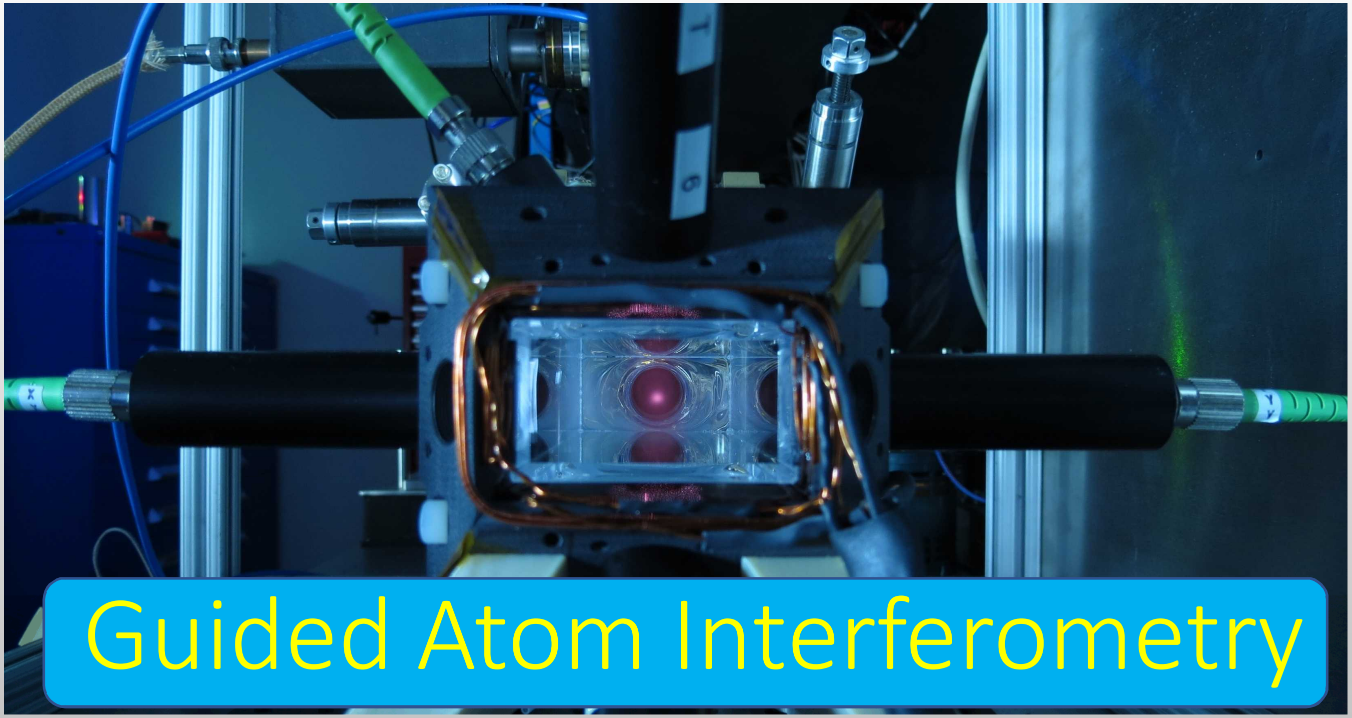
SAND2017-12858PE



Guided Atom Interferometry

Photo Courtesy of Rustin Nourshargh

Adrian Orozco

CQuIC at the University of New Mexico, Sandia National Laboratories

December 6th, 2017

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories

Matter Waves

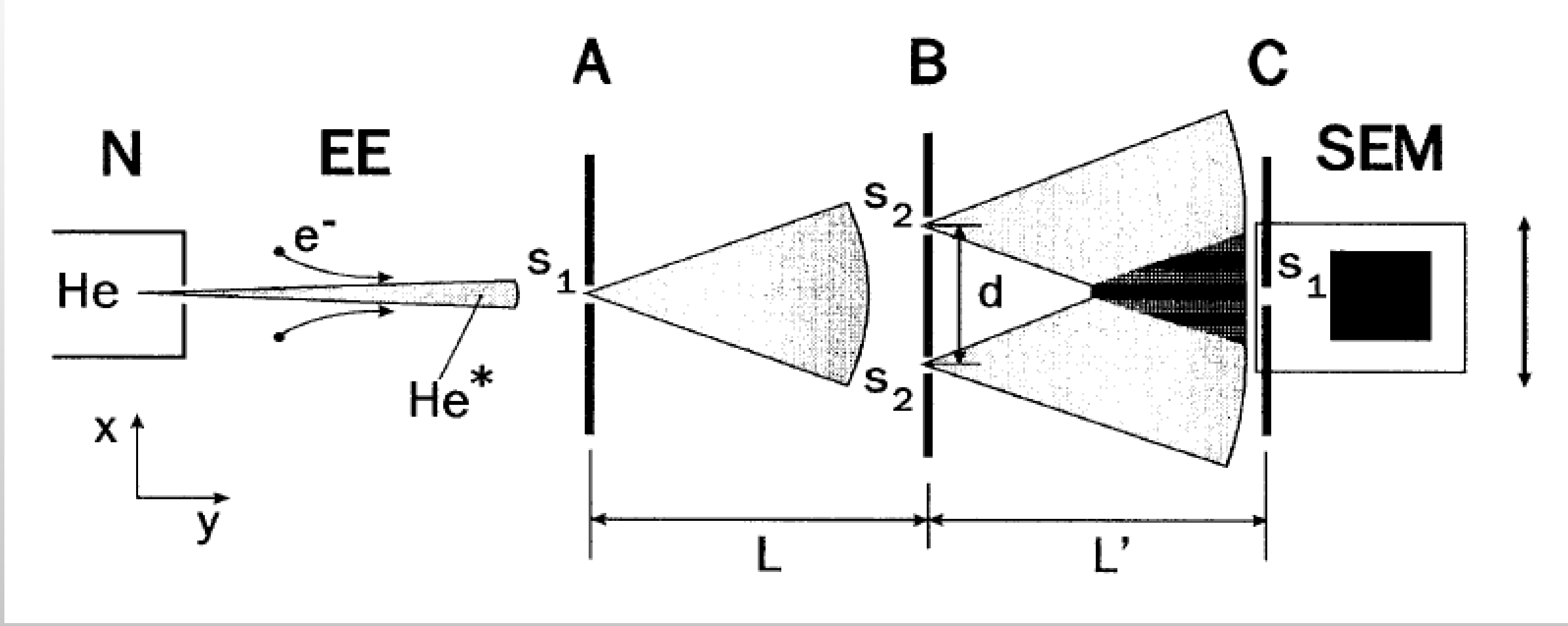
$$\lambda = \frac{h}{p}$$

"When I conceived the first basic ideas of wave mechanics in 1923–24, I was guided by the aim to perform a real physical synthesis, valid for all particles, of the coexistence of the wave and of the corpuscular aspects that Einstein had introduced for photons in his theory of light quanta in 1905."

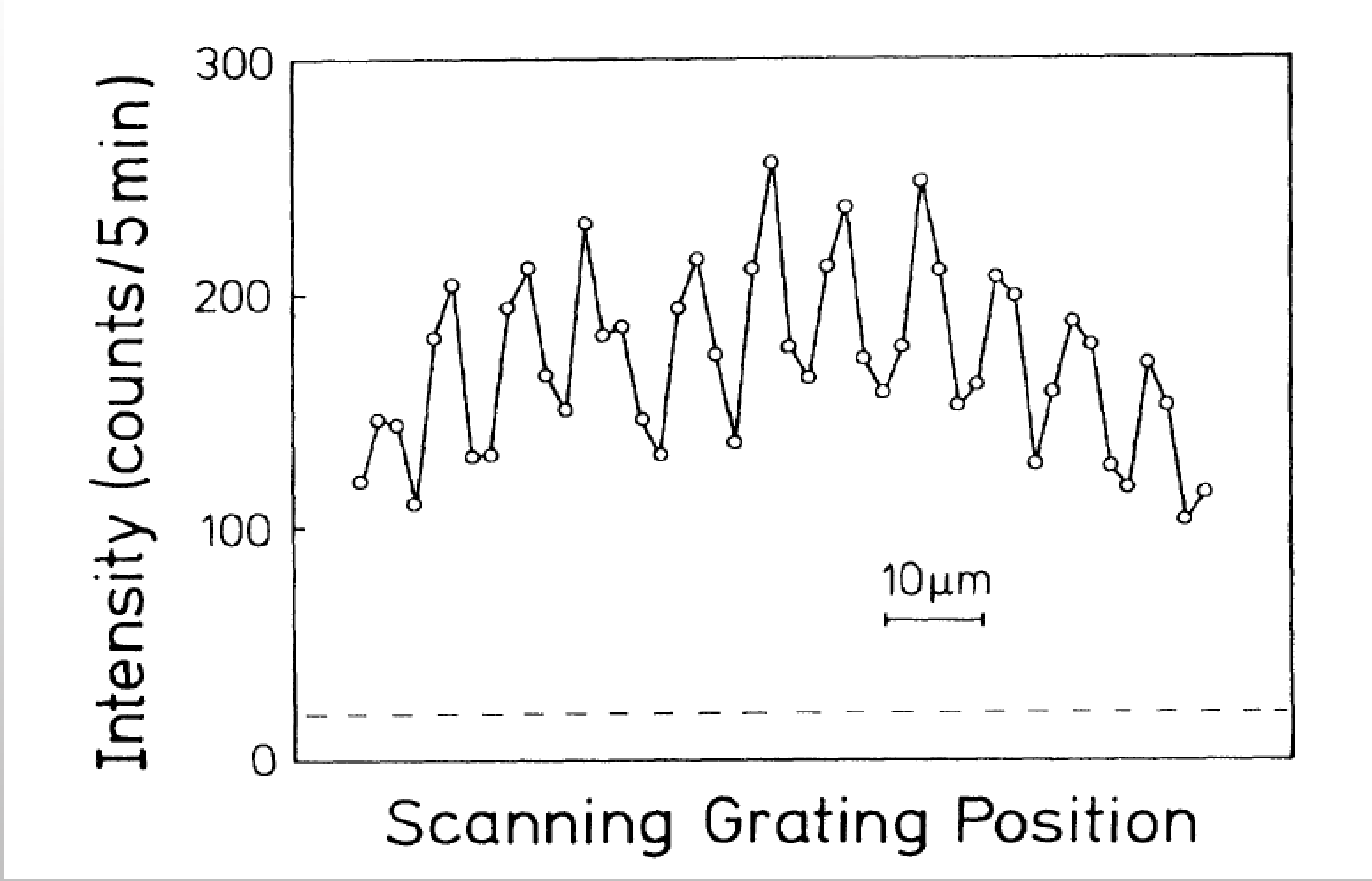
-de Broglie

www.nobelprize.org

Quote from: Louis de Broglie "The Reinterpretation of Wave Mechanics" Foundation of Physics, Vol.1 No.1 (1970)



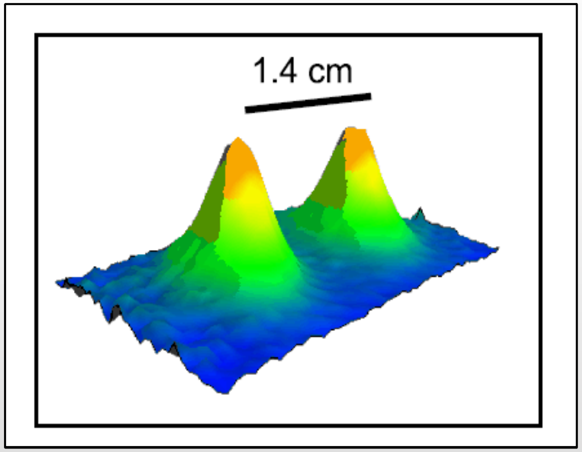
PRL Mlynek et. al. (1991)



PRL Mlynek et. al. (1991)

Atom Interferometer Sensors

- Optical interferometer length measurement resolution increases with decreasing wavelength
- Typical cold atom experiment temperatures ~1μK-10mK producing de Broglie wavelengths of 1-100s nm
  - 100s times smaller than visible light
- Atoms' inertial properties allow for precision measurements including:
  - Local gravimetry
  - Gradiometry
  - Rotation rates
  - Seismology



PRL S. M. Dickerson (2013)

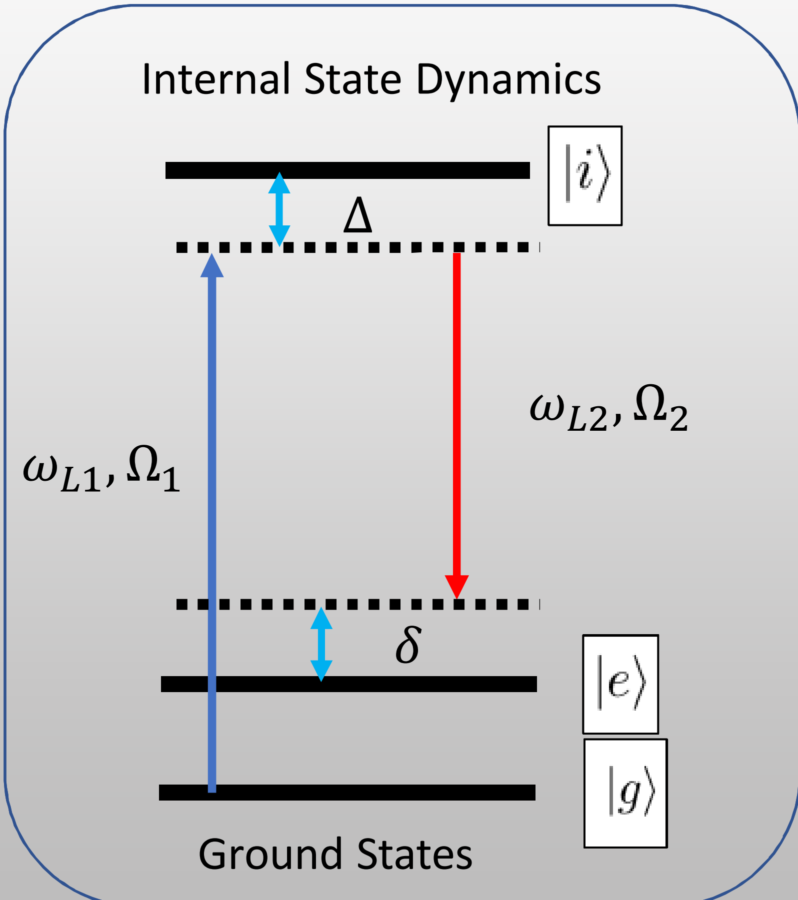
Sensitivity of measurements

$$\sigma_a \sim {}^{1}/_{T^2}$$

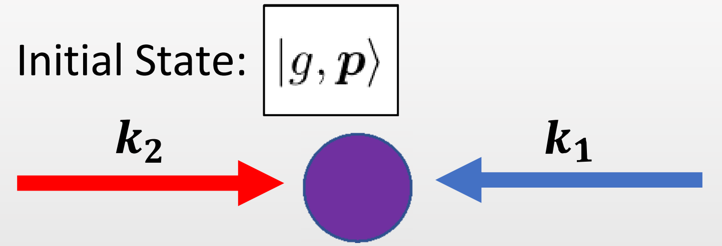
where T is the effective time of flight

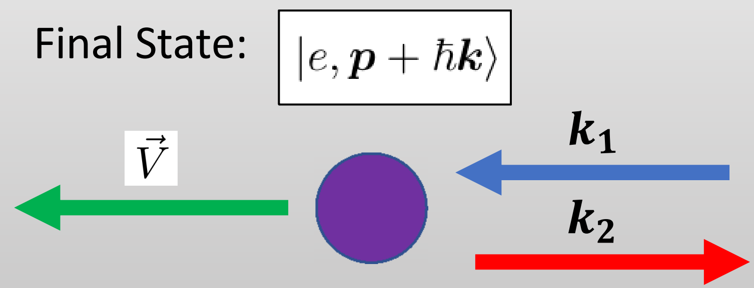
Light Pulse Atom Interferometry

Stimulated Raman Transition



Light Pulse Momentum Recoil

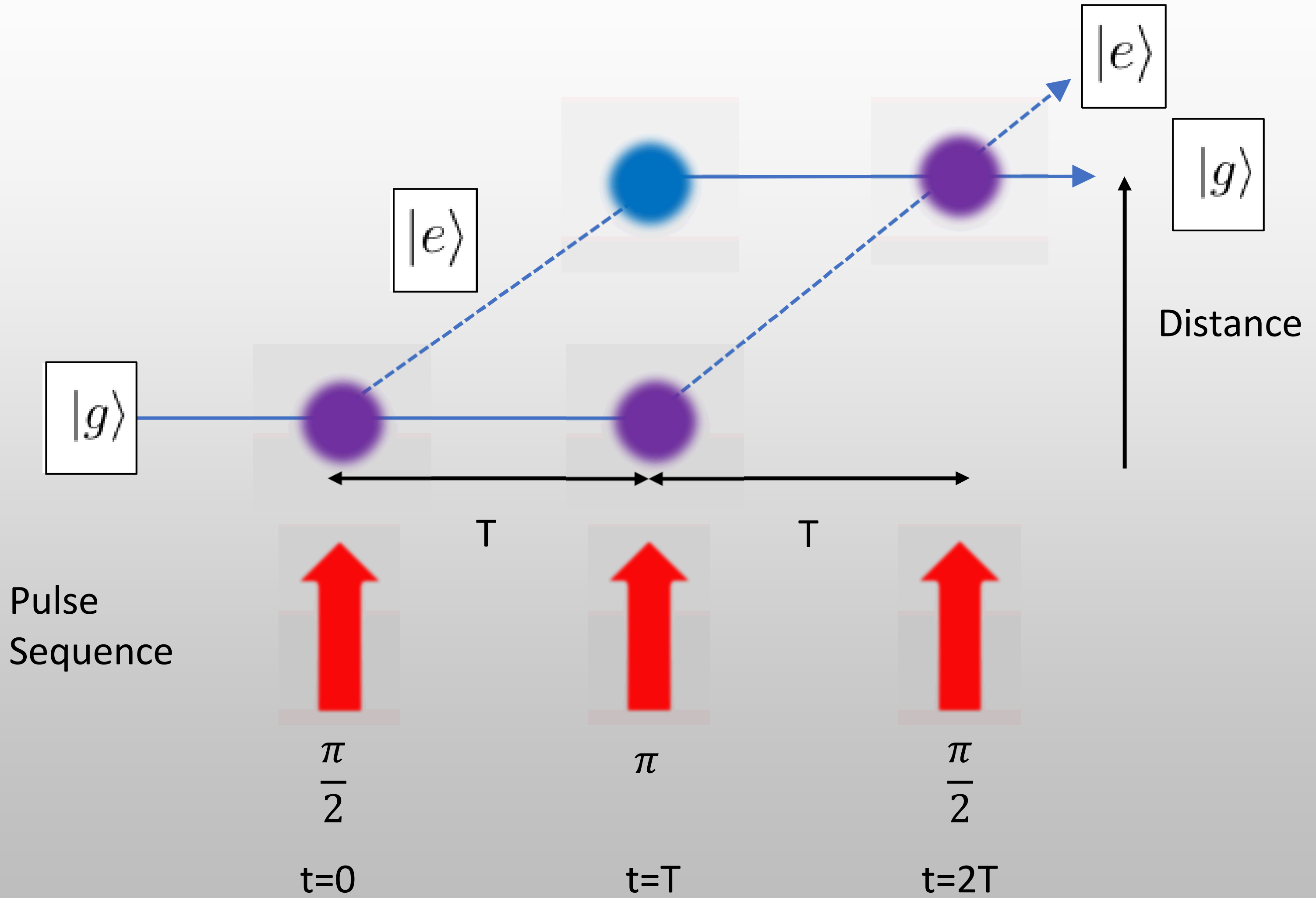




$$|\Delta \boldsymbol{p}| = \hbar|\boldsymbol{k}| = \hbar\,|k_1 - (-k_2)| \approx 2\hbar k$$

$$k_{eff} = 2k$$

Light Pulse Atom Interferometry



Phase Difference Along Paths

Three contribution to total phase shift

$$\Delta\phi_{total} = \Delta\phi_{prop} + \Delta\phi_{laser} + \Delta\phi_{sep}$$

Light-Interaction

$$\Delta\phi_{laser} = (\phi_1^A - \phi_2^A) - (\phi_2^B - \phi_3^A)$$

$$\phi_i = \boldsymbol{k}_{eff} \cdot \boldsymbol{x} - \omega_{eff} t$$

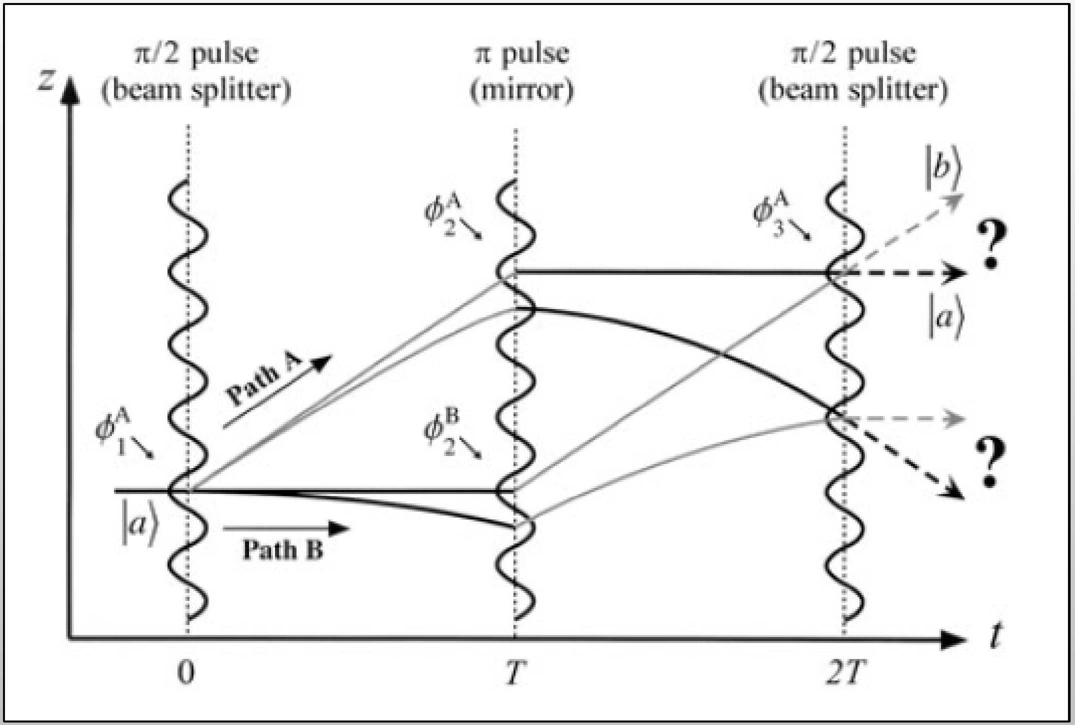
Propagation

$$\Delta\phi_{prop} = \frac{S_{cl}^B - S_{cl}^A}{\hbar}$$ → small

$$S_{cl} = \int_\Gamma \mathcal{L}(z(t), \dot{z}(t))dt$$

Wavepacket overlap

$$\Delta\phi_{sep} = \boldsymbol{p} \cdot \Delta\boldsymbol{r}/\hbar$$ → small

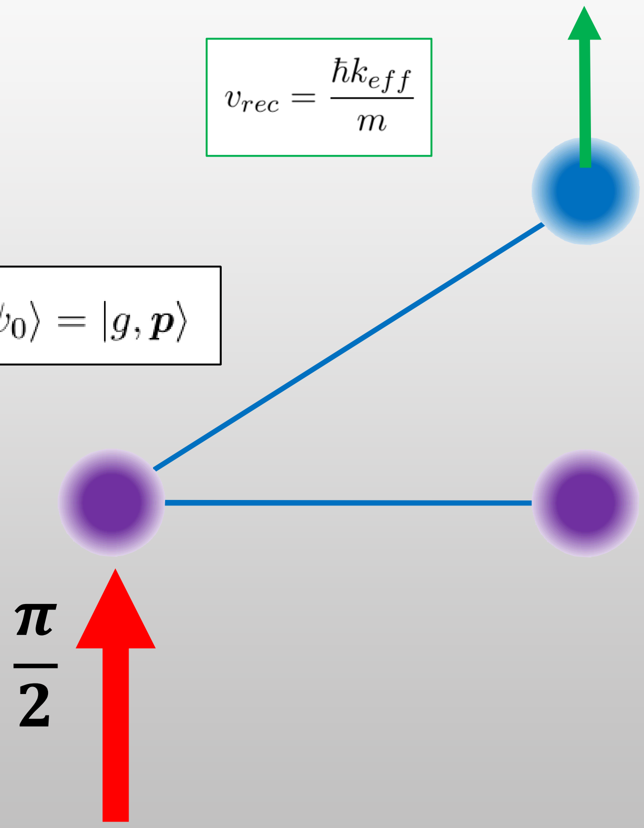


A. Peters et. al., Metrologia, 2001

1st Pulse Splits Wavepackets

$$v_{rec} = \frac{\hbar k_{eff}}{m}$$

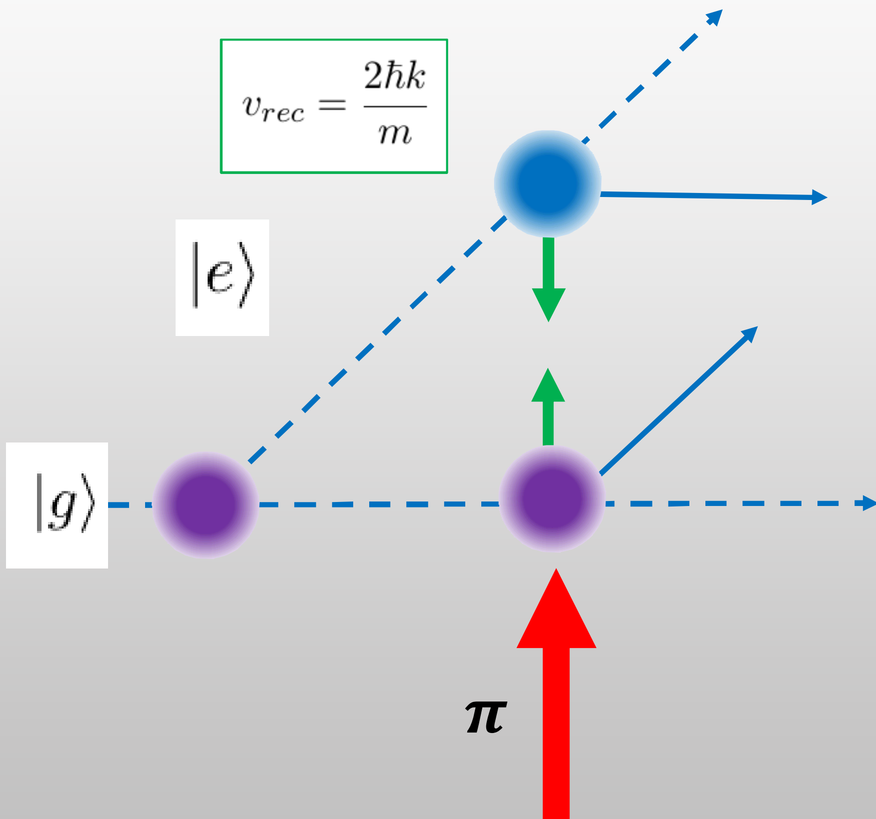
$$|\psi_0\rangle = |g, \boldsymbol{p}\rangle$$



Phase shift imprinted after photon absorption

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left(|g, \boldsymbol{p}\rangle + e^{i\phi_1}\,|e, \boldsymbol{p} + \hbar \boldsymbol{k}\rangle\right)$$

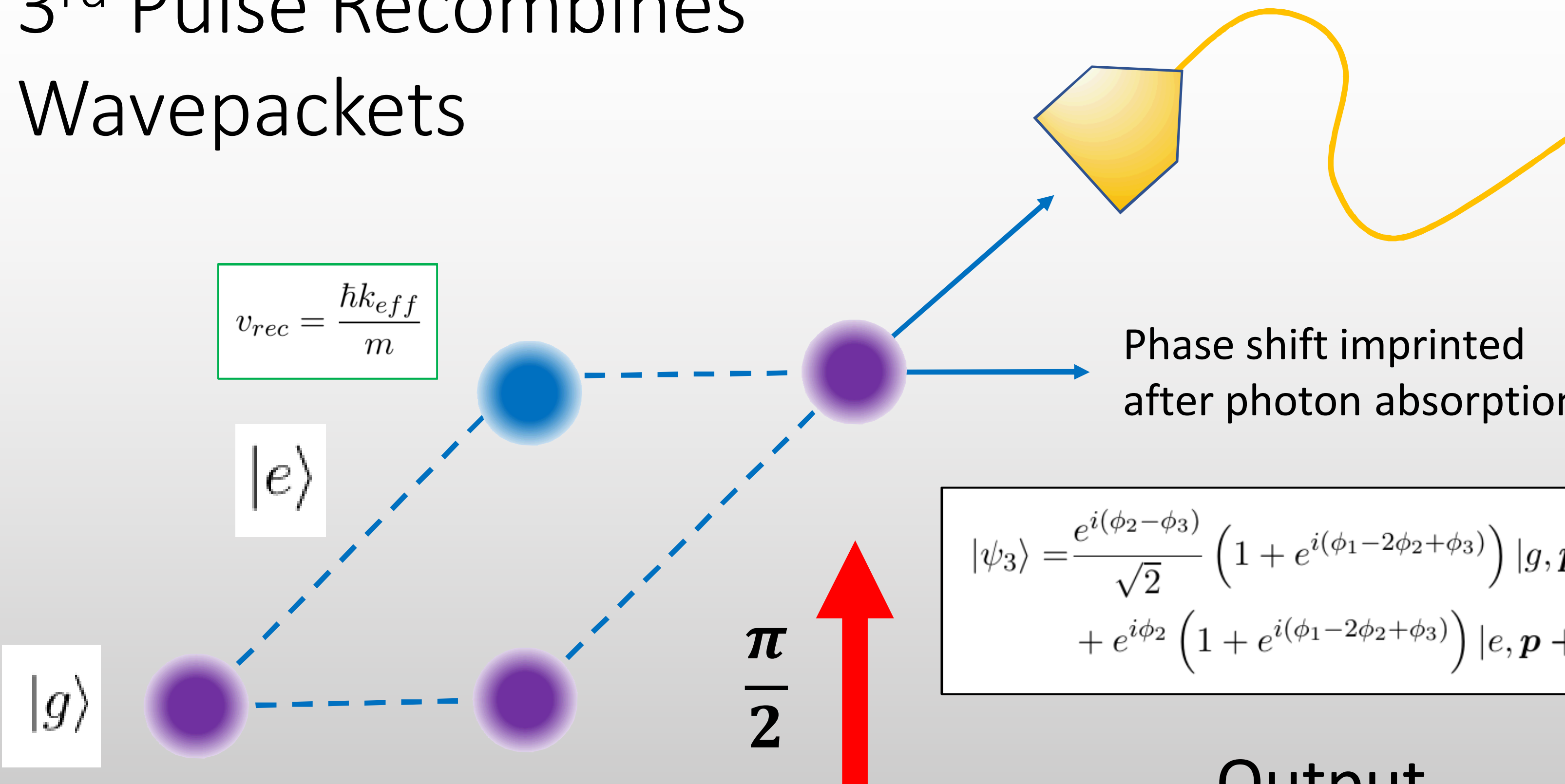
2^{nd} Pulse Redirects Wavepackets



Phase shift imprinted after photon absorption and emission

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\left(e^{i\phi_2}\,|e, \boldsymbol{p} + \hbar\boldsymbol{k_{eff}}\rangle + e^{i(\phi_1 - \phi_2)}\,|g, \boldsymbol{p}\rangle\right)$$

3rd Pulse Recombines Wavepackets



$$|\psi_3\rangle = \frac{e^{i(\phi_2-\phi_3)}}{\sqrt{2}}\left(1+e^{i(\phi_1-2\phi_2+\phi_3)}\right)|g,\boldsymbol{p}\rangle + e^{i\phi_2}\left(1+e^{i(\phi_1-2\phi_2+\phi_3)}\right)|e,\boldsymbol{p}+\hbar\boldsymbol{k}\rangle$$

Output

$$P_e(\Delta\phi) = |\langle e,\boldsymbol{p}+\hbar\boldsymbol{k}|\,\psi_3\rangle|^2 = \frac{1}{2}\left(1 - cos(\Delta\phi)\right)$$

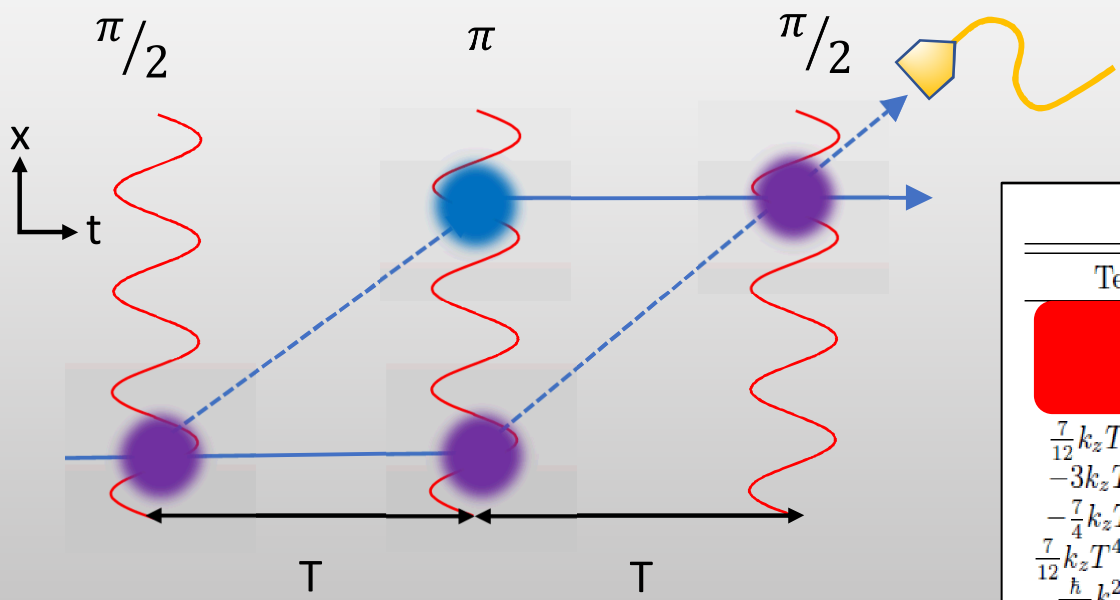
$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$$

Relative Phase and Finite Difference Formula

After $\frac{\pi}{2} - \pi - \frac{\pi}{2}$ pulse sequence

$$P_e(\Delta\phi) = \frac{1}{2}(1 - cos(\Delta\phi))$$

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$$



Relation to atom position

$$\Delta\phi = \boldsymbol{k}_{eff} \cdot (\boldsymbol{x}_1 - 2\boldsymbol{x}_2 + \boldsymbol{x}_3)$$

Relevant Phase Shift Table

TABLE I: Gravimeter phase shifts.

Term	Phase (rad)	Relative phase
[redacted]		
$\frac{7}{12}k_zT^4g_zT_{zz}$	-6.32	$2.7 \cdot 10^{-7}$
$-3k_zT^3v_z\Omega_y^2$	$-3.11 \cdot 10^{-2}$	$1.3 \cdot 10^{-9}$
$-\frac{7}{4}k_zT^4g_z\Omega_y^2$	$1.81 \cdot 10^{-2}$	$7.8 \cdot 10^{-10}$
$\frac{7}{12}k_zT^4T_{zz}\Omega_y^2R$	$1.21 \cdot 10^{-2}$	$5.2 \cdot 10^{-10}$
$\frac{\hbar}{2m}k_z^2T^3T_{zz}$	$9.71 \cdot 10^{-3}$	$4.2 \cdot 10^{-10}$
$-\frac{7}{4}k_zT^4\Omega_y^4R$	$-3.47 \cdot 10^{-5}$	$1.5 \cdot 10^{-12}$
$-\frac{3\hbar}{2m}k_z^2T^3\Omega_y^2$	$-2.79 \cdot 10^{-5}$	$1.2 \cdot 10^{-12}$
$-\frac{7}{4}k_zT^4\Omega_y^2\Omega_z^2R$	$-2.62 \cdot 10^{-5}$	$1.1 \cdot 10^{-12}$

- Gravitational field
- Earth rotation
- Gravity gradient

Finite Difference formula

$$\boldsymbol{a} = \frac{\boldsymbol{x}_1 - 2\boldsymbol{x}_2 + \boldsymbol{x}_3}{T^2}$$

$$\Delta\phi = \boldsymbol{k}_{eff} \cdot \boldsymbol{a}T^2$$

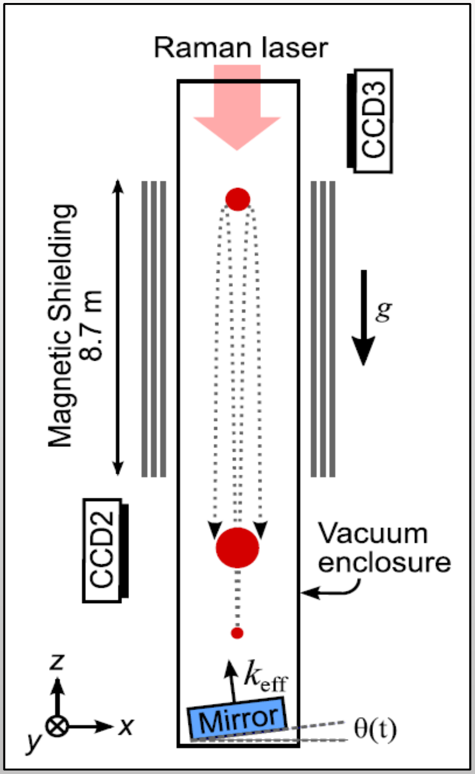
Stanford 10 m Tall Atom Drop Tower

Sensitivity of measurements

$$\sigma_g \sim {}^{1}/_{T^2}$$

Total time of 2T = 2.3 s produces maximum sensitivity for gravimetry $\sim 10^{-12} g$

Image From http://www.2physics.com



PRL S. M. Dickerson (2013)

The Bremen Drop Tower

2T = 4.7 s (drop) with max sensitivity of ~10^{-10} g

2T = 9.4 s (catapult) with max sensitivity of ~10^{-11} g

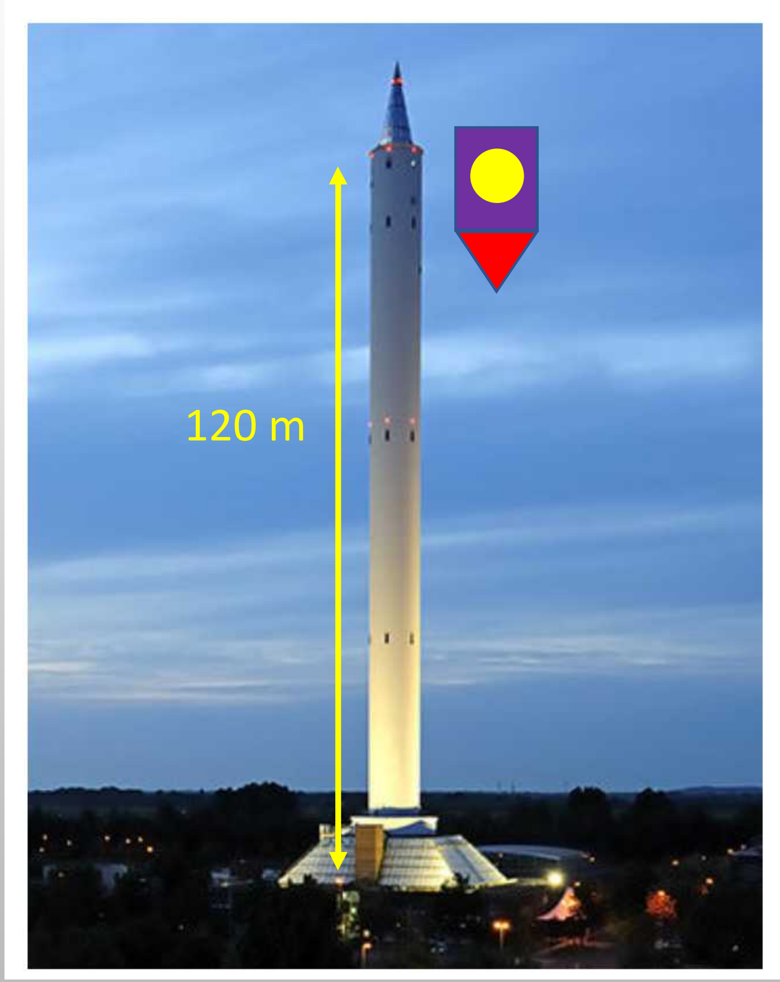
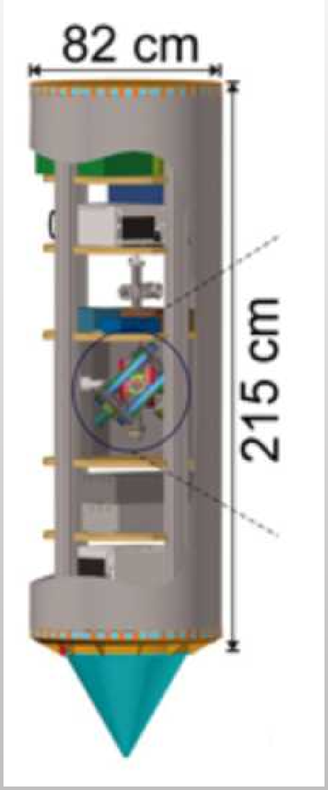


Image from sciencemag.org



PRL 110, 093602 (2013)

Tower is located at ZARM in Bremen, Germany

Ensemble Exchange Atom Interferometer

- Compact and fits in a 2x2x2 ft. cube
- Two ensembles
  - Launched (~2.5 m/s) in opposite directions
  - Recaptured on opposite side
- 2T = 10ms
- Atom interferometry is performed during flight
- Sensitivity of measurements
  - ~$10^{-6} g$ in 1s for acceleration
  - ~10^{-5} rad/s in 1s for rotation

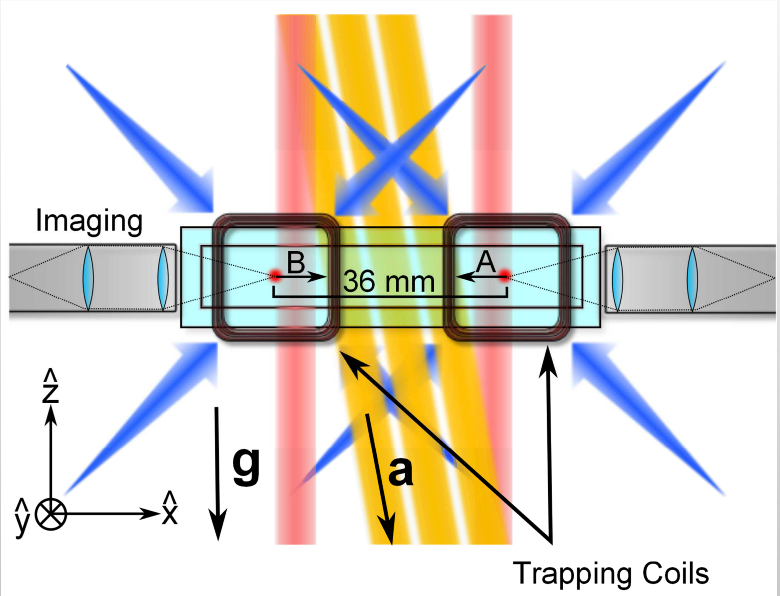
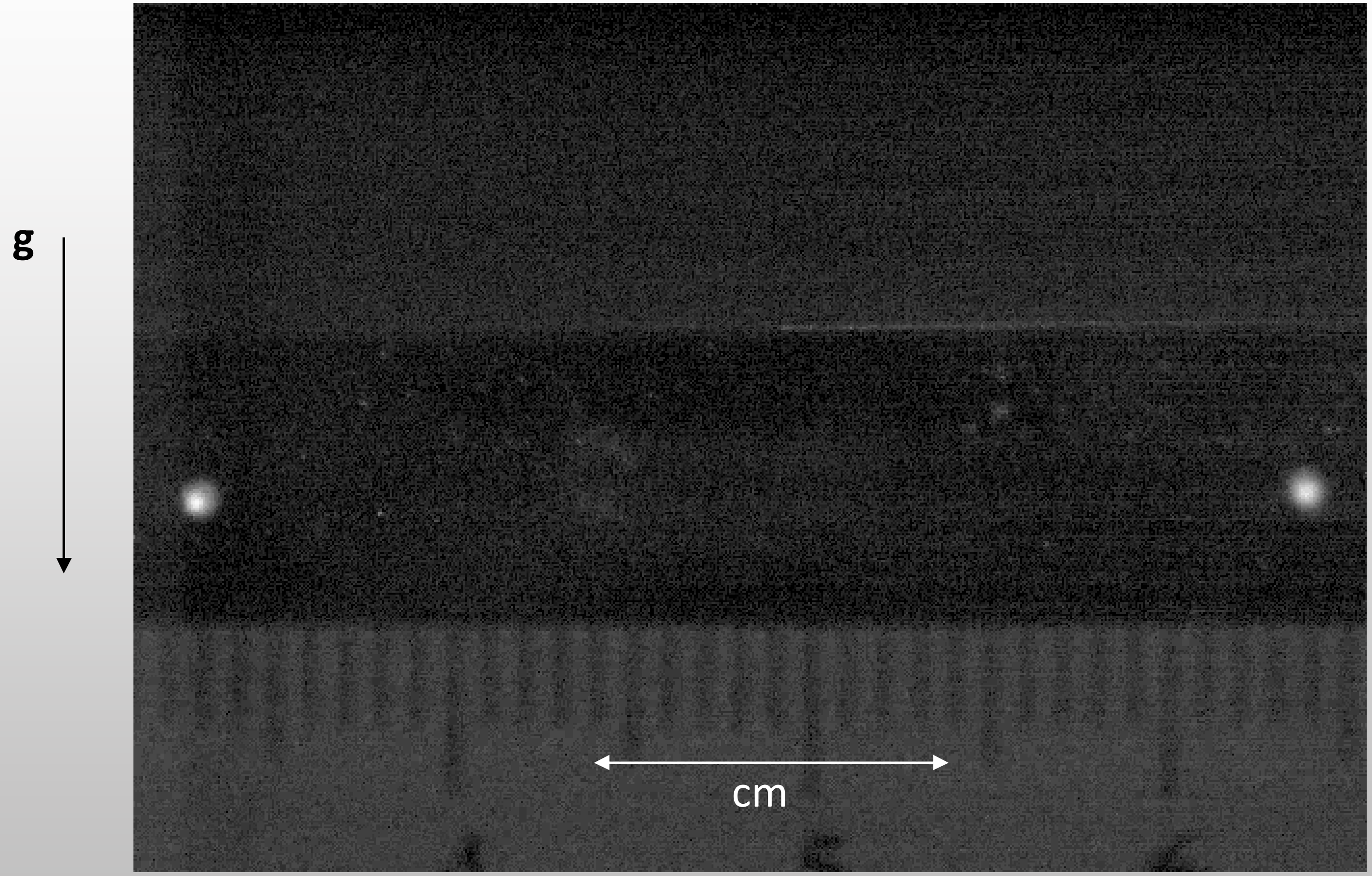
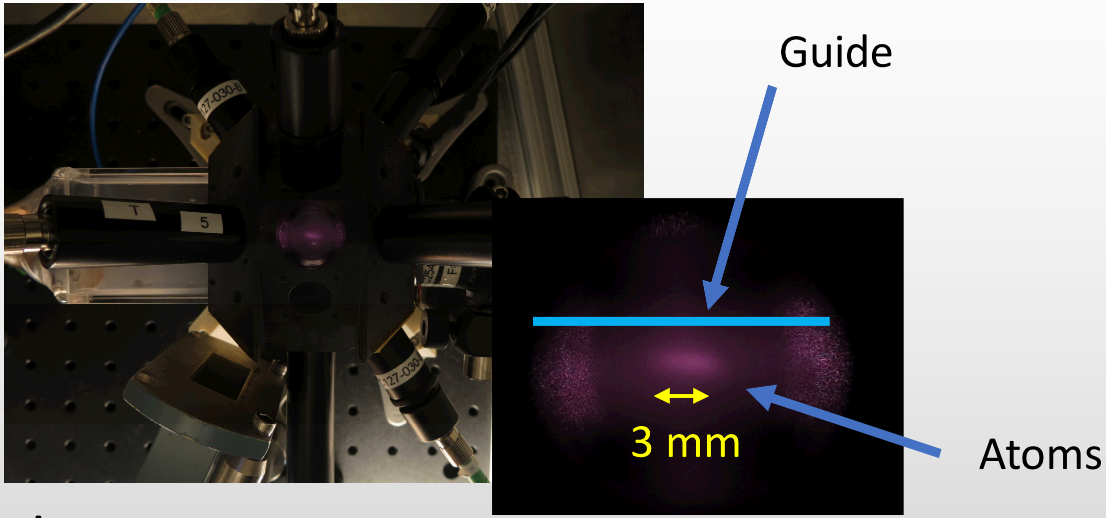


Image from PRA 2, 054012


g
cm

Requirements for Fieldable Sensors

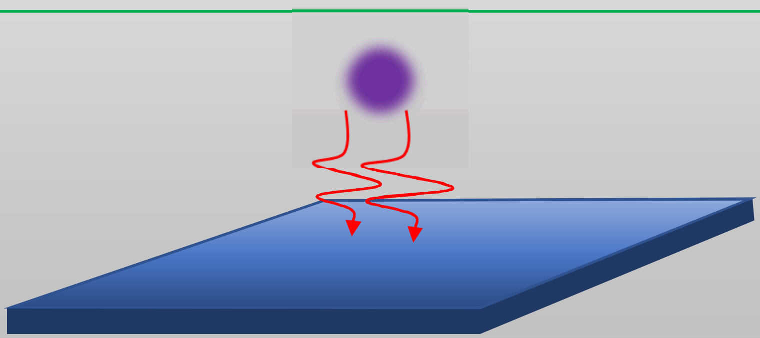
- Transportability
  - Compact
  - Robust
  - Light-weight
  - Low power

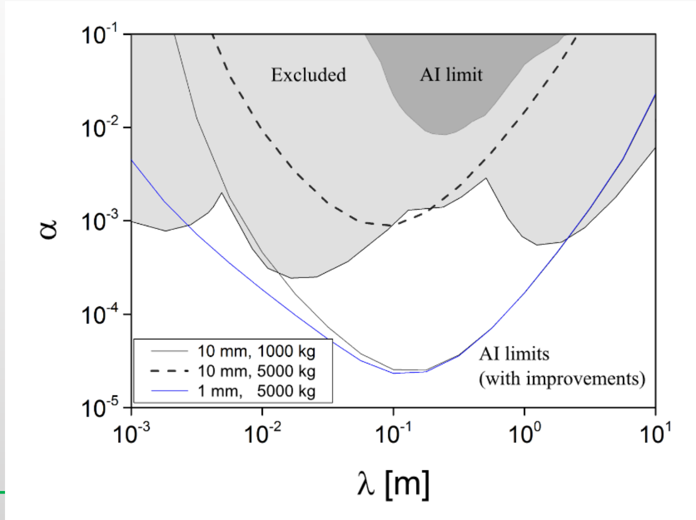


- Dynamic environments
  - inherently require ensemble to be spatially localized
    - Perform interferometry in short (~ms) time scales
    - Atomic guides
      - reduce power needed for Raman transitions
      - increase interrogation time
      - Reduce MOT expansion and size
      - Reduce Raman beam size lowering required laser power
      - Micron-scale confinement – platform to probe new physics

Surface Interaction Research

- Casimir-polder force* measurements
  - Atom interferometer sensitivity achieved: 3.2x10-27 N**
- Gravitational constant measurements
  - Source mass used in LPAI to measure $\delta G/_G$ = 3 x 10-4 ***
  - Current CODATA◊: $\delta G/_G$ =4.5x10^{-5}
- Inverse Square Law Violations

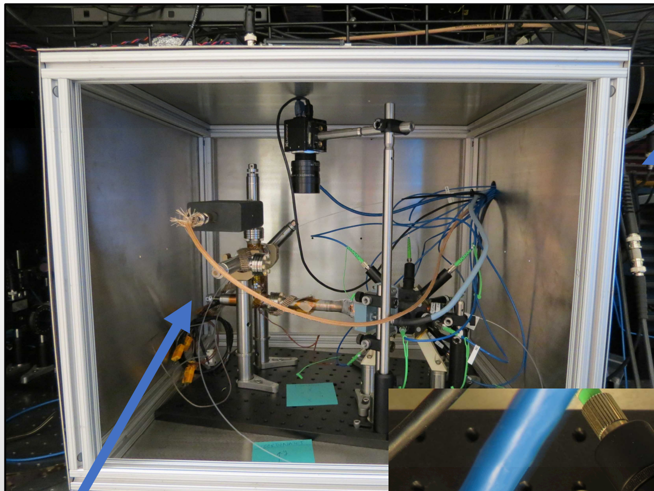


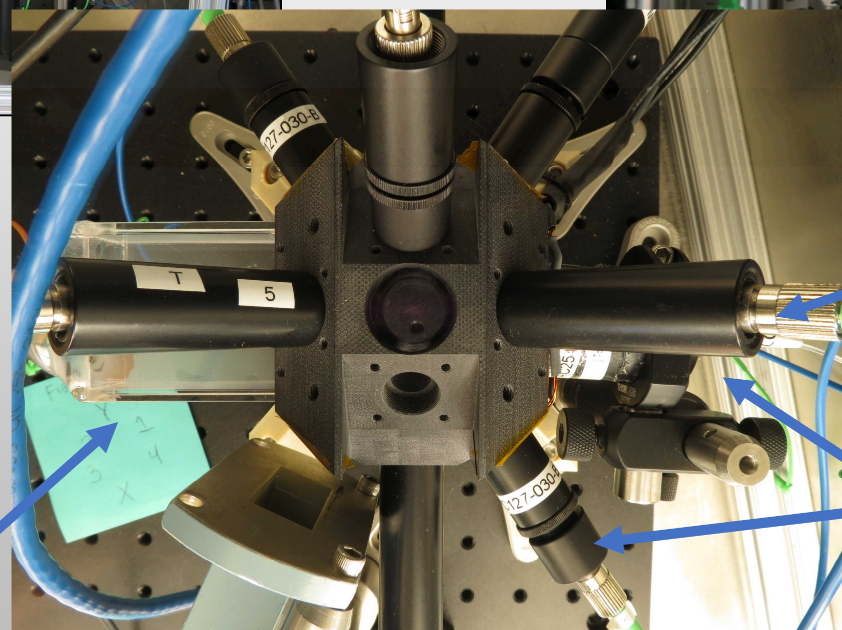


$$F = -G\frac{m_1 m_2}{r^2}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$

*Casimir et. al. Phys. Rev. 73, 360 (1948)
**L. P. Parazzoli et. al. PRL 109, 230401 (2012)
***G. W. Biedermann et. al. PRA 91, 033629 (2015)
◊ P. J. Mohr et. al. Rev. Mod. Phys. 88, 035009 (2016)

Experiment Underway





2 ft

Magnetic Shield

μW Horn

Ion Pump

Free expanding cooling beams

3 in

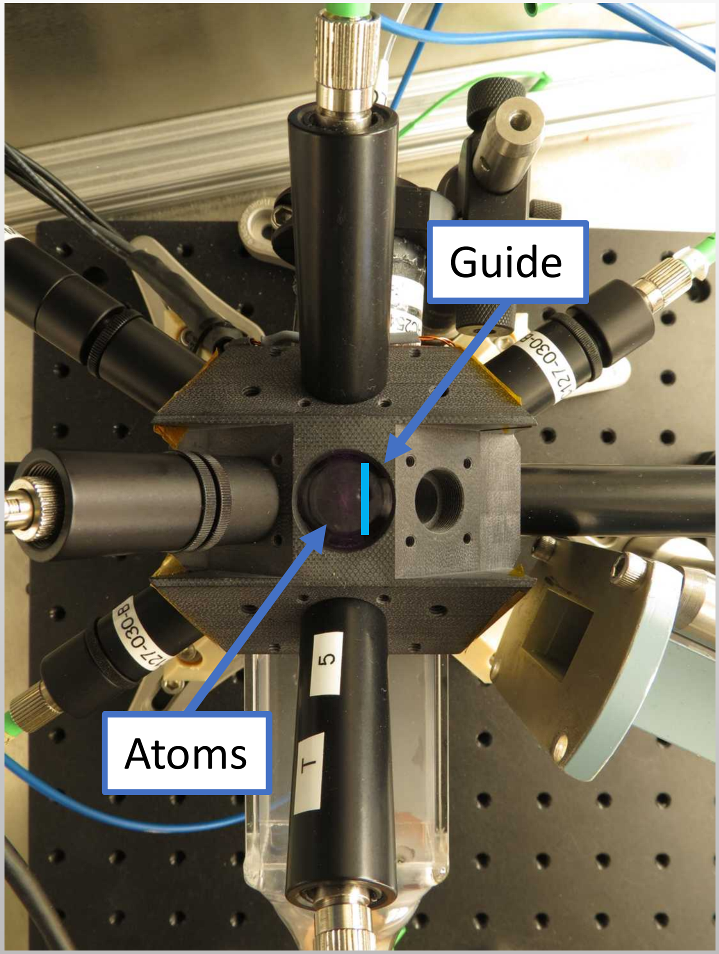
Detection beams

Quartz Vacuum Cell

2.75 in

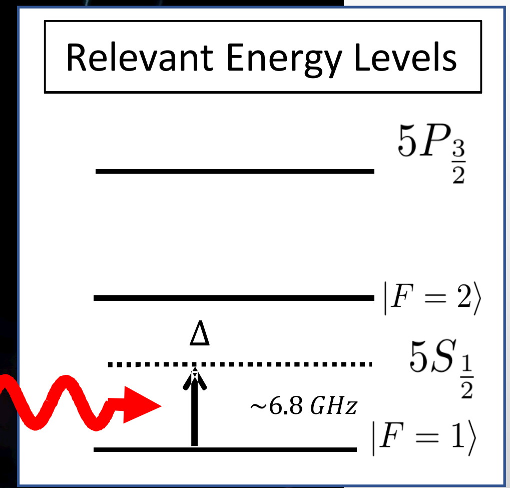
Experimental Design Highlights

- All laser beams are pre-aligned by design
- Trapping and cooling beams freely expand
  - Approximately 10^8 atoms captured in MOT
  - Capturing larger atomic ensemble increases signal-to-noise ratio
- MOT and bias coils located inside apparatus



Microwave Interrogation Demonstration

- MOT→ trap atoms
  - Reduces temperature ~200µK
- Turn off coils
- Polarization gradient cooling ensemble further ~µK [1ms]
- Optically pump into clock state [0.1ms]
- Perform microwave interrogation [~ms]
- Detection [0.200ms]
- Recapture [~2ms]
- Total sequence performed in ~20ms



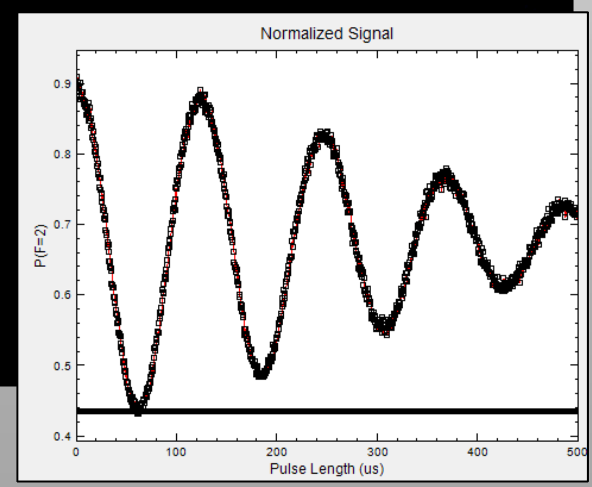


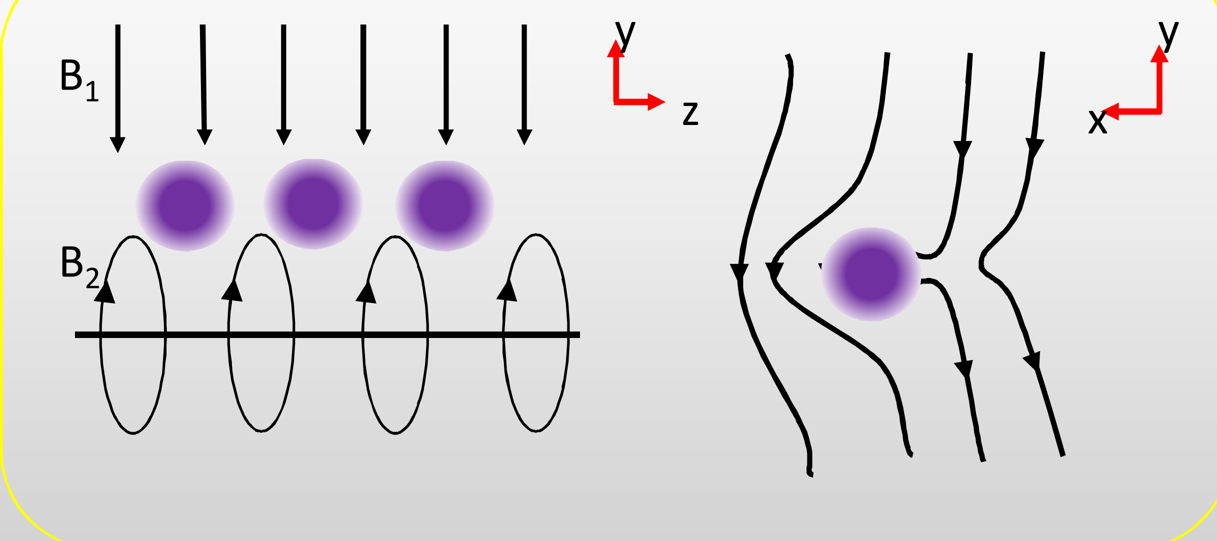
Photo Courtesy of Rustin Nourshargh

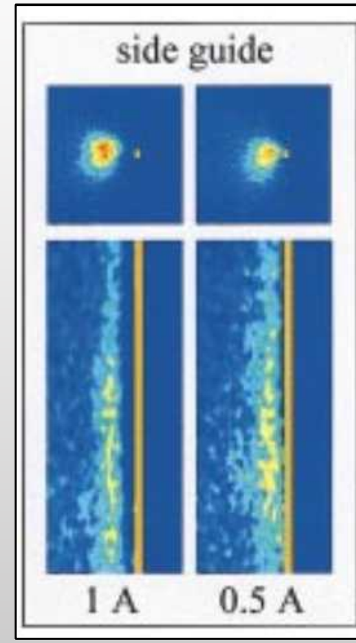
Atom Guiding

- Magnetic Guides
  - Trap atoms using static magnetic fields
  - Straight wires and coils produce trapping potentials
  - The Zeeman potential and magnetic field gradient confine atoms to a specific trajectories
- Optical Guides
    - Red-detuned light → attractive potential
    - Blue-detuned light → repulsive potential
  - Neutral atoms trapped using focused laser beams
  - Nanofibers traps use evanescent fields

Magnetic Guiding

$$\vec{F} = \vec{\nabla}\left(\hat{\vec{\mu}} \cdot \vec{B}\right)$$



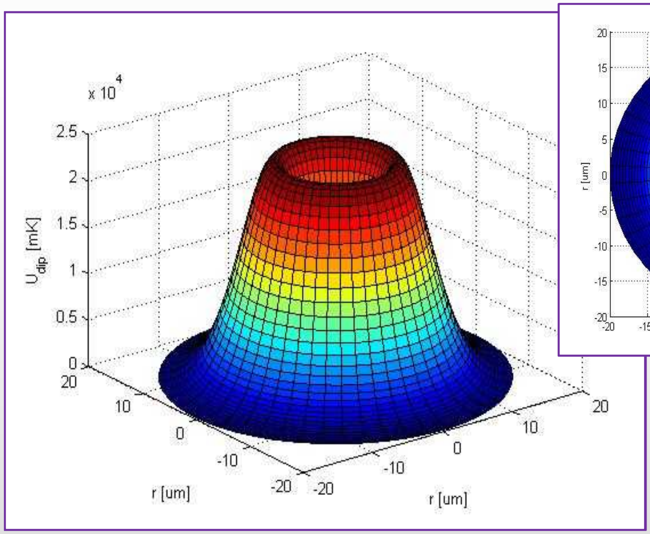


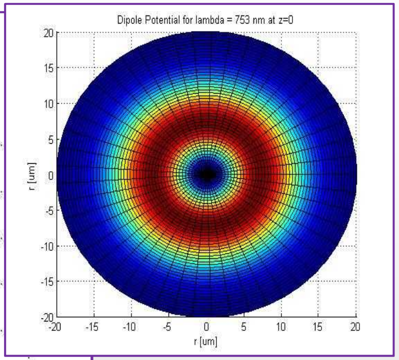
J. Denschlag et. al. PRL 82, 1998

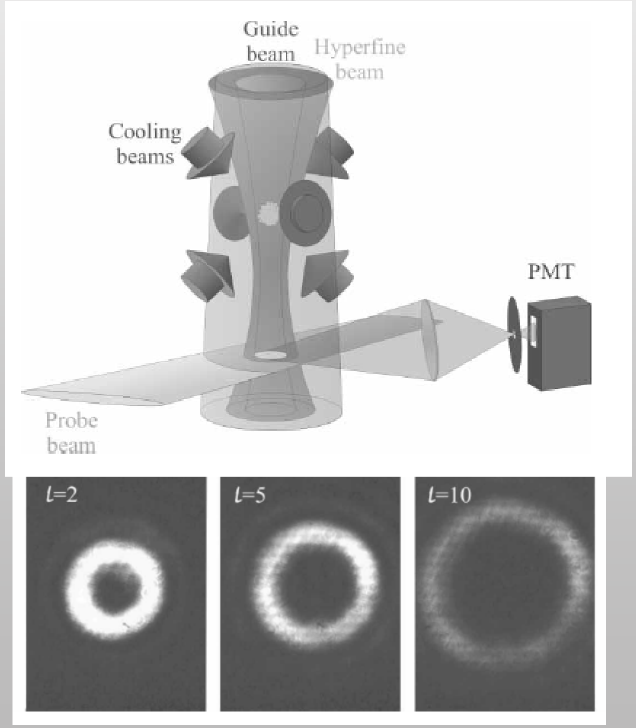
- Joffe-Pritchard trap exploits Zeeman potential to trap neutral atoms
- Current noise and wire vibrations must be controlled for pristine guide

Optical Guides: Doughnut Mode

- Utilize dipole force proportion to intensity gradient
- Blue detuned light repels atoms
- Axial accelerations exist
- Parameter space was explored to reduce axial acceleration

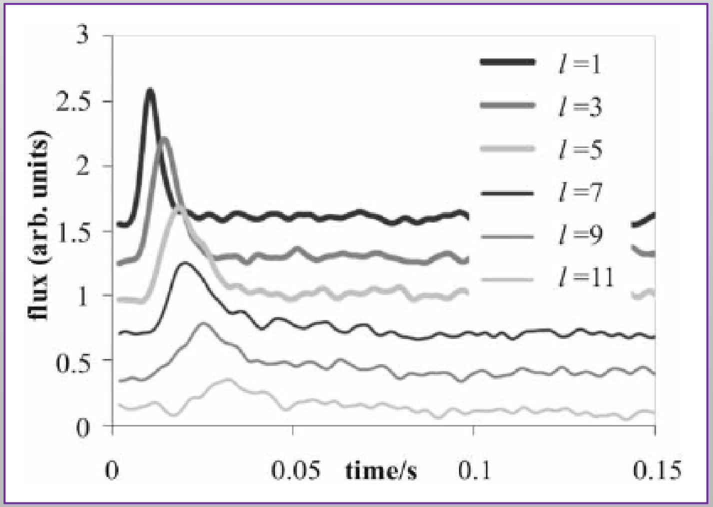






D. P. Rhodes et. al. J. Mod. Opt. 2006

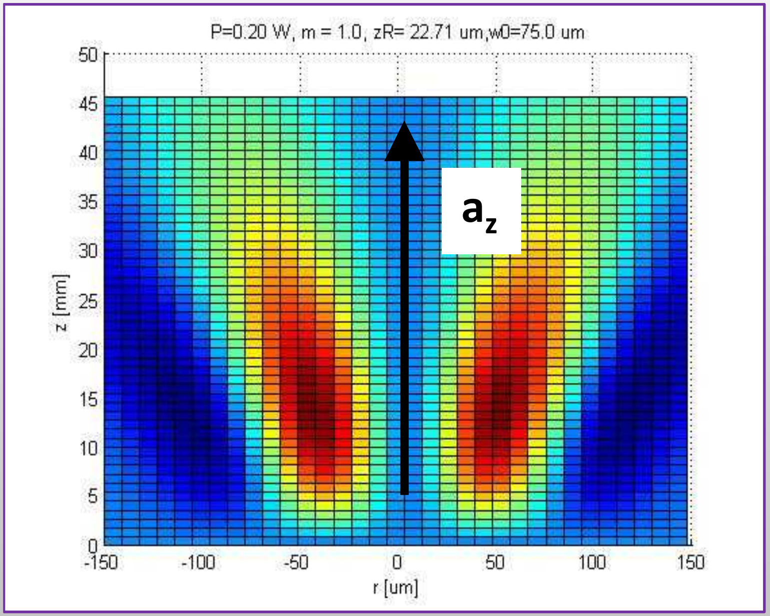
Atom Flux



Application to atom interferometry

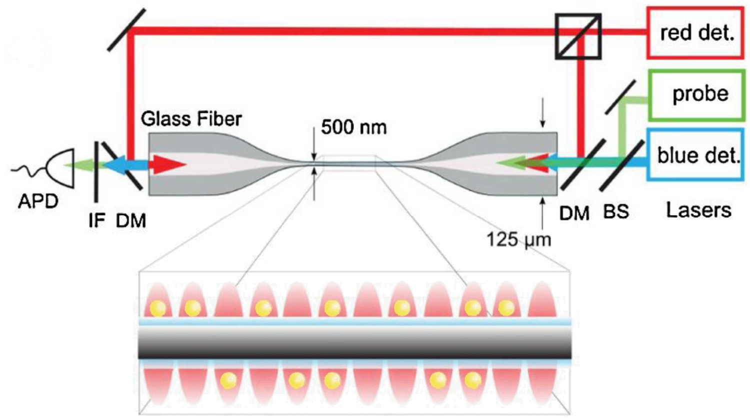
Axial acceleration reduces sensitivity

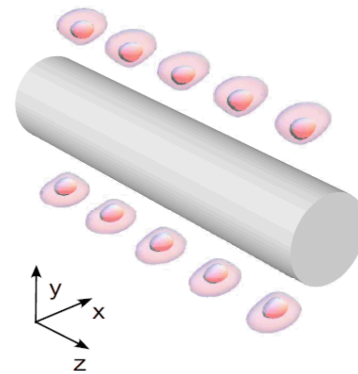
ω_0 (Beam waist) [um]	m (charge)	P_0 (Power) [mW]	a_z [g]	a_r [g]	Trap Depth [mK]
10	8	100	7.7e-3	500	1
20	7	200	6.7e-3	154	0.7
20	8	400	1.9e-3	254	1
25	7	400	5.5e-3	160	0.8
25	7	500	6.9e-3	197	1
25	8	400	7.9e-4	130	0.8
30	7	500	3.3e-3	110	0.7



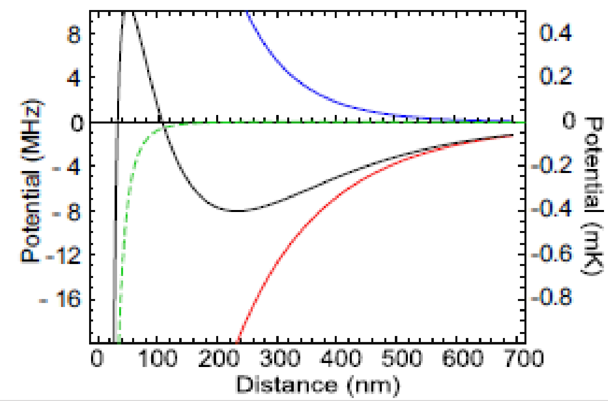
Nanofiber Optical Atom Trap

Atoms Trapped Around Fiber



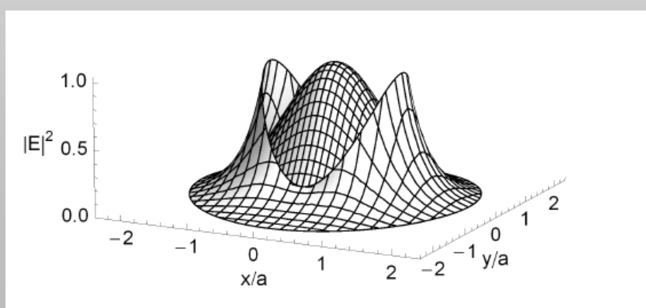


Van der Waals

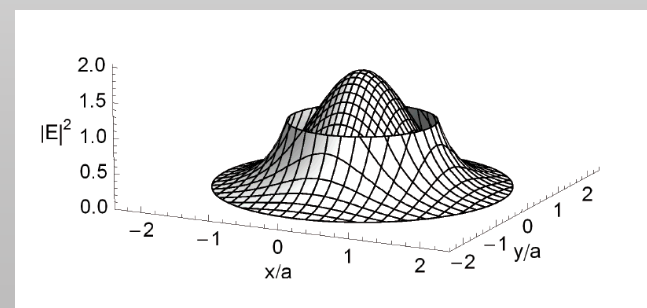


HE_{11} Intensity

Linearly Polarized Input

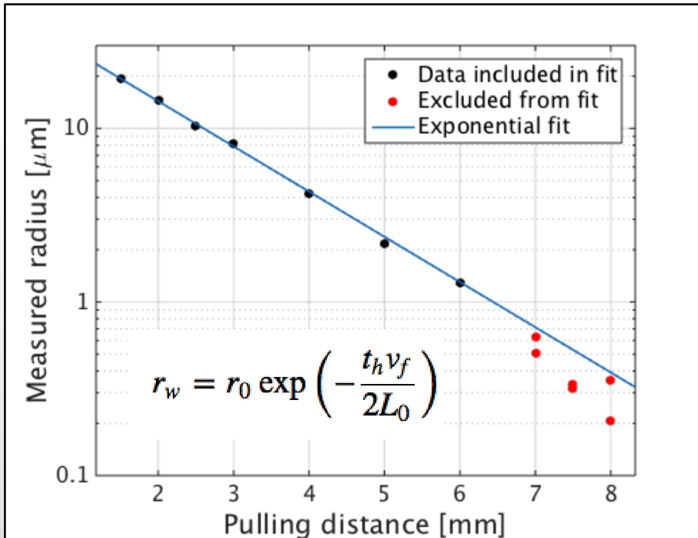


Circularly Polarized Input



Images borrowed from Vetsch PhD Thesis (2010)

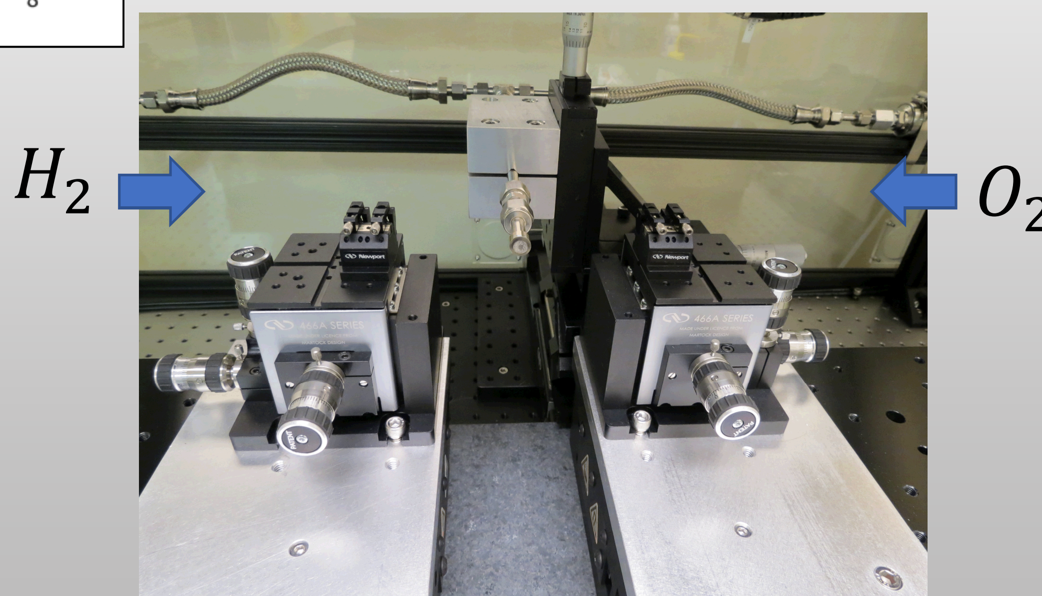
Fiber Pulling



Hydrogen flame
Heat in shell
Difficult to control L_0

Hydrogen/Oxygen flame
Uniform heat in larger volume
Better control of L_0

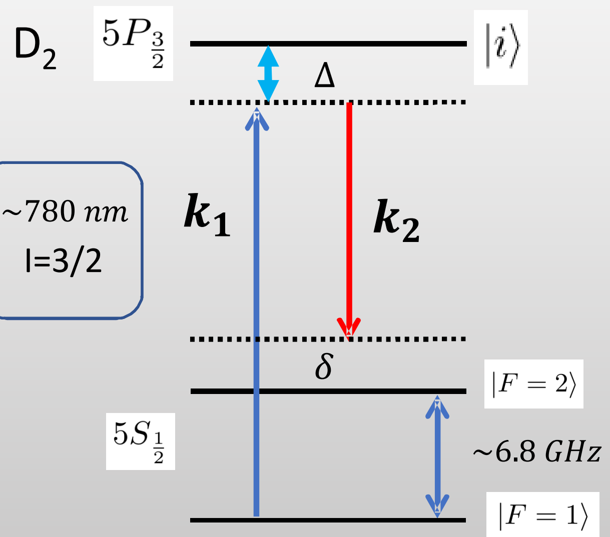
- Hydrogen Torch
  Unreliably produced fiber below 1μm
- OxyHydrogen Torch
  - Uniform width and heat
  - Unconstrained fiber to flame distance



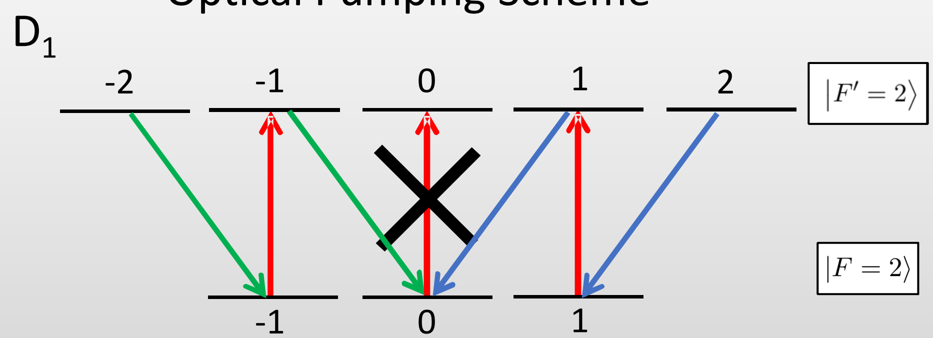
Apparatus

Atomic Source: Rubidium 87

Relevant Energy Levels



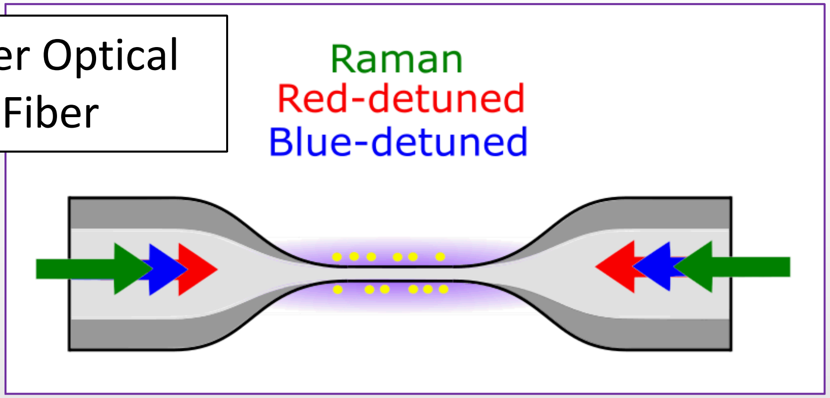
Optical Pumping Scheme



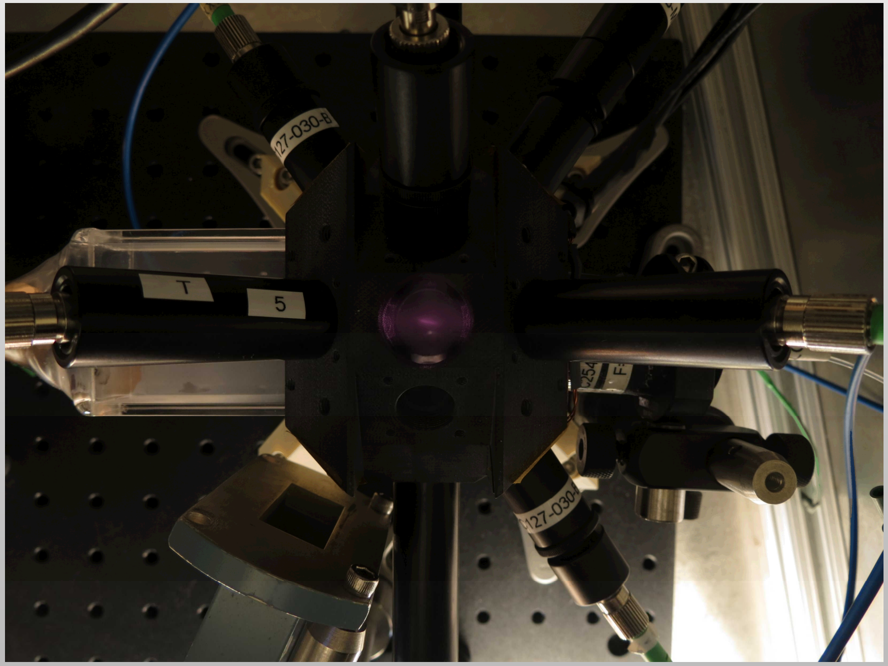
- π polarized beam prepares atoms in $m_{F=2} = 0$
- $m_{F=2} = 0 \rightarrow m_{F=2} = 0$ Clebsch-Gordon coefficient is 0

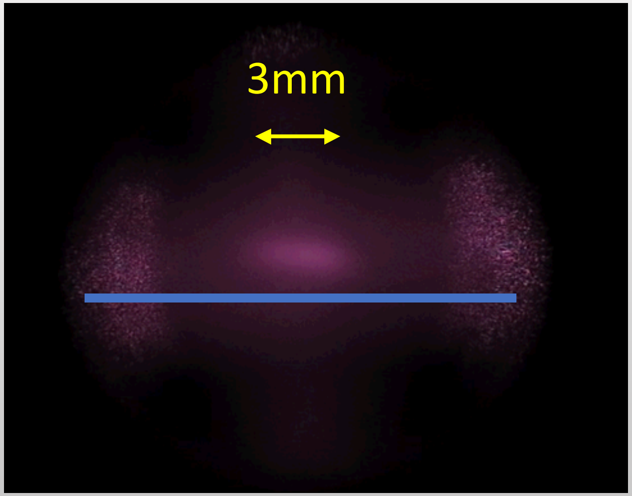
Cylindrically Shaped Atom Cloud

Taper Optical Fiber

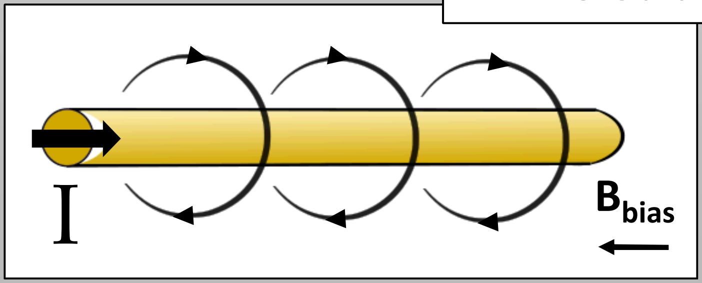


- Quadrupole coil aspect ratio is 5:1
- Cylindrically shaped ensemble could be used to efficiently load guide





Wire Guides



Coherent Raman transitions in tapered nanofiber

Coherent Raman transitions using co-propagating beams

- Evanescent mode intensity gradients leads to time-dependent coupling
- Stark shift canceled using phase modulated laser beam
- Coherent transfer of Cs hyperfine levels using Raman transition

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Optics Letters

Dipole force free optical control and cooling of nanofiber trapped atoms

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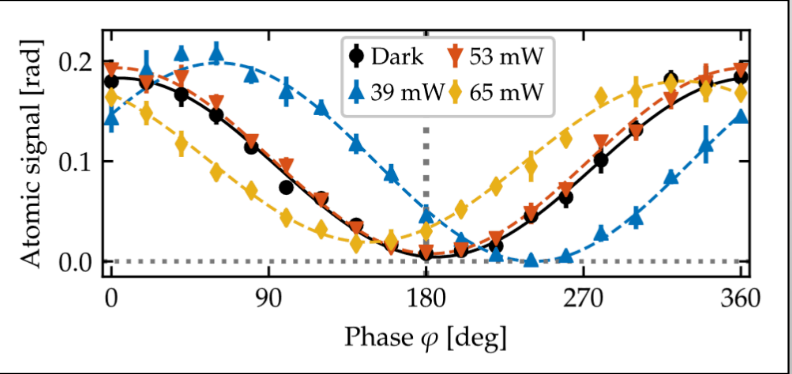
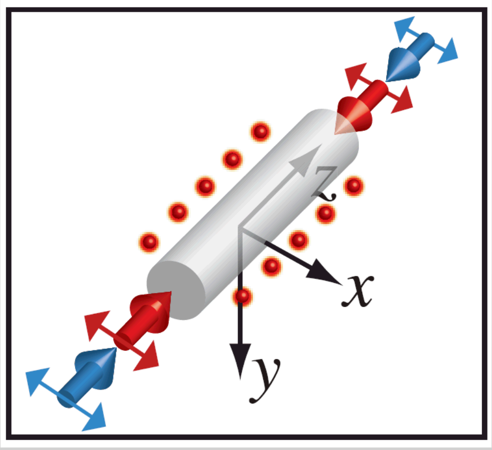


C. Ostfeldt et. al. Opt. Lett. 42, 2017

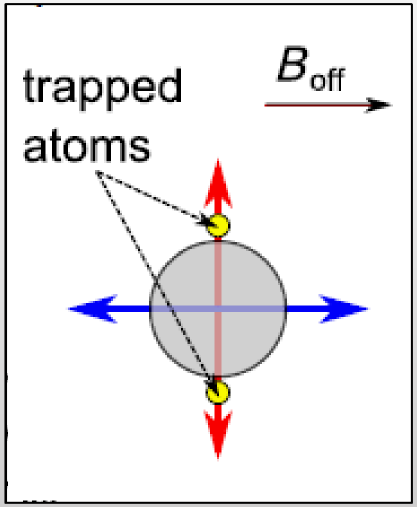
Vector Light Shifts In Taper Optical Nanofibers

Vector Light Shift:

- Canceled using blue-detuned counter-propagating beams
- Canceled by applying a homogeneous magnetic field parallel to blue-detuned beam polarization



A. Goban et. al. PRL 109, 2012

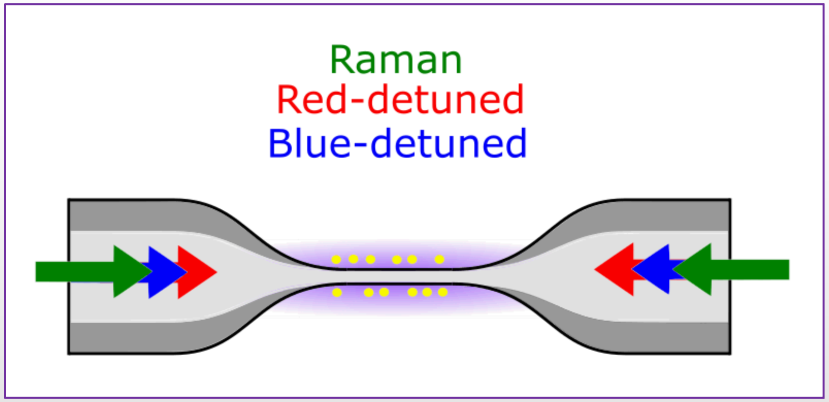


D. Reitz et. al. PRL 110, 2013

Current Research Project

Questions:

- Can we:
- drive coherent Raman transitions with counter-propagating beams?
- construct a free axis for interferometry?
- can we cancel vector light shifts associated with the ellipticity of the electric field?
- control radial phonon excitations induced by Raman transitions?
- minimize state dependent differential light-shifts in trap?
- tolerate spatial inhomogeneities associated with evanescent Raman field?



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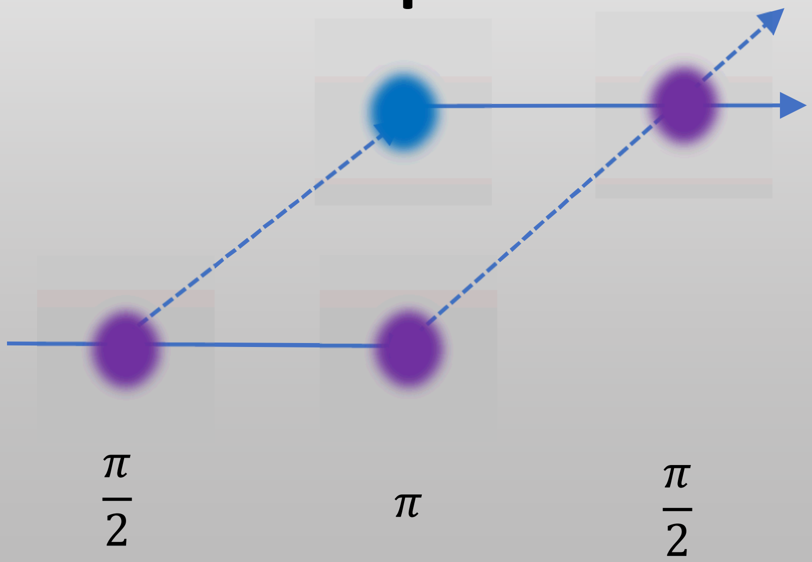

Thank you!