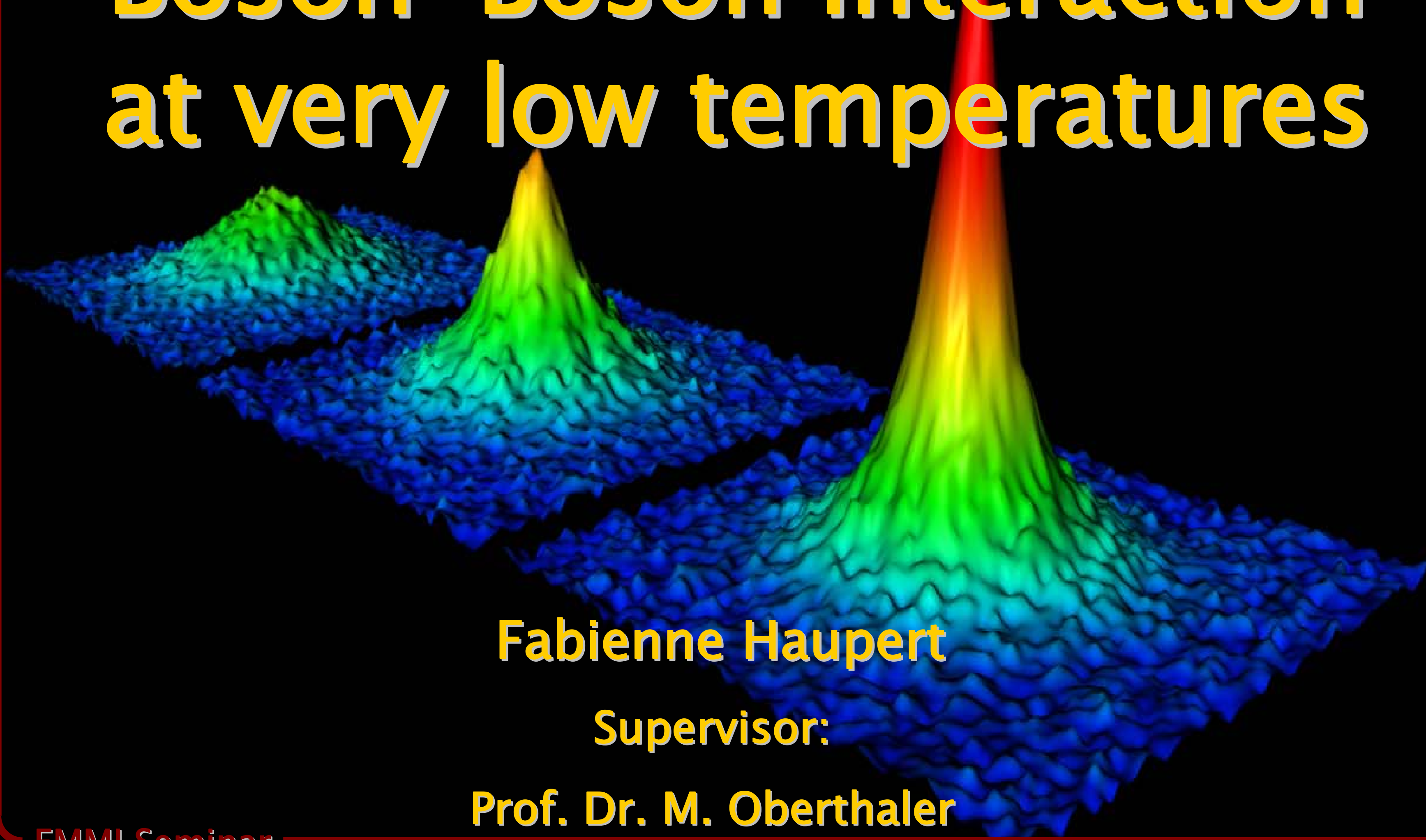
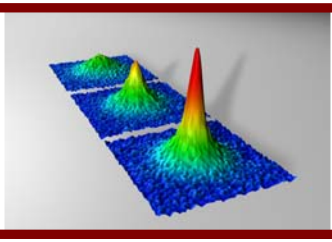
Fermion–Fermion and Boson–Boson Interaction at very low temperatures



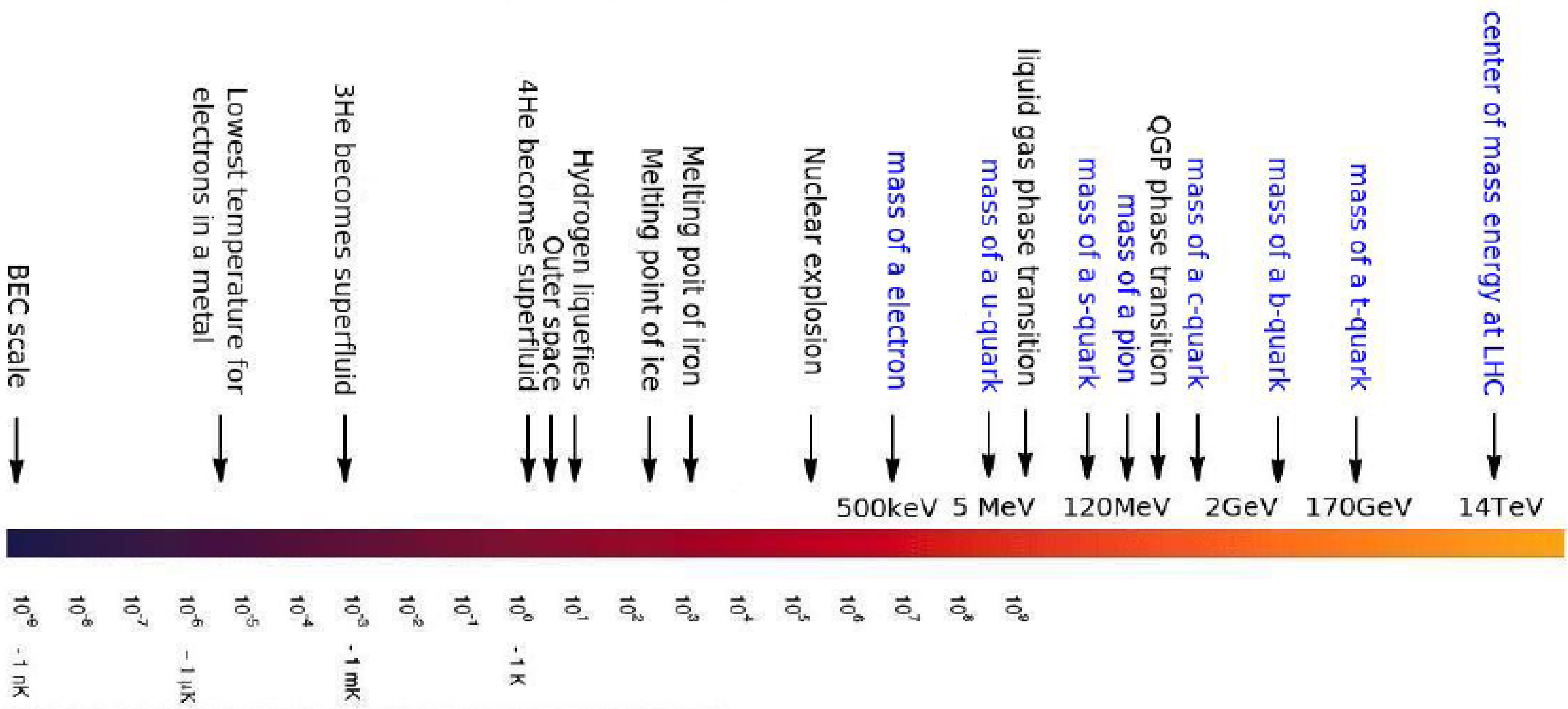
Fabienne Haupert

Supervisor:

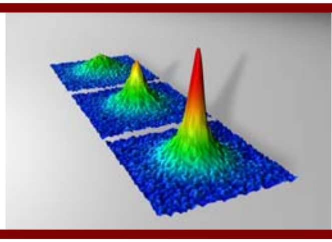
Prof. Dr. M. Oberthaler



Implication



$$[\text{Kelvin}]/11605 = [\text{eV}]$$



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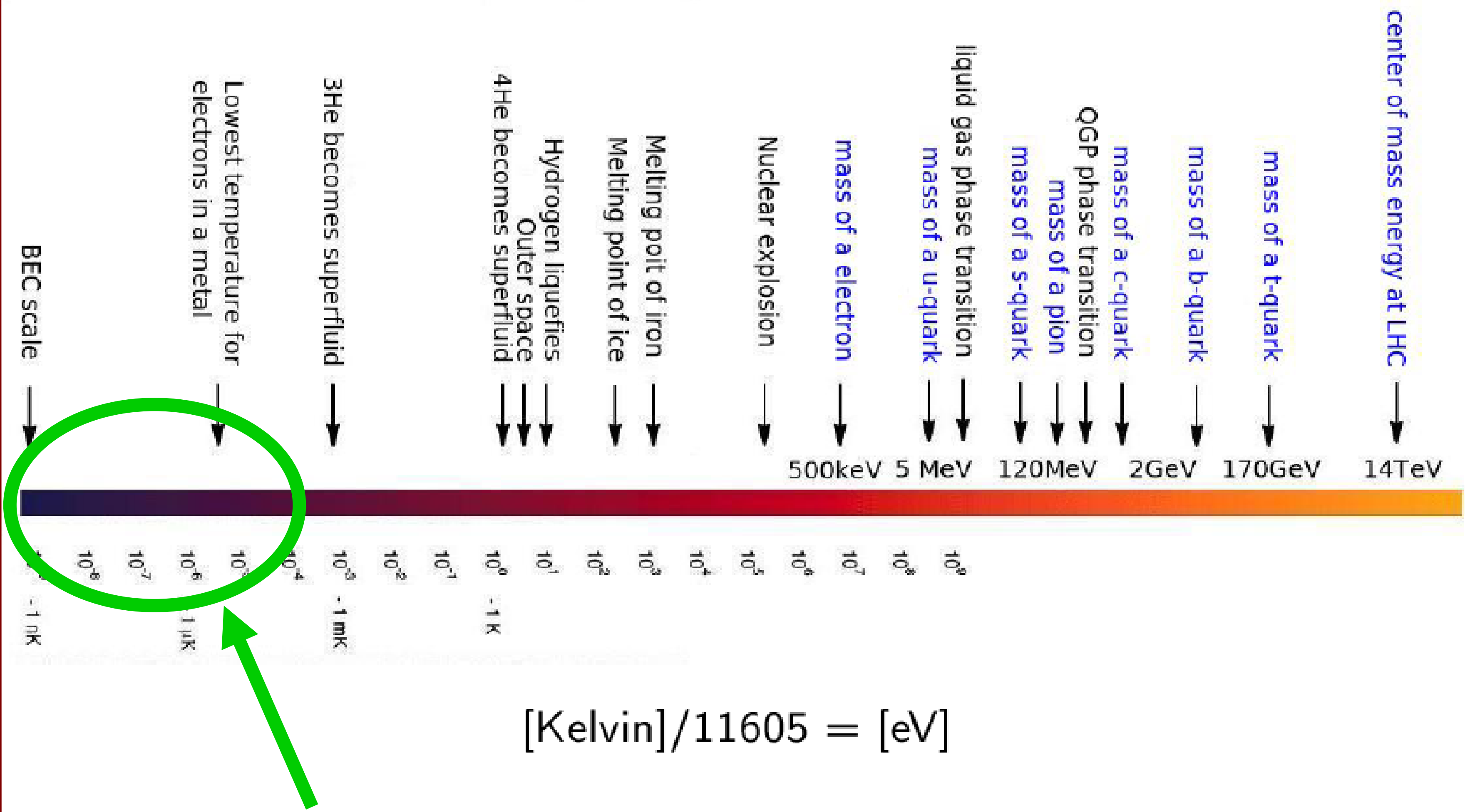

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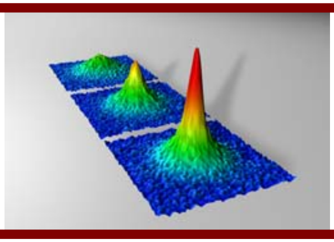
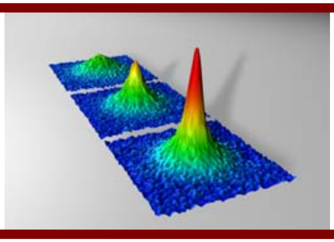
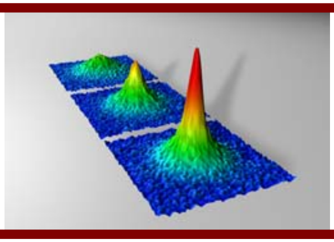


Outline



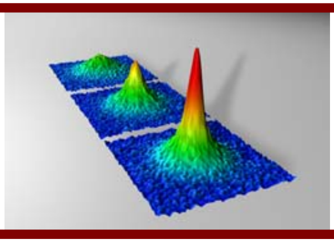
Outline

1. Interactions at very low temperatures:



Outline

1. **Interactions at very low temperatures:**
   - **1.1 Possible interactions**



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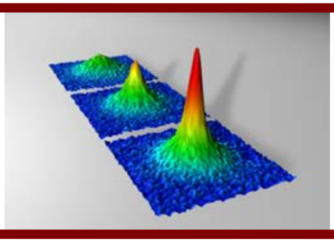
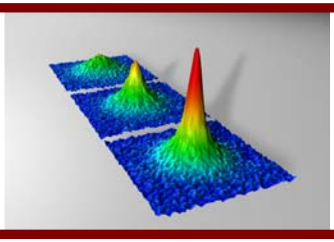
1. Interactions at very low temperatures:

- **1.1 Possible interactions**
- **1.2 Theoretical description**



Outline

1. Interactions at very low temperatures:
    - 1.1 Possible interactions
    - 1.2 Theoretical description
2. Feshbach Resonances



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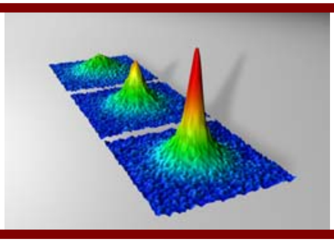
2. **Feshbach Resonances**
   - 2.1 The channel method



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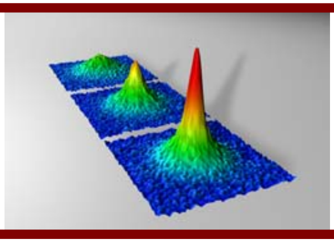
   - **2.2 Expectations for the experiments**



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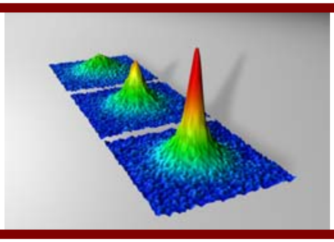

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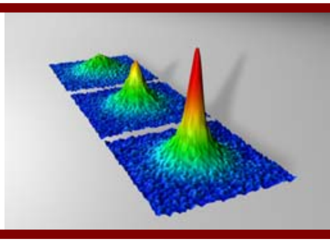
3. Experimental Observations

- **3.1 Feshbach Resonances**



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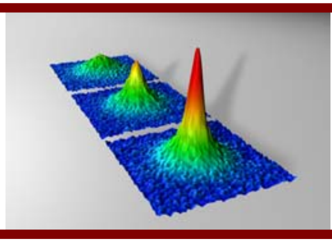
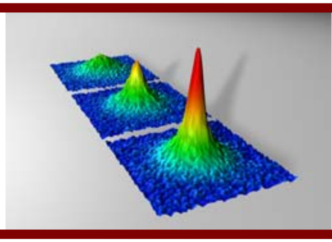
2. Feshbach Resonances
   - 2.1 The channel method
   - 2.2 Expectations for the experiments
3. Experimental Observations
   - 3.1 Feshbach Resonances
   - 3.2 Creation of a molecular condensate



Interactions at low T:

1. Good collisions (elastic):



Interactions at low T:

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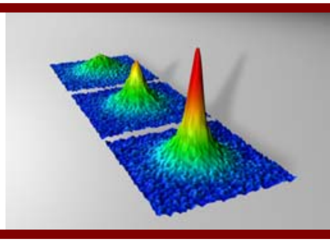
Scattering potential mainly determined by interatomic distances

(⇒ contribution of different electro-magnetic forces)



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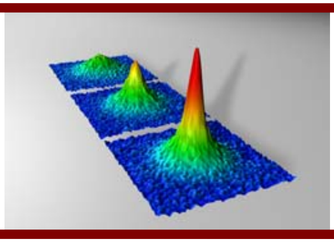

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Loss of internal energy +

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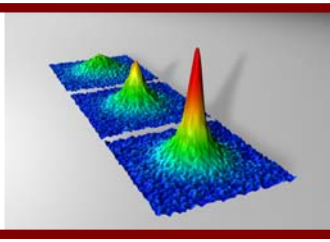
3-body-recombination



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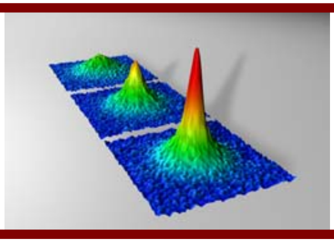
atoms are lost!



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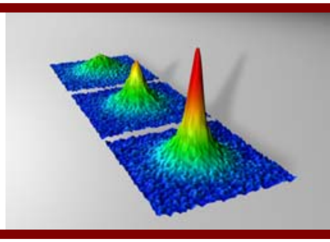
    1.1 Possible interactions



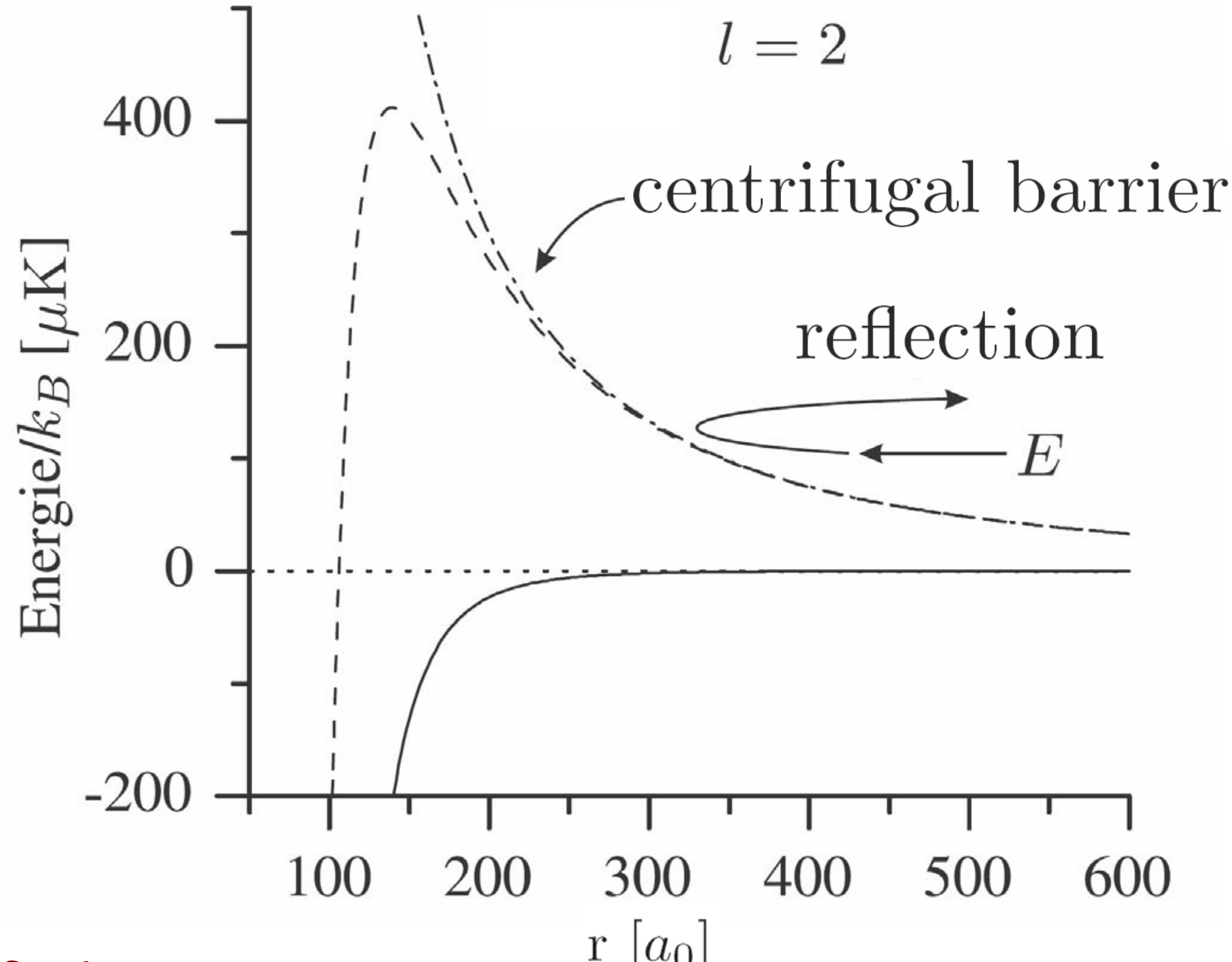
Outline

1. Interactions at very low temperatures:

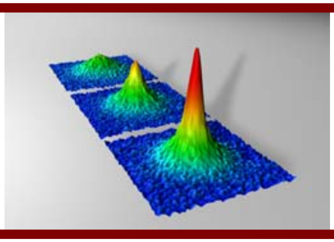
1.1 Possible interactions

1.2 Theoretical description

Scattering



$l = 2$
400
200
0
-200
Energie/k_B [μK]
centrifugal barrier
reflection
E
100
200
300
400
500
600
r [a_0]



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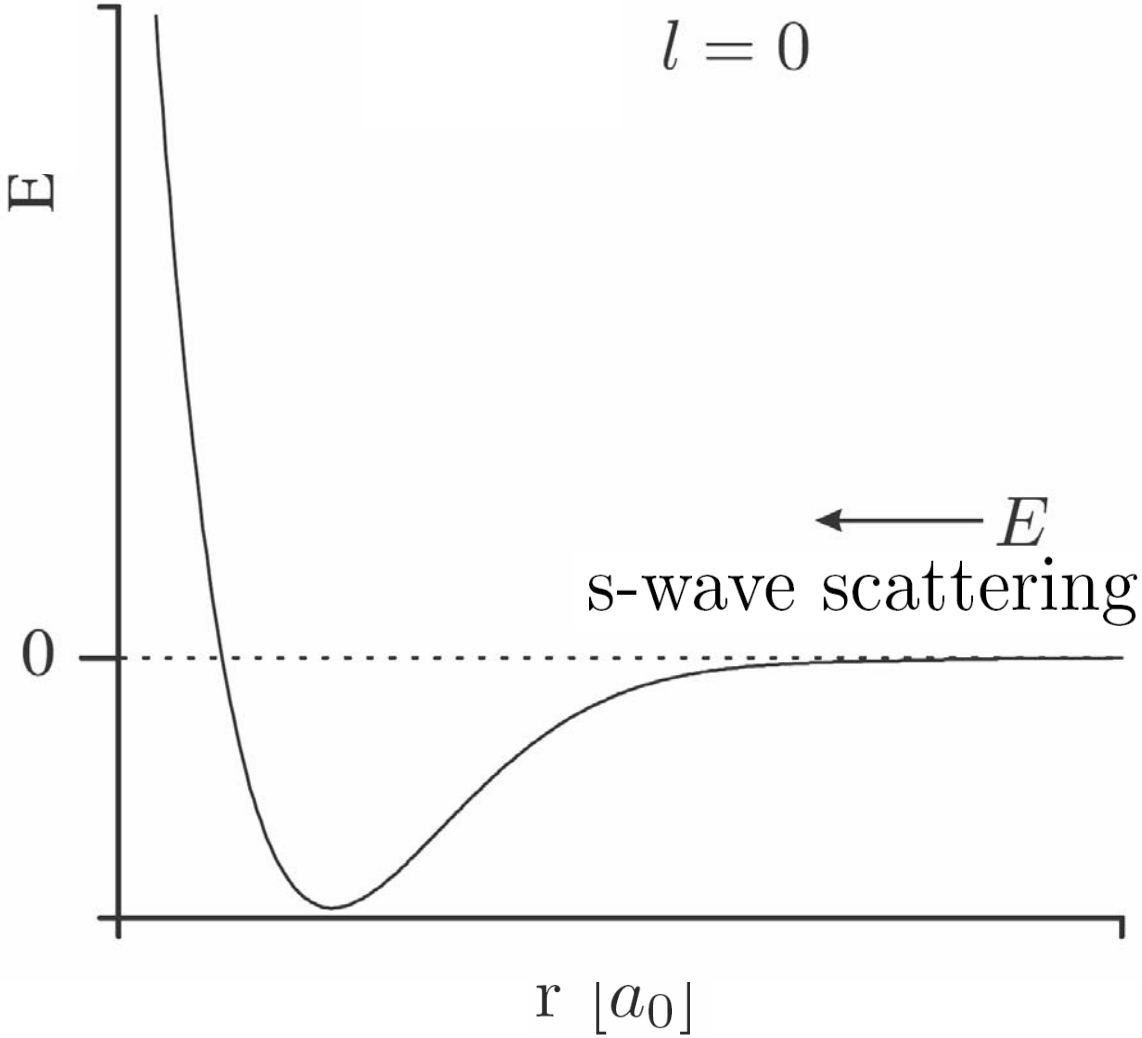
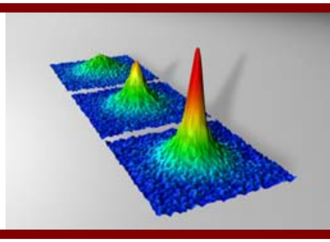
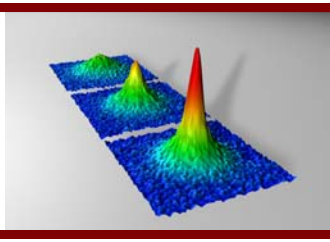




Scattering

Stationary SEQ:

$$\left(-\frac{\hbar^2}{2m_r}\vec{\nabla}^2 + V\left(\vec{r}\right)\right)\Psi_{\vec{k}}(\vec{r}) = E_k\Psi_{\vec{k}}(\vec{r})$$



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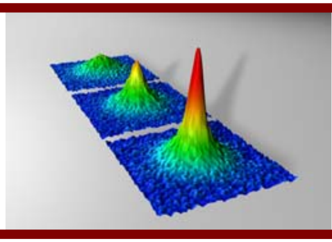
with: $$\lim_{r\to\infty}\Psi_{\vec{k}}(\vec{r}) \propto e^{i\vec{k}\vec{r}} + f(k)\frac{e^{ikr}}{r} \quad \text{für} \quad E_k \ll \frac{\hbar^2}{2m_r L^2}$$



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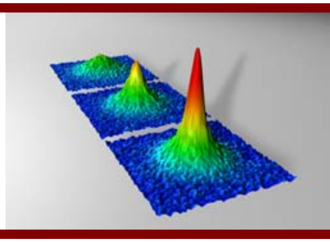
$$\boxed{\frac{d\sigma}{d\Omega} = |f(k)|^2}$$

$$\boxed{\sigma(k) = \int_\Omega |f(k)|^2 \, d\Omega}$$



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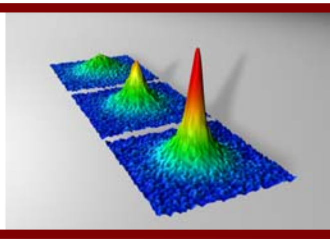

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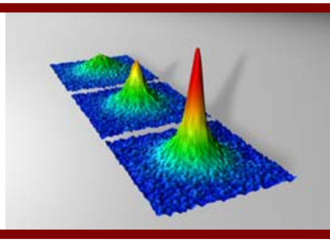

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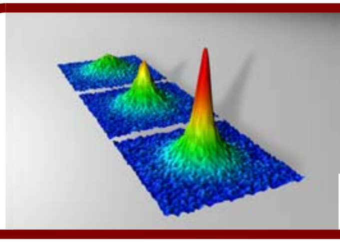
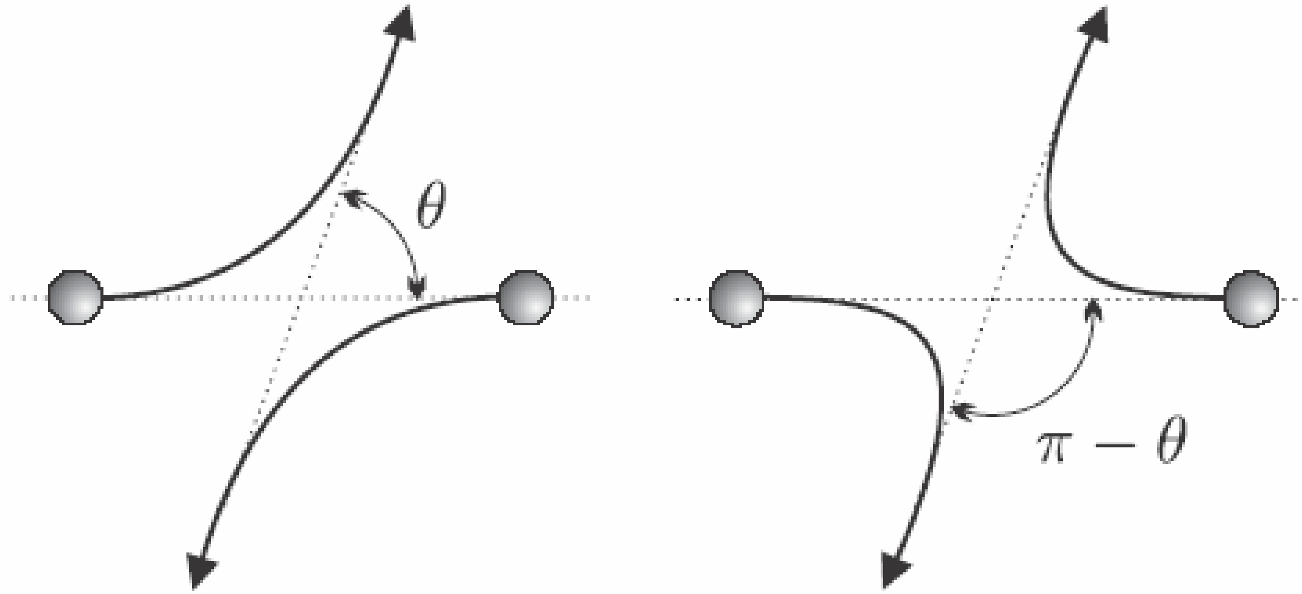
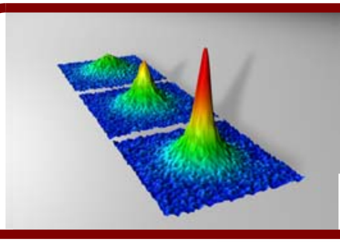
leads to
$$\boxed{\sigma_l(k) = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_l(k)}$$



Bosons vs. fermions



$$\frac{d\sigma}{d\Omega} = \left| f\left(k, \theta\right) \pm f\left(k, \pi - \theta\right) \right|^2 \qquad \left\{ \boxed{\begin{array}{l} +\text{for bosons} \\ -\text{for fermions} \end{array}} \right.$$



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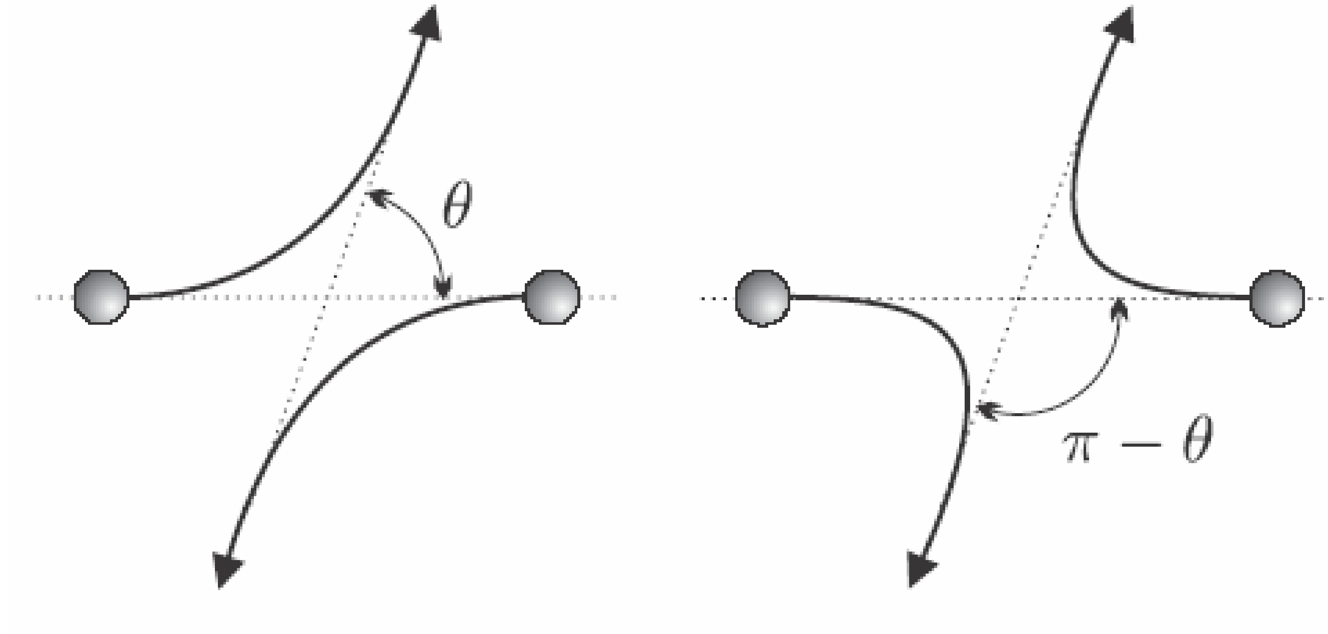

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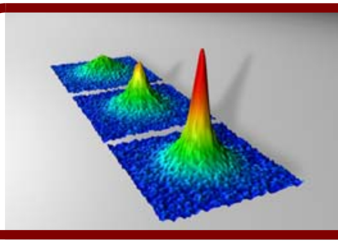
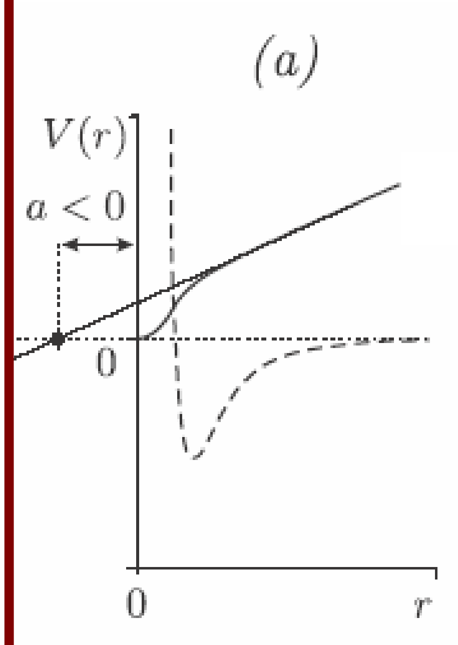
$$\Rightarrow \boxed{\sigma_s = 8\pi a^2}$$

with $a = -\dfrac{\delta_0}{k}$

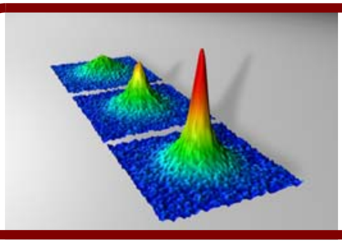


Scattering

Scattering length qualitatively:



see: $$\frac{\hbar^2}{2m_r}\frac{d^2}{dr^2}\psi = (V(r) - E)\,\psi$$



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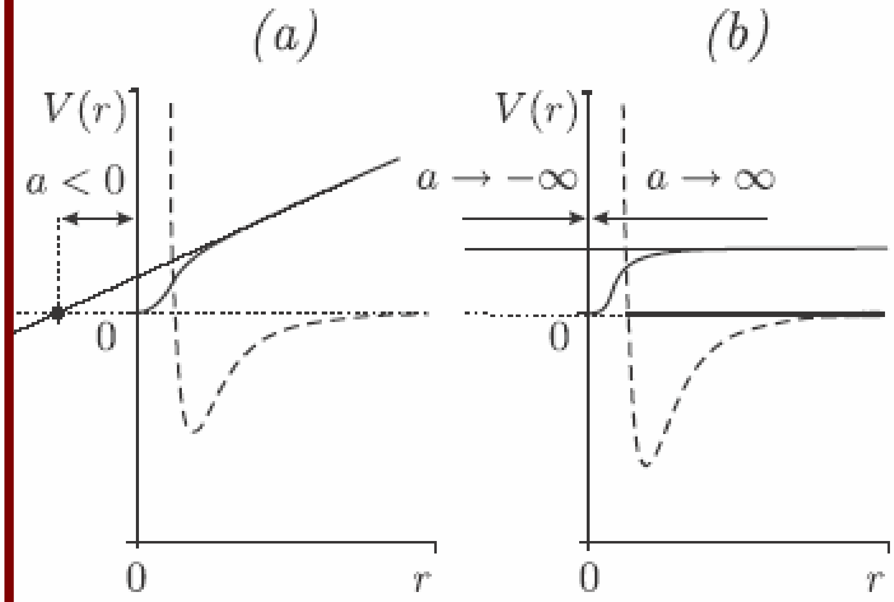

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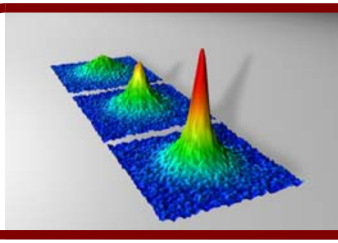

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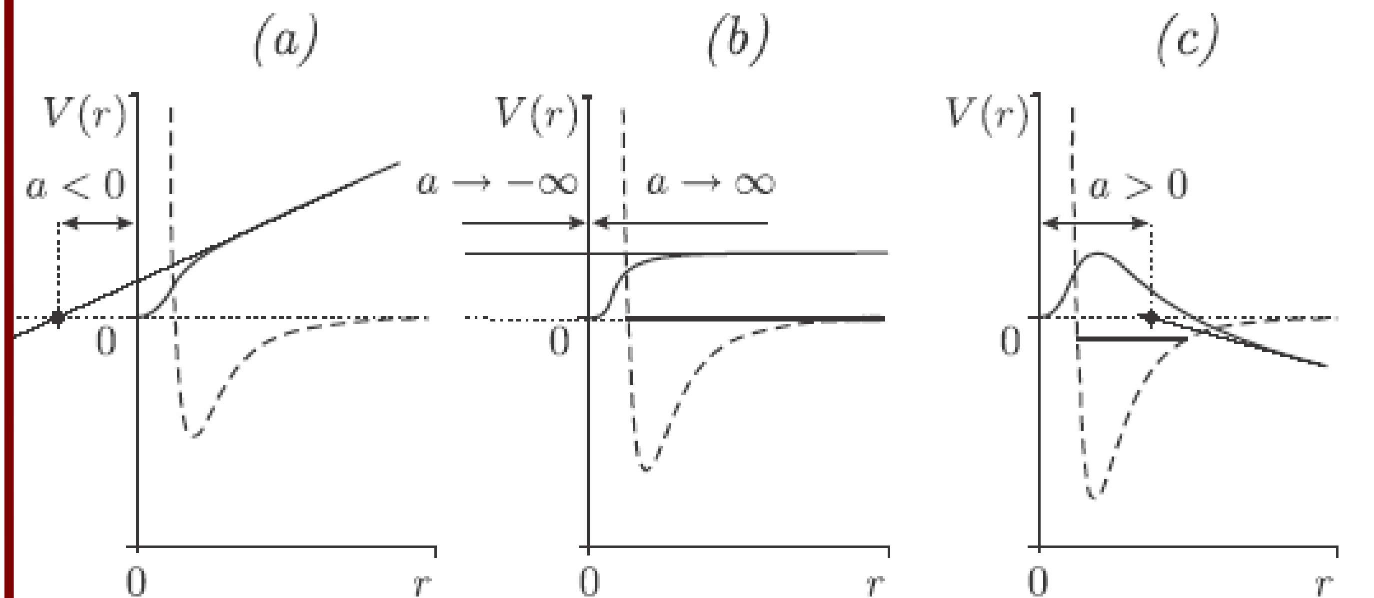

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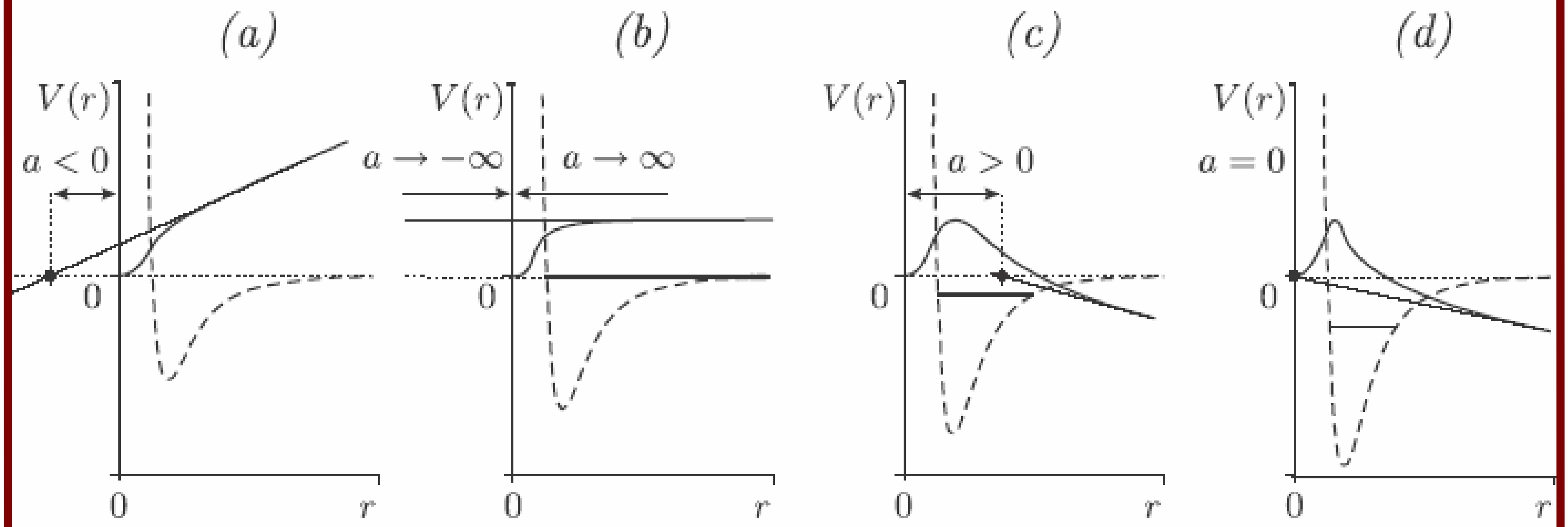

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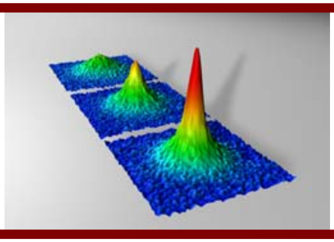

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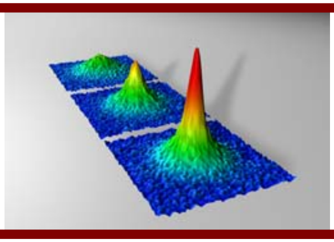

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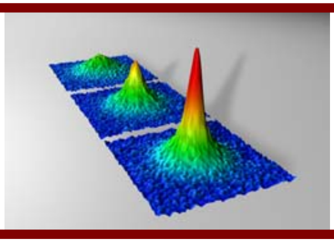
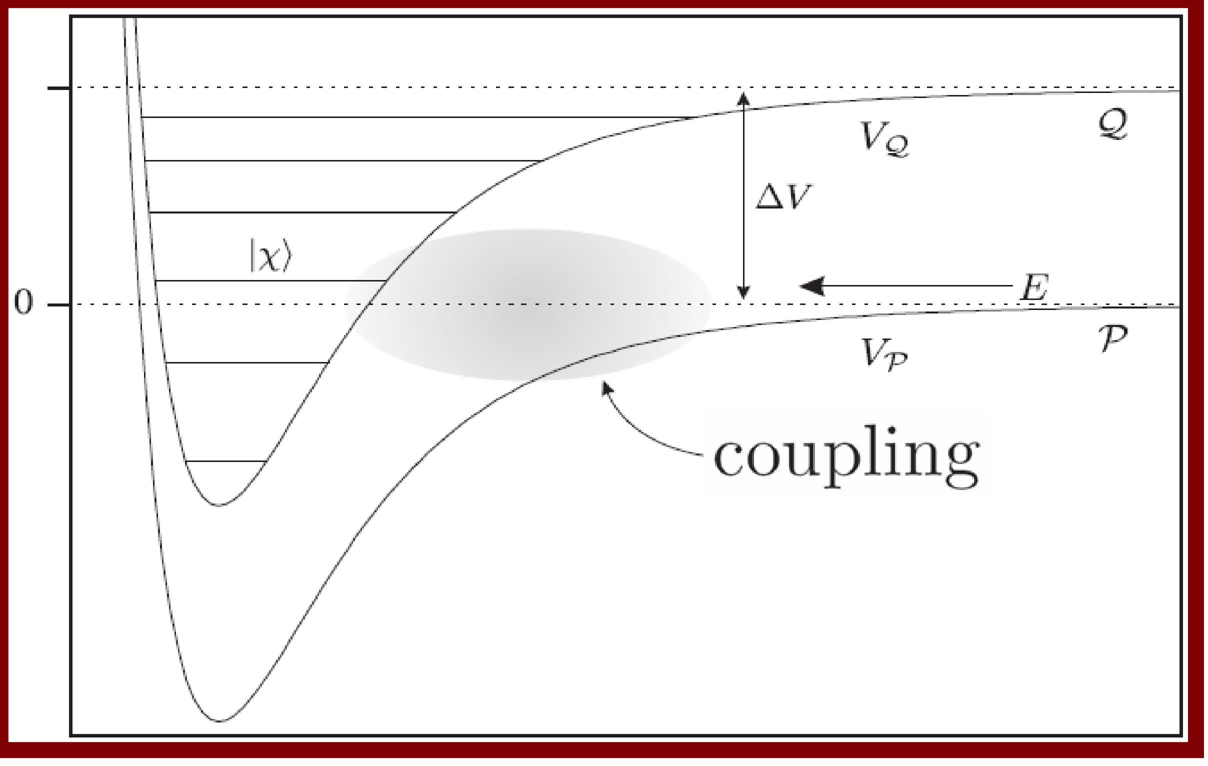
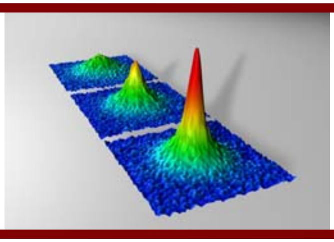


Feshbach Resonance

using the Coupled-Channels Method:

Channels $|\mathcal{P}\rangle, |\mathcal{Q}\rangle$ **:**





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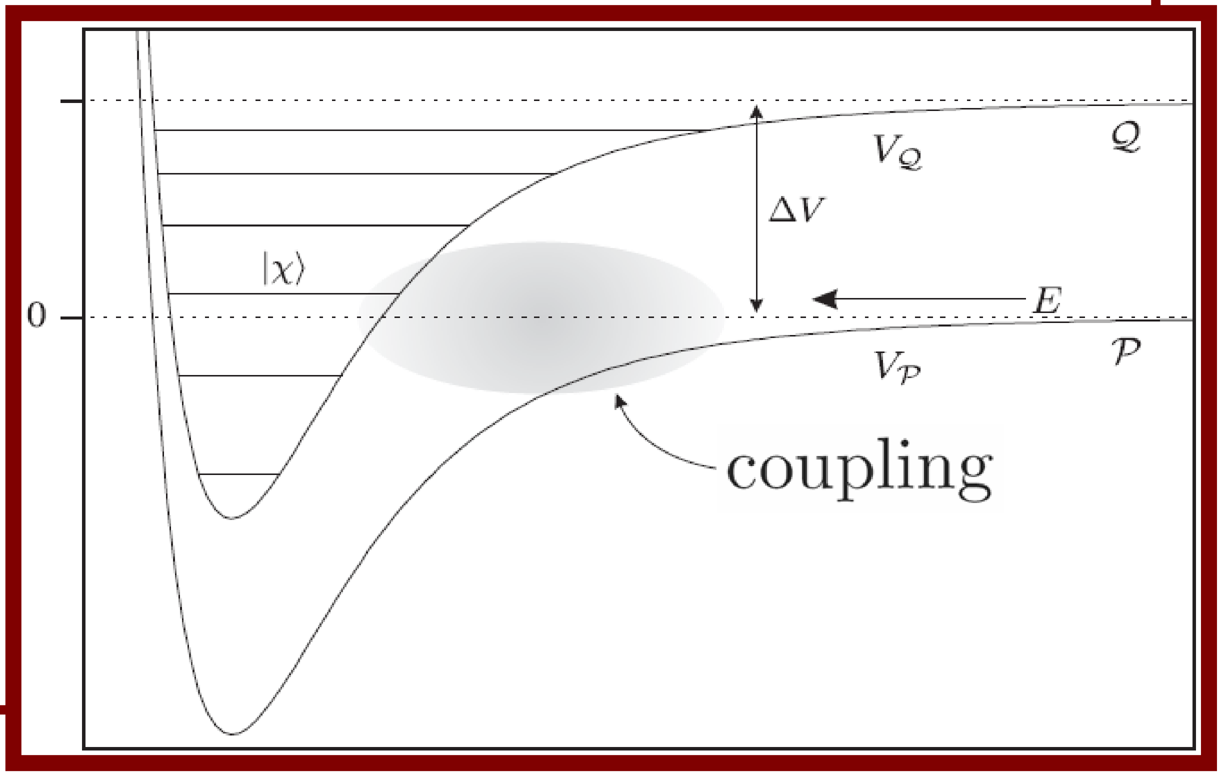
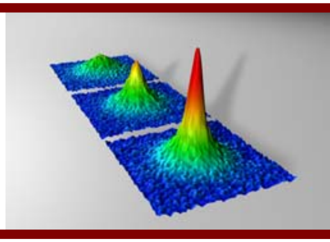
$$\mathcal{H}_0 \, |\mathcal{P}\rangle = E_Q \, |\mathcal{P}\rangle$$





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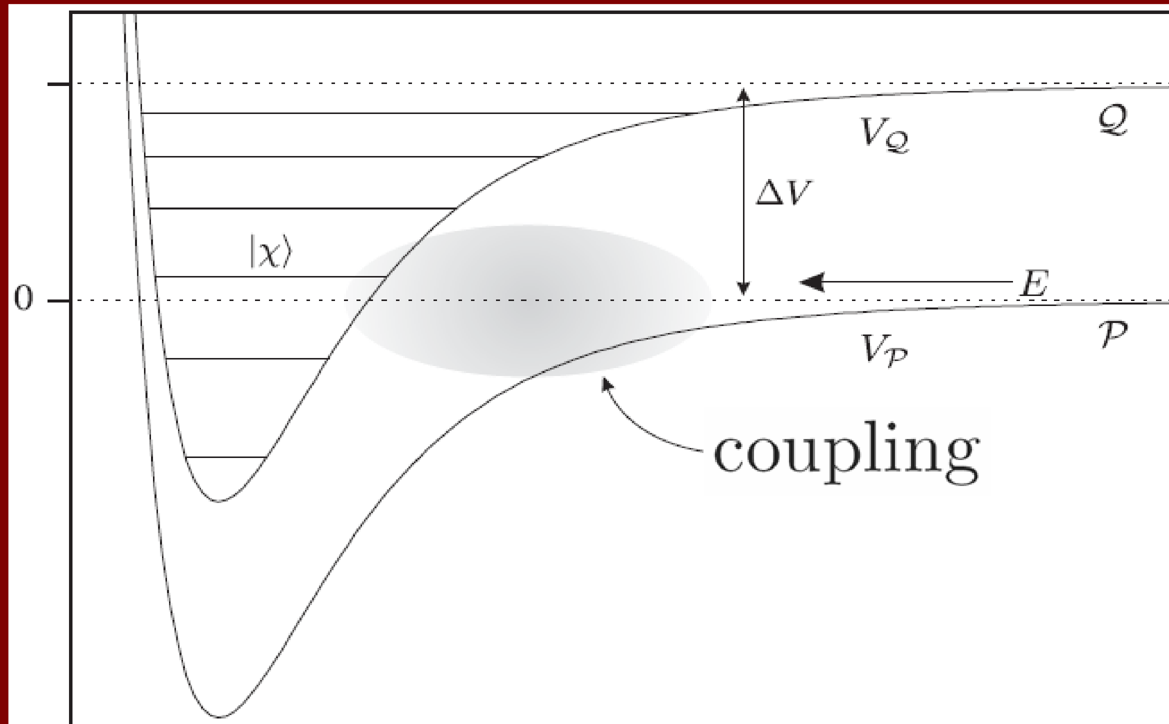
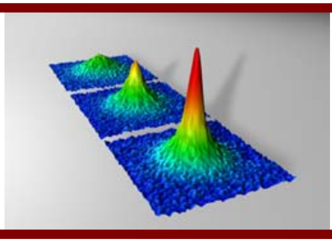




Feshbach Resonance

using the Coupled-Channels Method:

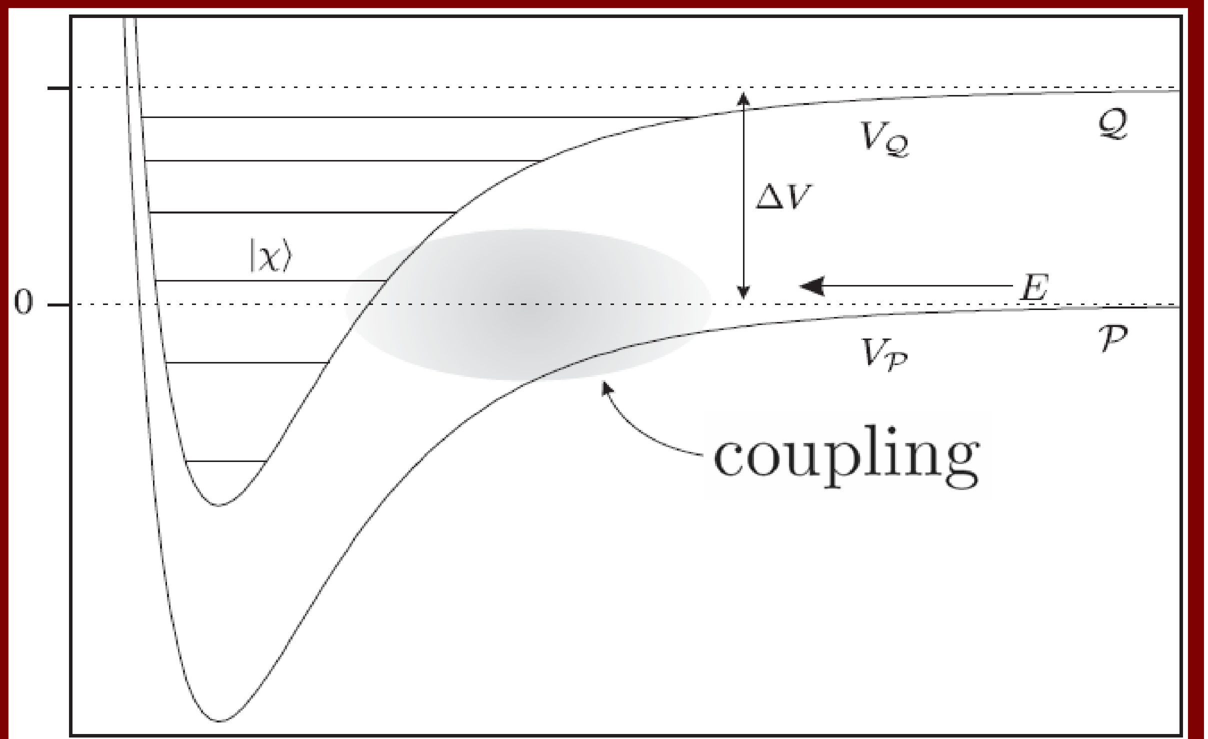
Channels $|\mathcal{P}\rangle, |\mathcal{Q}\rangle$: energy eigenstates of uncoupled system:

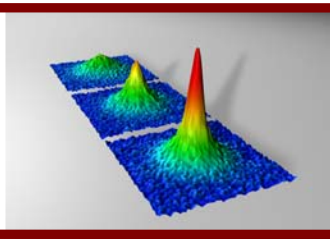
$$\mathcal{H}_0 |\mathcal{P}\rangle = E_Q |\mathcal{P}\rangle \, , \, \mathcal{H}_0 |\mathcal{Q}\rangle = E_P |\mathcal{Q}\rangle$$

Open Channel $|\mathcal{P}\rangle$:

$$E > V_P$$

unbound state





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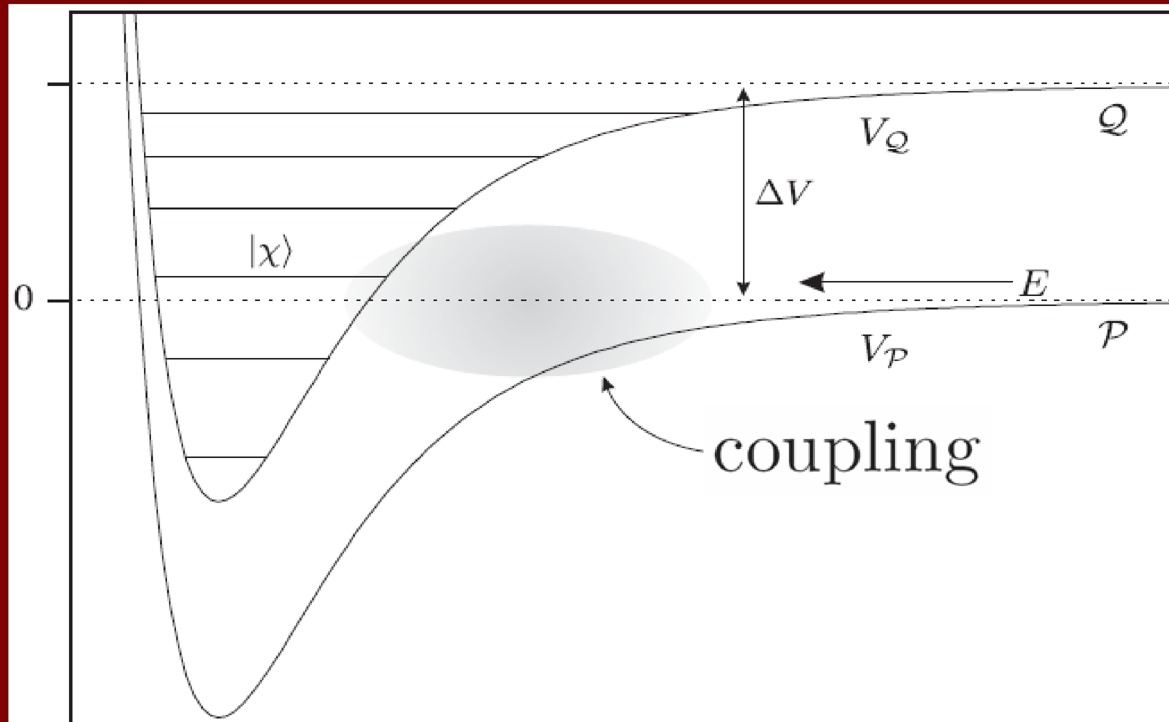
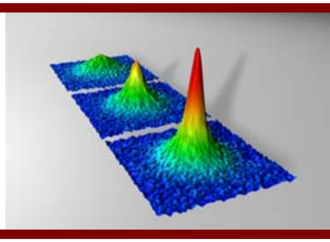
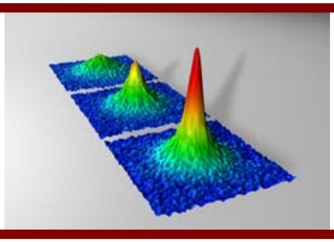




Feshbach Resonance

Theoretical Solution to this Resonance phenomena:



Feshbach Resonance

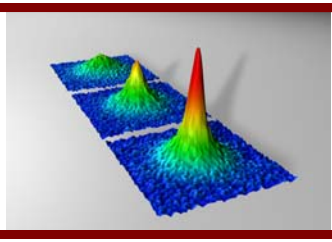
Theoretical Solution to this Resonance phenomena:

Project solution of stationary SGL onto two disjoint subspaces:

$$\mathcal{H} = \mathcal{H}_{\mathcal{P}} + \mathcal{H}_{\mathcal{Q}}$$

All open channels
(unbound states)

All closed channels
(bound states)



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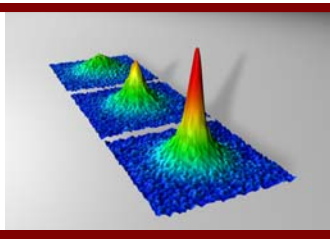
All closed channels (bound states)

⇒ **2 coupled differential equations that provide:**

with: $\mathcal{H}_{\mathcal{P}\mathcal{P}} = \mathcal{P}\mathcal{H}\mathcal{P}$ etc. ⇒



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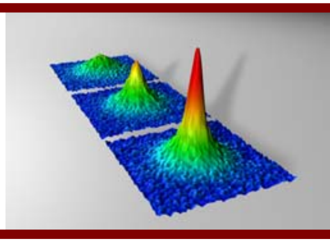
$$\left(\mathcal{H}_{\mathcal{P}\mathcal{P}} + \mathcal{H}_{\mathcal{P}\mathcal{Q}} \frac{1}{E^{+} - \mathcal{H}_{\mathcal{Q}\mathcal{Q}}} \mathcal{H}_{\mathcal{Q}\mathcal{P}} \right) |\psi_P\rangle = E \, |\psi_P\rangle$$



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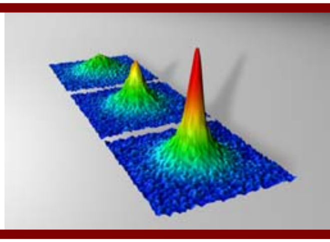
Coupling in the
open channel



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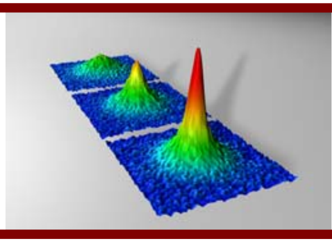
Coupling in the open channel

Transition in the closed channel



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All closed channels
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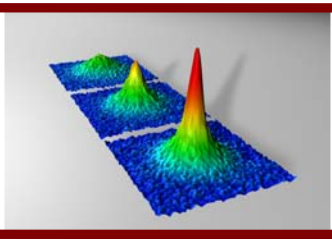
2 coupled differential equations that provide:

$$\left(\mathcal{H}_{\mathcal{PP}} + \mathcal{H}_{\mathcal{PQ}}\frac{1}{E^{+} - \mathcal{H}_{\mathcal{QQ}}}\mathcal{H}_{\mathcal{QP}}\right)|\psi_P\rangle = E\,|\psi_P\rangle$$

Coupling in the
open channel

Transition in
the closed channel

'free-propagation' in
the closed channel



Feshbach Resonance

Theoretical Solution to this Resonance phenomena:

Project solution of stationary SGL onto two disjoint subspaces:

$$\mathcal{H} = \mathcal{H}_{\mathcal{P}} + \mathcal{H}_{\mathcal{Q}}$$

All open channels (unbound states) → $\mathcal{H}_{\mathcal{P}}$

All closed channels (bound states) → $\mathcal{H}_{\mathcal{Q}}$

2 coupled differential equations that provide:

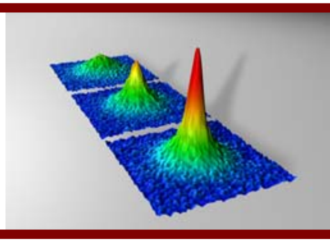
$$\left(\mathcal{H}_{\mathcal{PP}} + \mathcal{H}_{\mathcal{PQ}} \frac{1}{E^+ - \mathcal{H}_{\mathcal{QQ}}} \mathcal{H}_{\mathcal{QP}}\right) |\psi_P\rangle = E\, |\psi_P\rangle$$

Coupling in the open channel → $\mathcal{H}_{\mathcal{PP}}$

Transition in the closed channel → $\mathcal{H}_{\mathcal{PQ}}$

'free-propagation' in the closed channel → $\frac{1}{E^+ - \mathcal{H}_{\mathcal{QQ}}}$

Transition in the closed channel → $\mathcal{H}_{\mathcal{QP}}$



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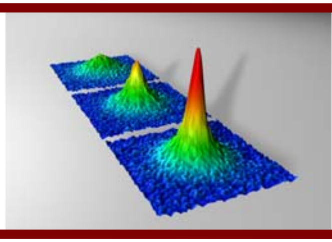
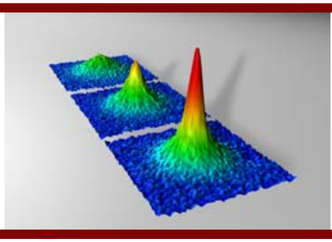


Feshbach Resonance

Theoretical Solution to this Resonance phenomena:

Transition amplitude ⇨ **scattering matrix** ⇨ **scattering length:**



Feshbach Resonance

Theoretical Solution to this Resonance phenomena:

Transition amplitude ⇒ **scattering matrix** ⇒ **scattering length:**

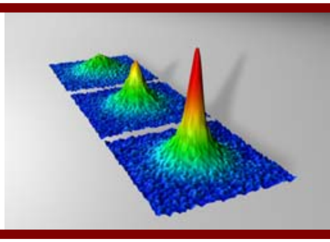
$$\boxed{a(B) = a_{nr}\left(1 - \frac{\Delta B}{B - B_0}\right)}$$

$a_{nr} \equiv a$ not resonant

$\Delta B \equiv$ width of the resonance

$B_0 \equiv$ B at resonance

$B = B_0$



Feshbach Resonance

Theoretical Solution to this Resonance phenomena:

Transition amplitude → scattering matrix → scattering length:

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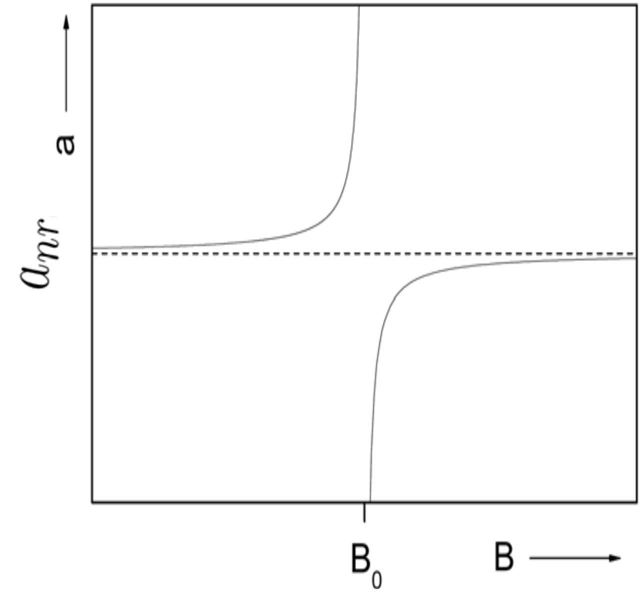
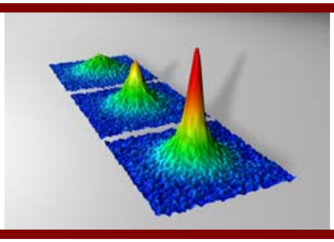
diverges for:

$$B = B_0$$





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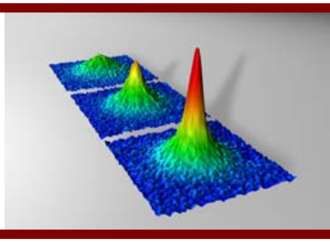

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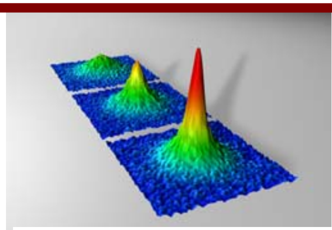
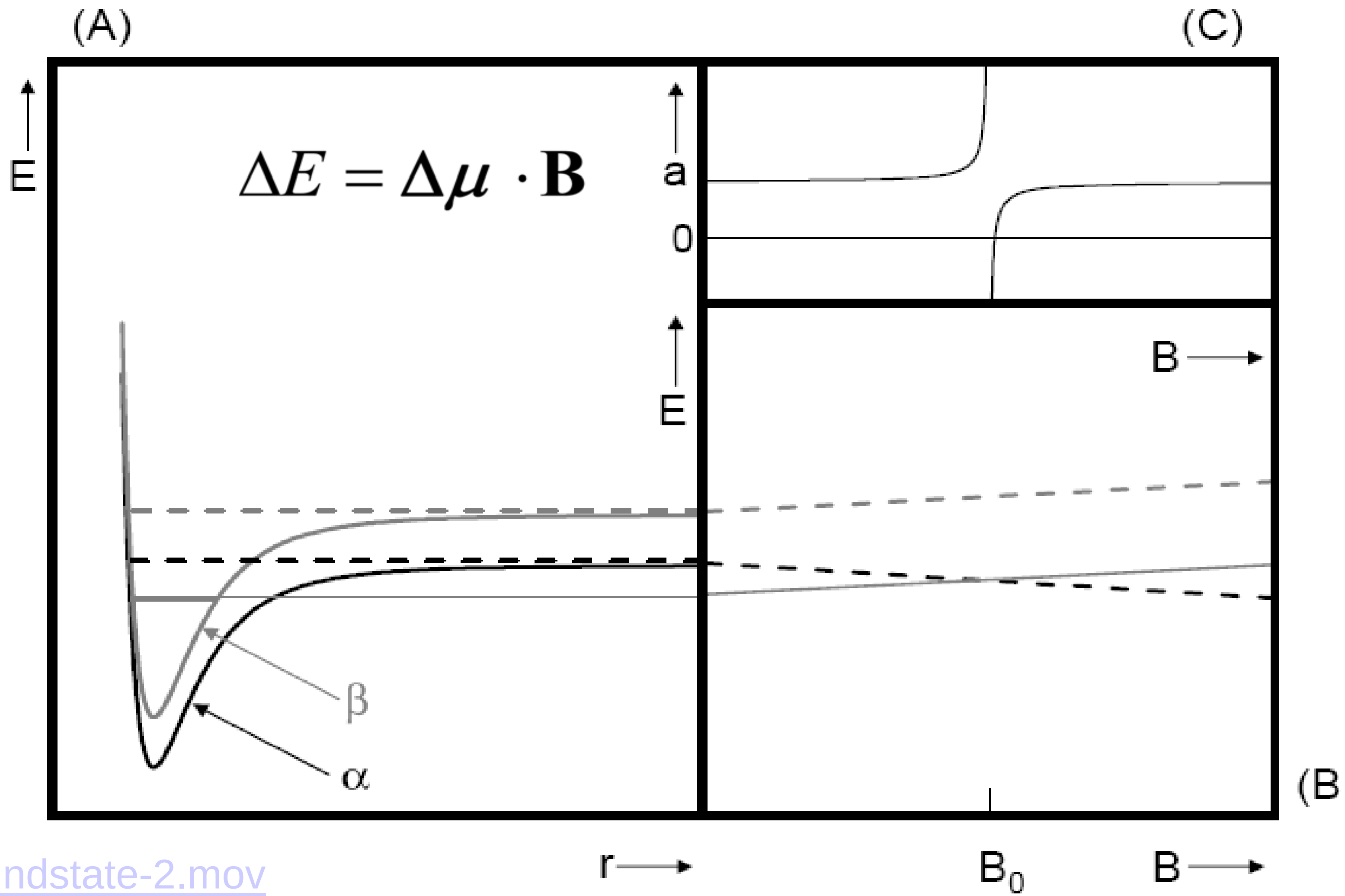
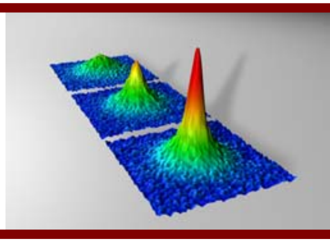


Feshbach Resonance prediction:



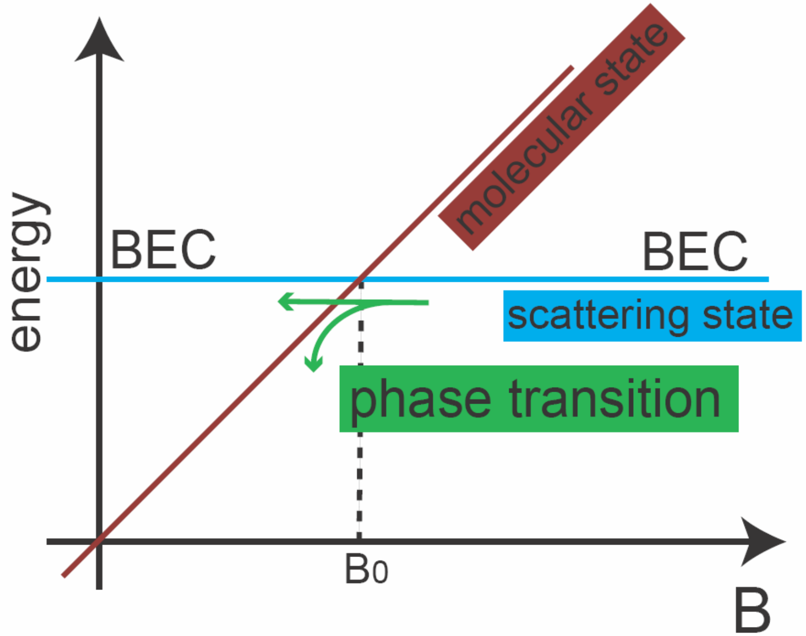
Boundstate-2.mov

N. Nygaard, B. I. Schneider, P. S. Julienne. Phys. Rev. A 73, 042705, 2006.

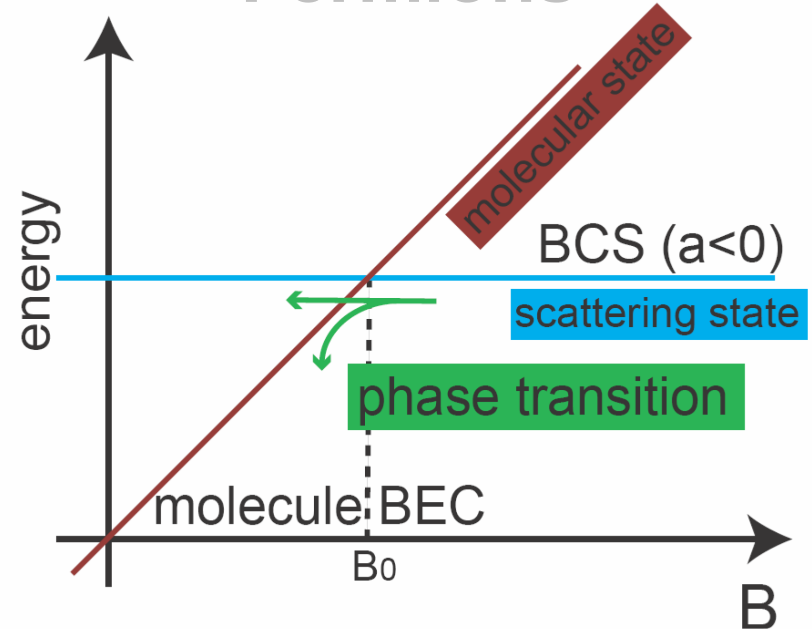


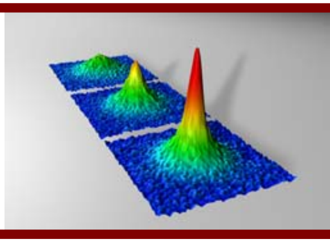
Feshbach Resonance prediction: bosons vs. fermions

Bosons



Fermions





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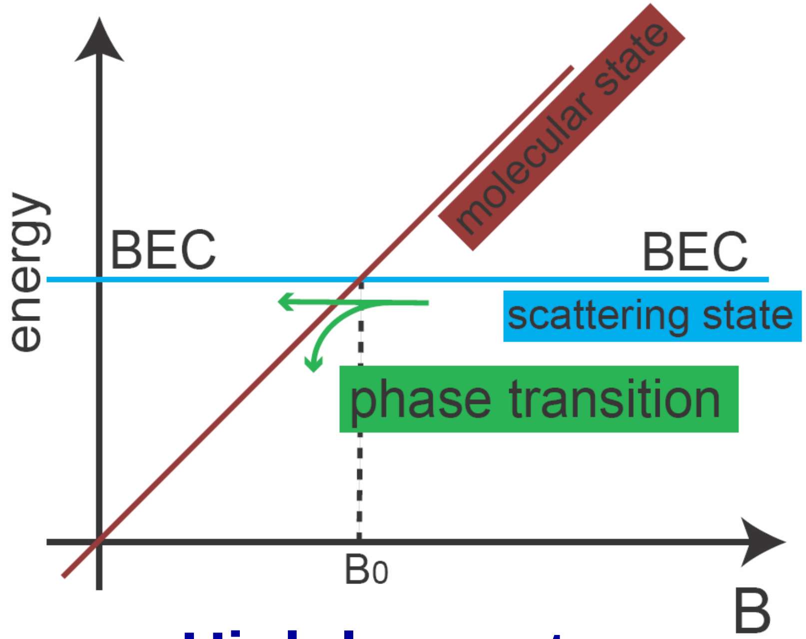
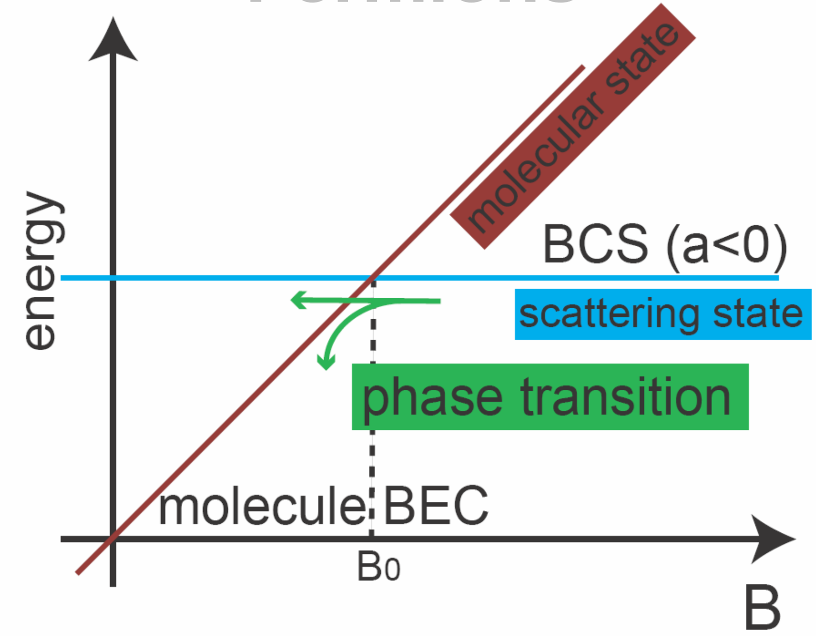
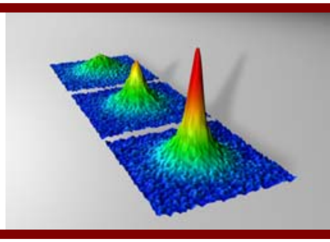


High loss rate

no molecule BEC

Fermions





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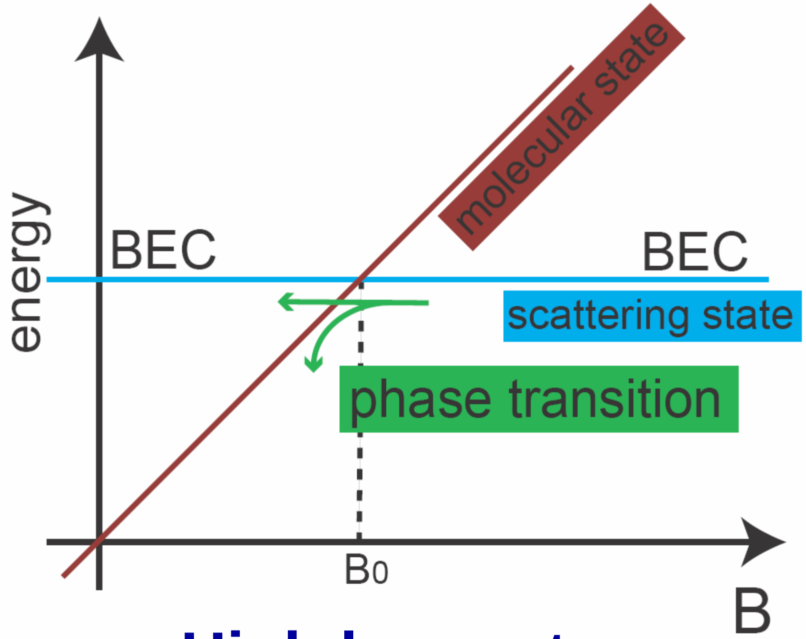

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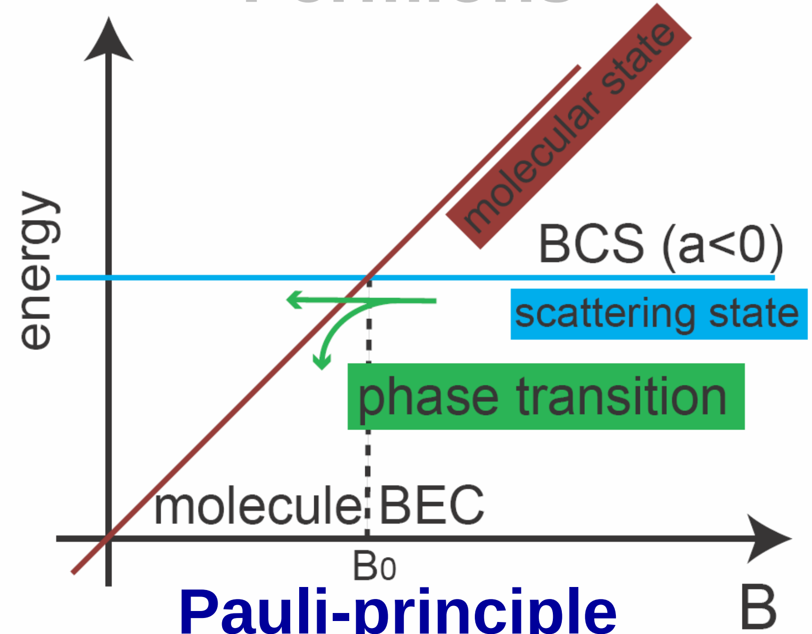
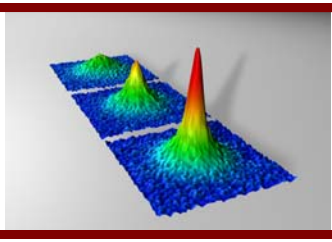


Pauli-principle

surpressed collisions

Continous transition between 2 states of matter possible



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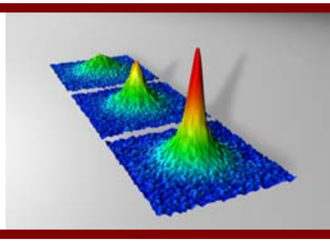

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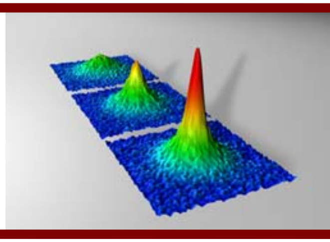
3. **Experimental Observations**



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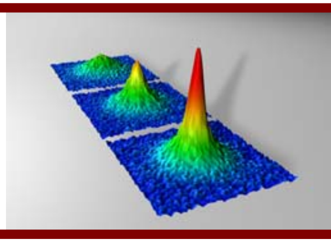
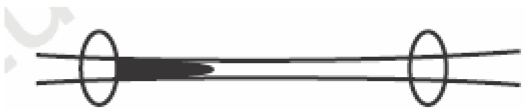


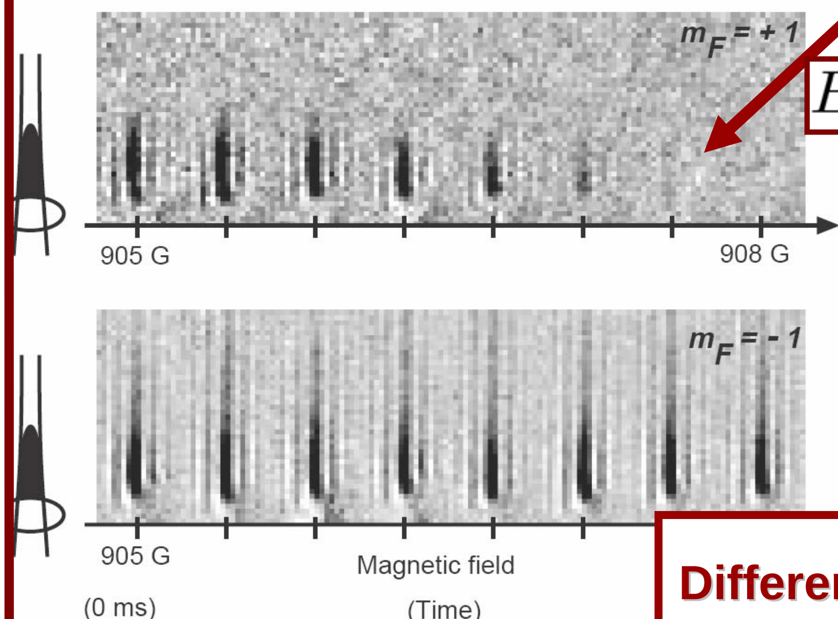
Feshbach Resonances in Experiments

bosonic ^{23}Na :

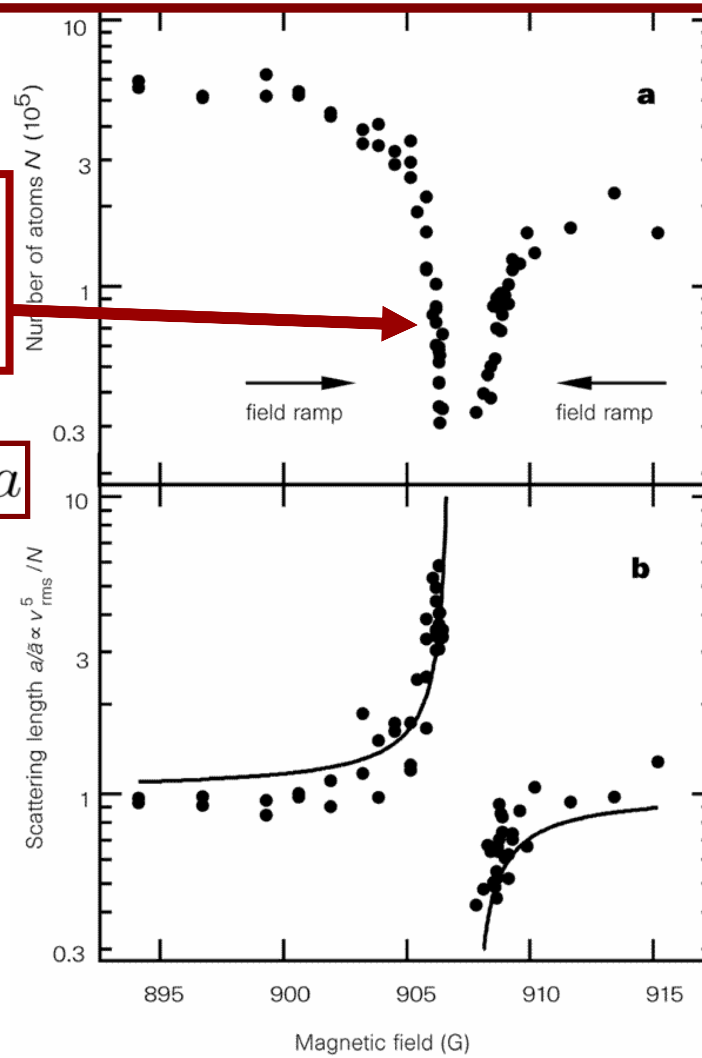


High lost at resonance

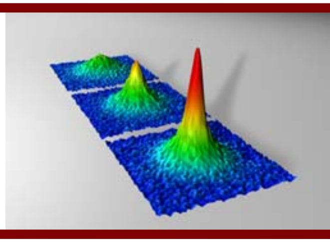
$E_{int} \propto a$



Different mag. sublevel



S. Inouye, M. R. Andrews, J. Stenger, H.-J. Miesner, D. M. Stamper-Kurn, und W. Ketterle. Nature, 392:151, 1998.



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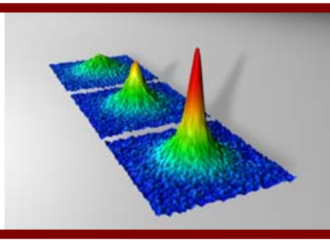

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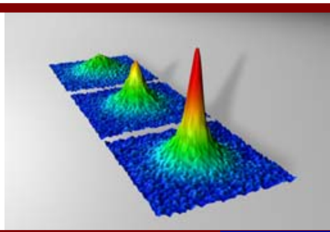
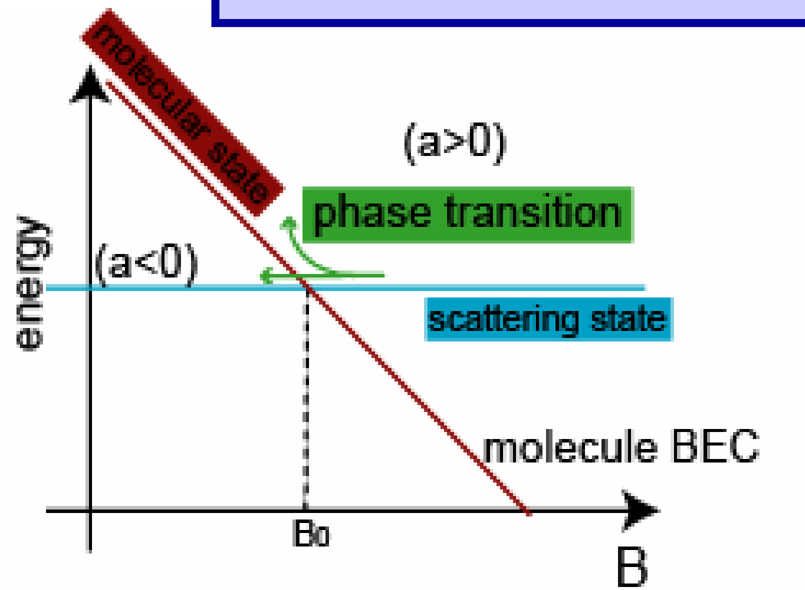
- **3.1** Feshbach Resonances
- **3.2** Creation of a molecular condensate



Feshbach Resonances to create molecules:

Controlled creation of molecular BEC:

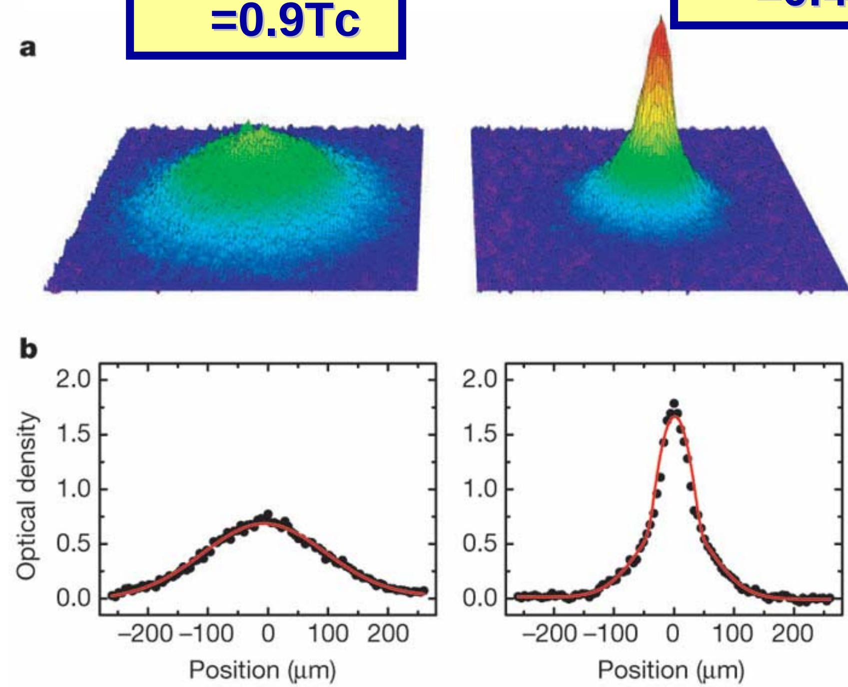


$n_{Peak}=7*10^{12}cm^{-3}$

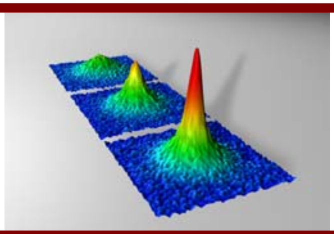
Fermionic ^{40}K:

T =250nK =0.9Tc

T =79nK =0.49Tc

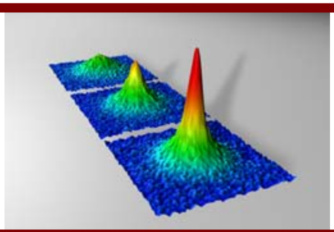


Markus Greiner, Cindy A. Regal, and Deborah S. Jin. Nature 426, 537 (2003).



Summary and Outlook

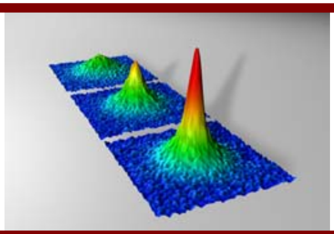
special type of interactions at very low temperatures:



Summary and Outlook

special type of interactions at very low temperatures:

Feshbach Resonances

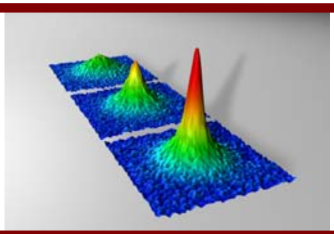


Summary and Outlook

special type of interactions at very low temperatures:

Feshbach Resonances

highly controlled experimental manipulation of the particle interaction at low T



Summary and Outlook

special type of interactions at very low temperatures:

↓

Feshbach Resonances

↓

highly controlled experimental manipulation of the particle interaction at low T

↓

creation of new particles (molecules and Cooper pairs)

Thank you for your attention