Quantum State Preparation in Microtraps

or

How to move an atom?

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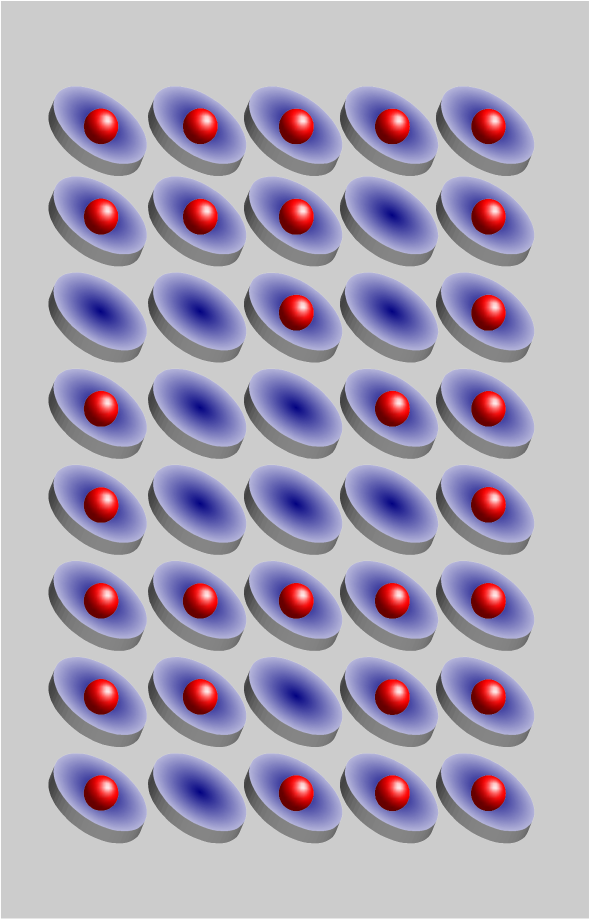
Motivation

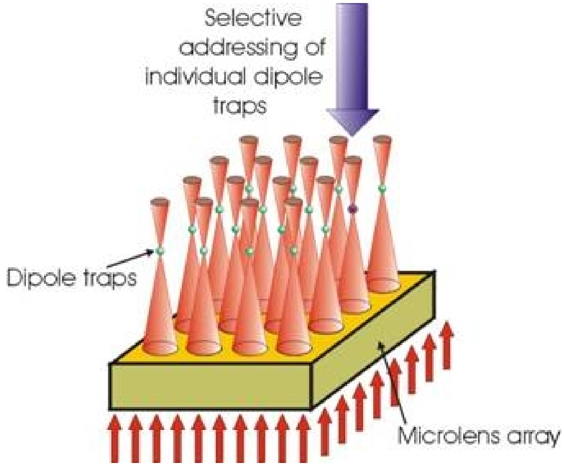
- single trapped neutral atoms are promising systems for observing effects in quantum information
- highly controllable microstraps for single neutral particles are developed in several labs wordwide
- storage, movement and preparation of atoms have to be addressed
- internal state manipulation well known, but ***spatial*** states to be addressed



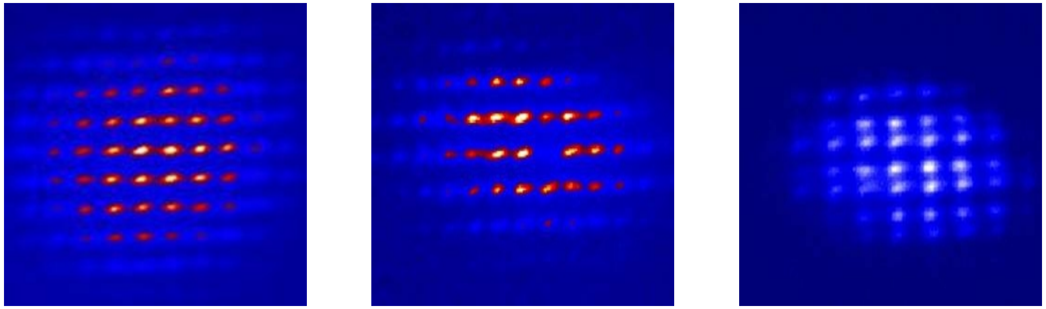
Overview

- Atom Trapping
- Movement of atoms in microtraps
- Three Level Atom Optics (spatial STIRAP)
- Four Level Atom Optics
- Outlook: Four Level Atom Optics in 2D
- Conclusions

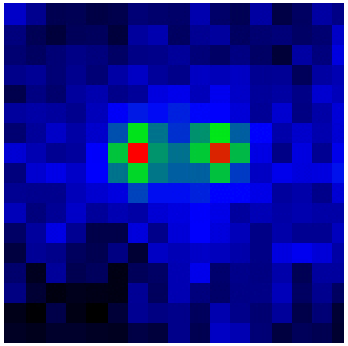
Experimental Sytems



G. Birkl, TU Darmstadt/ Hannover

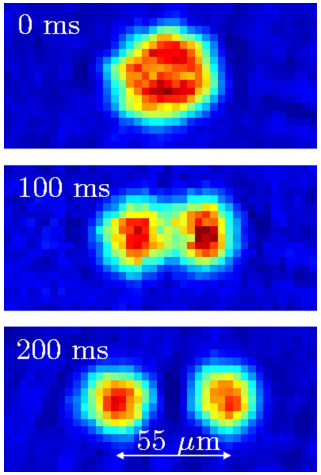


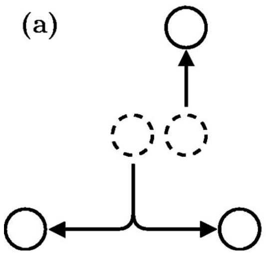
P. Grangier, CNRS

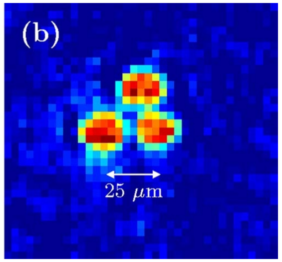


microscopic dipole traps

C. Foot, Oxford

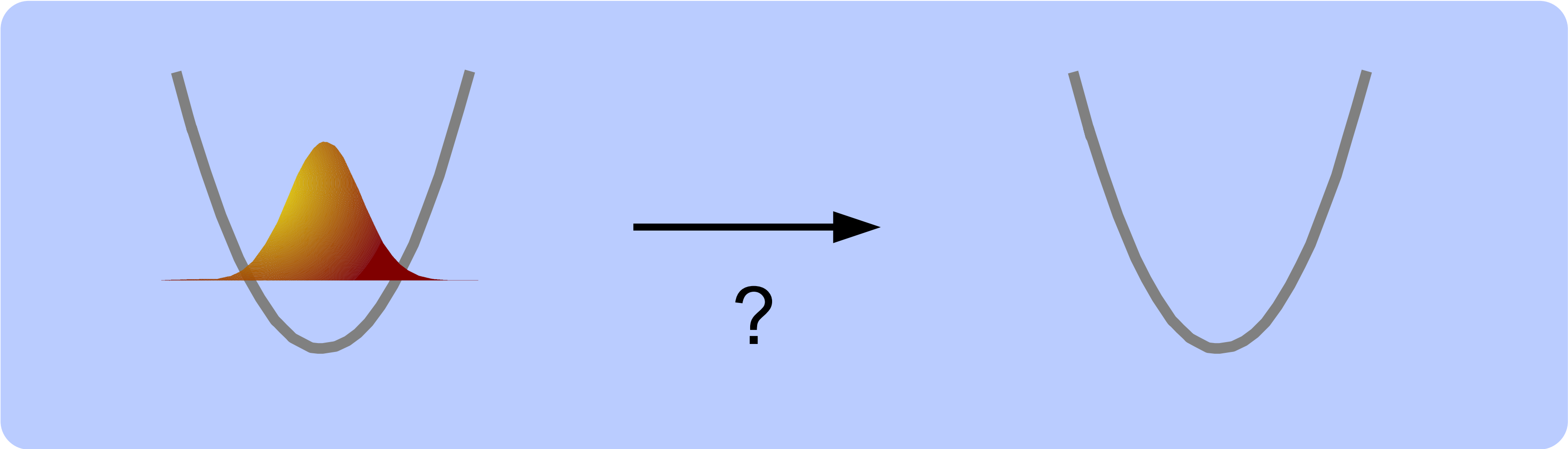






diffractive modulators

How to move an atom?



Solution: Tunneling (decrease and increase distance between traps)

Problem: Rabi Oscillations

→ success depends on control of three parameters:

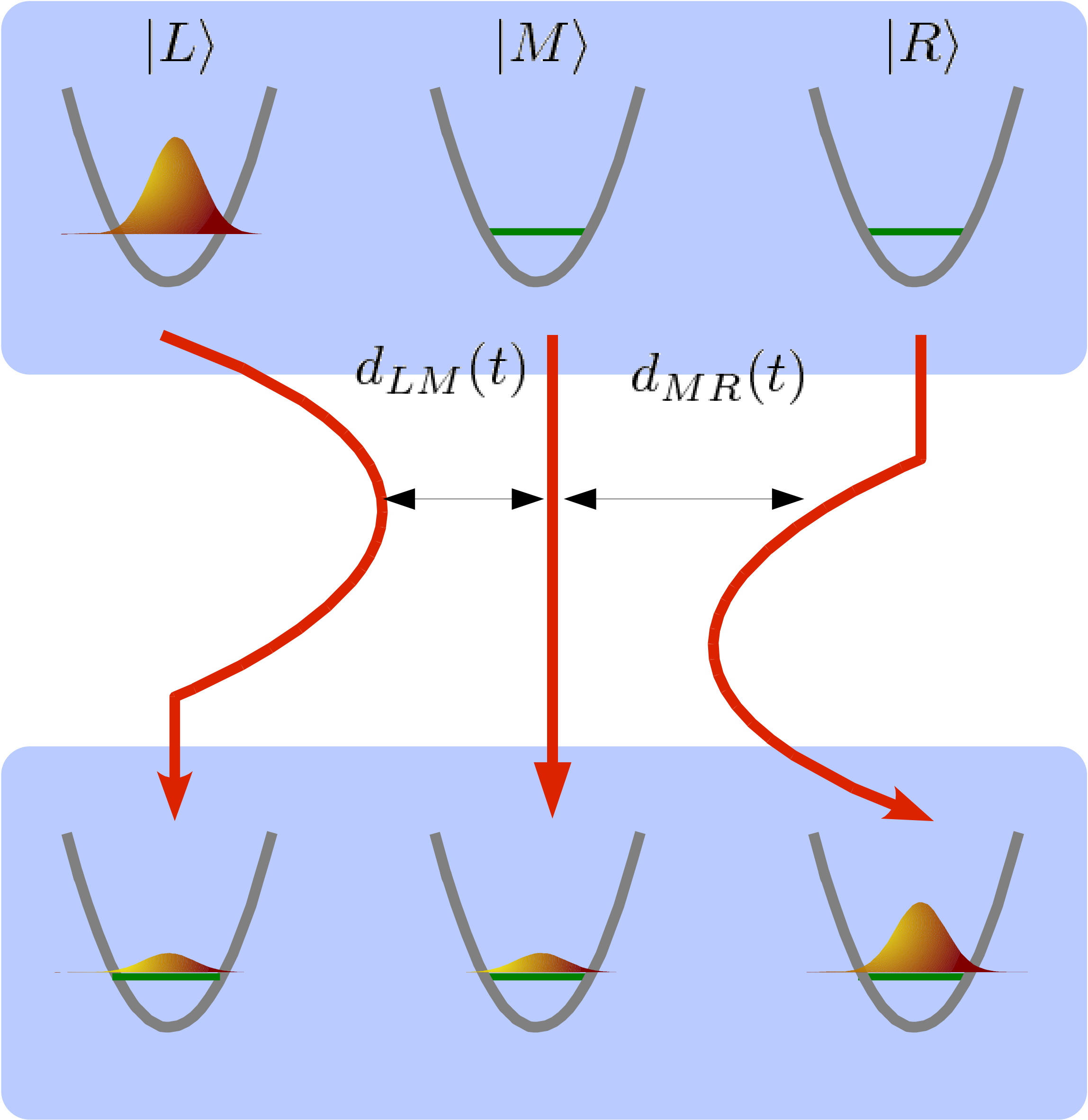
- t_i interaction time
- t_a approach time
- a_{min} minimum distance between traps

→ precise experimental control necessary for high fidelities

Three-Level Atom Optics

Sequential Tunneling

→ same problems, only twice!

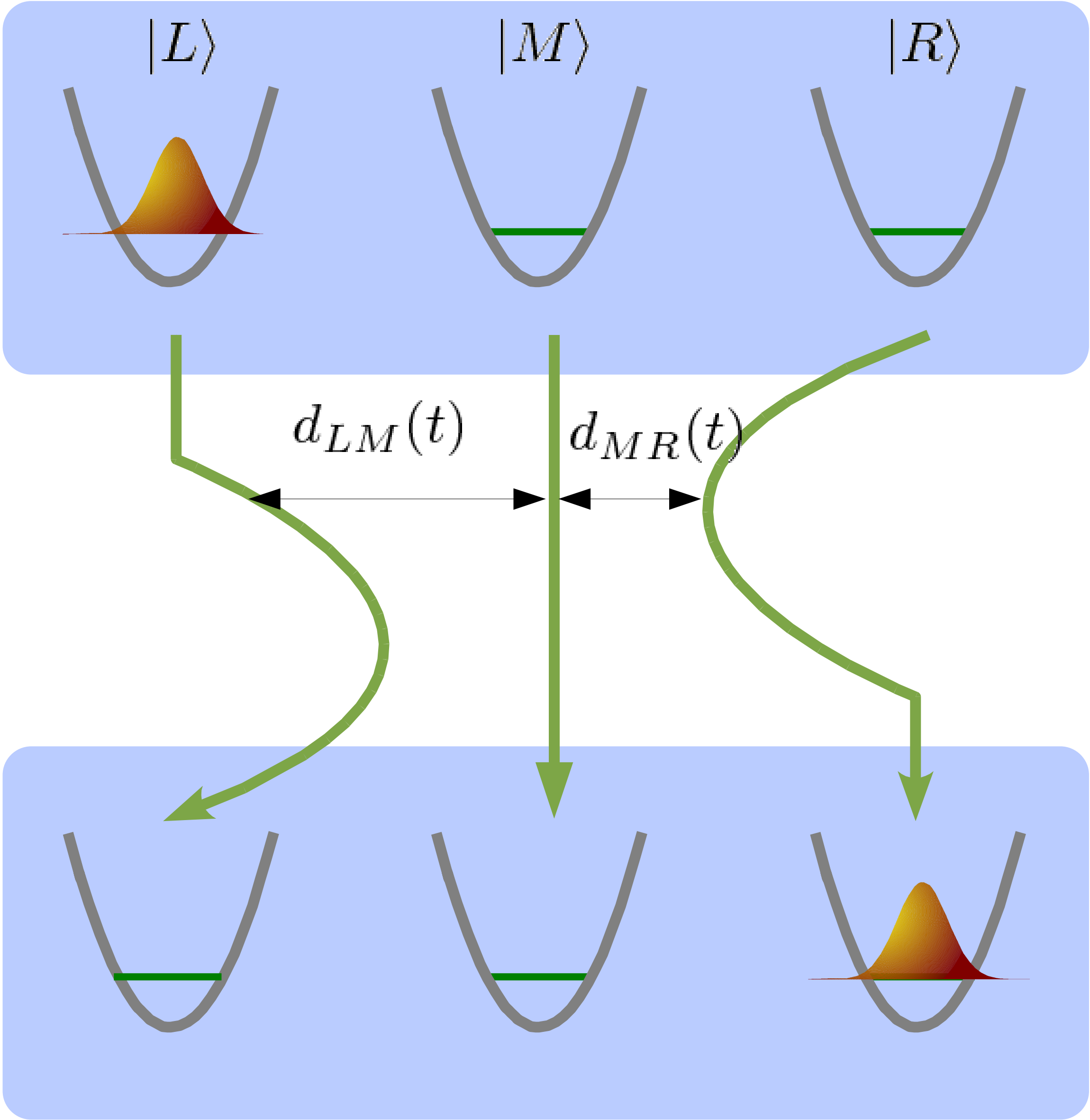


Three-Level Atom Optics

Eckert *et al.* PRA **70** (2004)

Counterintuitive Tunneling

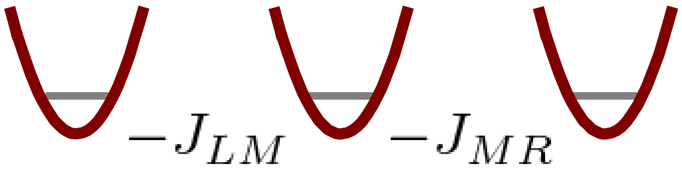
- 100% tansfer
- never any population in $|M\rangle$



see also:
Greentree *et al.*,
PRB 235317 (2004)

Three-Level Atom Optics

$$H = \begin{pmatrix} 0 & -J_{ML} & 0 \\ -J_{LM} & 0 & -J_{MR} \\ 0 & -J_{MR} & 0 \end{pmatrix}$$



- three level system possesses *dark state*

$$|\psi(\theta)\rangle = \cos\theta|L\rangle - \sin\theta|R\rangle \qquad \tan\theta = \frac{J_{LM}}{J_{MR}}$$

- STIRAP-like techniques can be developed

Counterintuitive scheme:

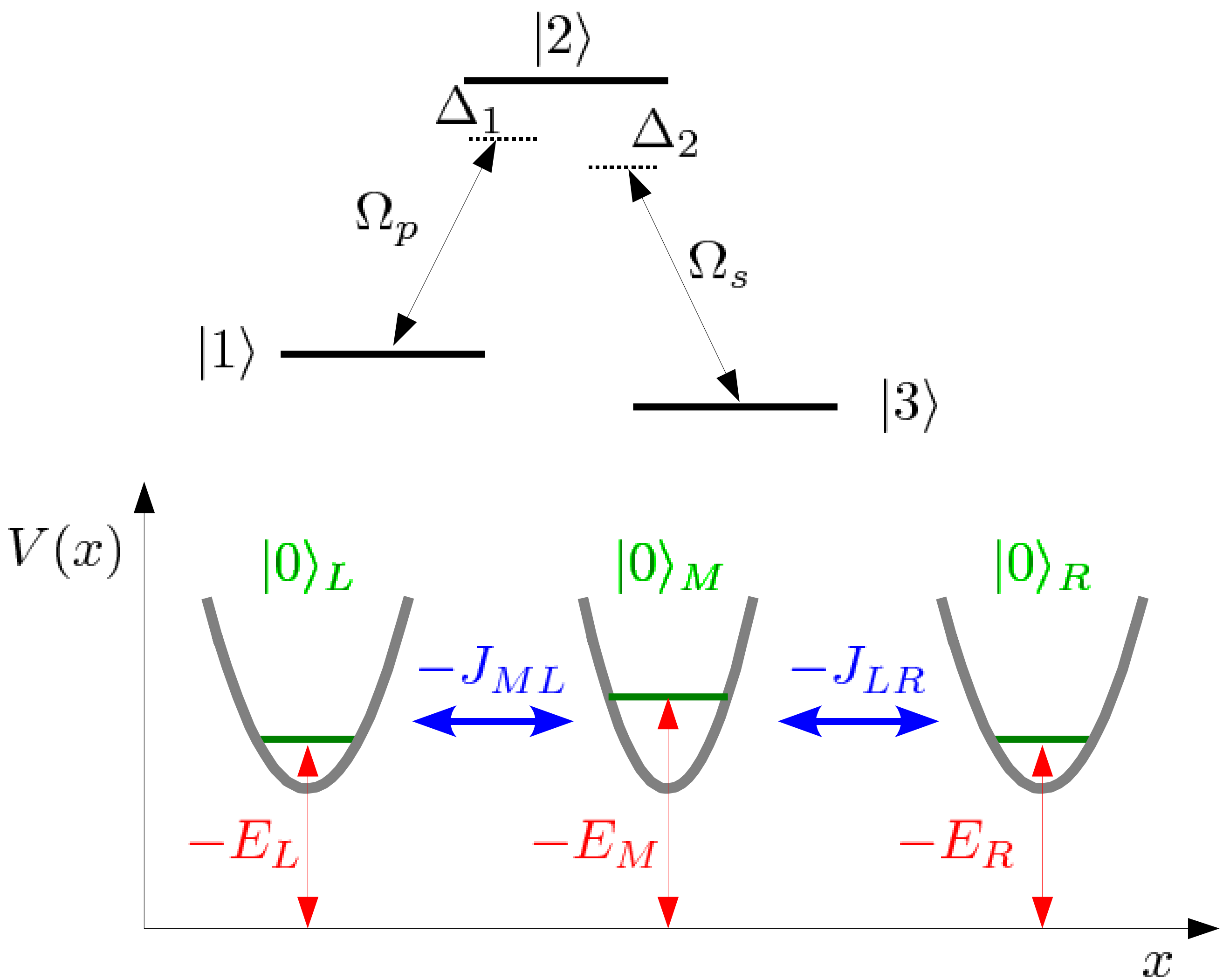
$$\tan\theta : 0 \to \infty$$

$$\theta : 0 \to \frac{\pi}{2}$$

$$\cos\theta : 1 \to 0$$

$$\sin\theta : 0 \to 1$$

Spatial STIRAP



States:

$|1\rangle \hat{=} |0\rangle_L$

$|2\rangle \hat{=} |0\rangle_M$

$|3\rangle \hat{=} |0\rangle_R$

Frequencies:

$\Omega_p \hat{=} - J_{LM}$

$\Omega_s \hat{=} - J_{MR}$

Detunings:

$\Delta_1 \hat{=} E_M - E_L$

$\Delta_2 \hat{=} E_M - E_R$

→ also: analogues to CPT and EIT can be constructed

Spatial STIRAP

- Moving an atom through an array of three traps can be easiest done by *first* increasing the transition probability between the two empty traps and then between the middle and the occupied trap
  ➝ *counterintuitive coupling scheme*

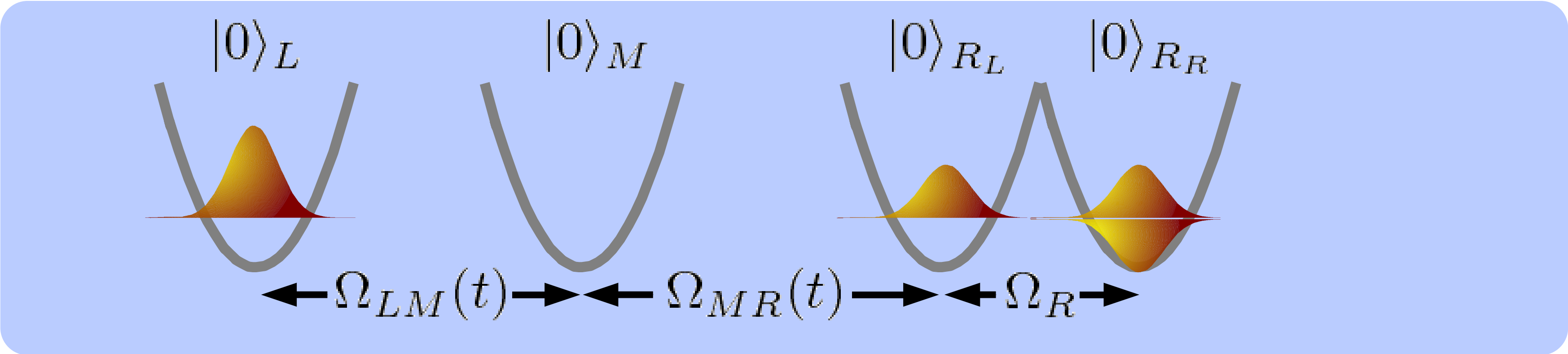
- makes use of a *dark state*, that only includes population in two states. No population in the transition state at any point.
  ➝ *valuable in optics to avoid losses due to spontaneous emission*

- translation has to be a zero mode
  ➝ *energy conservation*

- moving is only one aspect, large potential for
  ➝ *quantum state preparation*

Example: Quantum State Preparation

Aim: *Create a spatial superposition state with full control over the symmetry*



→ allow for different trapping frequency ω_R

$$H = \hbar \begin{pmatrix} 0 & -\Omega_{LM}(t) & 0 & 0 \\ -\Omega_{LM}(t) & 0 & -\Omega_{MR}(t) & 0 \\ 0 & -\Omega_{MR}(t) & \omega - \omega_R & -\Omega_R \\ 0 & 0 & -\Omega_R & \omega - \omega_R \end{pmatrix}$$

(in terms of the asymptotic ground states of the harmonic traps)

Double Dark State

→ this Hamiltonian has an eigenstate that is a *double dark state*

$$|\phi^{\pm}\rangle = \cos\theta|0\rangle_L - \sin\theta\left[(|0\rangle_{R_L} \pm |0\rangle_{R_R})/\sqrt{2}\right]$$
$$= \cos\theta|0\rangle_L - \sin\theta|0\rangle_R^{\pm}$$

$$\tan\theta = \sqrt{2}\frac{\Omega_{LM}}{\Omega_{MR}}$$

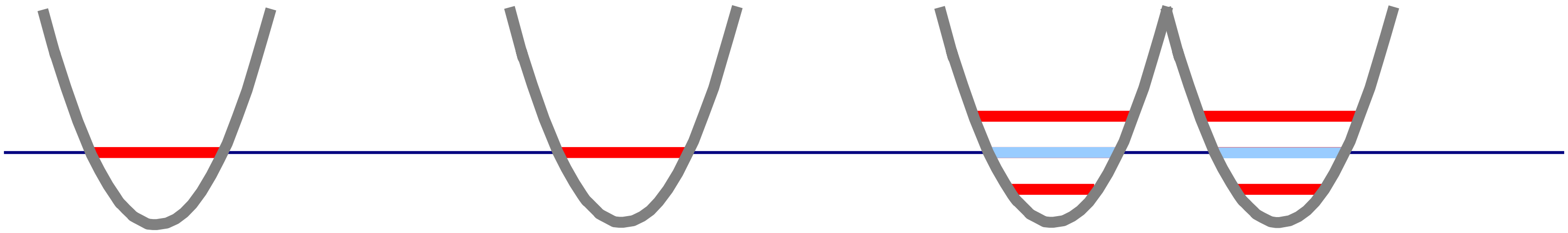
Condition: $\omega - \omega_R = \pm\Omega_R$

→ If the difference in trapping frequency between the traps is equal to the tunnel splitting in the double well trap, a dark state exists.

→ symmetric or antisymmetric state can be chosen by adjusting ω_R

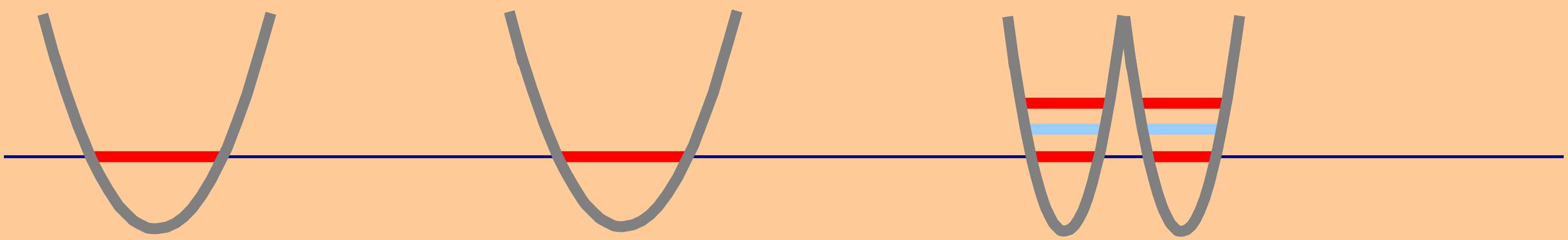
Double Dark State

For $\omega = \omega_R$ translation is a zero mode for the asymptotic states:



→ in the double well trap the ground states are the symmetric and anti-symmetric combination: no more zero mode!

$\omega < \omega_R$



→ *symmetric* state is part of the zero mode and therefore the final state of the STIRAP process!

Double Dark State

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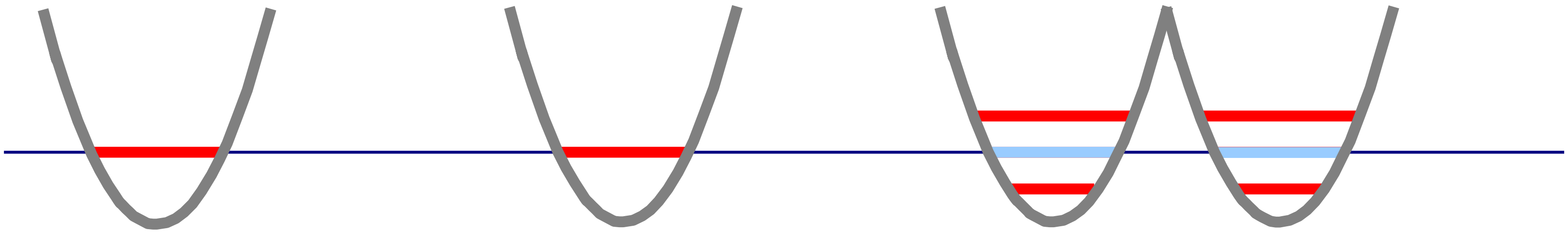

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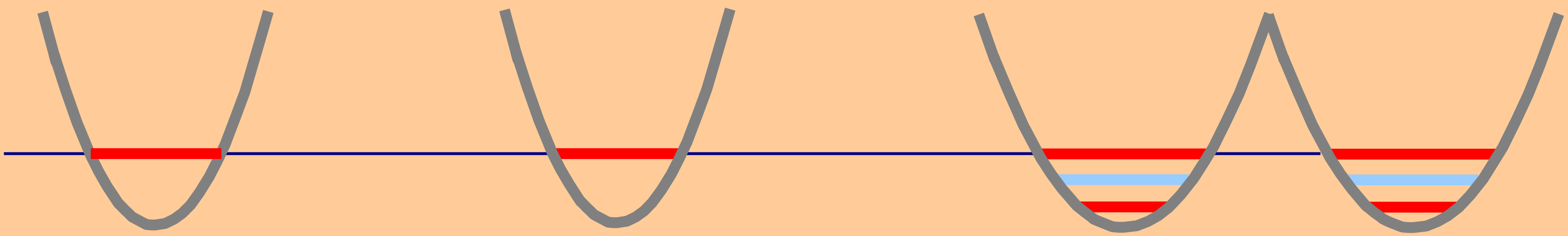
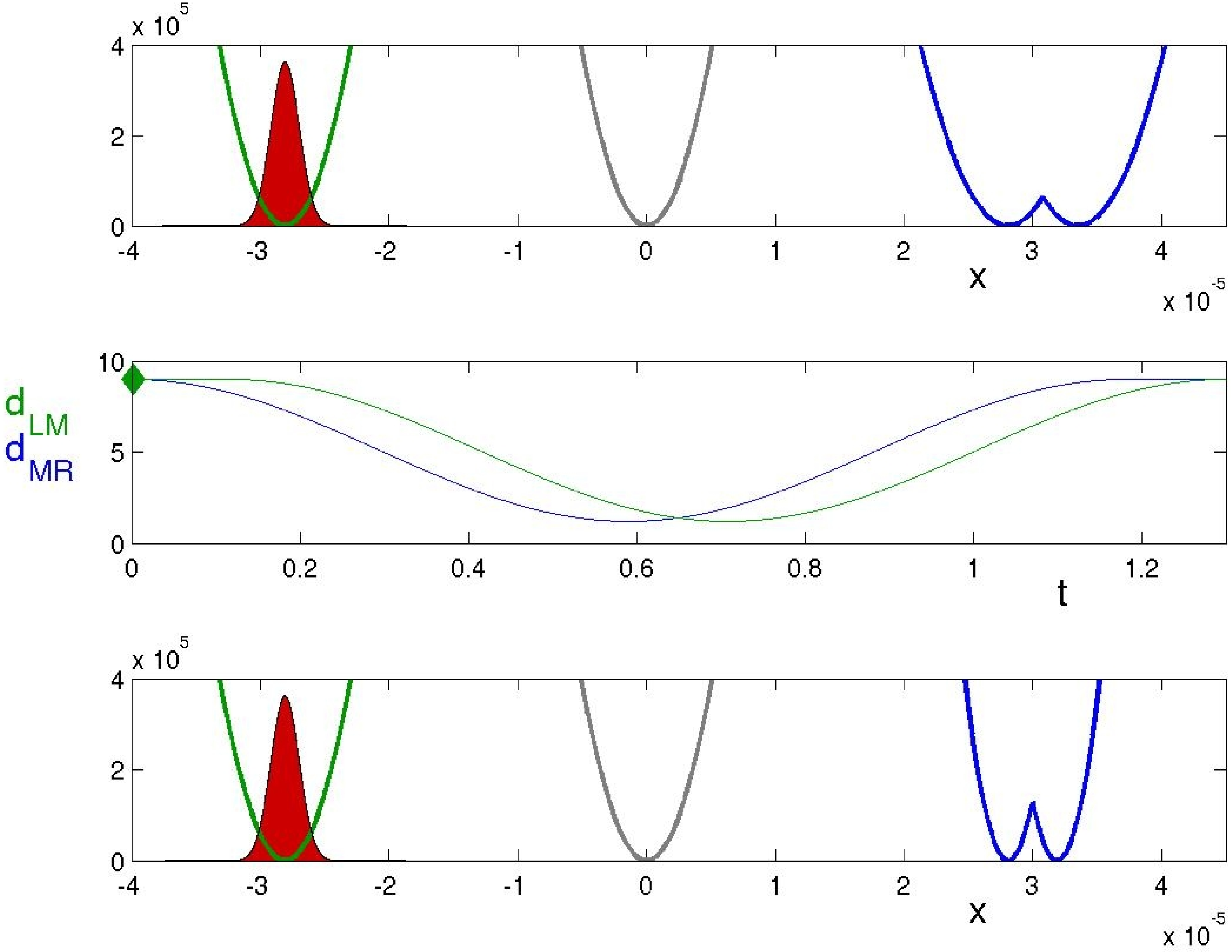
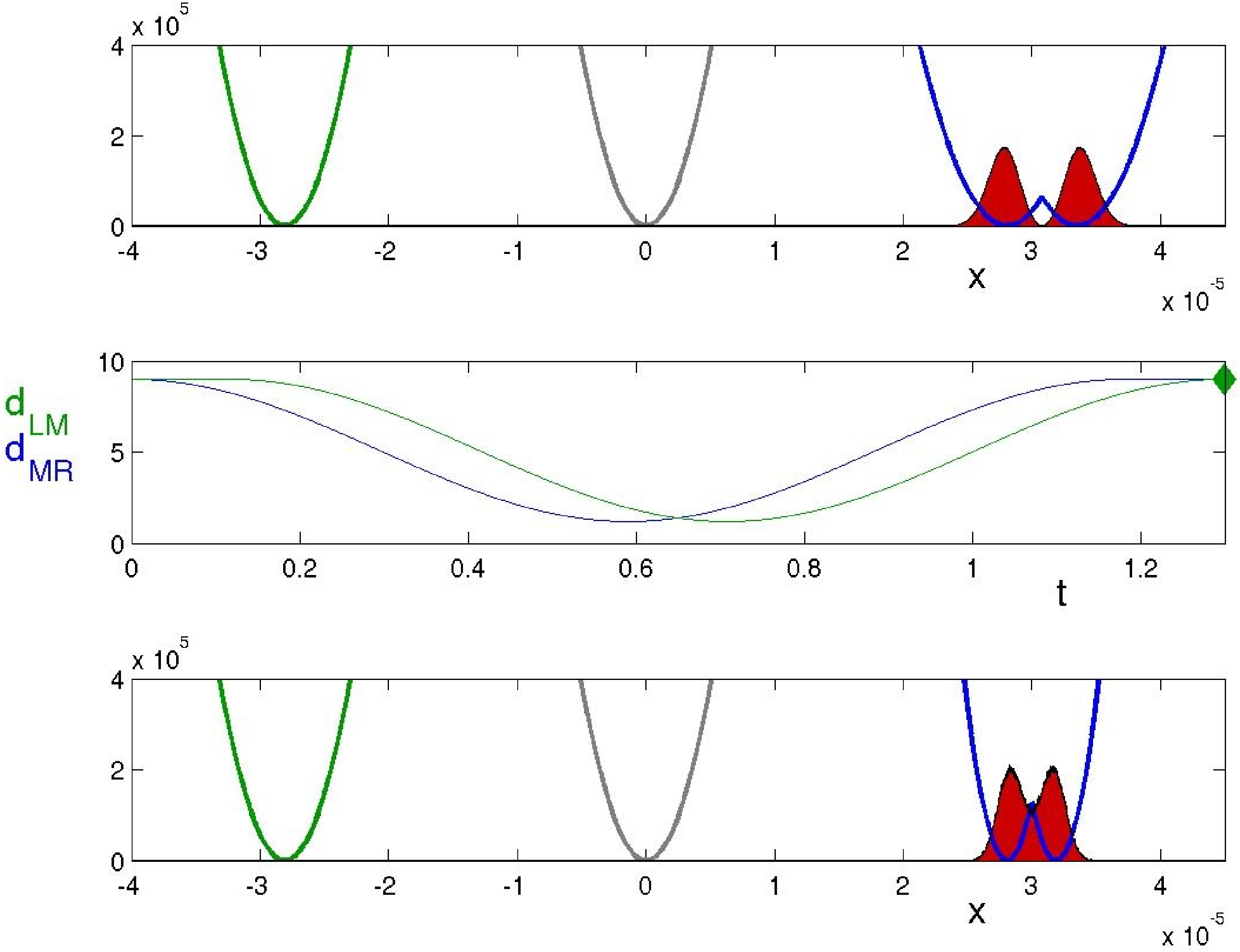


→ *anti-symmetric* state is part of the zero mode and therefore the final state of the STIRAP process!



x 10^5
4
2
0
-4
-3
-2
-1
0
1
2
3
4
x
x 10^-5
10
5
0
0.2
0.4
0.6
0.8
1
1.2
t
d_LM
d_MR



x 10^5
4
2
0
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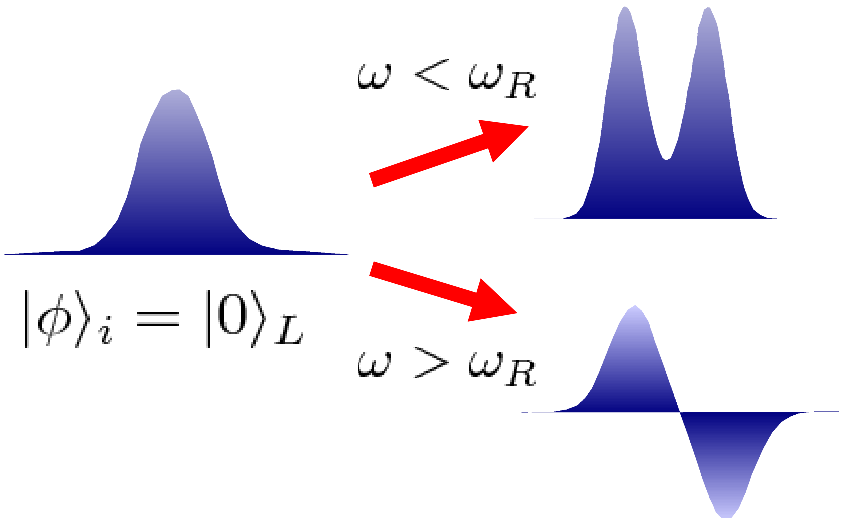
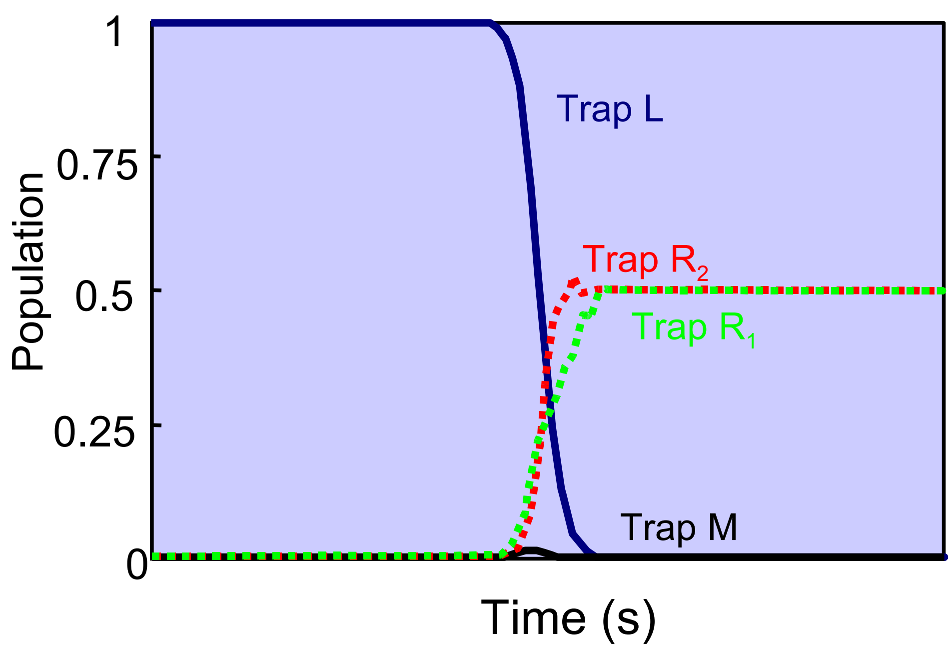
-1
0
1
2
3
4
x
x 10^-5
d_LM
d_MR
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
t
x 10^5
4
2
0
-4
-3
-2
-1
0
1
2
3
4
x
x 10^-5

Transfer



$$|\phi\rangle^+ = \frac{1}{\sqrt{2}}(|0\rangle_{R_L} + |0\rangle_{R_R})$$

$$|\phi\rangle^- = \frac{1}{\sqrt{2}}(|0\rangle_{R_L} - |0\rangle_{R_R})$$



Adiabaticity Criteria

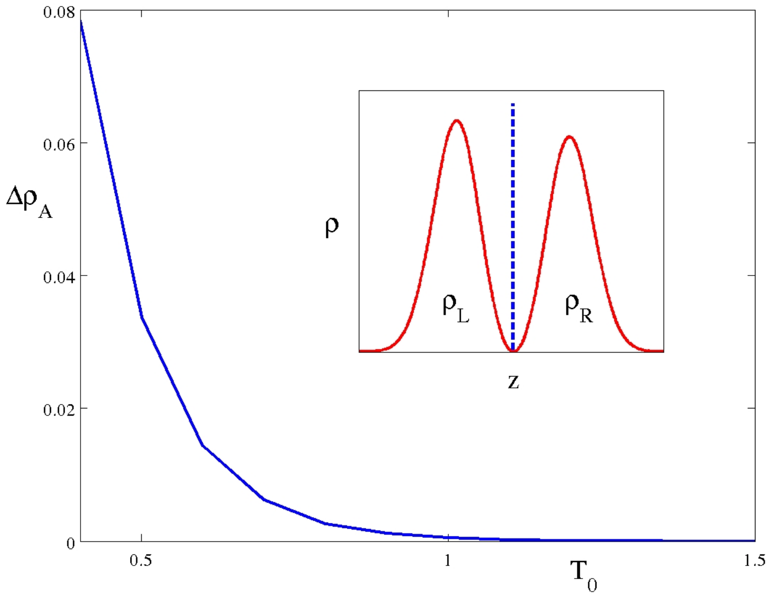
The whole process has to be *adiabatic*:

1) Avoid excitations into higher centre-of-mass states:

$$T + \Delta t > \frac{1}{\omega}$$

2) Avoid mixing between the symmetric and the antisymmetric state:

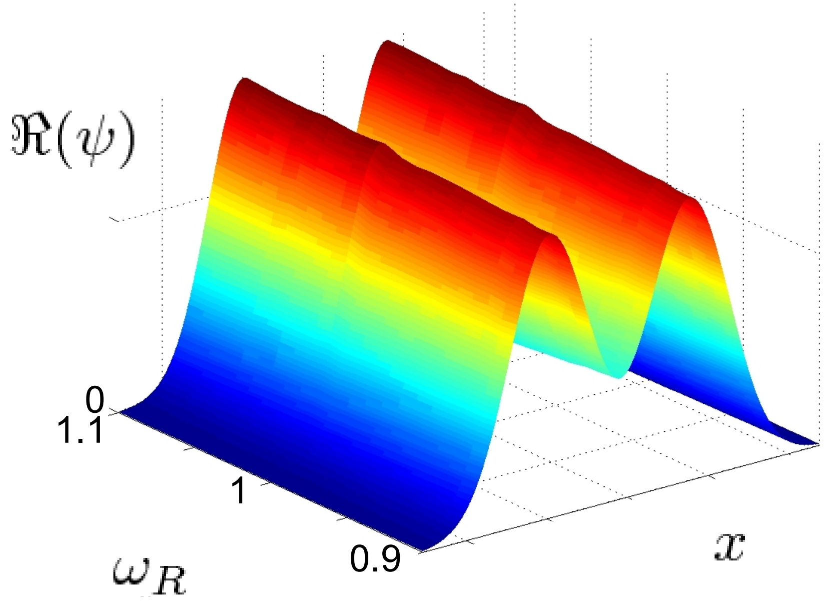
$$T + \Delta t > \frac{1}{\Omega_R}$$



Stability

Symmetric State

trapping frequency in double well trap is ±10% out of resonance

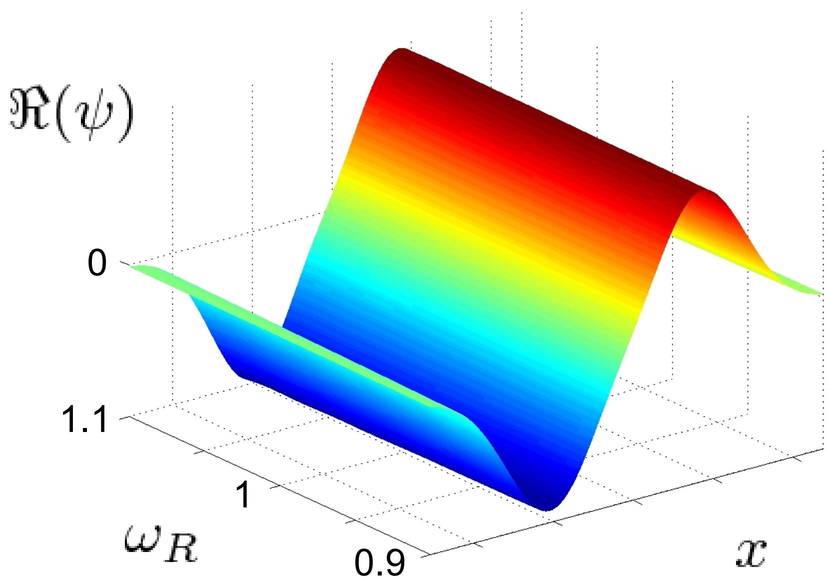


transfer still > 99% and symmetry perfectly kept

Stability

Anti-symmetric State

trapping frequency in double well trap is ±10% out of resonance



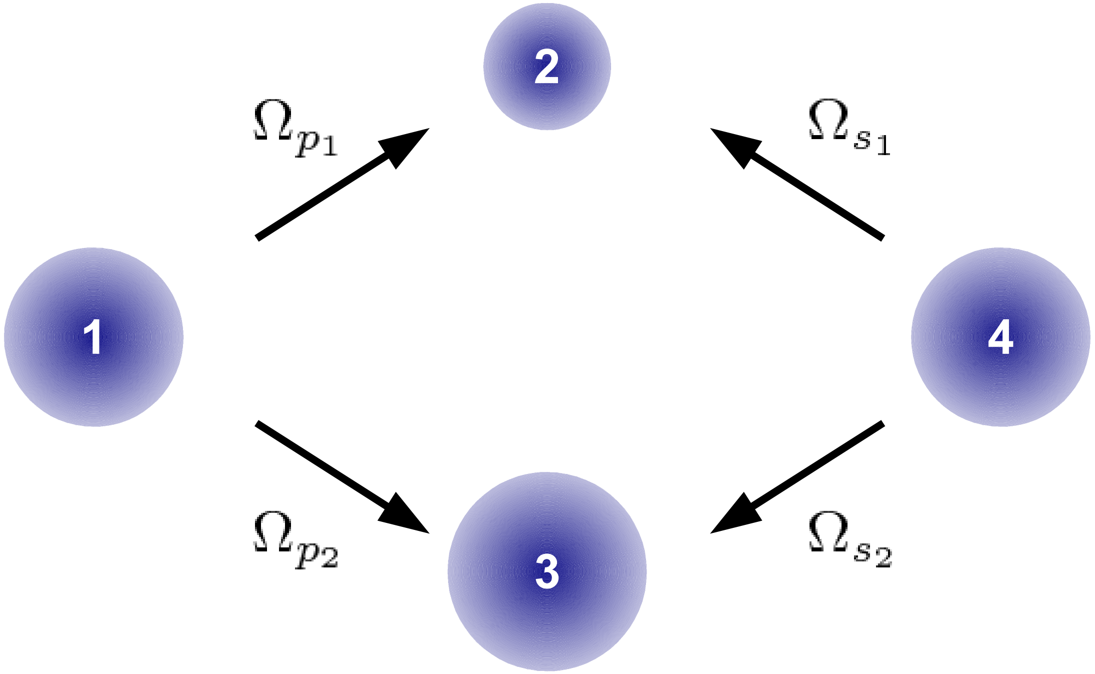
transfer still > 99% and symmetry perfectly kept

Outlook

$$H = \begin{pmatrix} 0 & \Omega_{p_1} & \Omega_{p_2} & 0 \\ \Omega_{p_1} & -\Delta_1 & 0 & \Omega_{s_1} \\ \Omega_{p_2} & 0 & -\Delta_2 & \Omega_{s_2} \\ 0 & \Omega_{s_1} & \Omega_{s_2} & 0 \end{pmatrix}$$

$$|\psi(\infty)\rangle_{\mathrm{CI}} = \sin\gamma|1\rangle - \cos\gamma|4\rangle$$

$$|\psi(\infty)\rangle_{\mathrm{I}} = -\sin\gamma|1\rangle + \cos\gamma|4\rangle$$



→ any arbitrary superpostion state can be prepared

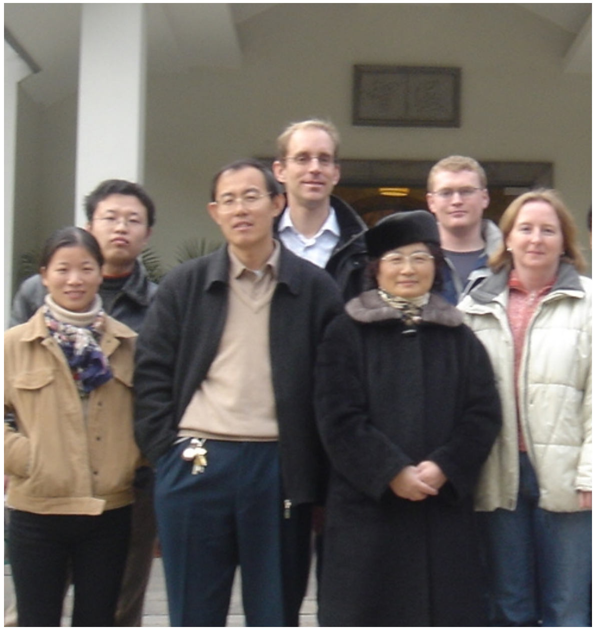
Collaborators

Shanghai

Prof. Shi Qi Jin

Prof. Shang Qing Gong

Dr. Yue Ping Niu



Cork

Kieran Deasy

Dr. Sile Nic Chormaic

TB

Conclusions

- ***Three-Level-Atom Optics*** allows for high fidelity manipulations of single atoms using a ***counter-intuitive*** approach and reproach sequence
- Shown a manipulation scheme to create a *centre-of-mass superposition state* for a single atom in a series of microtraps, with controlled symmetry
- Systems not only robust against experimental uncertainties, but also very robust against noise.
- Complete set of quantum gates can be constructed for centre-of-mass states.