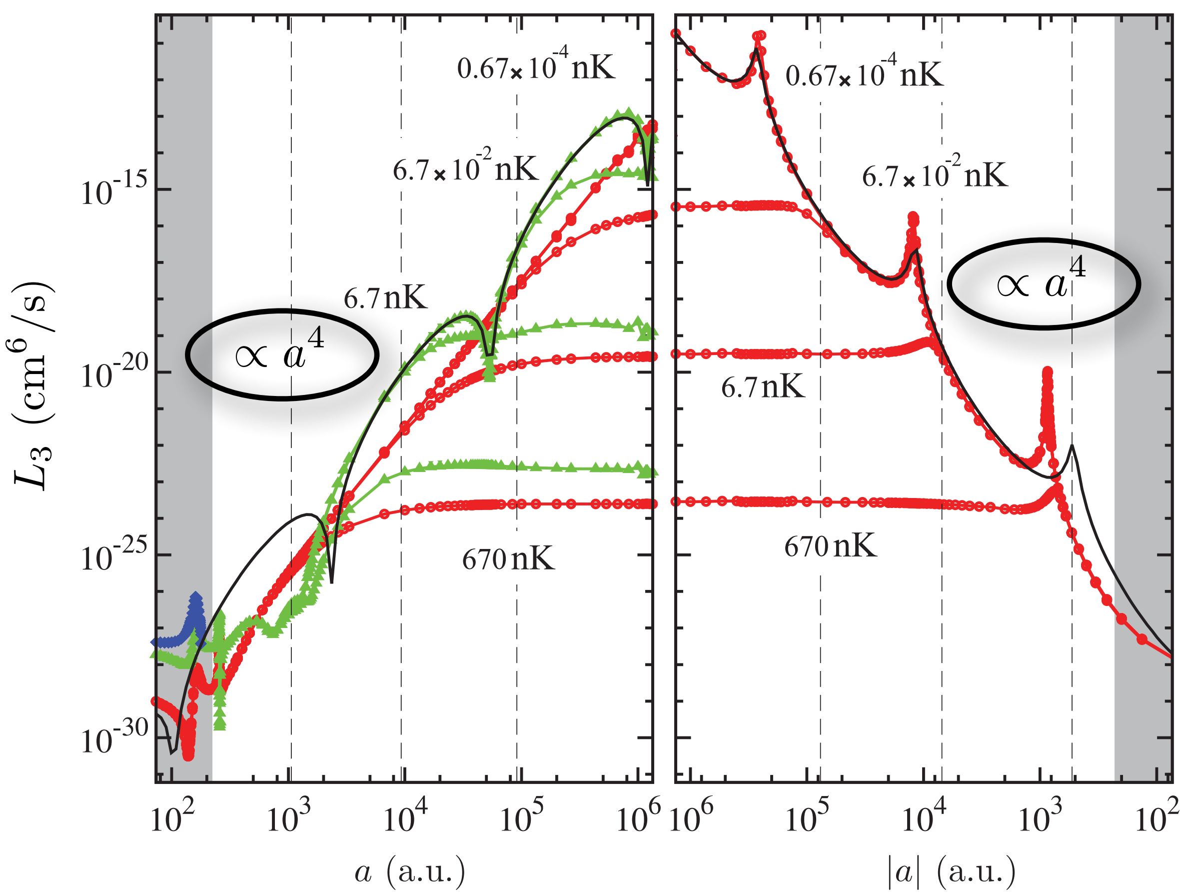
... at finite temperatures $(k|a| \gg 1)$

$$L_3 = \frac{36\sqrt{3}\pi^2}{m^3}\frac{(1-e^{-4\eta})}{(k_B T)^2}\hbar^5$$

η : 3-body inelasticity parameter

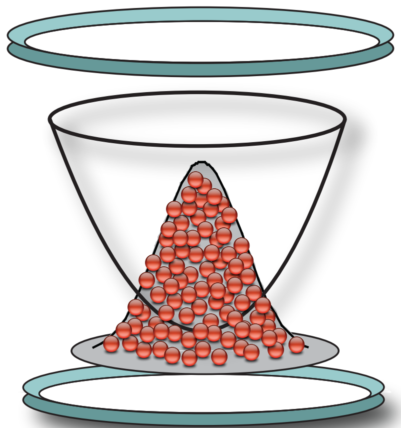
[See Rem et. all, PRL (2013), D'Incao& Esry, PRL (2004)]

D'Incao, Greene & Esry, JPB (2009)



Unitary Quantum Gases (n|a|^3>>1)

Unitary Bose Gases (fundamental interest)



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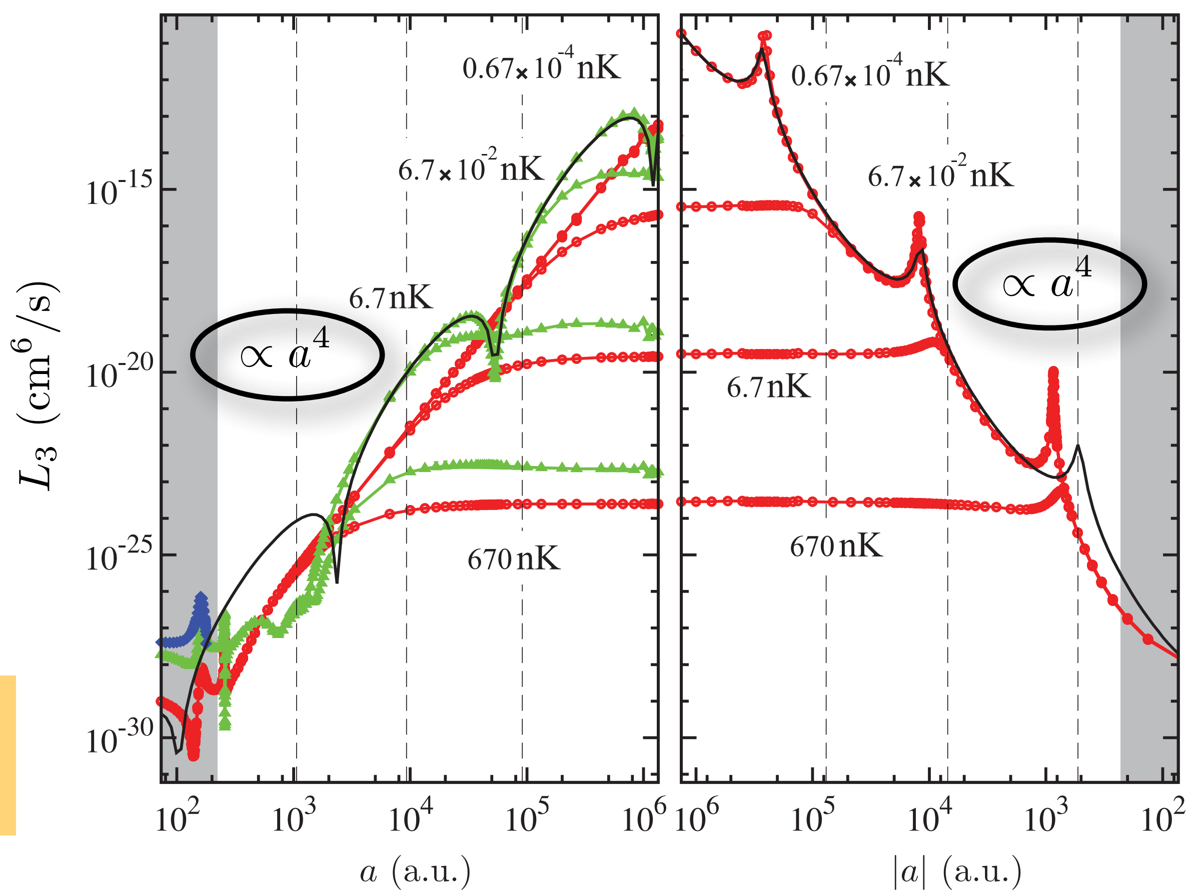

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η : 3-body inelasticity parameter

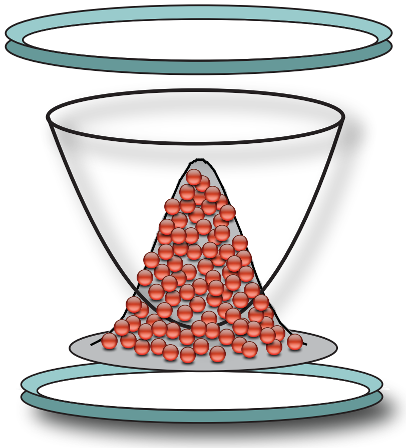
(for ^{85}Rb : $\eta \approx 0.06$)

$L_3 \approx 3 \times 10^{-20}\mathrm{cm}^6/\mathrm{s}$

$\tau = 1/n_{pk}^2 L_3 \approx$ 0.4μs !!

Unitary Quantum Gases (n|a|^3>>1)

Unitary Bose Gases (fundamental interest)



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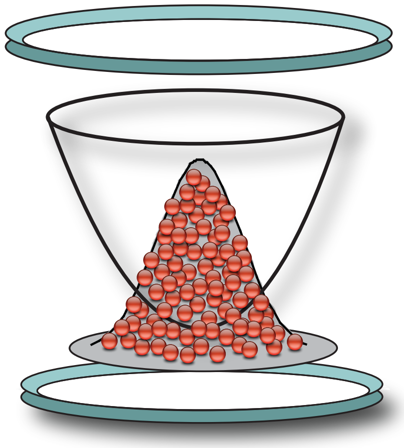

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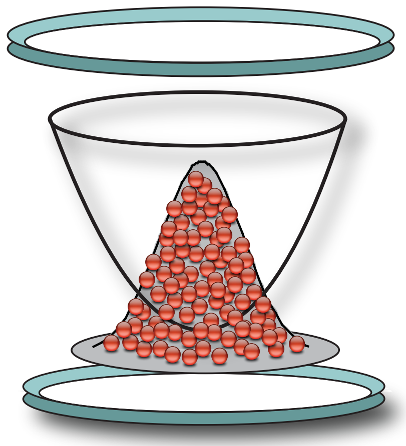

Experimental Scenario

Lifetime of the Bose Gas with Resonant Interactions (7Li)
Rem, Grier, Ferrier-Barbut, Eismann, Langen, Navon, Khaykovich, Werner, Petrov, Chevy, and Salomon
Phys. Rev. Lett. **110**, 163202 (2013)

Stability of a Unitary Bose Gas (39K)
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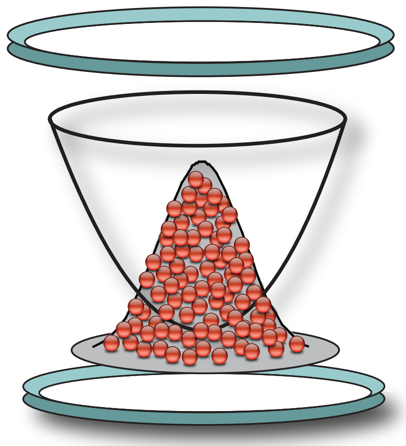

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$\ldots$ but still $n|a|^3 < 1$

Unitary Quantum Gases (n|a|^3>>1)

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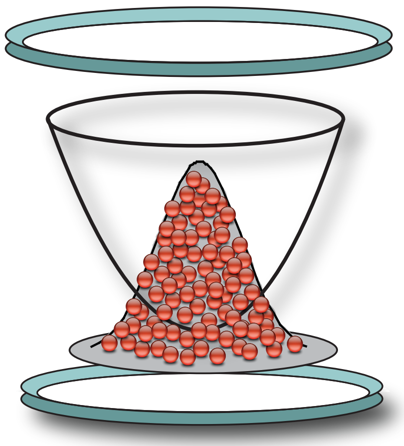
Unitary Bose Gases (fundamental interest)



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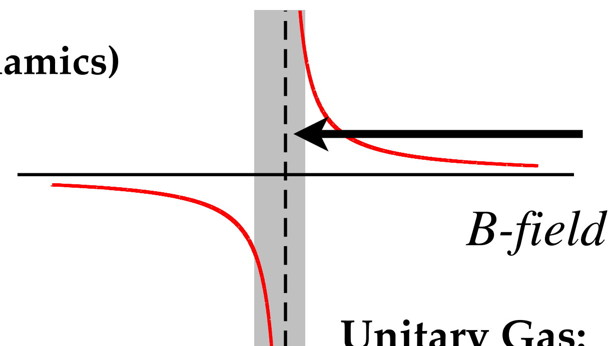
Univesal dynamics of a degenerate unitary Bose gas (85Rb)
Makotyn, Klauss, Goldberger, Cornell, and Jin
Nature Phys. **10**, 116 (2014)

(Quench Dynamics)



BEC: $n|a|^3 \ll 1$
(weak interactions)

Unitary Gas: $n|a|^3 \gg 1$
(strong interactions)

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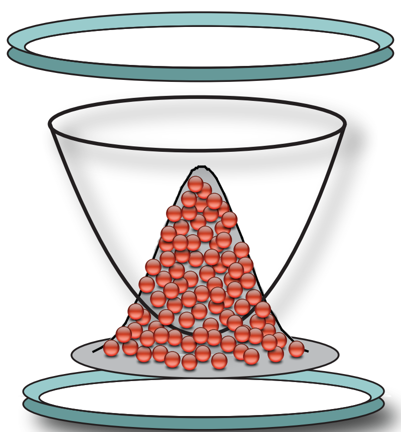
Unitary Bose Gases (fundamental interest)



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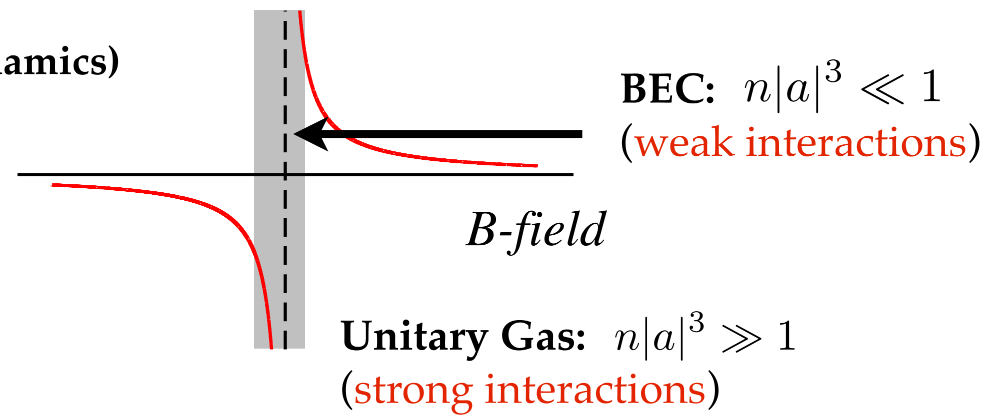
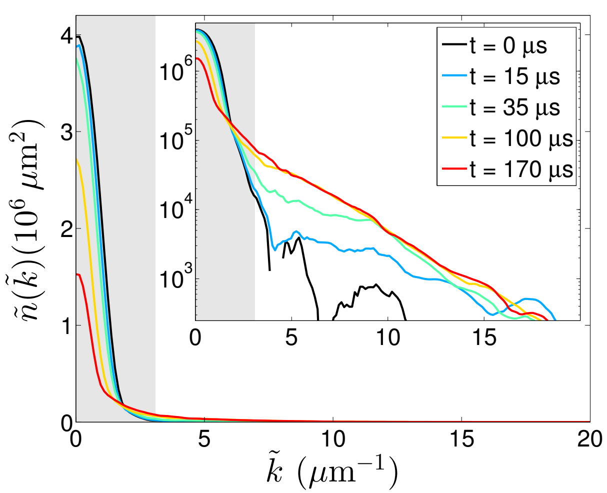
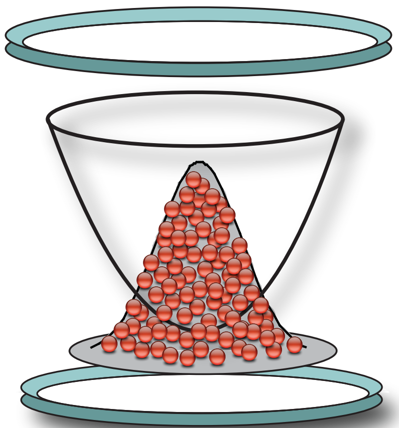




Found:

- **Non-equilibrium dynamics**
- metastable Bose gas (strongly interacting Bose liquid)
- dynamics at unitary (Tan's contact interaction)
- open new ways to explore unitary regime

Unitary Bose Gases (fundamental interest)



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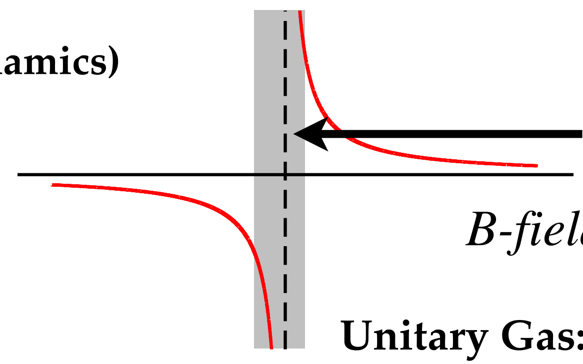

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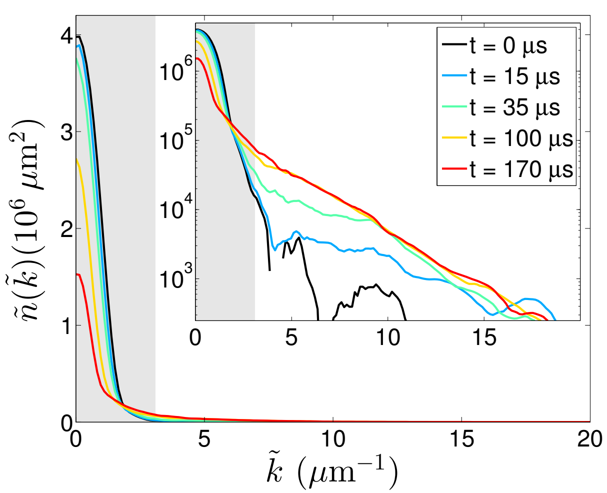

Key ingredient: **lifetimes ~0.6ms!!!**

$$\frac{\tau_{\text{loss}}}{\tau_{\text{mb}}} \gg 1 \longrightarrow$$ **What !?**

Unitary Quantum Gases (n|a|^3>>1)

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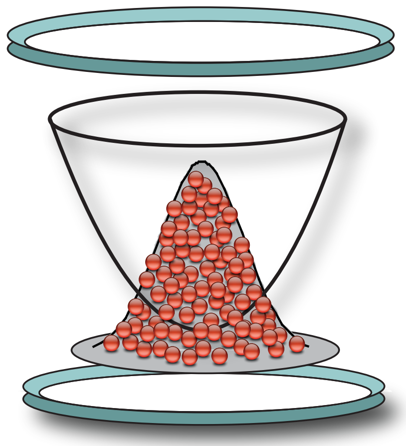
Unitary Bose Gases (fundamental interest)



Theoretical Scenario

Quench dynamics of a strongly interacting resonant Bose gas
Yin, Radzihovsky, PRA **88**, 063611 (2013)

Quenching to unitarity: Quantum dynamics in a 3D Bose gas
Sykes, Corson, D'Incao, Koller, Greene, Rey, Hazzard, Bohn, PRA **89**, 021601 (2014)

Two-body and three-body Contacts for identical bosons near unitarity
Smith, Braaten, Kang, Platter, PRL **112**, 110402 (2014)

Nonequilibrium states of a quenched Bose Gas
Ben, Ling, arXiv:1401.2390 (2014)

Momentum distribution of a dilute unitary Bose gas with three-body losses
Laurent, Leyronas, Chevy, arXiv:1312.0079 (2013)

Equilibrating dynamics in quenched Bose gases: characterizing multiple time regimes
Racon, Levin, arXiv:1403.0141 (2014)

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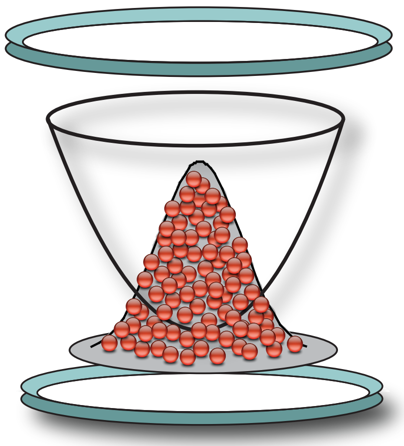

Theoretical Scenario

Quench dynamics of a strongly interacting resonant Bose gas
Yin, Radzihovsky, PRA **88**, 063611 (2013)

Quenching to unitarity: Quantum dynamics in a 3D Bose gas
Sykes, Corson, D'Incao, Koller, Greene, Rey, Hazzard, Bohn, PRA **89**, 021601 (2014)

Two-body and three-body Contacts for identical bosons near unitarity
Smith, Braaten, Kang, Platter, PRL **112**, 110402 (2014)

Nonequilibrium states of a quenched Bose Gas
Ben, Ling, arXiv:1401.2390 (2014)

Momentum distribution of a dilute unitary Bose gas with three-body losses
Laurent, Leyronas, Chevy, arXiv:1312.0079 (2013)

Equilibrating dynamics in quenched Bose gases: characterizing multiple time regimes
Racon, Levin, arXiv:1403.0141 (2014)

Unitary Quantum Gases (n|a|^3>>1)

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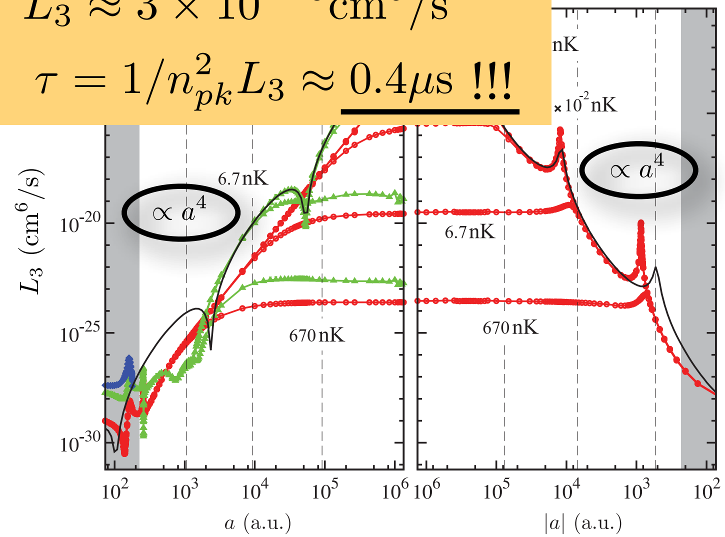
NIST
University of Colorado

$(\text{for } {}^{85}\text{Rb} : \eta \approx 0.06)$

$L_3 \approx 3 \times 10^{-20} \text{cm}^6/\text{s}$

$\tau = 1/n_{pk}^2 L_3 \approx \underline{0.4\mu\text{s}\ !!!}$



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Losses for a unitary *gas*: $(n|a|^3 \gg 1)$

$$k_B T \rightarrow \quad E_F = \frac{(6\pi^2 n)^{2/3}}{2m}\hbar^2 \qquad \text{and} \qquad \langle L_3 \rangle = \frac{\int L_3 n^3 d^3 r}{\int n^3 d^3 r}$$

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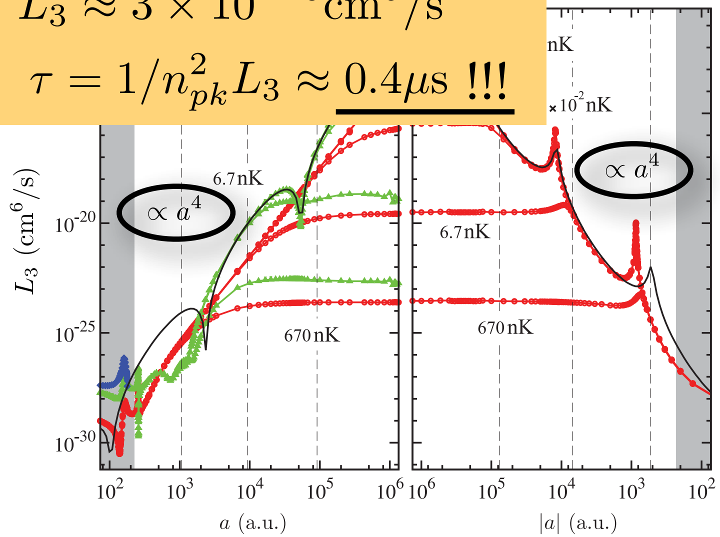

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$$L_3 = \frac{36\sqrt{3}\pi^2}{m^3}\frac{(1-e^{-4\eta})}{(k_B T)^2}\hbar^5 \longrightarrow \boxed{\langle L_3 \rangle = \frac{21 \times 45}{8 \times 2^{1/3}} \frac{\Gamma(\frac{8}{3})}{\Gamma(\frac{25}{6})} \left(\frac{3}{\pi}\right)^{1/6} \frac{(1-e^{-4\eta})}{n_{pk}^{4/3}} \frac{\hbar}{m}}$$

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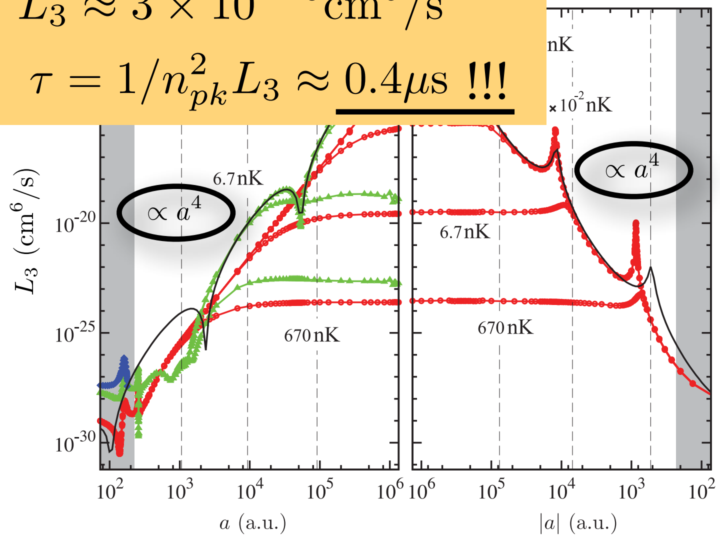

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$$\langle L_3 \rangle \approx 1.4 \times 10^{-22}\mathrm{cm}^6/\mathrm{s}$$

$$\langle \tau \rangle \approx \underline{0.20\mathrm{ms}\ !!!} \quad (\text{as opposed to } 0.4\mu\mathrm{s})$$

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JILA NIST University of Colorado

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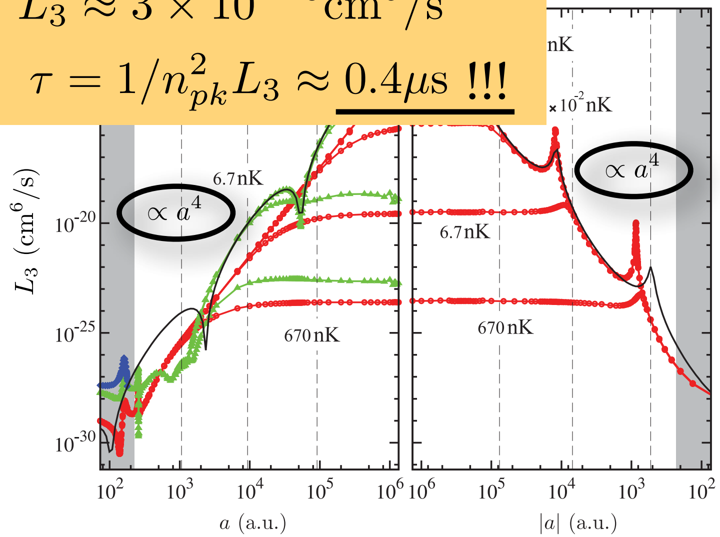

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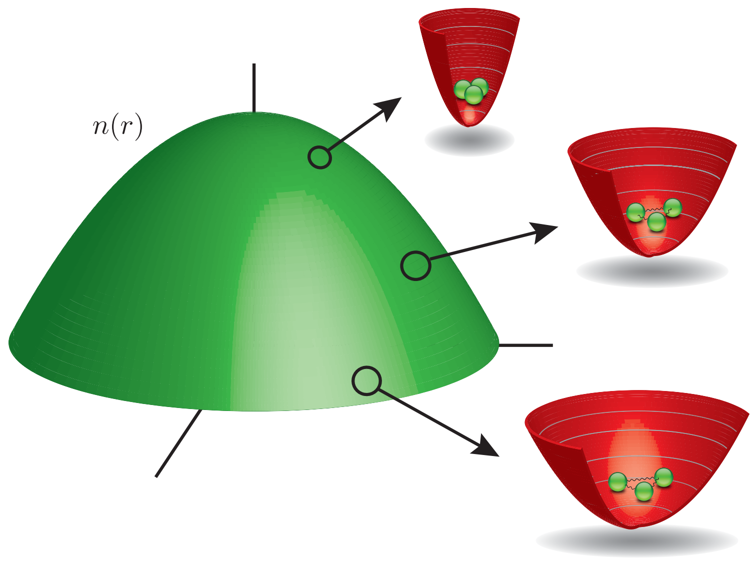
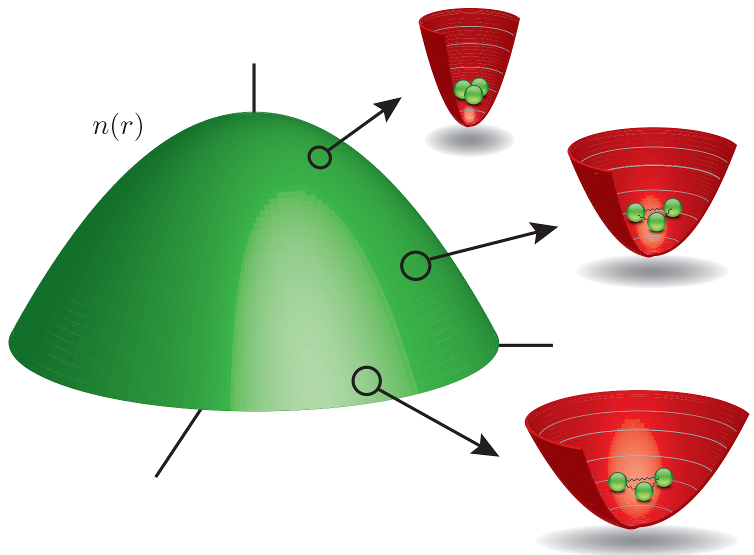
Local properties are important !
Scattering for $n|a|^3 \gg 1$?
What about Efimov states ?

Local model for three-body losses in an unitary Bose gas



Local model for three-body losses in an unitary Bose gas

NIST
University of Colorado



Solve the three-body problem (hyperspherical) in a harmonic trap whose frequency is determined by the "local" density:

$$n = \frac{9\ \sqrt{\pi/2}}{128\ a_{\mathrm{ho}}^3} \longrightarrow \quad \hbar\omega_{\mathrm{ho}} = \hbar^2 \frac{16(2/\pi)^{1/3}}{3^{2/3} m} n^{2/3}$$

Borca, Blume & Greene, NJP (2003)
Goral, Kohler, Gardiner, Tiesinga & Julienne, JPB (2004)

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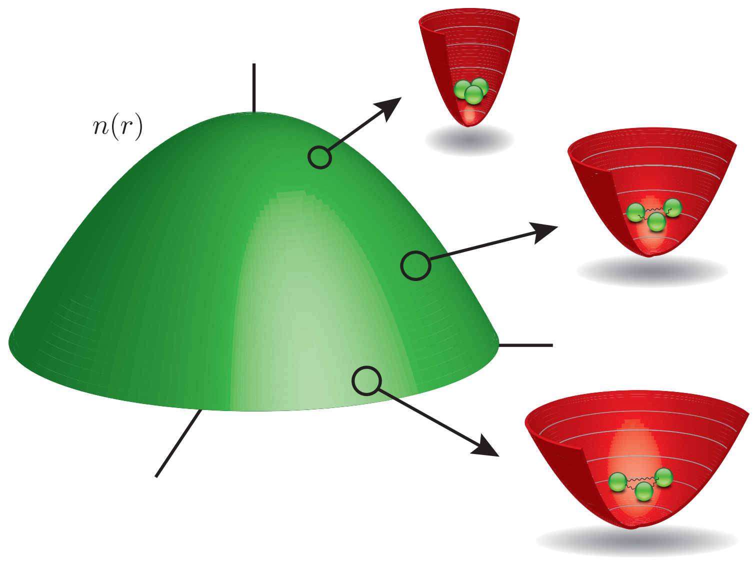

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$$(E_\beta = E_\beta^0 - i\Gamma_\beta/2)$$

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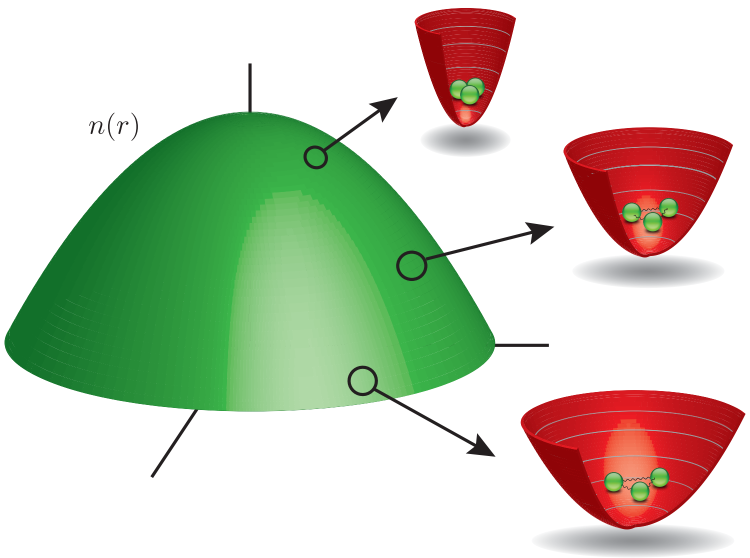

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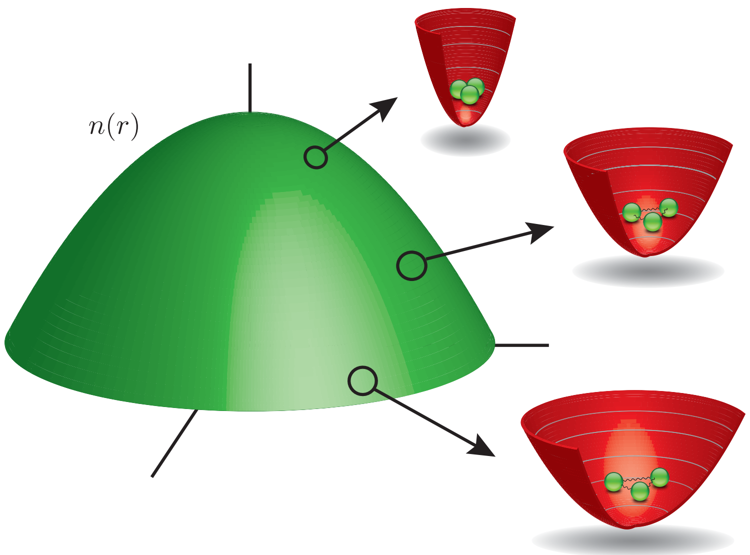
c_β^2 : Population

$\tau_\beta = \hbar/\Gamma_\beta$: Lifetime

Local model for three-body losses in an unitary Bose gas



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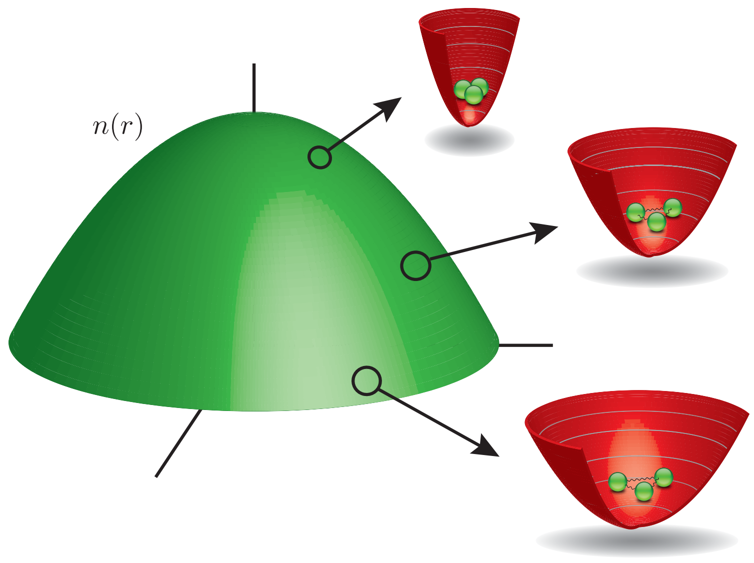
$\langle L_3^* \rangle \approx 2.6 \times 10^{-23} \mathrm{cm}^6/\mathrm{s}$

$\langle \tau^* \rangle \approx$ 1.1ms !!!

Local model for three-body losses in an unitary Bose gas



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Separation of timescales (universal relation)

$$\frac{\tau_{\rm loss}}{\tau_C} \approx \frac{1.89}{\eta}$$

^{85}Rb ($\eta \approx 0.06$): 31.5
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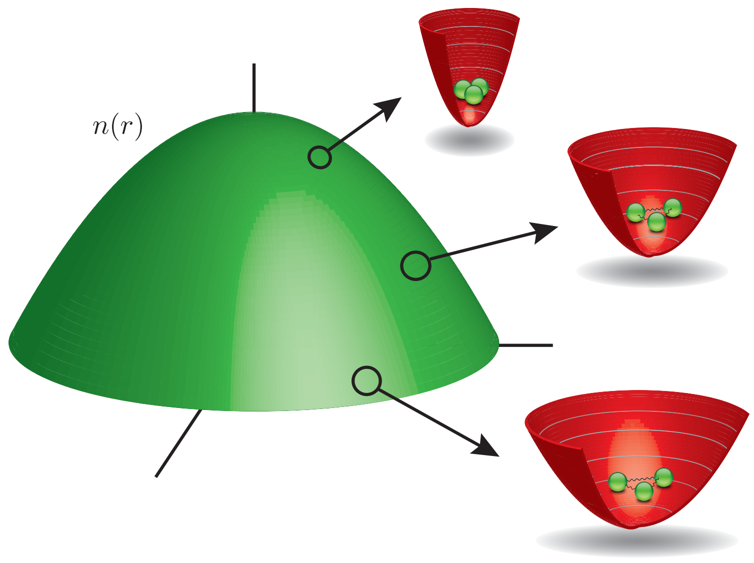

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Three-body inelasticity parameter !!!

Efimov states in Unitary Bose gases !?

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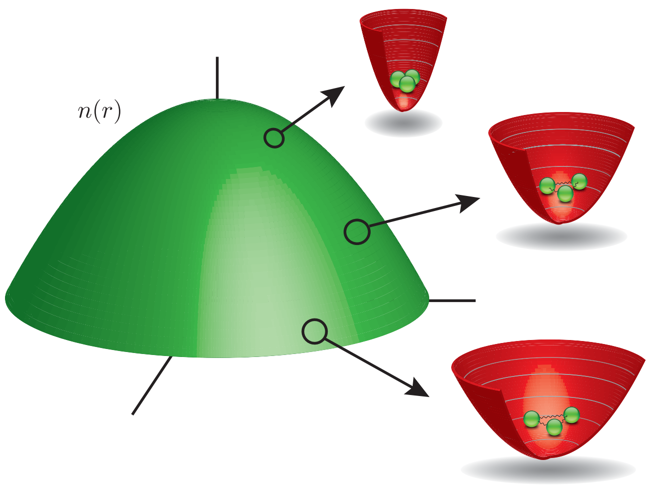

Efimov states and dynamics in ultracold unitary Bose gases
J. P. D'Incao and J. L. Bohn (in preparation)

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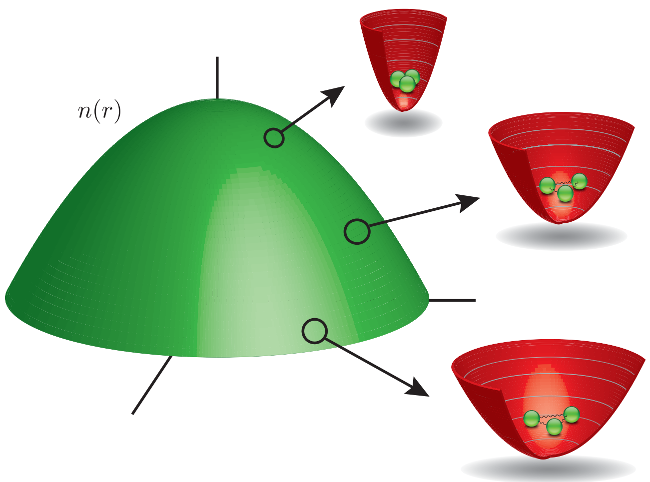

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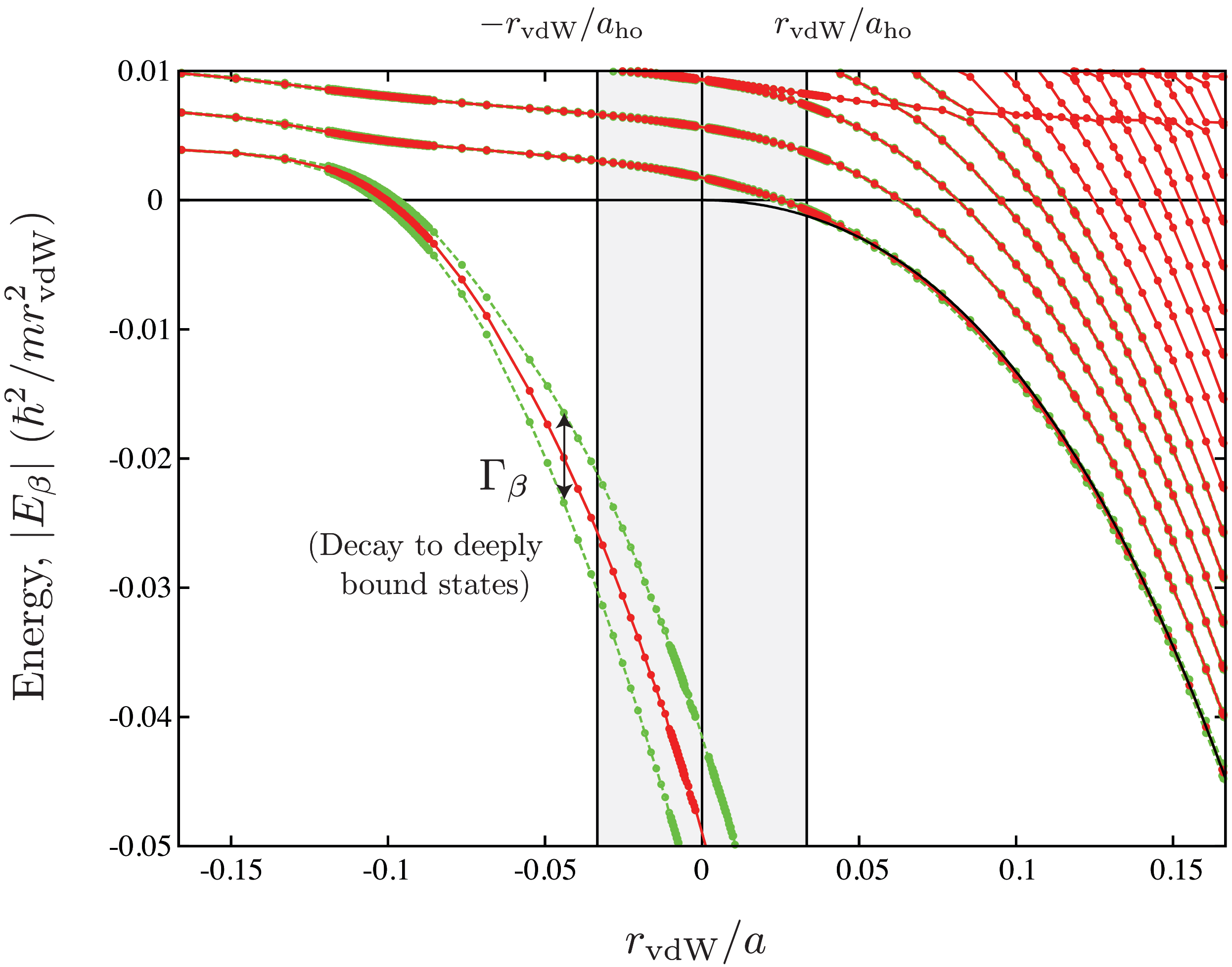
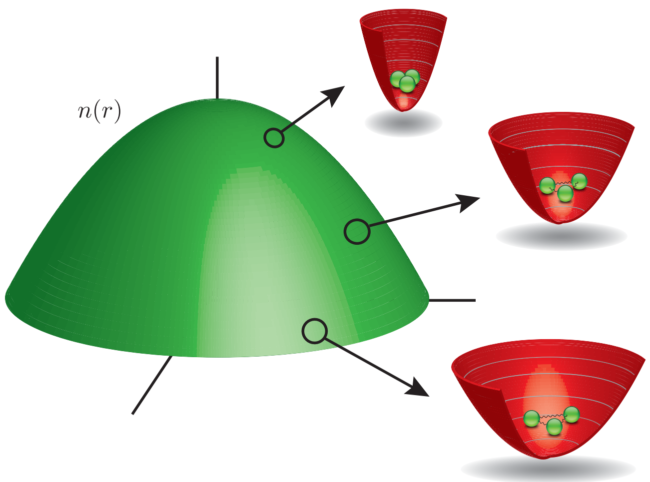


Local model for three-body losses in an unitary Bose gas



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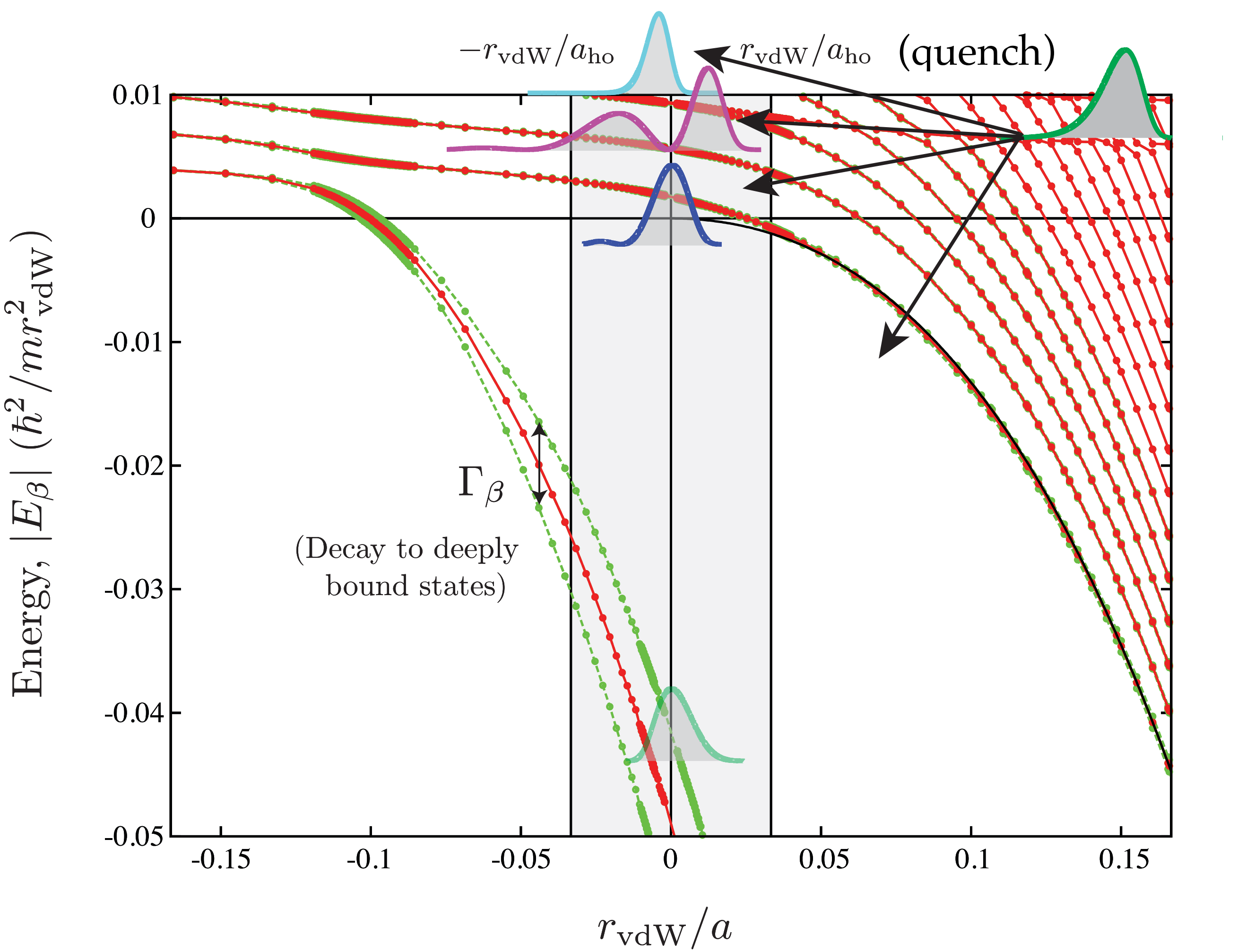

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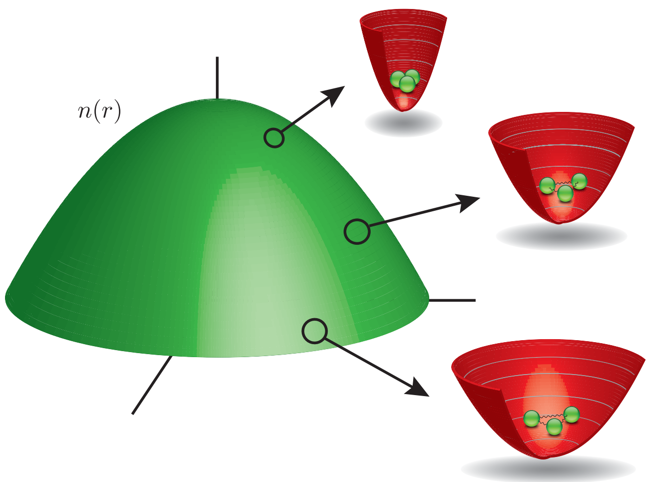

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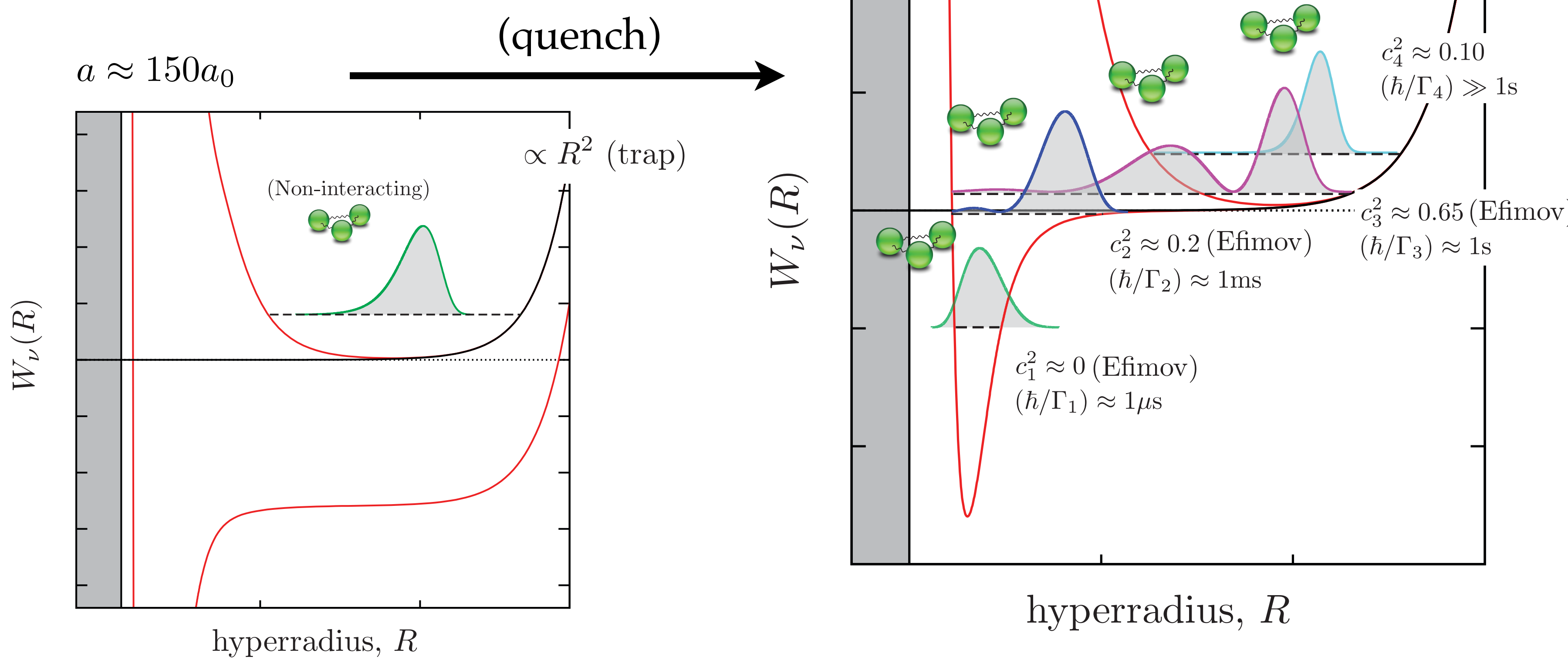
(In the hyperspherical picture)



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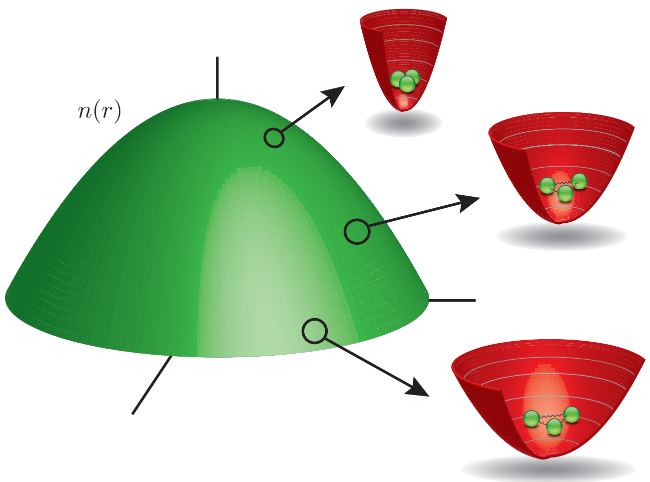

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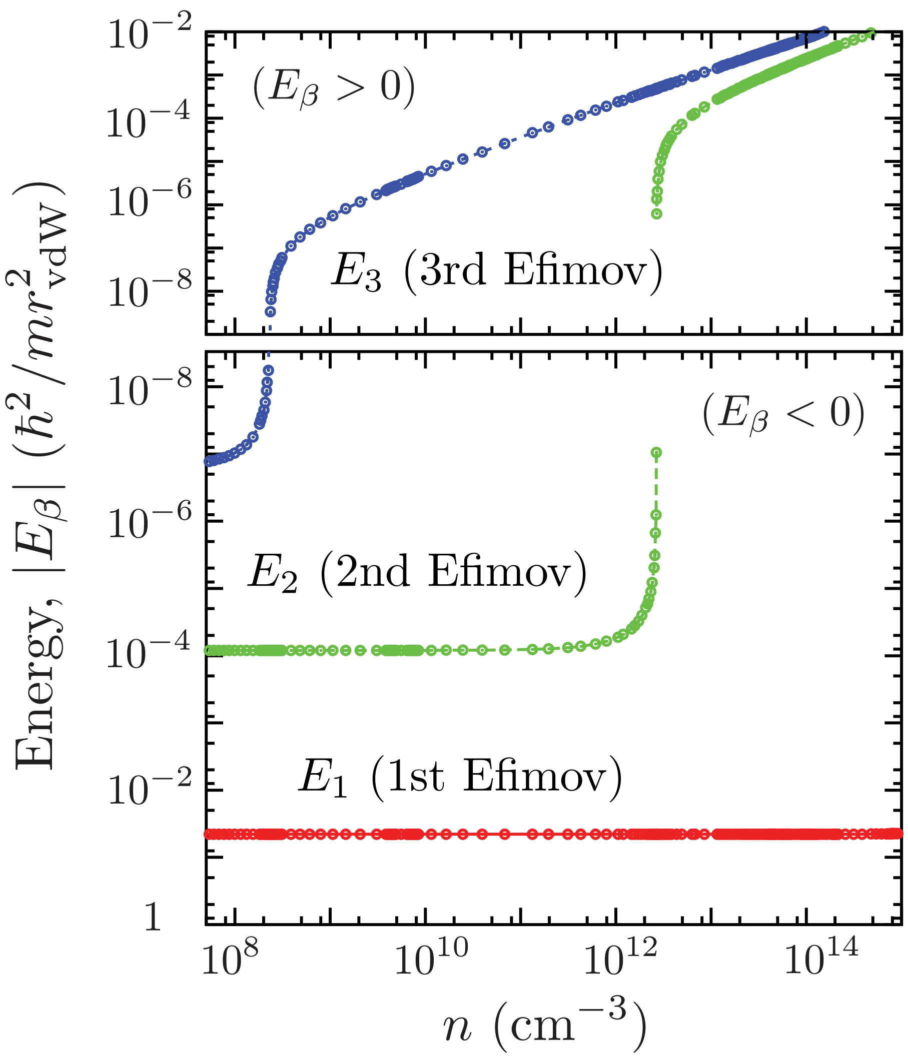

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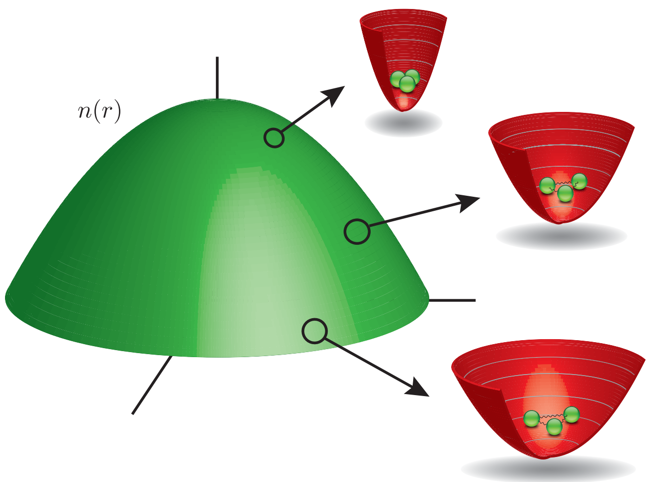

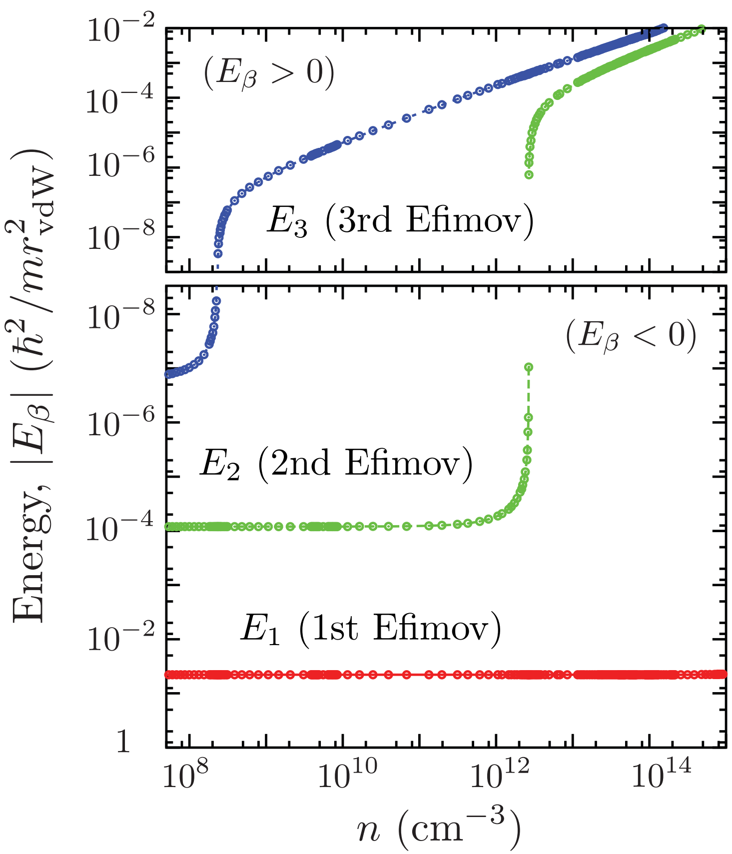

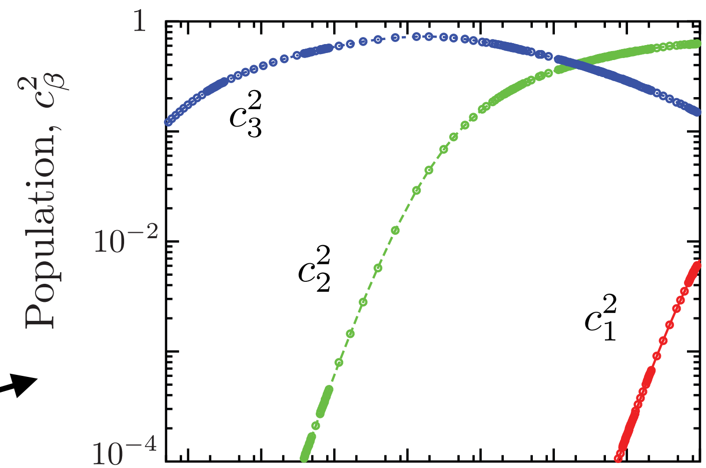

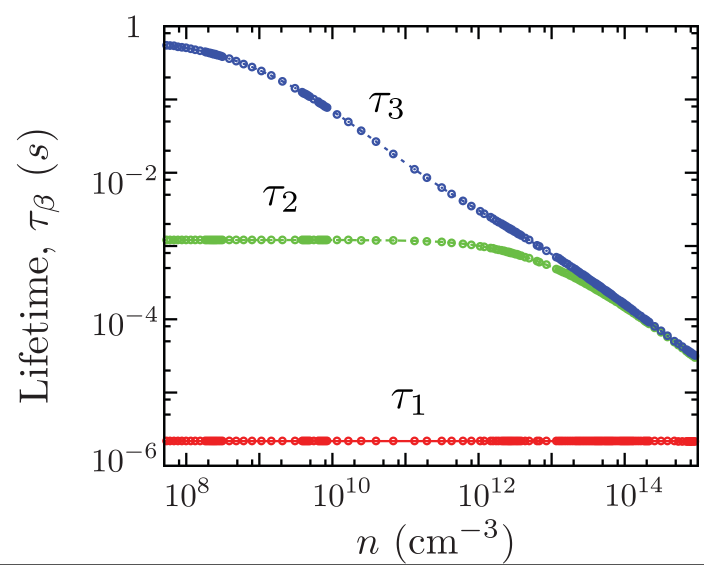

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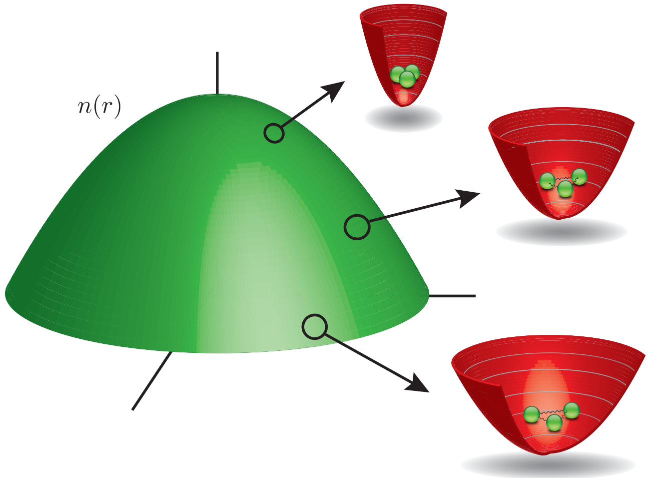

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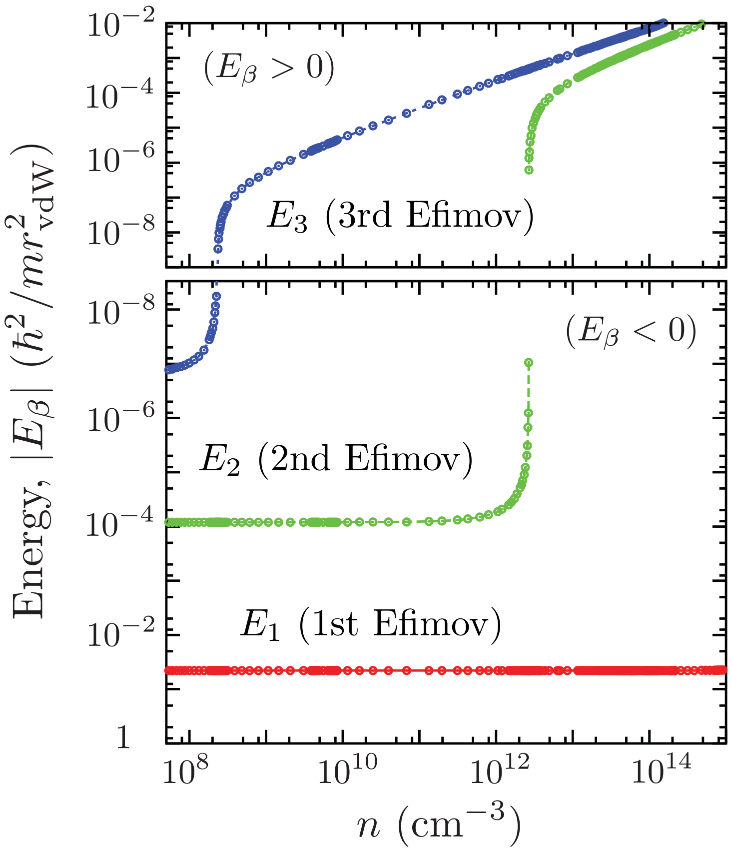
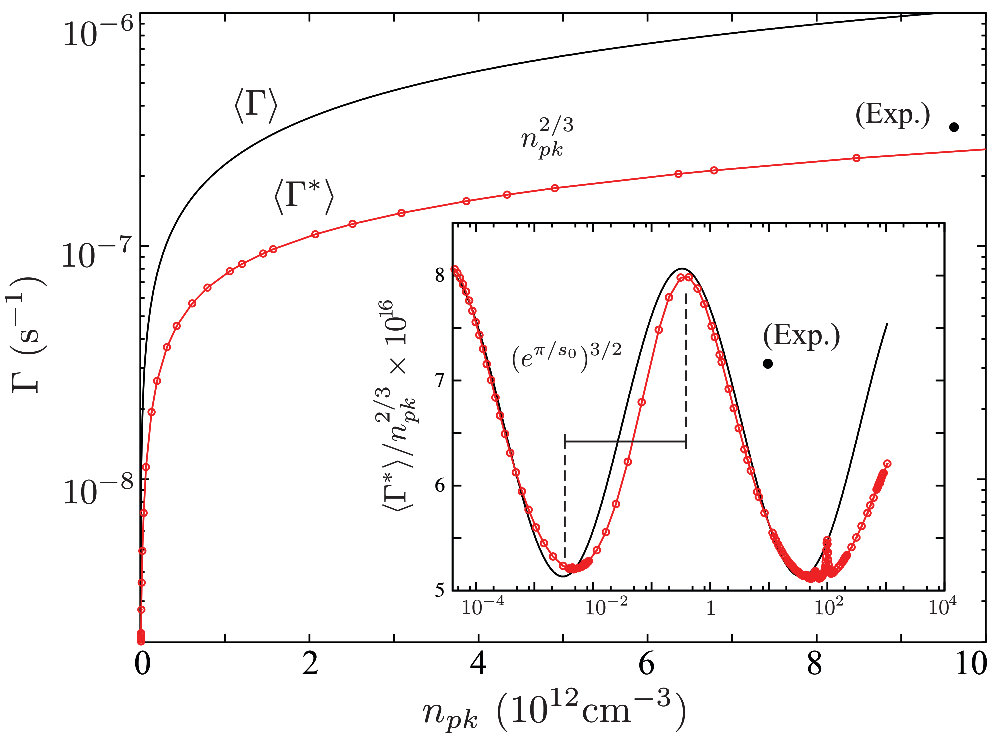


Efimov oscillations:

$$\langle\Gamma\rangle \approx [A + B\sin^2(s_0 \ln n^{1/3} + \phi)]\; n^{2/3}$$



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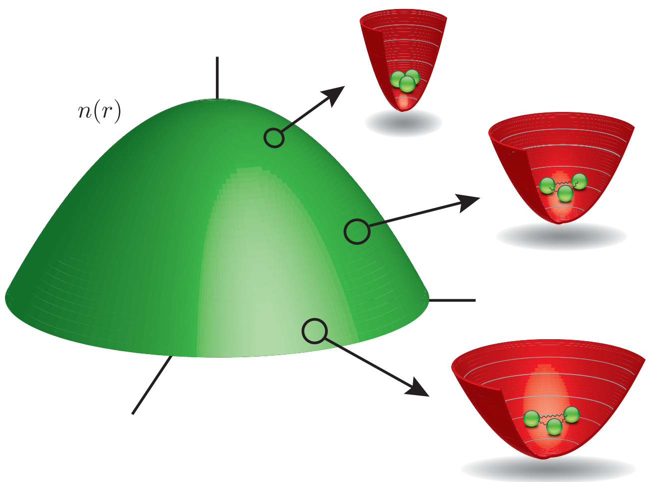

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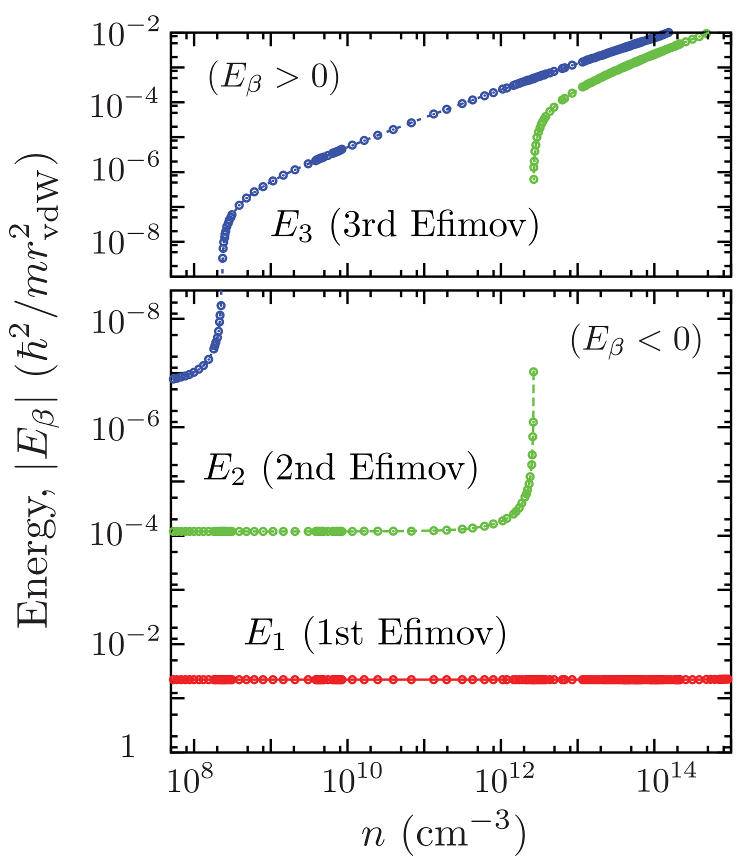

Bottom Line:

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>>> Lifetime controlled by Efimov states

Can we control Efimov state lifetime ?

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(with G. Pupillo, J. Wang, C. H. Greene)

Laser assisted collisions

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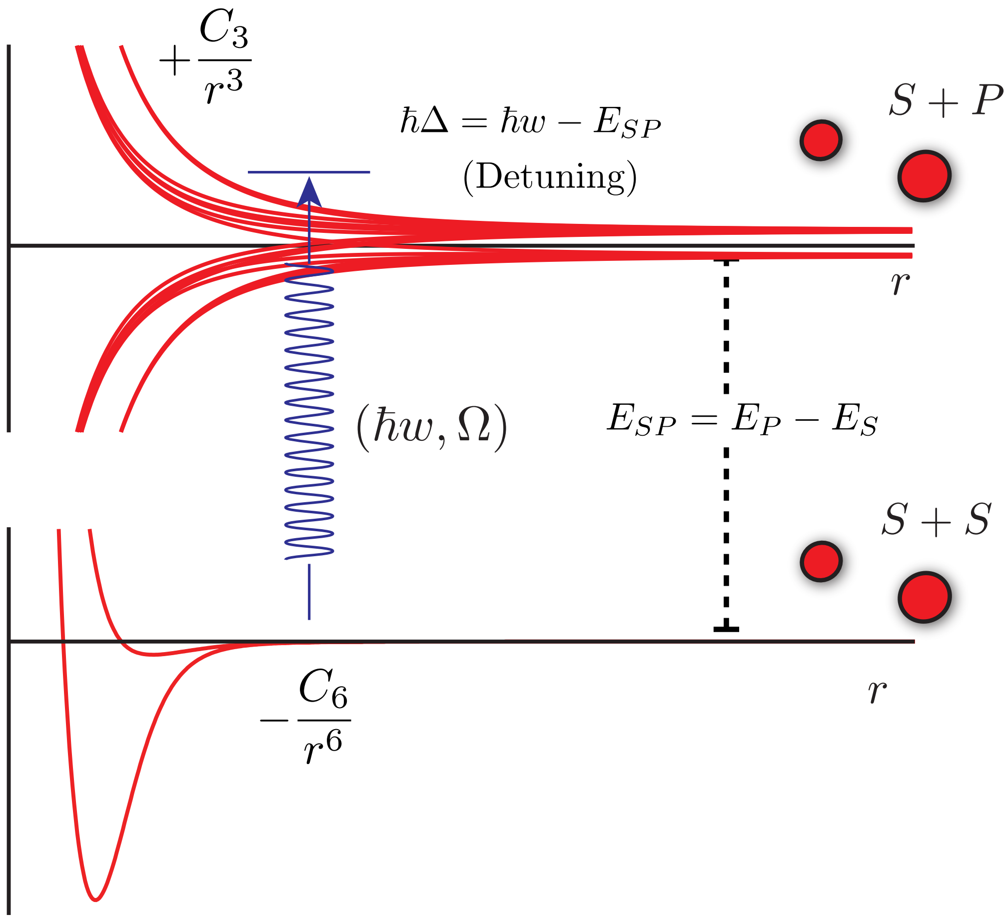
Schematic Two-body potentials:



Atom-Laser interaction

$$\hat{W}(t) = \hbar\Omega\Big(|S\rangle\langle P| + |P\rangle\langle S|\Big)\cos(wt)$$

$$\Omega \equiv \text{Rabi frequency}$$

$$w \equiv \text{Laser frequency}$$

Blue-Shielding:
blue-detuned Laser = coupling to a repulsive $1/r^3$ interaction = prevents atoms to approach short distances

(with G. Pupillo, J. Wang, C. H. Greene)

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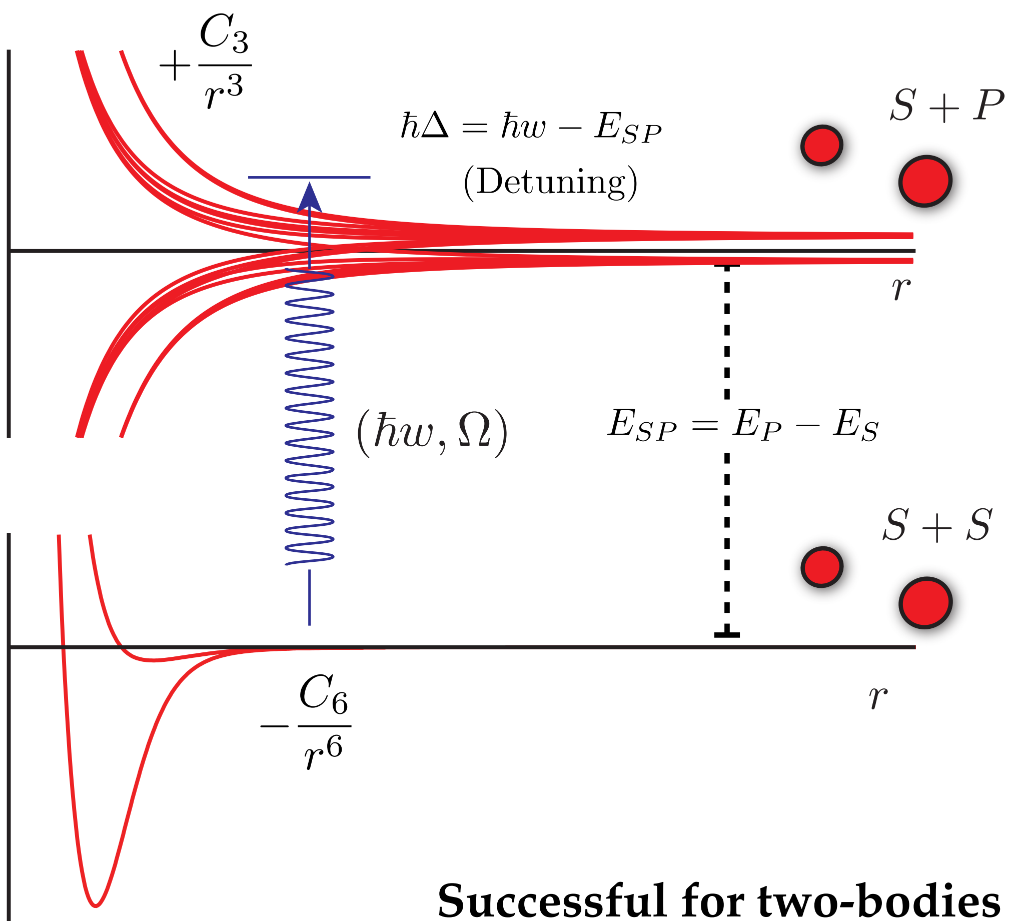

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Successful for two-bodies

Suominen, Holland, Burnett, Julienne, PRA **51**, 1446 (1995);
Weiner, Bagnato, Zilio, Julienne, RMP **71**, 1 (1999);
Gorshkov, Rabl, Pupillo, Micheli, Zoller, Lukin, Buchler, PRL **101**, 073201 (2008)

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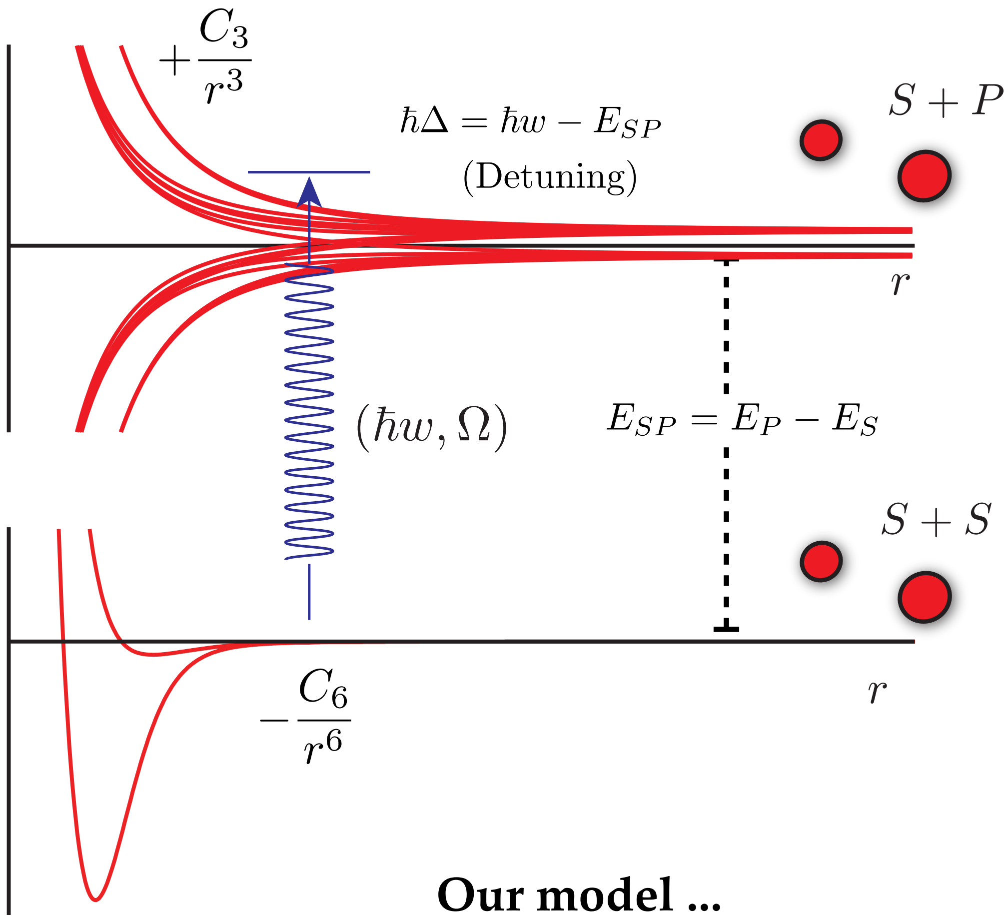

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Our model ...

- $S + S$ Interaction : $v_{SS}(r) = -\frac{C_6}{r^6}\left(1 - \frac{\lambda_*^6}{r^6}\right), \quad (a \to \pm\infty)$
- $S + P$ Interaction : $v_{SP}(r) = +\frac{C_3}{r^3}$

Extension to three-bodies ?

Laser assisted collisions

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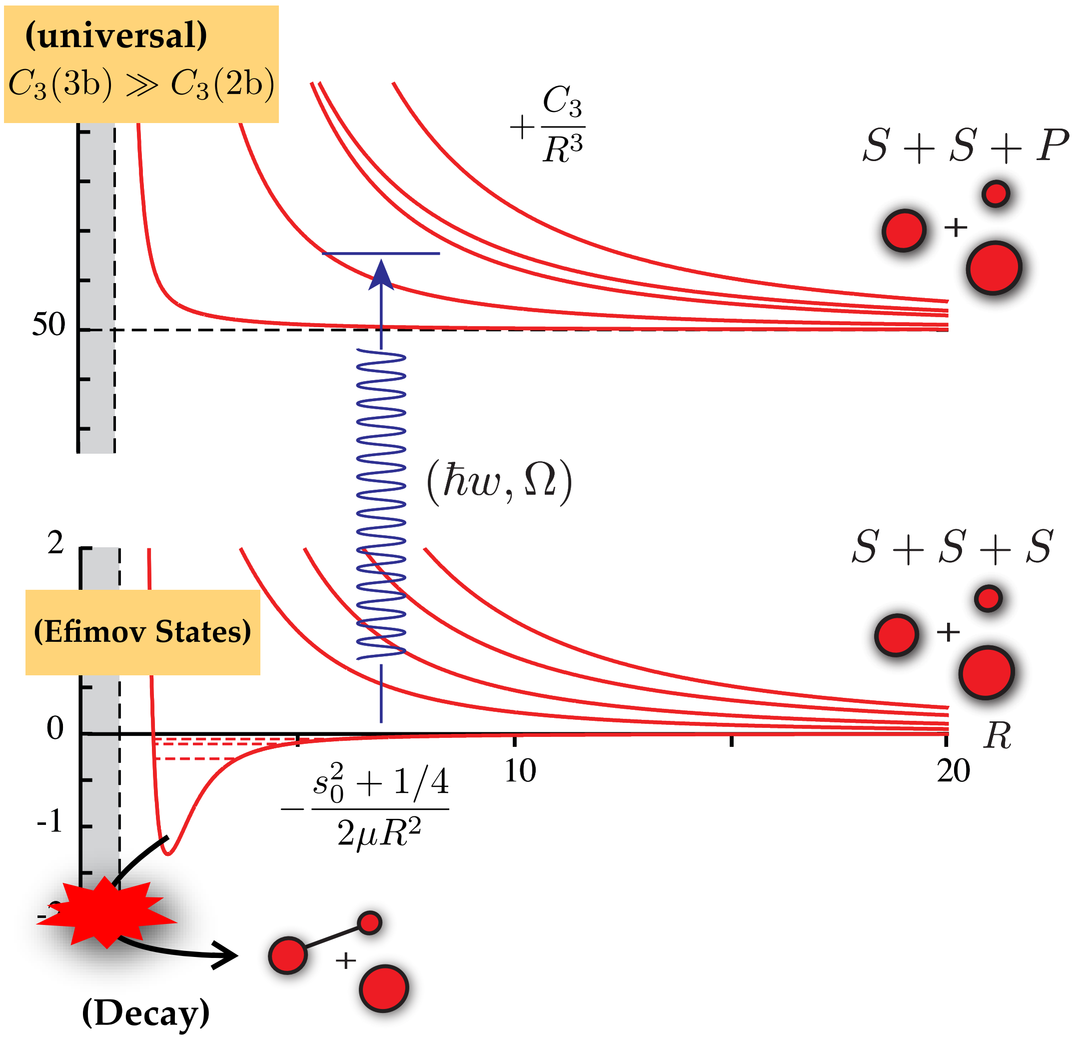
Laser assisted collisions

(with G. Pupillo, J. Wang, C. H. Greene)

Hyperspherical Three-body potentials: $(a \to \pm\infty)$



Hyperspherical Adiabatic Hamiltonian:

$$\hat{\mathscr{H}}_{\text{ad}}(\vec{R},t) = \hat{H}_{\text{ad}}(\vec{R}) + \hat{W}(t) - i\hbar\frac{d}{dt}$$

(Bare Interactions)

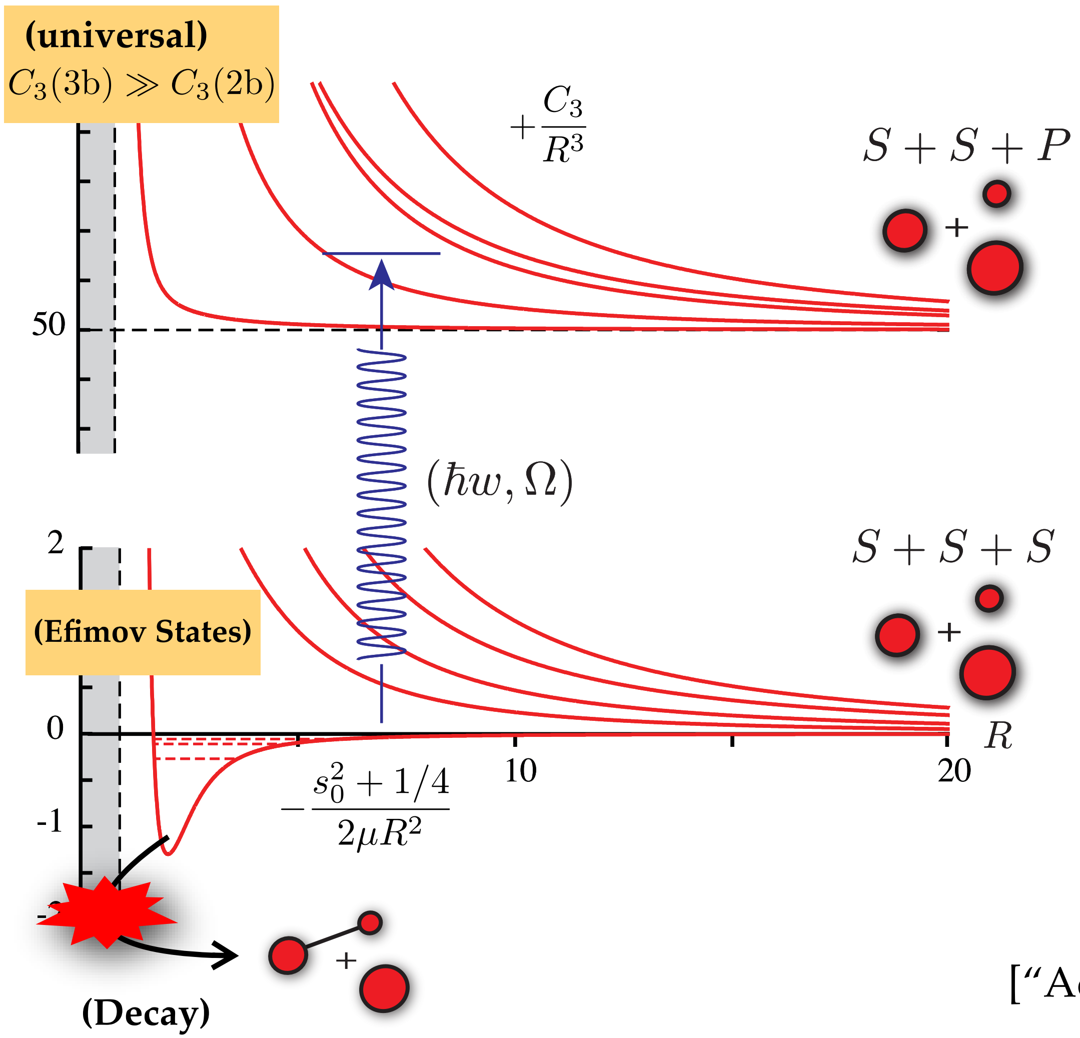
(External Field)

$$\hat{W}(t) = \hat{W}_1(t) + \hat{W}_2(t) + \hat{W}_3(t)$$

Laser assisted collisions

(with G. Pupillo, J. Wang, C. H. Greene)

Hyperspherical Three-body potentials: $(a \to \pm\infty)$



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(Bare Interactions)

(External Field)

$$\hat{W}(t) = \hat{W}_1(t) + \hat{W}_2(t) + \hat{W}_3(t)$$

$$\hat{\mathscr{H}}_{\text{ad}}(\vec{R},t)\Phi_\gamma(\vec{R},t) = U_\gamma(R)\Phi_\gamma(\vec{R},t)$$

$U_\gamma(R) \equiv$ Three-body dressed Potentials

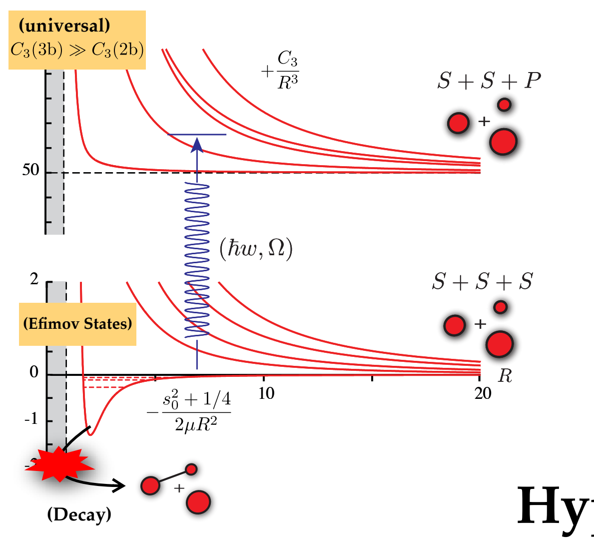
[“Adiabatic Floquet Formalism for few-body systems”,
J. P. D’Incao, in preparation]

[See Shih-I Chu and Dmitry A. Telnov, Phys. Rep. 390, 1 (2004)]

Laser assisted collisions

(with G. Pupillo, J. Wang, C. H. Greene)

Hyperspherical Three-body potentials: $(a \to \pm\infty)$



Hyperspherical Adiabatic Hamiltonian:

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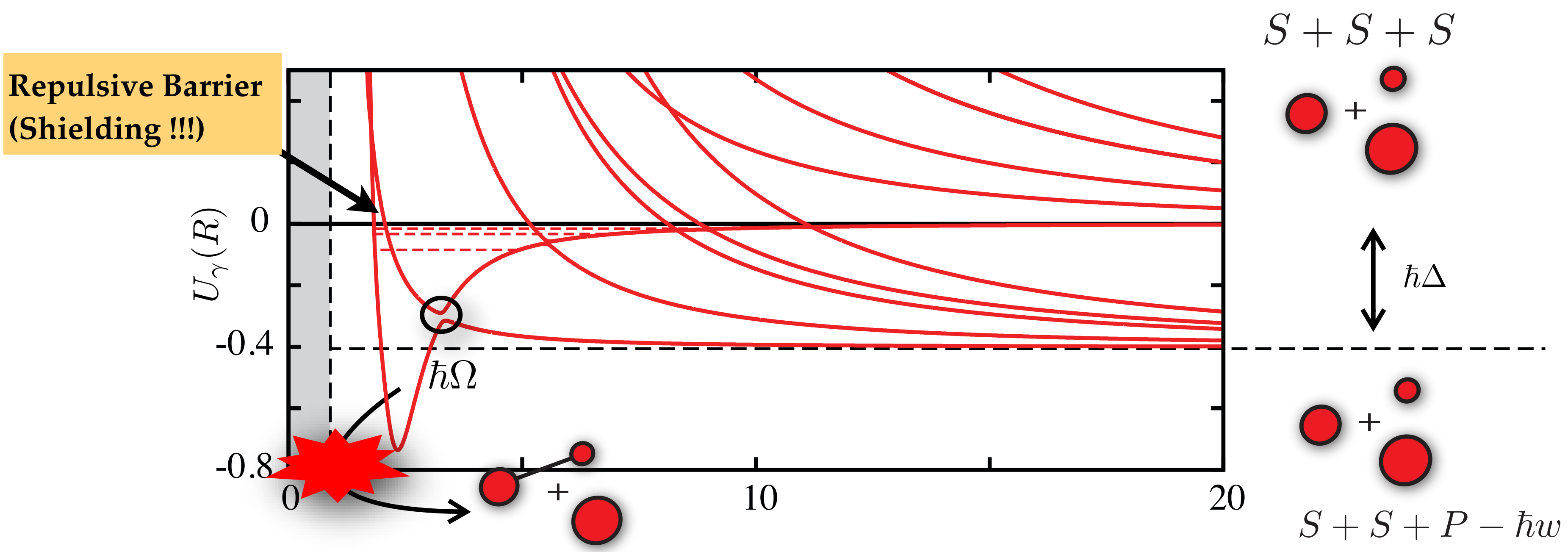
Hyperspherical Dressed Three-body potentials:

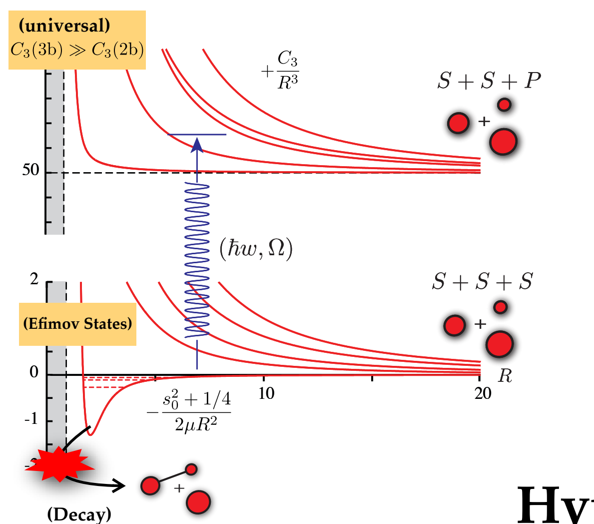


Laser assisted collisions

NIST
University of Colorado

(with G. Pupillo, J. Wang, C. H. Greene)

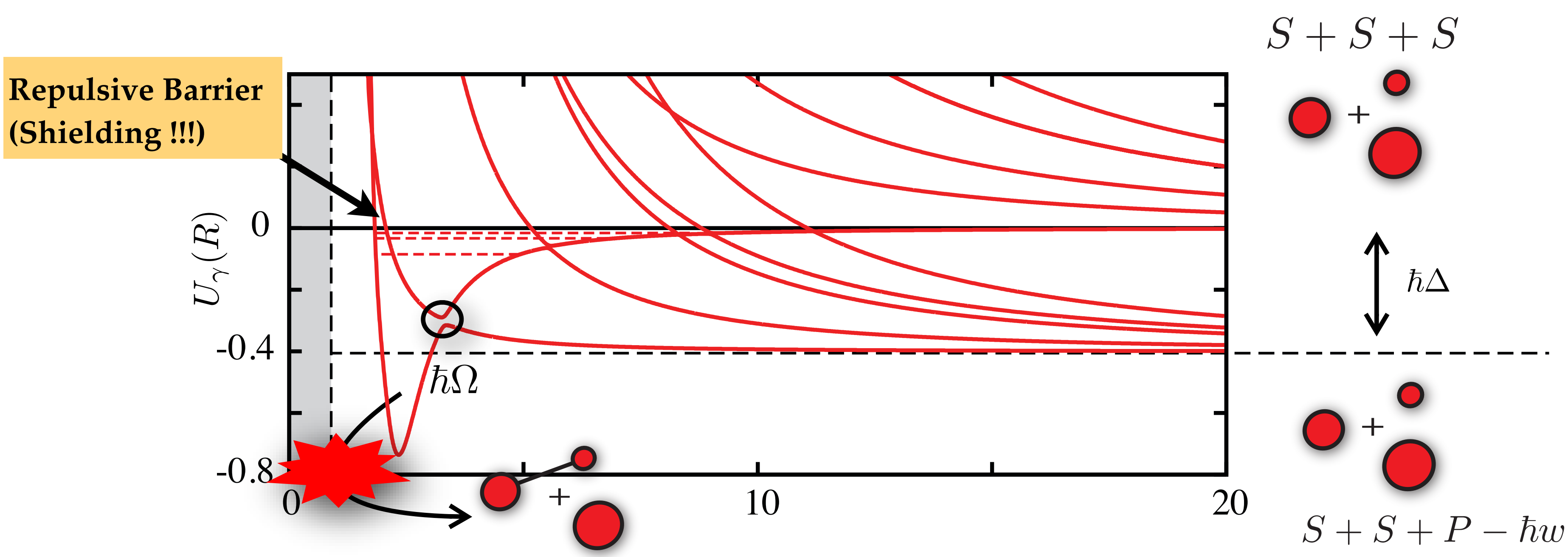
Hyperspherical Three-body potentials: $(a \to \pm\infty)$



Ω and Δ = Controllable parameters

- needs to find an optimal detuning
- keep Rabi frequency as low as possible

Hyperspherical Dressed Three-body potentials:



Preliminary Results (Blue-Shielding)

(with G. Pupillo, J. Wang, C. H. Greene)

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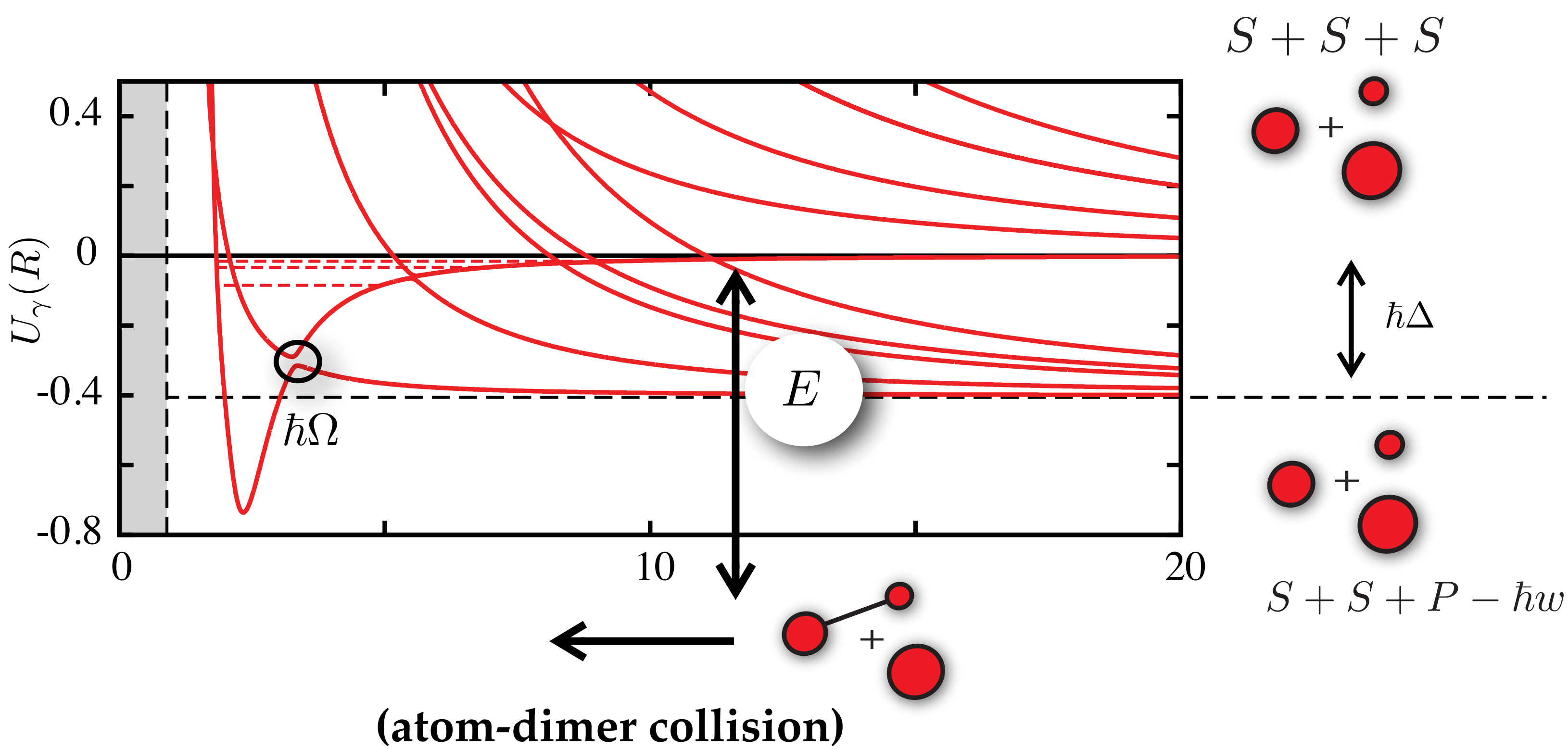
Determining Energy and width of Efimov States



Calculate:

$$\frac{d\delta_{\rm ei}}{dE} = \frac{\Gamma_R/2}{(E-E_R)^2+(\Gamma_R/2)^2} \quad \begin{cases} E_{\rm max} = E_R \\ \left.\frac{d\delta_{\rm ei}}{dE}\right|_{E_{\rm max}} = \frac{2}{\Gamma_R} \;(\propto \tau) \end{cases}$$

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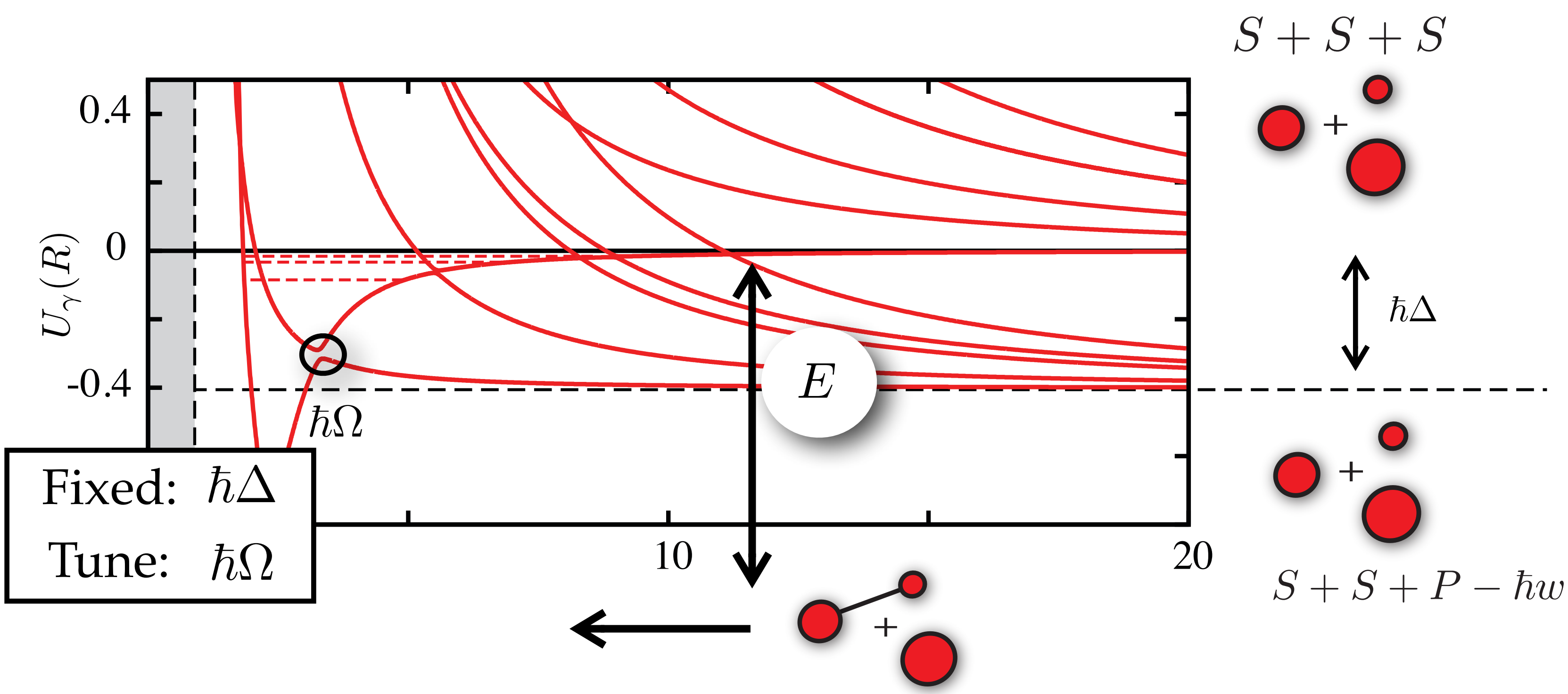
Determining Energy and width of Efimov States



(atom-dimer collision)

Calculate: $$\frac{d\delta_{\rm ei}}{dE} = \frac{\Gamma_R/2}{(E-E_R)^2 + (\Gamma_R/2)^2} \quad \begin{cases} E_{\rm max} = E_R \\ \left.\frac{d\delta_{\rm ei}}{dE}\right|_{E_{\rm max}} = \frac{2}{\Gamma_R} \; (\propto \tau) \end{cases}$$

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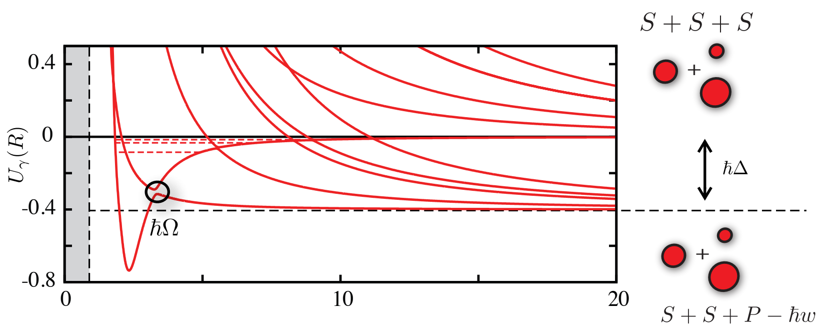

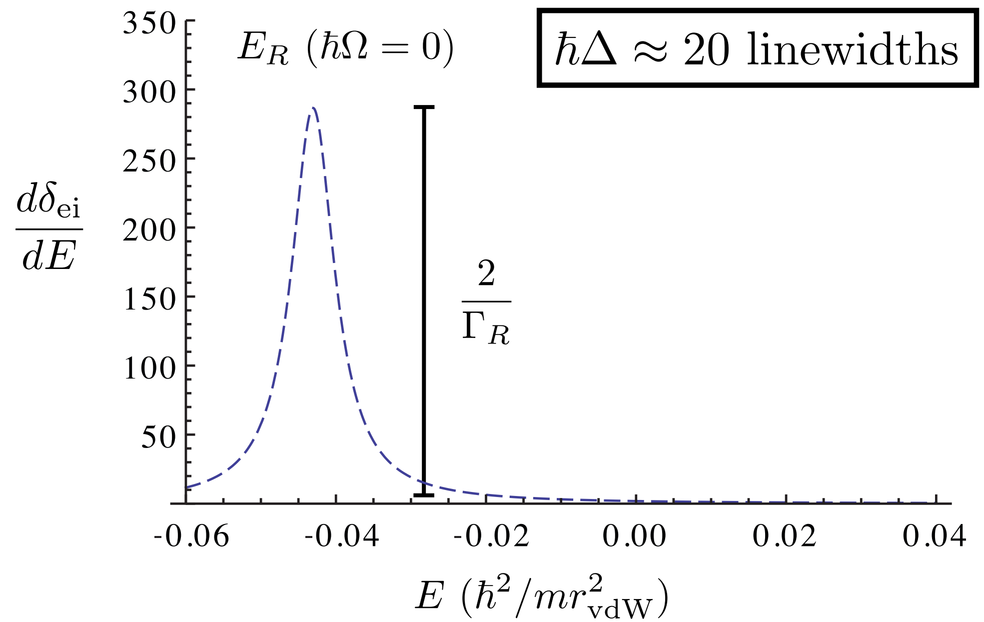

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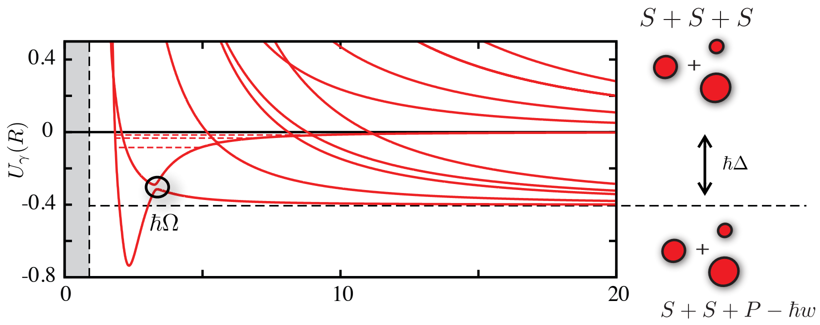

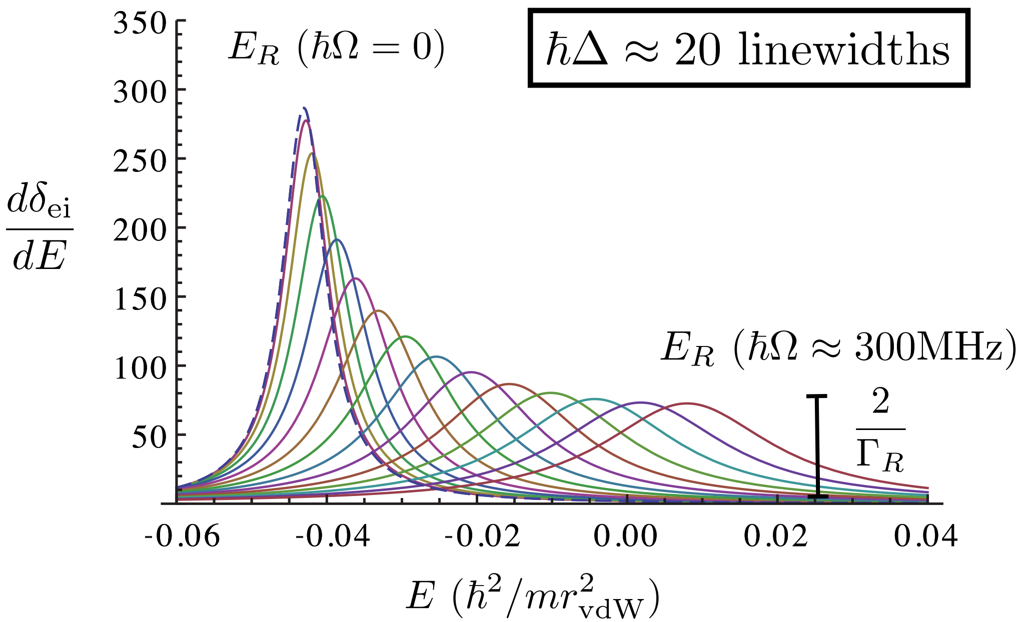

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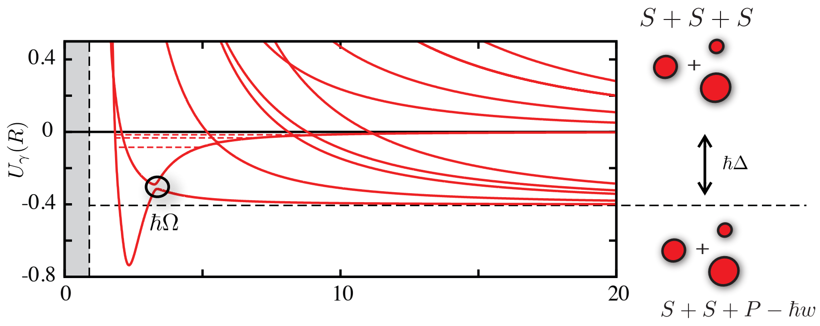
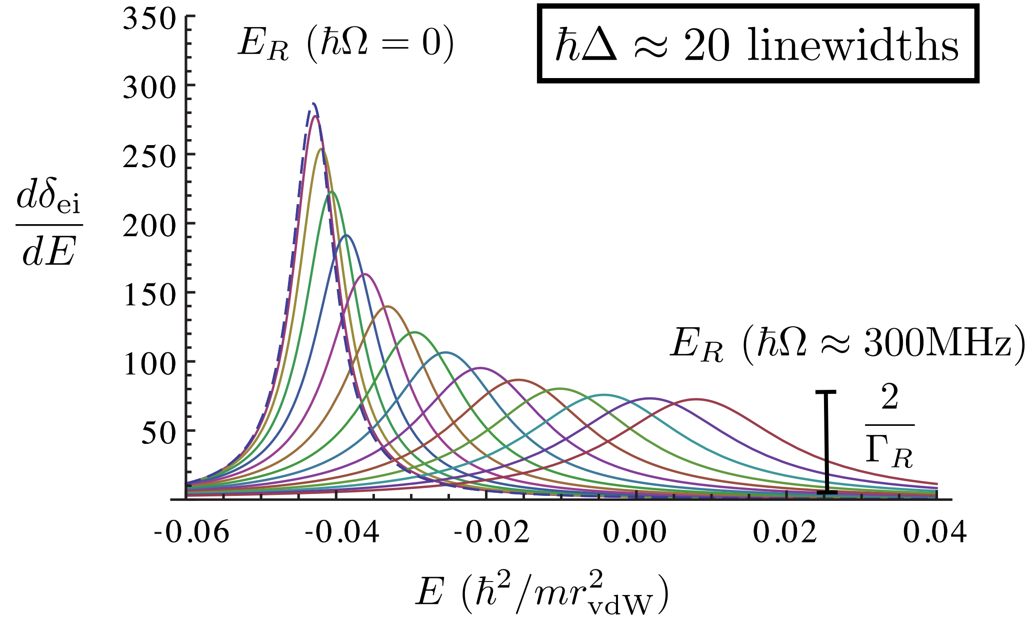
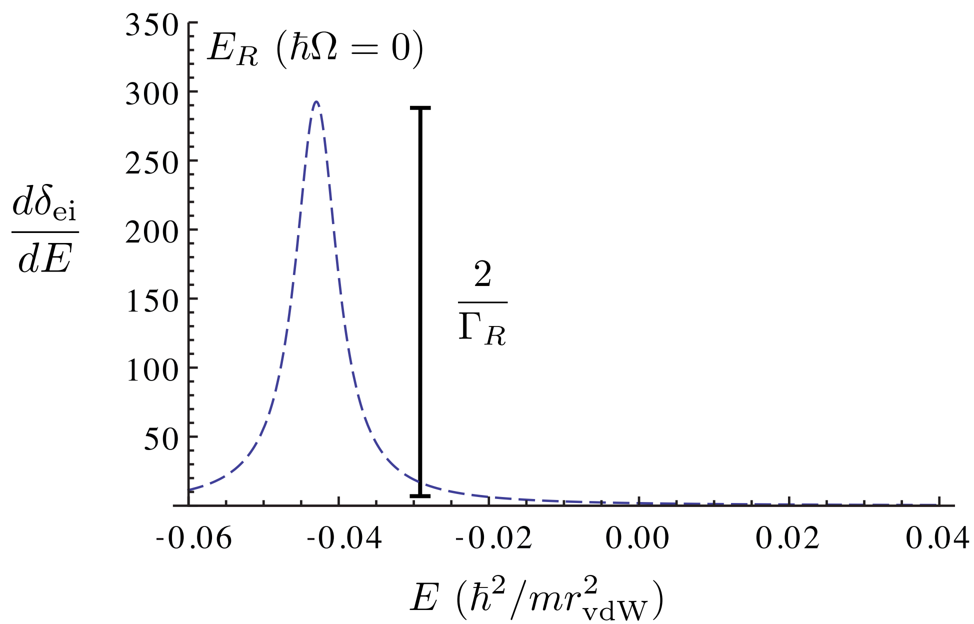




$\hbar\Delta \approx 80$ linewidths



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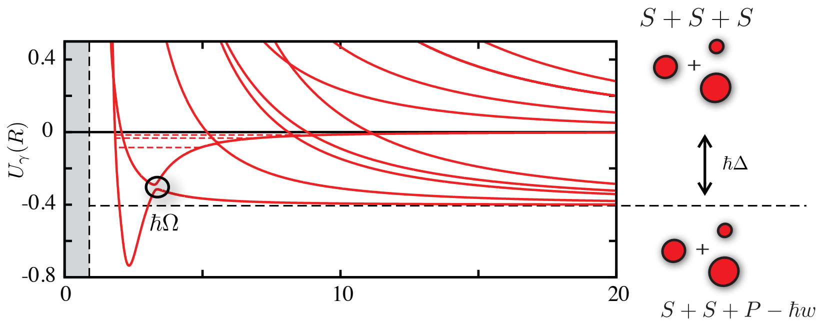

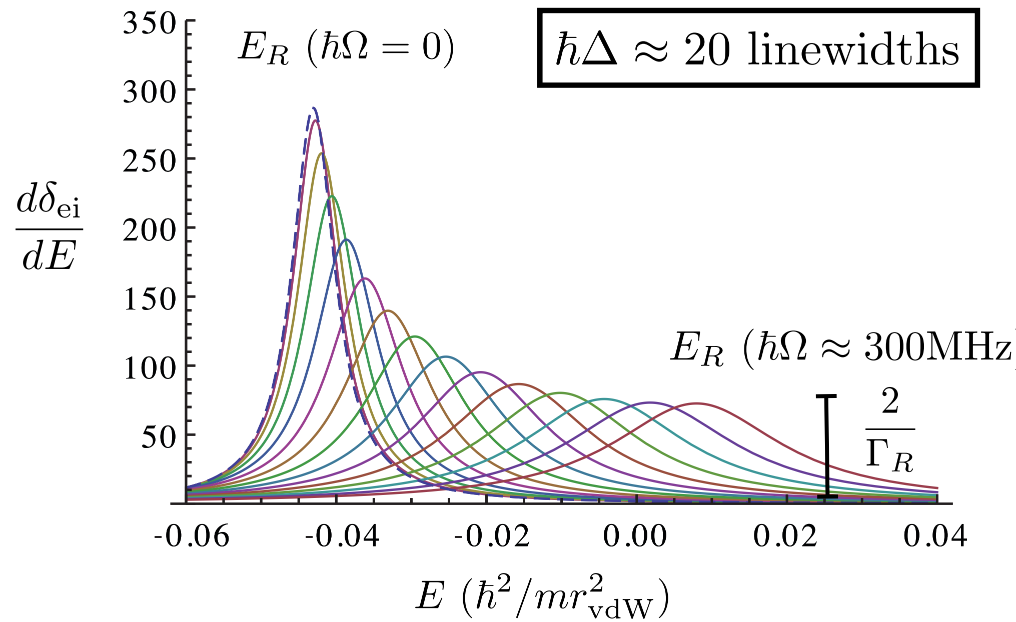

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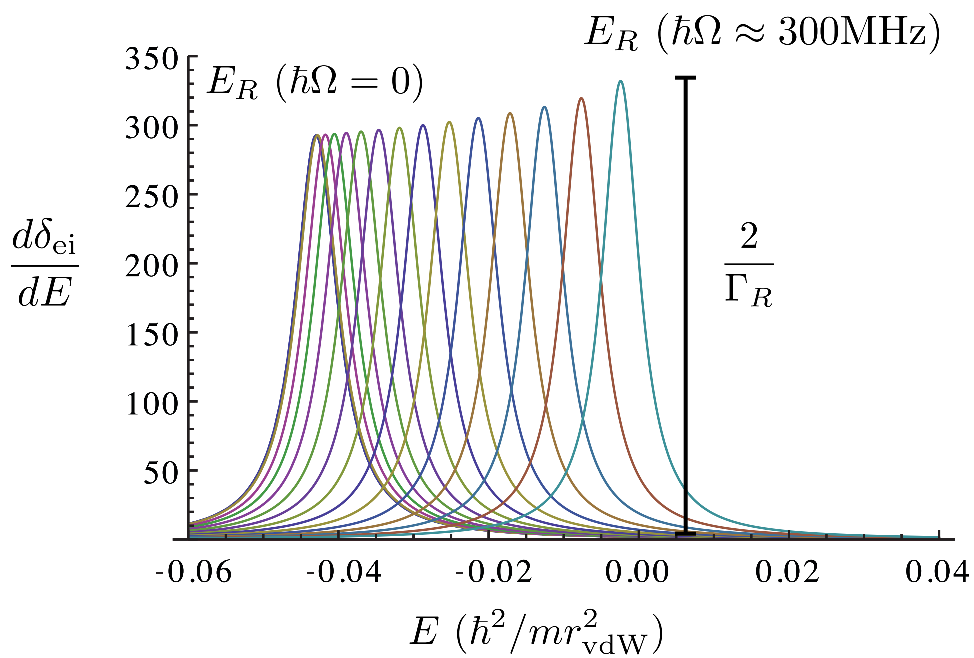

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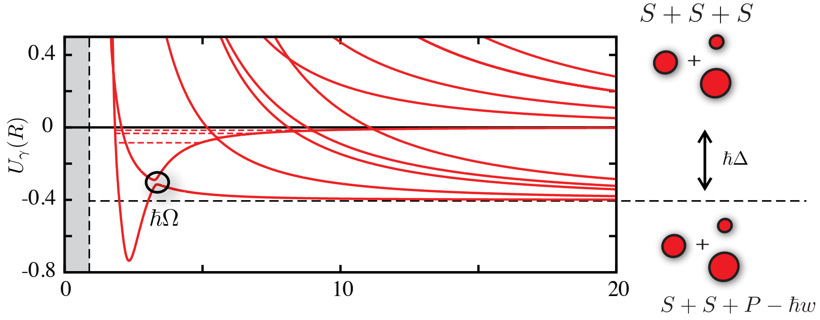

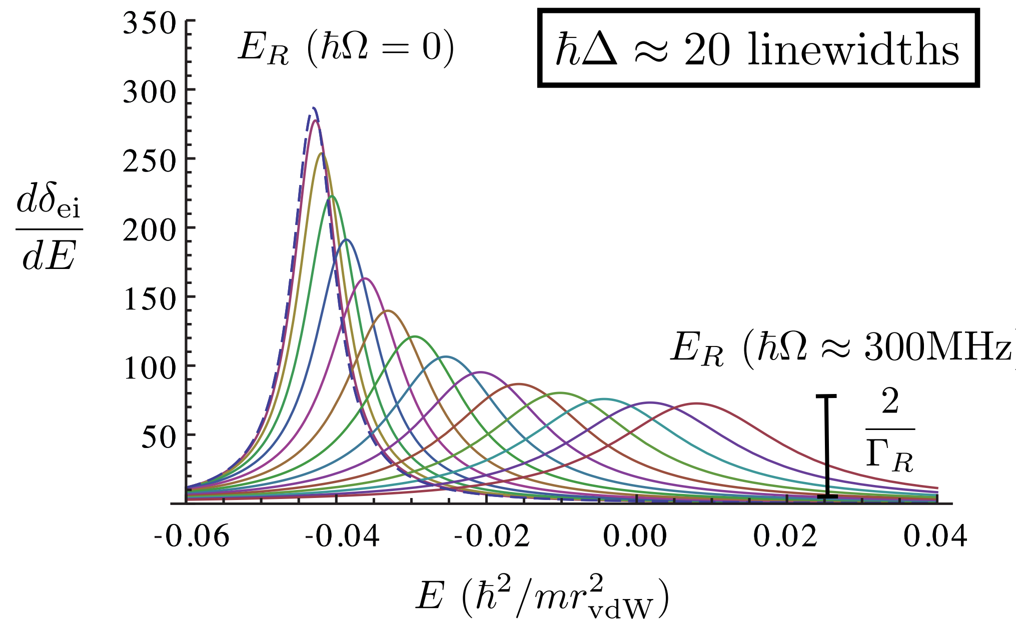

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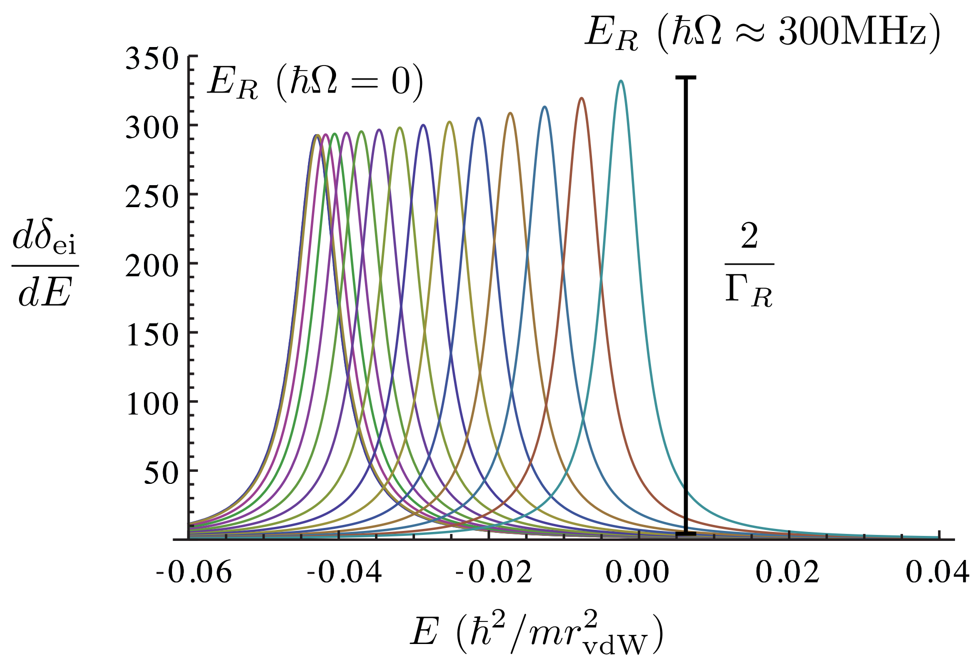

- Tunability of the 3BP (good)
- 10-20% improvement on lifetime (more?)
(Needs to explore more the parameter space)

Summary

Summary

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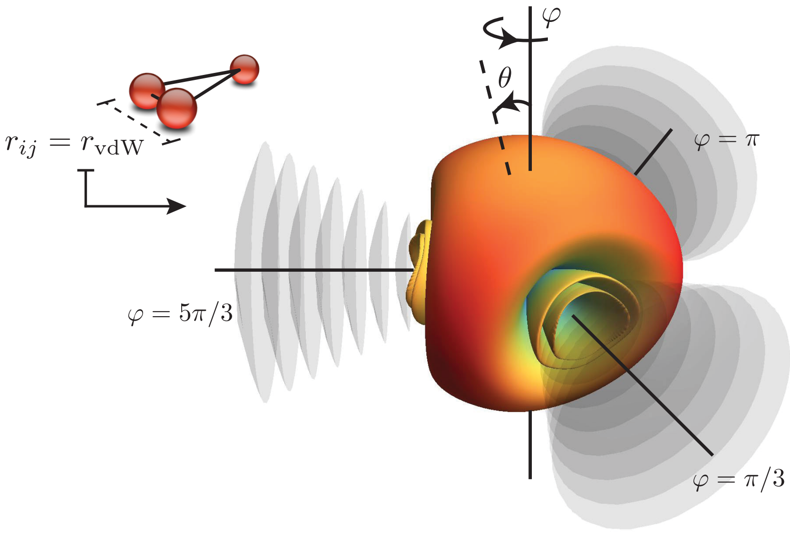

- Both the theoretical and experimental advances in ultracold quantum gases have demonstrated these systems to be ideal candidates to explore universal few-body physics

- Some of the physical aspects of unitary Bose gases can be understood from a few-body perspective

- Quench to unitary: The separation of time scales for losses and many-body physics is favorable and allows interesting regimes to explore universal few-body physics

- The use of a blue-detuned laser seems promising in order to allow for the control of both energy and lifetime of Efimov states. In particular, we expect a better control for Efimov states when the scattering is finite.