SAND2015-0457C

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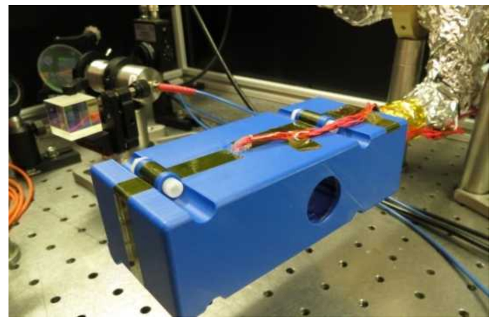

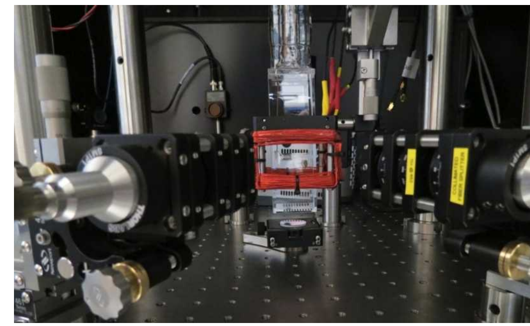

Inertial sensing with atom interferometers

Grant Biedermann

MICRO-TECHNOLOGY POSITIONING NAVIGATION TIMING

UNM

CQuIC

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD

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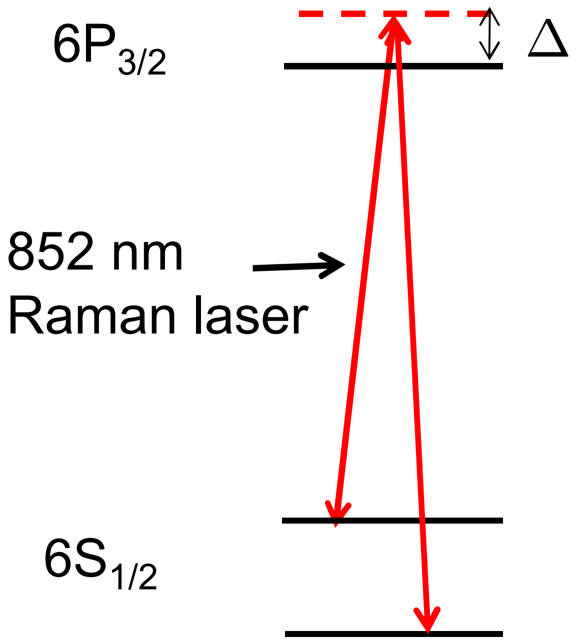
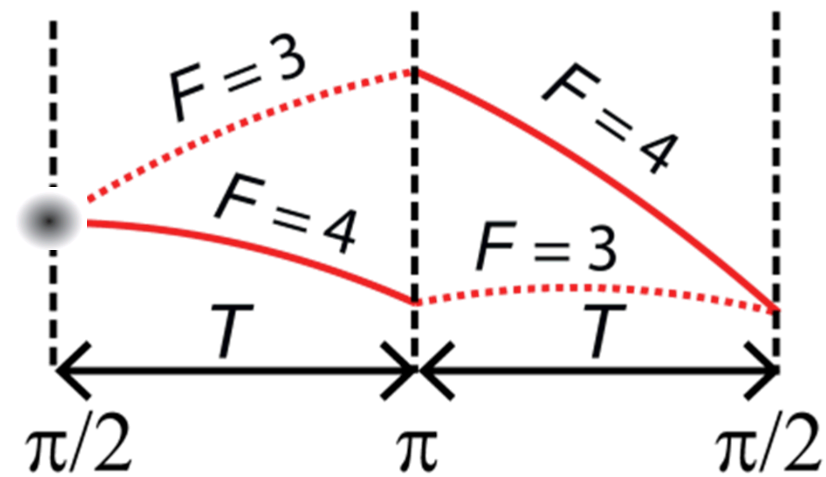
SAND #: ???

Light-pulse atom interferometry



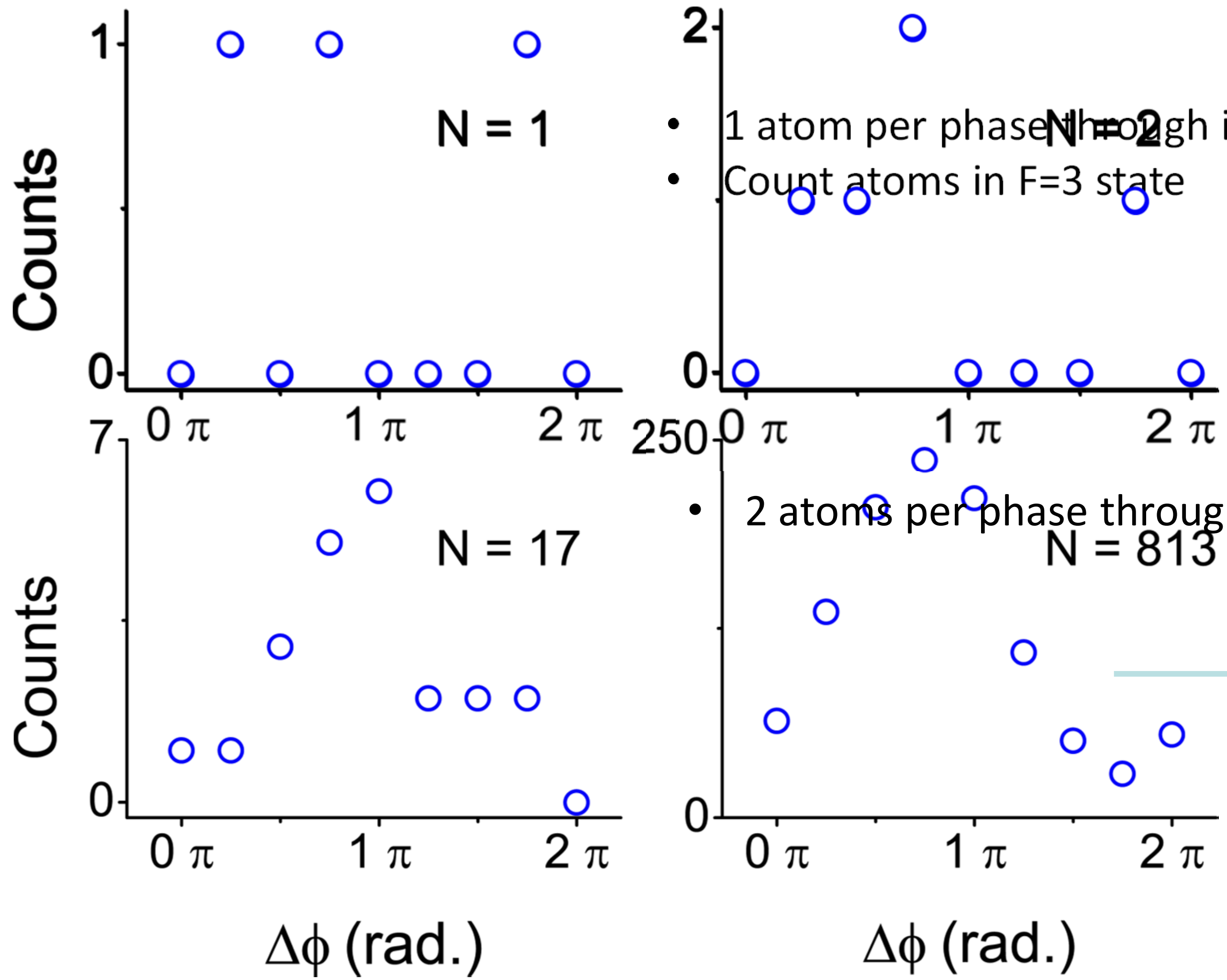
stimulated Raman transition

wavepacket trajectory



Building a fringe, one atom at a time

- 1 atom per phase through interferometer.
- Count atoms in F=3 state

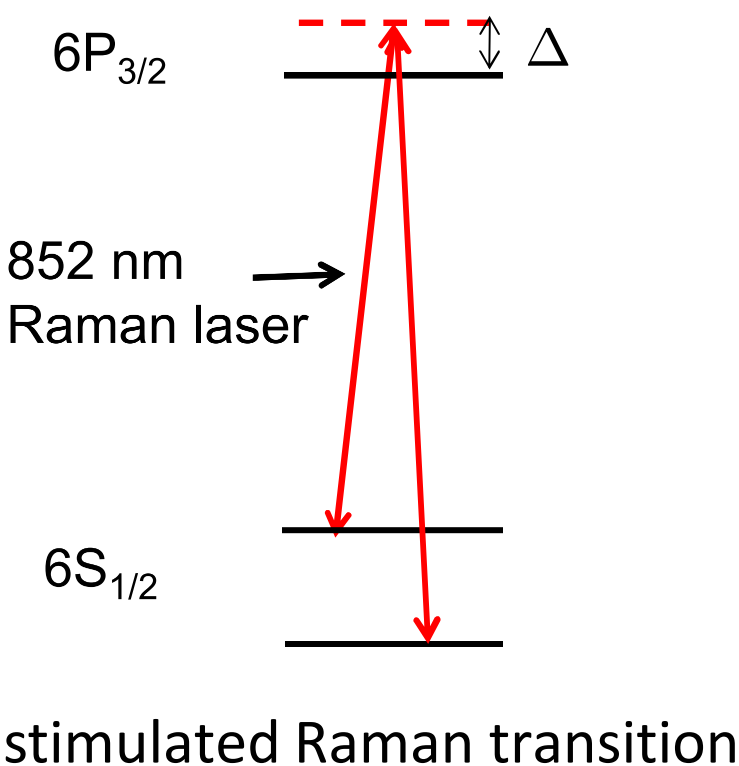


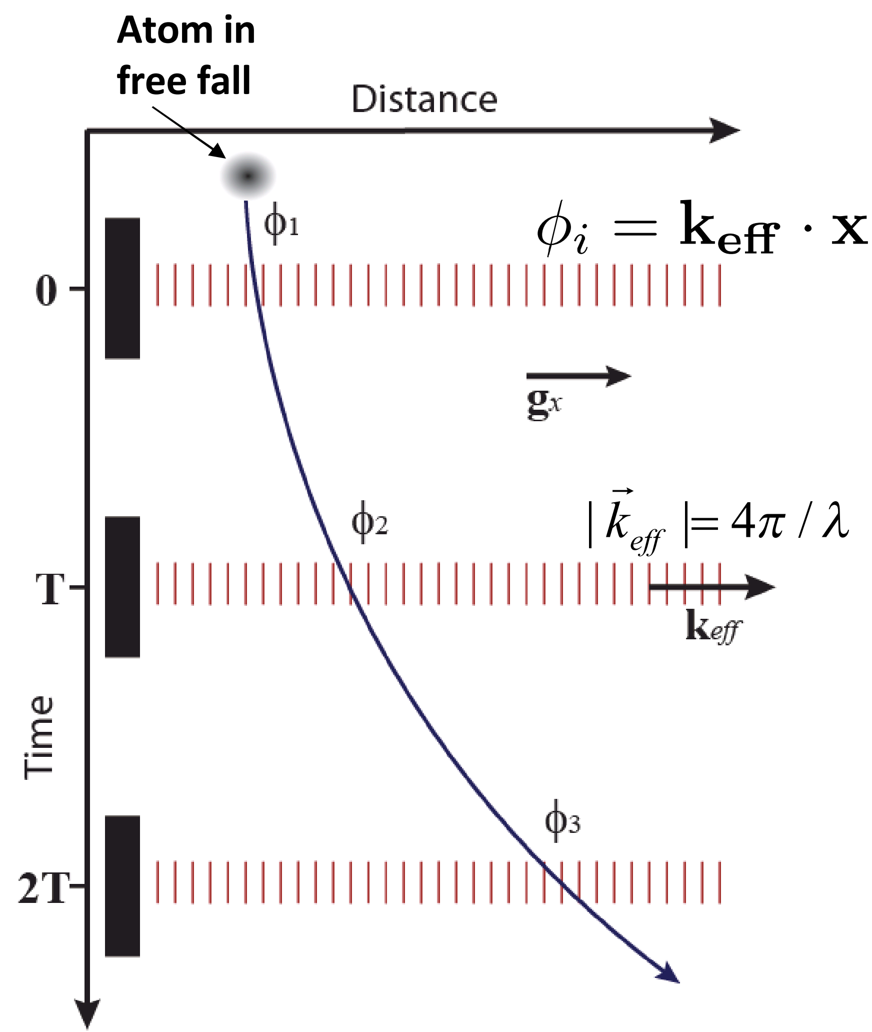
- 2 atoms per phase through interferometer.

7,317 atoms

Parazzoli, et al., "Observation of free-space single-atom matterwave interference", Phys. Rev. Lett. **109**, 230401 (2012)

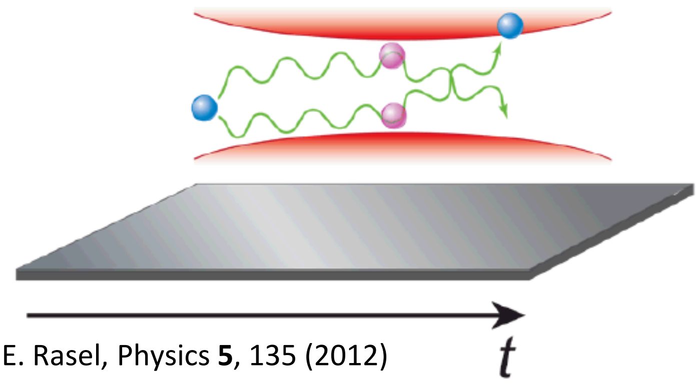
Light-pulse atom interferometry



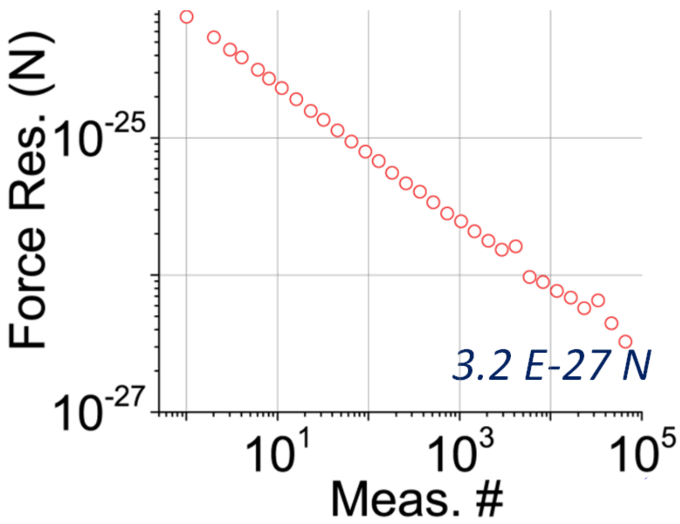


For an atom starting in F=4, P_3 = ½ (1 - cosΔϕ), $\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$

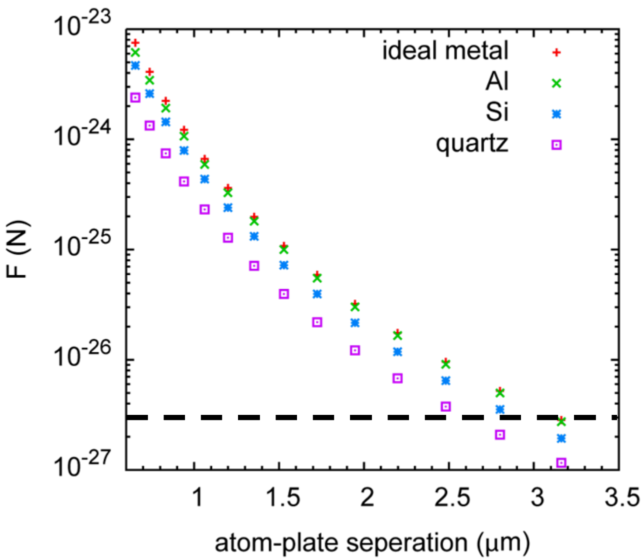
Force resolution of a single atom interferometer

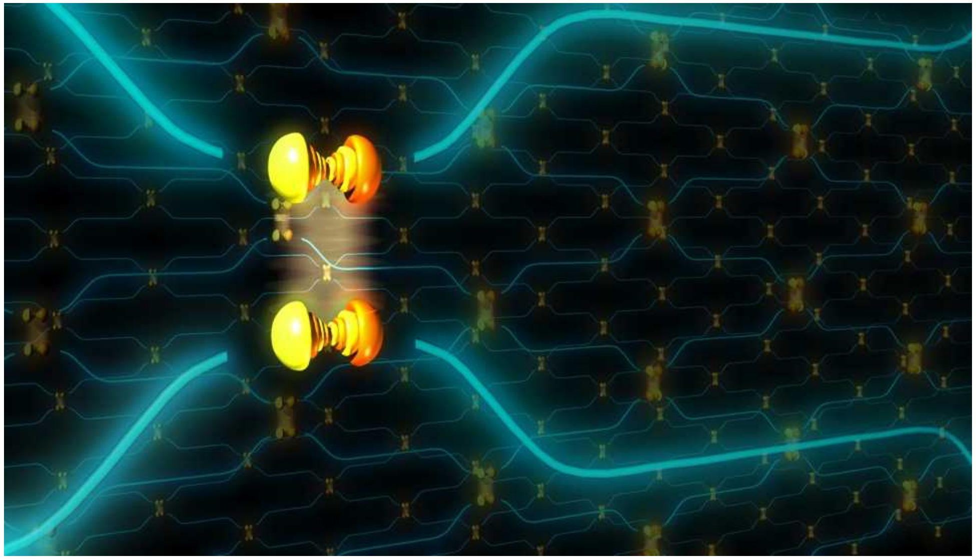


E. Rasel, Physics **5**, 135 (2012)



Casimir-Polder force

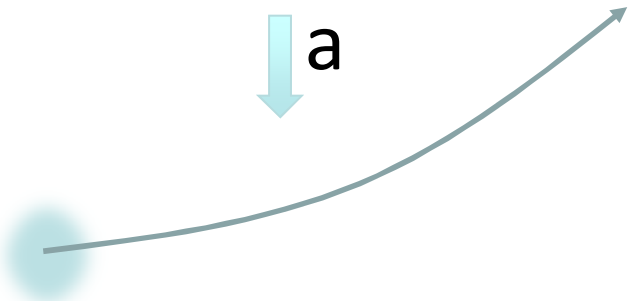


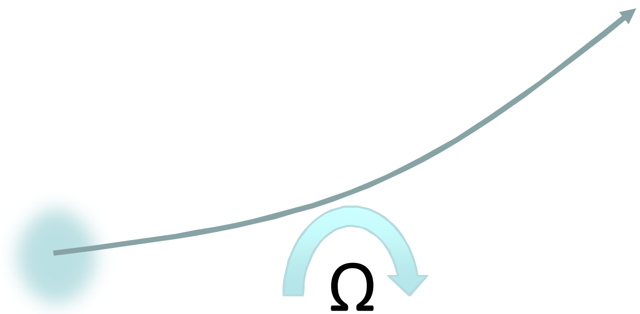


* For cesium 3.2 E-27 N is 1.5 mg

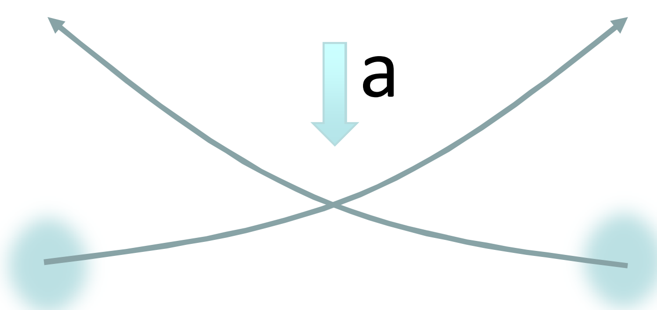
Demonstrated entanglement, arXiv:1501.03862

Rotation Measurement

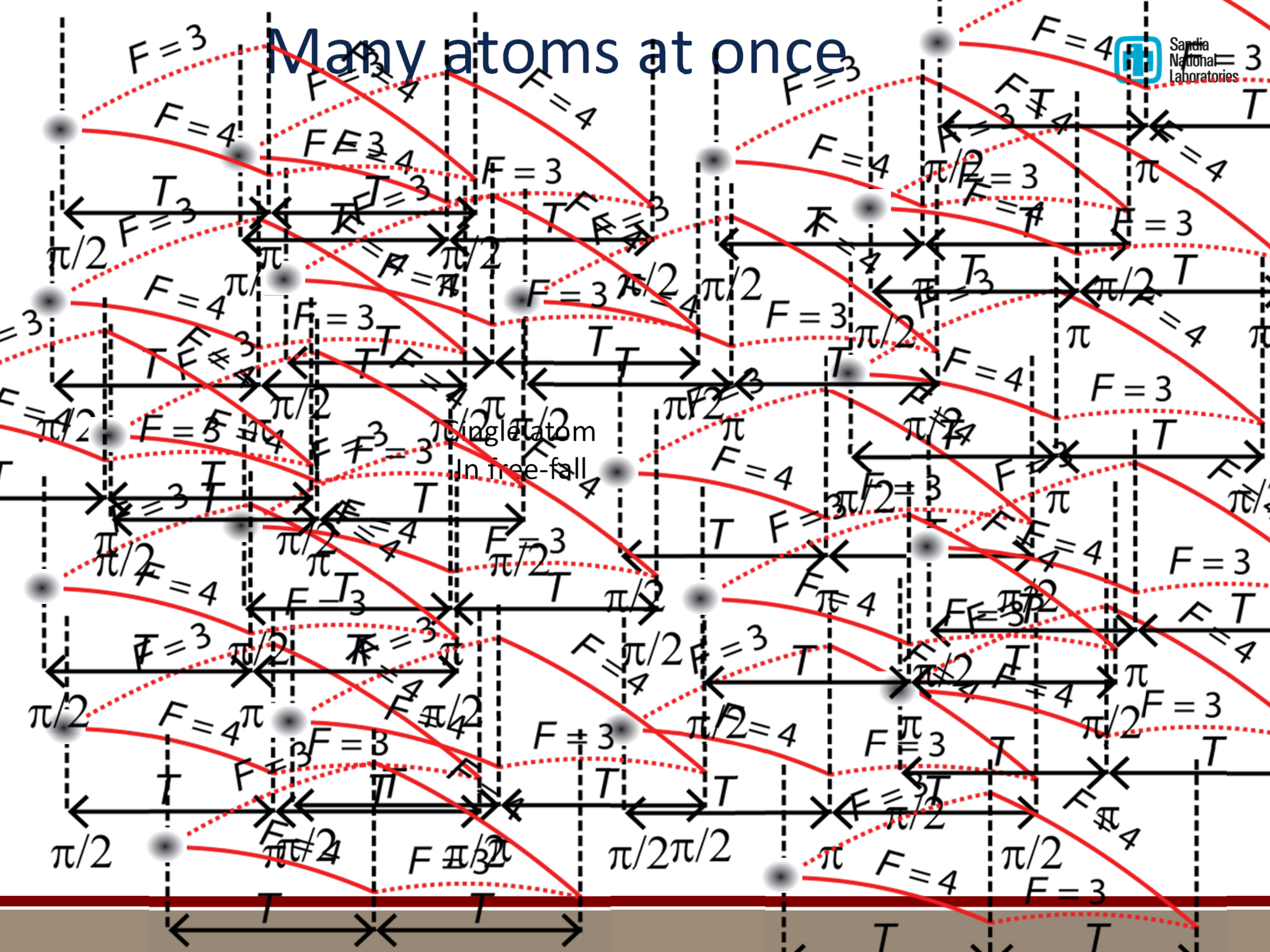




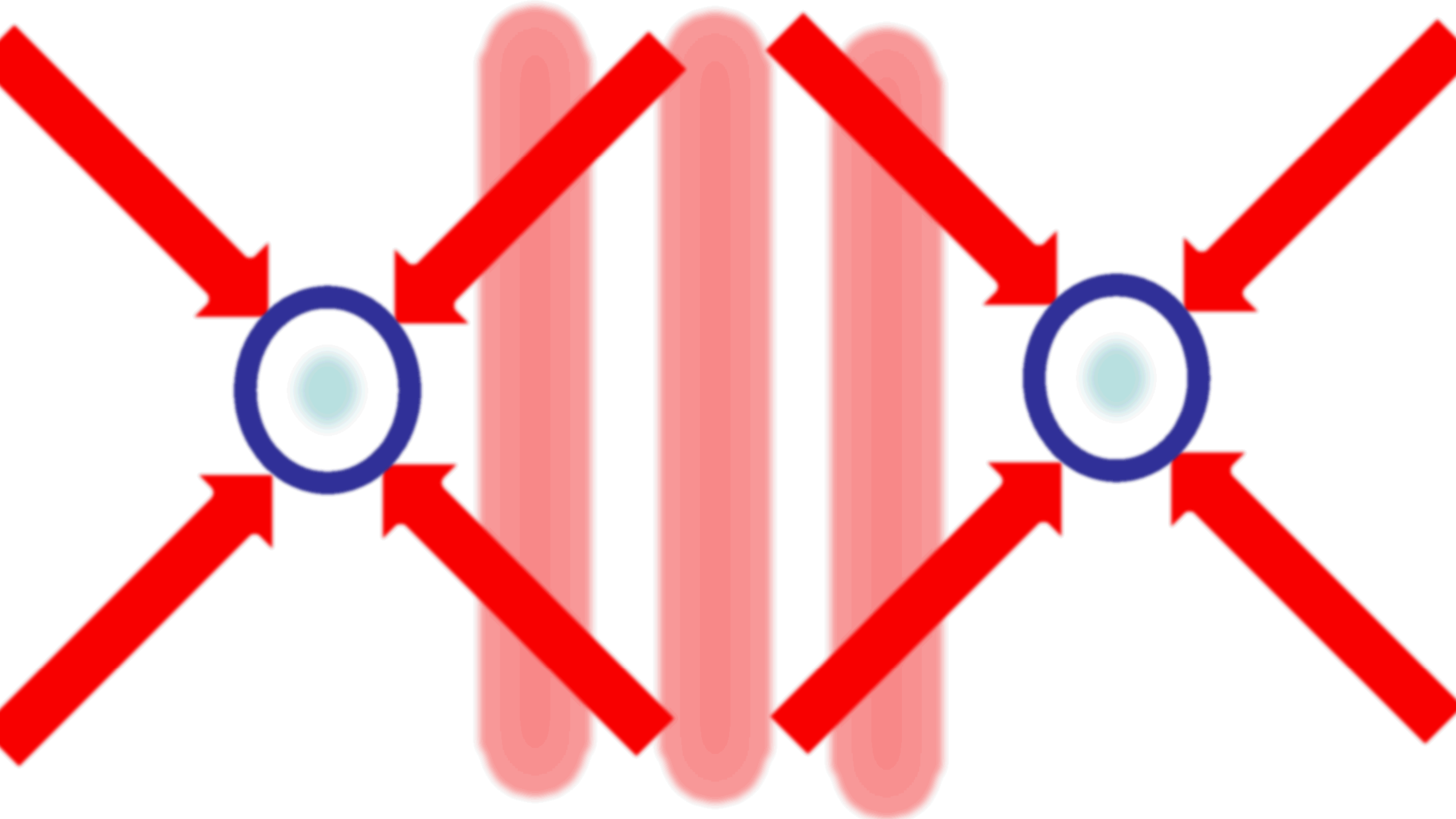
$$\Delta\phi = \vec{k}_{eff} \cdot (\vec{a}T^{2} - 2(\vec{v}\times\vec{\Omega})T^{2})$$



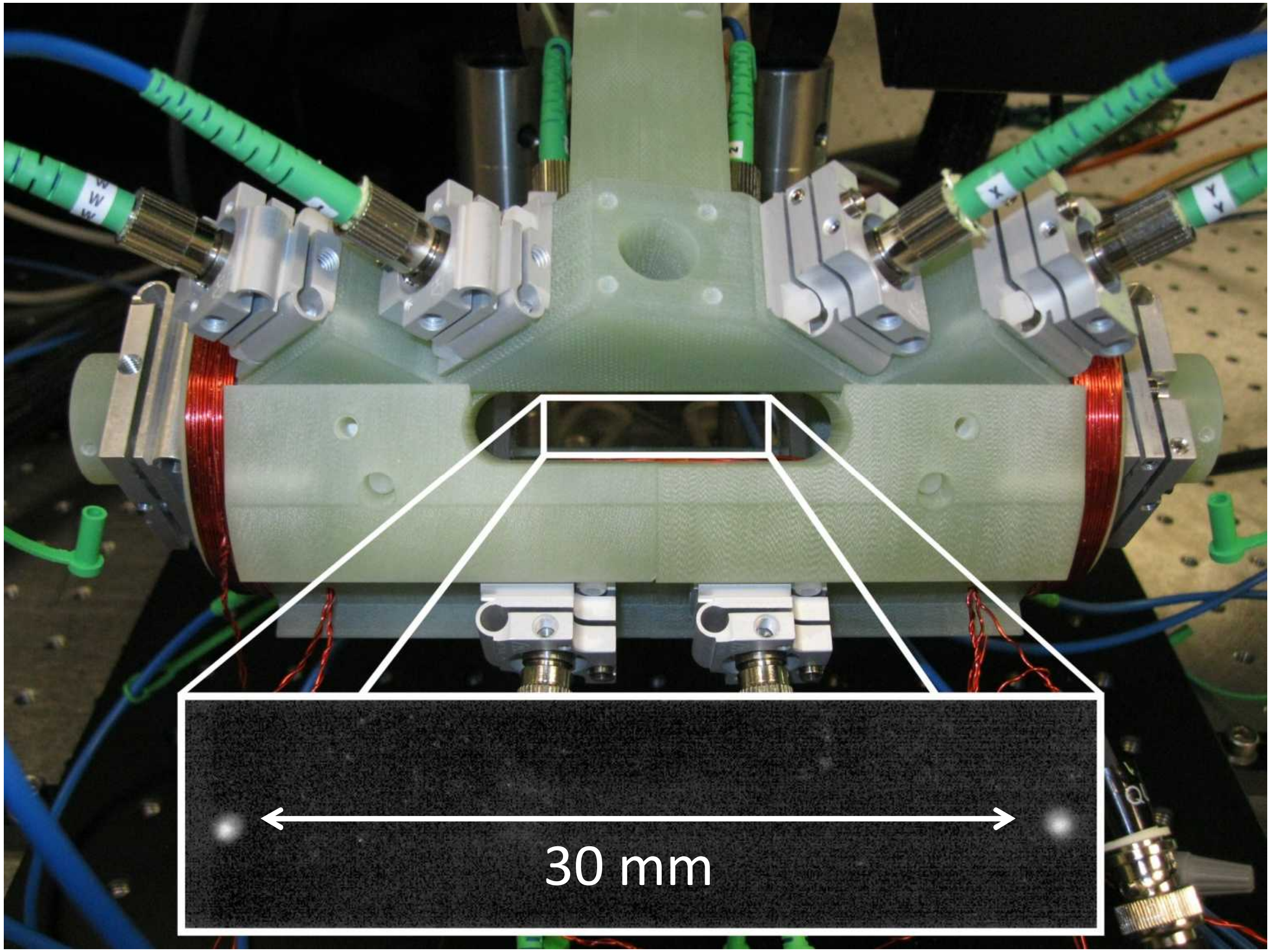
Many atoms at once



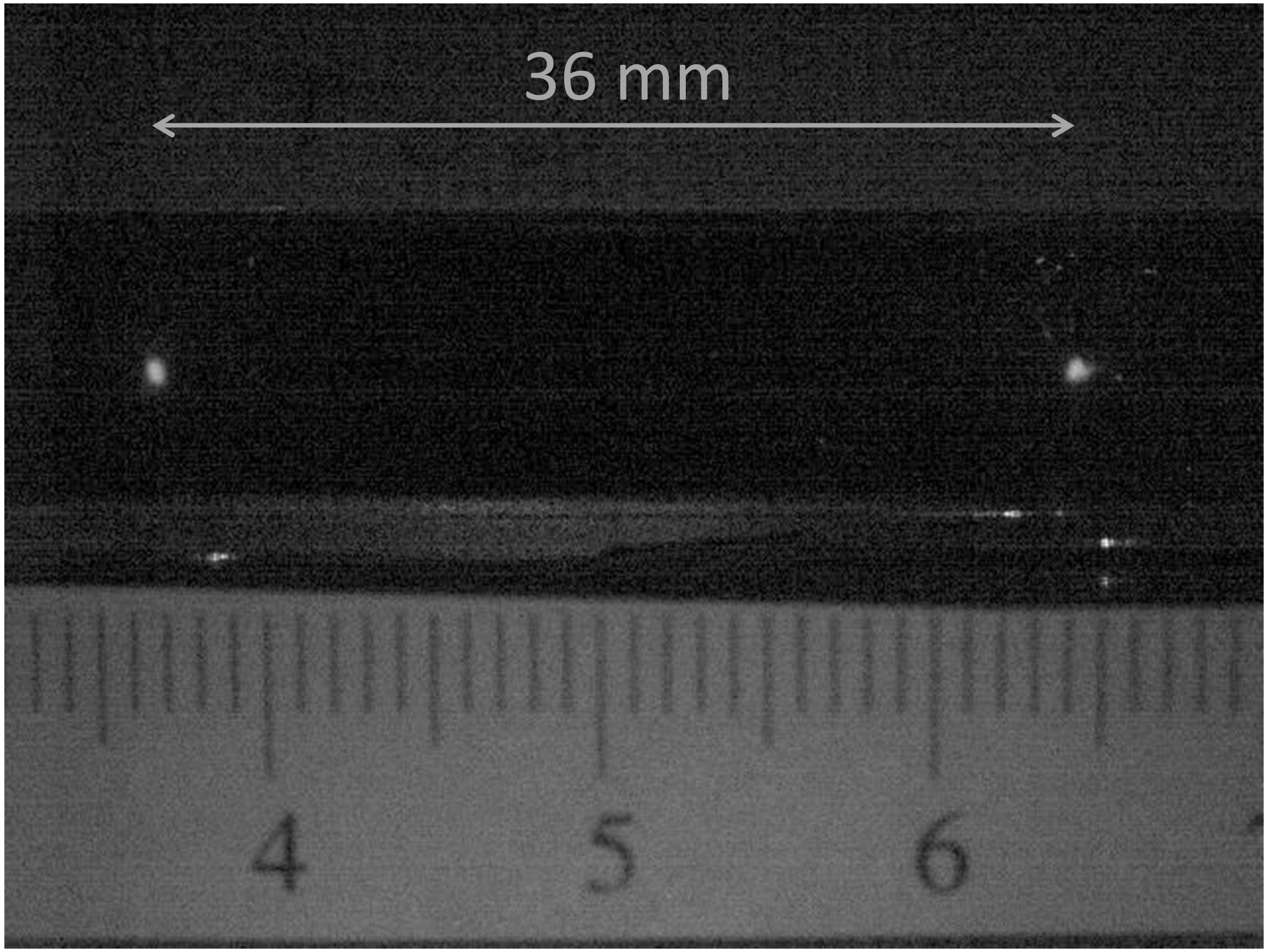
Ensemble Exchange



Dueling interferometers



LAUNCH AND RECAPTURE



LAUNCH AND RECAPTURE

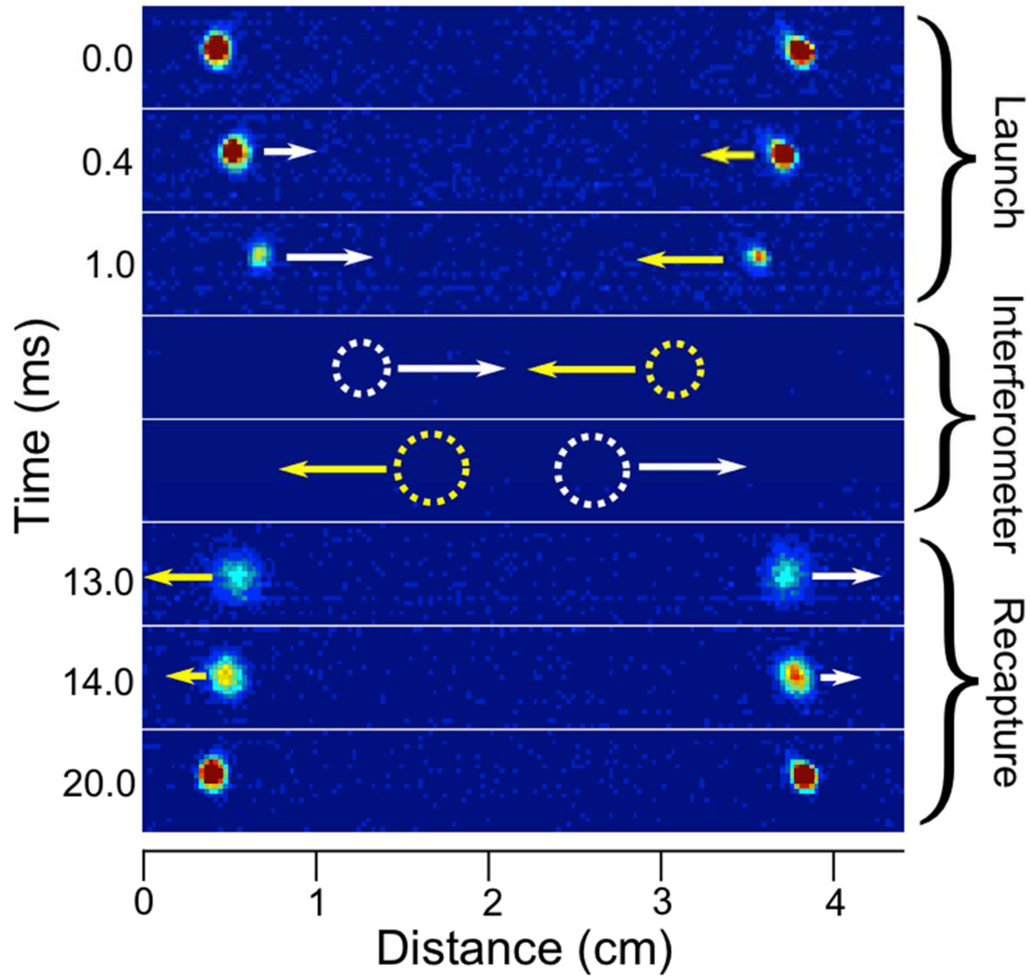
Steady state atom number:

$$N_s = \frac{\alpha\eta T_c}{\beta T_c + (1 - r_0)}.$$

Base recapture efficiency r_0 = 96 %

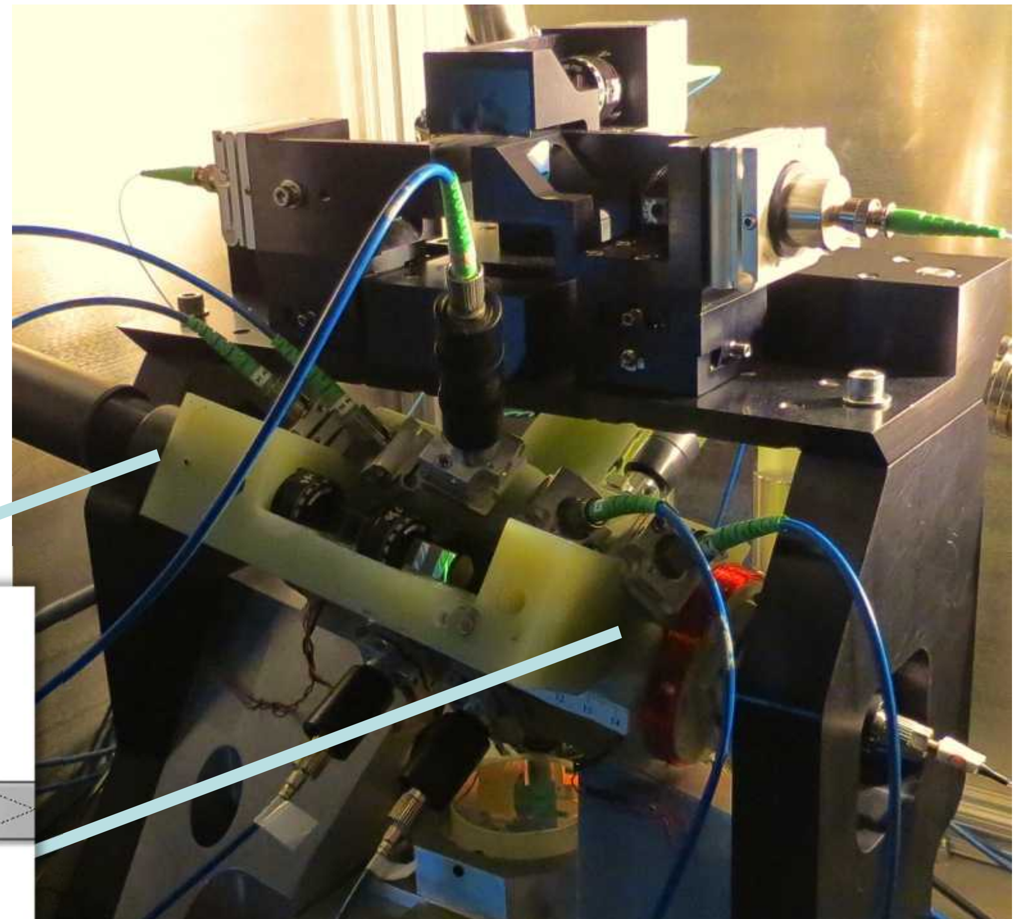
Benefits
- Increases signal by 10x
- Data rates > 50 Hz
- Minimizes cycle dead time
- Reduced complexity

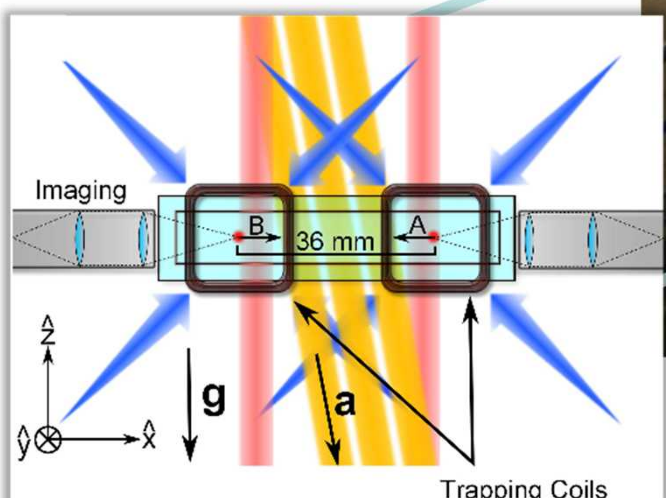
CCD images of ensemble exchange



EXPERIMENT PLATFORM

Picture of interferometer sensor





ENSEMBLE EXCHANGE TECHNIQUE

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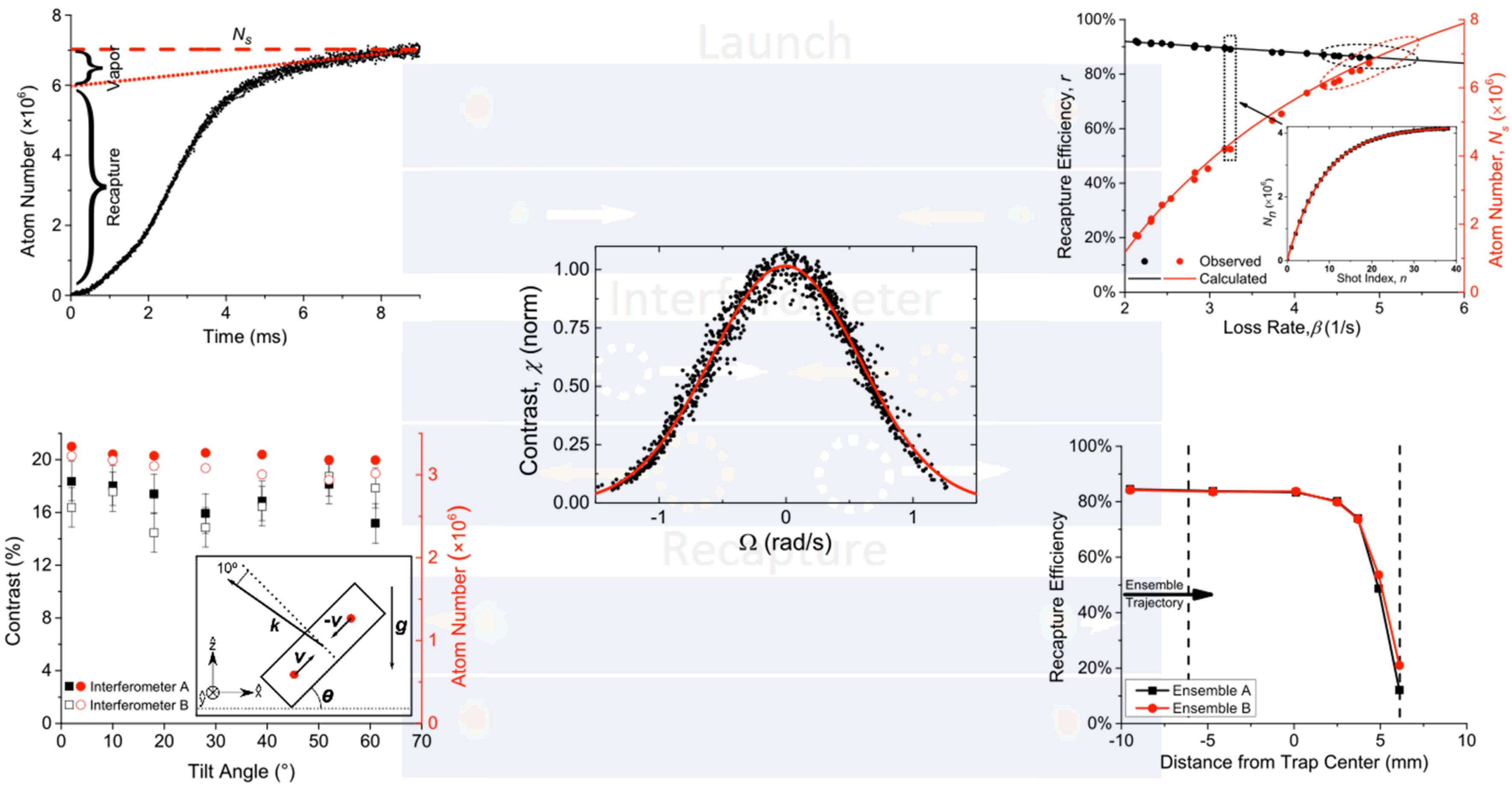
- Dynamic aspects of Ensemble Exchange characterized in previous work
- Robust to rotations, tilts and displacements



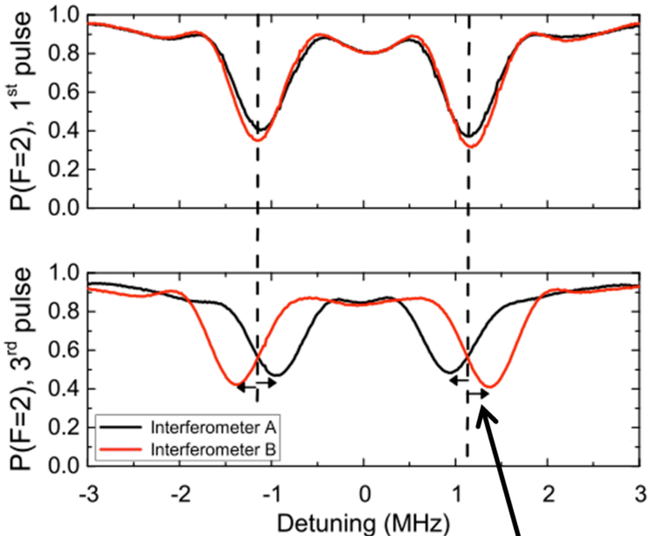
TECHNICAL CHALLENGE

Controlling frequency and phase in a dynamic environment

Raman laser frequency scan

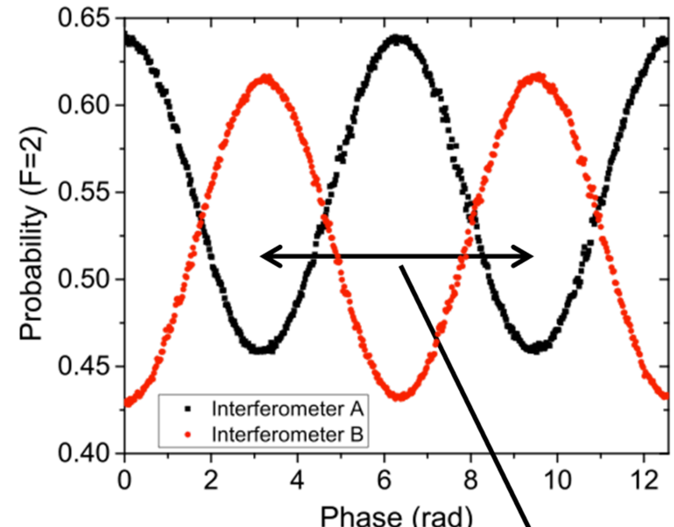
t = 0 ms

t = 10 ms



Significant detuning develops over 10 ms due to gravitationally-driven Doppler shift

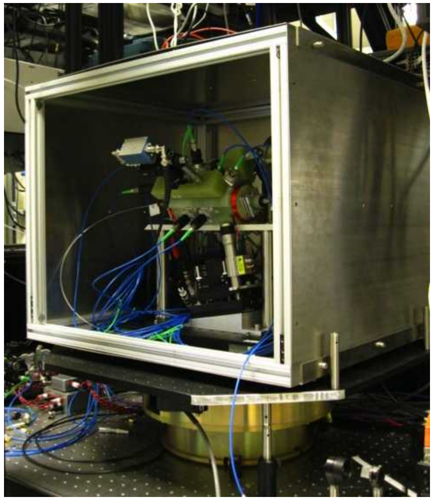
Raman laser phase scan



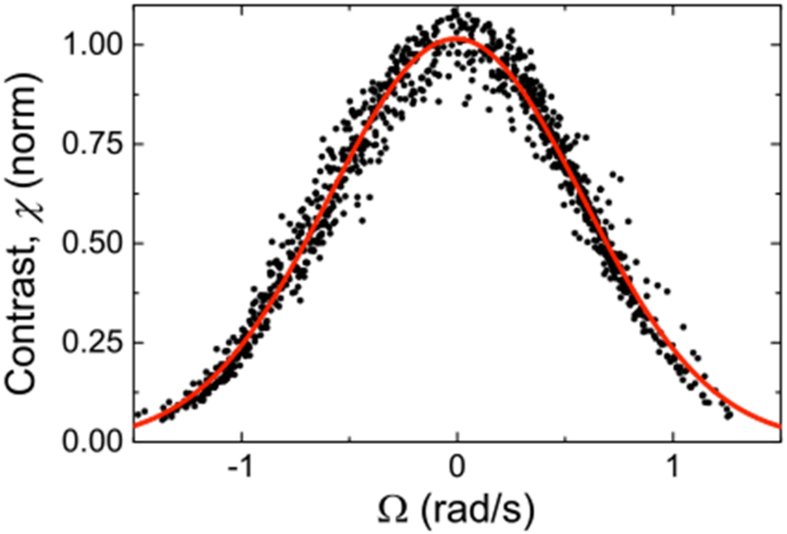
≈ m*g* OR ≈ mrad/s (400 deg/hr)

Small changes in acceleration or rotation during one interferometer cycle cause phase slip

Rotation rate limit



Sensor on rotation stage



$$\chi(\Omega_z) = \exp\left(\frac{-\Omega_z^2}{2\sigma_\Omega^2}\right)$$

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

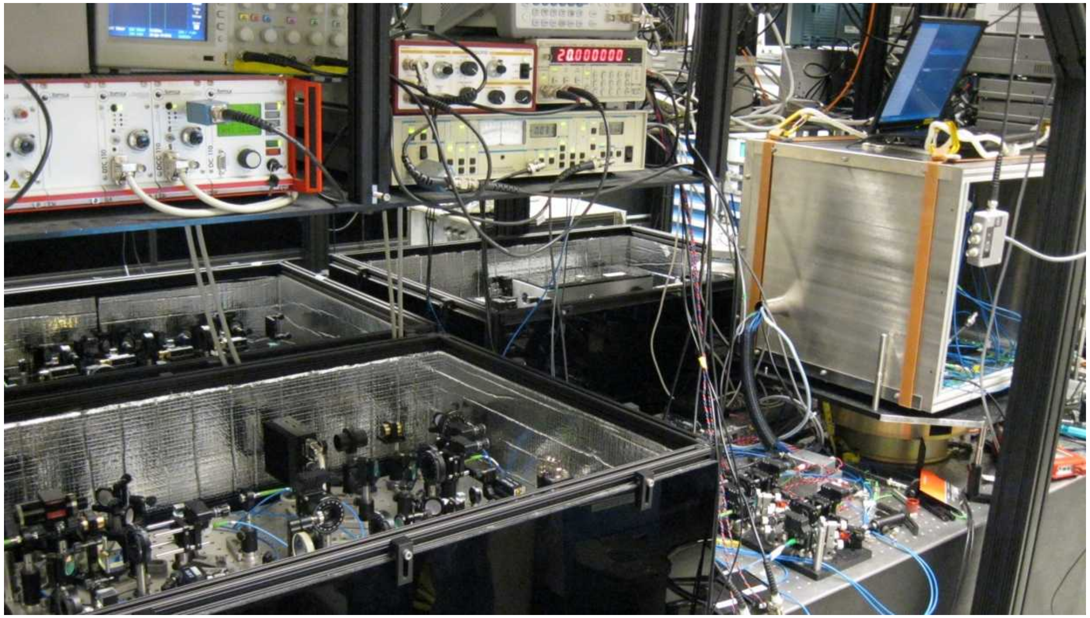
$$\sigma_\Omega = \frac{1}{2}\sqrt{\frac{m}{kT}}\frac{1}{k_e T^2 \sin\theta}$$

Contrast limited by temperature

Solutions: 3D readout or ultra-short T

Sugarbaker et al., Phys. Rev. Lett. 111, 113002 (2013).

Exploring ultra-short T



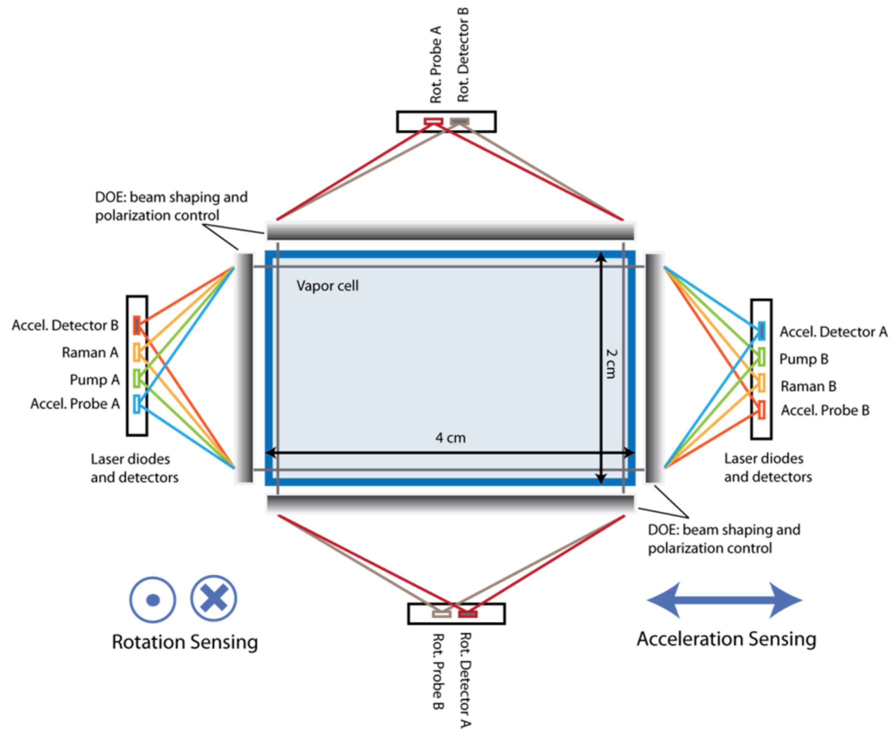
Sandia atom interferometer
- Laser cooled ensemble
- >1,000,000 cc

- Want a small, low-power, low-cost atomic accelerometer
- Warm vapor approach has historically made excellent gyros, clocks and magnetometers.
- What about accelerometers?

Symmetricom SA.45s CSAC
- Warm vapor ensemble
- 17 cc

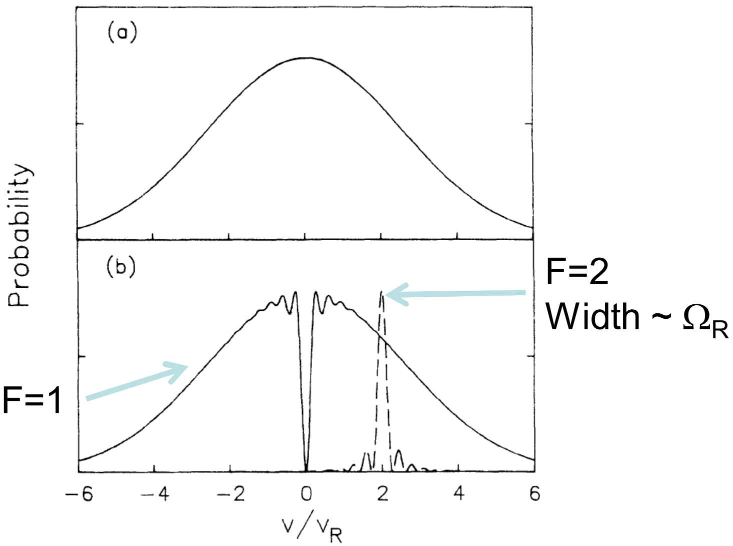
Warm vapor concept

- Using the Doppler sensitivity of Raman transitions, and ultra-short duration atom interferometry, LPAI is possible in a warm vapor
- The challenge: Target atom shot noise limit on 10^8 atoms



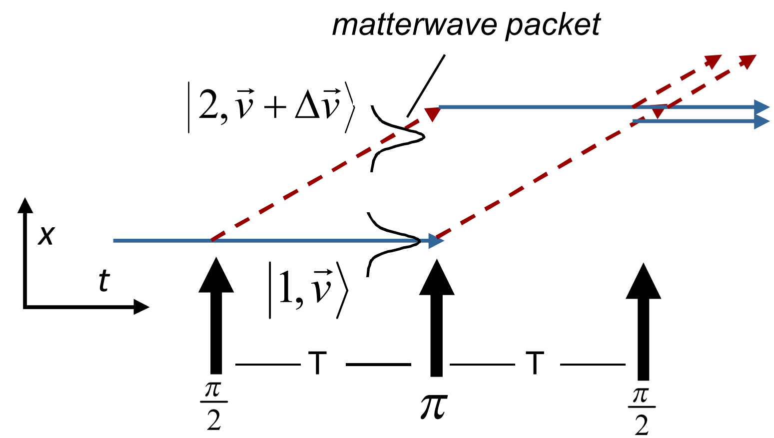
Motivation: potentially highly compact and simplified. Conceptual diagram (not to scale) of a 2-axis atomic sensor.

Basic Idea



Result of Raman transition used for LPAI

K. Moler, et al., *Phys. Rev. A,* 45, 342 (1992)

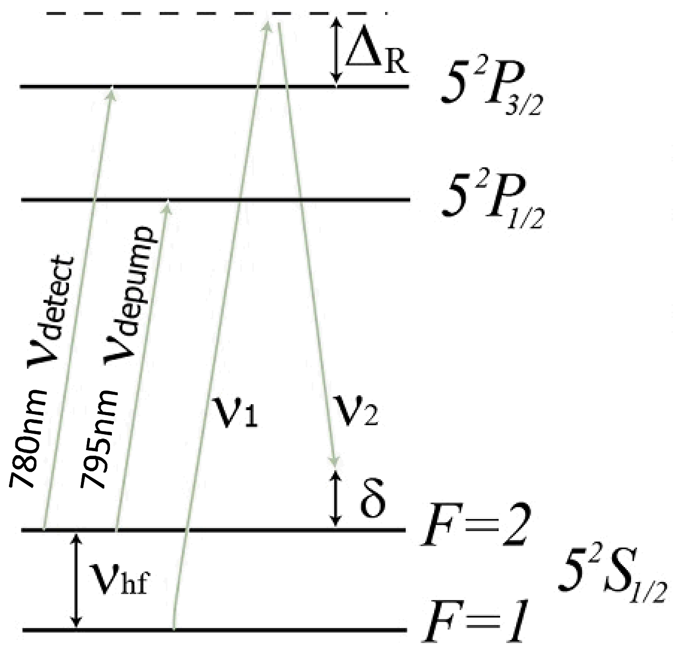


Analyze in momentum space

- each atom interferes with itself
- Non-ideal paths do not contribute to fringe

$$\Delta\phi = \mathbf{k}_{\text{eff}} \cdot (\mathbf{g} - \mathbf{2v} \times \mathbf{\Omega})\mathbf{T^2}$$

Basic Idea

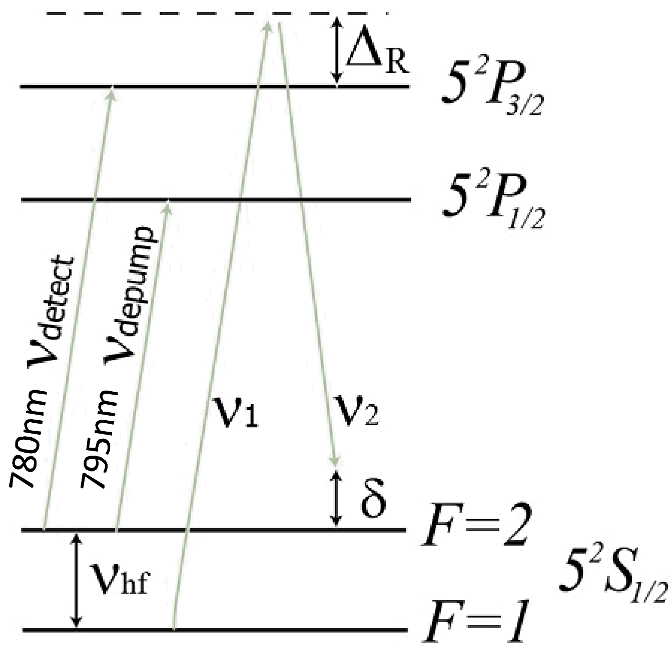


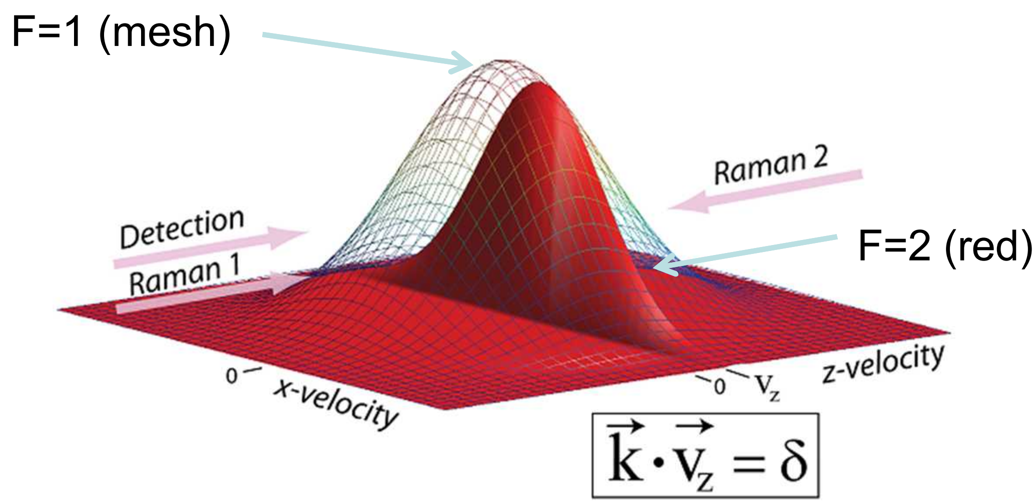
Simplified laser frequency requirements: potential for miniaturization

Sequence of events

- Prepare atoms in F=1 ground state
- Drive atom interferometer pulse sequence
- Detect in previously vacant state

Basic Idea

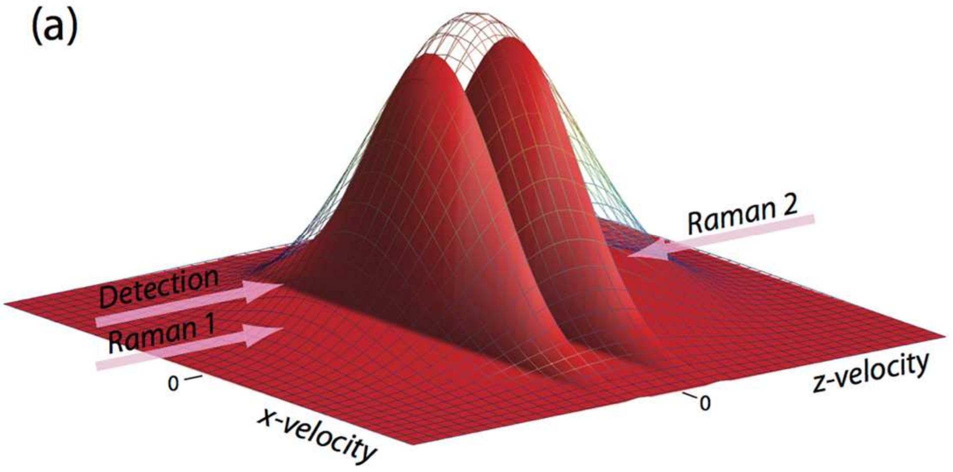




MB distribution with laser fields

- use detuning δ to drive and probe nonzero velocity class
- Width set by Rabi frequency

Basic Idea



(a)
Detection
Raman 1
Raman 2
0
0
x-velocity
z-velocity
(b)
Raman 1
Raman 2
Detection
0
0
x-velocity
z-velocity

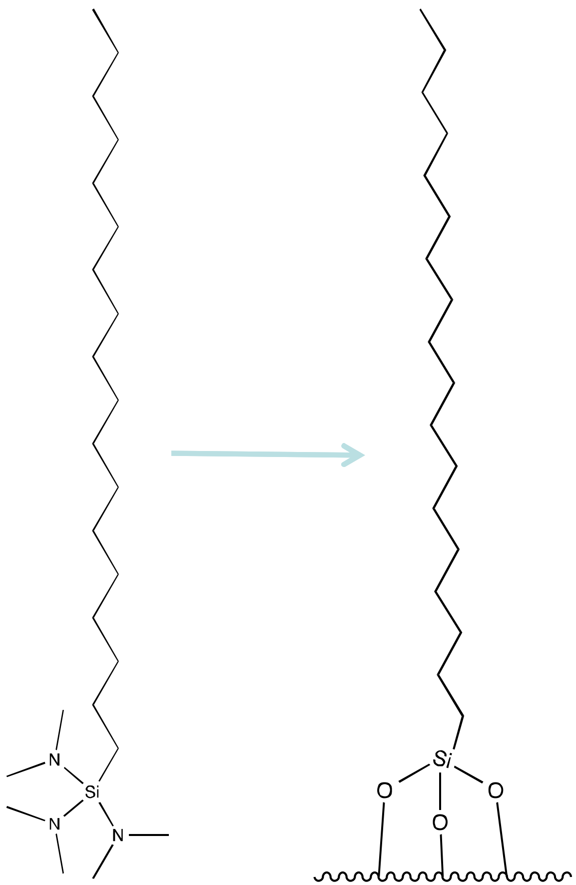
State preparation

To eliminate background signal, must depump all velocity classes

In-house coating development

Tris(N,N-dimethylamino)octadecylsilane

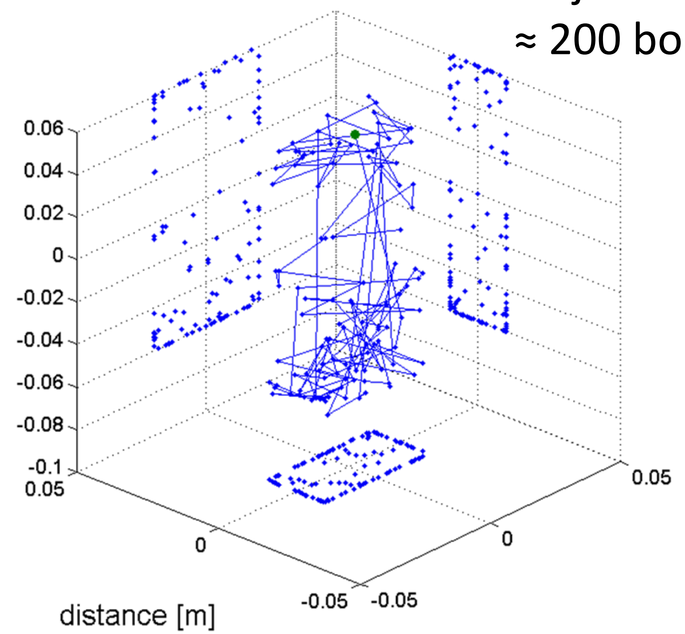
measured: τ = 23 ms hyperfine state lifetime



Idealized Bonding

Trajectory simulation

≈ 200 bounces



Must be inertially pure—no collisions!

Coating outgassing < 10^{-4} Torr

No buffer gas

The experiment

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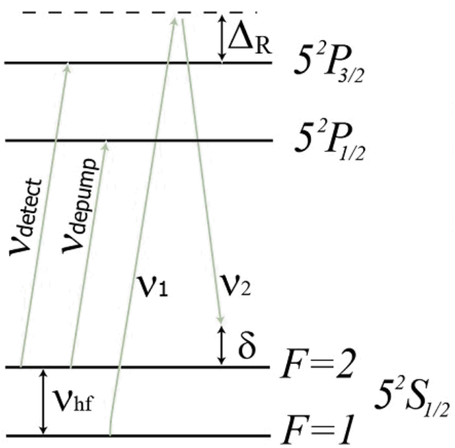
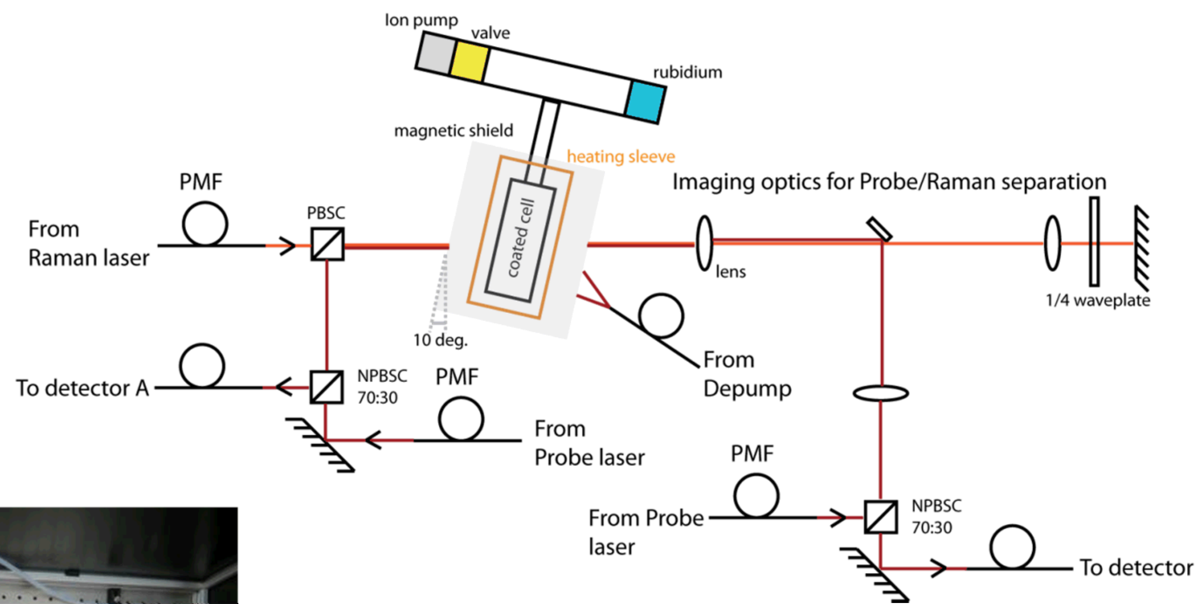
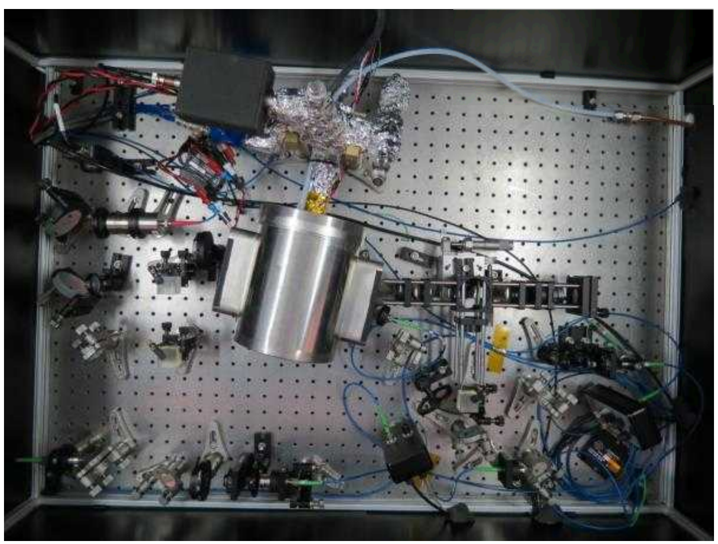




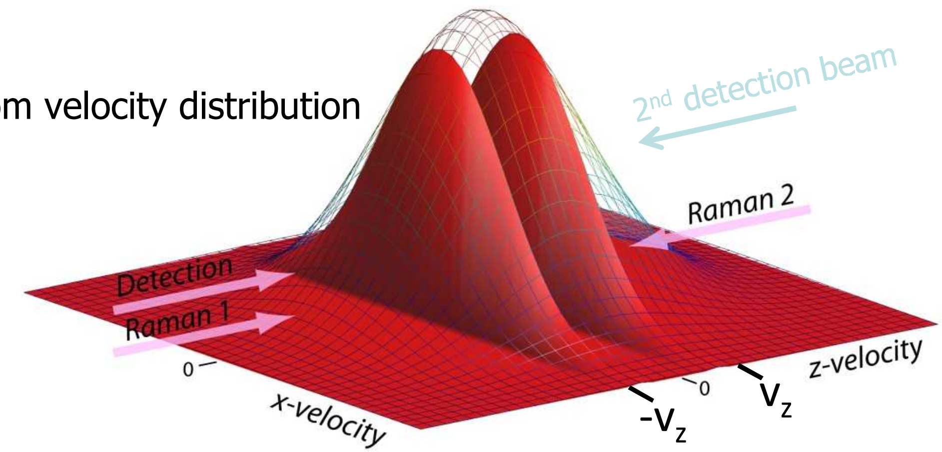
Experiment schematic

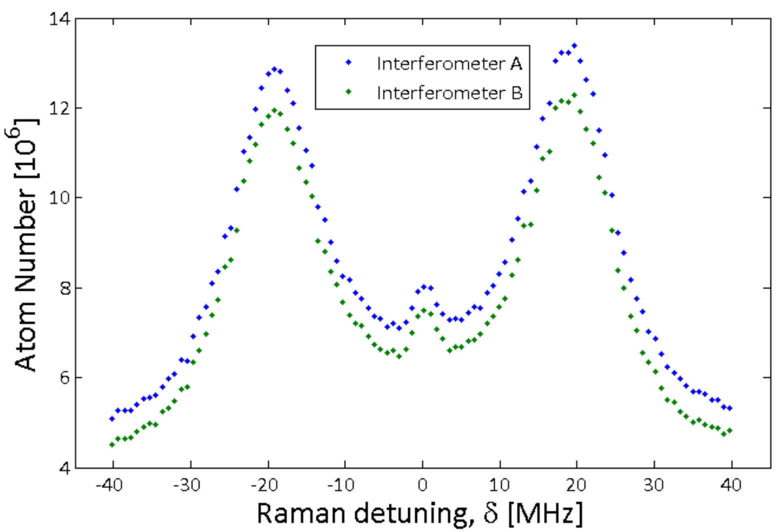


Experiment Photograph

New possibilities

Atom velocity distribution

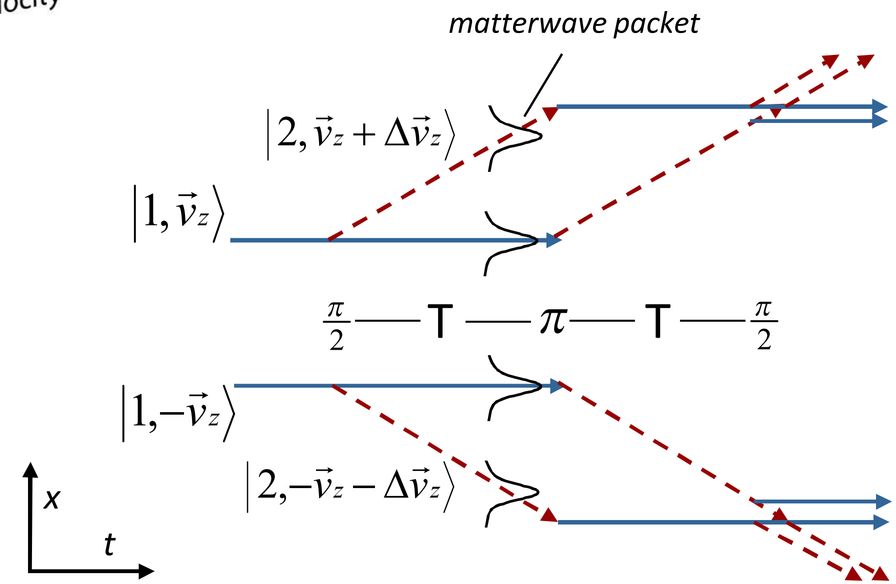




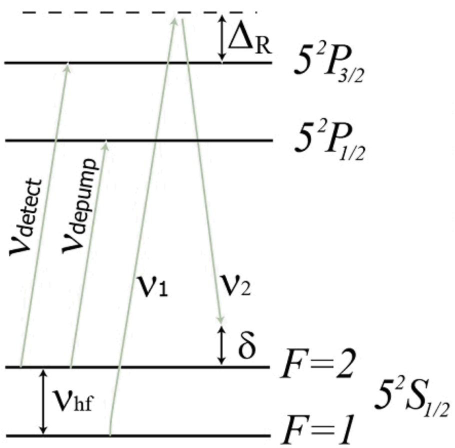
Common mode noise rejection

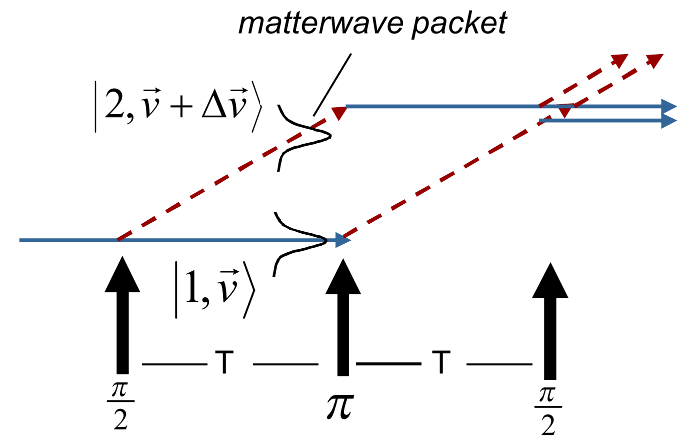
$$\Delta\Phi = \mathbf{k} \bullet \mathbf{a}\, T^2$$

Simultaneous interferometers

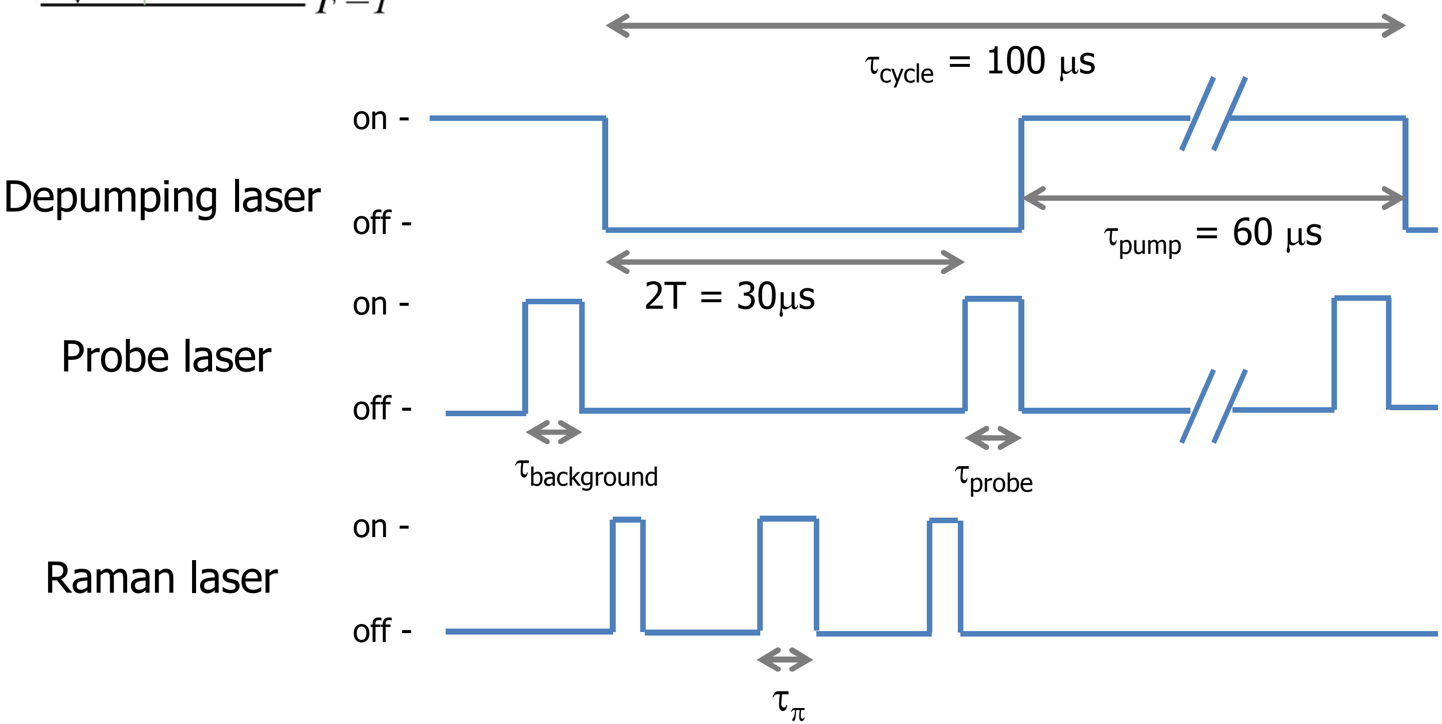


Experiment timing





Timing diagram



Wavepacket overlap in a “warm” vapor

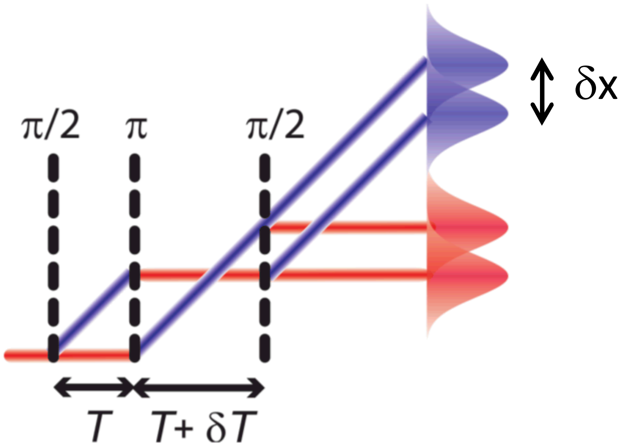
The contrast, $\chi(\delta T)$, is given by

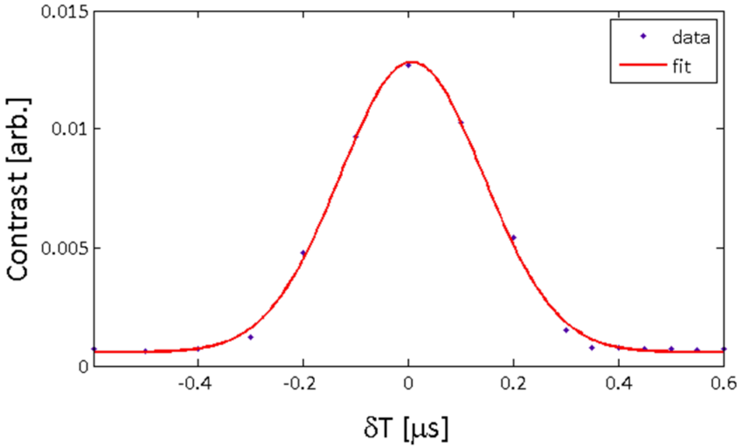
$$\chi(\delta T) = \exp\left(-\frac{v_r^2 \delta T^2}{8 x_a^2}\right)$$

where v_r is the recoil velocity (11.8 mm/s) and x_a is the average coherence length x_a = 0.81(3) nm.

This corresponds to a temperature of 1.44(6) mK

Consistent with a Doppler width of 0.95(4) MHz
Note: Rabi frequency is 1.61 MHz





$\delta x = v_r \, \delta T$

Wavepacket overlap in a "warm" vapor

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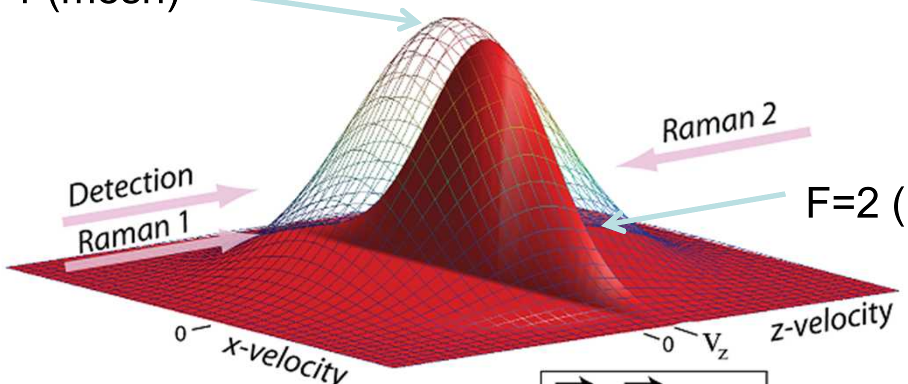
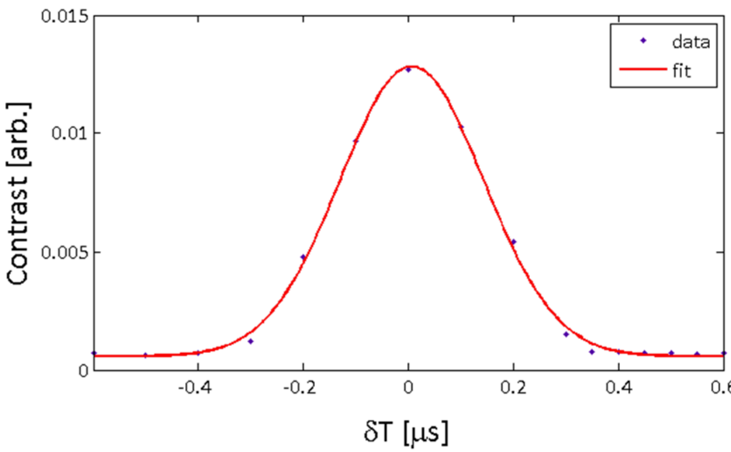
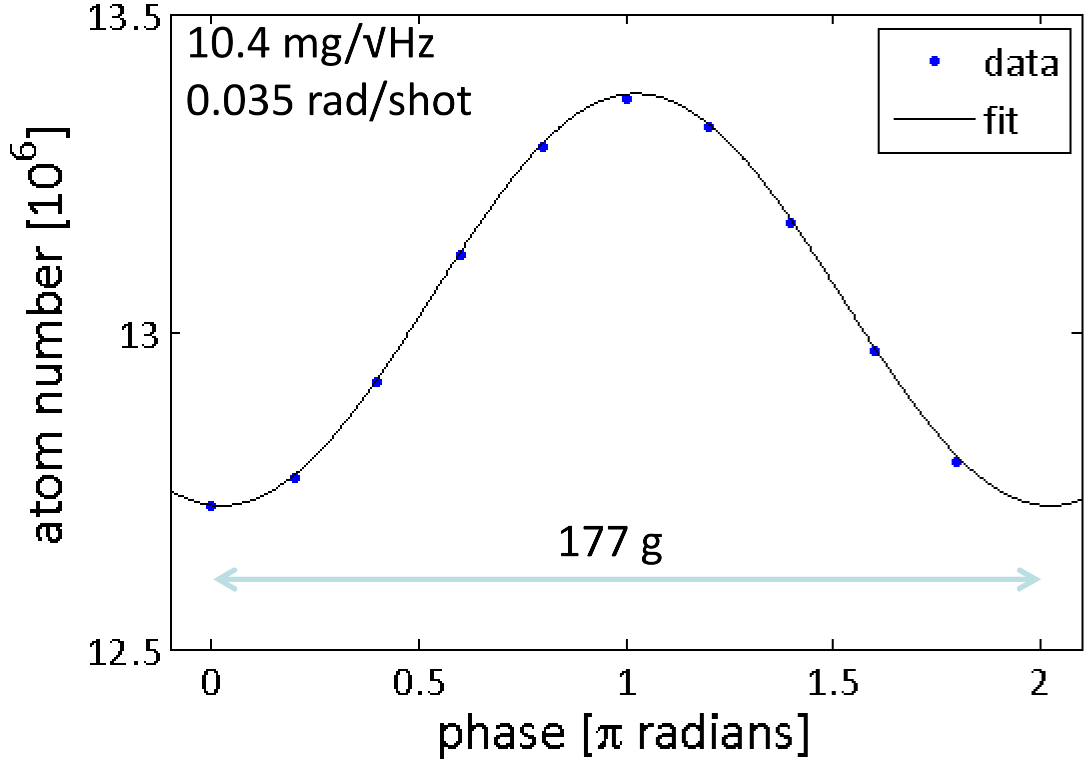


$$\vec{k} \cdot \vec{v}_z = \delta$$



$\delta x = v_r\, \delta T$

Results

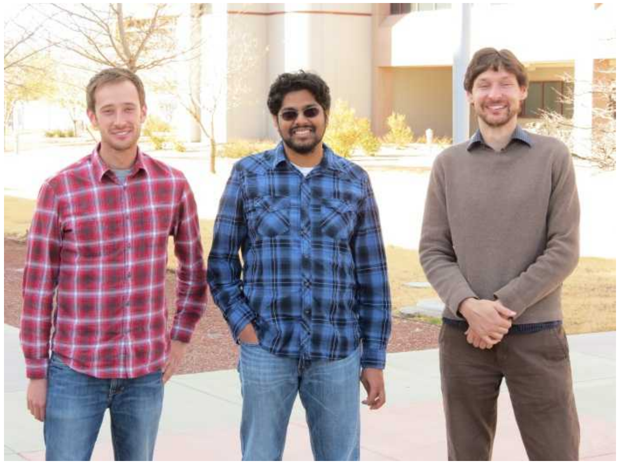


Measured:

- without CMR: 40 mg/√Hz
- With CMR: 10.4 mg/√Hz

Atom shot noise: 3.1 mg/√Hz

Thank you



G. Biedermann, A. Rakholia, H. McGuinness

Not pictured

- Yuan-Yu Jau
- David Wheeler