Atom Gravimetry, Accelerometery & Interferometry

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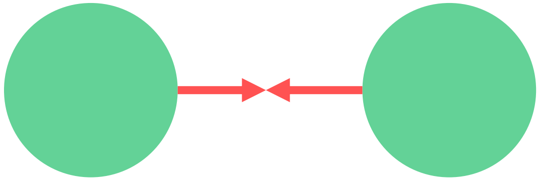
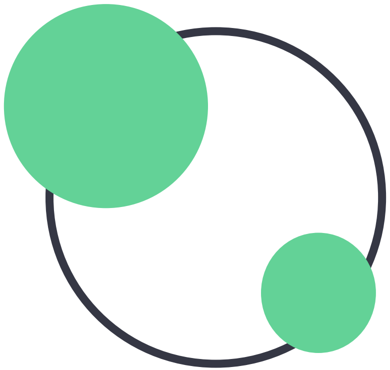
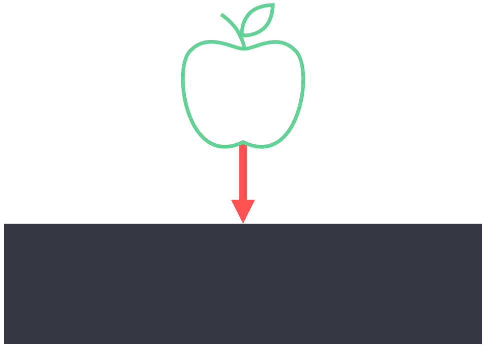
Outline

- Gravimetry and the Equivalence Principle
- Light Interferometry
- Laser Interactions with Atoms
- Creating an Atom Interferometer
- Physics Applications of Light-Pulse Atom Interferometry

Introduction – Gravity and the Equivalence Principle





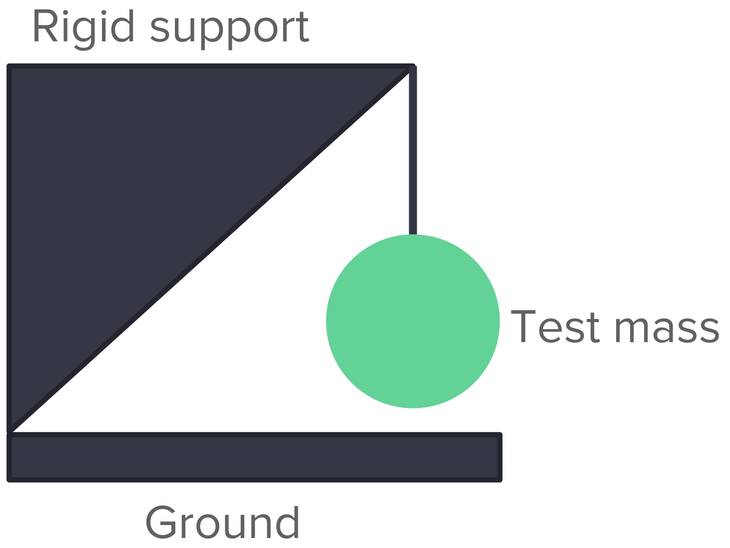


Equivalence principle: The equivalence of gravitational and inertial mass results in the indistinguishability between being in a gravitational field and an accelerating frame of reference.

Gravimetry

- Traditional gravimeter's measure the displacement of a suspended test mass with respect to a rigid support connected to the ground.

- The equivalence principle then provides a measure of the fluctuating gravitational field from the acceleration of the test mass.

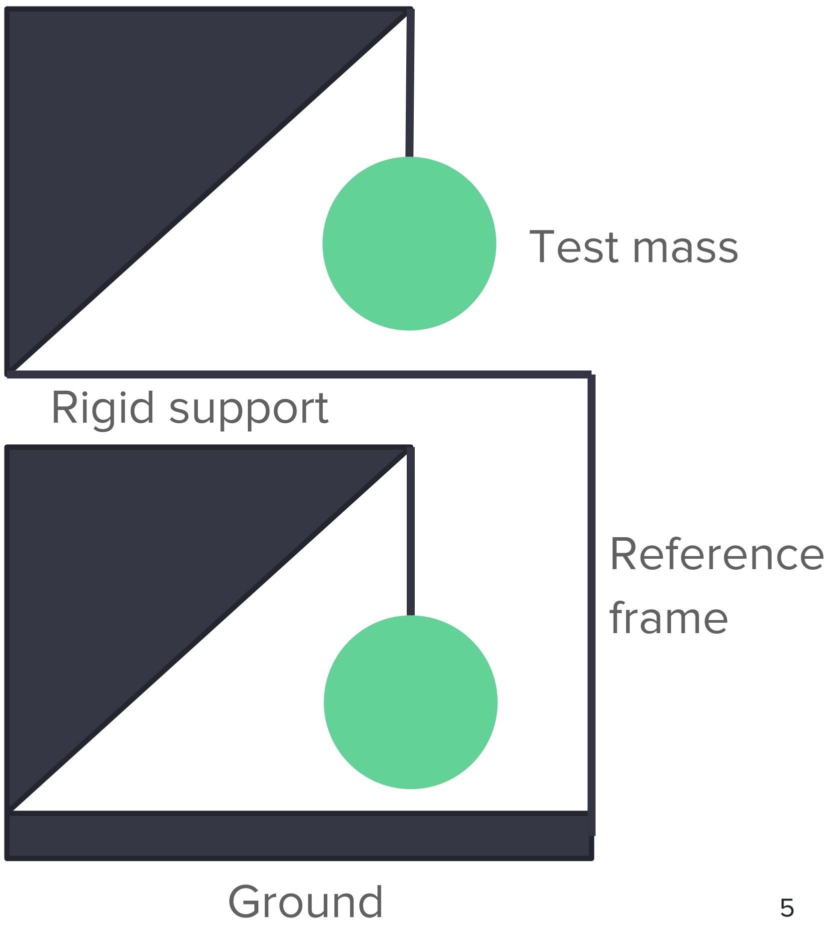


Gradiometry

- Gradiometers measure the relative acceleration between two separate gravimeters in response to a fluctuating gravity field. Their readouts are subtracted to cancel noise from seismic waves etc.

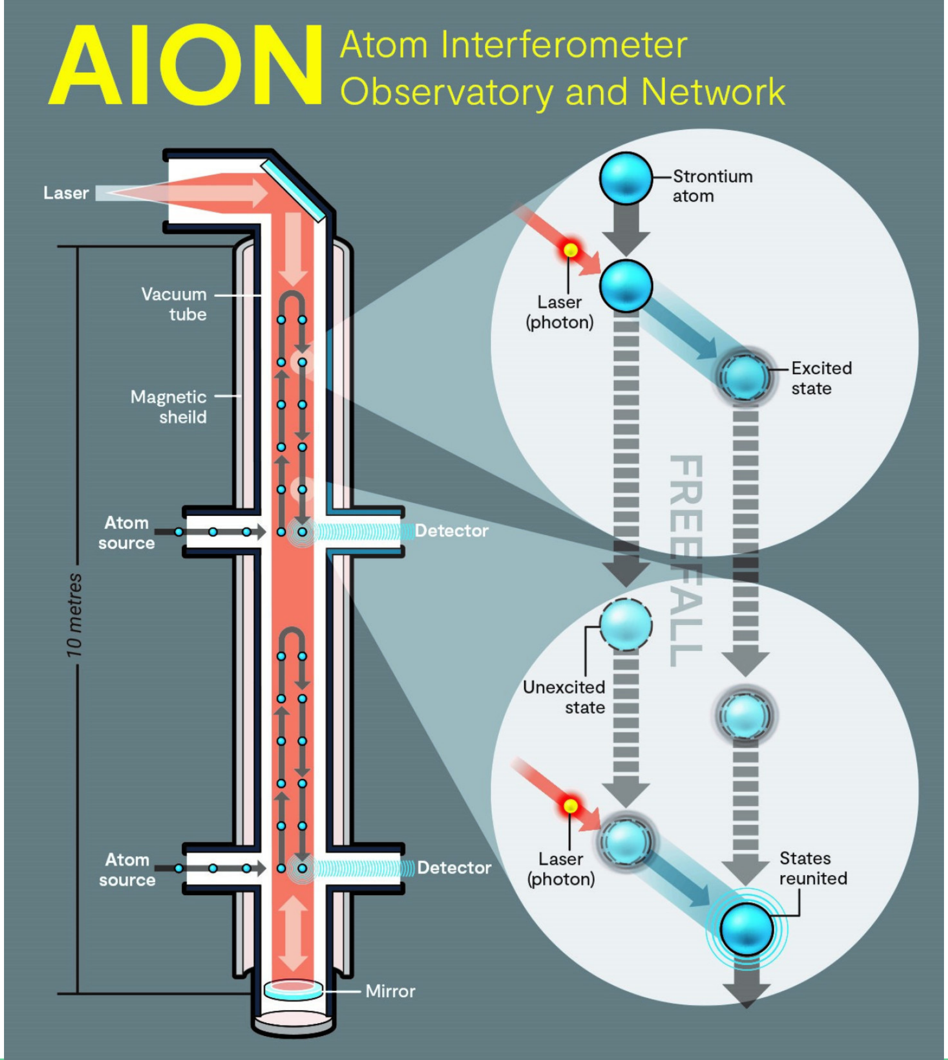
- Gradiometers are sensitive to the gradient of Earth's gravitational field:

$$g(z) = g + (\partial_z g)z = g + (T)z$$



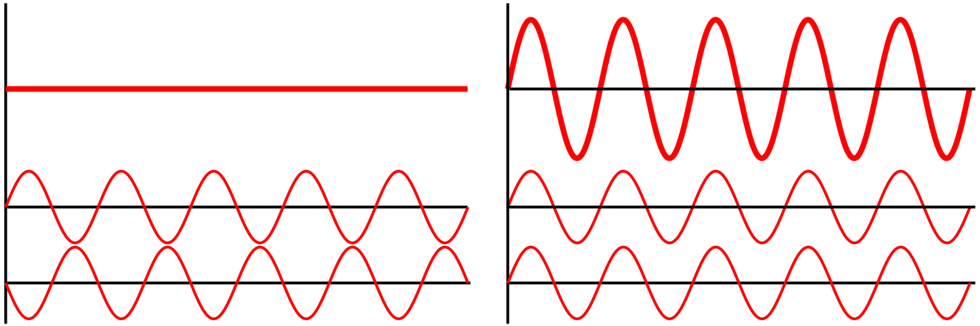
Atom Gradiometer

- AION is an example of an atom gradiometer.
- Free-falling cold atoms act as test masses for each interferometer.
- The atoms are split to travel along different paths before interfering and measuring the result.

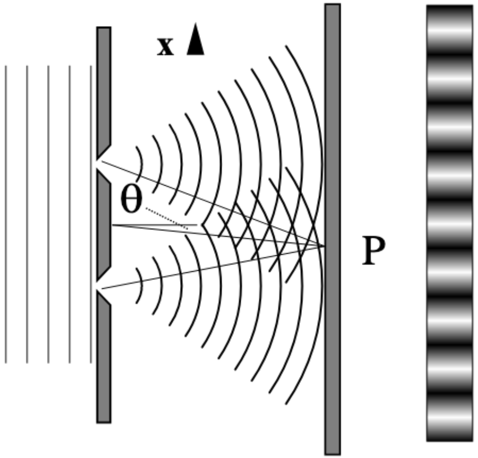


Interference

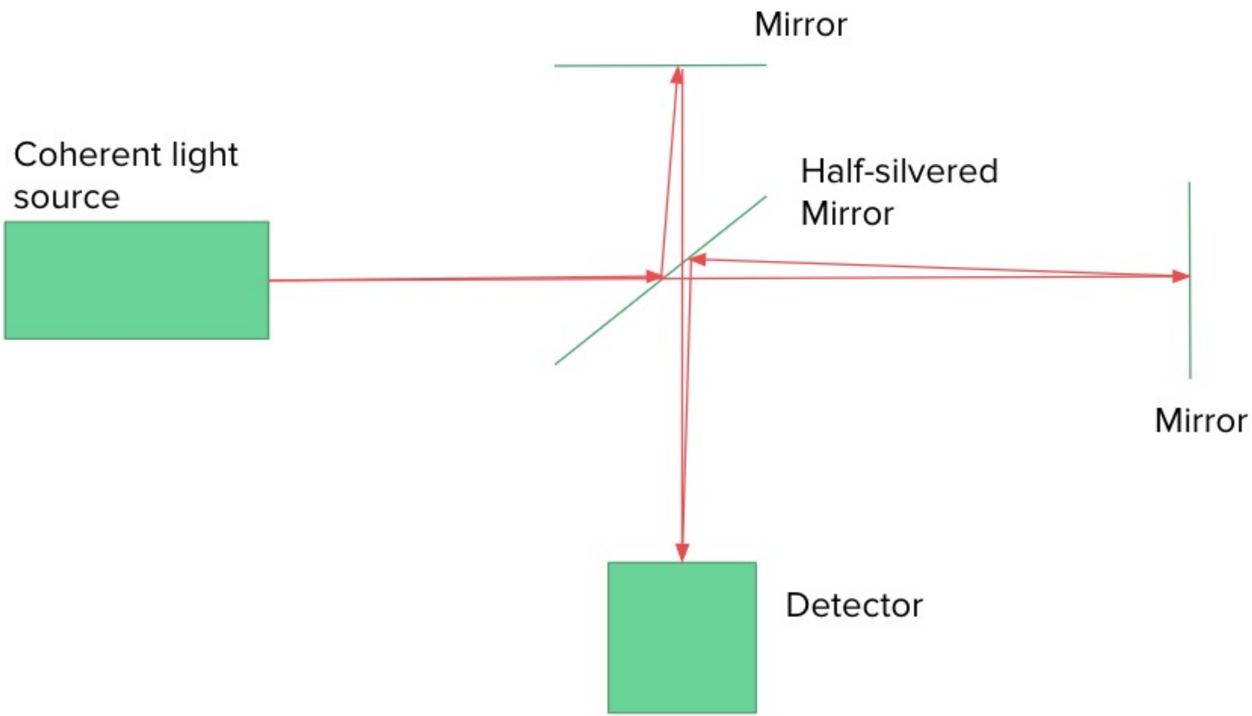
- Classically, waves “interfere” to produce a constructive or destructive outcome, simply by adding their amplitudes.

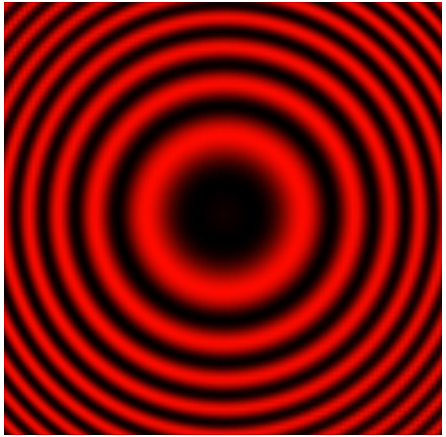


- Waves passing through two slits produce an interference pattern made up of light and dark regions.



Laser Interferometry

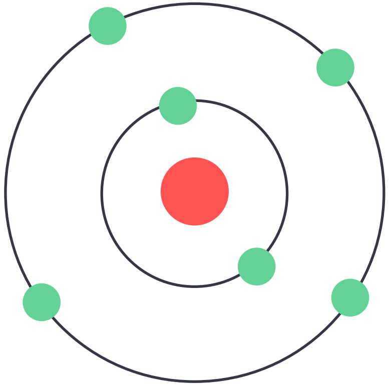


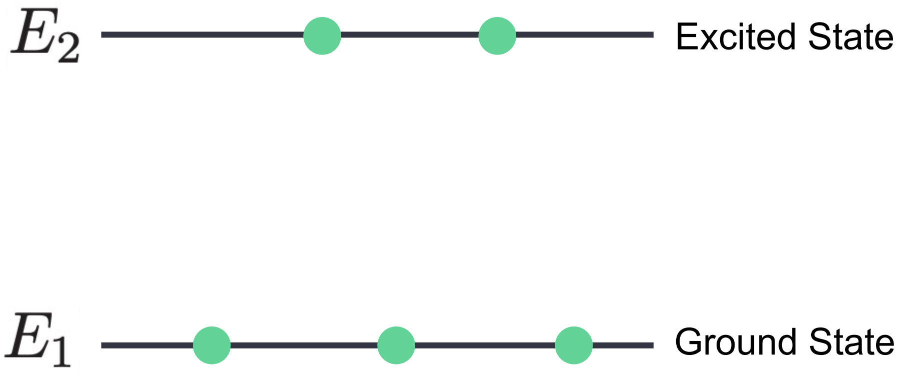


Light fringes

Towards Atom Interferometry

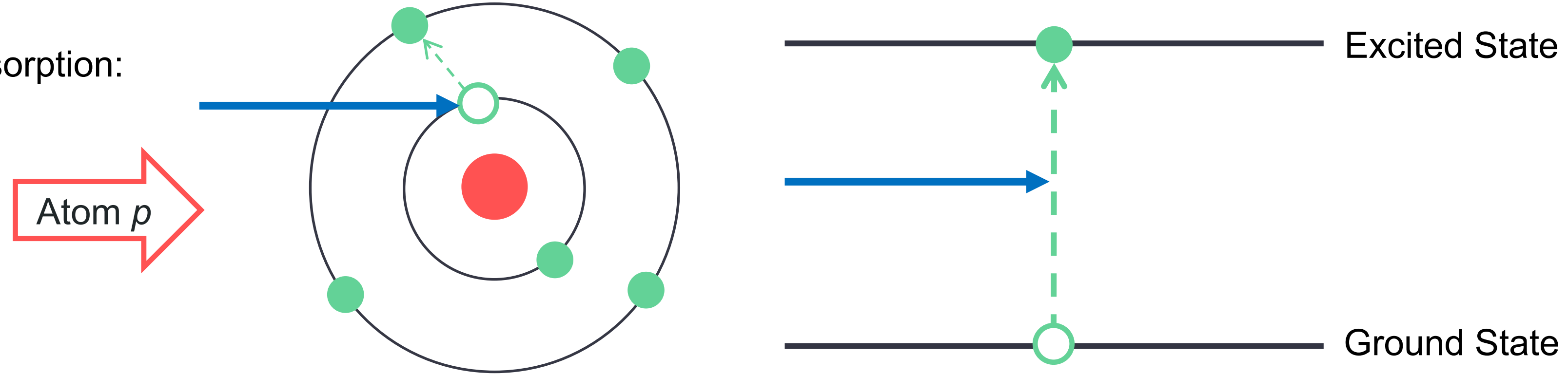
Consider a two-level atom:



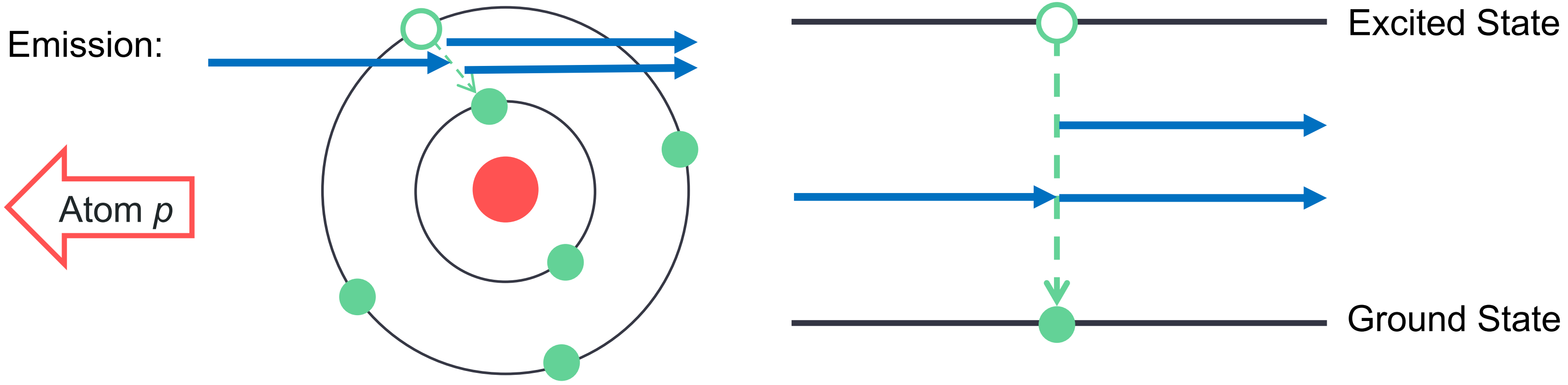


Laser Interactions with Atoms

Photon Absorption:



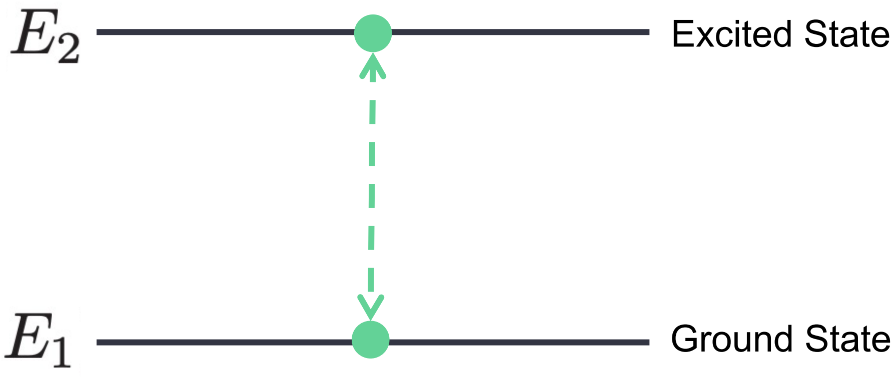
Stimulated Emission:



Rabi Oscillations and Laser Properties

- Frequency: A laser tuned to the resonant frequency of the energy gap in a two-level atom causes the system to undergo oscillations:

$$\omega_0 = (E_2 - E_1)/\hbar$$



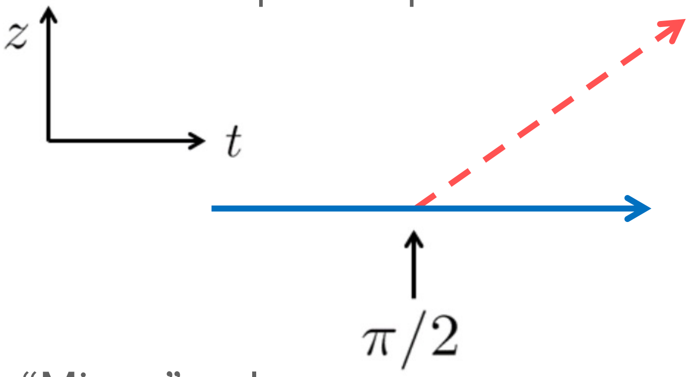
- Time: The laser splits the population of a cloud of atoms between the two states, depending on the time the laser is applied.

"Mirror" pulse: $t_\pi = \pi/\Omega$

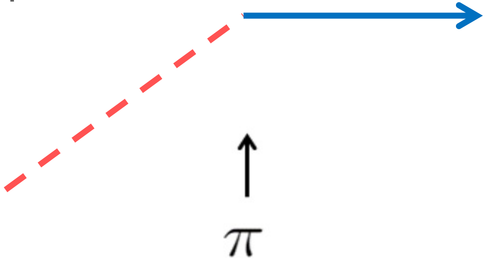
"Beam-splitter" pulse: $t_{\pi/2} = \pi/2\Omega$

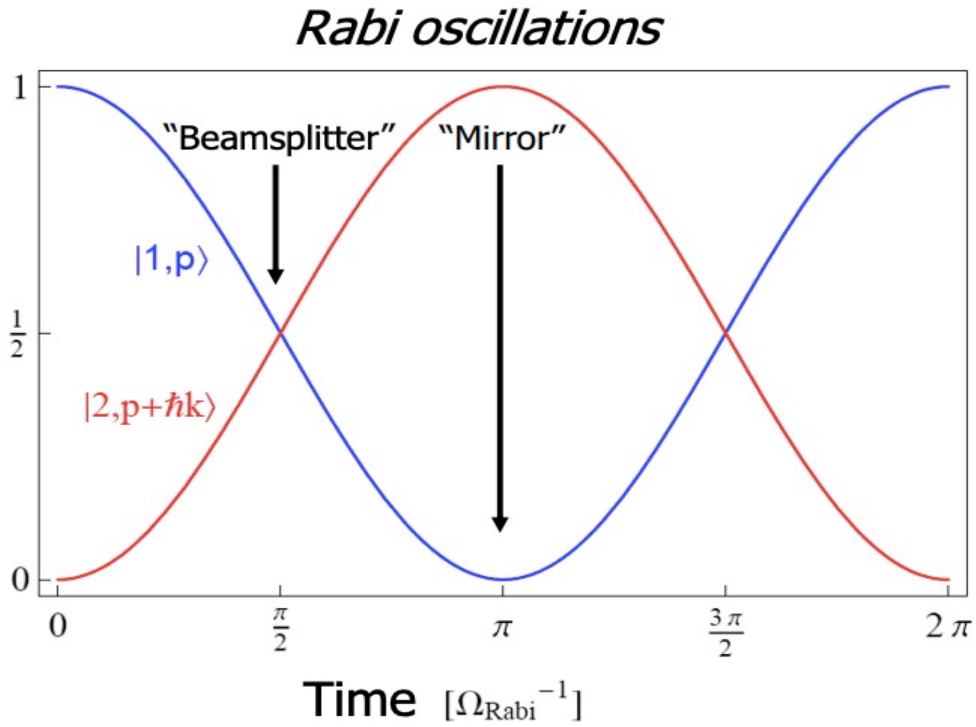
Constructing Atom Interferometer Sequences

“Beam-splitter” pulse:

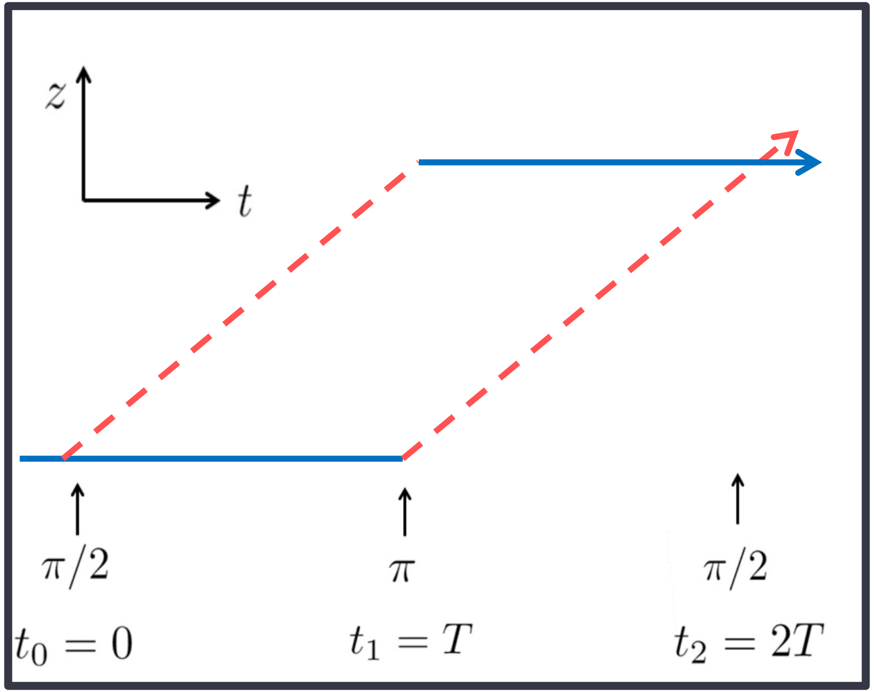


“Mirror” pulse:

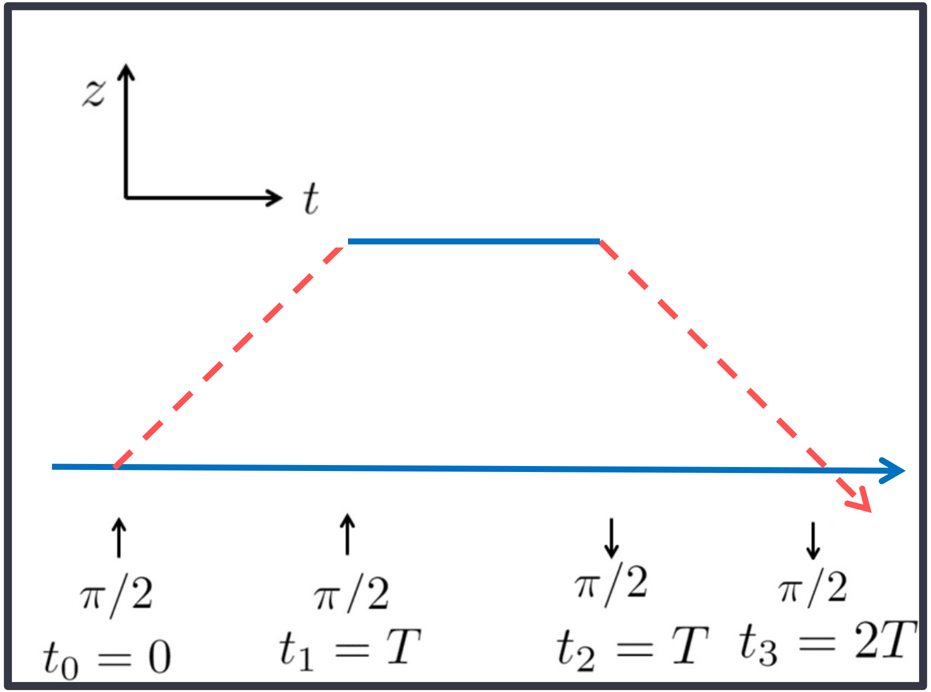




Constructing Atom Interferometer Sequences

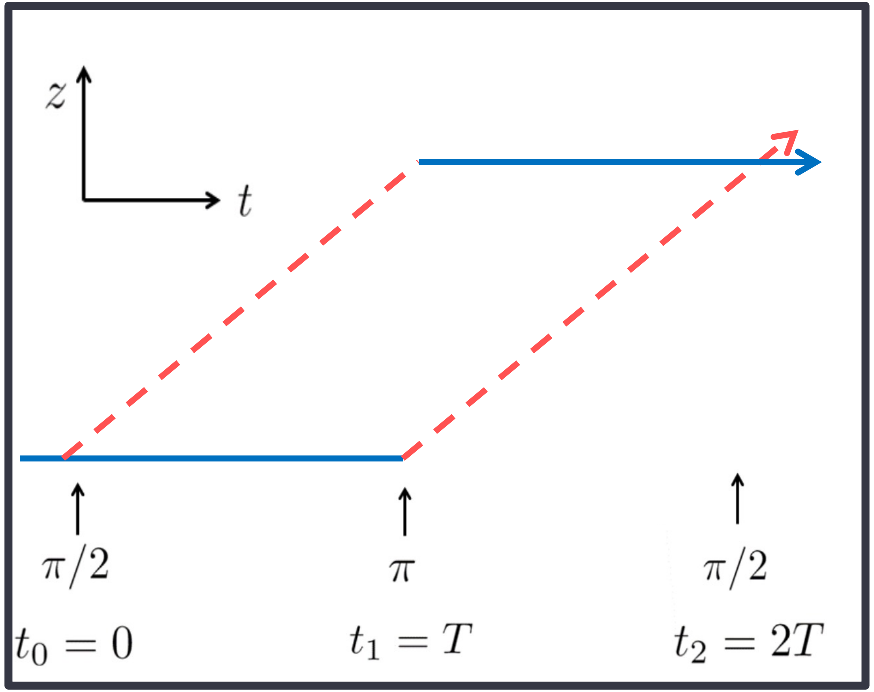


Mach-Zehnder
Interferometer

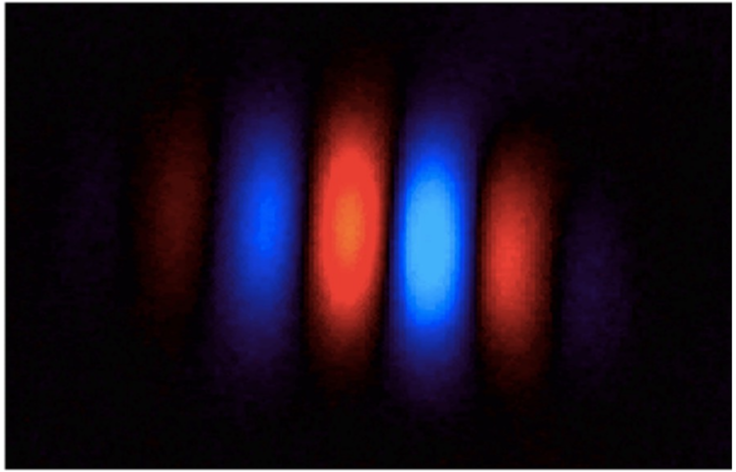


Ramsey-Bordé
Interferometer

Constructing Atom Interferometer Sequences



Mach-Zehnder Interferometer



Atom fringes

$$\Delta\phi_{MZ} = kgT^2$$

Atom Interferometer Phase Shifts

- The leading order phase shift of atoms in a MZ atom interferometer is:

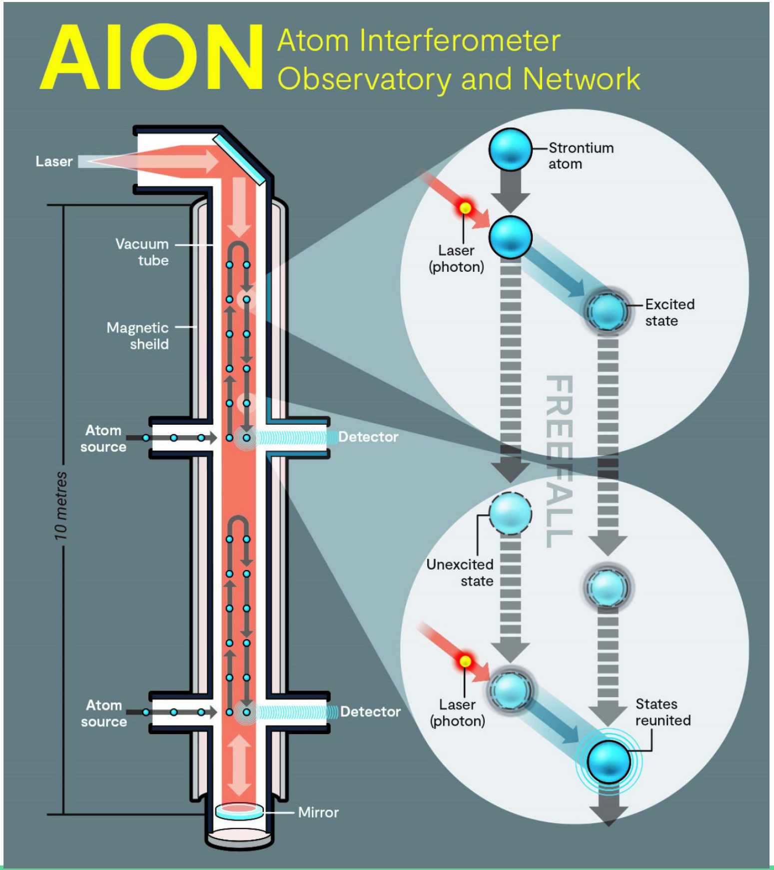
$$\Delta\phi_{MZ} = kgT^2$$

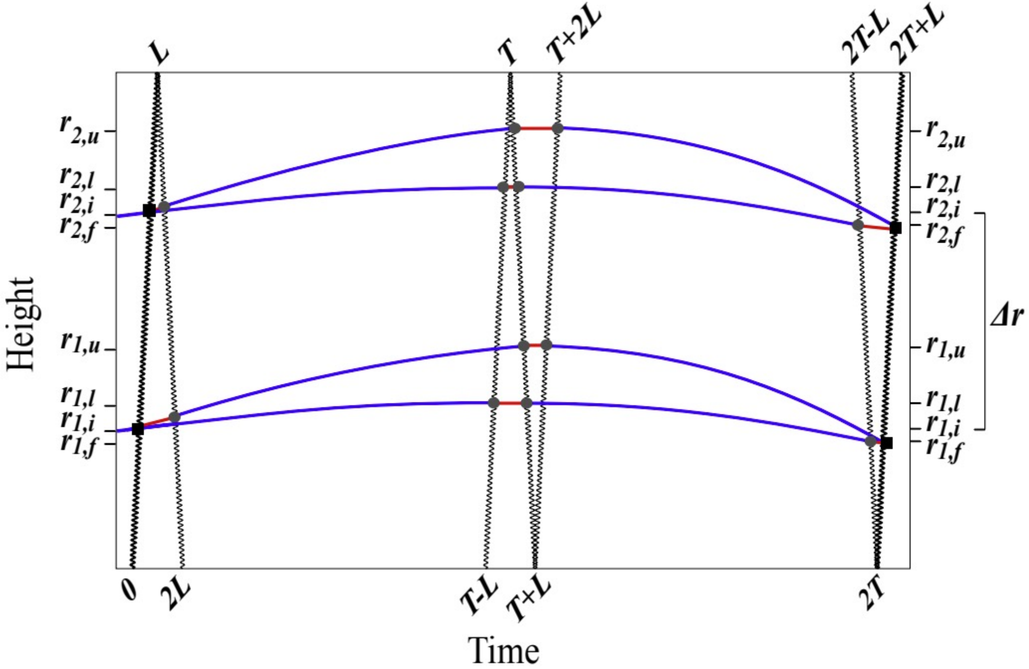
- The phase shift can be thought of in three separate components:

$$\Delta\phi_{\mathrm{Total}} = \Delta\phi_{\mathrm{Prop}} + \Delta\phi_{\mathrm{Laser}} + \Delta\phi_{\mathrm{Sep}}$$

- Atoms propagating in a gravitational field acquire phase shifts.
- Laser waves carry an intrinsic phase which is imprinted on the atoms as they interact through beam-splitter or mirror pulses.
- When the two paths of the atoms converge, small separations in space in the classical paths of the atoms at the output port may cause a phase shift.

Atom Gradiometers – AION





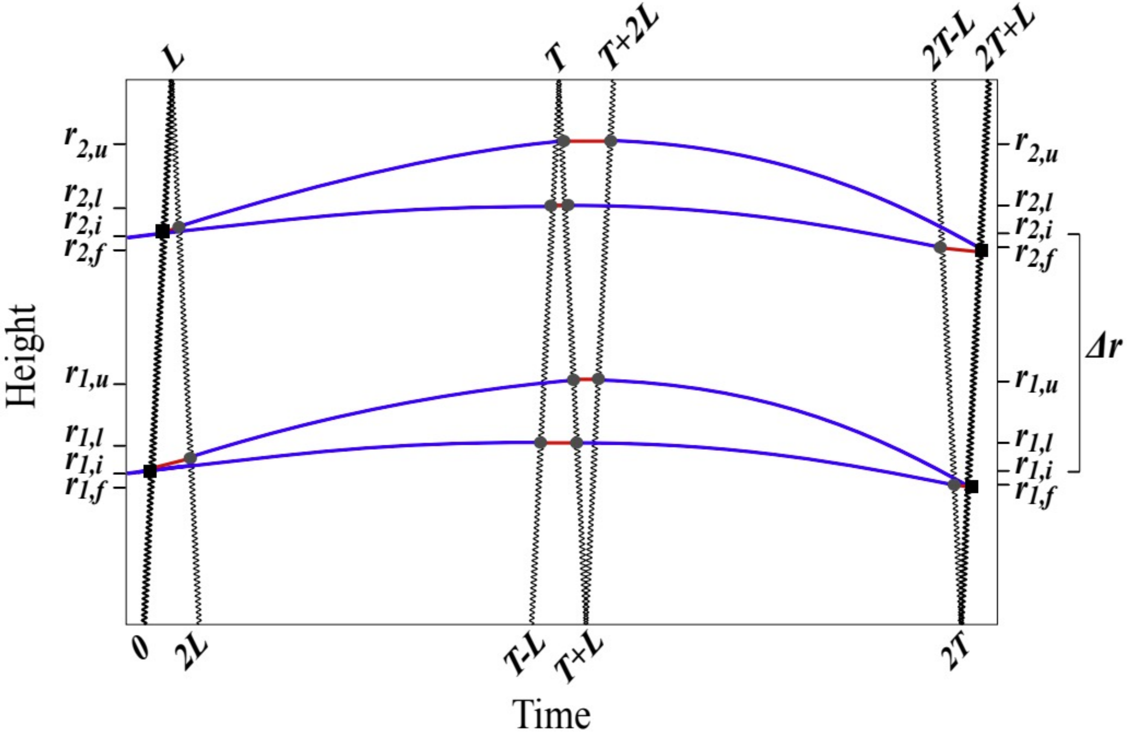
Badurina et al. (2109.10965)

Atom Interferometry for Fundamental Physics

AI setups are sensitive to changes in fundamental constants induced by Dark Matter:

$$m_e(t,\mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha(t,\mathbf{x}) \approx \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right] .$$



Badurina et al. (2109.10965)

Boosting Sensitivity

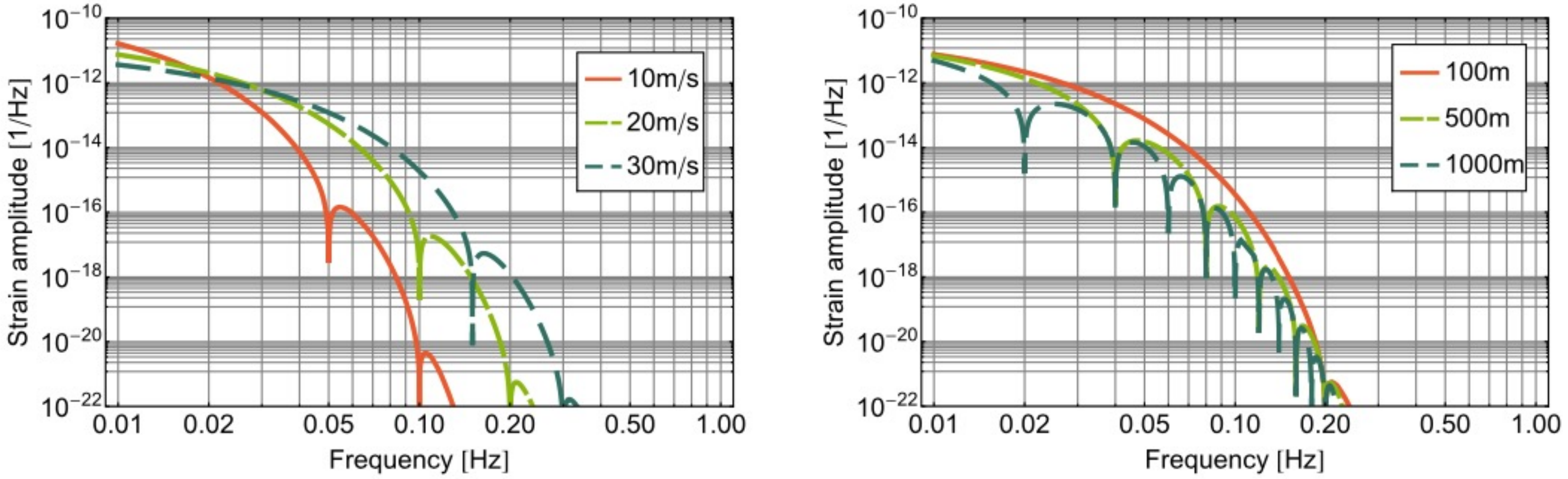


Fig. 31 Gravity perturbations from a uniformly moving point mass. In the left plot, distance between test masses is kept constant at $L = 500$ m, while in the right plot speed is kept constant at 20 m/s

Harms (1507.05850)

Summary

- The quantum properties of atoms allow the construction of interferometers which act as sensitive gradiometers with freely falling cold atoms as test masses.
- The phase shift measured in atom interferometers are sensitive to fluctuations in a gravitational field from a range of sources.
- Atom interferometers can be used to search for new fundamental physics with more work to be done characterising background sources.