a Bose-Einstein condensate with tunable interaction

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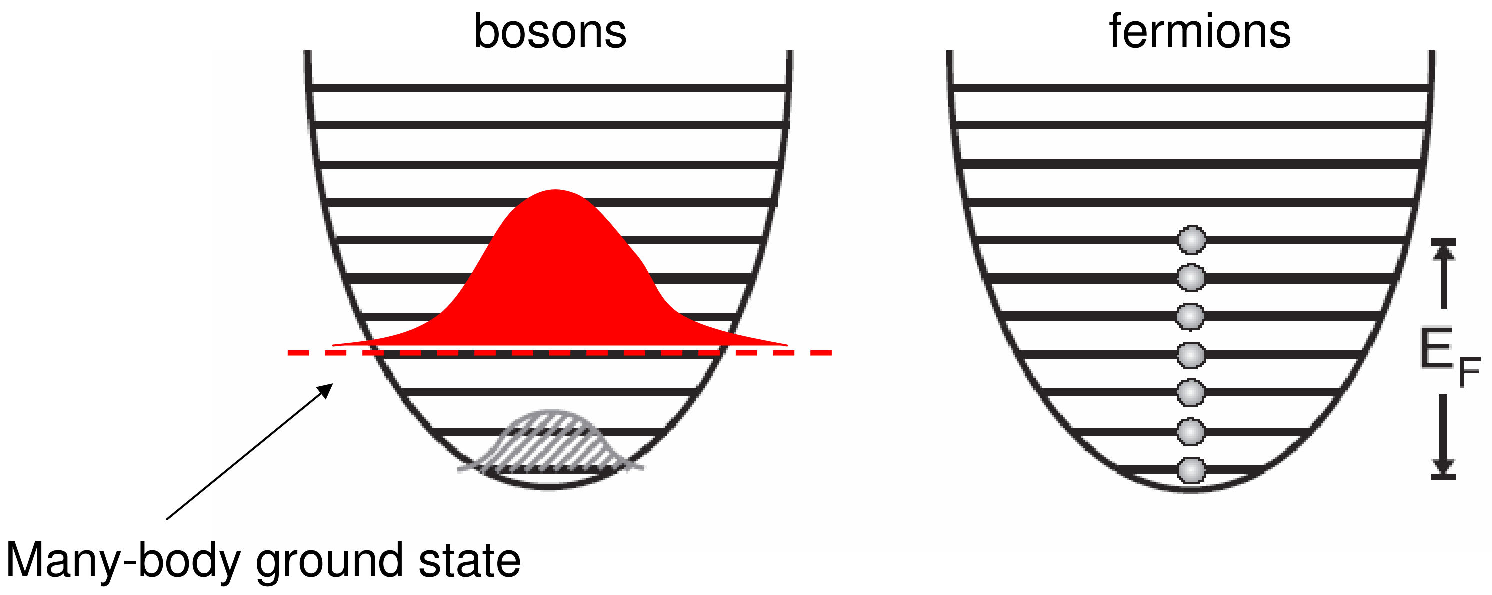
Weakly interacting BEC



The interaction energy cannot be neglected: $E = K + U + E_{int}$

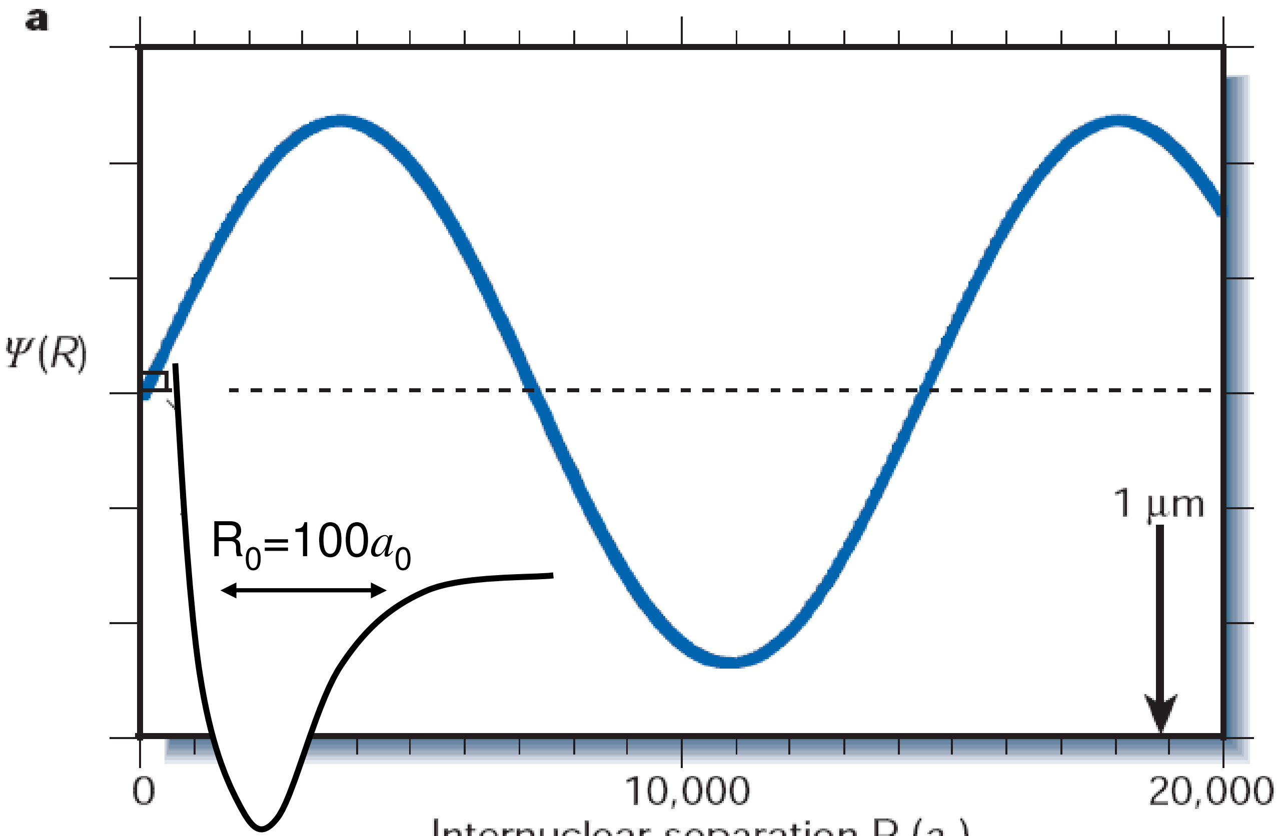
$$E_{int} = gn \qquad g = \frac{4\pi\hbar^2}{m}a$$

Interaction makes the BEC superfluid and interesting

Interaction can be tuned, turned from attractive to repulsive and in some cases almost cancelled

Scattering length

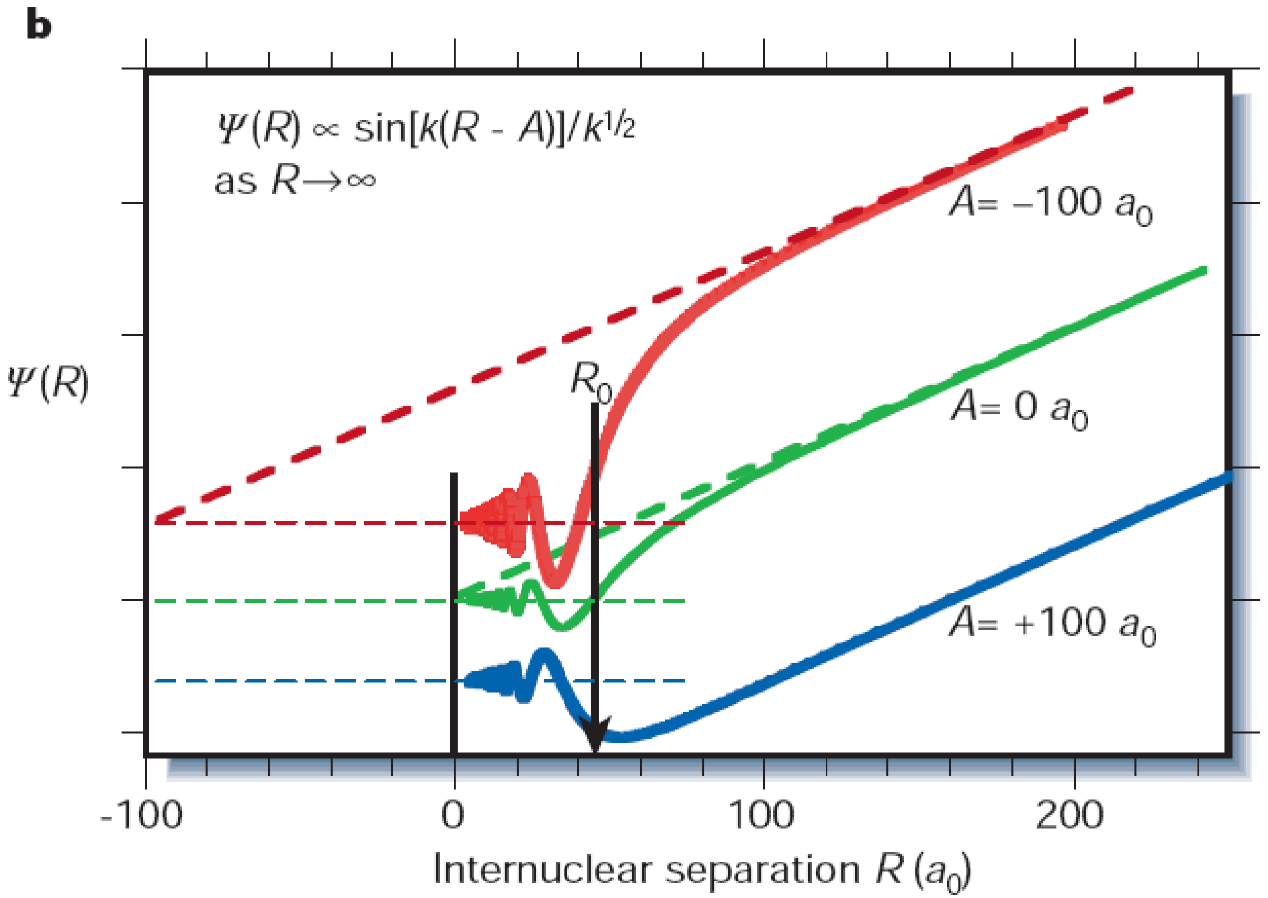
Ultracold atoms interact via a two-body isotropic contact potential



Burnett et al. Nature 416, 215 (2002)

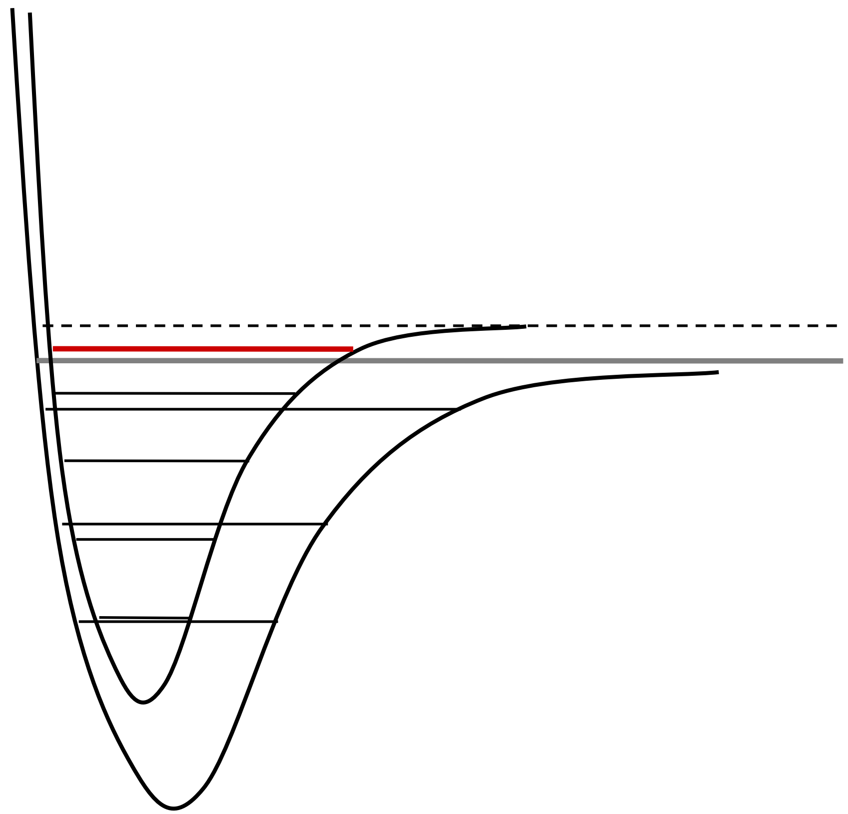
Scattering length

Ultracold atoms interact via a two-body isotropic contact potential



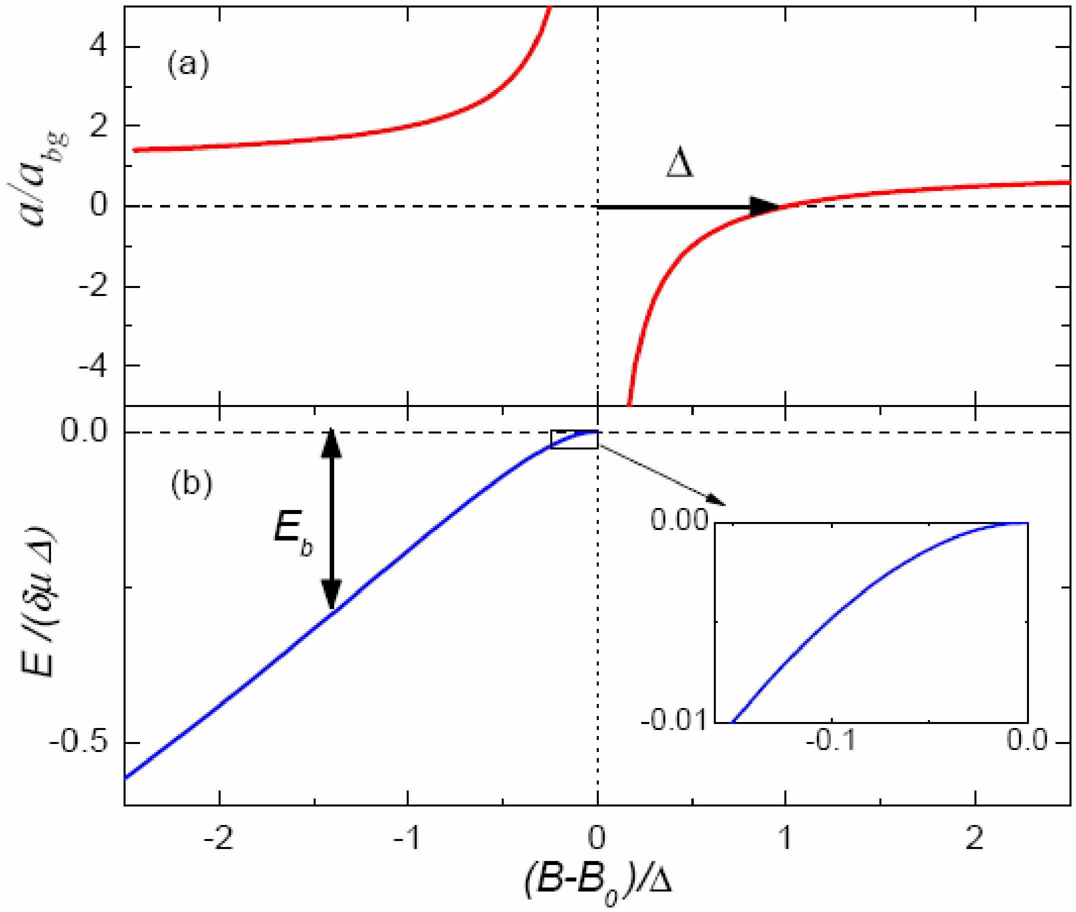
Scattering length

The scattering length depends on details of the molecular potential
(the position of the last bound state)



If the state has an internal structure and a magnetic moment, a can be varied

Feshbach resonances

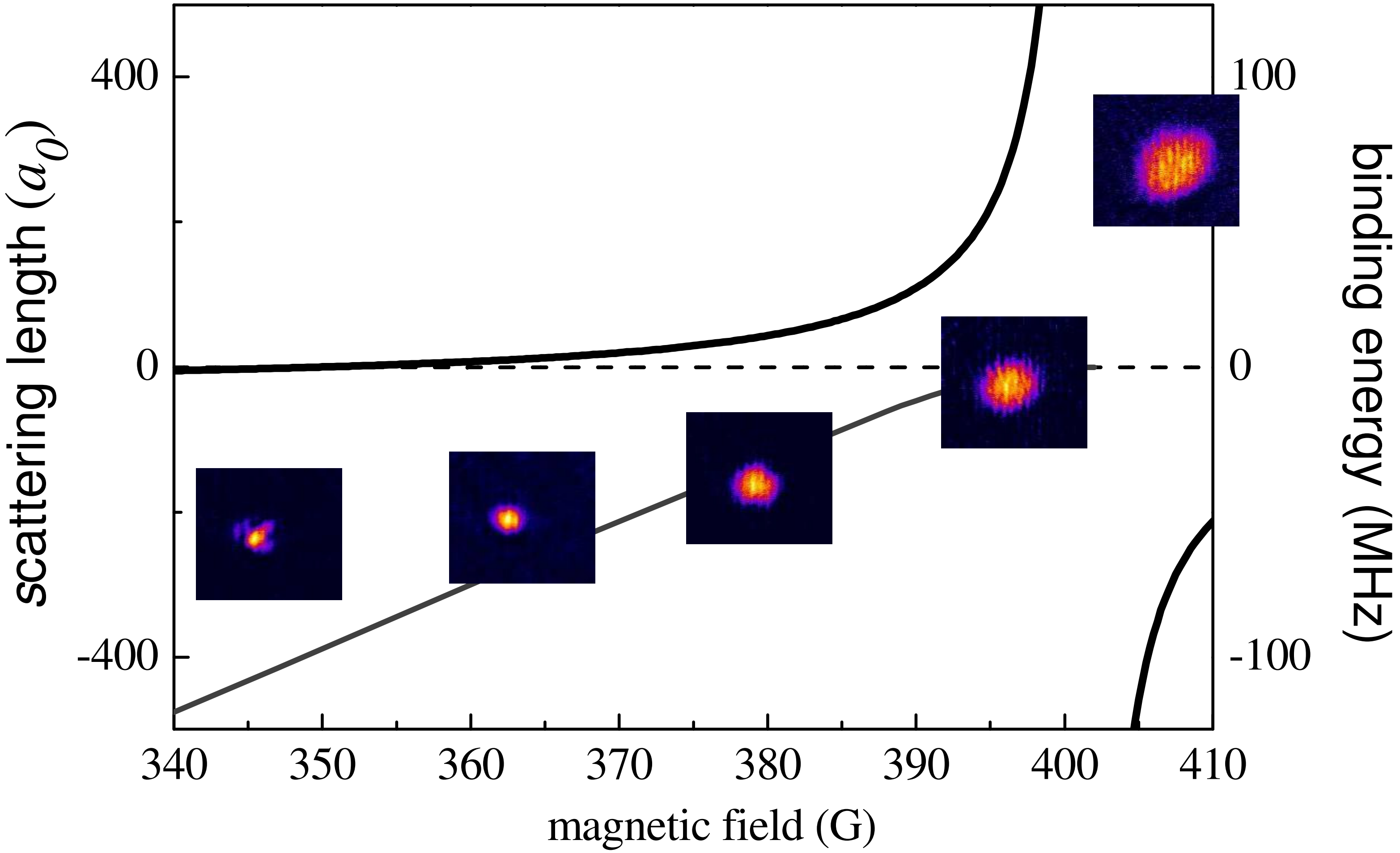


Original idea: H. Feshbach, Ann. Phys. (NY) 5, 357 (1958), U. Fano,Phys. Rev. A 124, 1866 (1961).

Ultracold gases: Moerdijk et al, Phys. Rev. A 51, 4852 (1995); Inouye et al, Nature 392, 151 (1998).

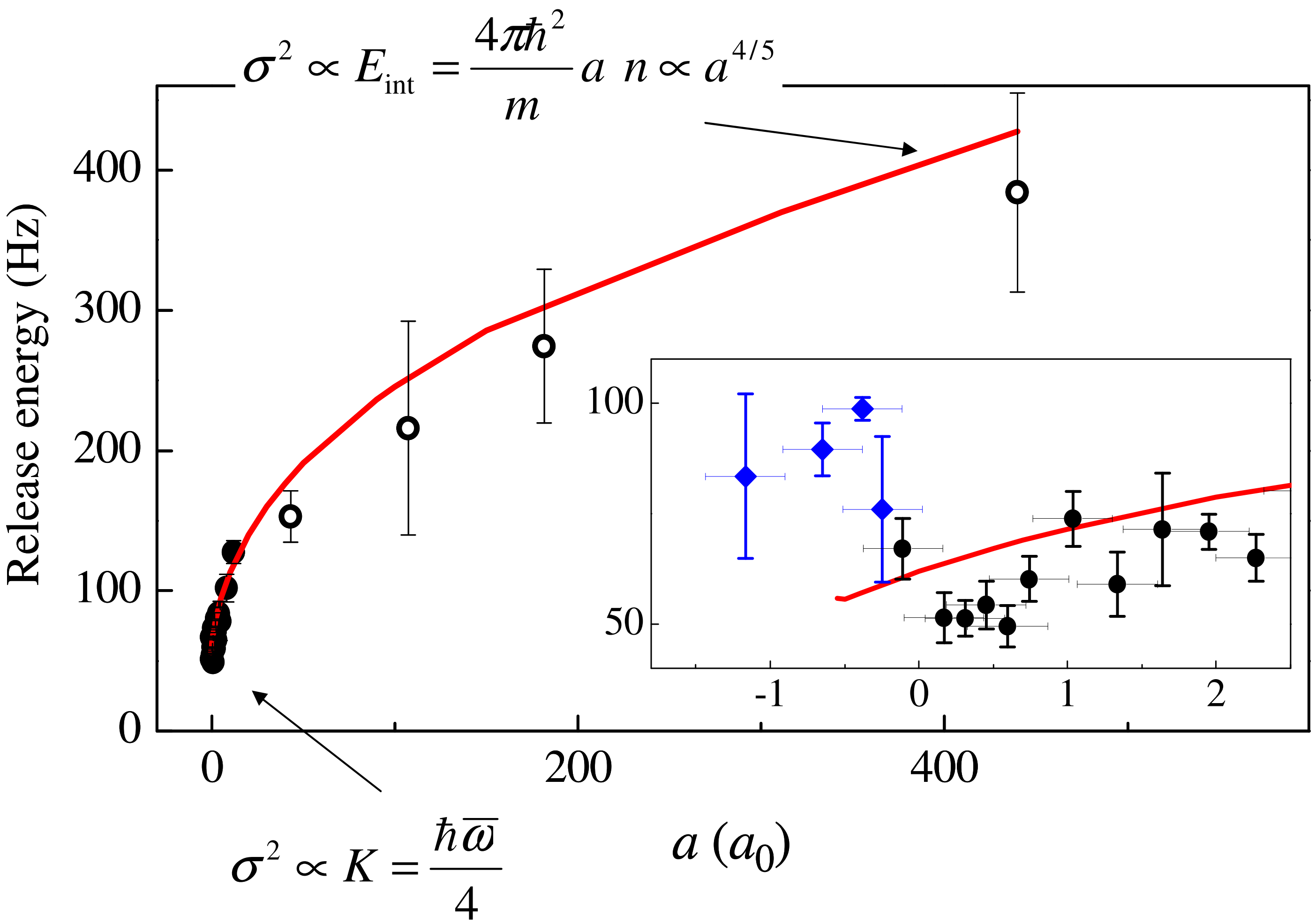
Recent review: C. Chin et al, arXiv:0812.1496

A Feshbach resonance (potassium-39)



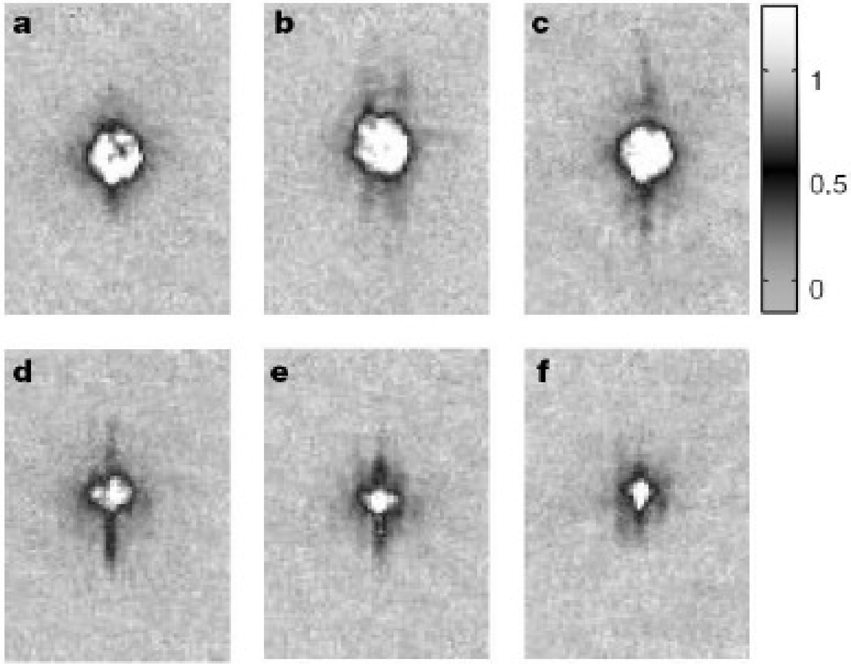
Free expansion: $E_{\mathrm{int}} \rightarrow K$

Interaction energy from free expansion



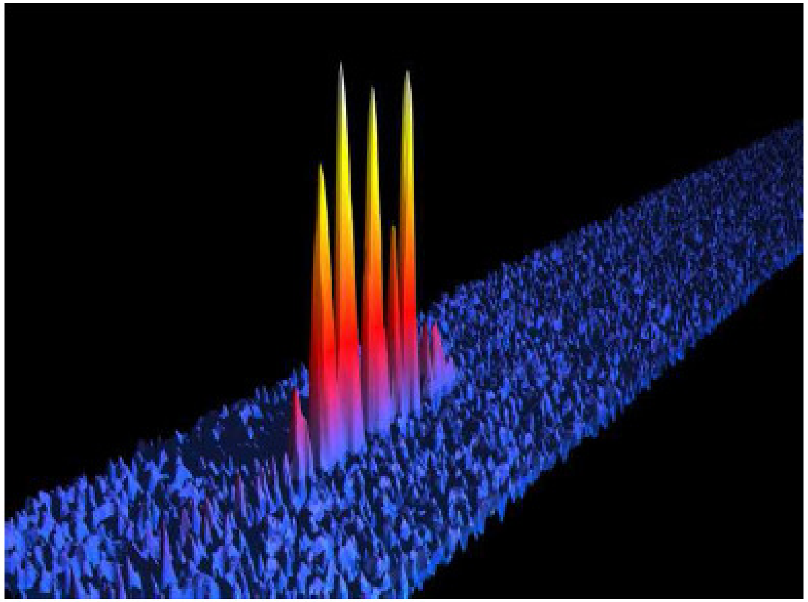
Attractive interaction

Collapse for $a < -0.57 \frac{a_{ho}}{N}$



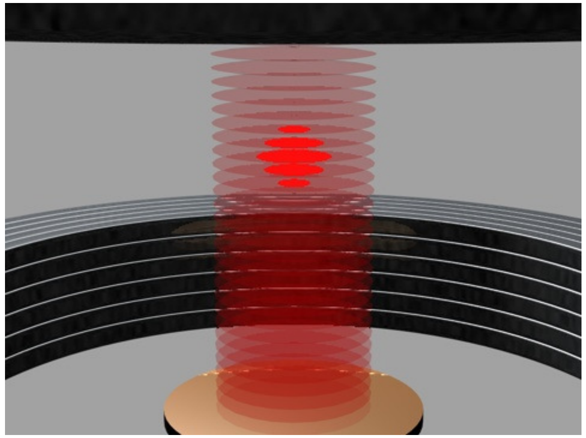
Donley et al., Nature 412, 295 (2001)

Solitons for intermediate attraction

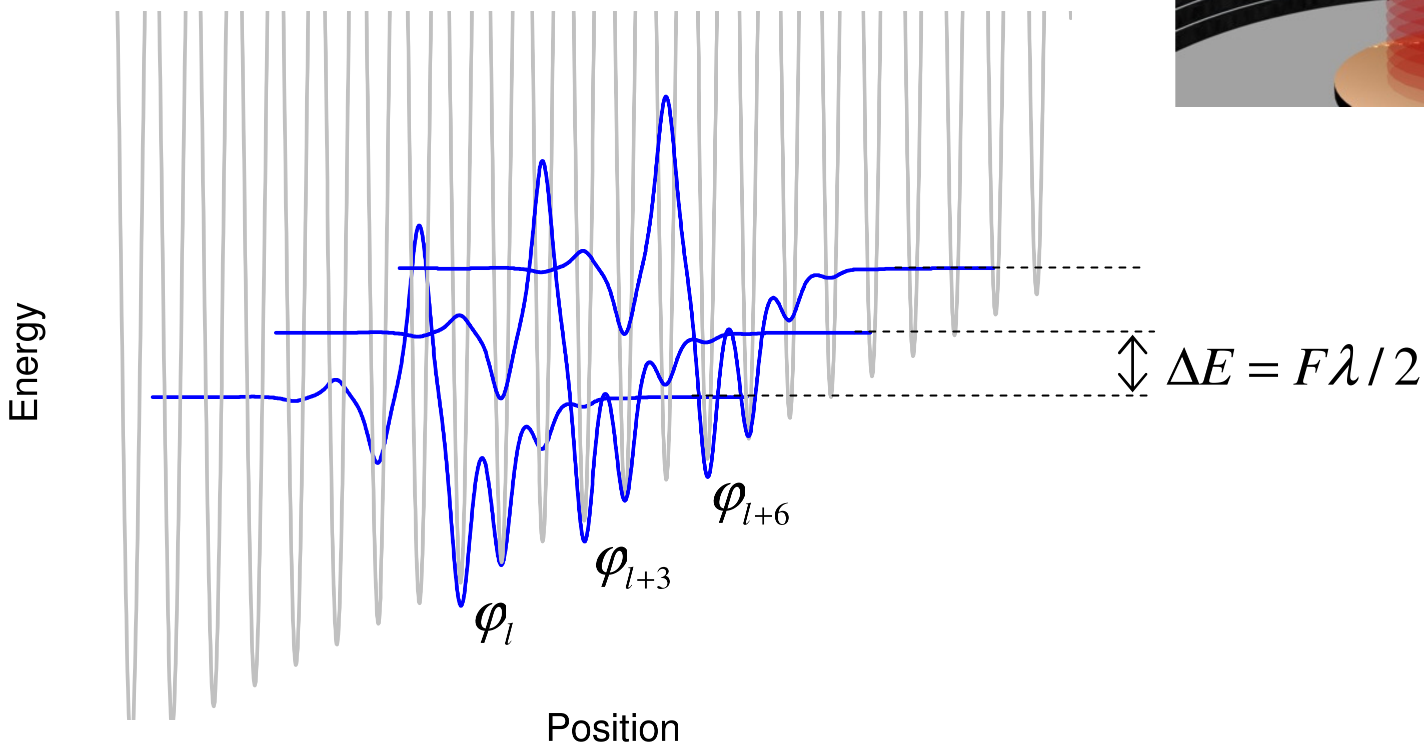


Strecker et al. Nature 417, 150 (2002); Khaykovich et al. Science 296, 1290 (2002).

Interaction energy from interferometry

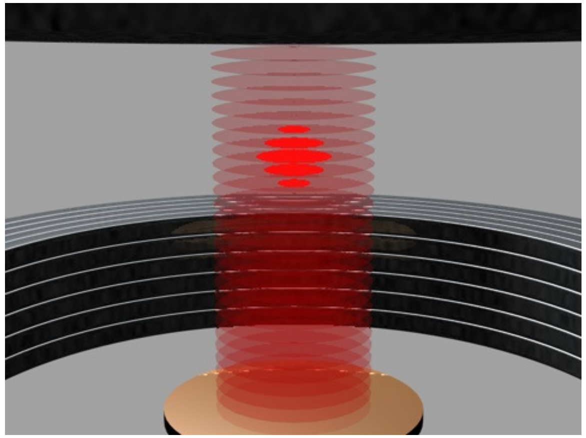


Take a series of equally-spaced energy states…

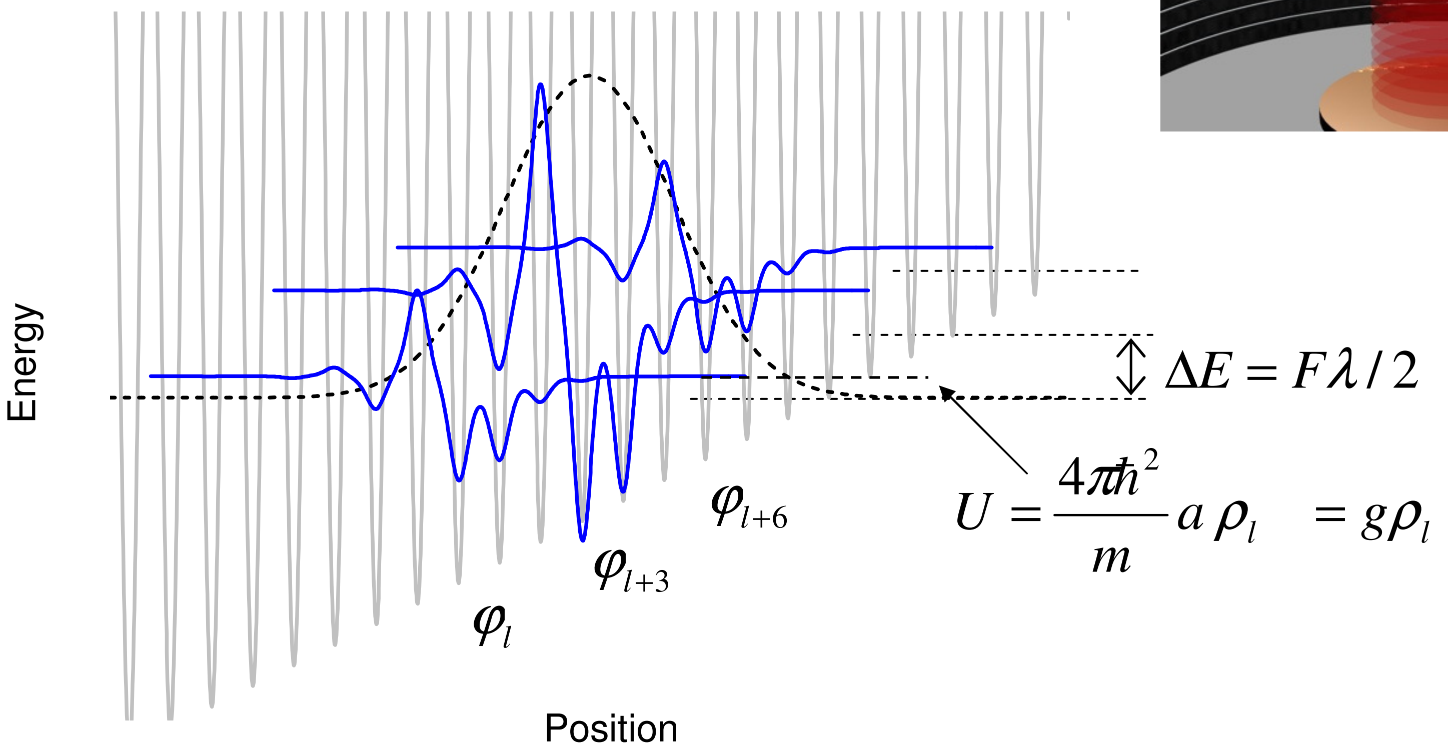


Let them interfere: Bloch oscillations $\psi = \sum_l \sqrt{\rho_l}\, e^{i\vartheta_l} \varphi_l$ $\vartheta_l(t) = \frac{Fl\lambda t}{2\hbar}$

Interaction energy from interferometry

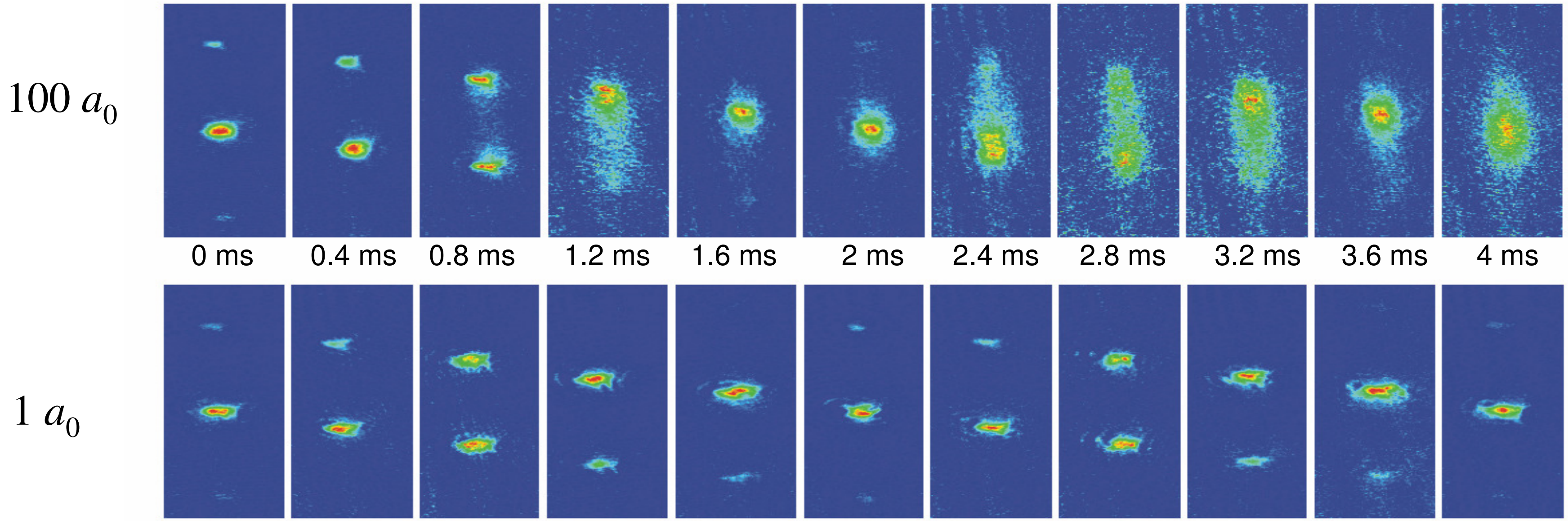


Add a repulsive interaction …



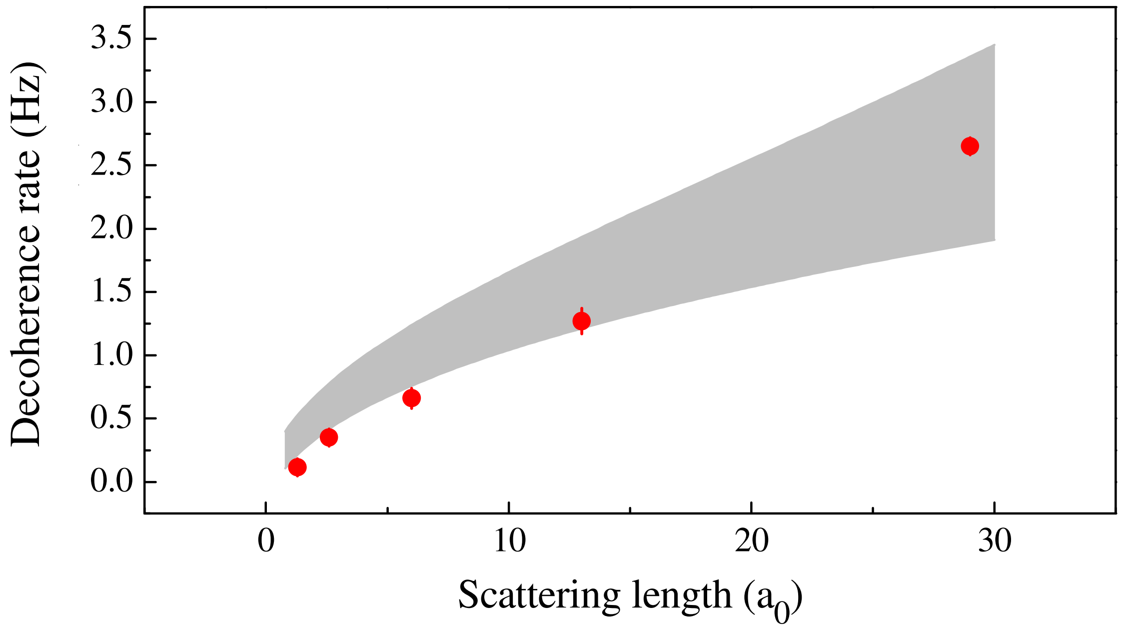
Inhomogeneous broadening: $\psi = \sum_l \sqrt{\rho_l}\, e^{i\vartheta_l} \varphi_l$ $\qquad \vartheta_l(t) = (Fl\lambda/2 + g\rho_l)t/\hbar$

Interaction energy from interferometry



To what level can E_{int} be cancelled?

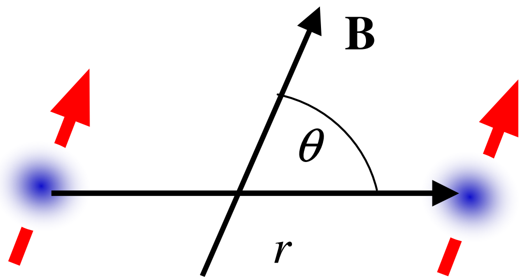
Dipole-dipole interaction is the next order

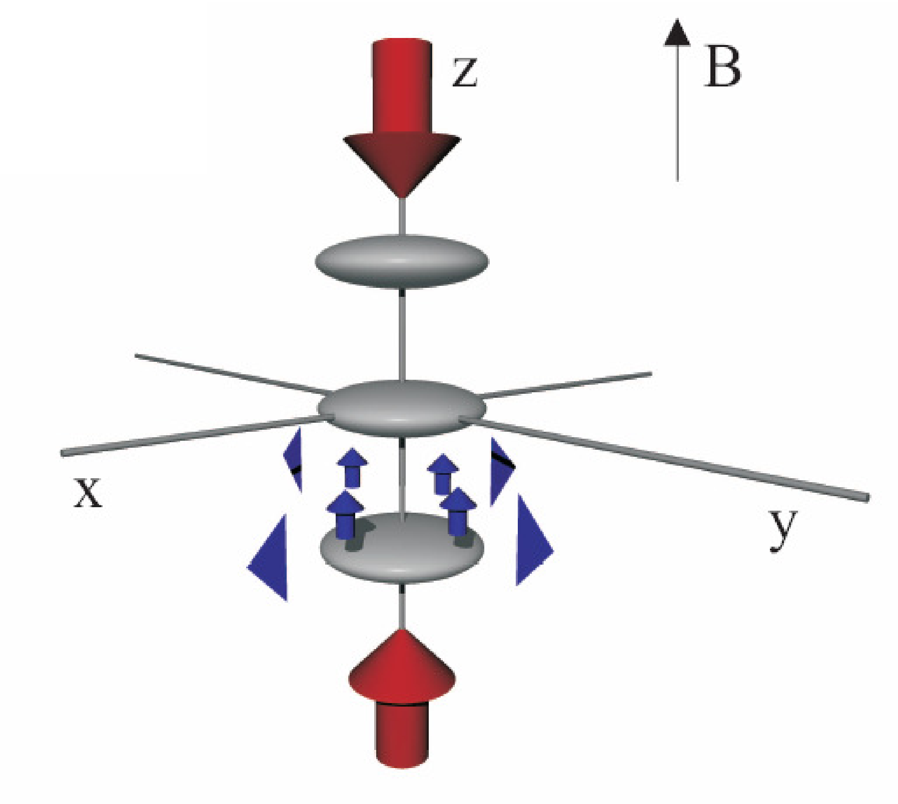


Magnetic dipolar interaction

Anisotropic and long-range

$$U_d = \frac{\mu_0 \mu^2}{4\pi\, r^3}(1 - 3\cos^2 \vartheta)$$





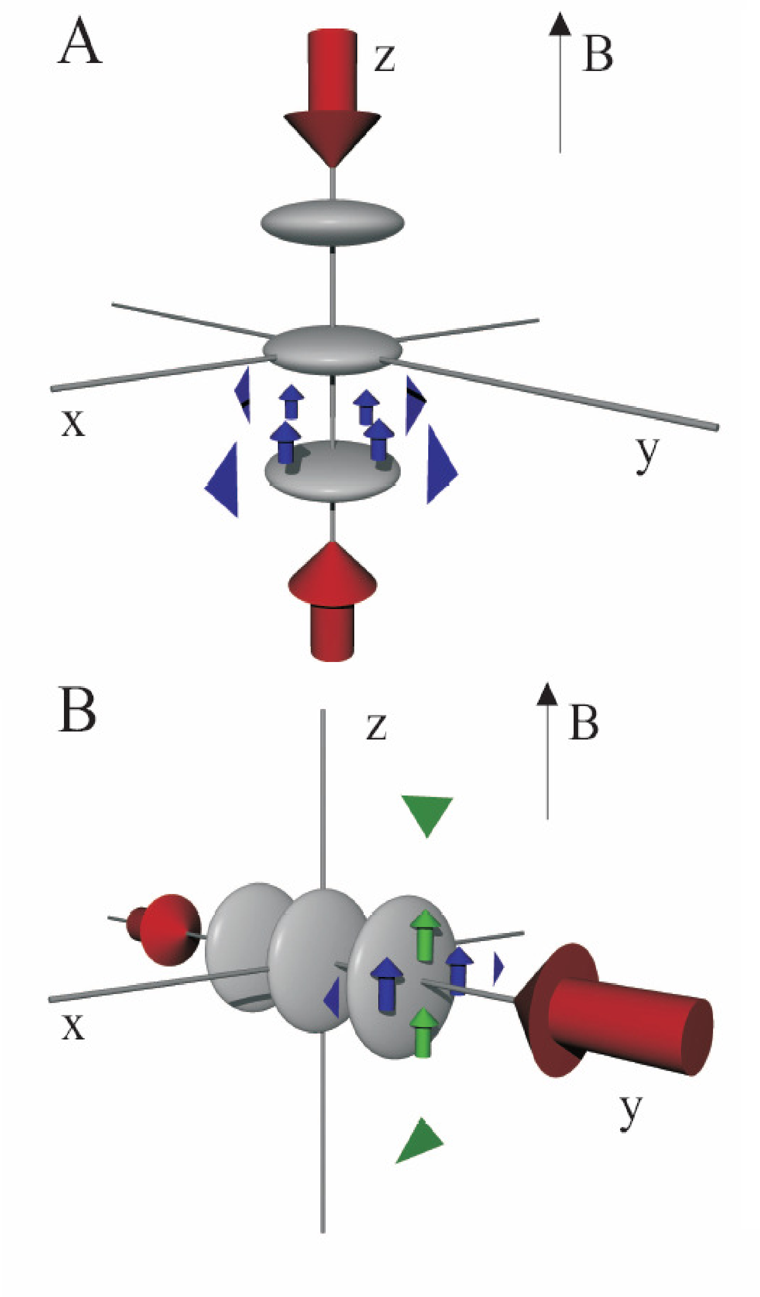
Repulsive dipolar interaction

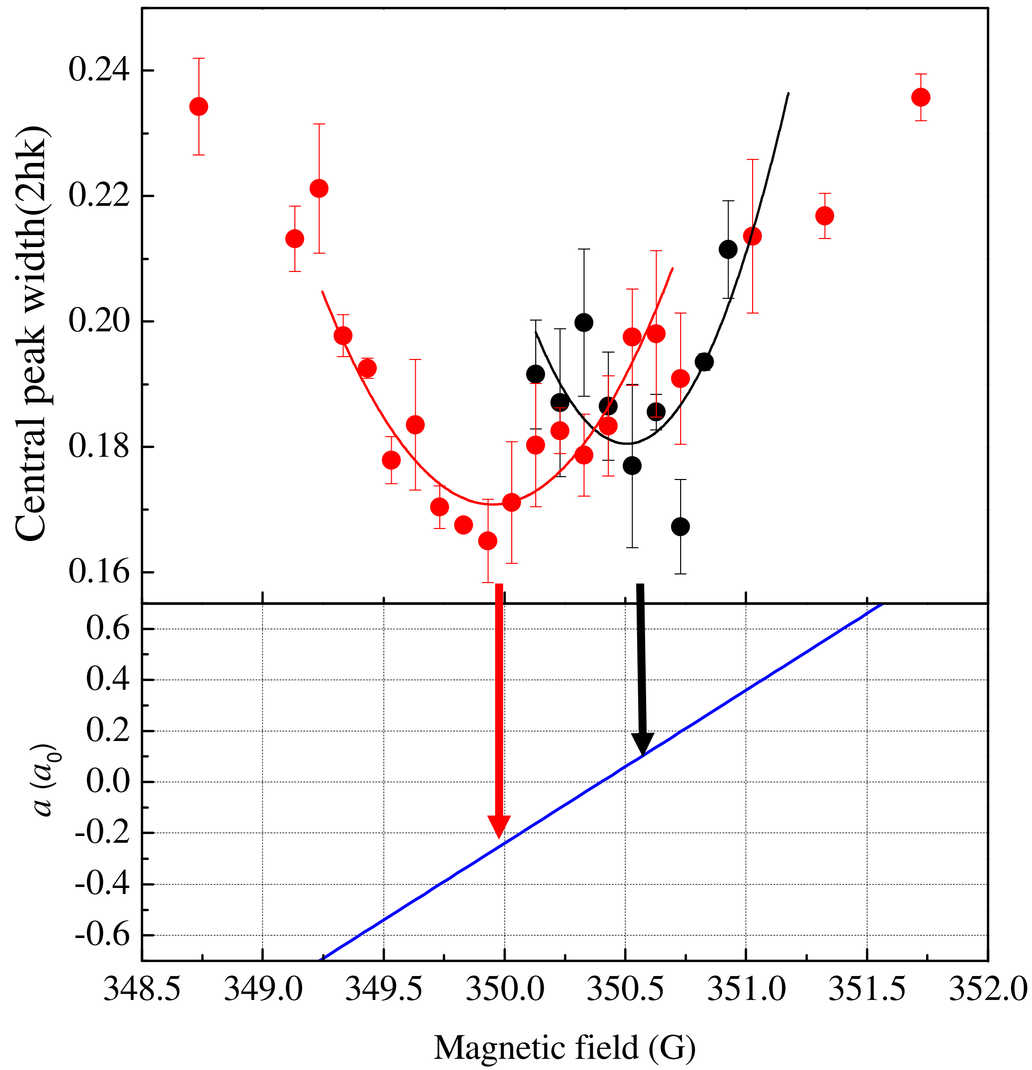
μ = 0.95 μ_B r=0.2 μm

U_d ~ 0.5a_0 ~ 10 Hz

M. Fattori, et al. Phys. Rev. Lett. 100, 080405; 101, 190405 (2008).

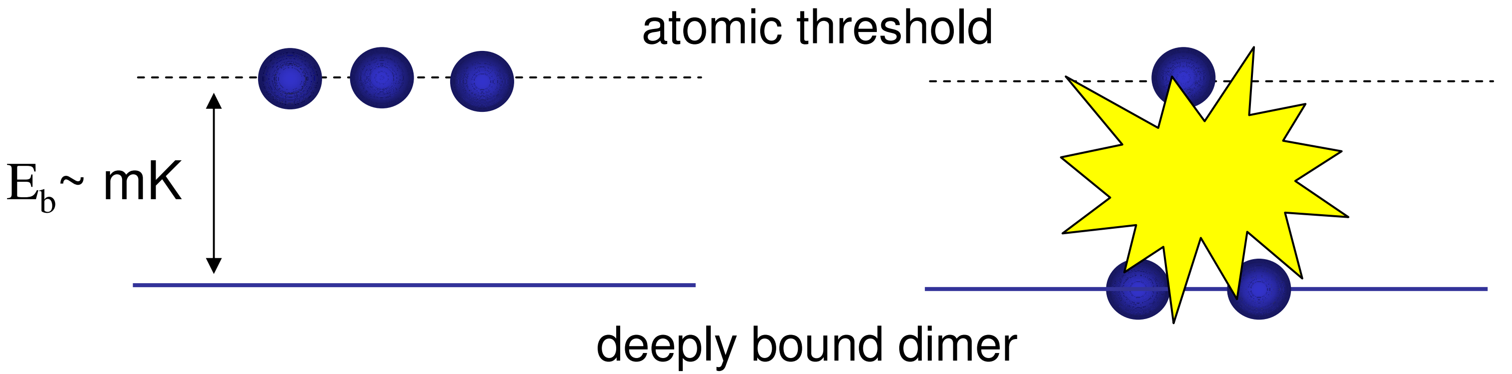
Magnetic dipolar interaction: experiment





Three-body losses

Three atoms can recombine into a molecule+atom: three-body loss



$$\dot{n}(t) = -K_3\, n^3(t)$$

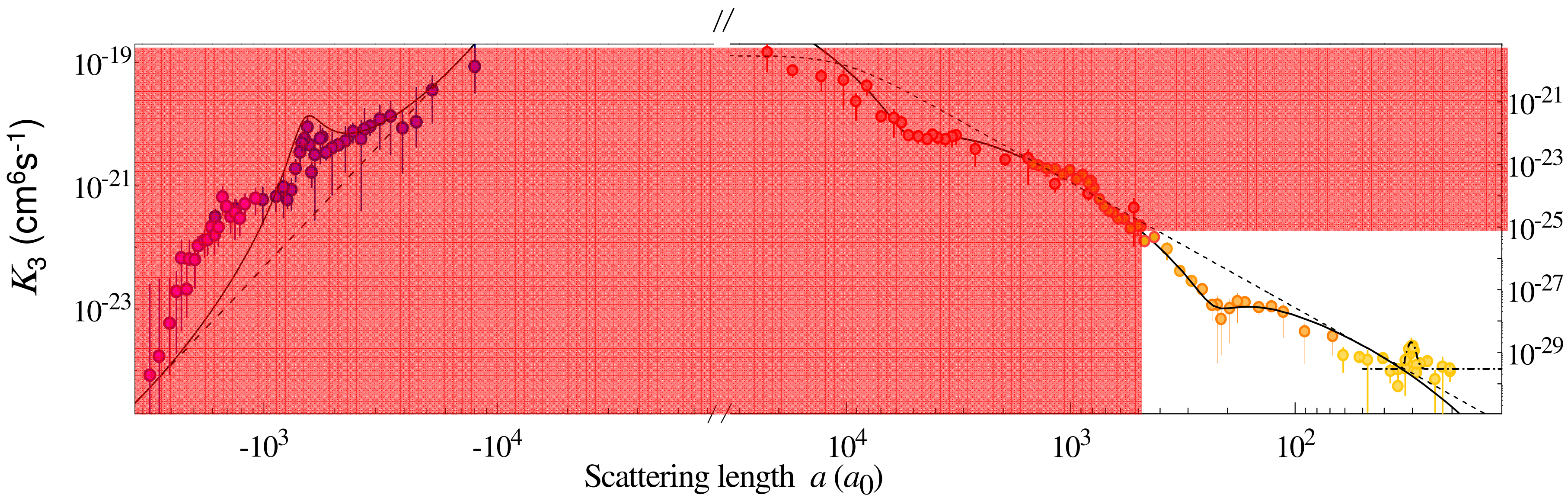
Large a enhance the recombination at short internuclear distances

$$K_3 \propto \frac{\hbar a^4}{m}$$

The useful range of a values is limited

Three-body losses

The picture can be much more complex, due to Efimov trimer states

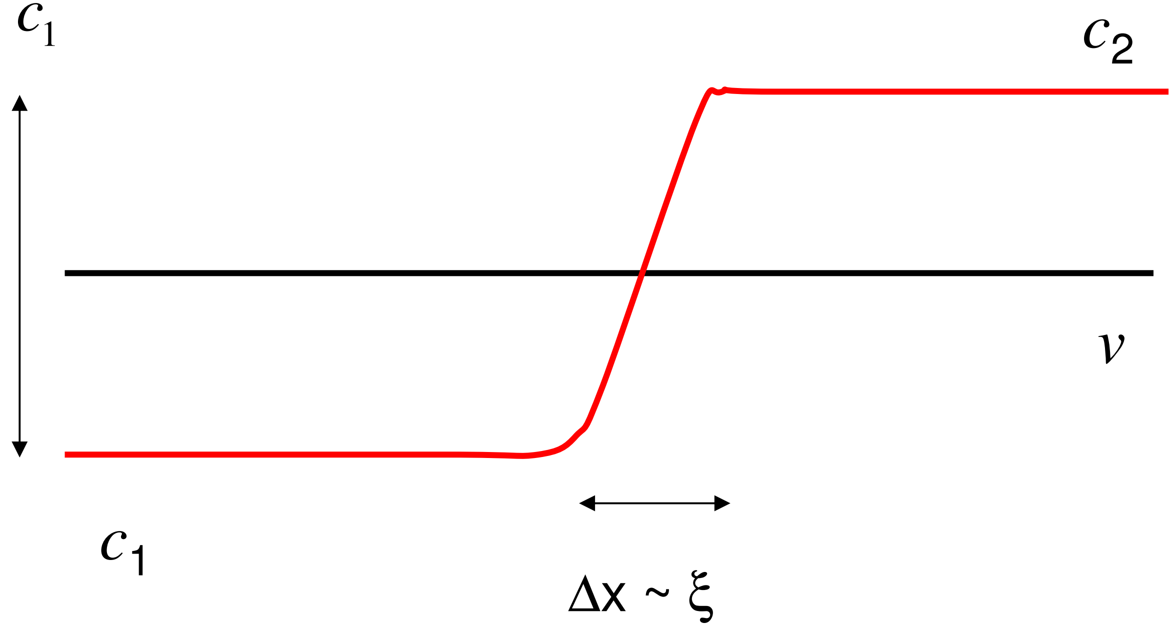


n~10^{13}cm^{-3} $\Rightarrow$ lifetime<100 ms for $K_3<3\times10^{-26}$

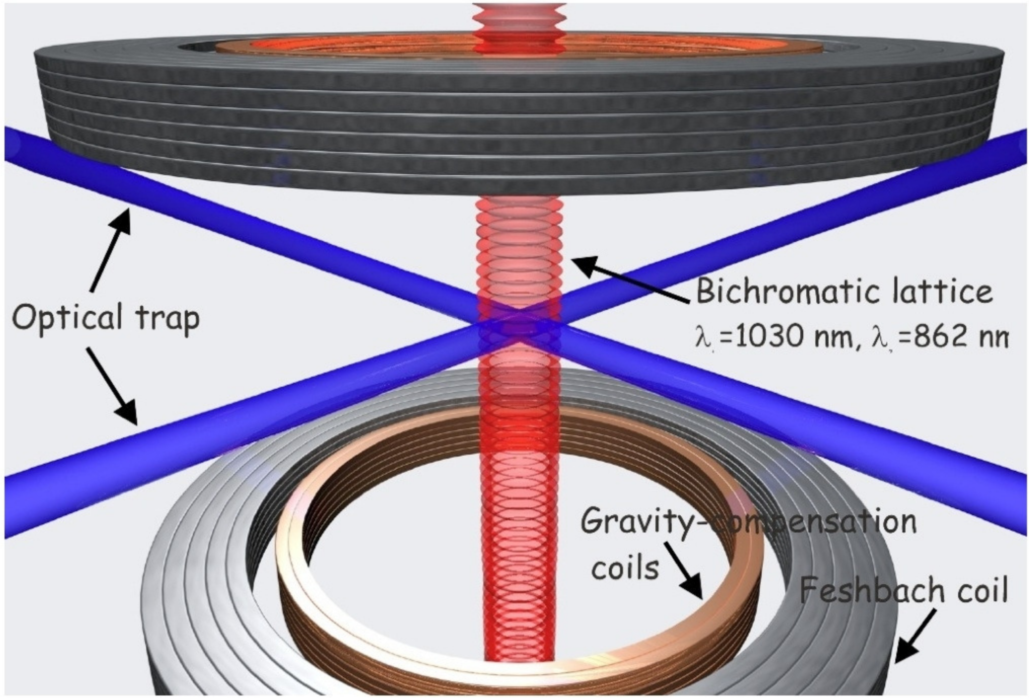
Feshbach resonances and Hawking radiation

Can one employ Feshbach resonances to make an interaction step in the prescribed way?

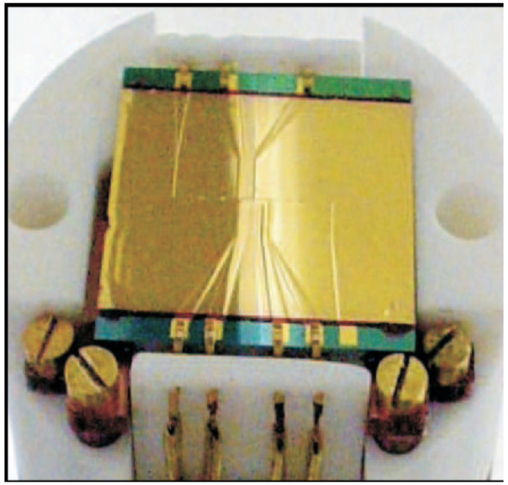
$$D = \frac{c_2 - c_1}{c_1} < 0.5 \qquad \Rightarrow \qquad a \rightarrow 2a$$



Feshbach resonances and Hawking radiation



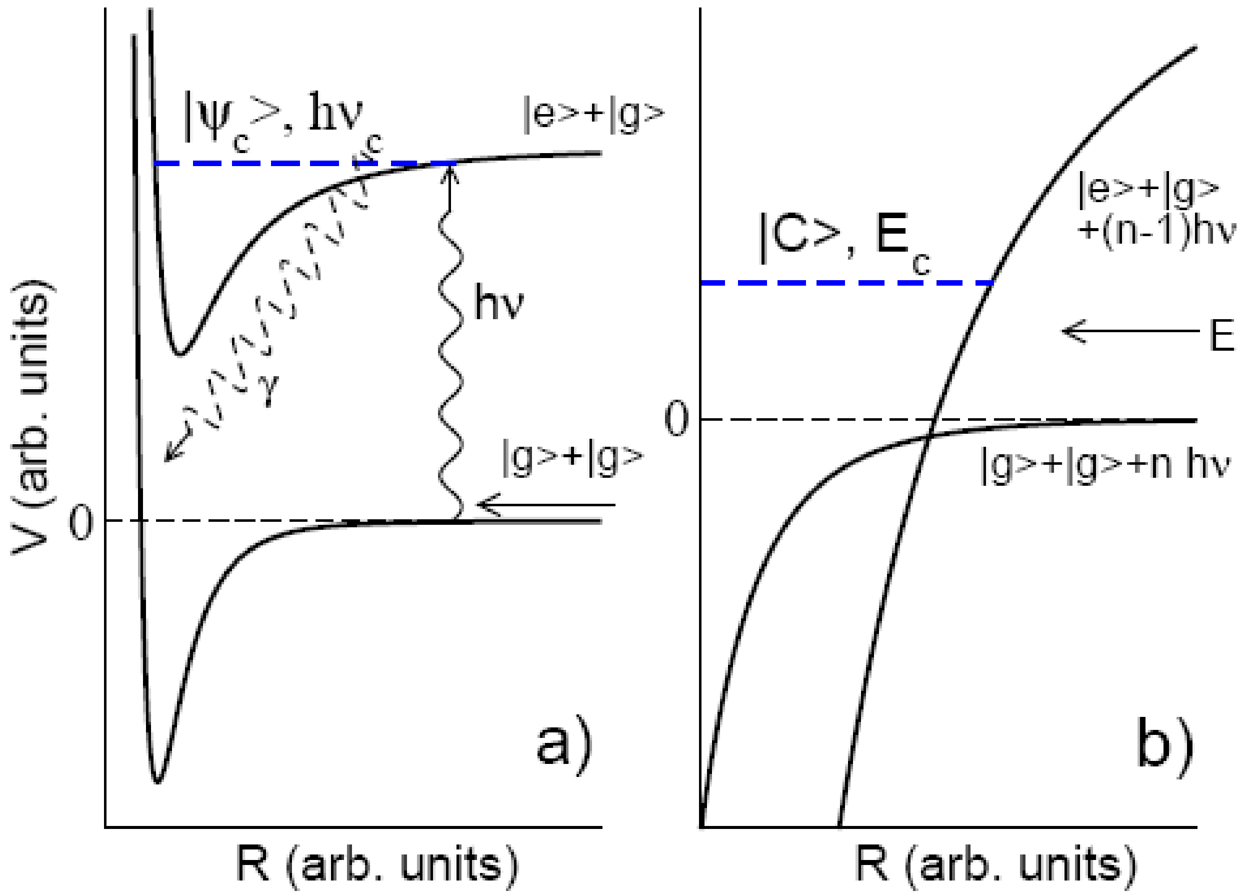
The magnetic coils are typically macroscopic



Easier for atom chips, but still hard

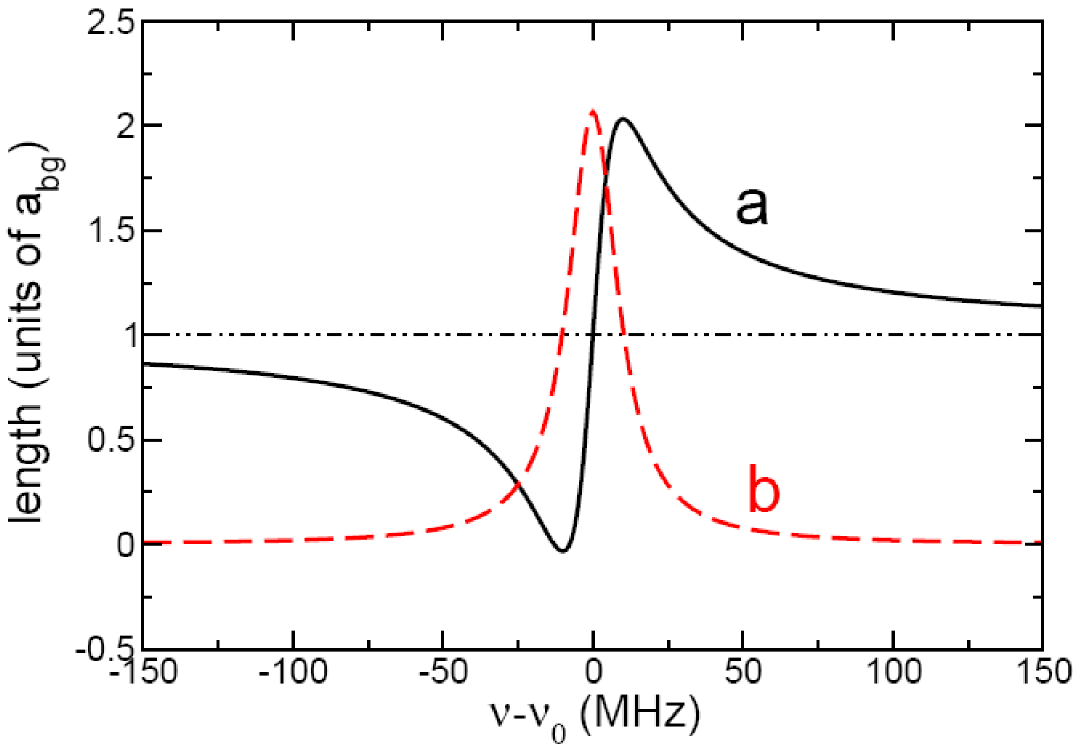
Optical Feshbach resonance

Laser beams can be focused down to a few μm, and scanned.



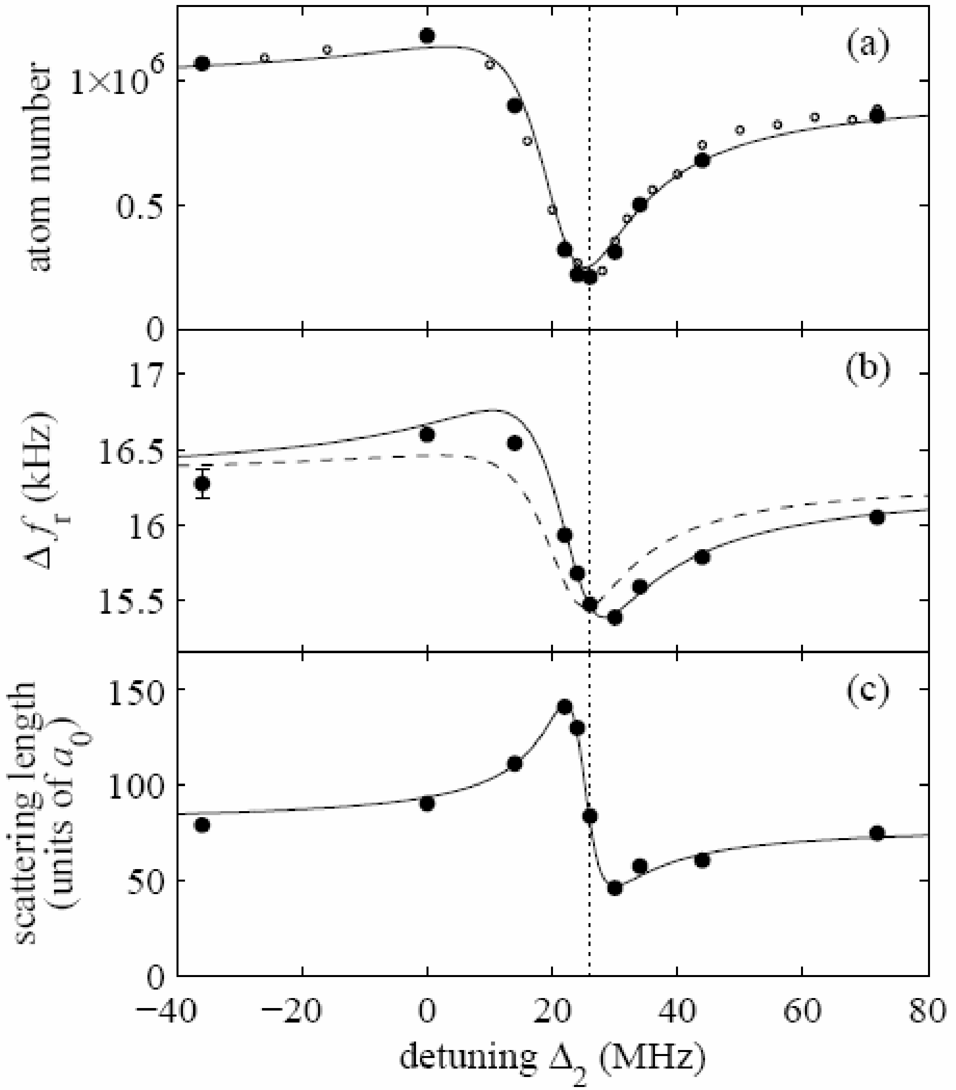
Fedichev et al. Phys. Rev. Lett. 77, 2913 (1996).

Optical Feshbach resonance



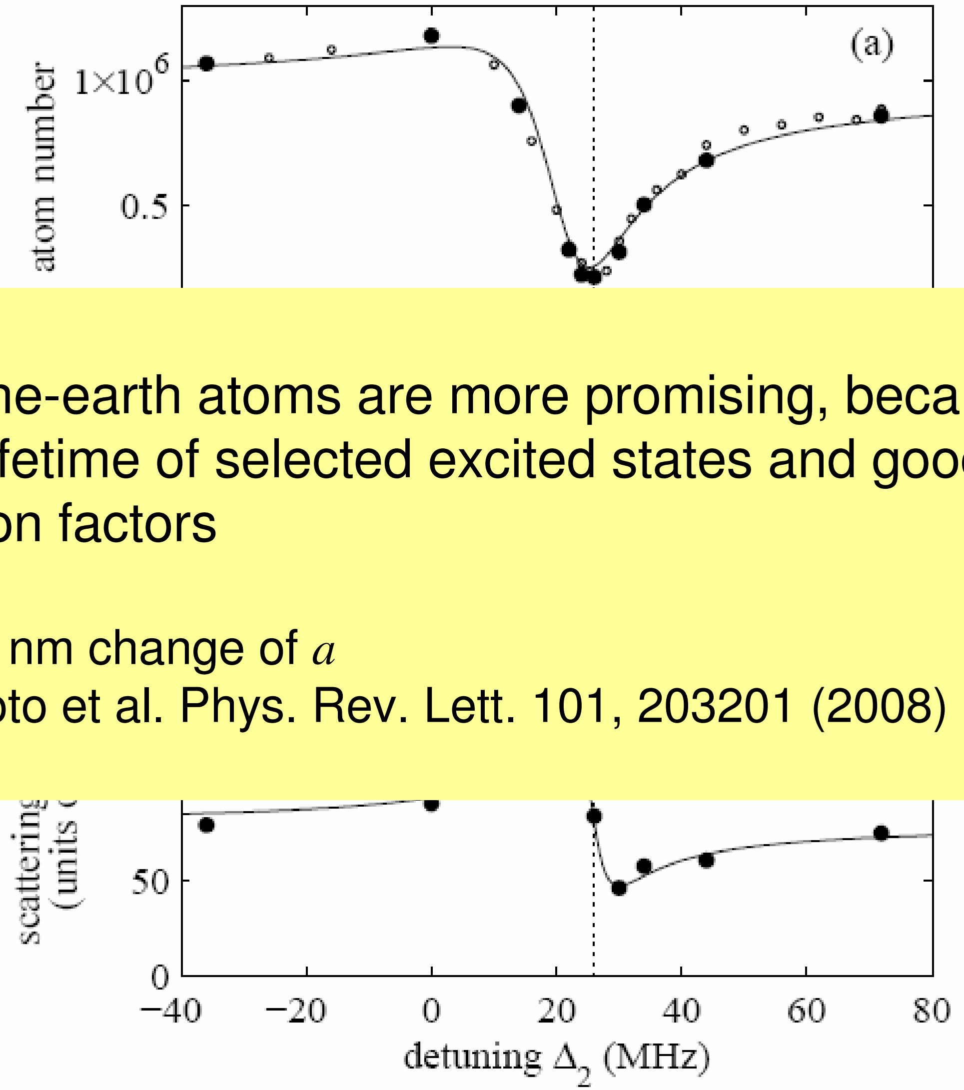
Unfortunately, there is spontaneous emission: $a \rightarrow a - ib$

Optical Feshbach resonance



Theis et al, Phys. Rev. Lett. 93, 123001 (2005)

Optical Feshbach resonance



Alkaline-earth atoms are more promising, because of the long lifetime of selected excited states and good Franck-Condon factors

Yb: 30 nm change of a
Enomoto et al. Phys. Rev. Lett. 101, 203201 (2008)

Theis et al, Phys. Rev. Lett. 93, 123001 (2005)