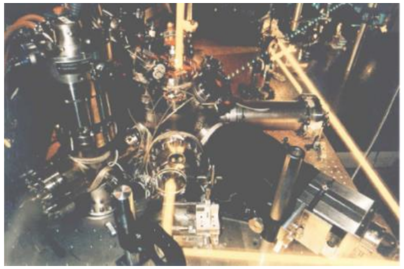
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Quantum Optics:

Shortcuts to Adiabaticity

Dr. Andreas Ruschhaupt



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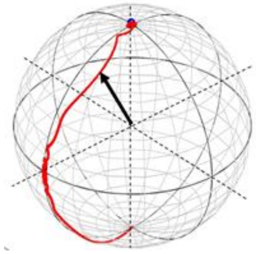
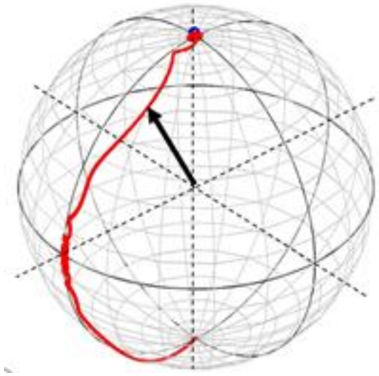


Quantum Technology

Quantum Information Processing



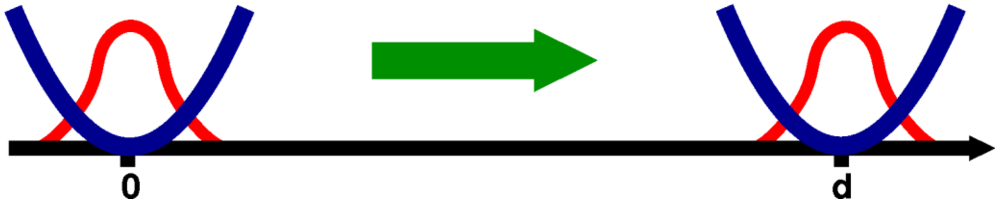
Quantum Simulation

Metrology

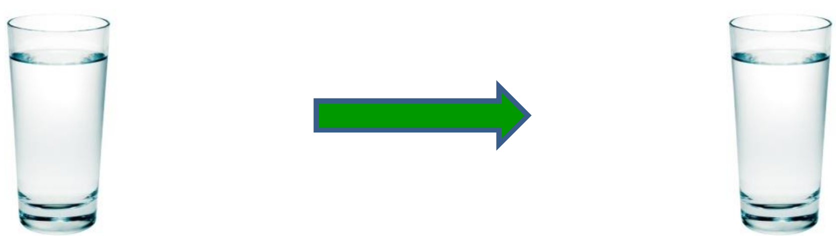
Essential: Preparation, control and manipulation of quantum states with high fidelity and in a fast and robust way

Shortcuts to Adiabaticity

Transport of an atom in a harmonic trap (e.g. an optical trap):

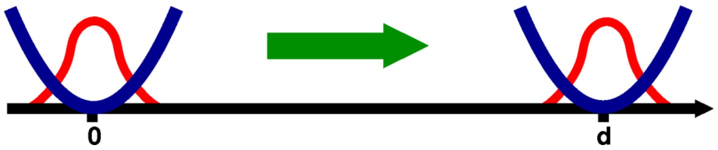


Important:
No excitations at the end!



Shortcuts to Adiabaticity

Transport of an atom in a harmonic trap (e.g. an optical trap):



Possibility: Do it slow:

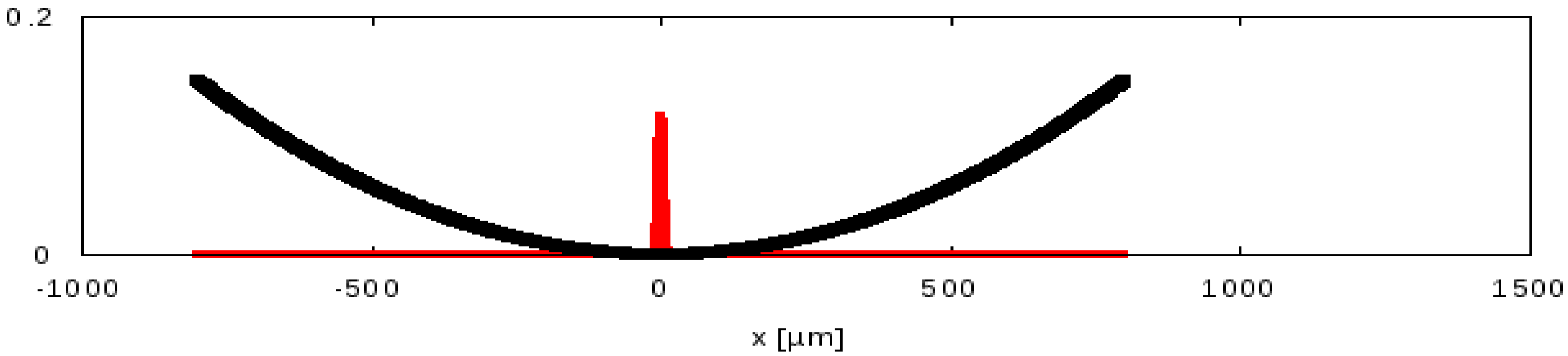
Adiabatic Transport

> **Adiabatic Theorem in Quantum Mechanics:**
>
> **The desired final ground state will be exactly achieved if the trap will be moved infinitely slow.**

Shortcuts to Adiabaticity

Adiabatic transport:

Example: duration of transport: t = 4000 ms



Shortcuts to Adiabaticity

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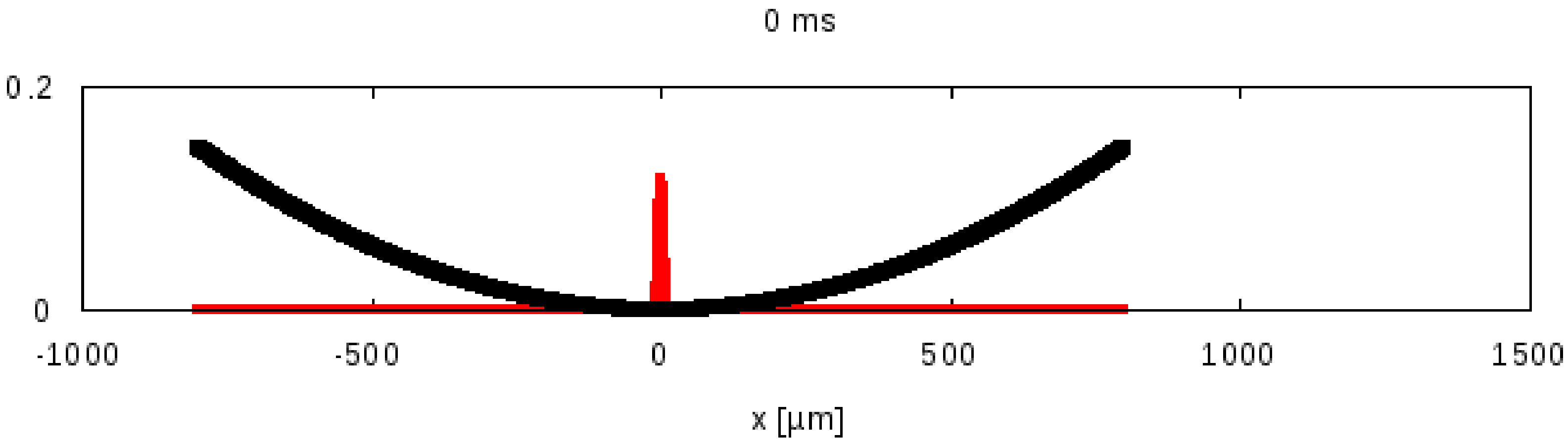


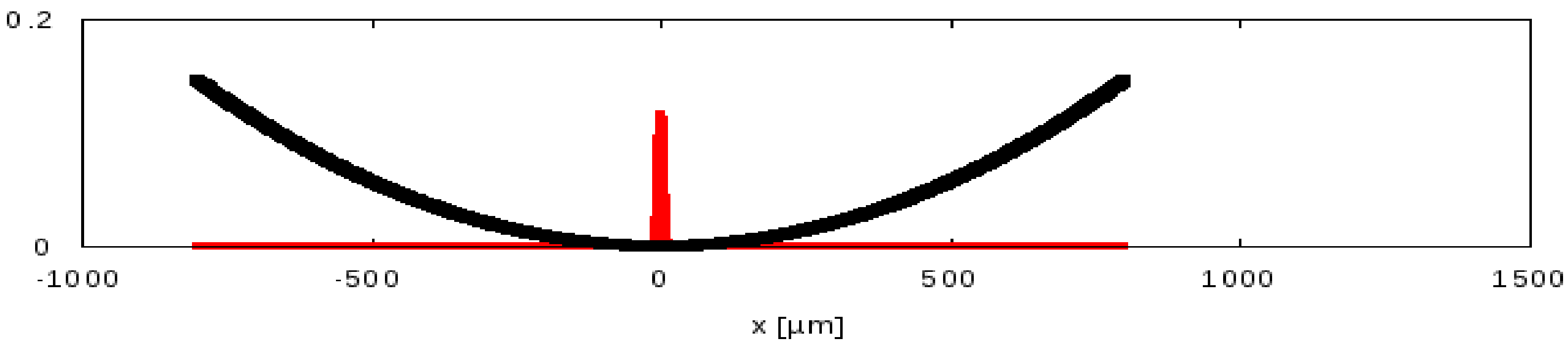
Adiabatic Schemes:

Advantage: Very robust
Disadvantage: Very slow

Shortcuts to Adiabaticity

Adiabatic transport:

Example: duration of transport: t = 100 ms



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Shortcuts to Adiabaticity

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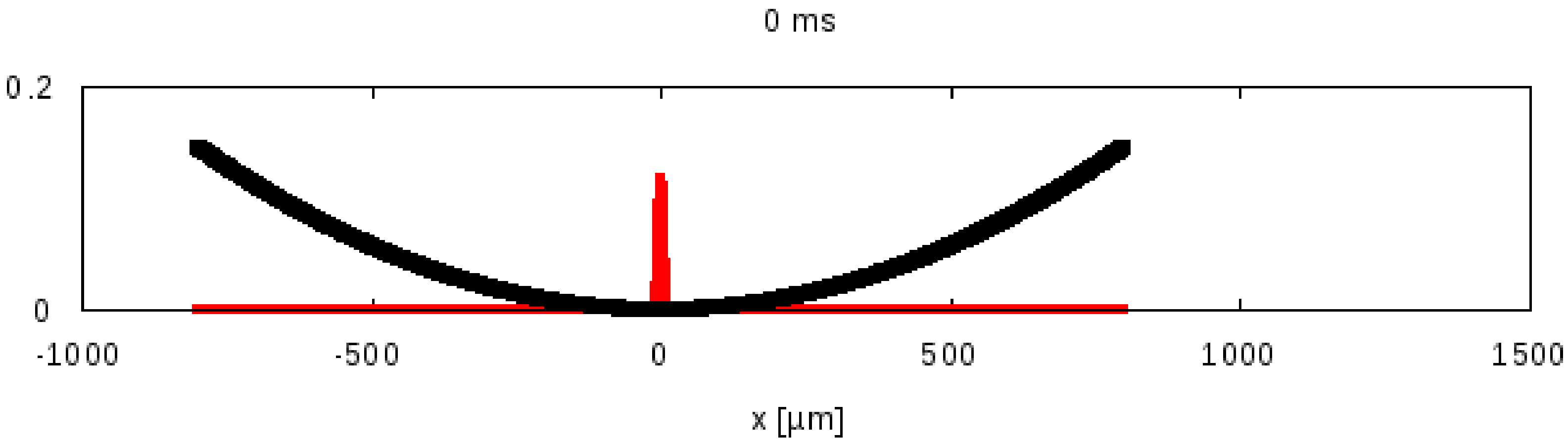

Adiabatic Schemes:

Advantage: Very robust
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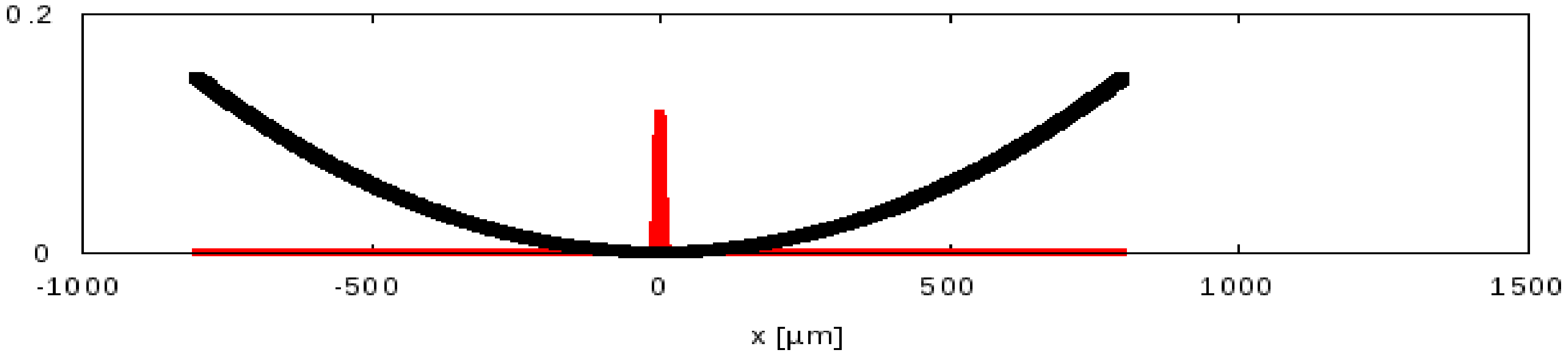
Shortcut to Adiabaticity

Goal: New Methods for a <u>fast and stable</u> manipulation of atomic states

Shortcuts to Adiabaticity

Example: Shortcut: duration of transport: t = 100 ms



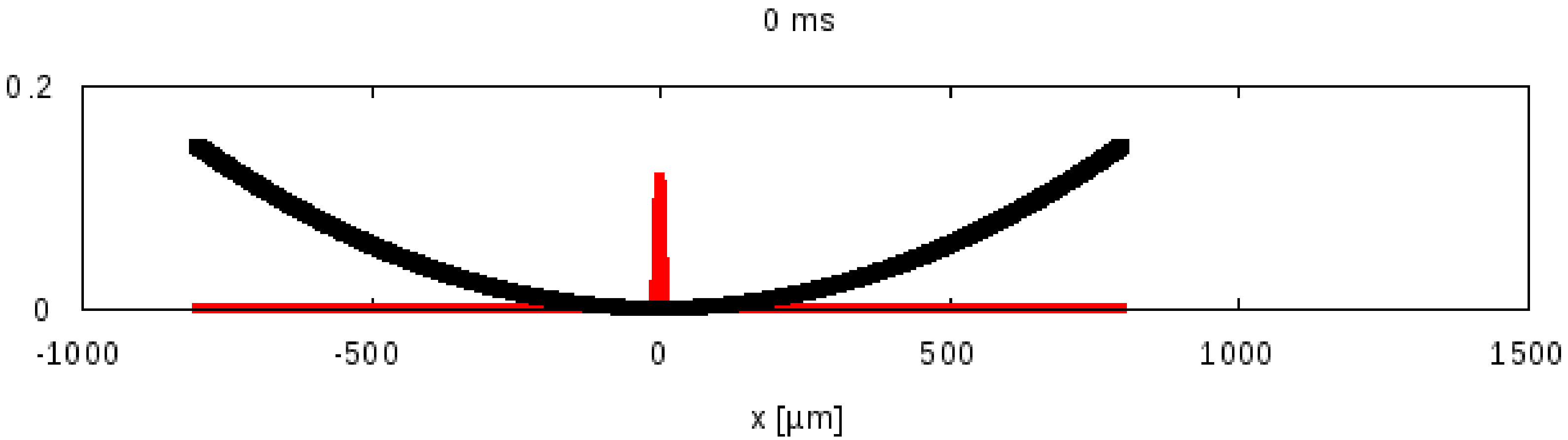
Fast and Stable

Shortcut to Adiabaticity

Goal: New Methods for a fast and stable manipulation of atomic states

Shortcuts to Adiabaticity

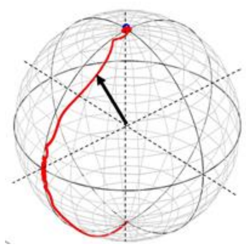
Example: Shortcut: duration of transport: t = 100 ms



Fast and Stable Transport in 1 dimension

Internal State Control

Goal: Manipulate the internal state of cold atoms



Two major routes to control internal state (for example population inversion 1 -> 2):

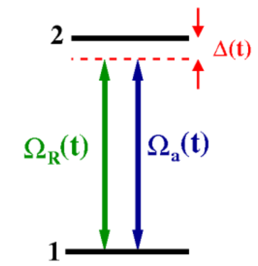
- **resonant pulses (pi, pi/2, etc…)**
  fast but unstable
- **adiabatic passage methods (RAP, STIRAP..)**
  robust but slow

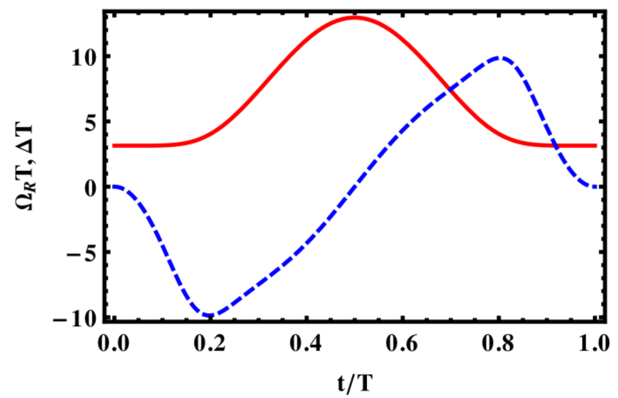
In general we would like fast & robust processes
=> speeded-up adiabatic methods

Shortcuts to Internal State Manipulation

Shortcut to Adiabatic State Transfer:

- based on Invariants and Inverse Engineering
- speeded-up Rapid Adiabatic Passage:
  perfect population transfer in arbitrarily short, finite time

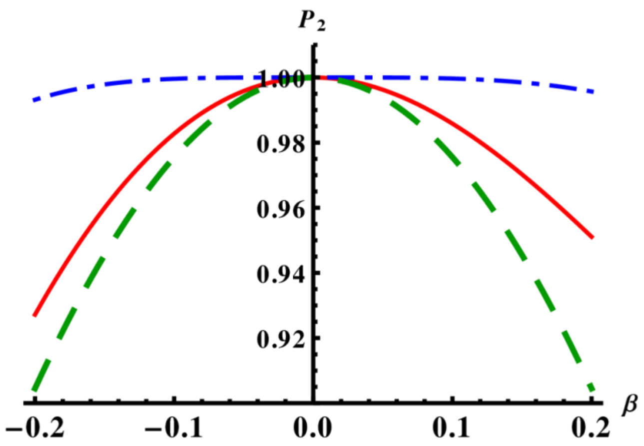




$\Delta(t)$ (blue, dashed line)

Ω_R (red, solid line)

Excitation Probability:

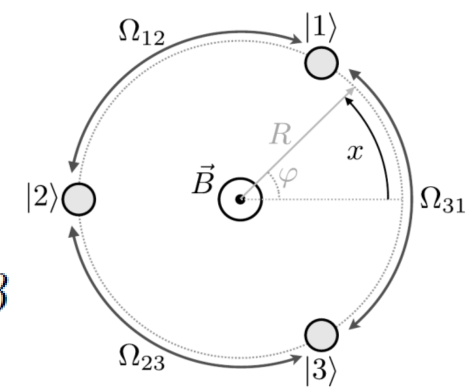


Example of Pi Pulse
(green, dashed line)

Shortcut pulse
(blue, dashed-dotted line)

Project 1: Shortcut to Spatial Adiabatic Passage

$$H = -\frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_{12} & -i\,\Omega_{31} \\ \Omega_{12} & 0 & \Omega_{23} \\ i\,\Omega_{31} & \Omega_{23} & 0 \end{pmatrix}$$



Invariant:

$$I = -\sin\beta\sin\alpha K_1 - \sin\beta\cos\alpha K_2 + \cos\beta$$

where

$$\Omega_{12} = 2\dot{\alpha}\sin\alpha\tan\beta - 2\dot{\beta}\cos\alpha - \Omega_{31}\sin\alpha\tan\beta,$$

$$\Omega_{23} = 2\dot{\alpha}\cos\alpha\tan\beta + 2\dot{\beta}\sin\alpha - \Omega_{31}\cos\alpha\tan\beta.$$

Instantaneous eigenstates of Invariant:

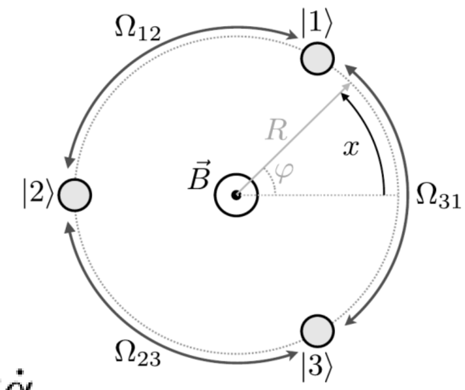
$$|\phi_0(t)\rangle = \begin{pmatrix} -\sin\beta\cos\alpha \\ -i\cos\beta \\ \sin\beta\sin\alpha \end{pmatrix}$$

Spatial Non-Adiabatic Passage (SNAP)

$$|\phi_\pm(t)\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \cos\beta\cos\alpha \pm i\sin\alpha \\ -i\sin\beta \\ -\cos\beta\sin\alpha \pm i\cos\alpha \end{pmatrix}$$

*Ref.: A. Benseny, A. Kiely, Y. Zhang, Th. Busch, and **AR**, EPJ Quantum Technology (2017) 4:3*

Project 1: Shortcut to Spatial Adiabatic Passage



Goal: **Transport Process: $|1> \rightarrow |3>$**

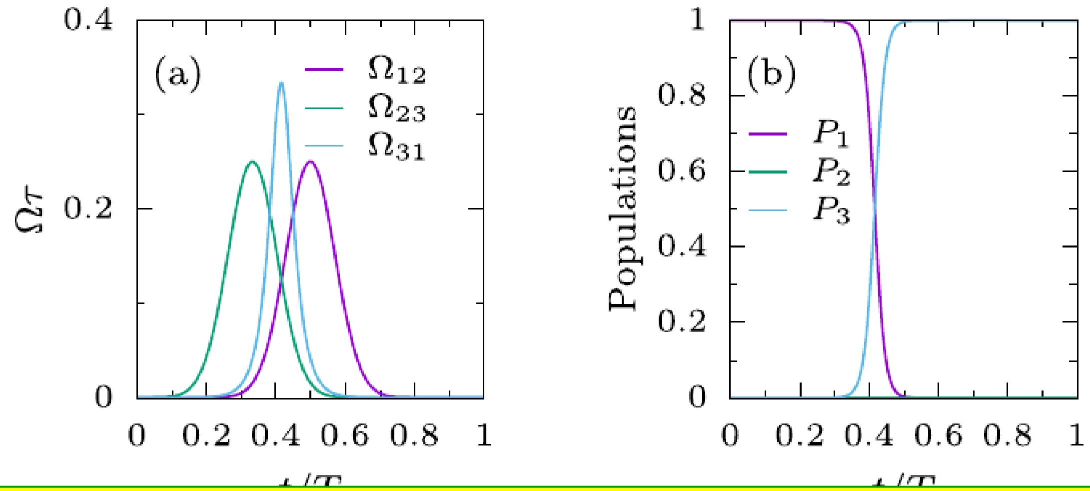
$$\left|\Psi(0)\right\rangle = |1\rangle \rightarrow |\Psi_{\text{target}}\rangle = \left|\Psi(T)\right\rangle = -|3\rangle$$

Boundary conditions for auxiliary functions:

$$\beta(0) = -\frac{\pi}{2}, \beta(T) = -\frac{\pi}{2}$$
$$\alpha(0) = 0, \qquad \alpha(T) = \frac{\pi}{2}$$

$$\tan\alpha = \frac{\Omega_{12}}{\Omega_{23}} \quad \text{and} \quad \Omega_{31} = 2\dot{\alpha}$$

Result (3L approximation):



Examination of the Stability of Shortcuts to Spatial Adiabatic Passage

Project 2: Effect of Poisson Noise on Adiabatic Processes (Further examples)

Hamiltonian with classical noise:

$$H\left(t\right)=H_{0}\left(t\right)+z\left(t\right)H_{1}\left(t\right)$$

Master equation: $\dot{\rho}=\mathcal{L}_{0}(\rho)+\mathcal{L}_{1}(\rho),$

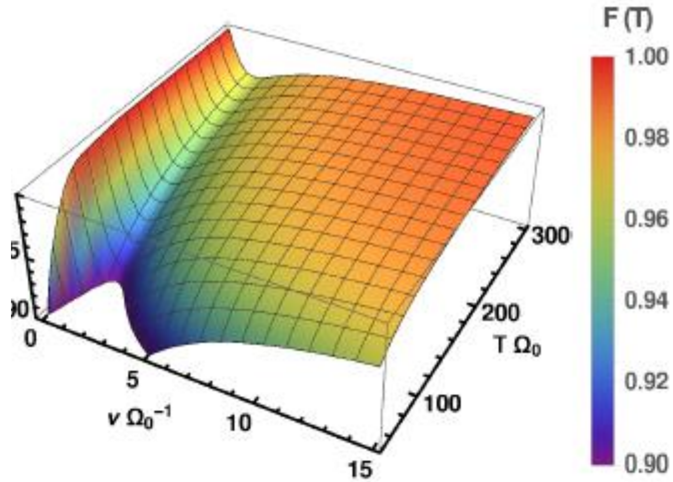
where

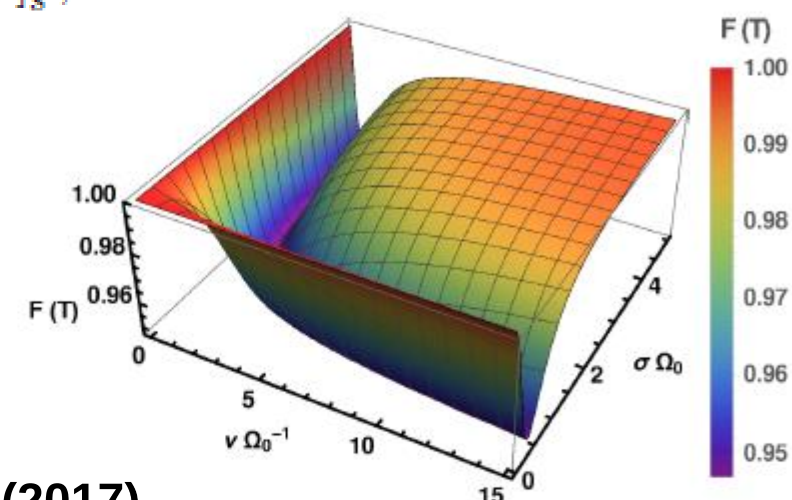
$$\mathcal{L}_{0}(\rho) = -\frac{i}{\hbar}\left[H_{0},\rho\right],$$

$$\mathcal{L}_{1}(\rho) = \nu\sum_{s=1}^{\infty}\frac{1}{s!}\left(-\frac{i}{\hbar}\right)^{s}\langle\xi^{s}\rangle\left[H_{1},\rho\right]_{s},$$

$$H_{0}(t) = \frac{\hbar}{2}\begin{pmatrix}0 & \Omega_{12}(t) & 0\\ \Omega_{12}(t) & 0 & \Omega_{23}(t)\\ 0 & \Omega_{23}(t) & 0\end{pmatrix}$$

$$H_{1} = \frac{\hbar}{2}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & i\Omega_{23}(t)\\ 0 & -i\Omega_{23}(t) & 0\end{pmatrix}$$

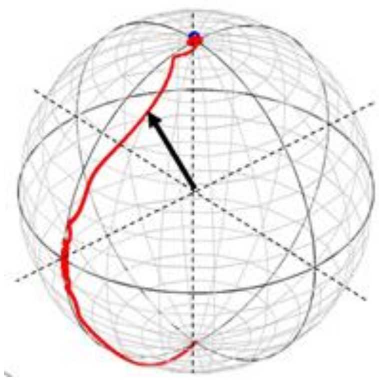




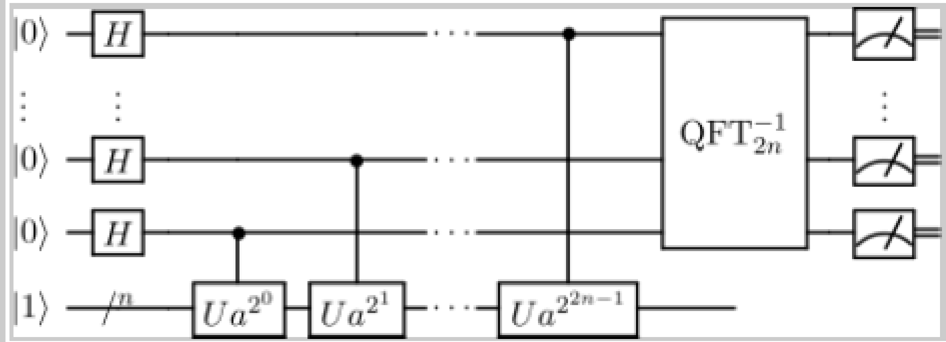
Ref.: A. Kiely et. al., Phys. Rev. A 95, 012115 (2017)

Project 3: Visualisation of Quantum Algorithms on a classical computer

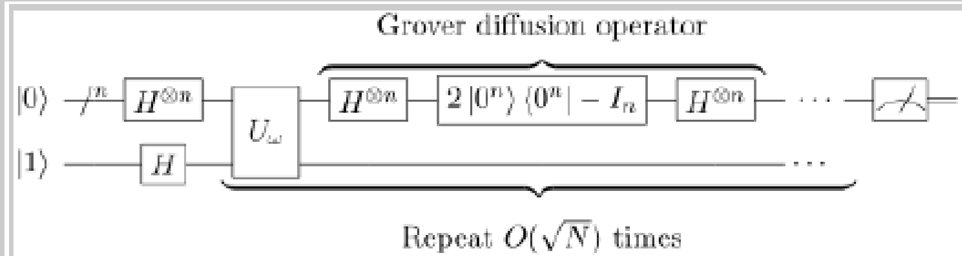
Quantum Information Processing



Adiabatic Quantum Computing



Quantum subroutine in Shor's algorithm. **(factorisation)**



Quantum circuit representation of Grover's algorithm **(Database search)**

Understanding of standard quantum algorithms and implementation using Mathematica or C/C++

Projects (all short or long)

Project 1: Stability of Shortcuts to Spatial Adiabatic Passage

The project will require understanding of a published paper, analytical calculations as well as numerical solutions of a 3 level system with Mathematica.

Project 2: Effect of Poisson noise on adiabatic processes

The project will require understanding of master equations and a published paper, analytical calculations as well as numerical calculations with Mathematica to examine further example settings (*Interesting/demanding project*).

Project 3: Visualisation of Quantum algorithms

The project will require literature work, analytical calculations as well as numerical calculations with Mathematica or C/C++.

Project 4: ???? (Very interesting/very difficult)

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