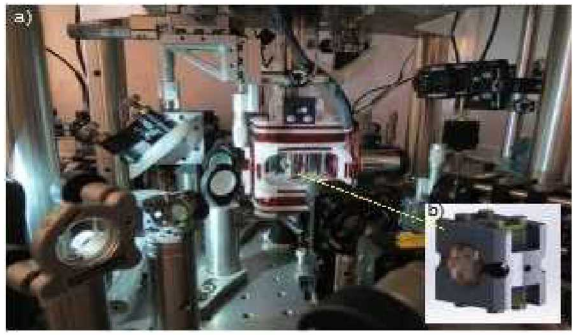
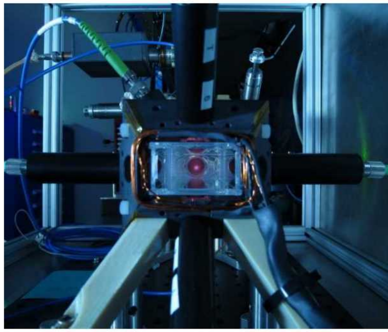
SAND2018-13018PE

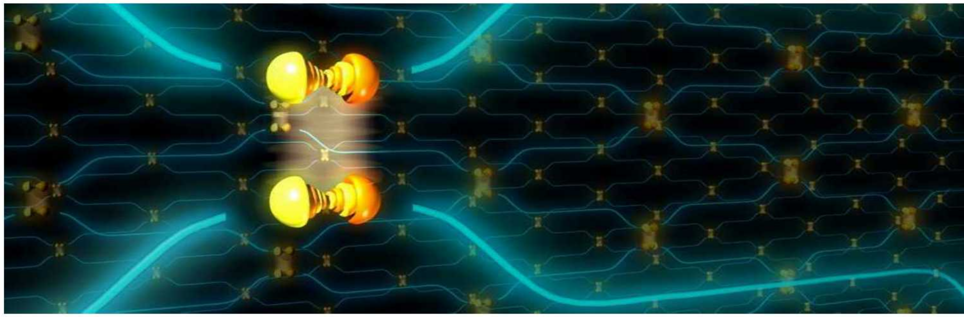
Measuring inertial forces with ultracold neutral atoms

Grant Biedermann

University of Oklahoma Seminar
November 13, 2018







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

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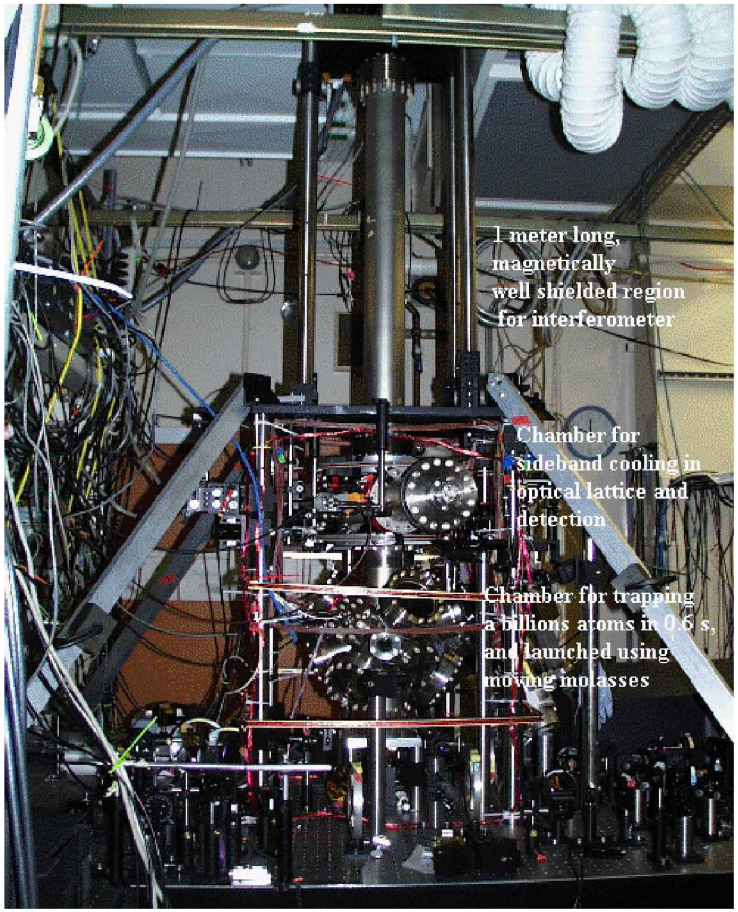
Outline

- Precision sensing with atom interferometers
- Sandia atom interferometer efforts
  - Single atom interferometer
  - Compact atom interferometer for field use
- Toward an atom interferometer with entangled spins
  - Rydberg-dressed physics and entanglement
  - Error budget and outlook

Light-pulse atom interferometers



Stanford atom interferometer gravimeter
Steven Chu, 1990's

Photograph by Charles Watkins, White House photographer
Text by GB

Superb gyroscopes and gravity gradiometers demonstrated as well

Applications of atom interferometer sensors

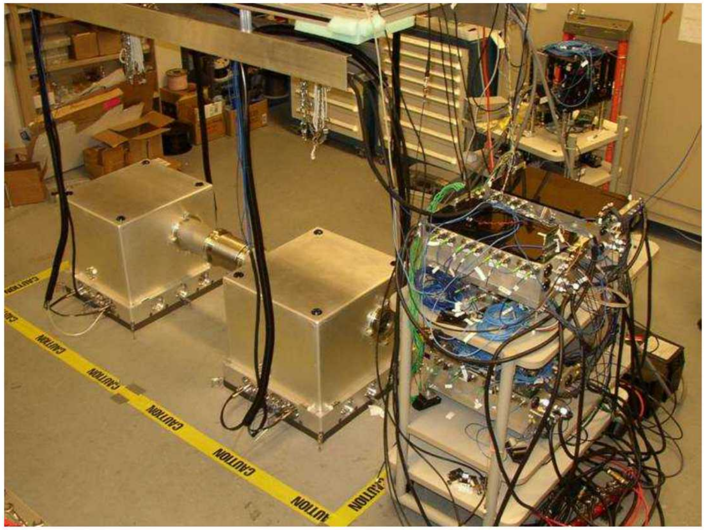
- AI Gravimeter
  - A. Peters *et al,* Metrologia **38**, (2001)
  - Capable of 20 nano-**g** in 1.3 s
  - Recent tower work infers pico-**g** level per shot →
  - Performance far exceeds commercial Nav. Grade

- AI Gyro
  - D. Durfee *et al*, PRL **97**, (2006)
  - Short-term stability ~3μDeg/hr$^{1/2}$
  - High-accuracy navigation grade
    - < 70μDeg/hr bias stability
  - Performance exceeds commercial Nav. Grade

- AI Gradiometer
  - Δa=4 nano-**g** Hz$^{-1/2}$, Biedermann, PRA 2015 →
  - Yale, 2002 (Fixler PhD thesis); Fixler, Science, 2007.
  - More recent: Florence, Nature, 2014
    - Precision δG/G~ 7.7x10^{-5}
    - Systematic uncertainty 6.2x10^{-5}
  - CODATA 2014 relative uncertainty: 4.7x10^{-5}

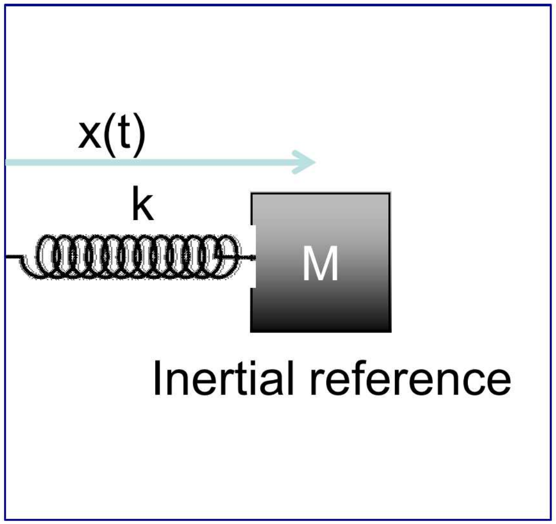
10 m tower
Prof. Kasevich
Stanford

Stanford gradiometer—G.B. and *many* others



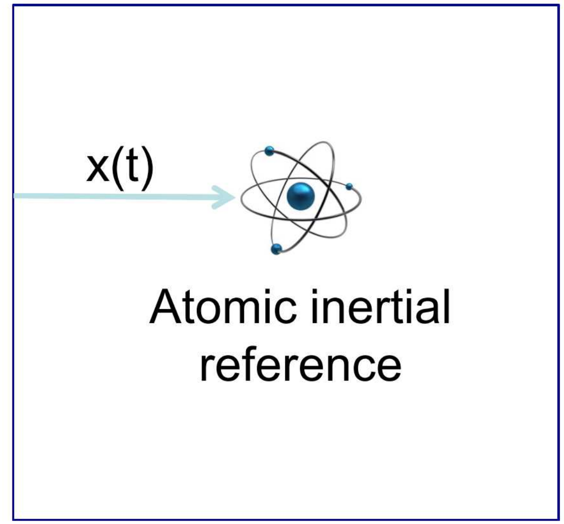
Inertial measurements

Mass-spring accelerometer



platform

Free-fall accelerometer



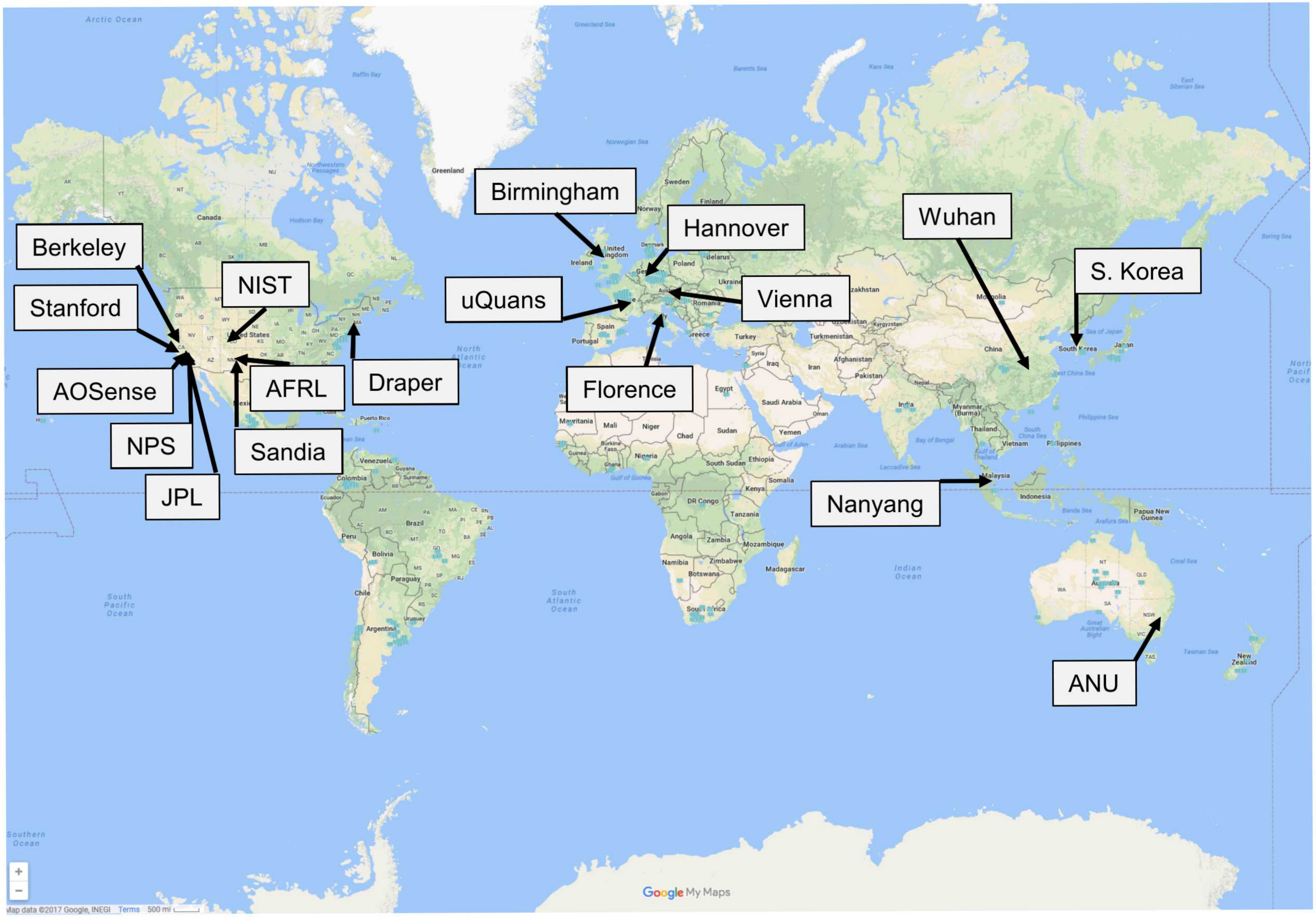
platform

Atom interferometers

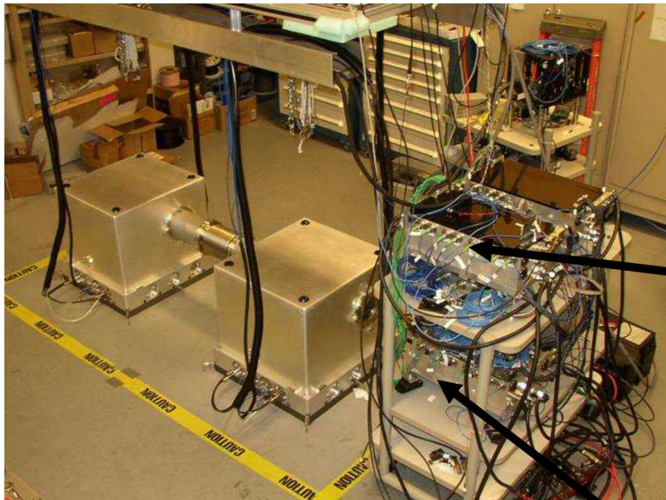
- Inertial reference: laser-cooled atoms falling freely
- Positioning: laser ranging
- Truly accurate, turn-on calibration

An incomplete map of AI efforts

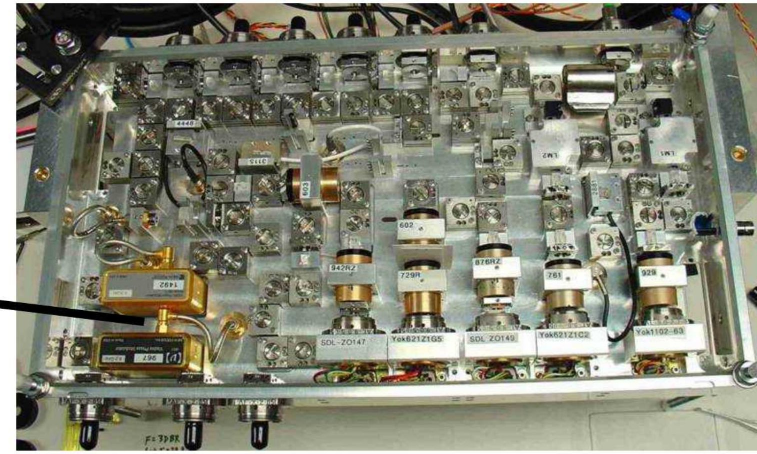
Sandia National Laboratories



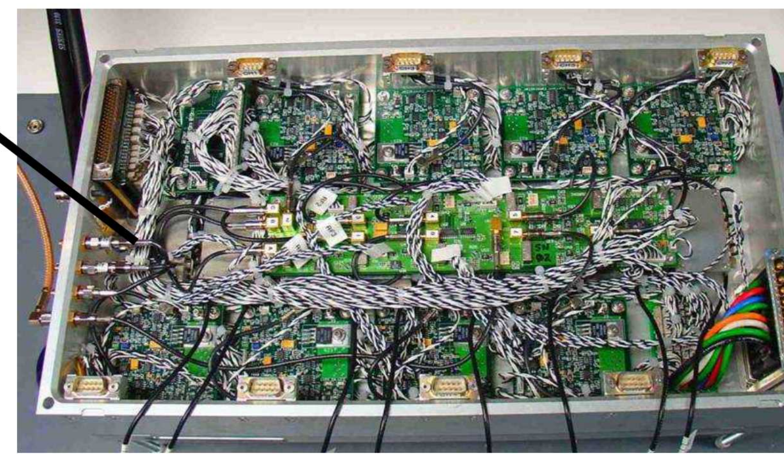
Mobile atom interferometer



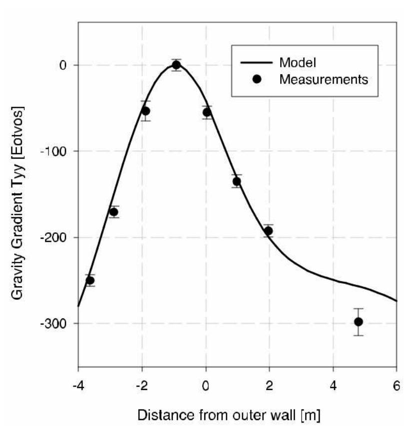
Biedermann, Ph.D. Thesis, Stanford, 2007



lasers 9″x15″

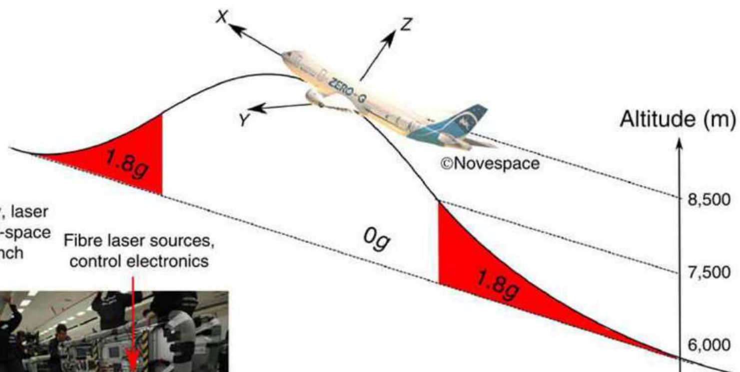


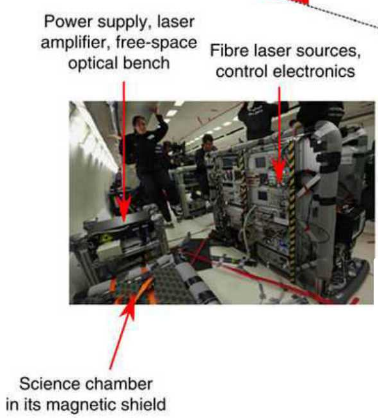
electronics 9″x15″



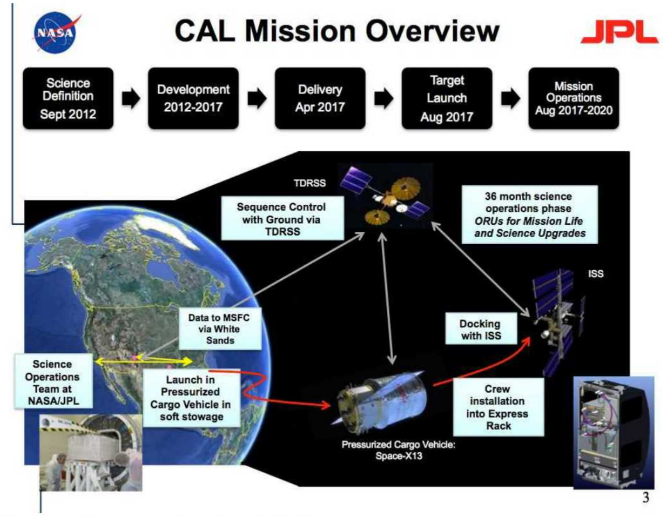
Wu, Ph.D. Thesis, Stanford, 2009

Micro-g atom interferometers

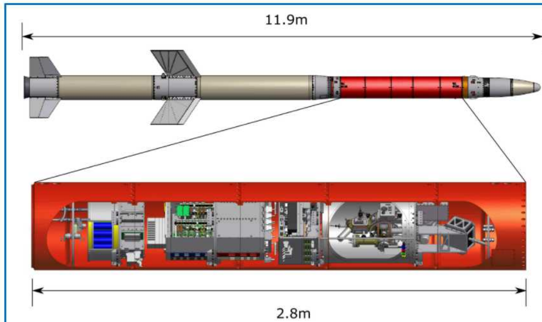




R. Geiger, et al. , Nat. Commun. 2, 474 (2011)



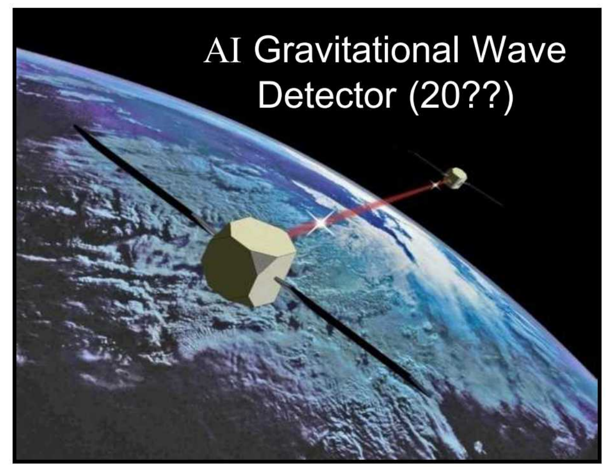
Cold Atom Lab, ISS, coldatomlab.jpl.nasa.gov



DLR program

Successful BEC in flight, Jan. 2017

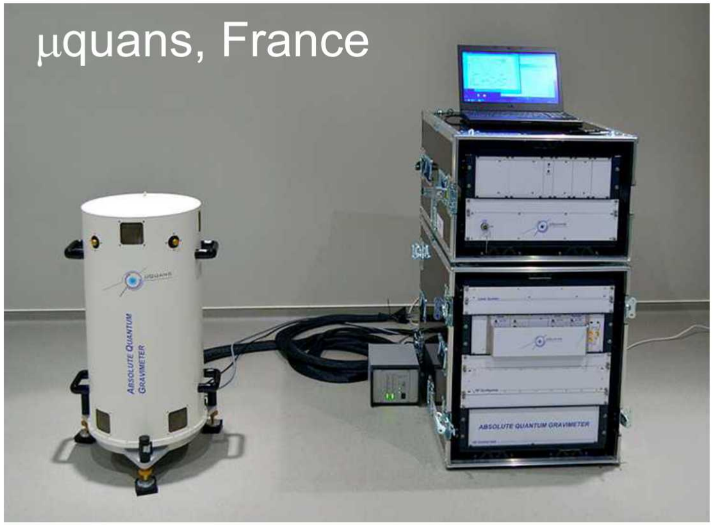
← 2.8 m →



Mark Kasevich, group website, Stanford

J. M. Hogan, et al., Gen. Rel. Grav. (2011)

State-of-the-art Atom Interferometer instrumentation



100 kg, 300 W, 50 ng/$\sqrt{\text{Hz}}$

U.K. University of Birmingham
gravity imager

NASA/JPL ISS CAL

AOSense gravimeter

Inertial Navigation

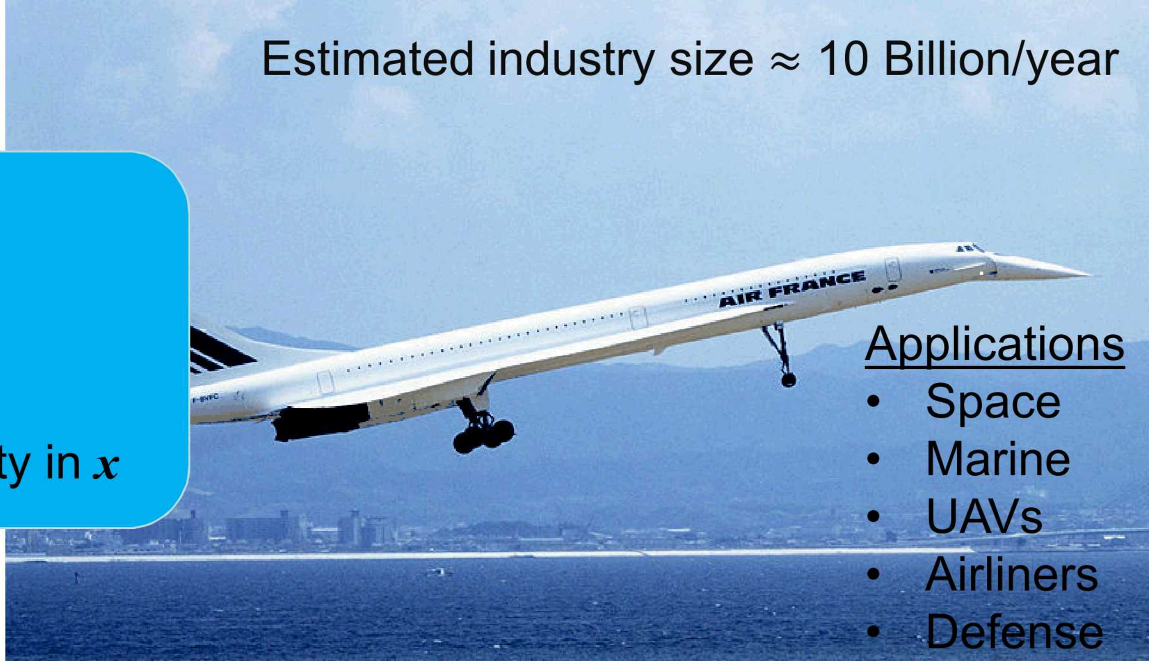
Estimated industry size ≈ 10 Billion/year

Basic idea:

$$x(t) = \iint a(t)\, dt$$

Uncertainty in $\boldsymbol{a}$ drives uncertainty in $\boldsymbol{x}$

Gyroscope gives heading information



Applications
- Space
- Marine
- UAVs
- Airliners
- Defense

Concorde: Wikipedia commons

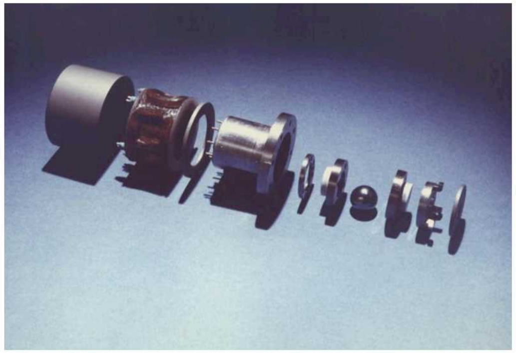
Tactical, MEMs

Analog Devices ADIS16385

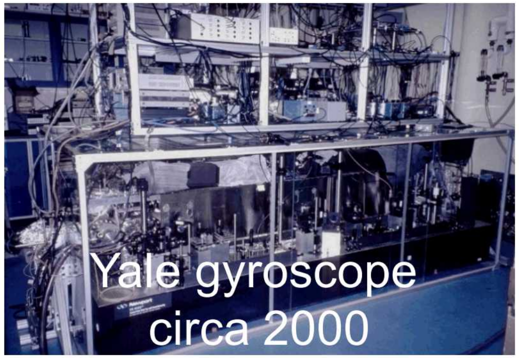
Navigation, HRG

Honeywell HG9900

Strategic, ESG



Atomic



Yale gyroscope circa 2000

stability

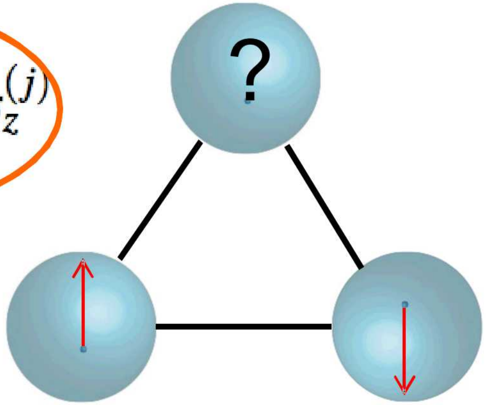
Applications

Quantum simulation

Single spin coherence

$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

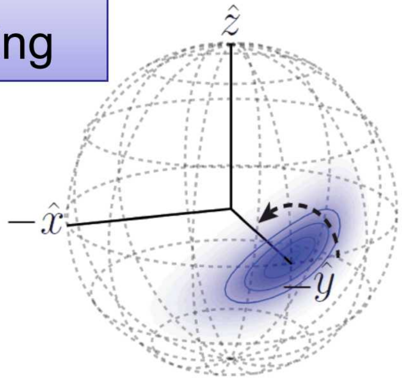
Entangling interactions



Frustrated magnetism

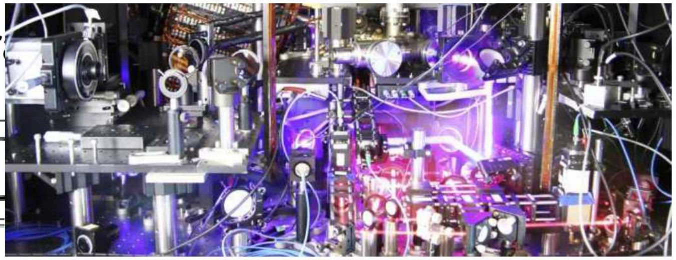
arge-scale/rapid
ntanglement for sensing

Sr lattice clock, Ye lab JILA



Quantum Fourier tr

$$QFT : |x\rangle \mapsto \frac{1}{\sqrt{N}} \sum_{k=}^{N-}$$



AI phase shift: a simple perspective

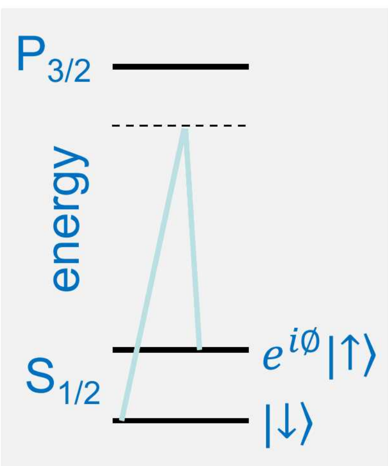
Sandia National Laboratories

Use atom to stroboscopically measure lateral position (optical phase) at three equal-spaced points in time

$$\varphi_i = \vec{k}_{eff} \cdot \vec{x}_i$$

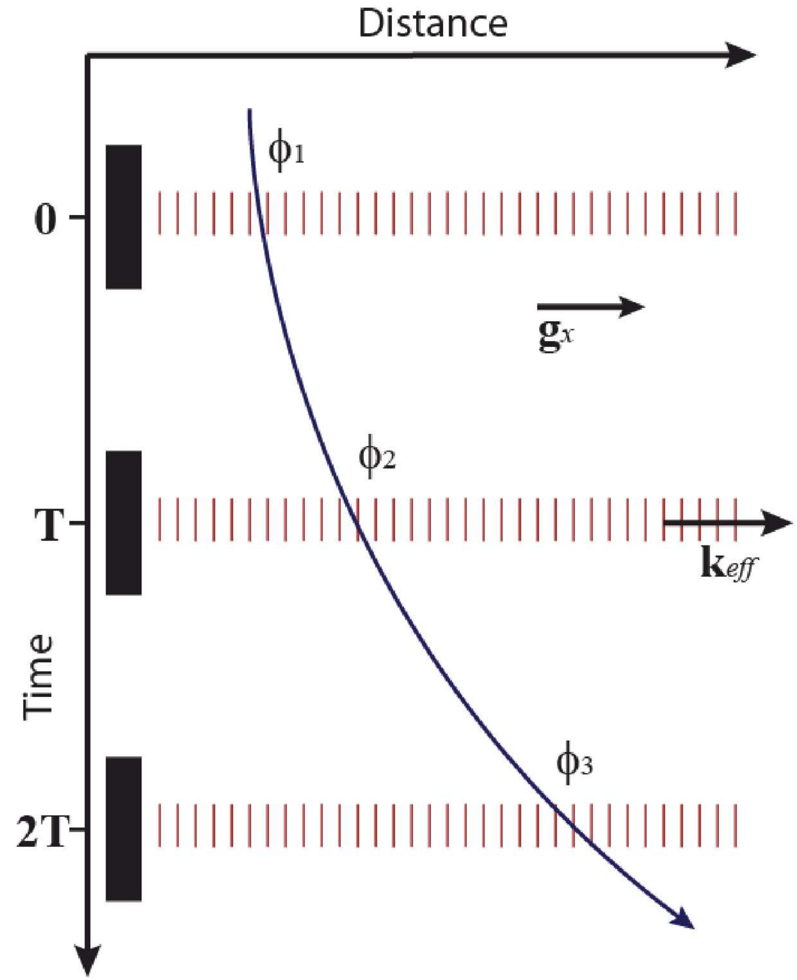
calculate curvature via finite difference method

$$\Delta\varphi = \varphi_1 - 2\varphi_2 + \varphi_3$$



…and then

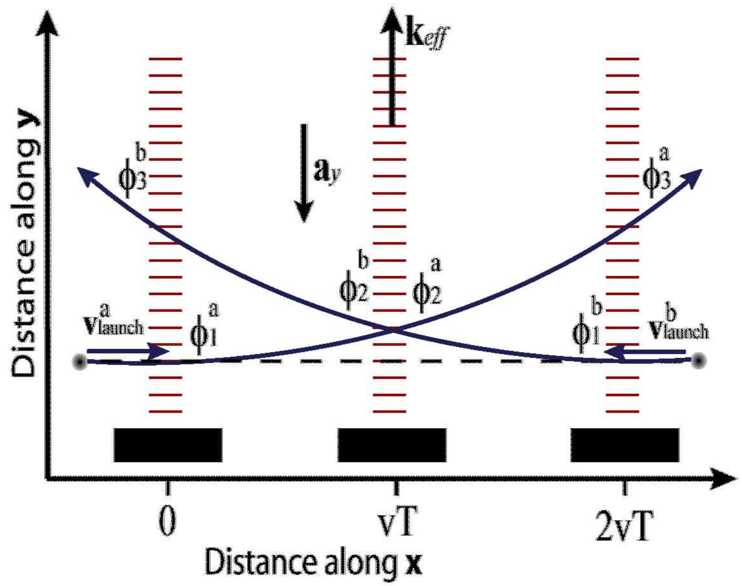
$$g_x = \frac{\Delta\varphi}{k_{eff} T^2}$$



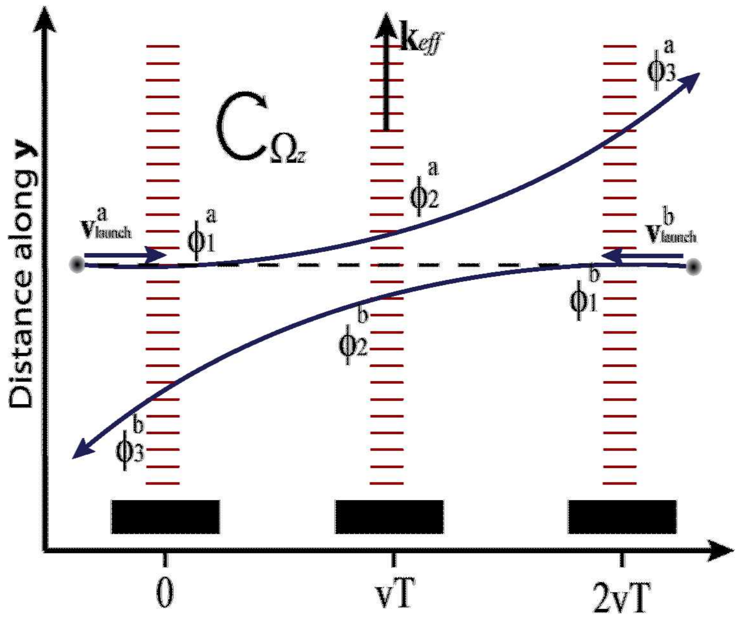
$$P_{|1\rangle} = \frac{1}{2}(1 - \cos(\Delta\phi + \phi_0))$$

…$S_{1/2}$ states behave as a pristine oscillator with phase memory

Simultaneously measure rotation and acceleration



Platform acceleration

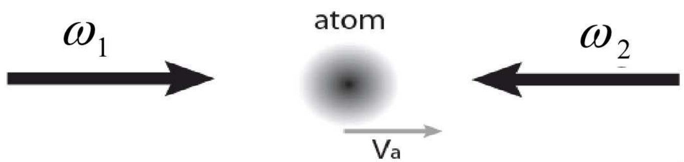


Platform rotation

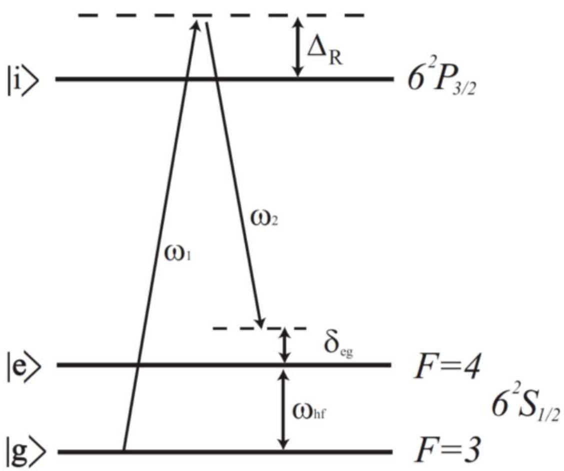
$$\Delta\phi = \vec{k}_{eff} \cdot (\vec{a}T^2 - 2(\vec{v} \times \vec{\Omega})T^2)$$

Stimulated Raman transition

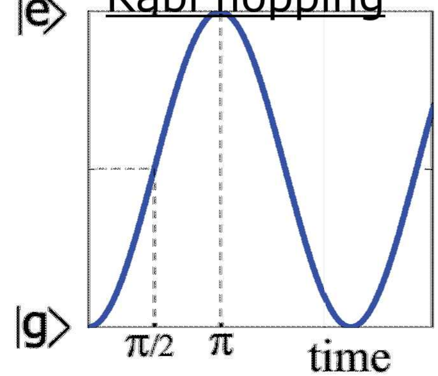
Laser configuration



Relevant energy diagram (Cs)



Rabi flopping



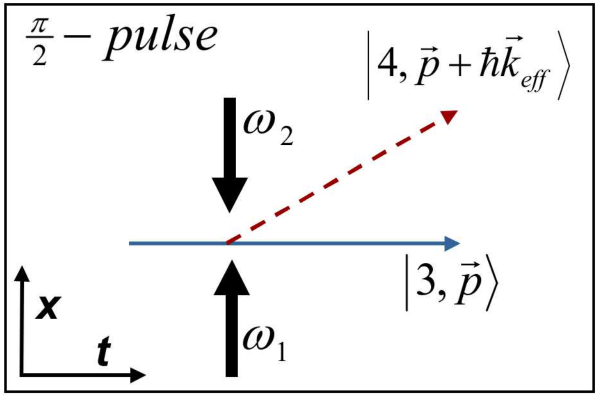
Effective 2-level system

$$H'_{\text{int}} = -\vec{\mu}_{eff} \cdot \vec{E}_{eff} e^{i(\vec{k}_{eff} \cdot \vec{x} - \omega_{hf} t)}$$

$$\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2 \approx 2\vec{k}_1$$

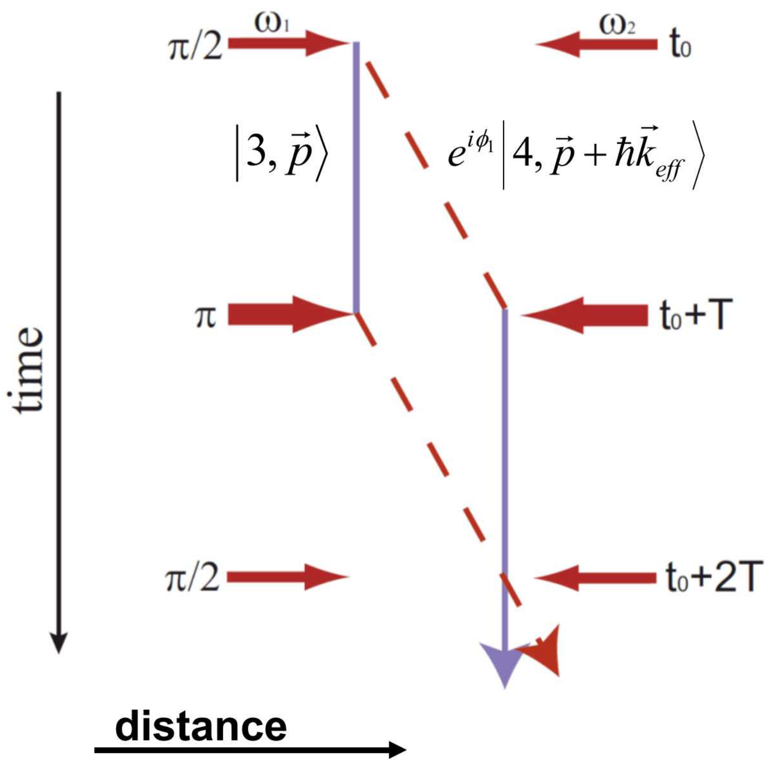
Valid for $\Omega_{eff} << \Delta$

Atom optics beamsplitter



AI phase shift

Interferometer Recoil diagram



Transition rules

$$|3,\vec{p}\rangle \rightarrow e^{i\phi}|4,\vec{p}+\hbar\vec{k}_{eff}\rangle$$

$$|4,\vec{p}+\hbar\vec{k}_{eff}\rangle \rightarrow e^{-i\phi}|3,\vec{p}\rangle$$

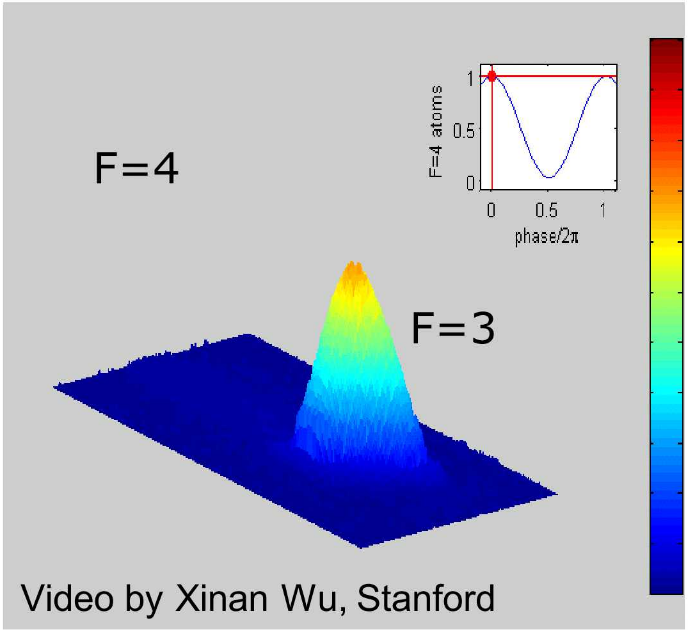
$$\phi = \vec{k}_{eff}\cdot\vec{x}$$

$$\left.\right\}\Delta\phi = \phi_1 - 2\phi_2 + \phi_3 = \vec{k}_{eff}\cdot(\vec{a}T^2 - 2(\vec{v}\times\vec{\Omega})T^2)$$

Interferometer transition probability

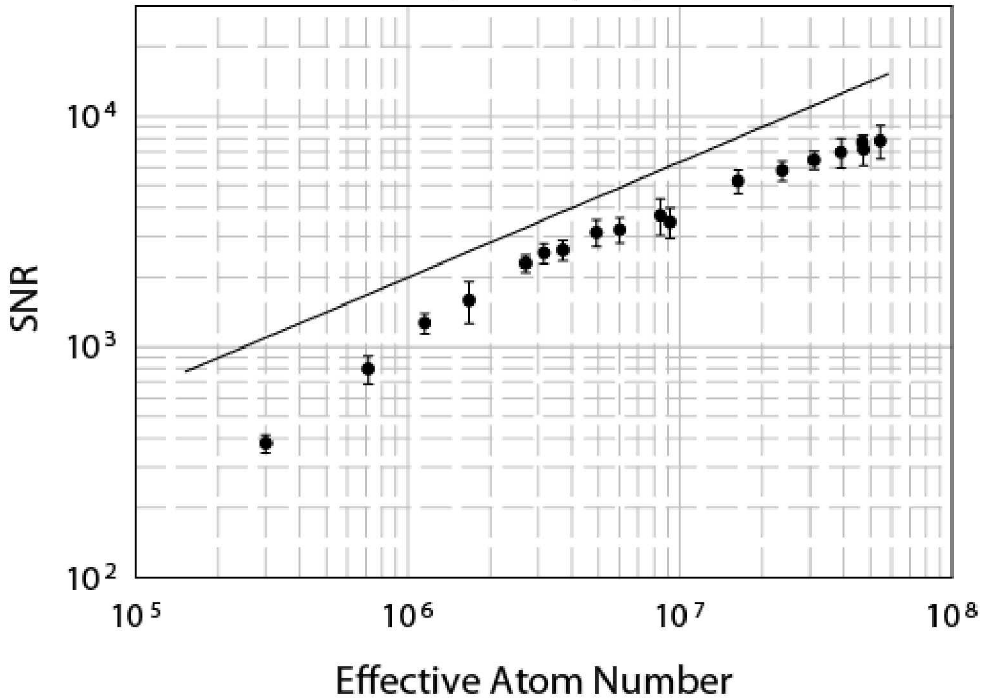
$$|\langle 4|\Psi\rangle|^2 = \tfrac{1}{2}(1-\cos\Delta\phi)$$

State detection

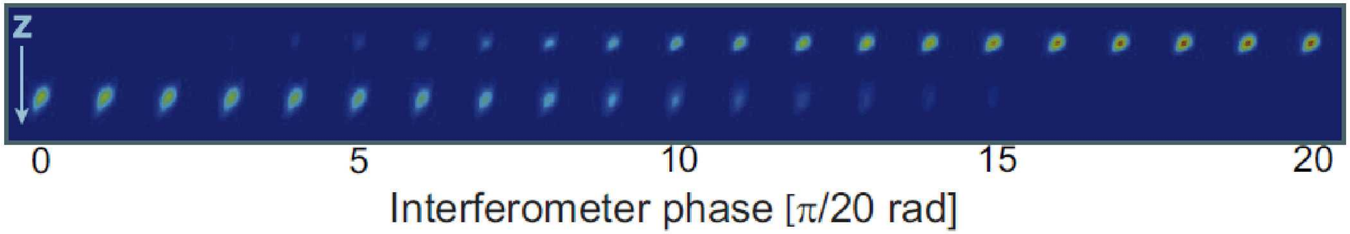


Radiation pressure spatially separates F=3 and F=4 atoms

Biedermann, et al., Opt. Lett. 2007



Achieves near atom shot-noise limited performance.



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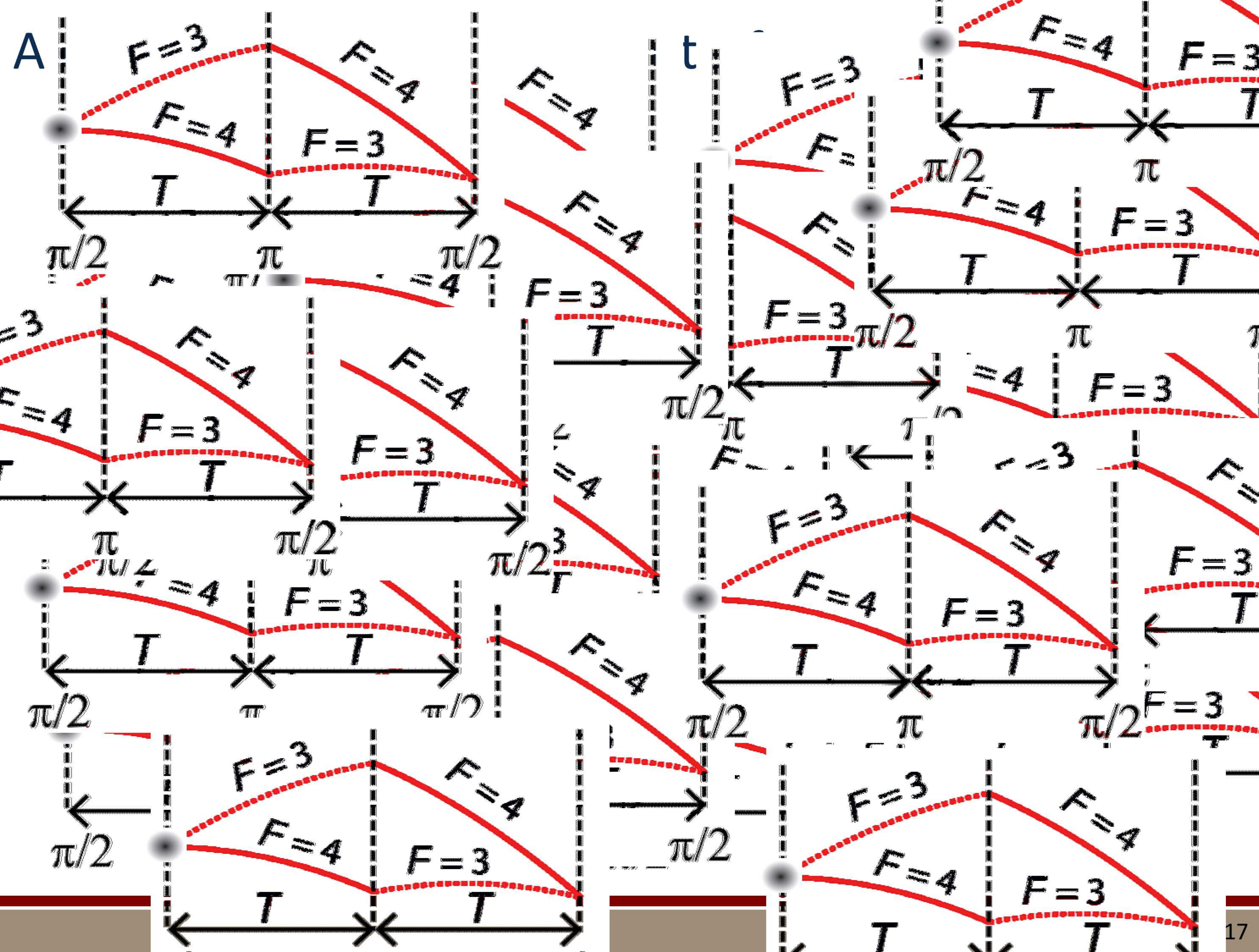
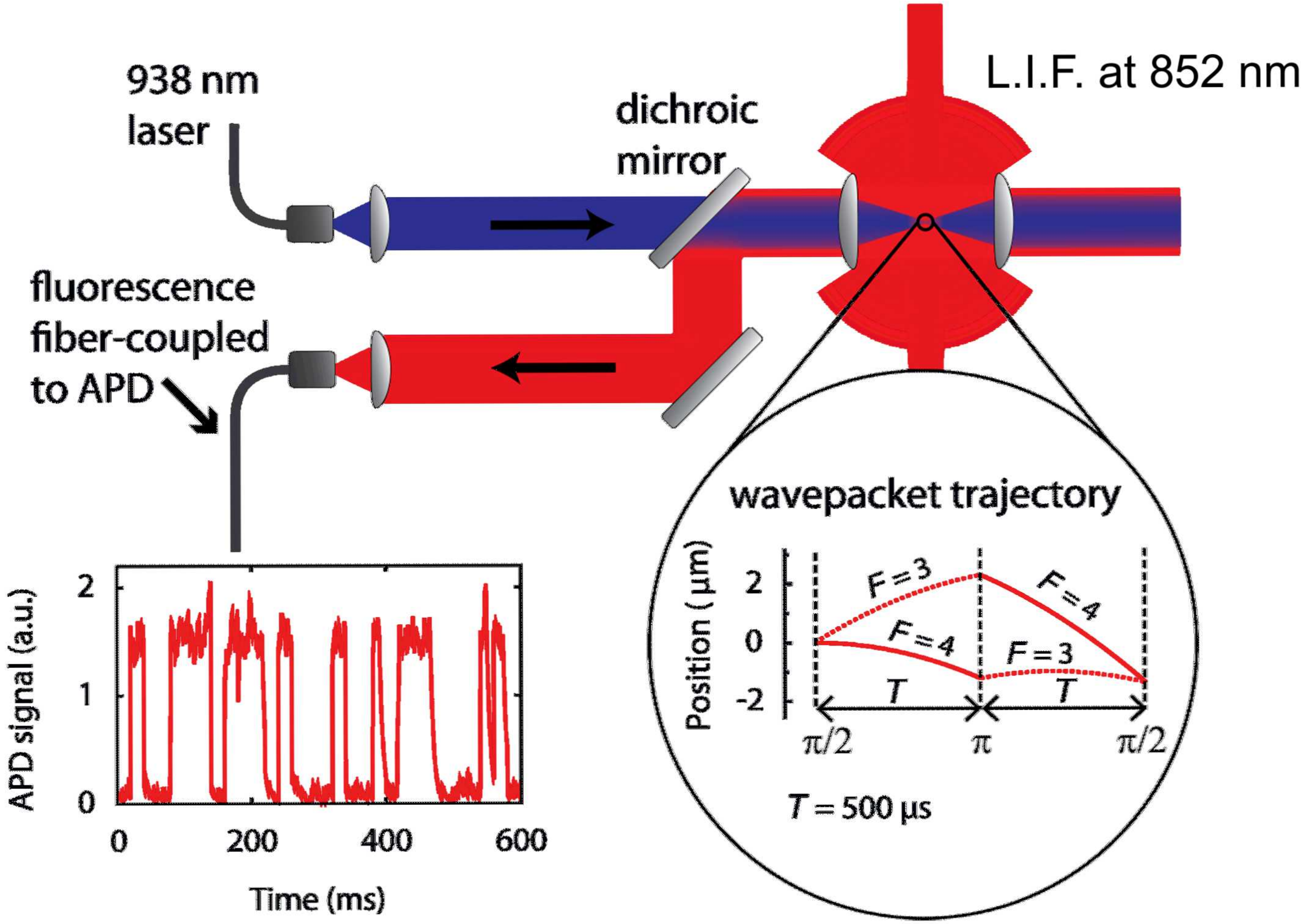
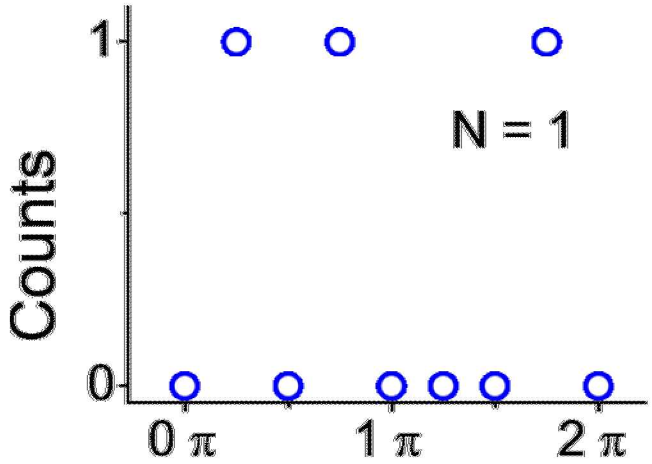


Free-space matterwave interference with a single atom



Building fringe one atom at a time

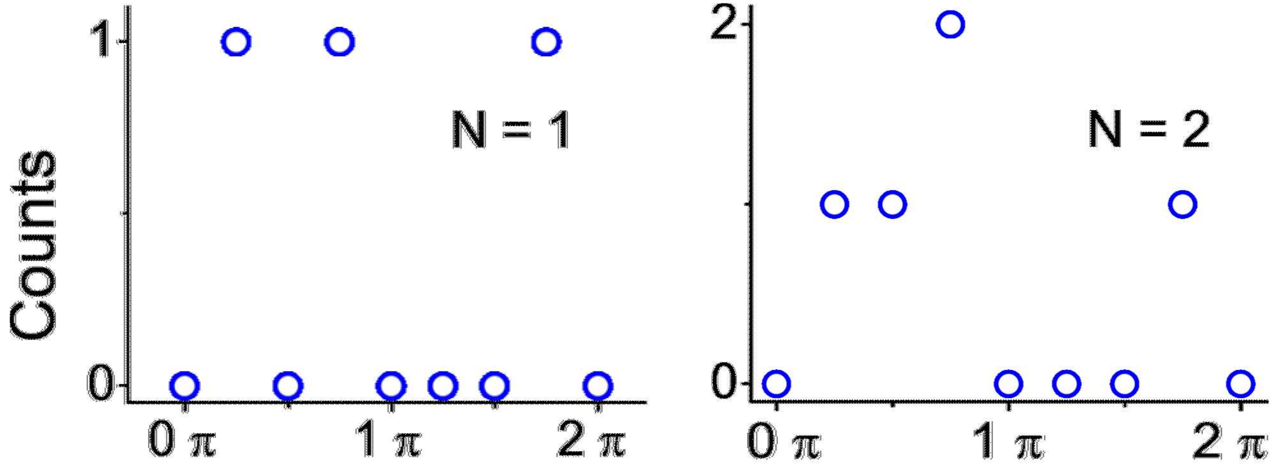


- 1 atom per phase through interferometer.

$$H'_{\text{int}} = -\vec{\mu}_{eff} \cdot \vec{E}_{eff} e^{i(\vec{k}_{eff} \cdot \vec{x} - \omega_{hf} t)}$$

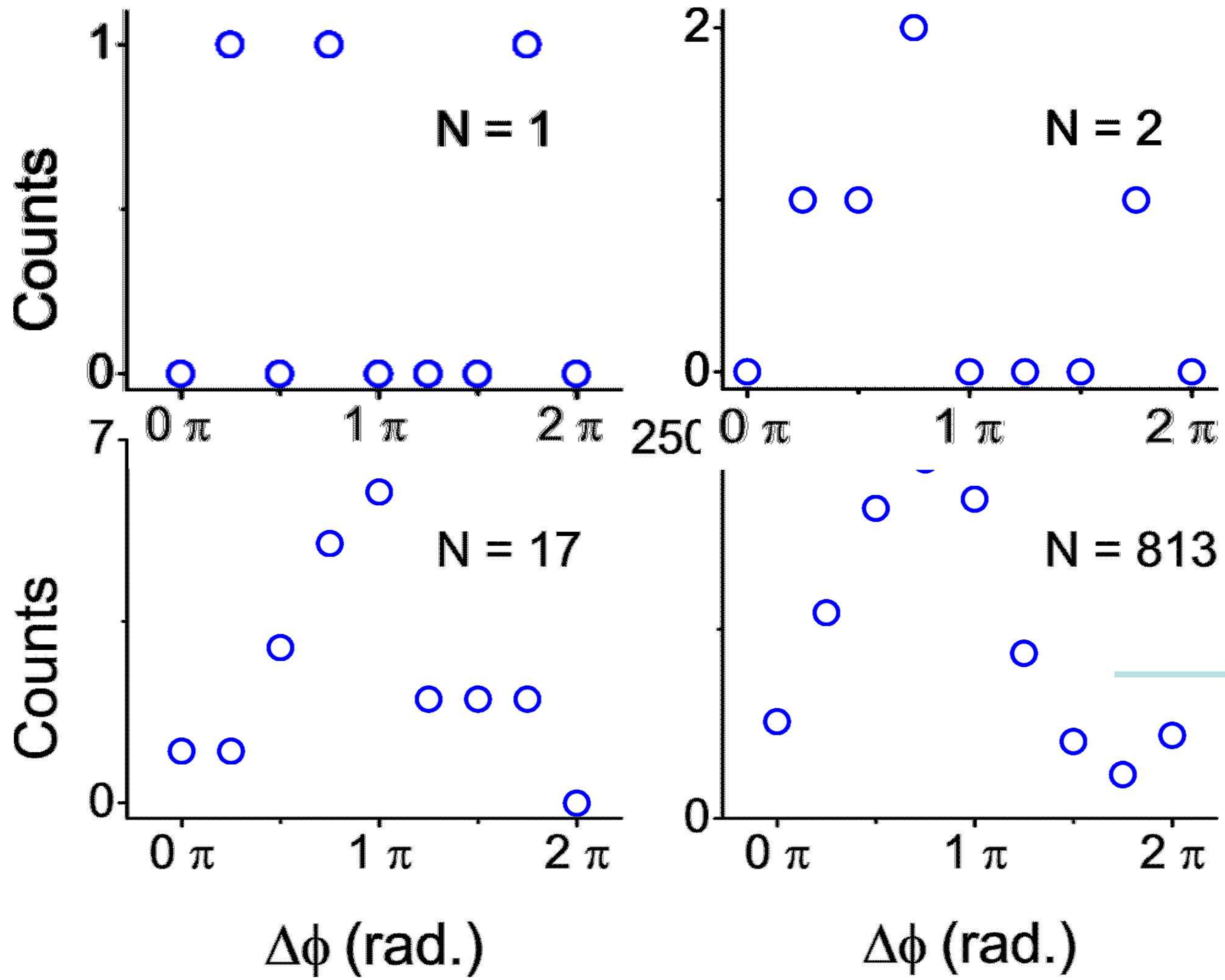
Scan laser phase

Building fringe one atom at a time



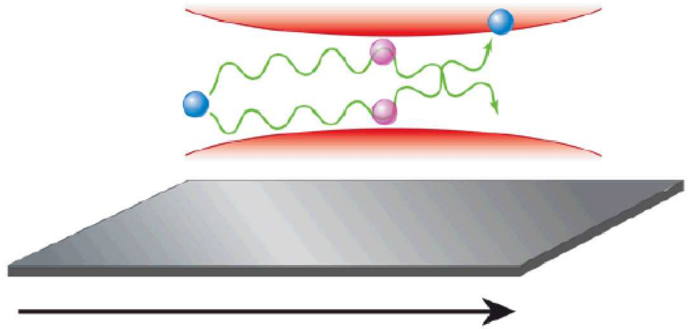
- 2 atoms per phase through interferometer

Building fringe one atom at a time



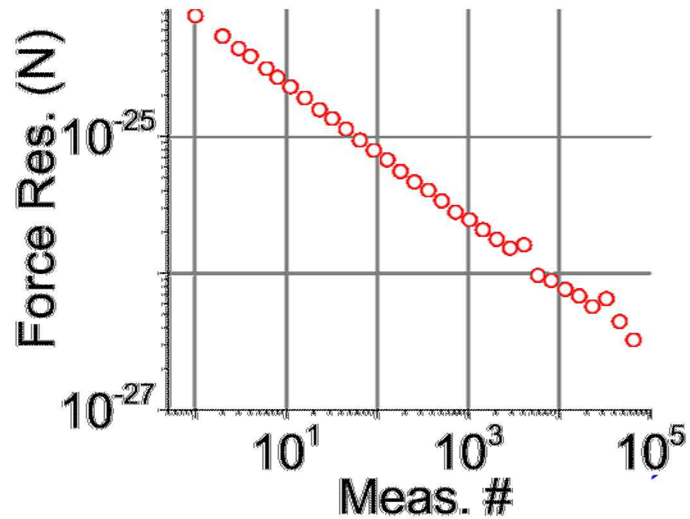
7,317 atoms

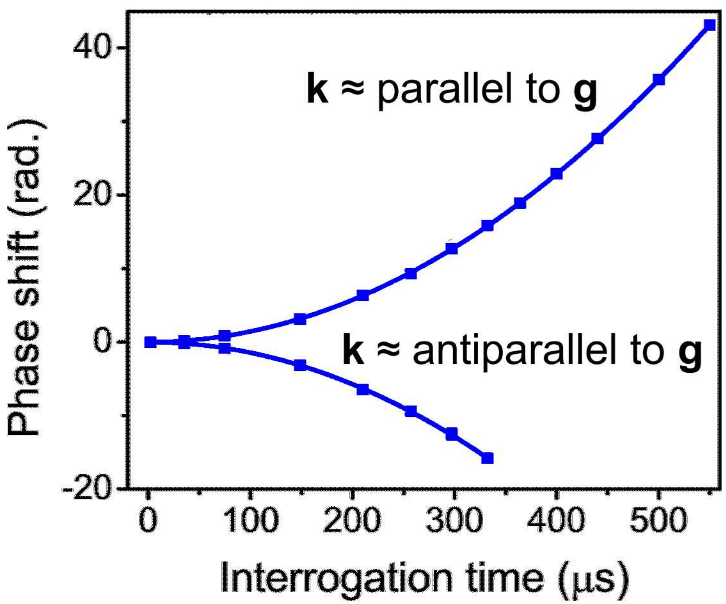
Force resolution of a single atom interferometer



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

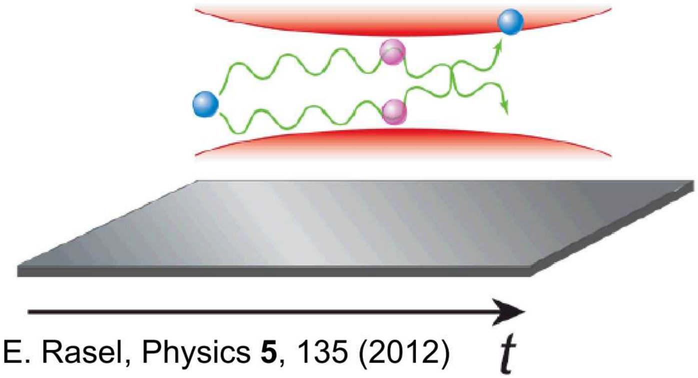
Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)





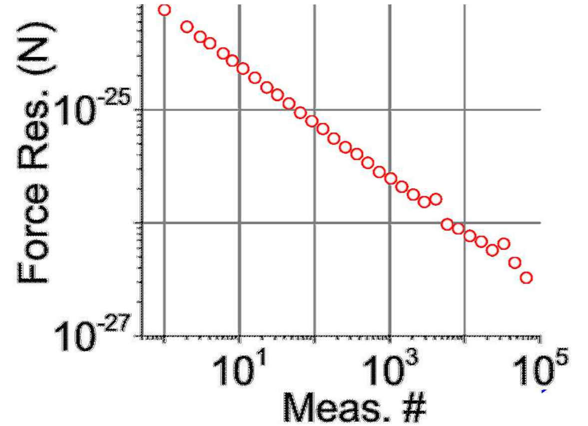
$$\Delta\phi = \vec{k}_{eff} \cdot \vec{g}\, T^2$$

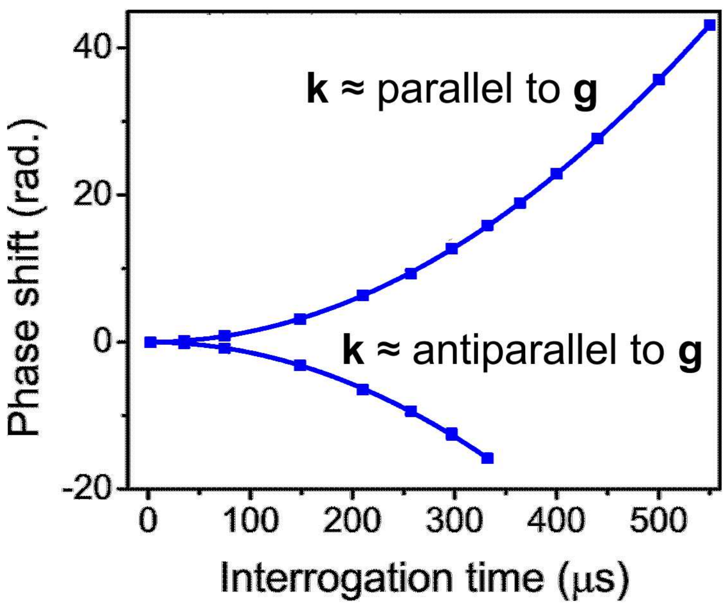
Force resolution of a single atom interferometer

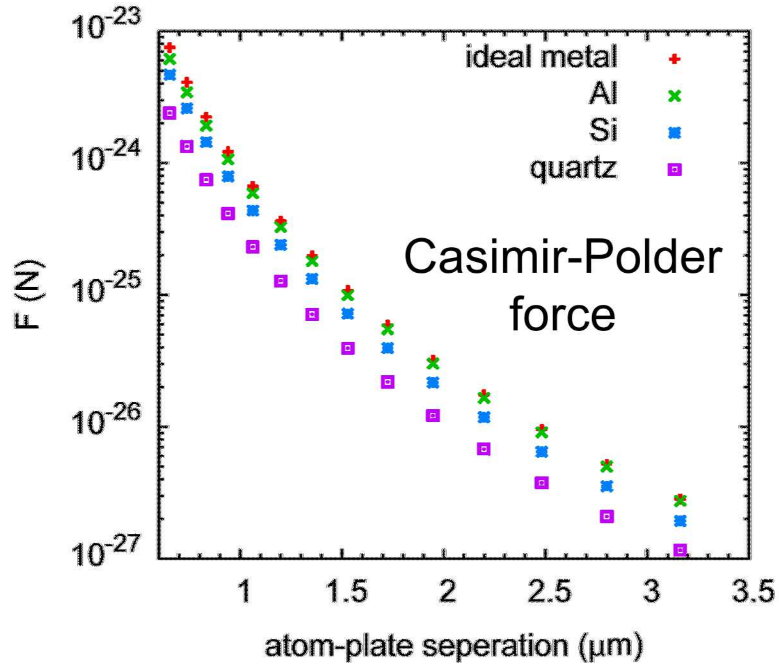


E. Rasel, Physics **5**, 135 (2012)

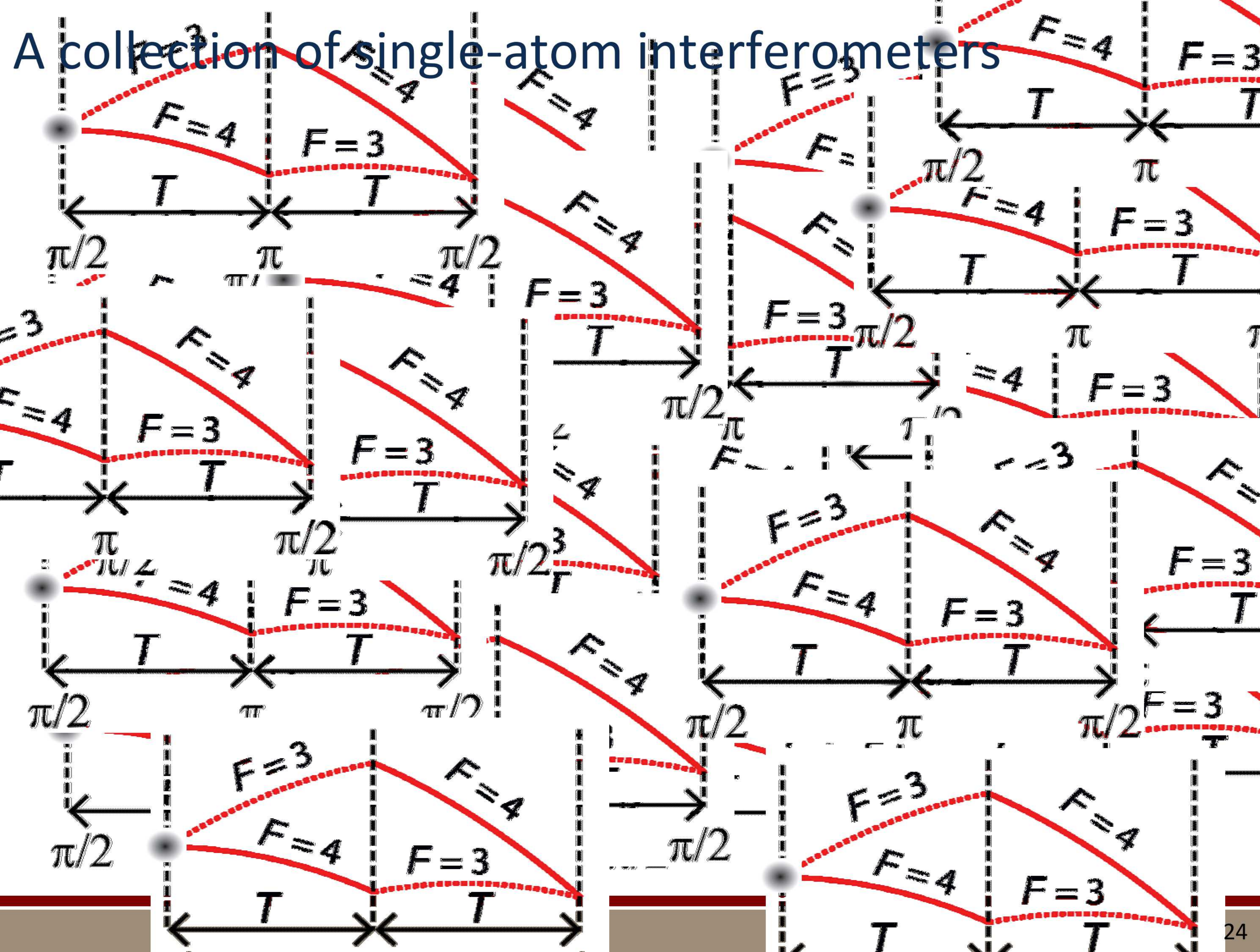
Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)





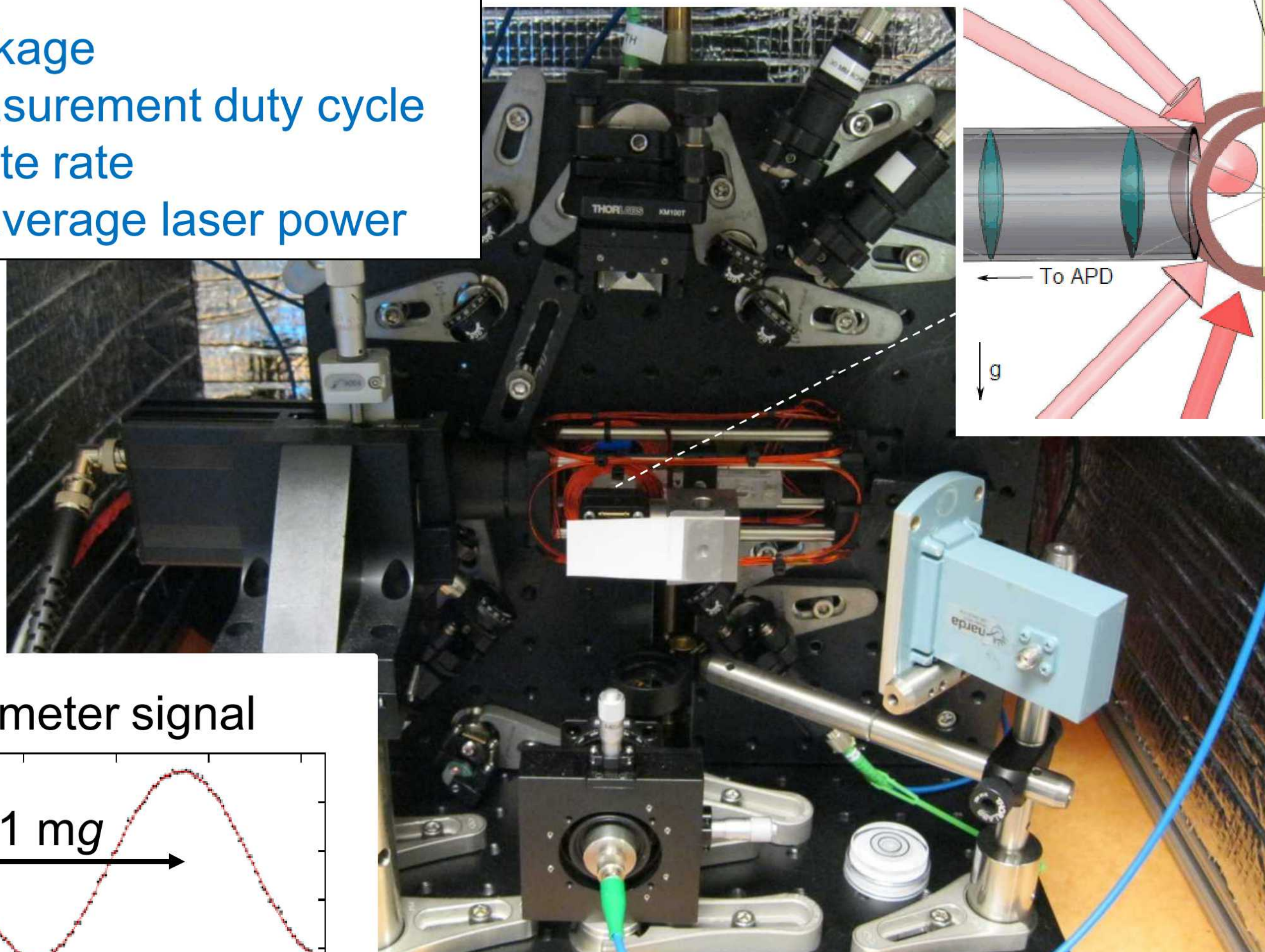


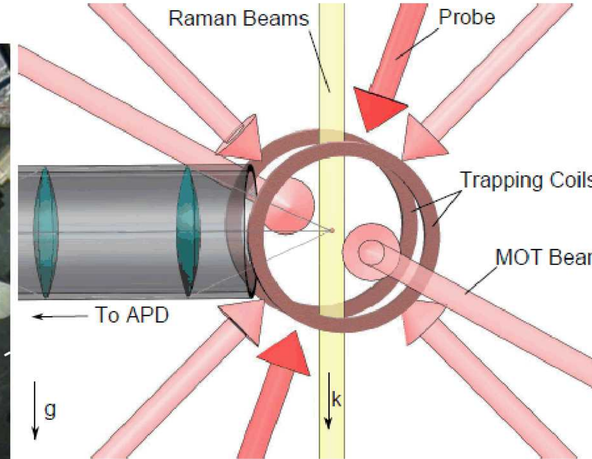
A collection of single-atom interferometers



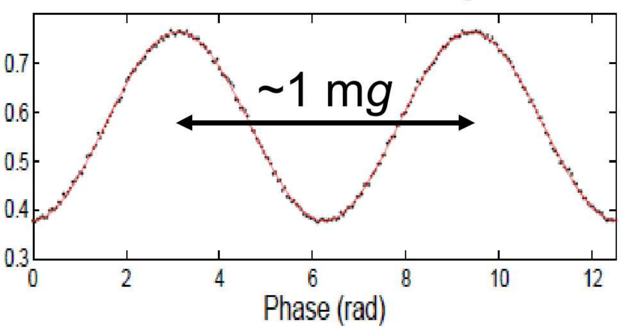
High-bandwidth interferometer

Key features
- small package
- large measurement duty cycle
- high update rate
- reduced average laser power





Interferometer signal

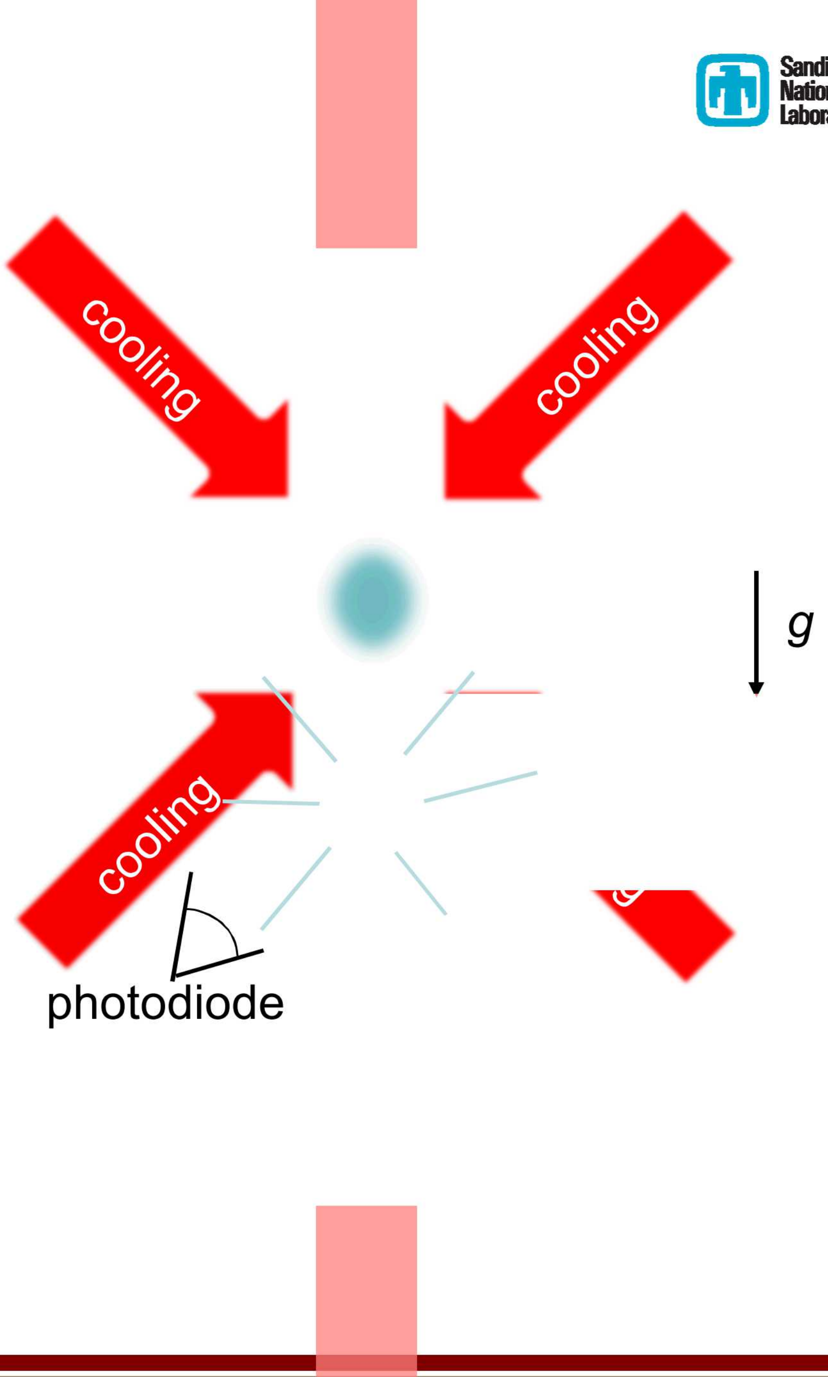


600 $ng/\sqrt{Hz}$ at 50 Hz

One measurement cycle

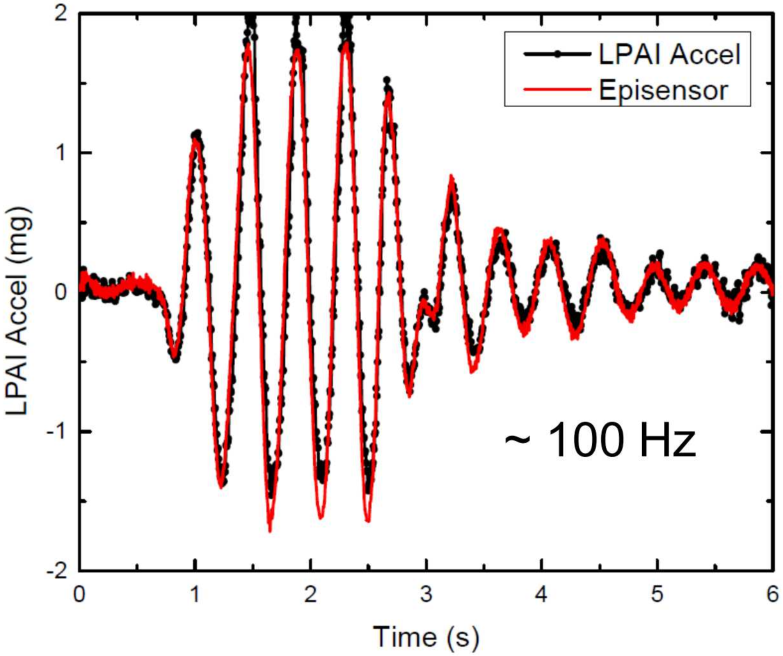
Example, (50 Hz)$^{-1}$ cycle:

- Laser cool 10^6 atoms (4.3 ms)
  - $T \approx 5\ \mu$K
- Release atoms
- Raman pulse sequence (14 ms, T = 7 ms)
- Detect
- Recapture (1.7 ms)

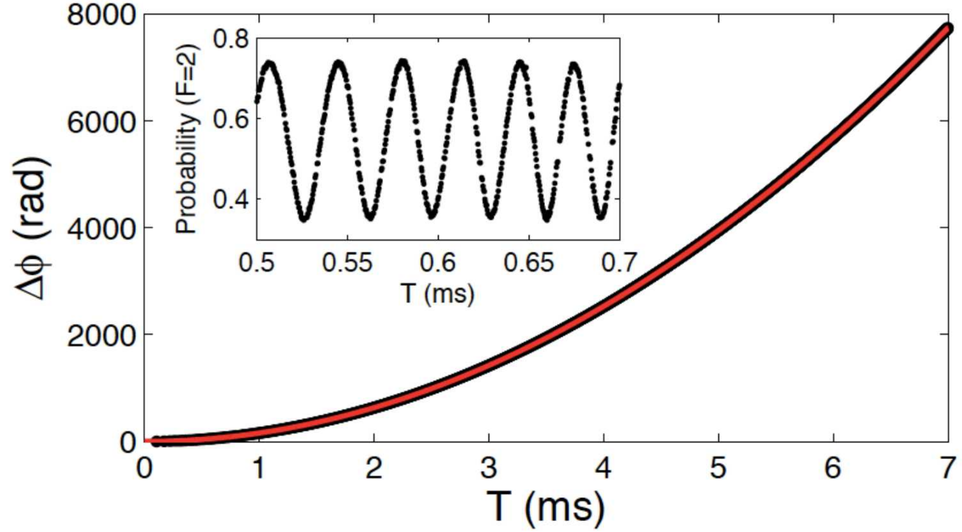


High bandwidth interferometer results

Operating under dynamics



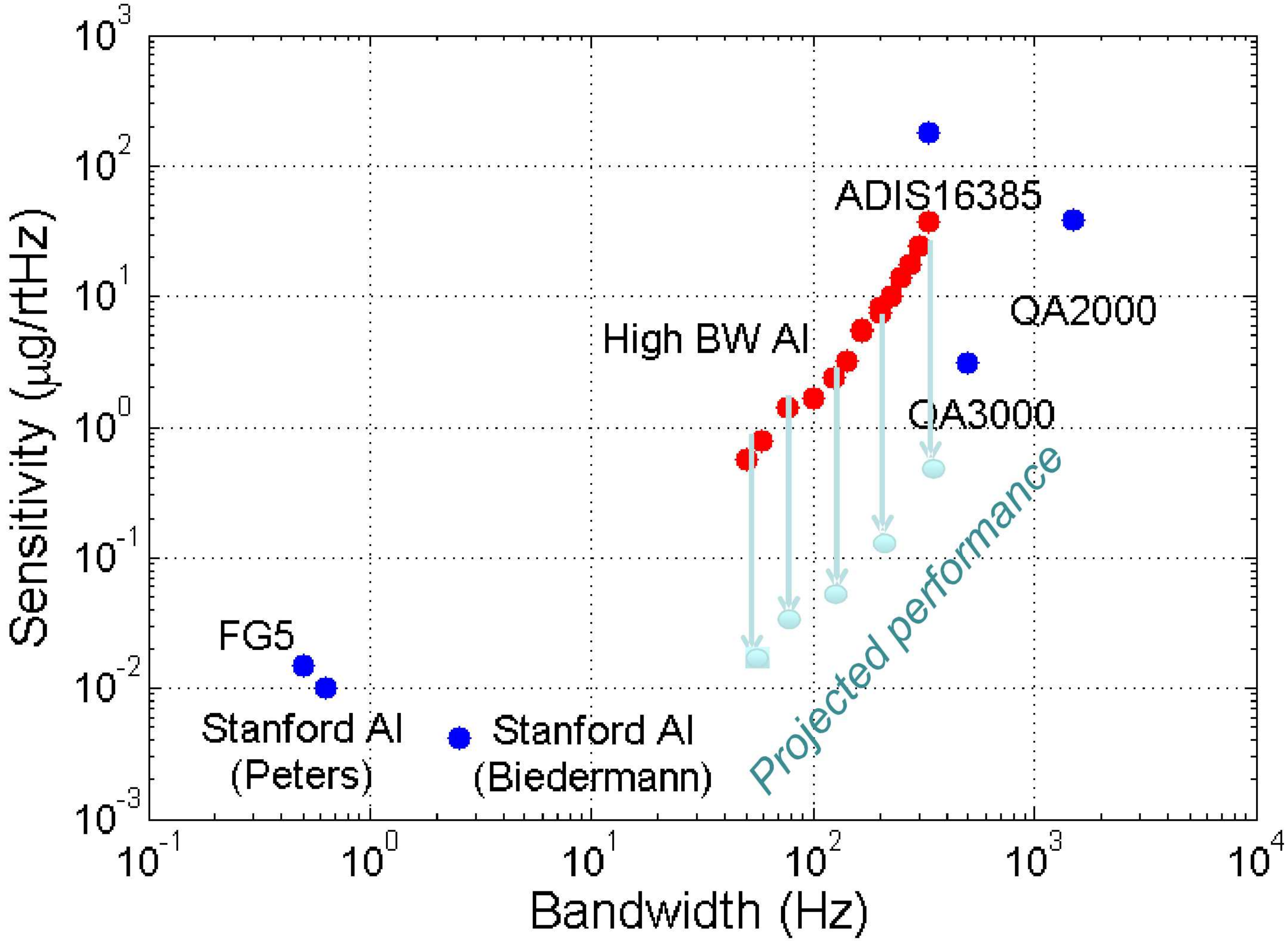
Measurement of *g*



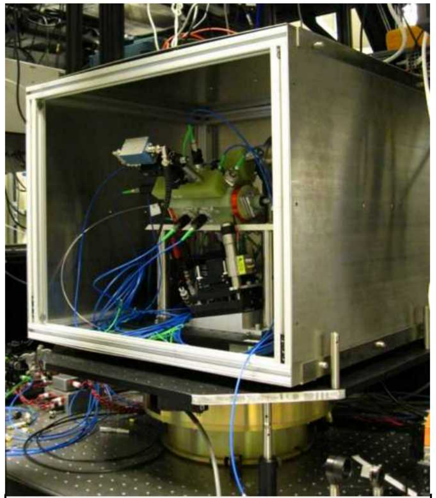
$$\Delta\phi = \boldsymbol{k}_{eff} \cdot \boldsymbol{a}T^2$$

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

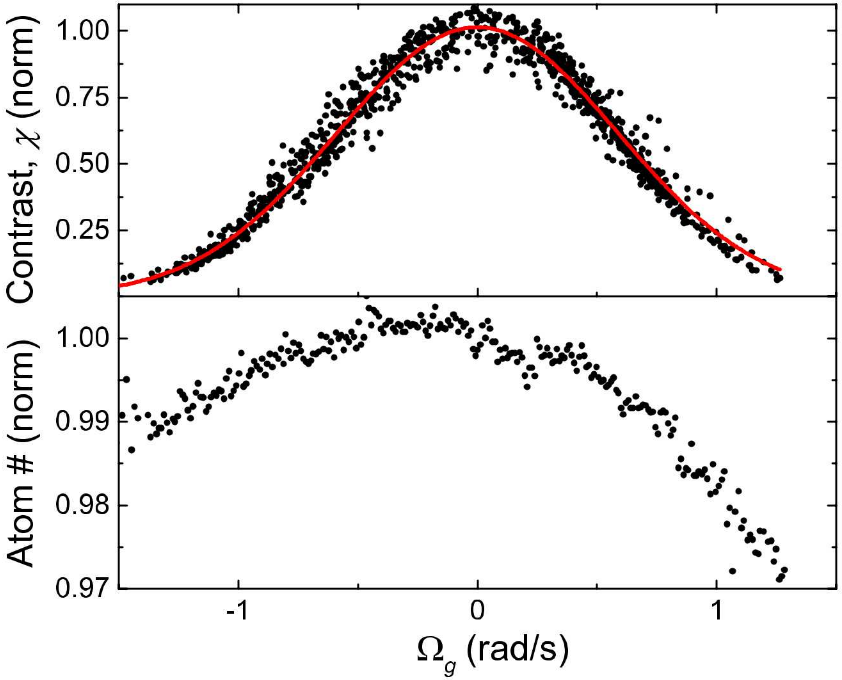
Interferometer comparison



Rotation rate limit



Mechanized A.I. Sensor



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

Limited by temperature
&
Wavepacket overlap

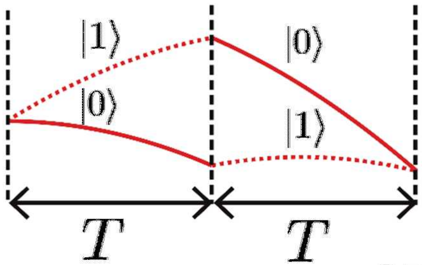
Contrast envelope $\chi(\Omega_z) = \exp\left(\frac{-\Omega_z^2}{2\sigma_\Omega^2}\right)$

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

What will it take?

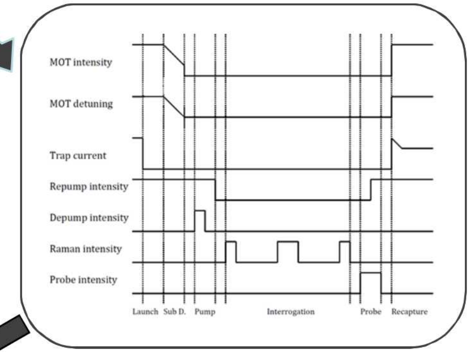
UHV vacuum system

Atom interferometer physics

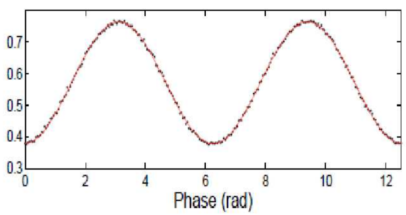


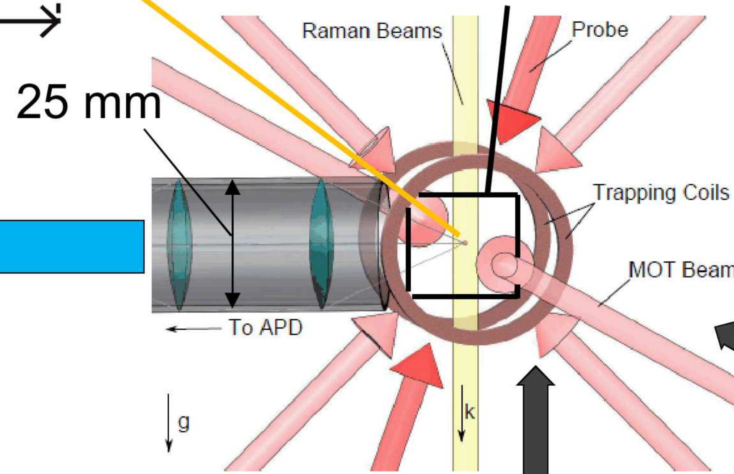
Dynamic range servo

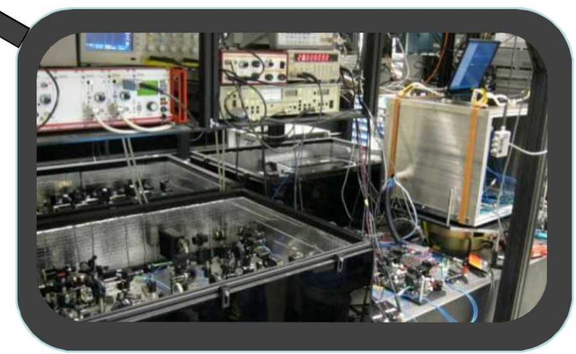
Control electronics



Acceleration →

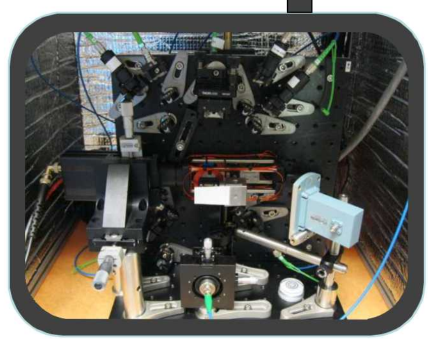






Agile & stable laser system

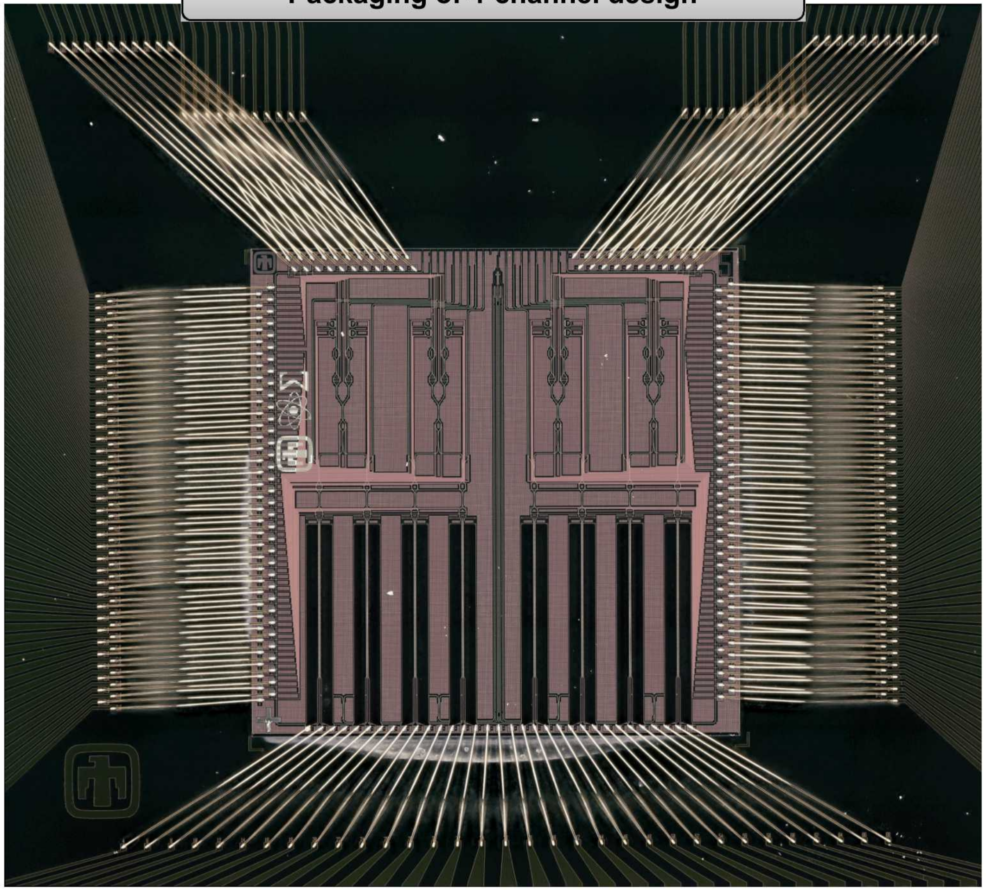
New project at SNL



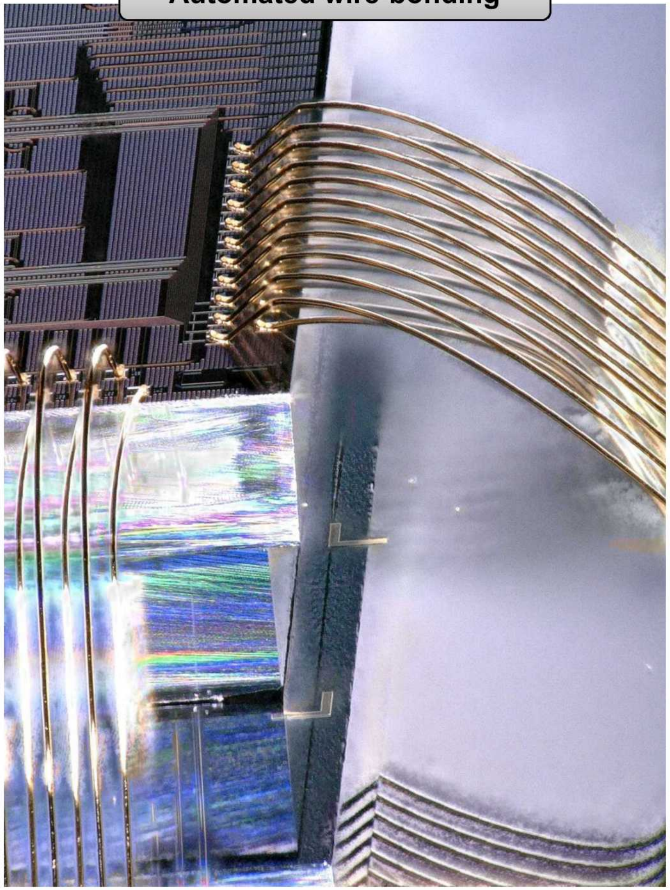
Custom optomechanics

A multi-channel laser system front end

Packaging of 4-channel design

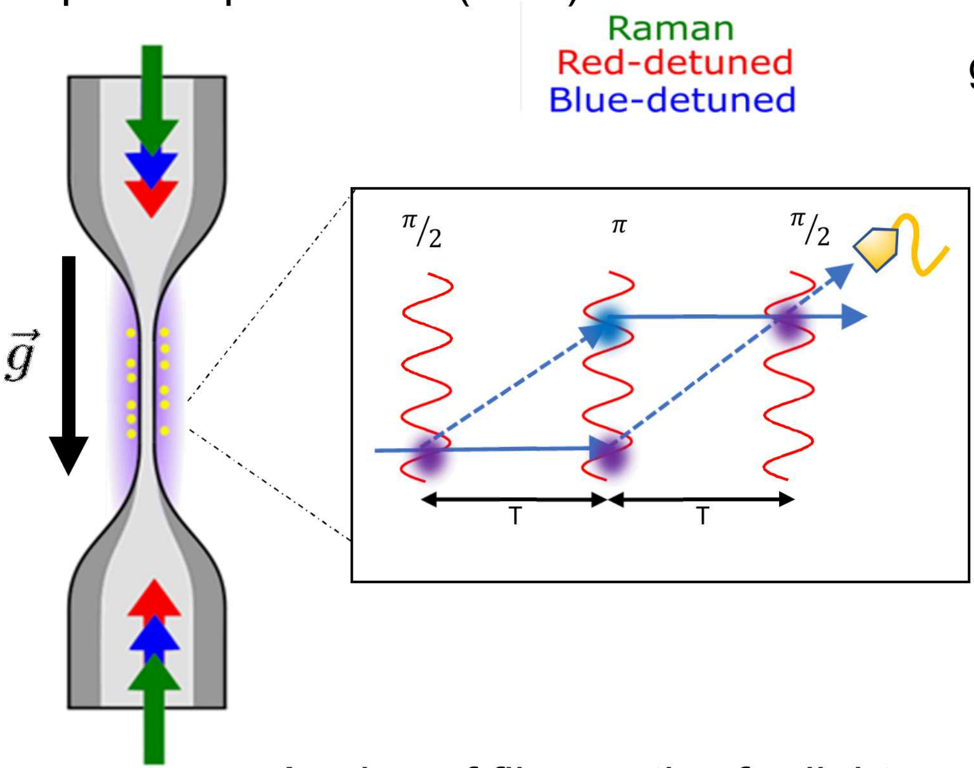


Automated wire-bonding



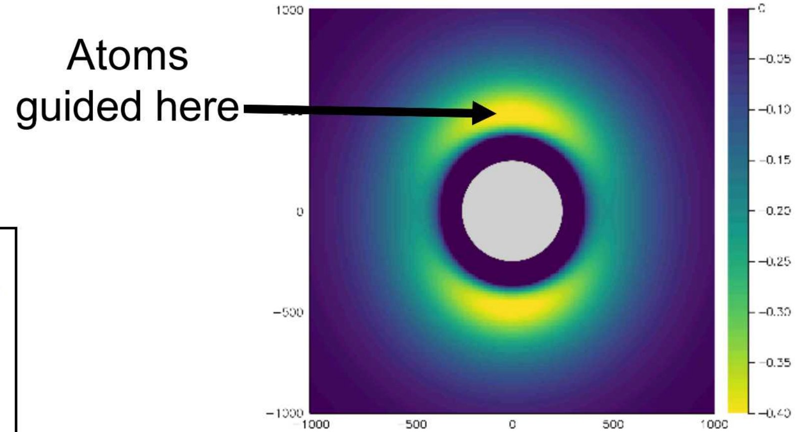
A nanofiber guide for matterwaves

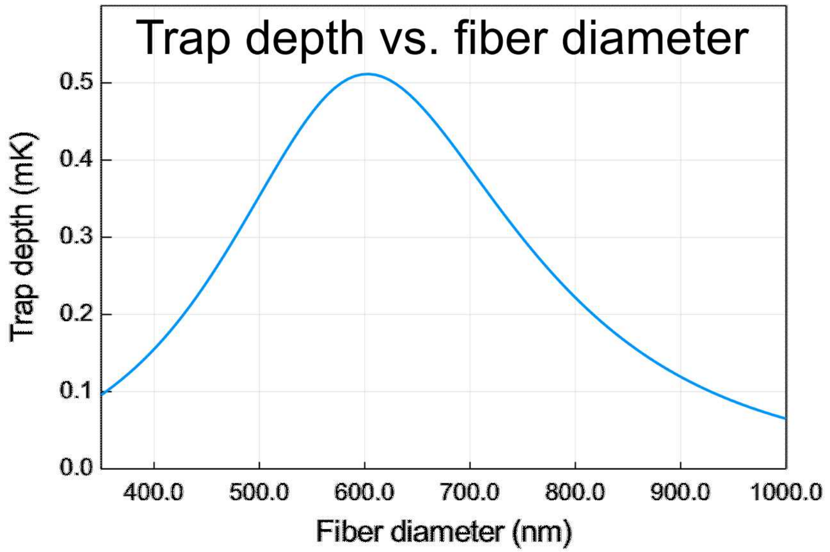
Atom Interferometer guided via tapered optical fiber (TOF)



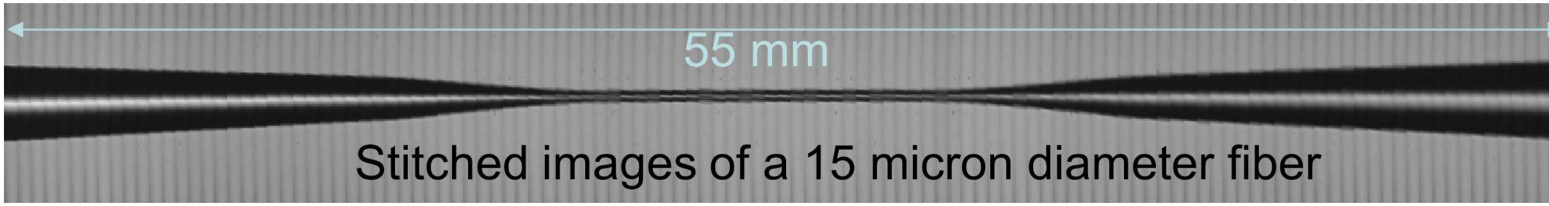
- Analog of fiber optics for light
- Guide atoms near surfaces
  - Casimir-Polder effect
  - Constrain 5th force theories

Calculated intensity distribution



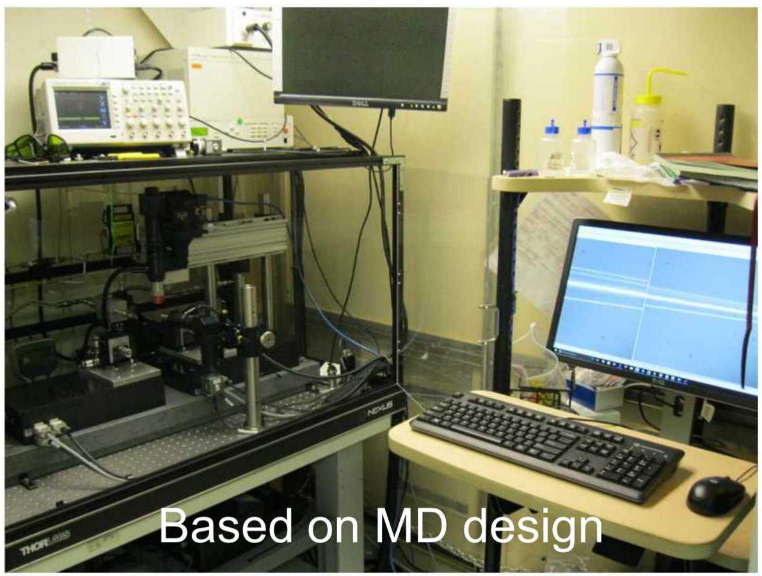


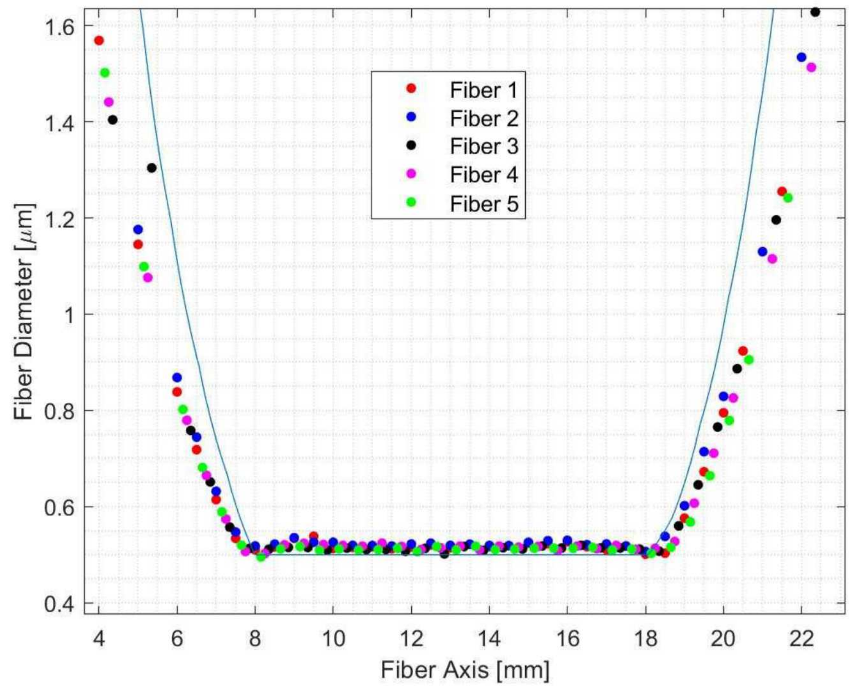
A nanofiber guide for matterwaves



Stitched images of a TOF

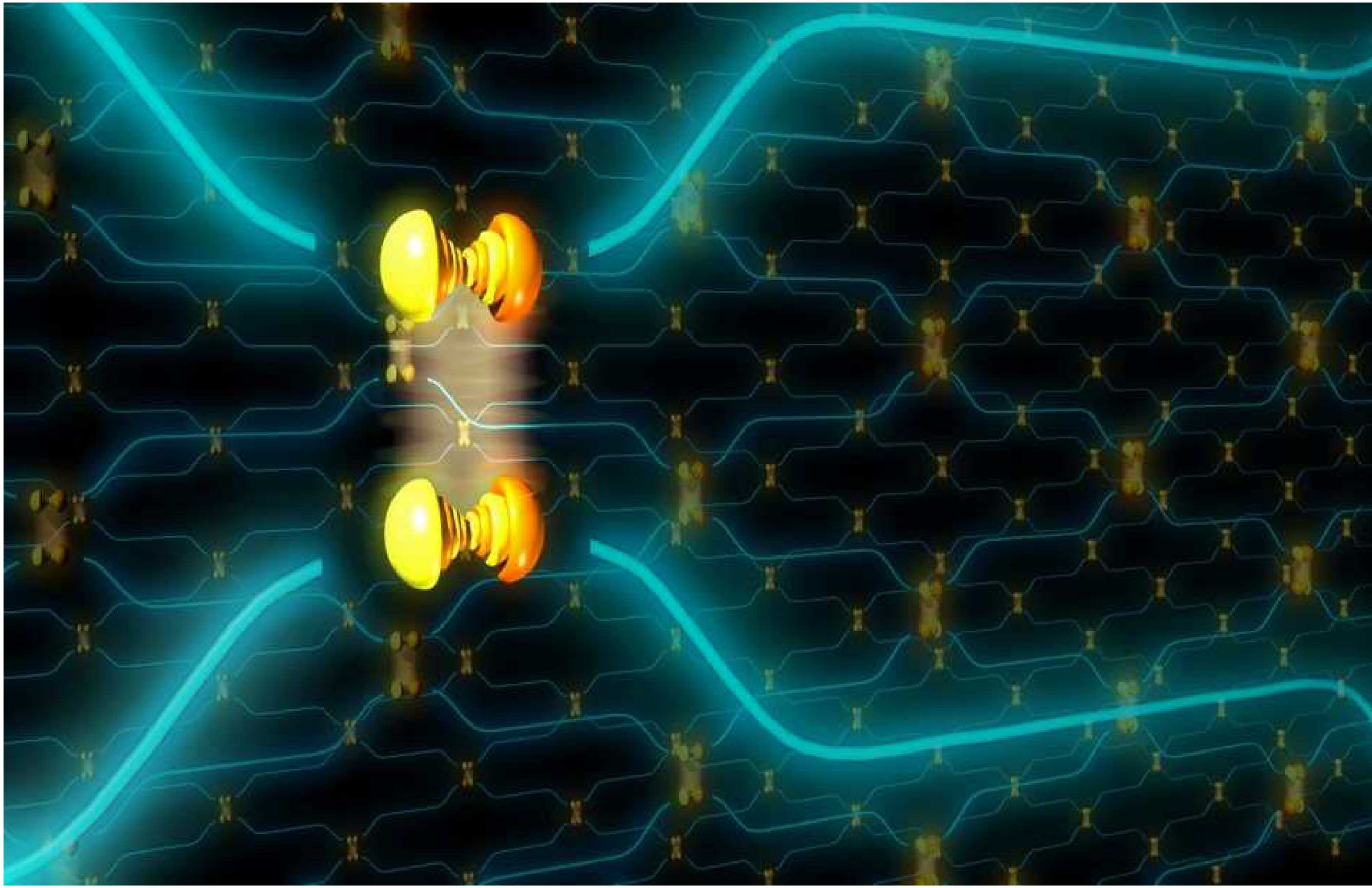
Sandia nanofiber rig—NEW





Entangled states of neutral atoms

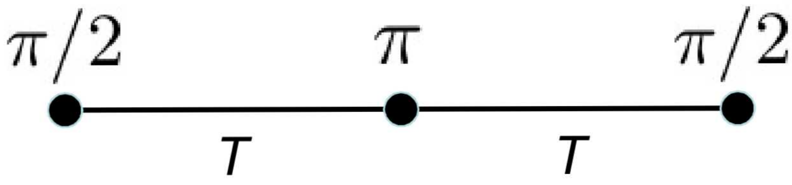
Sandia National Laboratories



AI operated with entangled atoms

Single atom

$$\frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

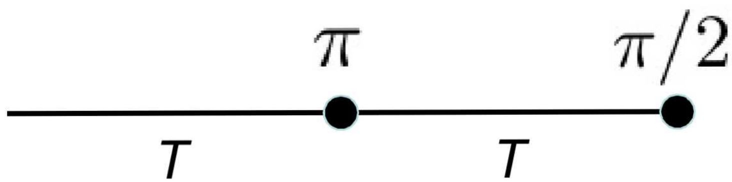


$$\langle \Pi \rangle = \cos \Theta_1$$

$$\Theta_1 = \mathbf{K} \cdot \mathbf{a}\, T^2$$

Two entangled atoms

$$\frac{|gg\rangle + |ee\rangle}{\sqrt{2}}$$

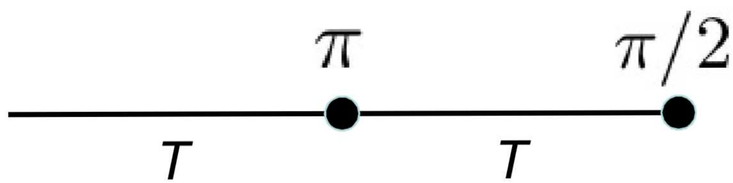


$$\langle \Pi \rangle = \cos \Theta_2$$

$$\Theta_2 = \mathbf{K} \cdot (\mathbf{a}_1 + \mathbf{a}_2)\, T^2$$

N entangled atoms

$$\frac{|g \dots g\rangle + |e \dots e\rangle}{\sqrt{2}}$$



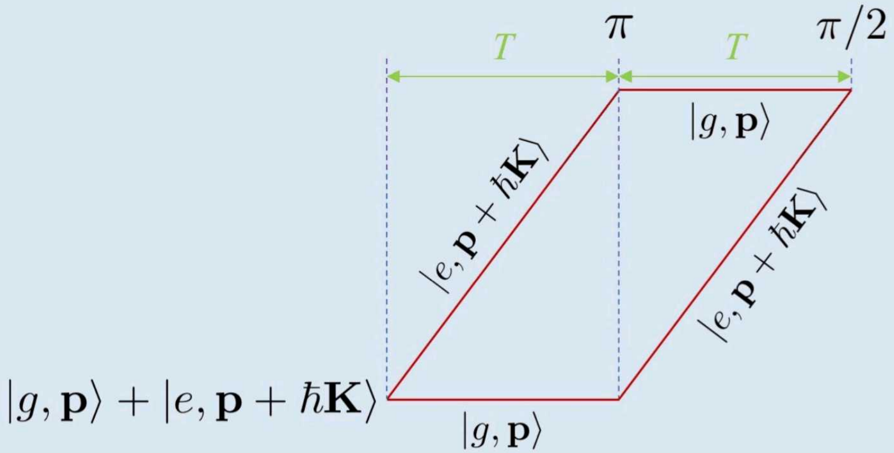
$$\langle \Pi \rangle = \cos \Theta_N$$

$$\Theta_N = \mathbf{K} \cdot \sum_{\alpha=1}^{N} \mathbf{a}_\alpha\, T^2$$

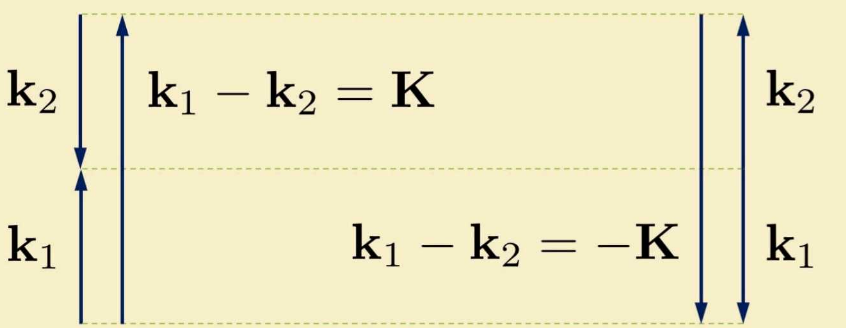
$$\langle \Pi \rangle = (-1)^{\mathrm{N}_\uparrow}$$

New pulse sequences for AI operation

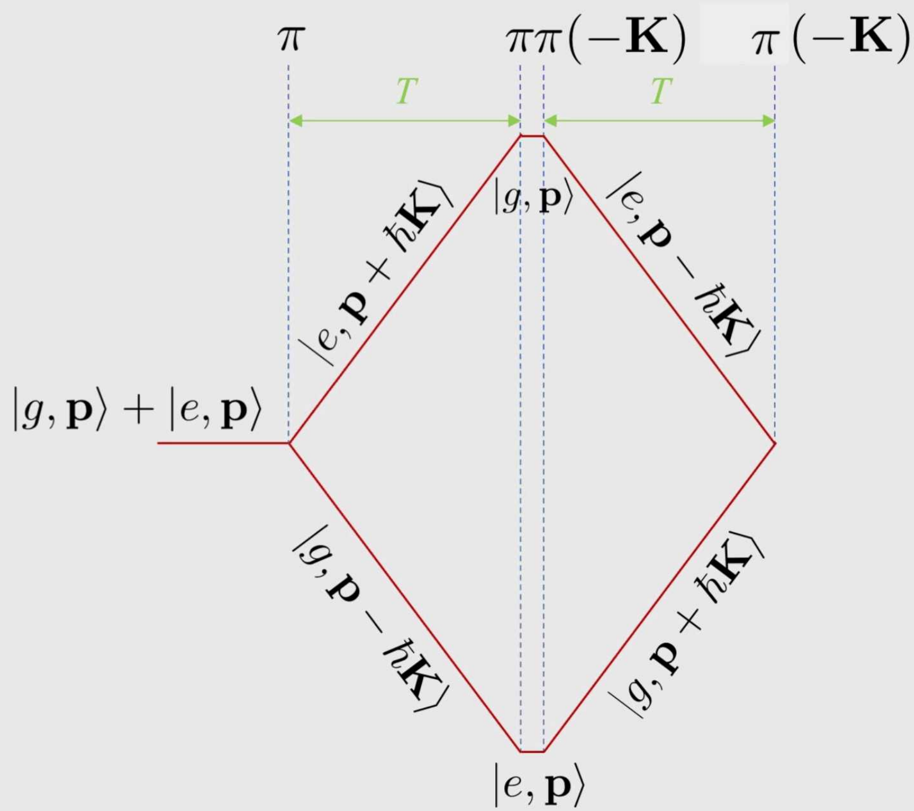
AI with Doppler-sensitive initial entangled state



Raman beam configurations for $\mathbf{K}$ and $-\mathbf{K}$ pulses

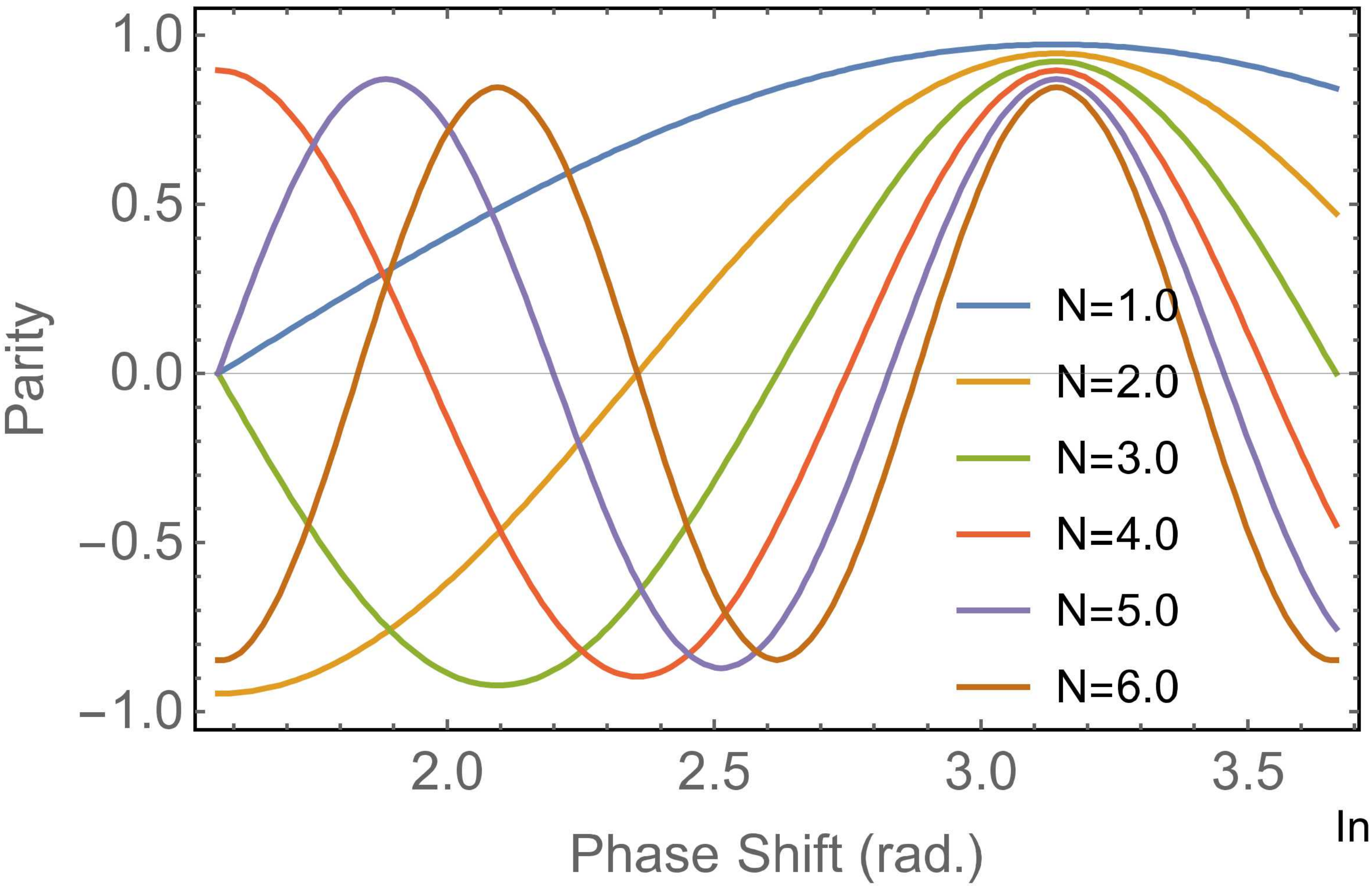


AI with Doppler-free initial entangled state and two additional pulses: $\pi(\mathbf{K})$ and $\pi(-\mathbf{K})$

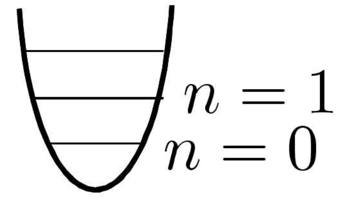


Effect of temperature

N = # atoms



Harmonic oscillator



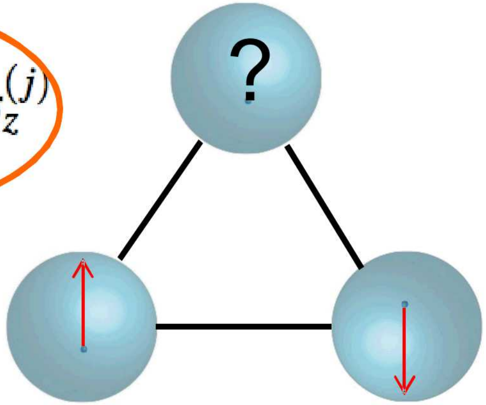
In these simulations

$$\langle n \rangle = 1$$

Applications

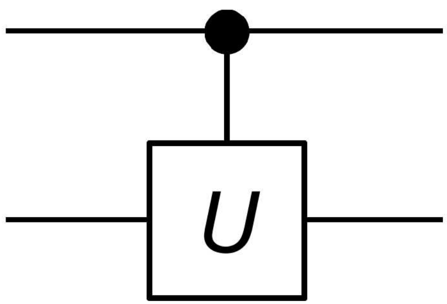
Quantum simulation

$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$



Frustrated magnetism

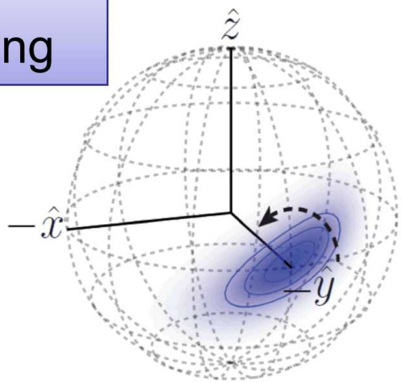
Pairwise entangling gates between two neutral atoms



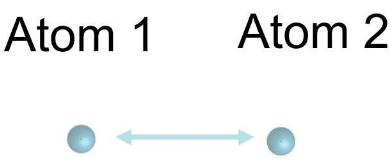
Goal of our research

Achieve exquisite control of interactions

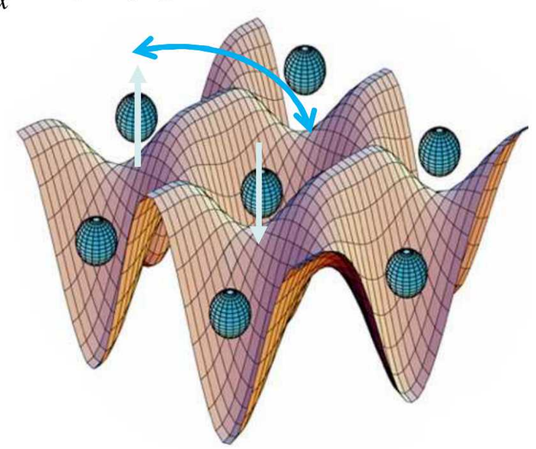
Large-scale/rapid entanglement for sensing



Interaction between *neutral* atoms



$$J_{ex} \propto J^2 / U$$



- Interaction between ground state atoms is small ~100 Hz
- Thermal energy scales too large (*e.g.,* QSIM)
- Long gate times (*e.g.,* QIP)

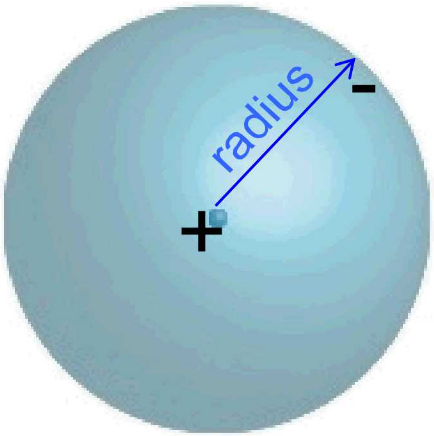
One solution: use Rydberg states

S. Trotzky *et al.*, Science **319**, 295-299 (2008)

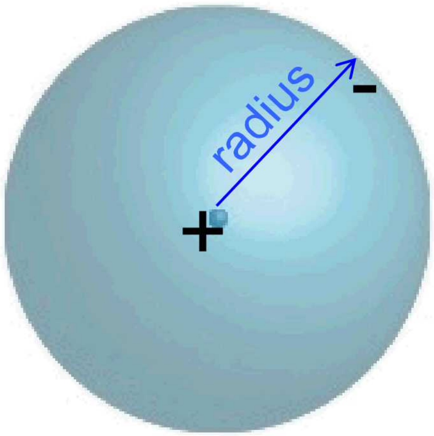
I. Bloch, J. Dalibard, and S. Nascimbène, Nat. Phys. **8**, 267-276 (2012)

Interaction between *neutral* atoms

Valence electron
in Rydberg state



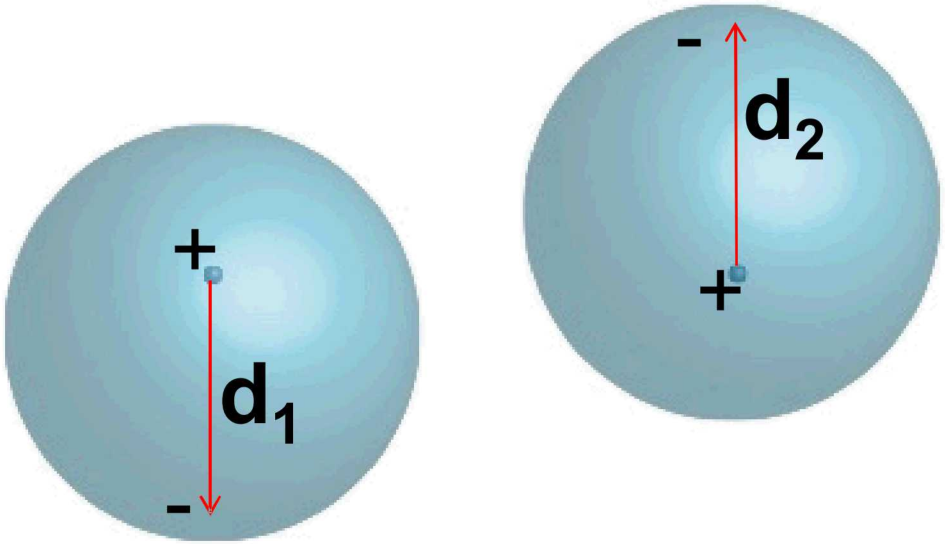
Valence electron
in Rydberg state



orbital radius α n^2

- Excite valence electron to Rydberg state—nearly ionized
- Atom becomes highly polarizable—strong interactions

Interaction between *neutral* atoms



van der Waals interaction

Parameter scaling

van der Waals
$U \propto n^{11}$

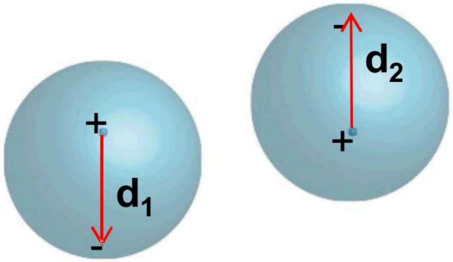
Lifetime
$\tau \propto n^3$

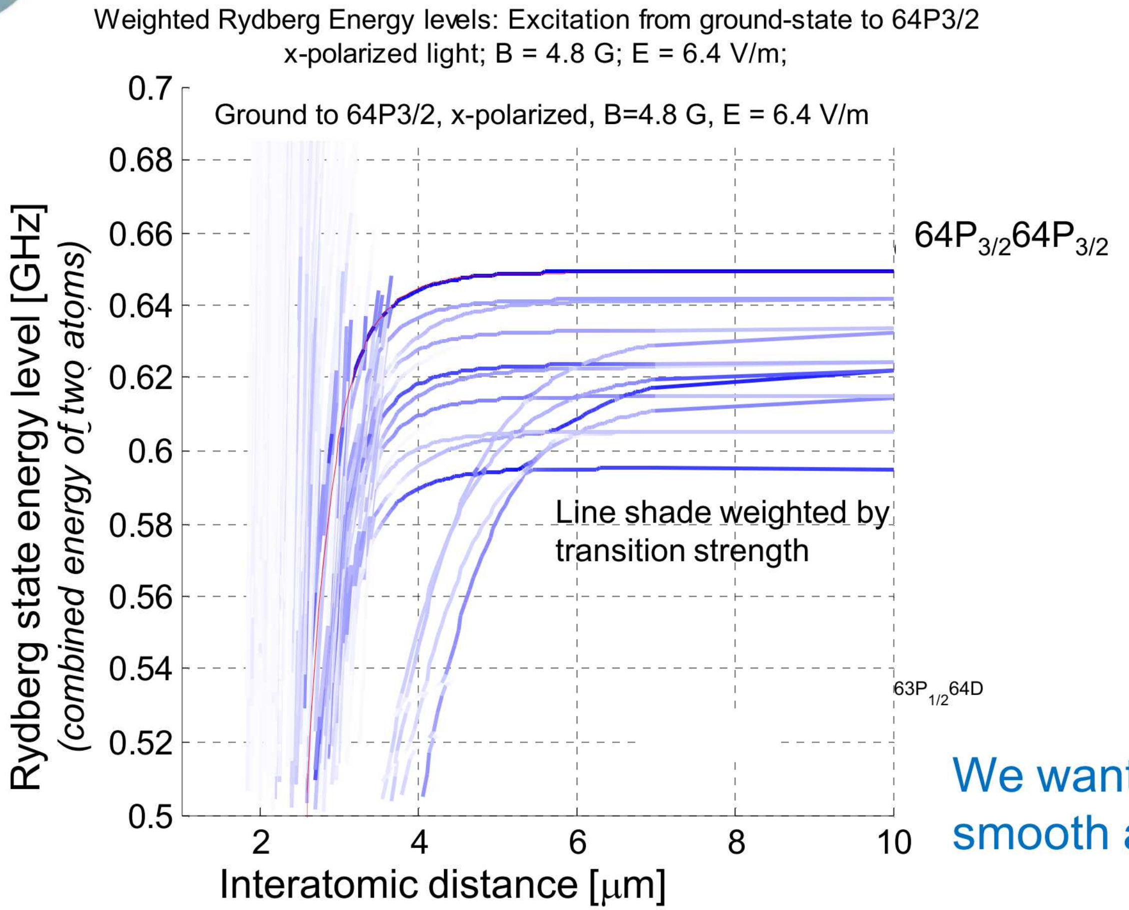
DC polarizability
$\alpha(0) \propto n^7$

- Even the presence of another atom can cause a massive response >> 10 MHz
- Induced Electric Dipole-Dipole Interaction $\propto 1/r^6$

Entanglement demonstrations
- Madison: Phys. Rev. Lett. 104, 010503 (2010)
- Paris: Phys. Rev. Lett. 104, 010502 (2010)

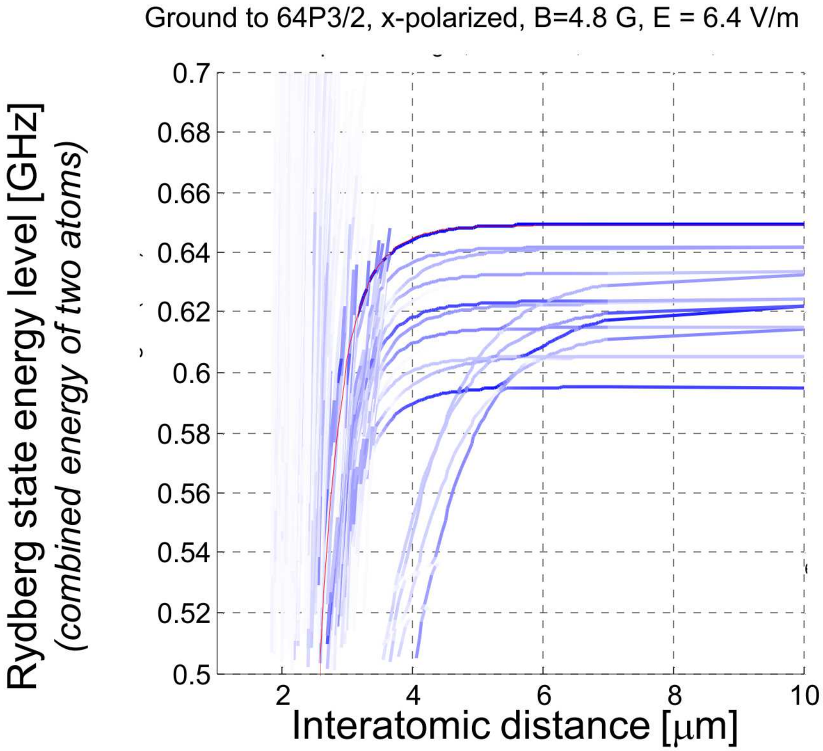
Rydberg blockade—the nitty gritty

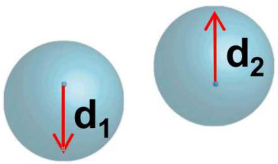


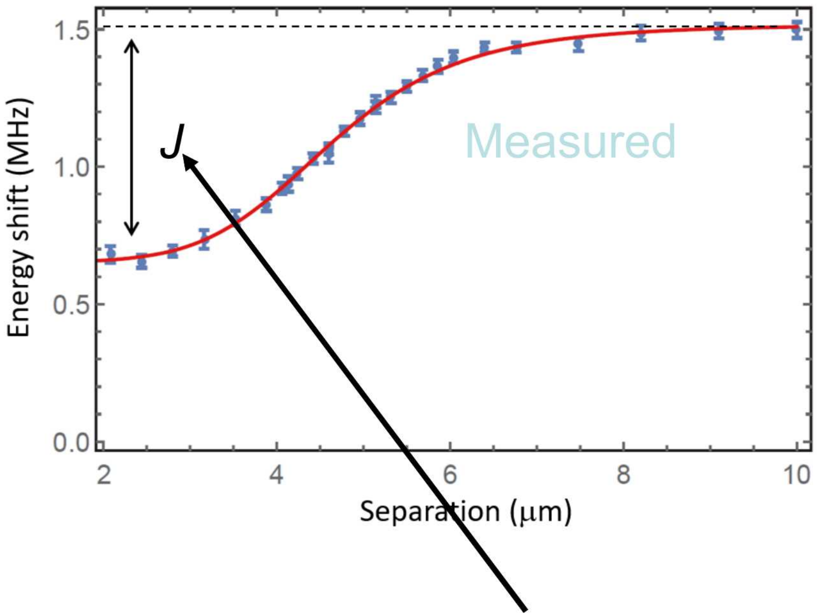


We want something smooth and tunable

Direct Rydberg → Rydberg-Dressed

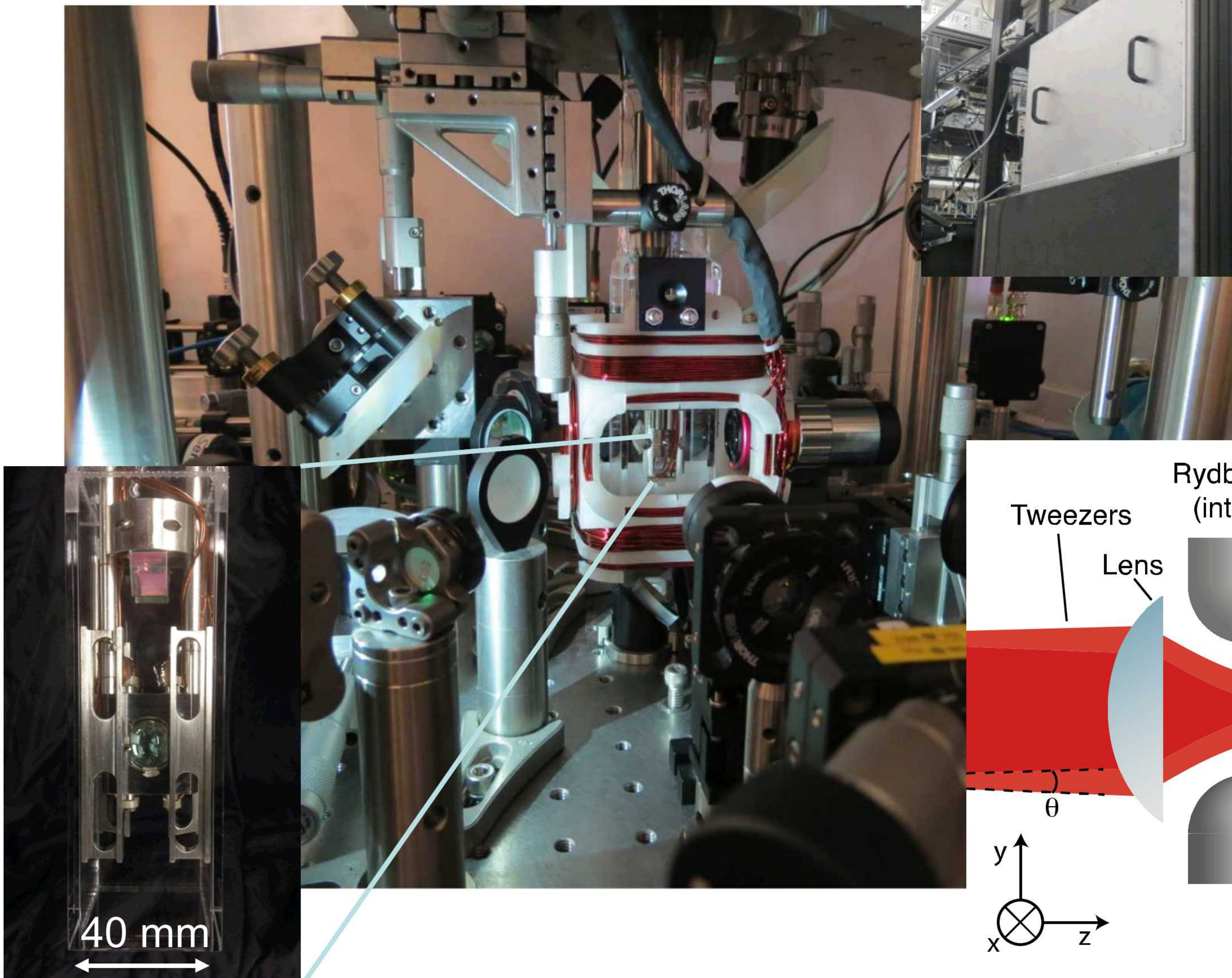


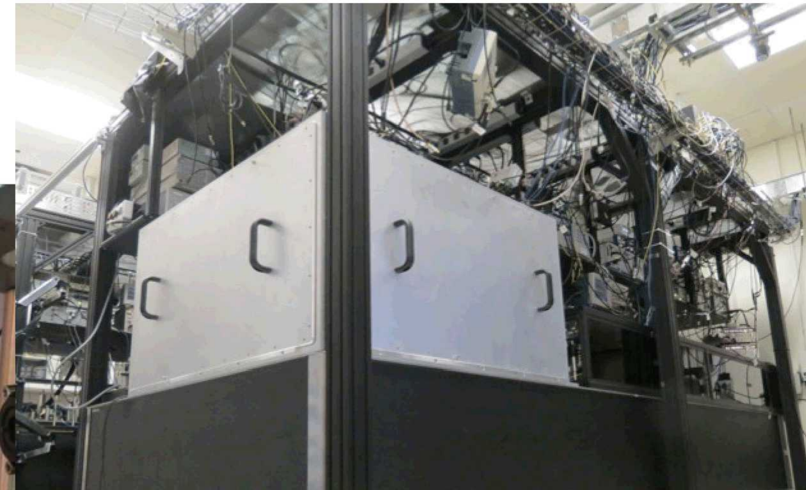


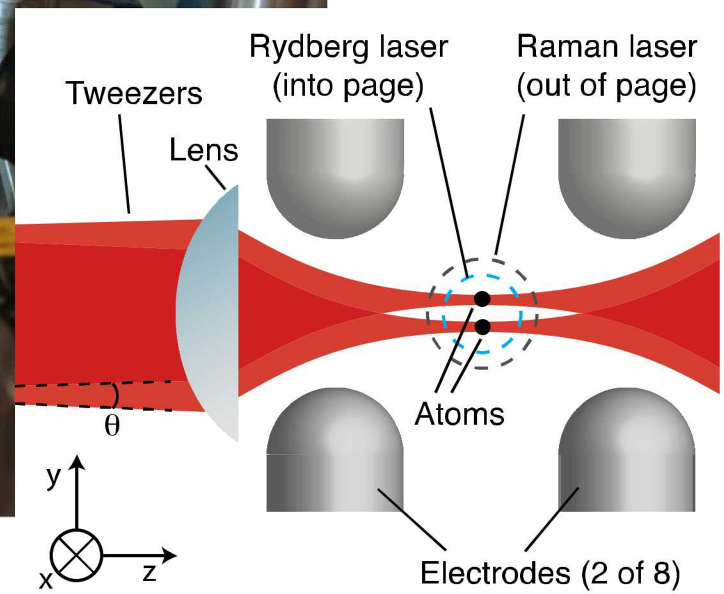


$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

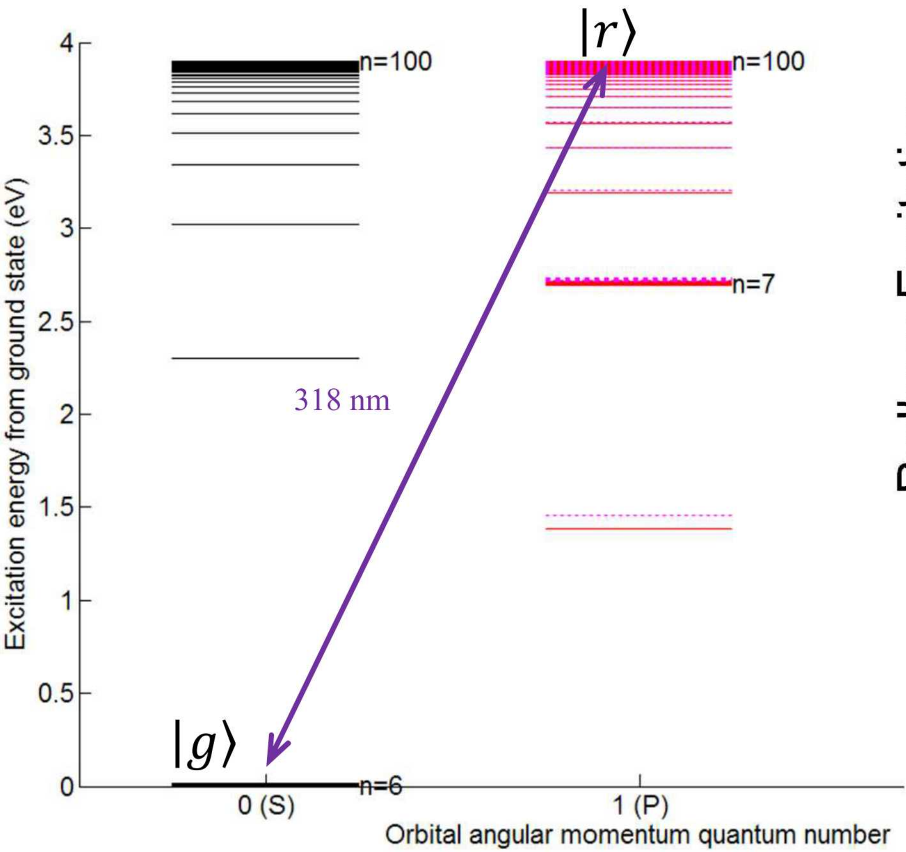
Apparatus

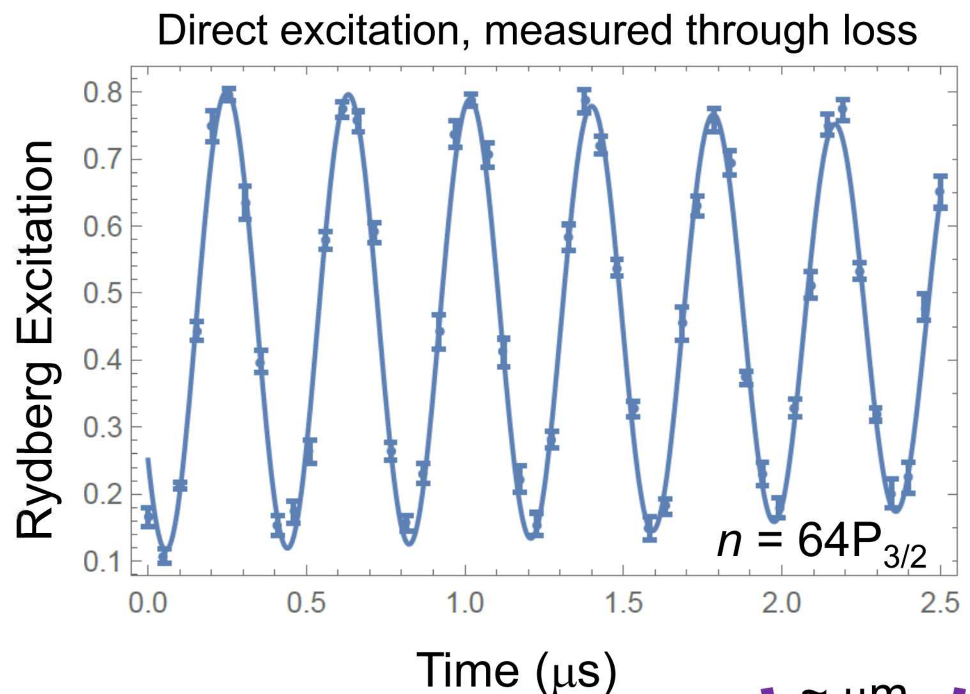

40 mm

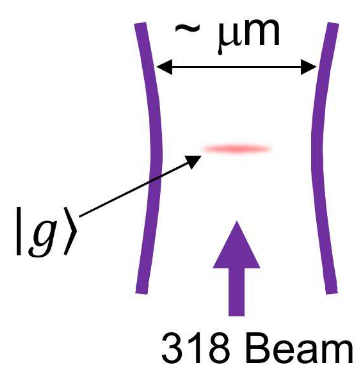



Rydberg laser
(into page)
Raman laser
(out of page)
Tweezers
Lens
θ
Atoms
y
x
z
Electrodes (2 of 8)

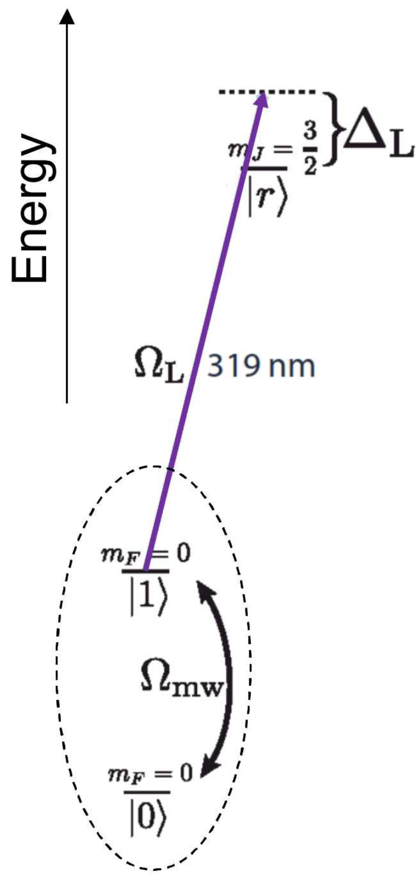
Rydberg Rabi oscillations with 318 nm laser







Creating Rydberg-Dressed states

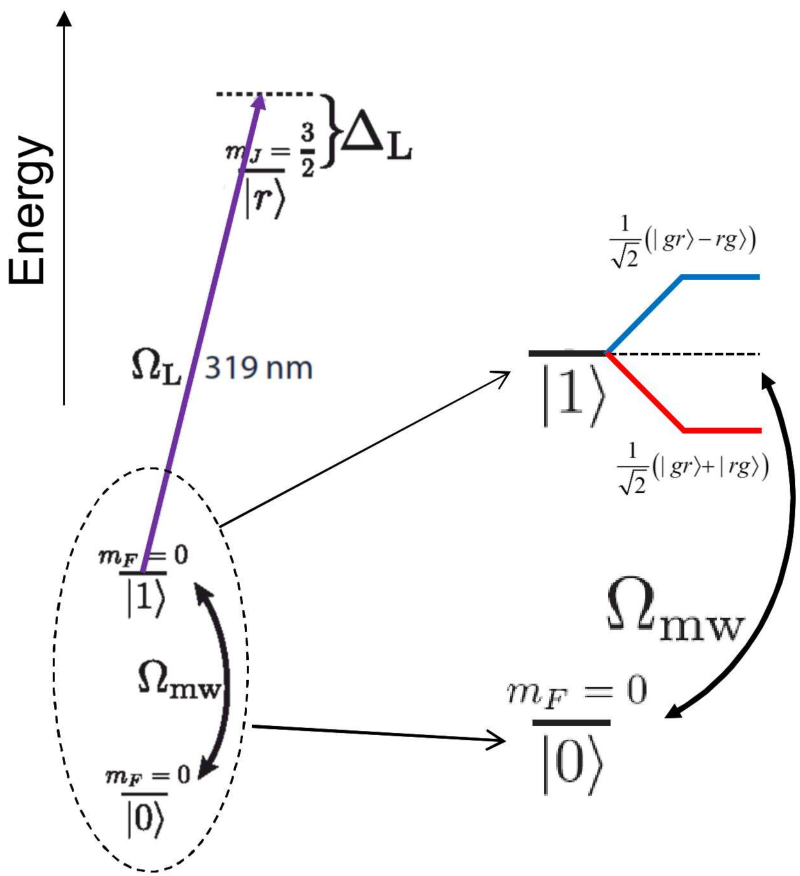


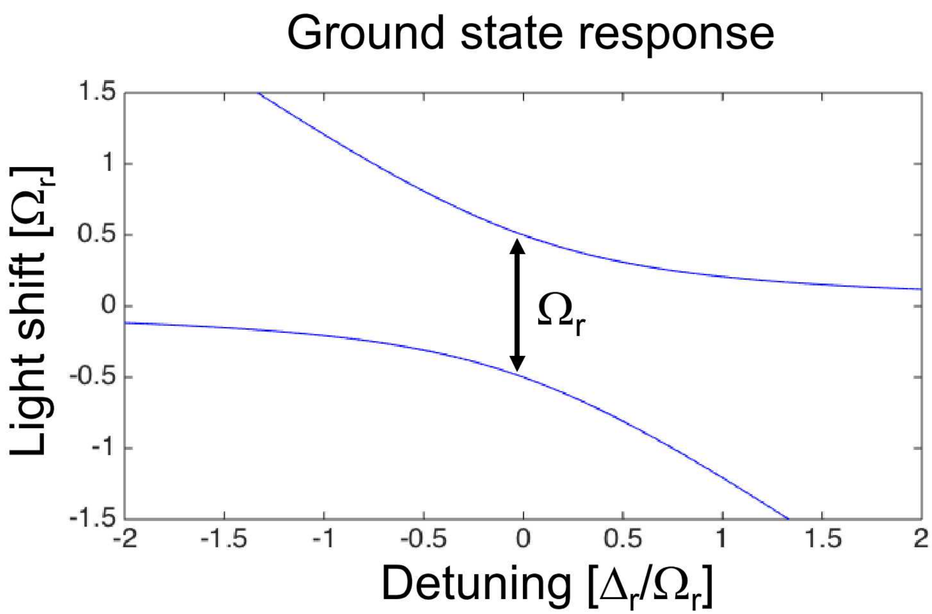
Light-shift Hamiltonian

$$H = \frac{\hbar}{2}\begin{pmatrix} -2\Delta_L & \Omega_L \\ \Omega_L & 0 \end{pmatrix}$$

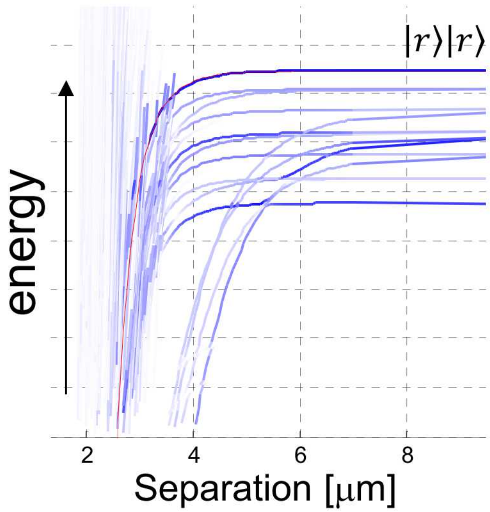
$$\Delta = \frac{\hbar\, \Omega_L^2}{4\, \Delta_L}$$

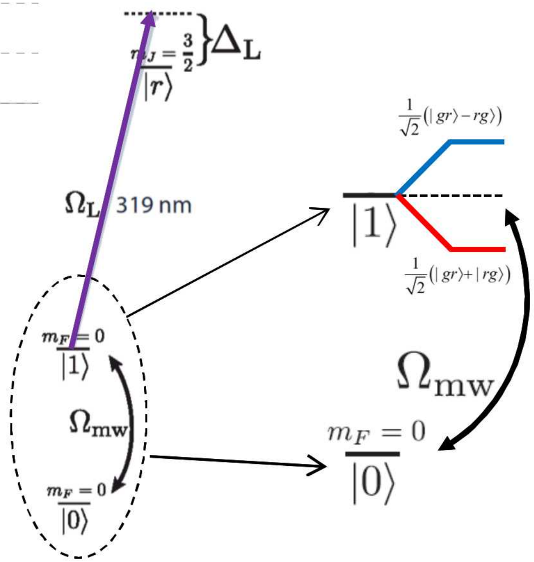
Creating Rydberg-Dressed states

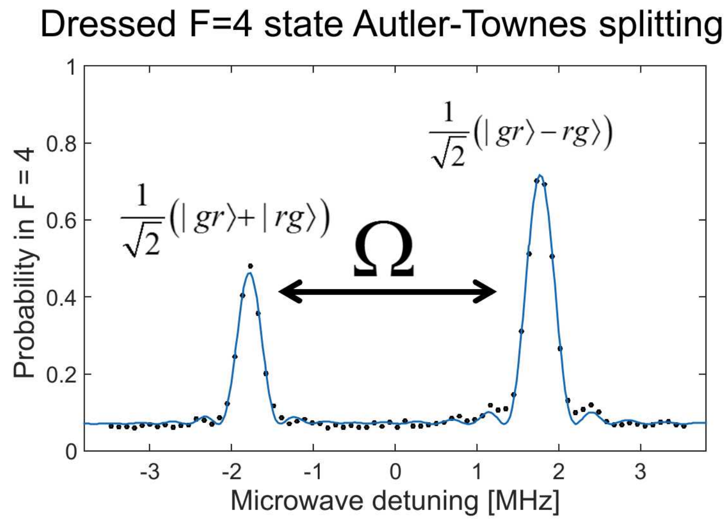


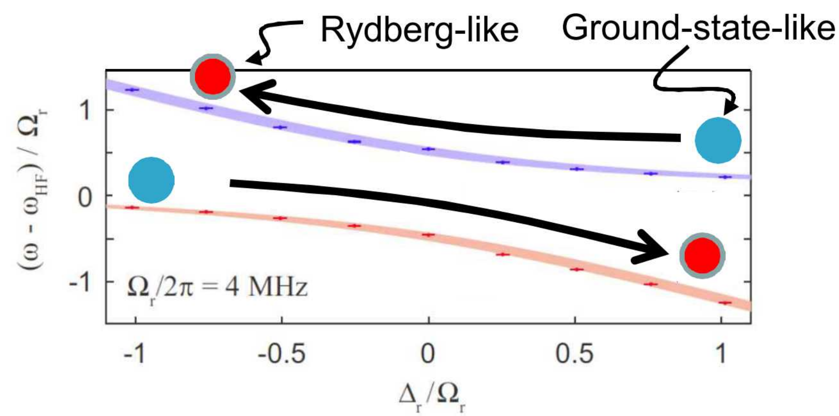


1-atom Rydberg-dressed states

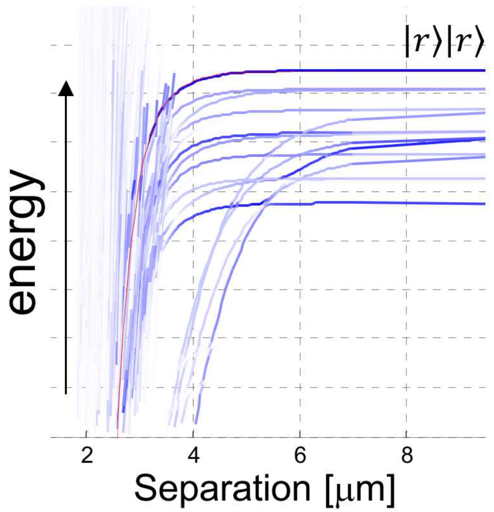


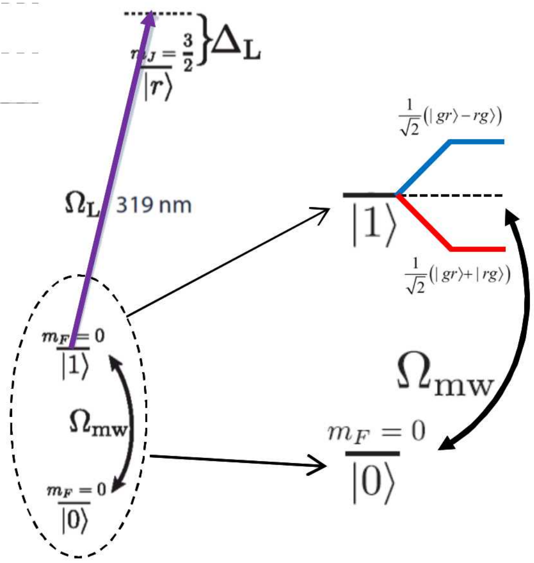


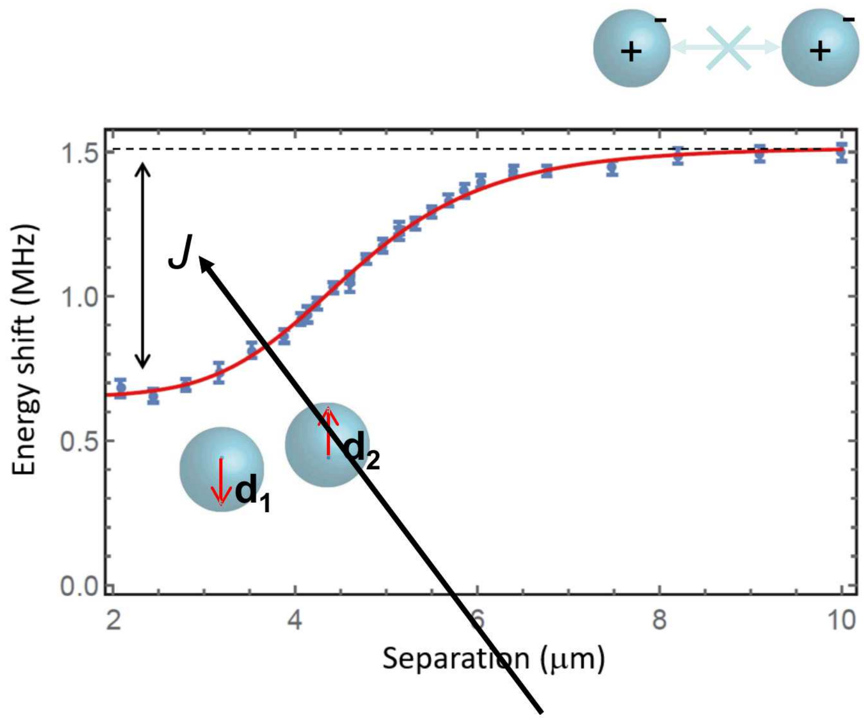




Rydberg-Dressed interaction

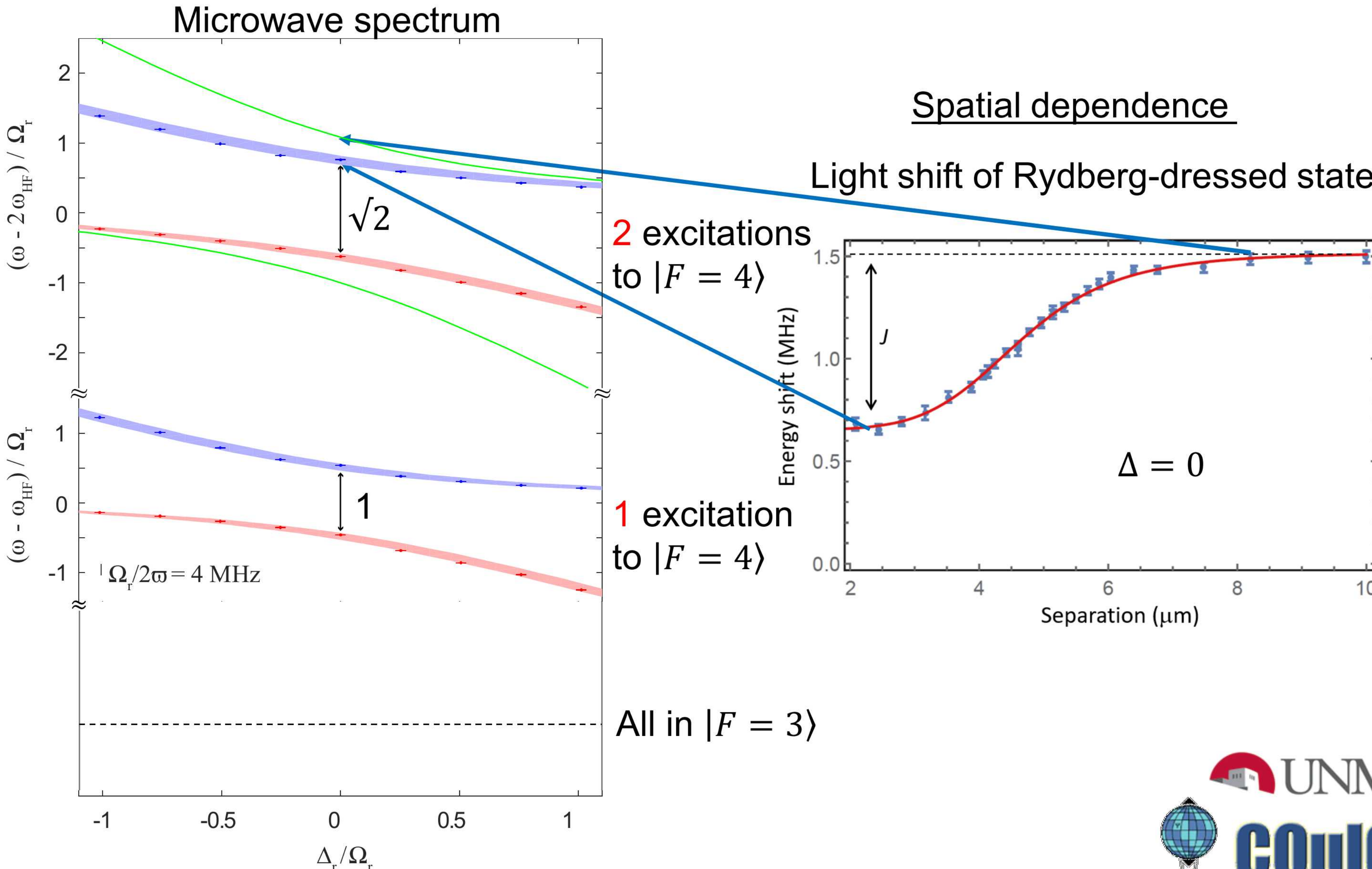






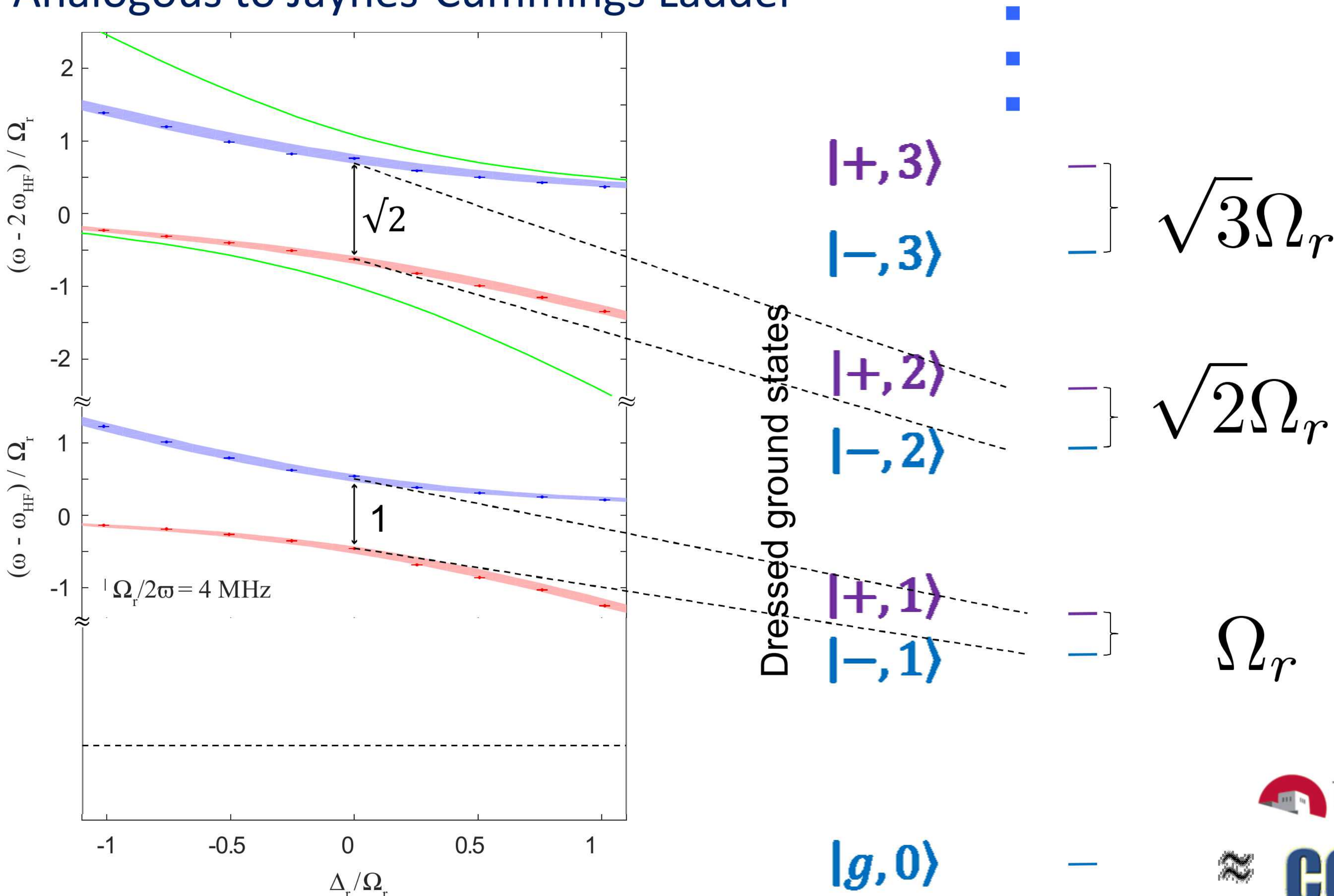
$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

2-atom Rydberg-dressed states



Extending to *N* atoms—symmetric

Analogous to Jaynes-Cummings Ladder



Sample Control Task

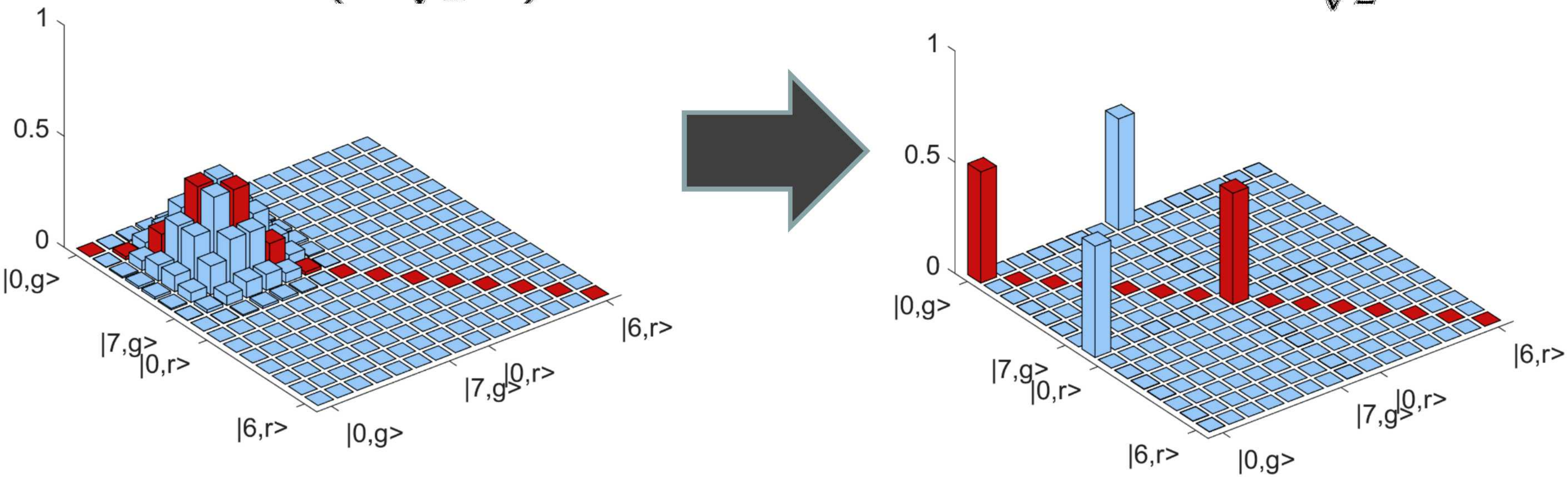
Sandia National Laboratories

$$2\pi * \Omega_r = 5 \text{ MHz}$$
$$2\pi * \delta_r = -2.5 \text{ MHz}$$
$$2\pi * \kappa \approx 600 \text{ kHz}$$

- Create a 7-atom cat state:

$$\rho_{in} = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes 7}$$

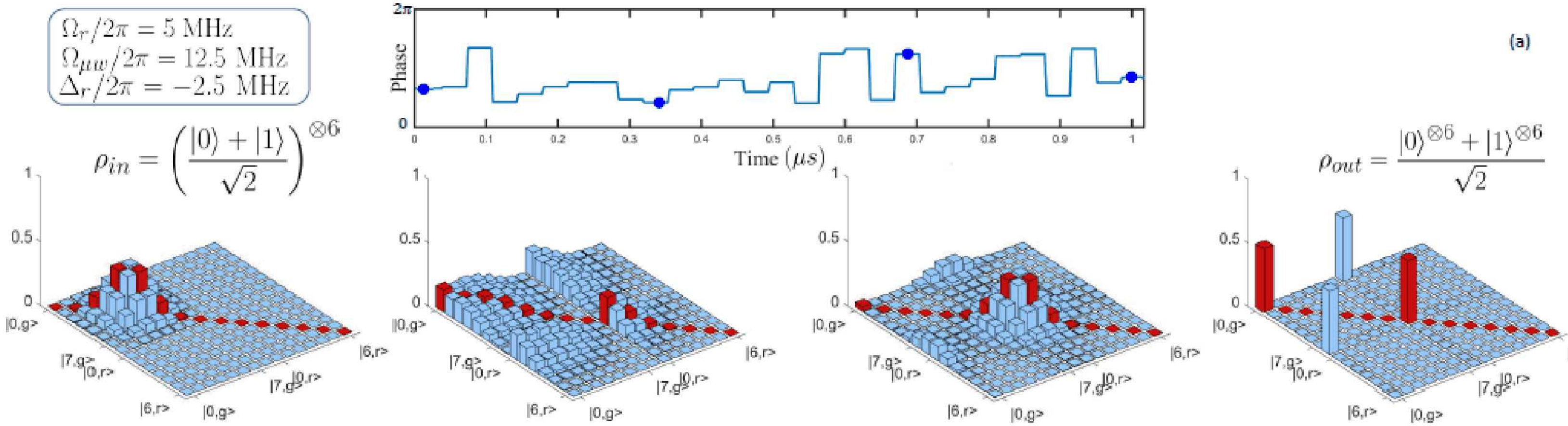
$$\rho_{out} = \frac{|0\rangle^{\otimes 7} + |1\rangle^{\otimes 7}}{\sqrt{2}}$$



- Find the sequence of microwave phases that does this with maximum fidelity

Arbitrary control

T. Keating *et al.*, Phys. Rev. Lett **117**, 213601 (2016)



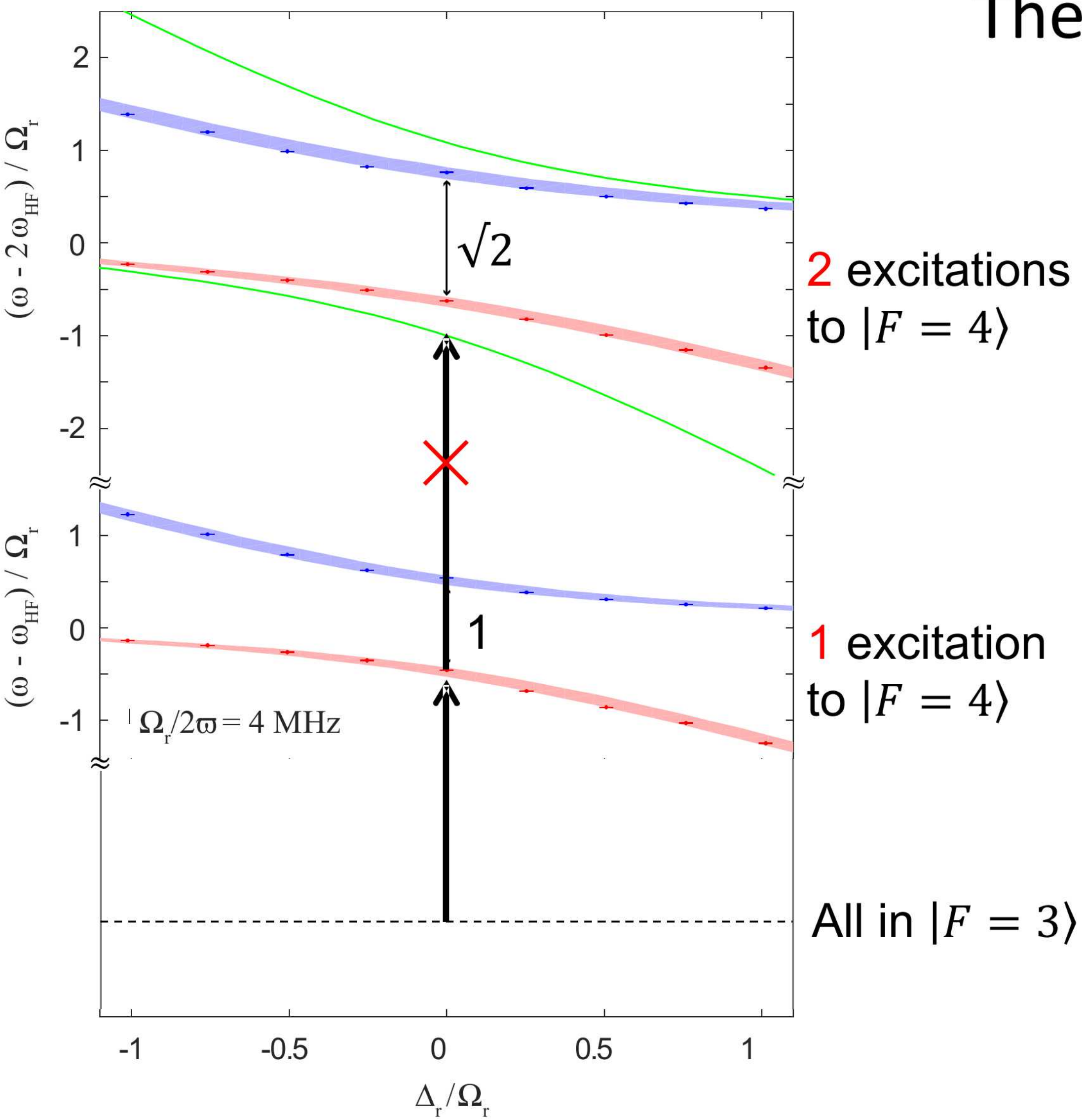
$$\hat{H}_c[\phi_{\mu w}(t)] = \frac{\hbar\Omega_{\mu w}}{2}\sum_{i=1}^{N}\left(e^{-i\phi_{\mu w}(t)}|1\rangle_i\langle 0| + e^{+i\phi_{\mu w}(t)}|0\rangle_i\langle 1|\right) = \hbar\Omega_{\mu w}(\cos[\phi_{\mu w}(t)]\hat{J}_x + \sin[\phi_{\mu w}(t)]\hat{J}_y)$$

control
$\phi_{\mu w}(t)$

The nonlinearity of the JCM, together with externally applied fields makes the system fully controllable on the symmetric Dicke space; we can generate an arbitrary superposition state.

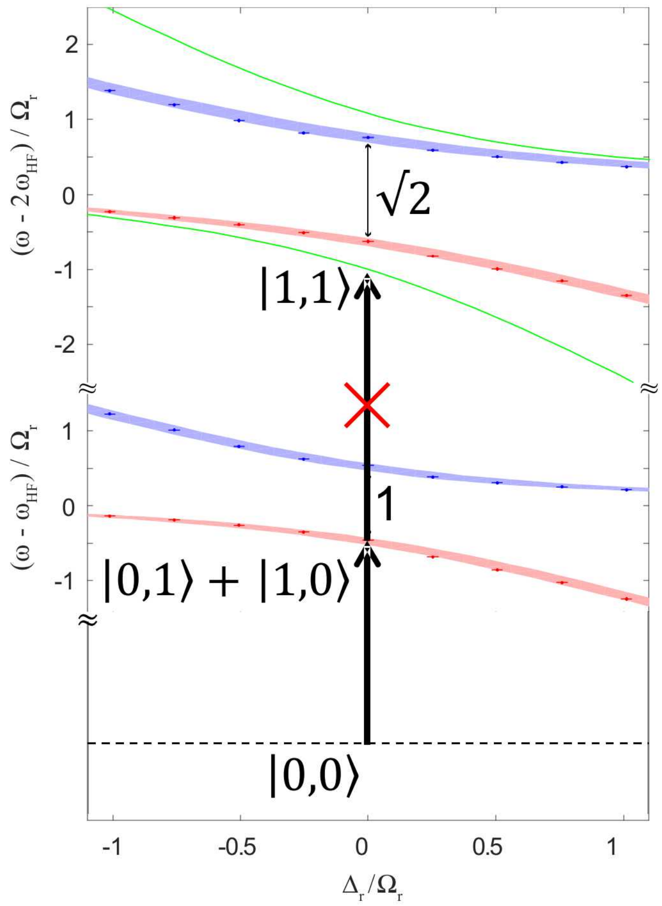
Creating entanglement with a single step

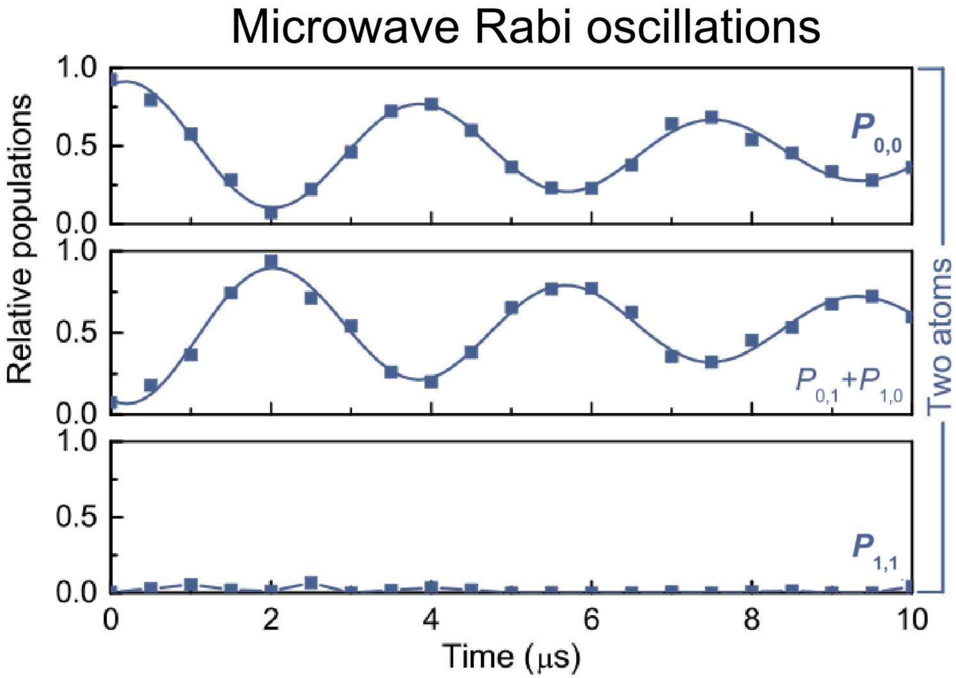
The “spin-flip blockade”



Creating entanglement with a single step

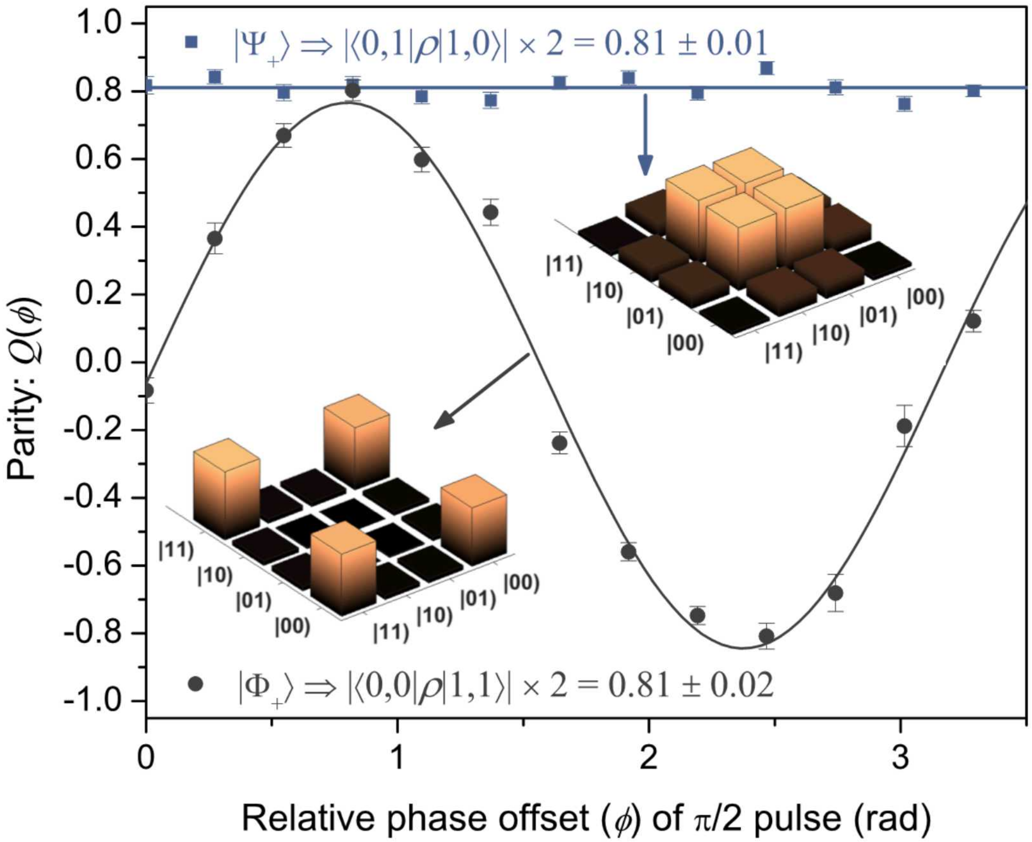
The "spin-flip blockade"





Spin-flip blockade

Verify the entanglement via parity measurements



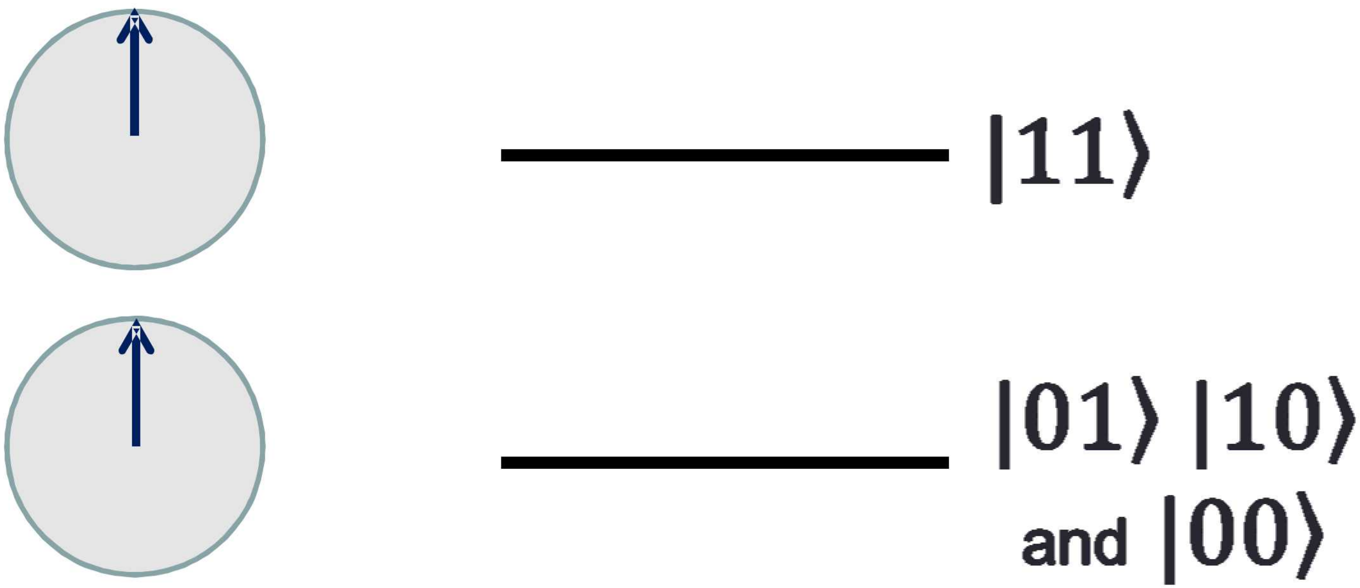
1. Prepare Bell state
2. Apply global $\pi/2$ with given phase
3. Measure parity Q
4. Obtain bound on fidelity =0.81(2)

Generating Entanglement

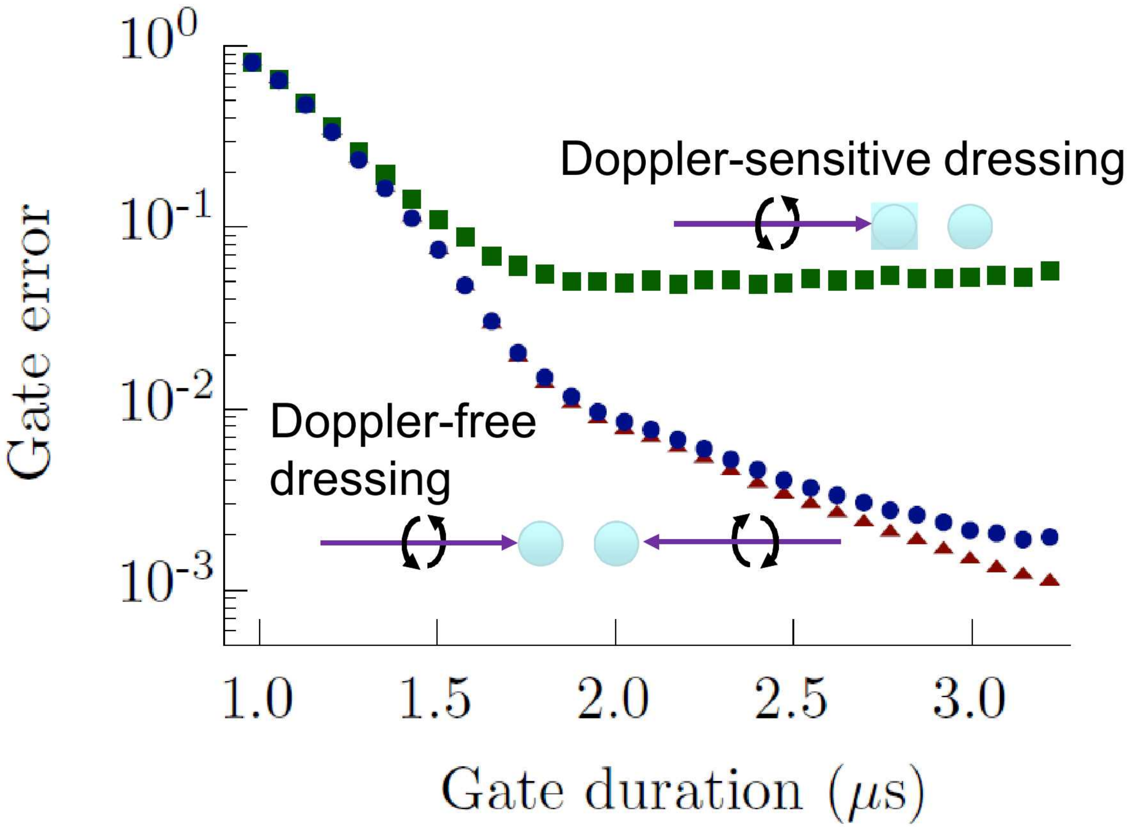
$$\hat{H}_{DD} = J\,|11\rangle\langle 11|$$

Laser ON OFF

Phase:



Simulated CPHASE gate fidelities

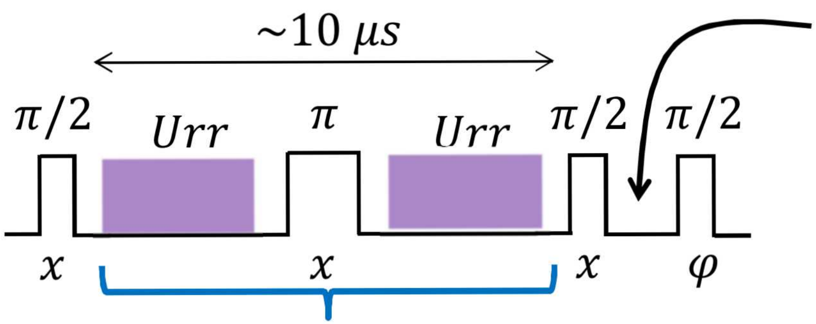


$\Omega = 0 \to 3$ MHz
$\Delta/2\pi = 6 \to 0$ MHz
$\Gamma = 3.7$ kHz
$T = 16\ \mu$K

- Motional errors set a high floor on error for the single-beam scheme.
- The Doppler-free scheme is limited by the much smaller photon scattering rate.

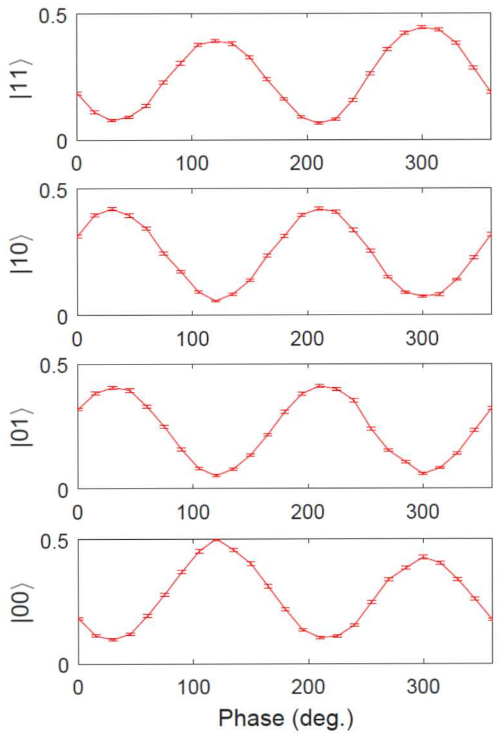
T. Keating, G.B., I.D., et al., Phys. Rev. A 91, 012337 (2015)

Dressed CPHASE gate

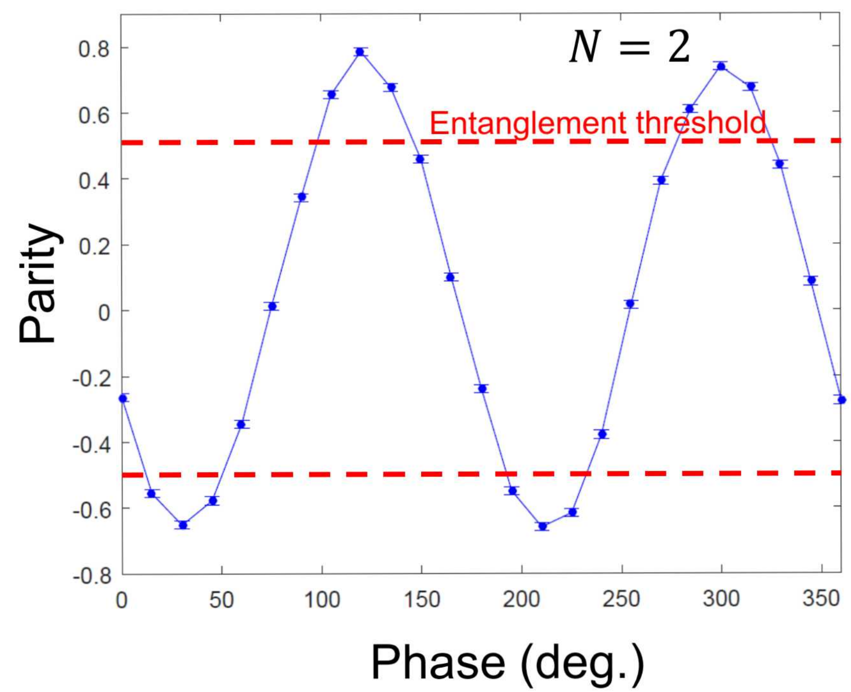


$$|\psi\rangle = \frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

$$\hat{H}_{\mathrm{eff}} = J \times \left(\hat{S}_z\right)^2$$



$$\langle\hat{\Pi}\rangle \propto \sin N\varphi$$

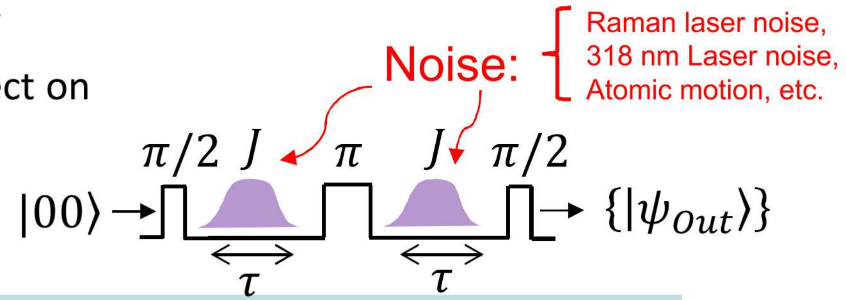


Error budget for CPHASE gate

Error budget: informing an experimental strategy

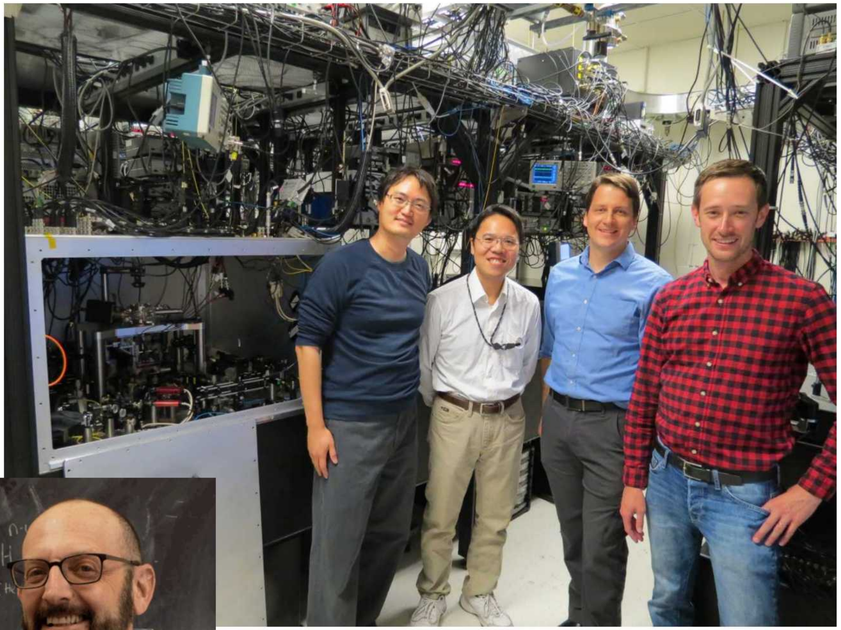
- Trace over external parameters to calculate effect on state fidelity, using measured parameters.

Fidelity = $\langle \psi_{tar} | \rho_{out} | \psi_{tar} \rangle$



Effect	Fidelity reduction	Mitigation
LO noise	10% ±0.1%(stat.) ±2%(sys.)	**Clean Raman laser/μWave cavity**
State purity	<3%	**Clean Raman laser/μWave cavity**
Atomic position spread	3%±0.5%	**Sideband cooling to ground state**
Wave-packet overlap	<0.1%	**Sideband cooling to ground state**
Atomic velocity spread	<0.1%	**Sideband cooling to ground state**
318 nm Laser frequency noise	0.2%±0.1%	**Pre-stabilized seed lasers, different detuning, dynamical decoupling**
Spontaneous emission	0.4%±0.2%	**Higher principal quantum #**
318 nm laser amplitude noise	<0.1%	**Install "noise eater" on laser**

CQuIC-Sandia Team



J. Lee, Y-Y. Jau, M. Martin, G. B.

I.Deutsch (UNM)

Sandia mountains viewed from the Rio Grande near Albuquerque, New Mexico

LDRD
Laboratory Directed Research and Development

Current team members

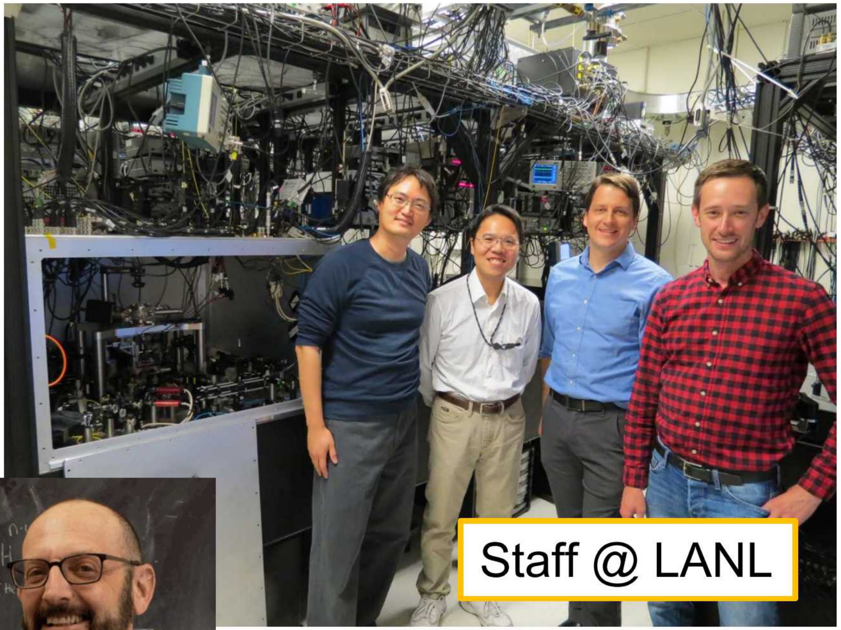
J. Bainbridge (UNM)

A. Orozco (UNM)

UNM CQuIC

Sandia National Laboratories

CQuIC-Sandia Team



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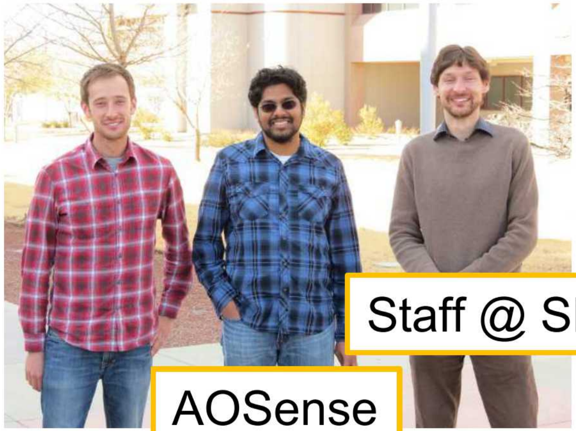
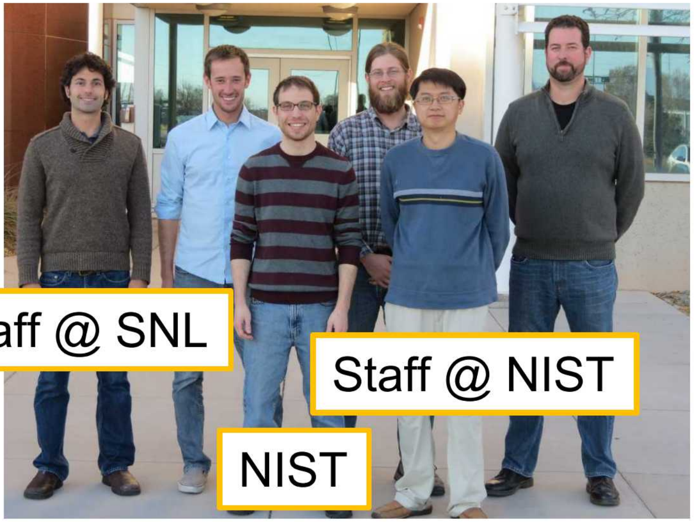
Sandia mountains viewed from the Rio Grande near Albuquerque, New Mexico

Previous team members



G. B., A. Rakholia, H. McGuinness



L. Parazzoli, G. B., A. Hankin, A. Ferdinand, J. Chou, G. Burns

!!!Wanted: Postdocs and students!!!