# RF dressed atoms: matter-wave bubbles

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## Abstract

RF-dressed cold atom traps [1, 2] confine ultracold atoms using spin dependent adiabatic potentials, formed by the atomic interaction with a static and spatially dependent magnetic field and a radio frequency (RF) magnetic field. These traps offer an easy way to manipulate atoms coherently, making them favourable for atom interferometry, and have a range of potential applications such as rotation sensors and quantum simulators. The possibility of miniaturisation using atom chip technology leads to applications in quantum technology.
Here we look at the potential for matter-wave bubbles to be explored using RF dressed atoms in space.

## Magnetic resonance and adiabatic potentials

Magnetic trapping of cold atoms such as Rb87 uses the energy of the atomic dipole with a magnetic dipole moment $\boldsymbol{\mu}$ in a static magnetic field $\mathbf{B}_0$ and this energy is

$$U(\mathbf{r}) = -\boldsymbol{\mu}\cdot\mathbf{B}_0(\mathbf{r}) = m_F g_F \mu_B |\mathbf{B}_0(\mathbf{r})|\,.$$

The Hamiltonian for the interaction of the atom with a RF field, assumed to be a cosine oscillation, is

$$\begin{aligned} H(\mathbf{r}) = {} & \frac{g_F\mu_B}{\hbar}|\mathbf{B}_0(\mathbf{r})|\hat{F}_z \\ & + \frac{g_F\mu_B}{2\hbar}|\mathbf{B}^{\perp}_{\text{rf}}(\mathbf{r})|[\hat{F}_+\exp(\mp i\omega_{\text{rf}}t) \\ & + \hat{F}_-\exp(\pm i\omega_{\text{rf}}t)]\,, \end{aligned}$$

Magnetic resonance occurs where

$$\omega_{\text{rf}} = \frac{|g_F|\mu_B|\mathbf{B}_0(\mathbf{r})|}{\hbar}\,,$$

If we diagonalise this problem in the rotating frame we obtain

$$H'(\mathbf{r}) = \Omega(\mathbf{r})\hat{F}_{z'}\,,$$

where the $z'$ label indicates the new, local basis, direction and we introduce the *generalised* Rabi frequency

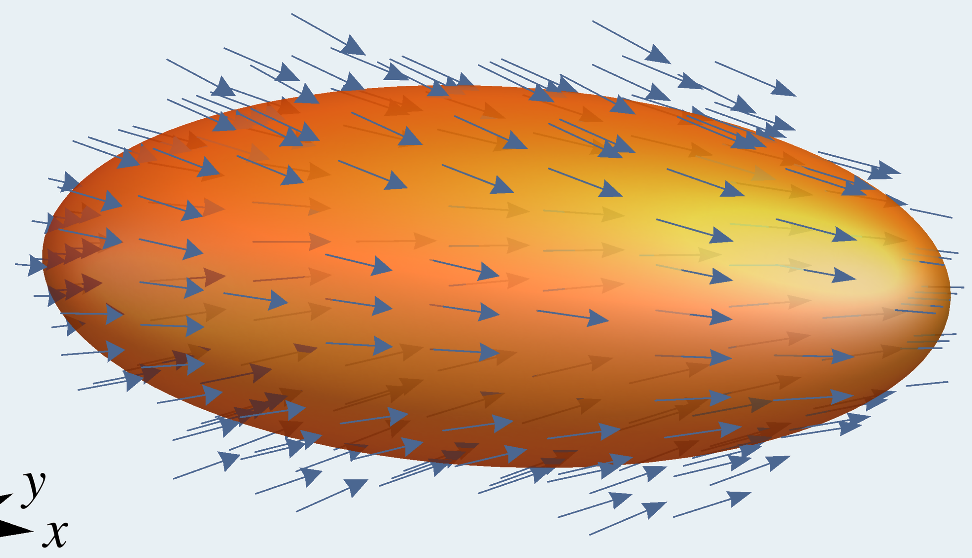
$$\Omega(\mathbf{r}) = \sqrt{\delta^2(\mathbf{r}) + \Omega_0^2(\mathbf{r})}\,,$$

with detuning $\delta(\mathbf{r}) = \omega_{\text{rf}} - \omega_L(\mathbf{r})$ and Rabi frequency $\Omega_0(\mathbf{r}) = \frac{g_F\mu_B}{2\hbar}|\mathbf{B}^{\perp}_{\text{rf}}(\mathbf{r})|$.
Then the dressed potentials, in space, are

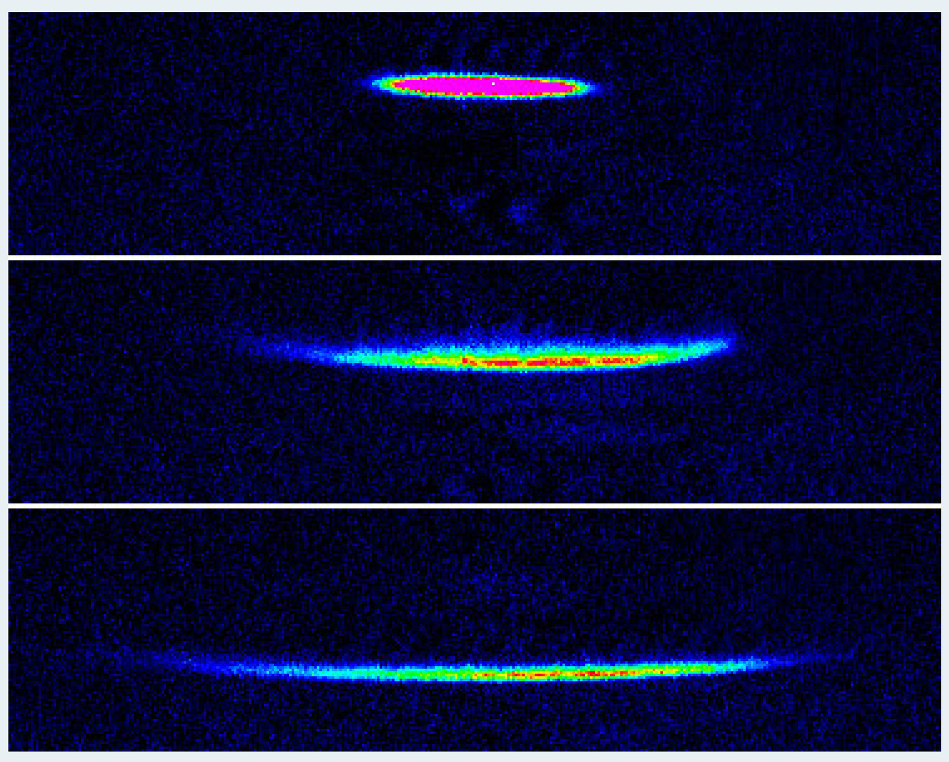
$$\begin{aligned} U(\mathbf{r}) &= m'_F\hbar\Omega(\mathbf{r}) = m'_F\hbar\sqrt{\delta^2(\mathbf{r}) + \Omega_0^2(\mathbf{r})} \\ &= m'_F\sqrt{[\hbar\omega_{\text{rf}} - \hbar\omega_L(\mathbf{r})]^2 + [g_F\mu_B|\mathbf{B}^{\perp}_{\text{rf}}(\mathbf{r})|/2]^2} \end{aligned}$$

## Making matter-wave bubbles on earth

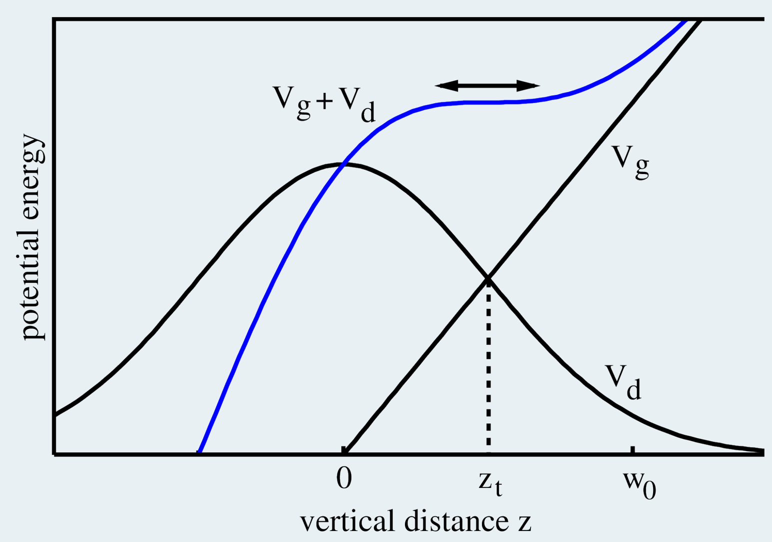
Typical magnetic traps have a minimum in $|\mathbf{B}_0(\mathbf{r})|$ in the centre and magnetic resonance occurs over a spheroidal surface in space.




The dressed potentials result in a trapping *bubble* which is located on an iso-$B$ surface; i.e. where we have magnetic resonance. *Figure for the iso-$B$ surface of an Ioffe-Pritchard trap taken from Ref. [1].*



When atoms are placed in this trapping potential they fall to the bottom of the bubble because of gravity. *Figure taken from Ref. [1] shows two different radio-frequencies (middle and bottom, and the initial atoms in the centre of the magnetic trap (top).*




It is possible to devise a scheme to compensate for gravity by using the off-resonant dipole force from an off-centre laser [3]. However, for large bubbles more powerful lasers are required, and it would require great care to compenasate for gravity evenly. Nobody has done this to date. *Figure taken from Ref. [3].*

## Better solution: CAL

A better solution is to put the experiment in space. The ISS offers a micro-gravity environment for cold atoms.

Image courtesy of NASA.

The Cold Atom Laboratory (CAL) is planned to fly on the ISS in 2017. Matter-wave bubbles can be formed underneath an atom chip in the absence of gravity (Lundblad et al.)

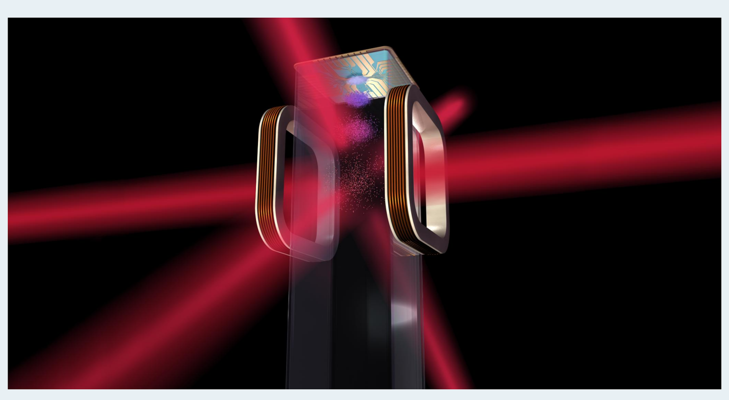
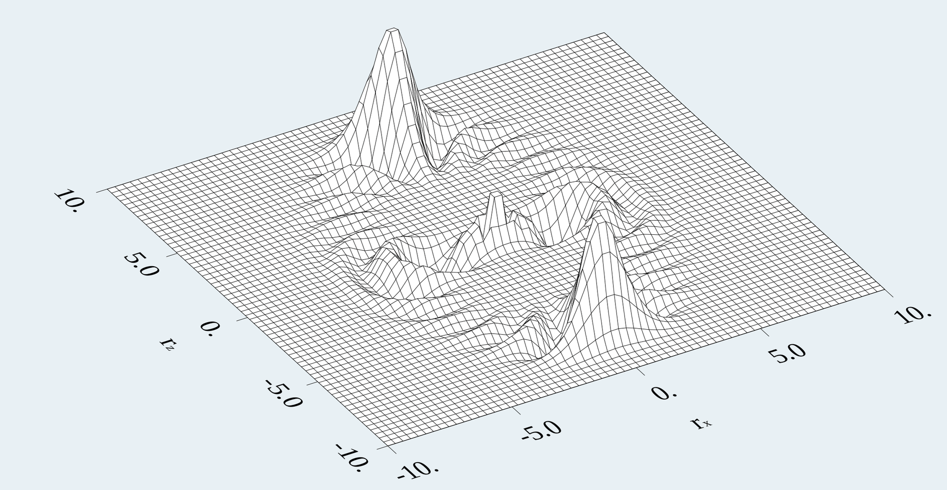


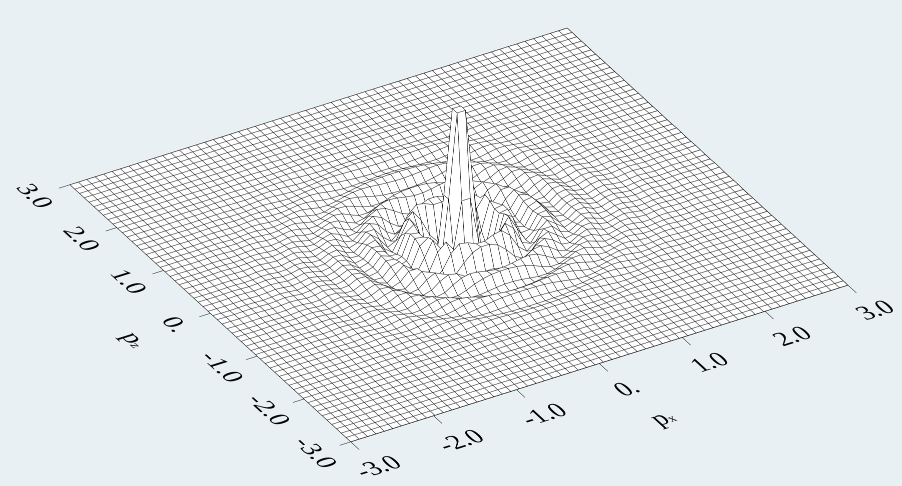
Image courtesy of NASA/JPL-Caltech.

## What can we do with matter-wave bubbles?

• Collapse them [5] • Stir them • Study vortices in bubbles • Matter-wave interference • Tunnelling • Probe microgravity • Make ring traps [4]



Wigner function for a matter-wave bubble (radius $\sqrt{60}$). We show the position distribution for finite momentum (scaled $p = 2.5$) [6].



Wigner function for a matter-wave bubble (radius $\sqrt{60}$): we show the momentum distribution at the centre of the bubble [6].

**References:**

[1] B.M. Garraway and H. Perrin, Topical Review: *Recent developments in trapping and manipulation of atoms with adiabatic potentials*, J. Phys. B **49**, 172001 (2016).
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