Title: Atom interferometry, atomic clocks

Speakers: Jason Hogan

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 19, 2022 - 3:15 PM

URL: https://pirsa.org/22090006

Atom interferometry, atomic clocks

School on Table-Top Experiments for Fundamental Physics

Perimeter Institute

Jason Hogan
Stanford University
September 19, 2022

Outline

Lecture 1

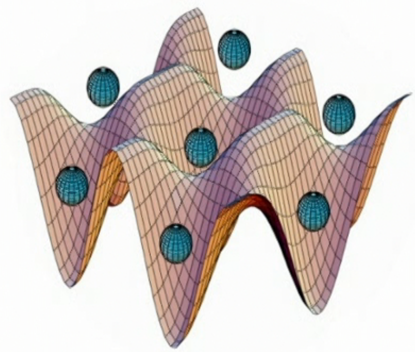
- General introduction and motivation
- Atom interferometer phase response
- Example applications: Spacetime curvature, EP tests, gravitational Aharonov-Bohm, atom charge neutrality

Lecture 2

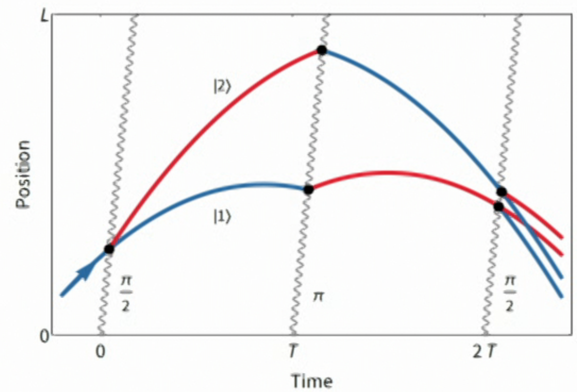
- Gravitational wave detection
- Clock atom interferometry and MAGIS
- MAGIS-100: design, systematic error mitigation, and construction
- Advanced atom optics (large momentum transfer techniques)

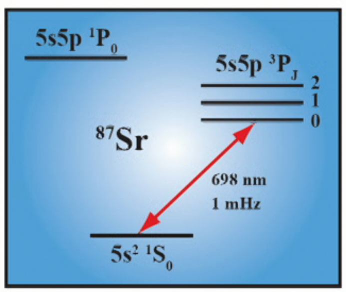
Atomic clocks and atom interferometers

Optical lattice clocks



Atom interferometers





- How can we leverage the incredible gains in stability and accuracy of clocks for fundamental physics?
- Atomic clocks and interferometers offer the potential for gravitational wave detection in an unexplored frequency range
- Development of new "clock" atom interferometer inertial sensors based on narrow optical transitions

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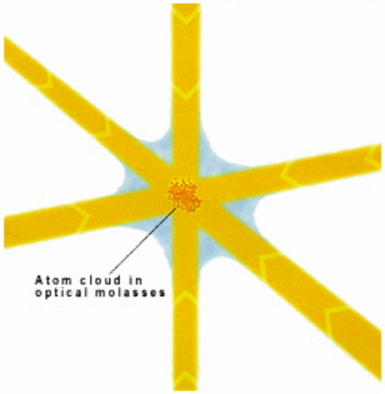
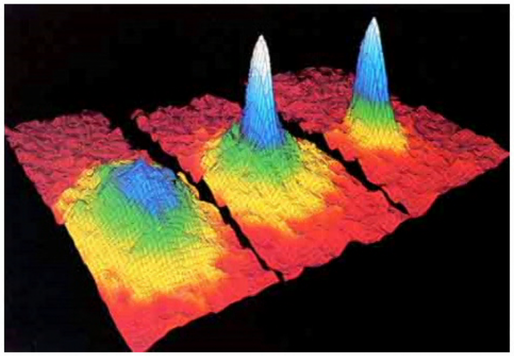
Cold atoms

Laser Cooling (MOT)



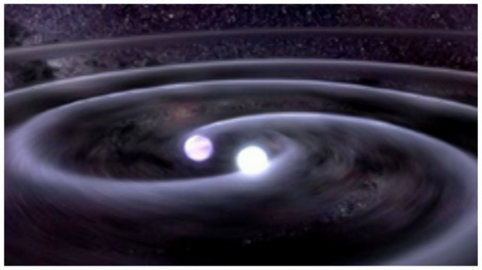
BEC



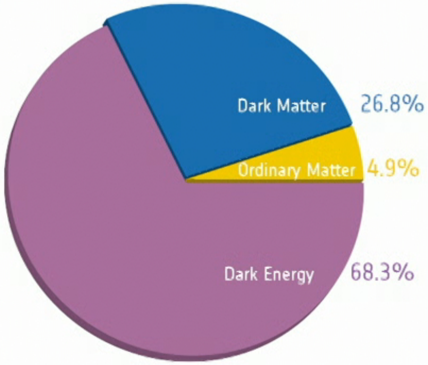
Images: http://www.nobelprize.org

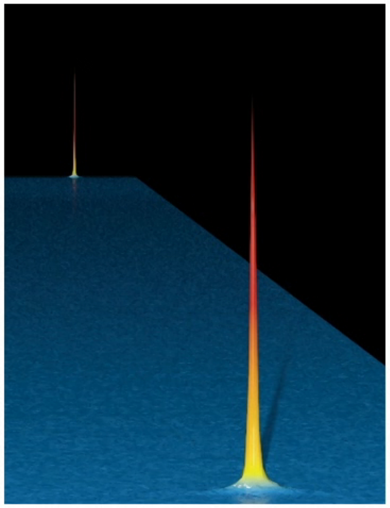
Science applications

- Gravitational wave detection
- Quantum mechanics at macroscopic scales
- QED tests (alpha measurements)
- Quantum entanglement for enhanced readout
- Equivalence principle tests, tests of GR
- Short distance gravity
- Search for dark matter
- Atom charge neutrality



Compact binary inspiral



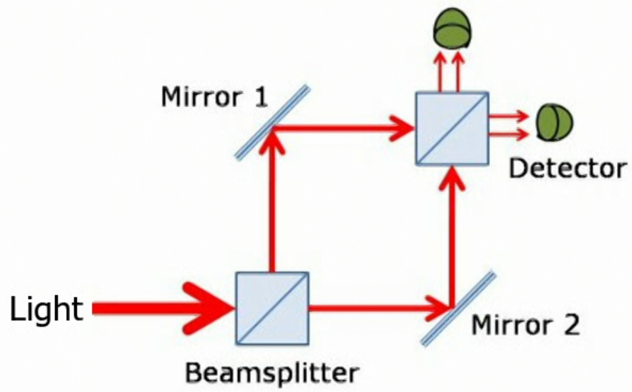


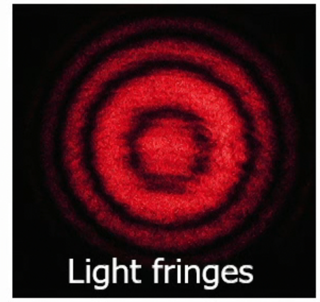
Rb wavepackets separated by 54 cm

Image: https://www2.physics.ox.ac.uk/research/dark-matter-dark-energy

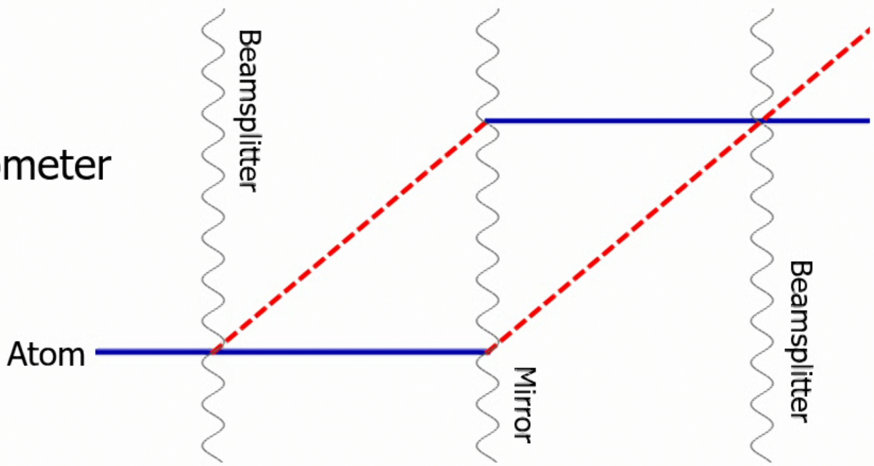
Atom interference

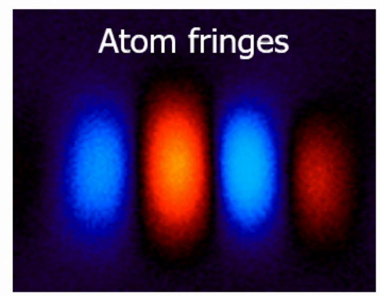
Light interferometer





Atom interferometer

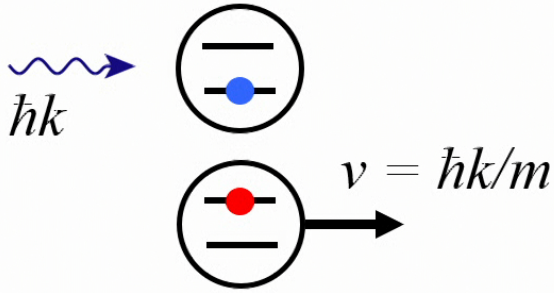




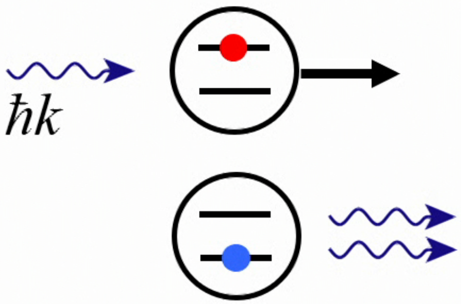
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

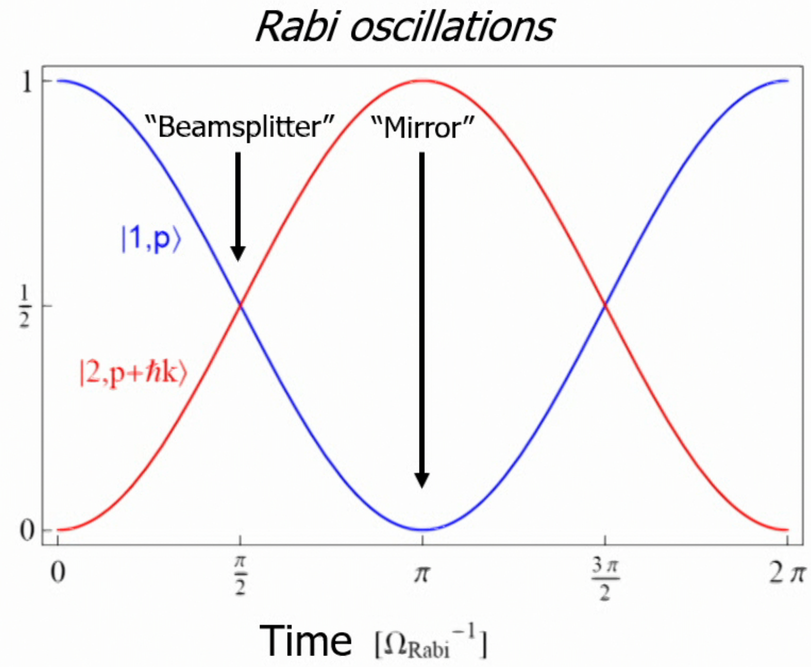
Atom optics using light

(1) Light absorption:



(2) Stimulated emission:





Light Pulse Atom Interferometry

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

π/2 pulse "beamsplitter"

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

π pulse "mirror"

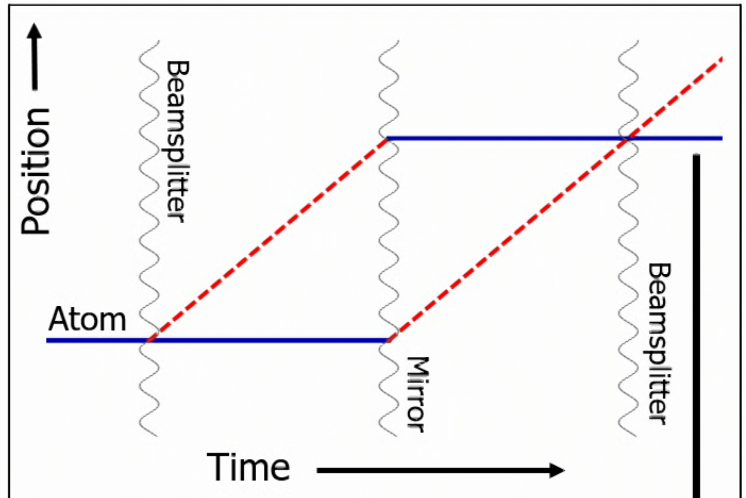
$$\frac{1}{\sqrt{2}}(|p+\hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

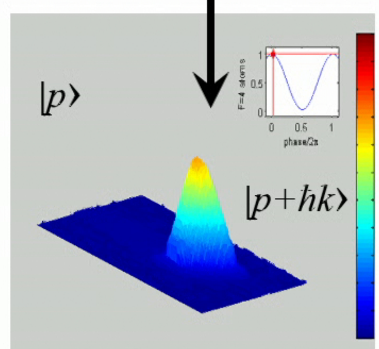
π/2 pulse "beamsplitter"

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

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

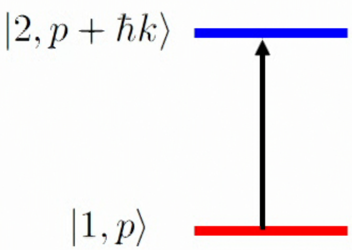
$$\text{Probability in State } |p+\hbar k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

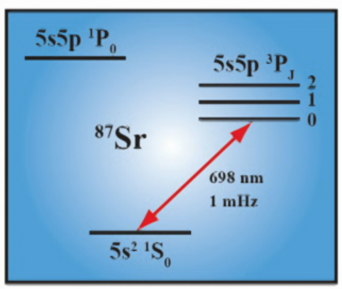




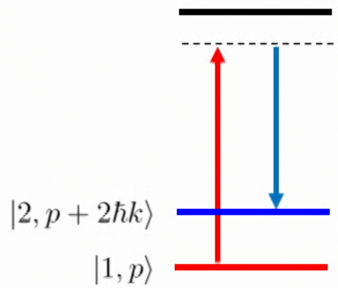
Common atom optics processes

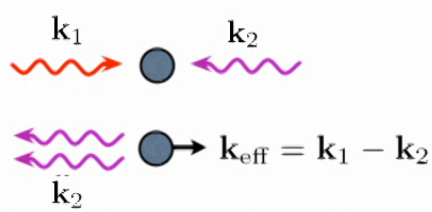
Single photon



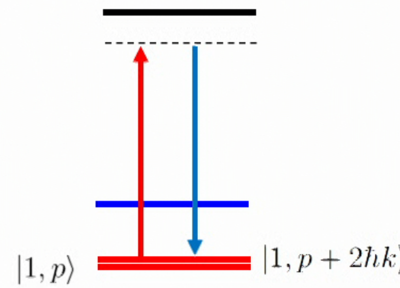


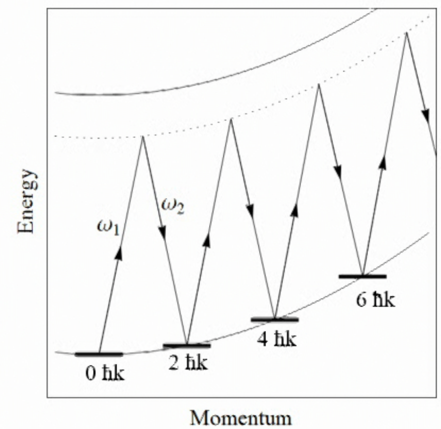
Raman





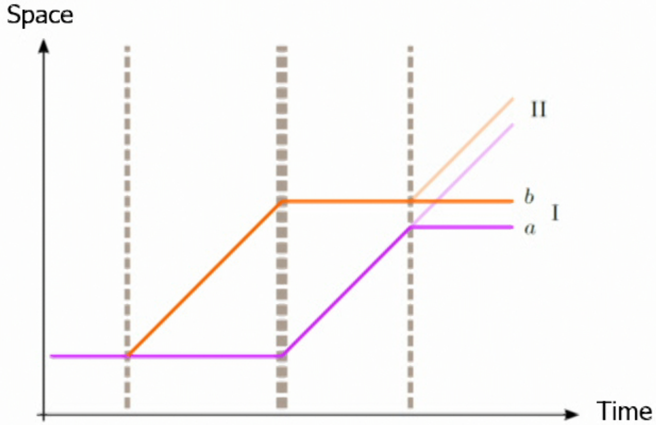
Bragg

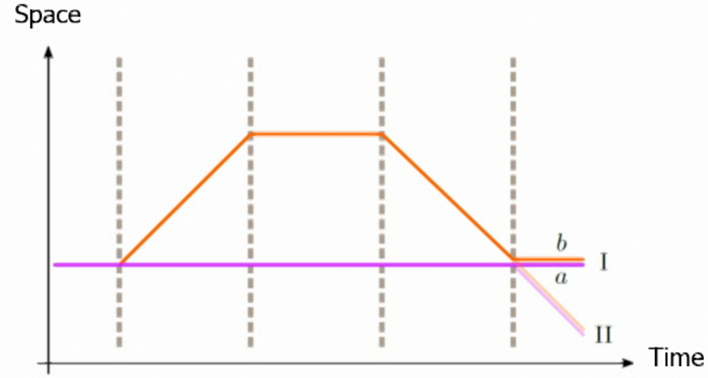




Spontaneous emission in alkali atoms require 2-photon atom optics

Example interferometer geometries





Mach-Zehnder interferometer

Phase shift measures acceleration

Example: Equivalence principle tests, inertial sensing

Also: Gyroscopes (space-space instead of space-time)

Ramsey-Borde interferometer

Phase shift measures kinetic energy difference (due to absorbed photons)

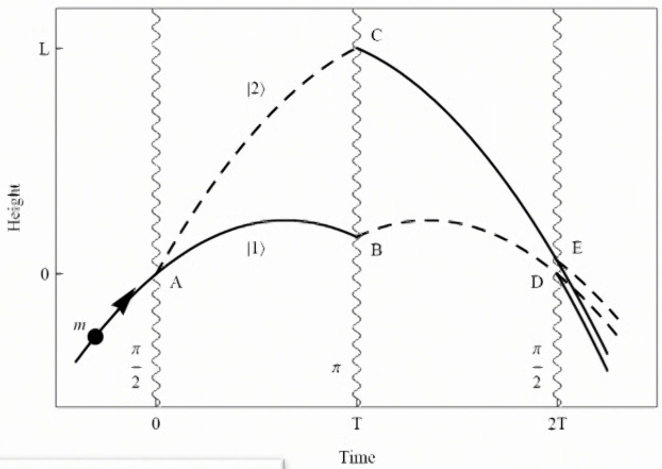
Example: fine structure constant measurements

Figures from: A. Roura, Phys. Rev. X 10, 021014 (2020)

Atom interferometer phase shift analysis

Phase shift can be decomposed as:

- **Laser** phase at each node
- **Propagation** phase along each path
- **Separation** phase at end of interferometer



$$\Delta\phi_{\text{tot}} = \Delta\phi_{\text{propagation}} + \Delta\phi_{\text{separation}} + \Delta\phi_{\text{laser}}$$

This approach mostly follows "Light-pulse atom interferometry" (2008), as well as Bongs/Kasevich (2006) and others.

Other approaches:

- C. Borde, ABCD formalism, midpoint theorem, e.g., Metrologia 39, 435-463, (2002)
- Storey, Cohen-Tannoudji. "The Feynman path integral approach to atomic interferometry. A tutorial" (1994)
- Representation-free approach: Kleinert (2015)
- Wigner function approach: Dubetsky (2006)

Propagation phase

Time evolution of atom's state between laser pulses:

Galilean transformation operator: $\hat{G}_c \equiv \hat{G}(\mathbf{x}_c, \mathbf{p}_c, L_c) = e^{i\int L_c dt} e^{-i\hat{\mathbf{p}}\cdot\mathbf{x}_c} e^{i\mathbf{p}_c\cdot\hat{\mathbf{x}}}$

Phase Translation Boost

Initial state

$$\langle \mathbf{x}|\psi, A_i\rangle = \langle \mathbf{x}|\,\hat{G}_c\,|\phi_{CM}\rangle\,|A_i\rangle = e^{i\int_{t_I}^{t_F} L_c dt} e^{i\mathbf{p}_c\cdot(\mathbf{x}-\mathbf{x}_c)} \phi_{CM}(\mathbf{x}-\mathbf{x}_c)\,|i\rangle\, e^{-iE_i(t_F-t_I)}$$

External Internal

Action | Plane wave (carrier) | Wavepacket (envelope) | Internal

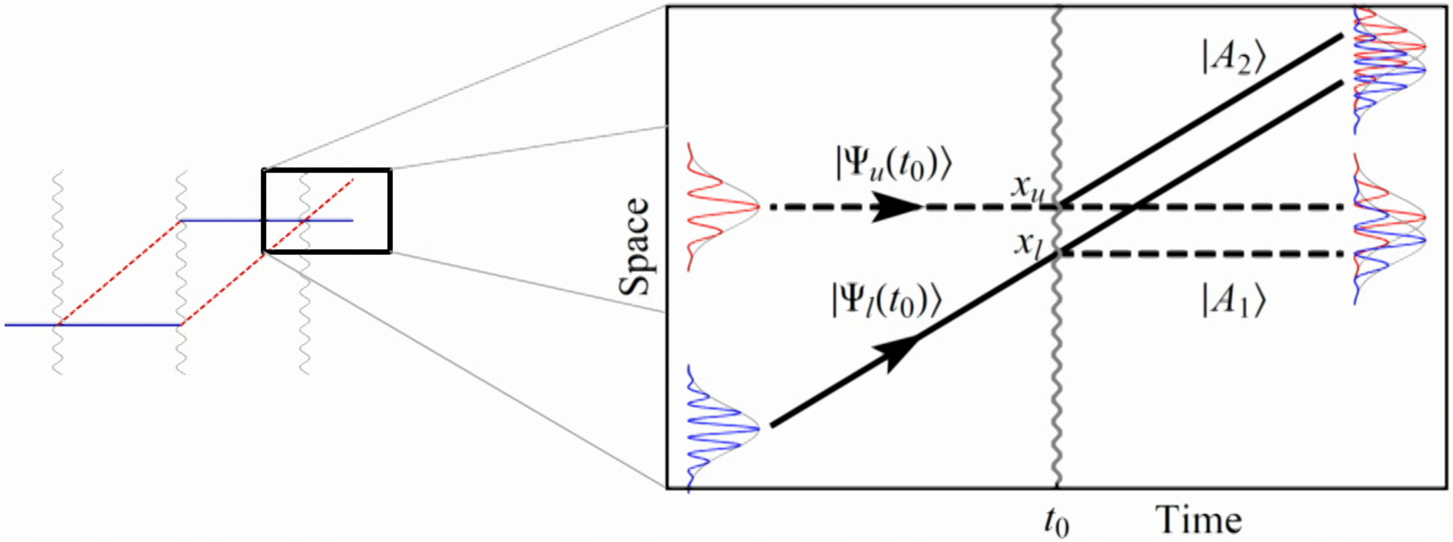
Propagation phase

- The phase of the center of the wavepacket is the classical action
- The carrier and wavepacket envelope move together along the classical path

$$\Delta\phi_{\text{propagation}} = \sum_{\text{upper}} \left(\int_{t_I}^{t_F} (L_c - E_i) dt \right) - \sum_{\text{lower}} \left(\int_{t_I}^{t_F} (L_c - E_i) dt \right)$$

Separation phase

Wavepackets do not always perfectly overlap at the final beamsplitter, due to tidal forces across wavepacket separation



$$\Delta\phi_{\text{separation}} = \bar{\mathbf{p}} \cdot \boldsymbol{\Delta}\mathbf{x}$$

$$\boldsymbol{\Delta}\mathbf{x} \equiv \mathbf{x}_l - \mathbf{x}_u$$

Conceptually similar to propagation phase; completes the loop.

Laser phase

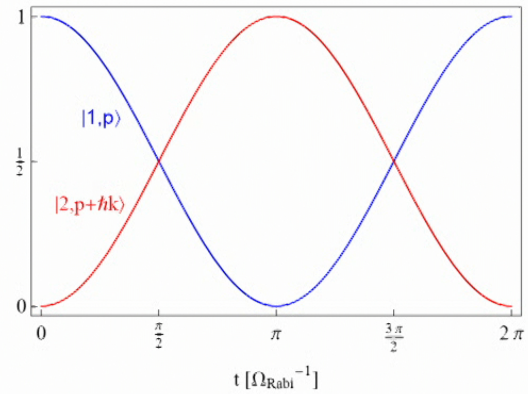
$$|\Psi\rangle = \int d\mathbf{p} \sum_i c_i(\mathbf{p})\, |\psi_{\mathbf{p}}\rangle\, |A_i\rangle$$

Atom-light interactions follow from Schrodinger equation (interaction picture):

$$\dot{c}_1(\mathbf{p}) = \frac{1}{2i}\Omega\, c_2(\mathbf{p}+\mathbf{k})e^{-i\phi_L}e^{-i\int_{t_0}^{t}\Delta(\mathbf{p})dt}$$

$$\dot{c}_2(\mathbf{p}+\mathbf{k}) = \frac{1}{2i}\Omega^* c_1(\mathbf{p})e^{i\phi_L}e^{i\int_{t_0}^{t}\Delta(\mathbf{p})dt}$$

Rabi oscillations



Transition rules:

$$|\mathbf{p}\rangle \rightarrow |\mathbf{p}+\mathbf{k}\rangle\, e^{i\phi_L}$$
$$|\mathbf{p}+\mathbf{k}\rangle \rightarrow |\mathbf{p}\rangle\, e^{-i\phi_L}$$

$$\phi_L \equiv \mathbf{k}\cdot\mathbf{x}_c(t_0) - \omega t_0 + \phi$$

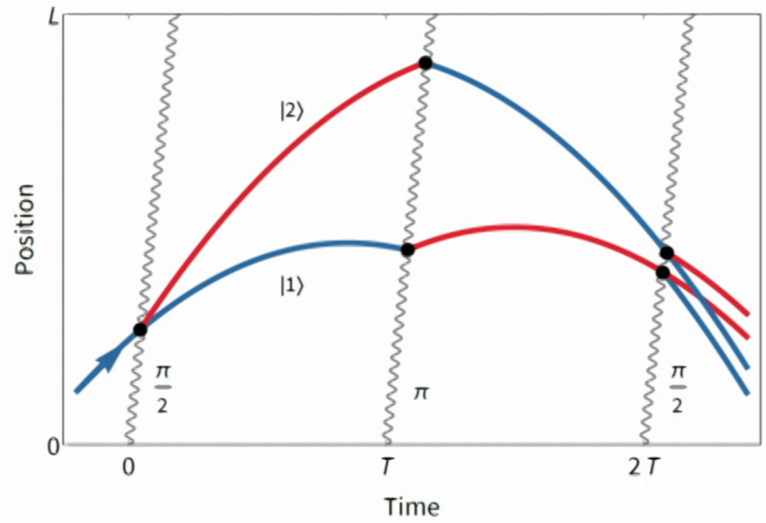
Atom position

- Laser phase is imprinted on the wavefunction at each pulse
- The position of the atom (at time of pulse) is encoded in the atom's wavefunction
- "Measures" the atom position with a wavelength-scale "ruler" → *corresponding momentum kick* (uncertainty principle)

General relativistic phase shifts

Light-pulse interferometer phase shifts in GR:

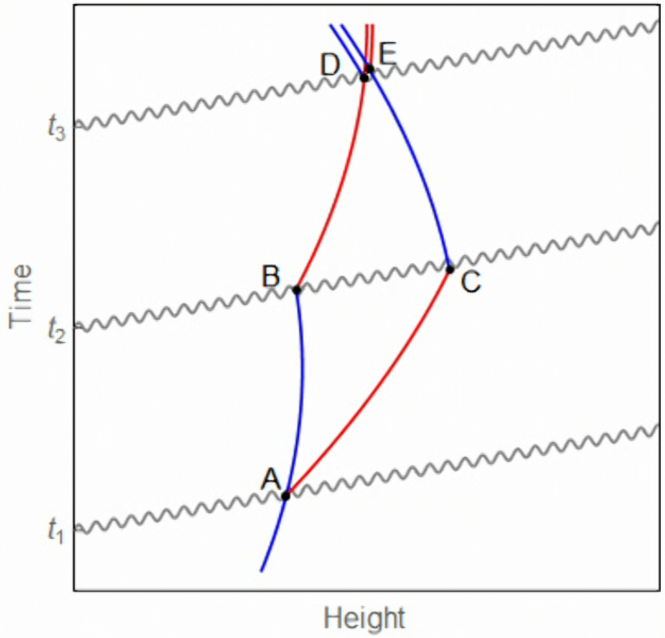
- Geodesic propagation for atoms and light.
- Path integral formulation to obtain quantum phases.
- Atom-field interaction at intersection of laser and atom geodesics.

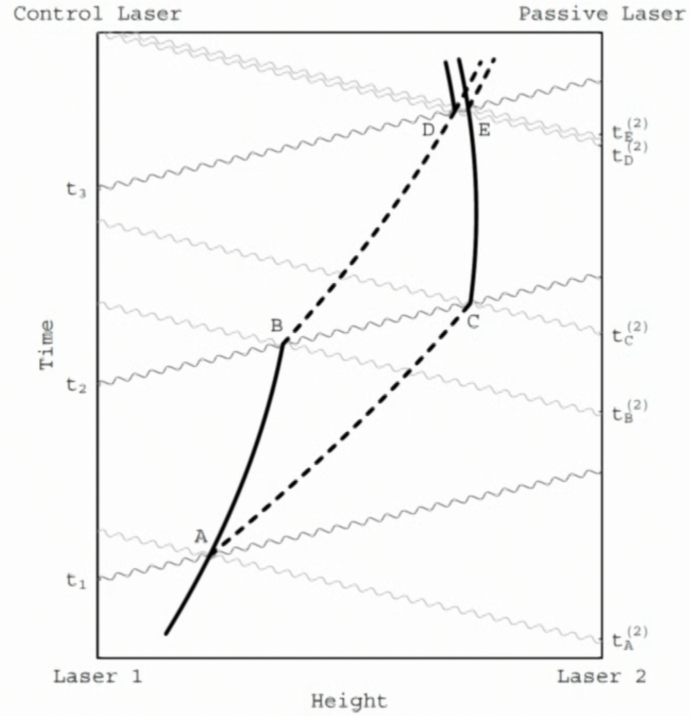


Atom and photon geodesics

Dimopoulos et al., PRD 78, 042003 (2008)

Single photon vs two photon atom optics





Consequential differences:

- For 2-photon, light pulses must leave at different times
- By convention, "passive" laser is on before "control" pulse arrives
- Arrival of control pulse determines passive null geodesic (and its laser phase)
- No passive laser for single photon atom optics

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Atom interferometer phase shift calculation

The atom interferometer phase shift can be decomposed as

$$\Delta\phi_{\text{tot}} = \Delta\phi_{\text{propagation}} + \Delta\phi_{\text{separation}} + \Delta\phi_{\text{laser}}$$

non-relativistic

$$\Delta\phi_{\text{propagation}} = \sum_{\text{upper}} \left(\int_{t_I}^{t_F} (L_c - E_i) dt \right) - \sum_{\text{lower}} \left(\int_{t_I}^{t_F} (L_c - E_i) dt \right)$$

$$\Delta\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \mathbf{x}_u(t_j)) \right)_{\text{upper}} - \left(\sum_j \pm\phi_L(t_j, \mathbf{x}_l(t_j)) \right)_{\text{lower}}$$

$$\Delta\phi_{\text{separation}} = \bar{\mathbf{p}} \cdot \mathbf{\Delta x}$$

relativistic

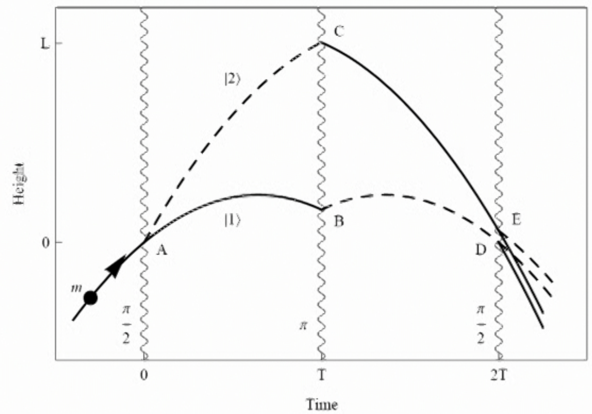
$$\phi_{\text{propagation}} = \int L dt = \int m d\tau = \int p_\mu dx^\mu$$

$$\Delta\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \mathbf{x}_u(t_j)) \right)_{\text{upper}} - \left(\sum_j \pm\phi_L(t_j, \mathbf{x}_l(t_j)) \right)_{\text{lower}}$$

$$\phi_{\text{separation}} = \int_E^D \overline{p}_\mu dx^\mu$$

Mach-Zehnder as discrete derivative sensor

Simple picture: Atom interferometer records the positions of the atom with respect to a wavelength-scale "laser ruler"



$$\phi_L \equiv \mathbf{k} \cdot \mathbf{x}_c(t_0) - \omega t_0 + \phi$$

- For Mach-Zehnder, propagation + separation phase tend to cancel
  …Except for high-order potentials (e.g., Aharonov Bohm effects)

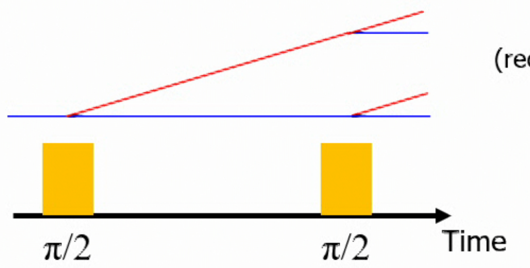
See Overstreet et al., Am. J. Phys. 89, 324 (2021)

- Laser phase records the position of the atom at each pulse
- Total phase encodes differences (motion) between pulses
- "Discrete derivative sensor": Records any spatial (or temporal) variation of atom (or background fields).

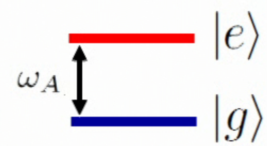
Two pulse atomic clock sequence

Atomic clocks are closely related to atom interferometers

Consider a *microwave* atomic clock (Ramsey sequence)



(recoil exaggerated)



Laser phase: $\phi_L \equiv \mathbf{k}\cdot\mathbf{x}_c(t_0) - \omega t_0 + \phi$

Can ignore separation phase (recoil is negligible for a microwave transition)

$$\Delta\phi = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} = -\omega_A T + \phi_1 - \phi_2$$

$$= (\omega - \omega_A)T + kx_1 - kx_2$$

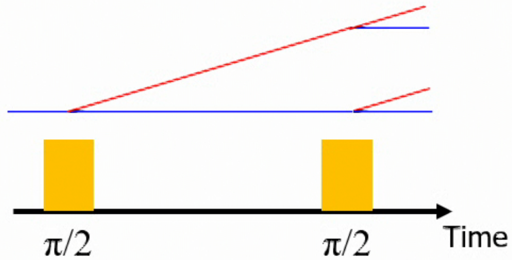
$$= (\omega - \omega_A)T + kvT$$

(atom velocity v)

Sensitive to atom velocity (Doppler shift)

Atom interferometer as discrete derivative sensor

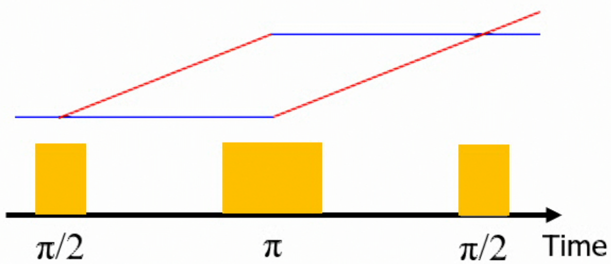
Ramsey sequence (clock)



$$\Delta\phi = \phi_1 - \phi_2 = (\omega - \omega_A)T + kx_1 - kx_2$$
$$= (\omega - \omega_A)T + \underline{kvT}$$

- Measures velocity

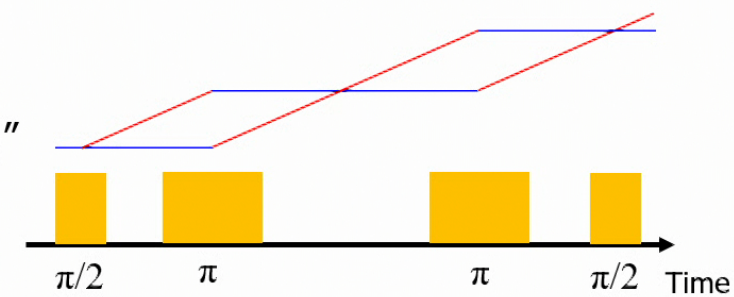
Mach-Zehnder



$$\Delta\phi = (\phi_1 - \phi_2) - (\phi_2 - \phi_3)$$
$$= kv_1T - kv_2T = \underline{kaT^2}$$

- "Difference" of two Ramsey sequences
- Measures acceleration

"Double diamond"



$$\Delta\phi = ka_1T^2 - ka_2T^2 = k\,\delta a\,T^3$$

- Difference of two MZ loops
- Measures acceleration gradient (in space and/or time)

Tune response using pulse timing

Three pulse (accelerometer) gravity gradient phase shifts:

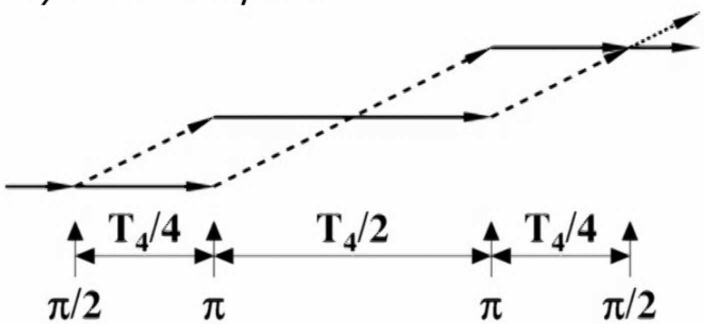
$k_{\rm eff} T_{zz} v_z T^3$

$\frac{\hbar k_{\rm eff}^2}{2m} T_{zz} T^3$

Can causes sensitivity to kinematic errors/noise

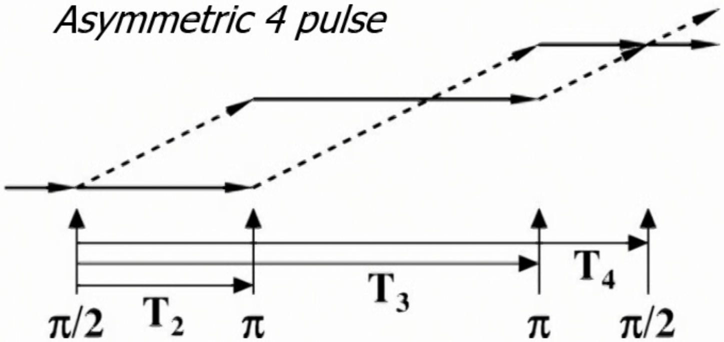
Can selectively suppress gravity gradient or acceleration response, etc.

Symmetric 4 pulse



Eliminates all T^2 terms

Asymmetric 4 pulse



Golden ratio diamonds: $T_{2,3} = \frac{\sqrt{5} \mp 1}{4} T_4$

Eliminates all T^3 terms

B. Dubetsky et al., PRA 74, 023615 (2006).

Tune response using pulse timing

Three pulse (accelerometer) gravity gradient phase shifts:

$$k_{\text{eff}} T_{zz} v_z T^3$$

$$\frac{\hbar k_{\text{eff}}^2}{2m} T_{zz} T^3$$

Can causes sensitivity to kinematic errors/noise

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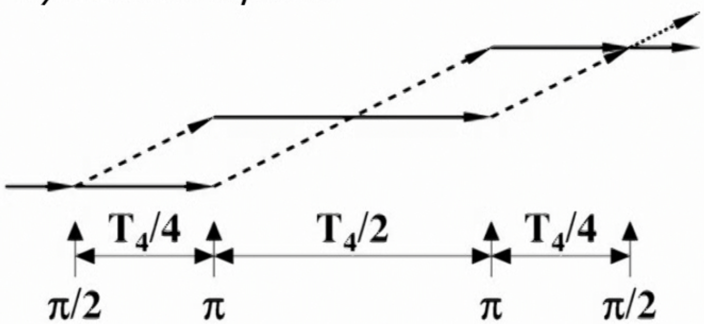
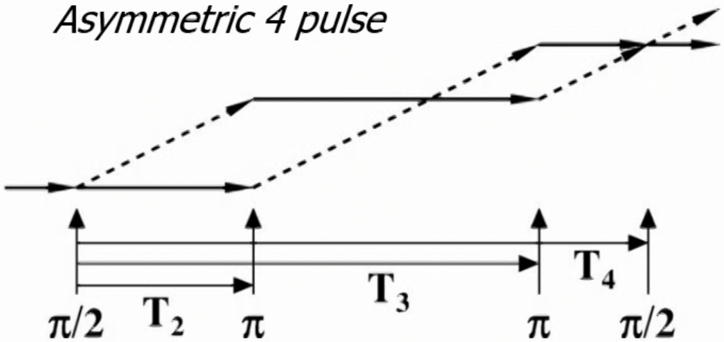
Symmetric 4 pulse



Eliminates all T^2 terms

Asymmetric 4 pulse

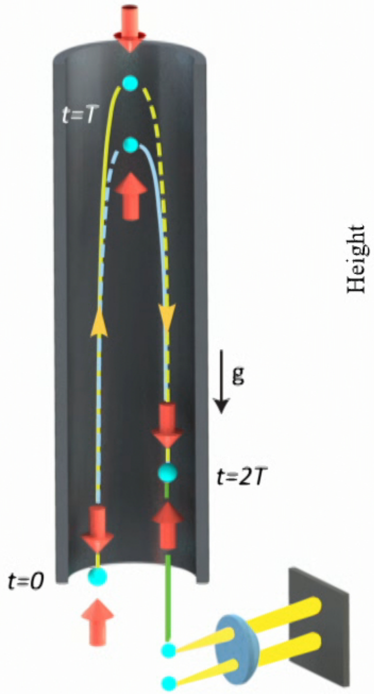


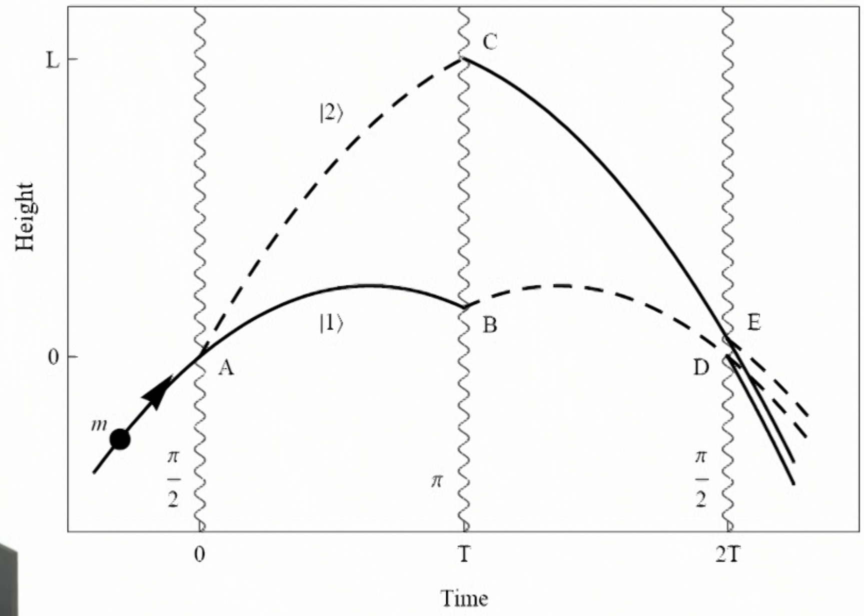
Golden ratio diamonds: $T_{2,3} = \frac{\sqrt{5} \mp 1}{4} T_4$

Eliminates all T^3 terms

B. Dubetsky et al., PRA 74, 023615 (2006).

Accelerometer sensitivity





$$\Delta\phi = k_{\rm eff}\, g T^2$$

Proportional to spacetime area enclosed.

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\rm eff}\, g T^2}$$

Sensitivity

$$\delta\phi \sim \frac{1}{\sqrt{N}}$$

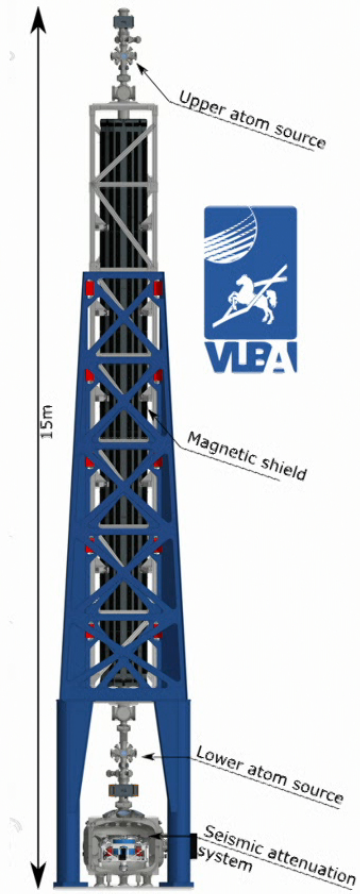
Shot noise

T : Long duration

$k_{\rm eff}$: Large wavepacket separation

$\delta\phi$: High flux, spin squeezing

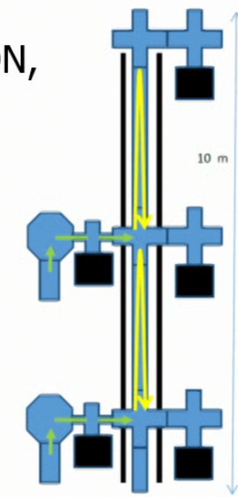
10-meter scale atom drop towers



Hannover, Germany

Wuhan, China

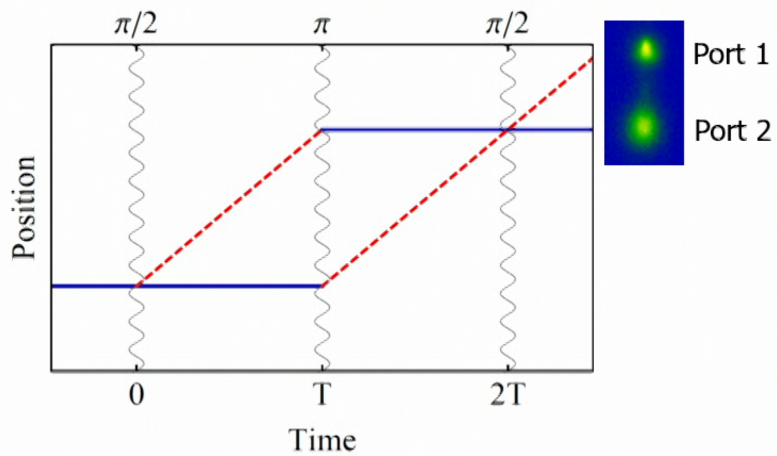
AION, UK



Stanford University

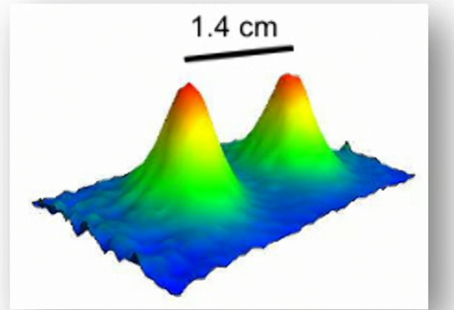
25

Interference at long interrogation time



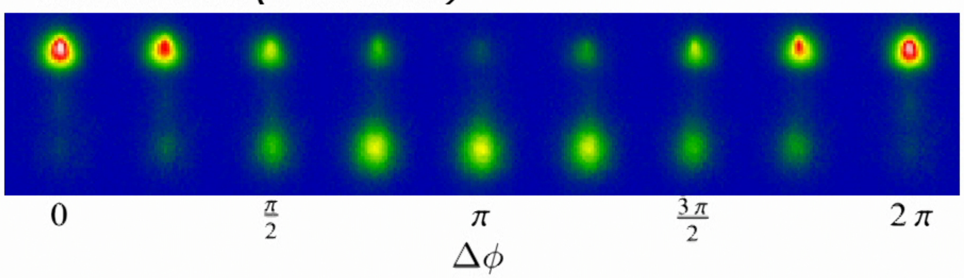
2T = 2.3 seconds

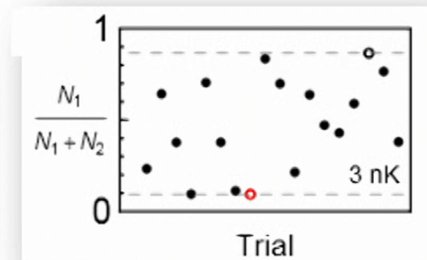
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

Interference (3 nK cloud)



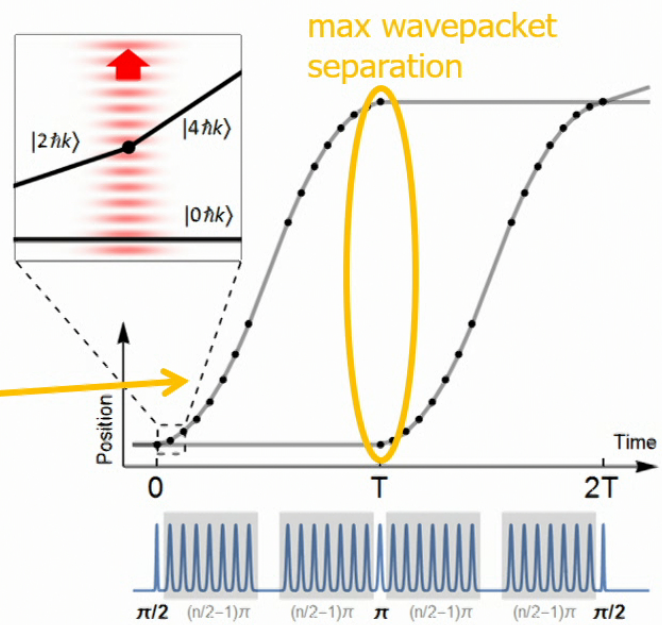


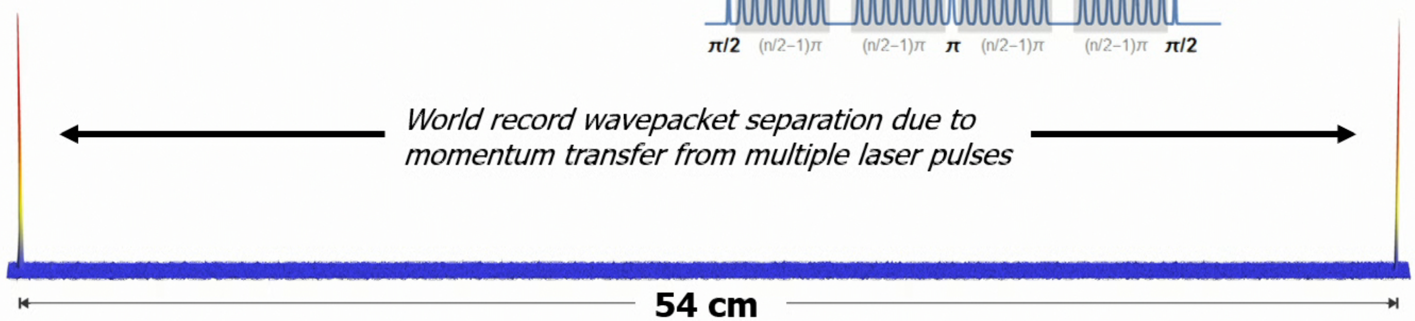
Dickerson, et al., PRL **111**, 083001 (2013).

Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer

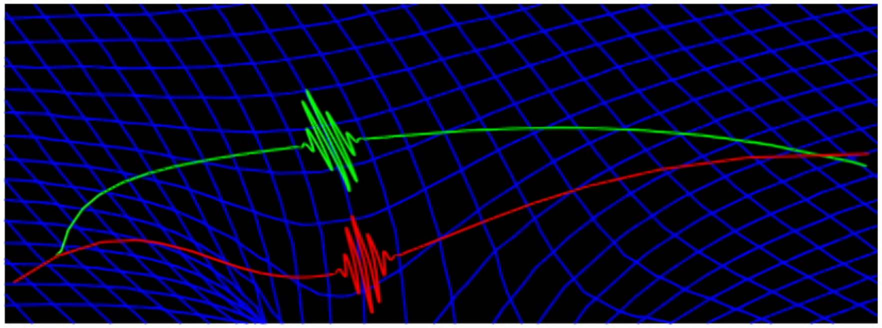
90 photons worth of momentum





Kovachy et al., *Nature* 2015

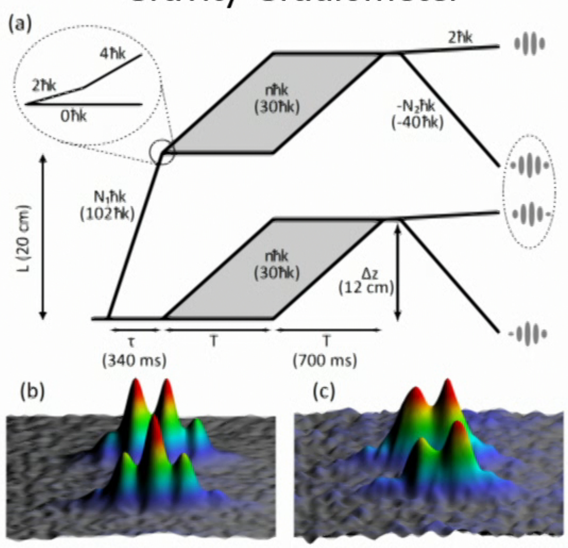
Phase shift from spacetime curvature



In general relativity, gravity is a result of *spacetime curvature*.

Observed the effect of spacetime curvature across a *single particle's wavefunction.*

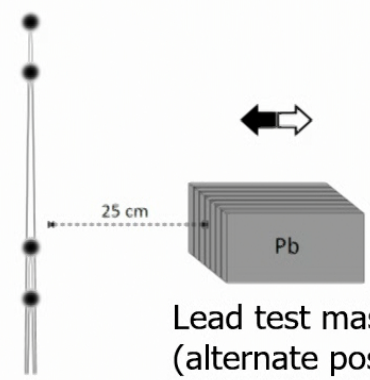
Gravity Gradiometer



Measure *phase difference*

Phase shift due to gravity gradient of test mass

Interference fringes



Lead test mass (alternate position)

Asenbaum et al., PRL **118**, 183602 (2017)