Gravity Mapping with Cold Atoms

Tristan Valenzuela
Quantum Sensors Group

Quantum Technologies in Space

Earth Observation

Atom Interferometers **for**
Next Generation Gravity Missions:
- Geodesy

Earth & planetary interiors

- Climatic Effects

Ocean circulation & Hydrological cycle
Glacial movements
Earthquake monitoring

Fundamental Physics

Atomic clocks & Atom Interferometers:
- Tests of the Equivalence Principle
- Gravity Red Shift Measurements
- Gravity Wave detection

Telecommunications

Atomic clocks:
- Global time reference,
- High accuracy satellite navigation,
- Internet synchronisation.

Optical links:
- Deep space ranging & communications,
- Increased spectral efficiency and data rates compared with RF comm links

- Secure communications via QKD.

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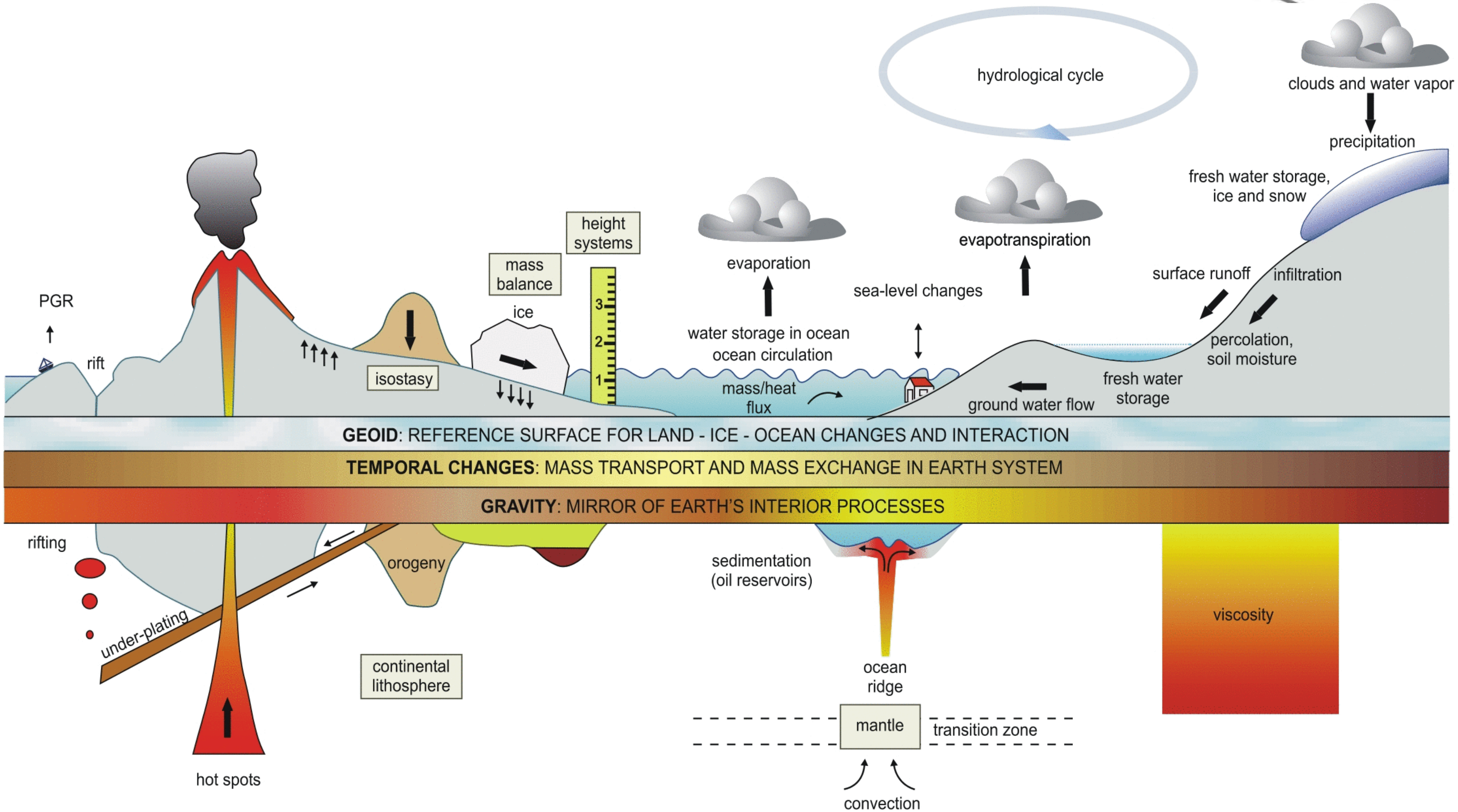
What are we looking for?



Source: Ilk, K.-H., Flury, J., et al. (2005). Mass Transport and Mass Distribution in the Earth System.

How to measure Gravity?

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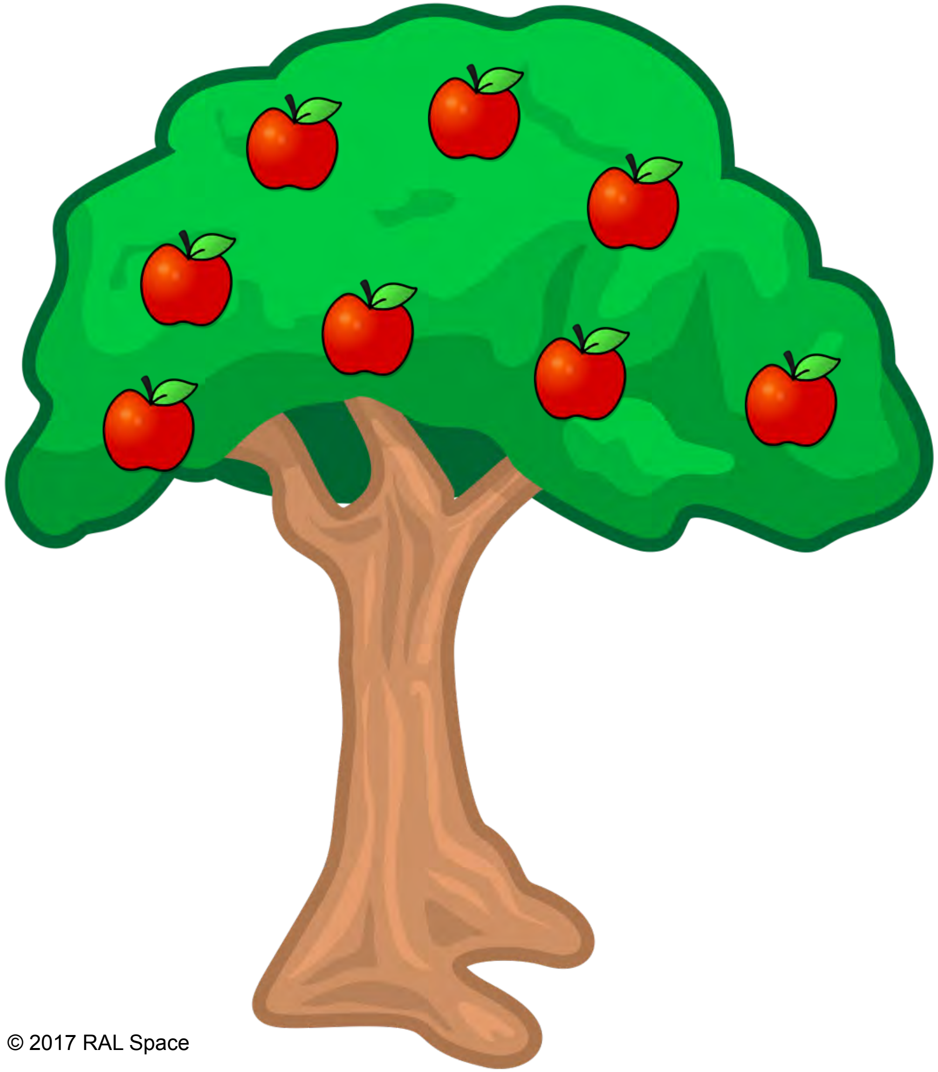

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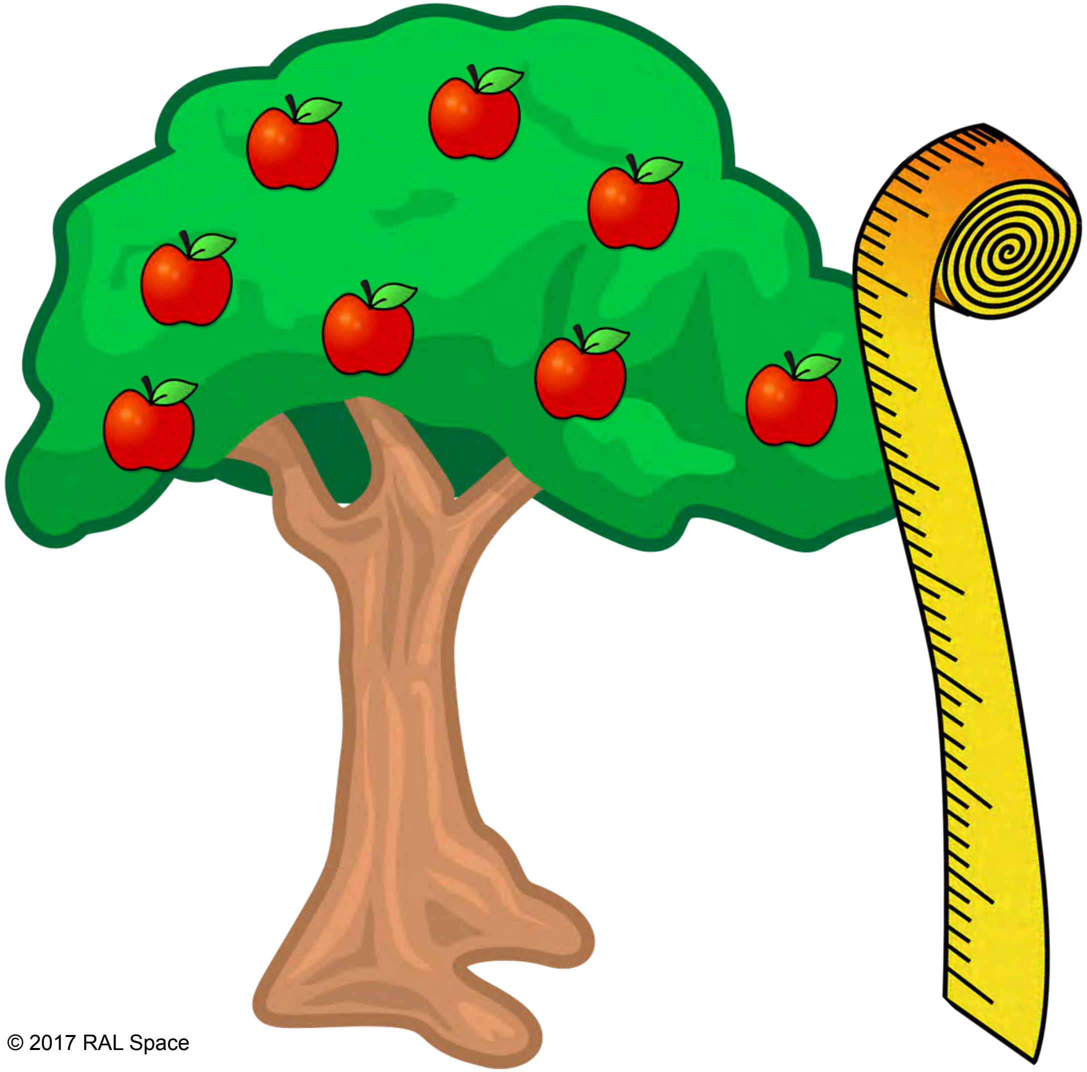

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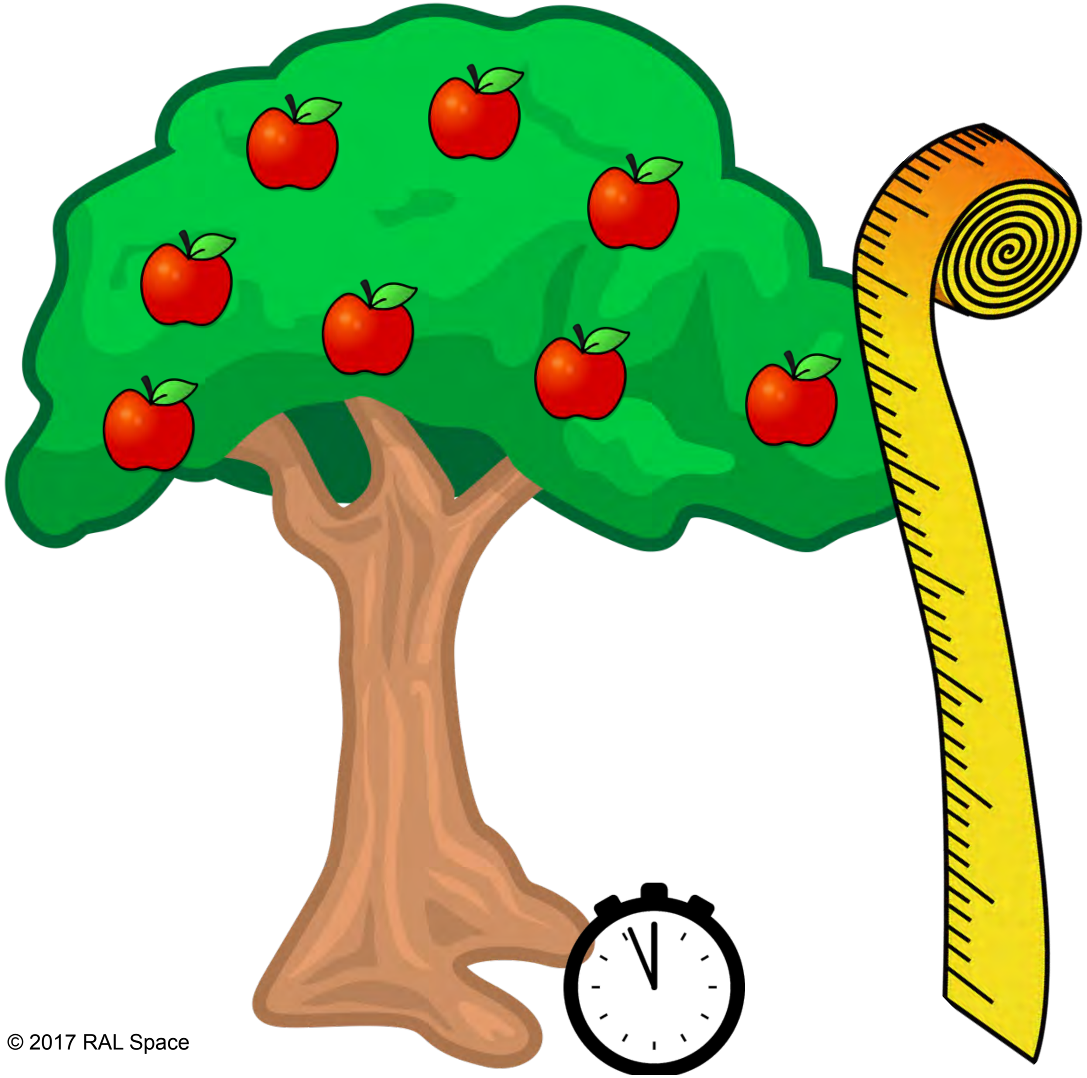

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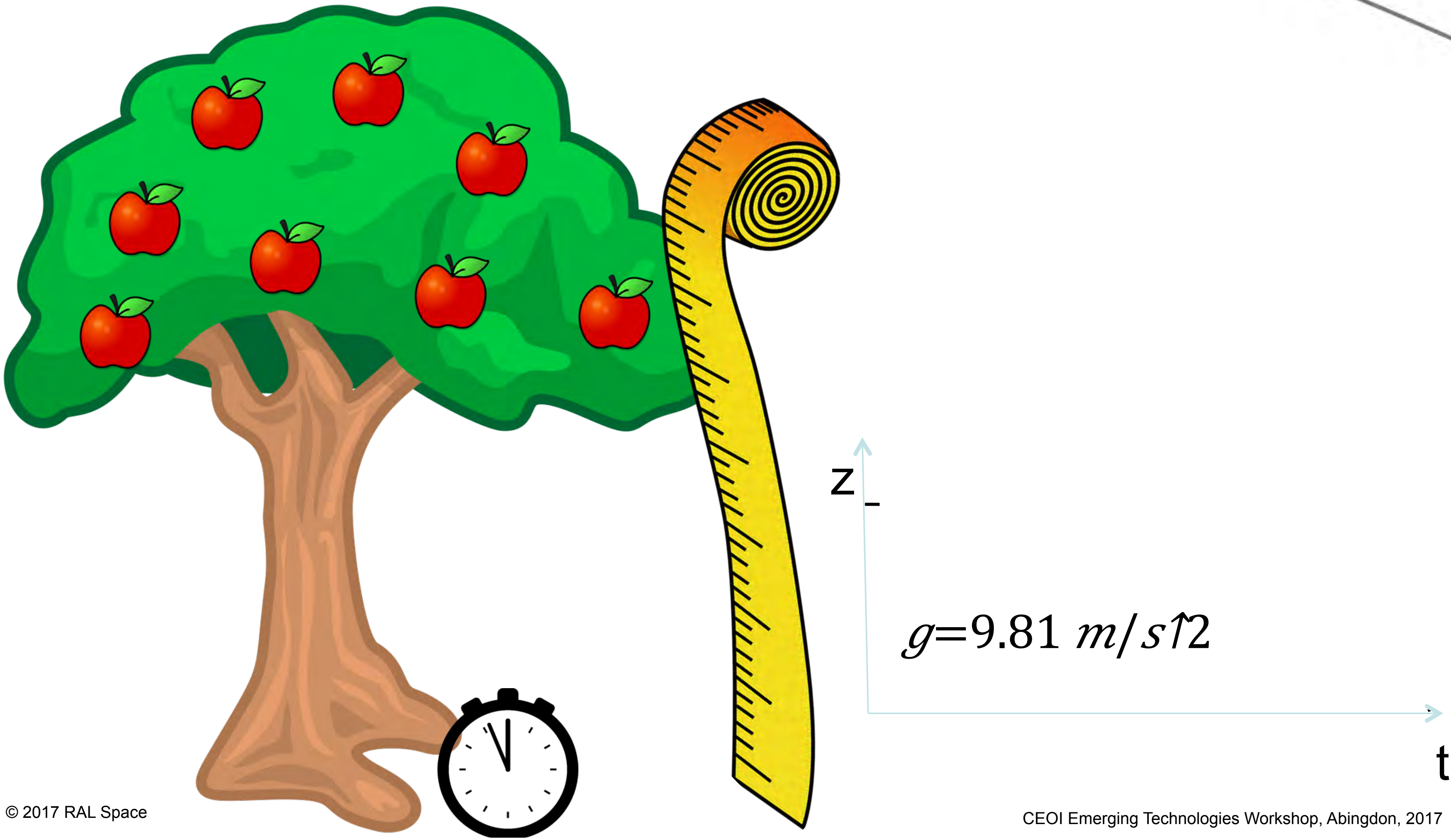
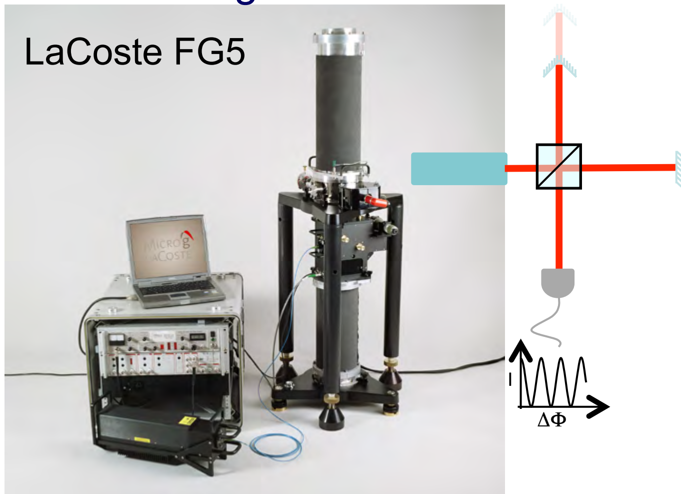


$$g = 9.81\ m/s\uparrow 2$$

How to measure Gravity?

Falling Corner Cube



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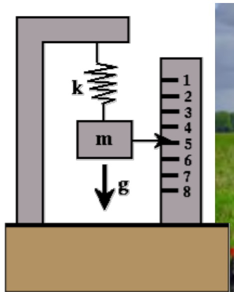
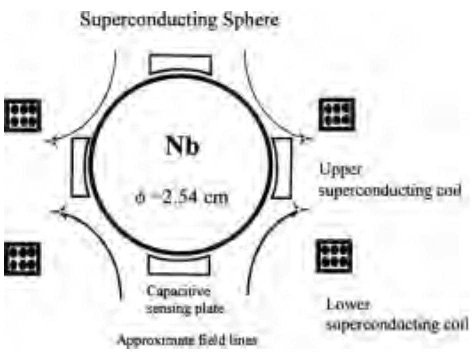
Lockheed Martin FTG

Zero Length Spring

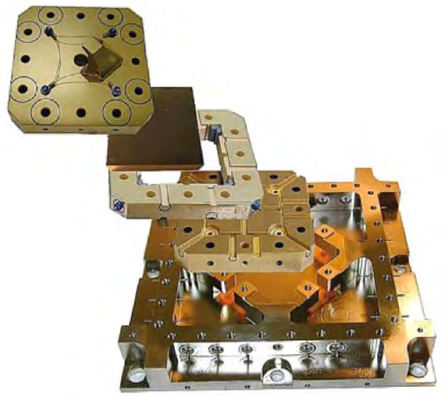


Scintrex CG5

Superconductor Levitation

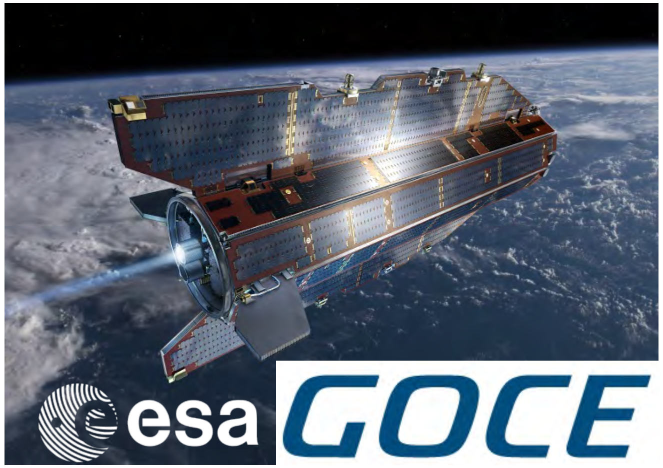


Electrostatic Sensor

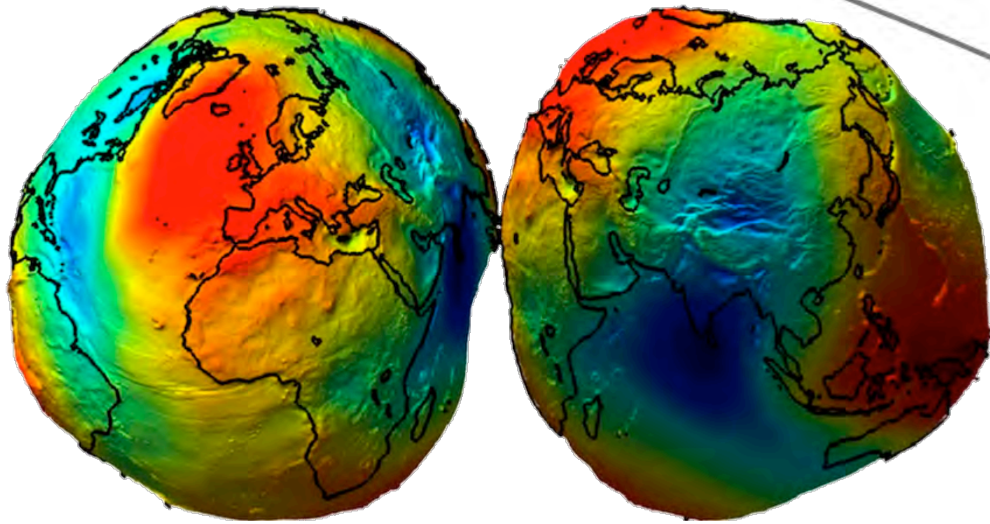


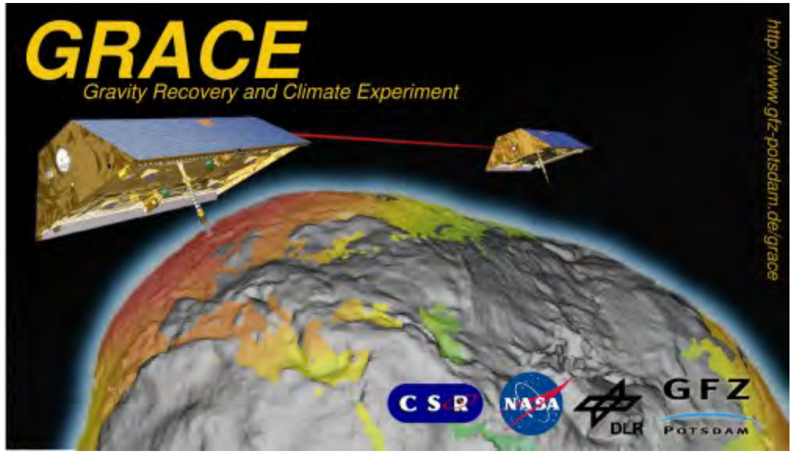
K Douch et al, Meas. Sci. Technol. 25 (2014) 105902

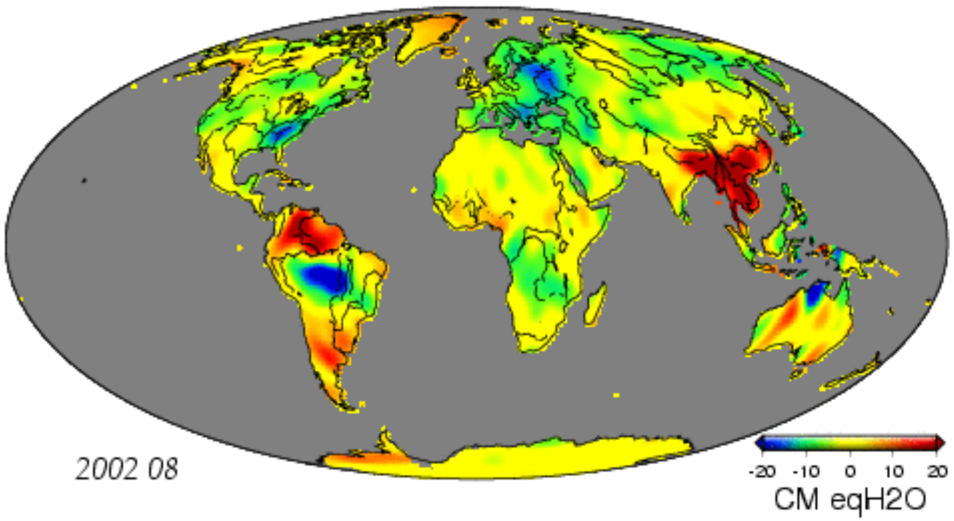
Gravity measurements



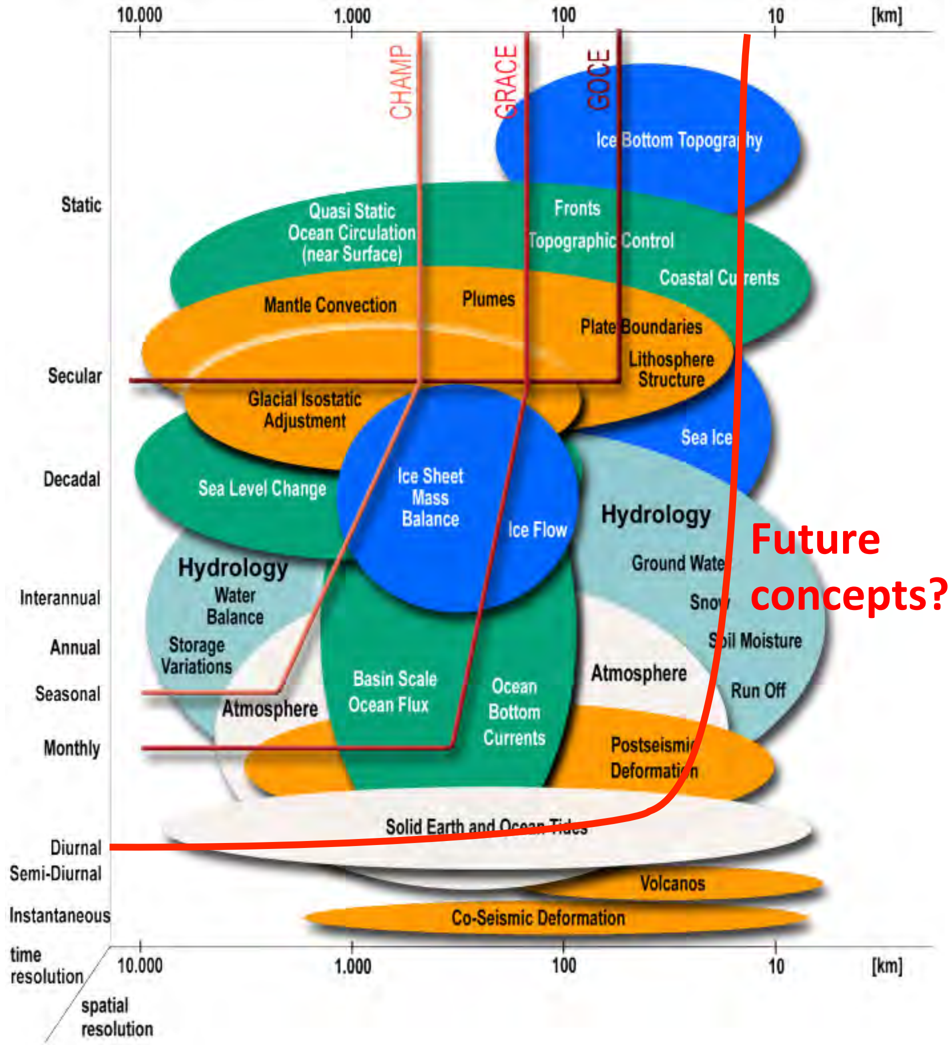
Gravity field and steady-state Ocean Circulation Explorer







Sensitivity



Source: Applications and Implementations of Atom-Based Inertial Quantum Sensors, ESA contract n. 21583/08/NL/HE, Subcontract n. C08-023 AO/1-5421/07/NL/HE, St14.April 2009

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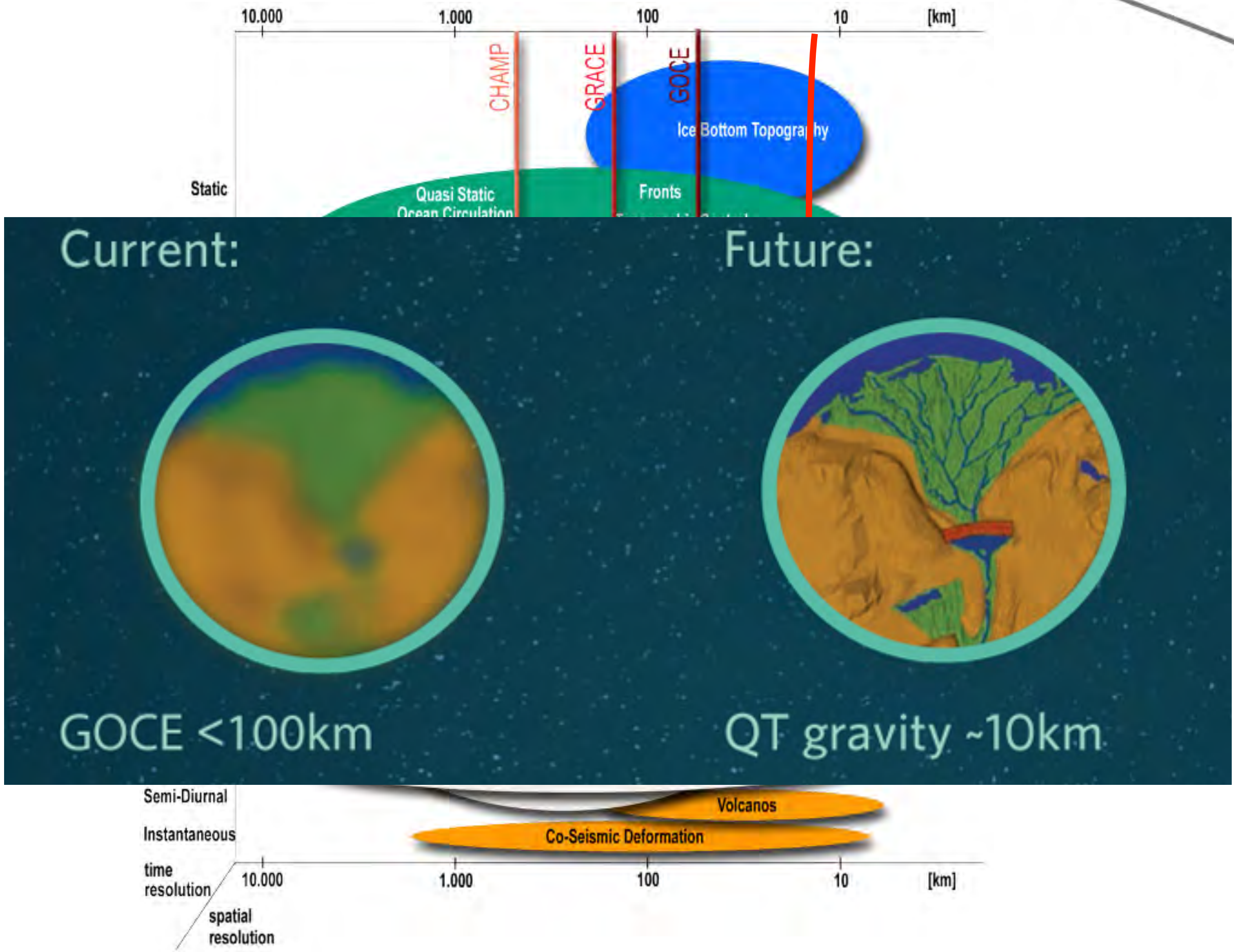

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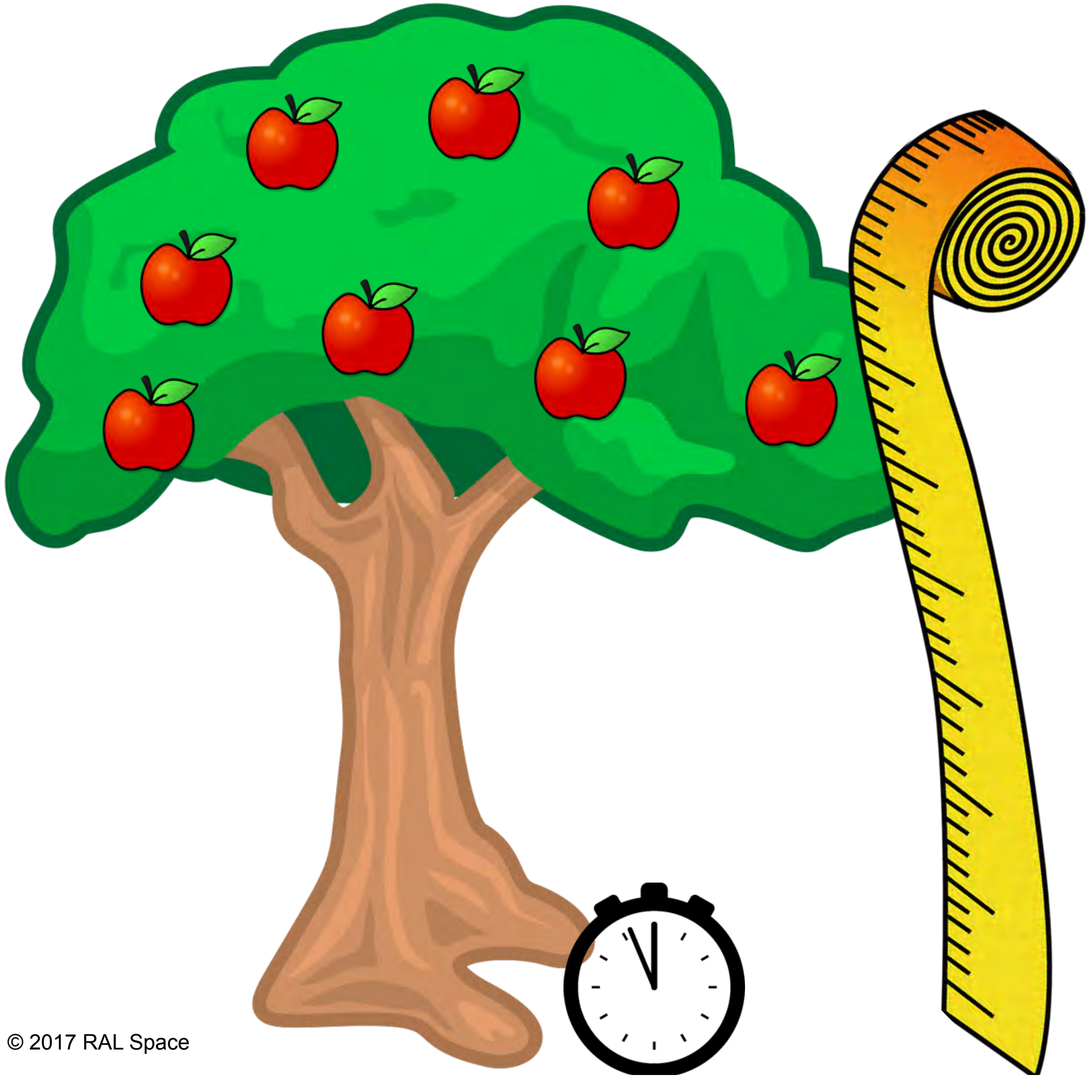
How we can improve?



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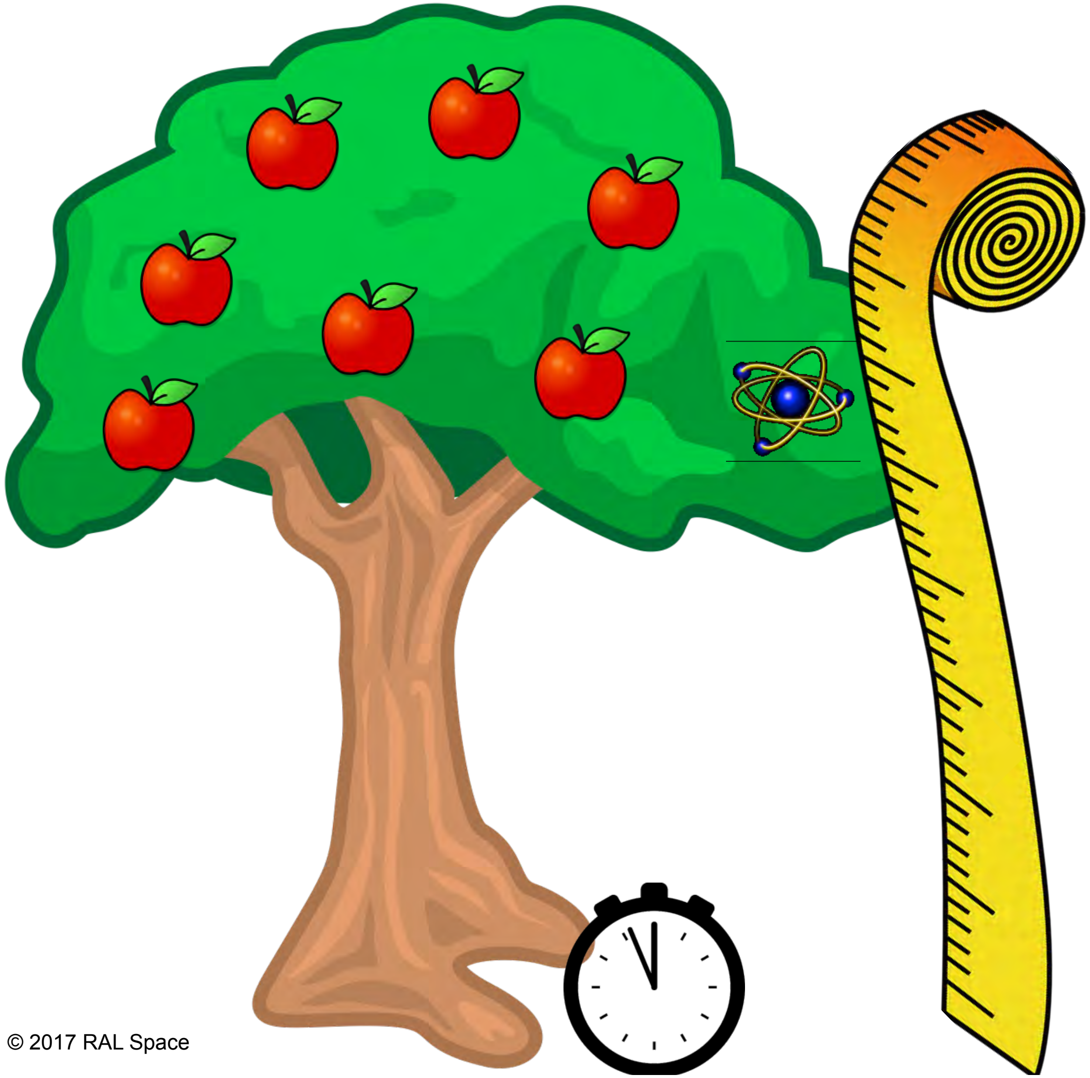

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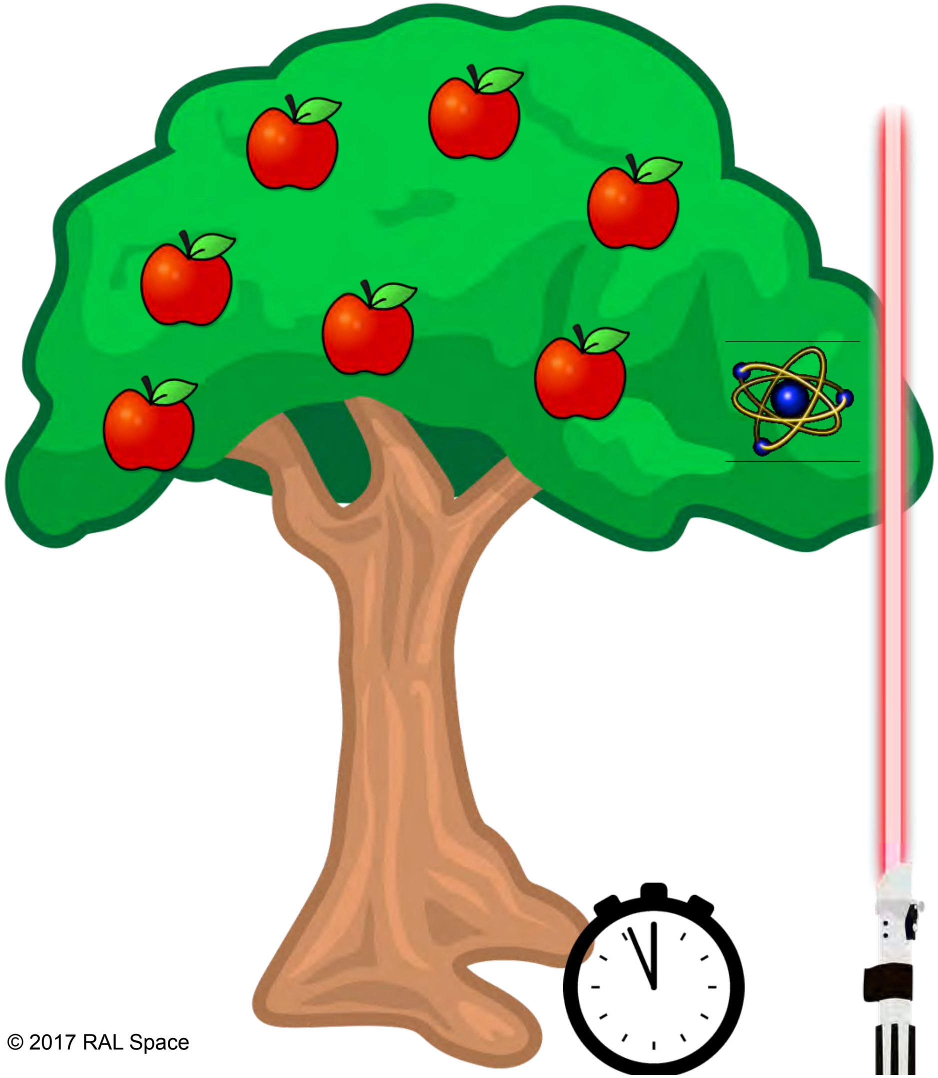

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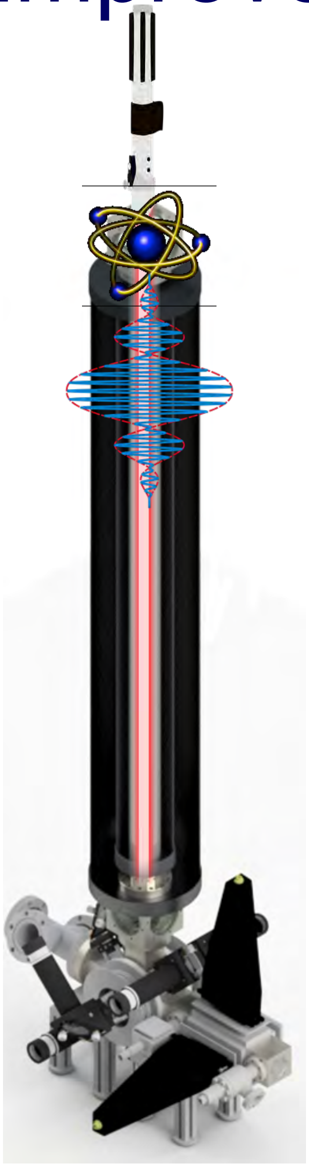
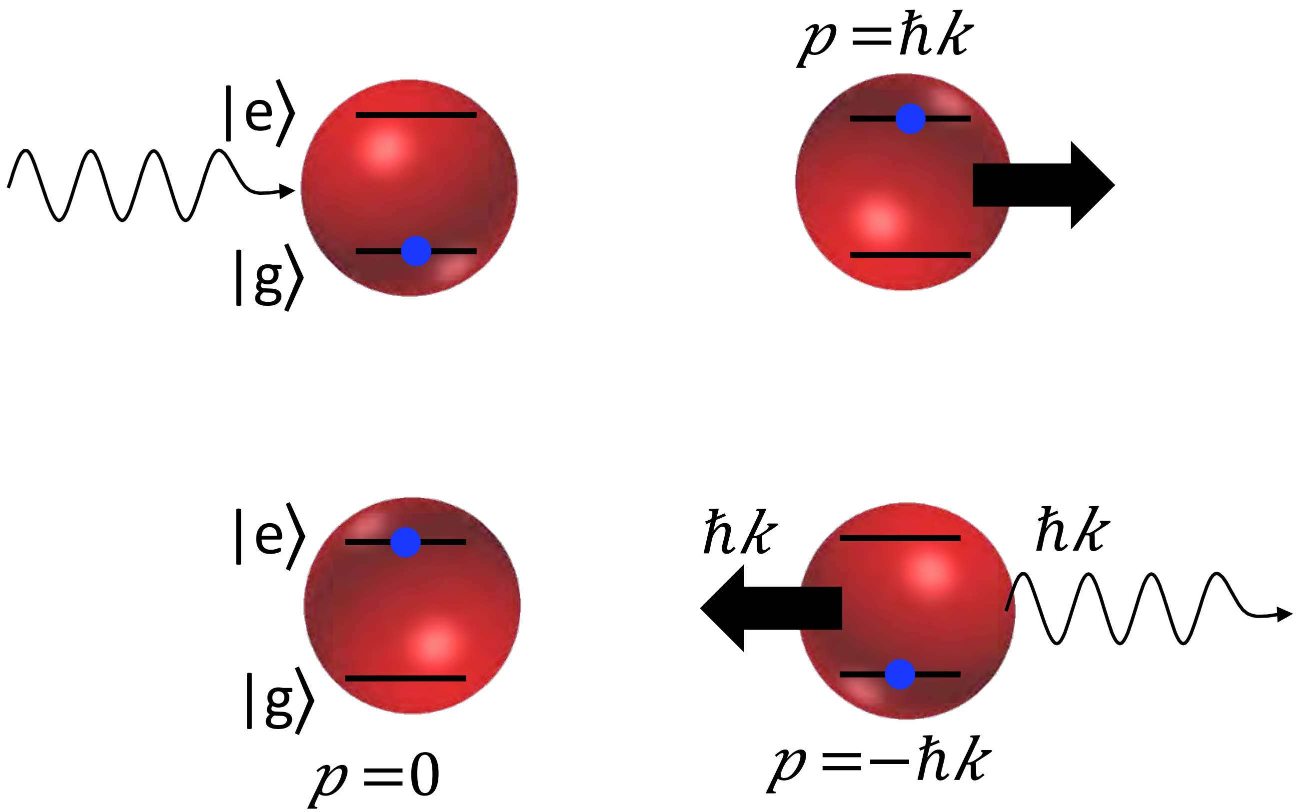


Momentum Conservation

Two level atom

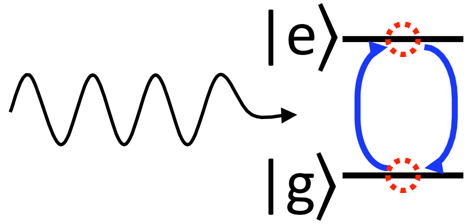
$E = \hbar\omega$
$p = \hbar k$



$|p| = E/c$
$|k| = \omega/c = 2\pi/\lambda$

Rabbi Oscillation

Two level atom



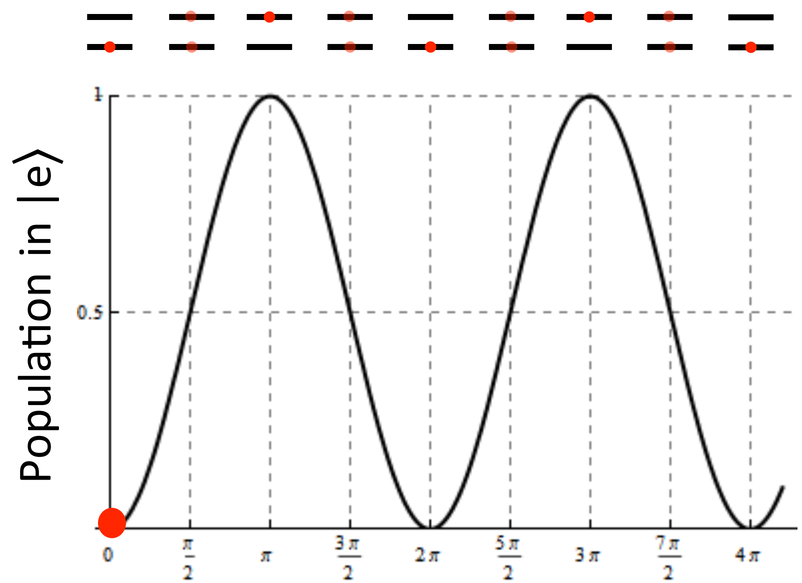
Population in |e⟩ ~ $\cos^2(\Omega_r t)$

Rabi frequency → $\Omega_r = \sqrt{\Omega_{eg}^2 + \delta^2}$

$$\Omega_{eg} = e d \cdot E_0 \; g / \hbar$$

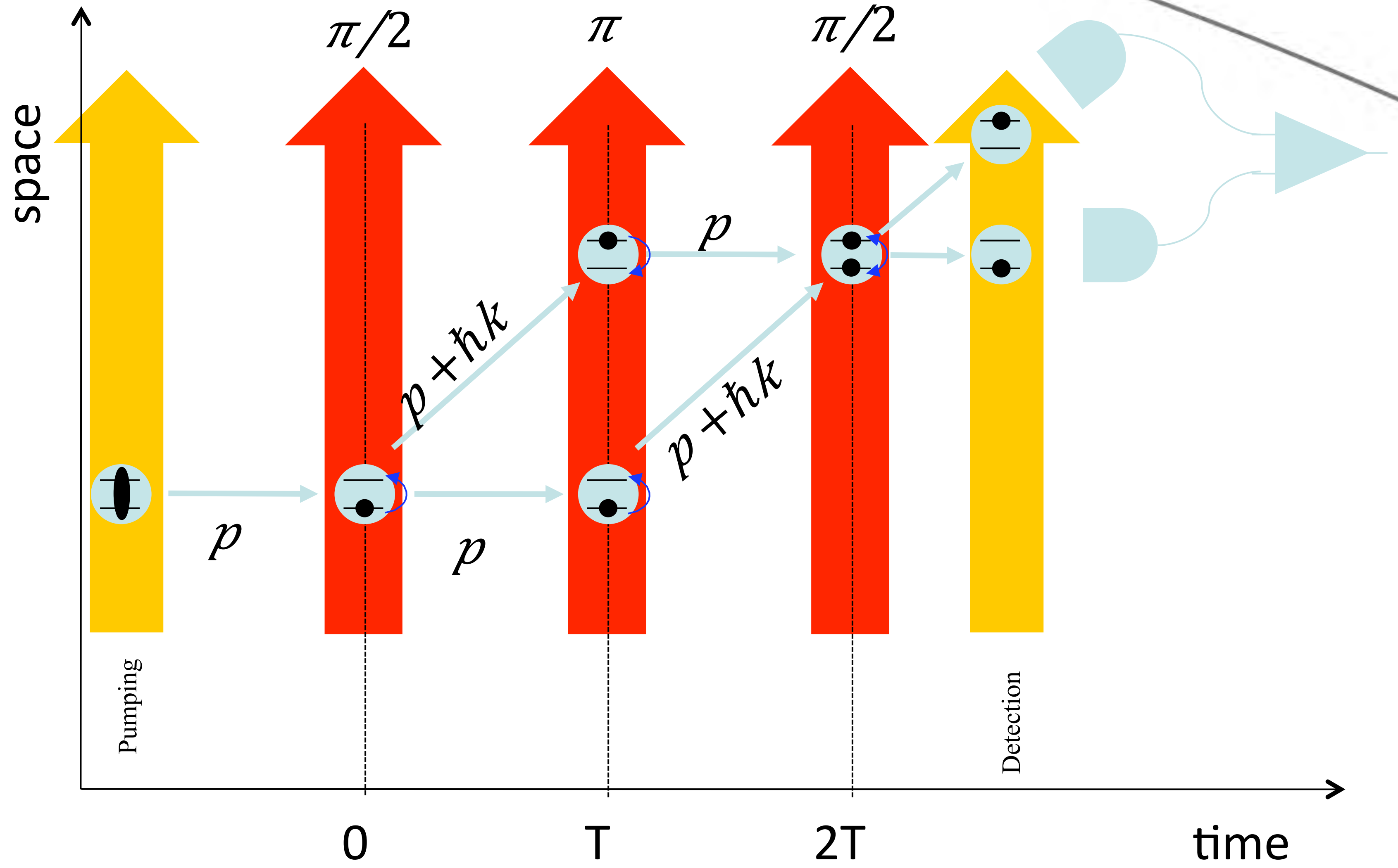
$$\delta = \omega_L - \omega_{eg}$$

$$\omega_{eg} = E_{eg} / \hbar$$

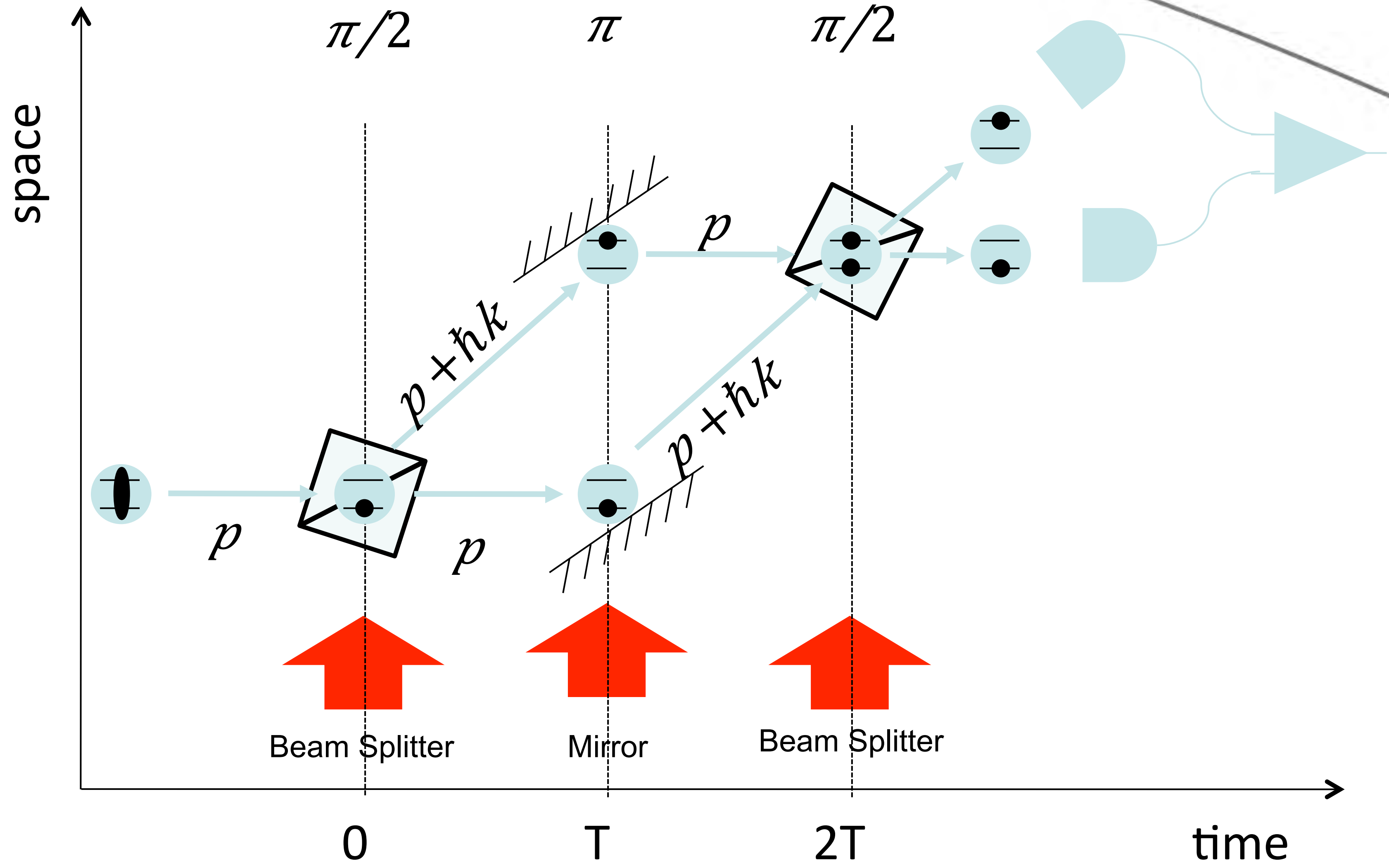


Pulse length $\times \Omega_r$

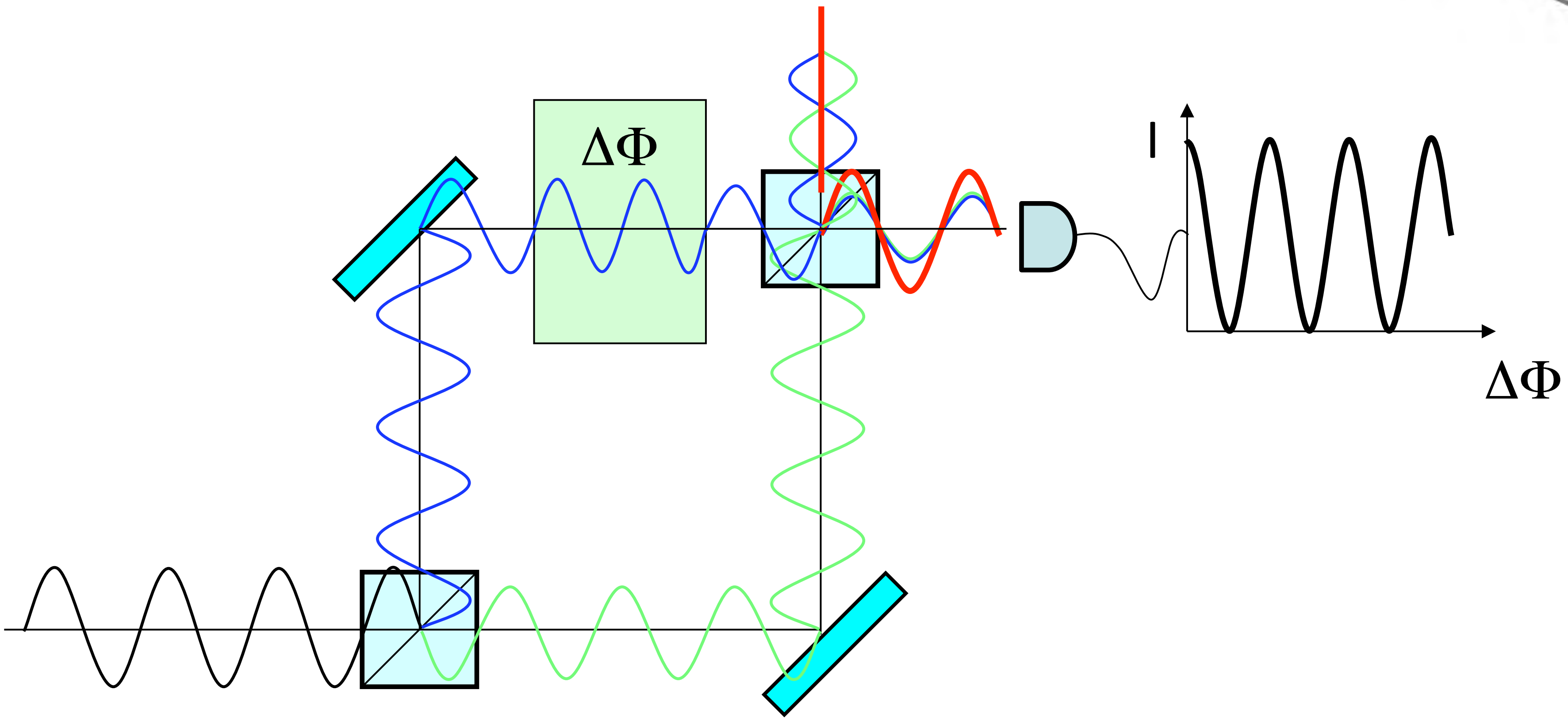
Atom Interferometer



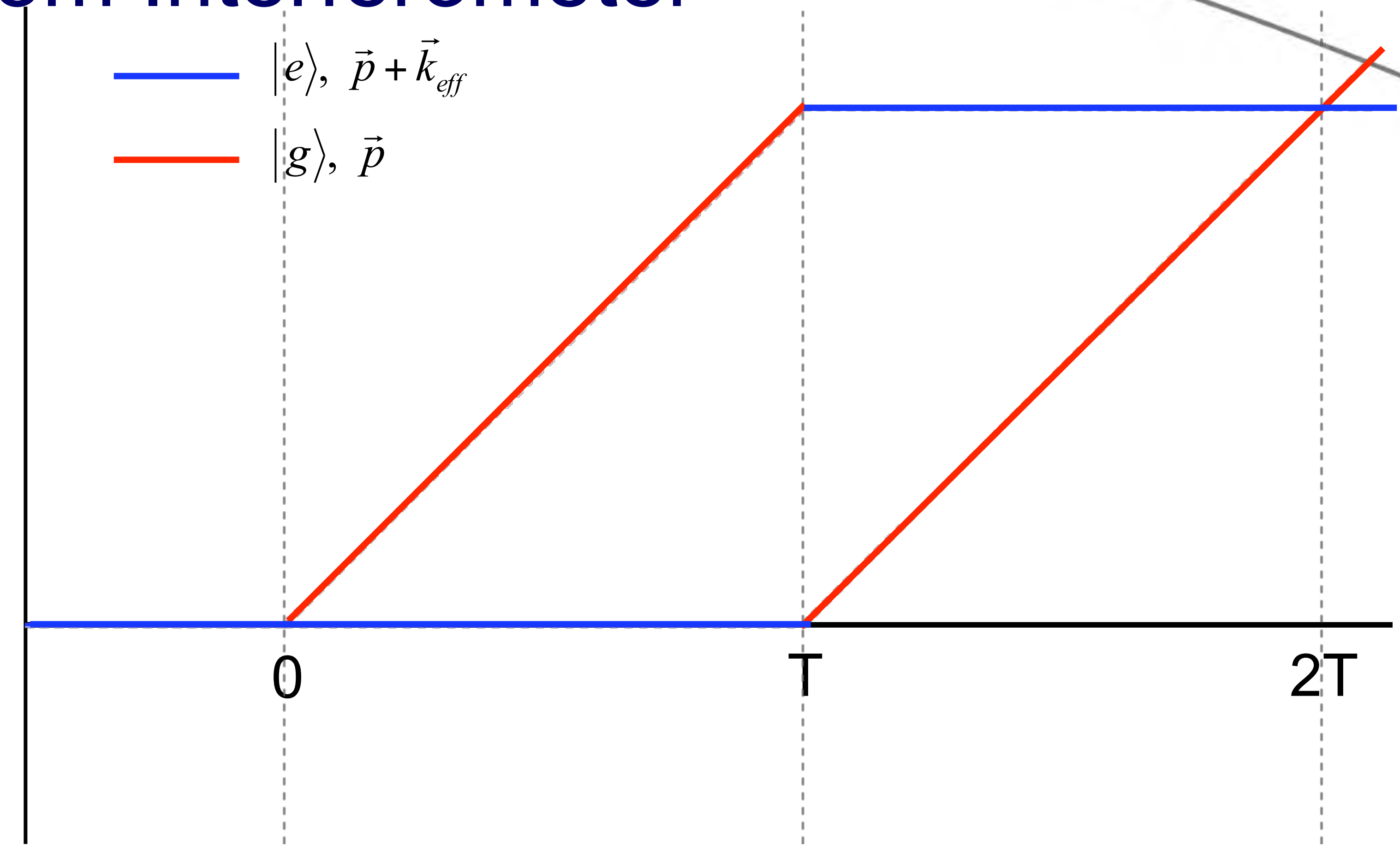
Atom Interferometer



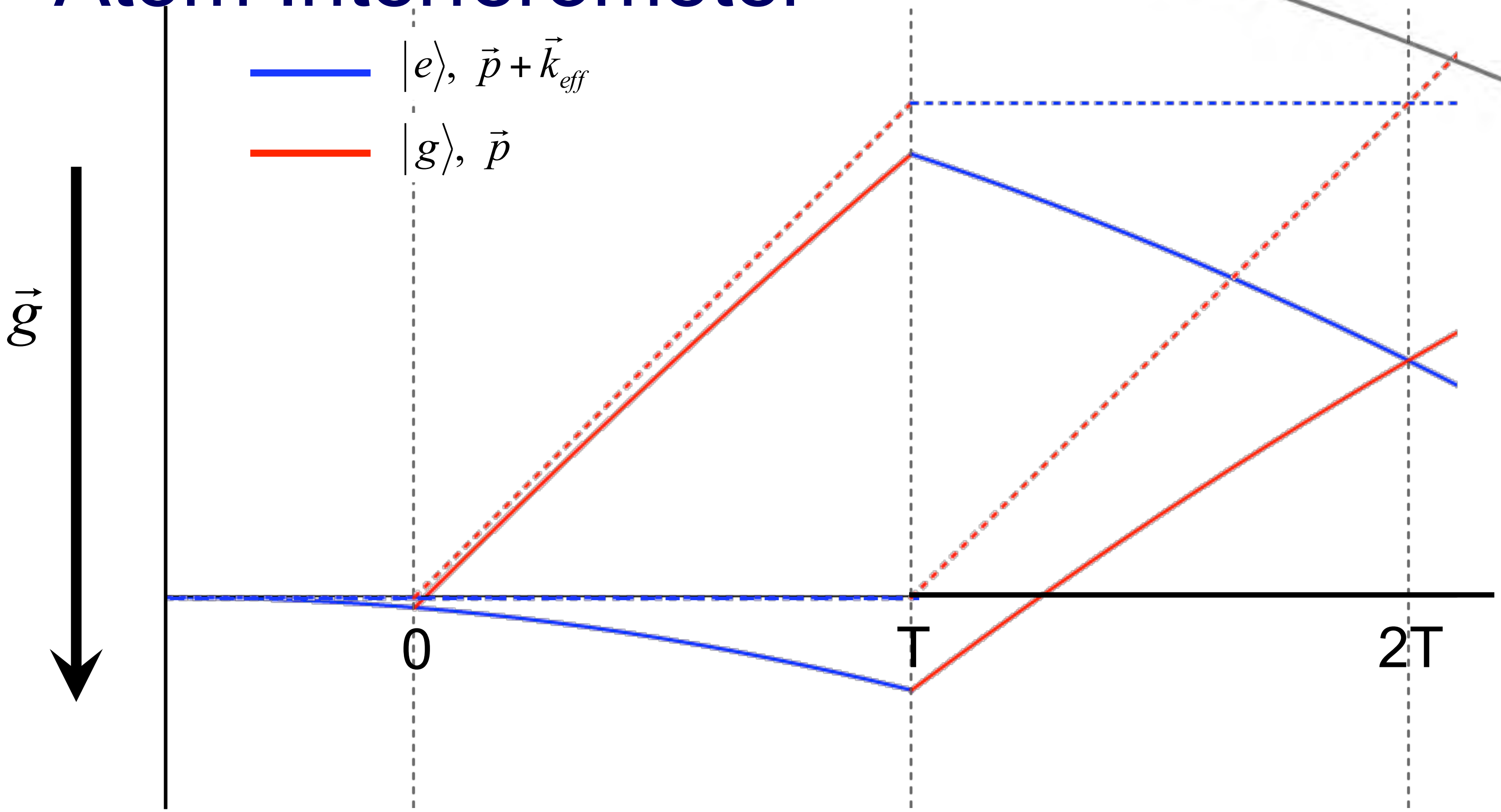
Mach-Zehnder Interferometer



Atom Interferometer



Atom Interferometer



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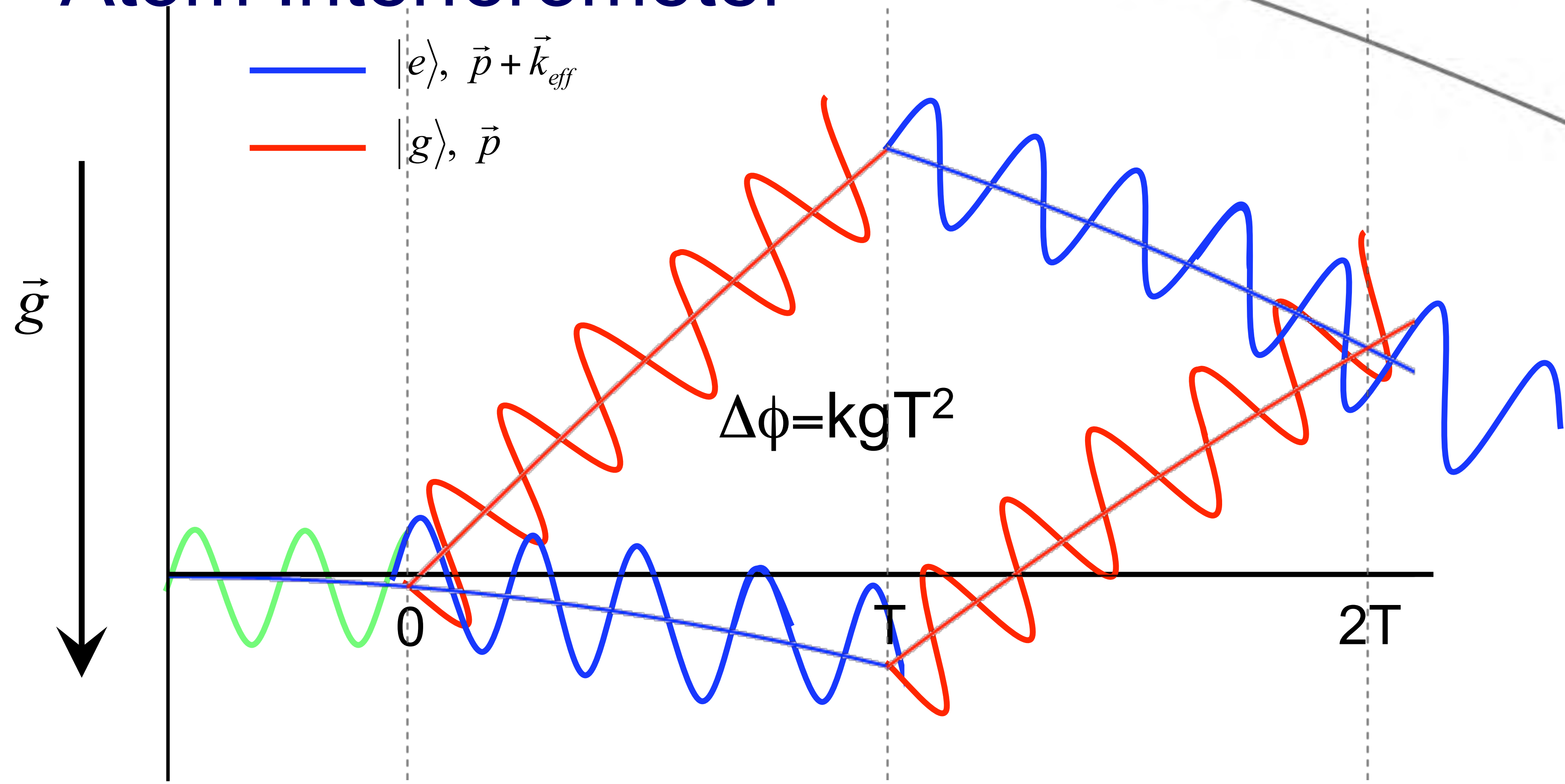
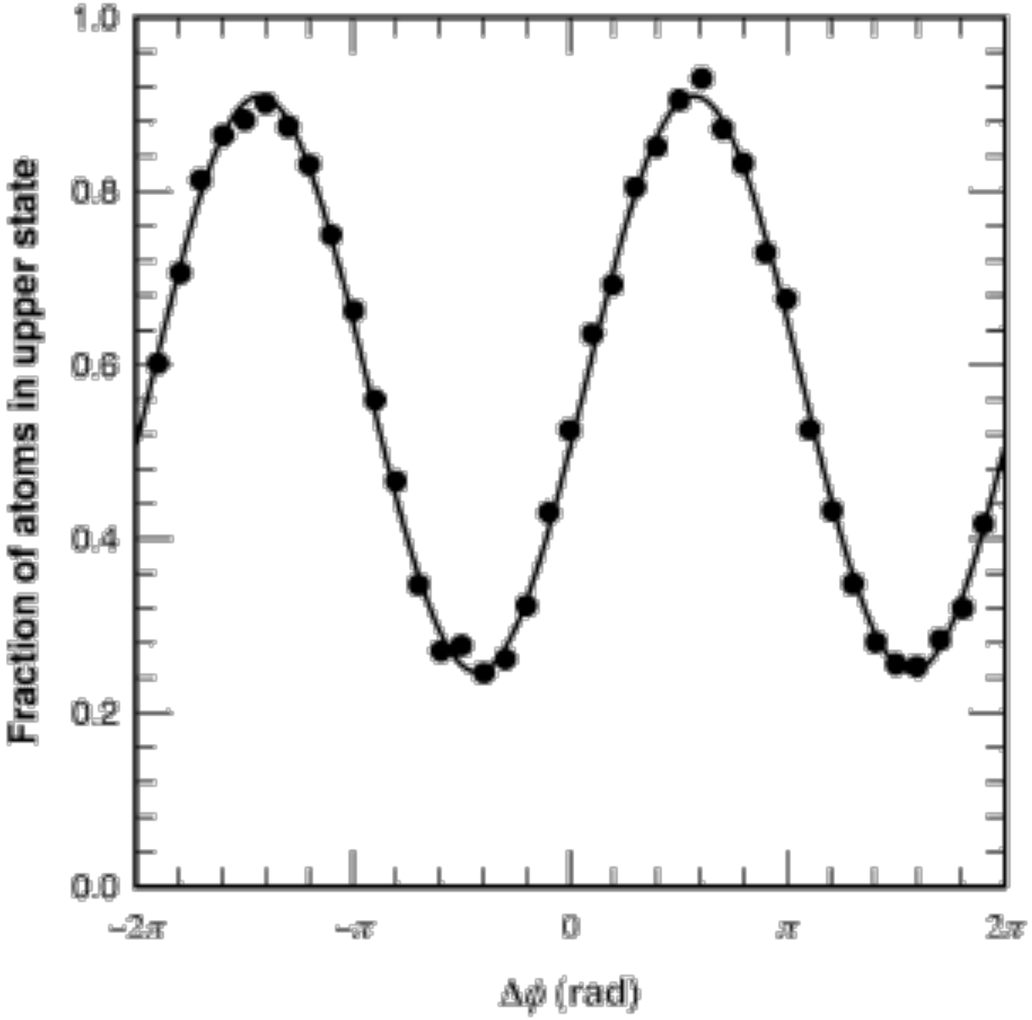


Measurement Example



A. Peters, *et al.* Phil. Trans. R. Soc. Lond. A **355**, 2223 (1997).

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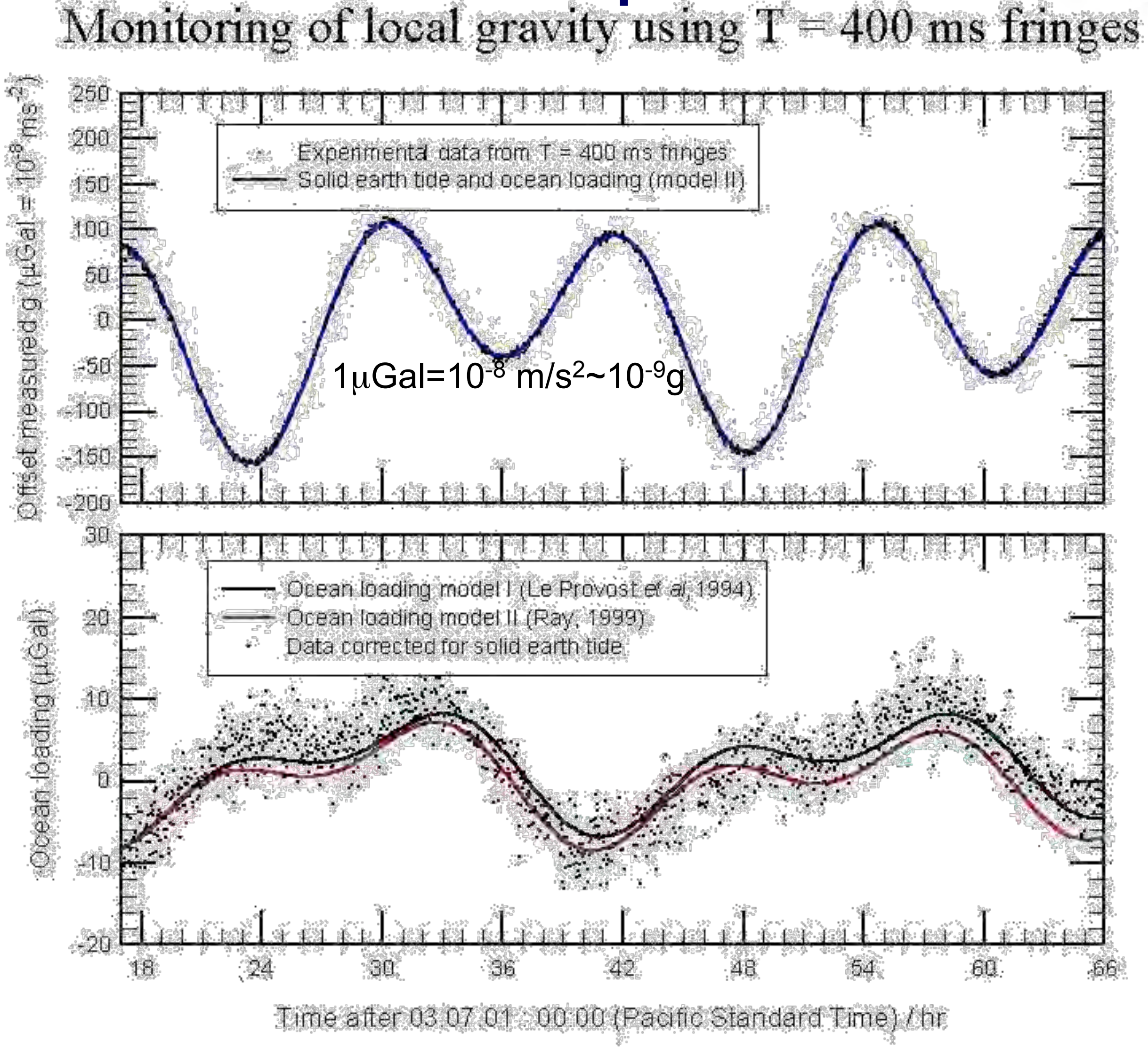
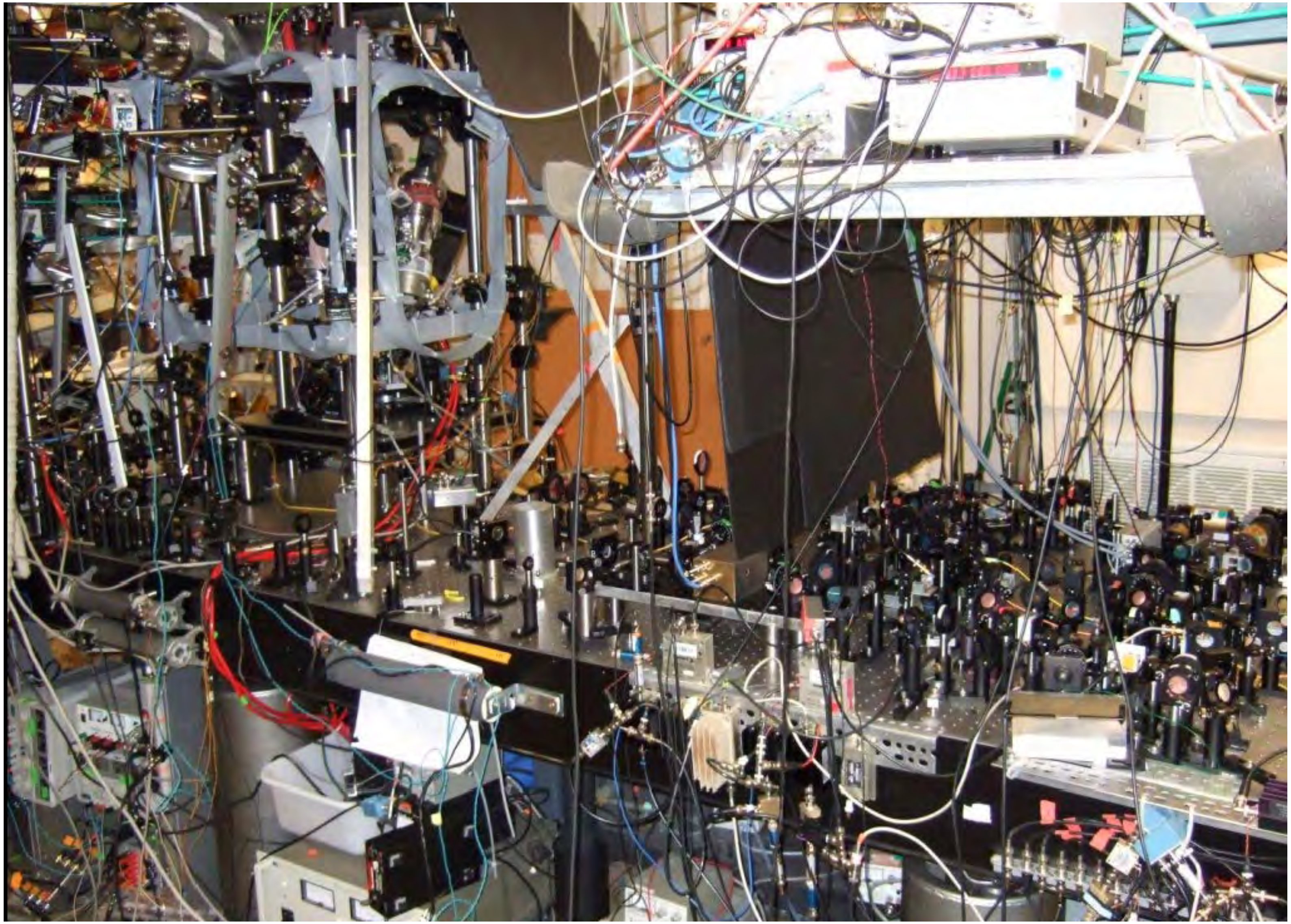


A. Peters, *et al.* Phil. Trans. R. Soc. Lond. A **355**, 2223 (1997).

Typical Lab Setting



H. Müller lab @ Berkeley (http://matterwave.physics.berkeley.edu/)

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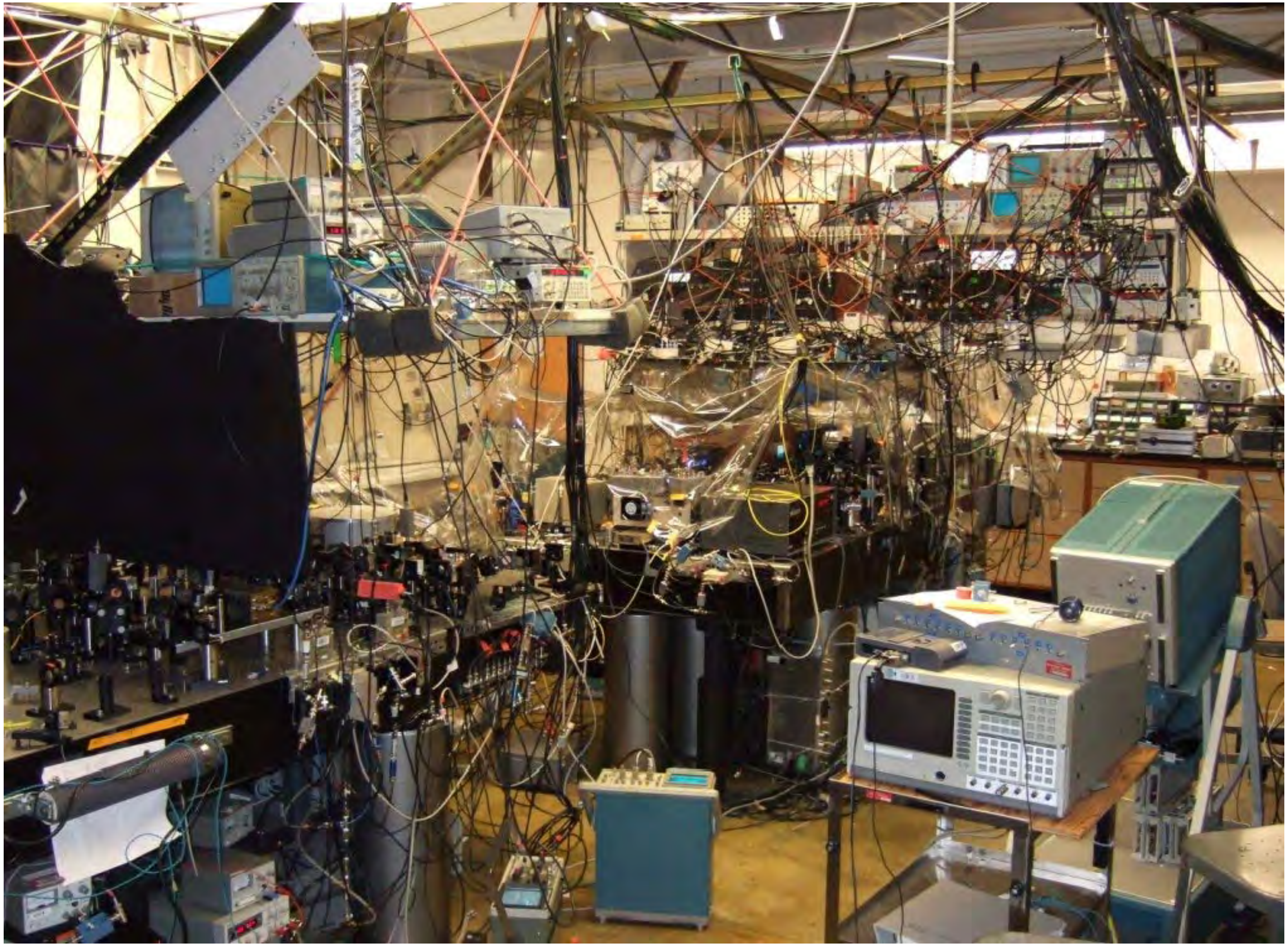

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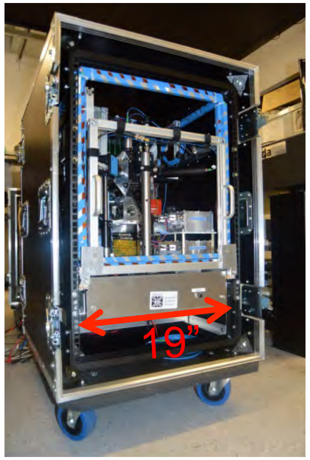
RAL Space

Projects outside of the Lab: UK

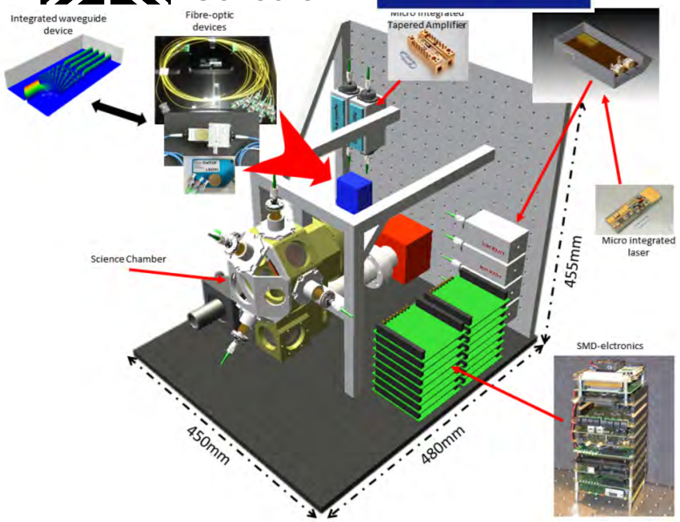


EPSRC

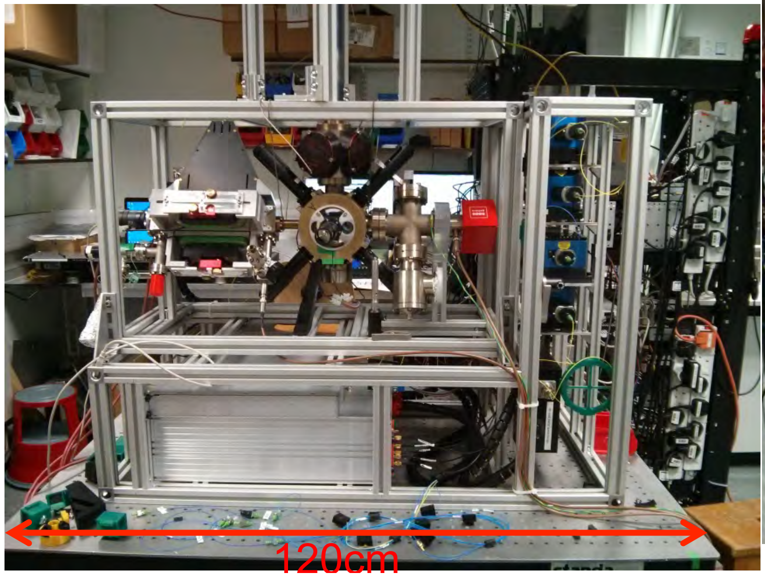
GG top

UNIVERSITY OF BIRMINGHAM

iSENSE Integrated Quantum Sensors



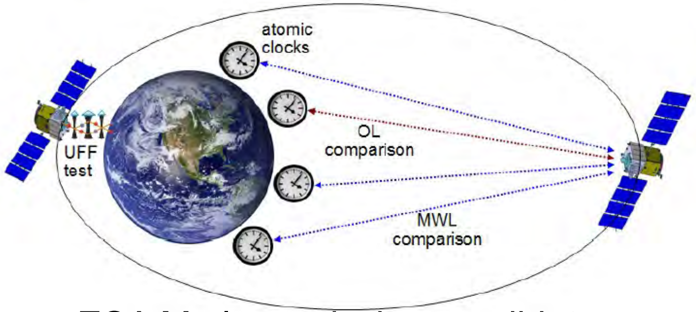
www.isense-gravimeter.eu



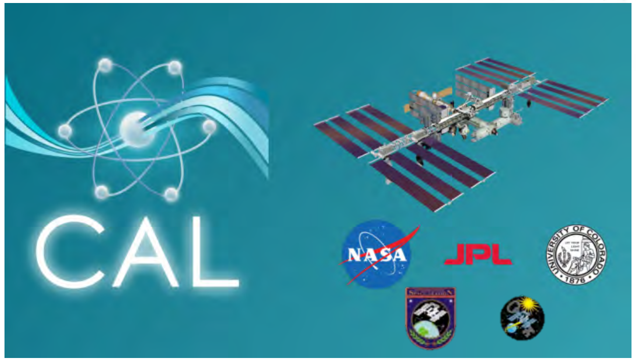
www.gg-top.org

Other Projects outside of the Lab

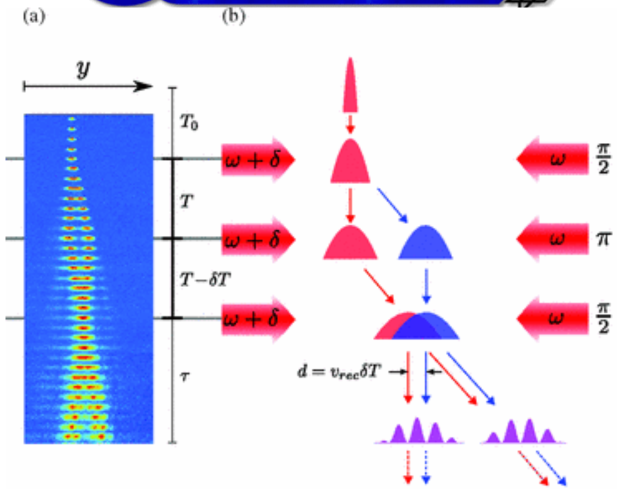
STE-QUEST



ESA M-class mission candidate



QUANTUS



Science **328**, 1540 & Phys. Rev. Lett. **110**, 093602

Launched 2017

MAIUS: DLR 50 WM 0346

Quantum Tech at RALSpace

Leading an ESA TRP activity

⇒ Design and characterize a vacuum chamber able to deliver an ultracold atomic clouds at a 1Hz rate

concept: Microgravity Science and Technology, v. 26, pp 139-145 (2014)

Development of Ancillary Technologies

⇒ Partnering in Innovate UK projects for the development of

- ❖ Space qualified lasers (in the visible domain)
- ❖ Space qualified laser control electronics

Development of Own Capabilities

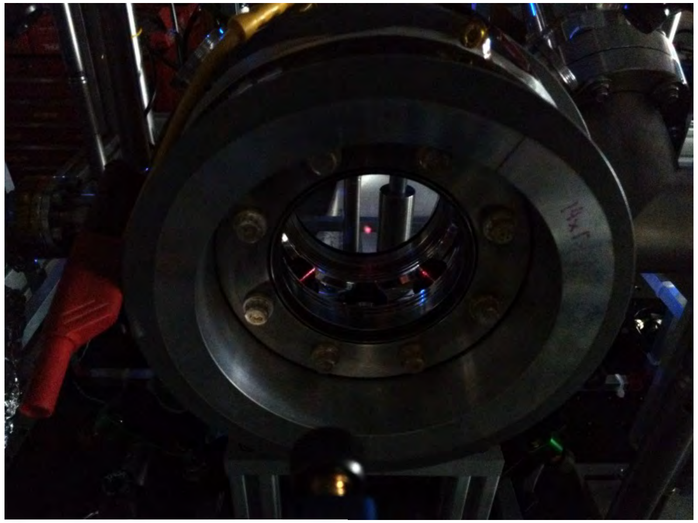
⇒ Full experiment control electronics (to be space qualified)

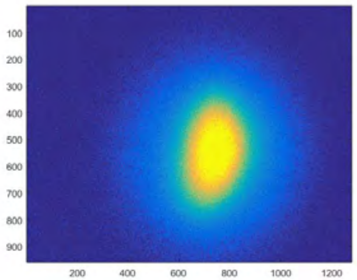
⇒ Cold Atoms test bed facility and optimization studies

Quantum Tech at RALSpace

Cold Atoms @ RAL

Magneto Optical Trap

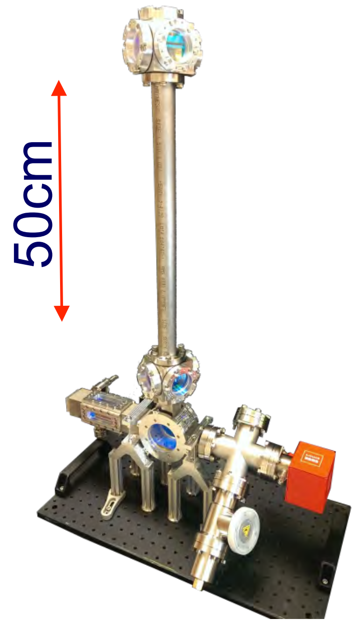




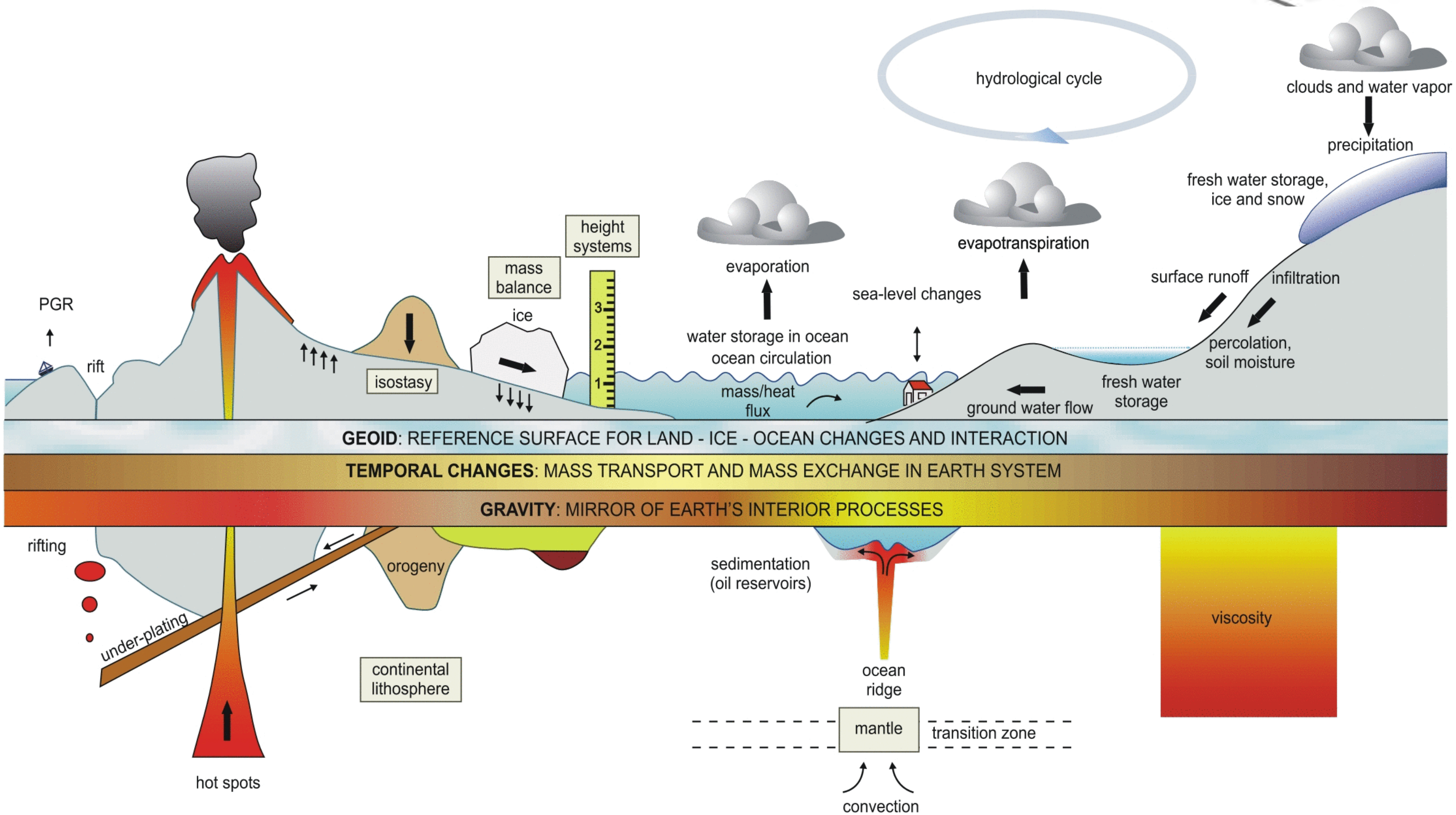
T=15(2)μK

N~10^9 Atoms

Gravity Gradiometer



Thank you!

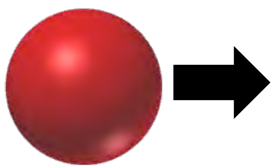


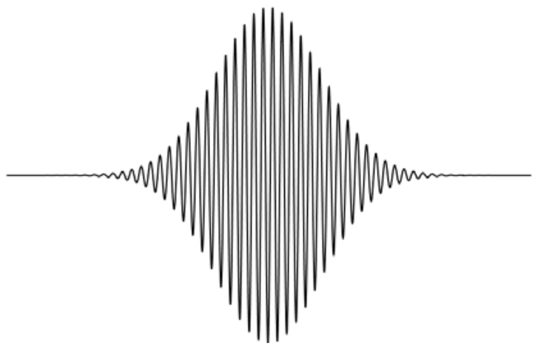
Source: Ilk, K.-H., Flury, J., et al. (2005). Mass Transport and Mass Distribution in the Earth System.

Wave-Particle Duality

- de Broglie, Ann. Phys. **3**, 32 (1925)
  $\lambda = \mathbf{h/p} = \mathbf{h/mv}$ de Broglie wavelength

- Electron diffraction by Davisson and Germer, Phys. Rev. **30**, 705 (1927)





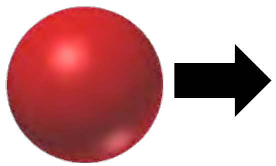
Wave-Particle Duality

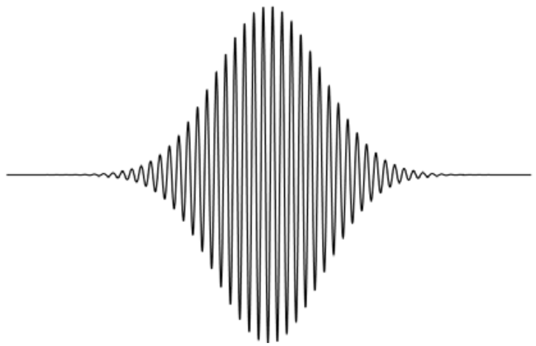
de Broglie wavelength of an Atom

$$\lambda = h/p$$

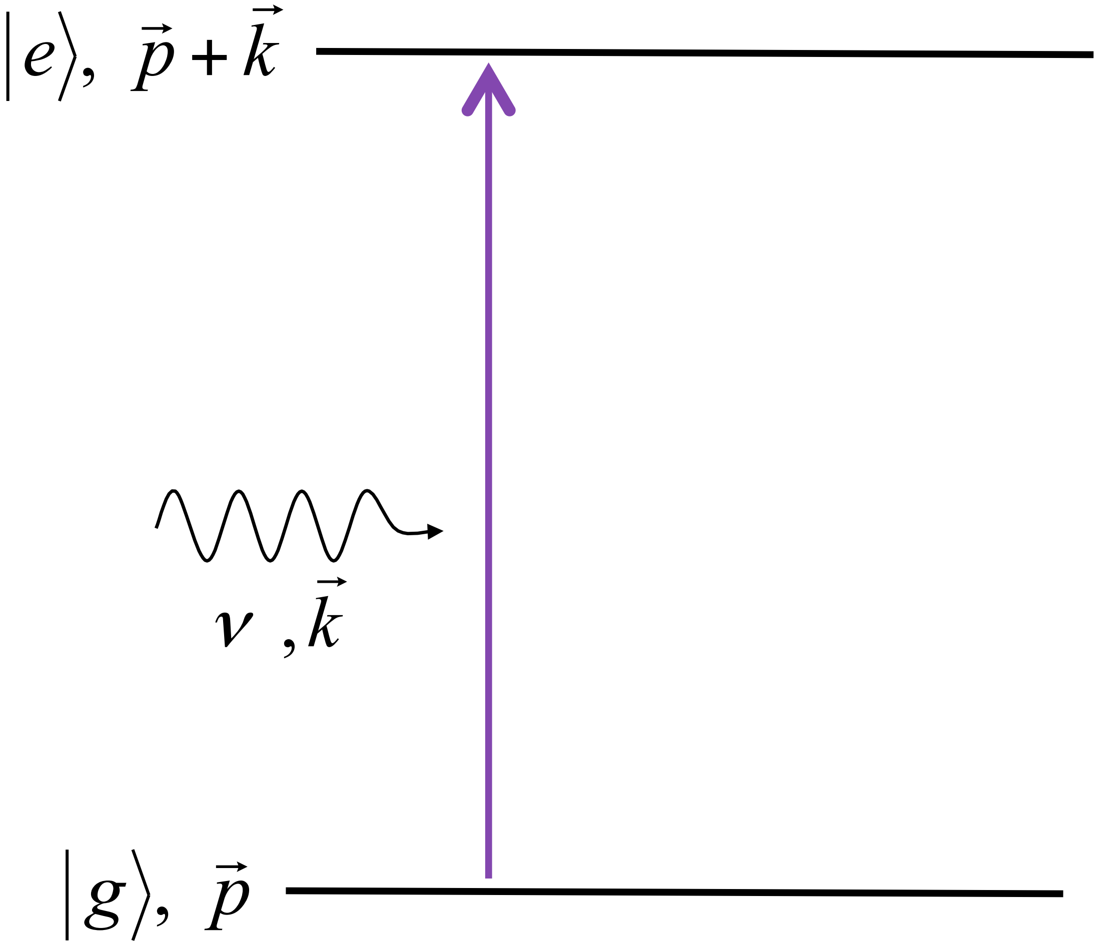
$$p = (3\ m\ k_B T)^{1/2}$$

eg. ^{87}Rb $\left.\begin{array}{l} m = 1.4\times10^{-25}kg \\ T = 10\mu K \end{array}\right\} \lambda\sim 100nm$

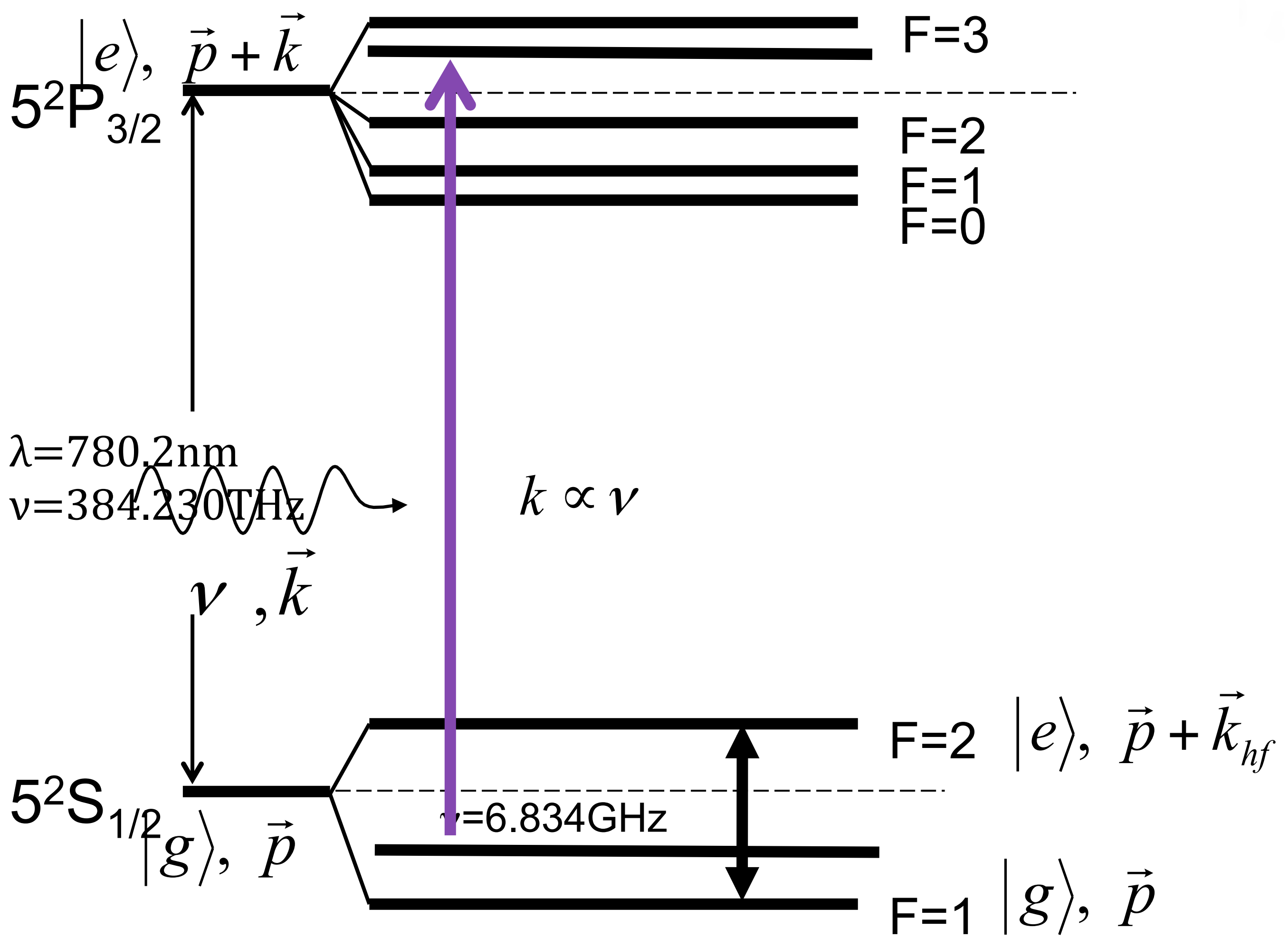




Two Level Atom?



Rubidium Atom



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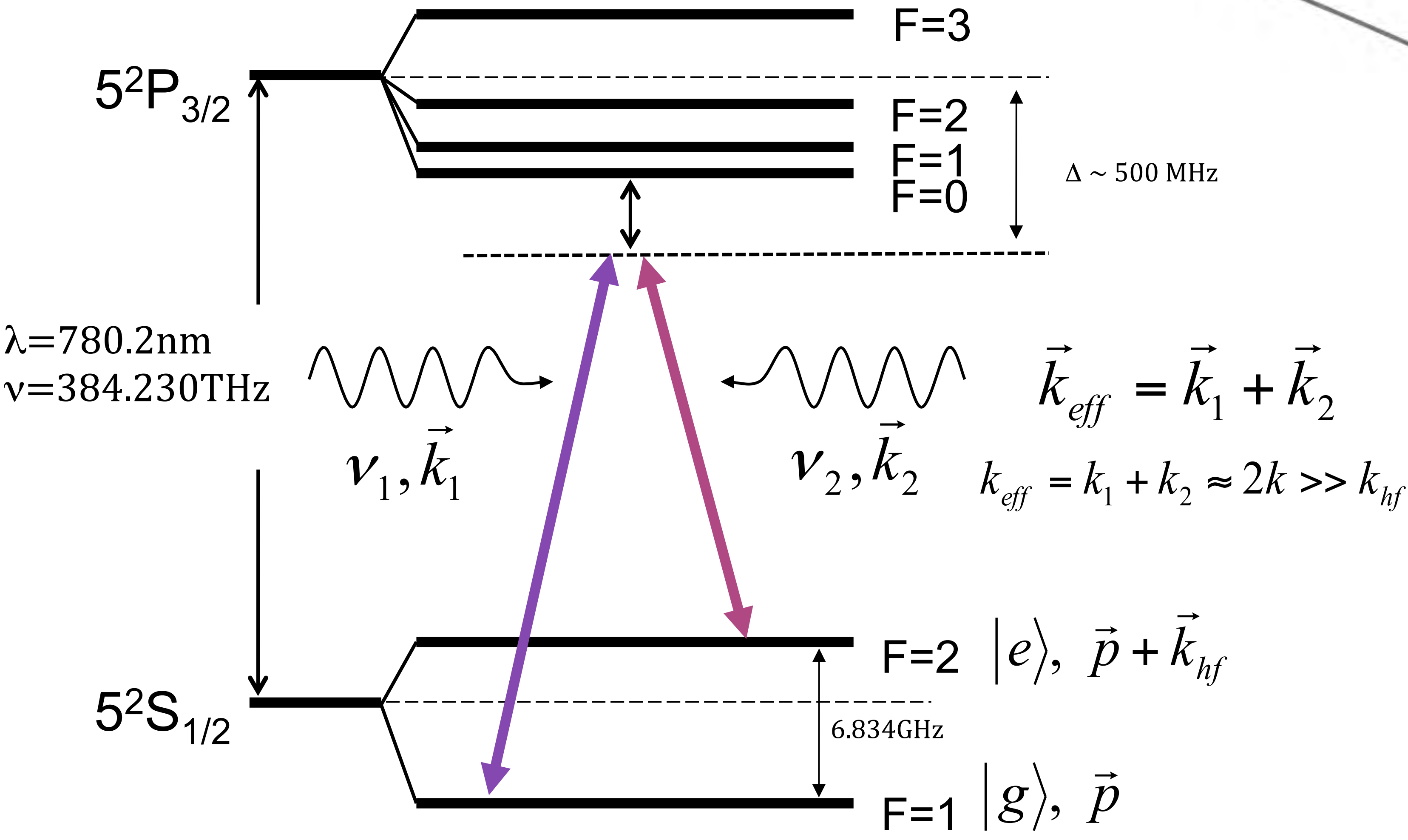
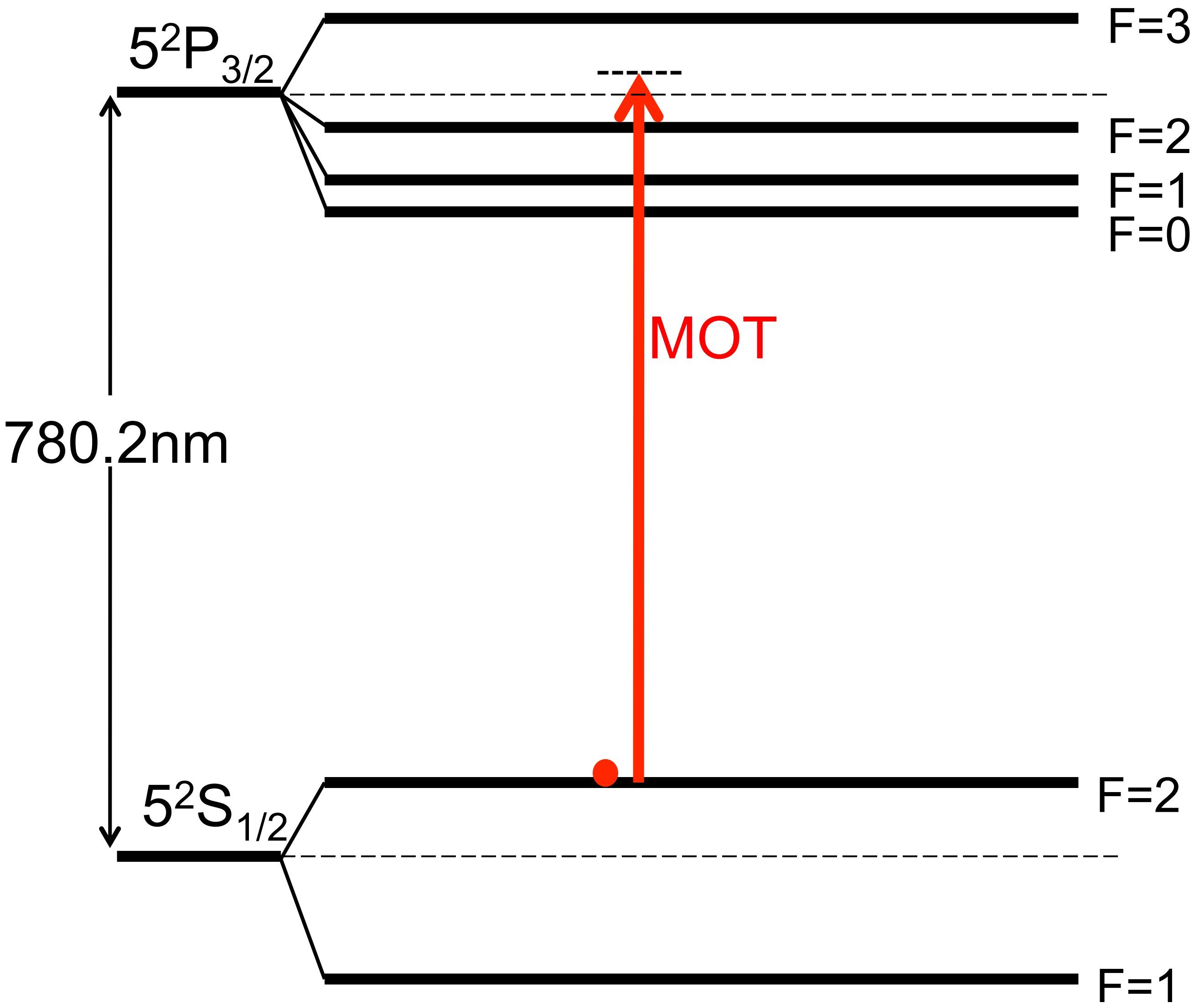


Measurement Cicle



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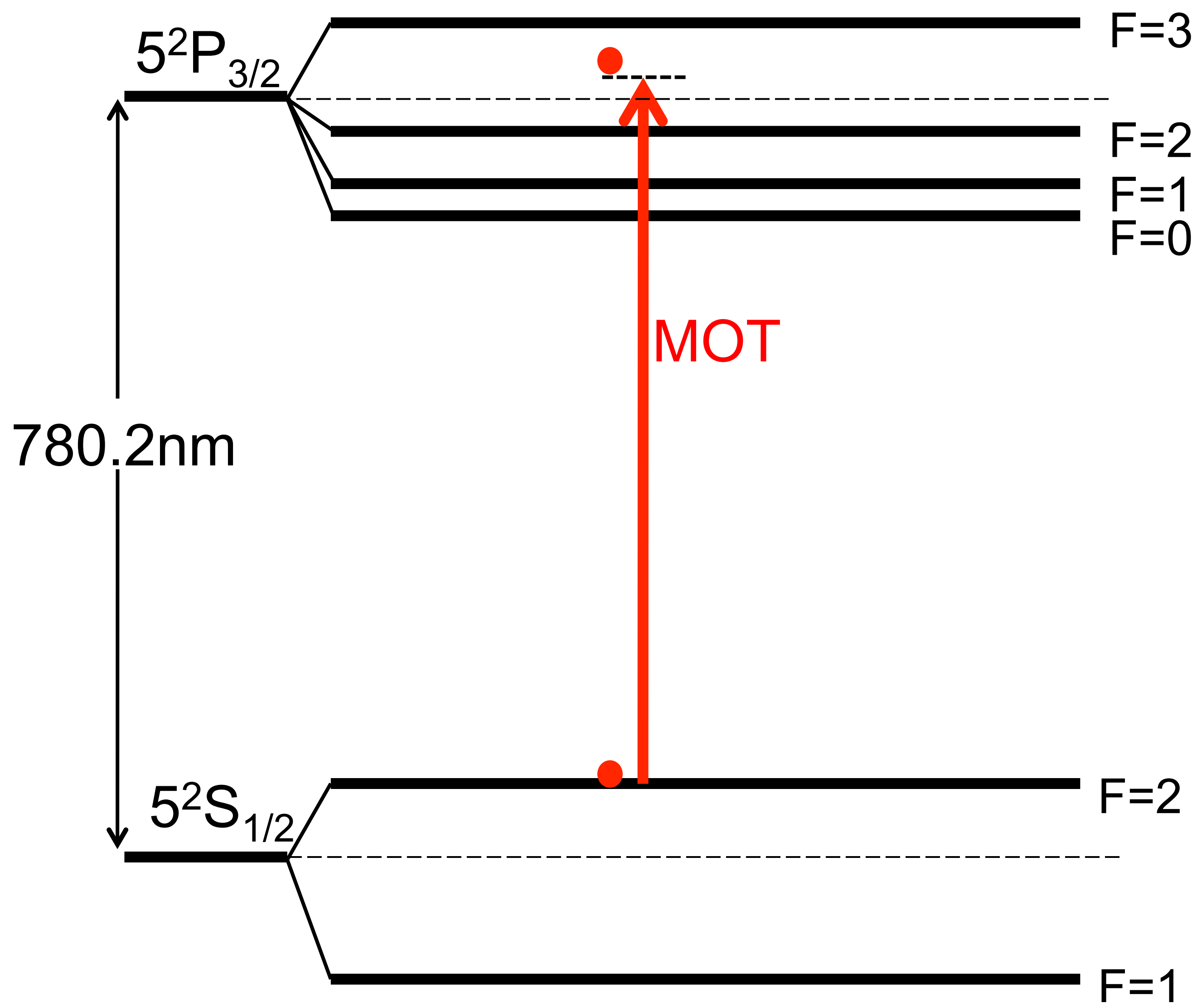

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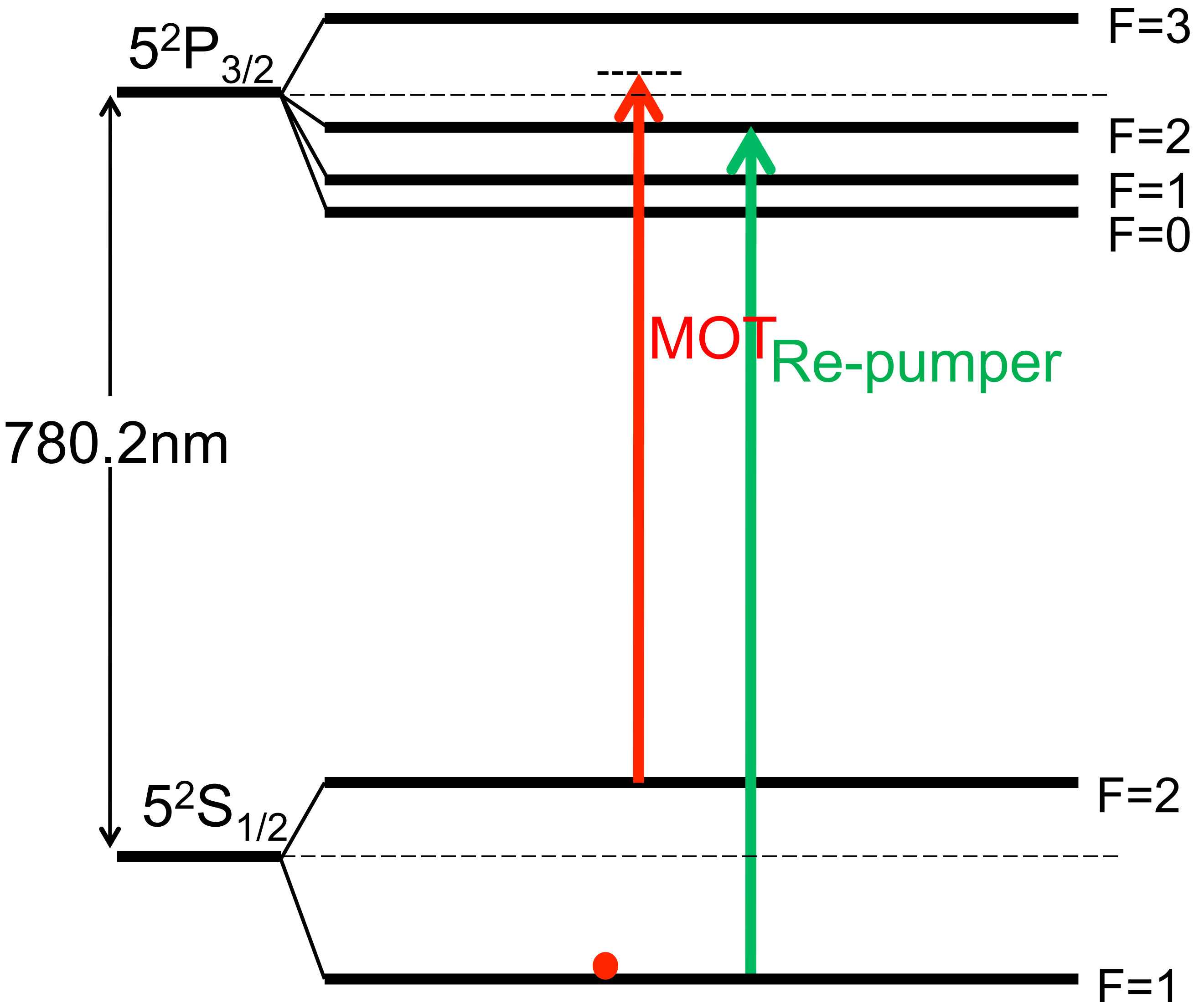

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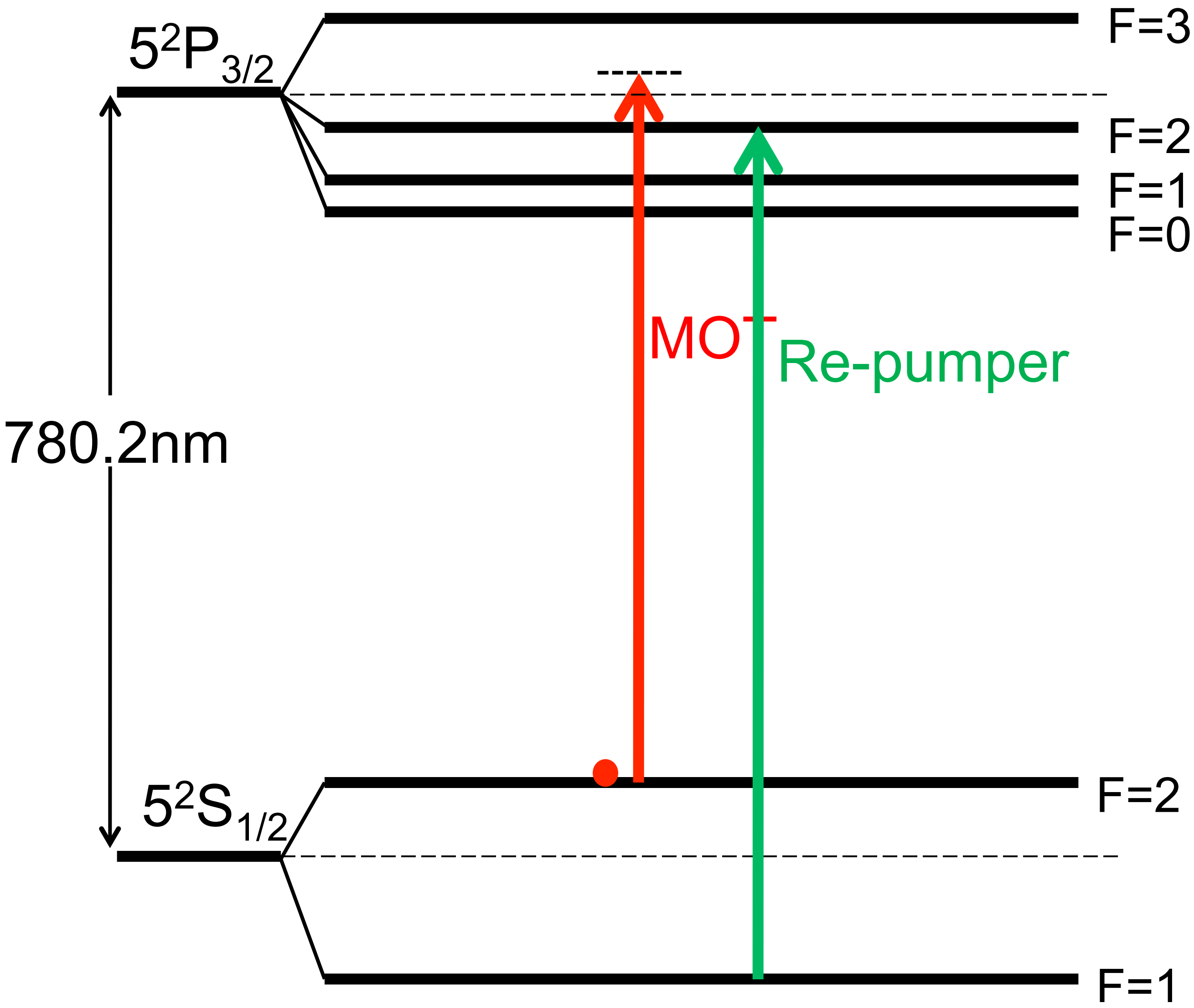

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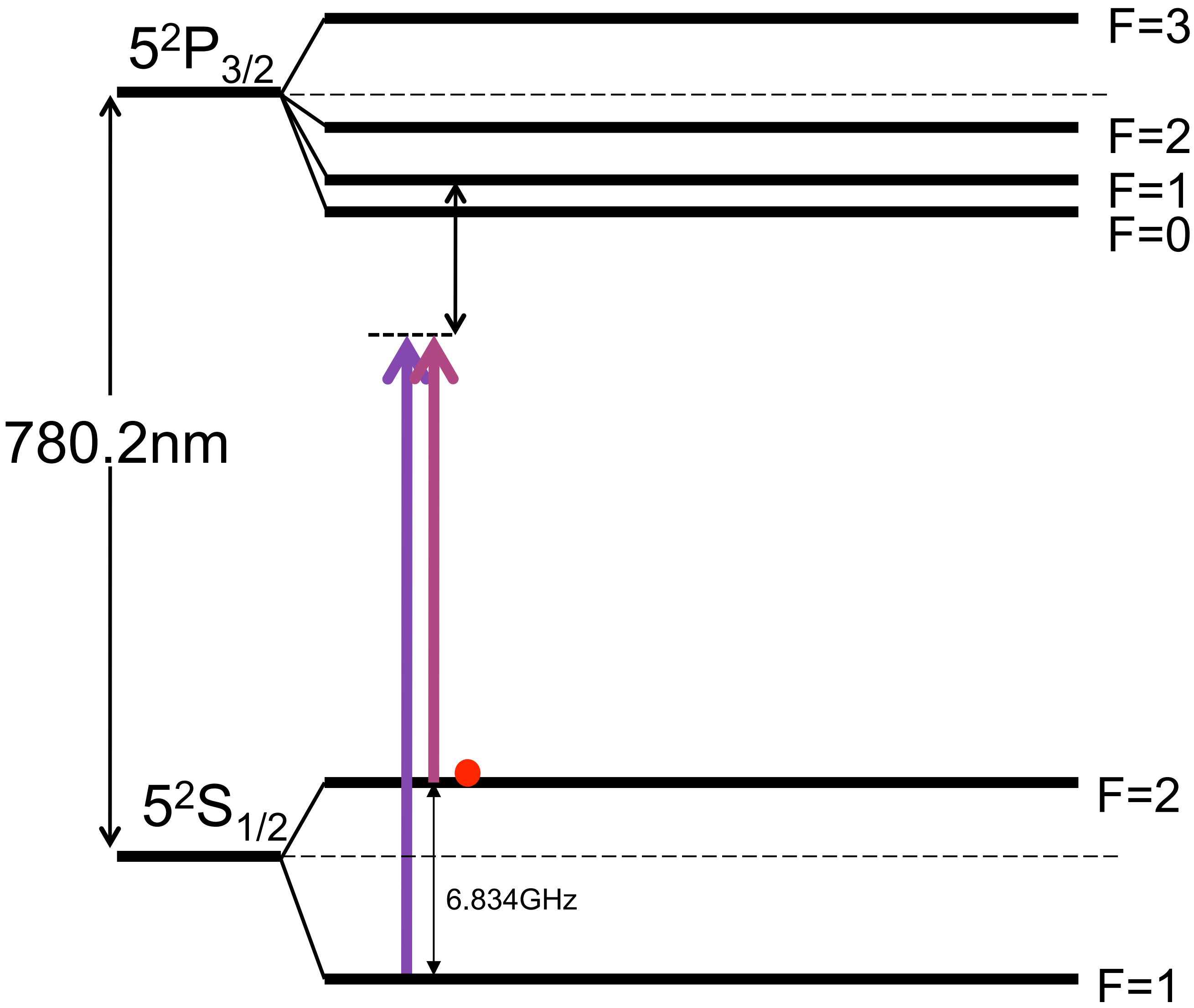

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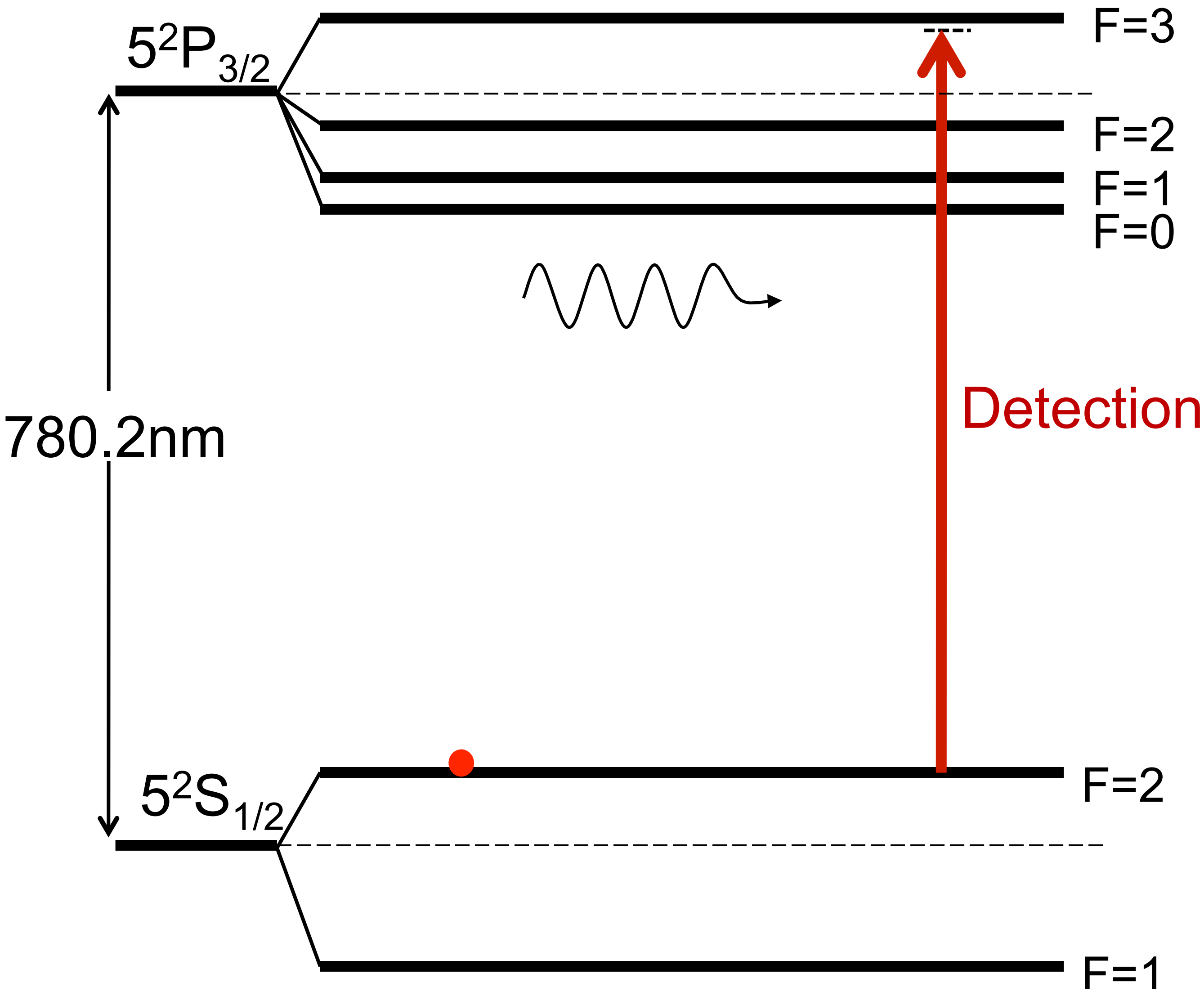
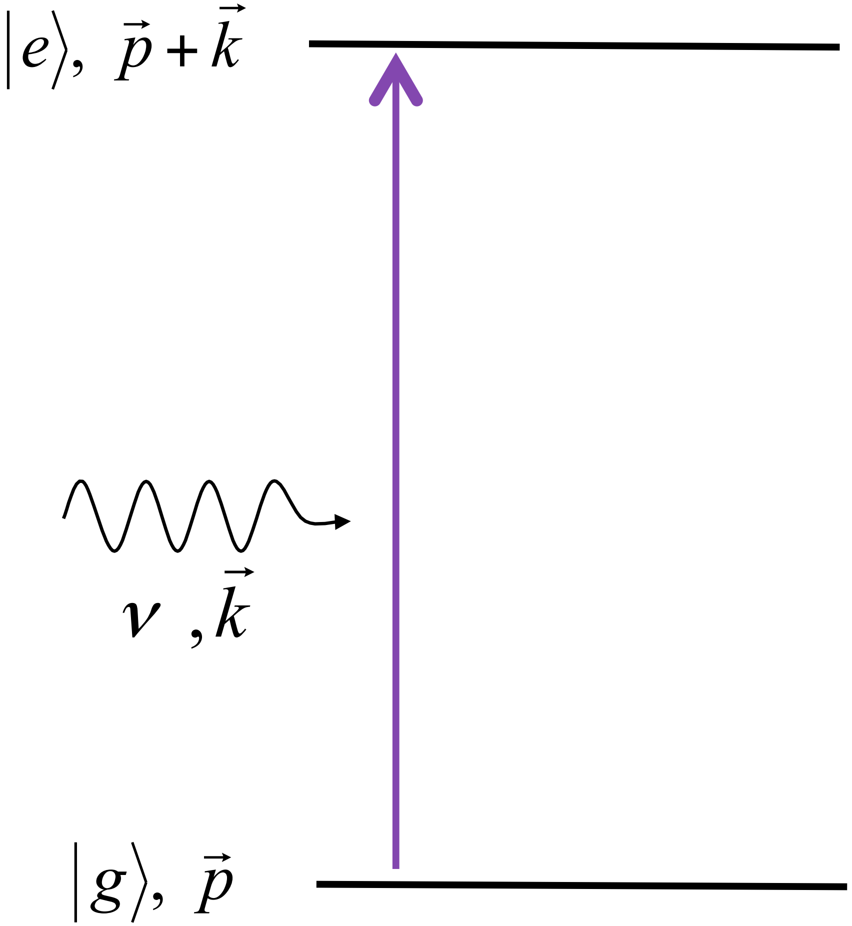
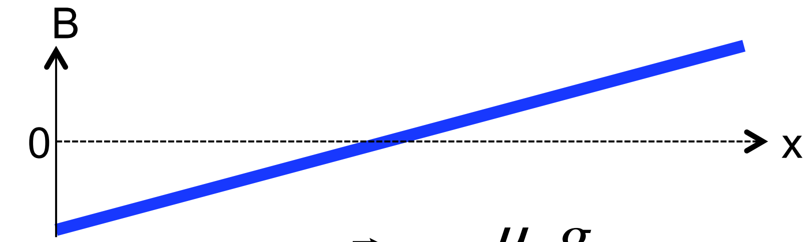


Two Level Atom

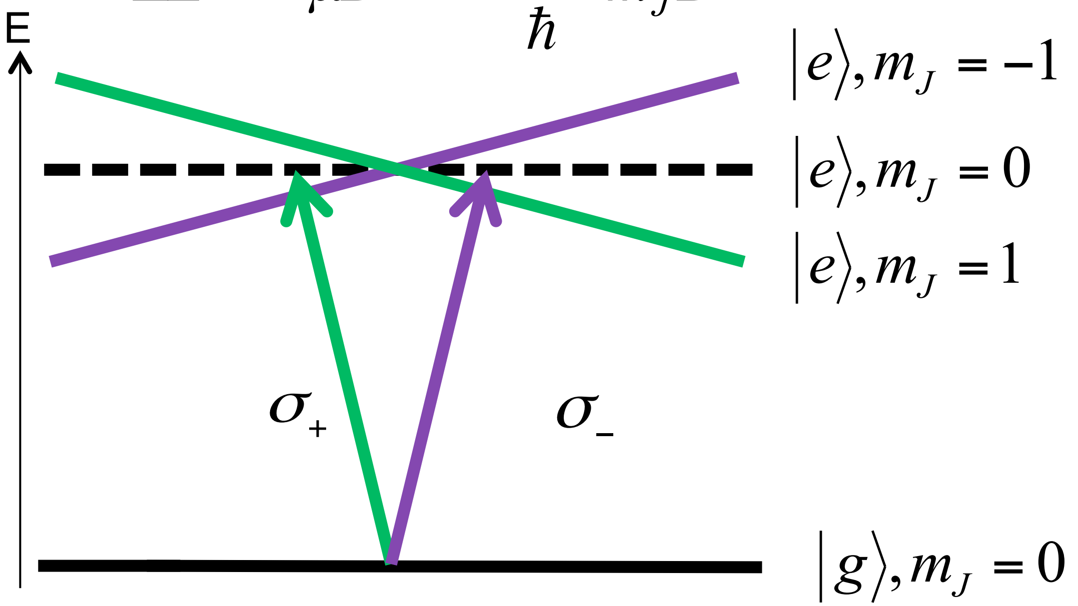


Magneto Optical Trap

Zeeman Effect

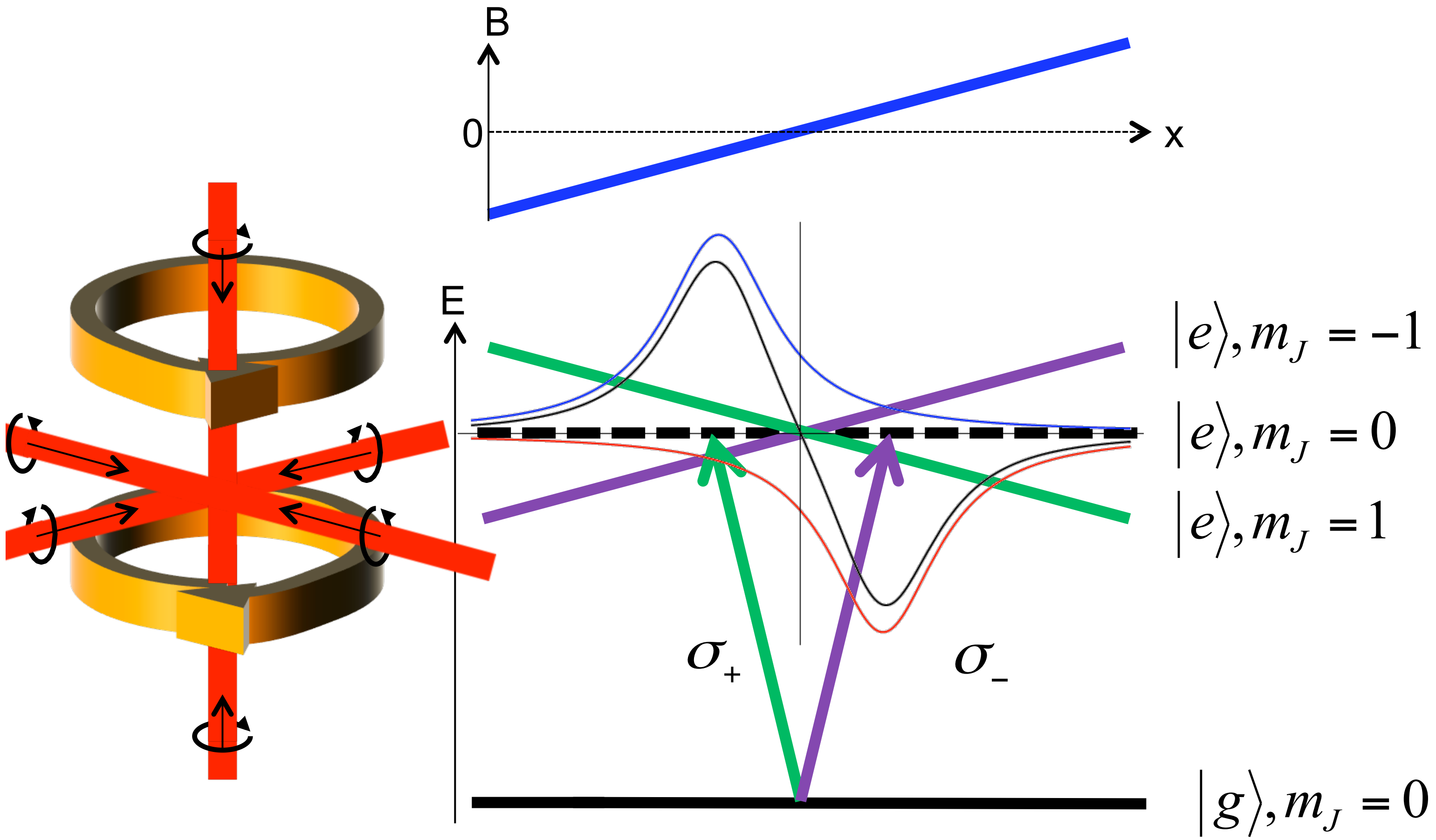


$$\Delta E = -\vec{\mu}\vec{B} = -\frac{\mu_B g}{\hbar} m_J B$$

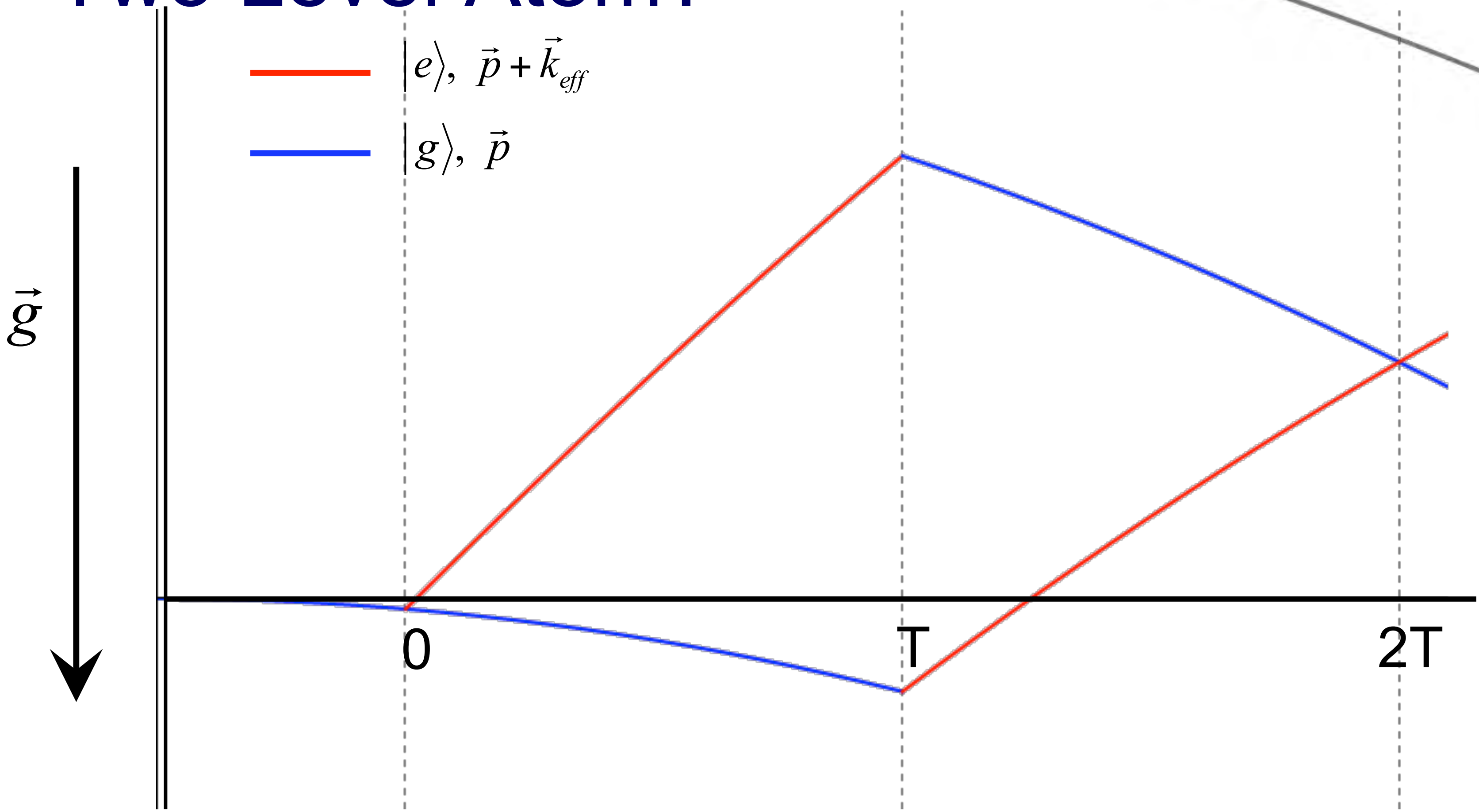


Magneto Optical Trap

Force



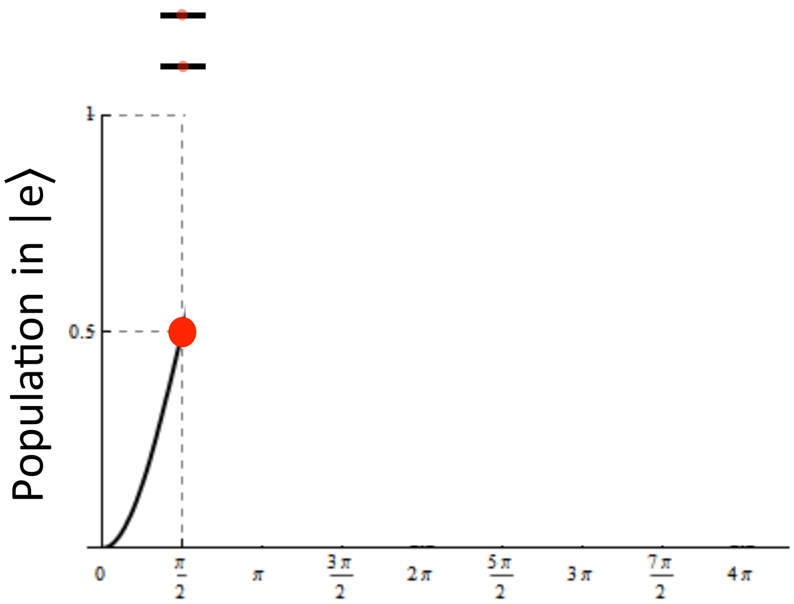
Two Level Atom?



Rabbi Oscillation

Pulse length = $\pi/2\ /\Omega r$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right) \qquad P_{|e\rangle} = \frac{1}{2}$$



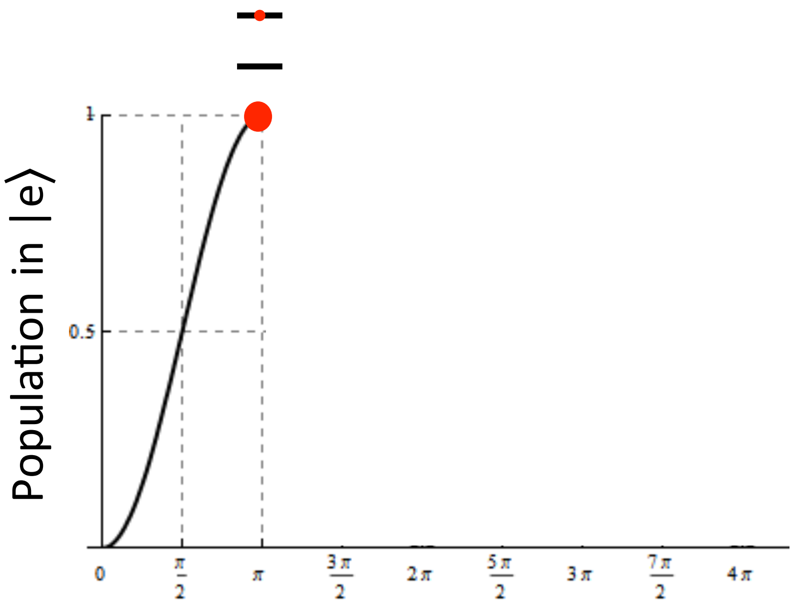
Pulse length $\times\Omega r$

Rabbi Oscillation

Pulse length $=\pi/\Omega r$

$|\psi\rangle = |e\rangle$

$P_{|e\rangle} = 1$



Pulse length $\times \Omega r$

Magneto Optical Trap

Two level atom