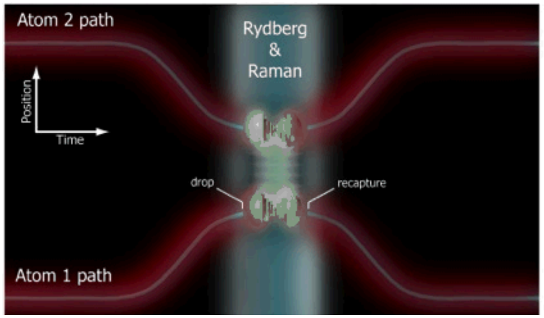
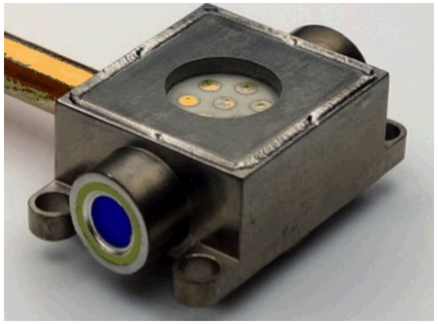
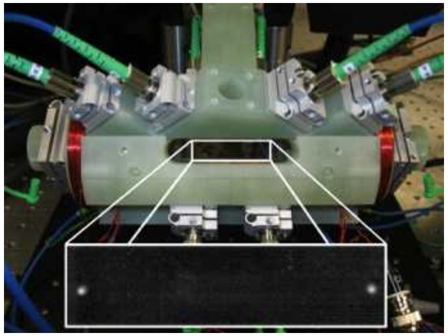
SAND2015-4985PE





# Quantum sensors


Grant Biedermann

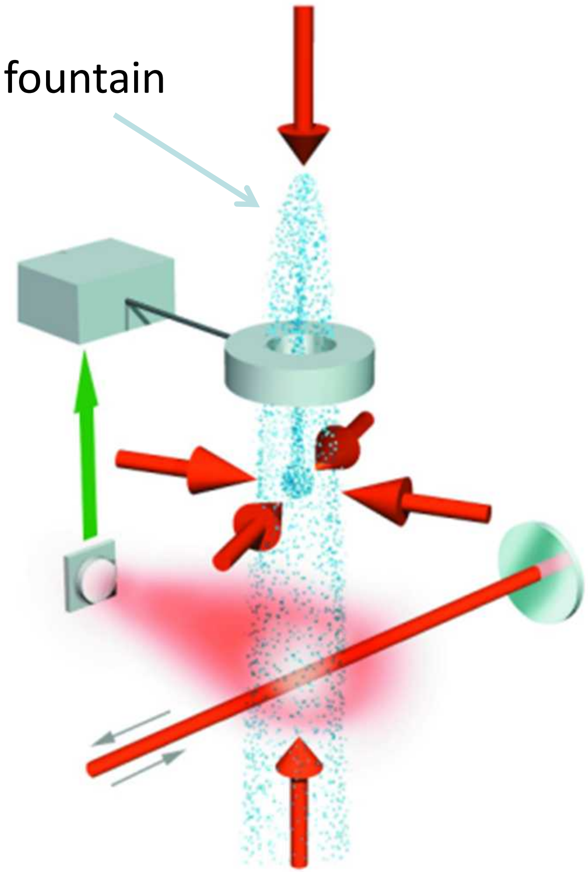


Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Quantum-Coherence

Sandia National Laboratories

Qubit fountain



Atomic fountain principle

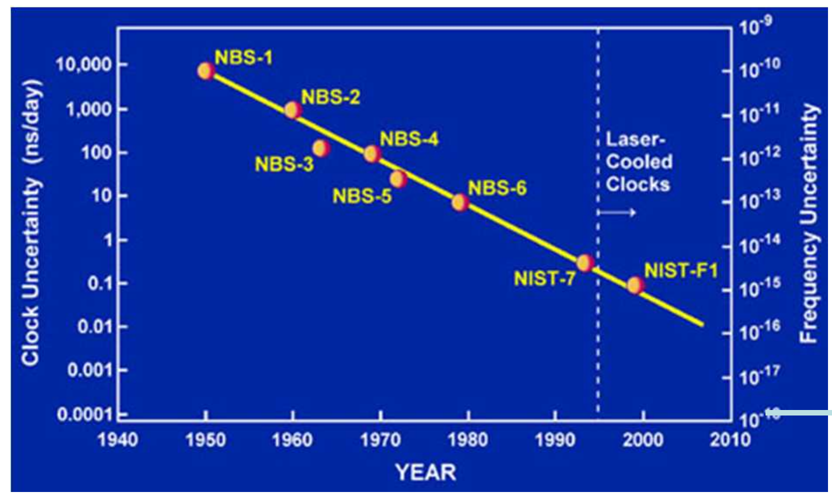
http://smsc.cnes.fr/PHARAO/GP_instrument.htm

Outstanding quantum coherence in neutral atoms enables precision metrology and quantum information

- Example: atomic clocks

$$\left|6^2 S_{1/2}; F=3, M_F=0\right\rangle \leftrightarrow \left|6^2 S_{1/2}; F=4, M_F=0\right\rangle$$

$$\left|0\right\rangle \leftrightarrow \left|1\right\rangle$$



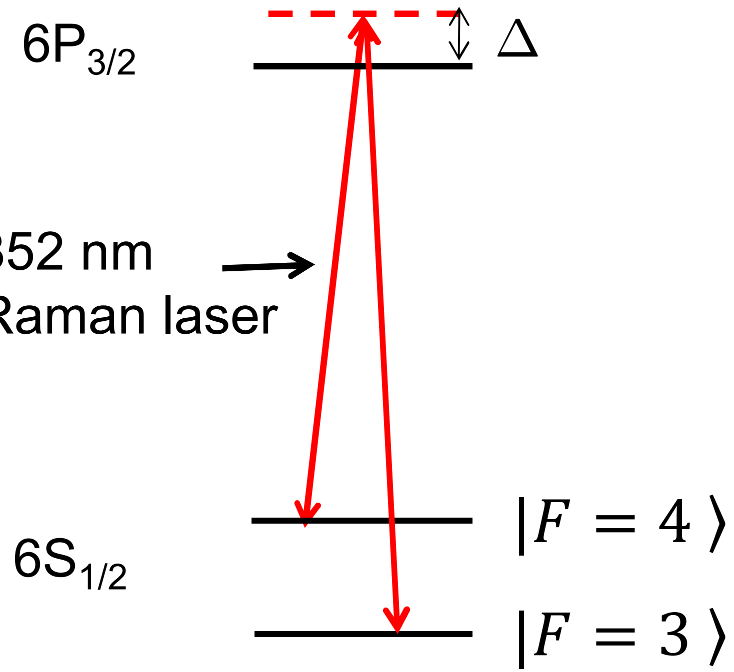

Optical clocks

http://www.nist.gov

Typical accuracy now better than one part in $10^{15}$

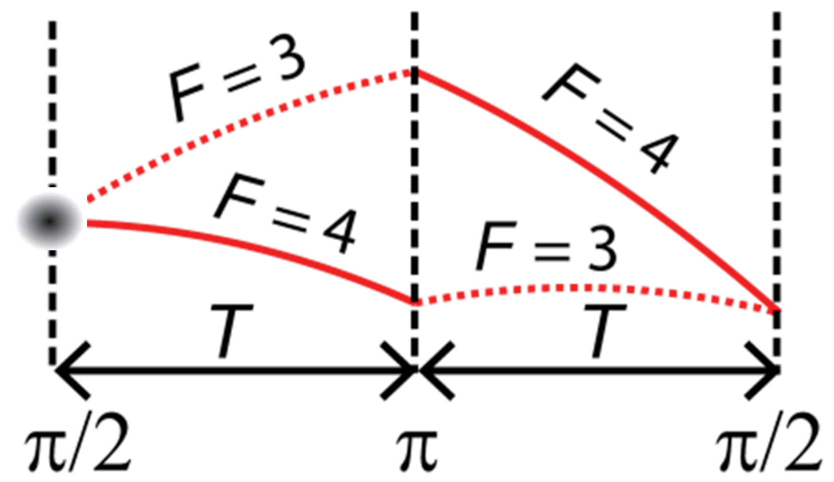
# Light-pulse atom interferometry

Sandia National Laboratories




stimulated Raman transition

wavepacket trajectory

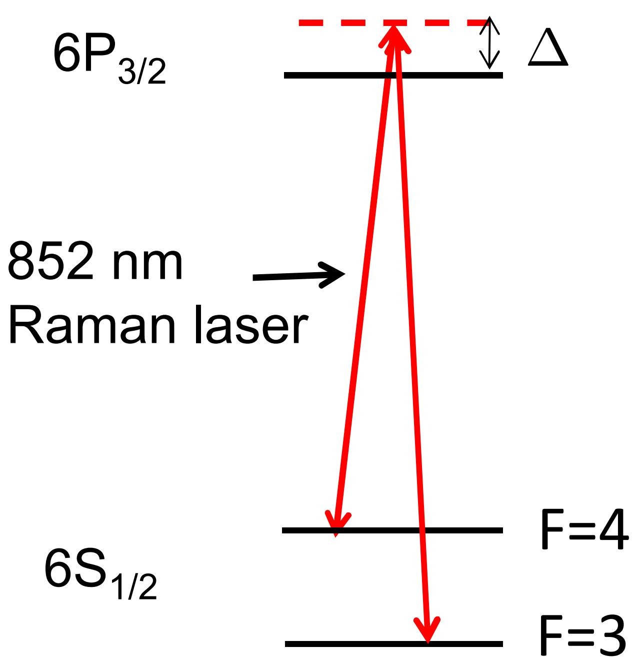



- Exceptional accelerometers and gyroscopes nrad/s/√Hz, n*g*/√Hz to p*g*/√Hz
- Growing commercial and govt. interest in fielding this technology

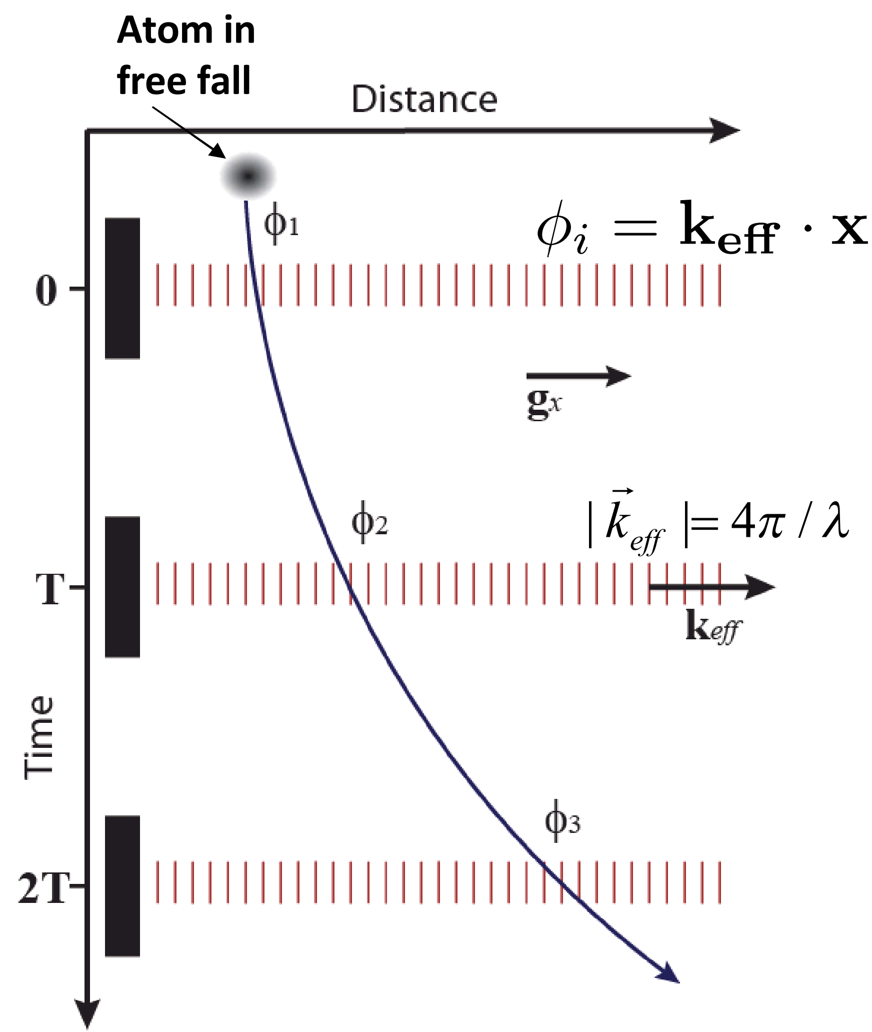
Kasevich, and Chu, Phys. Rev. Lett. 67, 181–184 (1991)

Gustavson, Landragin, and Kasevich, Class. Quantum. Grav 17, 2385–2398 (2000).

# Light-pulse atom interferometry



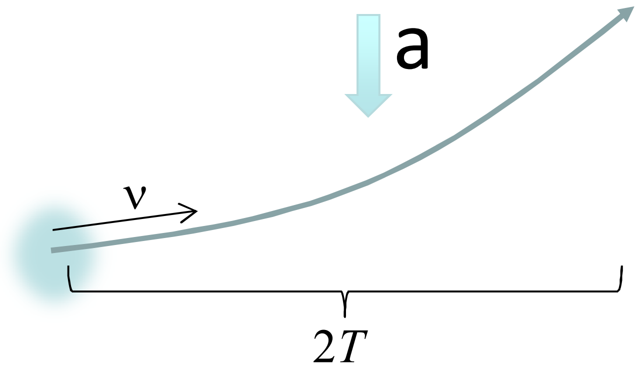

stimulated Raman transition

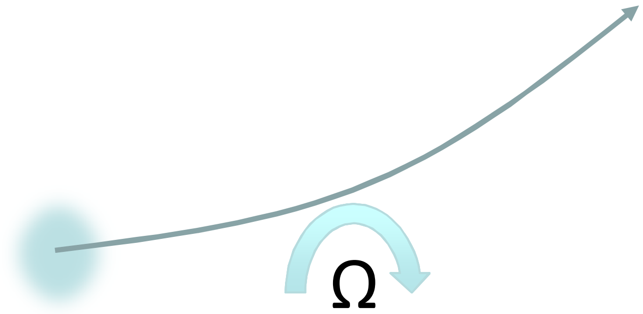



For an atom starting in F=3: $P_{\mathrm{F=4}} = \frac{1}{2}(1 - \cos\Delta\phi)$ & $\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$

# Measuring acceleration and rotation with a particle in free-fall

1-particle

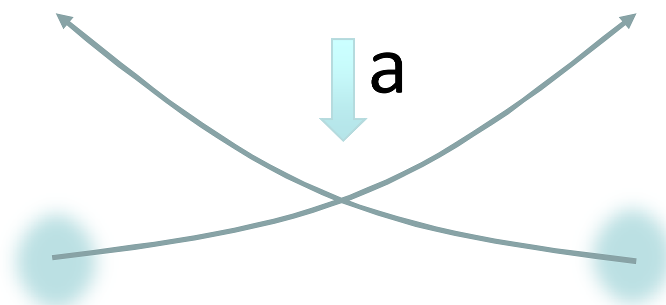


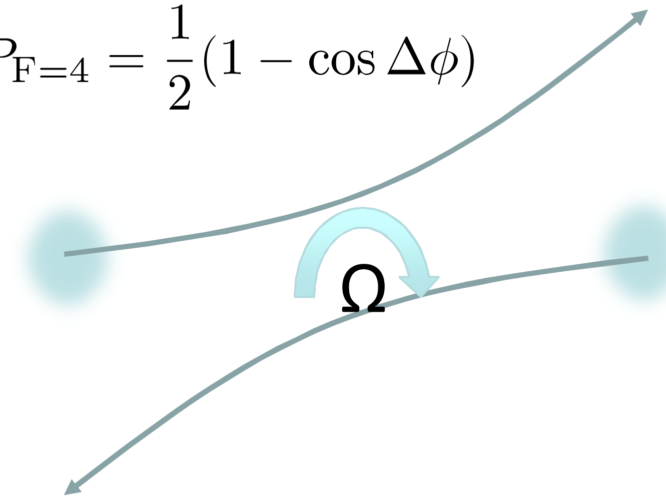




Interferometer phase shift: $\Delta\phi = \vec{k}_{eff} \cdot \left(\vec{a}T^2 - 2(\vec{v} \times \vec{\Omega})T^2\right)$

$$P_{\mathrm{F}=4} = \frac{1}{2}(1 - \cos\Delta\phi)$$

2-particles




Sensitivity increases with $T^2$

# 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 %

<u>Benefits</u>

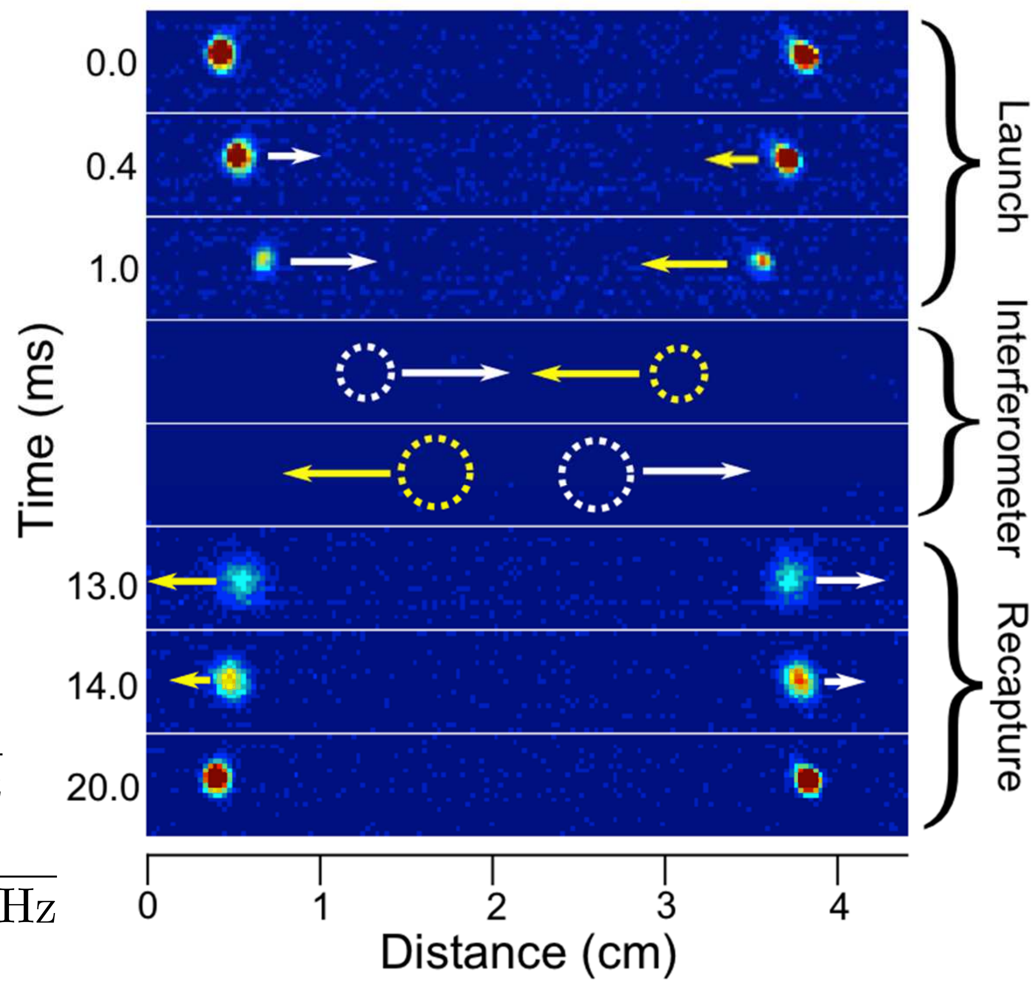
- Increases signal by 10x
- Data rates > 50 Hz
- Minimizes cycle dead time
- Reduced complexity
- Sufficient for:

$33\ \mathrm{ng}/\sqrt{\mathrm{Hz}}\ \&\ 70\ \mathrm{nrad/s}/\sqrt{\mathrm{Hz}}$

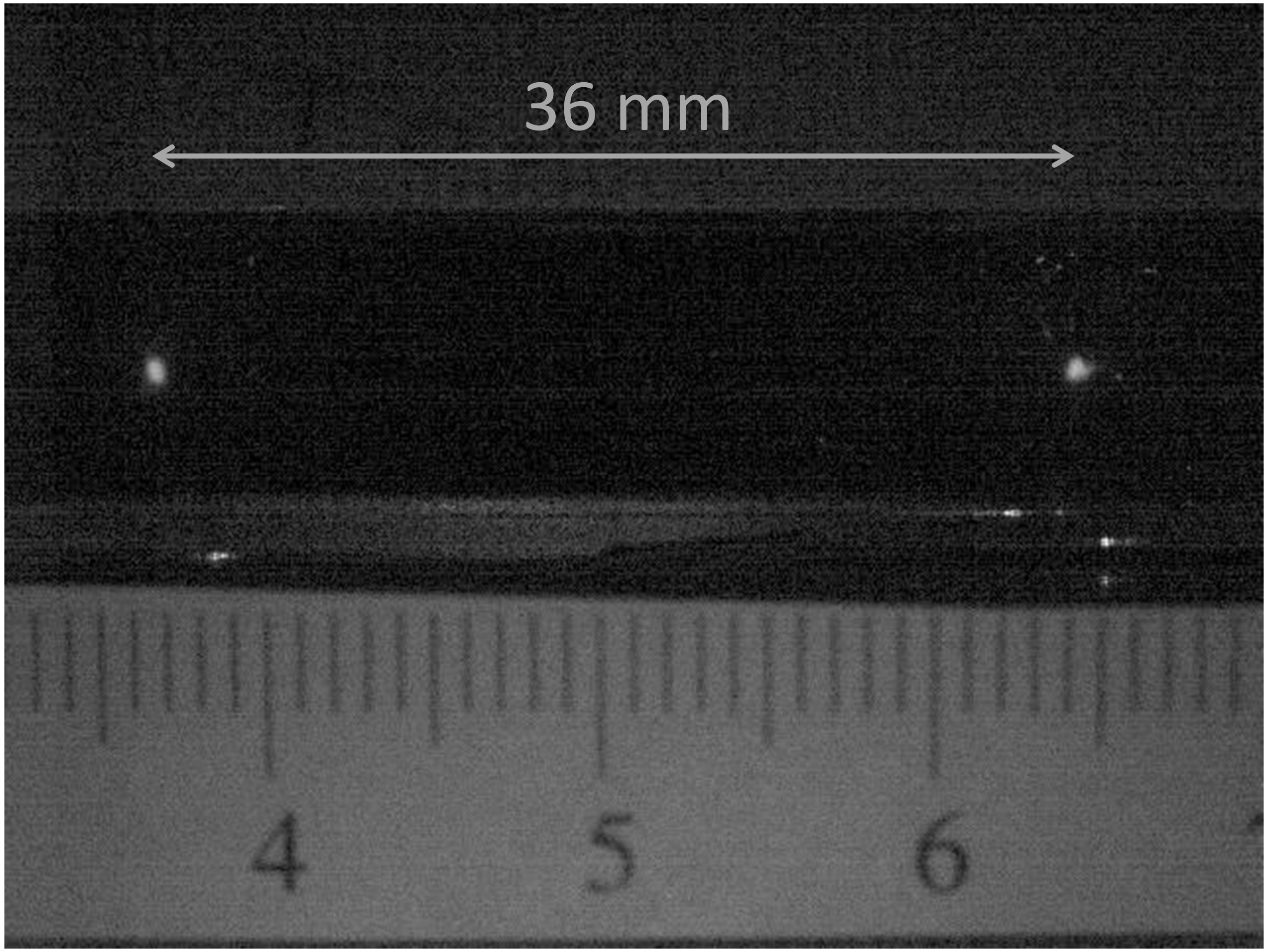
- Demonstrated:

$900\ \mathrm{ng}/\sqrt{\mathrm{Hz}}\ \&\ 1100\ \mathrm{nrad/s}/\sqrt{\mathrm{Hz}}$

CCD images of ensemble exchange



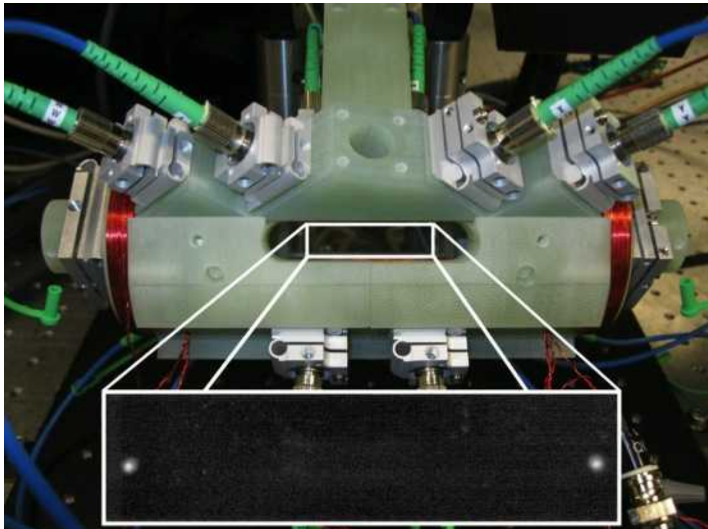
# Launch and recapture



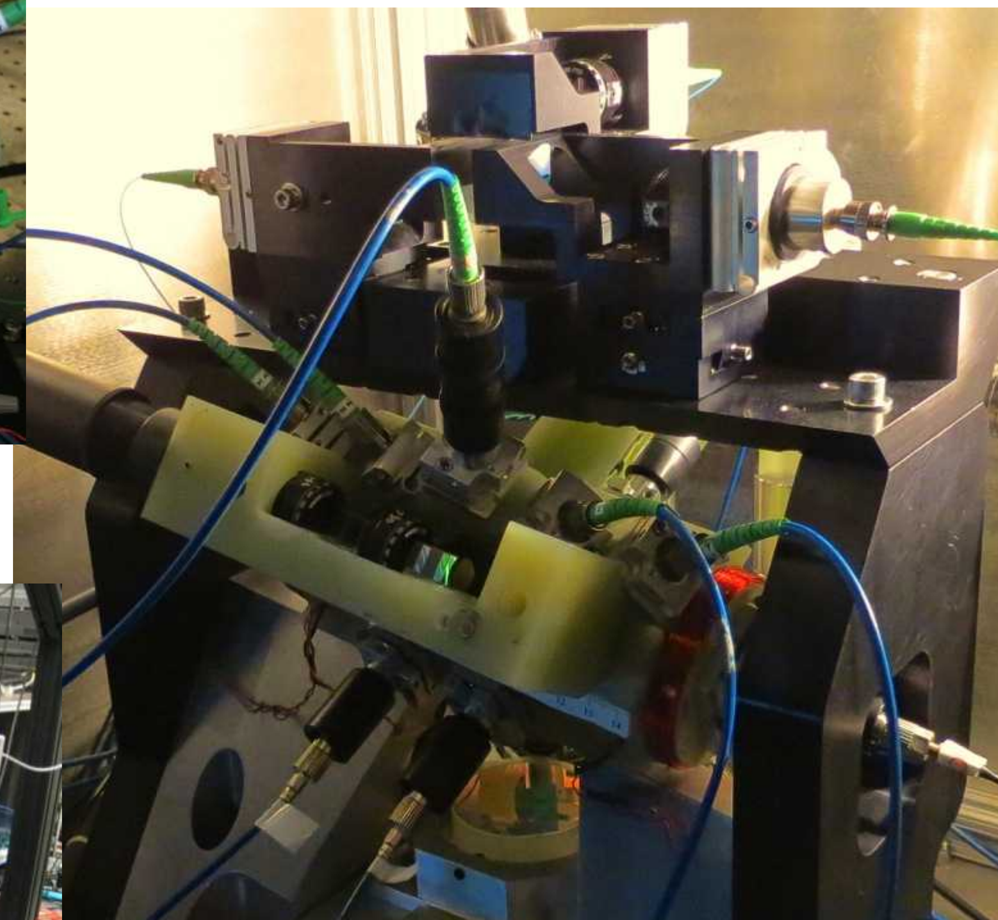

- Repeats at ≈ 60 measurements per second

# Experiment platform

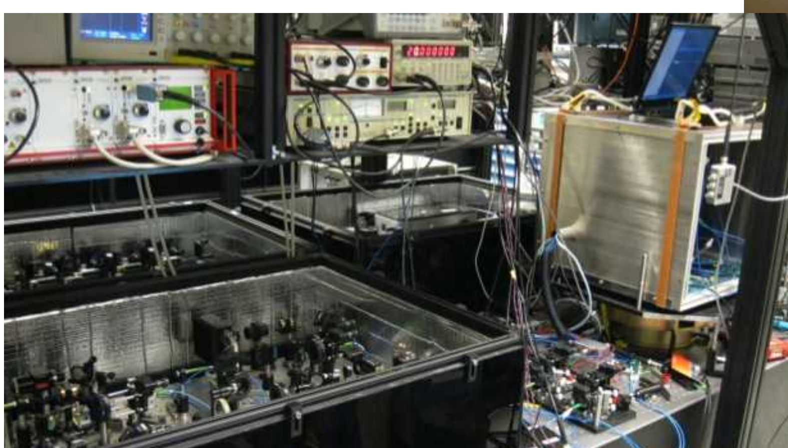
Sandia National Laboratories



Picture of interferometer sensor

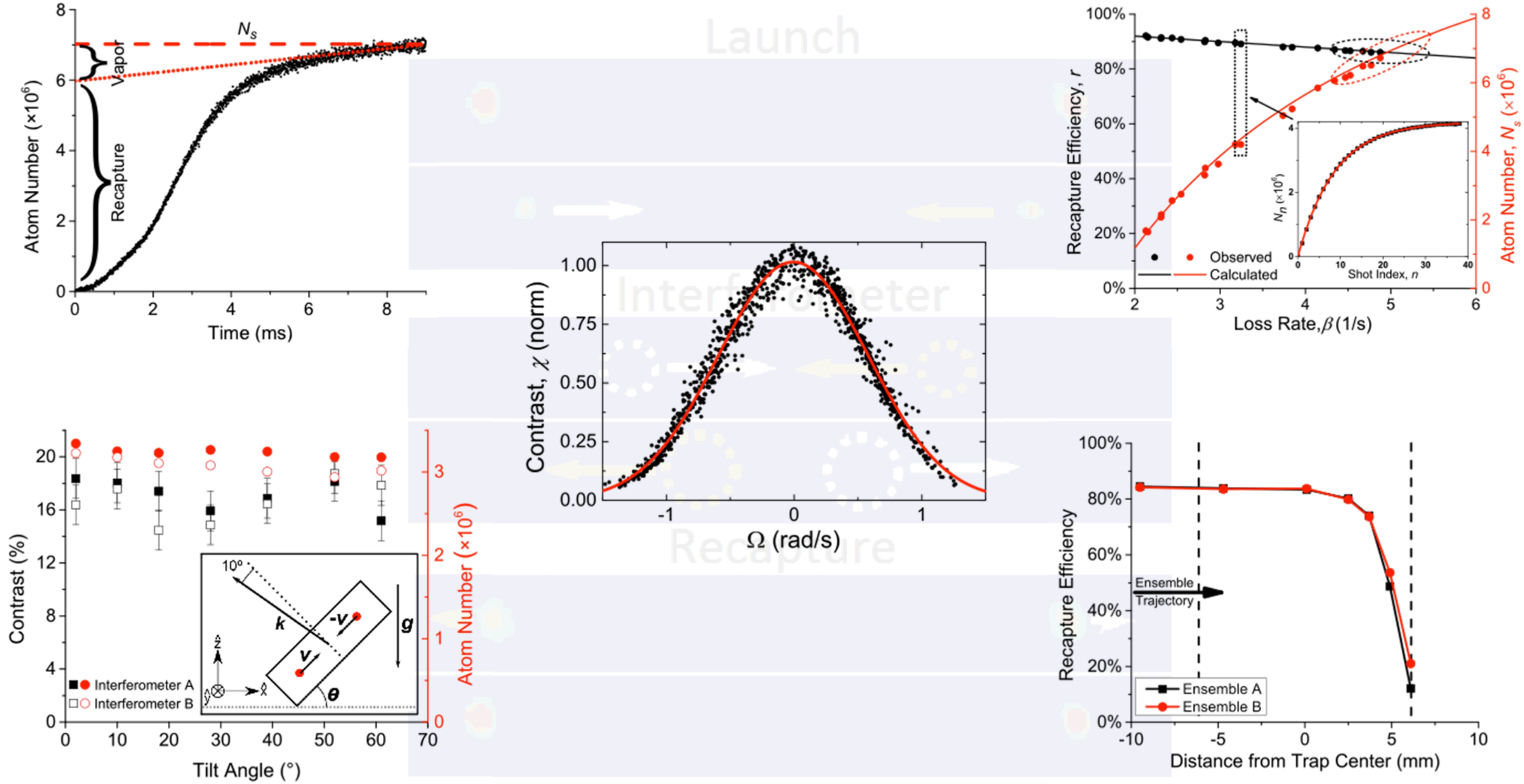


Picture of system hardware



# Characterizing ensemble exchange

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



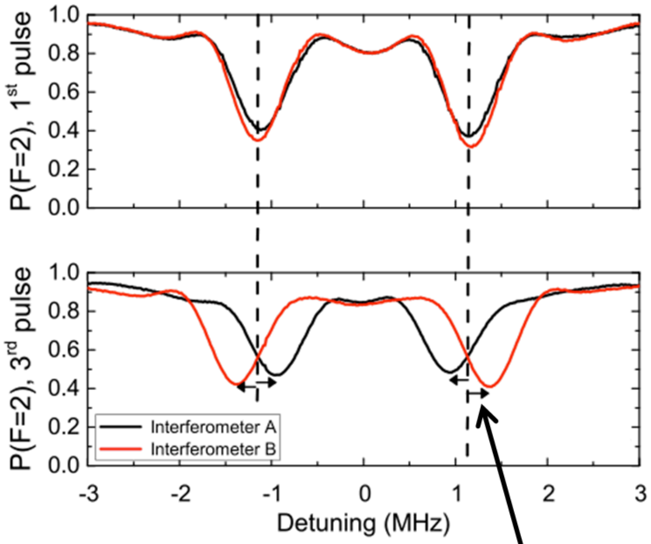
# Controlling jerks

Controlling frequency and phase in a dynamic environment

Raman laser frequency scan

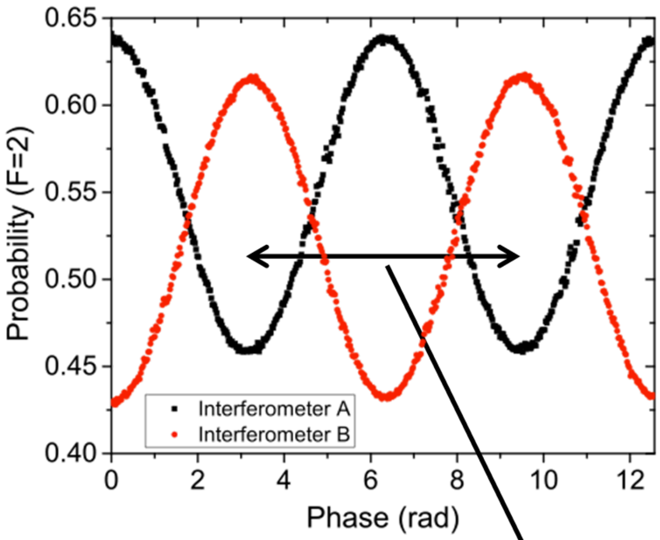
t = 0 ms

t = 10 ms




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

Raman laser phase scan

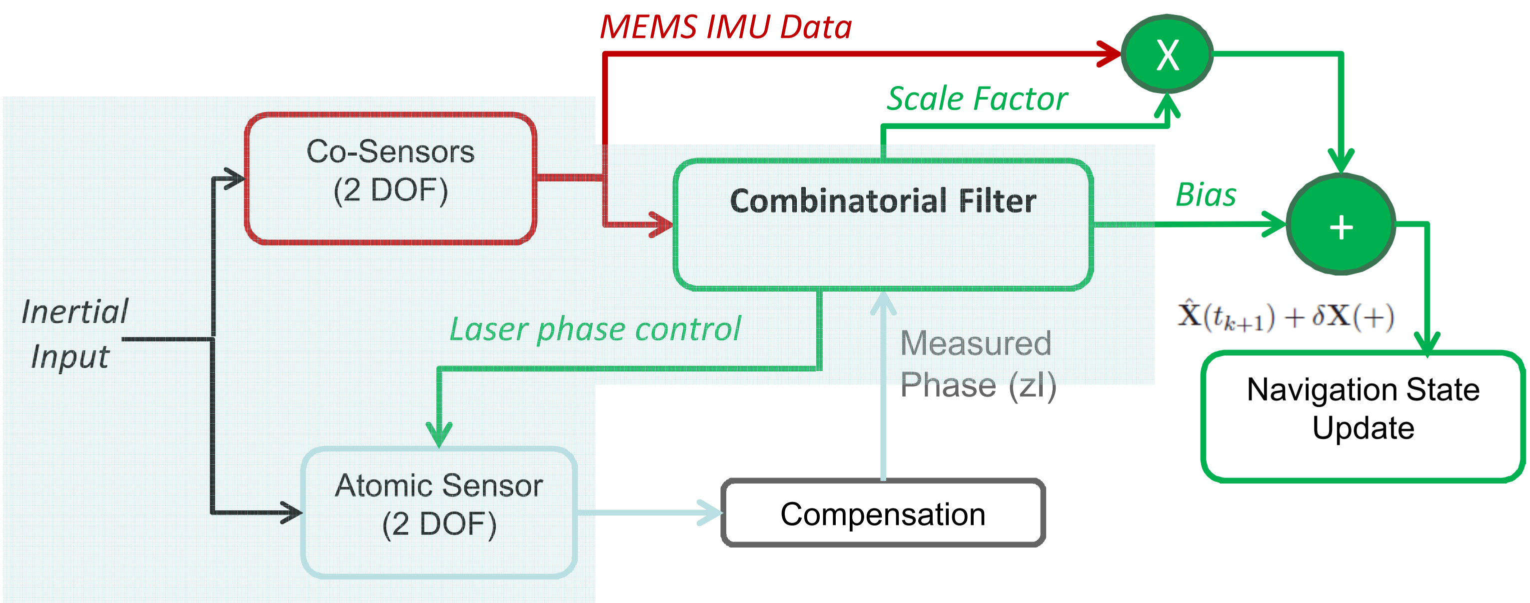


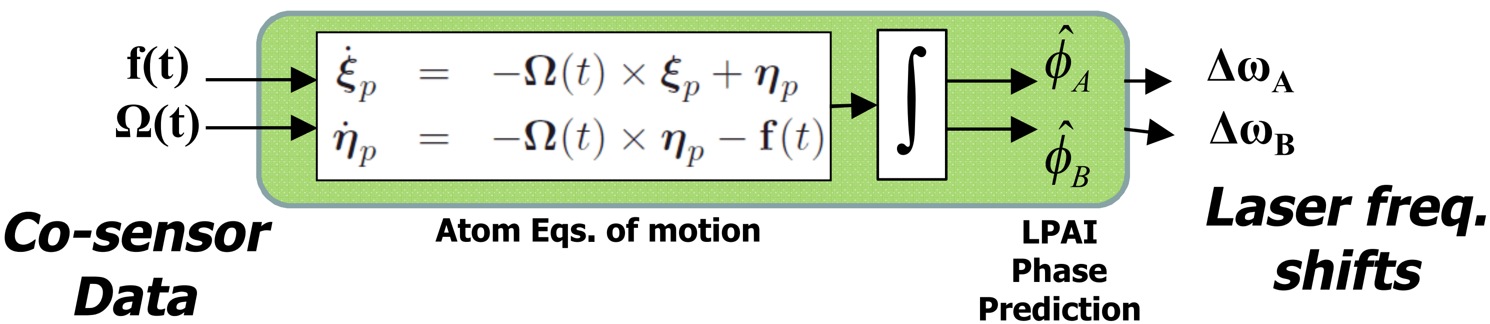

≈ m*g* OR ≈ mrad/s (400 deg/hr)

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

# Technical challenge

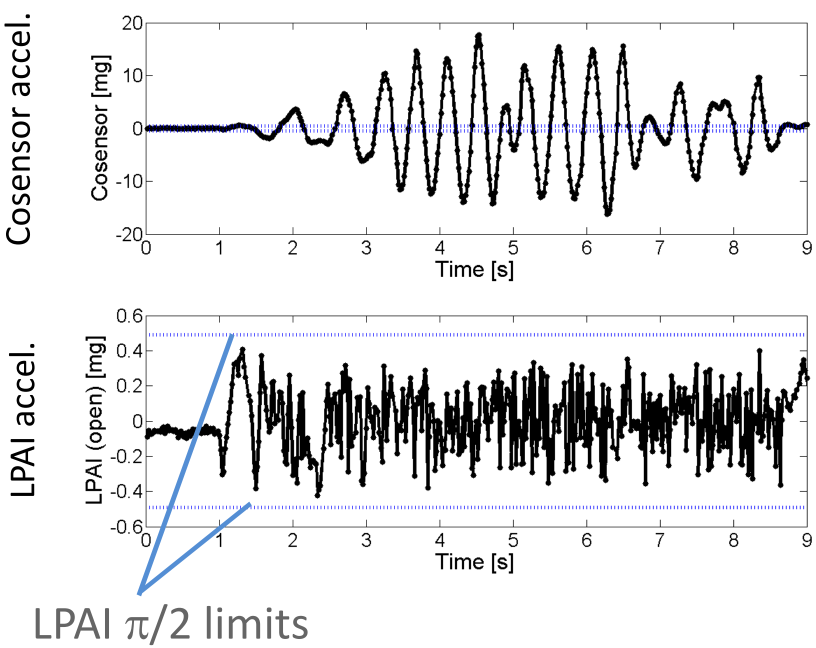
- Real-time cosensor read, Runge-Kutta propagator calculation, and phase/frequency write to interferometer laser in less than 0.5 ms (note: T = 4.5 ms)



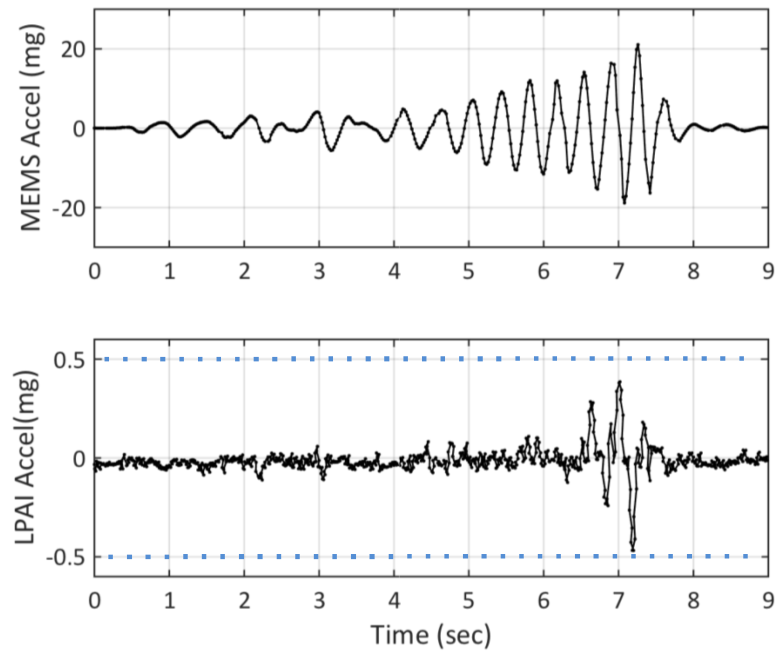



# Phase feed-forward results

OPEN LOOP




FEED FORWARD

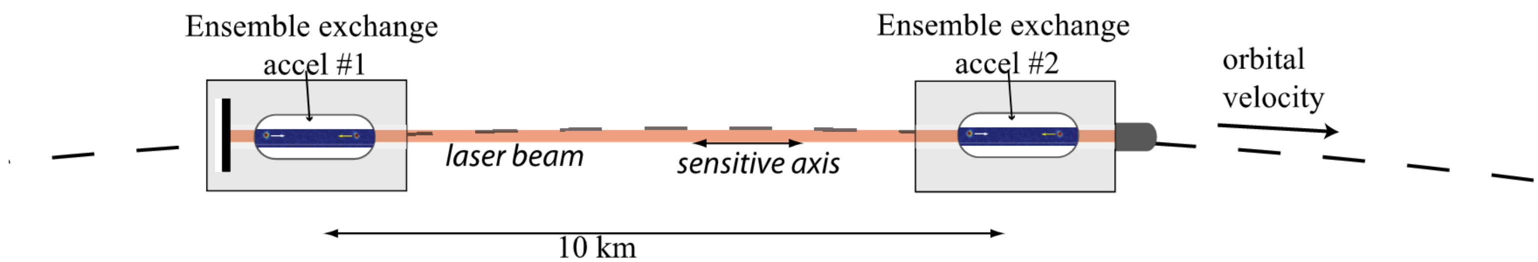



Initial results:

- Accelerometer only
- Feed forward successfully locks LPAI phase to within π radians
- Extends dynamic range to ≈ +/- 10 mg

# Gradiometer survey—path finder

Simultaneous opposed gradiometers—bias rejection

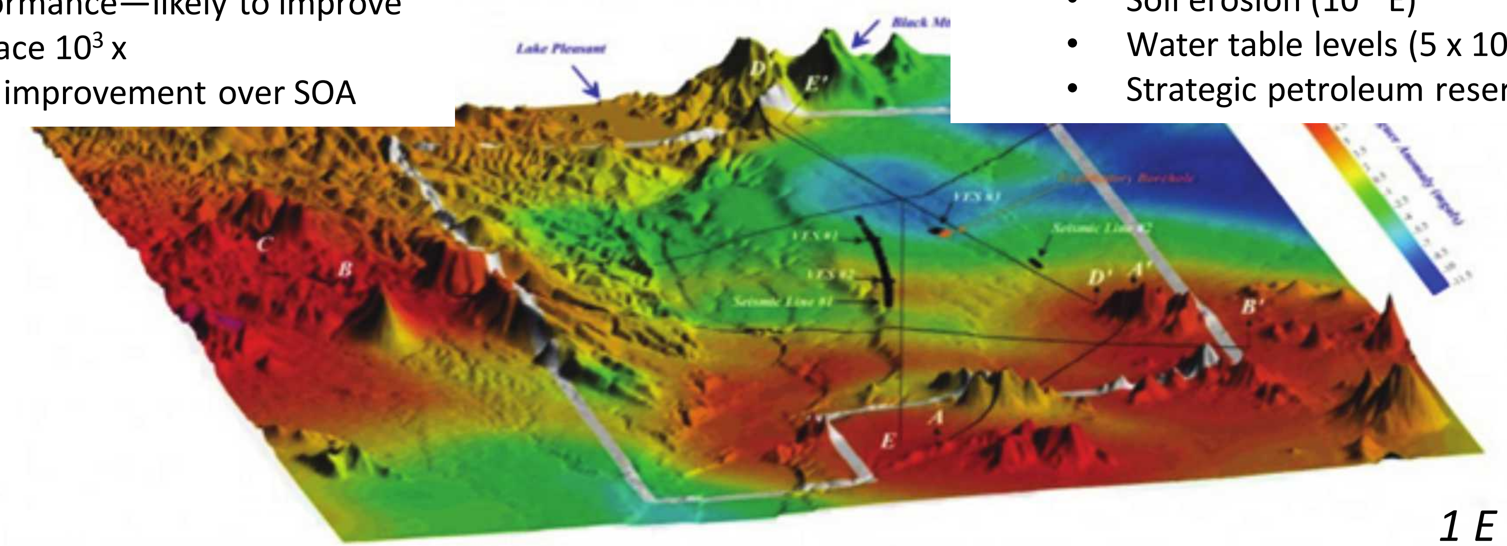



GOALS

- $10^4$ s stability—multiple orbital passes (SOA < 1 s)
- $10^{-3}$ E per shot with ground based performance—likely to improve in space $10^3$ x
- $10^4$ x improvement over SOA

UTILITY

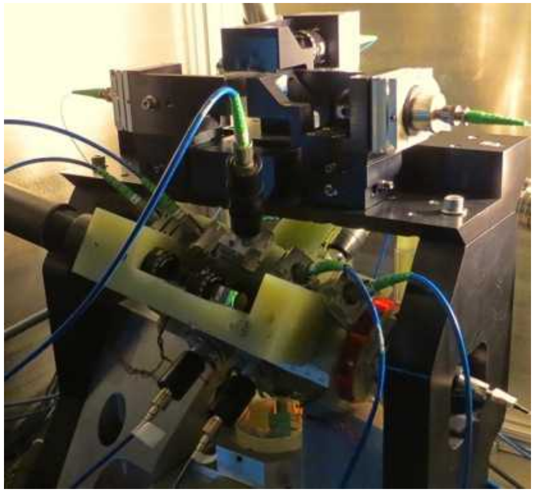
- Improved gravity maps in contested areas for GPS-denied navigation
- Other targets
    - Soil erosion ($10^{-3}$ E)
    - Water table levels ($5 \times 10^{-3}$ E)
    - Strategic petroleum reserves ($10^{-6}$E)

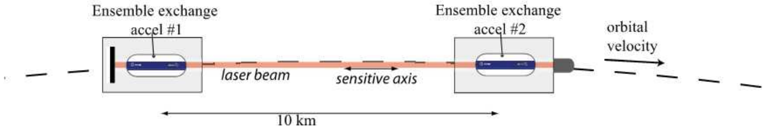


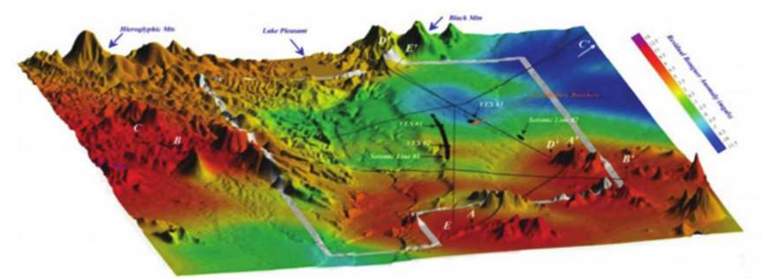
*$1\ E = 10^{-9}\ /s^2$*

# Challenges and Opportunities

- Exquisite precision demonstrated
- Challenging system hardware
- Foreign investments
  - Inertial measurement units
  - Space programs
- Natural technology for a calibrating reference
- Natural technology for large measurements systems
- Natural technology for entanglement-enhanced precision

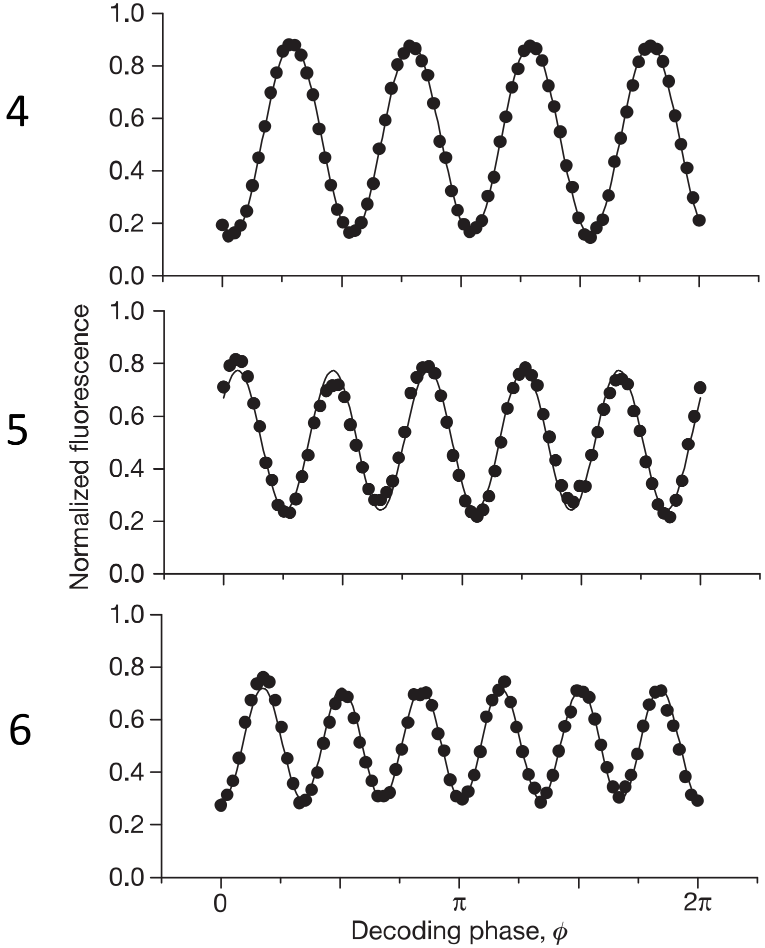


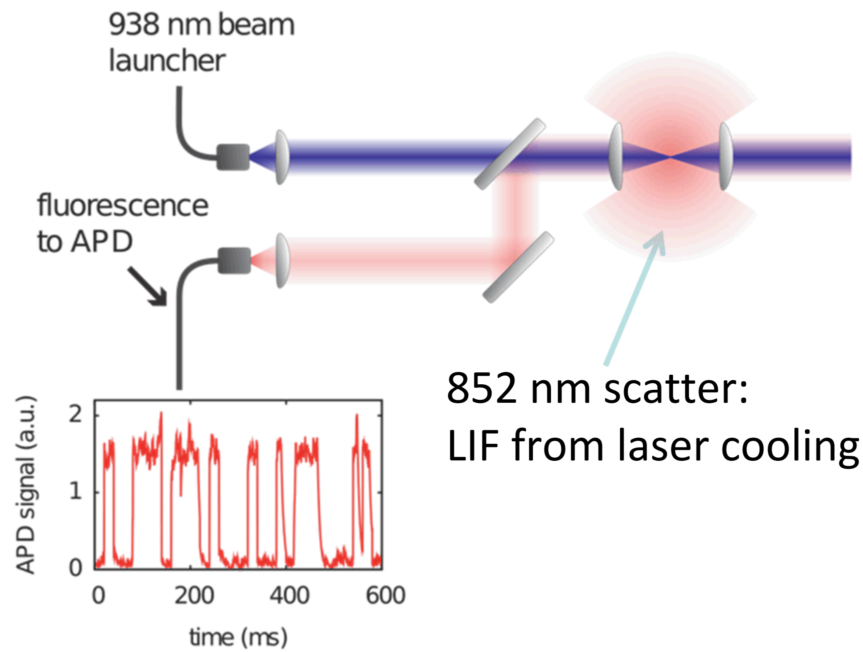


# Entangled states for metrology

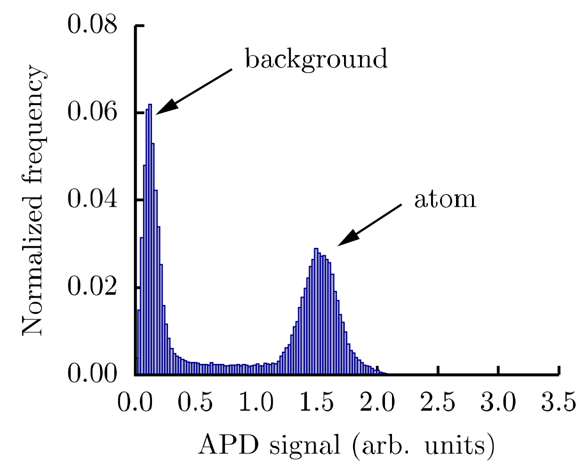
Cat states with ions [1]



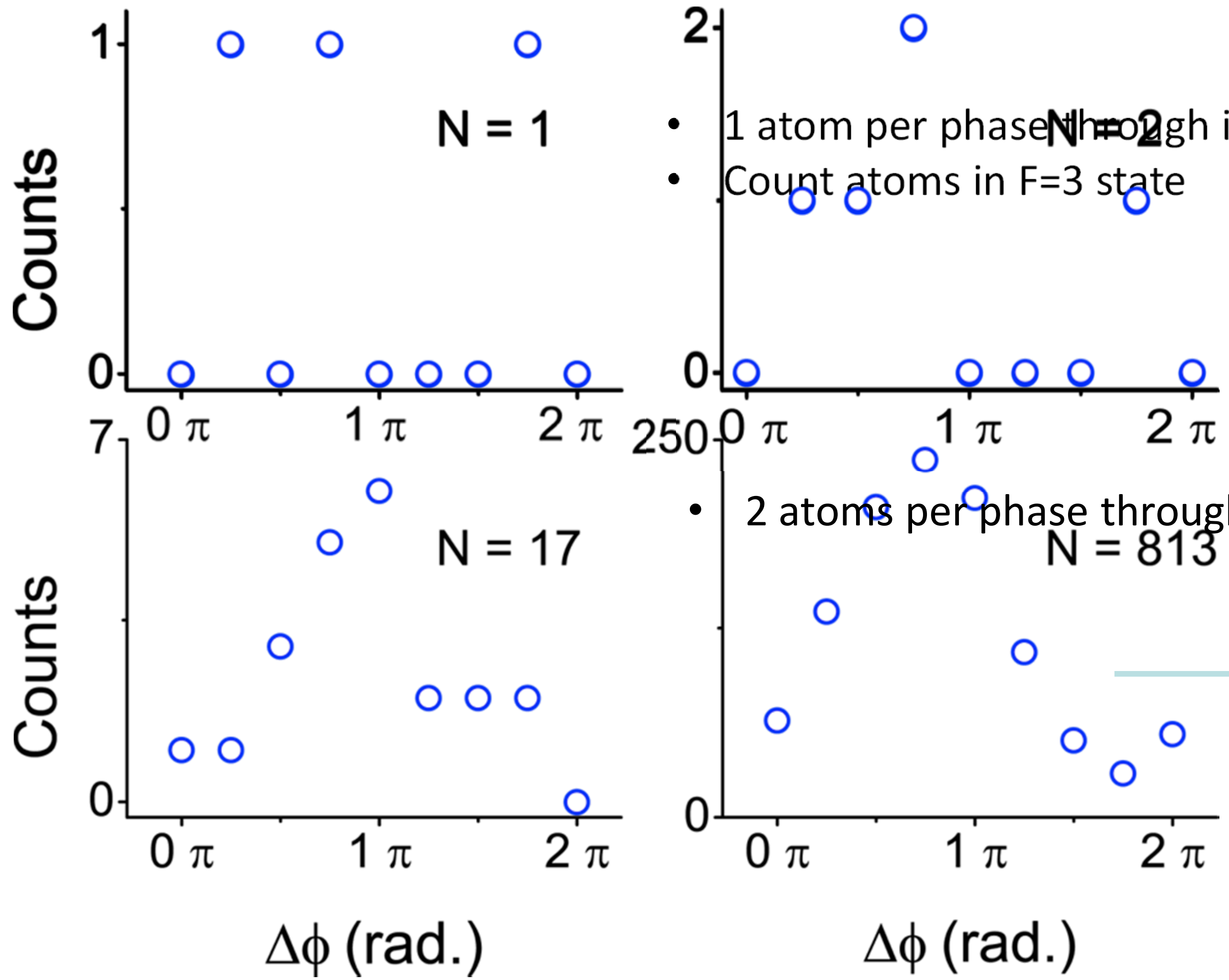

852 nm scatter:
LIF from laser cooling light

*Micron-scale: inherently low power*




[1] Leibfried, et al., "Creation of a six-atom 'Schrödinger cat' state", *Nature* **438**, 639 (2005)

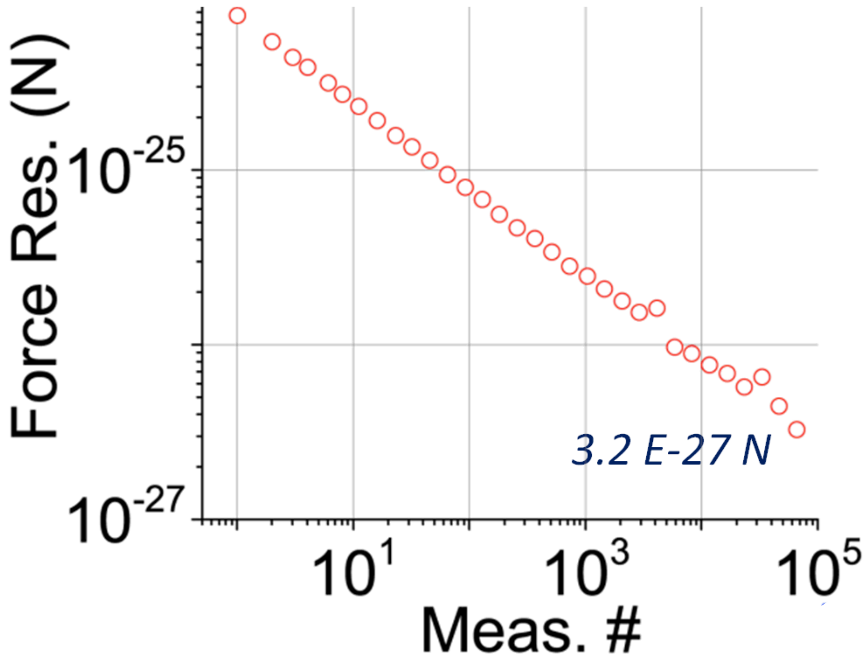
# Building a fringe, one atom at a time



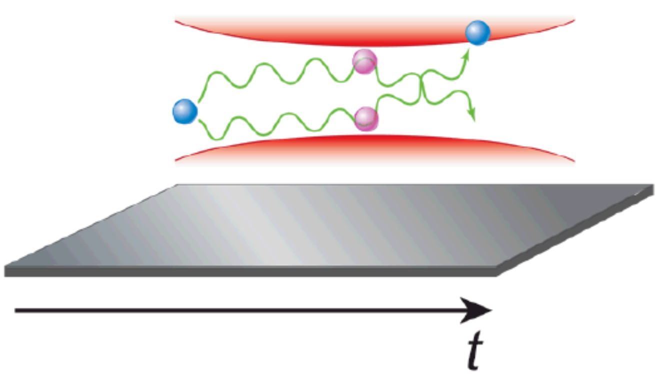

- 1 atom per phase through interferometer.
- Count atoms in F=3 state
- 2 atoms per phase through interferometer.

→ 7,317 atoms

# Single atom interferometry




Atom interferometer with single atoms

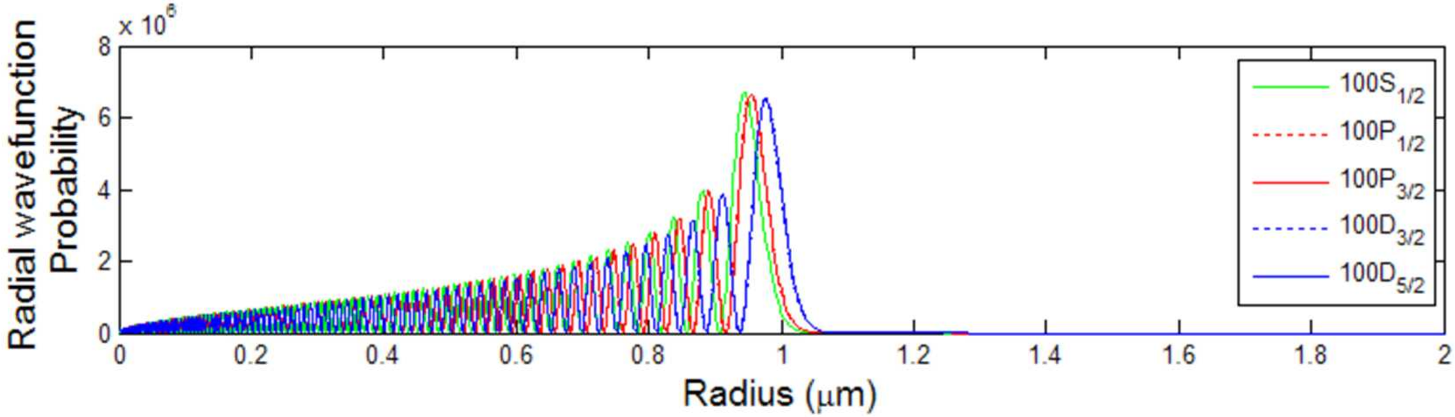



E. Rasel, Physics **5**, 135 (2012)

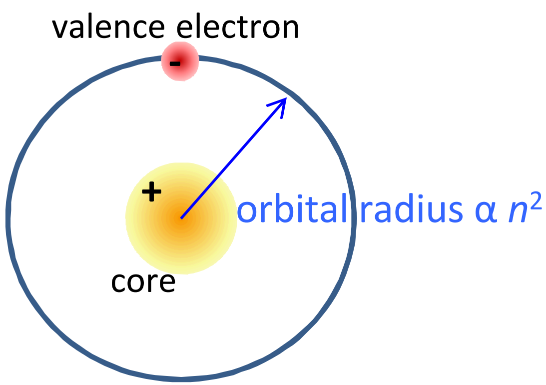
- We showed one can use single atoms
- Single atom control: gateway to harnessing quantum control in sensing
- $10^{-27}$ N ≈ m*g* for a cesium atom

# Rydberg state mediated interaction

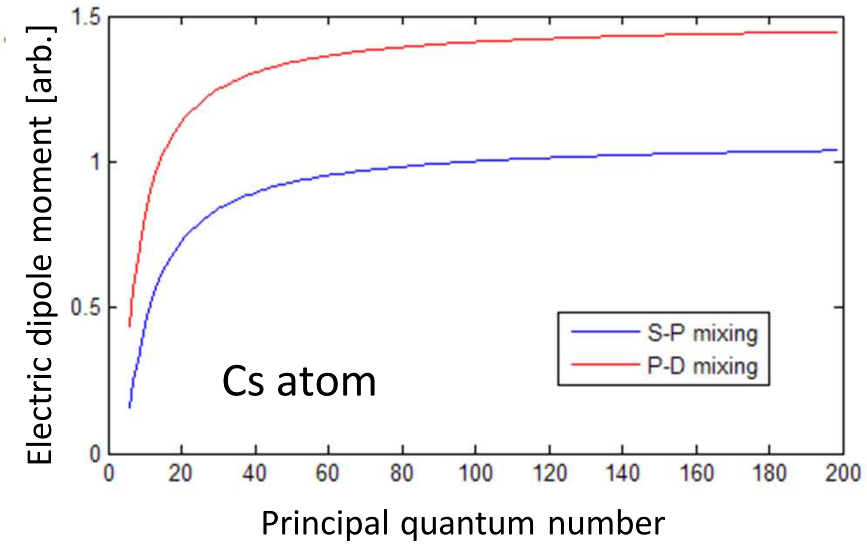
An example of the radial wavefunctions of a Cs atom at $n$ = 100:




A Rydberg atom can have a strong electric dipole moment.



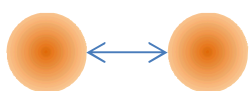

A classical picture of an atom



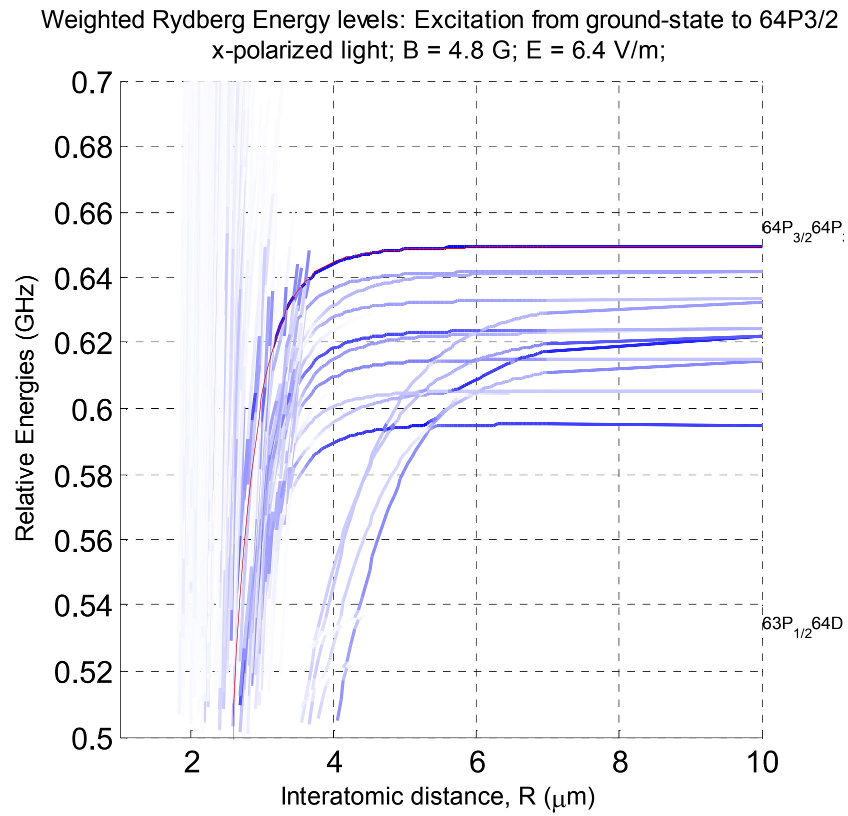
# Blockade & electric dipole-dipole interaction

$$H_{\text{atoms}} = \sum_i H_0^{(i)} + \frac{1}{4\pi\varepsilon_0 r^3} \sum_{i \neq j} \left( \mathbf{D}^{(i)} \cdot \mathbf{D}^{(j)} - 3\mathbf{D}^{(i)} \cdot \hat{\mathbf{r}}\hat{\mathbf{r}} \cdot \mathbf{D}^{(j)} \right)$$

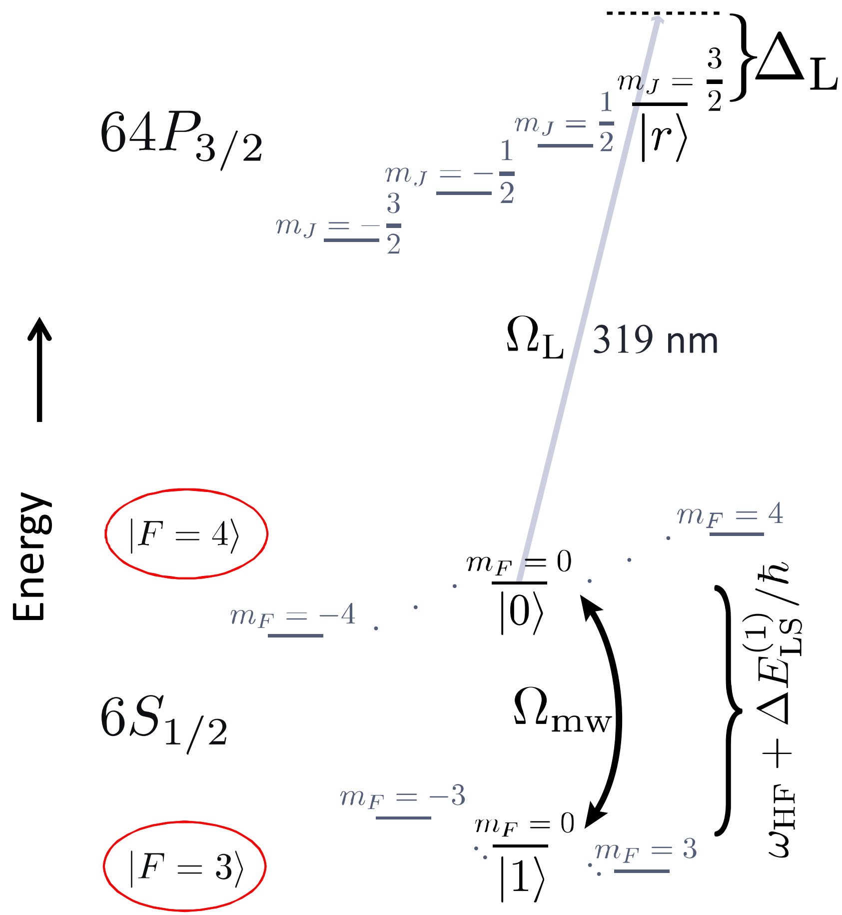
very far



close enough ( < 10 μm)



# Rydberg-dressed ground state interaction

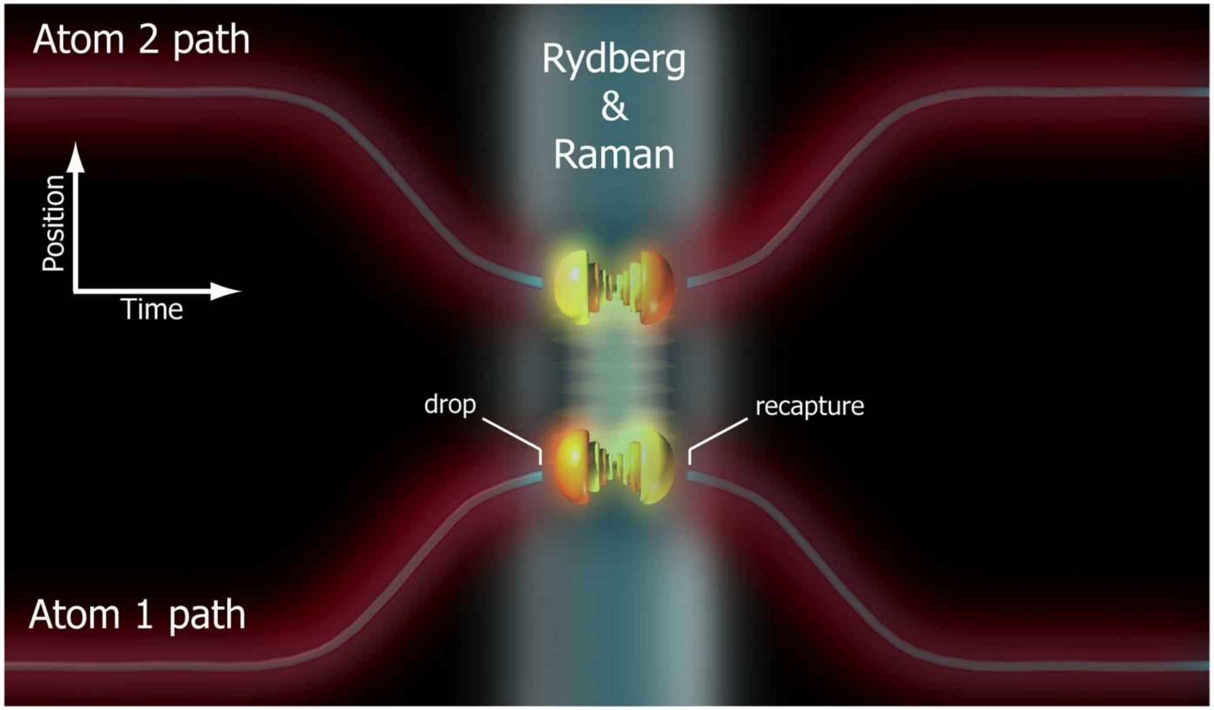



Single atom picture

- Interaction range increases as principal quantum number *n* increases
- However, oscillator strength decreases as *n* increases—making $\Omega_L$ smaller and thus *J*
- Target smallest *n* that your optical resolution can accommodate
- Solution—*dynamic postioning*

# Dynamic atom positioning

6.6 μm



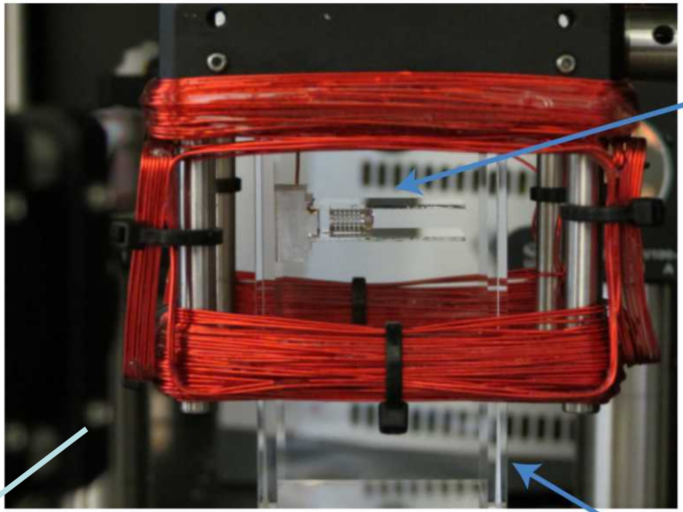

State preparation

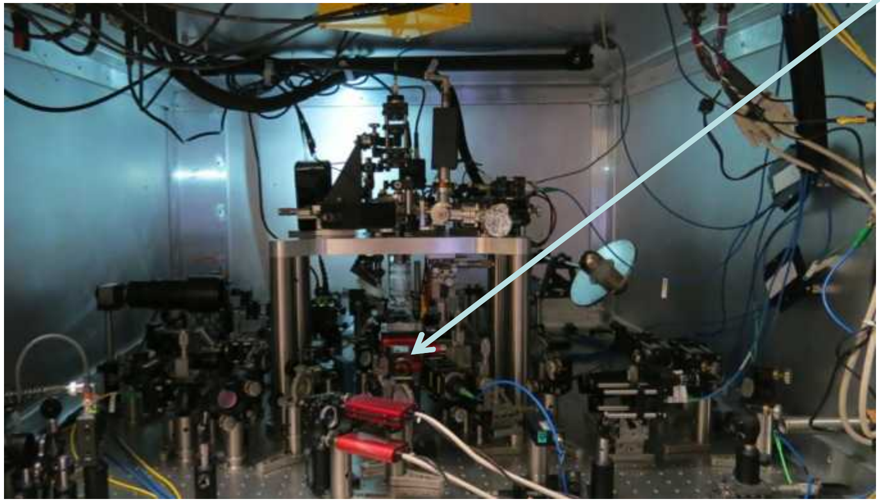
Rydberg dressing

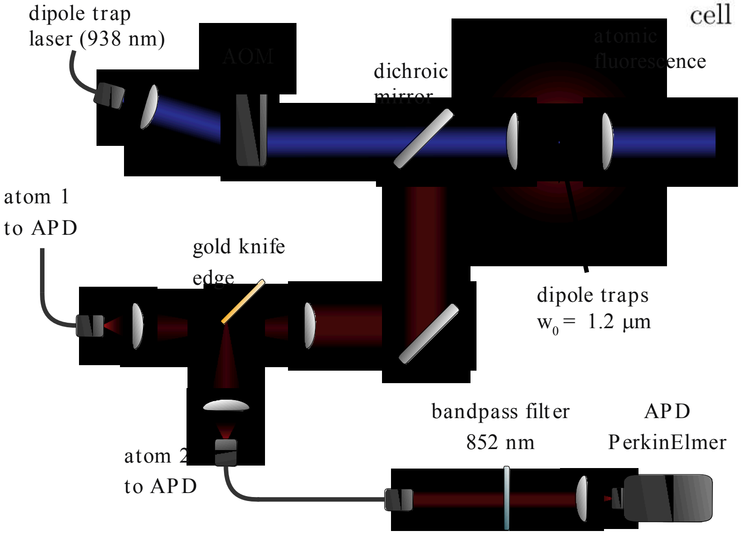
State detection

# Apparatus

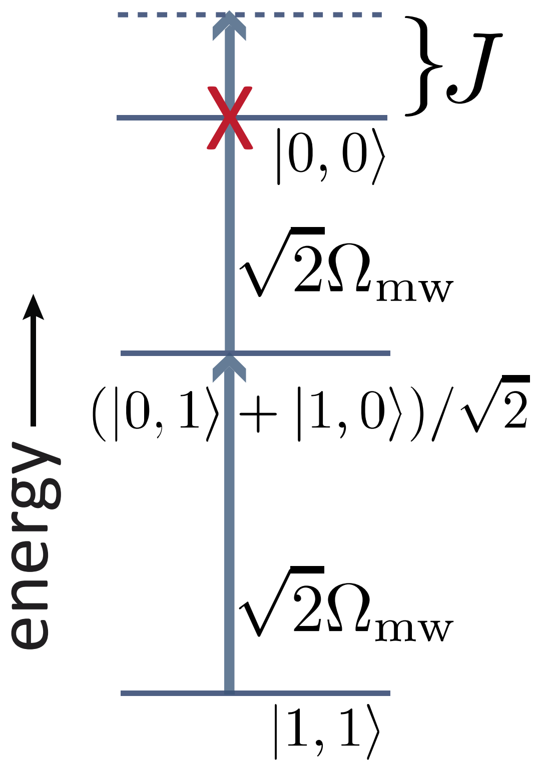


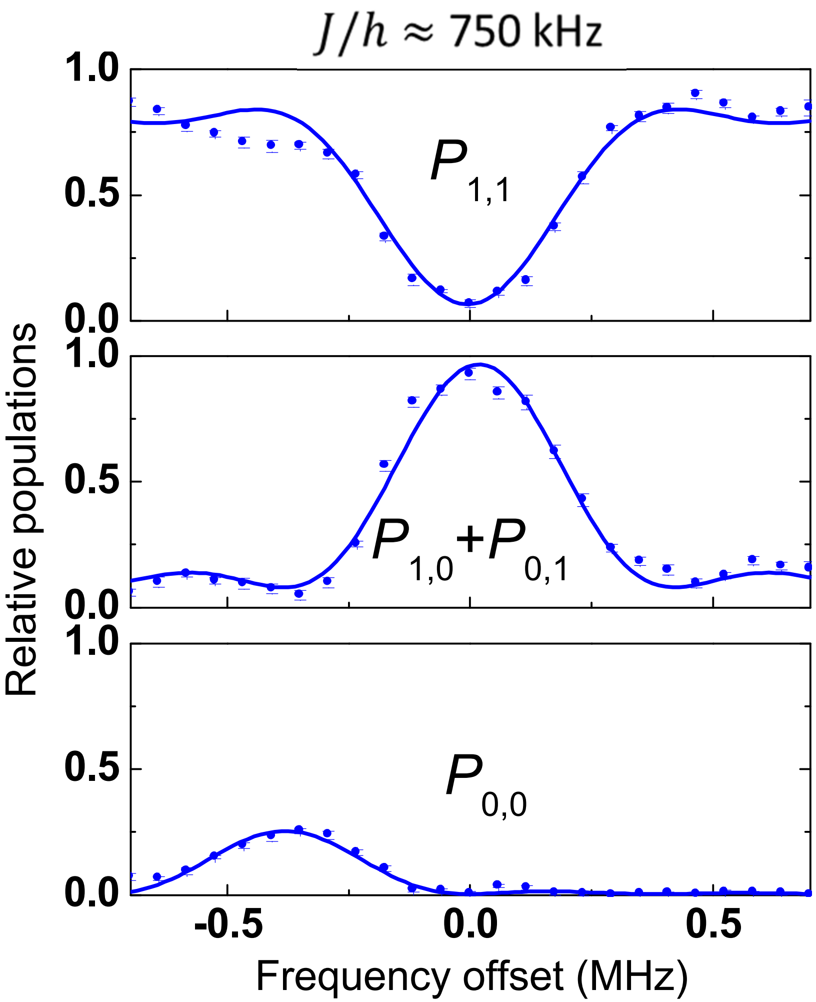

dipole-trap lens assembly
vacuum cell




dipole trap laser (938 nm)
dichroic
atom 1 to APD
gold knife
dipole traps $w_0 = 1.2$ µm
bandpass filter 852 nm
APD PerkinElmer
atom
to APD

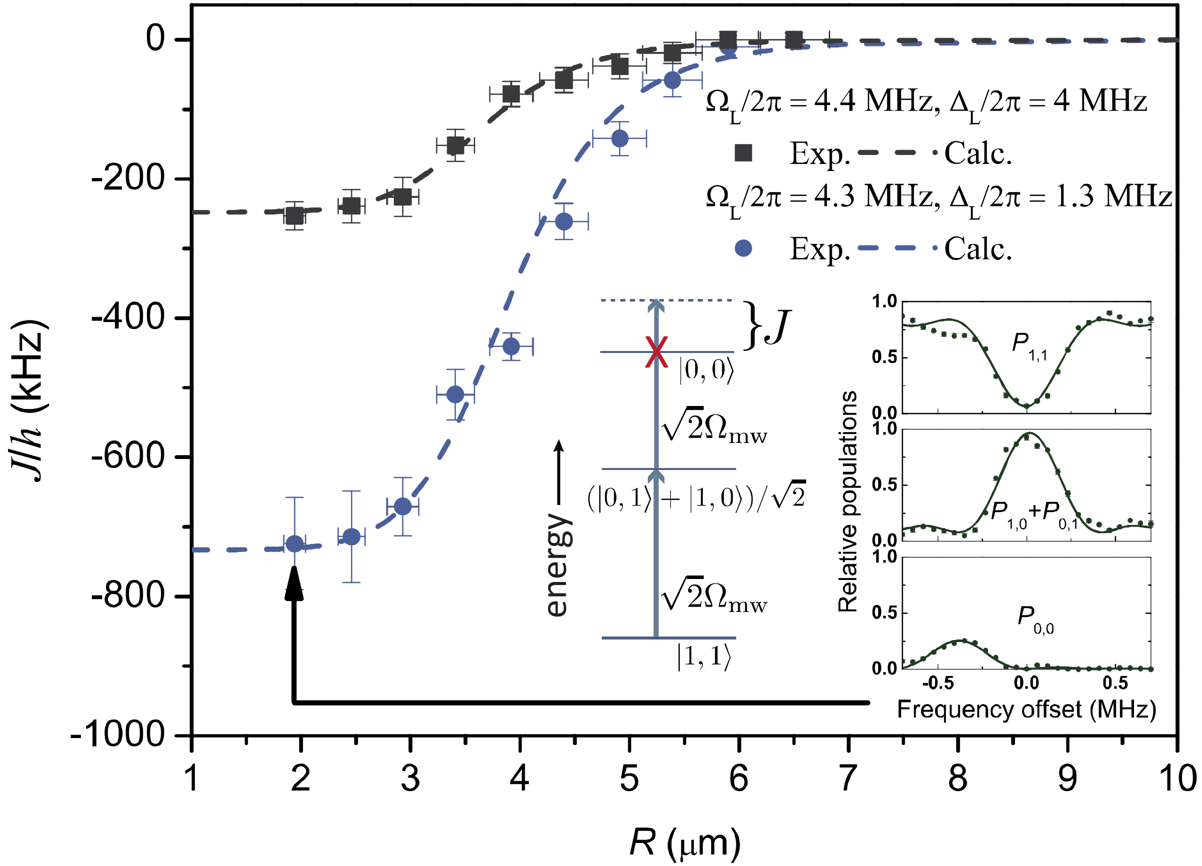
# Two-qubit microwave resonances



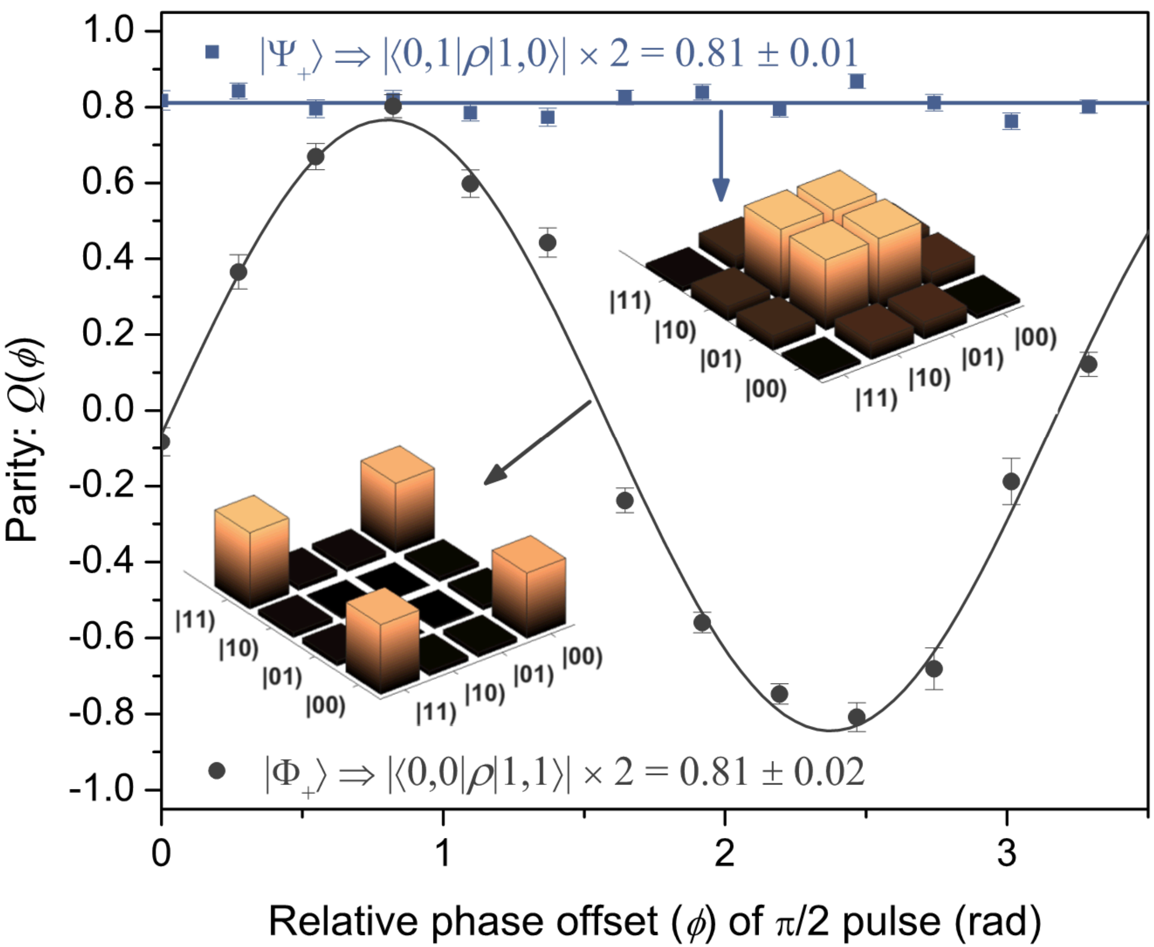
# $J$ vs. $R$, no longer elusive

Direct measurement of two-qubit interaction strength $J$ as a function of two-atom separation with two conditions.



# Entanglement Fidelity ≥ 81%

Verify the entanglement via parity measurements



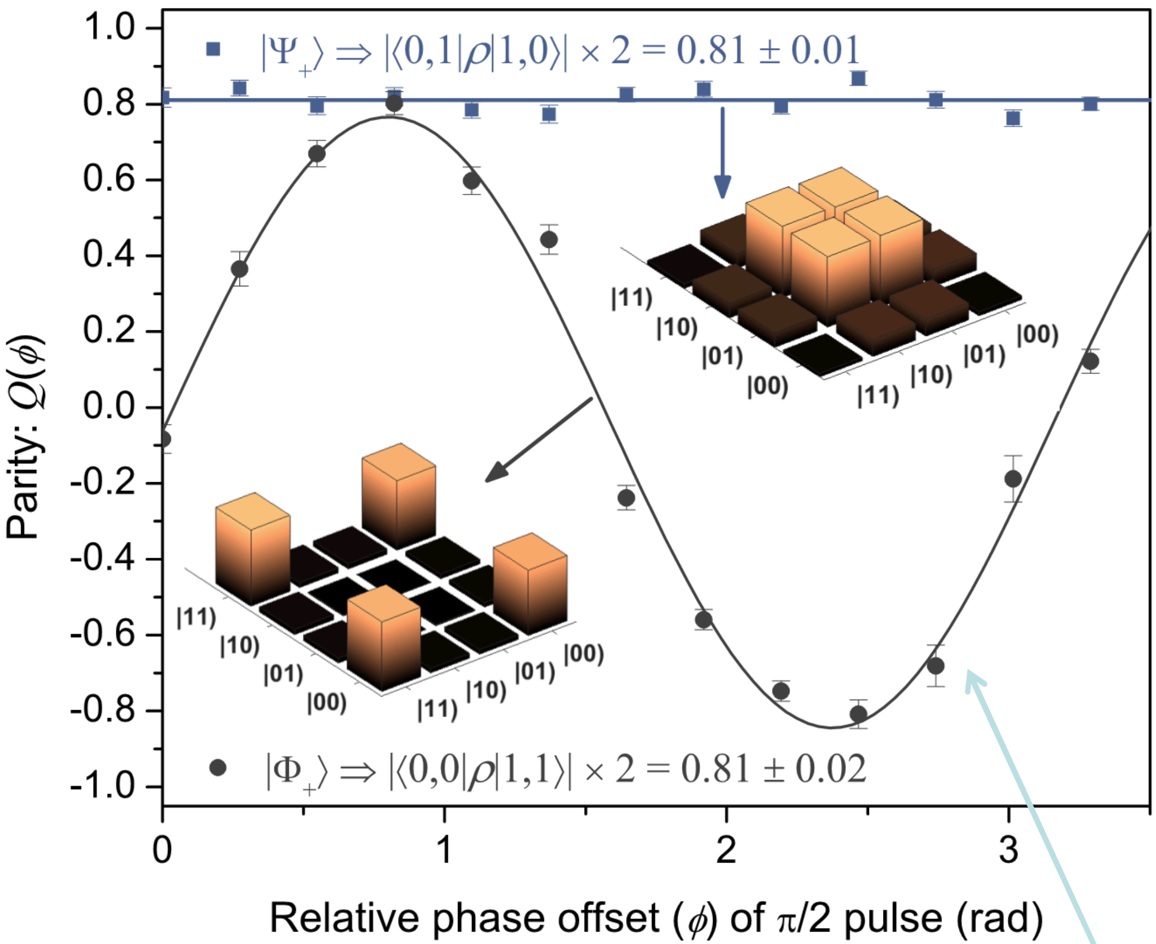

Prepare two Cs atoms in Bell state $|\Psi_+\rangle$ or $|\Phi_+\rangle$

Apply a global $\pi/2$ rotation with a given phase

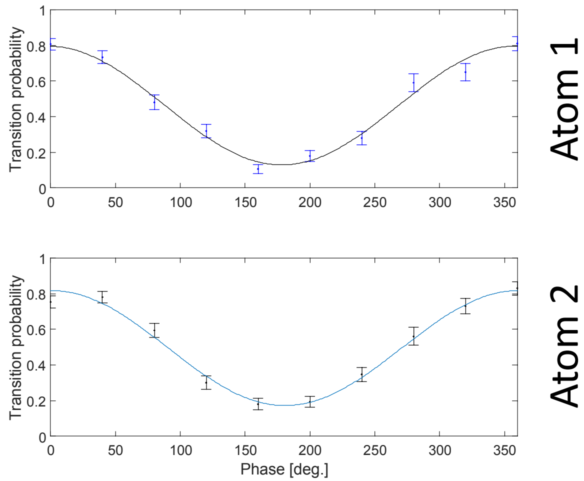
Perform parity measurement $Q = P_{11} + P_{00} - (P_{01} + P_{10})$

Obtain the two-qubit entanglement fidelity $F$, where $Q \leq F \leq 1$.

# Application to metrology



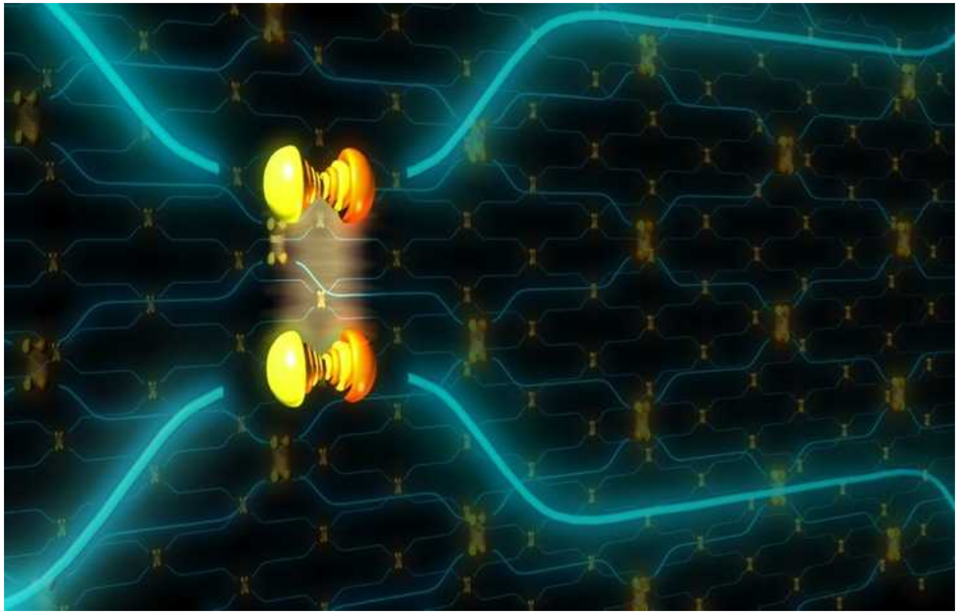

2-atom interferometer




Cat state 2x response to phase

# Challenges and Opportunities

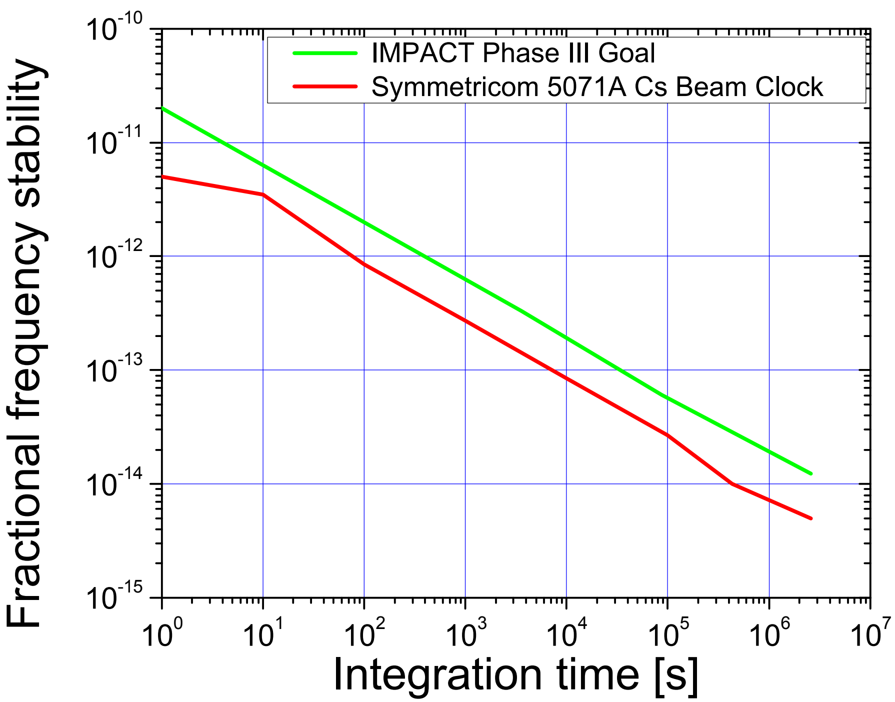
- System hardware naturally low power and compact
- Rydberg transition wavelength laser diode challenging
- Potential applications
  - Quantum computation/simulation
  - Quantum-enhanced metrology
- Low TRL



# IMPACT Project Goals

Sandia National Laboratories

- Achieve Cs Beam Clock performance in a mass and power constrained package
- 5 $cm^3$, 50 mW, $10^{-14}$ performance




Applications--Excellent timing for:

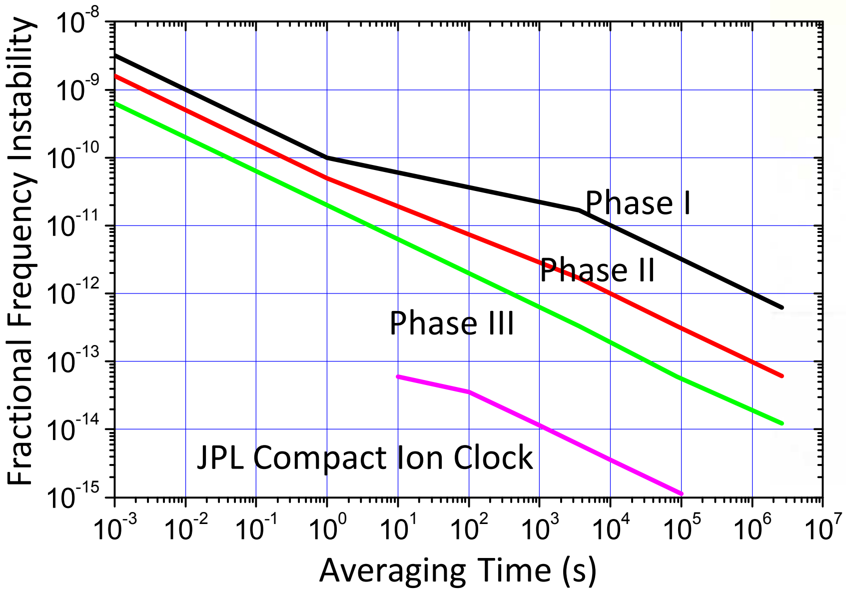
- Rapid GPS acquisition, and GPS denied navigation and timing
- Nano/pico (cube) satellites
- Pulsed radio and spread spectrum communications

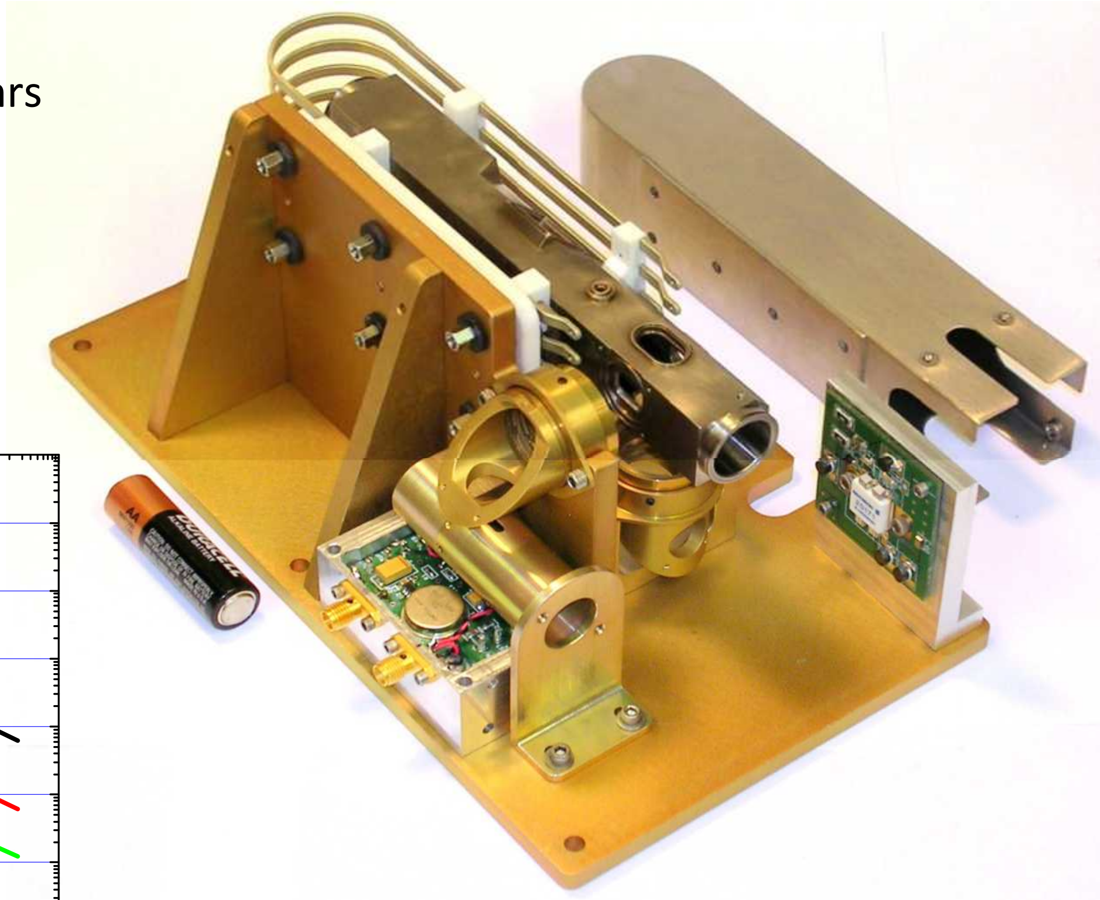
Symmetricom 5071A

Miniature primary frequency standard

# Trapped Ion Clock for Miniaturization

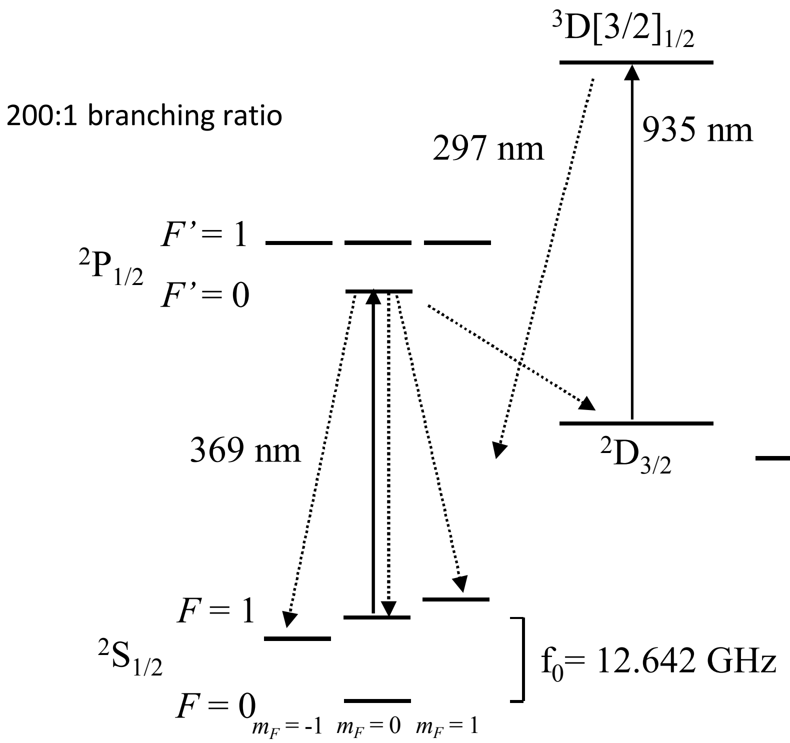
- Trapped ion clocks are already compact while delivering excellent performance.
- Low mass, size, power
- Trapped ion lifetime: up to 10,000 hrs
- Coherence time: > 100s
- Other approaches for IMPACT:
  - Miniature fountain clock
  - Locked optical frequency converted microwaves with WGM resonator

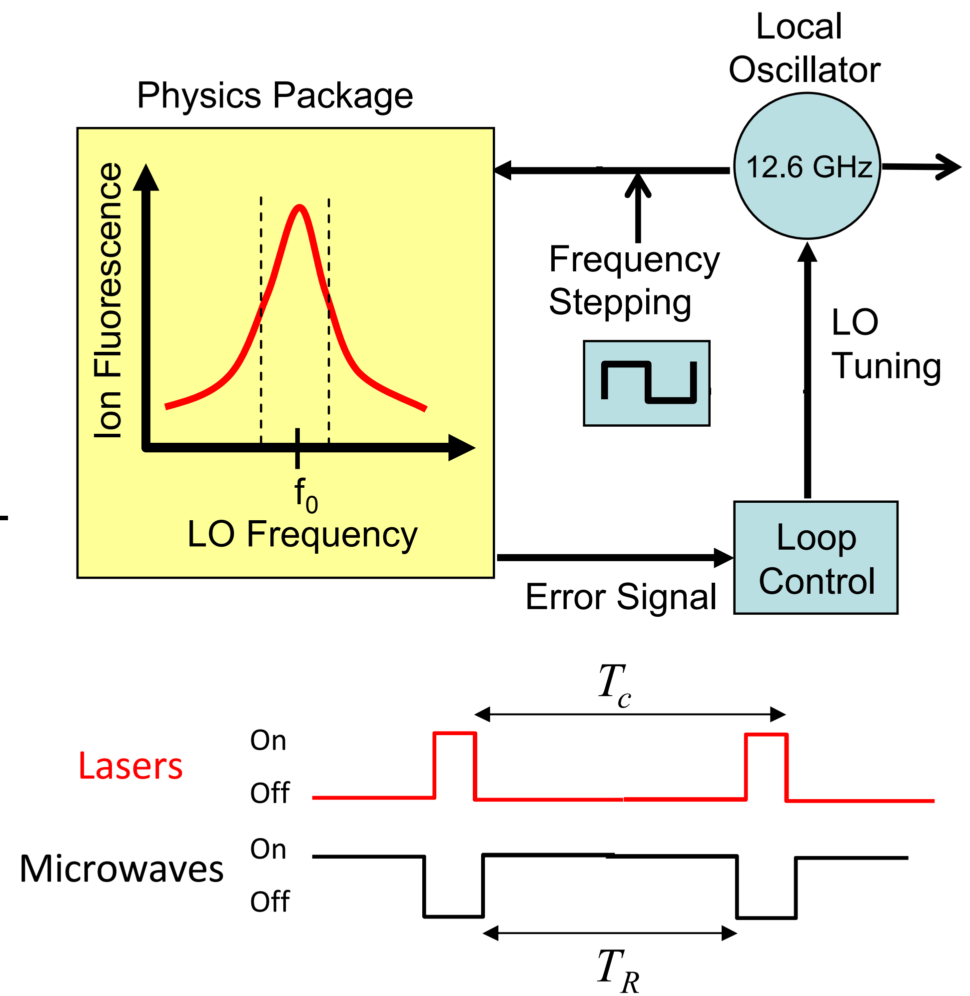


$^{199}Hg$ Trapped Ion Clock from JPL

# Atomic Frequency Reference with $^{171}Yb^{+}$

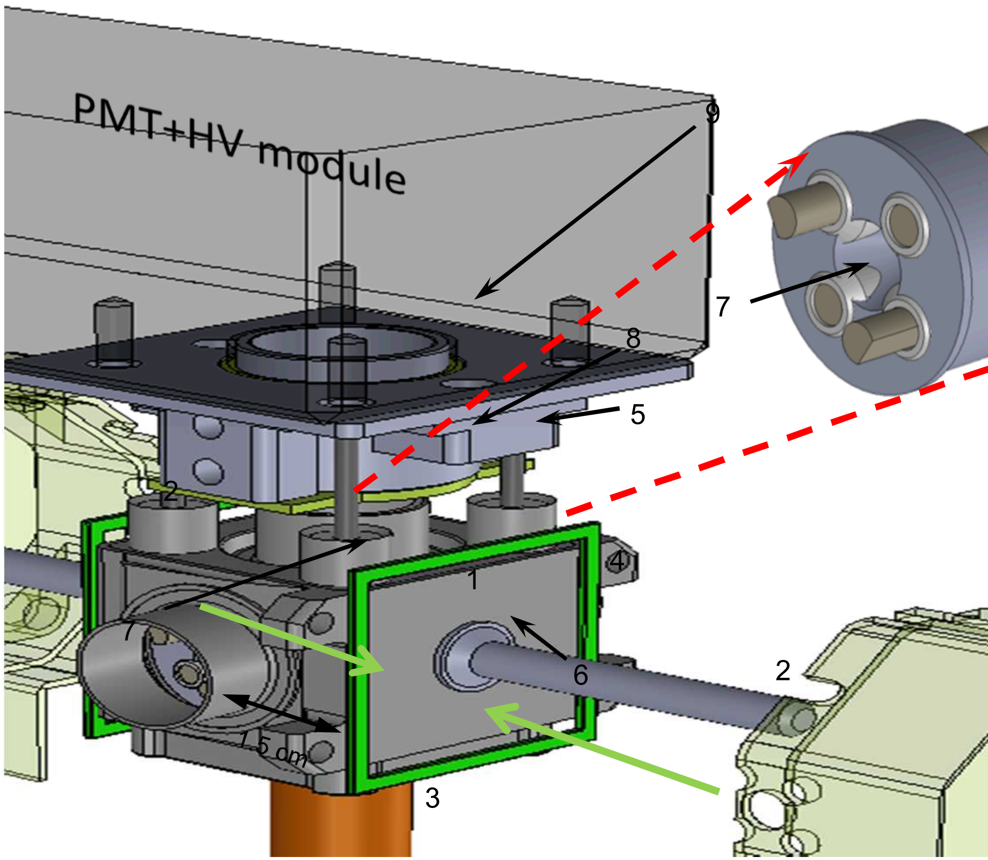


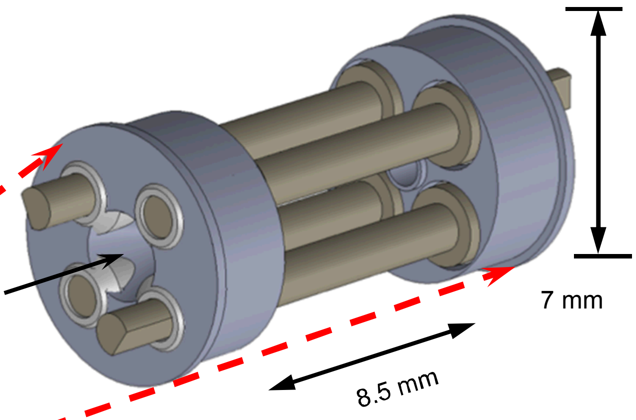
# 3 $cm^3$ Vacuum Package and Ion Trap

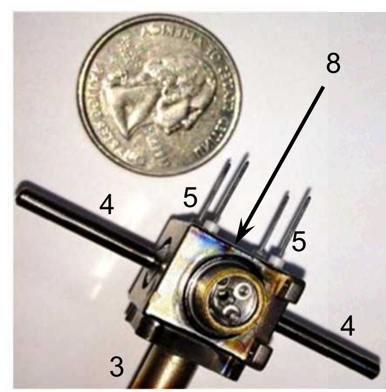
Sandia National Laboratories

### Vacuum package w/ Detector




### Ion-trap electrodes



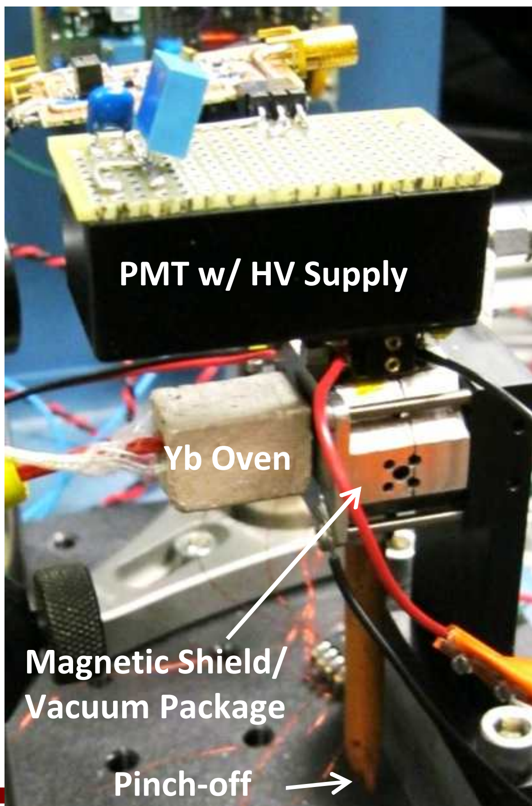

1. **Vacuum package**
2. **μ-metal shield**
3. **Copper pump-out tube**
4. **Yb oven appendage**
5. **Electrical feedthroughs**
6. **C-field coils**
7. **Laser port (sapphire)**
8. **Fluorescence collection window (sapphire)**
9. **Lens and filters tube**

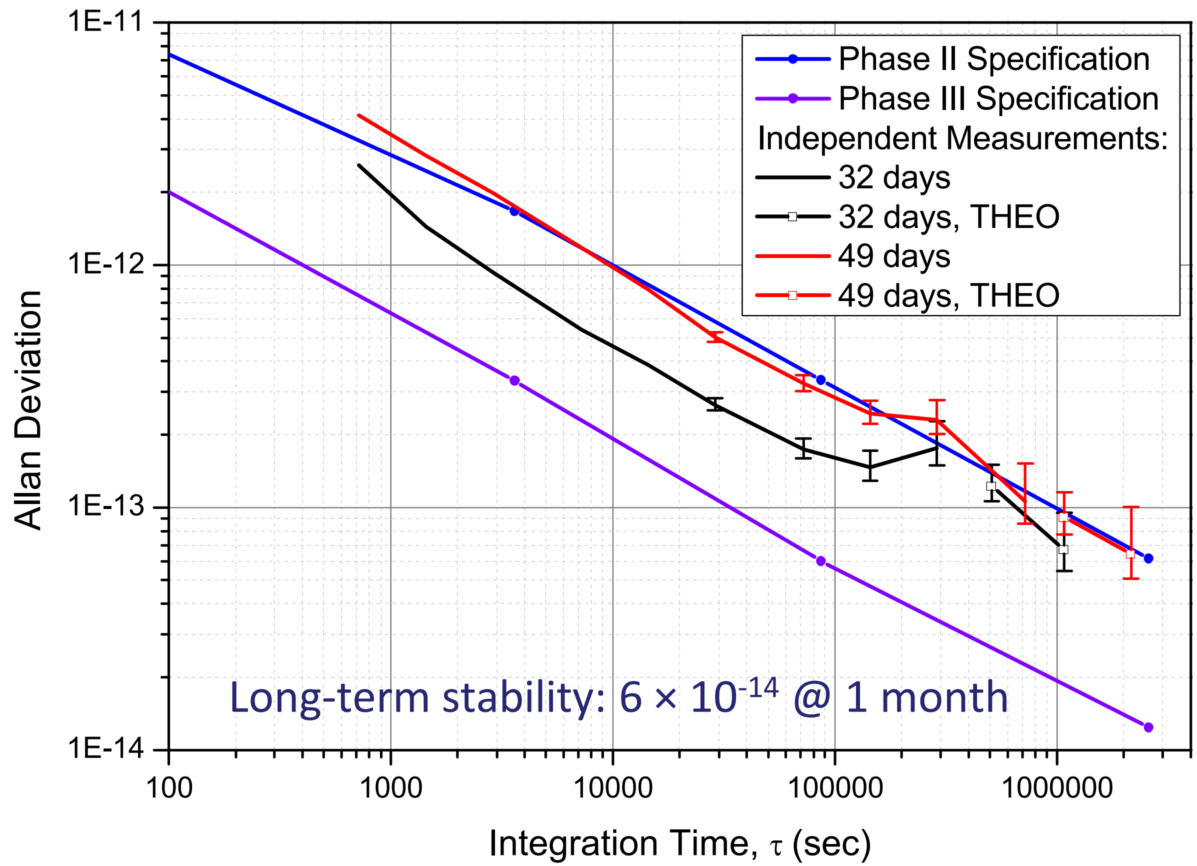
- Titanium body with sapphire windows.
- Linear Quadrupole RF Paul Trap
- Pinched off since April 25th, 2012
- Buffer gas cooling with He
- Getter Pumped.
- Trapped ion lifetime > 3 weeks.

# Independent Government Testing of Long-Term Stability

- Bread board clock with 935 nm VCSEL and MEMS shutter
- Large doubled 369 nm laser
- Blu-ray burner diode at 405 nm to create ions.
- Allan deviation derived from data sets of 6 days, 26 days, 3 days, 4 days, and 10 days.
- 49 days of data

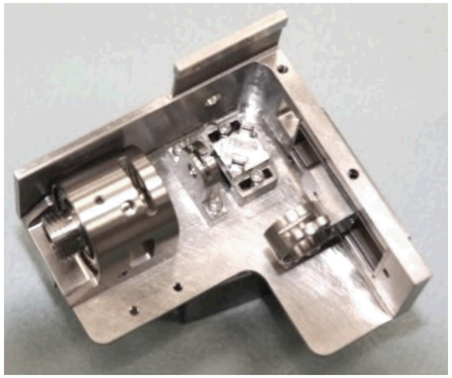
Integrated Vacuum Package



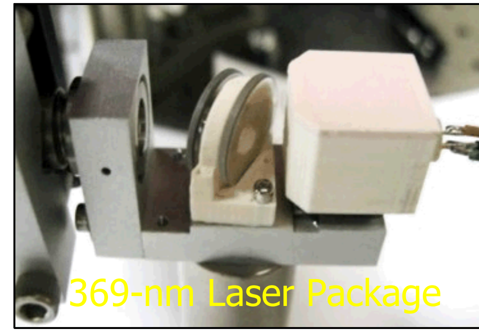



# Complete Physics Package

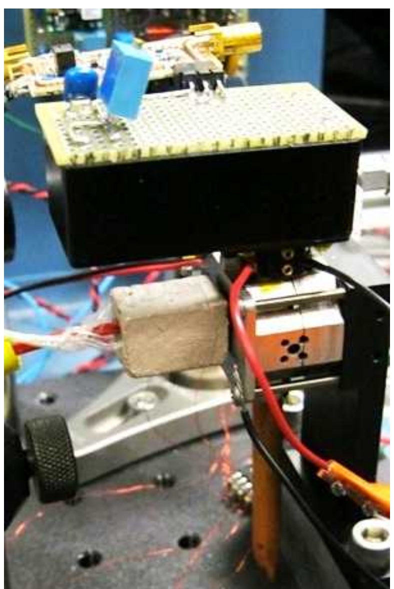
Integrated Optics

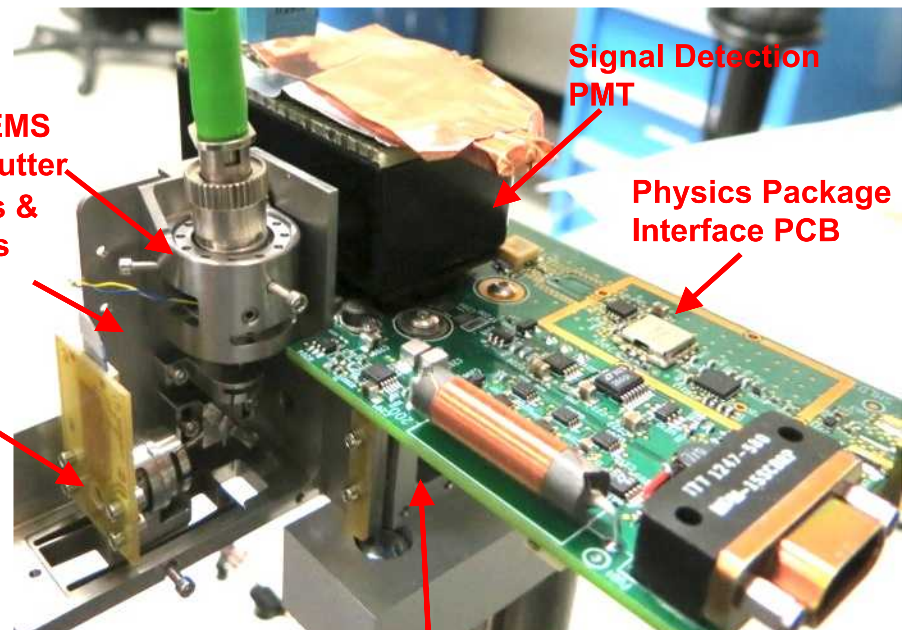


Physics Package Interface




Vacuum Package





# Integrated Clock Performance

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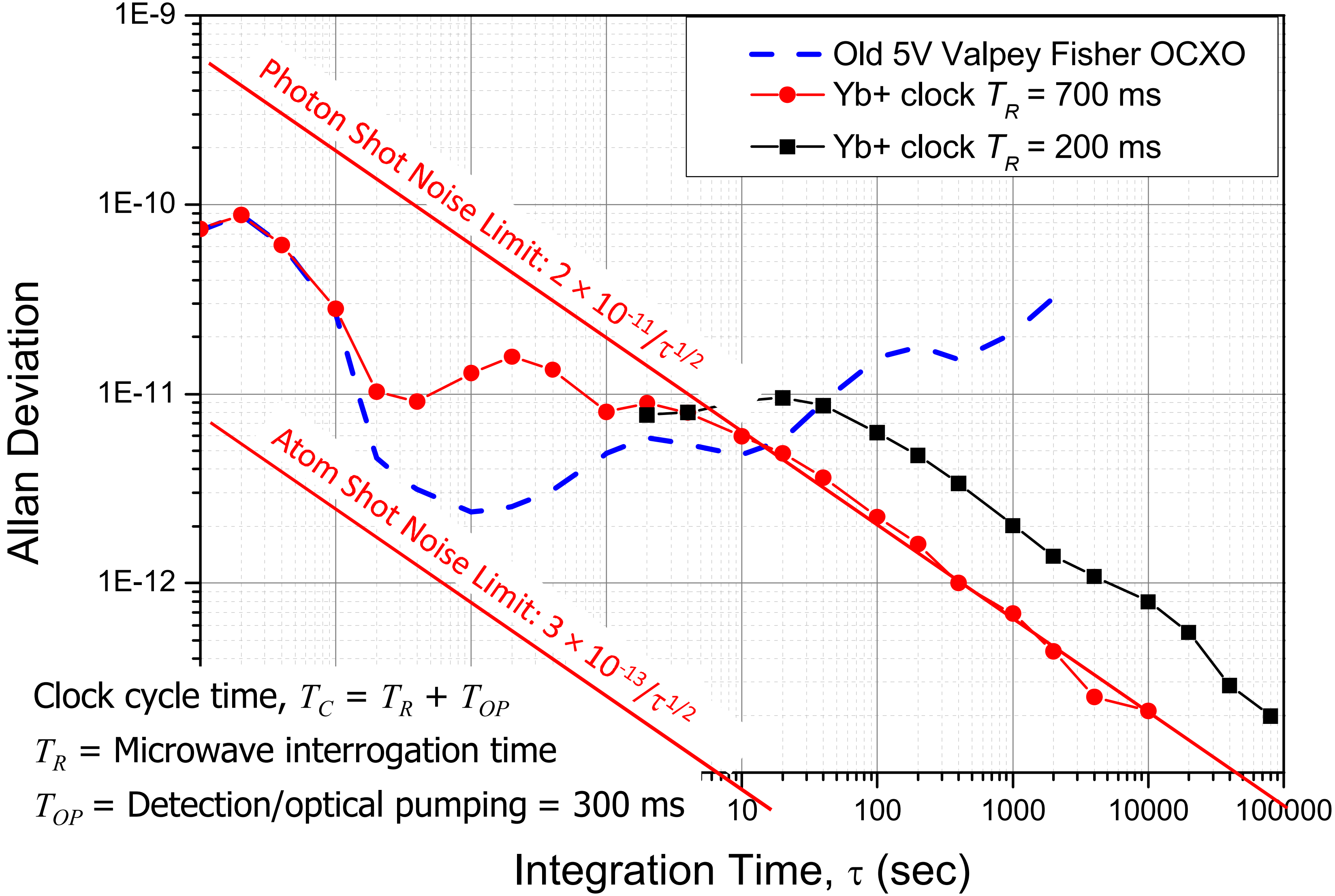



Clock cycle time, $T_C = T_R + T_{OP}$

$T_R$ = Microwave interrogation time

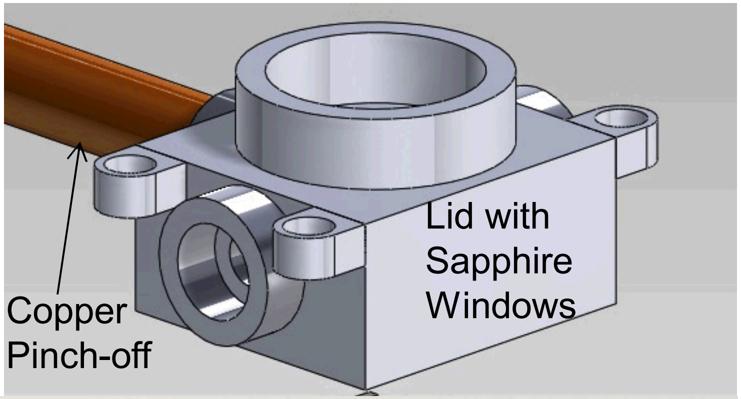
$T_{OP}$ = Detection/optical pumping = 300 ms

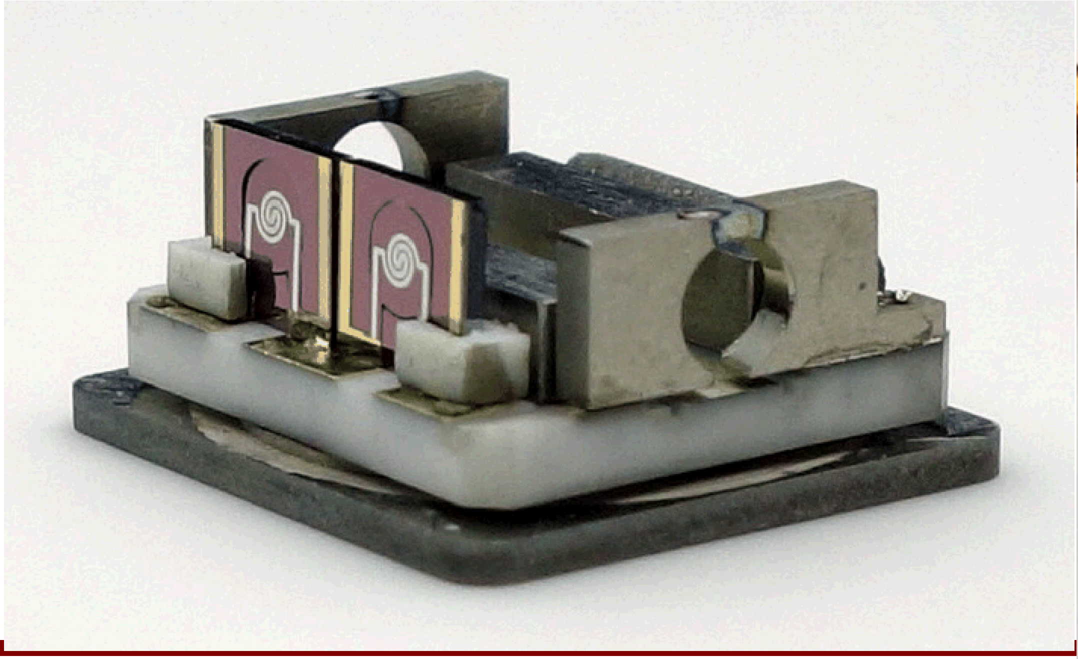
# Co-Fired Hybrid Ceramic/Titanium Package

Sandia National Laboratories

- High temperature co-fired ceramic (HTCC) simplifies the electrical vacuum feedthroughs and internal connections.
- Make the ion trap an integral part of the vacuum package for maximum miniaturization.
- Integrated Yb sources: Silicon micro hotplate
- CuAg braze the Ti parts to the HTCC
- AuGe solder Si hotplates to HTCC
- E-beam weld the base to the lid
- Size of package cube: 0.8 $cm^3$

Exploded View



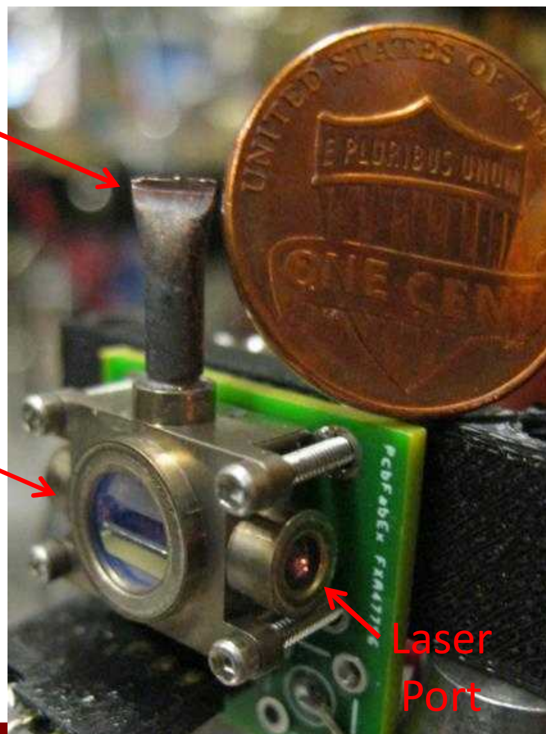
# Performance of the Phase III Vacuum Package

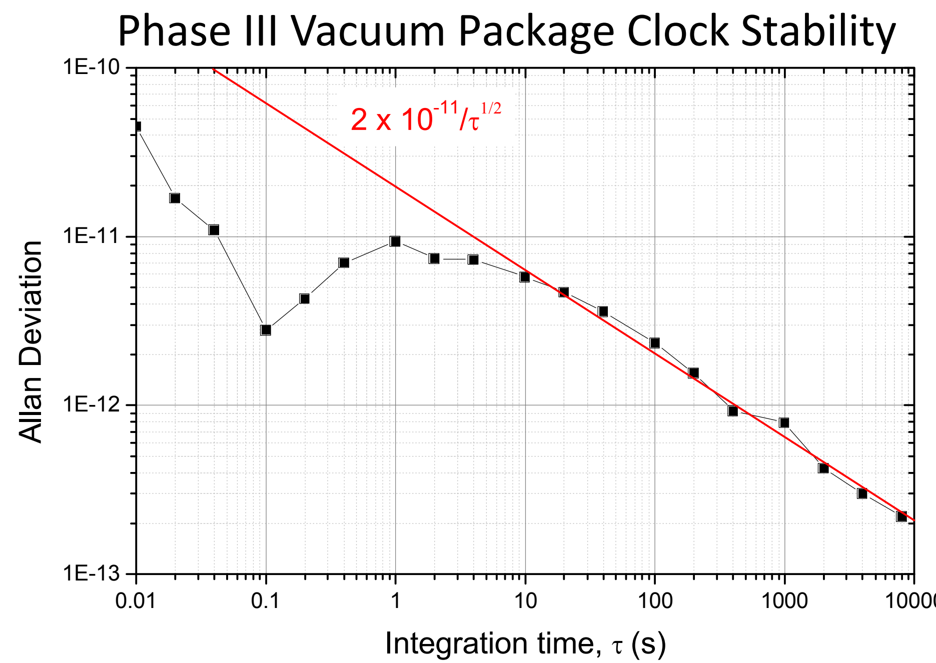
Sandia National Laboratories

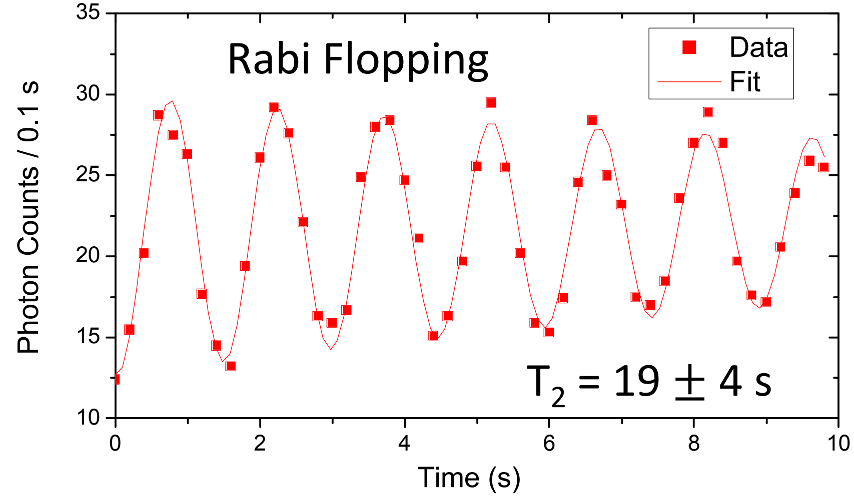
- The vacuum package was pinched-off on Thursday, October 30th, 2014.
- Trapped ion lifetime is ~50 hours.
- Achieving Phase III performance
  - $T_{microwave}$ = 700 ms
  - $T_{optical\ pumping}$ = 300 ms
- Magnetic field correlations removed

Copper Pinch-Off

Fluorescence Port



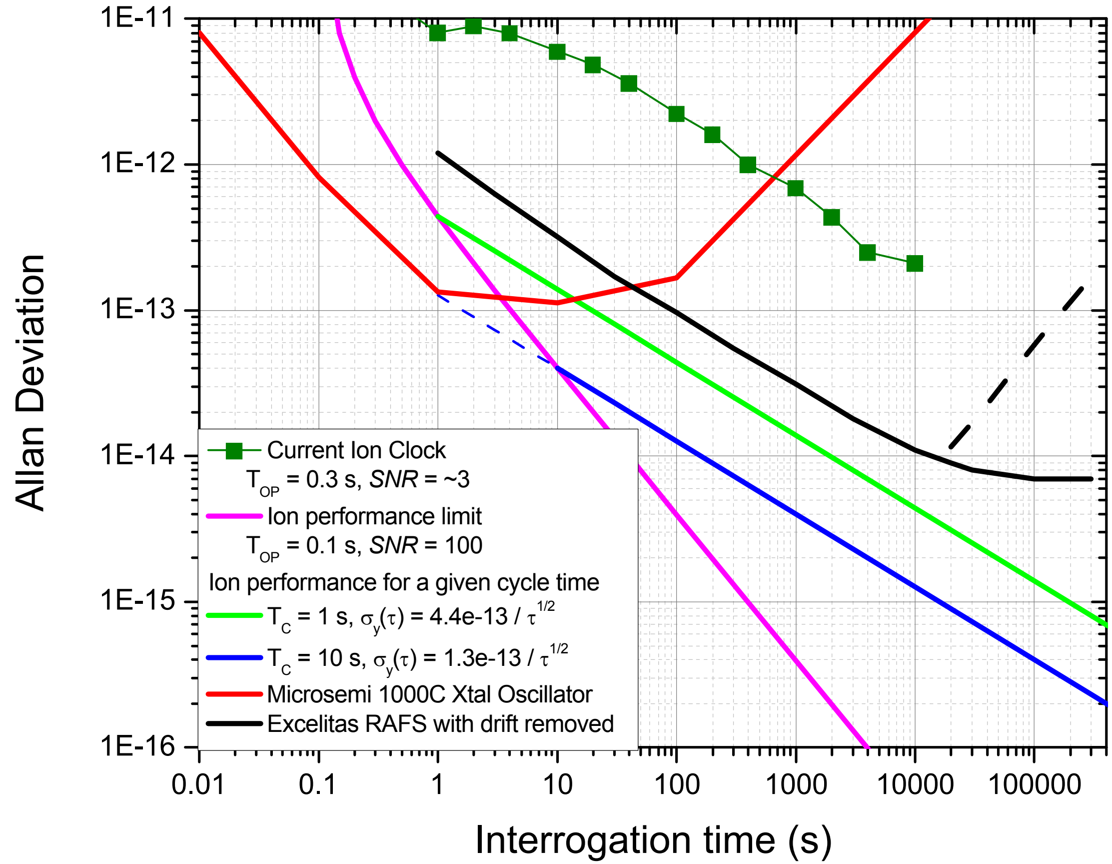



# Improving the Yb Ion Clock

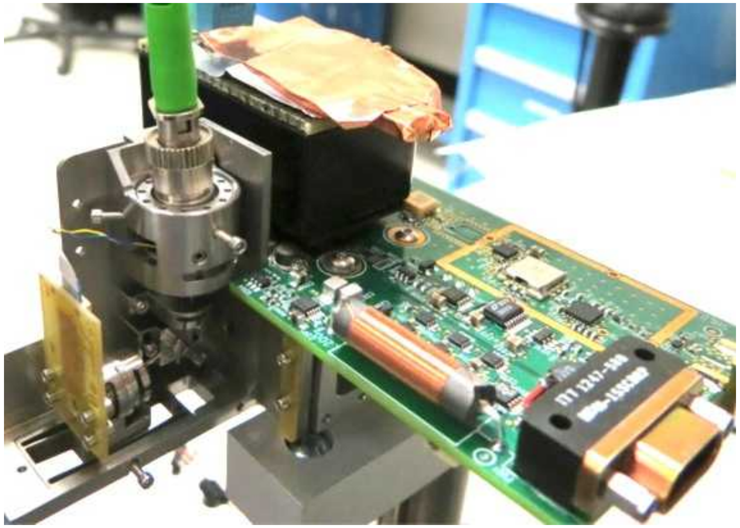
- Allan deviation for the ion clock: $\sigma_y(\tau) = \frac{1}{2T_R\nu_0}\sqrt{\frac{T_C}{\tau}}\frac{1}{SNR}$
- where $\tau$ is the averaging time, $T_R$ is the interrogation (Rabi) time, $\nu_0$ is the atomic hyperfine resonance frequency, $T_C$ is the cycle time, and $SNR$ is the signal-to-noise ratio of the fluorescence detection.

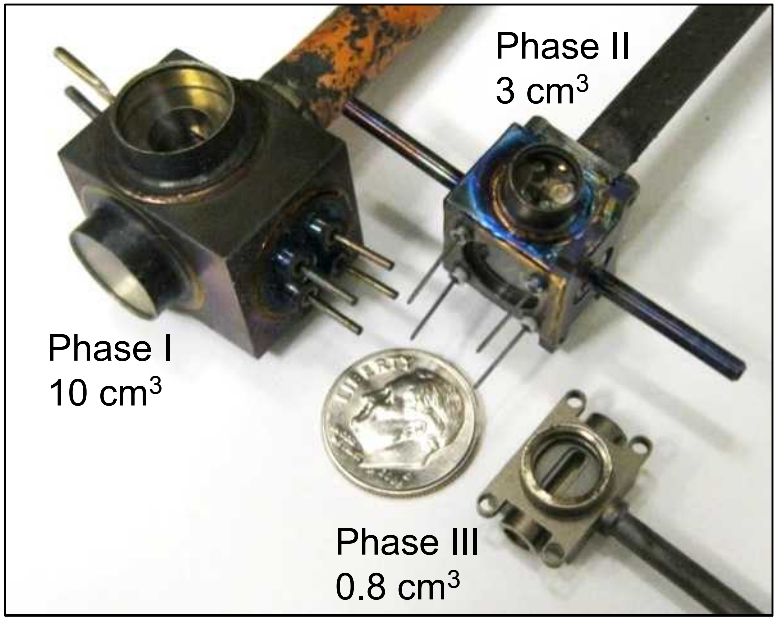
- SNR improvement
  - Switching to 369 nm detection
  - Collect more light
  - Reducing the F-state trapping
  - Trapping more ions
- Faster optical pumping:
  - More laser power: 200-400 $\mu$W
- Need a better local oscillator

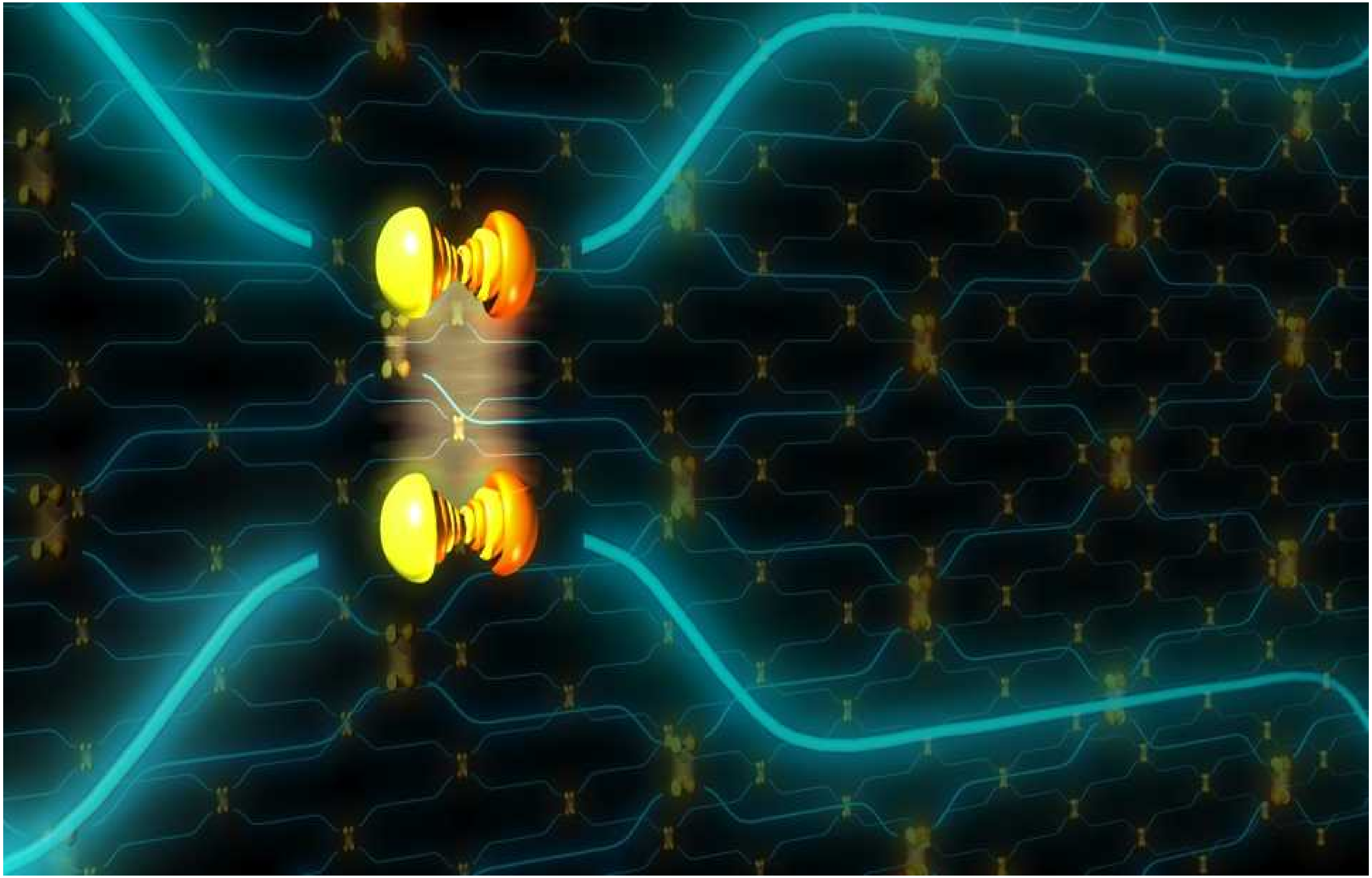


# Challenges and Opportunities

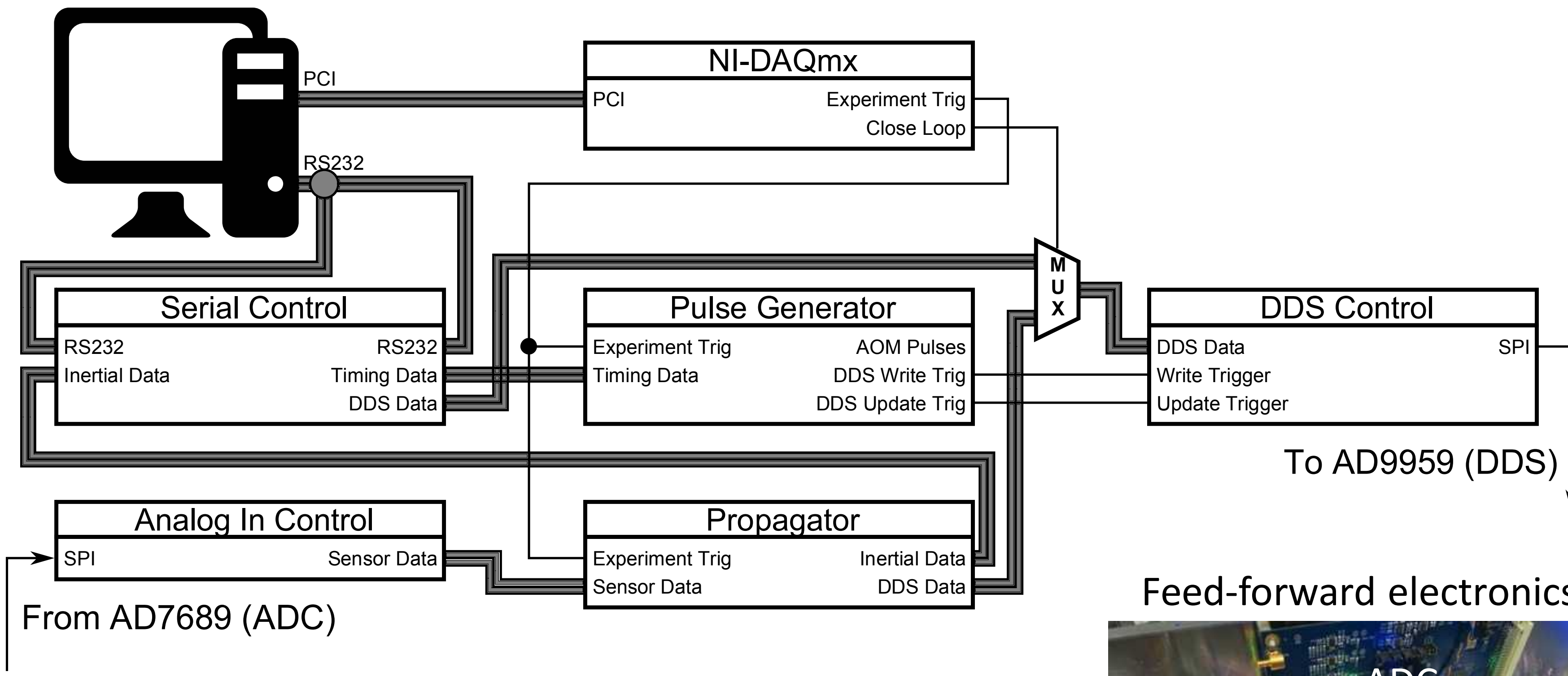
- Tremendous technology development
- Need for technological improvements
  - 369 nm laser with low-power and long-term stability
  - Low power local oscillator
  - Improve signal-to-noise ratio
- Potential for a very high performance miniature clock
  - $4 \times 10^{-13} /\sqrt{\tau}$



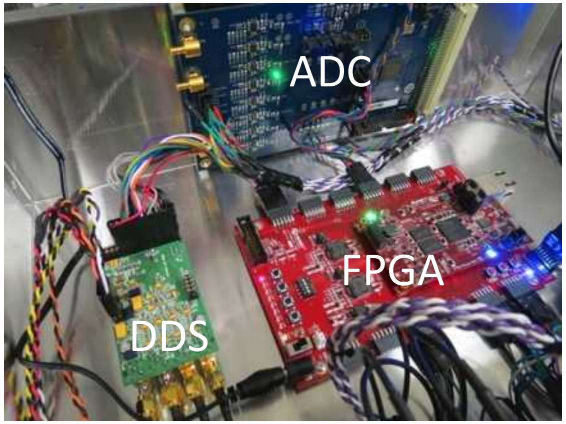




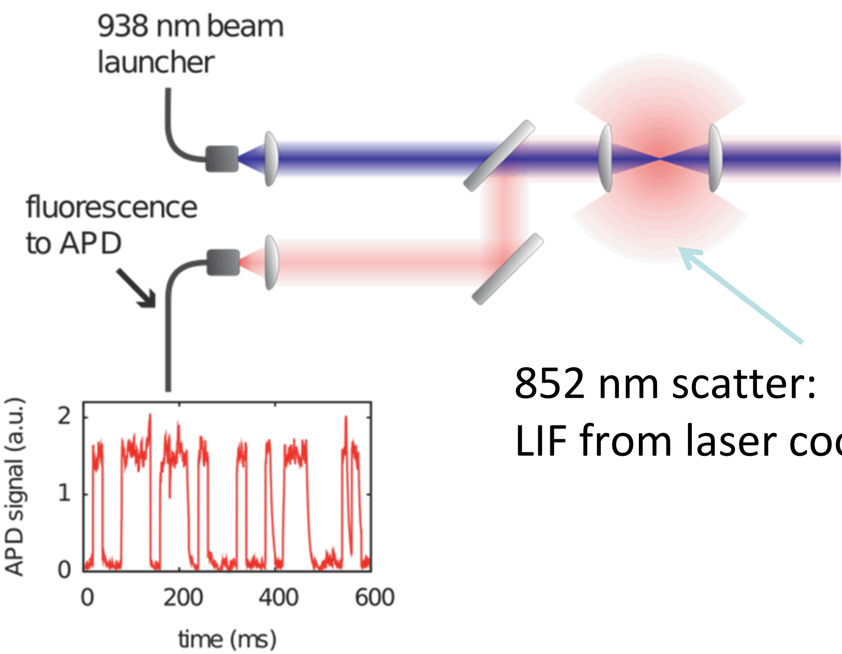
# Control hardware



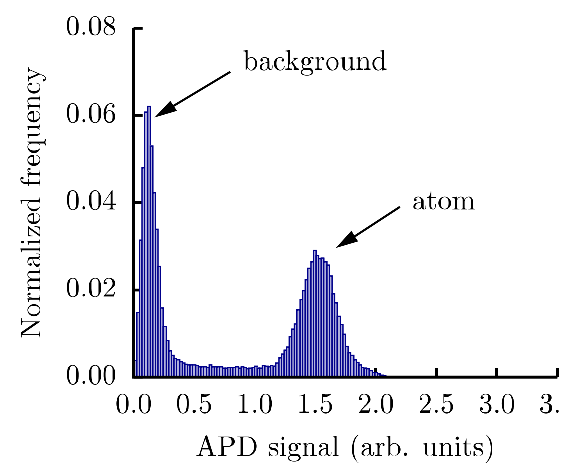

Feed-forward electronics



# Single atom control

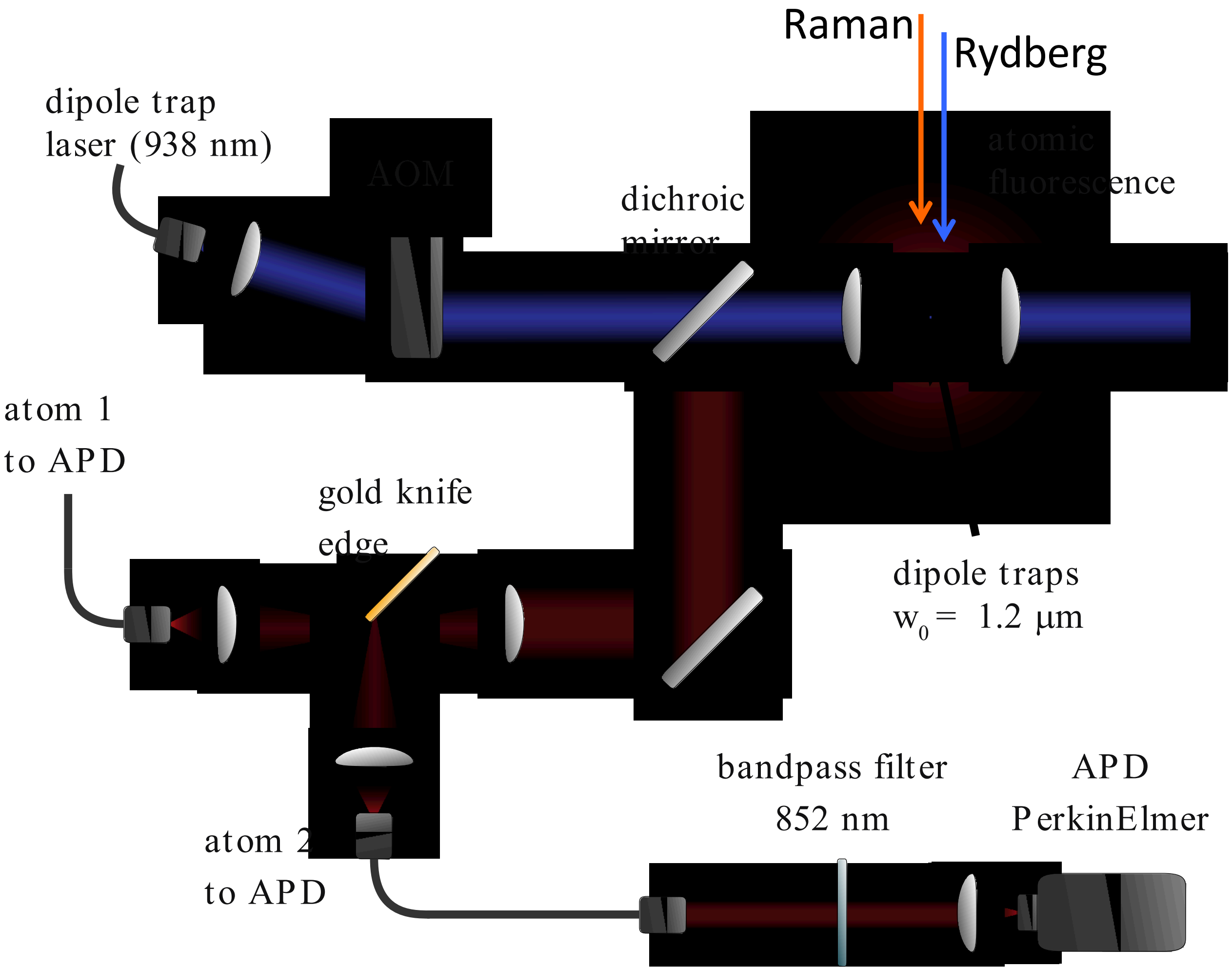



852 nm scatter:
LIF from laser cooling light

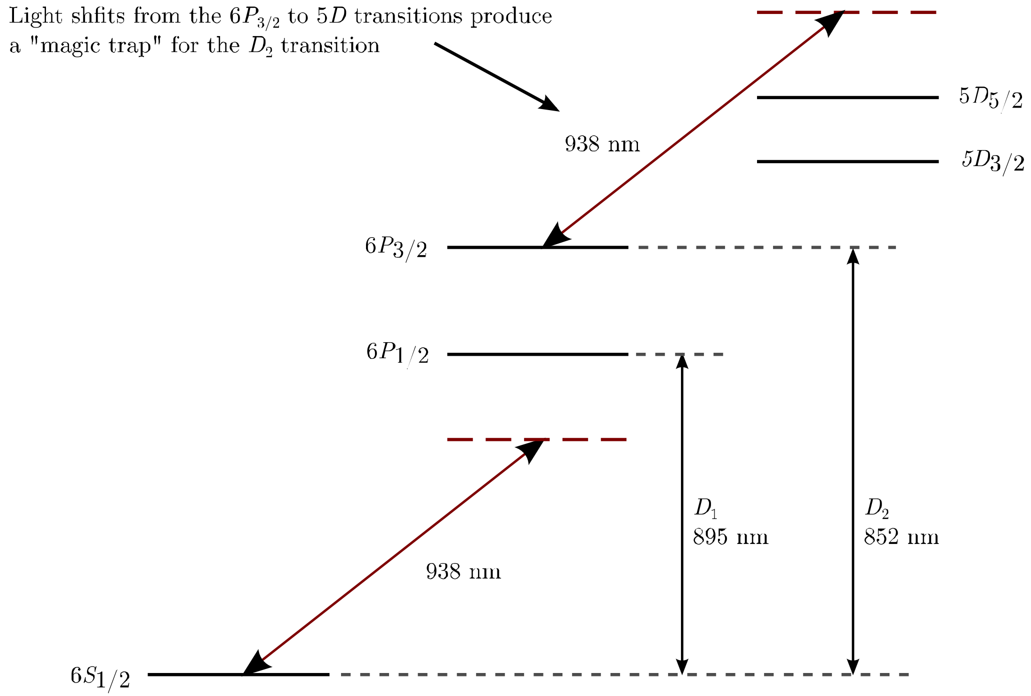


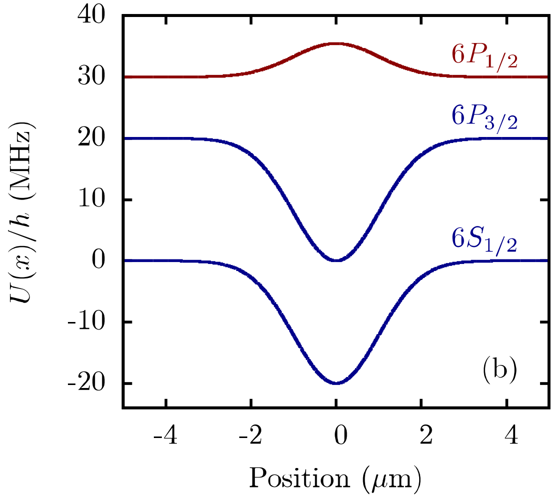

Spot size ≈ 1 μm—collisional blockade

# Experiment schematic



# Single atom control



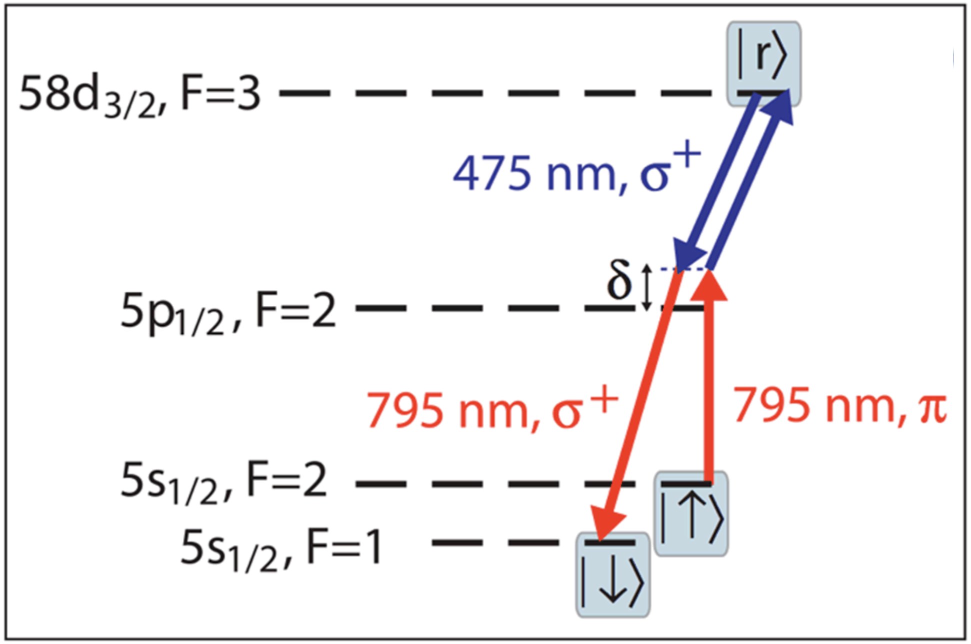



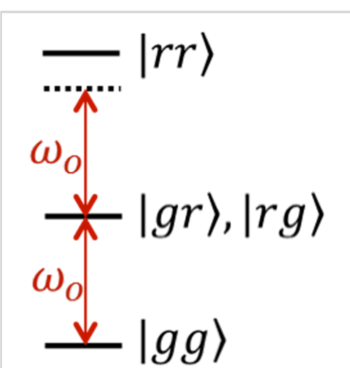

Why 938 nm? It's magic for the cooling transition.

- ≈ 5 mW, 43 nm red
- focused to ≈ 1 μm
- gives ≈ 20 MHz or ≈ 1 mK

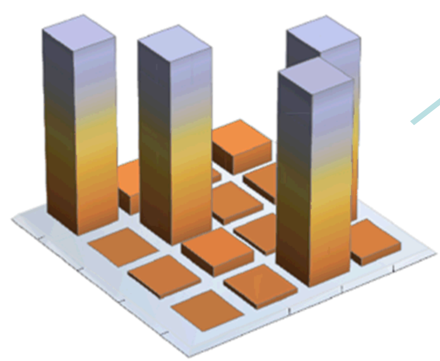
# On-demand interactions

Two-atom entanglement using Rydberg blockade

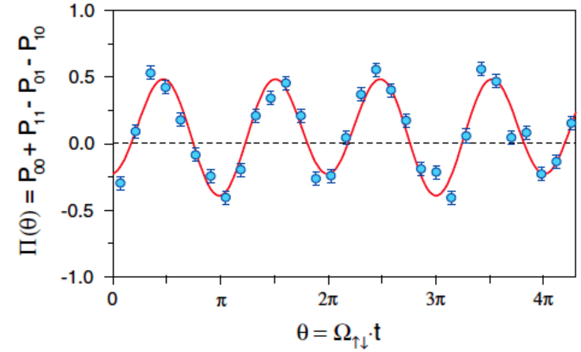



CNOT gate

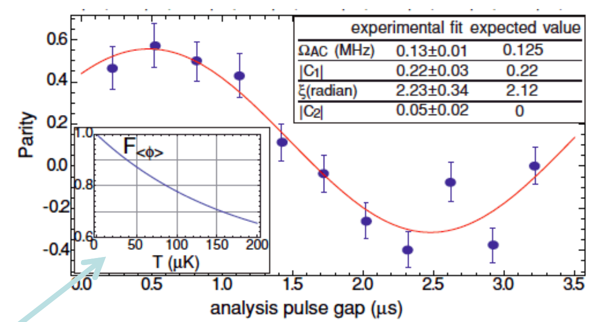


Paris




Wilk et al., PRL 104, 010502 (2010)

Wisconsin

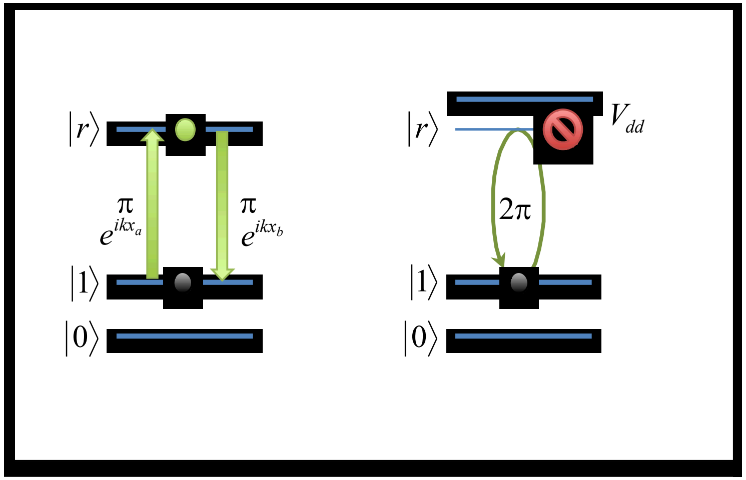



Zhang et al., PRA 82, 030306(R) (2010)

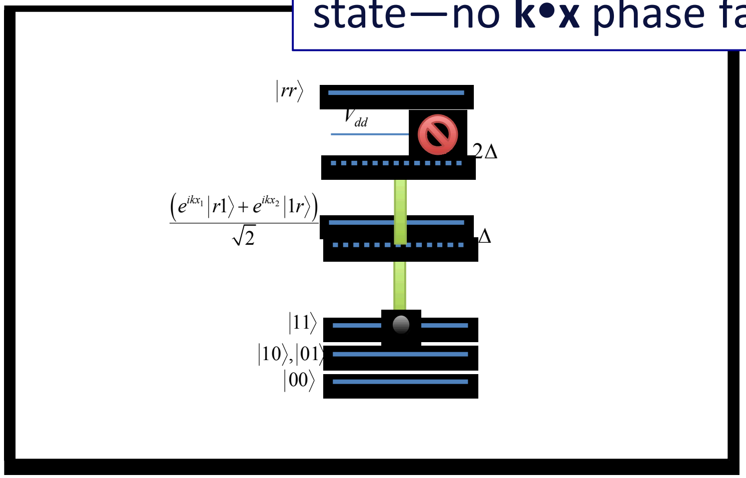
# New options for Rydberg-state-mediated interactions

Comparison of methods

Population remains in ground state—no **k•x** phase factors!




Direct excitation

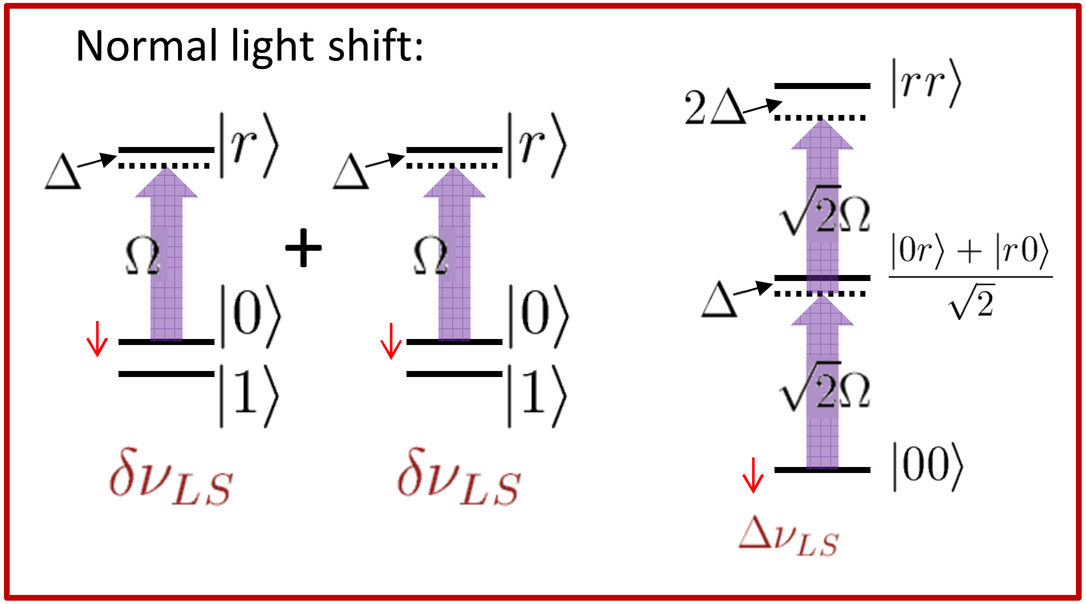


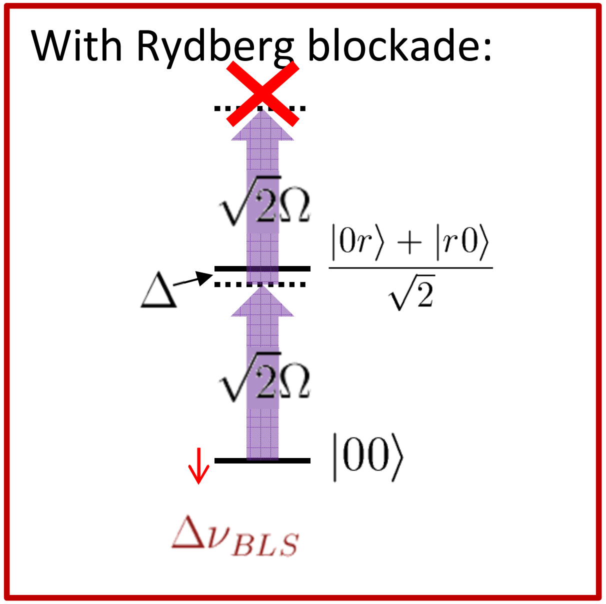

Rydberg dressed

"Elaborate theoretical proposals for the realization of various complex phases and applications in quantum simulation exist. Also a simple model has been already developed that describes the basic idea of Rydberg dressing in a two-atom basis. However, an experimental realization has been elusive so far."

T. Pfau's group, Stuttgart, Germany
J. B. Balewski, *et al.*, *N. J. Phys.* 16, 063012 (2014)

# Interaction between two Rydberg-dressed atoms




$$H_{BLS} = H_{LS} + H_{int} = \begin{bmatrix} 2\delta\nu_{LS} & 0 & 0 & 0 \\ 0 & \delta\nu_{LS} & 0 & 0 \\ 0 & 0 & \delta\nu_{LS} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} J & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{for} \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix}$$

$$J = \Delta\nu_{BLS} - \Delta\nu_{LS} = \frac{\Omega^4}{8\Delta^3} - \frac{3\Omega^6}{16\Delta^5} + \frac{35\Omega^8}{128\Delta^7} - \cdots$$

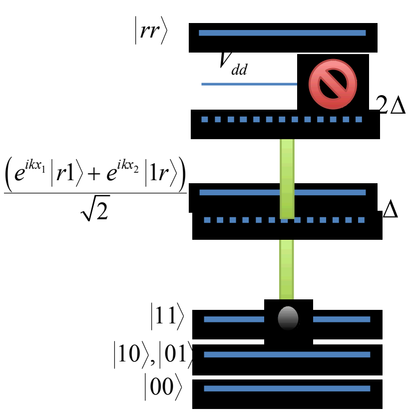
$$H_{int} = \frac{J}{4}(\sigma_z^{(1)} + 1)(\sigma_z^{(2)} + 1)$$

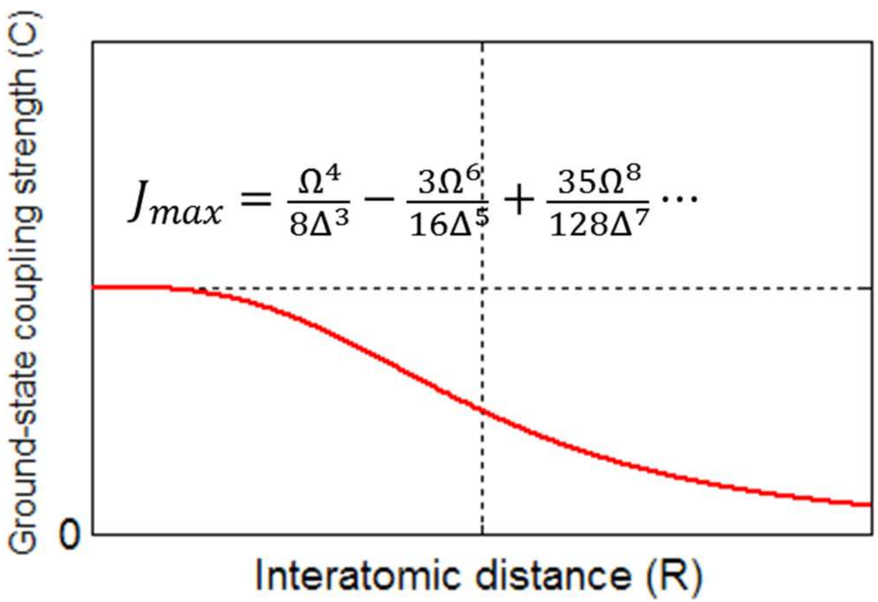
# Rydberg-dressed interactions

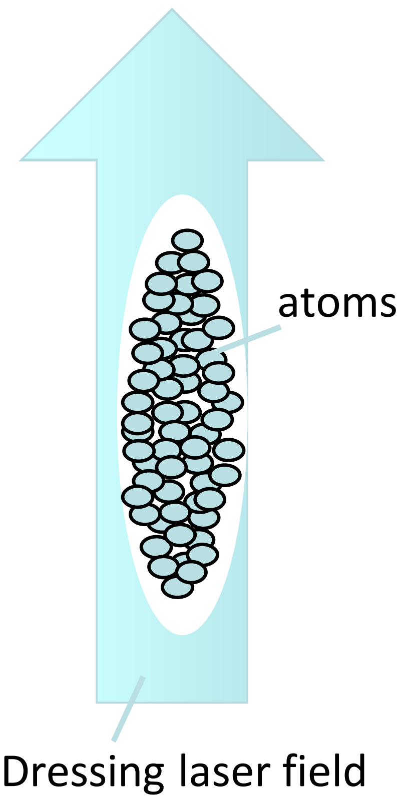


Tunable interaction strength ($J$), low sensitivity to atom motion, and effectively strong ground-state interactions.

$$H_{int} = \sum_{ij} \frac{J_{ij}}{4} (\sigma_z^{(i)} + 1)(\sigma_z^{(j)} + 1)$$



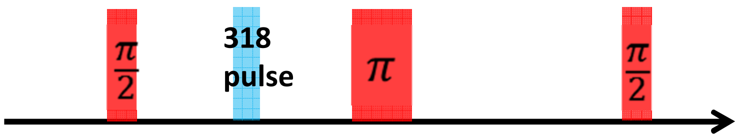




I. Bouchoule, K. Mølmer, Phys. Rev. A 65, 041803 (2002).
J. Johnson, S. Rolston, Phys. Rev. A 82, 033412 (2010).

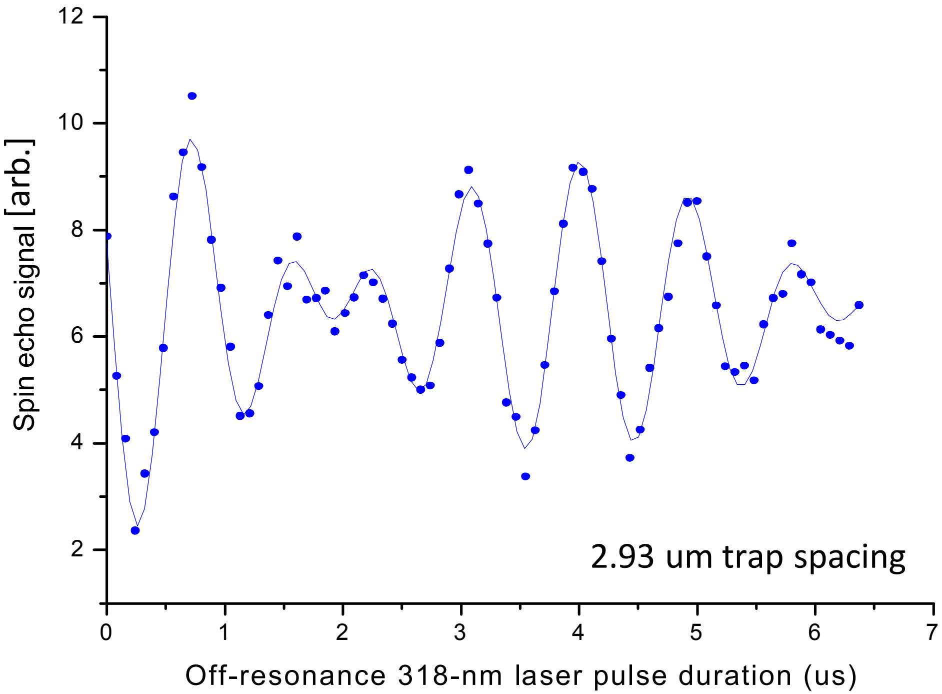
Favors small detuning

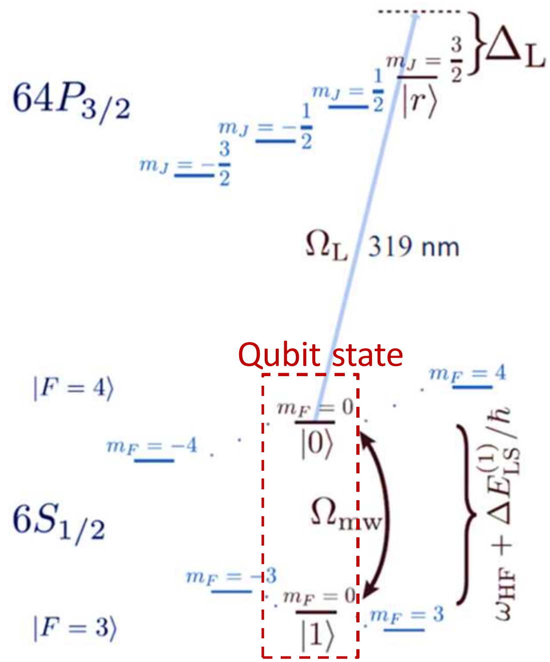
# First evidence of Rydberg-dressed interaction

Microwave transition is via Raman laser

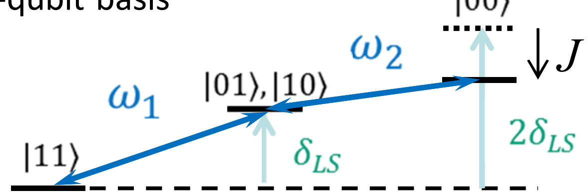



318-nm laser dressed spin echo sequence




2-qubit basis

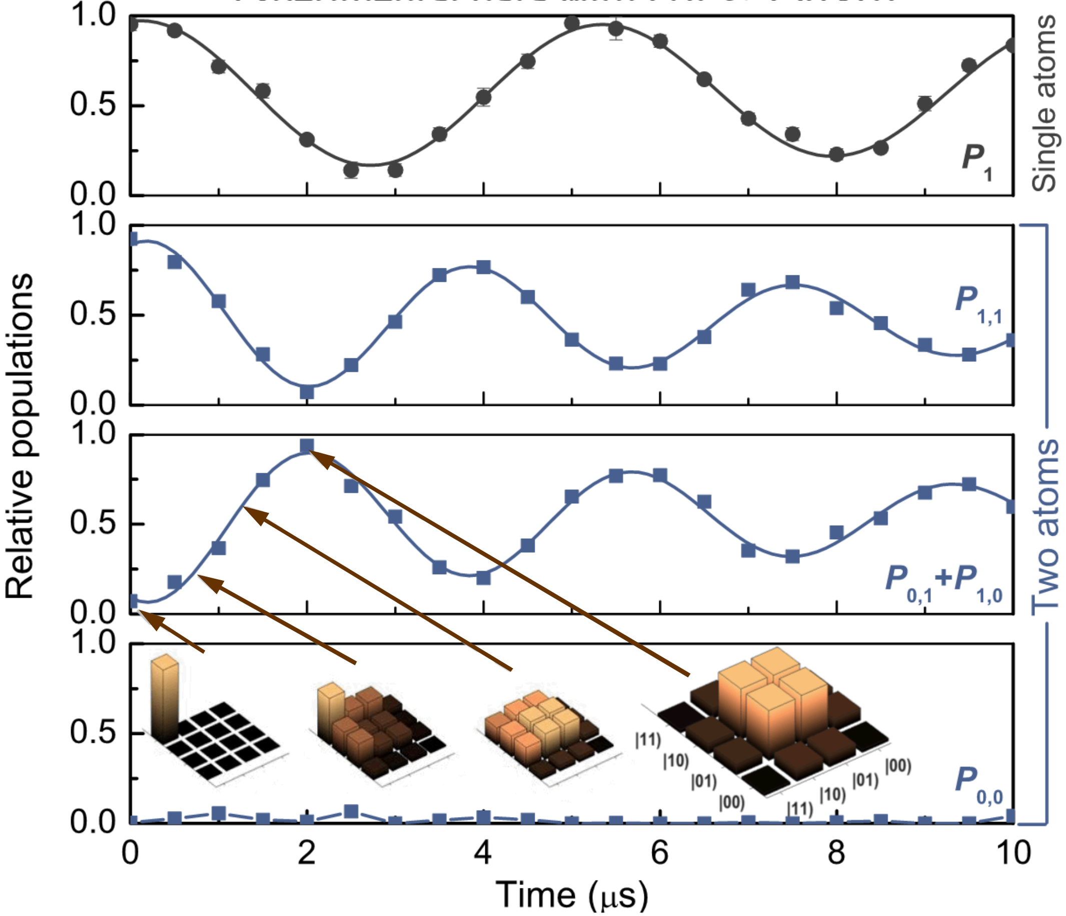



A frequency beat note is generated if $\omega_1 \neq \omega_2$

# Producing Bell-state entanglement

Initial state is $|1\rangle$ or $|11\rangle$, then apply 318-nm and Raman lasers

Experimental data with $J/h \approx 750$ kHz



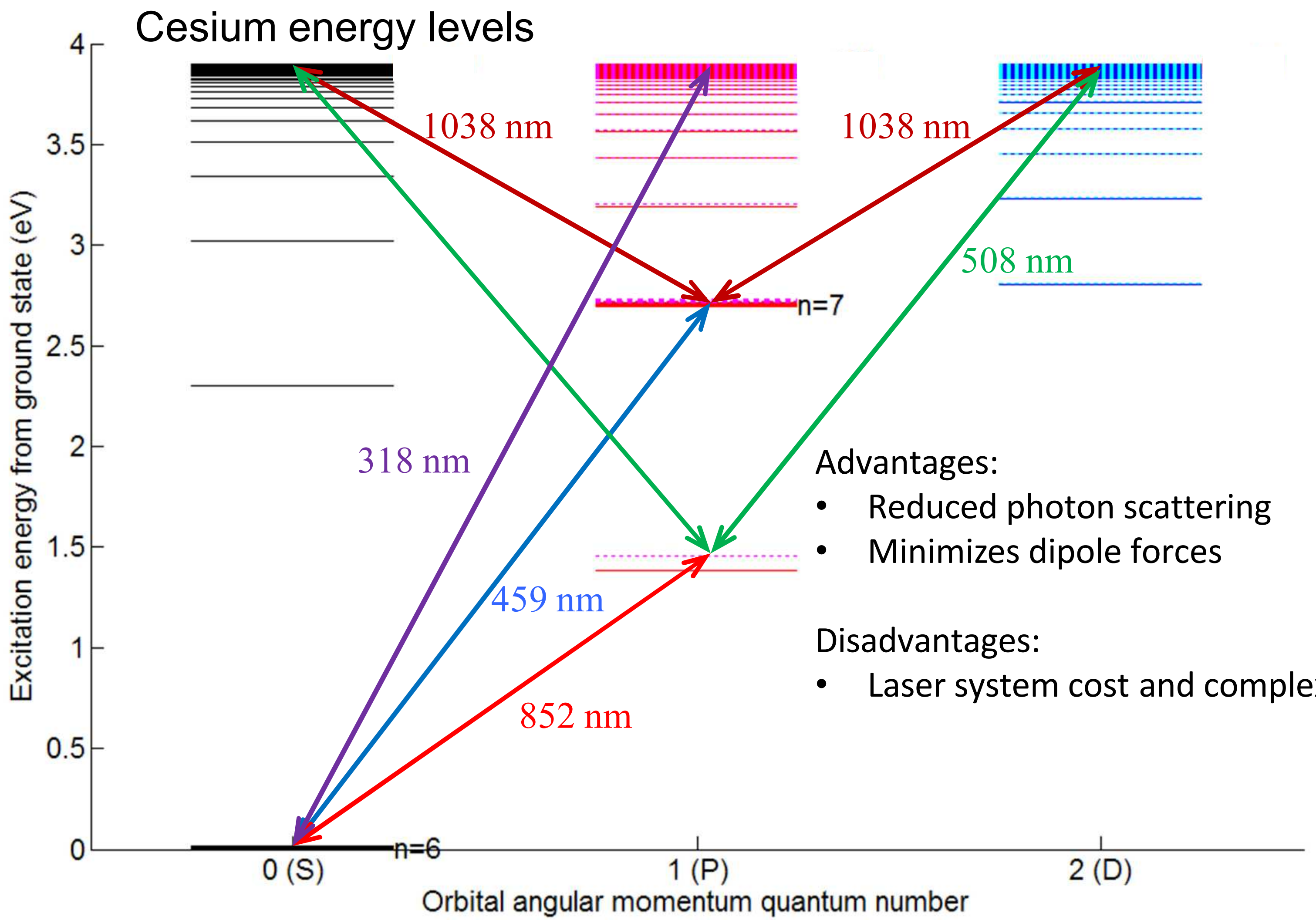

## Single-atom Rabi

## Two-atom Rabi oscillation:

- $\sqrt{2}$ times faster
- No significant population being transferred to $|00\rangle$
- Bell state $|\Psi_+\rangle$ is produced at $t = \pi/\sqrt{2}\Omega_{mw}$

Process occurs entirely and directly in the ground state

# Optimizing for long-term relationships




Advantages:

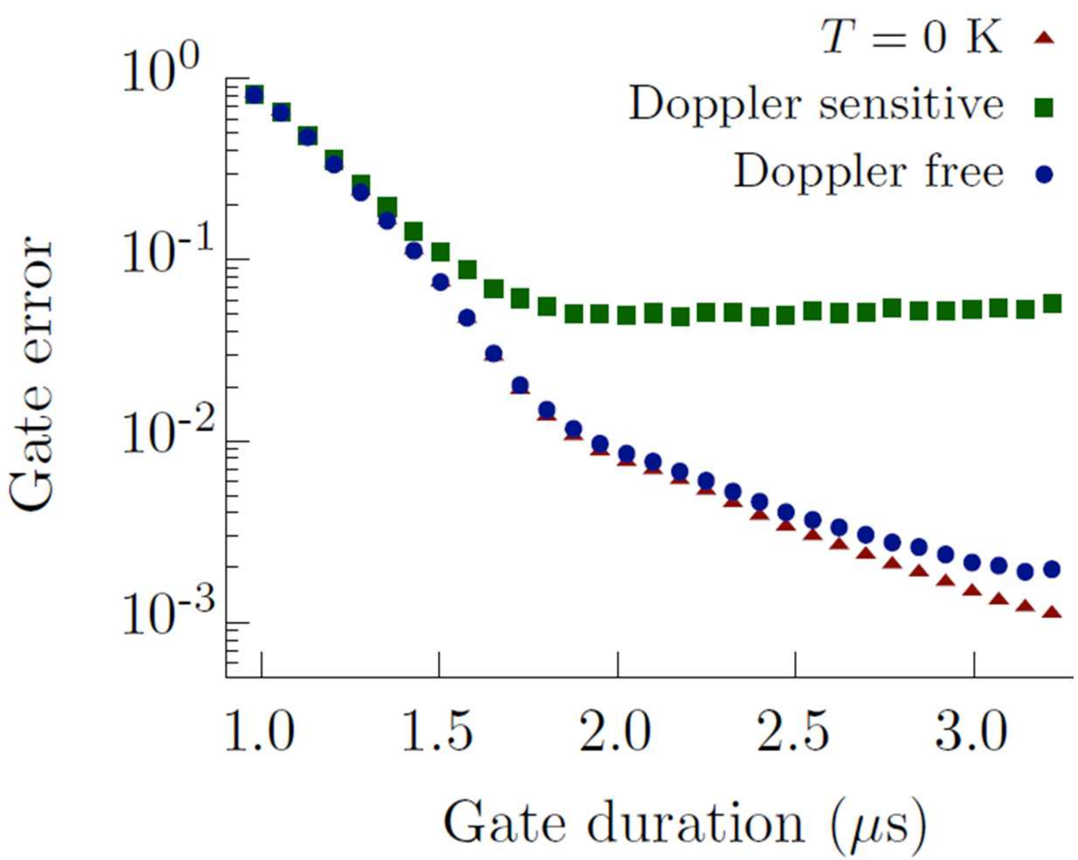
- Reduced photon scattering
- Minimizes dipole forces

Disadvantages:

- Laser system cost and complexity

Published: Phys. Rev. A 89, 033416 (2014)

# Simulated CPHASE gate fidelities



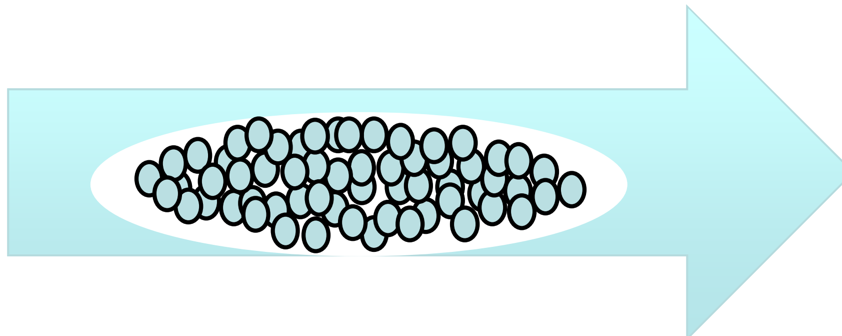

$\Omega = 0 \to 3$ MHz
$\Delta/2\pi = 6 \to 0$ MHz
$\Gamma = 3.7$ kHz
$T = 16\ \mu$K

- Motional errors set a high floor on error for the original scheme.
- The Doppler-free scheme is limited by the much smaller photon scattering rate.
- Entanglement fidelity expected to be even larger

Published: Phys. Rev. A 91, 012337 (2015)

# Quantum Control of Ensembles

Symmetrically couple ensemble of atoms localized with Rydberg blockade radius



Optimal Control $|\psi\rangle_0 \rightarrow |\psi\rangle_{\text{target}}$

$$H\underbrace{\left[\phi(t)\right]}_{\text{Control}}$$

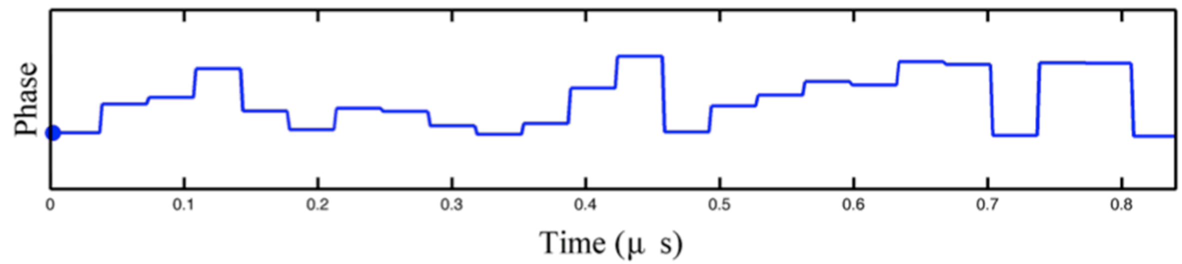
<u>For *n* atoms</u>

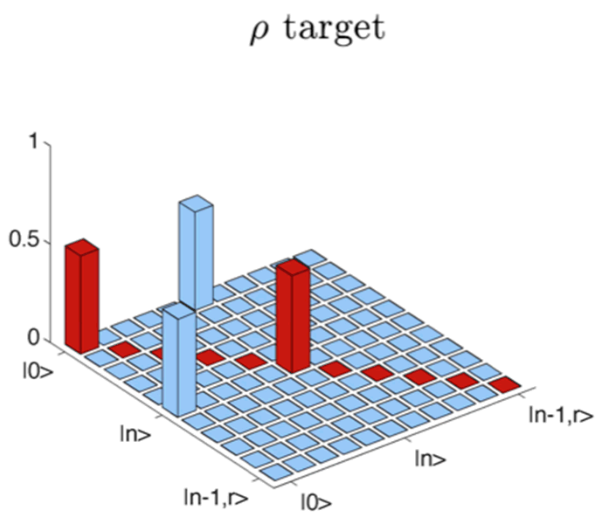
$$H = \sum_n \left[ \frac{\Omega_{\mu w}}{2} \left( e^{i\phi(t)} |0\rangle\langle 1| + e^{-i\phi(t)} |1\rangle\langle 0| \right)^{(n)} + \frac{\Omega_R}{2} \left( |1\rangle\langle r| + |r\rangle\langle 1| \right)^{(n)} + \Delta |r\rangle\langle r|^{(n)} \right]$$

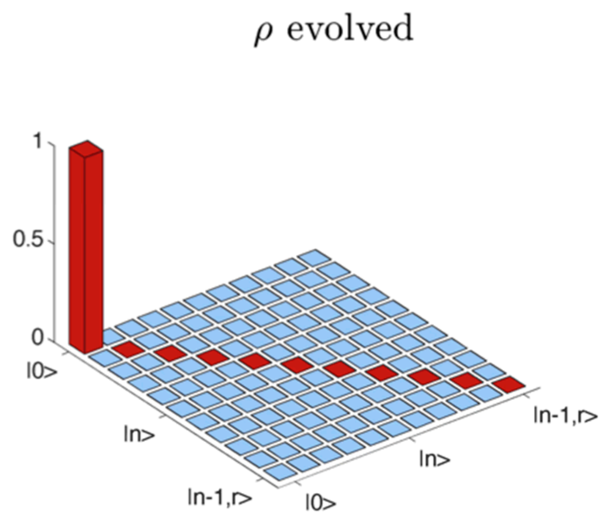
$$+ V_{dd} \sum_{n \neq m} |r\rangle\langle r|^{(n)} |r\rangle\langle r|^{(m)}$$

# Example: A 5-atom "Cat State"

Sandia National Laboratories




$$\left|\psi_{cat}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle\left|0\right\rangle\left|0\right\rangle\left|0\right\rangle\left|0\right\rangle + \left|1\right\rangle\left|1\right\rangle\left|1\right\rangle\left|1\right\rangle\left|1\right\rangle\right)$$

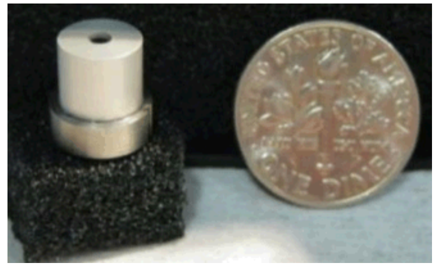
$$\left|\psi(t)\right\rangle$$

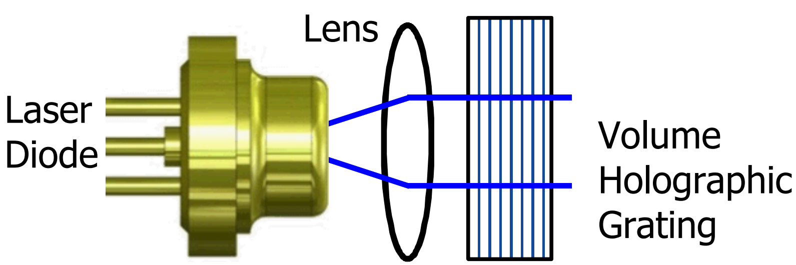
UNM CQuIC

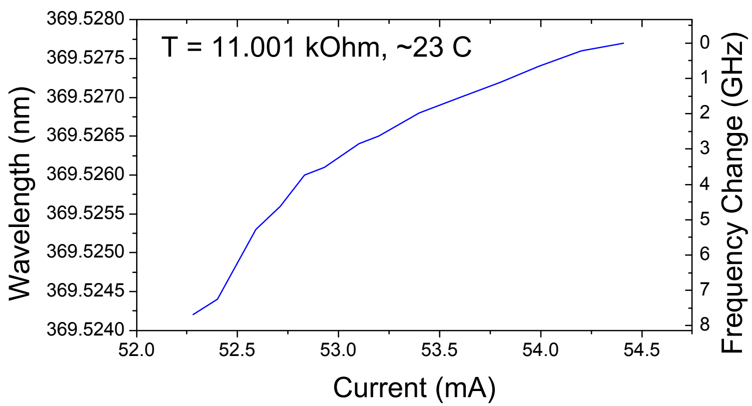
# Miniature Laser Sources

## 369 nm Direct Diode

- Nichia diode packaged by Ondax. Size: 1 $cm^3$
- Mode-hop free tuning: 8 GHz
- Power consumption: 260 mW (laser) + 100 mW (TEC)
- Power output: 1-5 mW



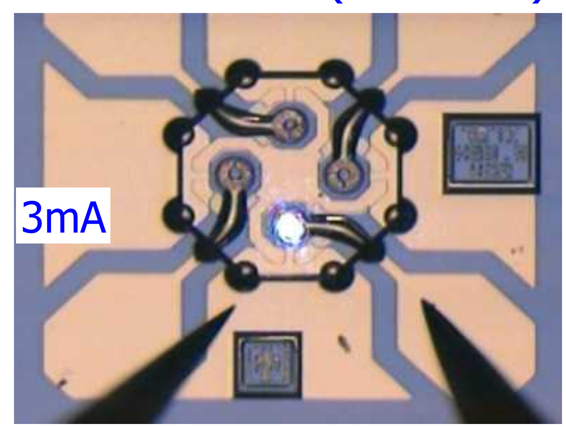



## 935 nm VCSEL

- 935 nm VCSEL fabricated at Sandia.
- Single mode P > 1 mW
- Power consumption: 2.5 mW (laser) + 18 mW (heater)

### 935nm VCSEL (V122571)



# Dynamic atom positioning

Sandia National Laboratories