Widths and shifts of magnetic Feshbach resonances in atomic traps

V.S.Melezhik

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FFK-2015, Budapest, 12-16 October 2015

Results were obtained in collaboration with

Peter Schmelcher (ZOQ,Hamburg)

Shahpoor Saeidian (IASBS,Zanjan,Iran)

Innsbruck experiment:

Elmar Haller

Hans-Chrisroph Nagerl

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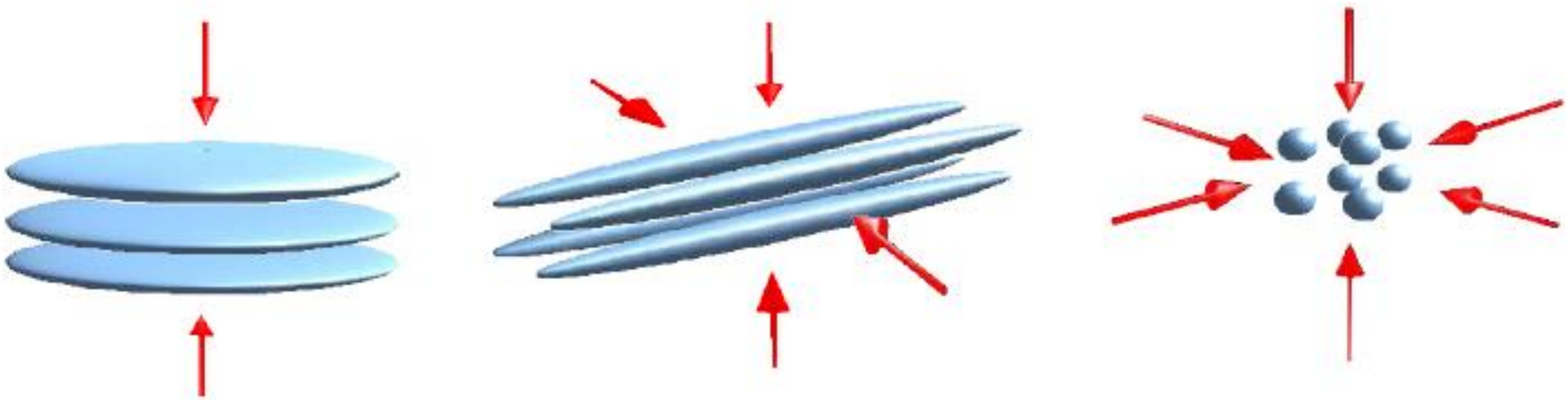
Outline

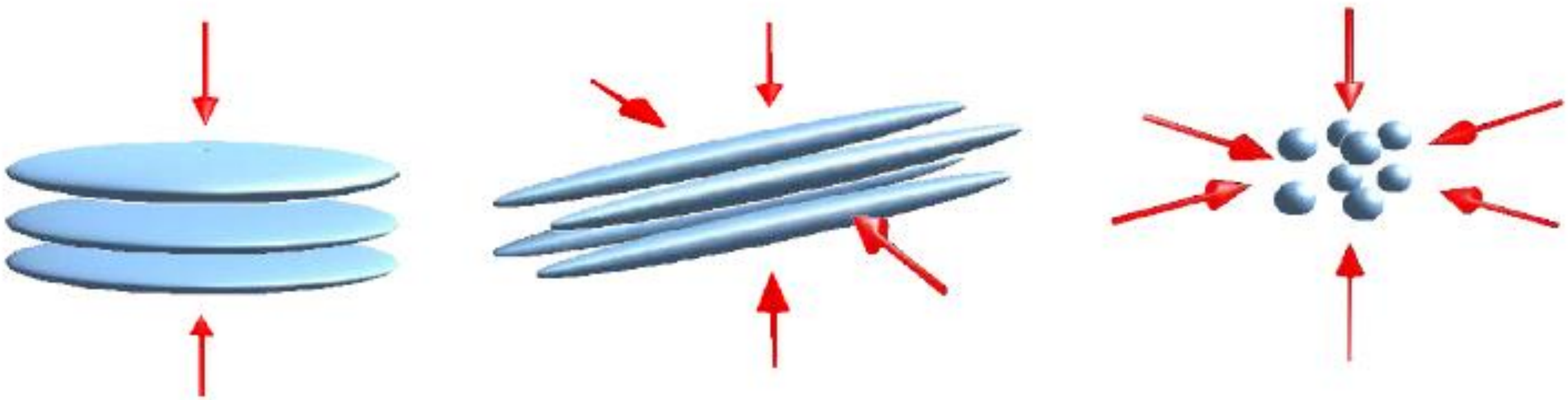
- Ultracold atoms and molecules in confined geometry of optical traps

  Why it is interesting, peculiarities

- Magnetic Feshbach resonances (MFR)
- Shifts of MFR in confining traps (simple model)
- Shifts and widths of MFR in atomic waveguides (quantitative analysis)
- Outlook



Lattices formed by applying orthogonal standing waves in one, two, and three directions.



Lattices formed by applying orthogonal standing waves in one, two, and three directions.

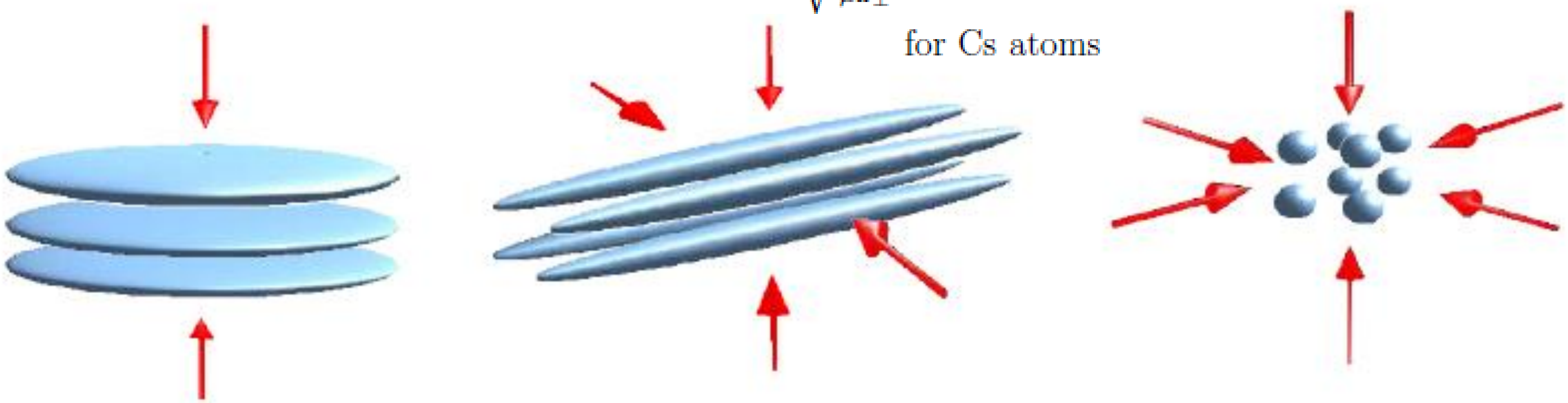
An electric field induces a dipole moment: $\vec{d} = \alpha \vec{E}$

Energy of a dipole in an electric field: $U_{dip} = -\dot{d} \cdot \vec{E}$

$\omega_\perp \sim 14\text{kHz}$

$a_\perp = \sqrt{\frac{\hbar}{\mu\omega_\perp}} \sim 70 - 100nm$

for Cs atoms



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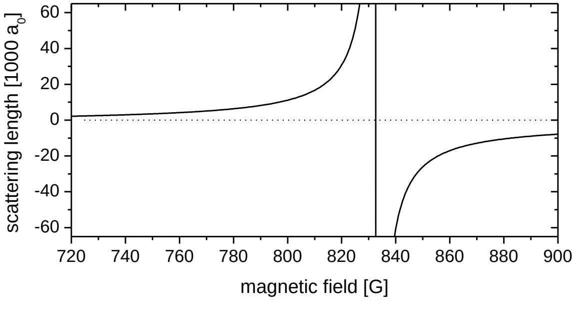
motivation in brief

experimental aspects

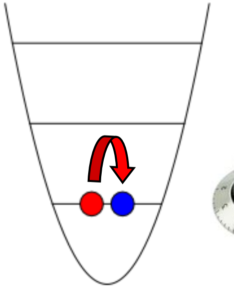
Experiments with deterministically prepared quantum systems

- **control interparticle interaction**

2 interacting particles in a 1D potential



magnetic Feshbach resonance



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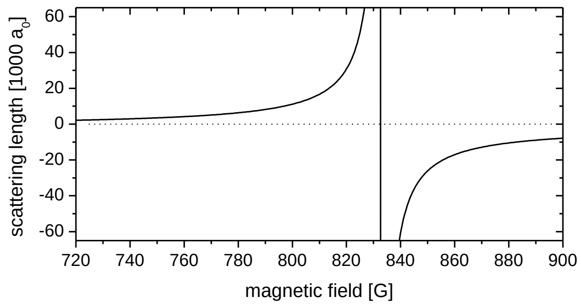

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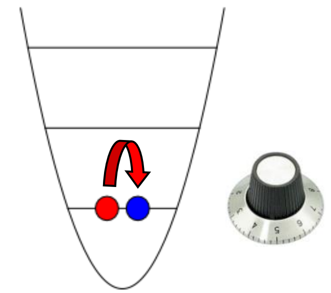
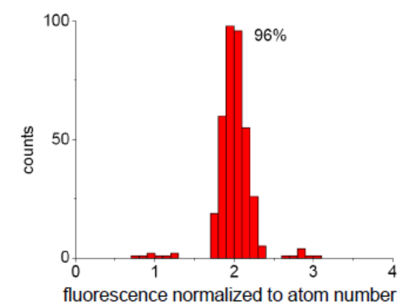


- **control over quantum states and particle number with long lifetime**



Experiments with deterministically prepared quantum systems

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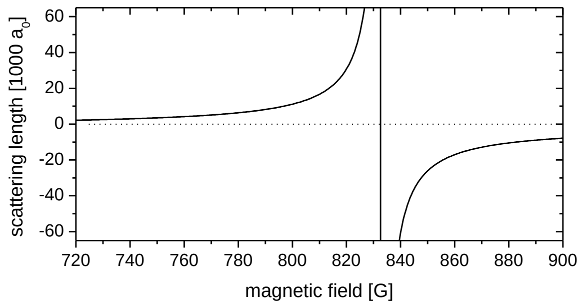

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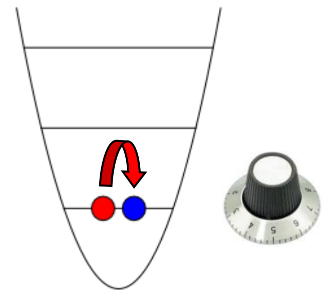

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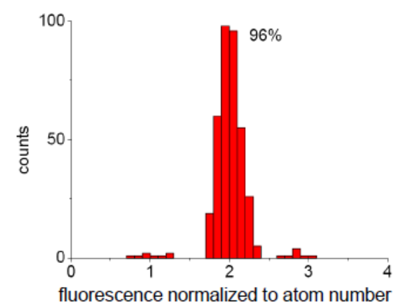

quantum simulation with fully controlled few-body systems

G.Zürn et. al. Phys. Rev. Lett. 108, 075303 (2012)

Quantum simulation with fully controlled few-body systems

control over: quantum states, particle number, interaction

- attractive interactions ➡ BCS-like pairing in finite systems
- repulsive int.+splitting of trap ➡ entangled pairs of atoms
  (quantum information processing)
- + periodic potential ➡ quantum many-body physics
  (systems with low entropy to explore
  such as quantum magnetism)
- ...

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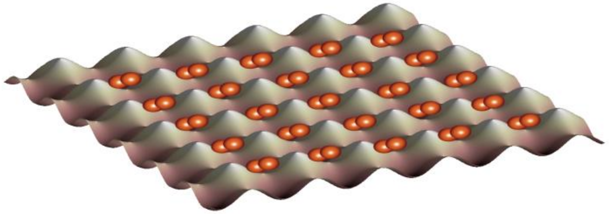
Bose-Hubbard Physics



R. P. Feynman's Vision

A Quantum Simulator to study the quantum dynamics of another system.

R.P. Feyman, Int. J. Theo. Phys. (1982)
R.P. Feynman, Found. Phys (1986)

motivation in brief

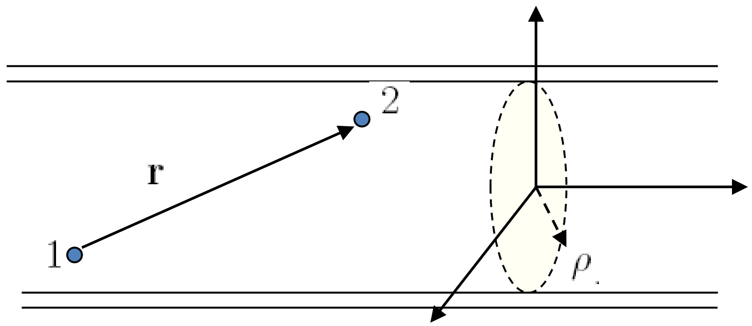
theoretical aspects

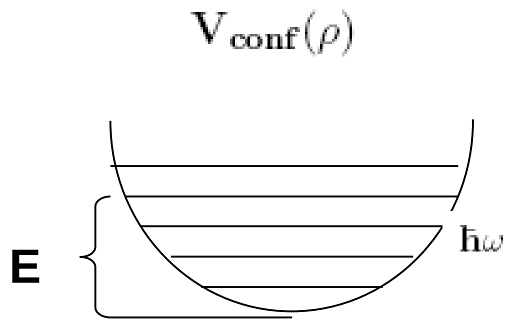
motivation in brief

theoretical aspects

3D free-space scattering theory is no longer valid and development of low-dimensional theory including influence of the trap is needed

What happens if atoms scatter in confined geometry (quasi-1D) ?





What happens in collision of two distinguishable atoms in harmonic trap, or identical atoms in anharmonic trap ?

$$H'(\boldsymbol{\rho_R}, \boldsymbol{r}) = -\frac{1}{2M}\left(\frac{\partial^2}{\partial \rho_R^2} + \frac{1}{4\rho_R^2}\right) - \frac{1}{2M\rho_R^2}\frac{\partial^2}{\partial \phi_R^2} + \frac{1}{2}(m_1\omega_1^2 + m_2\omega_2^2)\rho_R^2$$

$$-\frac{1}{2\mu}\frac{\partial^2}{\partial r^2} + \frac{L^2(\theta,\phi)}{2\mu r^2} + \frac{\mu^2}{2}\left(\frac{\omega_1^2}{m_1} + \frac{\omega_2^2}{m_2}\right)\rho^2 \underline{+ \mu(\omega_1^2 - \omega_2^2)\rho\rho_R cos(\phi - \phi_R)} + V(r)$$

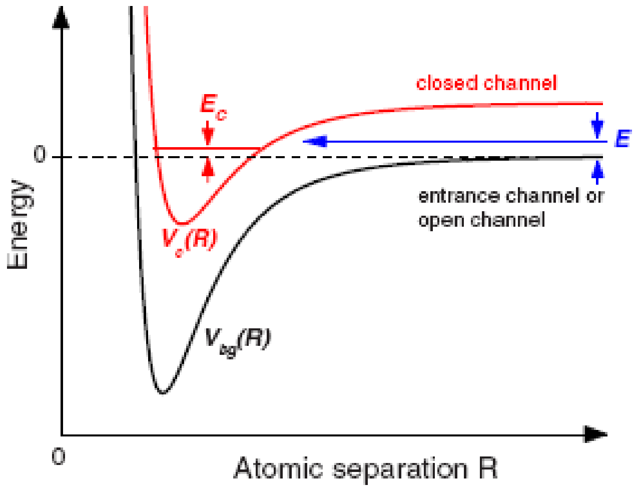
$$\mathbf{5D} \quad \longrightarrow \quad \{r, \theta, \phi, \rho_R, \phi_R\}$$

non-separable two-body problem

Shifts and widths of spectral lines in confining traps ?

Feshbach resonances

phenomenon occurs when particles in an entrance channel resonantly couple to bound state supported by the closed channel potential



H.Feshbach, Ann.Phys.5(1958);19(1961)

(nuclear reactions)

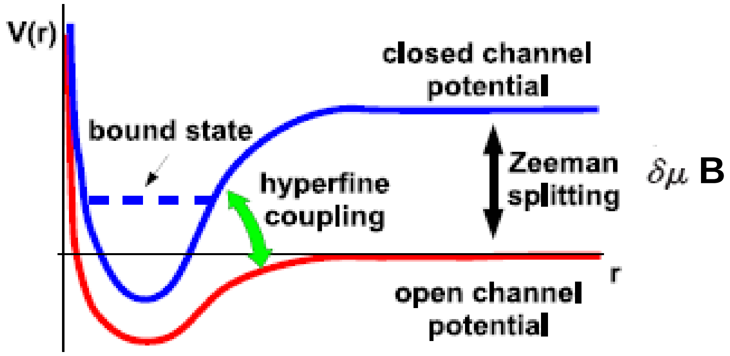
U.Fano, Phys.Rev.124(1961)

(atomic collisions)

the resonances occur when the scattering energy is varied

Magnetic Feshbach resonances

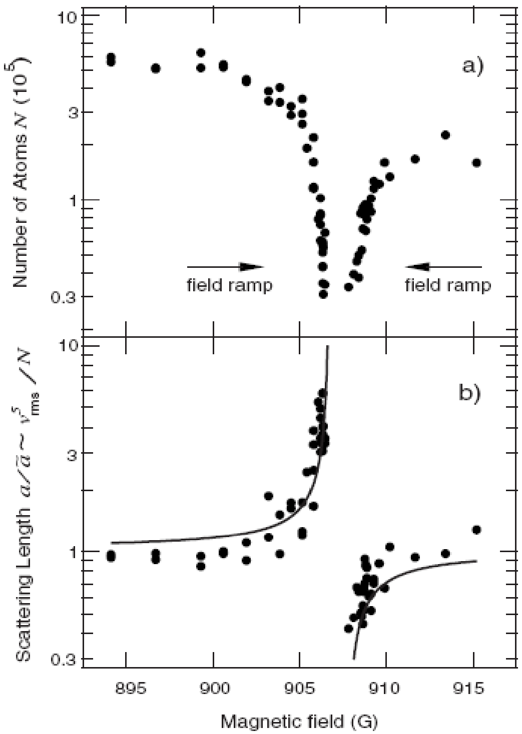
in ultracold gases scattering takes place in the zero-energy limit and the resonances occur when an external field B tunes bound state near threshold

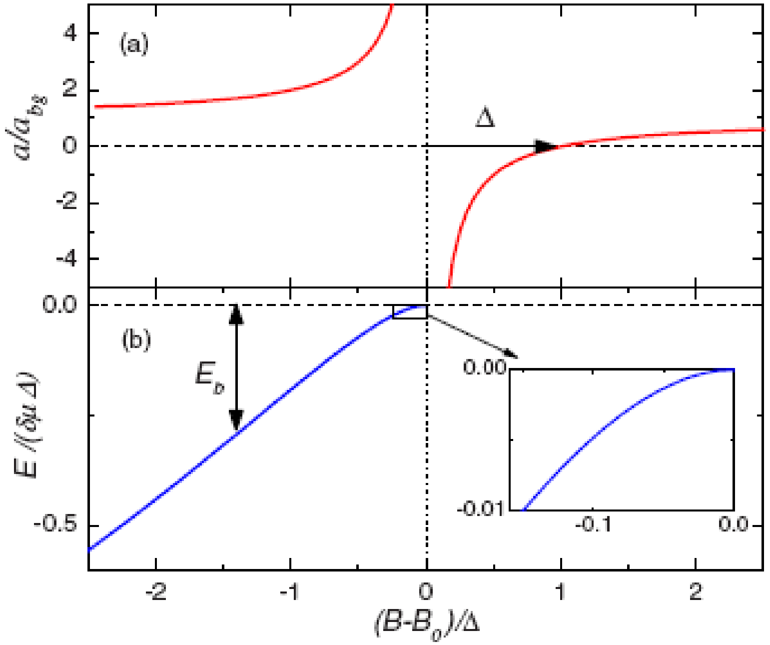


Simplified sketch of two collision potentials for atomic scattering in a magnetic field. The closed channel potential is for a predominantly singlet total electronic spin state, and the open channel is predominantly triplet.

Magnetic Feshbach resonances

S.Innouye et. al. Nature 392 (1998): Observation of FR in BEC





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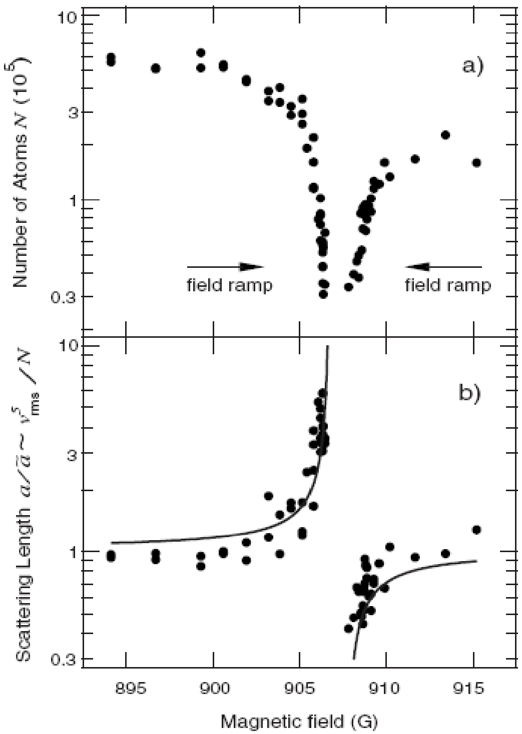

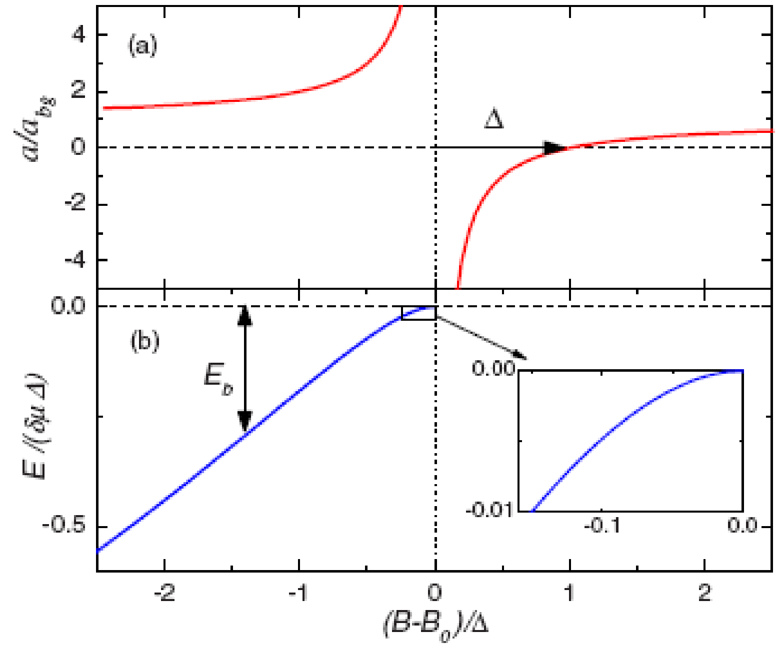

possibility to tune the interaction from strong attraction to strong repulsion

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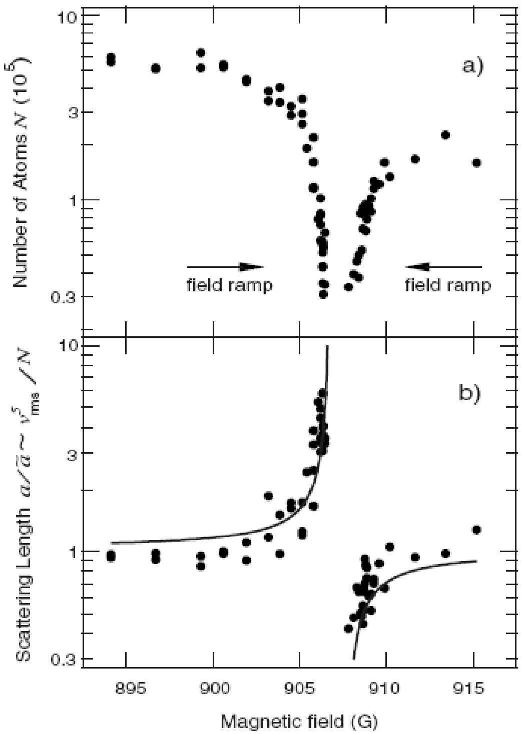

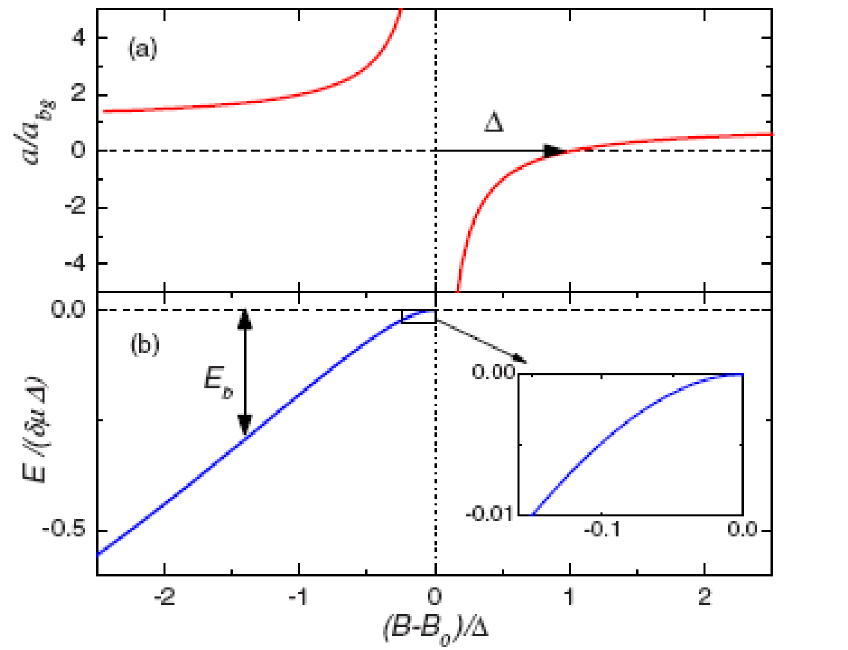

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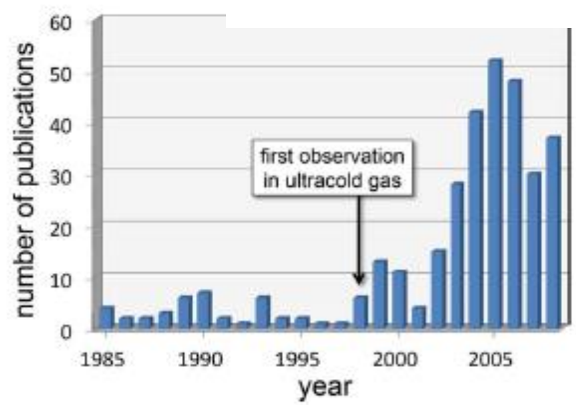
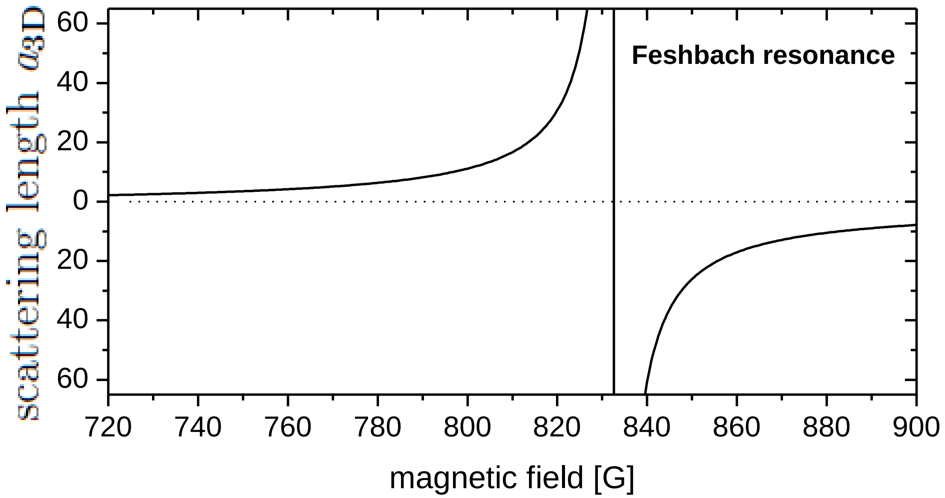


Number of publications per year (from 1985 to 2008) with Feshbach resonances appearing in the title. Data from ISI Web of Science.

Tuning the interaction in 3D

3D



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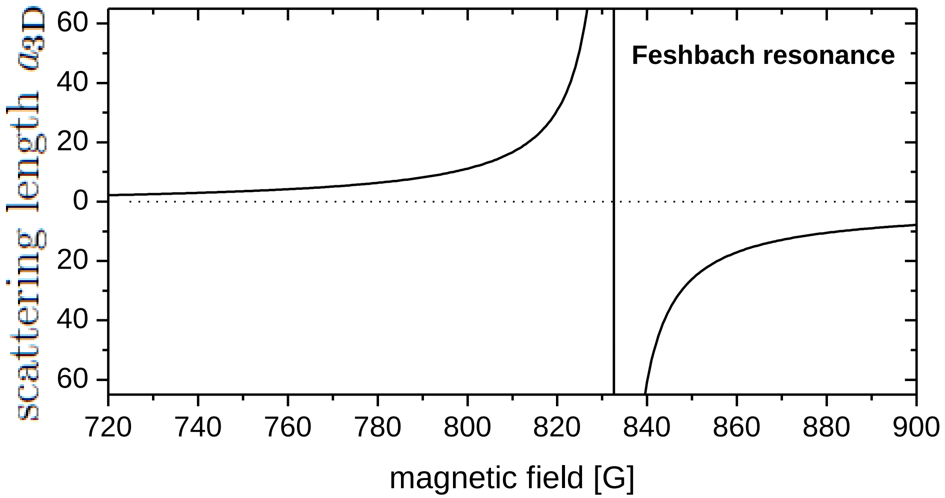
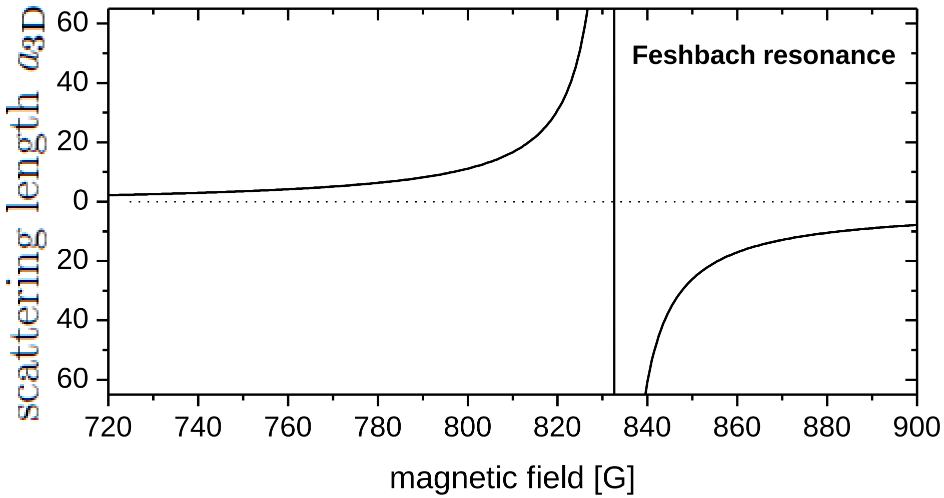


single-channel pseudopotential

$$\frac{2\pi\hbar^2 a_{3D}(B)}{\mu}\delta(\mathbf{r})$$

Tuning the interaction in 1D: B and ω

3D



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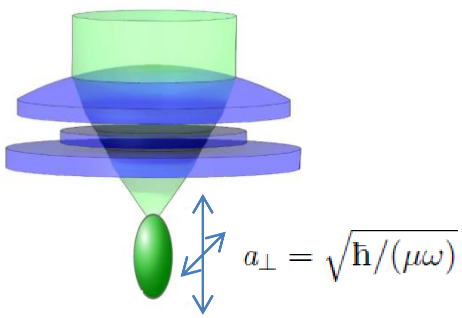
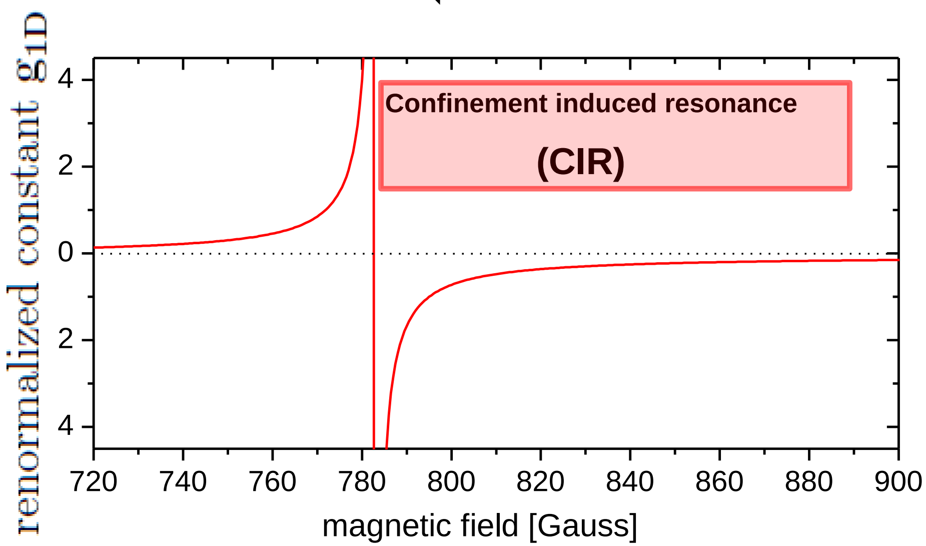
strong confinement



1D



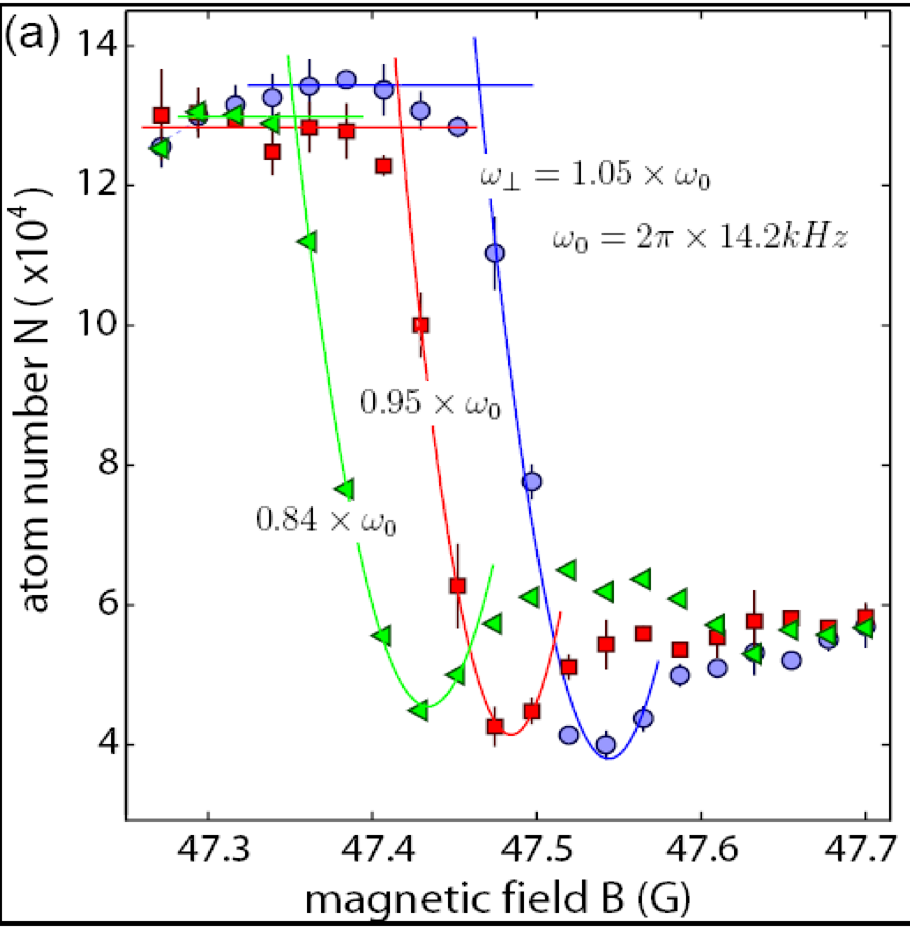
single-channel pseudopotential with renormalized interaction constant

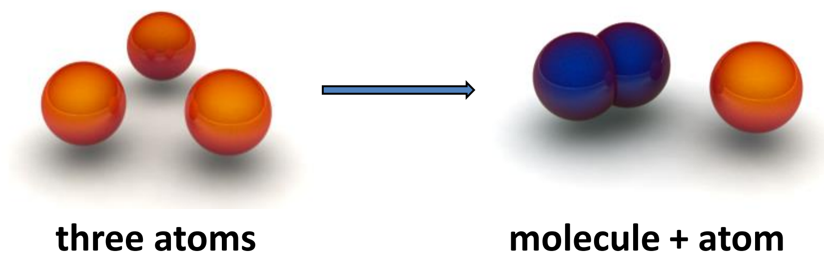
$$g_{1D} = \frac{2\hbar^2 a_{3D}(B)}{\mu a_\perp^2}\frac{1}{1-C a_{3D}/a_\perp}$$

M. Olshanii, PRL 81, 938 (1998).

E.Haller, M.J. Mark, R. Hart, J.G. Danzl, L. Reichsoellner, V.Melezhik, P. Schmelcher and H.-C. Naegerle, Phys.Rev.Lett. 104 (2010)153203

isotropic traps $\omega_1 = \omega_2 = \omega_\perp$





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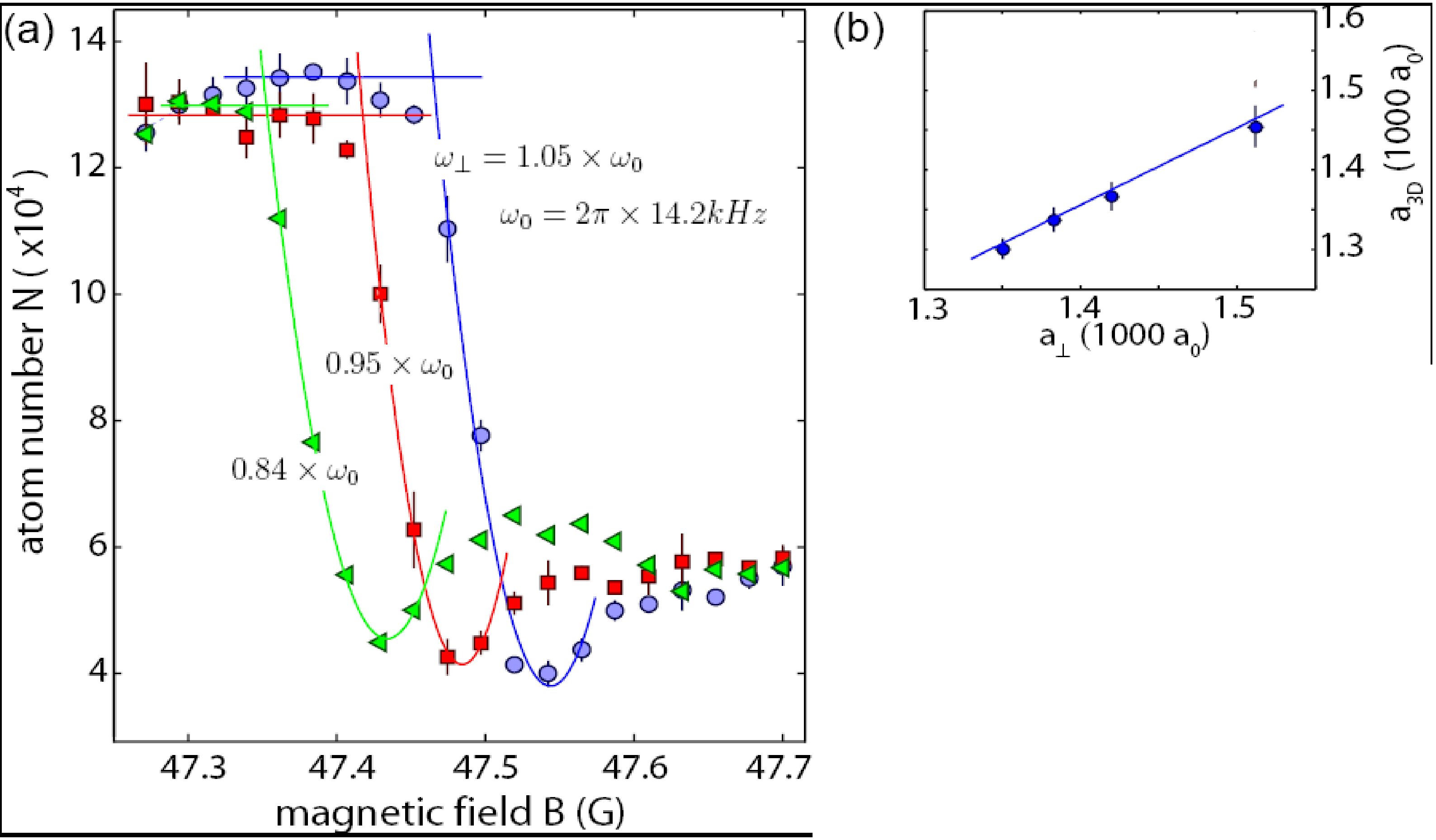

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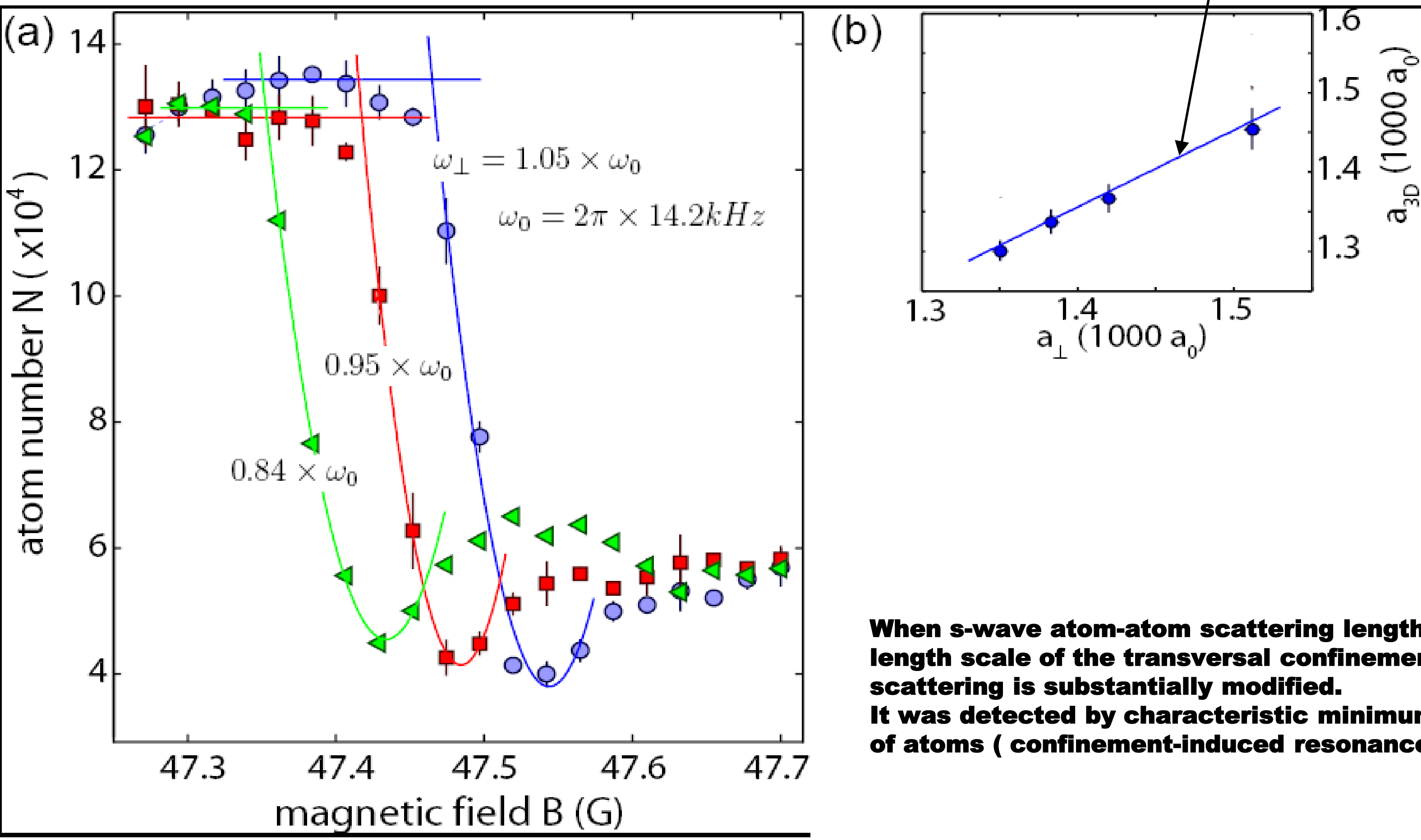
isotropic traps $\omega_1 = \omega_2 = \omega_\perp$

$$a_\perp = \sqrt{\frac{\hbar}{m\omega_\perp}}$$

$$C a_{3D} = a_\perp \quad C_{theor} = 1.0326$$

$$C_{exp} = 1.0326$$



When s-wave atom-atom scattering length approaches the length scale of the transversal confinement, atom-atom scattering is substantially modified.
It was detected by characteristic minimum of the number of atoms (confinement-induced resonance) in the 1D tubes

tensorial structure of the interatomic interaction V(r)

Feshbach Resonanzen

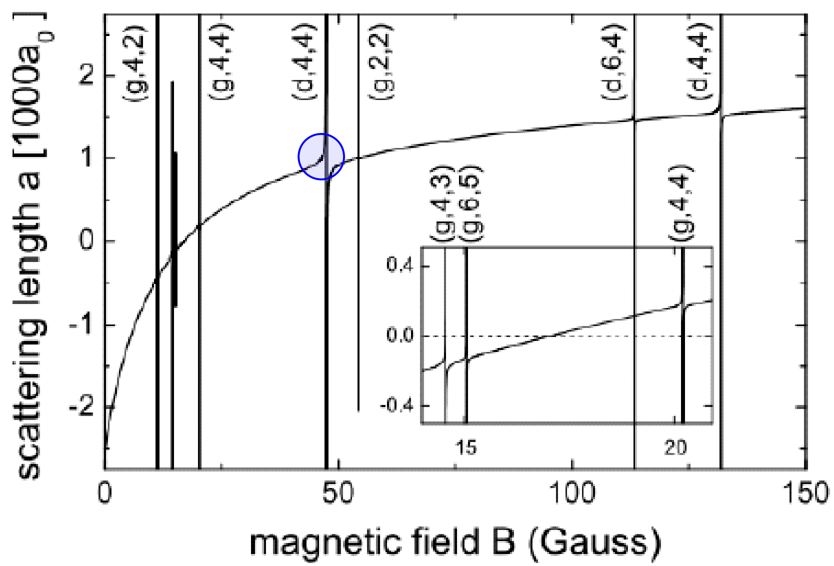
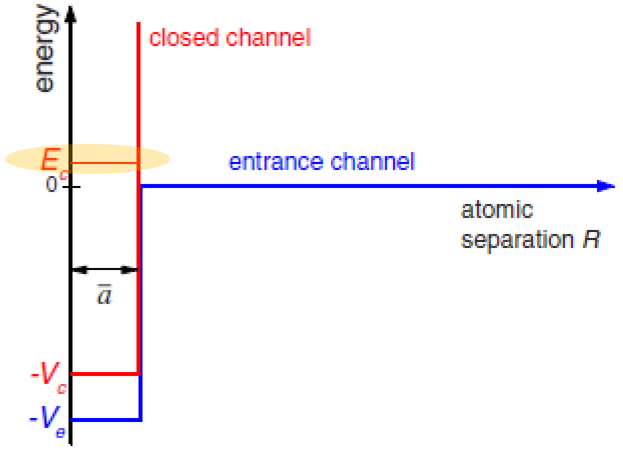


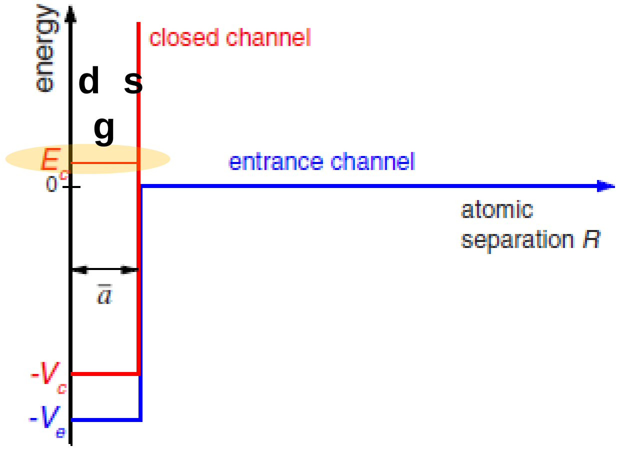
Figure 2.7.: Scattering length as a function of magnetic field for the state $F = 3$, $m_F = 3$. There is a Feshbach resonance at 48.0 G due to coupling to a d-wave molecular state. Several very narrow resonances at 11.0, 14.4, 15.0, 19.9 and 53.5 G are visible, which result from coupling to g-wave molecular states. The quantum numbers characterizing the molecular states are indicated, here as (l, f, m_f).

two-channel problem



two-channel problem

tensorial sructure of molecular state



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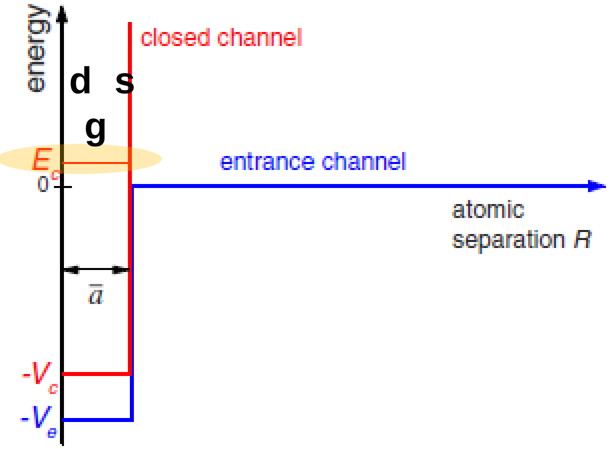
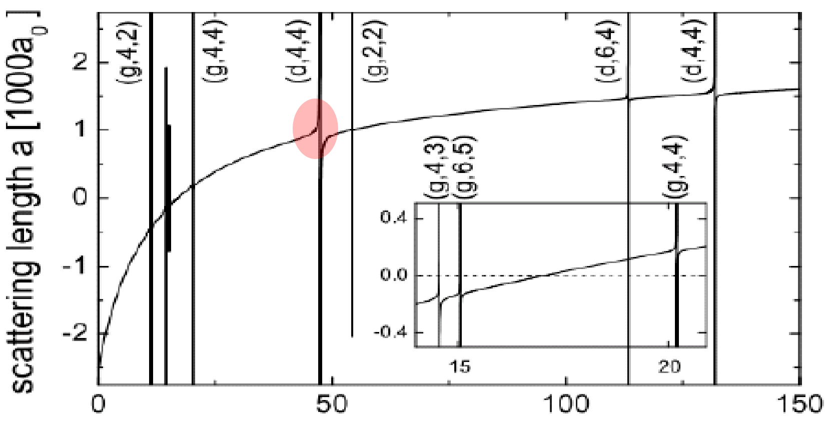


Innsbruck experiment with Cs atoms:

Feshbach Resonanzen

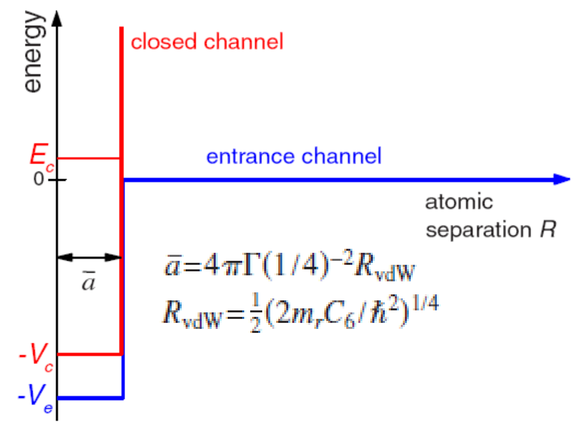


$$\cancel{\mathbf{V}(\mathbf{r}) = \frac{2\pi\hbar^2 a}{\mu}\delta^3(r)}$$

two-channel model of Lange et. al. Phys.Rev.79,013622(2009)

$$\hat{H}(r) = -\frac{\hbar^2}{2\mu}\hat{I}\frac{d^2}{d^2r} + \hat{V}(r)$$

$$\hat{V} = \begin{bmatrix} -V_c & \hbar\Omega \\ \hbar\Omega & -V_e \end{bmatrix} \quad (\text{for } R < \bar{a}) = \begin{bmatrix} \infty & 0 \\ 0 & 0 \end{bmatrix} \quad (\text{for } R > \bar{a})$$



3 fitting parameters:

$$\frac{1}{a-\bar{a}} = \frac{1}{a_{\rm bg}-\bar{a}} + \frac{\Gamma/2}{\bar{a}E_c}$$

$$E_c = \delta\mu(B - B_c)$$

$$\longrightarrow \quad V_e \; V_c \; \Omega$$

$$\Gamma = \delta\mu\Delta$$

TABLE I. Fitting parameters for the s-, d-, and g-wave Feshbach resonances, determining the scattering length in the magnetic-field range of interest; see Fig. 3. The background scattering length $a_{\rm bg} = 1875a_0$, the mean scattering length of cesium, $\bar{a} = 95.7a_B$, and the bare s-wave state magnetic moment $\delta\mu_1 = 2.50\mu_B$ [28] are set constant. Poles $B_{0,i}$ and zeros B_i^* of the scattering length are derived; see text. Uncertainties in the parentheses are statistical. The systematic uncertainty of the magnetic field is 10 mG.

Res.	Γ_i/h (MHz)	$\delta\mu_i/\mu_B$	$B_{c,i}$ (G)	$B_{0,i}$ (G)	B_i^* (G)
s-wv.	11.6(3)	2.50	19.7(2)	−11.1(6)	18.1(6)
d-wv.	0.065(3)	1.15(2)	47.962(5)	47.78(1)	47.944(5)
g-wv.	0.0042(6)	1.5(1)	53.458(3)	53.449(3)	53.457(3)

extension of two-channel model of Lange et. al. to 1D geometry

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

A four-channel square-well potential

$$\hat{V} = \begin{pmatrix} -V_{c,3} & 0 & 0 & \hbar\Omega_3 \\ 0 & -V_{c,2} & 0 & \hbar\Omega_2 \\ 0 & 0 & -V_{c,1} & \hbar\Omega_1 \\ \hbar\Omega_3 & \hbar\Omega_2 & \hbar\Omega_1 & -V_e \end{pmatrix}$$

$$|\psi\rangle = \sum_\alpha \psi_\alpha(\mathbf{r})|\alpha\rangle = \sum_\alpha \phi_\alpha(r) Y_{l_\alpha 0}(\hat{r})|\alpha\rangle$$

$\omega_\perp = 0$

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{\hbar^2 l_\alpha(l_\alpha+1)}{2\mu r^2} + B_{\alpha\alpha}\right]\phi_\alpha(r) + \sum_\beta V_{\alpha\beta}(r)\phi_\beta(r) = E\phi_\alpha(r)$$

4-coupled radial equations

$$\psi_e(\mathbf{r}) \to \exp\{ikz\} + f(k,\theta)/r\ \exp\{ikr\}, \qquad \psi_{c,i}(\mathbf{r}) \to 0$$

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$\omega_\perp \neq 0$

$$\left(\left[-\frac{\hbar^2}{2\mu}\nabla^2 + \frac{1}{2}\mu\omega_\perp^2\rho^2\right]\hat{I} + \hat{B} + \hat{V}(r)\right)|\psi\rangle = E|\psi\rangle$$

4-coupled 2D equations in the plane $\{r, \theta\}$

$$\psi_e(\mathbf{r}) = [\cos(k_0 z) + f_e \exp\{ik_0|z|\}]\Phi_0(\rho), \quad \psi_{c,i}(\mathbf{r}) \to 0$$

$$T(B) = |1 + f_e(B)|^2$$

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$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{\hbar^2 l_\alpha(l_\alpha+1)}{2\mu r^2} + B_{\alpha\alpha}\right]\phi_\alpha(r) + \sum_\beta V_{\alpha\beta}(r)\phi_\beta(r) = E\phi_\alpha(r)$$

4-coupled radial equations

$$\psi_e(\mathbf{r}) \to \exp\{ikz\} + f(k,\theta)/r \, \exp\{ikr\}, \qquad \psi_{c,i}(\mathbf{r}) \to 0$$

$\omega_\perp \neq 0$

$$\left(\left[-\frac{\hbar^2}{2\mu}\nabla^2 + \frac{1}{2}\mu\omega_\perp^2\rho^2\right]\hat{I} + \hat{B} + \hat{V}(r)\right)|\psi\rangle = E|\psi\rangle$$

4-coupled 2D equations in the plane $\{r, \theta\}$

$$\psi_e(\mathbf{r}) = [\cos(k_0 z) + f_e \exp\{ik_0|z|\}]\Phi_0(\rho), \quad \psi_{c,i}(\mathbf{r}) \to 0$$

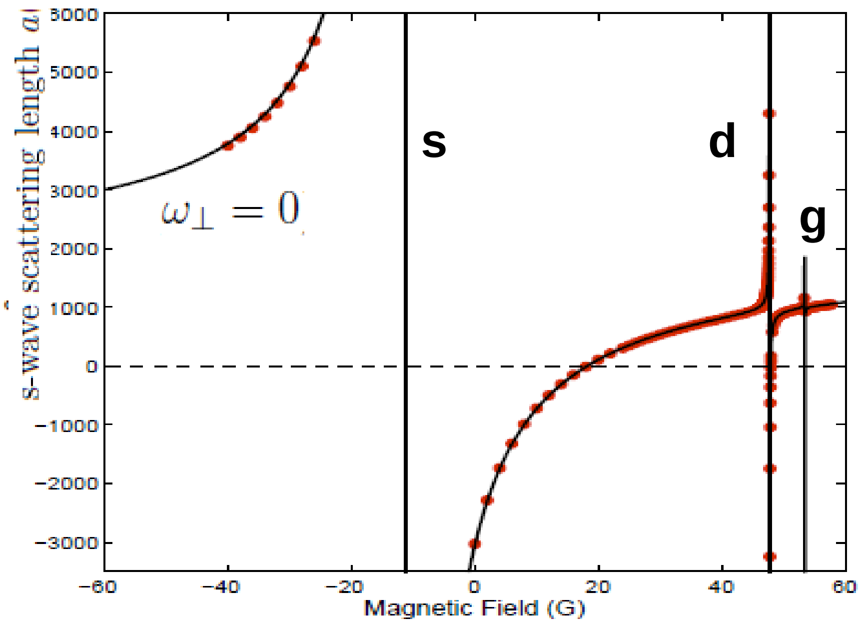
$$T(B) = |1 + f_e(B)|^2$$

scattering problem → boundary-value problem

V.Melezhik,C.Y.Hu,Phys.Rev.Lett.90(2003)083202
S.Saeidian,V.Melezhik,P.Schmelcher,Phys.Rev.A77(2008)042701

Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)



Feshbach resonances in the Cs ultracold gas in the 3D free space

$$H(r,\theta) = [-\frac{\hbar^2}{2\mu}\nabla^2 + \frac{1}{2}\mu\omega_\perp^2\rho^2]\hat{I} + \hat{V}(r)$$

$$V = \begin{pmatrix} -V_{C_3} & 0 & 0 & \hbar\Omega_3 \\ 0 & -V_{C_2} & 0 & \hbar\Omega_2 \\ 0 & 0 & -V_{C_1} & \hbar\Omega_1 \\ \hbar\Omega_3 & \hbar\Omega_2 & \hbar\Omega_1 & -V_e \end{pmatrix}$$

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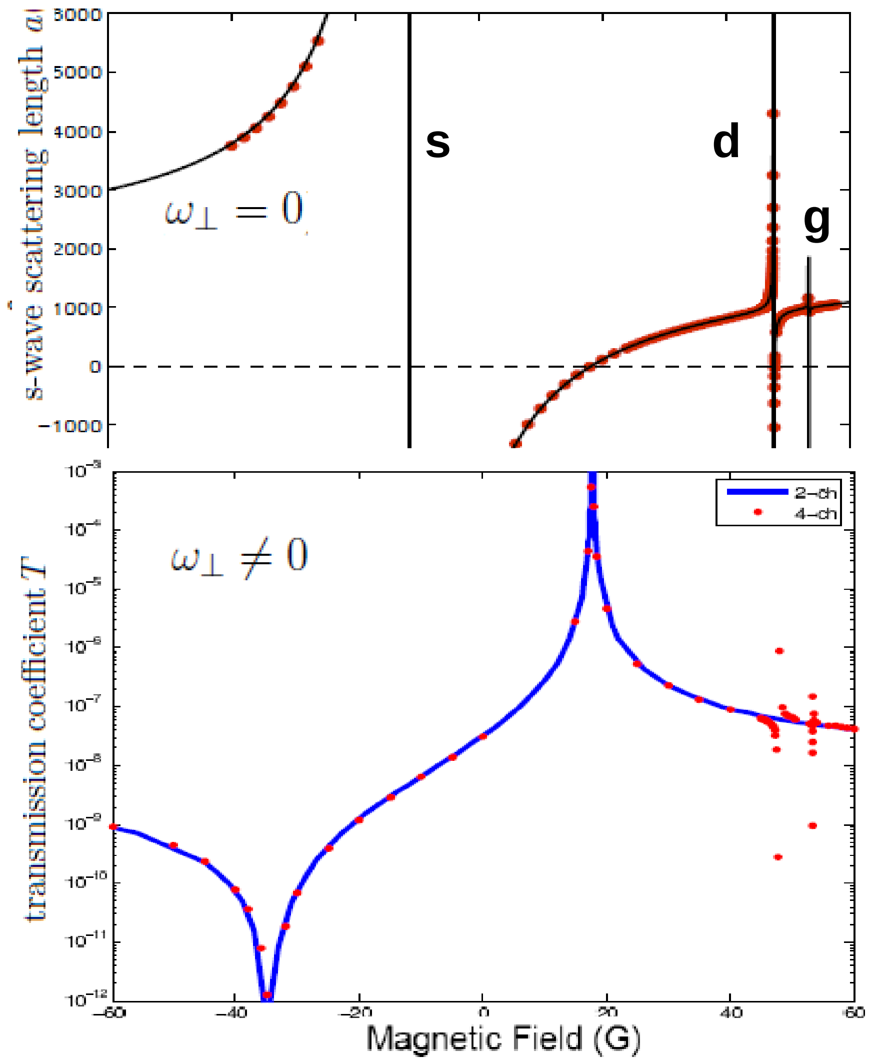

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in harmonic waveguides

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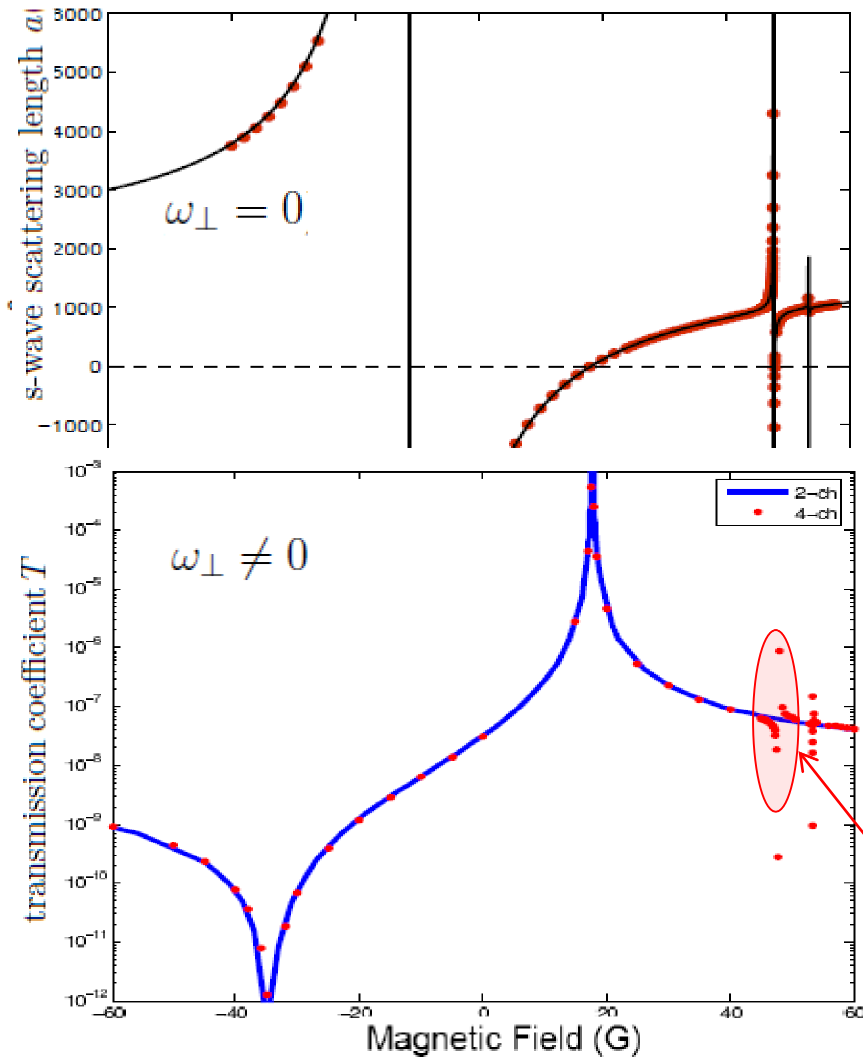

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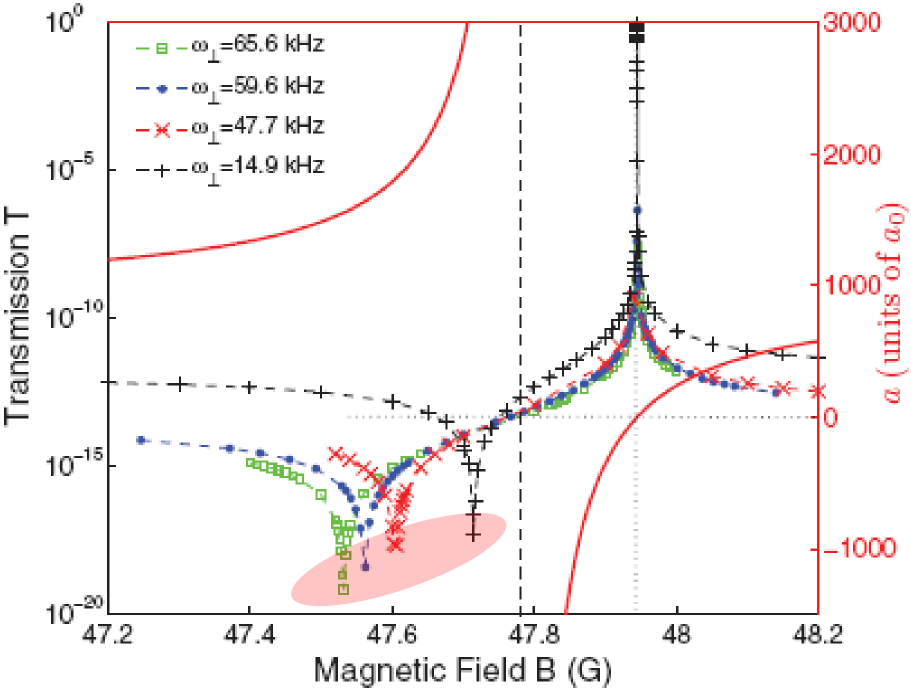
in harmonic waveguides

region of Innsbruck experiment
(d-wave Feshbach resonance)

Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

$$a_\perp = \sqrt{\hbar/(m\omega_\perp)}$$



d-wave FR at 47.8G develops in waveguide as depending on $\omega_\perp$ minimums and stable maximum of transmission coefficient T

Shifts and widths of Feshbach resonances in atomic waveguides

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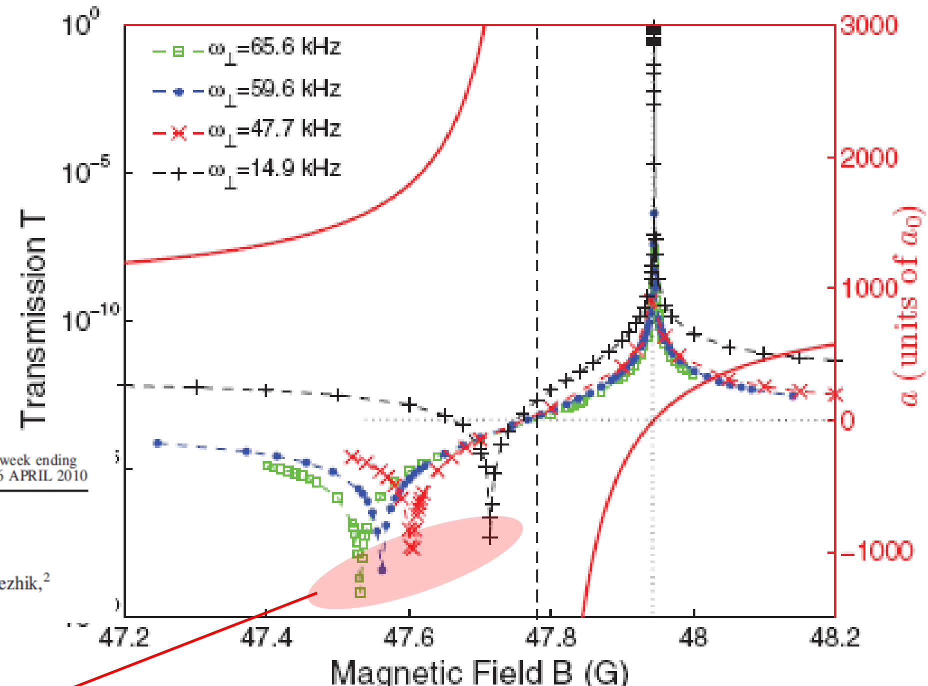
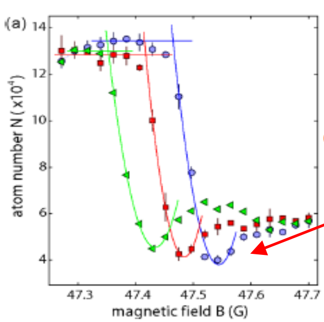


PRL 104, 153203 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

Confinement-Induced Resonances in Low-Dimensional Quantum Systems

Elmar Haller,[1] Manfred J. Mark,[1] Russell Hart,[1] Johann G. Danzl,[1] Lukas Reichsöllner,[1] Vladimir Melezhik,[2] Peter Schmelcher,[3] and Hanns-Christoph Nägerl[1]



experiment

Shifts and widths of Feshbach resonances in atomic waveguides

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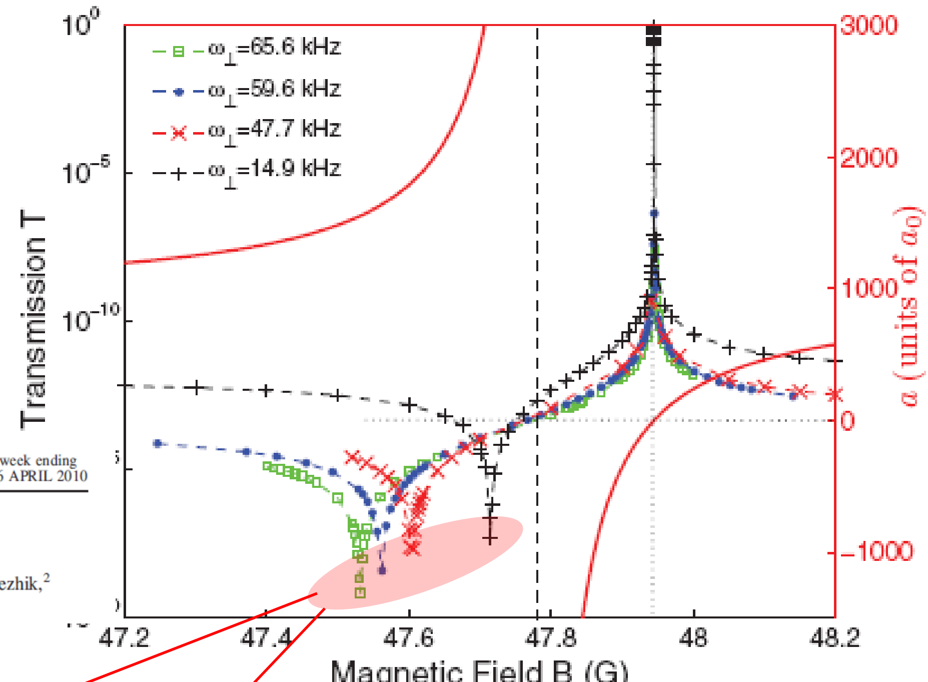

PRL **104,** 153203 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

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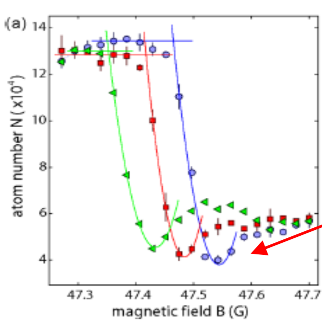
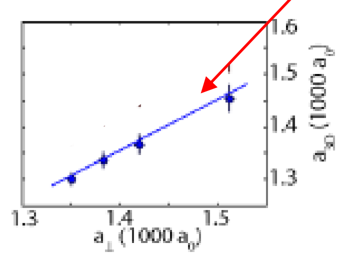


experiment

theory



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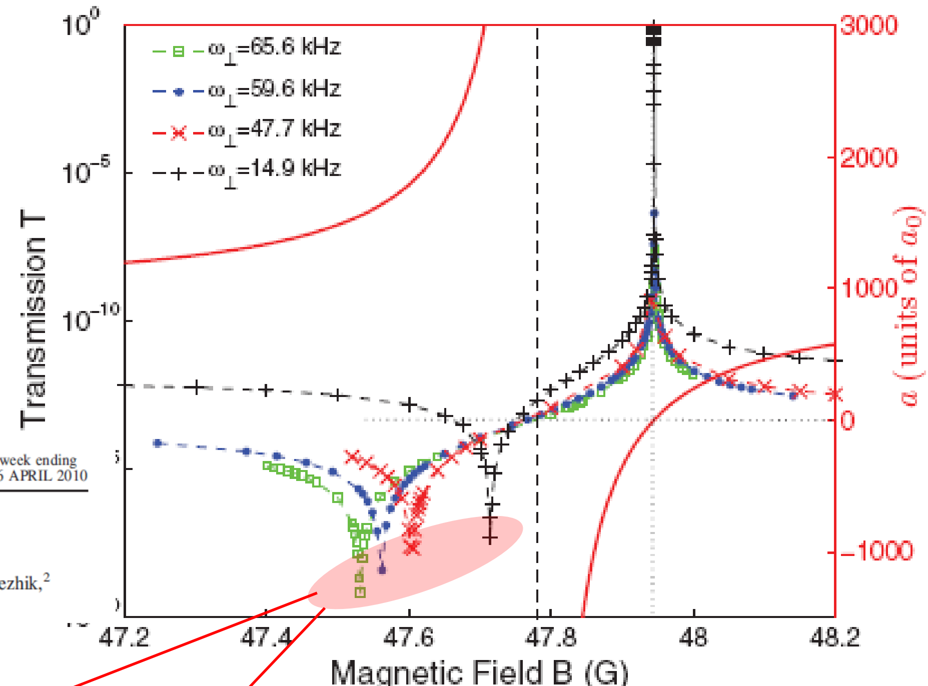

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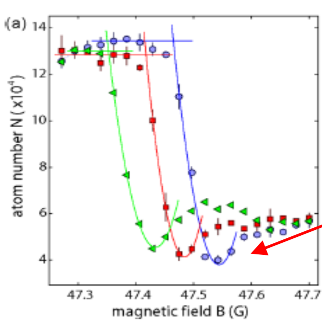

experiment

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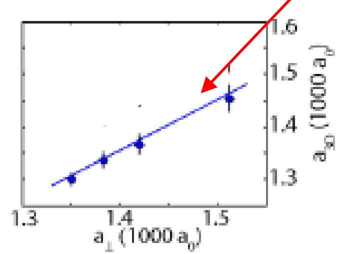

Olshanii formula works for s,d,and g FRs

$$a = 0.68 a_\perp$$

Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

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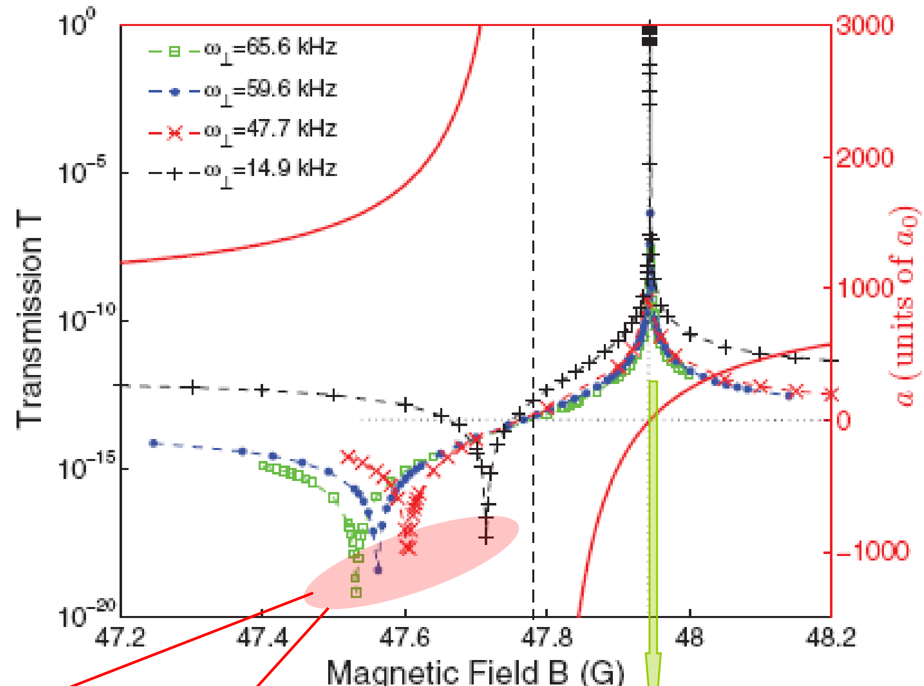
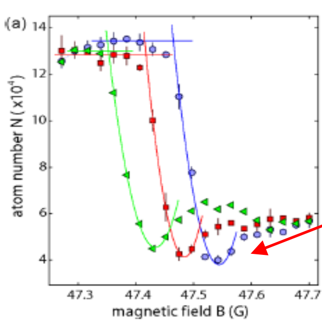
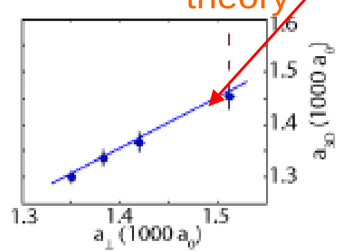




experiment

theory



narrowing width $\Gamma_i^* = \Delta_i \frac{\sqrt{2E_{\parallel}}}{\sqrt{\mu} a_{\rm bg} \omega_{\perp} \gamma_i}$

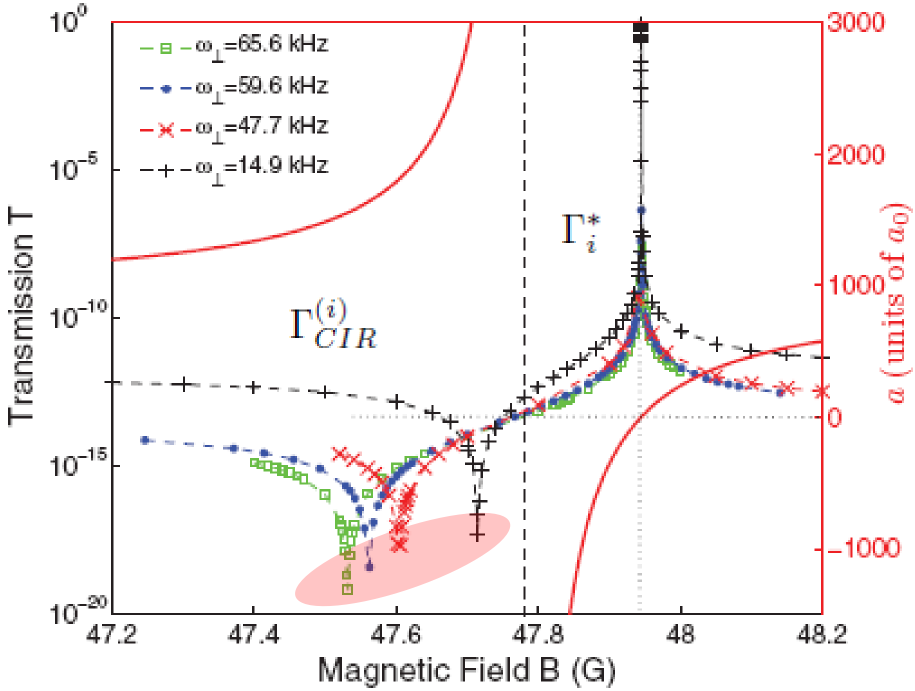
with increasing of waveguide $\omega_{\perp}$

can potentially be used experimentally

Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

$$a_\perp = \sqrt{\hbar/(m\omega_\perp)}$$



$$\frac{1}{2}\Gamma_{CIR}^{(i)} = \Delta_{CIR}^{(i)} - \frac{1}{2}\Gamma_i^* \xrightarrow[(k_0\to 0)]{} \Delta_i\left[\frac{1}{1 - C\gamma_i \frac{a_{bg}}{a_\perp}} - \frac{a_\perp^2 k_0}{2a_{bg}\gamma_i}\right]$$

The above expression describes the narrowing of the CIR width $\Gamma_{CIR}^{(i)}$ with decreasing trap frequency $\omega_\perp$, opposite to $\Gamma_i^* = \Delta_i \frac{\sqrt{2E_\parallel}}{\sqrt{\mu}a_{bg}\omega_\perp\gamma_i}$

Shifts and widths of Feshbach resonances in atomic waveguides

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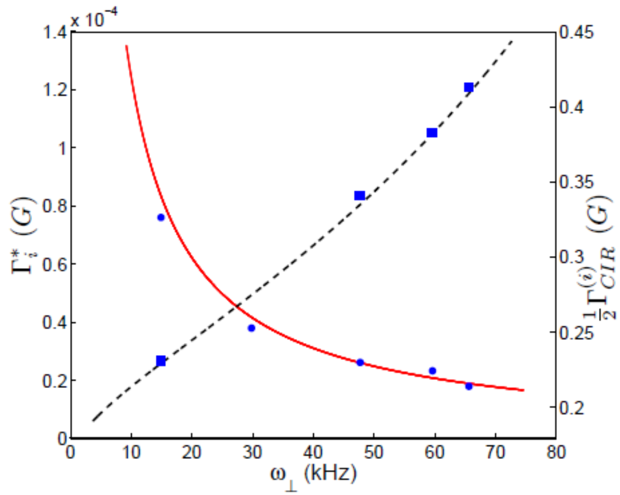

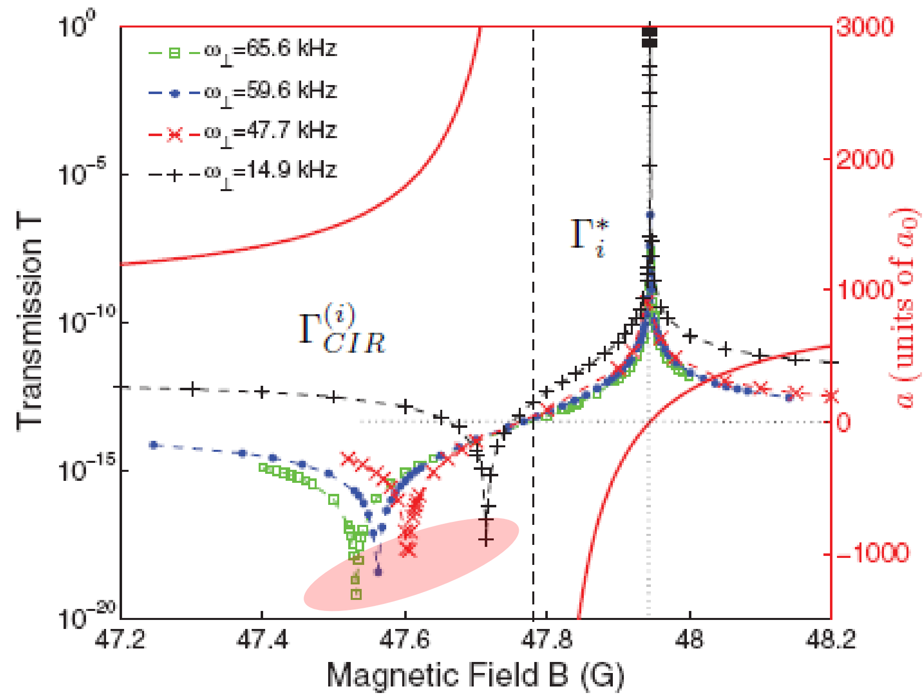

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Feshbach resonances in quasi-1D atomic traps (fermions)

S.Saeidian, V.S.Melezhik and P.Schmelcher, J. Phys B48 (2015) 155301

p-wave magnetic Feshbach resonances of ^{40}K atoms emerging in harmonic waveguides as p-wave CIRs

bosons: only s-wave in entrance channel $\frac{a}{a_\perp} = 0.68$

fermions: only p-wave in entrance channel $\frac{V_p}{V_\perp} = ?$

$$V_\perp = a_\perp^3$$

$$k^3 cot\delta_1(k,B) = -\frac{1}{V_p(B)}$$

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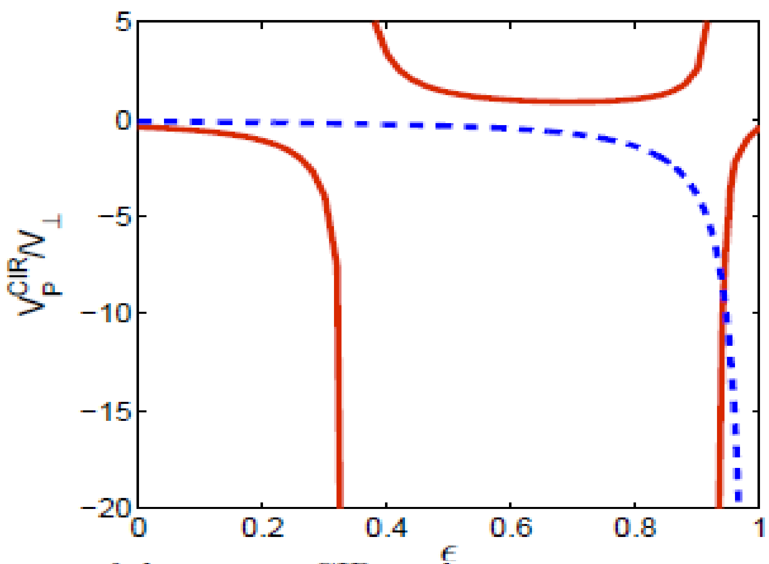

position of the p-wave CIR in the state $|F=9/2, m_F=-7/2\rangle$ of Potassium atoms as a function of the the rescaled energy ϵ

$$\cancel{\frac{a}{a_\perp} = 0.68}$$

$$\frac{V_p}{V_\perp} \neq const$$

$$k^3 cot\delta_1(k,B) = -\frac{1}{V_p(B)}$$

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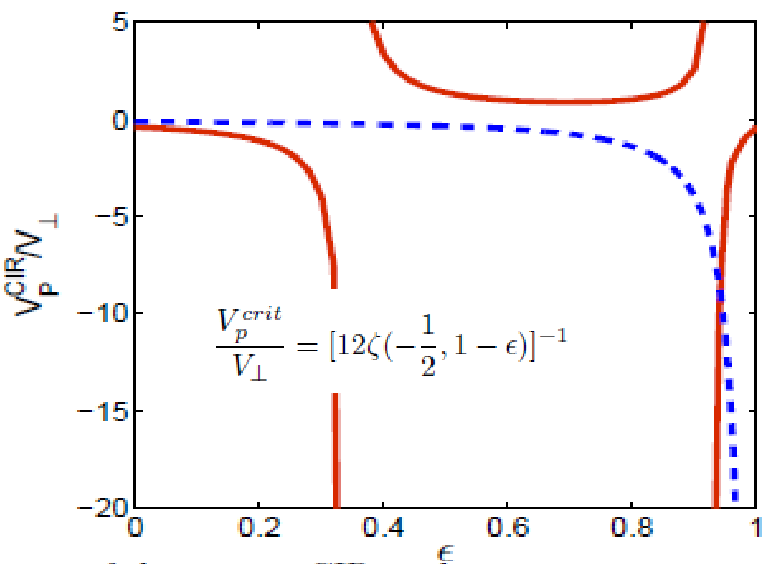

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B.E. Granger and D. Blume, Phys. Rev. Lett. **92**, 133202 (2004).

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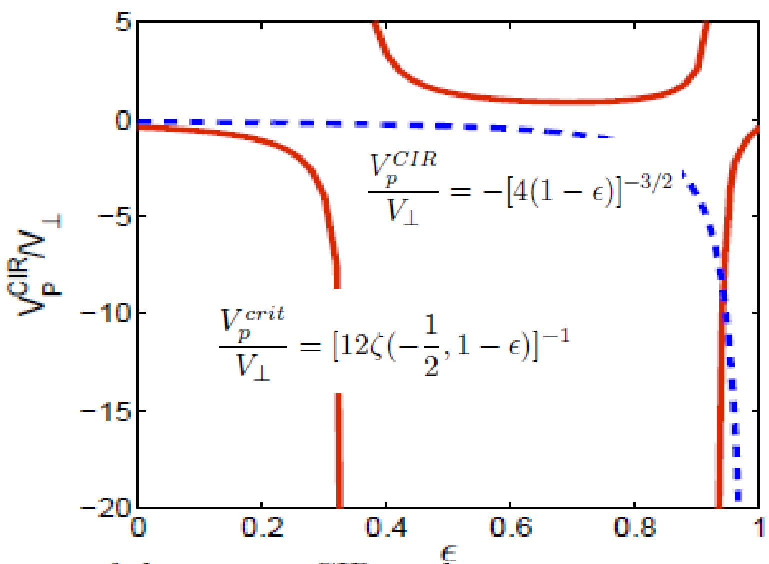
Feshbach resonances in quasi-1D atomic traps (fermions)

S.Saeidian, V.S.Melezhik and P.Schmelcher, J. Phys B48 (2015) 1553001

p-wave magnetic Feshbach resonances of ^{40}K atoms emerging in harmonic waveguides as p-wave CIRs



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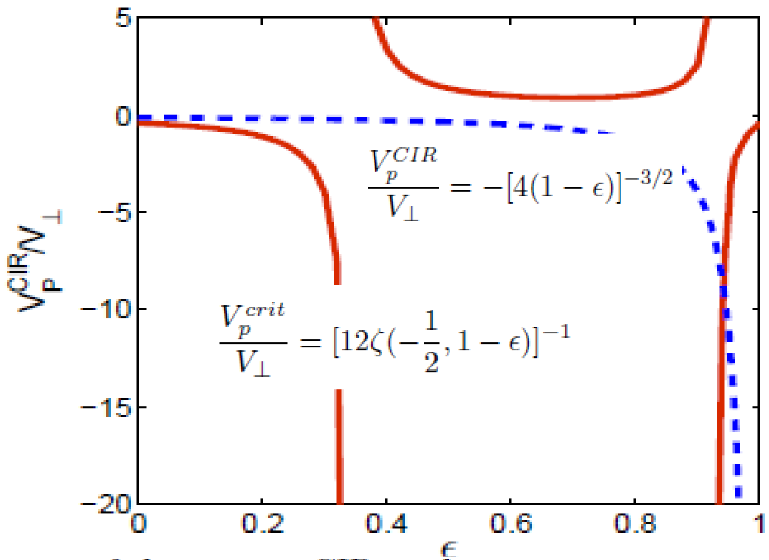

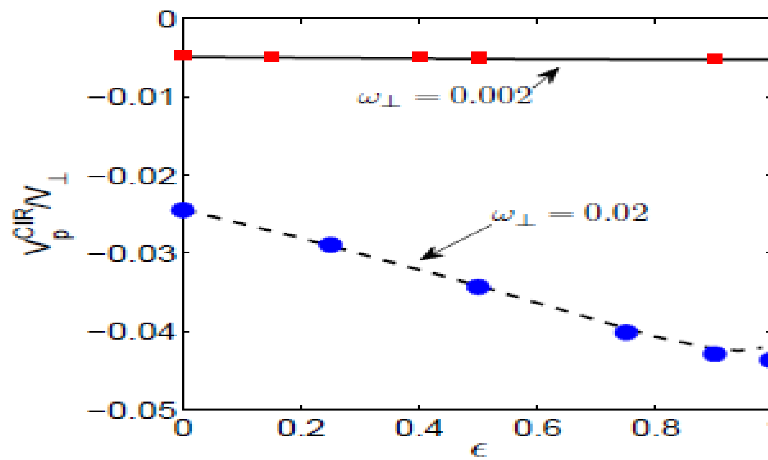

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$$\frac{V_p^{crit}(k)}{V_\perp} = [\frac{2a_\perp}{R} + 12\zeta(-\frac{1}{2}, 1-\epsilon)]^{-1}$$

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Shi-Guo Peng, S. Tan, and K. Jiang, arXiv:1312.3392v2

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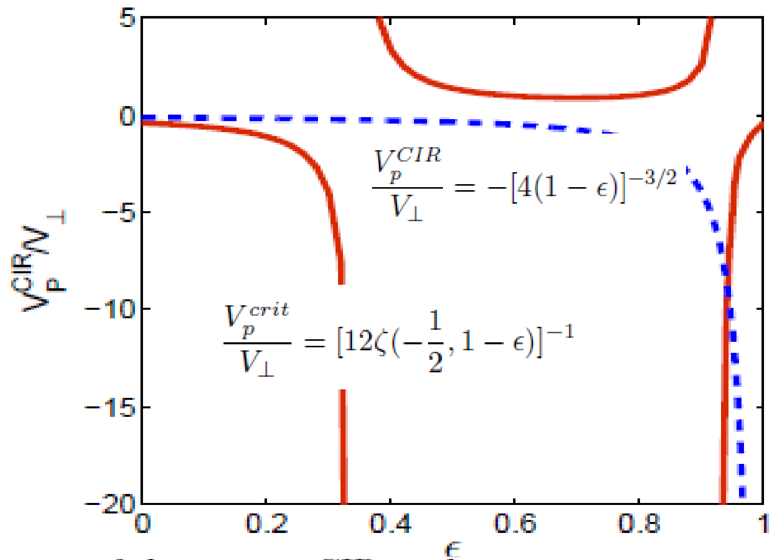

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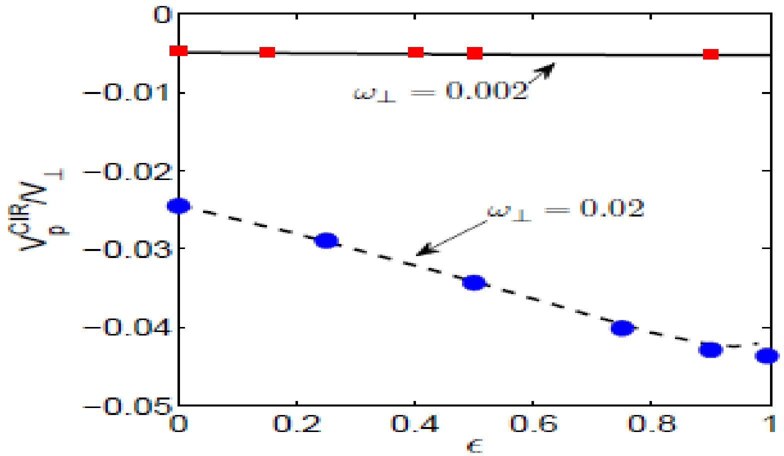

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Shi-Guo Peng, S. Tan, and K. Jiang, arXiv:1312.3392v2

Experimental setups in:

MIT (Boston), Boulder, NIST (Washington), Munich, Heidelberg, Shtutgart, Hamburg, Innsbruck, Vienna, Paris, Firenze, Barselona, FIAN, N.Novgorod, Troitsk …

Rb,Cs,K,Sr,Li …

Rb_2 , Cs_2 , RbK … **1D, 2D, 3D**

~ 80 experimental groups worldwide

theory including confined geometry of traps

Outlook

- model → widths and shifts of FRs in atomic waveguides

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- Feshbach resonances in fermionic systems

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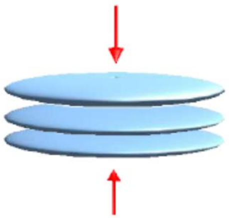
extension to quasi-2D geometry

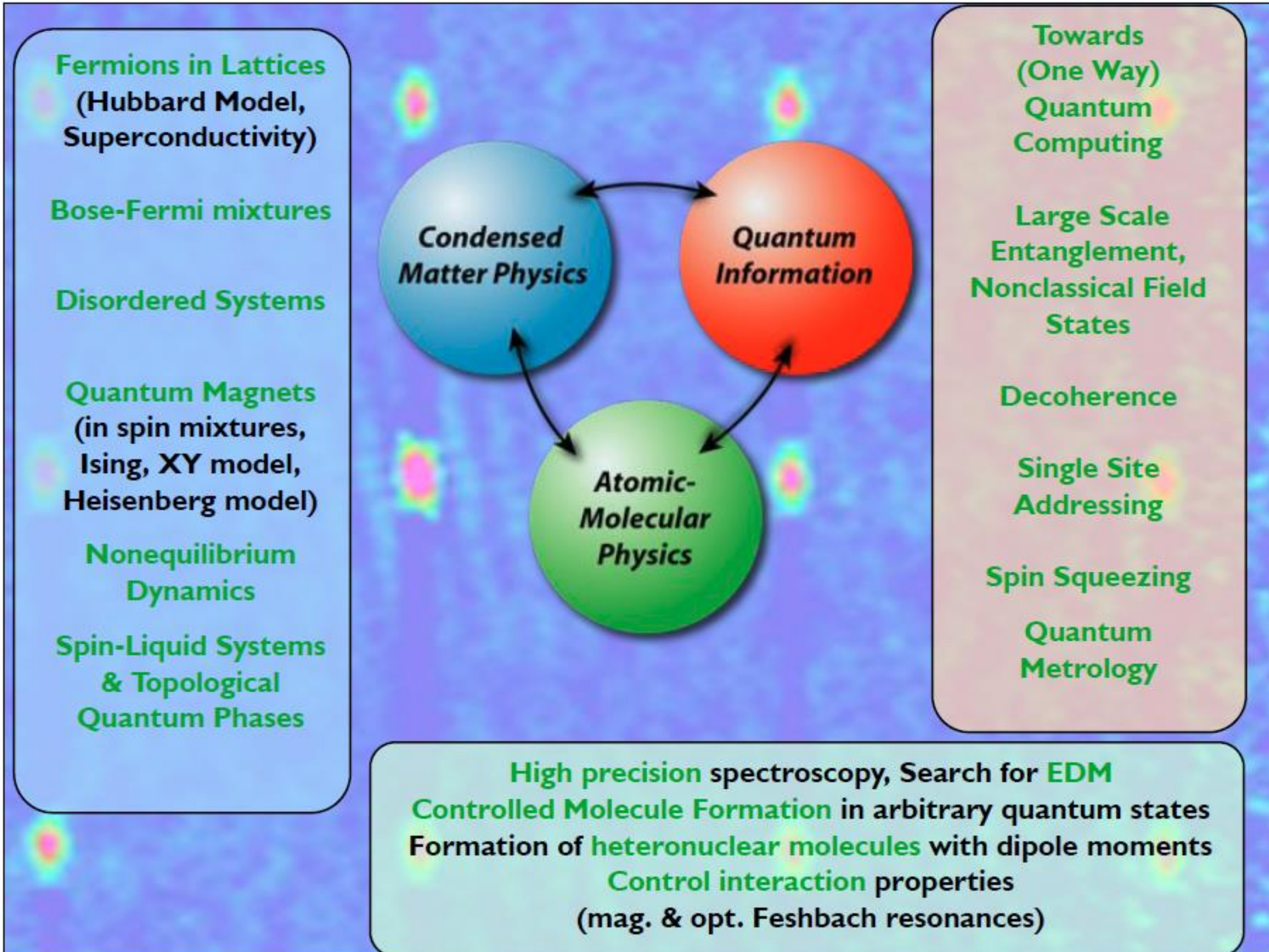


extension to ion-atom

including anharmonicity of traps, tunneling …

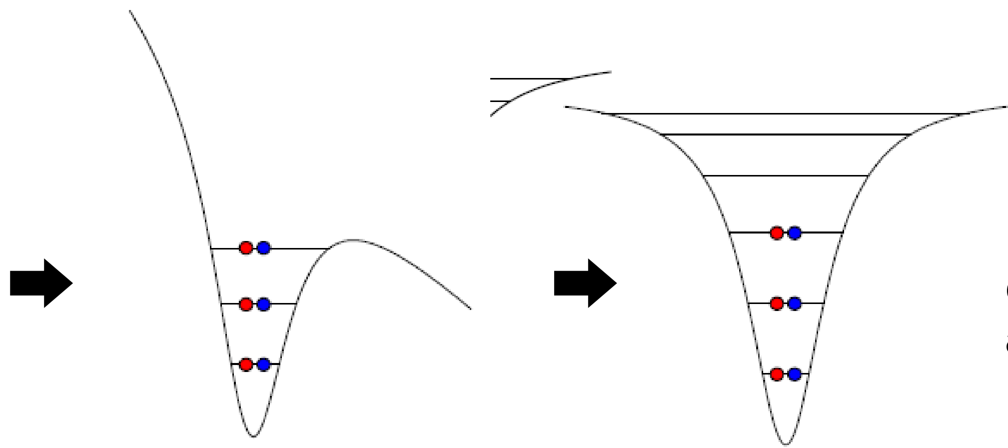
Quantum simulation with fully controlled few-body systems

control over: quantum states, particle number, interaction


Fermions in Lattices
(Hubbard Model,
Superconductivity)
Bose-Fermi mixtures
Disordered Systems
Quantum Magnets
(in spin mixtures,
Ising, XY model,
Heisenberg model)
Nonequilibrium
Dynamics
Spin-Liquid Systems
& Topological
Quantum Phases
Condensed
Matter Physics
Quantum
Information
Atomic-
Molecular
Physics
Towards
(One Way)
Quantum
Computing
Large Scale
Entanglement,
Nonclassical Field
States
Decoherence
Single Site
Addressing
Spin Squeezing
Quantum
Metrology
High precision spectroscopy, Search for EDM
Controlled Molecule Formation in arbitrary quantum states
Formation of heteronuclear molecules with dipole moments
Control interaction properties
(mag. & opt. Feshbach resonances)

Preparation

- 2-component mixture in reservoir T=250nK
- superimpose microtrap
  - scattering → thermalisation
  - expected degeneracy: $T/T_F = 0.1$
- switch off reservoir



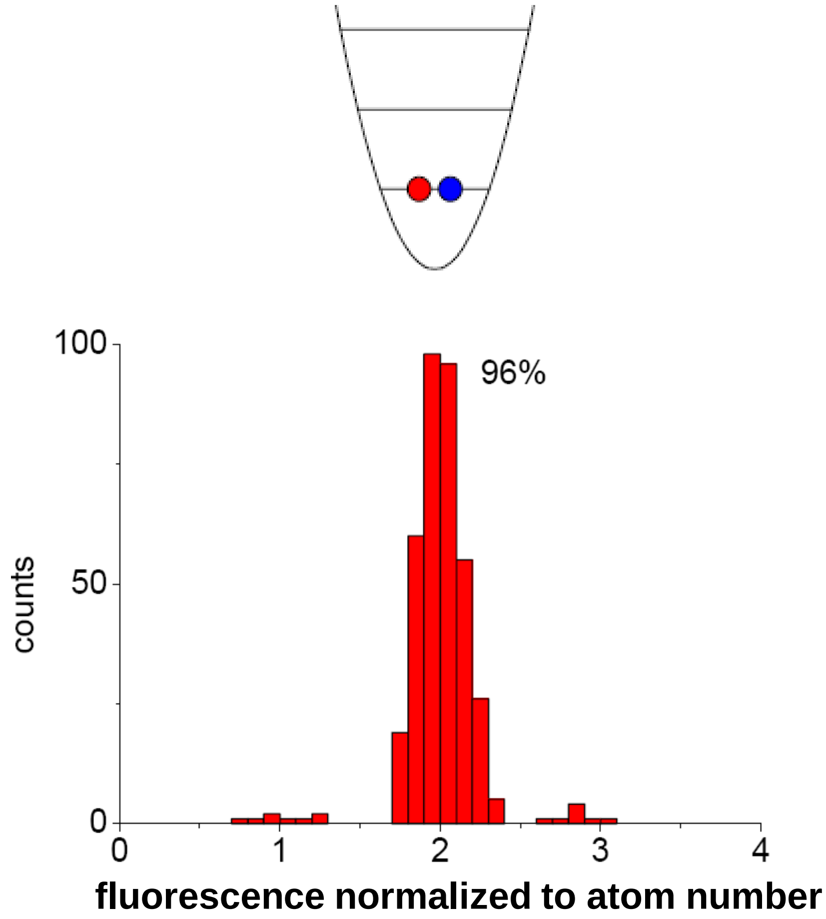
count the atoms

+ magnetic field gradient in axial direction

S.Serwane et.al. Science 332 (2011)

High fidelity preparation

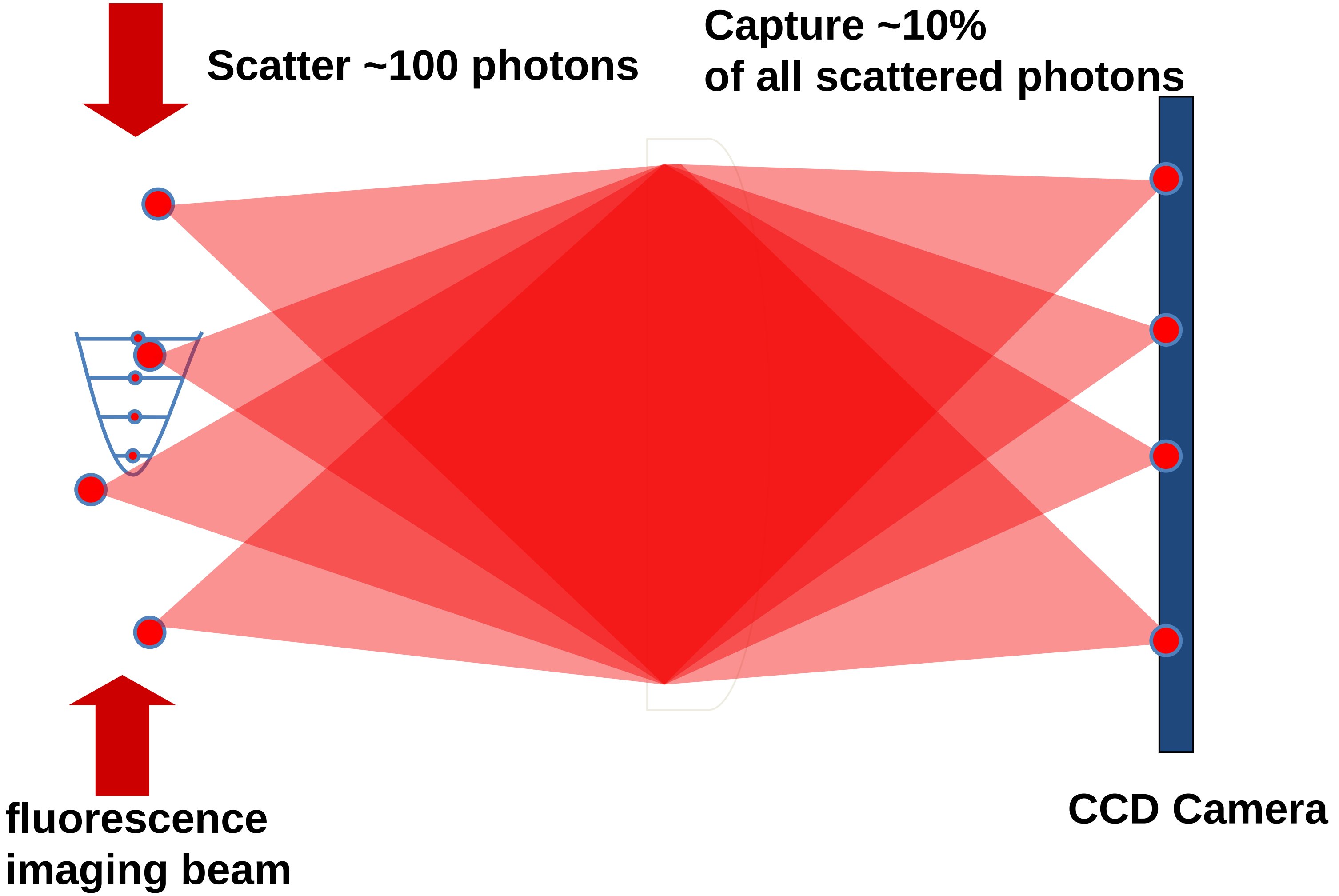
2 fermions



F. Serwane et al., Science 332, 336-338 (2011)

Detection:

Modern CCD Cameras allow detection of single photons:



S.Serwane et.al. Science 332 (2011)