Photonic engineering of atomic sensors

Jennifer T. Choy

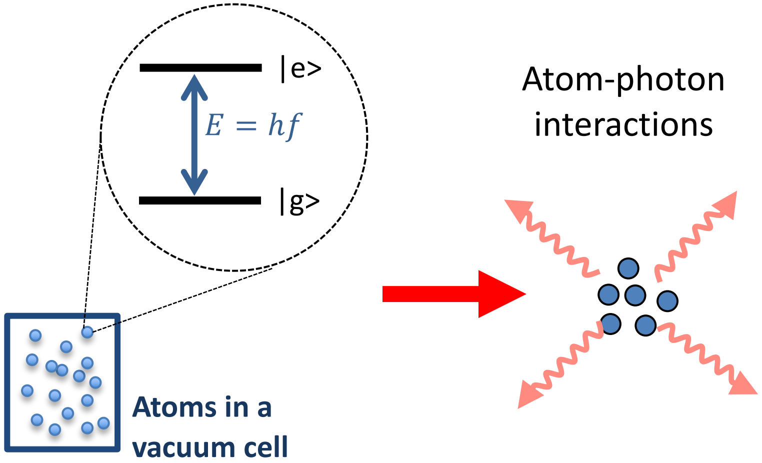
Department of Engineering Physics, University of Wisconsin - Madison

Photonics for Quantum 2

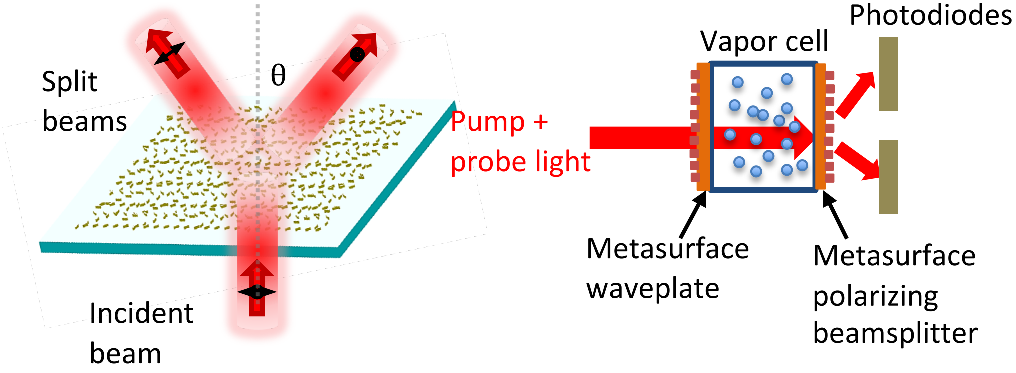
July 15, 2020

Outline

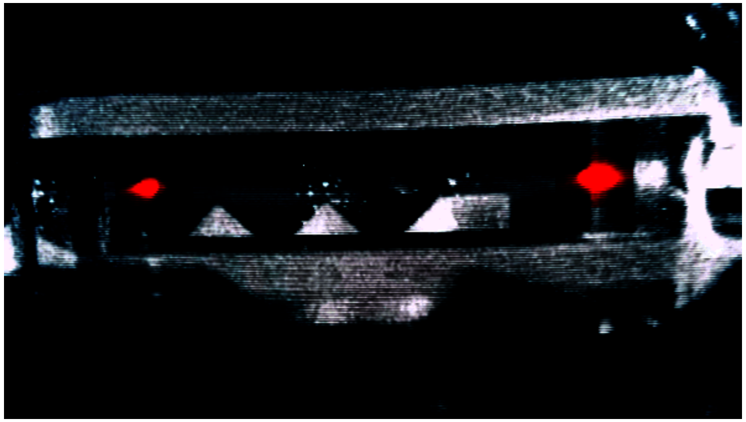
Introduction: Atom-based quantum sensing

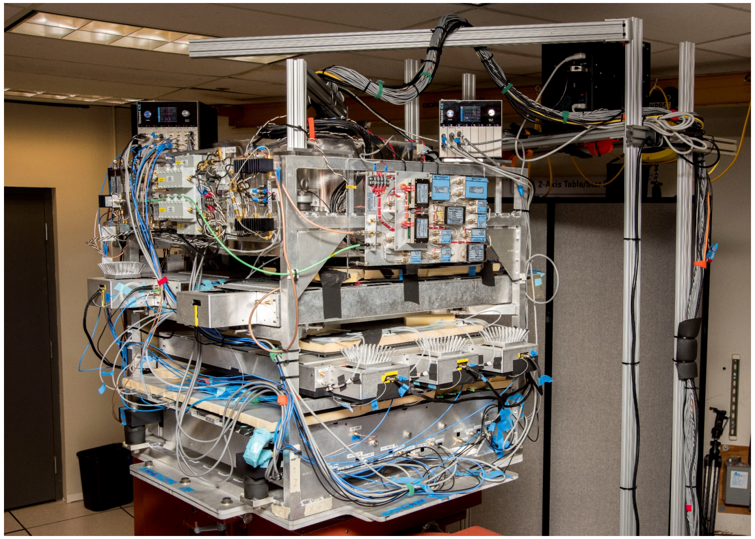


Opportunities for integrated nanophotonics in next-generation atomic sensors



Atomic sensor example: Cold-atom accelerometer and gyroscope





Draper Laboratory

Contributors and funding support on presented work

Chip-Scale Combinatorial Atomic Navigator development at Draper:

- Dave Johnson (Program manager)
- Jen Choy (Technical director)
- Alex Gill
- Christine Wang
- Steve Byrnes
- Krish Kotru

Part of this work was supported by the Defense Advanced Research Projects Agency (DARPA), under the Chip-Scale Combinatorial Atomic Navigator (C-SCAN) program.

The views, opinions, and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Team at UW-Madison:

- Xuting Yang
- Ricardo Vidrio
- Sarah Francis
- John (Jack) Doyle

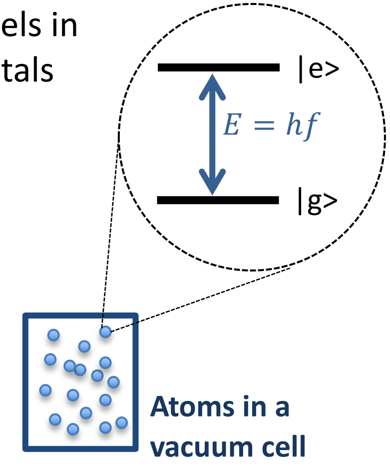
Collaborators at UW-Madison

- Mikhail Kats
- Ray Wambold
- Thad Walker

Funding support from the Office of Naval Research (N00014-20-1-2598) and the Wisconsin Alumni Research Foundation

Concept of atom-based quantum sensing

Discrete electronic energy levels in atoms, ions, or defects in crystals

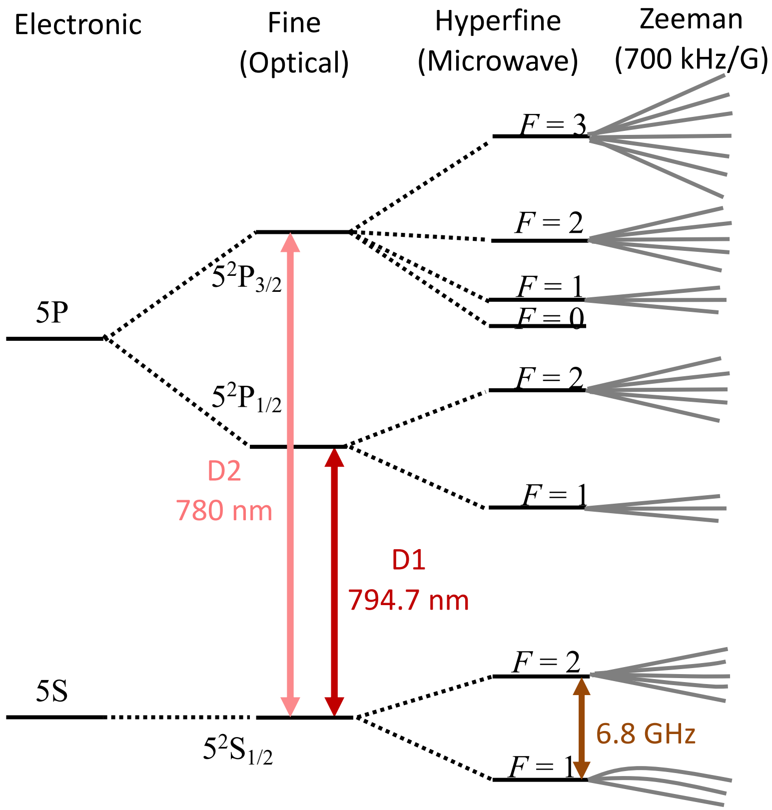


f = *fn* (external EM field, motion, temperature, …)

Precise frequency reference

Deterministic interactions with the environment that can be strong

Rb-87 transitions



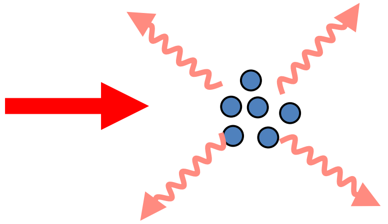
Why useful:

- Transitions with high frequencies lead to high measurement resolution
- Strong interactions between atoms and physical quantities enable sensitive measurements
- Properties of well-isolated atoms, including their interactions with the environment, are stable over time
- Atoms of the same element and isotope are identical → ideal measurement standards!

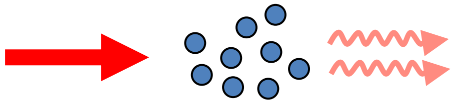
Essential atom-photon interactions for quantum measurements

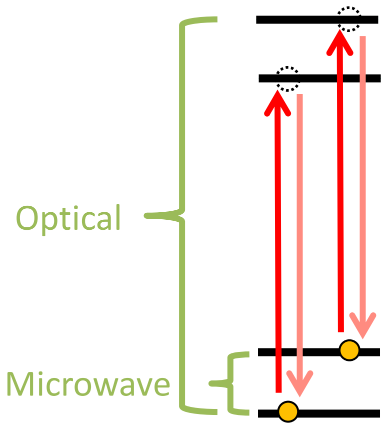
Absorption and emission

Spontaneous emission

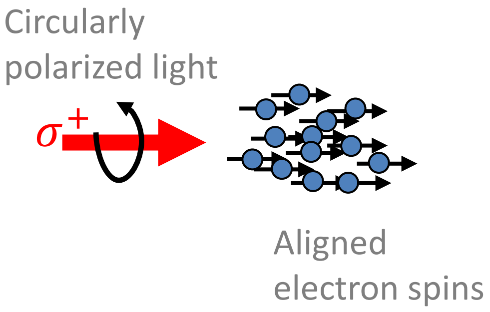


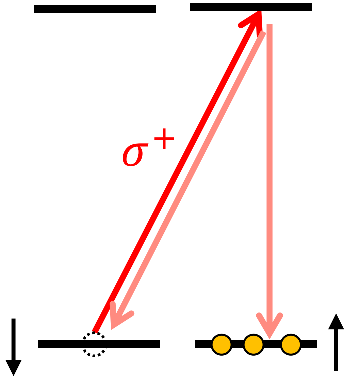
Stimulated emission



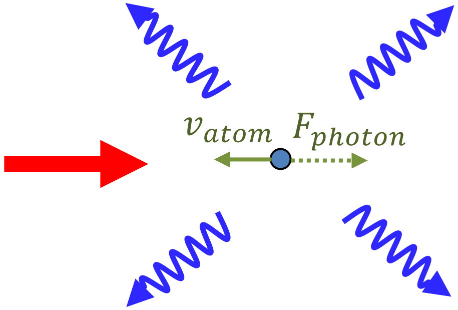


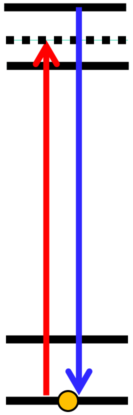
Optical pumping





Laser cooling





Current and future applications of quantum sensing platforms

Precise and accurate time and frequency standards

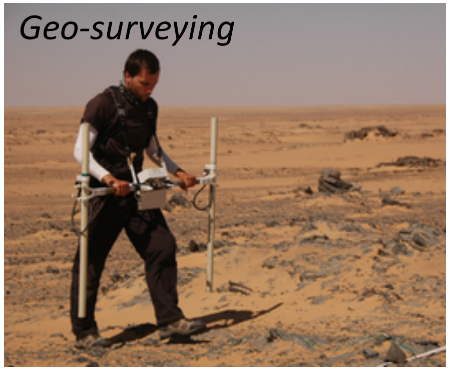
GPS

Communications

Time/frequency distribution

Magnetometry with high sensitivity and spatial resolution

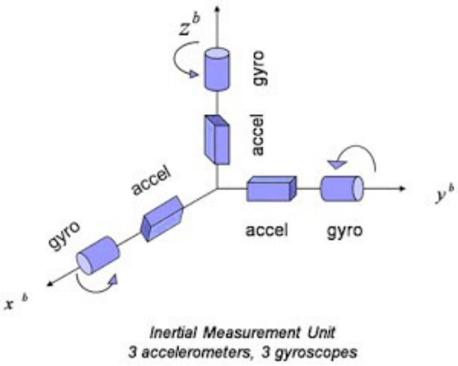
Neural activity sensing

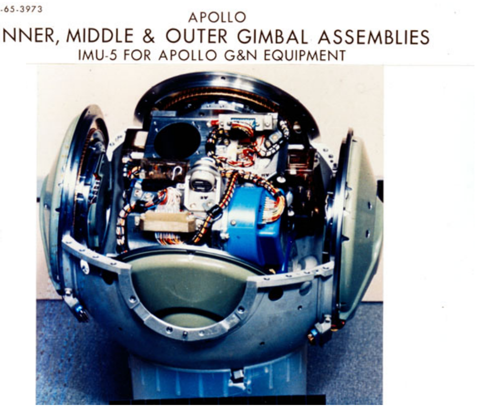


Geo-surveying

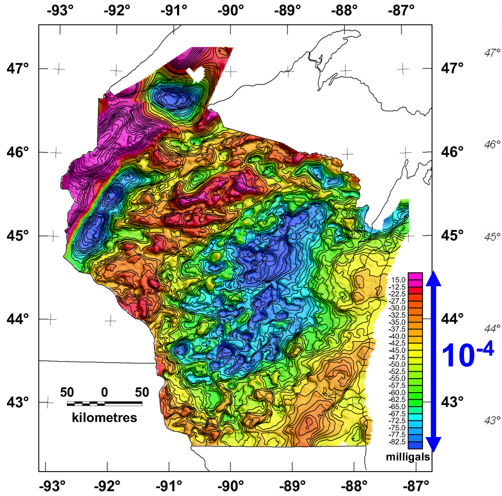
Accurate navigation and guidance

Navigation systems

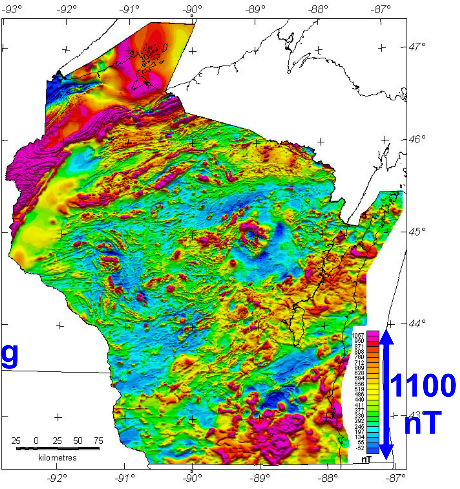




Gravity map



Magnetic field map

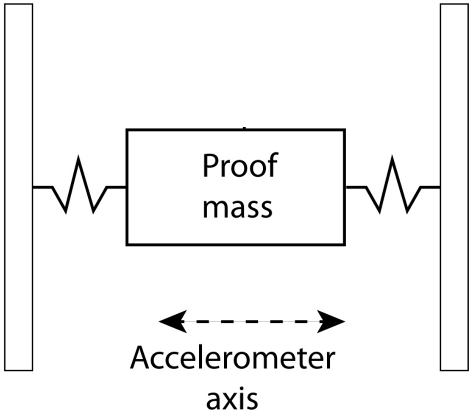


Source: https://pubs.usgs.gov/

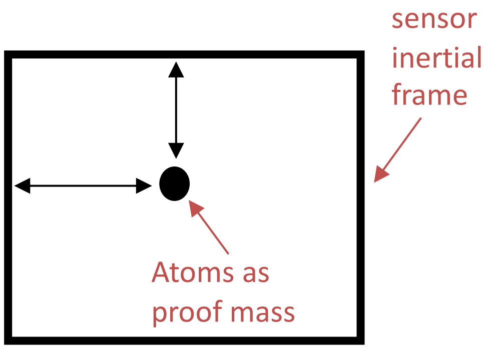
Classical vs quantum ways to measure inertial motion

Inertial sensors measure the displacement of some object ("proof mass") in response to acceleration or rotation

Classical



Atomic



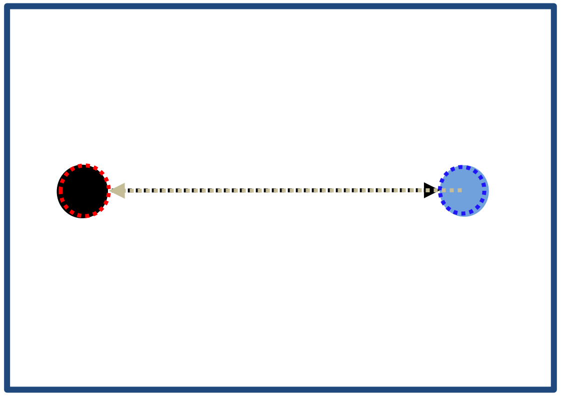
- Tethered mechanical proof mass
- Variability in manufacturing
- Sensor response can degrade with changing environment

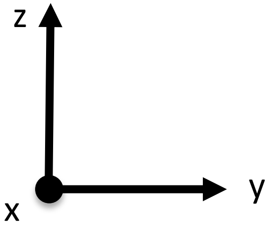
- Frictionless, reproducible, identical proof masses
- Stable electron energy levels provide both sensitivity and stability
- Implementation challenges
  - Size and complexity of setups
  - Performance degrades under dynamic environments (data rate and physical constraints)

Inertial sensing with atoms

Proof masses (atom clouds) thrown towards each other at speed v

Case at rest



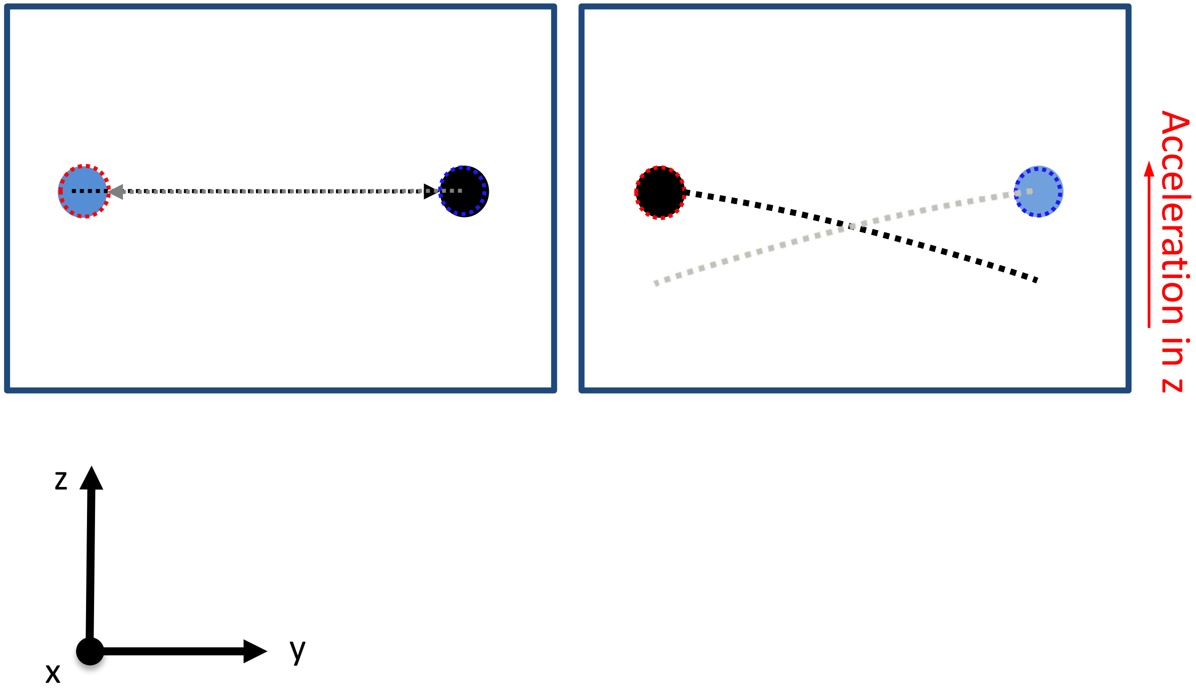


Inertial sensing with atoms

Proof masses (atom clouds) thrown towards each other at speed v

Case at rest

Case under acceleration



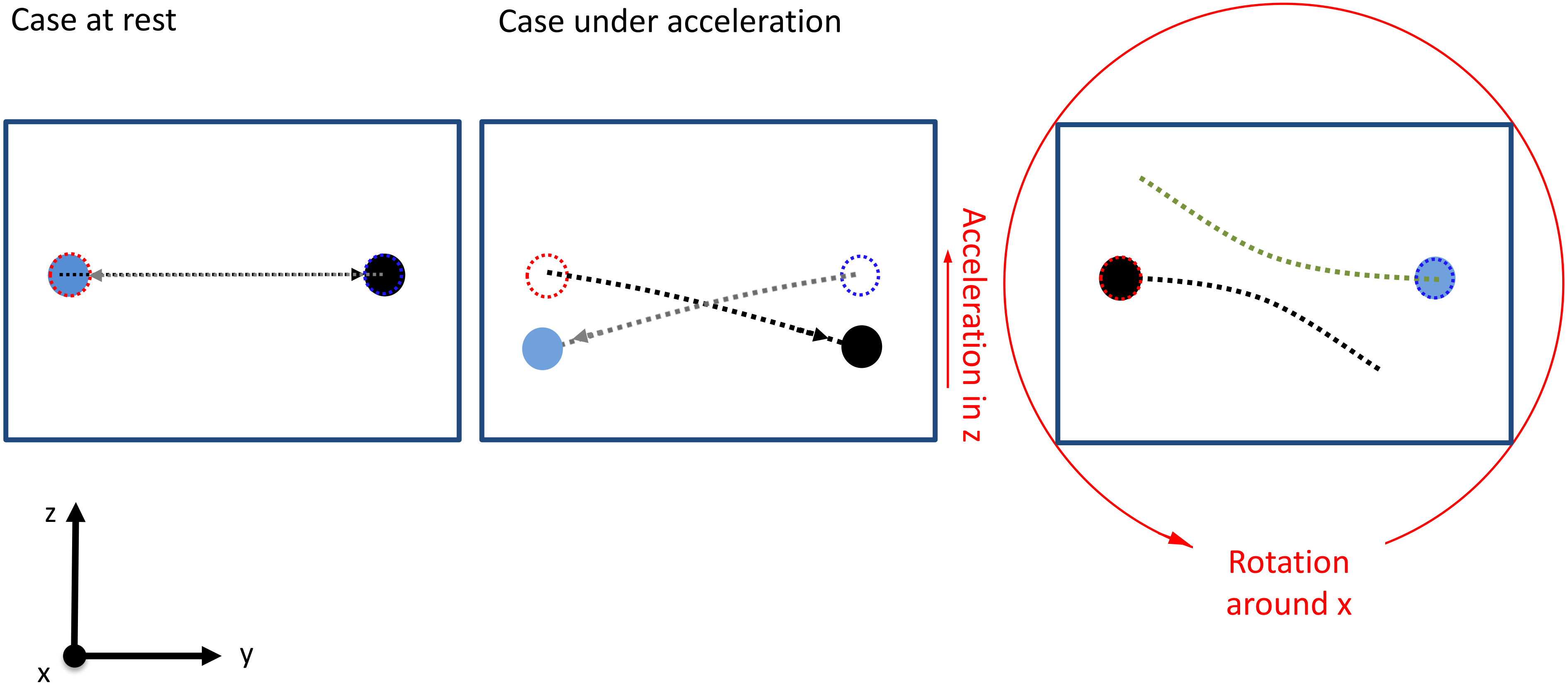
Inertial sensing with atoms

Proof masses (atom clouds) thrown towards each other at speed v

Case at rest

Case under acceleration

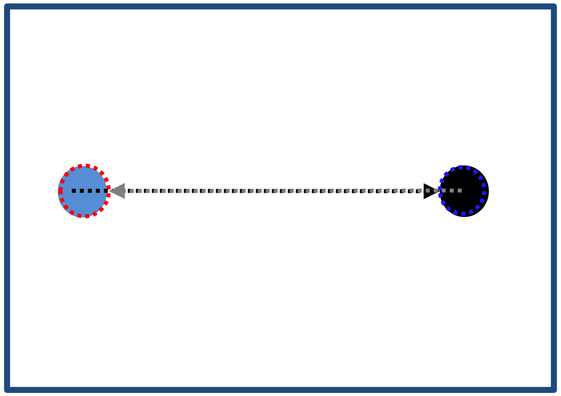
Case under rotation



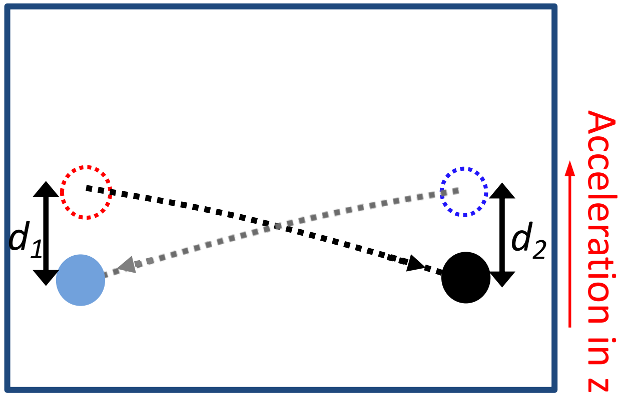
Inertial sensing with atoms

Proof masses (atom clouds) thrown towards each other at speed v

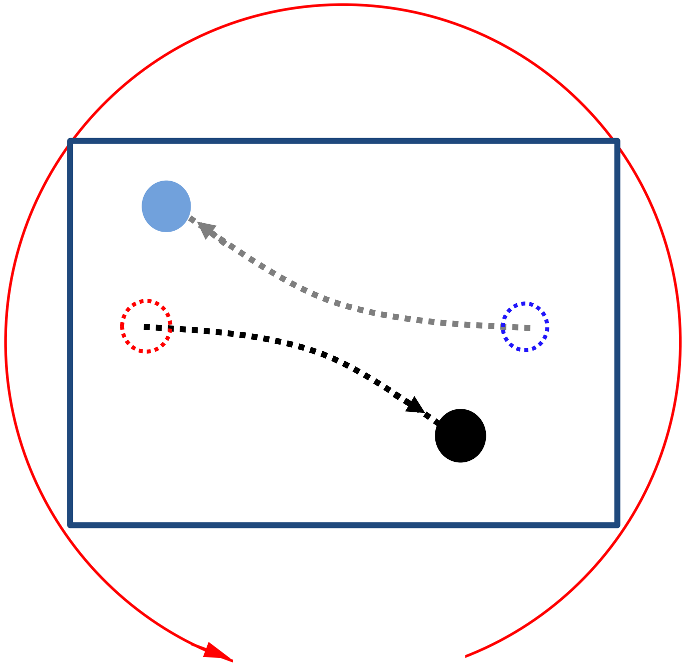
Case at rest



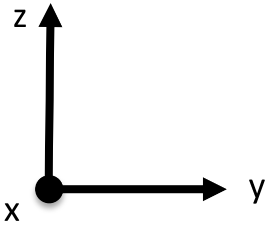
Case under acceleration



Case under rotation



Rotation around x



$$d_1 + d_2 \propto a\, T^2$$

$$d_1 - d_2 \propto \Omega \times v\, T^2$$

acceleration

time of flight

rotation rate

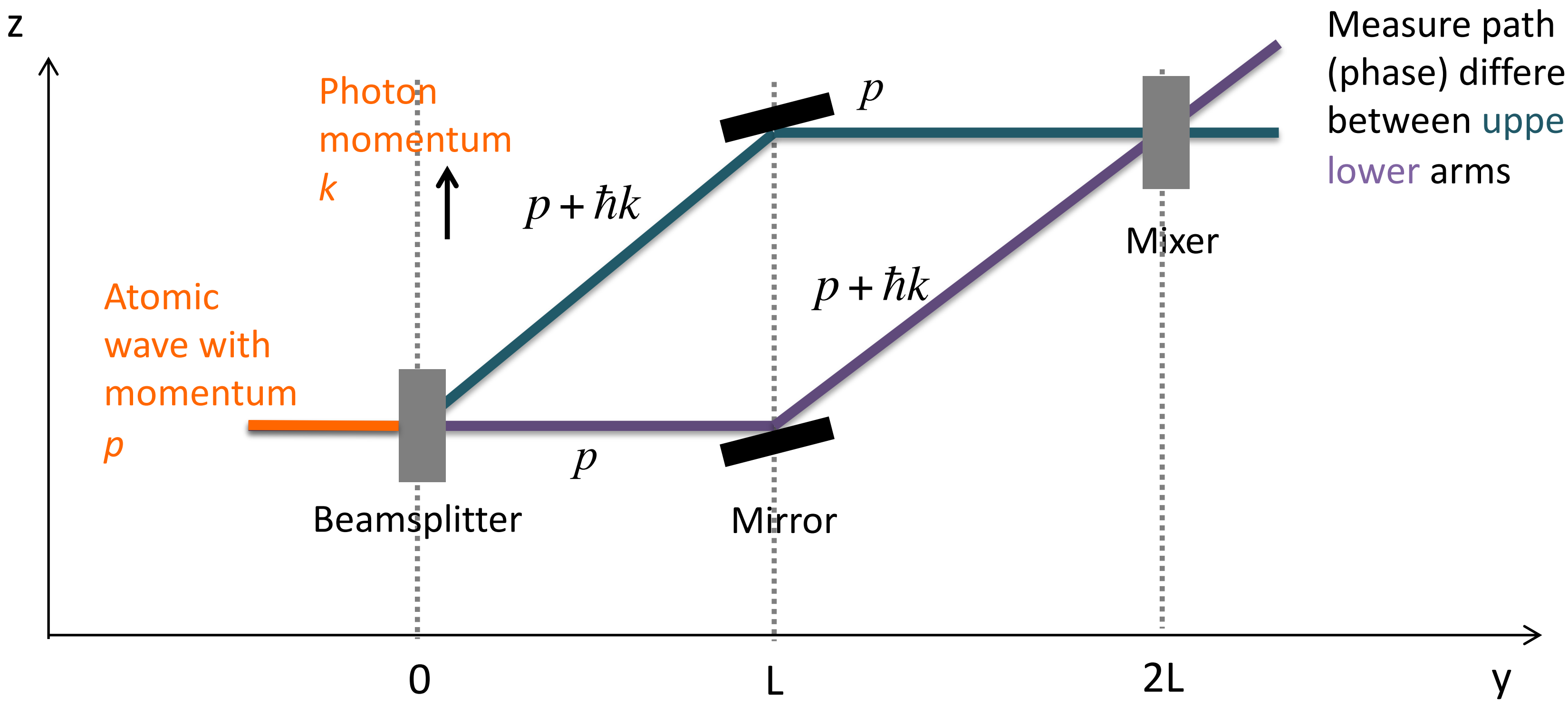
launch velocity

- Sensitivity scales with time-of-flight
- We use atom interferometry to measure displacements

Measuring displacements: Atom Interferometry

Implement a Mach Zehnder Interferometer… with atoms

Trajectory of 1 atom shown (at rest)

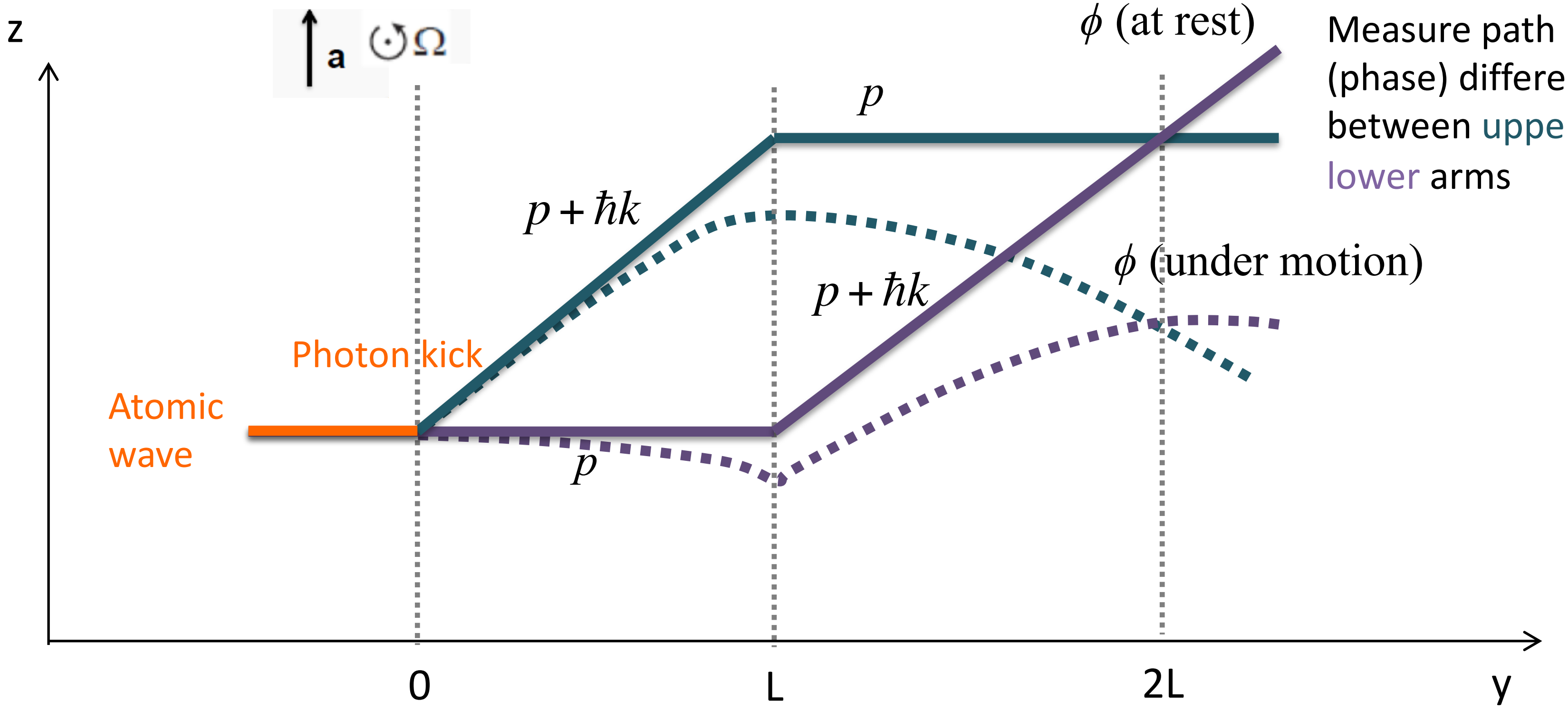


Measure path length (phase) difference between upper and lower arms

We will use laser pulses to implement the beamsplitter, mirror, and mixer, via two-photon Raman transitions.

Measuring displacements: Atom Interferometry

Trajectory of 1 atom shown (at rest and under acceleration)



Measure path length (phase) difference between upper and lower arms

Difference between ϕ (under motion) and ϕ (at rest):

$$\Delta\phi = (\vec{k}\cdot\vec{a})T^2 + 2\vec{k}\cdot(\vec{\Omega}\times\vec{v})T^2$$

, where $T = v\,L$

wavevector

acceleration

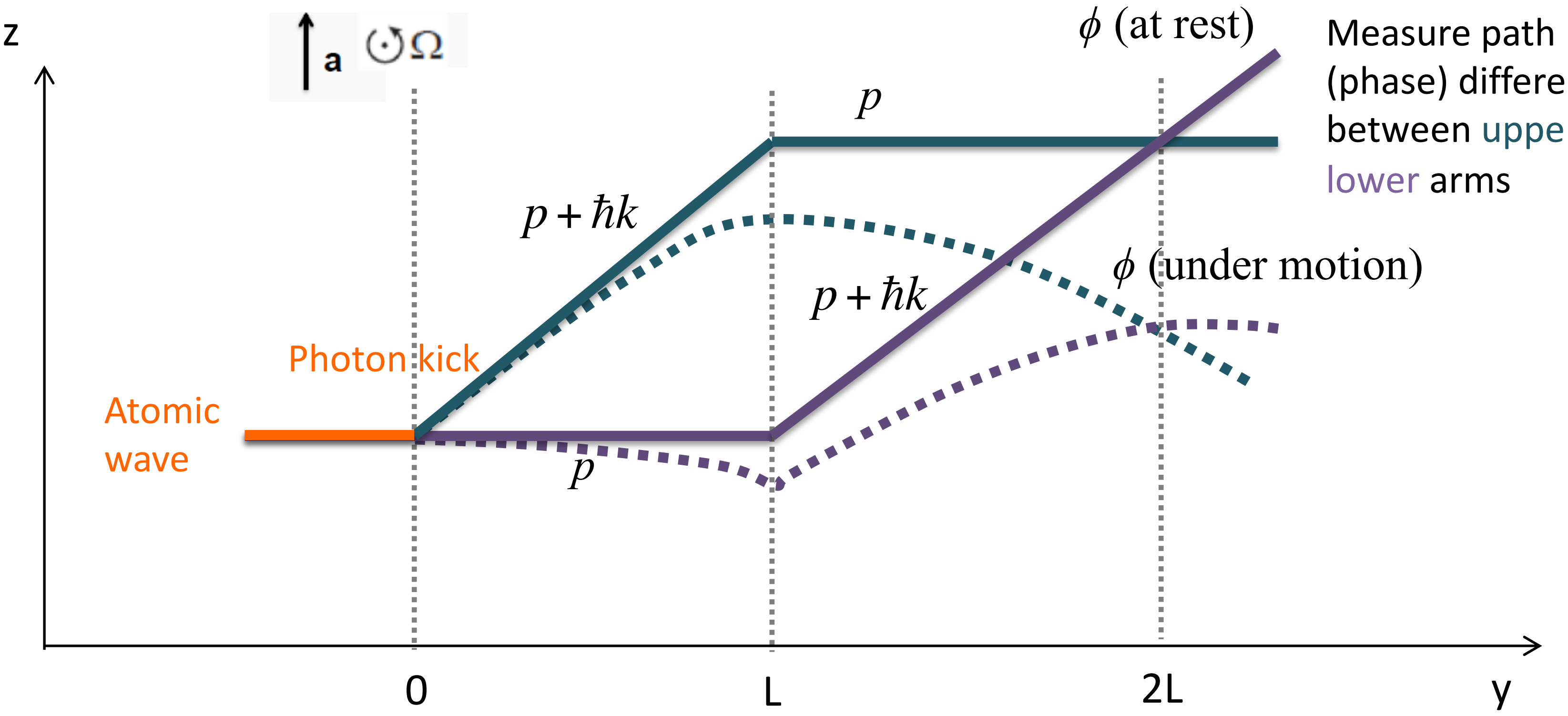
rotation rate

launch velocity

time-of-flight / dwell time

Measuring displacements: Atom Interferometry

Trajectory of 1 atom shown (at rest and under acceleration)



Measure path length (phase) difference between upper and lower arms

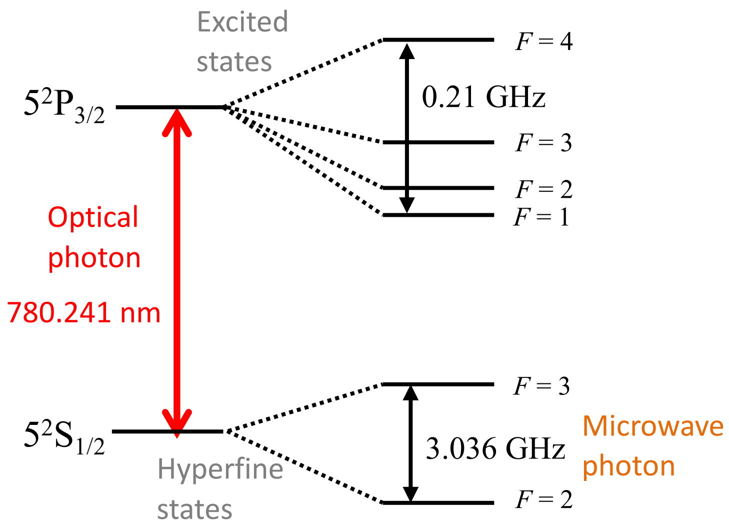
To obtain both acceleration and rotation, we need two interferometers with opposite **v**

$$\Delta\phi(acceleration) = \frac{\Delta\phi_{cloud\ 1} + \Delta\phi_{cloud\ 2}}{2} = \vec{k}\cdot\vec{a}\,T^2$$

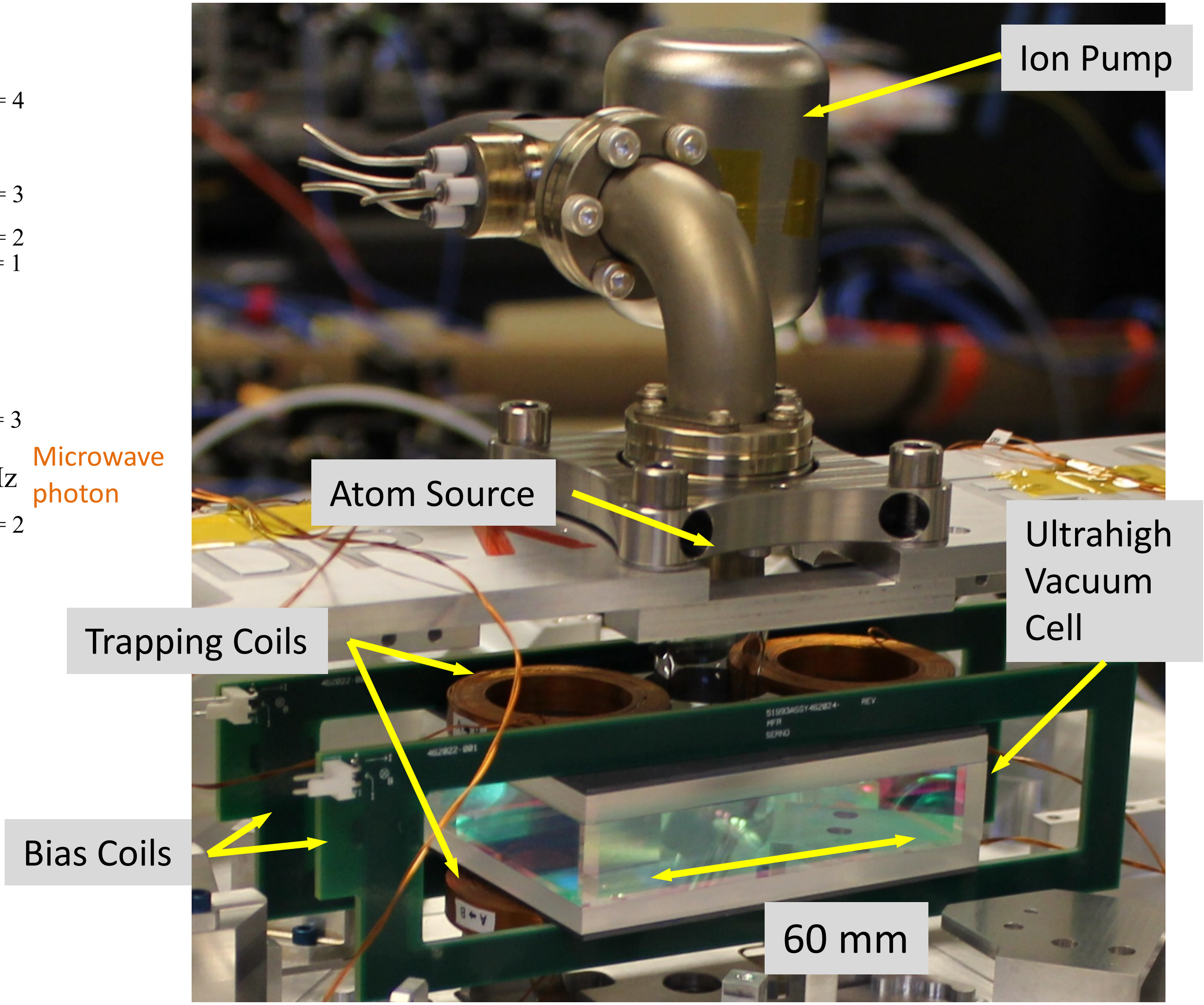
$$\Delta\phi(rotation) = \frac{\Delta\phi_{cloud\ 1} - \Delta\phi_{cloud\ 2}}{2} = 2\vec{k}\cdot(\vec{\Omega}\times\vec{v})\,T^2$$

Cold atom dual accelerometer-gyroscope (DARPA C-SCAN)

Neutral atom: ^{85}Rb

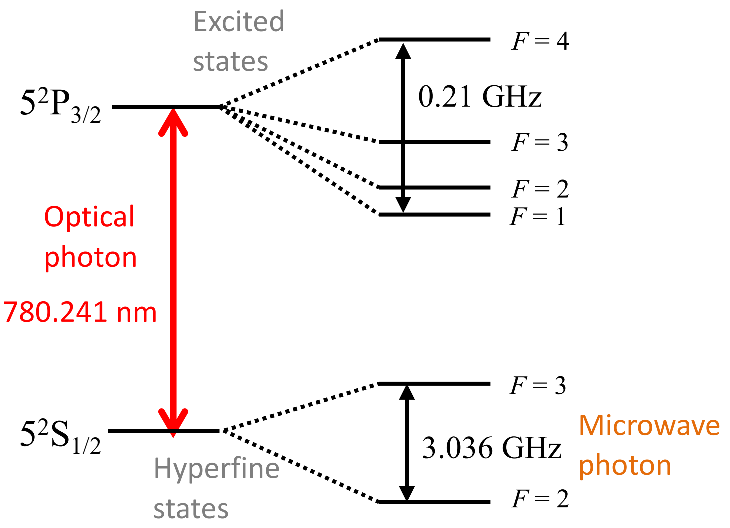


Utilize microwave and optical transitions to excite/de-excite electrons between energy levels

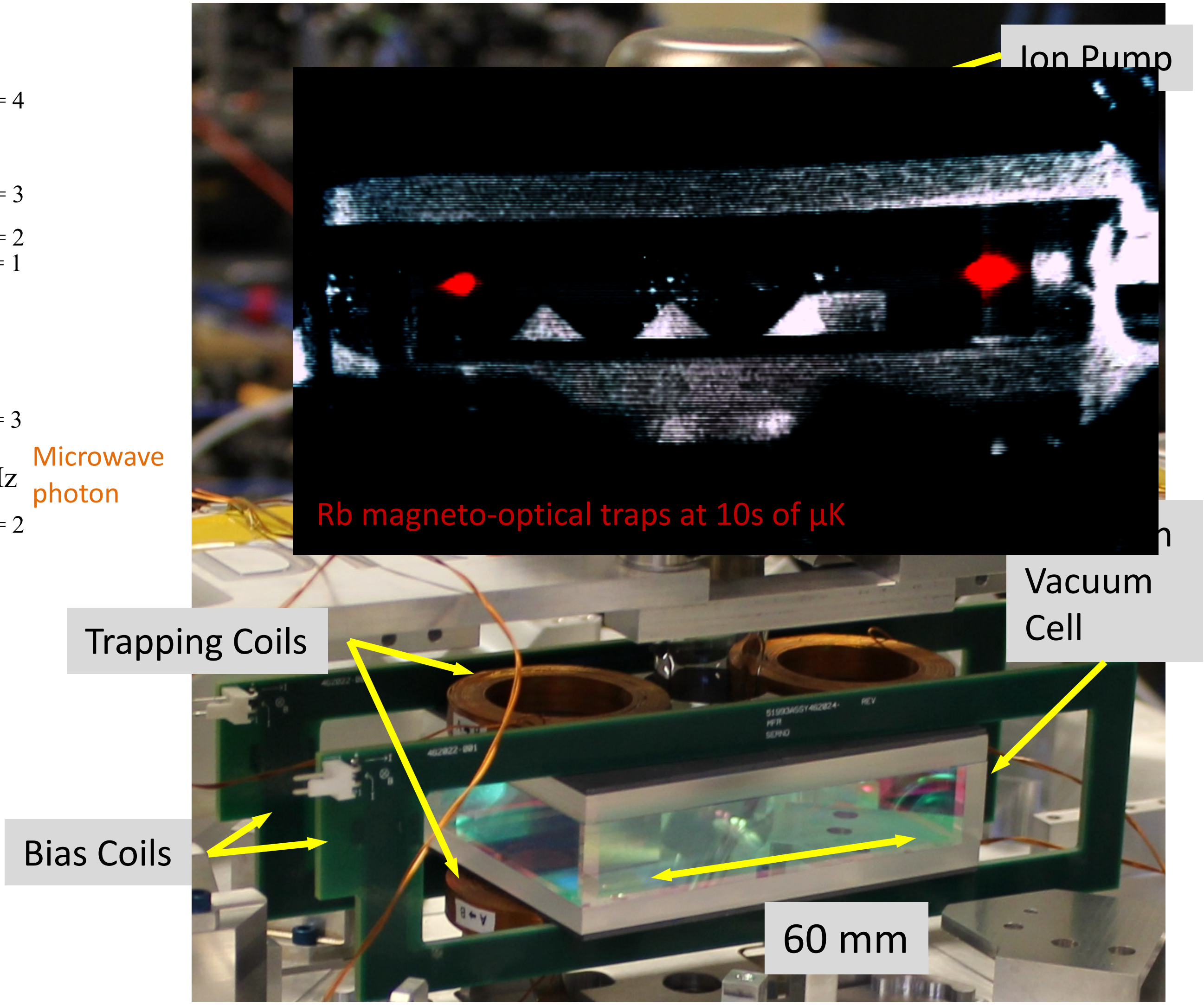


Cold atom dual accelerometer-gyroscope (DARPA C-SCAN)

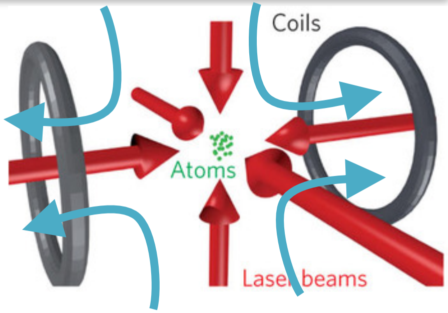
Neutral atom: ^{85}Rb



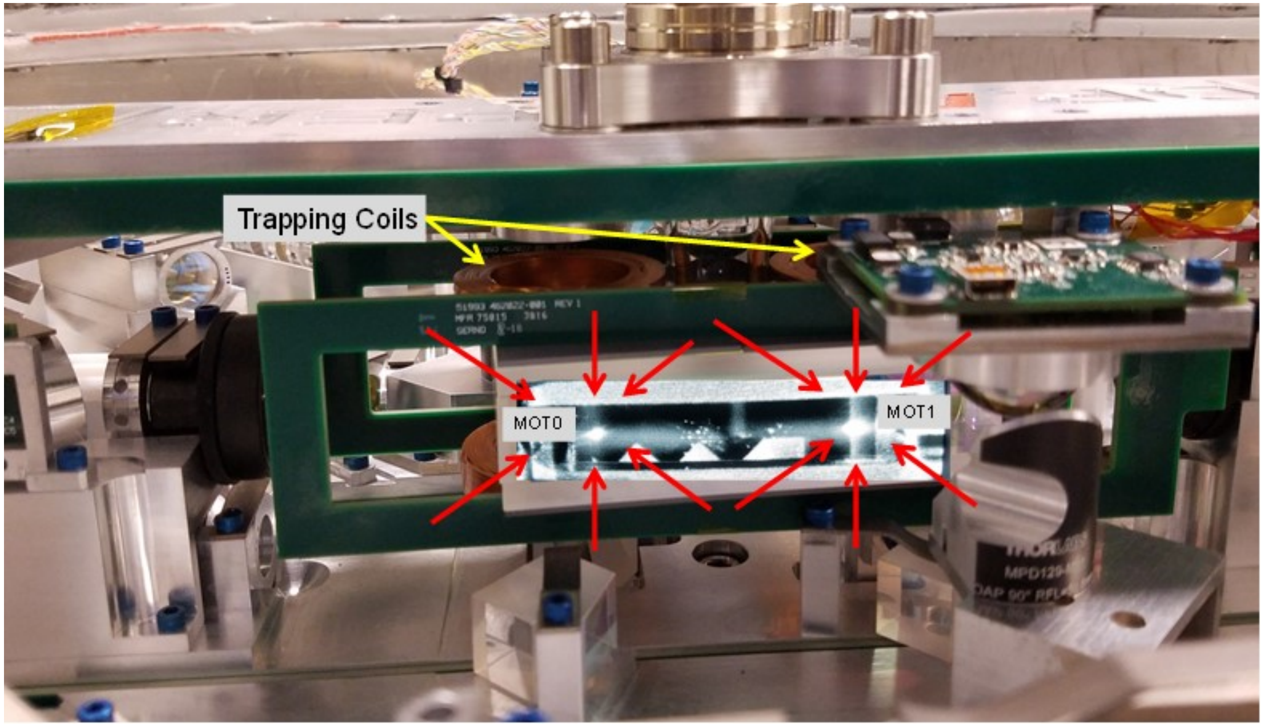
Utilize microwave and optical transitions to excite/de-excite electrons between energy levels



Measurement sequence: Atom Cooling and Trapping



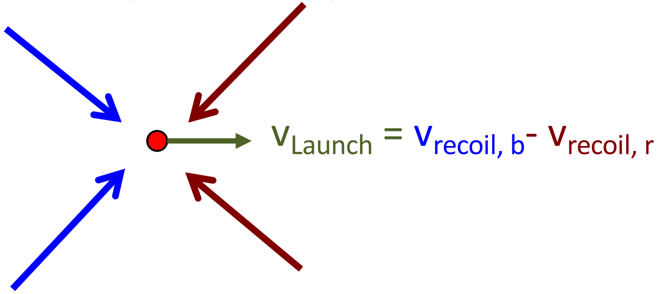
Magneto-optical trap (MOT)



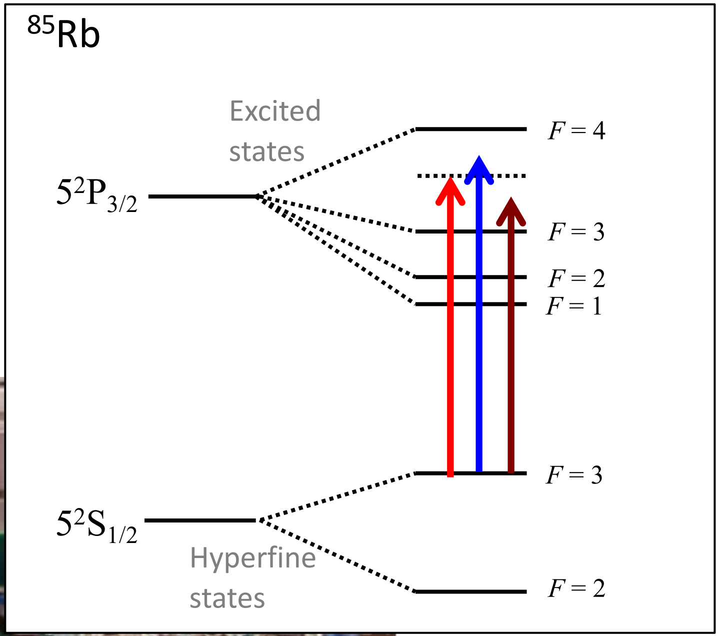
DRAPER

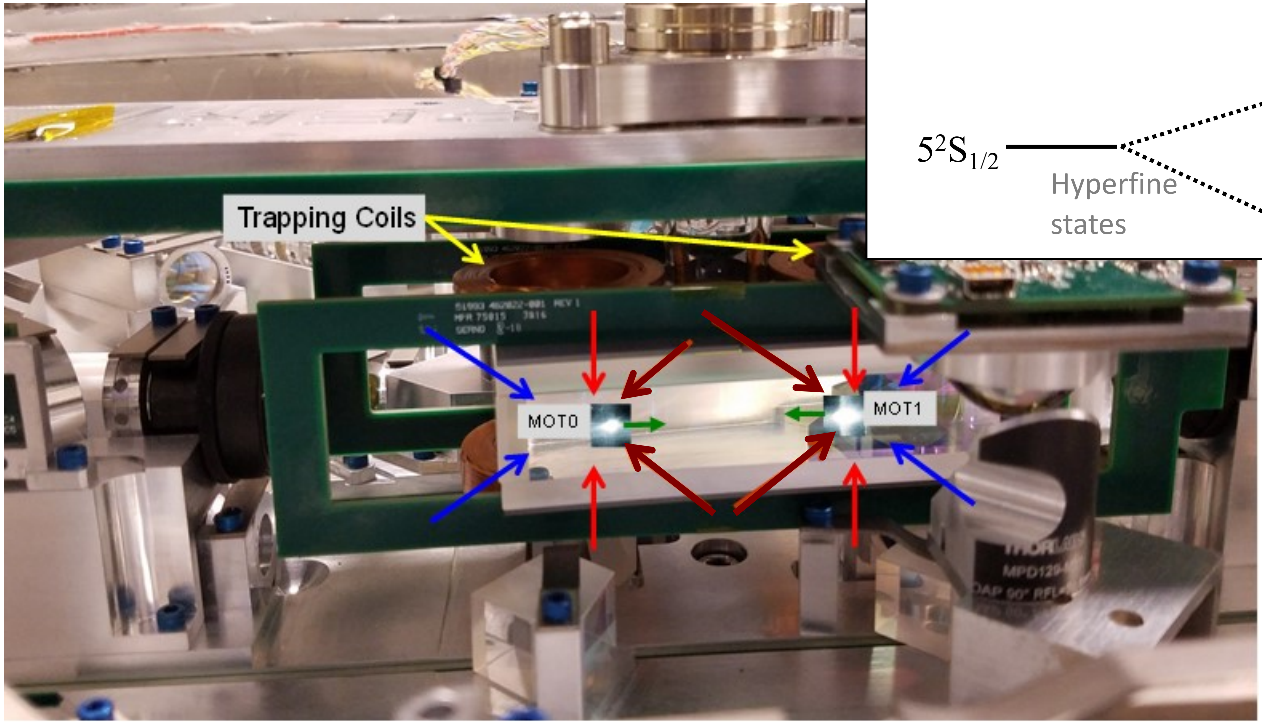
Measurement sequence: Launching

Doppler cooling in moving frame:

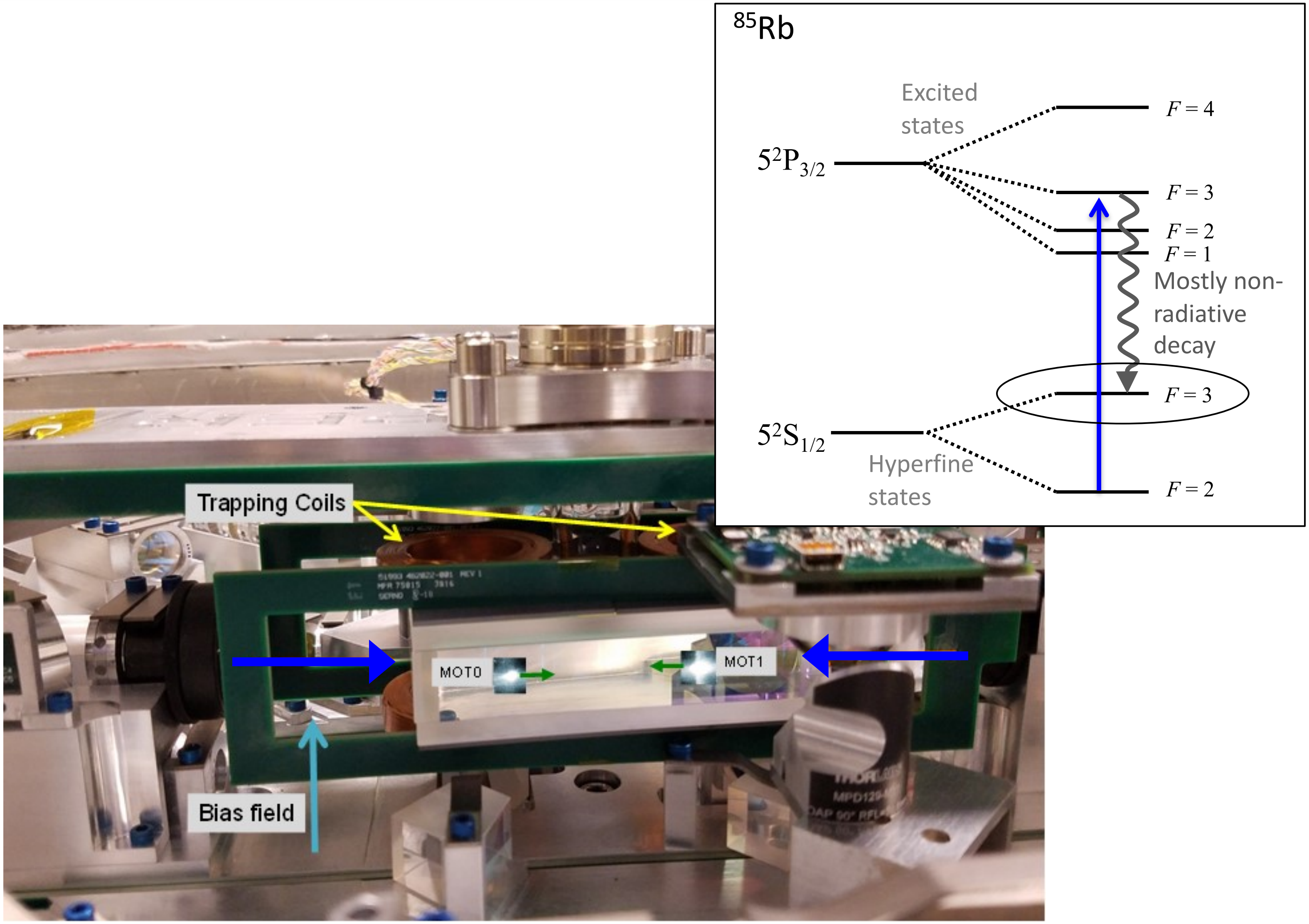


$v_{Launch} = v_{recoil,\,b} - v_{recoil,\,r}$



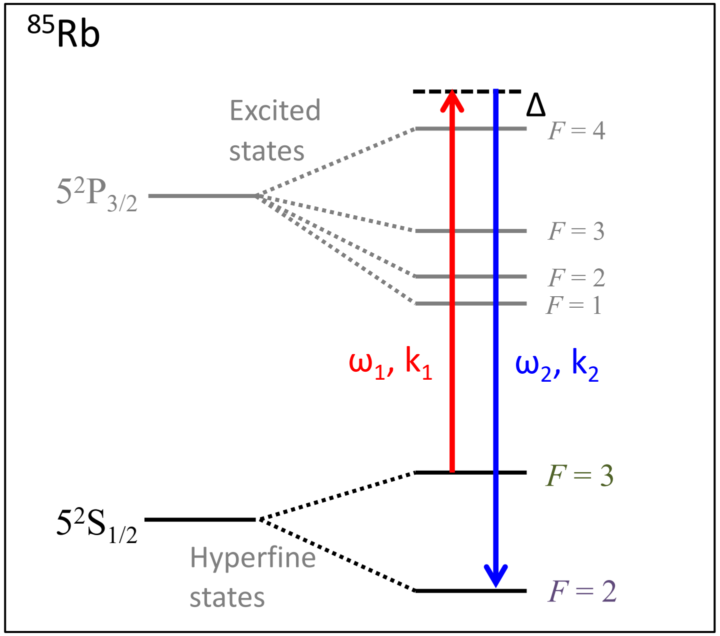


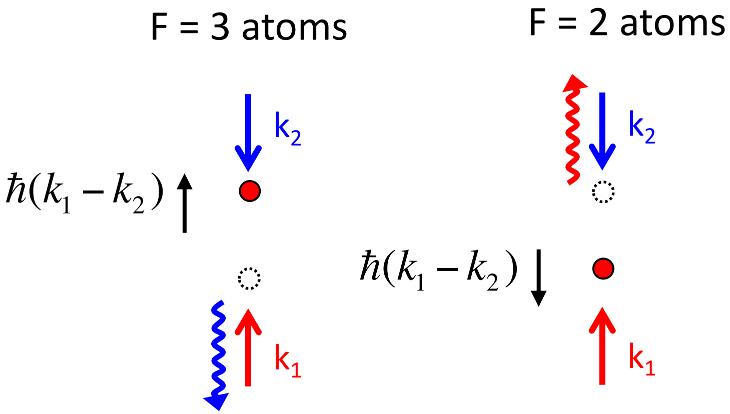
Measurement sequence: State Preparation



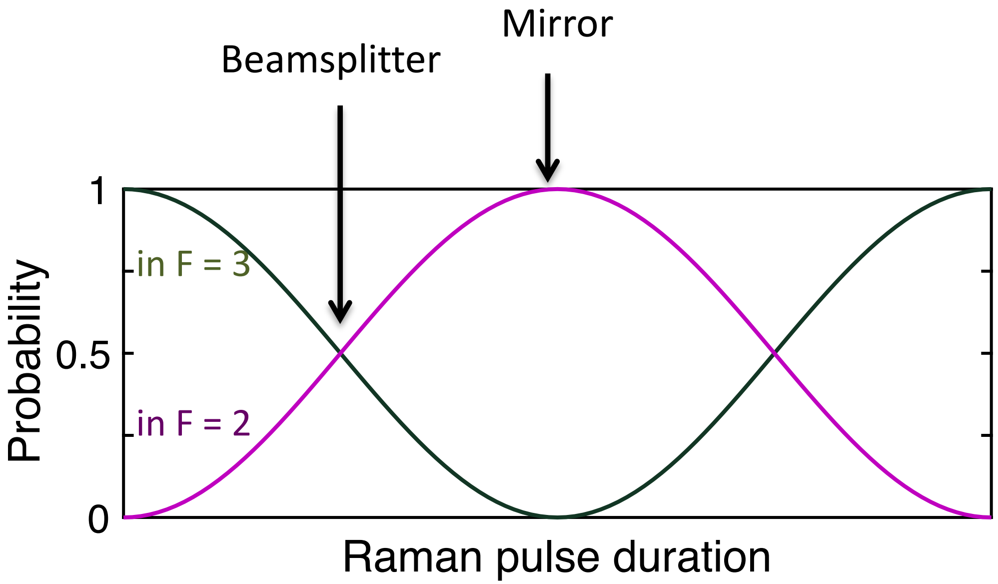
Measurement sequence: Interferometry

Two-photon Raman transitions:





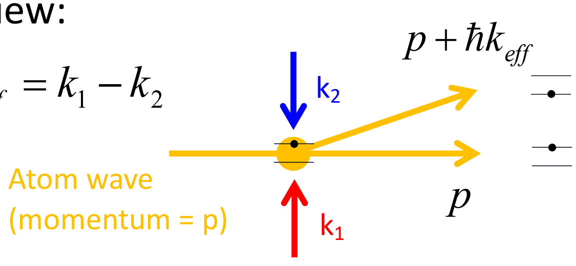
Energy state is entangled to wave propagation direction

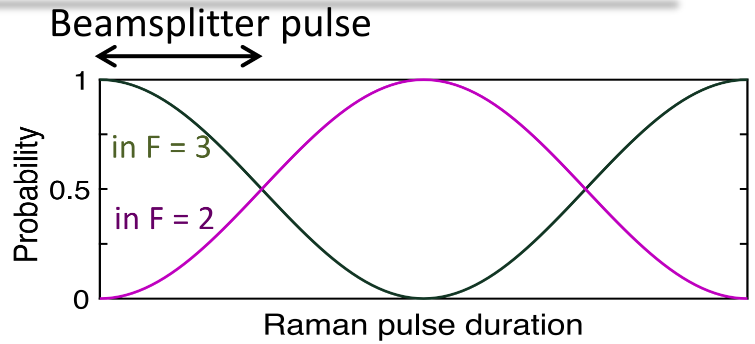


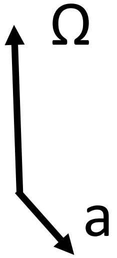
Measurement sequence: Interferometry (Beamsplitter)

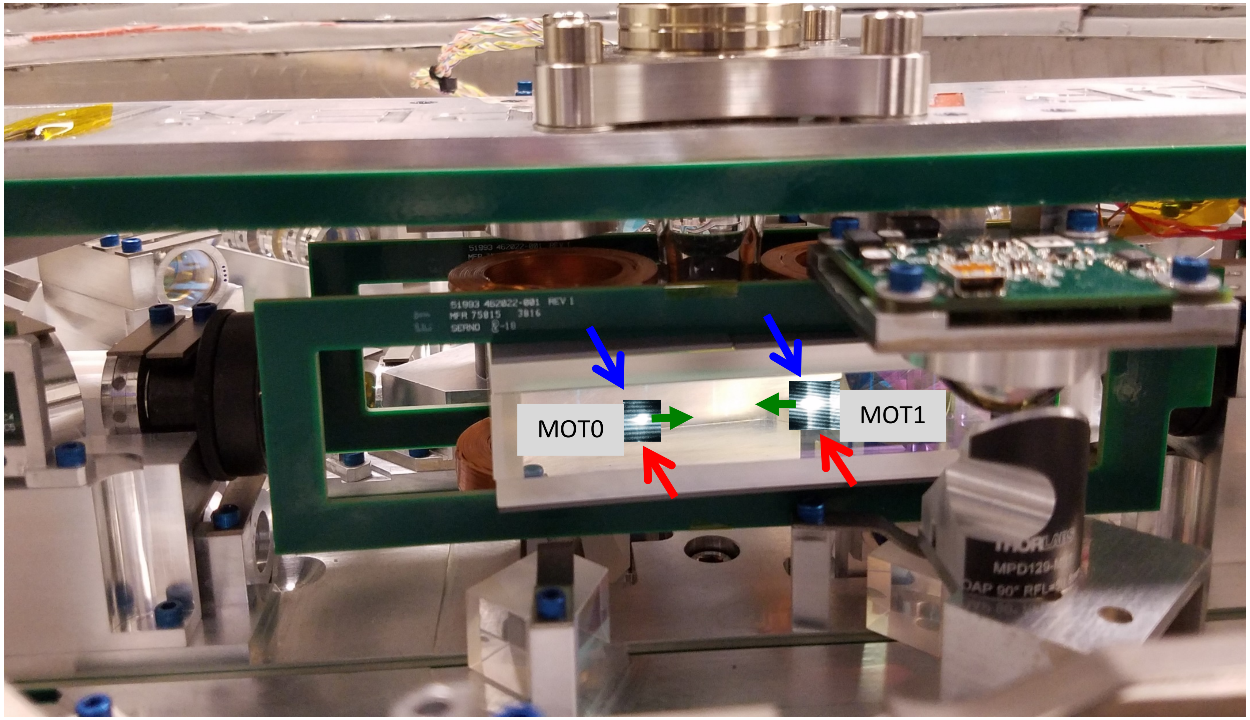
Top view:

$$k_{eff} = k_1 - k_2$$



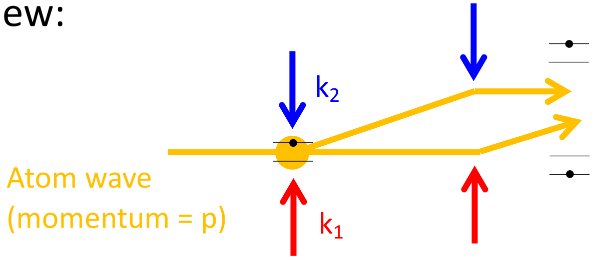


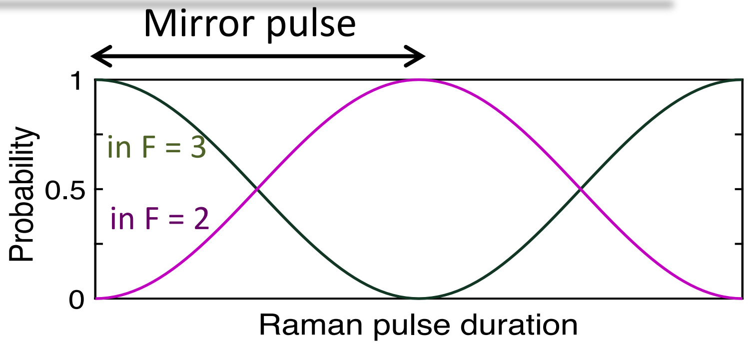


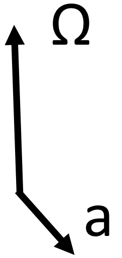


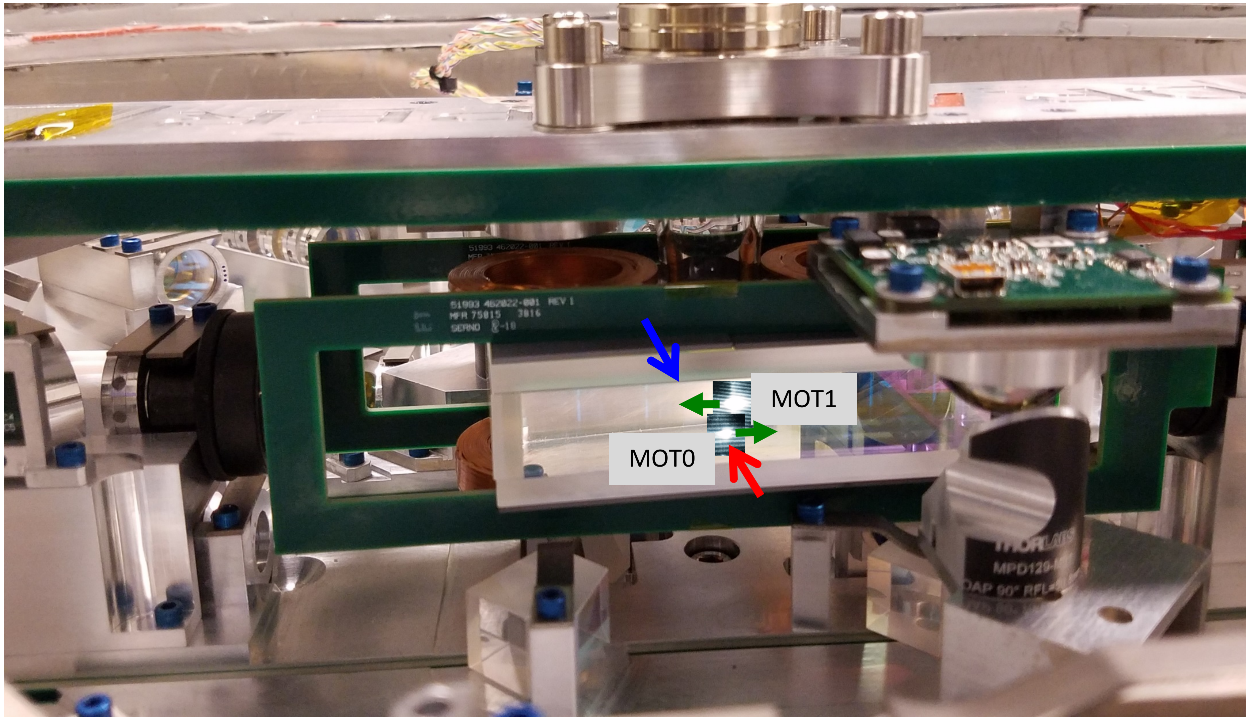
Measurement sequence: Interferometry (Beamsplitter – Mirror)

Top view:



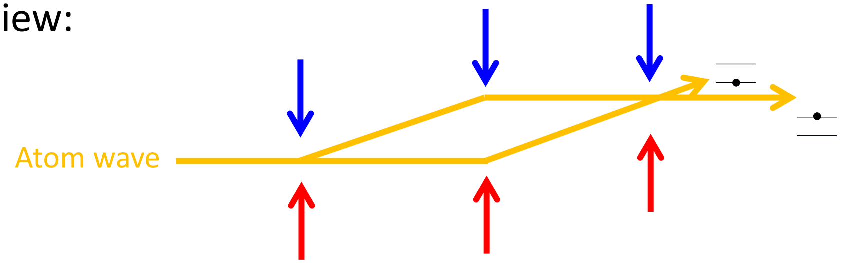


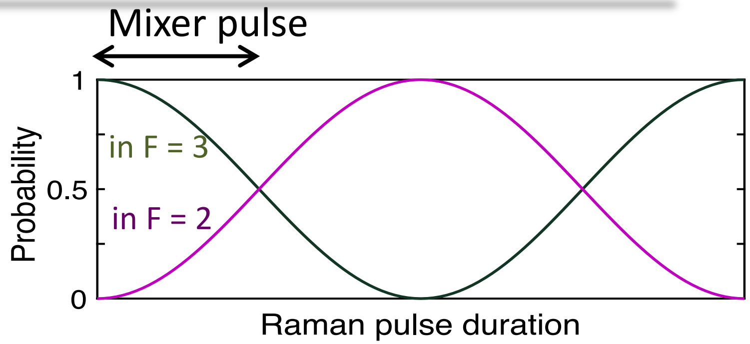


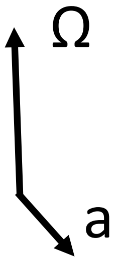


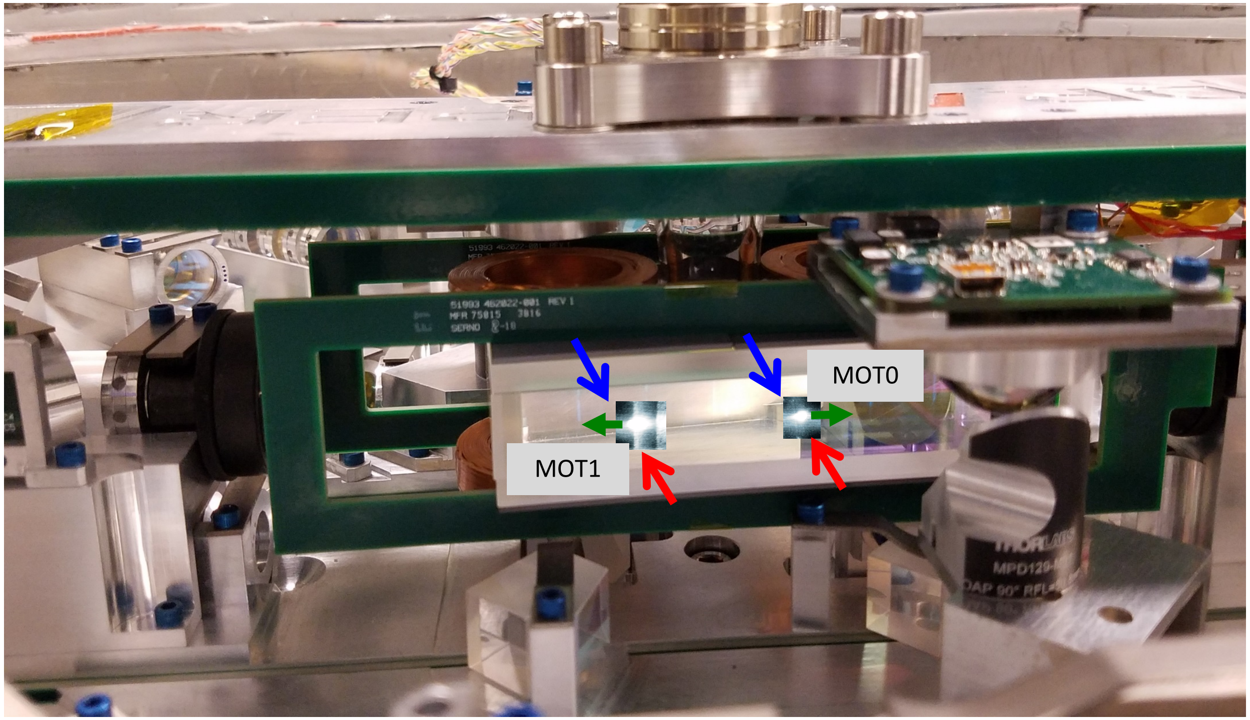
Measurement sequence: Interferometry (Beamsplitter – Mirror – Mixer)

Top view:

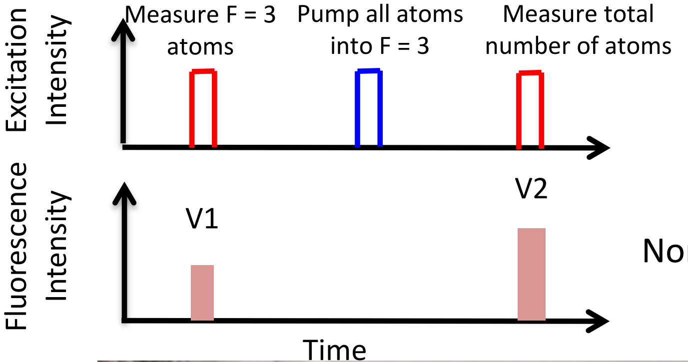




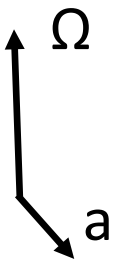


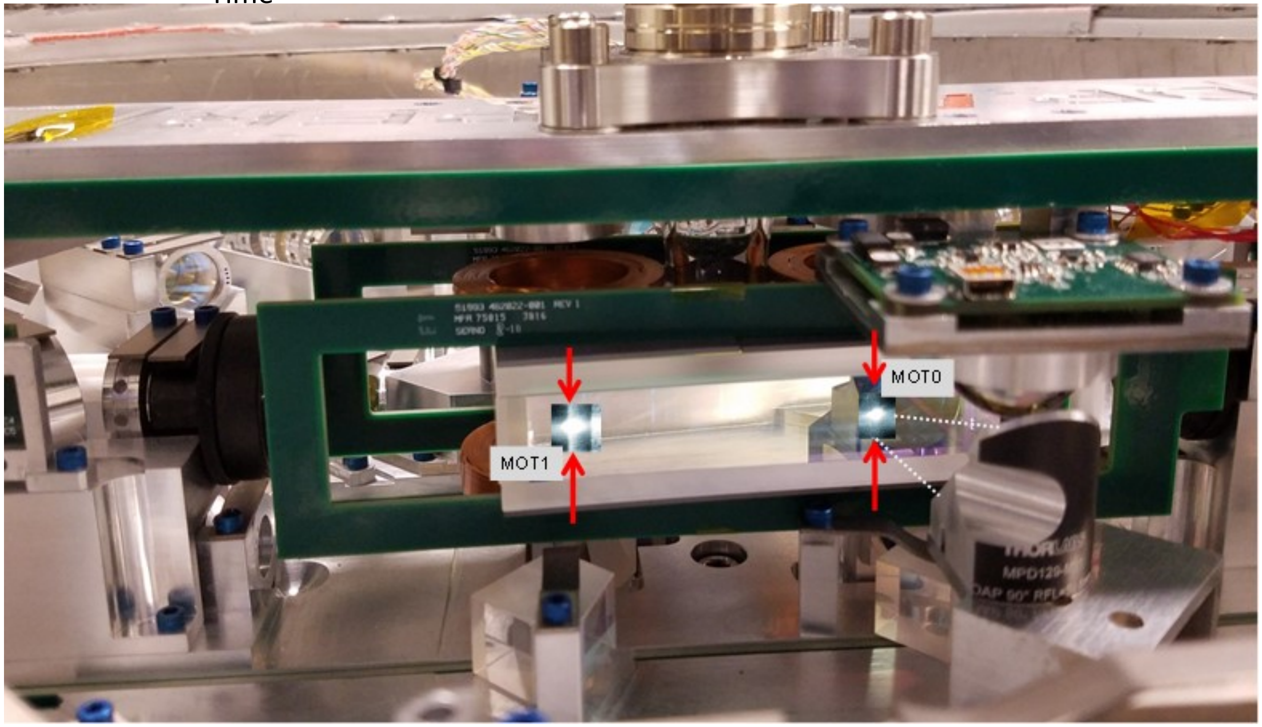


Measurement sequence: State Detection



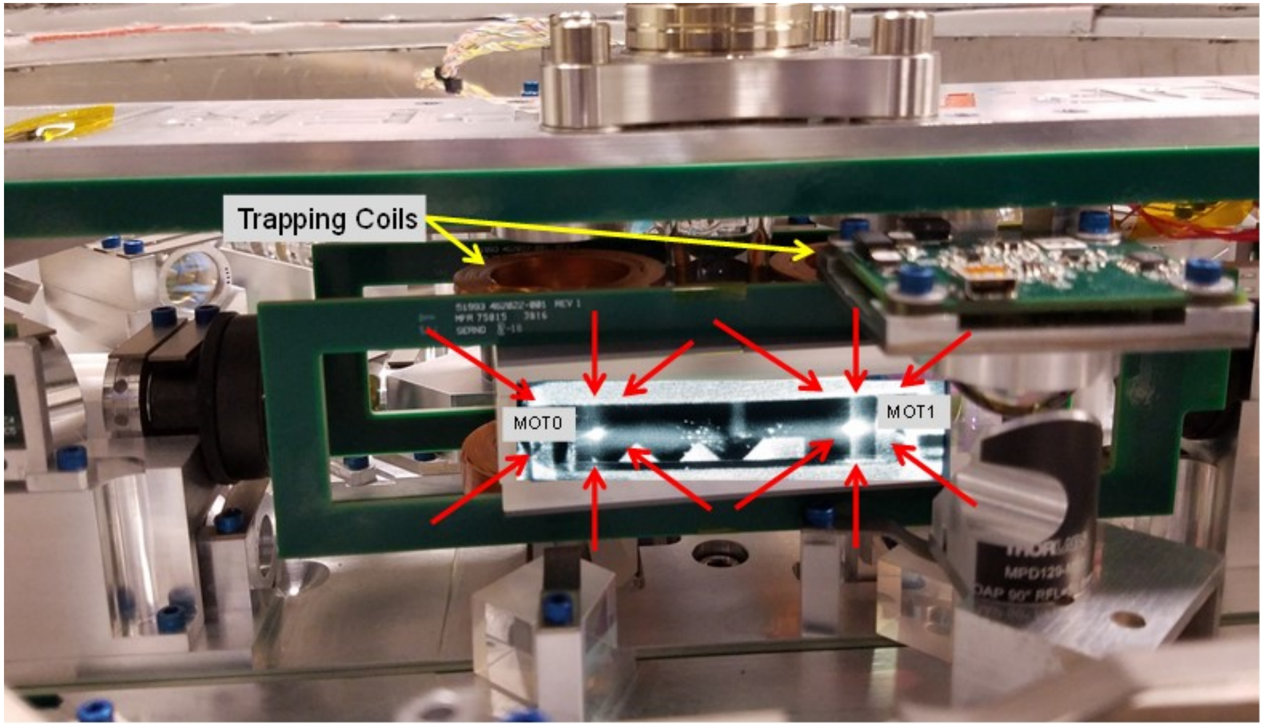
Normalized population = V1/V2





Recapture

- Fast loading of atoms (few milliseconds vs seconds)
- Comparatively high data rates (> 30 Hz) for an atom interferometer → better suited for dynamic environments than most existing cold atom interferometers

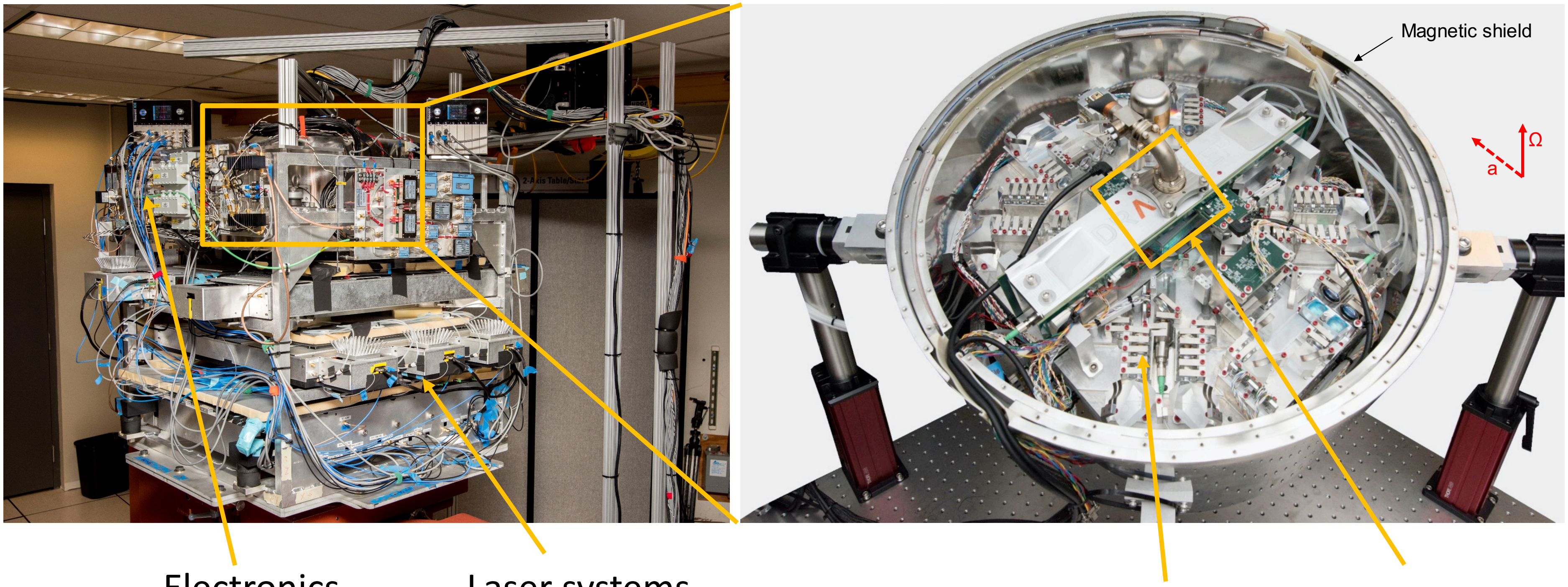


Similar work on an atomic gyroscope with atom recapturing:
A. Rakholia, H. McGuinness, and G. Biedermann, Phys. Rev. Appl. **2**, 054012 (2014)

Assembled sensor

Full system with two integrated sensors

Optical assembly for one sensor



Electronics

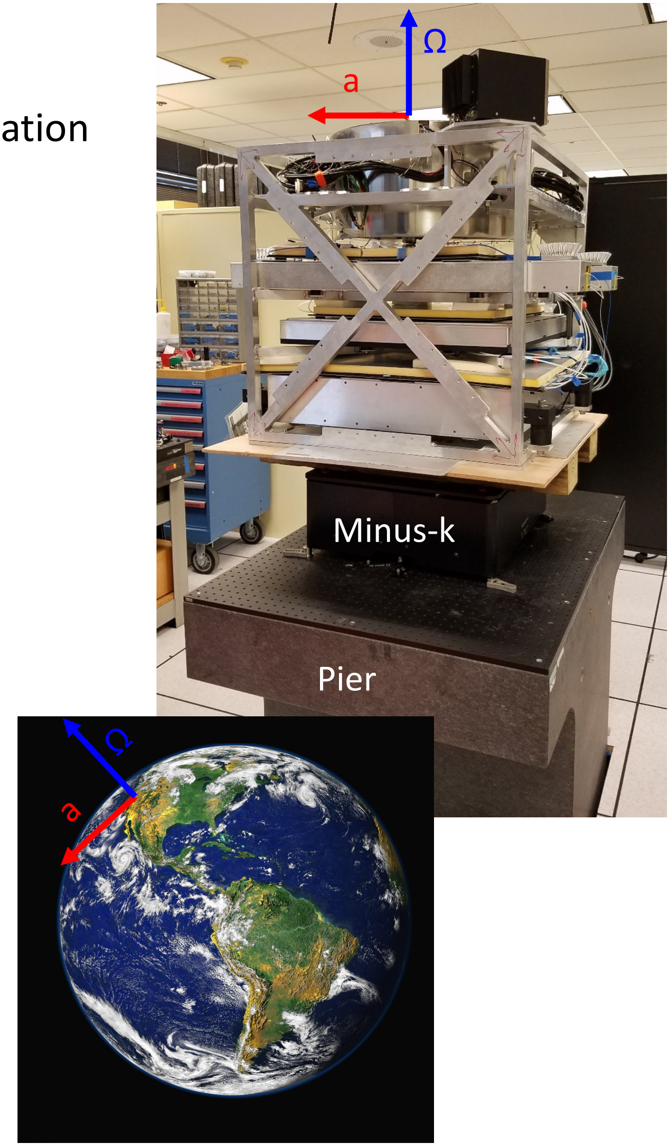
Laser systems

Beam routing and polarizing optics

Vacuum cell

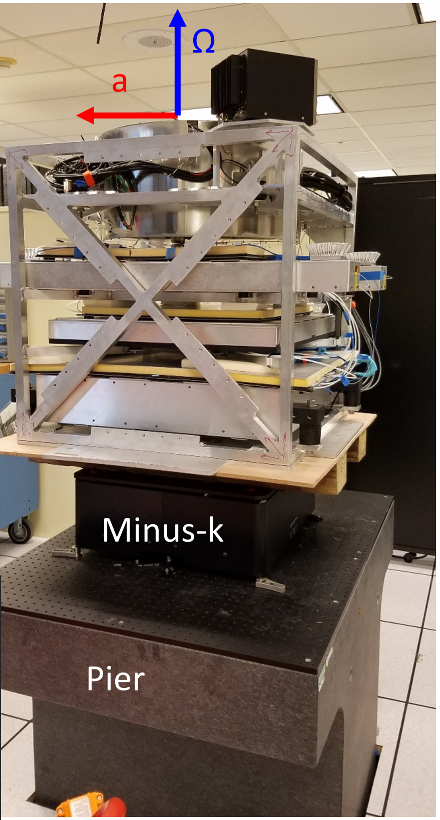
Static measurements

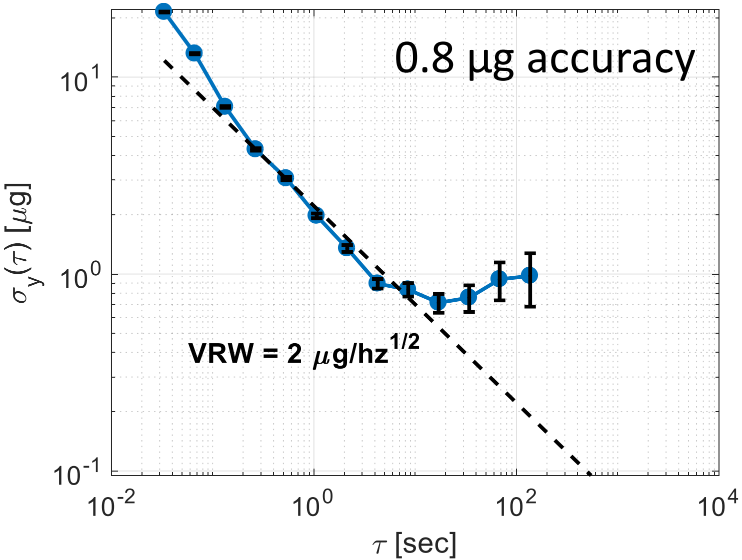
- Acceleration-sensitive axis parallel to ground (~ 0 *g*)
- Rotation-sensitive axis pointing up (~10.5 deg/hr from Earth's rotation in Cambridge, MA)

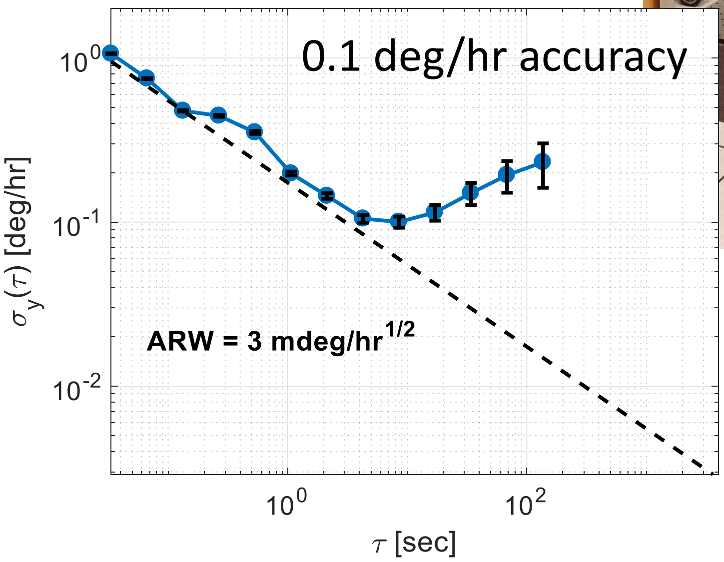


Static measurements

- Acceleration-sensitive axis parallel to ground (~ 0 *g*)
- Rotation-sensitive axis pointing up (~10.5 deg/hr from Earth's rotation in Cambridge, MA)

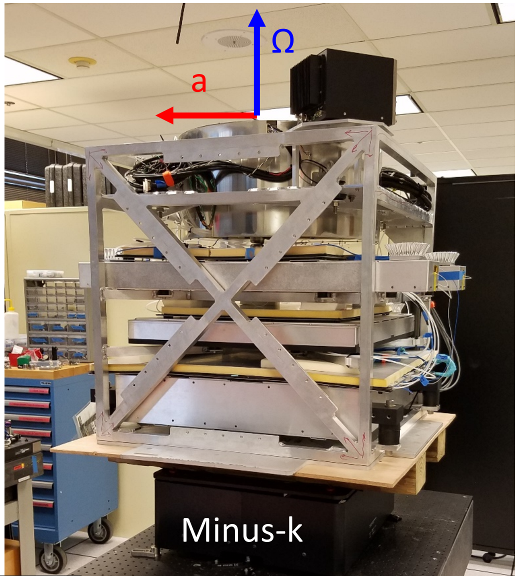






Static measurements

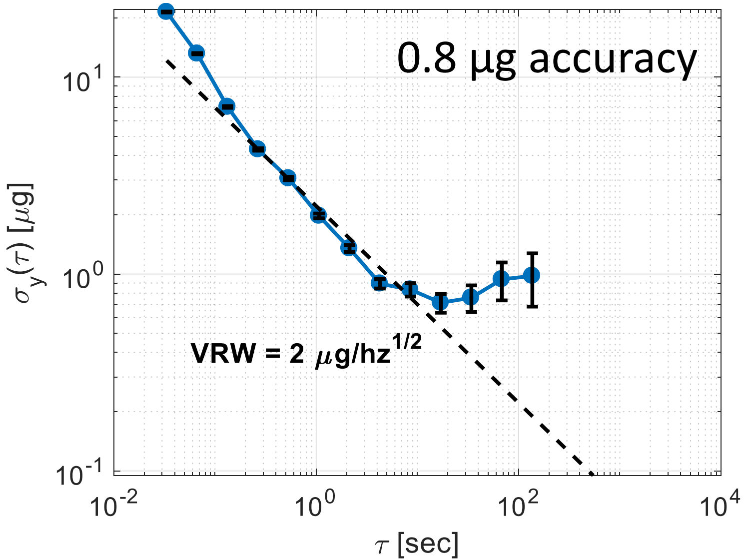
- Acceleration-sensitive axis parallel to ground (~ 0 *g*)
- Rotation-sensitive axis pointing up (~10.5 deg/hr from Earth's rotation in Cambridge, MA)

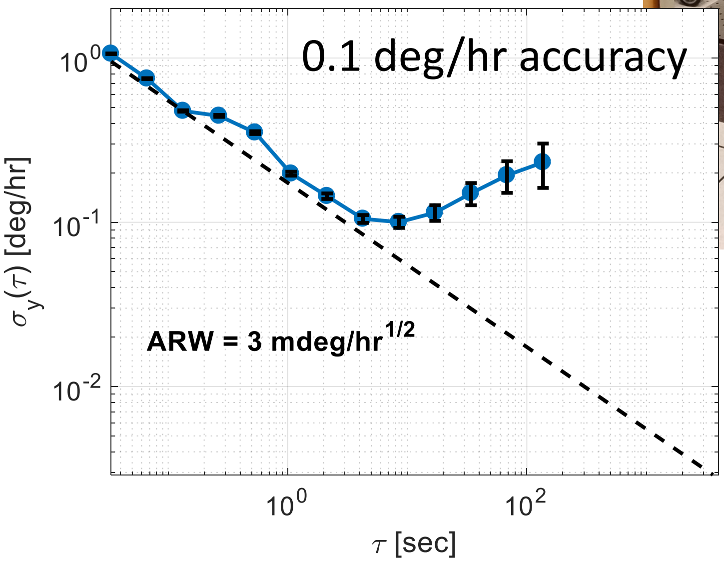


1000x better accuracy than consumer devices

1 mg (consumer MEMS accelerometer)
100 deg/hr (consumer MEMS gyroscope)

For reference, ~ 1 μg gravity difference between floors of a building

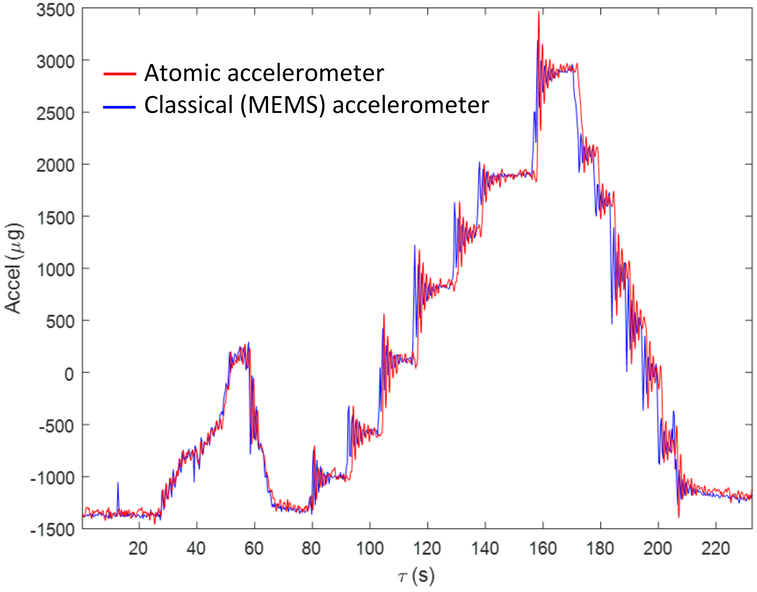




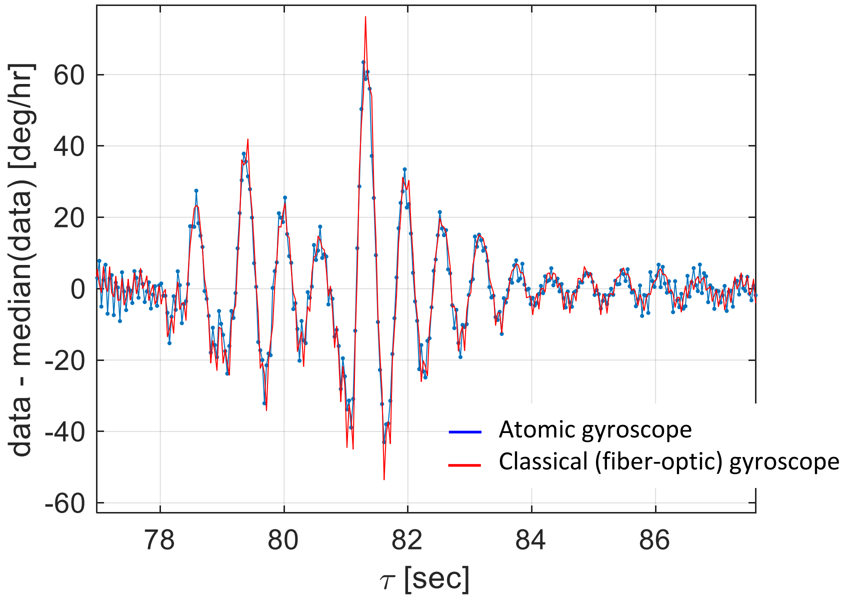
Dynamic measurements

- Classical and atomic sensors mounted on same platform
- Good agreement between atomic and classical sensors
- Sensitivity of atomic sensor matches simple analytical expression: $\Delta\phi = \underbrace{(\vec{k}\cdot\vec{a})T^2}_{\text{Acceleration}} + \underbrace{2\vec{k}\cdot(\vec{\Omega}\times\vec{v})T^2}_{\text{Rotation}}$

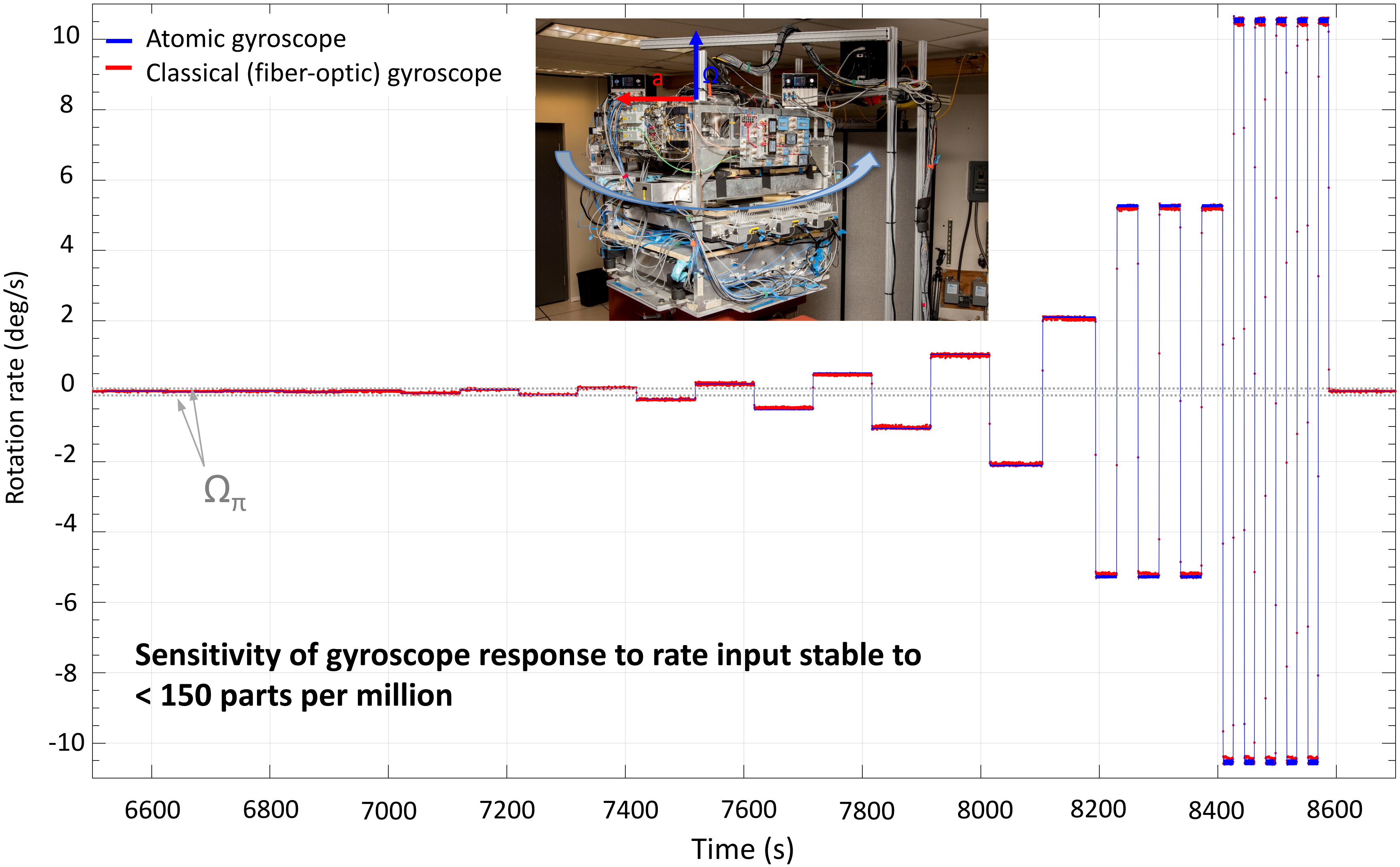
Apply small tilts to platform:



Gentle rotation:



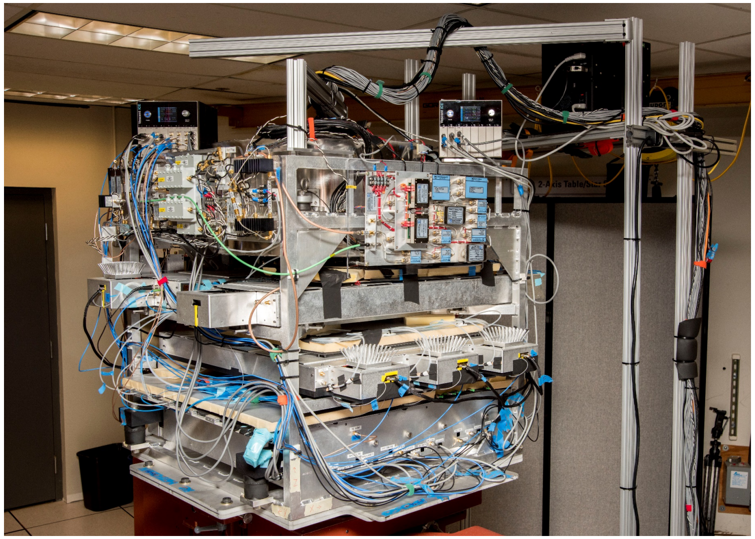
Dynamic measurements on a rate table



Sensitivity of gyroscope response to rate input stable to < 150 parts per million

Size and complexity of most atomic sensors today

Cold-atom accelerometer-gyroscope at Draper Lab



Muqans atomic gravimeter

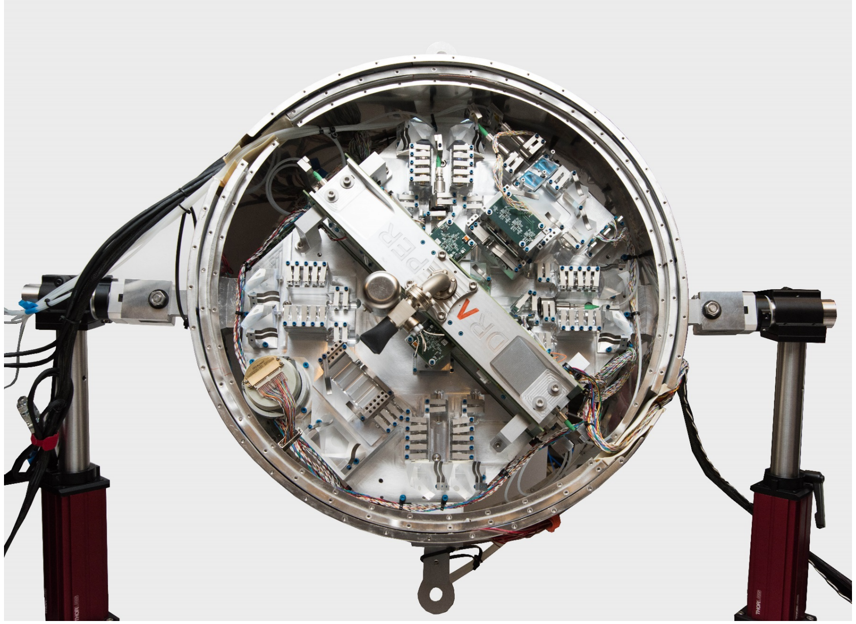
Mobile atomic gravimeter from Mueller lab (UC Berkeley)

Xuejian Wu et al. Sci Adv 2019;5:eaax0800

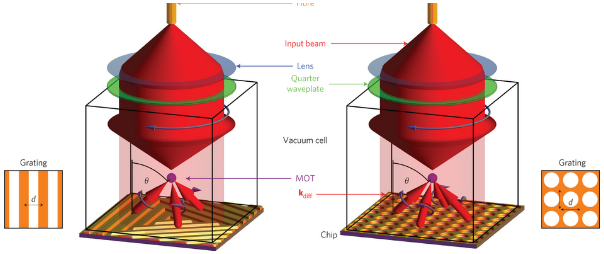
Challenges

- Thermal and mechanical instability
- Performance degradation during motion
- Assembly time and costs

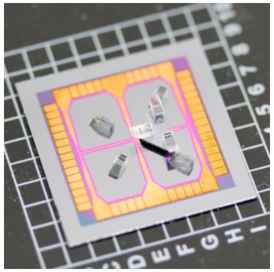
From labscale to chipscale



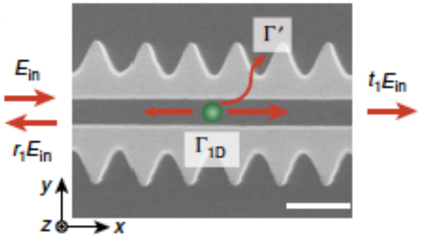
Atom-photon interface



Nshii et al, Nature Nano (2013)

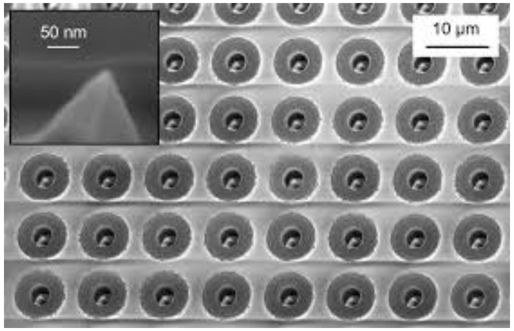


Cold Quanta



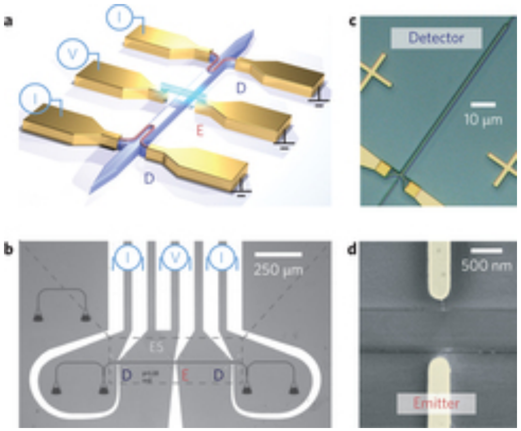
Goban et al, Nat Comm (2014)

Vacuum Technology



Basu et al, Solid-State Sensors (2015)

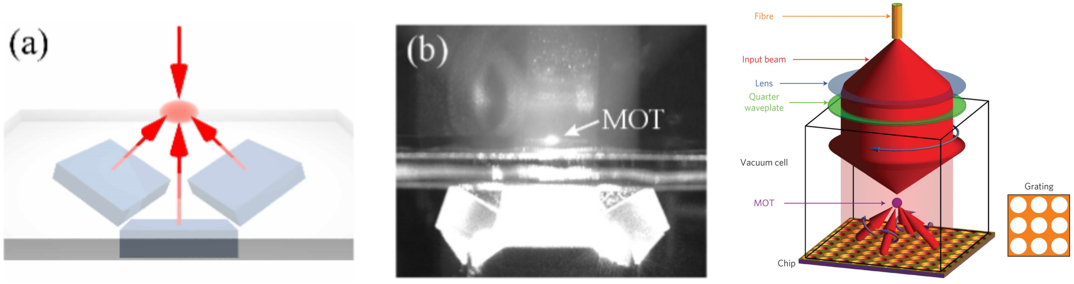
Photonic front-end



Khasminskaya et al, Nature Photonics (2016)

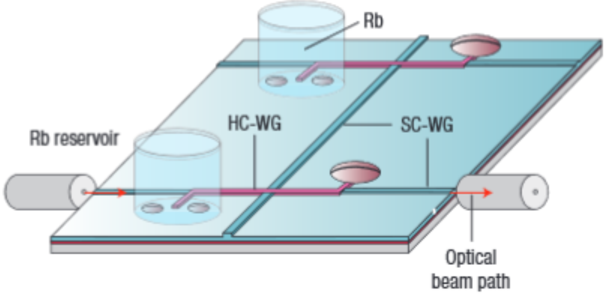
Integrated nanophotonics for atoms

Chip-scale tetrahedral magneto-optical traps



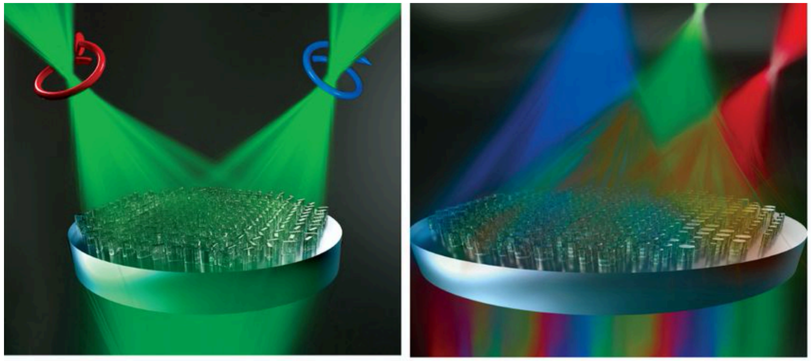
Vangeleyn et al, *Optics Express*, **17**, 16 (2009)
Nshii et al, *Nat. Nanotechnol.*, **8**, 321-324 (2013)

Atomic spectroscopy on a chip



Yang et al, *Nature Photon* **1,** 331–335 (2007)

Metasurfaces



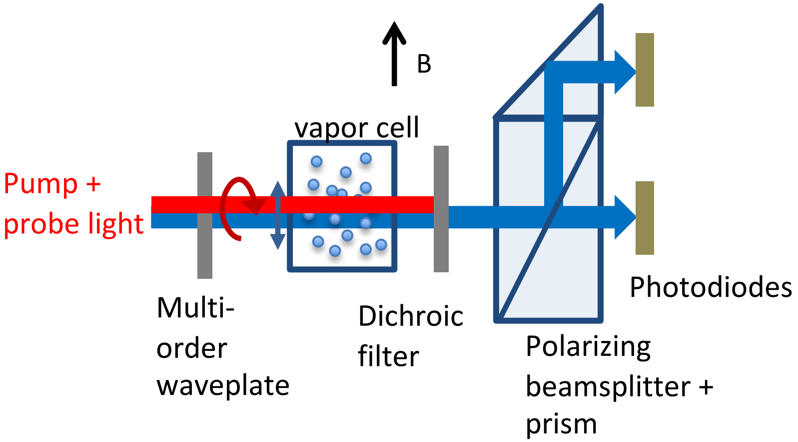
M. Khorasaninejad and F. Capasso, *Science* **358** 6367 (2017)

Useful functionalities for atoms

- Polarization control
- Beam shaping and steering

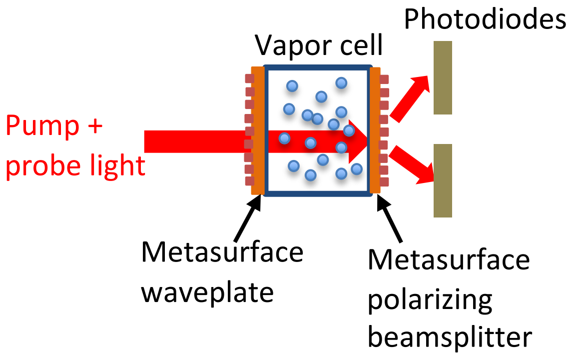
Optically pumped atomic magnetometer with flat optics

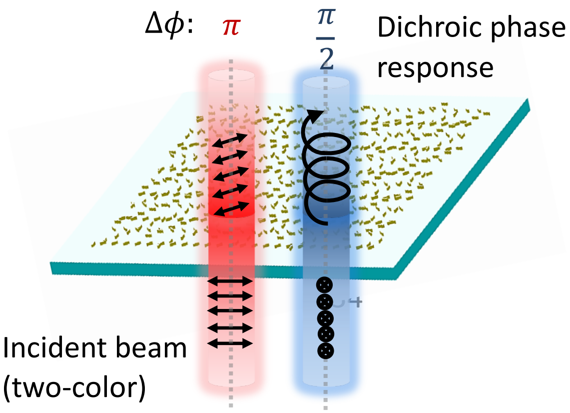
Inline atomic magnetometer designs using discrete optics:

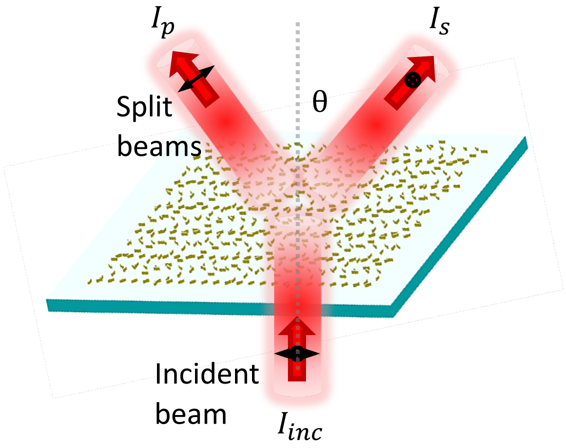


Johnson et al, *Applied Physics Letters* 97(24) (2010)

Our proposed design with integrated nanophotonics:



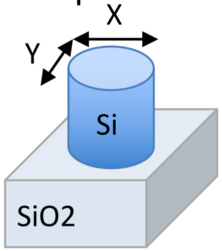




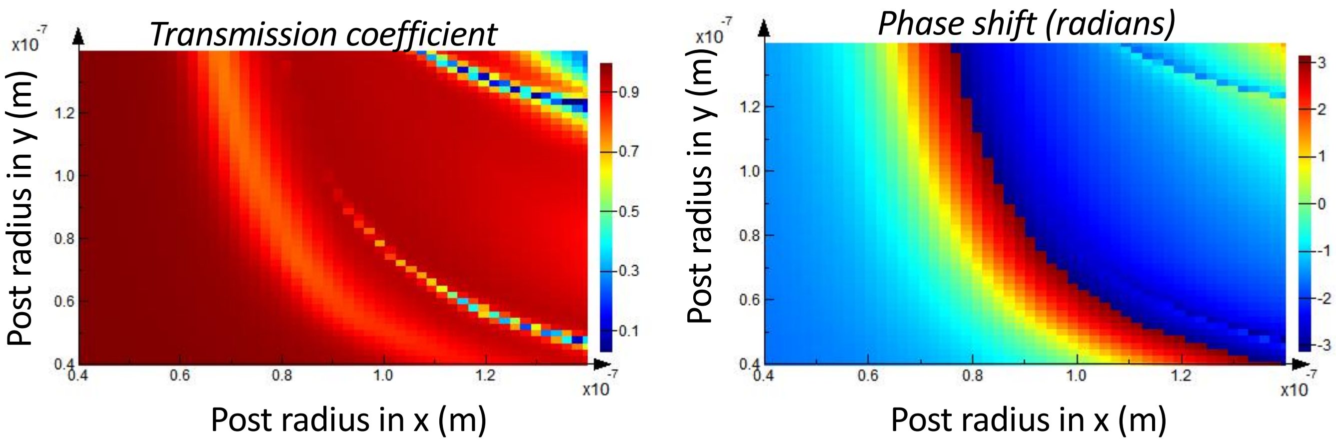
Design of metasurface polarization components

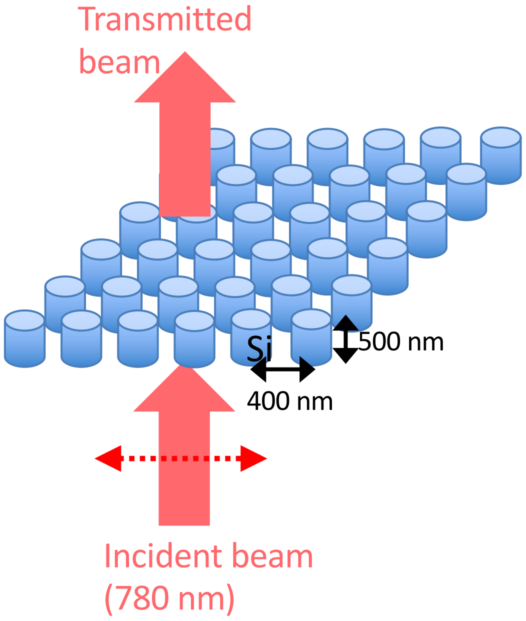
- Approach based on Arbabi *et al*, Nature Nano **10**, 937–943 (2015)
- Metasurface implemented by arrays of elliptical posts which provide independent phase shifts for different polarization axes

Elliptical post unit cell

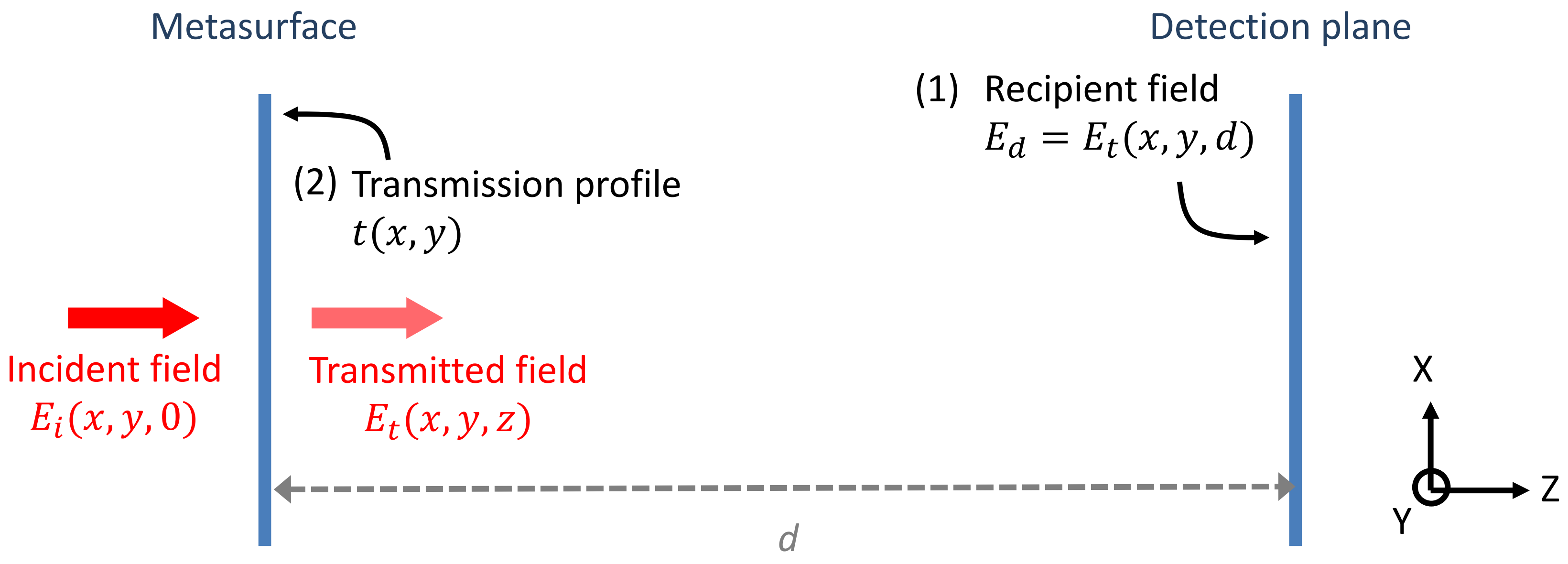


Simulated transmission





Back-propagation of desired vector field



Metasurface

Detection plane

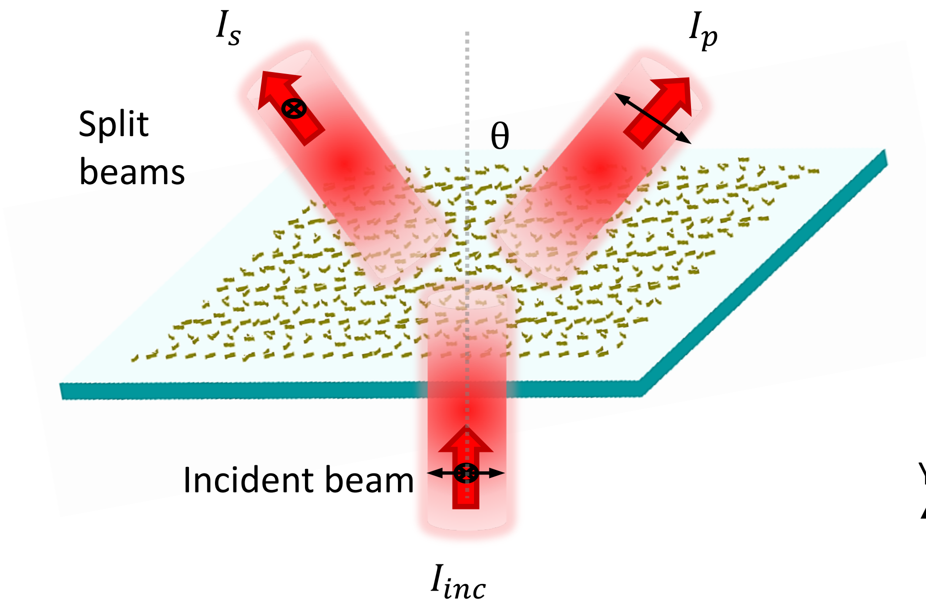
(1) Recipient field
$E_d = E_t(x, y, d)$

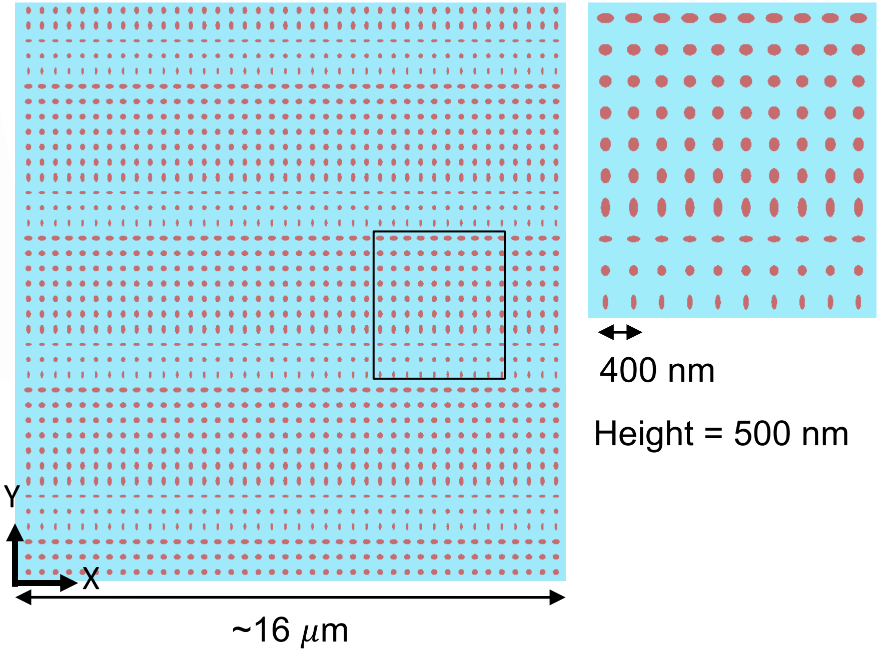
(2) Transmission profile
$t(x, y)$

Incident field
$E_i(x, y, 0)$

Transmitted field
$E_t(x, y, z)$

Our polarizing beamsplitter design





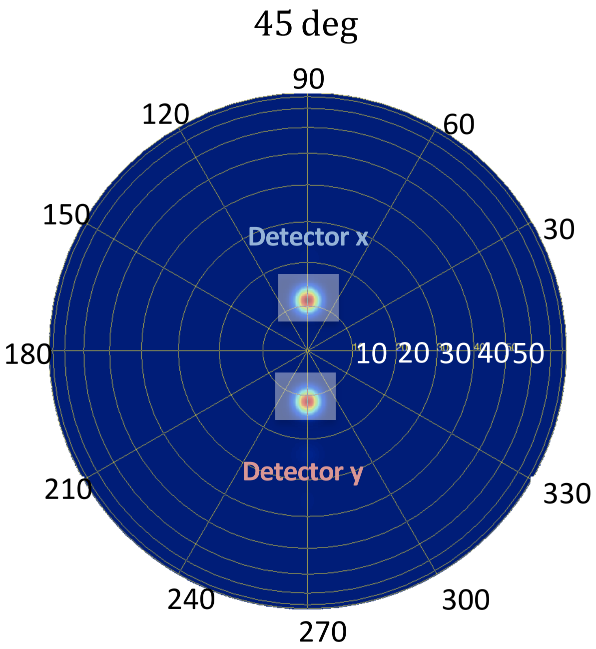
See other implementations of metasurface polarization beamsplitting:

[1] M. Khorasaninejad et al, *Optica* Vol. 2, Issue 4, pp.378-382(2015)

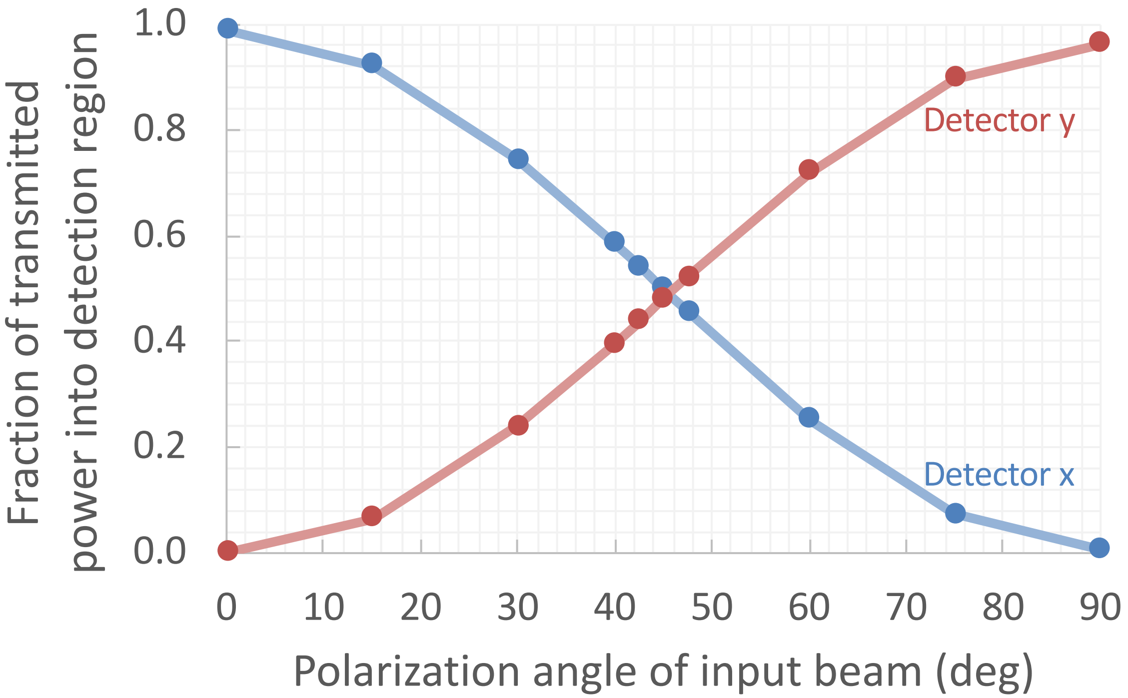
[2] B. A. Slovick et al, *Phil. Trans. R. Soc*. A375: 0072 (2016)

[3] E. Arbabi et al, ACS Photonics 5, 3132−3140 (2018)

Simulated polarizing beamsplitter performance



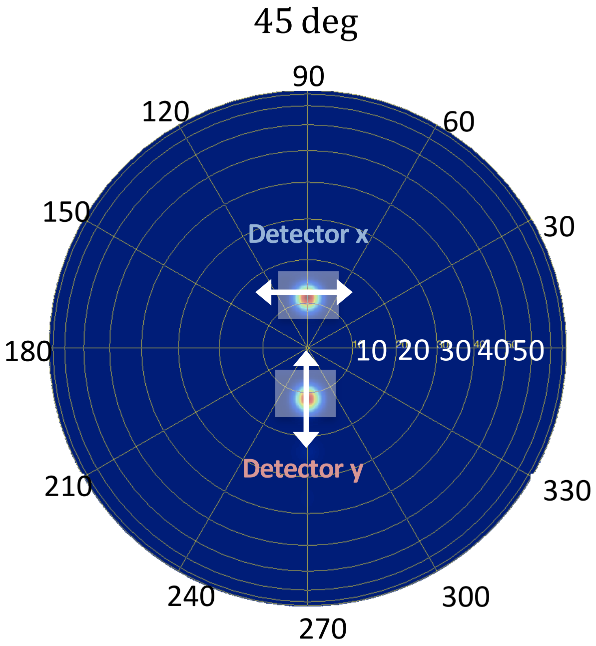
Total transmission at 780 nm ~ 89%



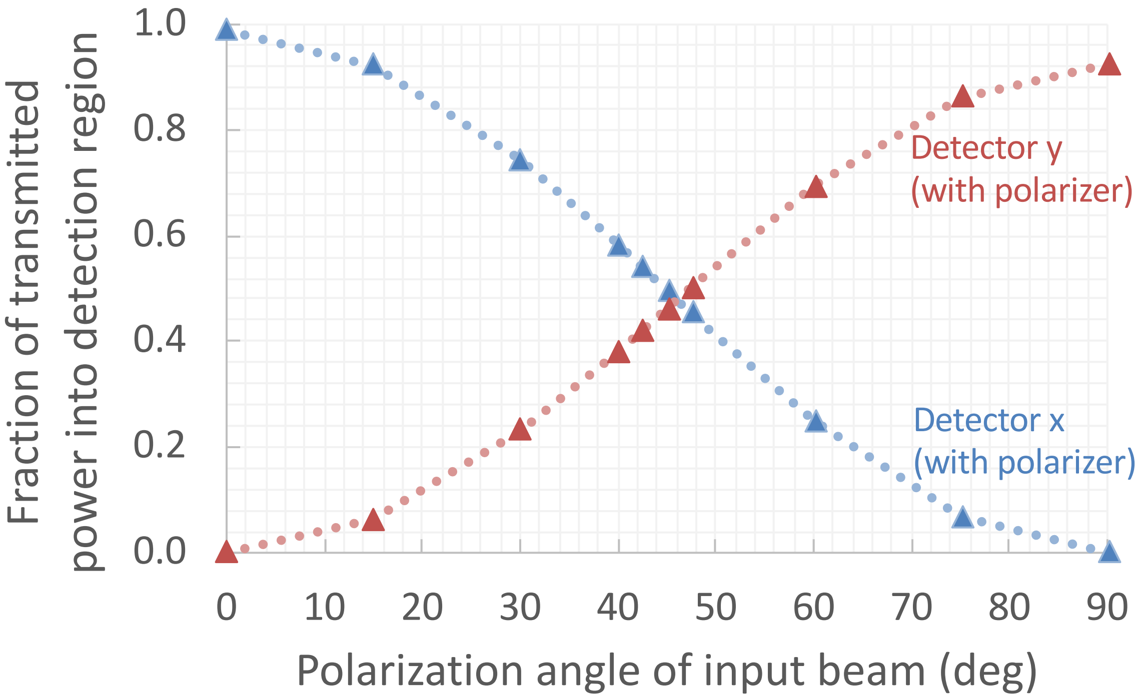
Extinction ratios:	150 for x-polarization
	1100 for y-polarization

Broadband polarizing beamsplitter (Thorlabs):
Transmission $> 90\%$
Extinction ratio > 1000

Simulated polarizing beamsplitter performance



Total transmission at 780 nm ~ 89%



Extinction ratios: > 22000 for x-polarization
> 28000 for y-polarization

Broadband polarizing beamsplitter (Thorlabs):
Transmission > 90%
Extinction ratio > 1000

Summary

- Atom-photon interactions are at the heart of all quantum sensing measurements
  - Photonic engineering crucial for atomic sensor development

- Cold-atom accelerometer and gyroscope demonstrated high sensitivity but presented integration and mobility challenges

- Integrated nanophotonics can address size and integration challenges of atomic sensors
  - Development of photonic-integrated-atomic magnetometer underway