Imperial College London

Breakdown of adiabatic transfer schemes in the presence of decay or absorption

Eva-Maria Graefe

Department of Mathematics, Imperial College London, UK

joint work with

Nimrod Moiseyev and Alexei Mailybaev

Technion, Haifa, Isreal

Instituto Nacional de Matemática Pura e Aplicada, Rio de Janeiro, Brazil

PHHQP XI, APC, Paris Diderot University, Paris, France

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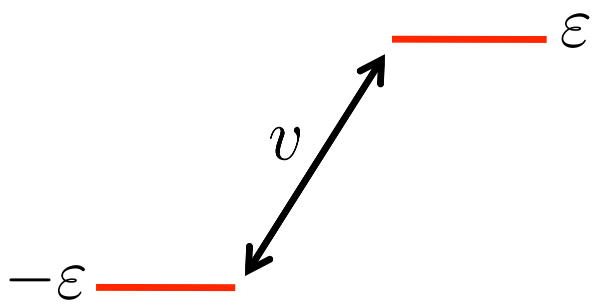
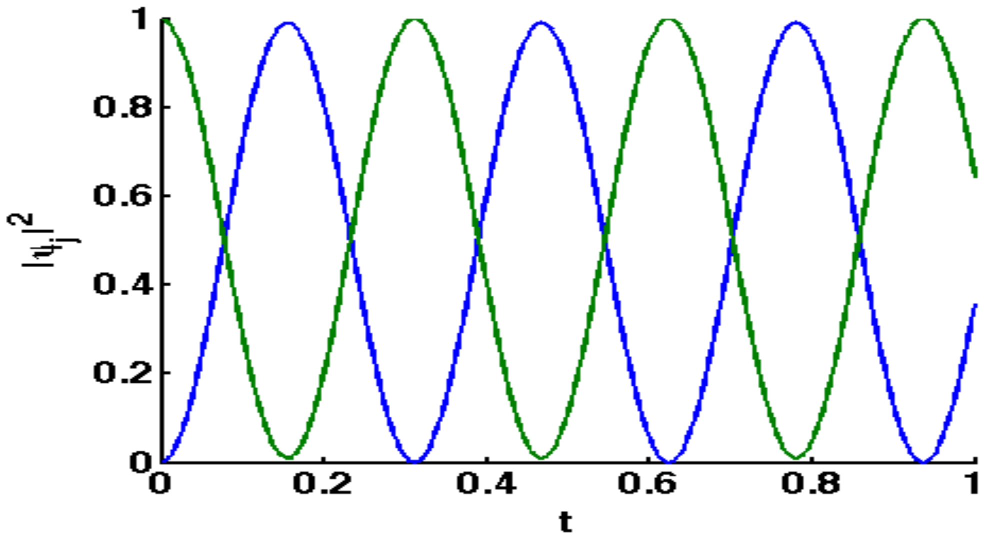
Quantum Population transfer

★ Task: Population transfer between two quantum states (e.g. in atomic system)

★ Coupling of the two states (e.g. via laser field of appropriate frequency)





$$H = \begin{pmatrix} \varepsilon & v \\ v & -\varepsilon \end{pmatrix}$$

★ Adiabatic state transfer: Slower, but efficient and robust

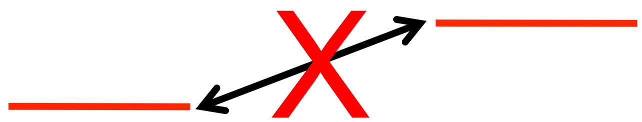
Adiabatic quantum evolution

Adiabatic theorem: System prepared in eigenstate stays in corresponding instantaneous eigenstate for infinitely slow parameter variation

★ Adiabatic state transfer: Slow parameter variation such that initial and target states are connected via instantaneous states

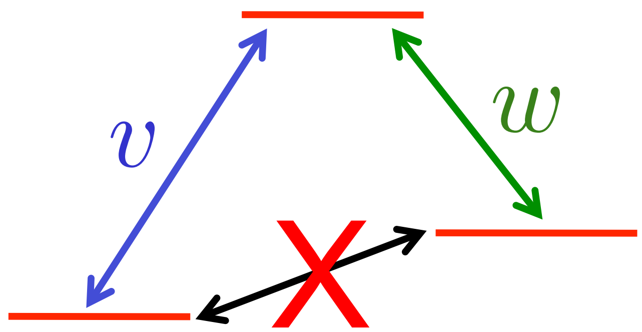
Adiabatic population transfer in three level systems - STIRAP

★ Population transfer in atomic systems between two states without direct transition



STIRAP

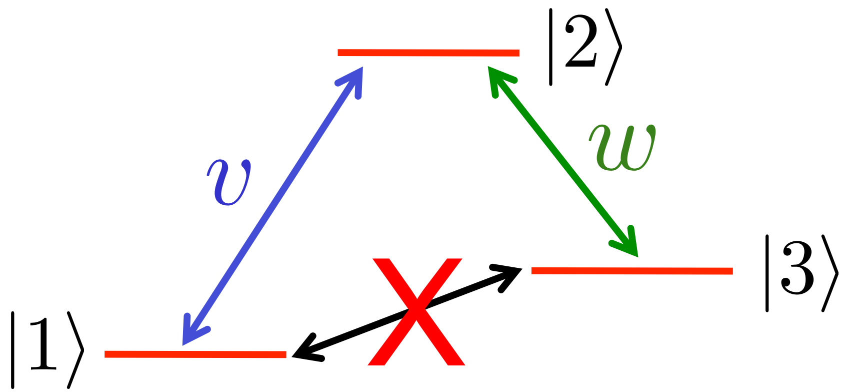
★ Population transfer in atomic systems between two states without direct transition



★ Via additional state

STIRAP

★ Population transfer in atomic systems between two states without direct transition

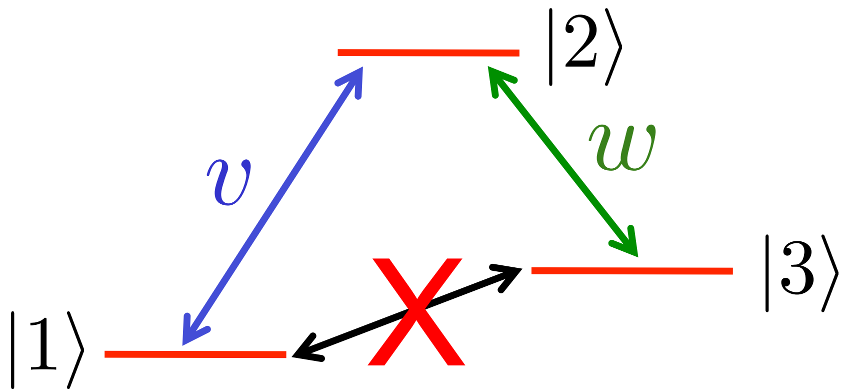


$$H = \begin{pmatrix} E_1 & v(t) & 0 \\ v(t) & E_2 & w(t) \\ 0 & w(t) & E_3 \end{pmatrix}$$

★ Via additional state

STIRAP

★ Population transfer in atomic systems between two states without direct transition



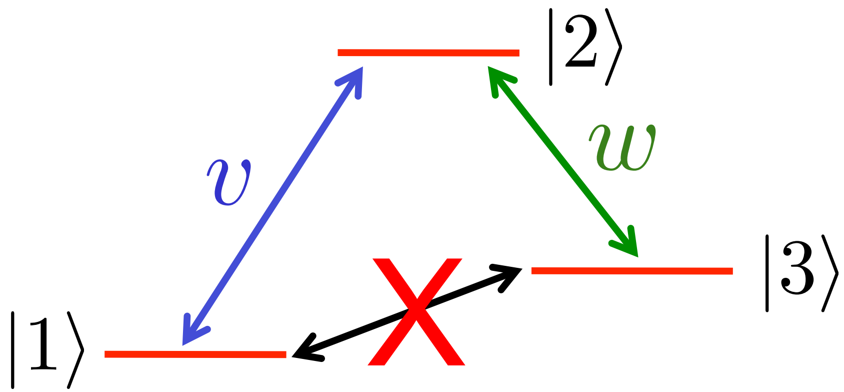
$$H = \begin{pmatrix} E_1 & v(t) & 0 \\ v(t) & E_2 & w(t) \\ 0 & w(t) & E_3 \end{pmatrix}$$

★ Via additional state

★ Intuitive scheme: First switch on v, then w. Nearly total transfer via state $|2\rangle$ possible (precise parameter control required)

STIRAP

★ Population transfer in atomic systems between two states without direct transition



$$H = \begin{pmatrix} E_1 & v(t) & 0 \\ v(t) & E_2 & w(t) \\ 0 & w(t) & E_3 \end{pmatrix}$$

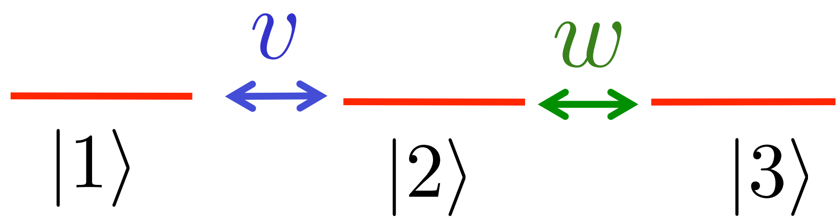
★ Via additional state

★ STIRAP: adiabatic nearly total population transfer from state $|1\rangle$ to state $|3\rangle$, without significant population of state $|2\rangle$ at any time

Bergmann, Theuer, and Shore Reviews of Modern Physics, Vol. 70 (1998) 1003

Eigenvalues and eigenstates

$$H(t) = \begin{pmatrix} 0 & v(t) & 0 \\ v(t) & 0 & w(t) \\ 0 & w(t) & 0 \end{pmatrix}$$



$$E_0 = 0$$

$$E_\pm = \pm\sqrt{v^2 + w^2}$$

★ Eigenstates:

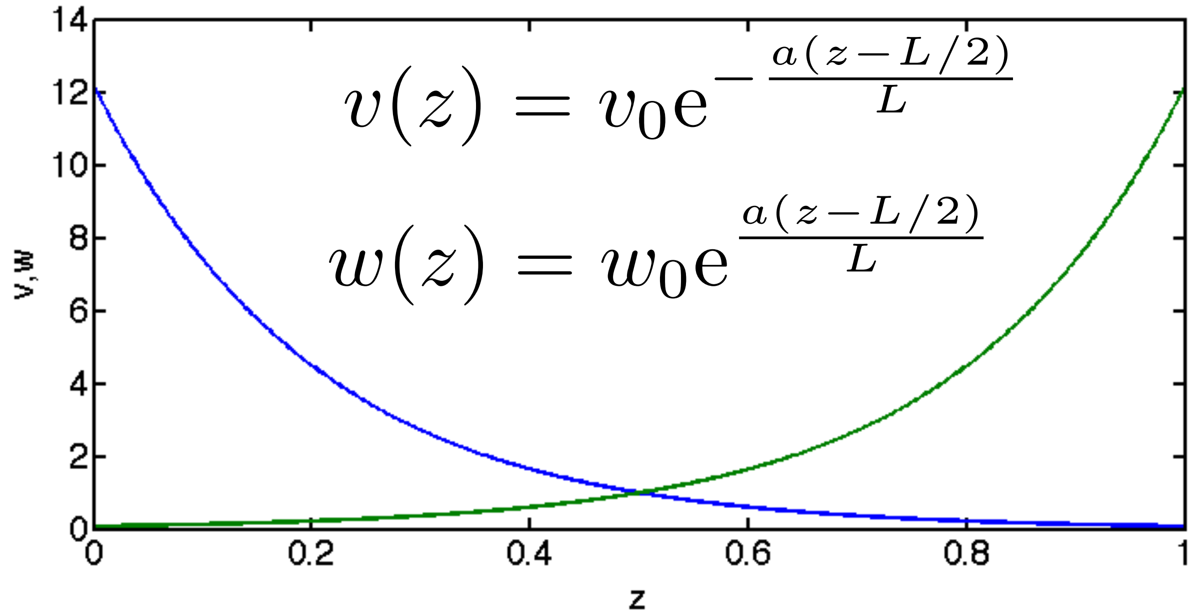
$$|0\rangle = \begin{pmatrix} \cos(\theta) \\ 0 \\ -\sin(\theta) \end{pmatrix}, \quad |\pm\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \sin(\theta) \\ \pm 1 \\ \cos(\theta) \end{pmatrix}$$

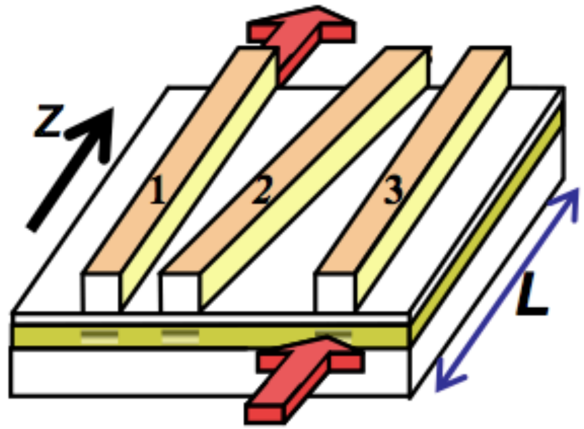
$$\tan(\theta) = \frac{v}{w}$$

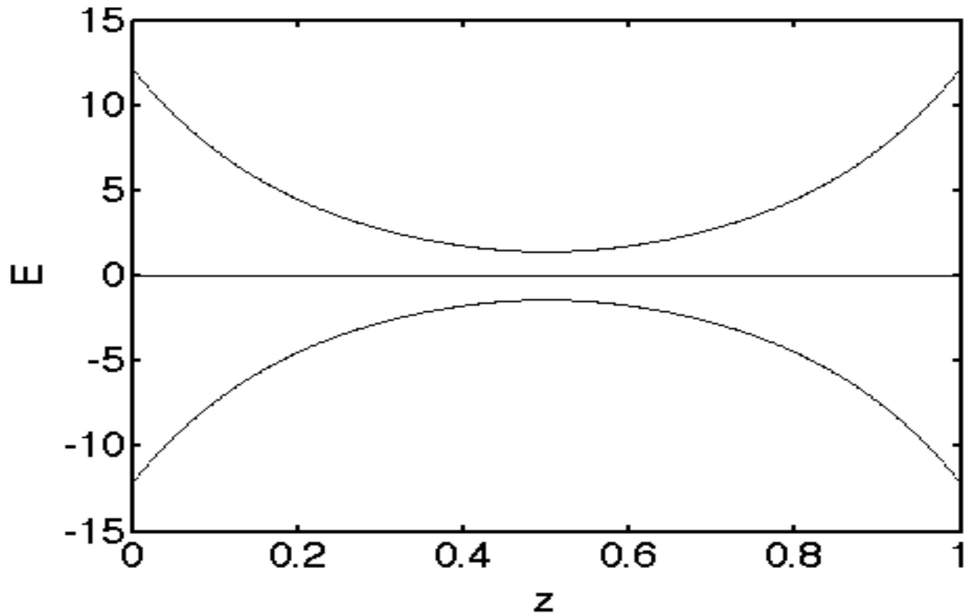
Adiabatic rotation from $|1\rangle \rightarrow |3\rangle$

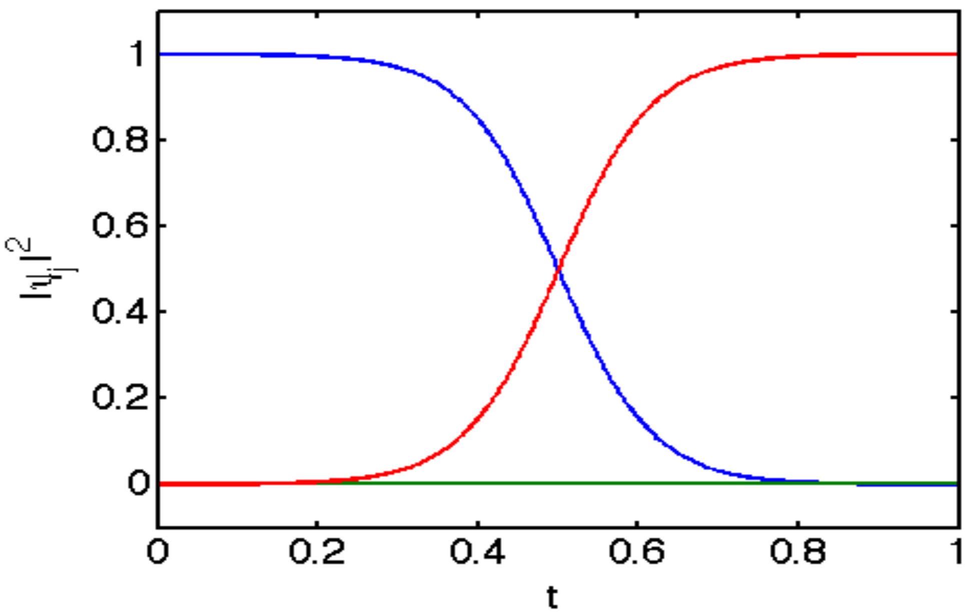
Bergmann, Theurer, and Shore Reviews of Modern Physics, Vol. 70 (1998) 1003

STIRAP type scheme in optical waveguides



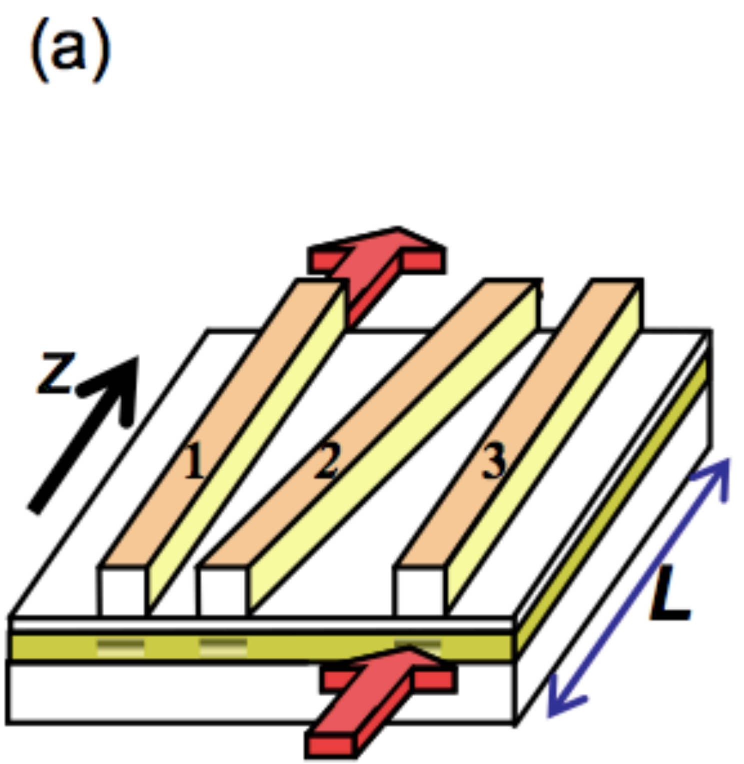






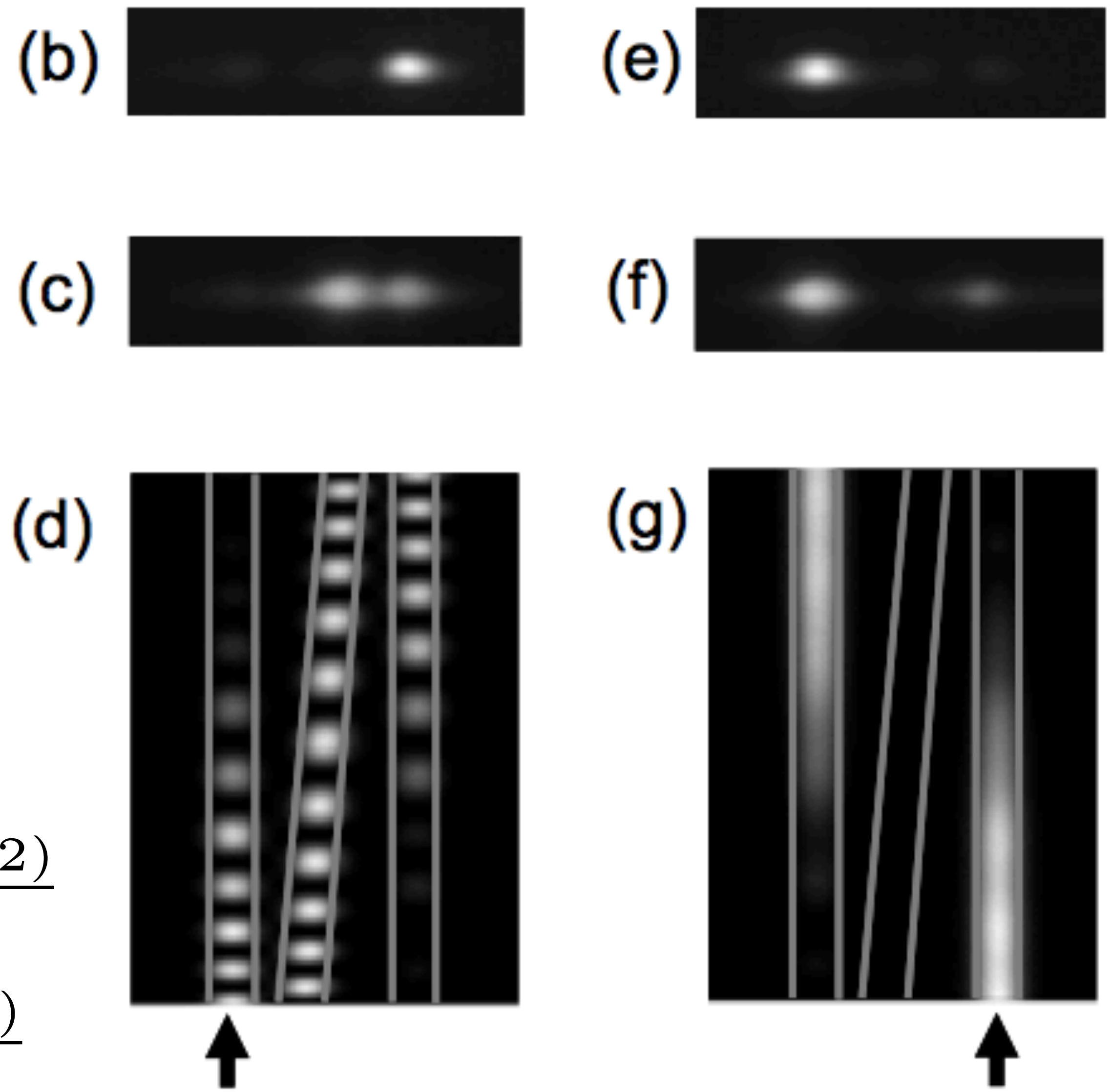
Lahini, Pozzi, Sorel, Morandotti, Christodoulides and Silberberg, Phys. Rev. Lett. 101 (2008) 193901

STIRAP type scheme in optical waveguides



$$v(z) = v_0 e^{-\frac{a(z-L/2)}{L}}$$

$$w(z) = w_0 e^{\frac{a(z-L/2)}{L}}$$



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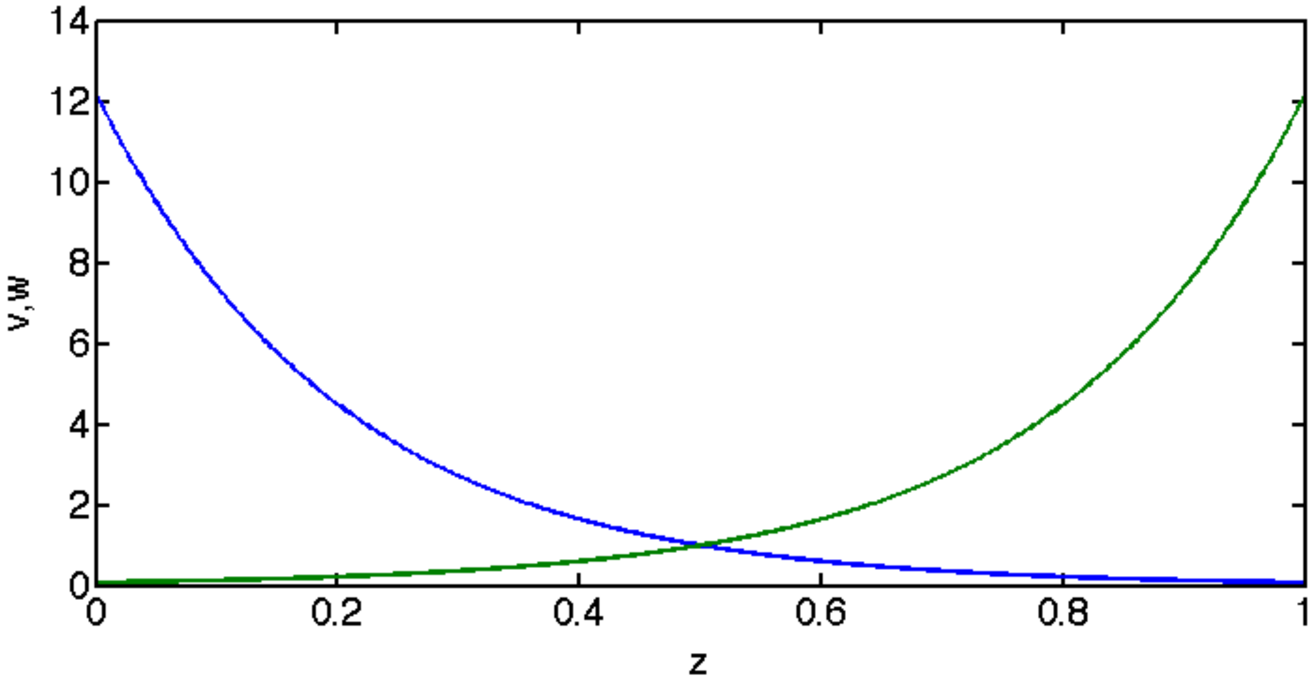
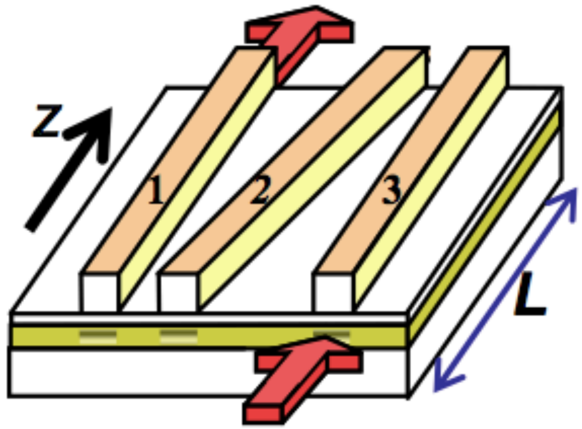
Additional decay/absorption



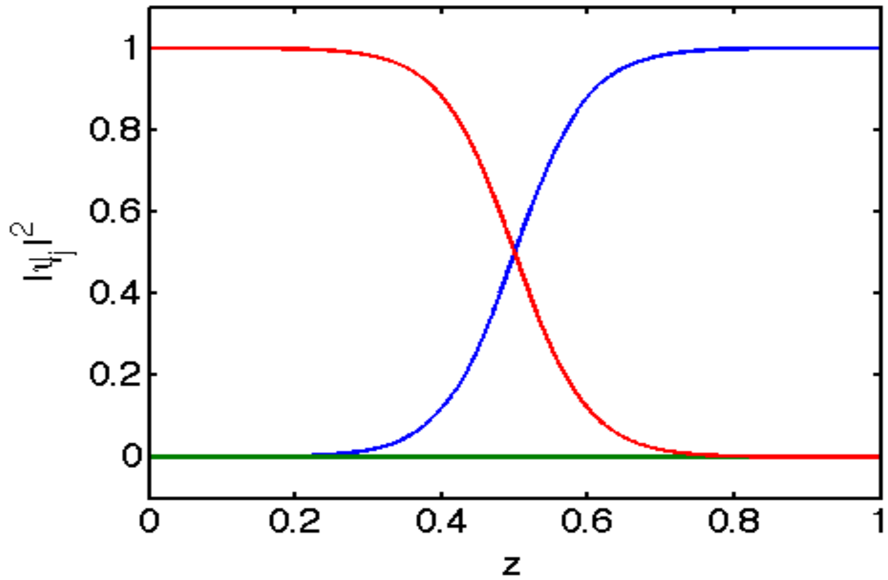


$$H = \begin{pmatrix} -i\gamma_1 & v(z) & 0 \\ v(z) & -i\gamma_2 & w(z) \\ 0 & w(z) & -i\gamma_3 \end{pmatrix}$$

Absorption in waveguides

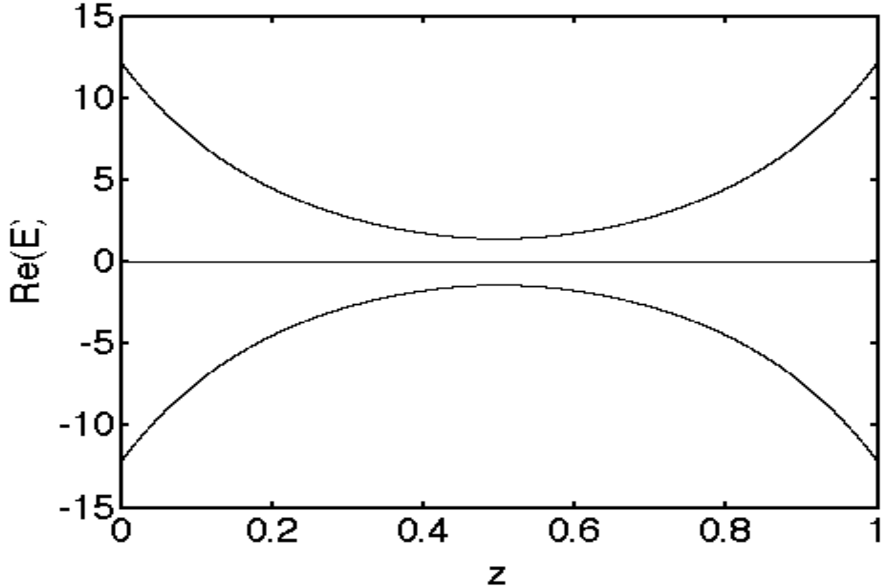
Independent of γ_2

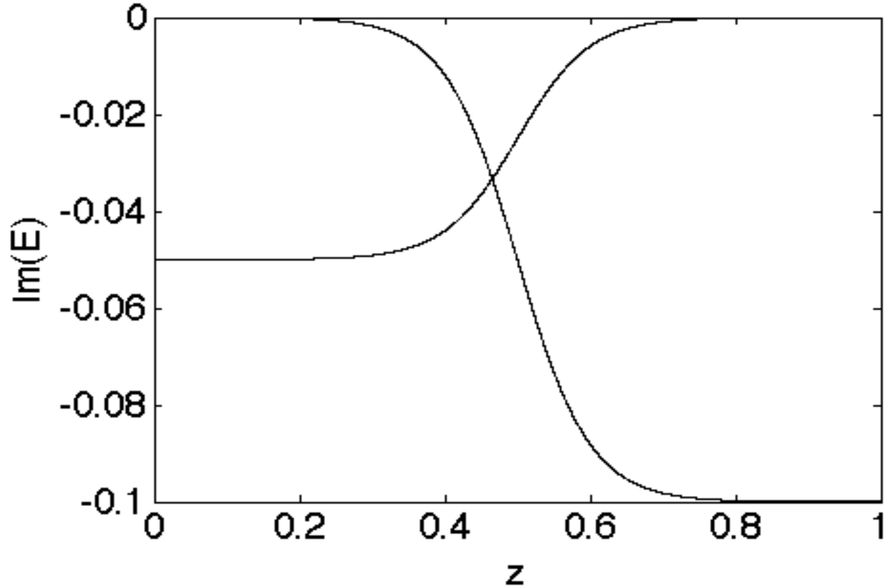
Decay/absorption in final state



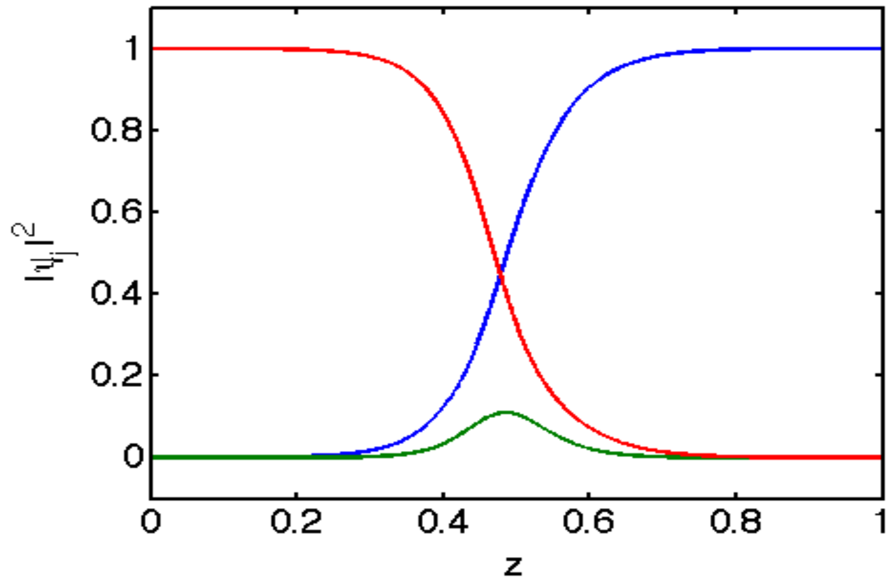
$$\gamma_1 = 0.1,\ \gamma_3 = 0$$

$$H = \begin{pmatrix} -\mathrm{i}\gamma_1 & v(t) & 0 \\ v(t) & -\mathrm{i}\gamma_2 & w(t) \\ 0 & w(t) & -\mathrm{i}\gamma_3 \end{pmatrix}$$



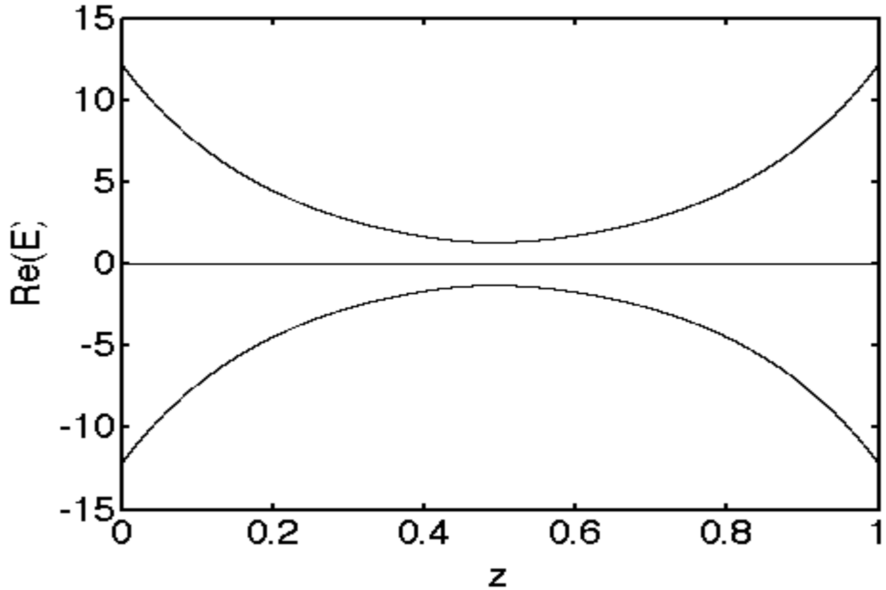


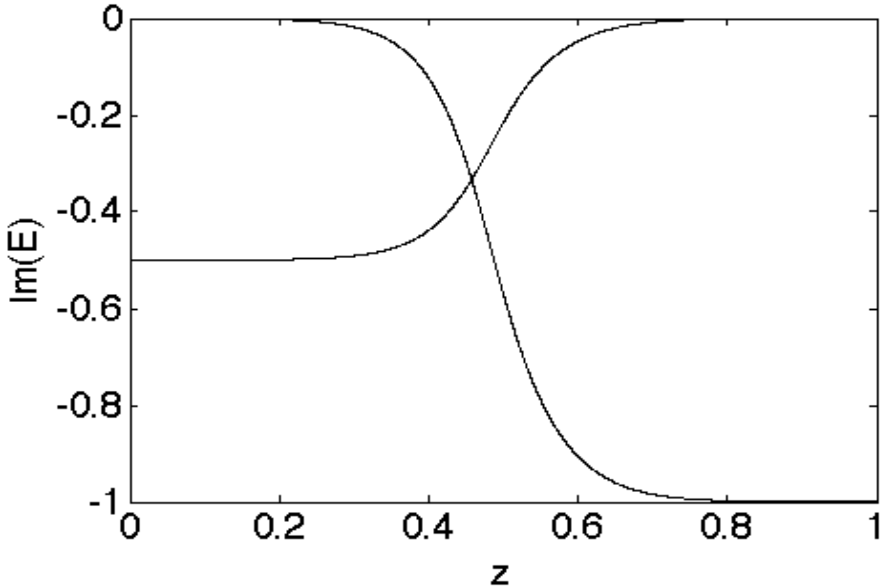
Decay/absorption in final state



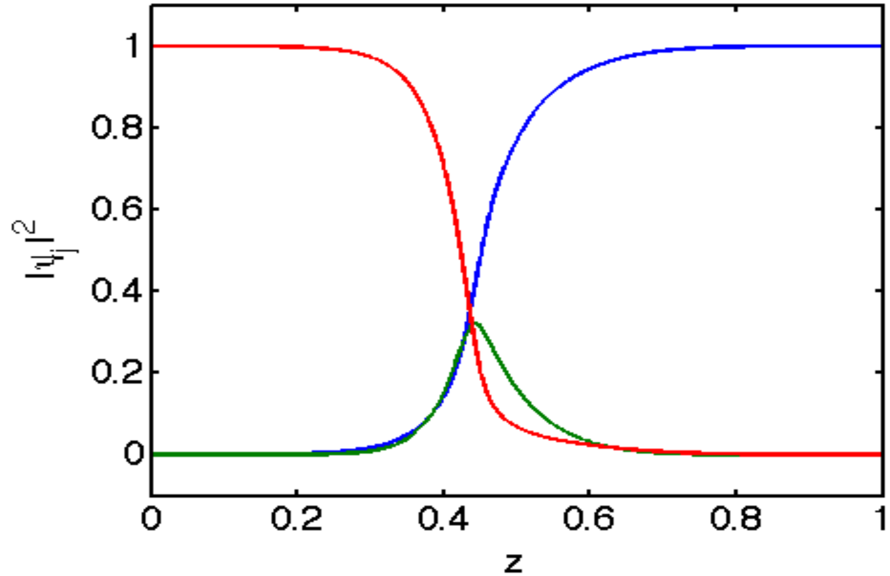
$$\gamma_1 = 1, \ \gamma_3 = 0$$

$$H = \begin{pmatrix} -i\gamma_1 & v(t) & 0 \\ v(t) & -i\gamma_2 & w(t) \\ 0 & w(t) & -i\gamma_3 \end{pmatrix}$$



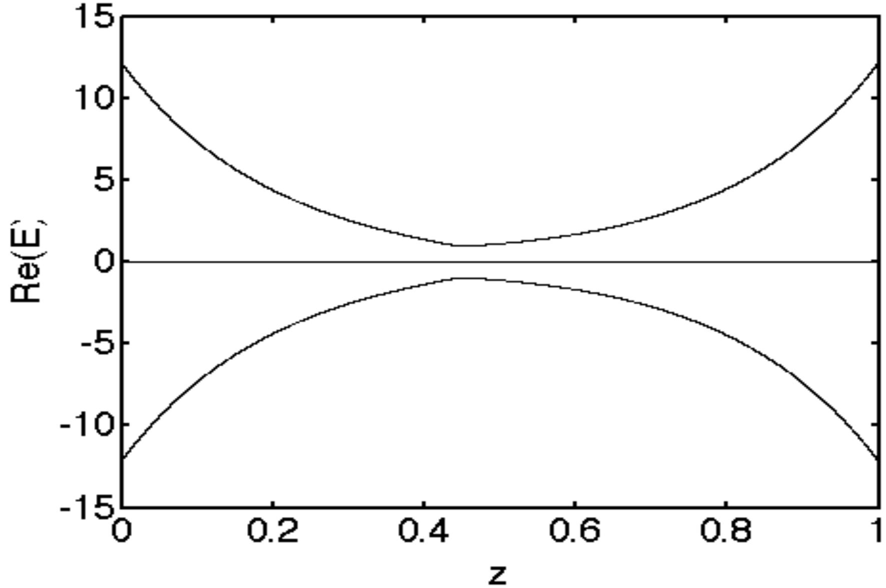


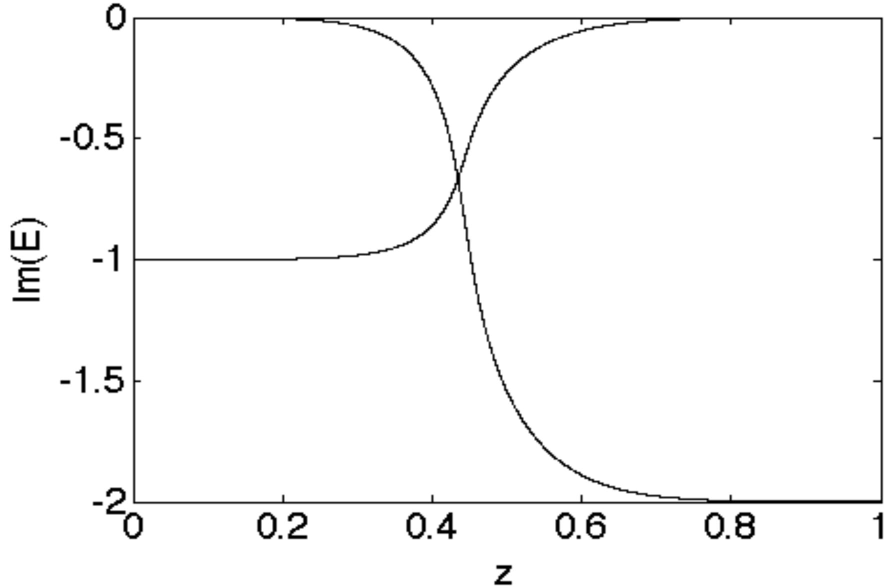
Decay/absorption in final state



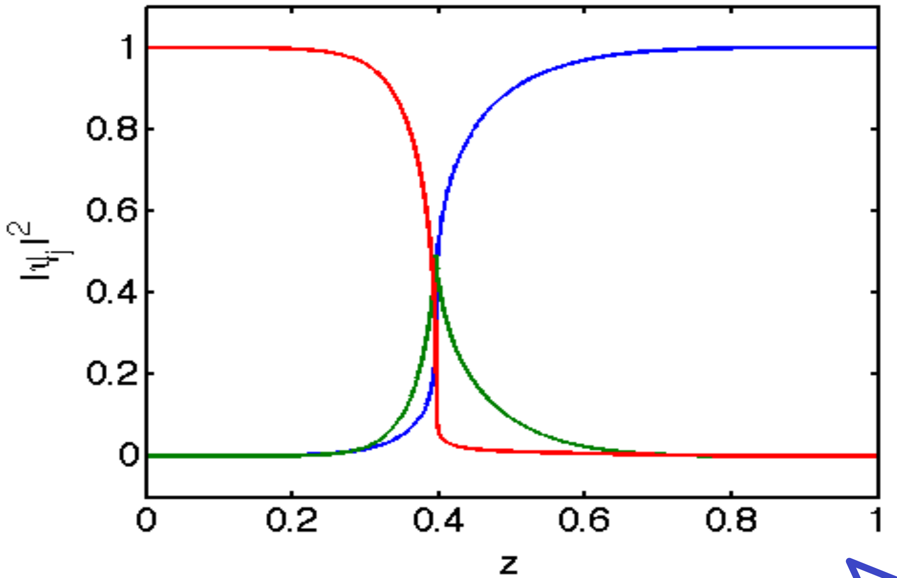
$$\gamma_1 = 2,\ \gamma_3 = 0$$

$$H = \begin{pmatrix} -i\gamma_1 & v(t) & 0 \\ v(t) & -i\gamma_2 & w(t) \\ 0 & w(t) & -i\gamma_3 \end{pmatrix}$$



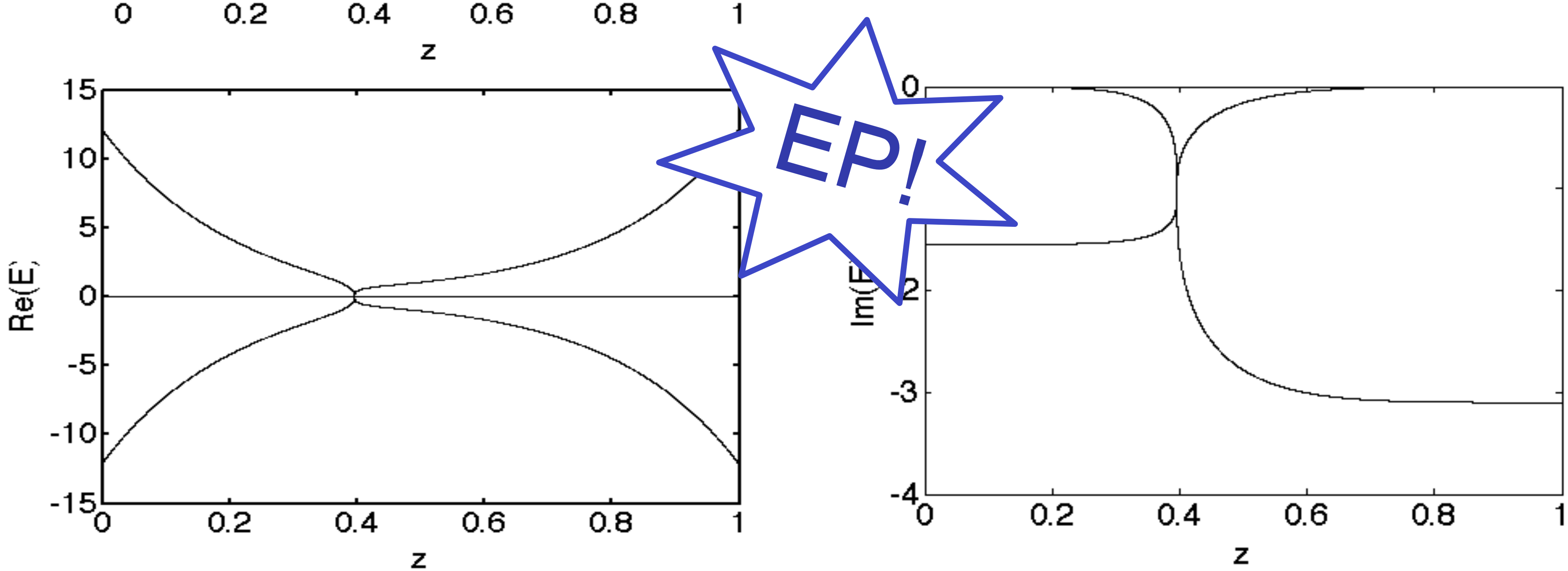


Decay/absorption in final state



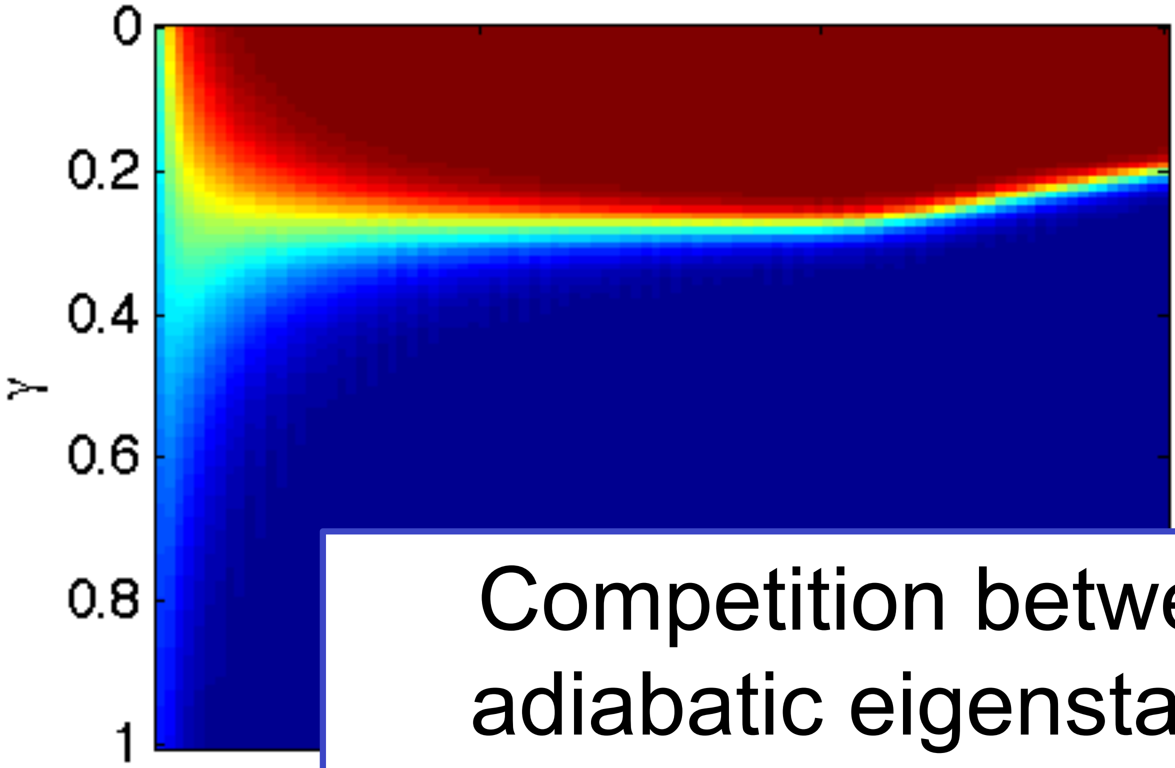
$$\gamma_1 = 3.1,\ \gamma_3 = 0$$

$$H = \begin{pmatrix} -i\gamma_1 & v(t) & 0 \\ v(t) & -i\gamma_2 & w(t) \\ 0 & w(t) & -i\gamma_3 \end{pmatrix}$$



Transfer efficiency: absorption in final state

$$P = \frac{|\langle 1|\psi(L)\rangle|^2}{\sum_{n=1}^{3} |\langle n|\psi(L)\rangle|^2} \qquad |\psi(0)\rangle = |\varphi^0(0)\rangle \approx -|3\rangle$$



Breakdown of STIRAP long before EP!

Competition between decay of adiabatic eigenstates and non-adiabatic transitions

Adiabatic quantum evolution

Adiabatic theorem: System prepared in eigenstate stays in corresponding instantaneous eigenstate for infinitely slow parameter variation

★ Adiabatic state transfer: Slow parameter variation such that initial and target states are connected via instantaneous states

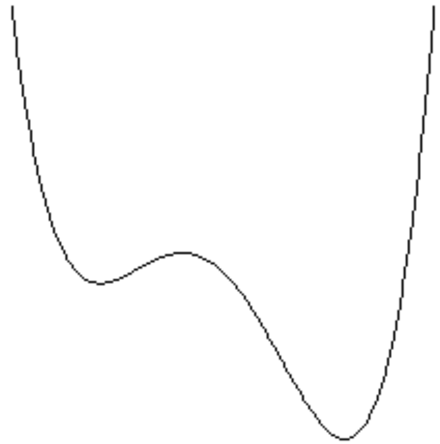
★ Parameter variation in finite time: Small non-adiabatic corrections

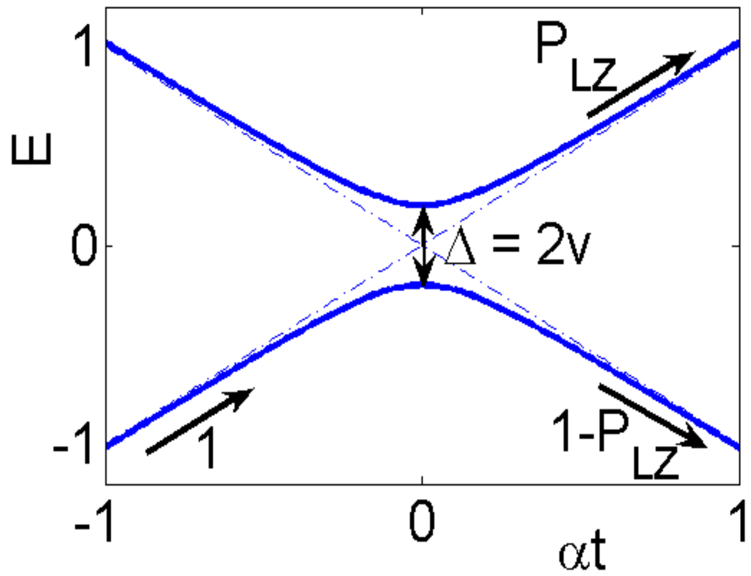
★ Typical non-adiabatic corrections: Landau-Zener

Landau Zener model

$$i\frac{d}{dt}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \begin{pmatrix}\alpha t & v\\ v & -\alpha t\end{pmatrix}$$

$$t \in (-\infty, \infty)$$





$$P_{LZ} = \frac{|\psi_1(t \to +\infty)|^2}{|\psi_1(t \to -\infty)|^2}$$

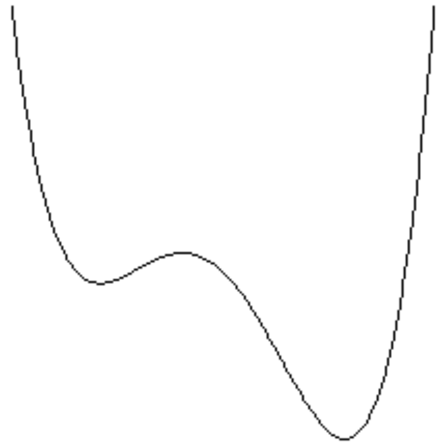
$$P_{LZ} = e^{-2\mathrm{Im}\int_0^{t_0}(E_+ - E_-)dt}$$

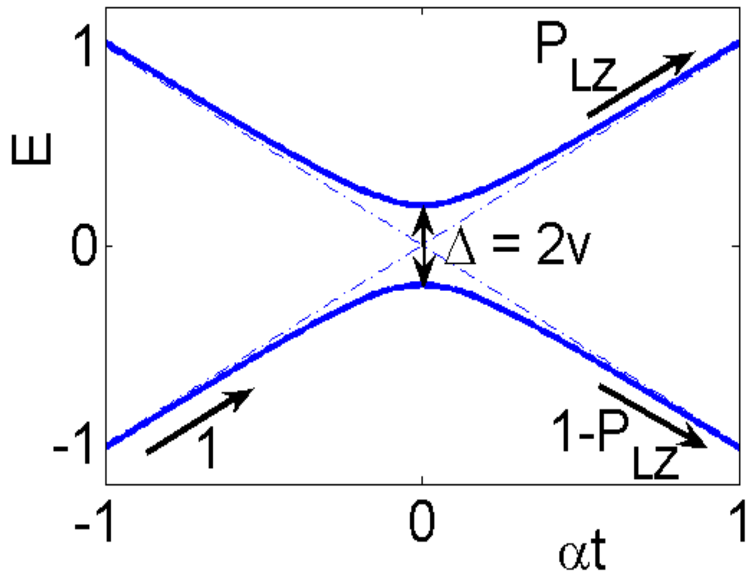
Landau, Zener, Majorana, Stückelberg (1932)

Landau Zener model

$$i\frac{d}{dt}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \begin{pmatrix}\alpha t & v\\ v & -\alpha t\end{pmatrix}$$

$t \in (-\infty, \infty)$





$$P_{LZ} = \frac{|\psi_1(t \to +\infty)|^2}{|\psi_1(t \to -\infty)|^2}$$

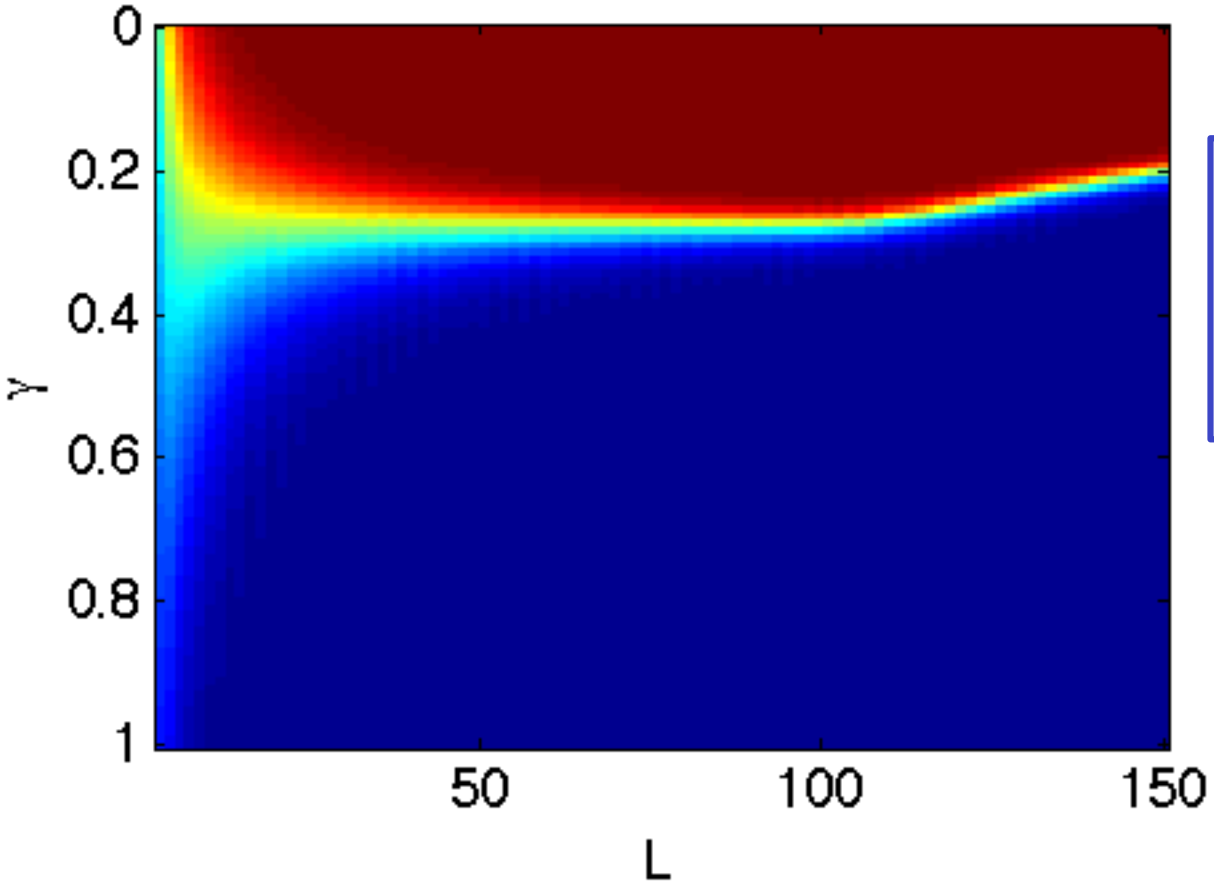
$$P_{LZ} = e^{-\pi v^2/|\alpha|}$$

Adiabaticity: $P_{LZ} = 0$ or $\alpha \to 0$

Landau, Zener, Majorana, Stückelberg (1932)

Transfer efficiency: absorption in final state

$$P = \frac{|\langle 1|\psi(L)\rangle|^2}{\sum_{n=1}^{3} |\langle n|\psi(L)\rangle|^2} \qquad |\psi(0)\rangle = |\varphi^0(0)\rangle \approx -|3\rangle$$



Breakdown of STIRAP long before EP!

Adiabatic transfer boundary

$$P = \frac{|\langle 1|\psi(L)\rangle|^2}{\sum_{n=1}^{3} |\langle n|\psi(L)\rangle|^2} \qquad |\psi(0)\rangle = |\varphi^0(0)\rangle \approx -|3\rangle$$

★ Adiabatic and non-adiabatic contribution:

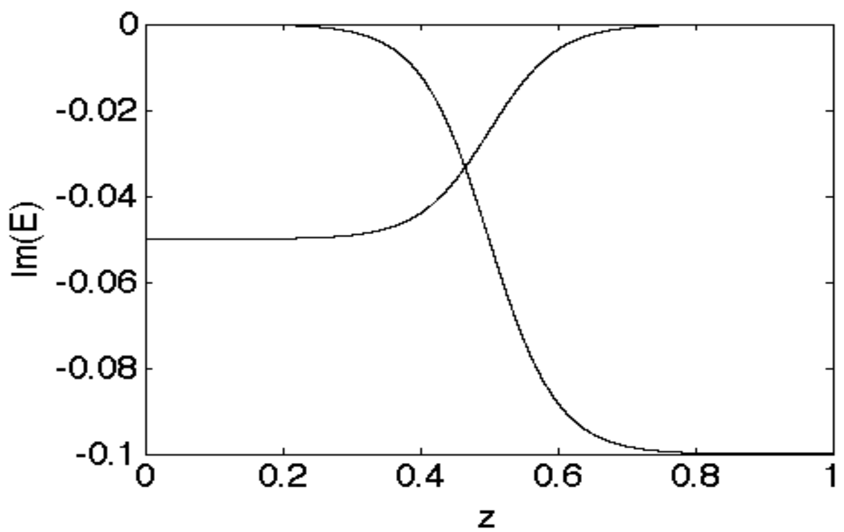
$$|\psi(z)\rangle = \psi_{ad}(z)|\varphi^0(z)\rangle + \sum_{j=\pm} \psi_{nonad}(z)|\varphi^j(z)\rangle$$

$$P = \frac{|\psi_{ad}(L)|^2}{|\psi_{ad}(L)|^2 + 2|\psi_{nonad}(L)|^2}$$

★ Estimate (non-)adiabatic contributions!

Adiabatic transfer boundary

$$|\psi(z)\rangle = \psi_{ad}(z)|\varphi^0(z)\rangle + \sum_{j=\pm} \psi_{nonad}(z)|\varphi^j(z)\rangle$$



★ Transition happens around $z = L/2$

★ $|\varphi^{\pm}(z)\rangle$ almost stable after transition:

$$|\psi_{nonad}(L)| \approx \sqrt{P_{nonad}}$$

★ $|\varphi^0(z)\rangle$ almost stable before transition:

$$|\psi_{ad}(L)| = \sqrt{1 - 2P_{nonad}}\, \exp\left(\int_0^L \mathrm{Im}\, E_0 dz\right)$$

$$\approx \sqrt{1 - 2P_{nonad}}\, \mathrm{e}^{-\gamma L/2}$$

Adiabatic transfer boundary

$$P = \frac{|\psi_{ad}(L)|^2}{|\psi_{ad}(L)|^2 + 2|\psi_{nonad}(L)|^2}$$

- ★ $|\psi_{nonad}(L)| \approx \sqrt{P_{nonad}}$
- ★ $|\psi_{ad}(L)| \approx \sqrt{1 - 2P_{nonad}}\,\mathrm{e}^{-\gamma L/2}$

$$P \approx \frac{1}{2} \quad \Rightarrow \quad \gamma \approx \ln\left(\frac{1}{2P_{nonad}} - 1\right)/L$$

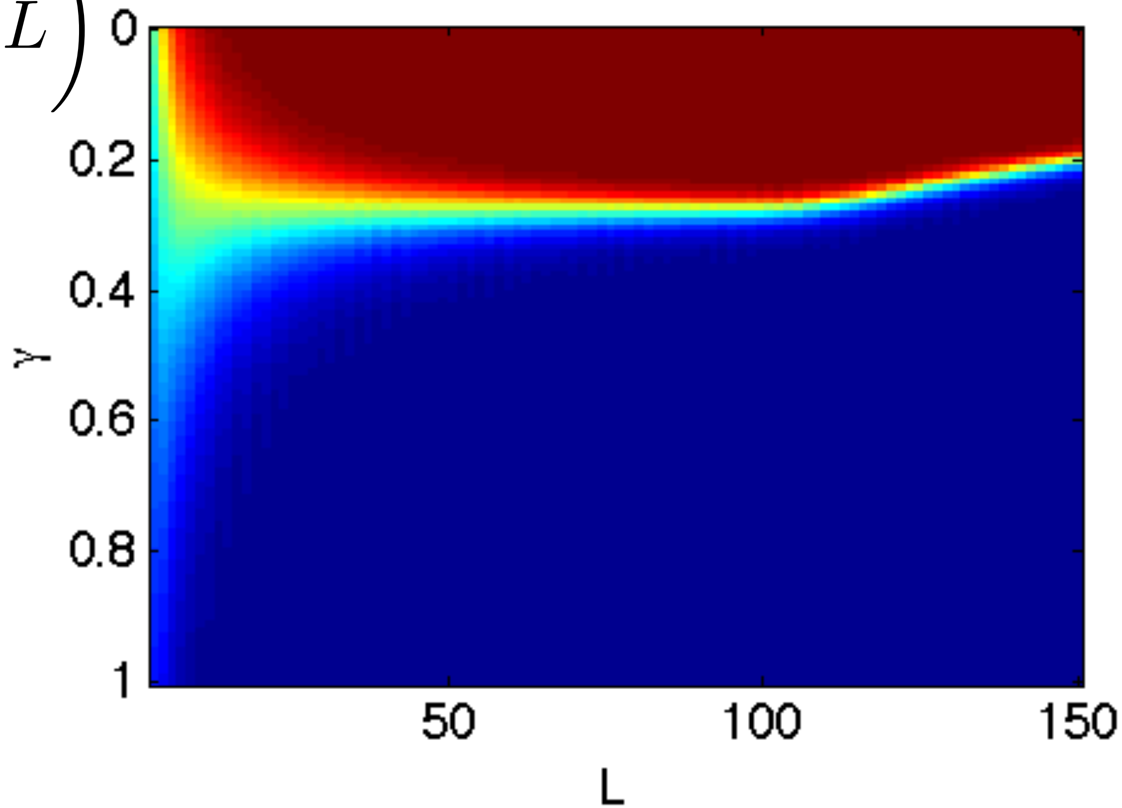
- ★ Landau-Zener type approximation for $\gamma \doteqdot 0$

$$P_{nonad} \approx \exp\left(-\frac{2}{a\sqrt{\pi}}\Gamma^2\left(\tfrac{3}{4}\right)L\right)$$

Adiabatic transfer boundary

$$\gamma \approx \ln\left(\frac{1}{2P_{nonad}} - 1\right)/L$$

$$P_{nonad} \approx \exp\left(-\frac{2}{a\sqrt{\pi}}\Gamma^2\left(\tfrac{3}{4}\right)L\right)$$



$$\gamma_{cr}^{LZ} \approx \frac{2}{a\sqrt{\pi}}\Gamma^2\left(\tfrac{3}{4}\right) - \frac{\ln(2)}{L}$$

- ★ Deviation due to LZ approximation and $\gamma \neq 0$
- ★ Use numerically obtained P_{nonad}!

Adiabatic transfer boundary

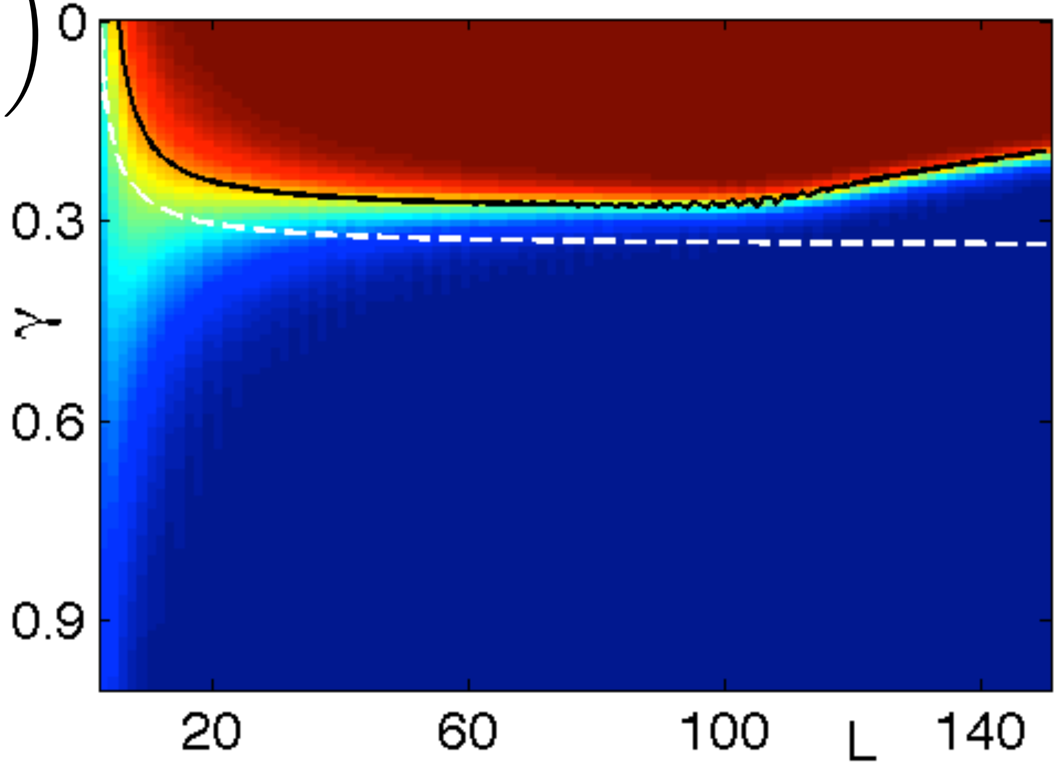
$$\gamma \approx \ln\left(\frac{1}{2P_{nonad}} - 1\right)/L$$

$$P_{nonad} \approx \exp\left(-\frac{2}{a\sqrt{\pi}}\Gamma^2\left(\tfrac{3}{4}\right)L\right)$$

$$\gamma_{cr}^{LZ} \approx \frac{2}{a\sqrt{\pi}}\Gamma^2\left(\tfrac{3}{4}\right) - \frac{\ln(2)}{L}$$

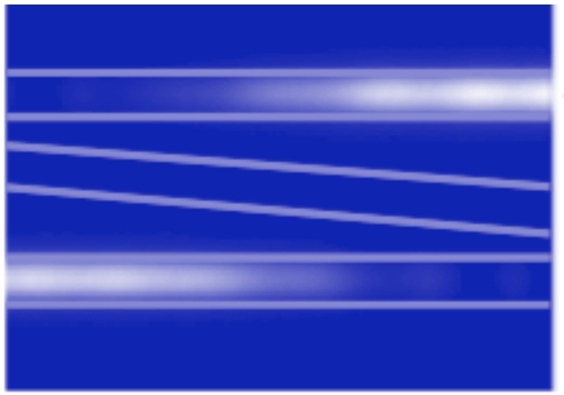
★ Deviation due to LZ approximation and $\gamma \neq 0$

★ Use numerically obtained P_{nonad}!



Summary

★ Robust population transfer via adiabatic parameter variation



★ Example: STIRAP in optical waveguide structures

★ Even small absorption can destroy adiabaticity due to competition with non-adiabtic corrections

Summary

★ Robust population transfer via adiabatic parameter variation

★ Example: STIRAP in optical

Thank you for your attention!

★ Even small absorption can destroy adiabaticity due to competition with non-adiabtic corrections

arxiv:1207.5235