Atom Interferometry for Mass Detection

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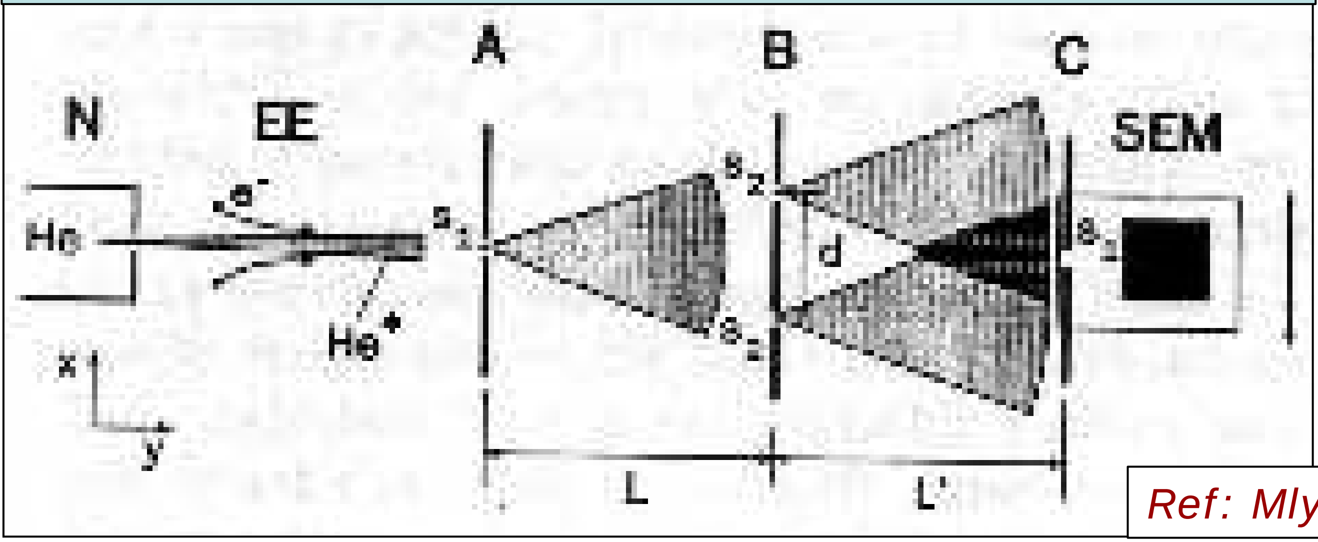
Sensor based on Atom Interferometry (AI) can measure acceleration, rotation, gravity, and gravity gradients

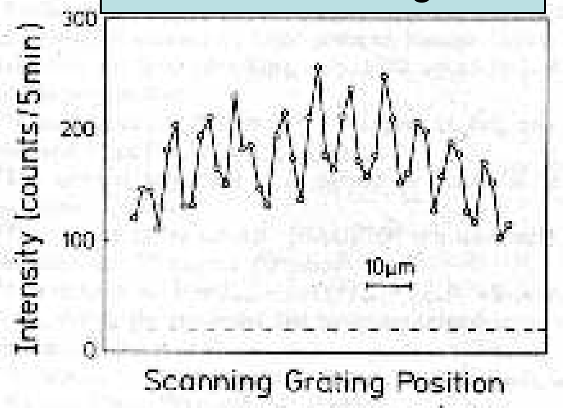
- What is an atom interferometric (AI) sensor?
- How does an AI sensor work?
- Why use an AI sensor?

Young's double slit interferometer with He atoms

Experimental Set-up



Measured Signal



Ref: Mlynek, PRL (1991)

- *Atom optics analog to light interference.*
- *One of the first experiments to demonstrate de Broglie wave interference with atoms.*

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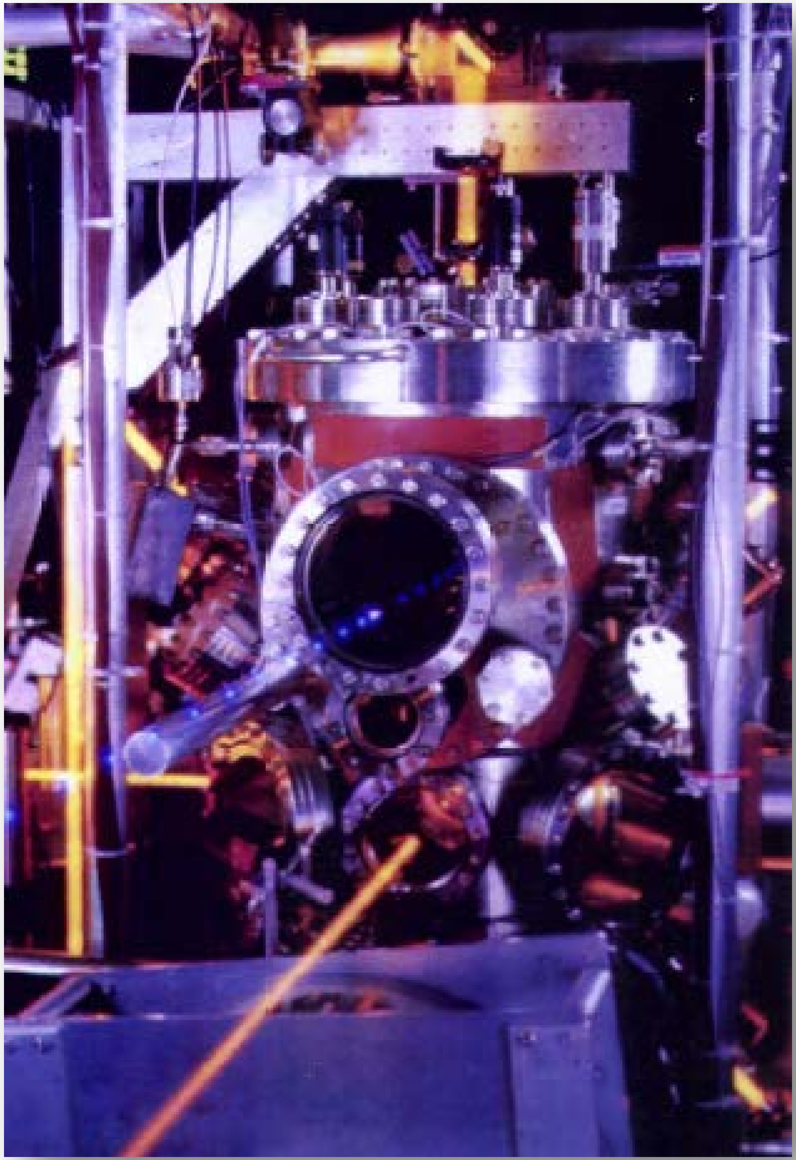
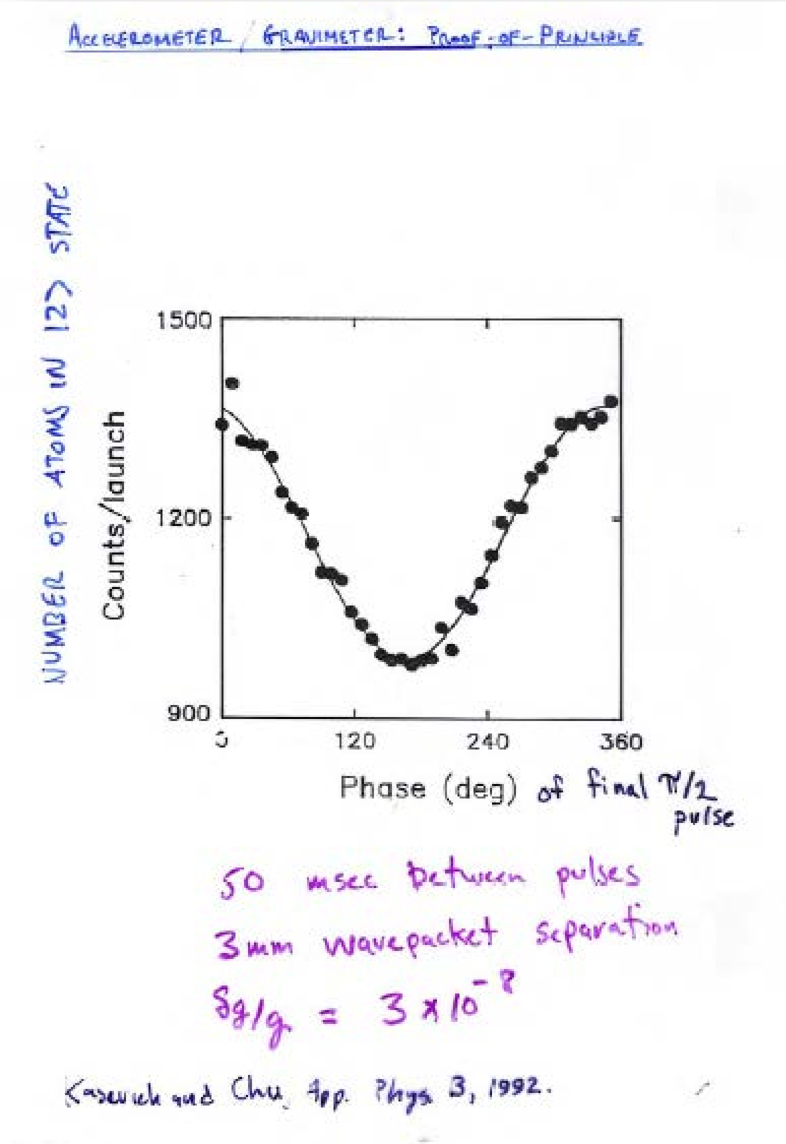
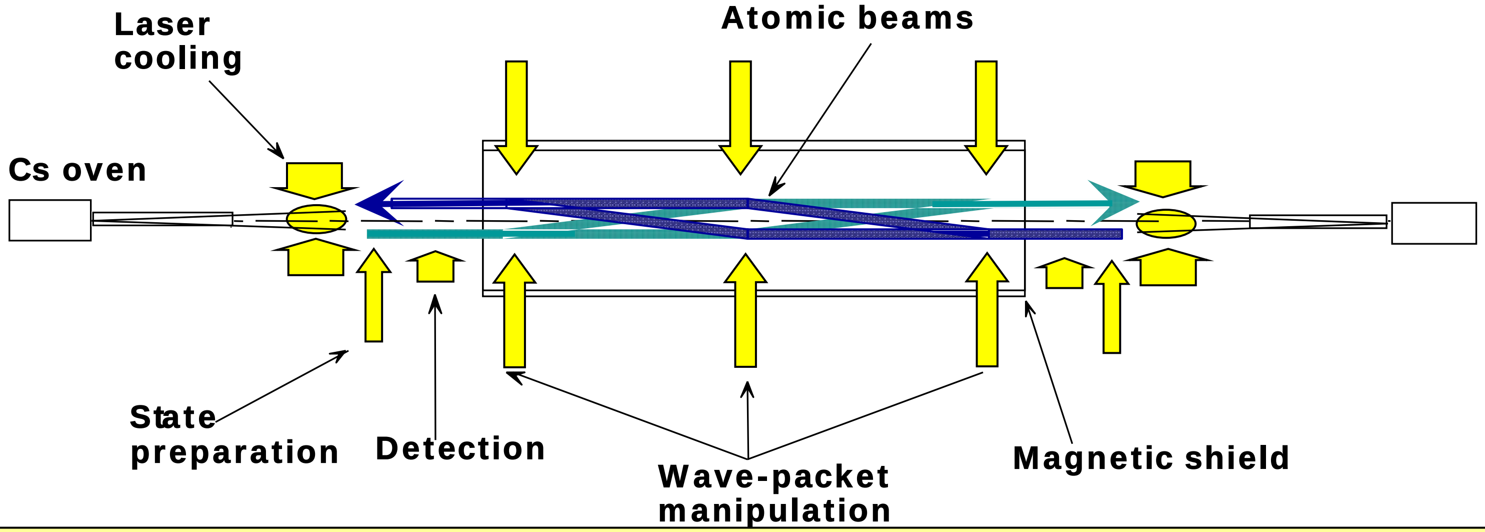
1991 Light-Pulse Atom Interferometer





Courtesy of M. Kasevich, Stanford

Light-pulse atom interferometer basics



1. Laser cool atoms
   - Microkelvin temperatures are routinely achieved with polarization gradient cooling
2. Launch atoms
   - Ramping laser frequencies launches cold atoms at velocity ~ m/s
3. Prepare internal atomic states
   - All atoms are put into the same initial quantum state
4. Interferometer pulse sequence
   - Laser pulses interact with atoms to produce atom interference
5. Determine inertially sensitive interferometer phase
   - Measure atomic level population

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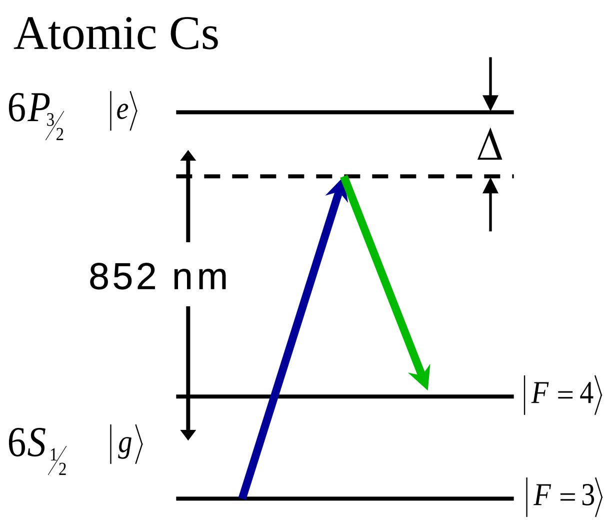
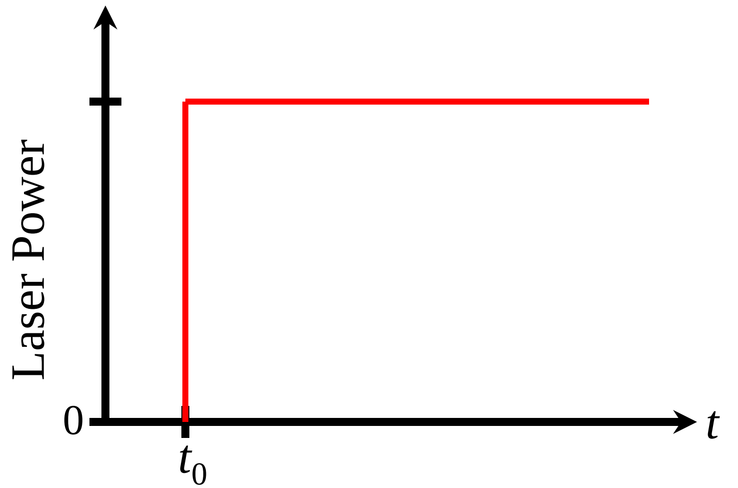
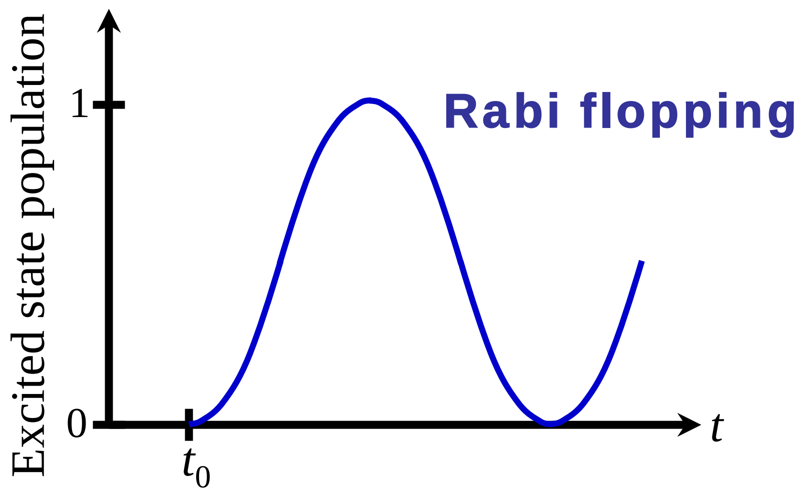
Applying a properly tuned laser pulse transfers atomic population between two levels

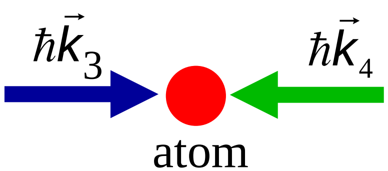
Level scheme







Excitation Geometry



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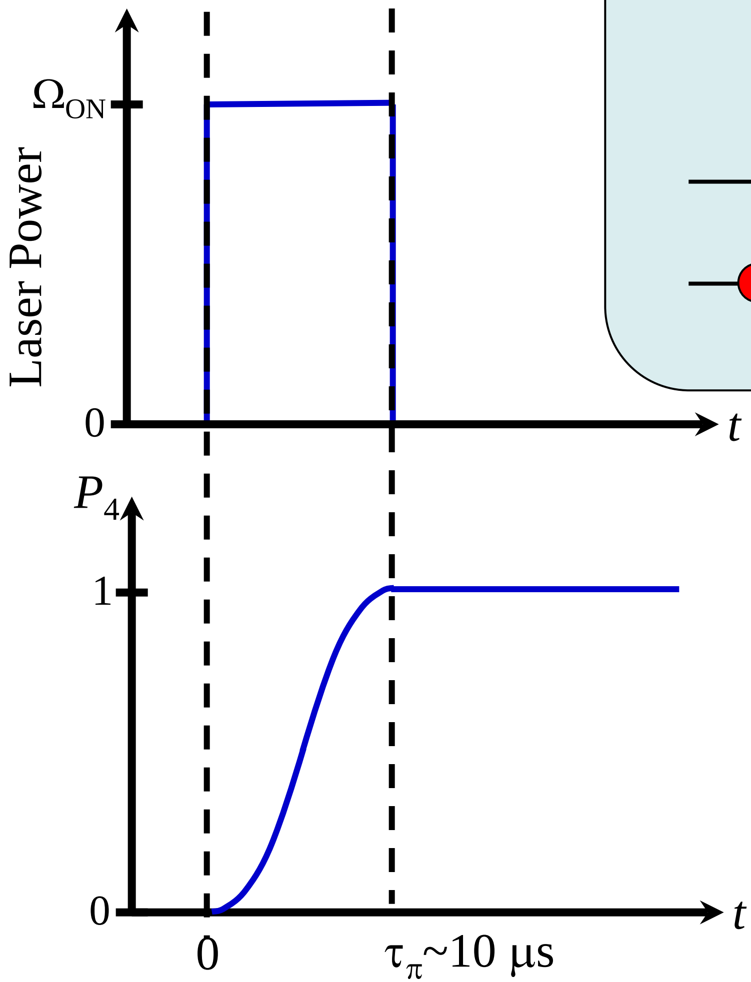
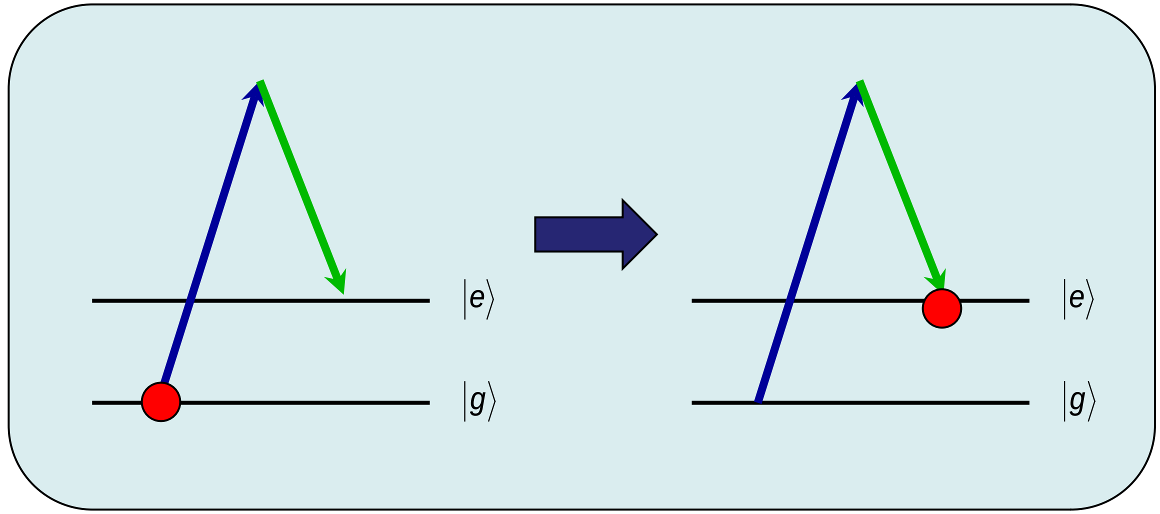
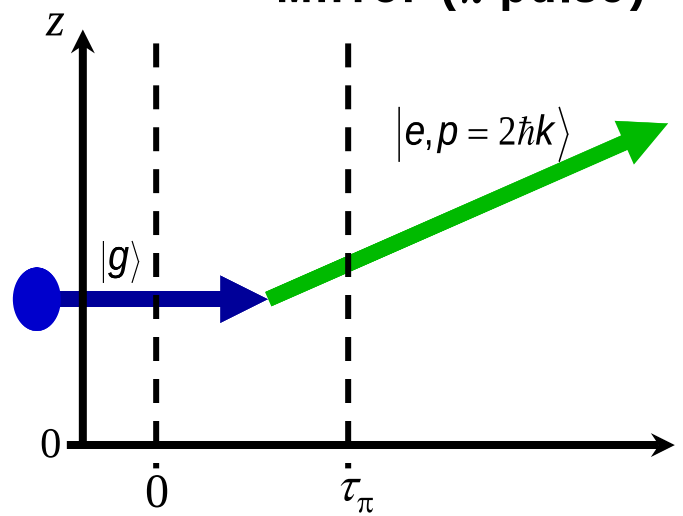
Atom optic mirrors are realized with laser pulses





Mirror (π pulse)



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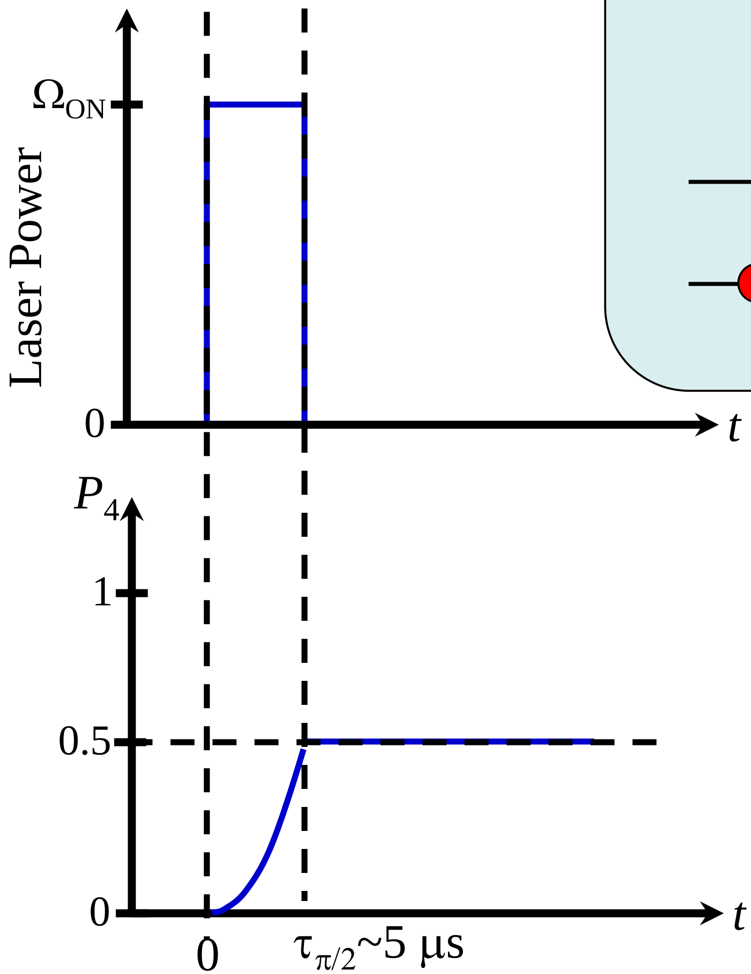
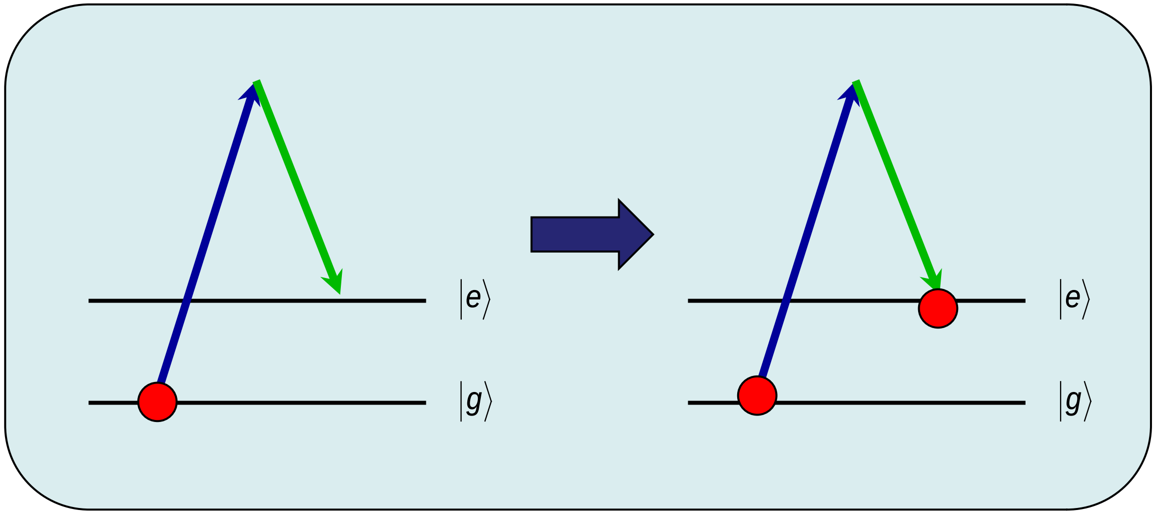
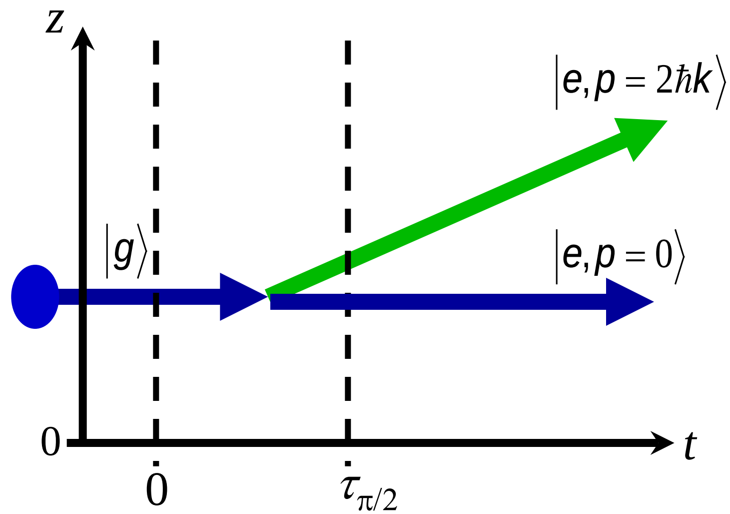
Atom optic beam splitters realized with laser pulses

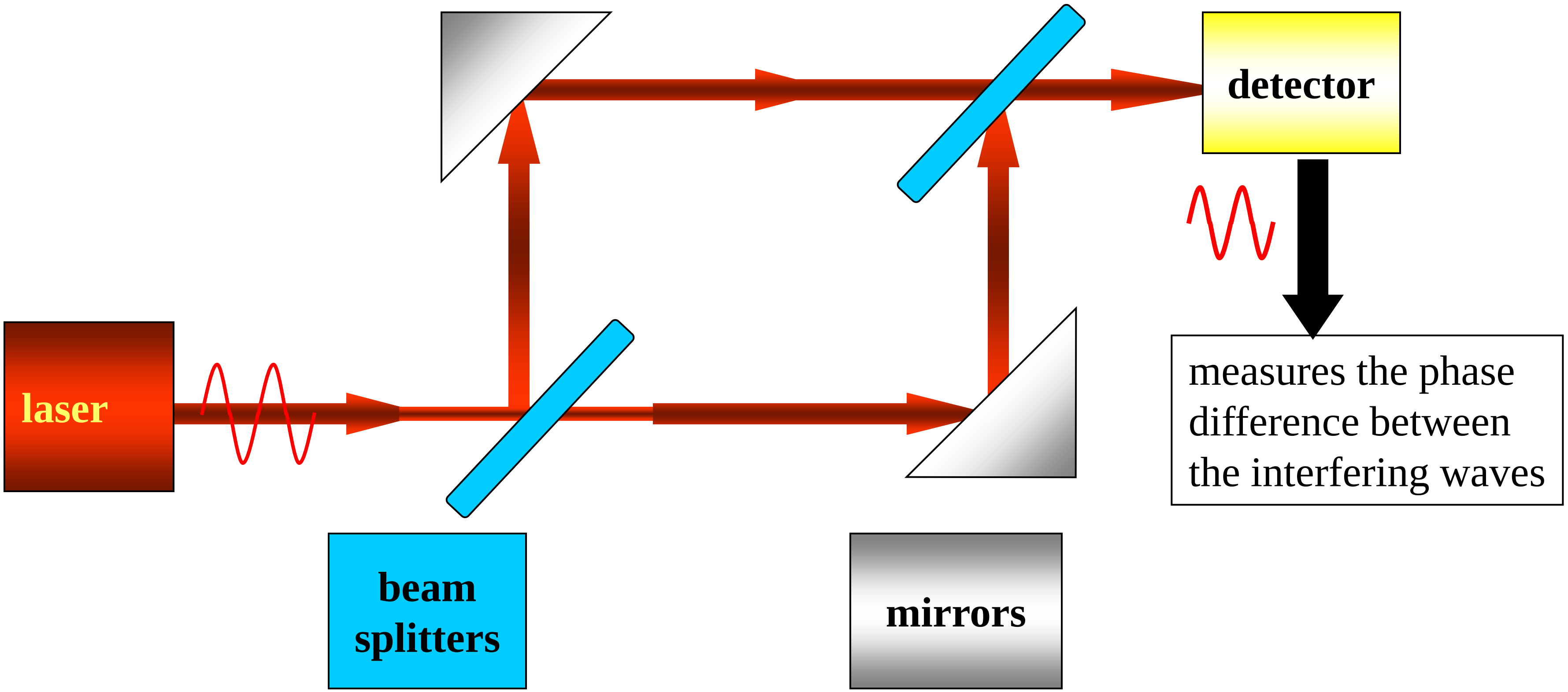




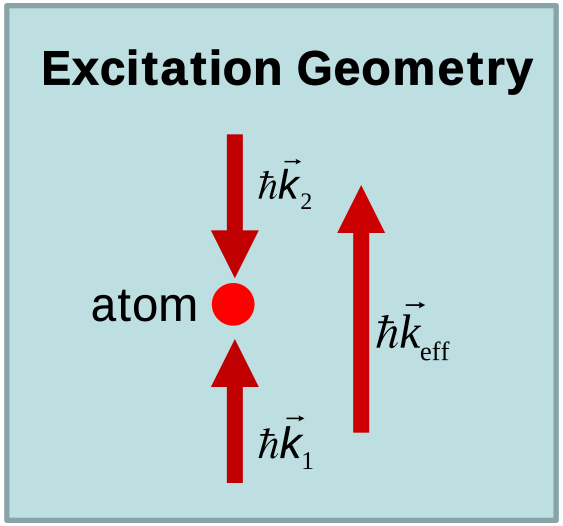
Beam splitter (π / 2 pulse)

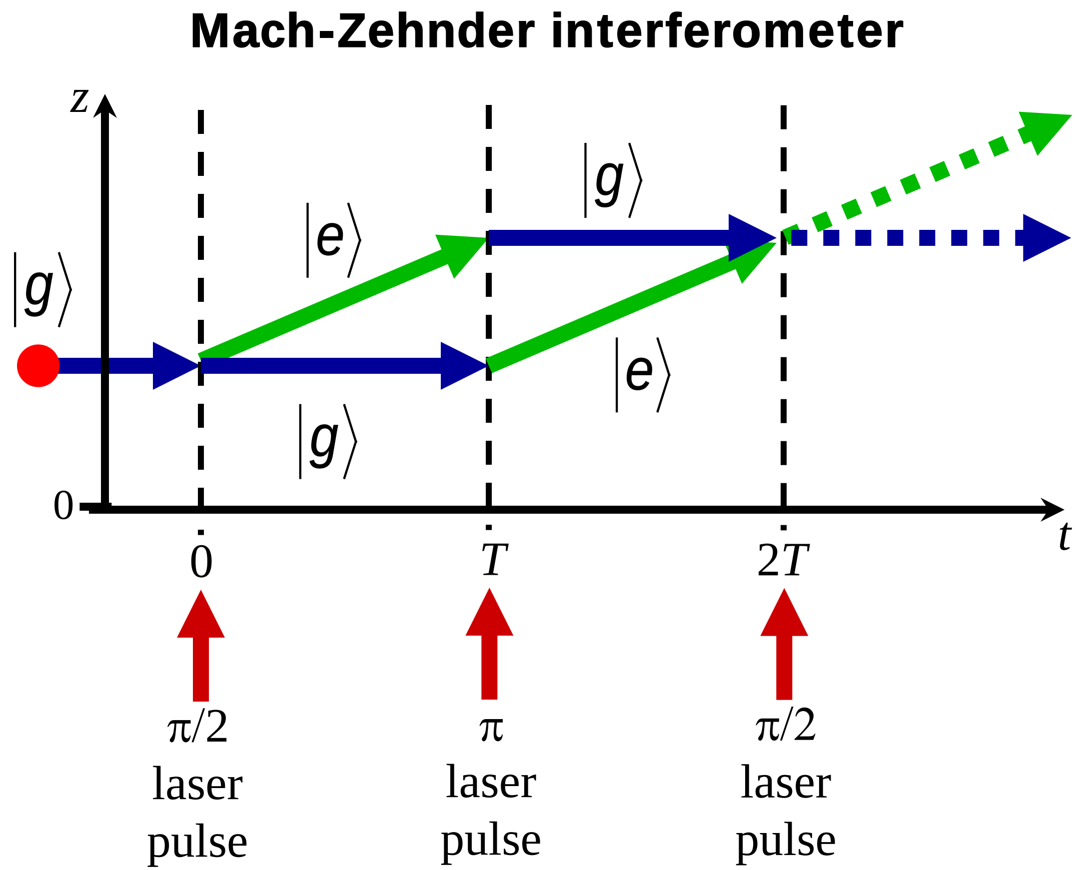


Optical Mach-Zehnder interferometer



Atom Mach-Zehnder interferometer





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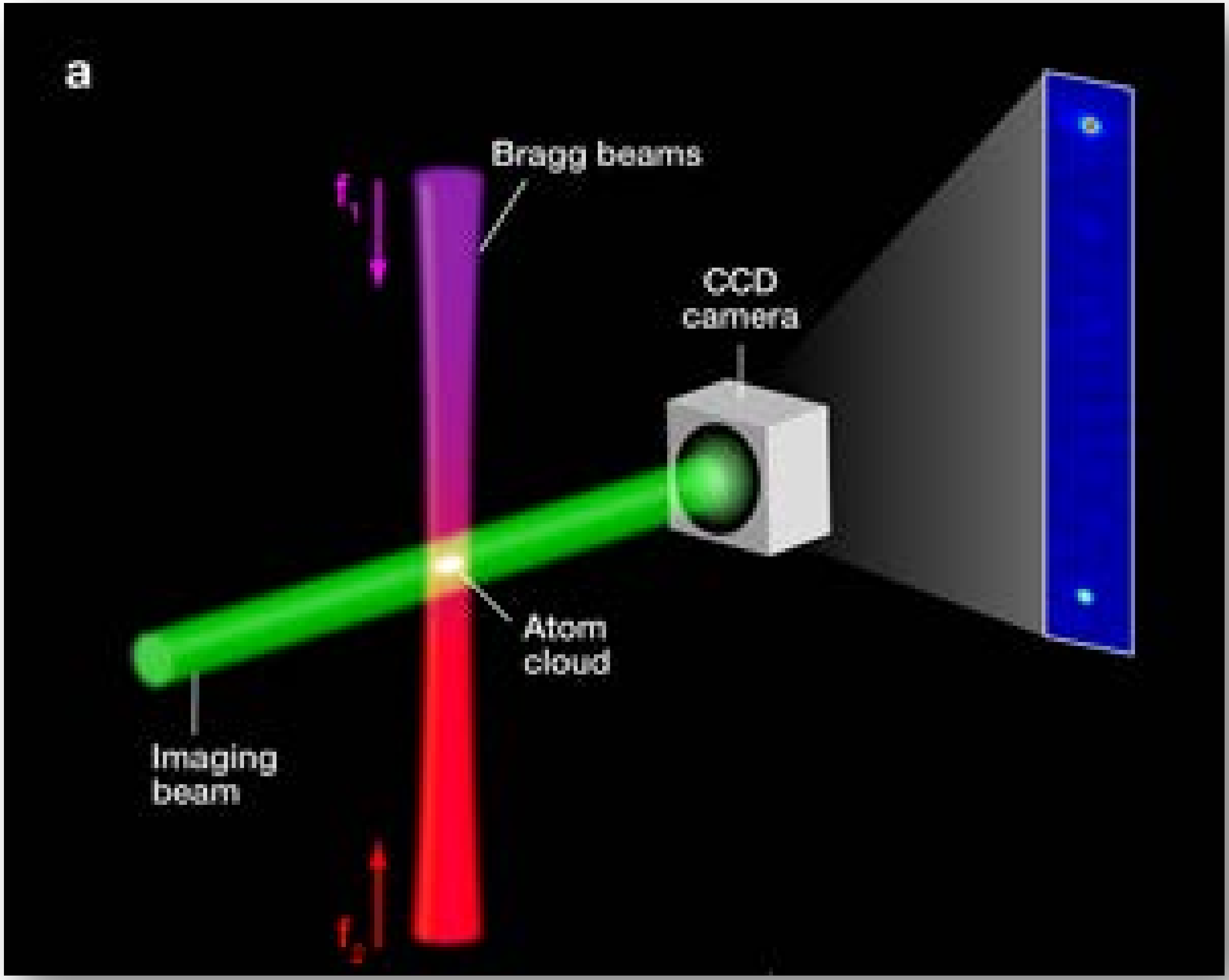
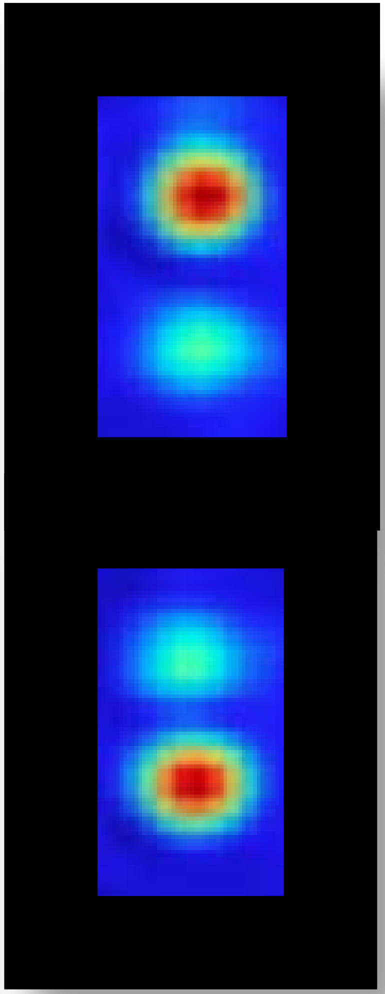
Atom interference after the interferometer sequence can be measured



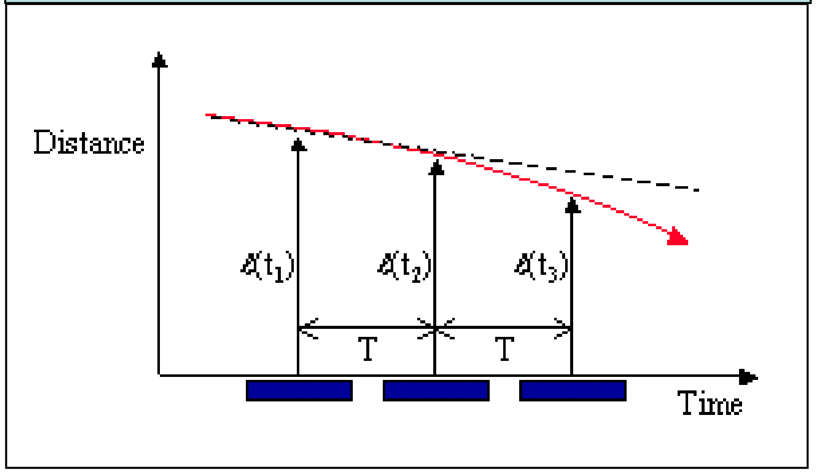


Chiow, PRL, 2011

Courtesy of M. Kasevich, Stanford

Classical picture of Light-pulse atom sensor

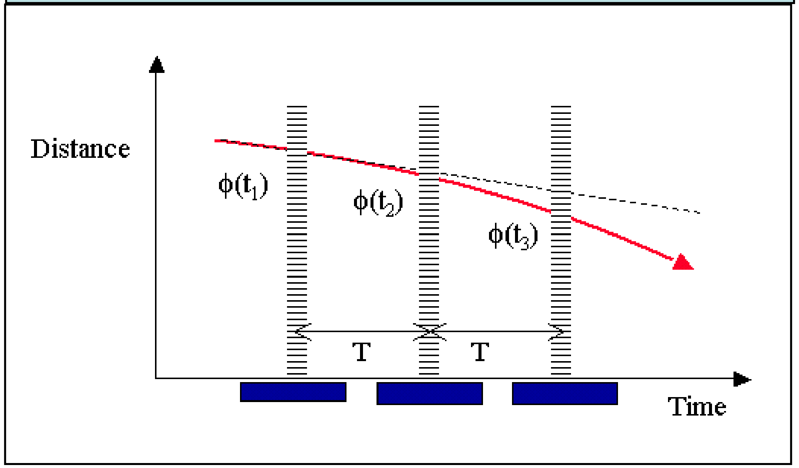
Falling rock



- Three distance measurements $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$ determine rock trajectory curvature.
- Acceleration **a** produces trajectory curvature.

$$\mathbf{a} \sim [\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$$

Falling atom



- Distances are precisely measured by laser phases $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$

$$\mathbf{a} \sim [\phi(t_1) - 2\phi(t_2) + \phi(t_3)]$$

Ref: Kasevich and Chu, *Appl Phys B* **54** (1992).

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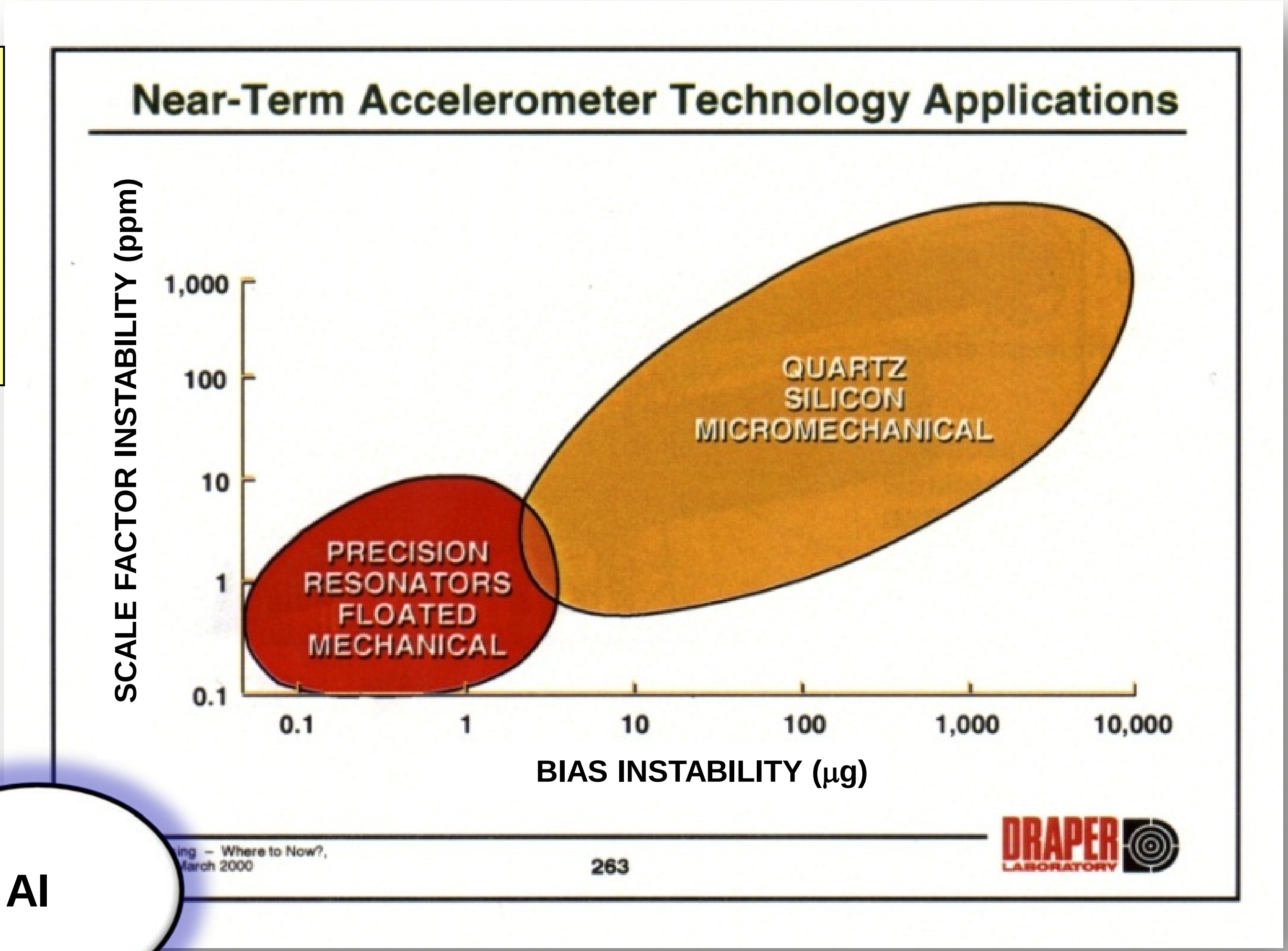
Off-the-chart performance

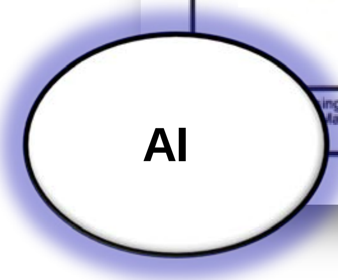
AI sensor performance in open literature:

- Bias stability: $<10^{-10}$ g
- Noise: 4×10^{-9} g/Hz$^{1/2}$
- Scale Factor: 10^{-10}

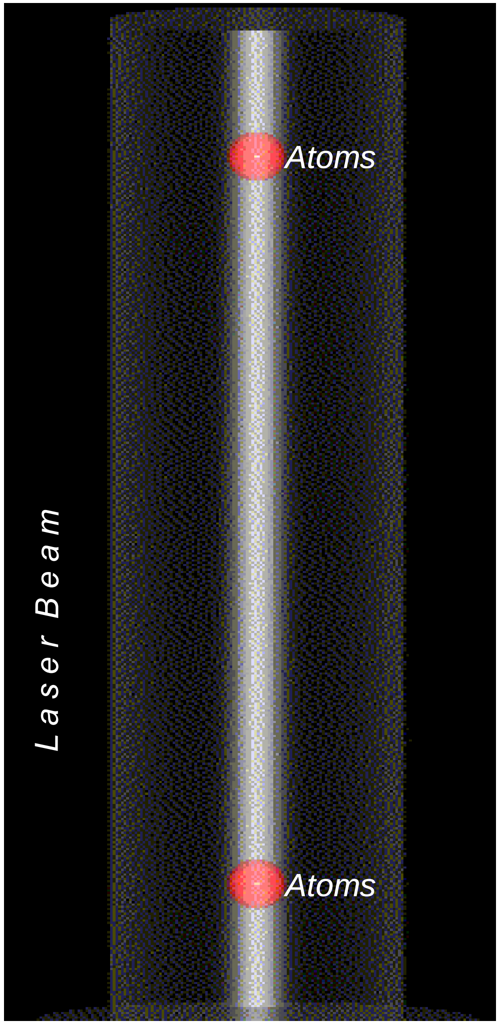
Bias – DC offset under zero applied acceleration

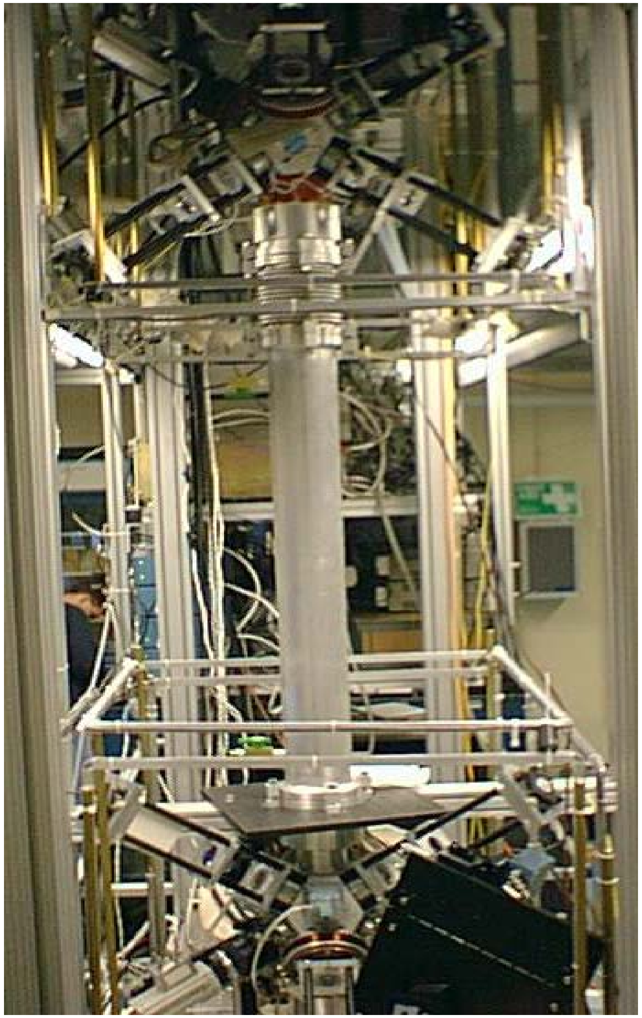
Scale factor – sensitivity relating applied acceleration to sensor output





Yale gravity gradiometer (2001)





Demonstrated differential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

Courtesy Mark Kasevich, Stanford

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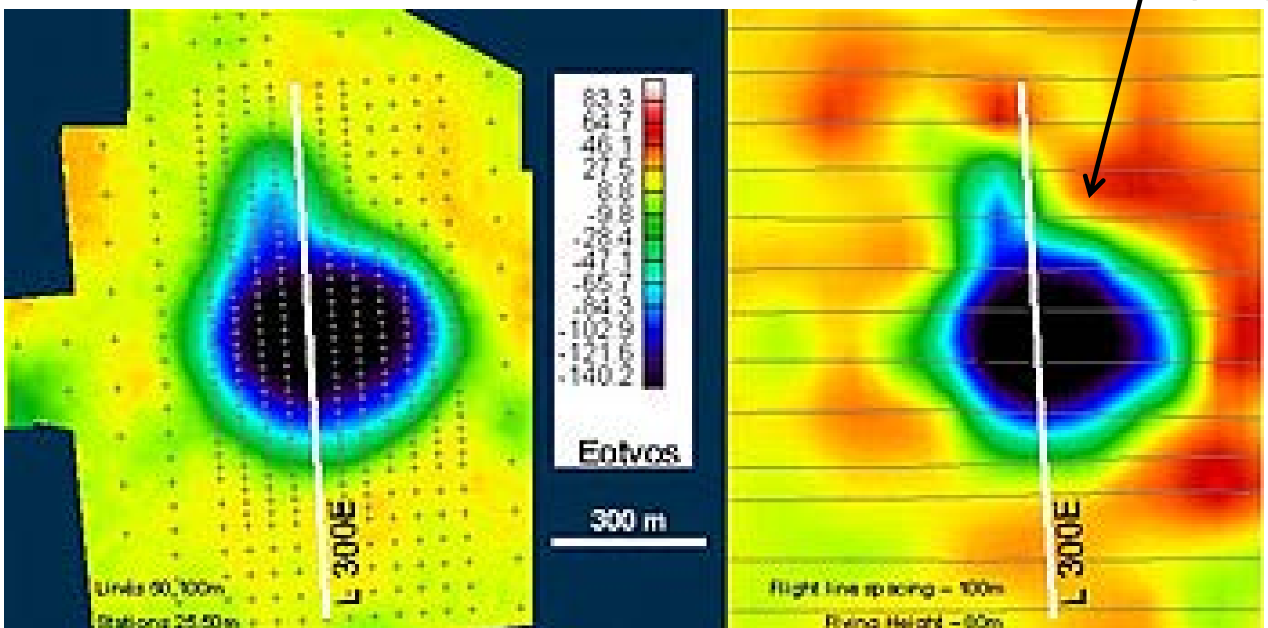
Airborne gravity gradient surveys with conventional gradiometer

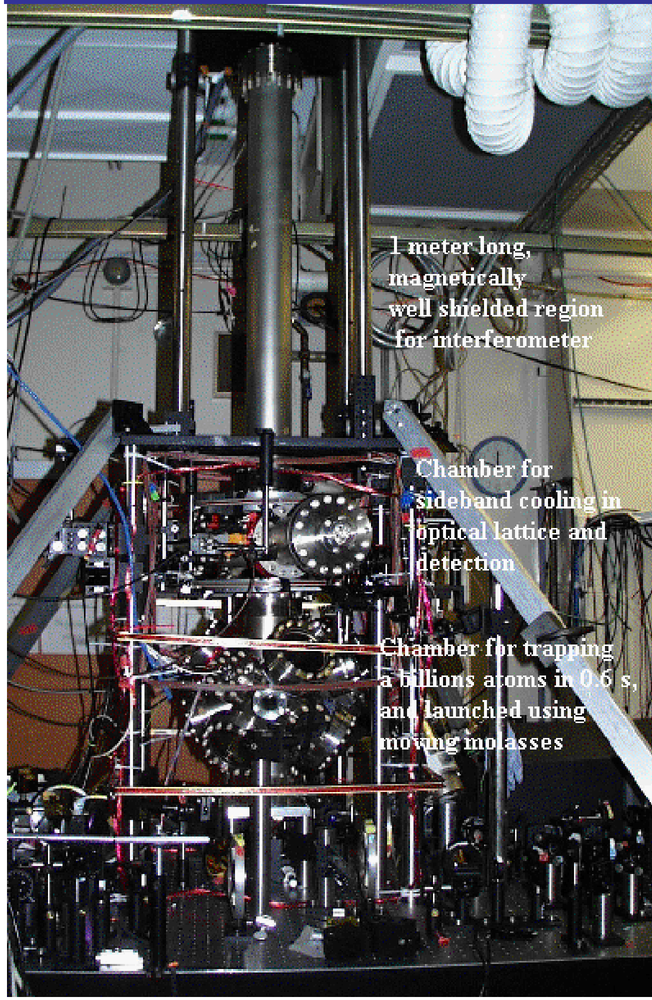
Diamonds are here (maybe)



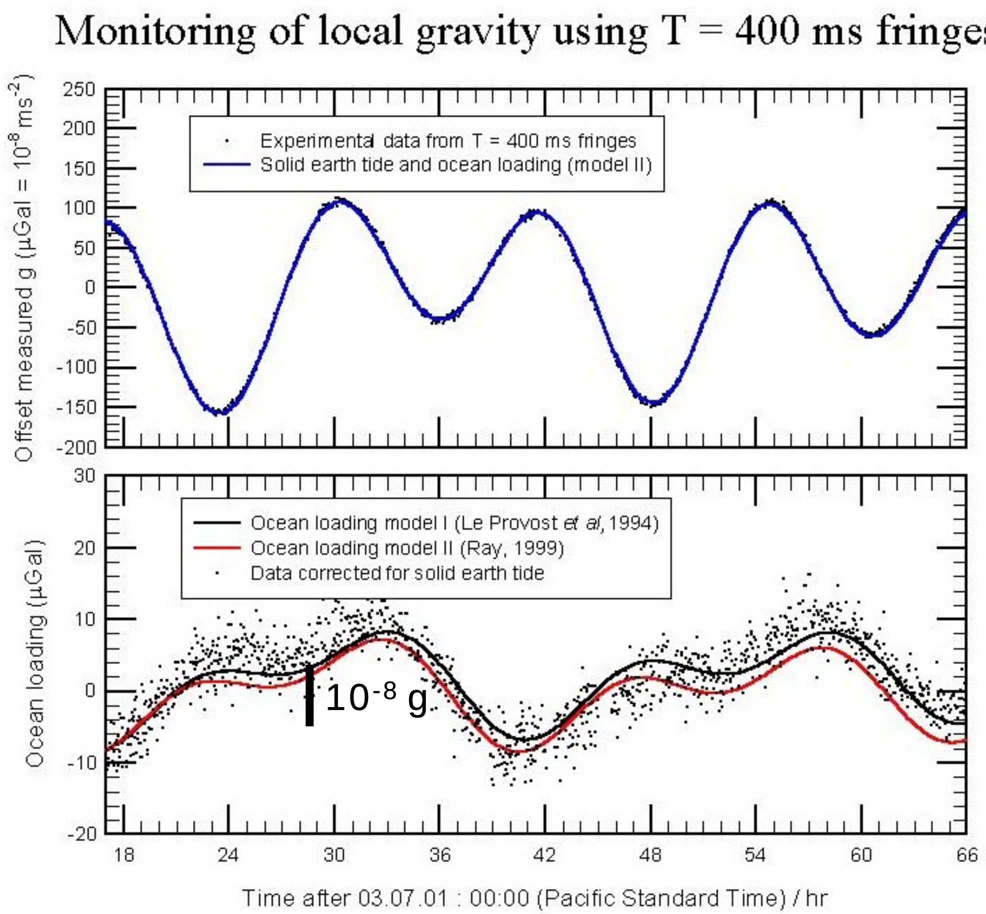
Land: 3 wks.	**Air: 3 min.**

AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

Stanford laboratory gravimeter



Courtesy of S. Chu, Stanford

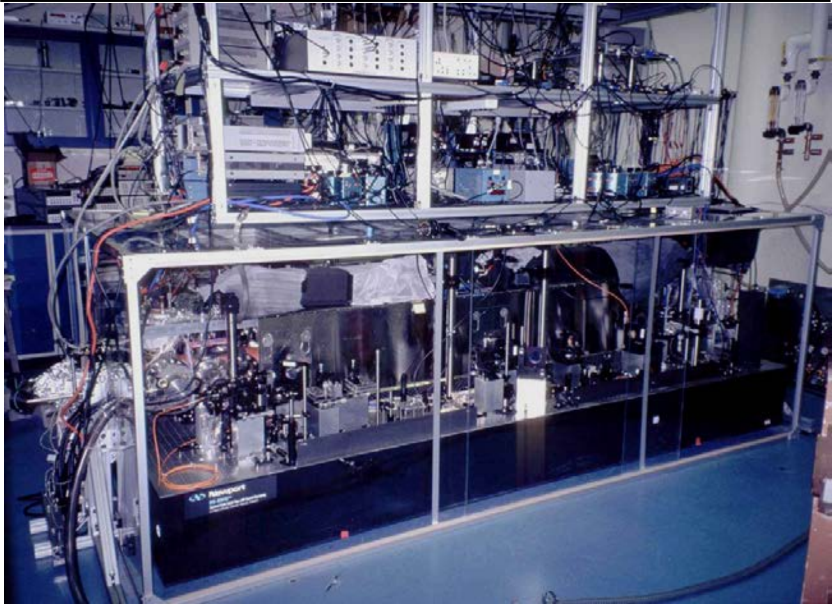


Raman sideband cooling used to achieve very long interrogation times (200 nK launch temperature!)

Ref: Peters *et al.*, *Metrologia* **38** (2001).

Laboratory gyroscope

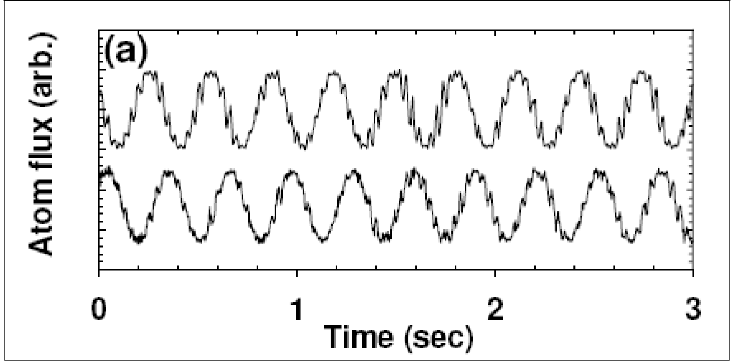
AI gyroscope



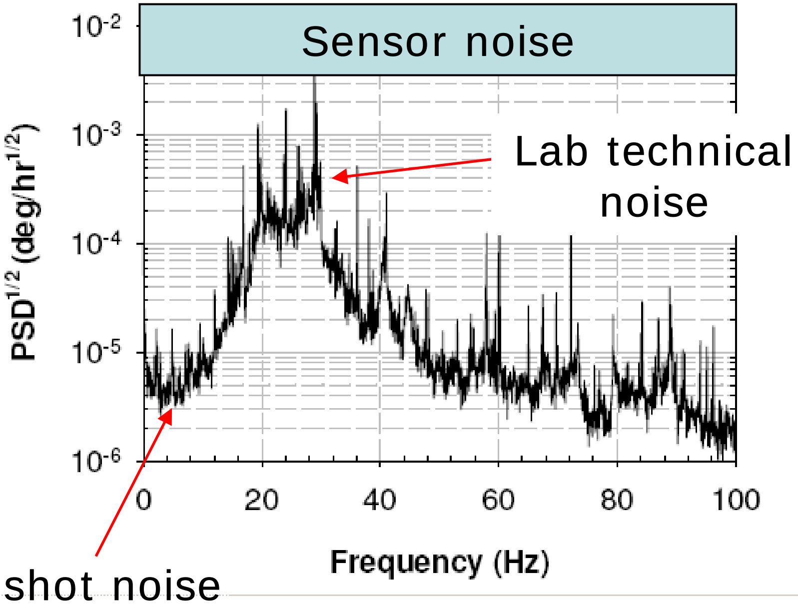
Courtesy Mark Kasevich, Stanford

ARW	**3 μdeg/h$^{1/2}$**
Bias stability:	**< 60 μdeg/h**
Scale factor:	**< 5 ppm**

Gyroscope interference fringes



Sensor noise



Ref: Gustavson *et al.*, PRL **78** (1997); Durfee *et al.*, PRL **97** (2006)

AOSense Commercial Compact Gravimeter

Commercial Cold Atom Gravimeter

- Noise < 1 $\mu g/Hz^{1/2}$
- Shipped 11/22/10
- First commercial atom optics sensor

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AOSense, Inc.

- Founded in 2004 to develop cold-atom technology (Brent Young CEO).
- Core capability is design, fabrication and testing of sensors based on cold-atom technologies.
- Staff of 33

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