# Quantum superposition at the half-metre scale

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LETTER

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# Quantum superposition at the half-metre scale

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(Thesis: "Atom interferometry in an atomic fountain")

Professor, Physics Dept., Stanford University, 2002-present
Professor, Physics Dept., Yale University, 2001-2002
Associate Professor, Physics Dept., Yale University, 1997-2001
Assistant Professor, Physics Dept., Stanford University, 1992-1997

https://physics.stanford.edu/people/faculty/mark-kasevich

# Research Interest


- Atom Interferometric Test of the Equivalence Principle
- Measurement of gravitational waves

Eötvös-parameter

$$\eta = \left|\frac{\Delta a}{\bar{a}}\right| = \frac{|a_1 - a_2|}{\frac{1}{2}\,|a_1 + a_2|}$$

http://web.stanford.edu/group/kasevich/cgi-bin/wordpress/?page_id=11#Introduction

# Contents

- Principle of the atom interferometer
- Preparation of the state of atoms
- Large momentum transfer Beam splitter
- Experimental result

VOLUME 67, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1991

# Atomic Interferometry Using Stimulated Raman Transitions

Mark Kasevich and Steven Chu

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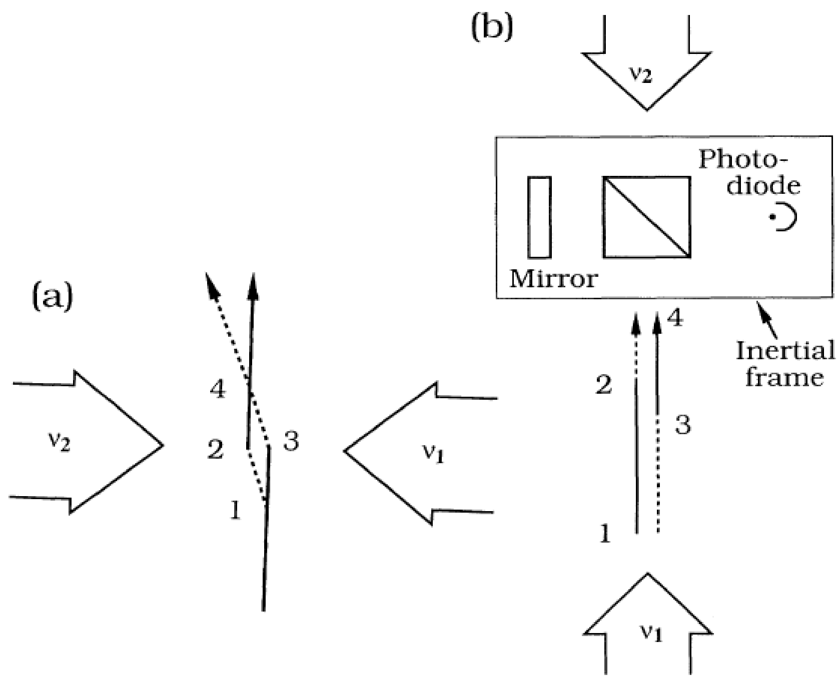
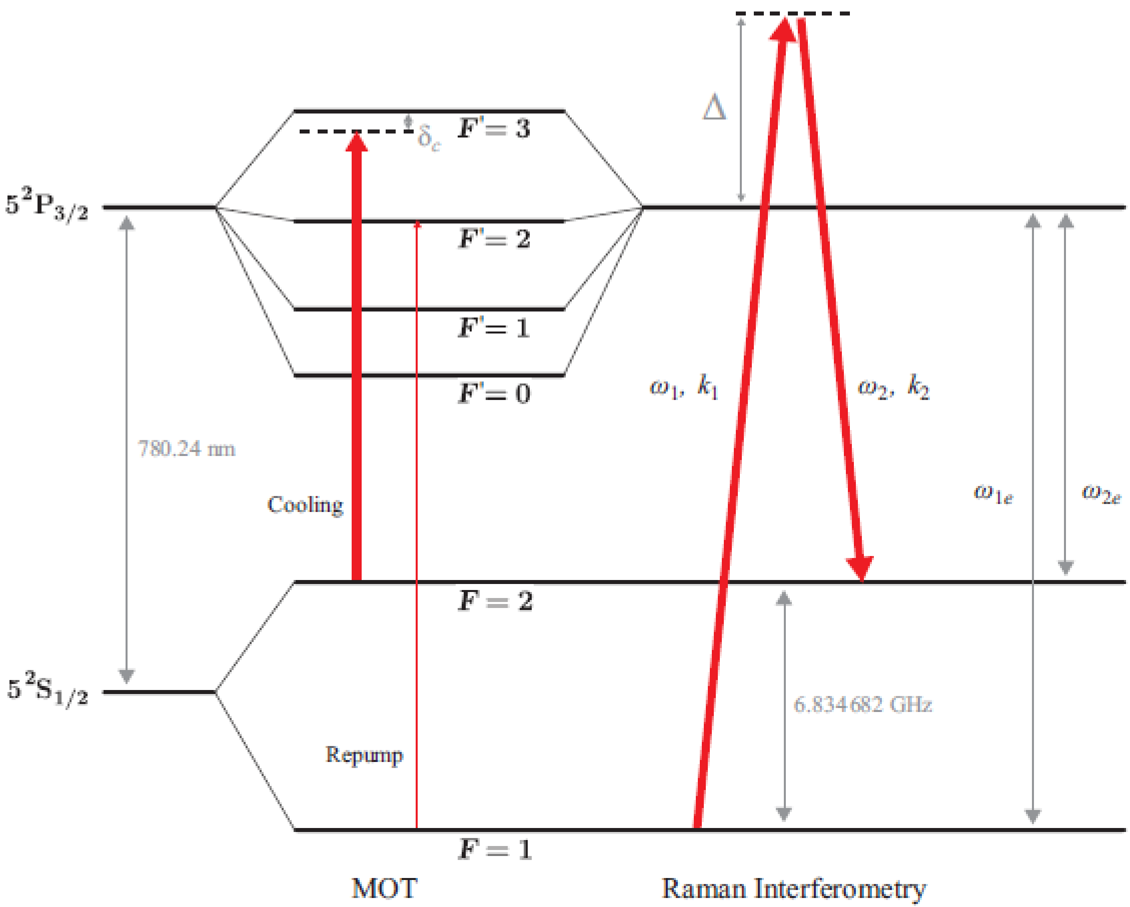
(Received 23 April 1991)

The mechanical effects of stimulated Raman transitions on atoms have been used to demonstrate a matter-wave interferometer with laser-cooled sodium atoms. Interference has been observed for wave packets that have been separated by as much as 2.4 mm. Using the interferometer as an inertial sensor, the acceleration of a sodium atom due to gravity has been measured with a resolution of $3\times10^{-6}$ after 1000 sec of integration time.



# Energy diagram and Raman transition

$^{87}Rb$

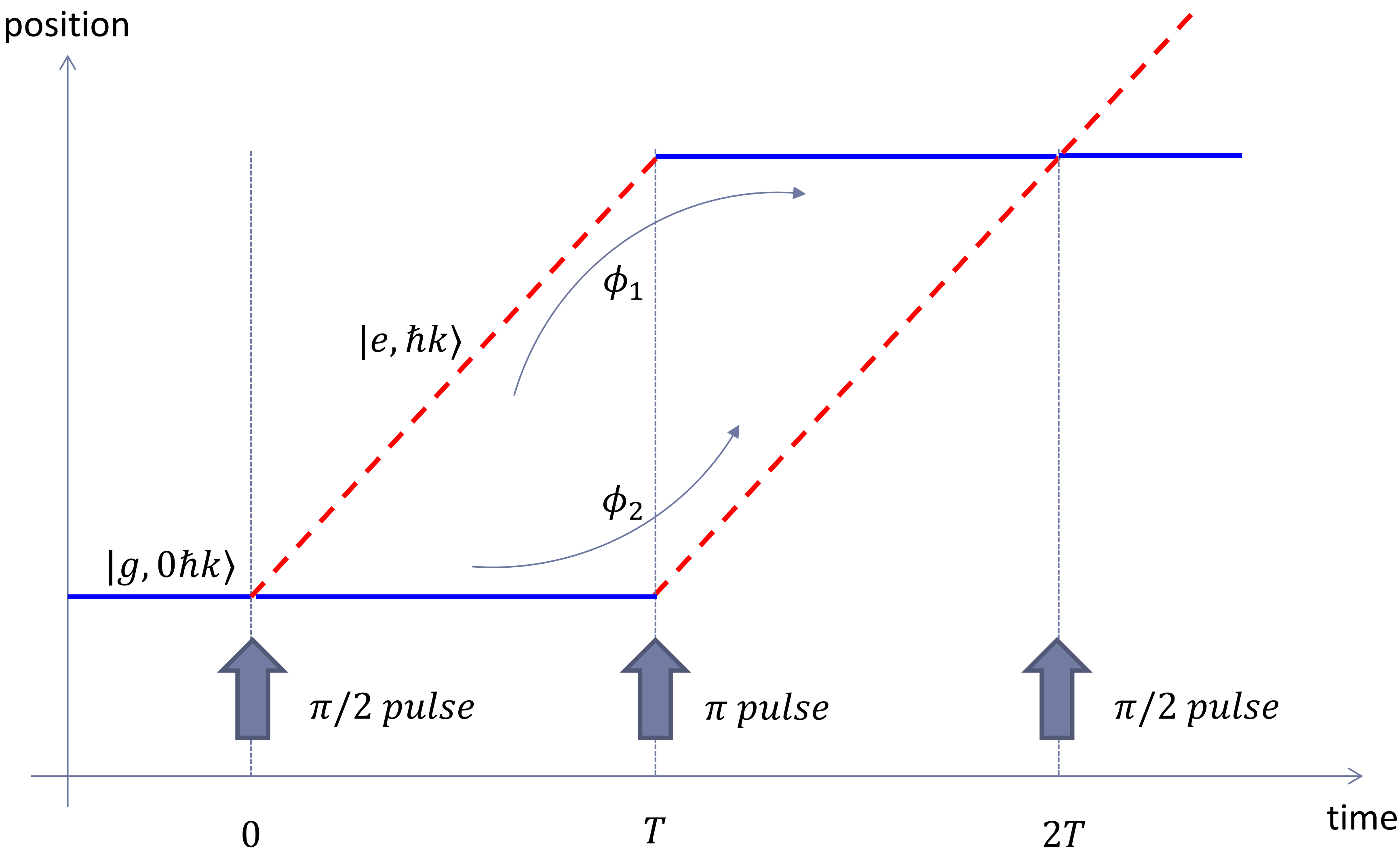



$|F' = 2, m_f{}' = 0\rangle$ $|e\rangle$

$|F = 1, m_f = 0\rangle$ $|g\rangle$

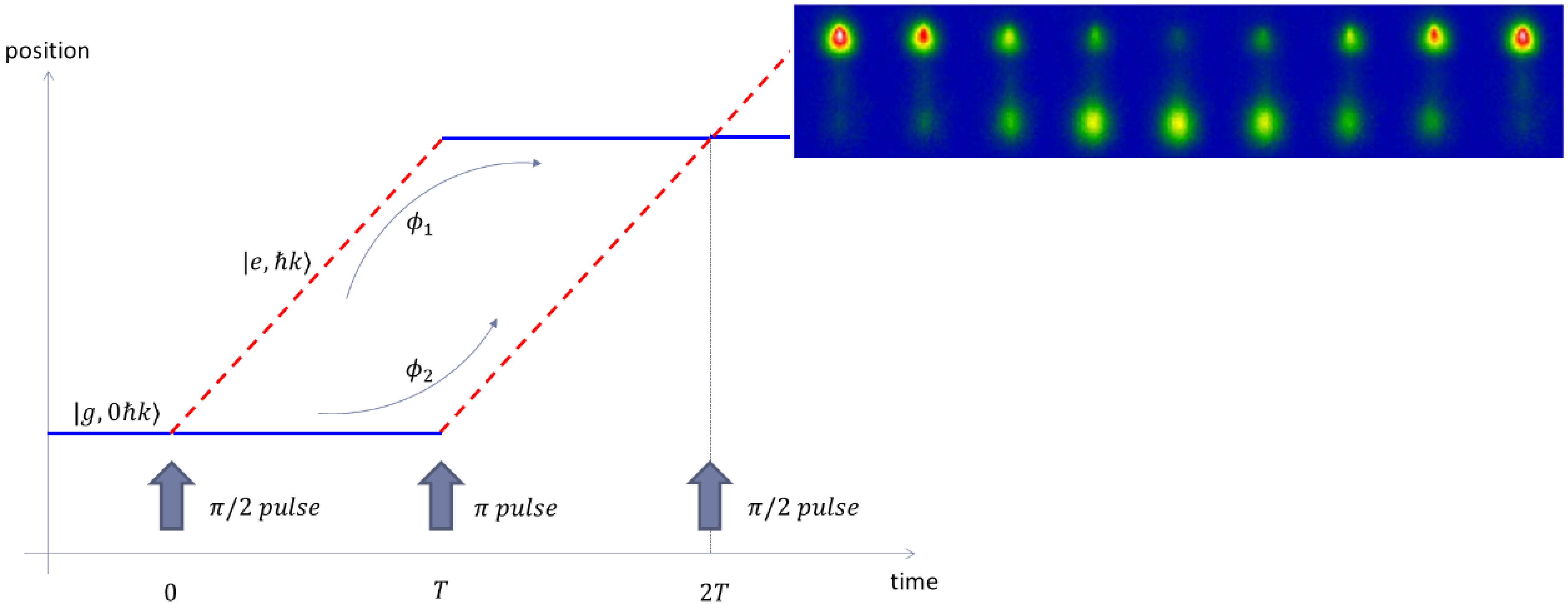
A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

# Raman Mach-Zehnder interferometer



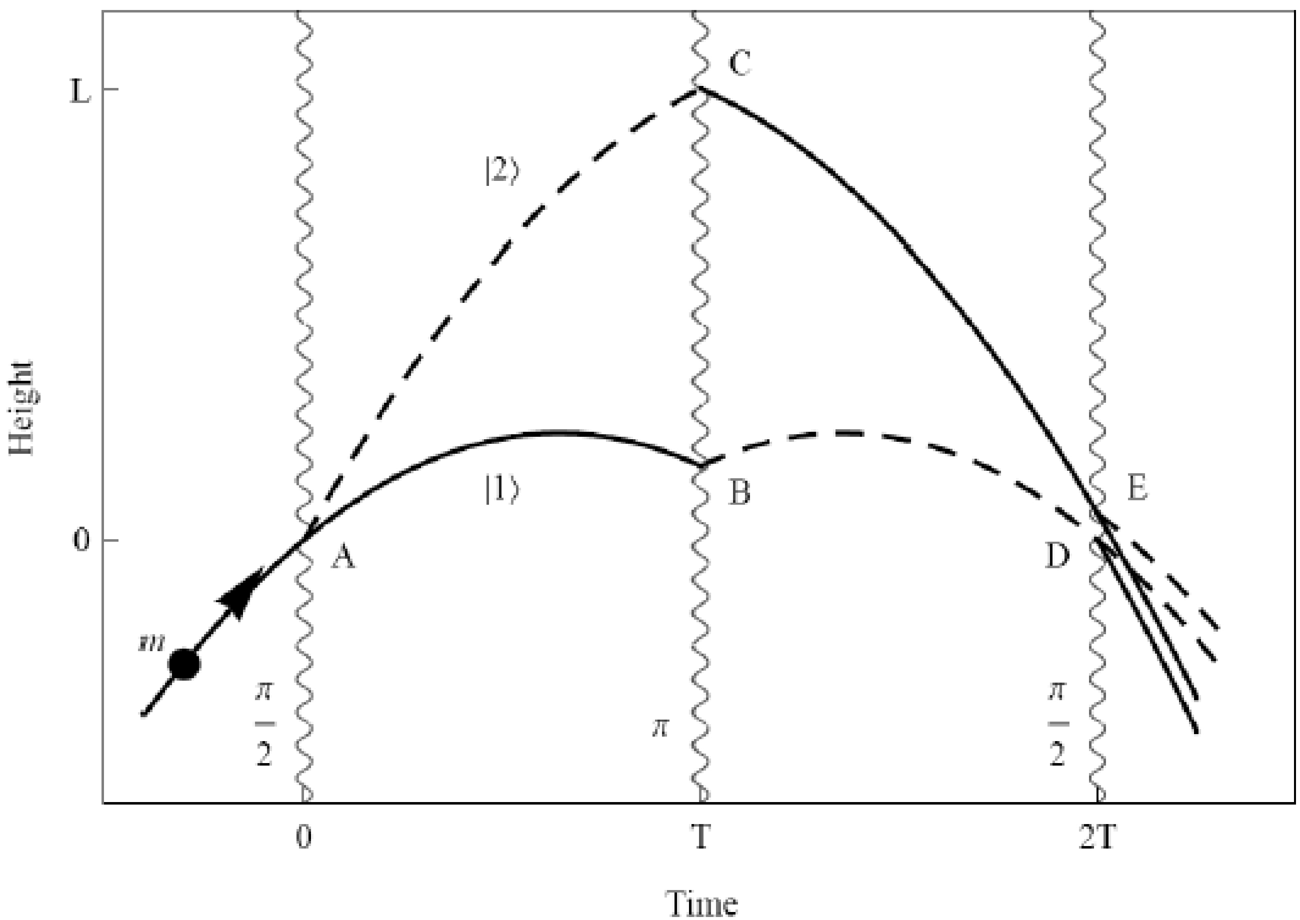

A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

# Raman Mach-Zehnder interferometer




A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

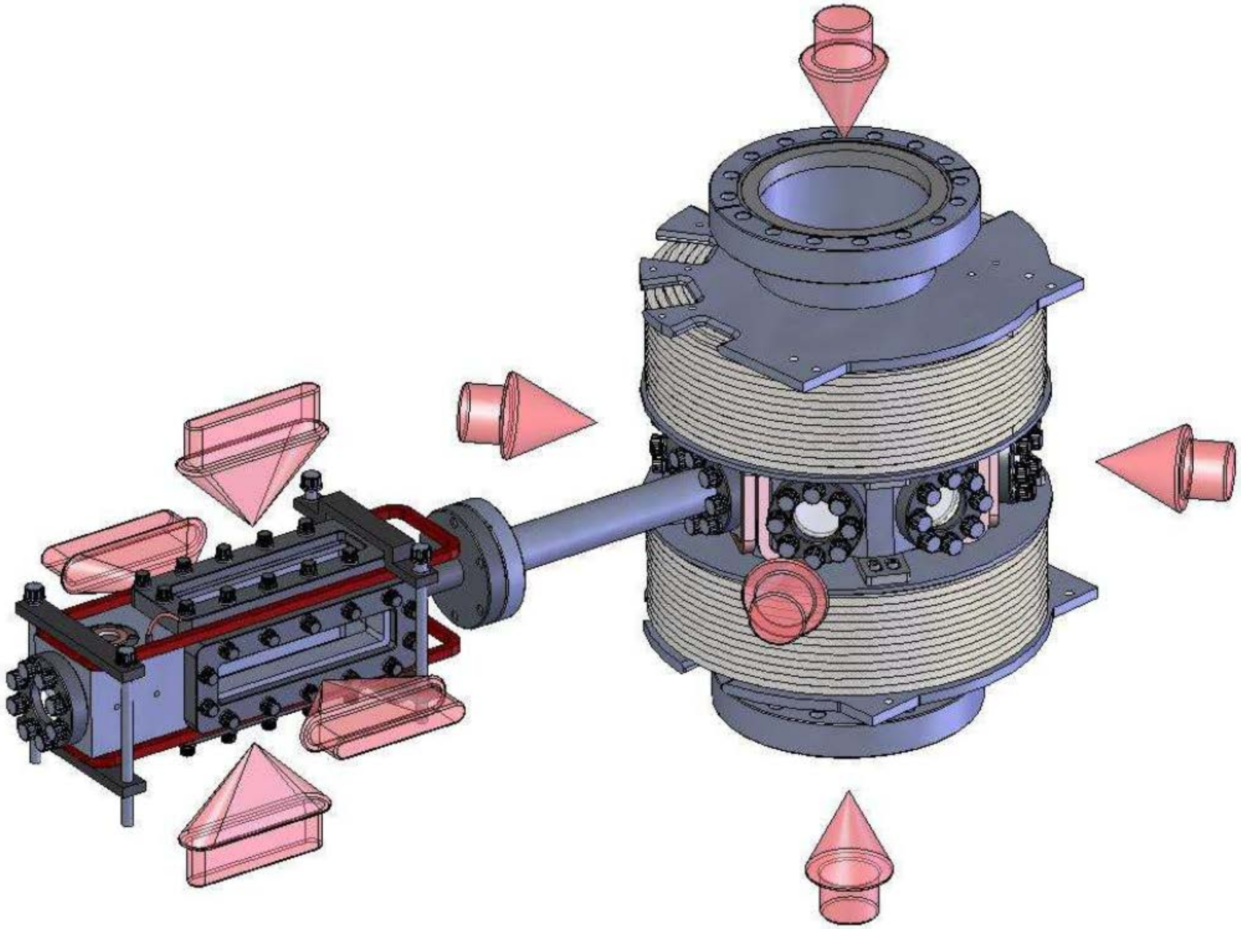
# Gravitational effect




$$\Delta\phi_g \simeq 2nkgT^2$$

https://www.rtg1729.uni-hannover.de/fileadmin/grk1729/pdf/Colloquium_WS_13/hoganRTGLecture1.pdf

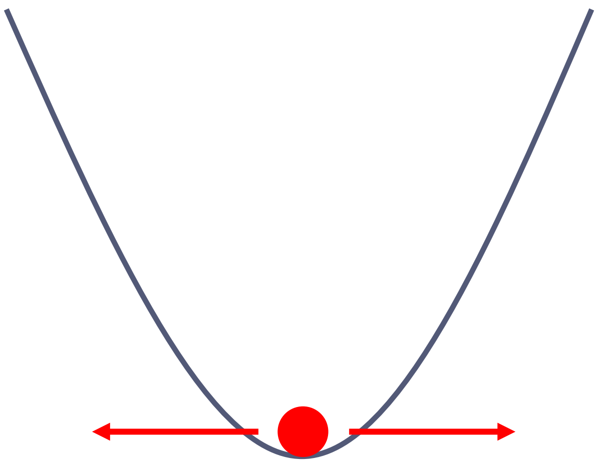
# Preparation of the atomic state



A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

# Magnetic lens

$t = 0$

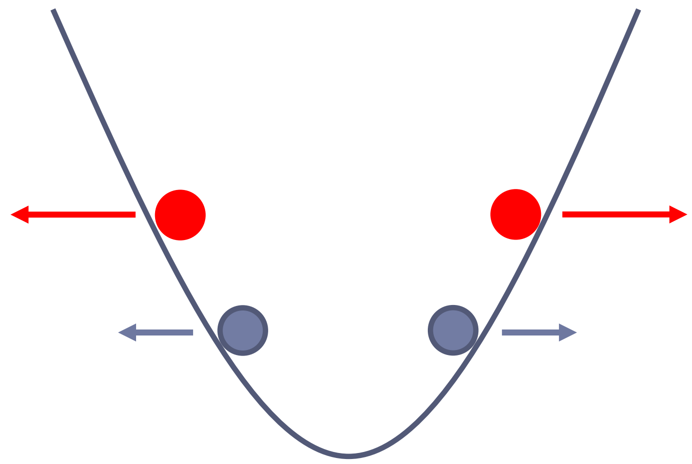


2.6 kHz trap

https://www.rtg1729.uni-hannover.de/fileadmin/grk1729/pdf/Colloquium_WS_13/hoganRTGLecture1.pdf

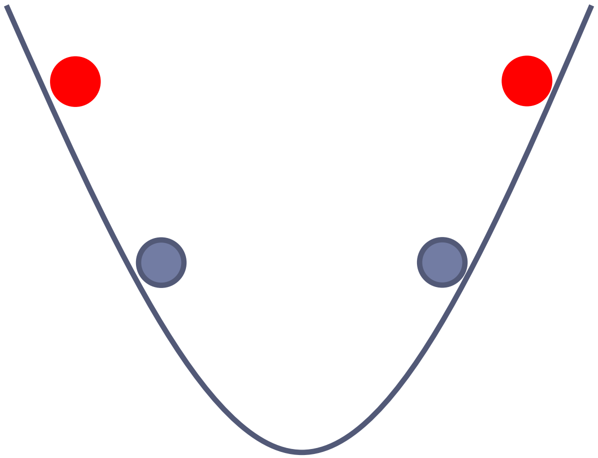
# Magnetic lens

$$t < t_{lens}$$



# Magnetic lens

$$t = t_{lens}$$



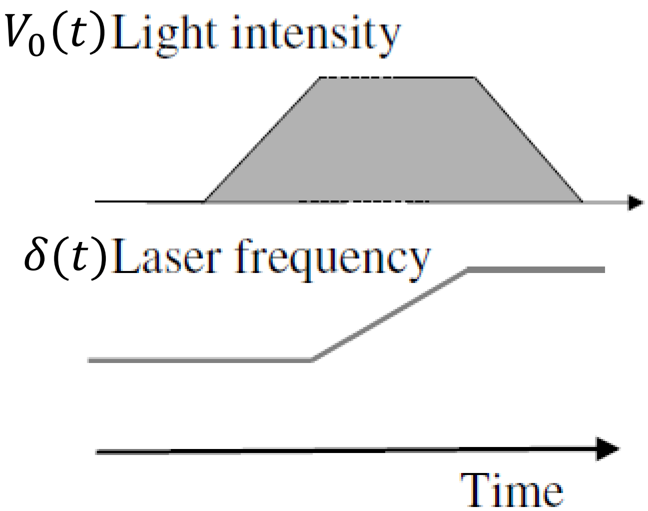
# Magnetic lens

$$t = t_{lens}$$

$$\frac{T_f}{T_i} = \left(\frac{\Delta x_i}{\Delta x_f}\right)^2$$

$subnanokelvin\ 10^5\ {}^{87}Rb\ atoms$

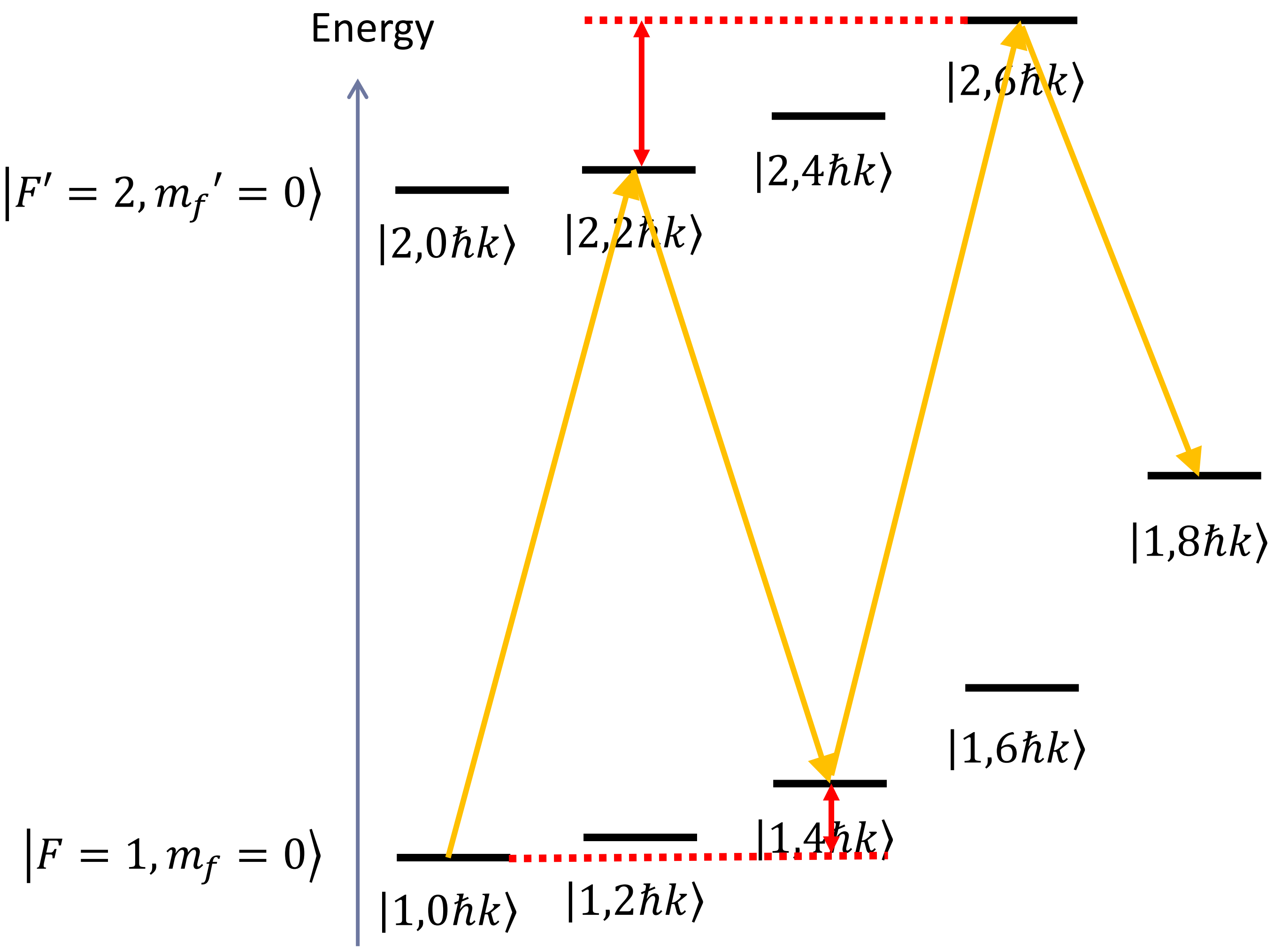
# Optical lattice launch



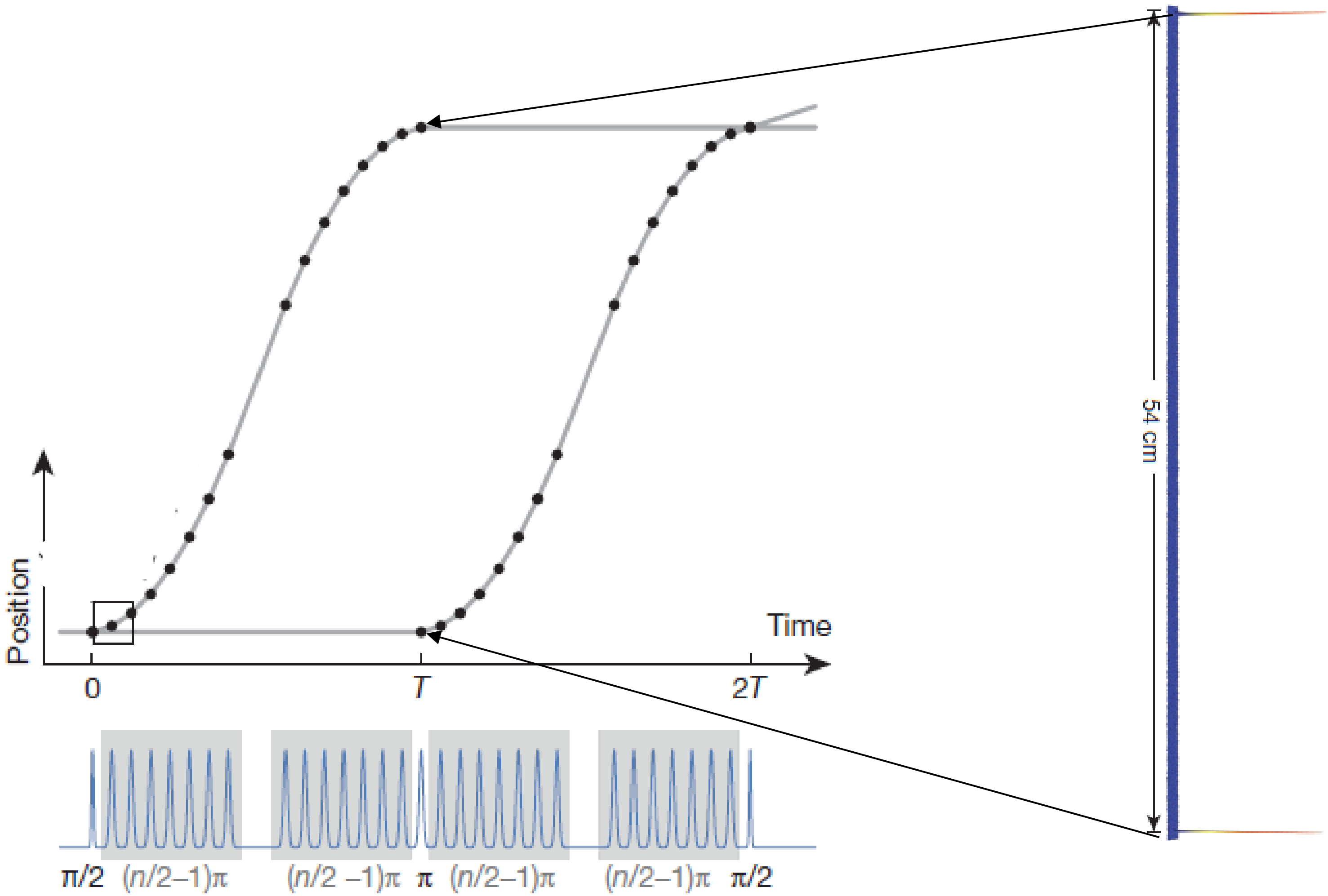

$$V(x,t) = \frac{V_0(t)}{2}(1 + \cos(2kx + \delta(t)t))$$

J Hecker Denschlag *et al,* J. Phys. B: At. Mol. Opt. Phys. **35** ,3095 (2002).

# Sequential Raman transition

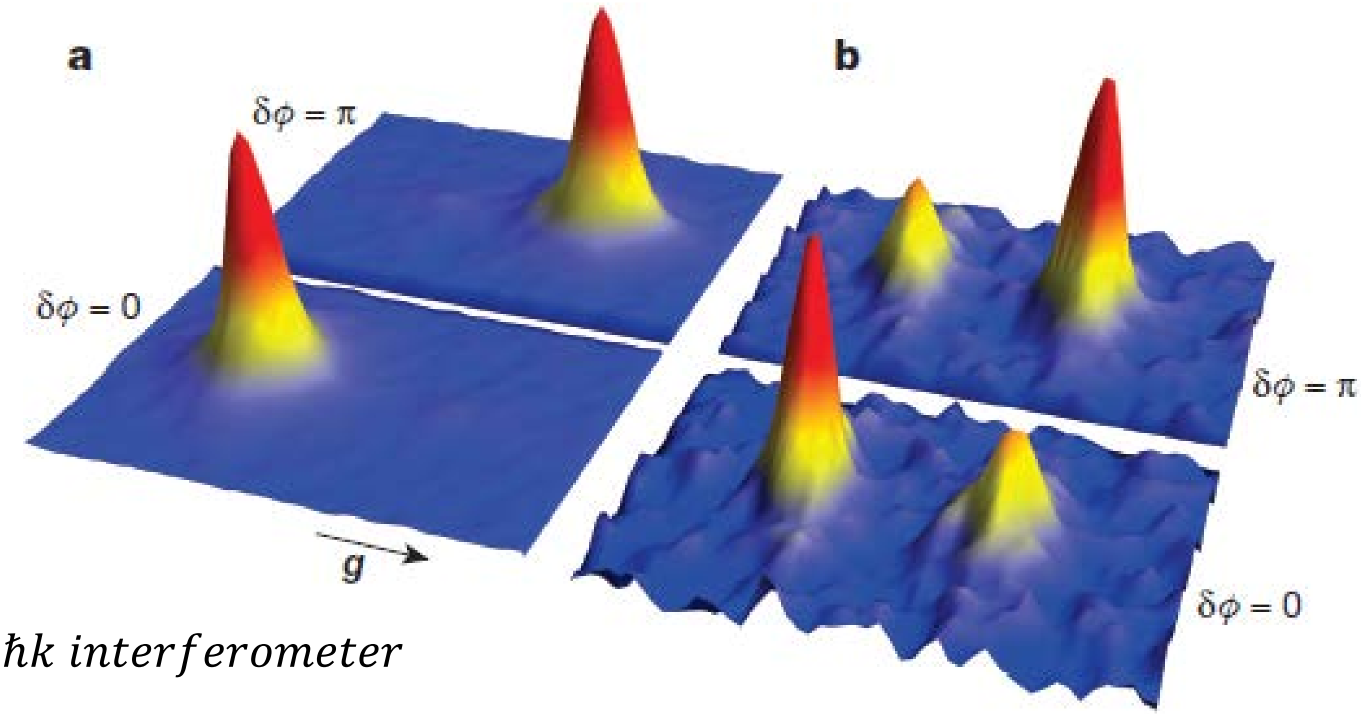


# Large momentum transfer atomic beamsplitter




T. Kovachy *et al,* Nature **528** ,530-533 (2015).

# Fluorescence images of outputports

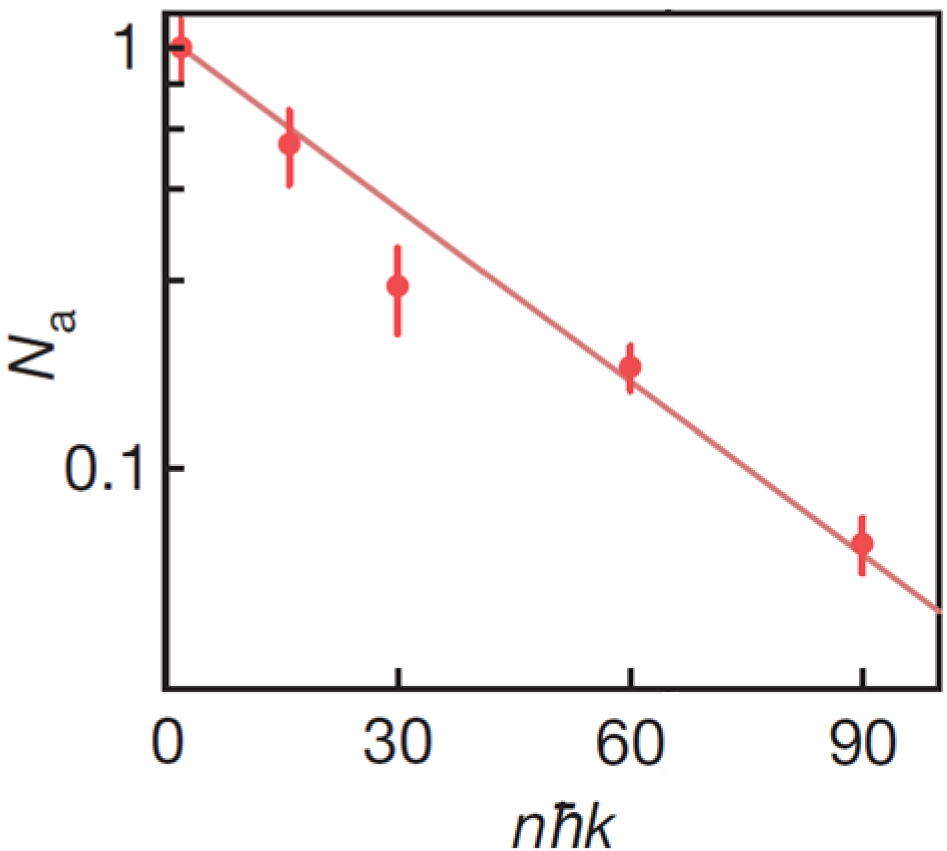


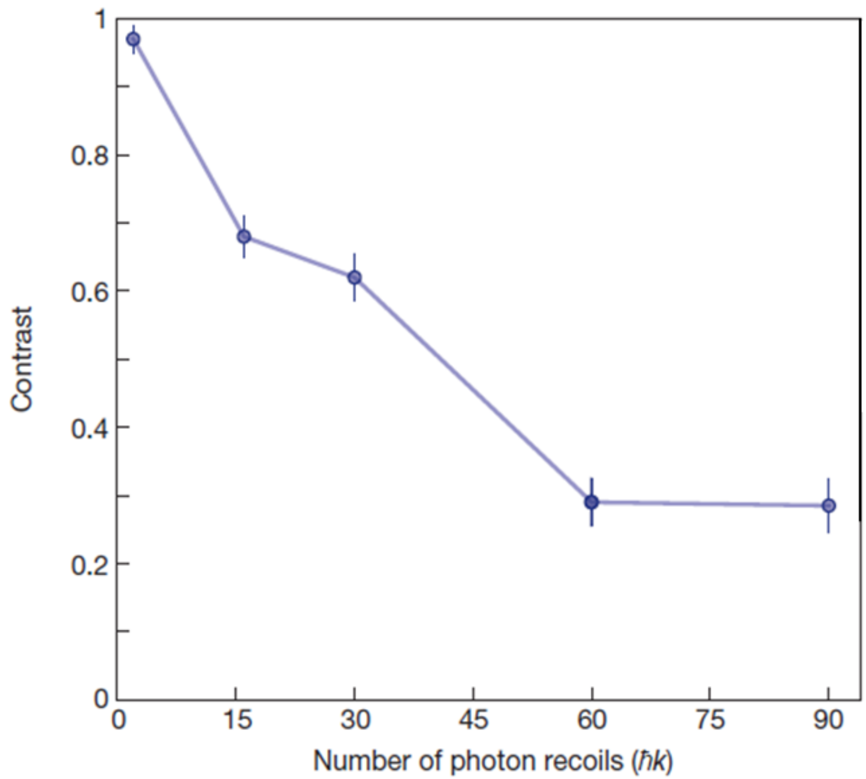

$2\hbar k\ interferometer$

$90\hbar k\ interferometer$

T. Kovachy *et al,* Nature **528** ,530-533 (2015).

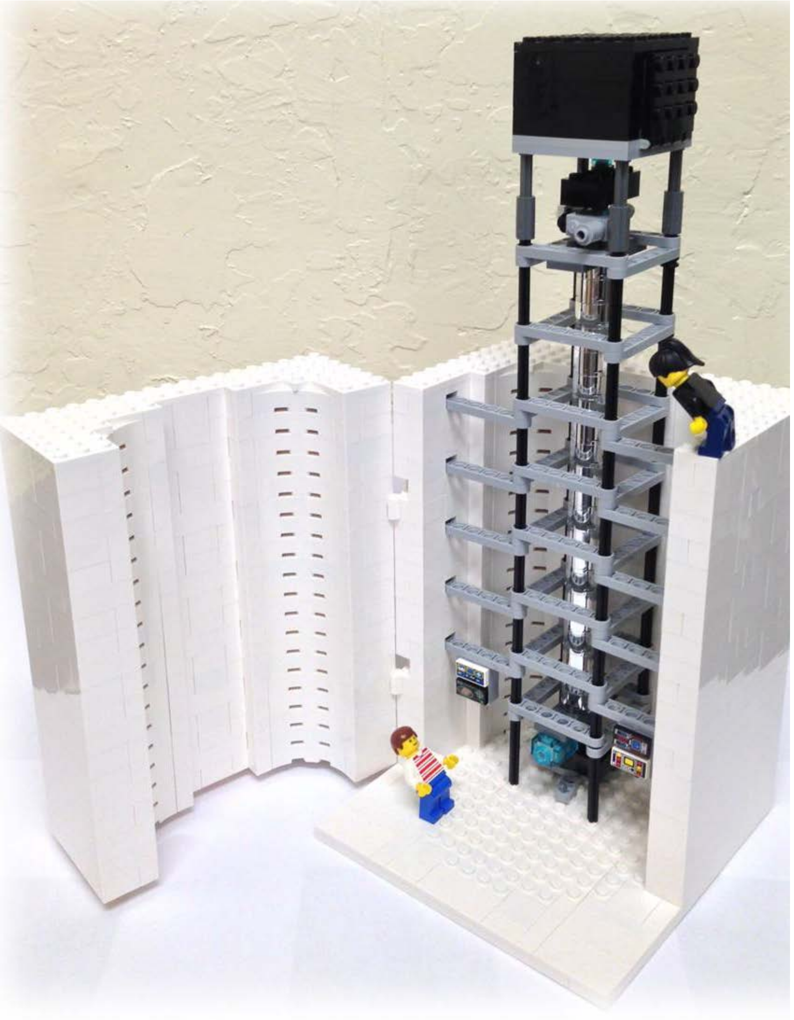
# Loss of atoms and Contrast




T. Kovachy *et al,* Nature **528** ,530-533 (2015).

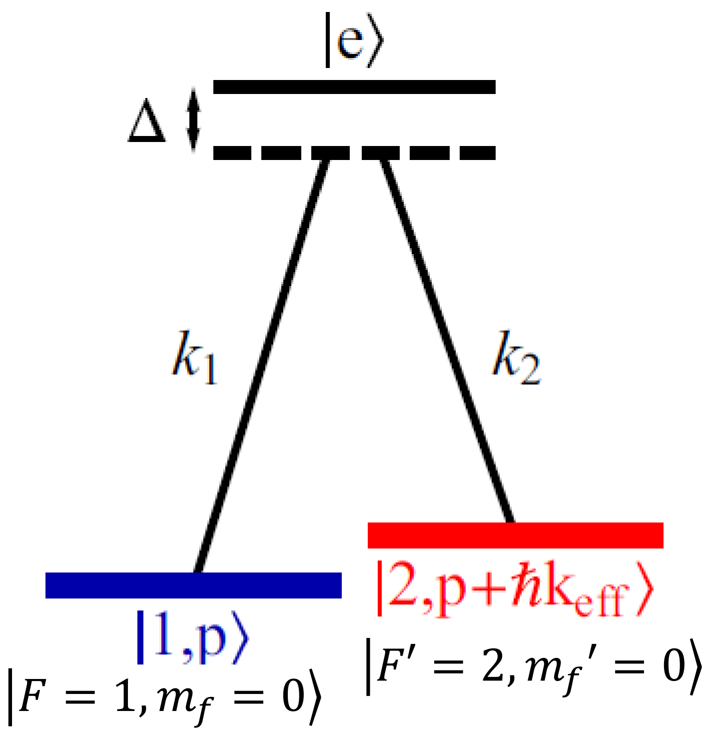
# Q&A

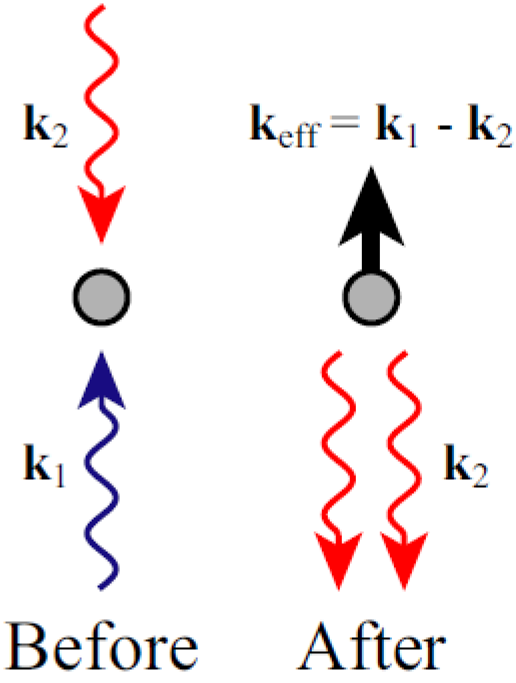


A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

# Supplementary materials

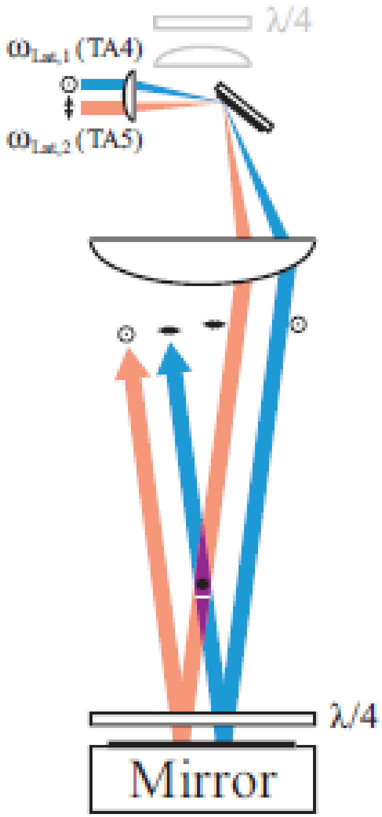
# Raman transition




A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

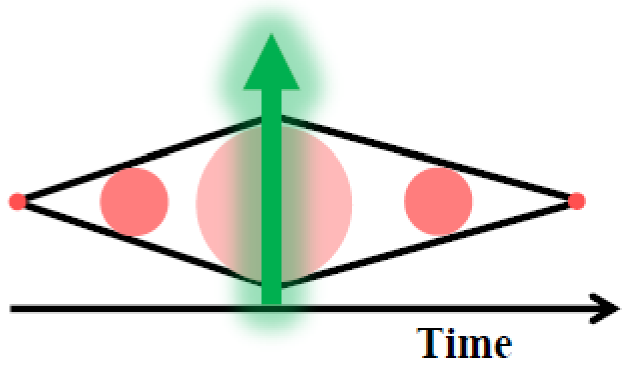
# Raman beam configuration

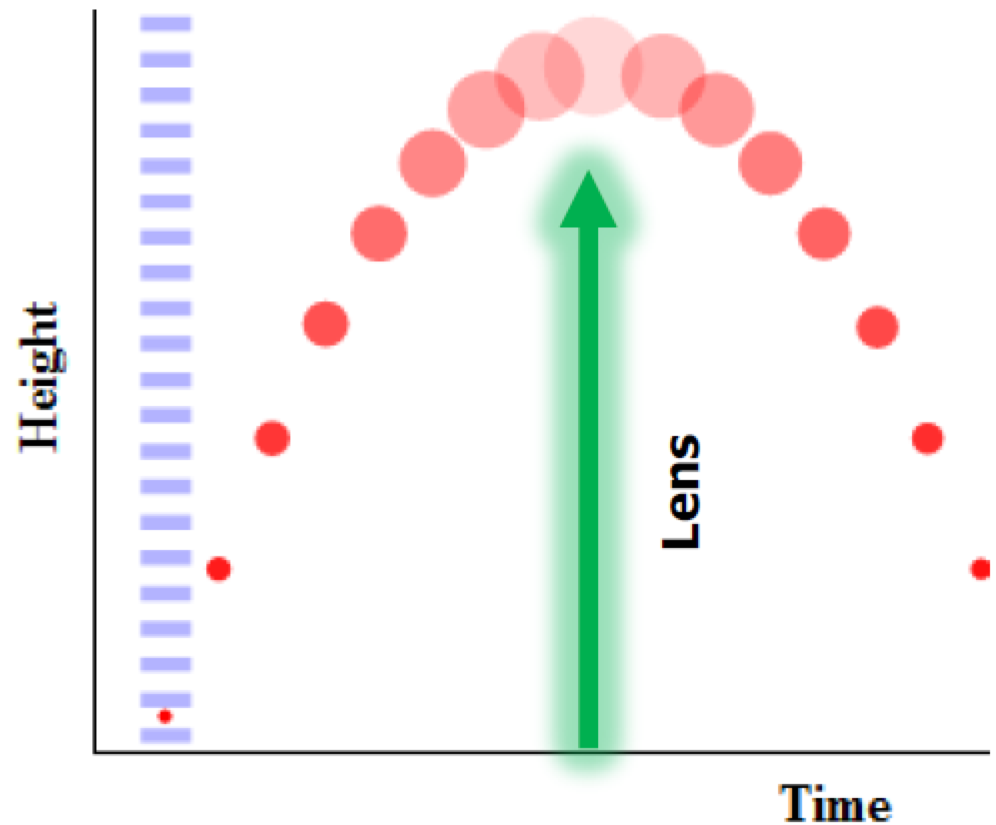



A. Sugarbaker, Ph.D. thesis, Stanford University, (2014)

# Atomic lens

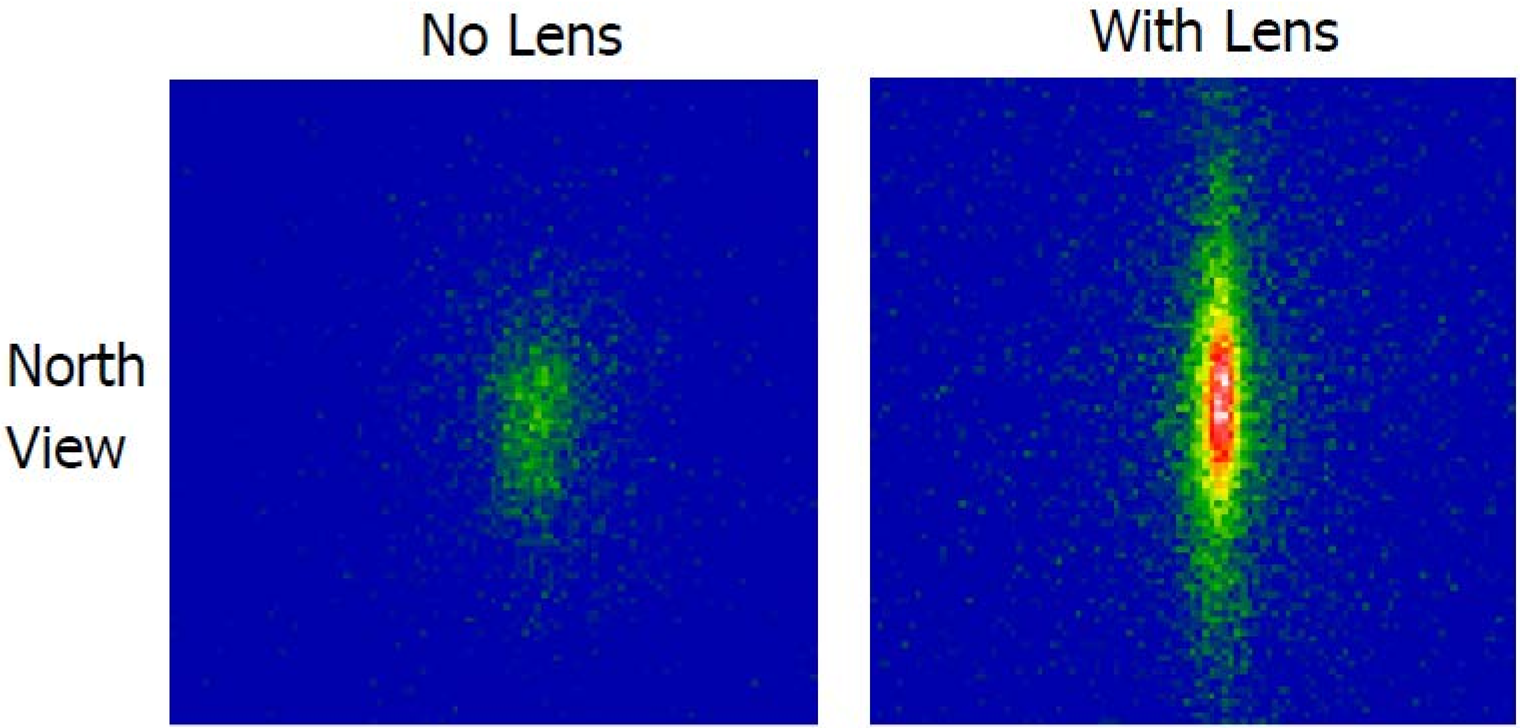
Refocusing lens:



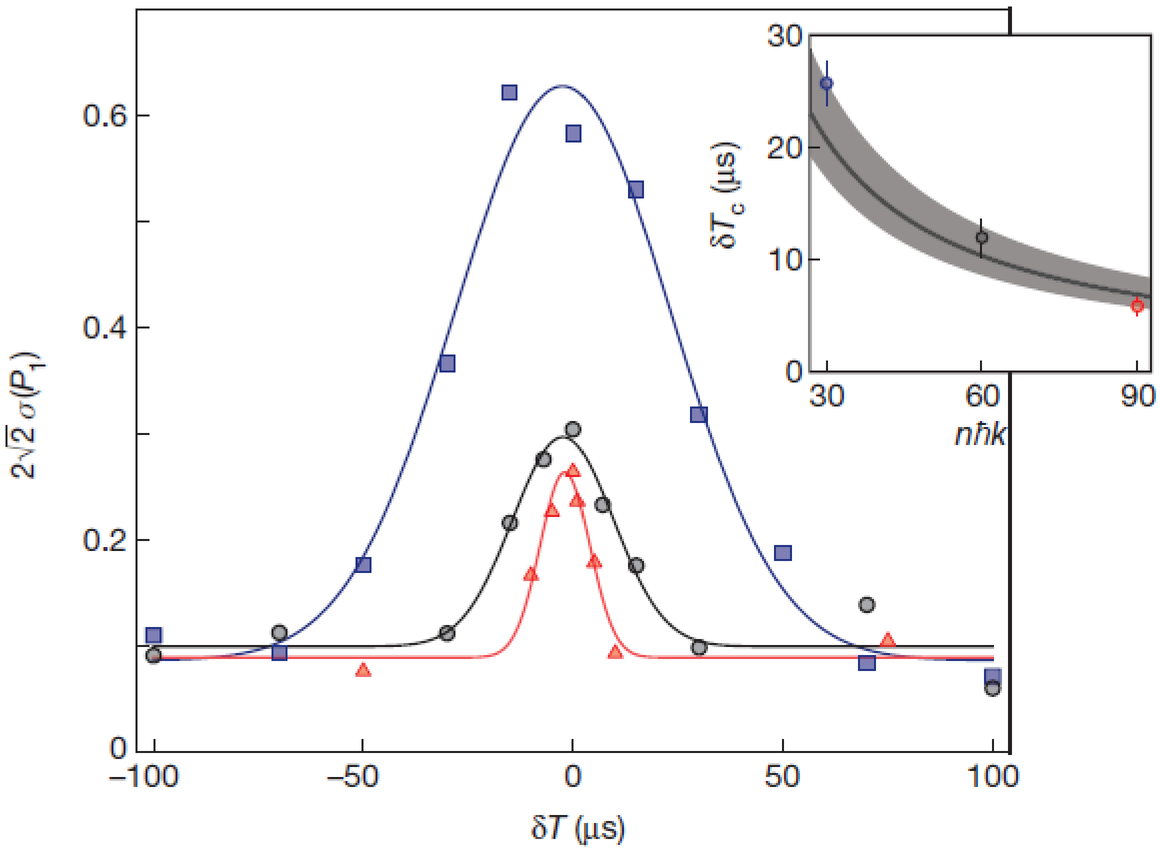

https://www.rtg1729.uni-hannover.de/fileadmin/grk1729/pdf/Colloquium_WS_13/hoganRTGLecture2.pdf

# Atomic lens

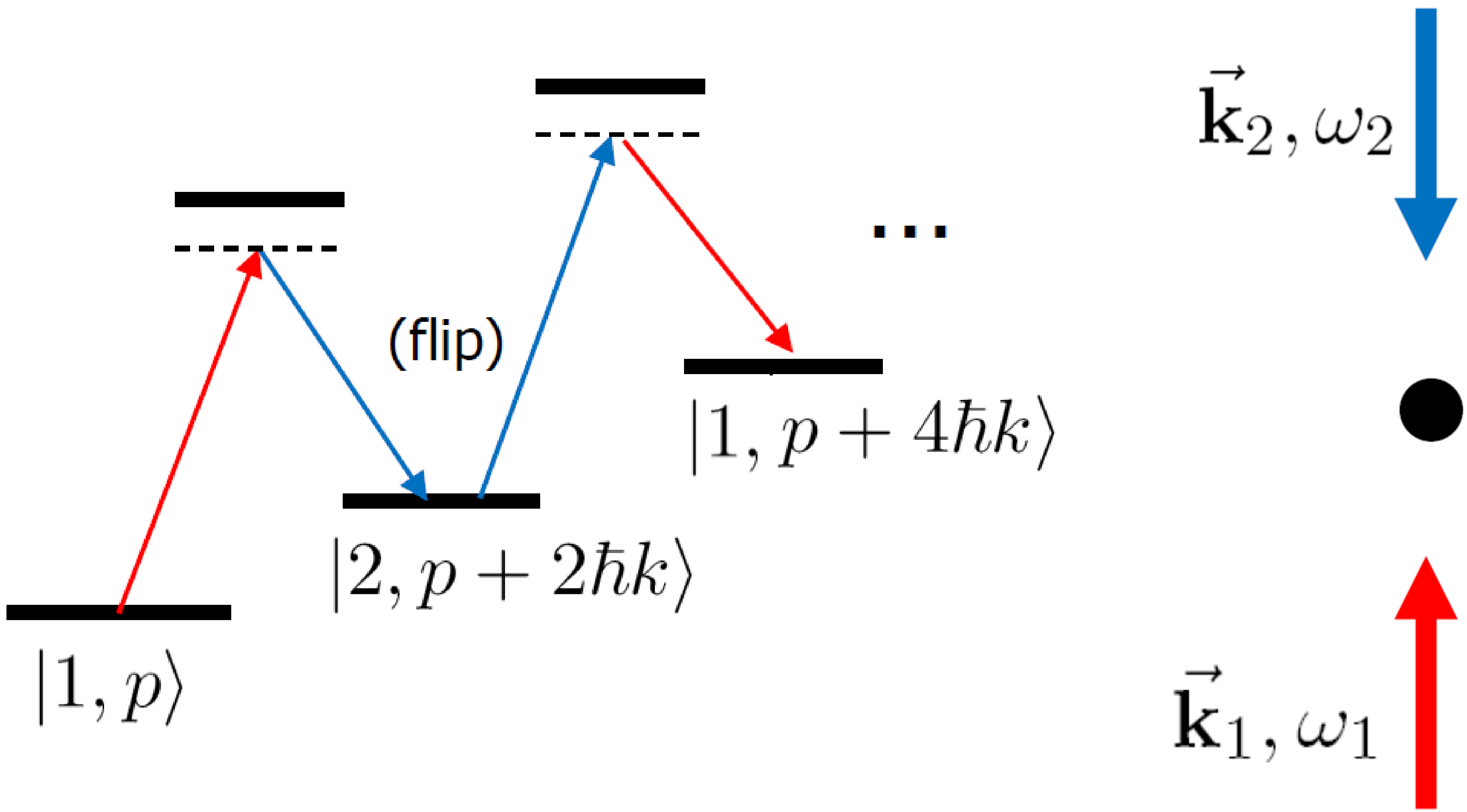



https://www.rtg1729.uni-hannover.de/fileadmin/grk1729/pdf/Colloquium_WS_13/hoganRTGLecture2.pdf

# Coherece time

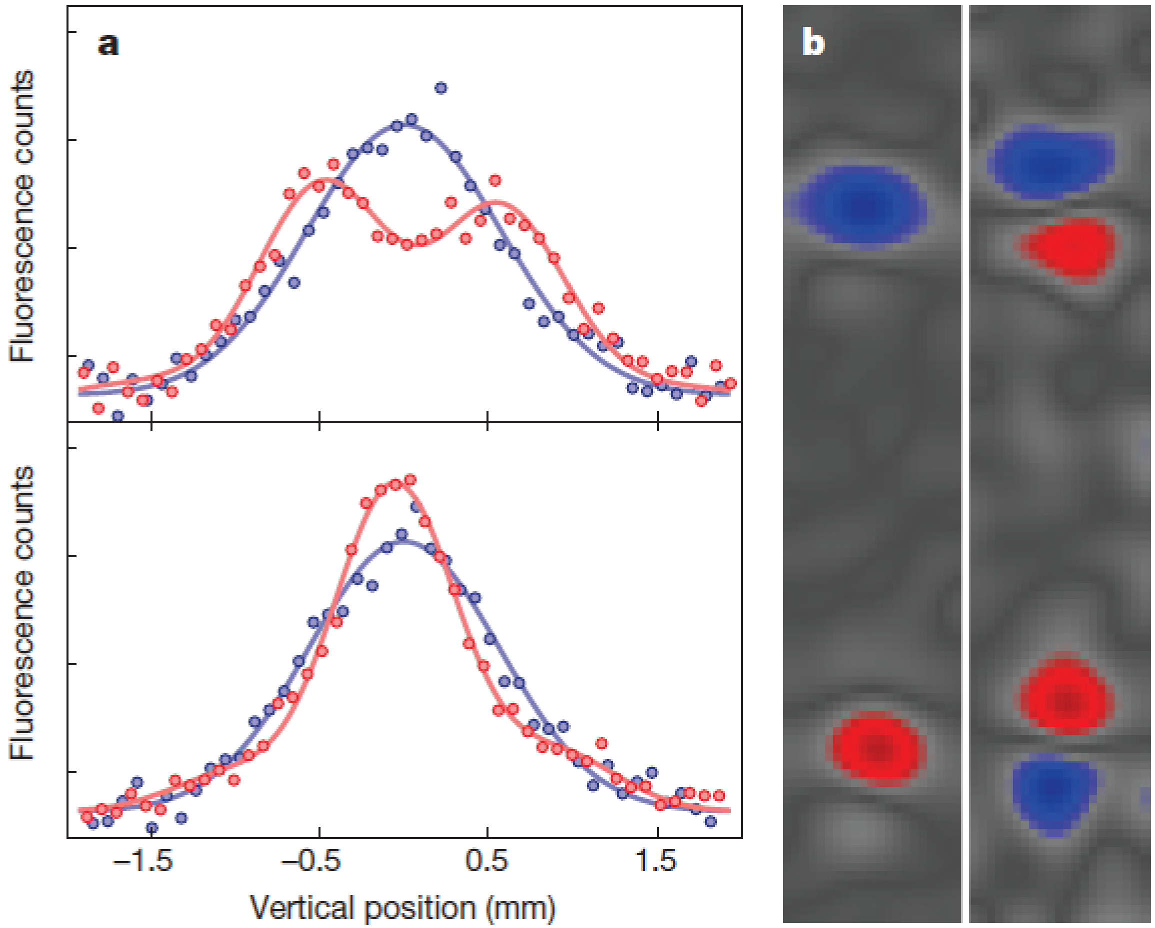


# Sequential Raman transitions




https://www.rtg1729.uni-hannover.de/fileadmin/grk1729/pdf/Colloquium_WS_13/hoganRTGLecture2.pdf

# Spatial interference fringes



# Light Pulse Atom Interferometry

$$|\mathrm{atom}\rangle = |p\rangle$$

**π/2 pulse** "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p+k\rangle)$$

**π pulse** "mirror"

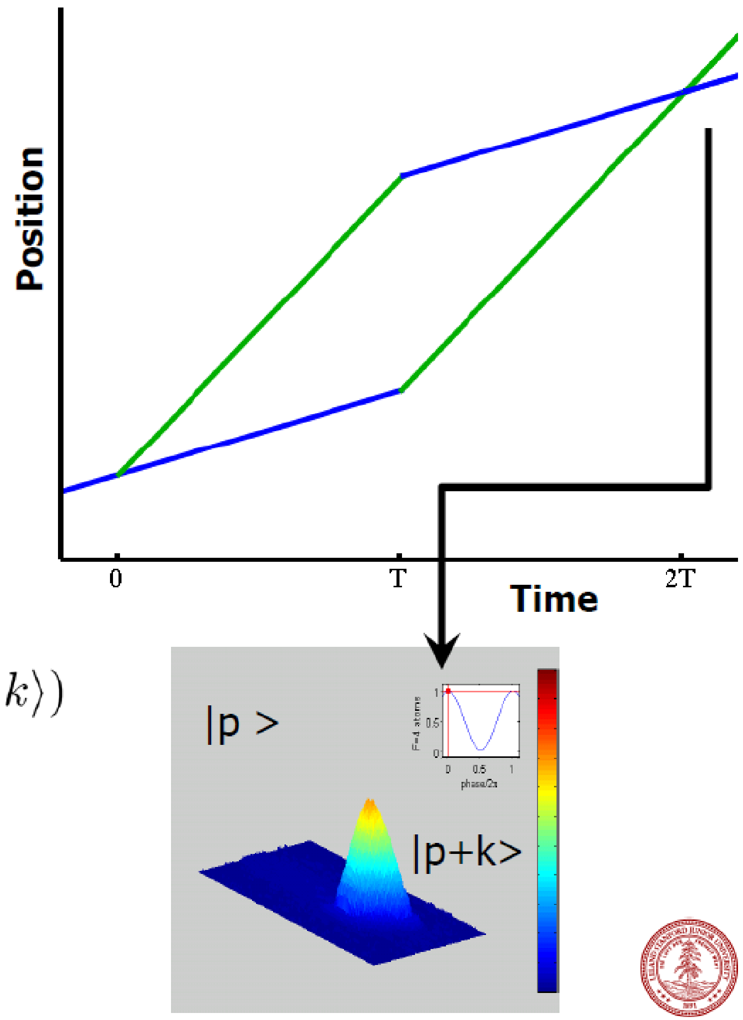
$$\frac{1}{\sqrt{2}}(|p+k\rangle + e^{i\Delta\phi}|p\rangle)$$

**π/2 pulse** "beamsplitter"

$$\frac{1}{2}((1+e^{i\Delta\phi})|p\rangle + ((1-e^{i\Delta\phi}))|p+k\rangle)$$

$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |p+k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

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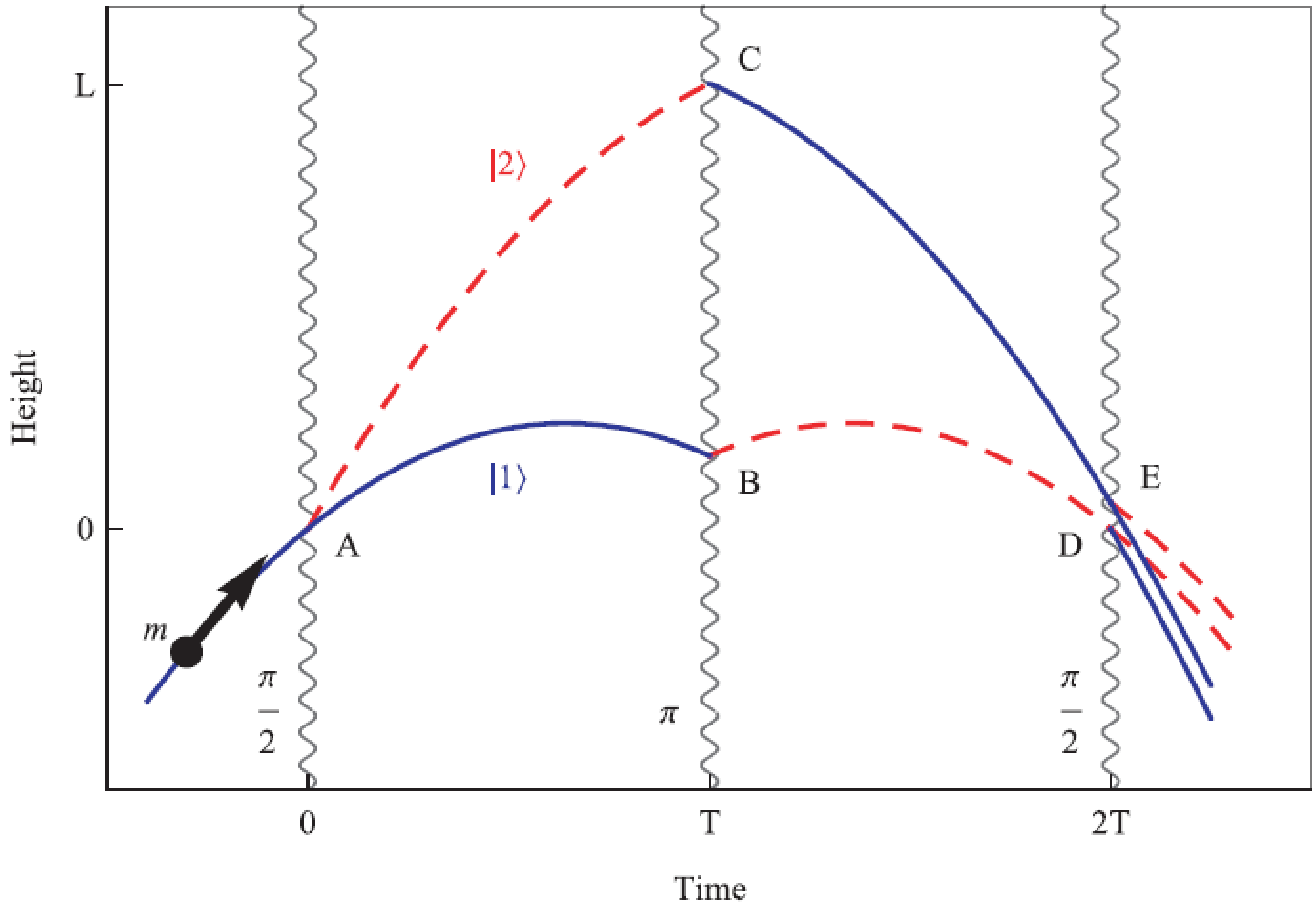
# Lagrangian of atoms



# Lagrangian of atoms

Each of these terms depends on the trajectory of the atom through the interferometer, as determined by the optical pulses and the atom's free evolution with Lagrangian

$$L = \frac{1}{2}m(\dot{\mathbf{r}} + \mathbf{\Omega} \times (\mathbf{r} + \mathbf{R}_e))^2 - m\phi(\mathbf{r} + \mathbf{R}_e) \pm \frac{1}{2}\hbar\alpha \mathrm{B}(\mathbf{r})^2 \qquad (1.6)$$

where $m$ and $\mathbf{r}$ are the mass and position of the atom, and $\mathbf{R}_e$ and $\mathbf{\Omega}$ are Earth's radius and rotation rate. The gravitational potential is $\phi(\mathbf{r}+\mathbf{R}_e) = -(\mathbf{g}\cdot\mathbf{r} + \frac{1}{2!}(T_{ij})r_i r_j + \ldots)$, where g is Earth's local gravitational field and $T_{ij} \equiv \partial_j g_i$ is the gravity gradient tensor. The magnetic field $\mathbf{B}$ affects the atoms only through their second-order Zeeman shift $\alpha$ since they are kept in $|m_F = 0\rangle$ states throughout the interferometer.[9]

arm (AC and CE). The phase shift is

$$\Delta\phi_{\text{prop}} = \frac{1}{\hbar}\Big((\tilde{S}_{AC} + \tilde{S}_{CE}) - (\tilde{S}_{AB} + \tilde{S}_{BD})\Big) \qquad (1.7)$$

where $\tilde{S}_{ij} = \int_{t_i}^{t_j}(L - E_f)dt$ accounts for both the classical action and the atom's internal energy ($E_f$ in state $|f\rangle$) along the segment connecting vertices $\mathbf{r}_i$ and $\mathbf{r}_j$.