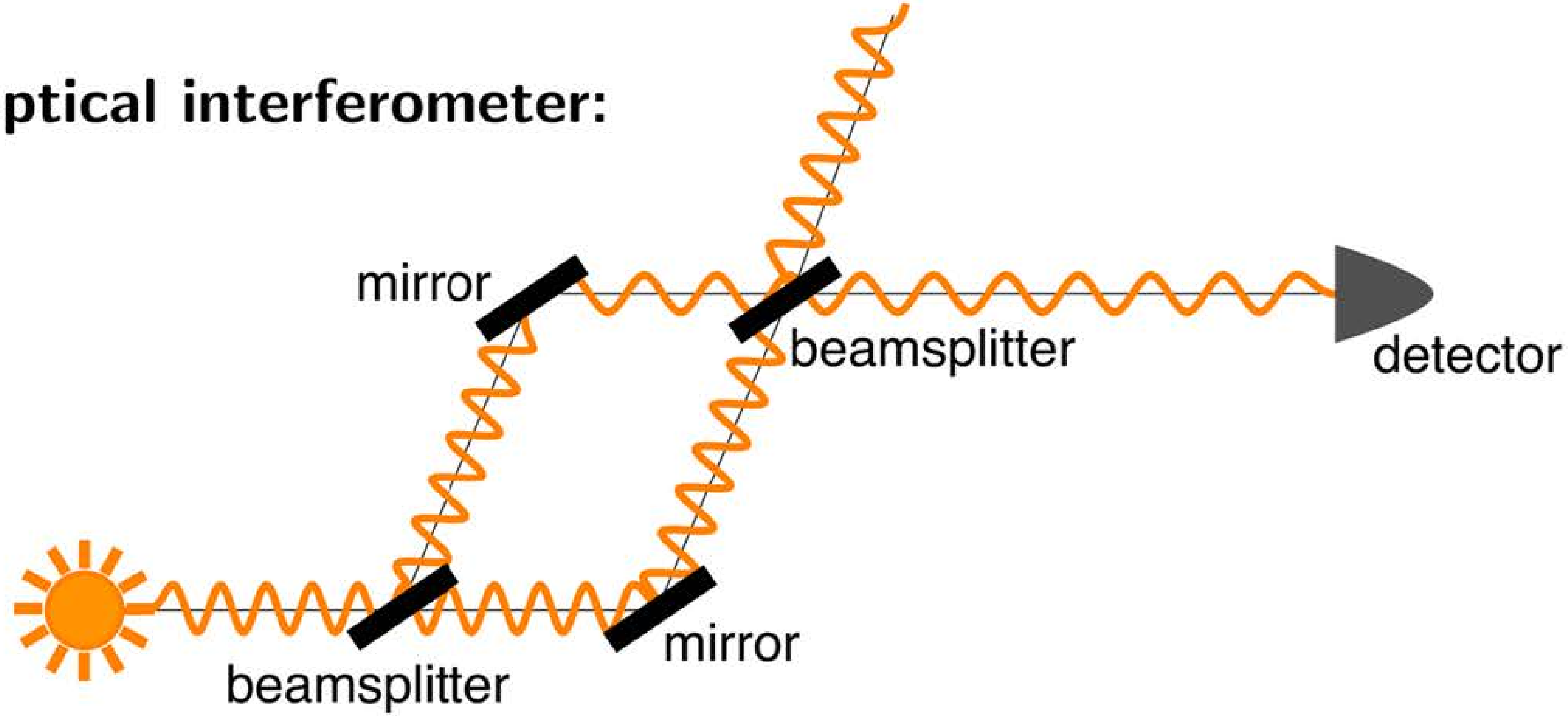
U.S. ARMY RDECOM ARL RESEARCH LABORATORY

Optimal pulse schemes for high-precision atom interferometry

Michael Goerz[1], Paul Kunz[1], Mark Kasevich[2], Vladimir Malinovsky[1]

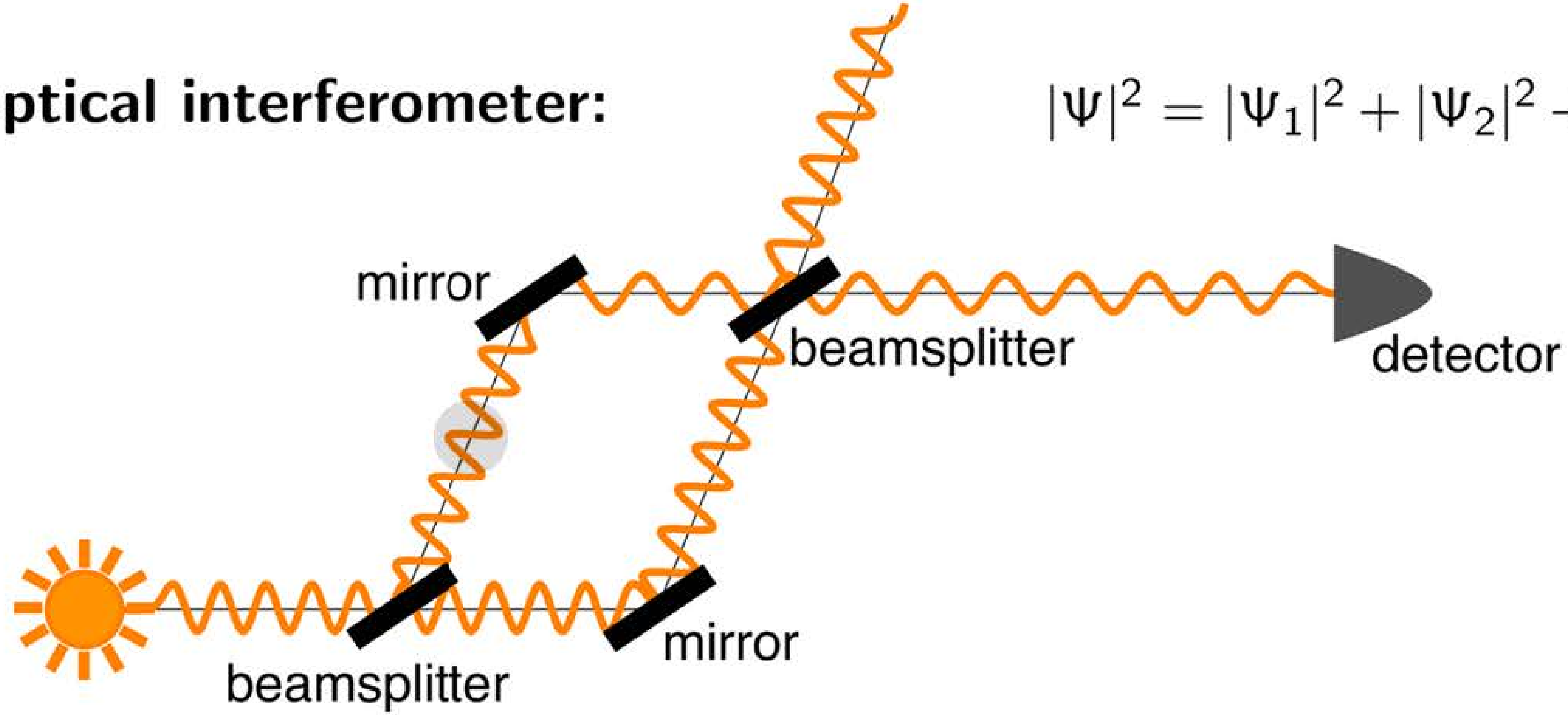
[1]U.S. Army Research Lab, [2]Stanford University

optical interferometer:



optical interferometer:

$$|\Psi|^2 = |\Psi_1|^2 + |\Psi_2|^2 + 2\Psi_1\Psi_2\cos(\phi_1 - \phi_2)$$



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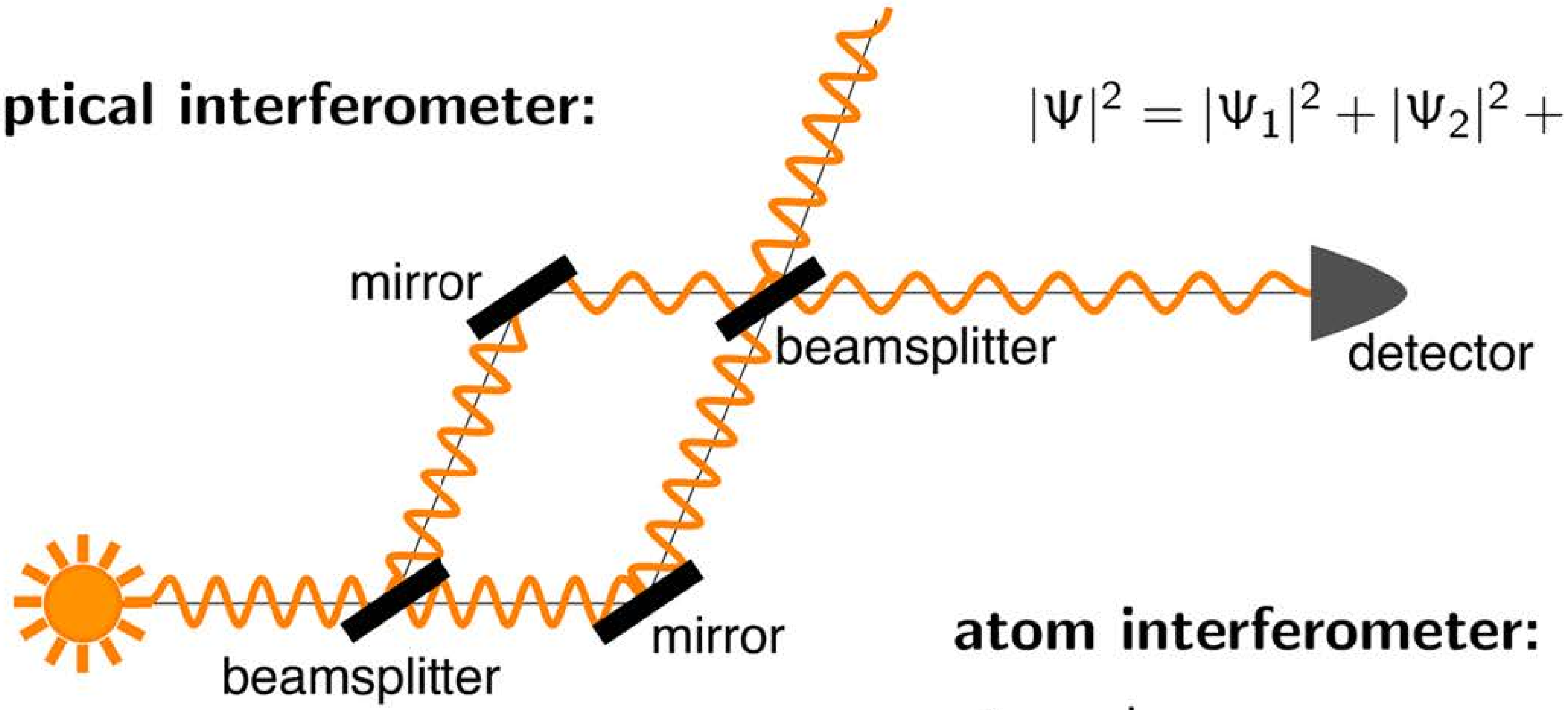

atom interferometer:

atoms have *mass*
and *internal structure*
$\Rightarrow$ couple to more external perturbations (gravity)

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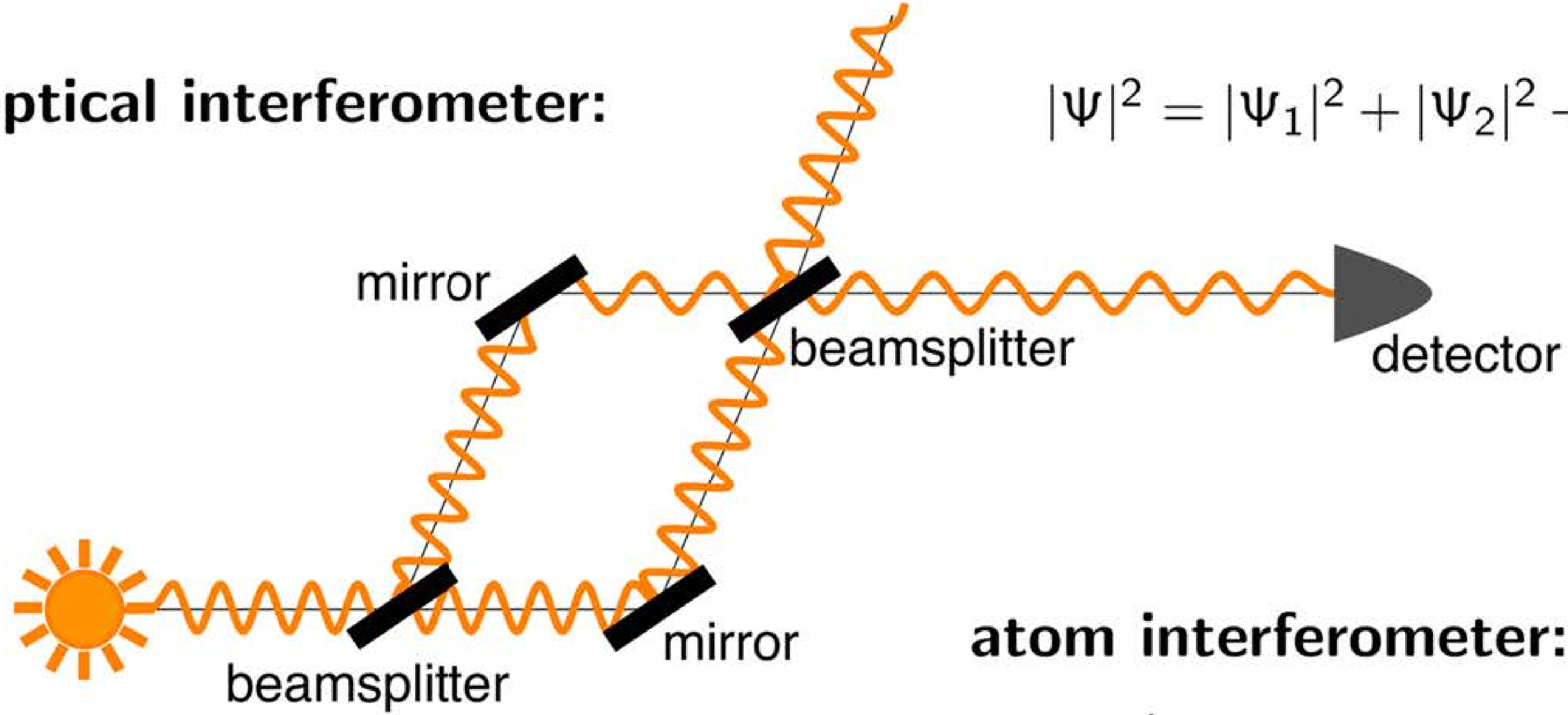

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atoms have *mass*
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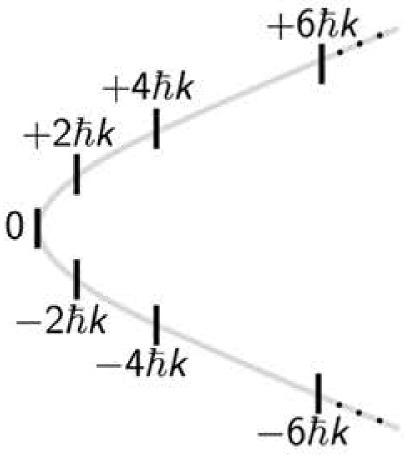
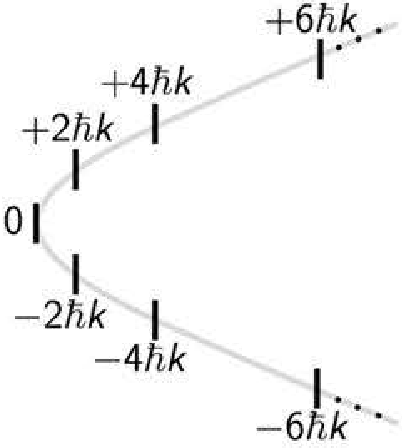
mirror? beamsplitter?



laser couples between electronic states: absorbs photon momentum

10 m atomic fountain at Stanford: ultracold ^{87}Rb atomic cloud



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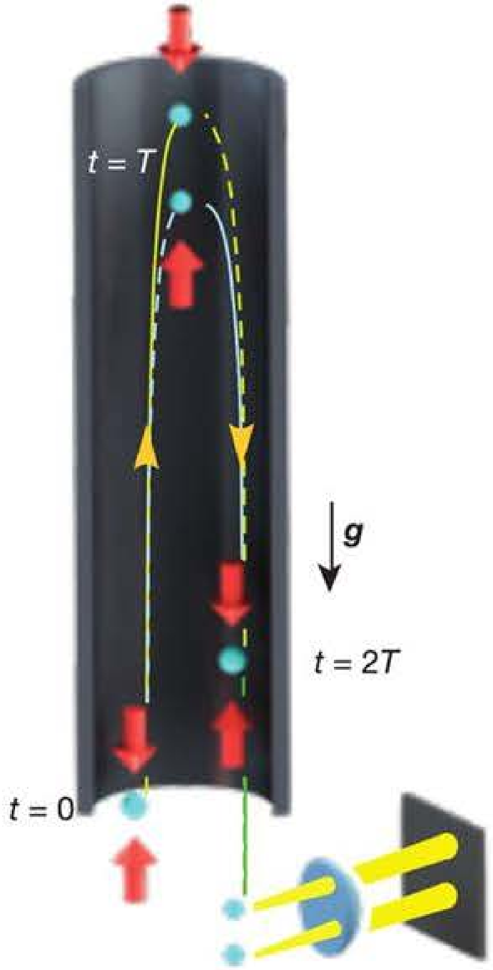

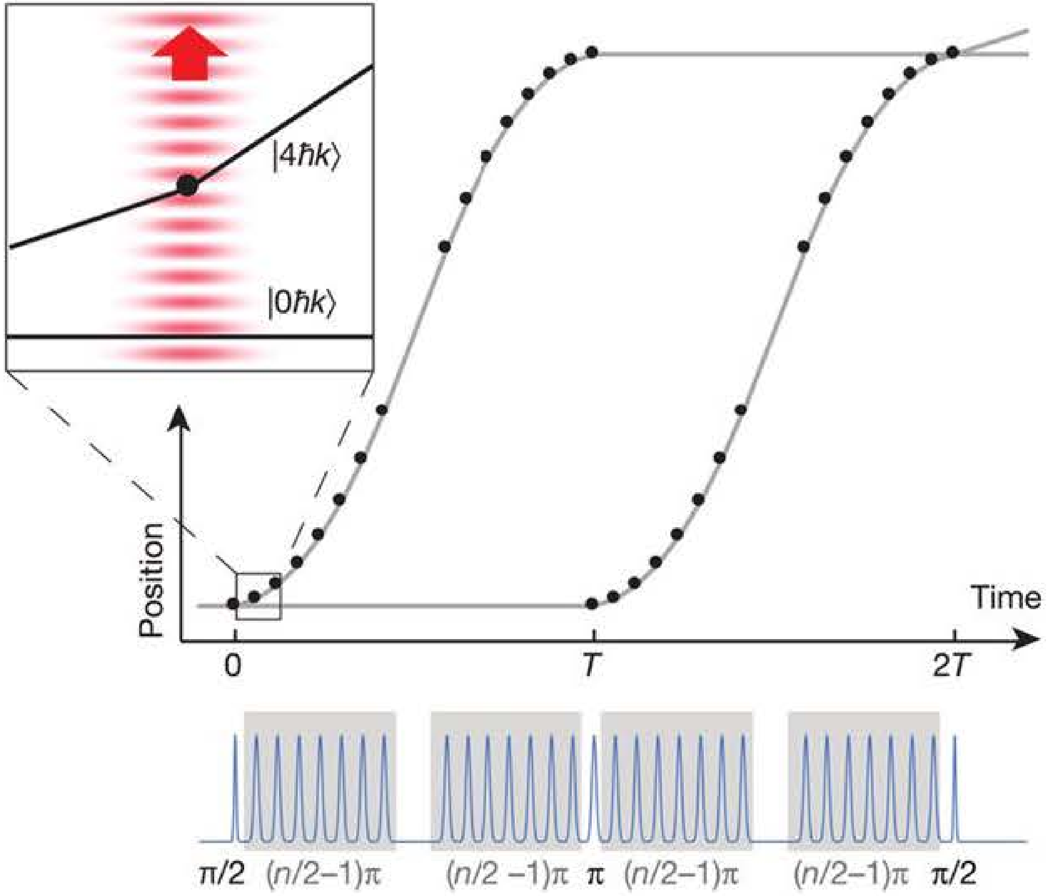

Kovachi et al. *Nature* **528**, 530 (2015)

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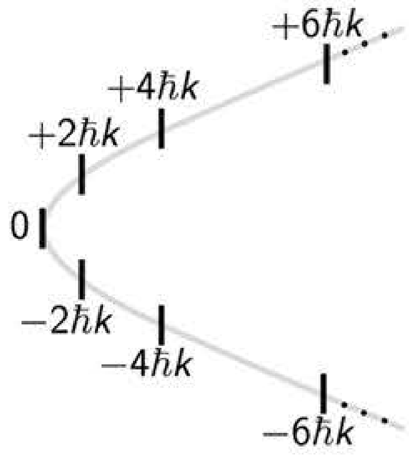
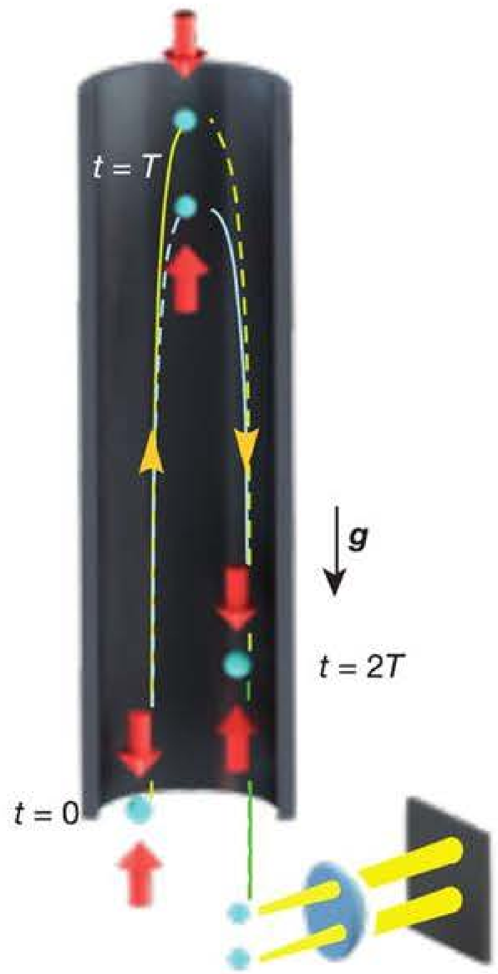
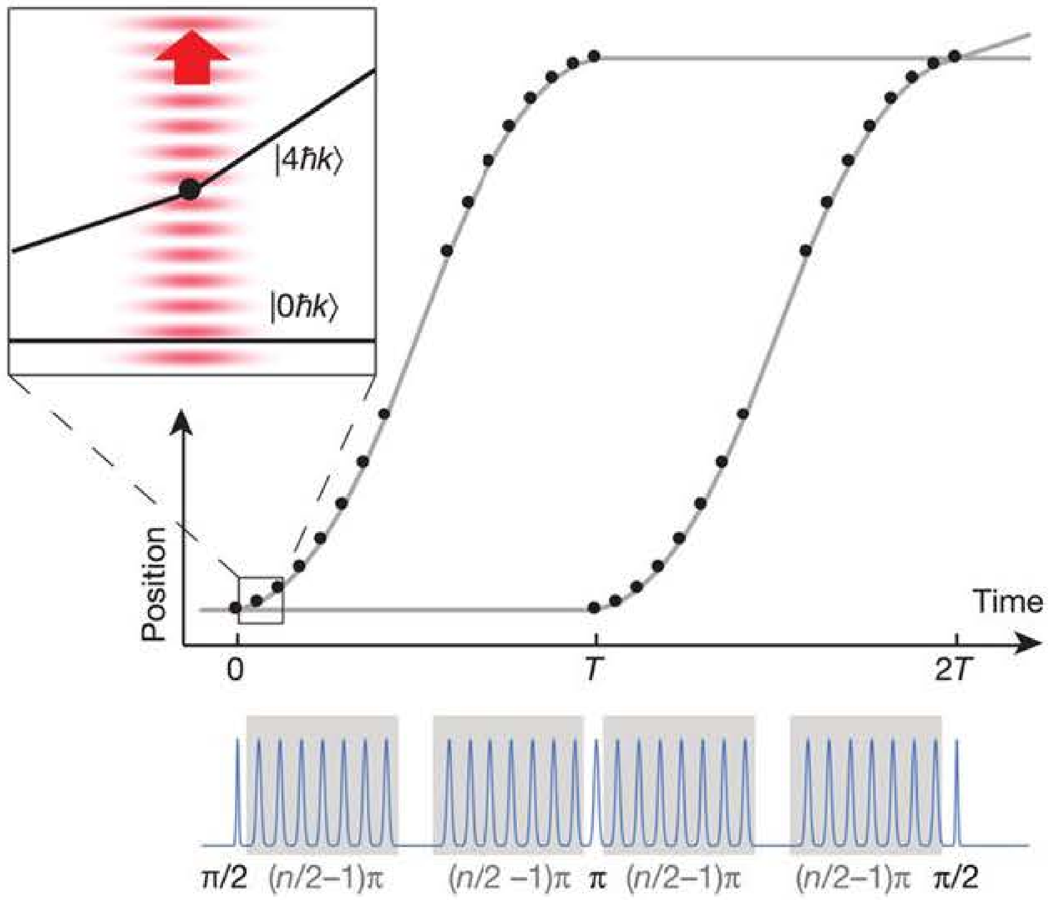


laser couples between electronic states: absorbs photon momentum

$$\Delta\phi = -2k_{\mathrm{max}} g T^2$$

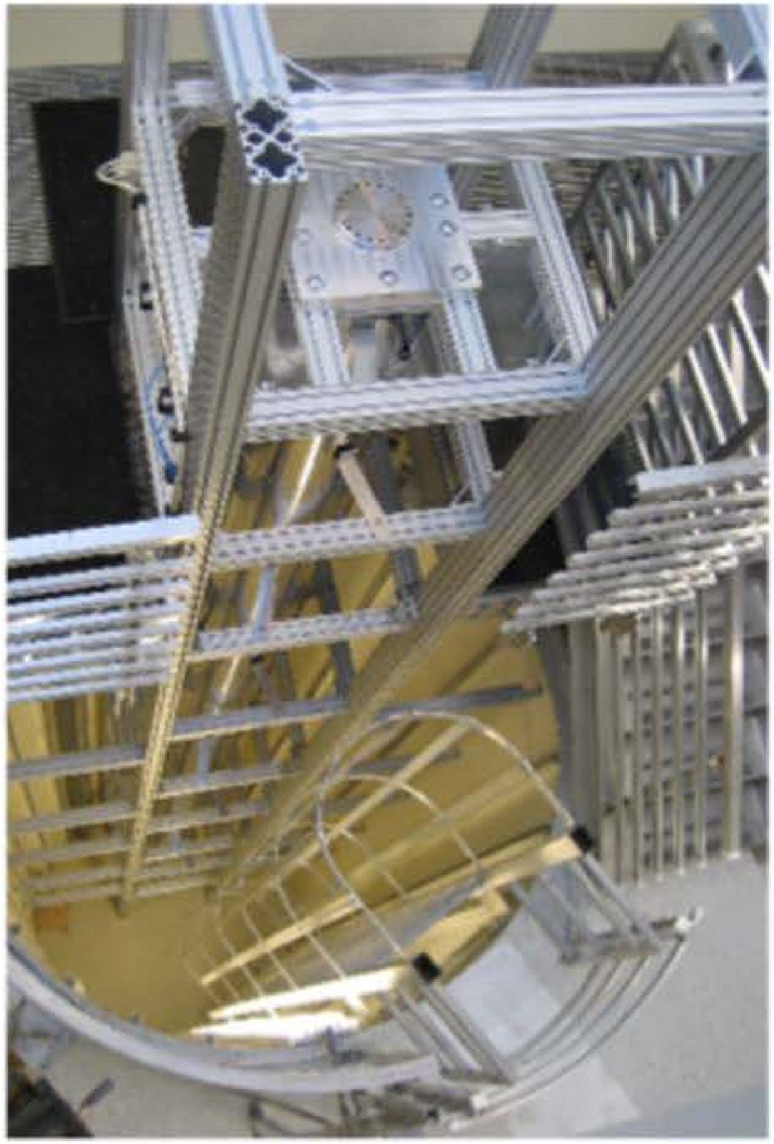




Kovachi et al. *Nature* **528**, 530 (2015)

Army applications:
ultra-precise measurement
of acceleration / gravity

- inertial navigation:
  submarines, autonomous vehicles
  —not jammable!
  - gyroscopes
  - gravity gradient sensors
- weapons system control
- geospatial mapping
- drone or satellite based
  detection of underground structures

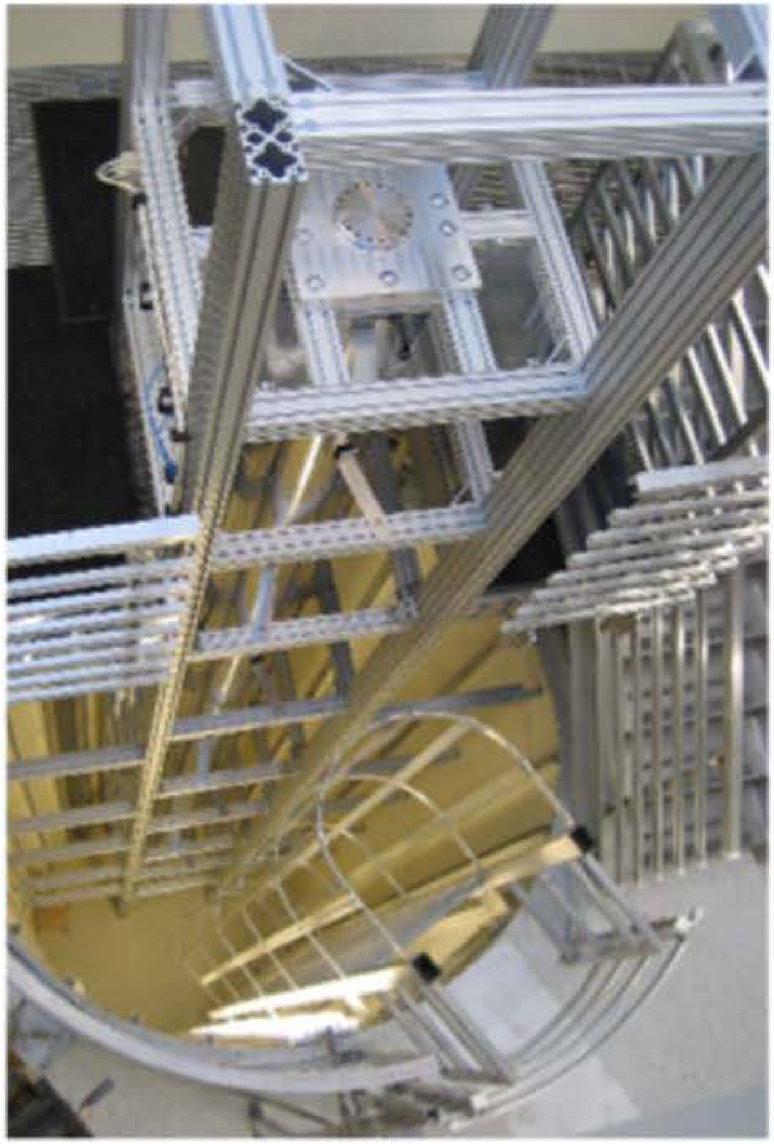


10 m atomic fountain: sensitivity $10^{-13}\ g/\sqrt{Hz}$

AOSense (2010)
$10^{-6}\ g/\sqrt{Hz}$

state of the art
$10^{-9}\ g/\sqrt{Hz}$

10 m atomic fountain: sensitivity $10^{-13}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$



factors:

- signal to noise ratio
- large momentum transfer

?

AOSense (2010)
$10^{-6}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$

state of the art
$10^{-9}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$

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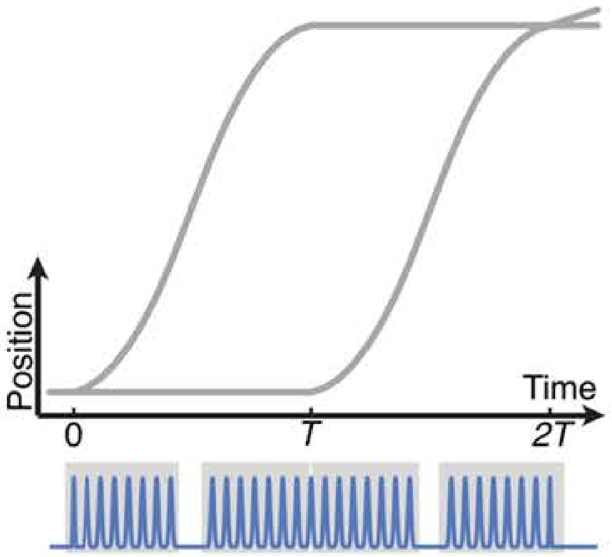
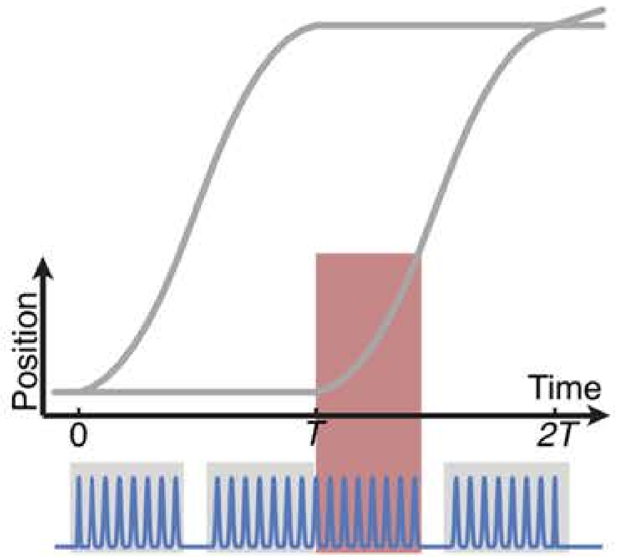
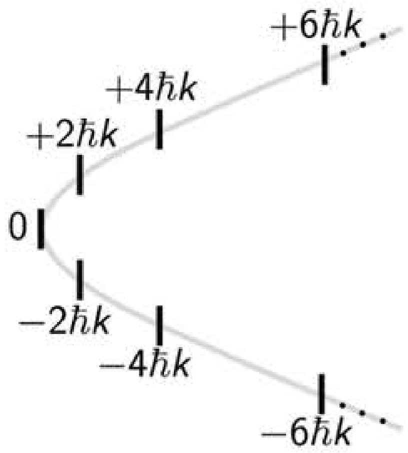
Apply optimal control to atom optics pulses

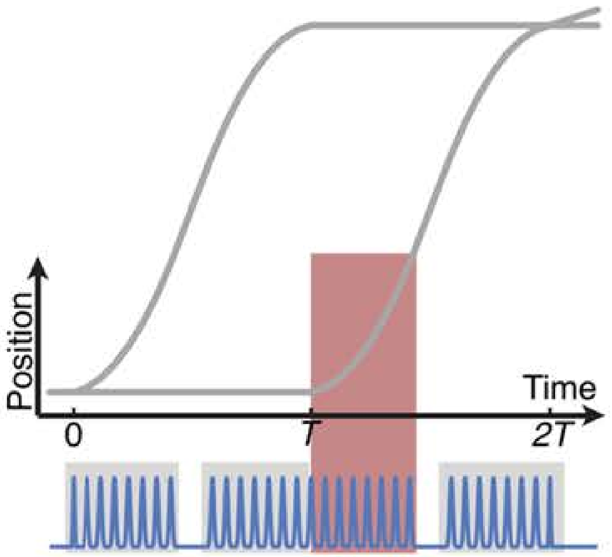
$\Rightarrow$ increase fidelity

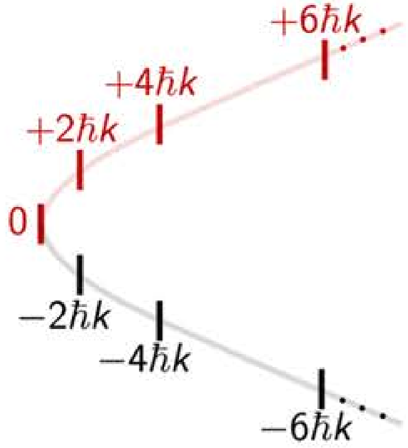
$\Rightarrow$ robustness against fluctuations

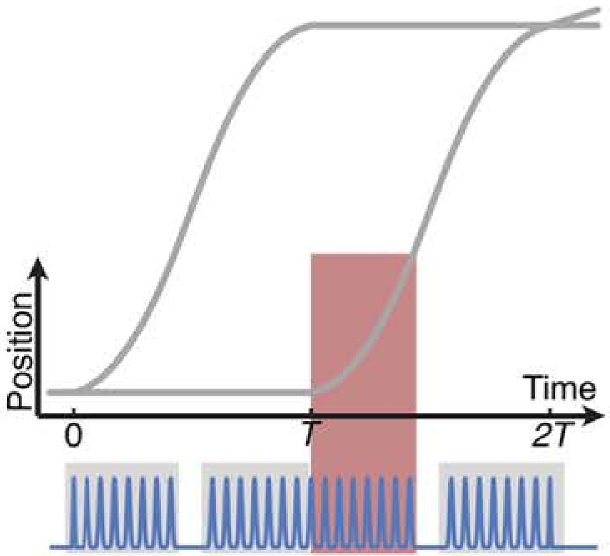

Position
Time
0
T
2T

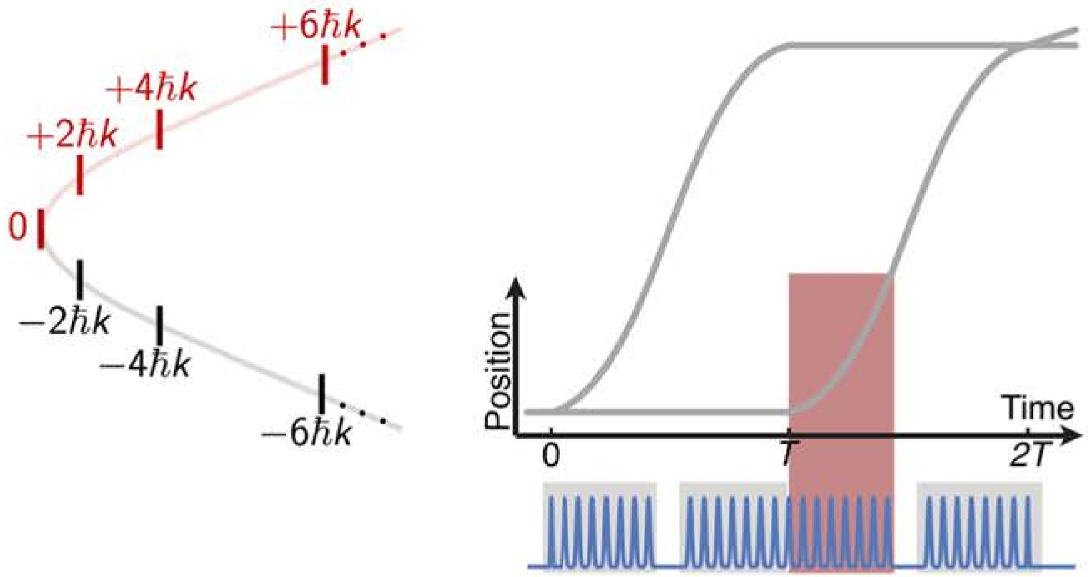

Position
Time
0
T
2T


+6ħk
+4ħk
+2ħk
0
−2ħk
−4ħk
−6ħk

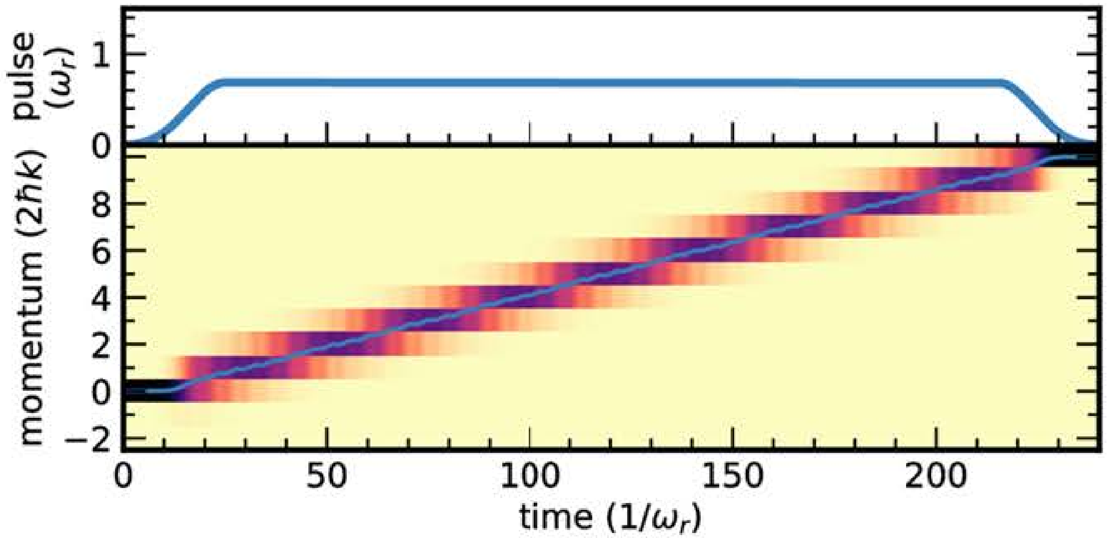

Position
Time
0
T
2T

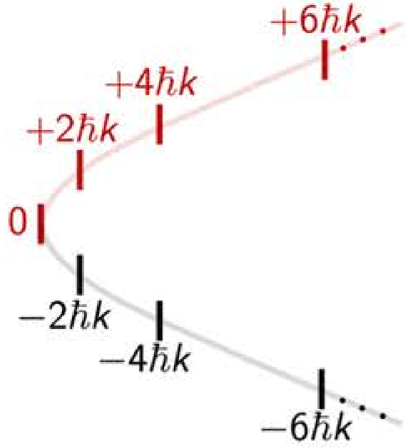

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$

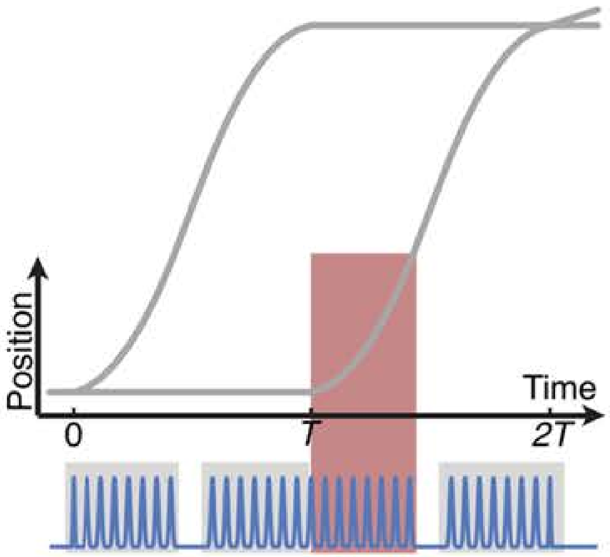

Position
Time
0
T
$2T$



train of pulses ⇒ rapid adiabatic passage:
tune through laser frequency at constant amplitude







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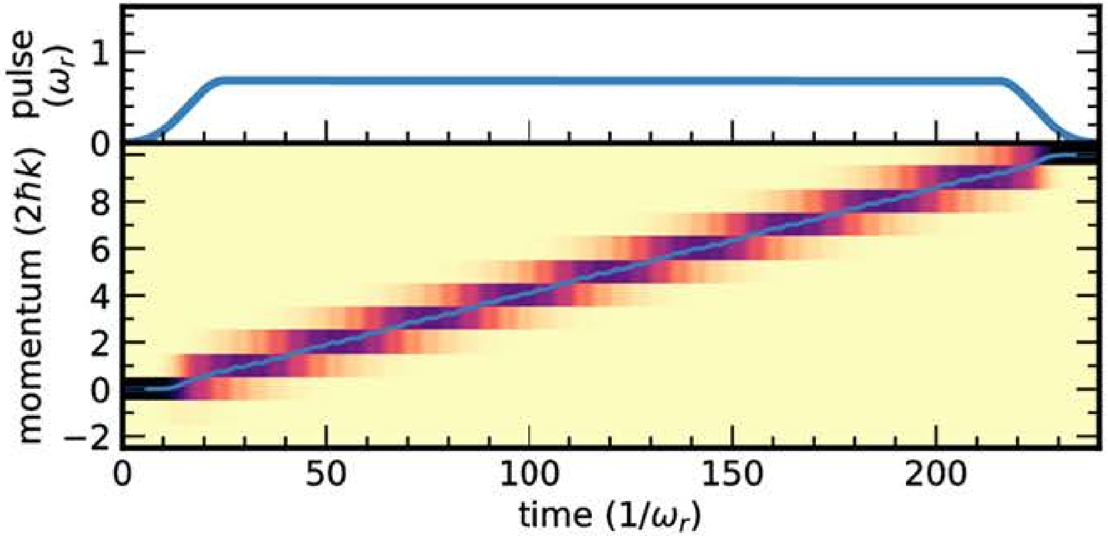
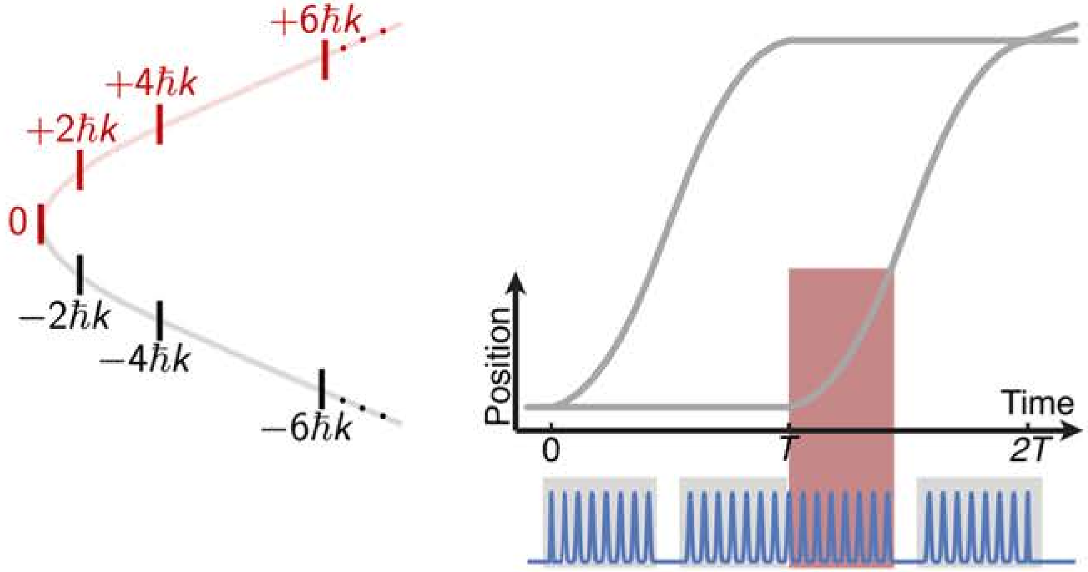
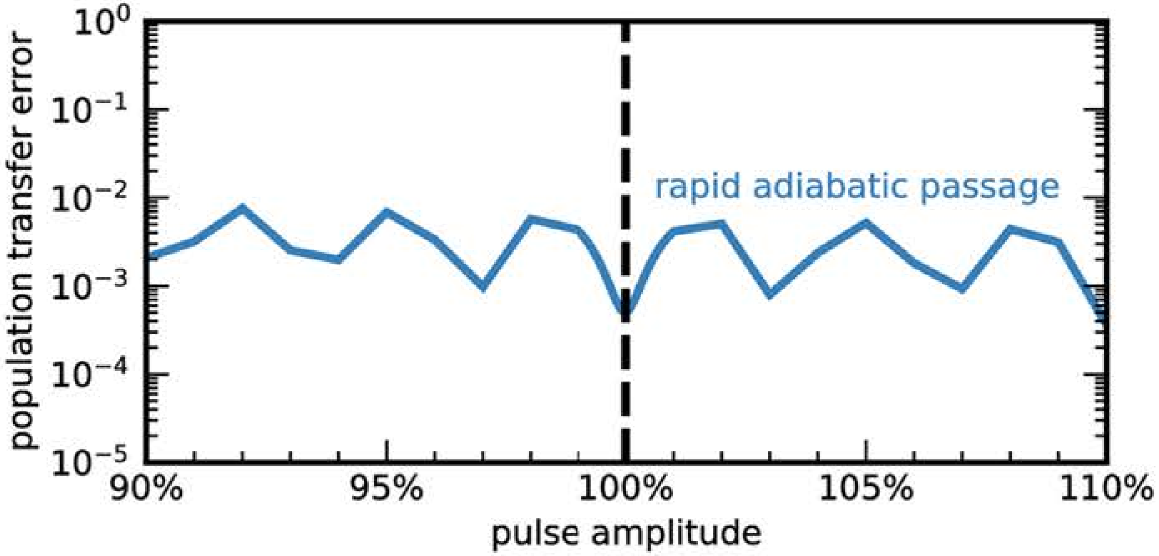
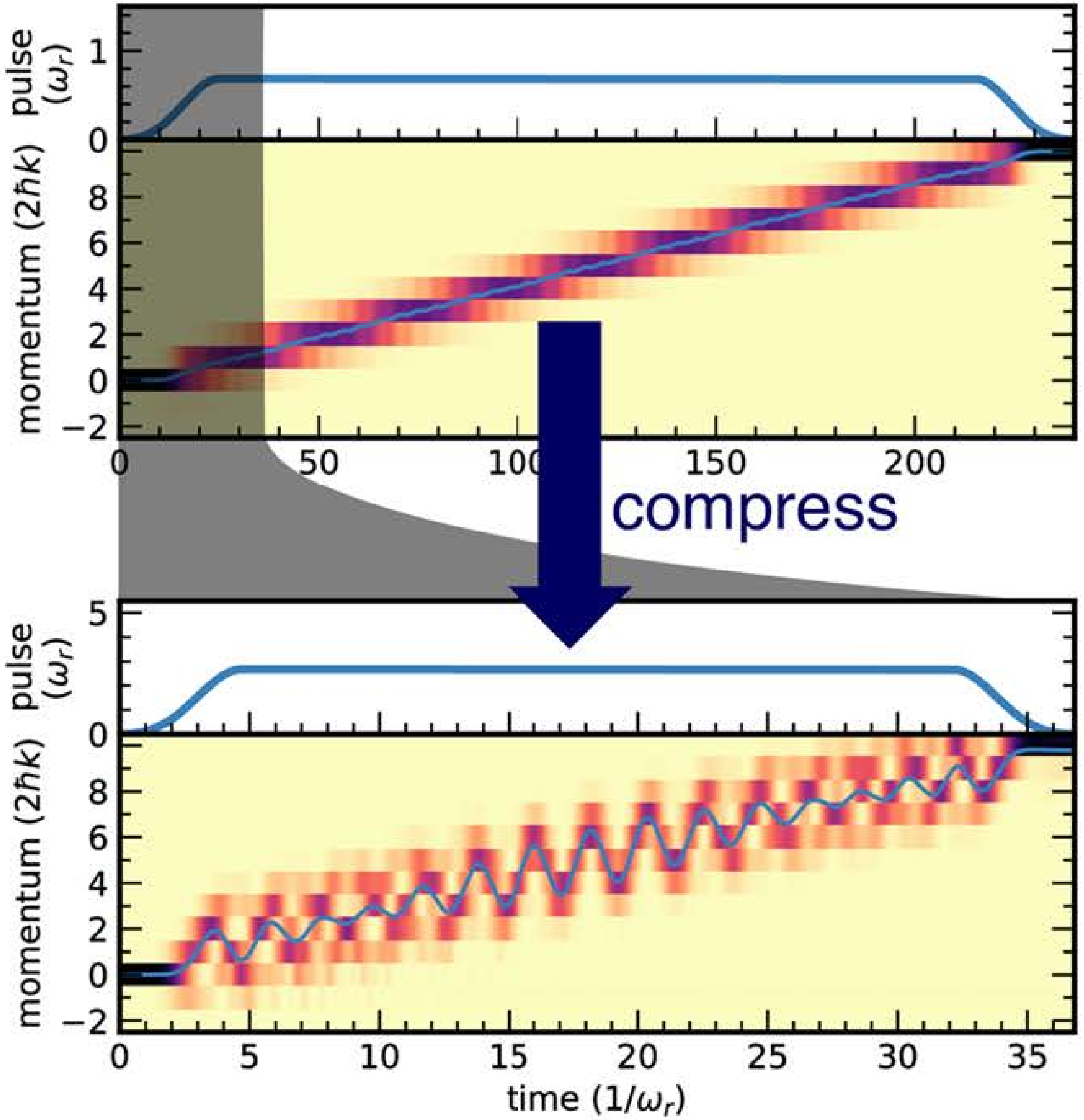
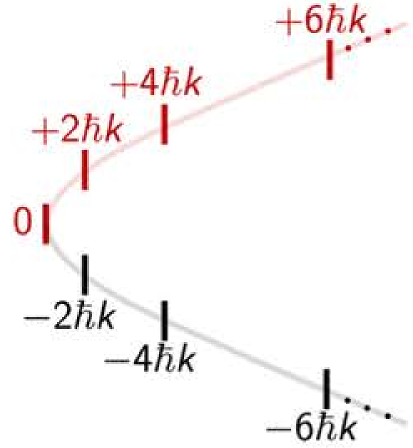
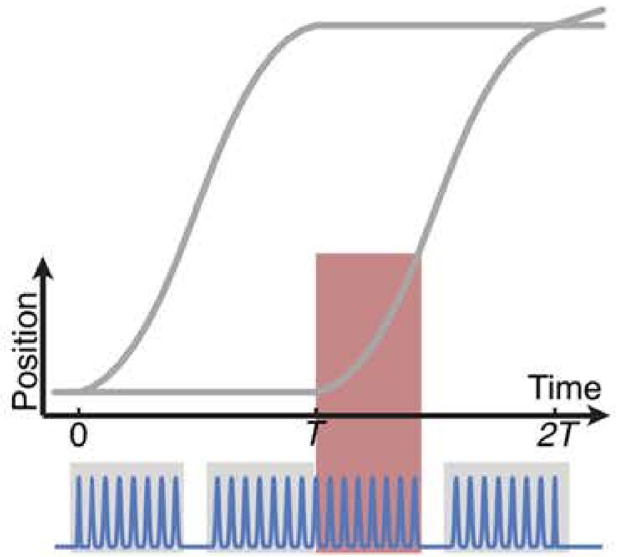

pulse (ω_r)
1
0
momentum ($2\hbar k$)
8
6
4
2
0
−2
0
50
100
150
200
time ($1/\omega_r$)

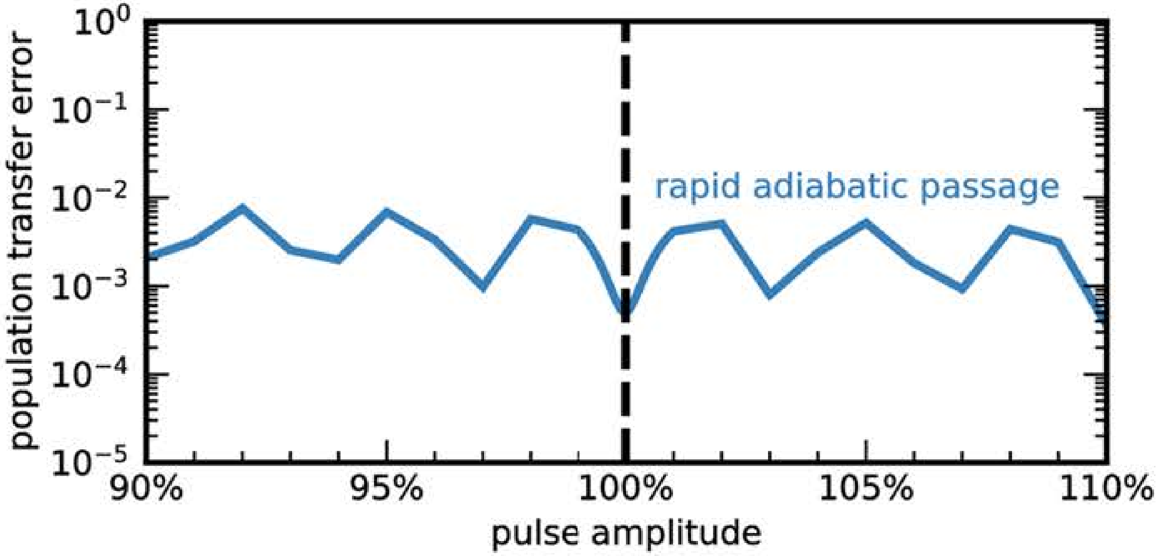

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
$2T$

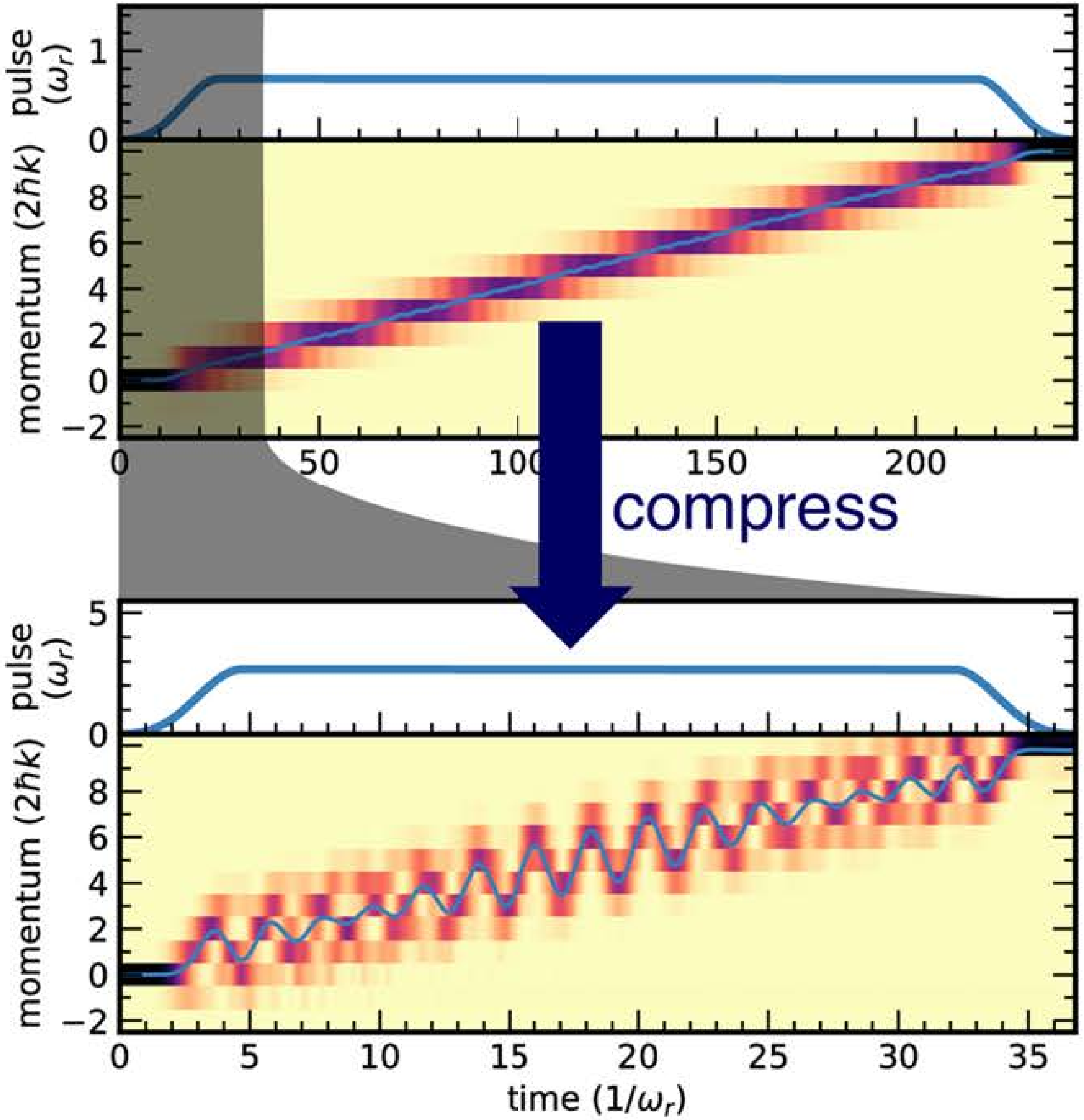

population transfer error
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
rapid adiabatic passage
90%
95%
100%
105%
110%
pulse amplitude

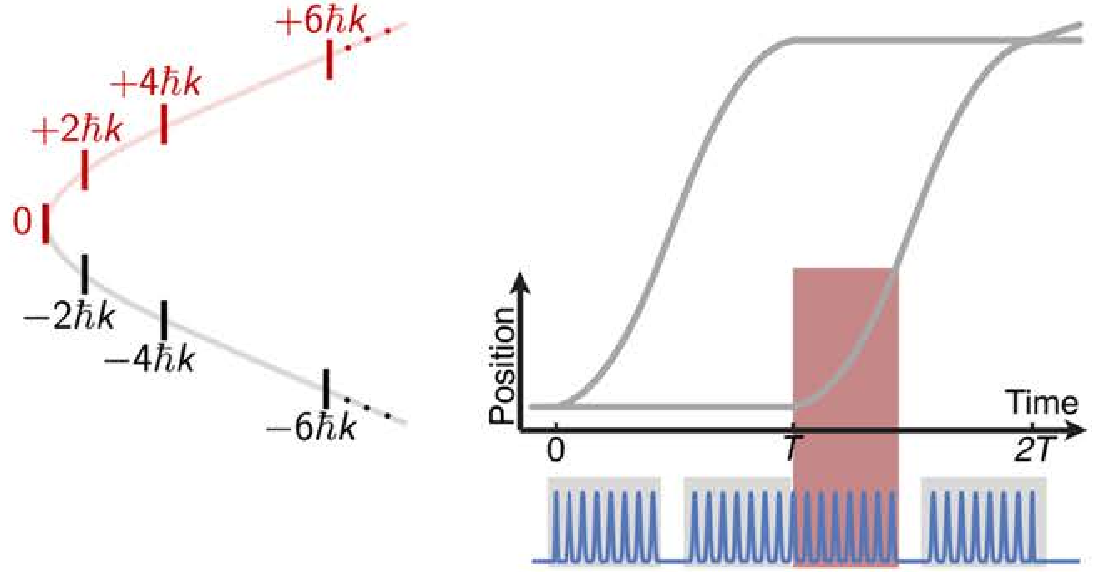

pulse (ω_r)
momentum ($2\hbar k$)
compress
time ($1/\omega_r$)

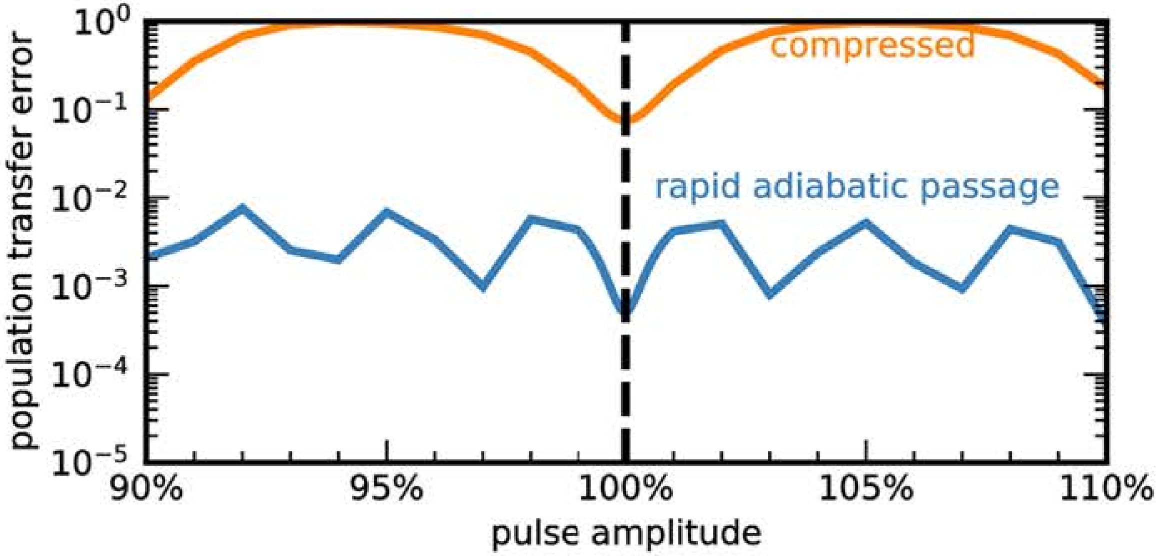

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$

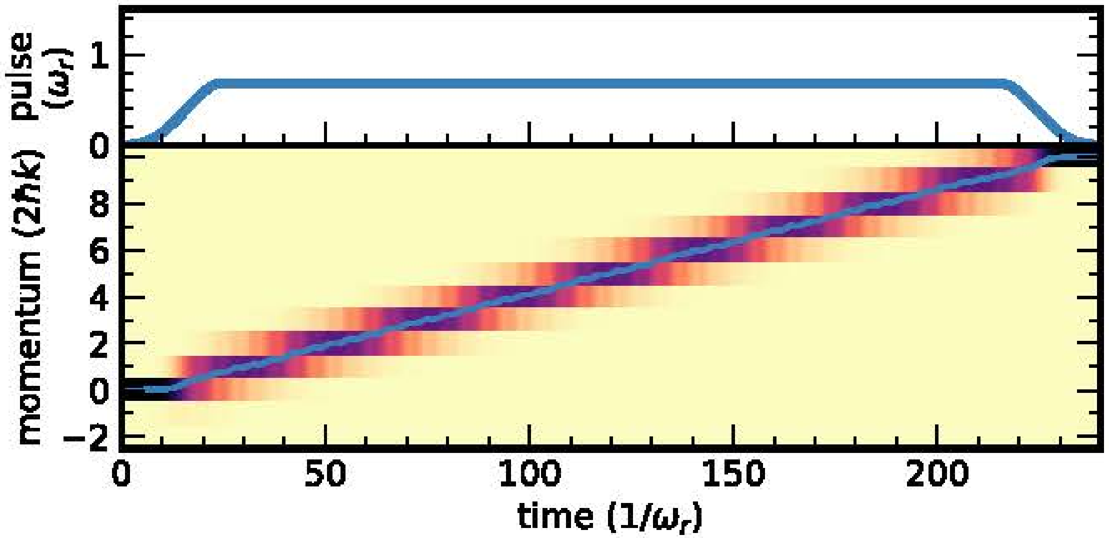

Position
Time
0
T
$2T$

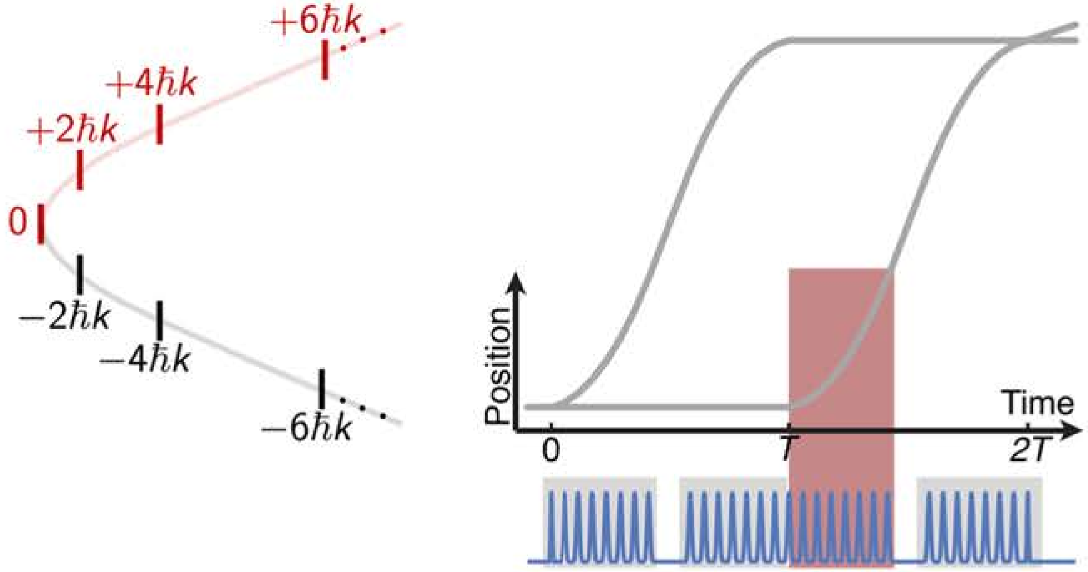

population transfer error
rapid adiabatic passage
pulse amplitude

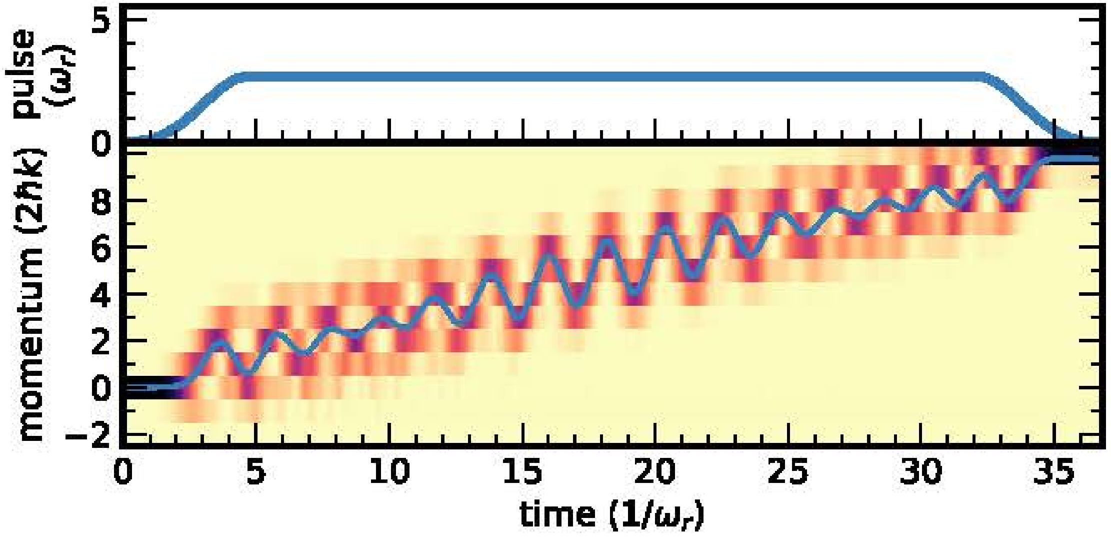

pulse (ω_r)
momentum ($2\hbar k$)
compress
time ($1/\omega_r$)

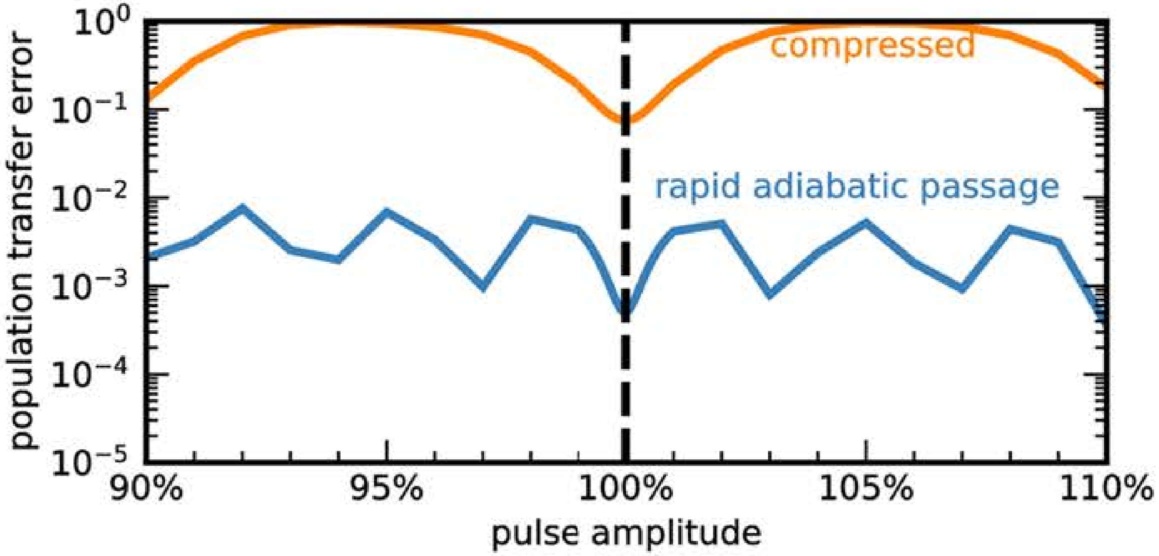

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
$2T$

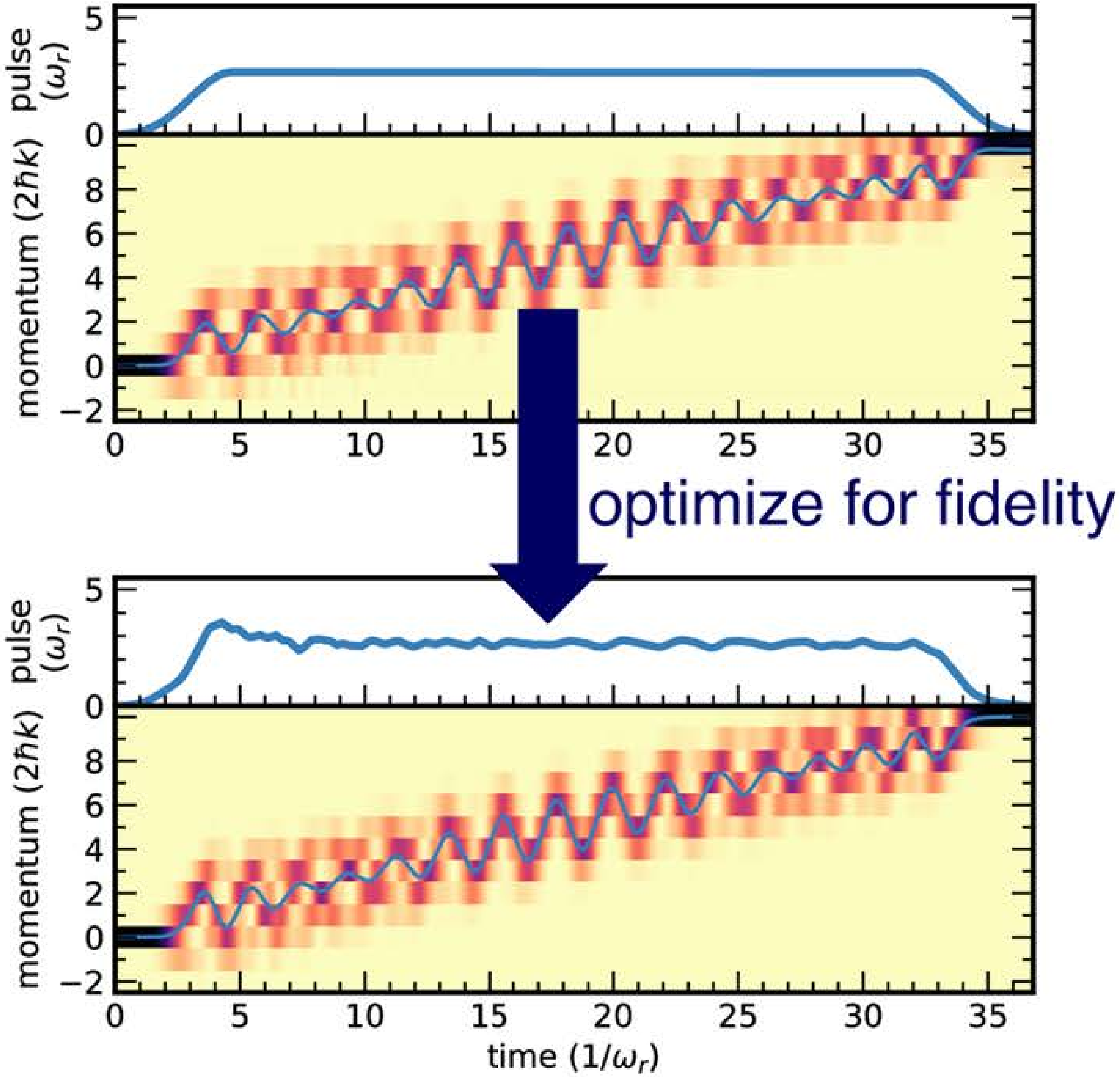

population transfer error
compressed
rapid adiabatic passage
pulse amplitude

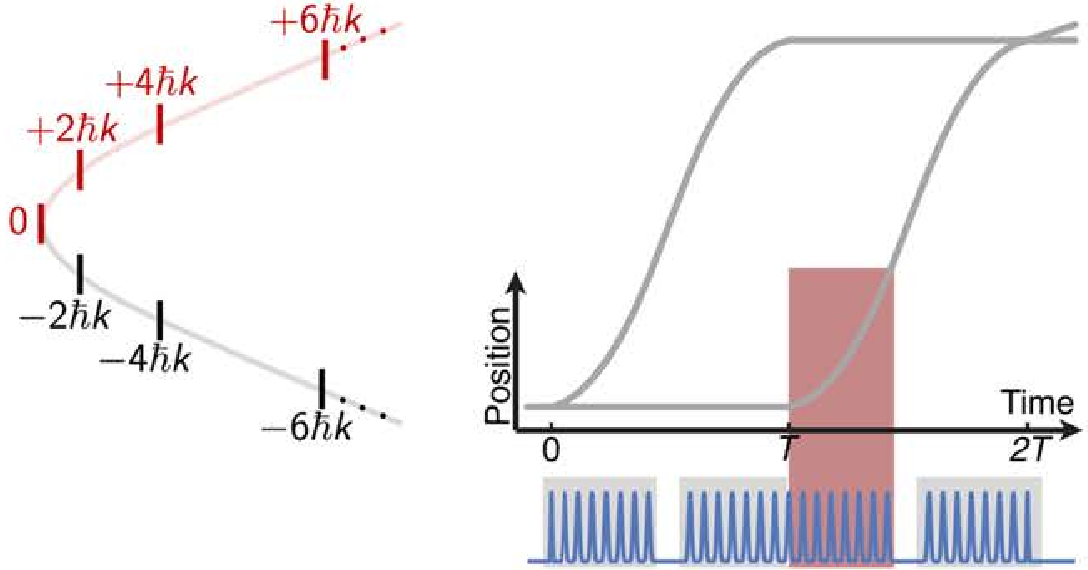

pulse
(ω_r)
momentum $(2\hbar k)$
time $(1/\omega_r)$

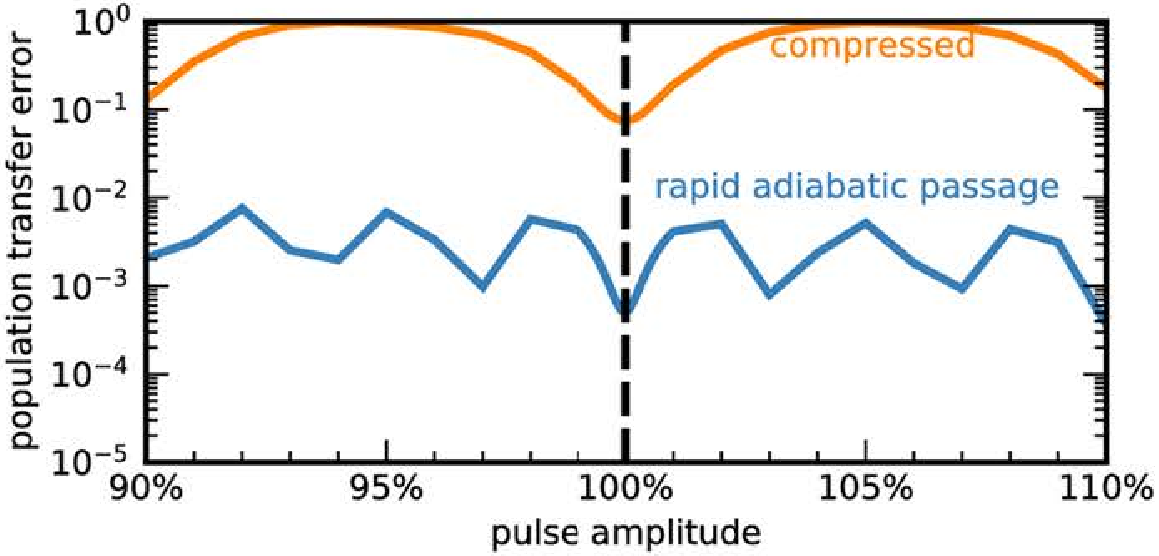

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
$2T$

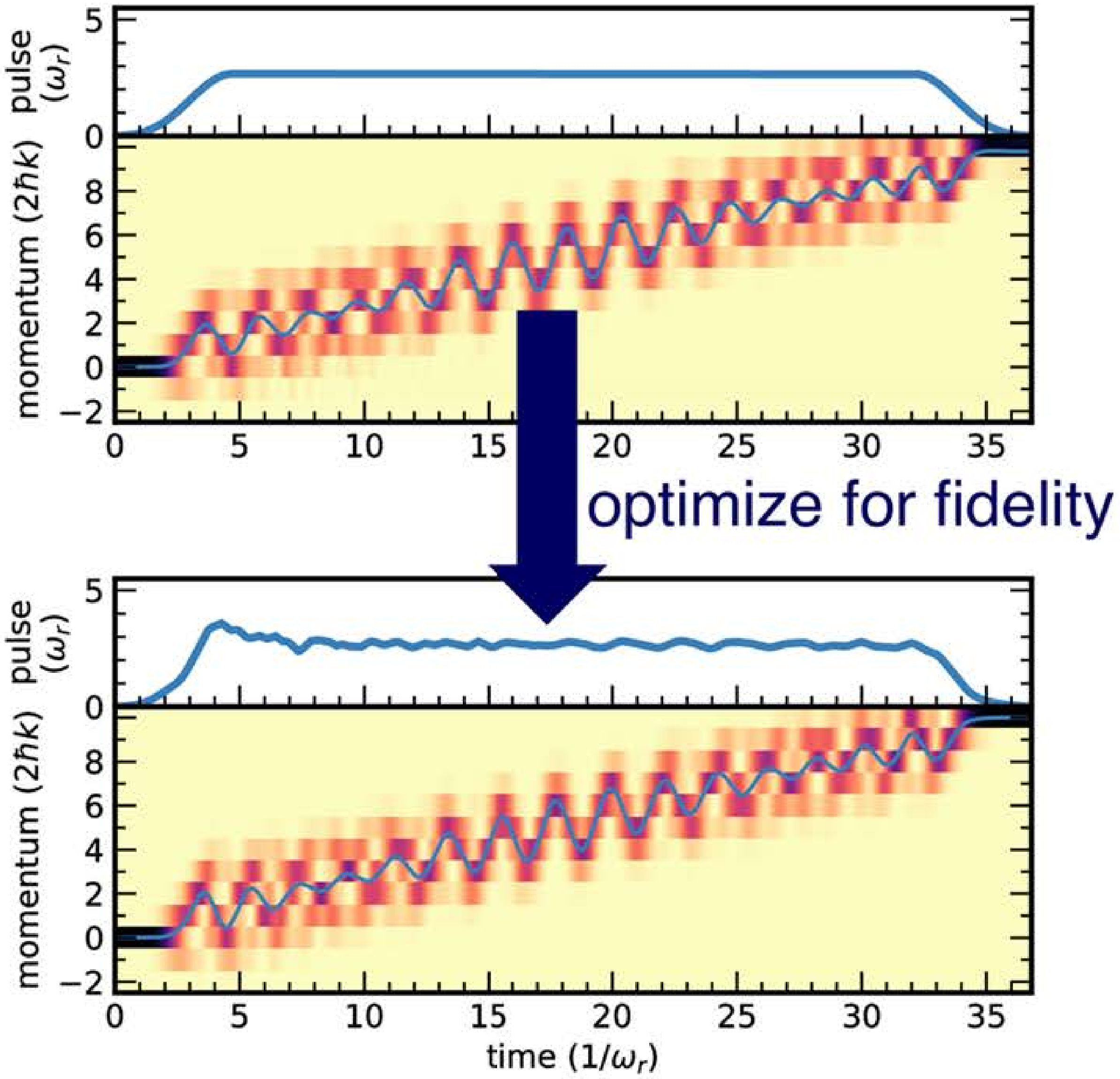

pulse
(ω_r)
momentum $(2\hbar k)$
time $(1/\omega_r)$

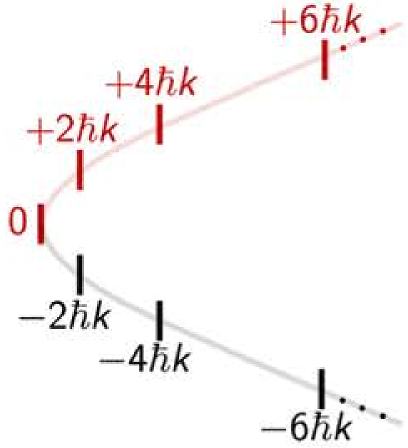

compressed
rapid adiabatic passage
population transfer error
pulse amplitude

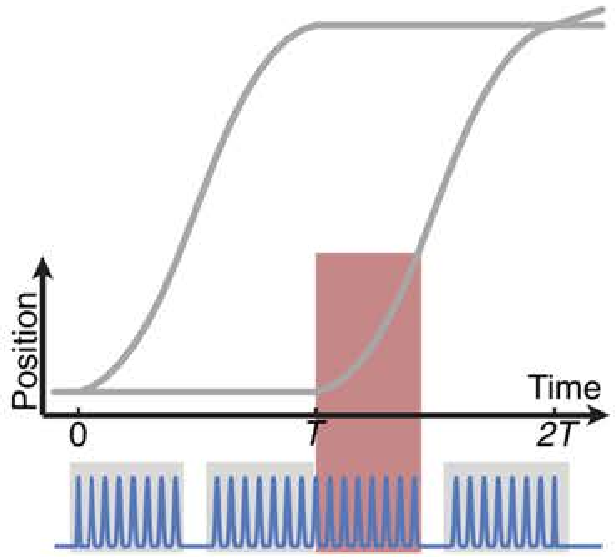

pulse (ω_r)
momentum ($2\hbar k$)
optimize for fidelity
time ($1/\omega_r$)

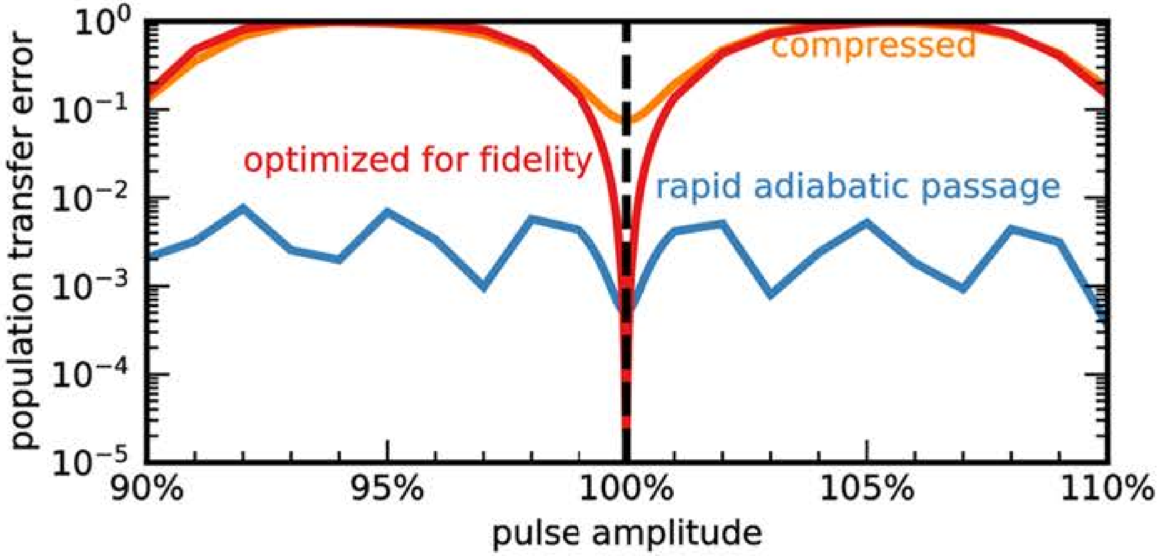

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
$2T$

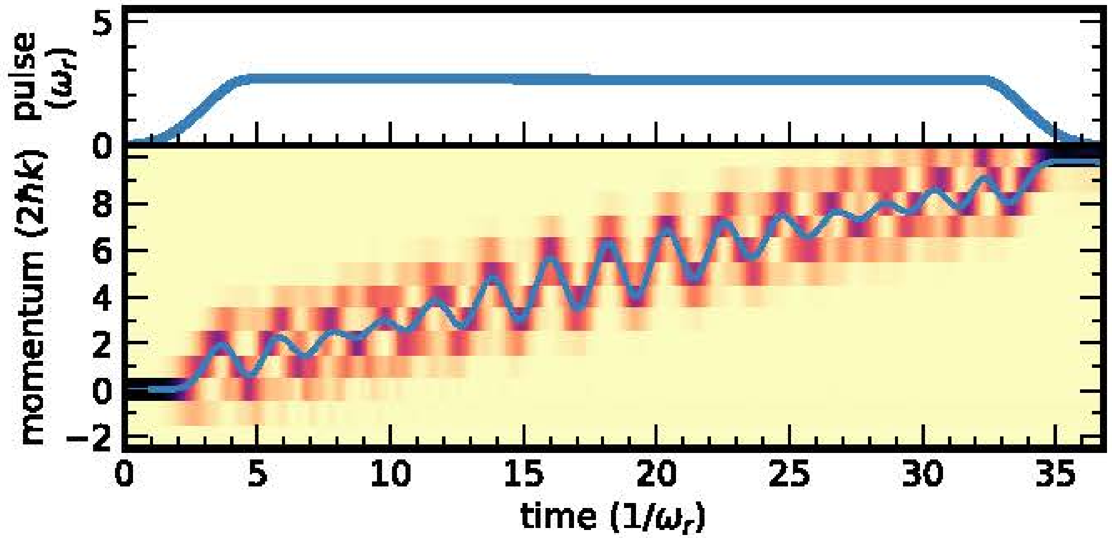

population transfer error
compressed
rapid adiabatic passage
pulse amplitude

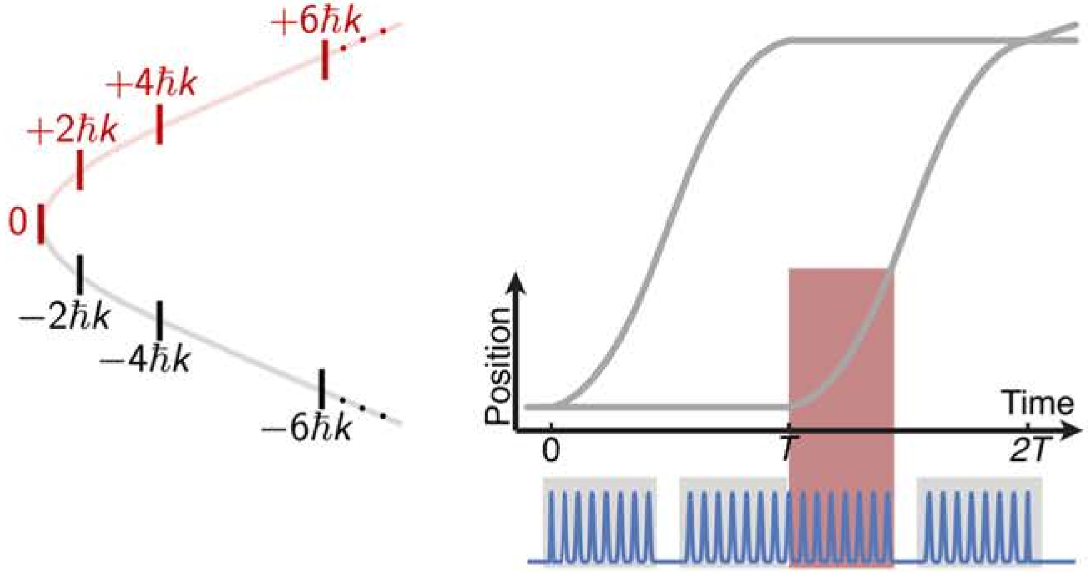

pulse (ω_r)
momentum ($2\hbar k$)
optimize for fidelity
time ($1/\omega_r$)

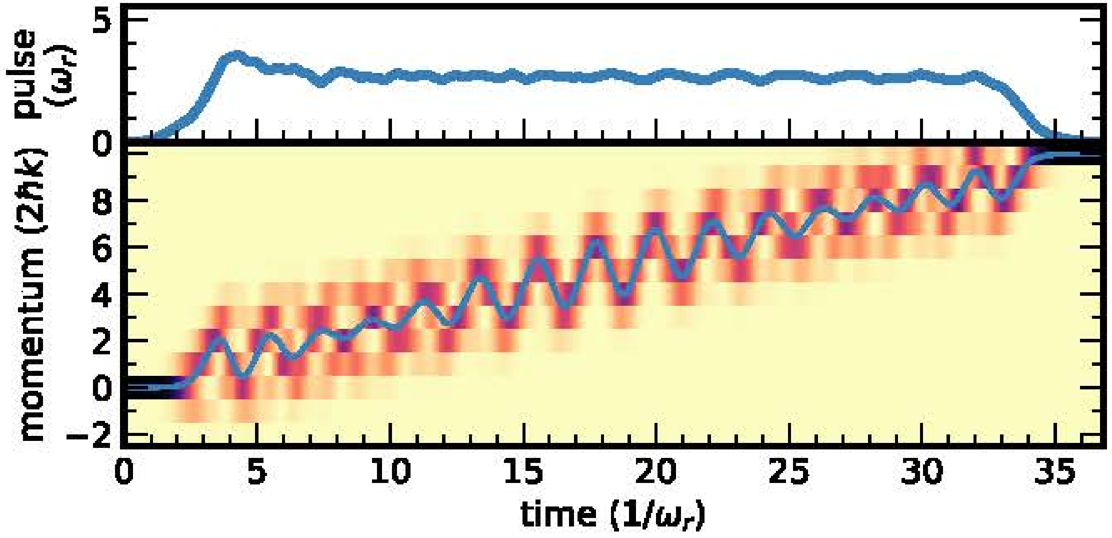

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$

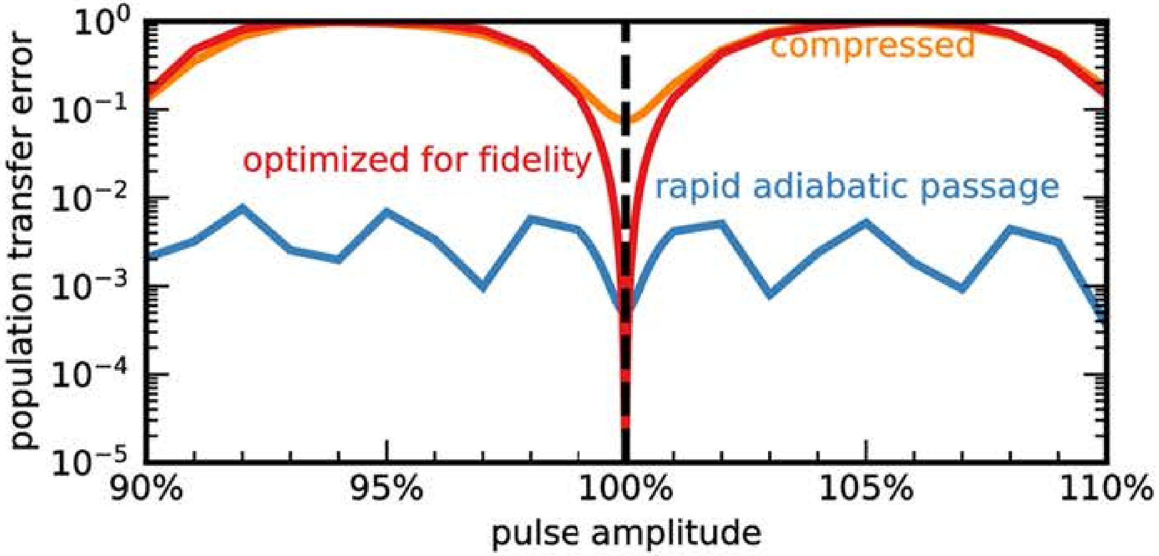

Position
Time
0
T
2T

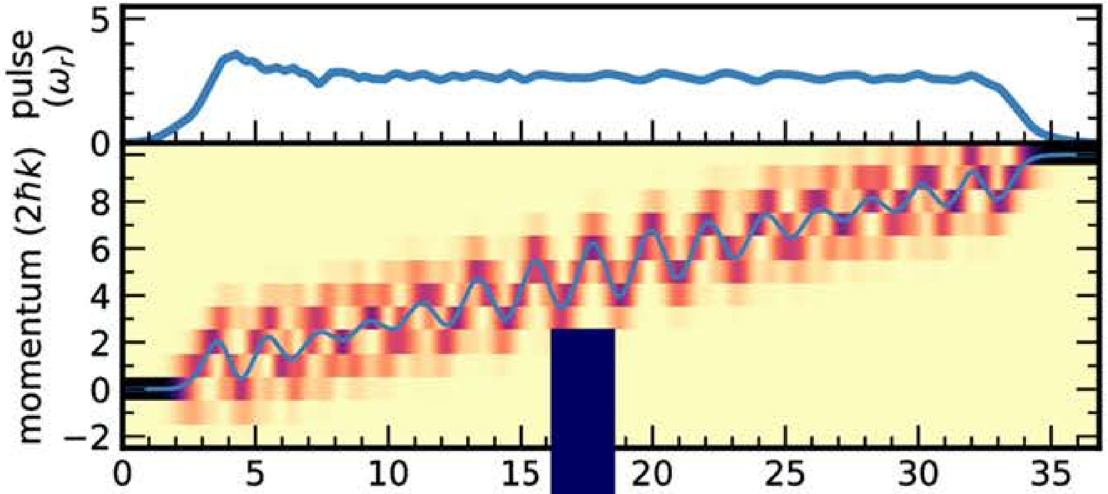

compressed
optimized for fidelity
rapid adiabatic passage
population transfer error
pulse amplitude


pulse (ω_r)
momentum ($2\hbar k$)
time ($1/\omega_r$)

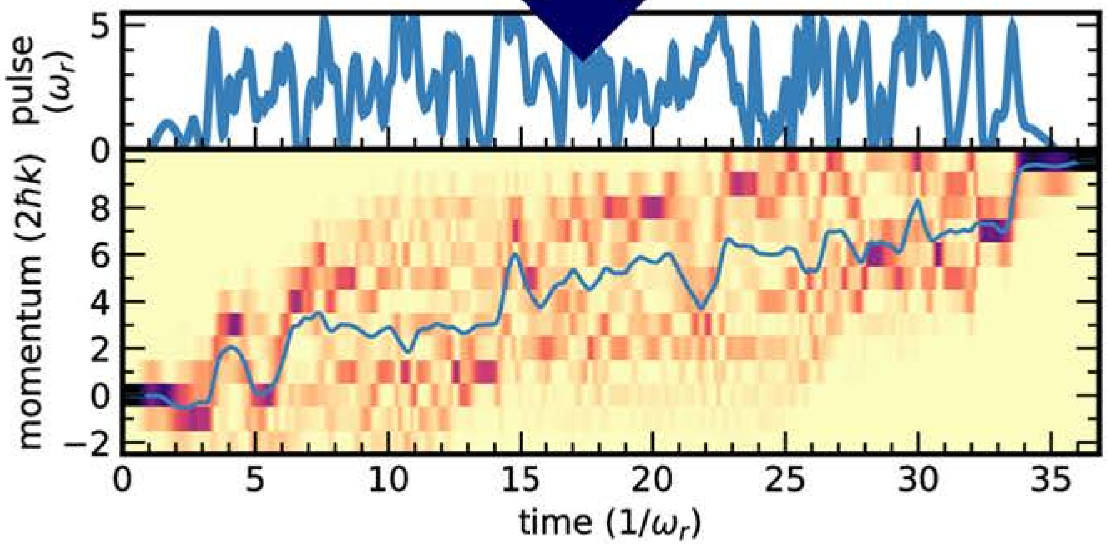

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
$2T$

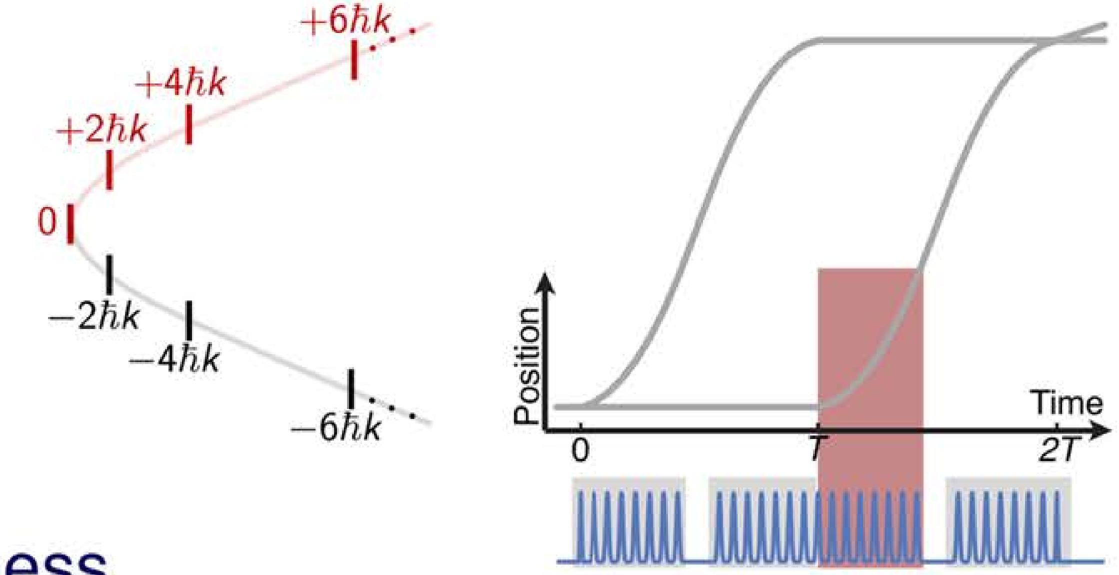

pulse (ω_r)
momentum ($2\hbar k$)
time ($1/\omega_r$)

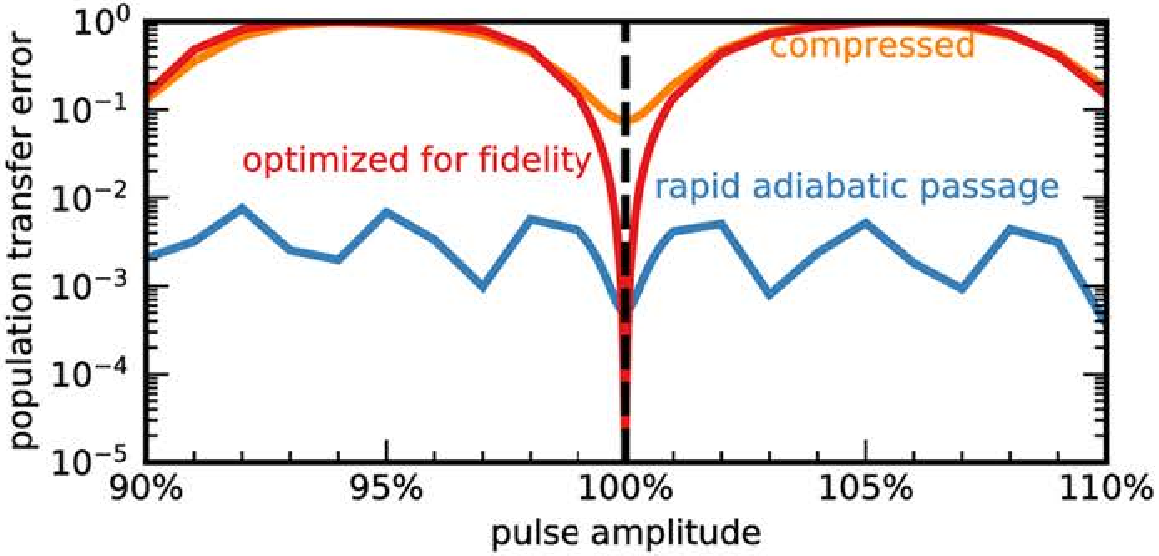

population transfer error
compressed
optimized for fidelity
rapid adiabatic passage
pulse amplitude

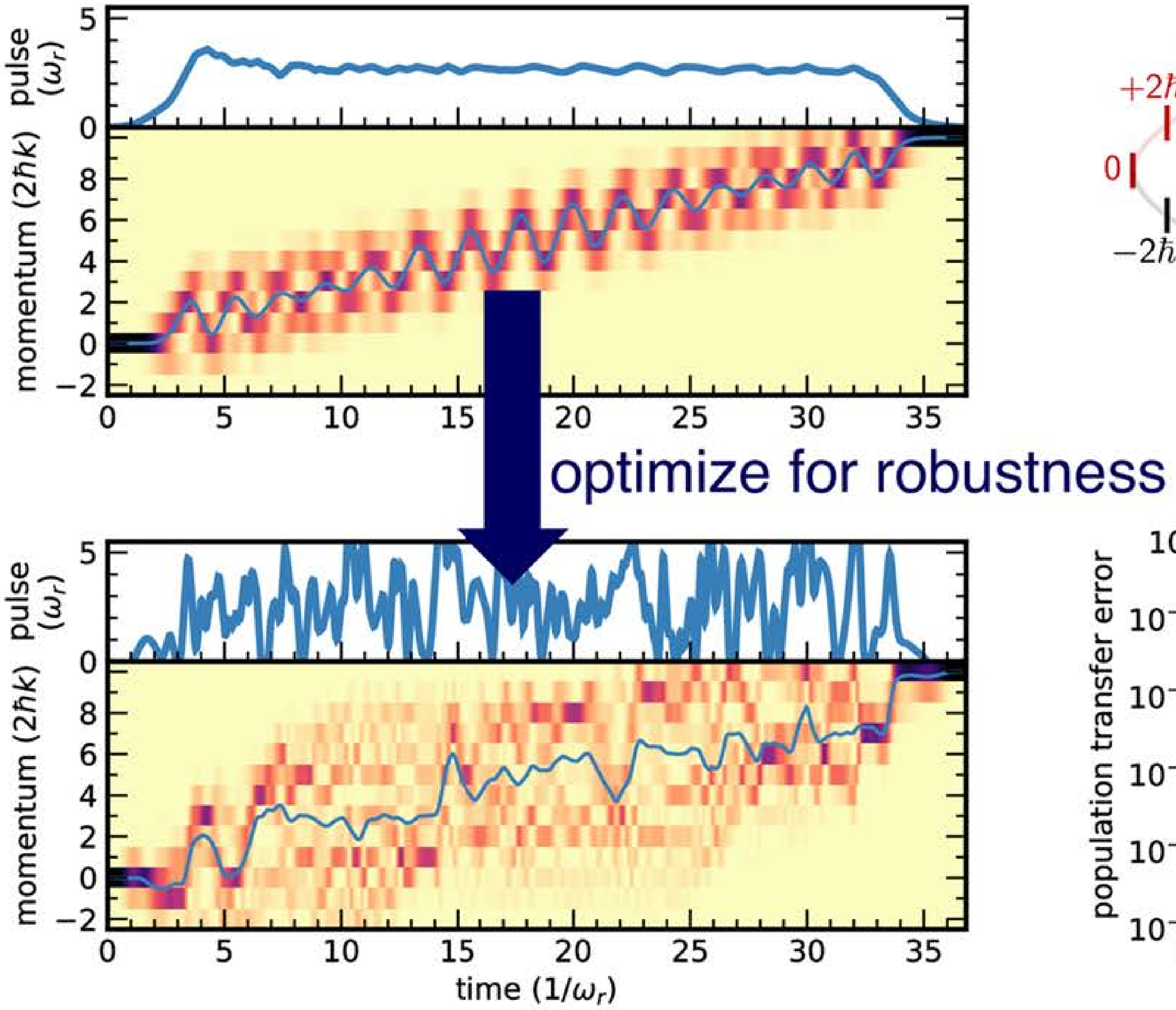


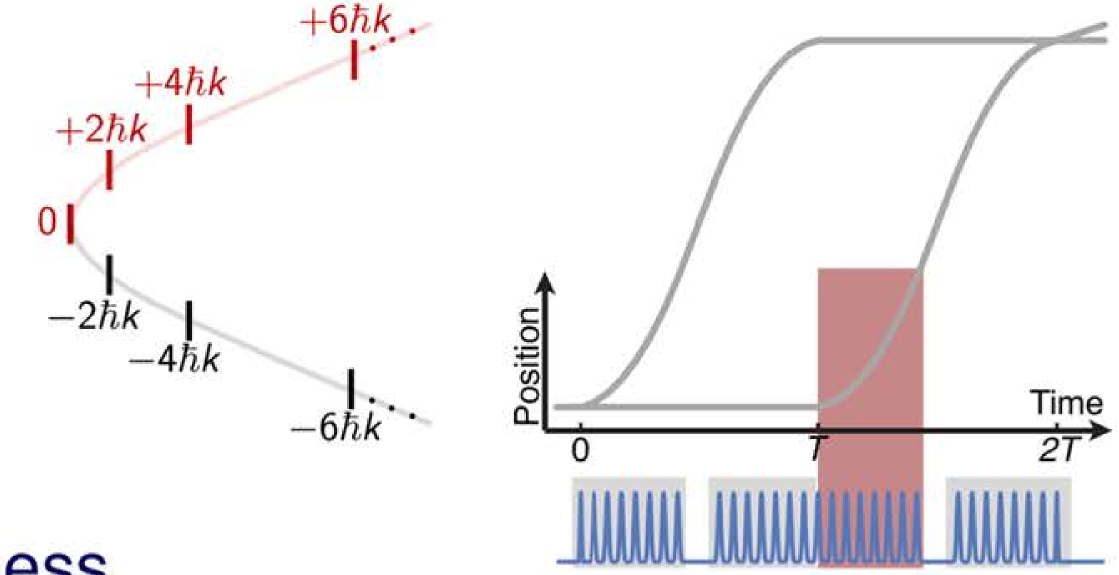
optimize for robustness

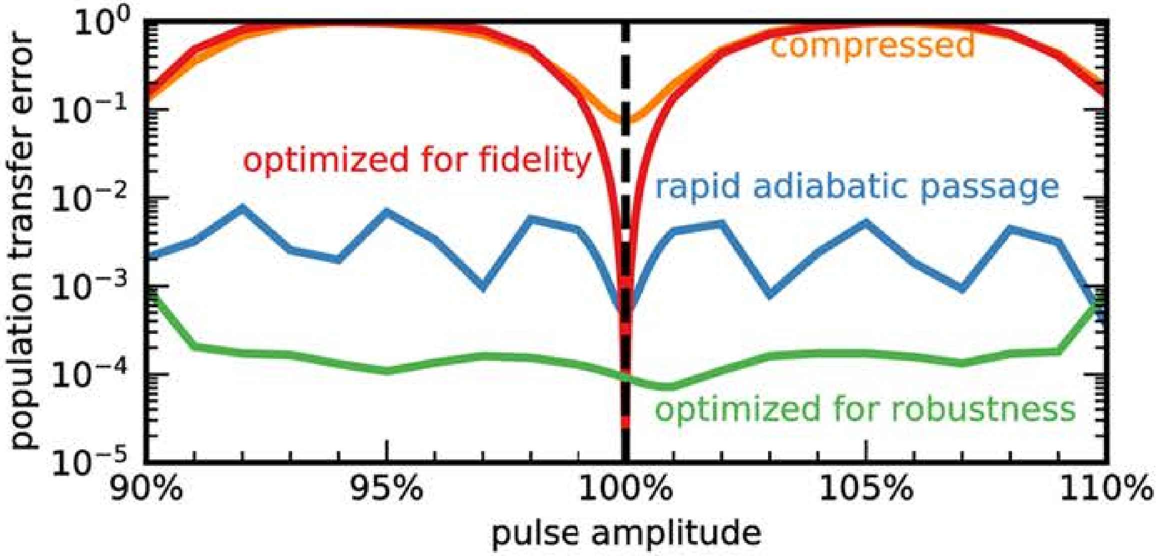




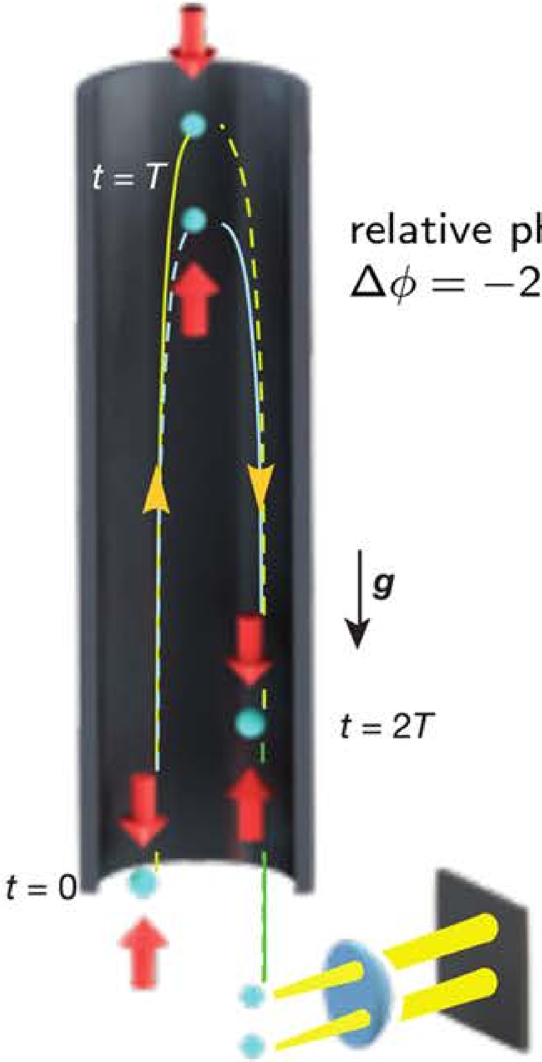



pulse (ω_r)
momentum ($2\hbar k$)
time ($1/\omega_r$)
optimize for robustness

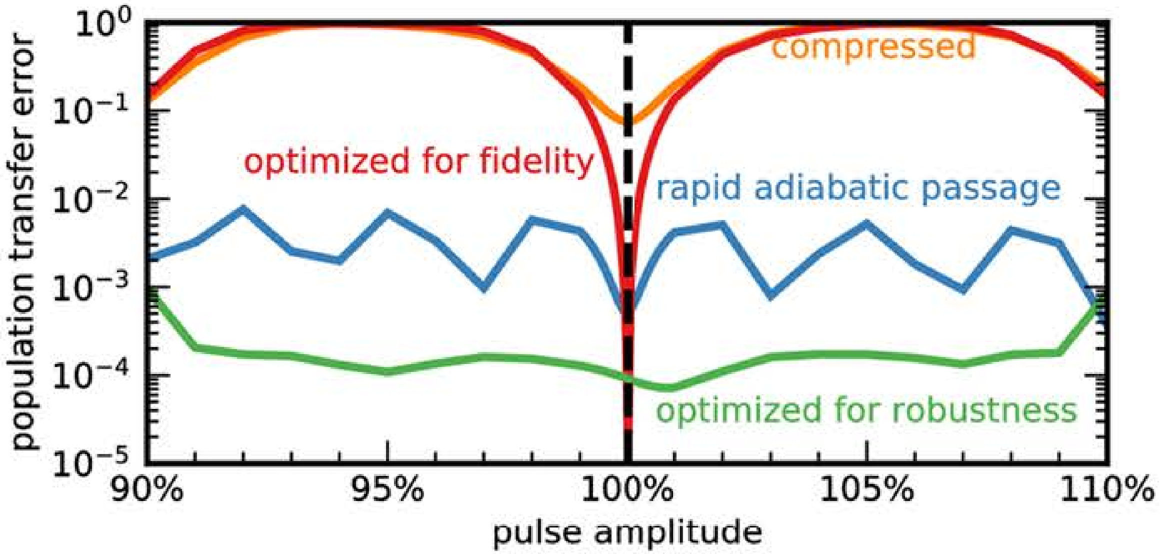

$+6\hbar k$
$+4\hbar k$
$+2\hbar k$
0
$-2\hbar k$
$-4\hbar k$
$-6\hbar k$
Position
Time
0
T
2T


population transfer error
compressed
optimized for fidelity
rapid adiabatic passage
optimized for robustness
pulse amplitude

Conclusion



relative phase difference:
$\Delta\phi = -2k_{\max} g T^2$



- optimal control can compress pulses by order of magnitude while guaranteeing robustness
- Army applications:
  ultra-precise measurement of acceleration / gravity
  $\Rightarrow$ inertial navigation,
  satellite based gravitational sensing