Measuring inertial forces with ultracold neutral atoms

SAND2018-4252PE

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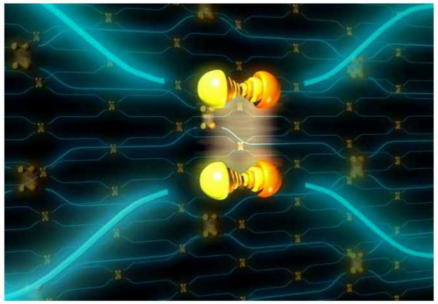
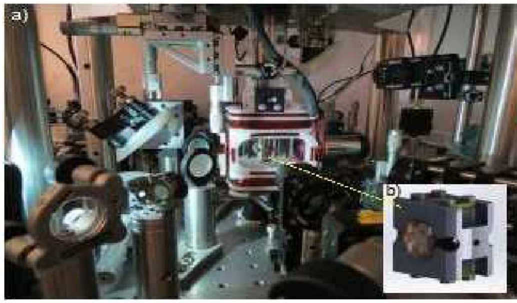
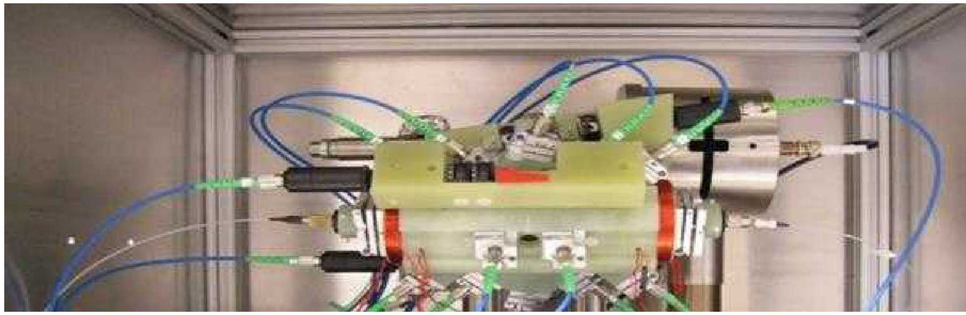
Naval Postgraduate School
April 20, 2018







UNM
CQuIC

LDRD
Laboratory Directed Research and Development

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

U.S. DEPARTMENT OF ENERGY

NNSA
National Nuclear Security Administration

SAND2018-XXXX

Outline

- Precision sensing with atom interferometers
- Sandia atom interferometer efforts
  - Single atom interferometer
  - High data rate atom interferometer
- Next generation in sensing
  - Rydberg-dressed physics and entanglement

Inertial Navigation

Basic idea:

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

Uncertainty in *a* drives uncertainty in *x*

However, must include gyroscope to get pointing information

U.S. Navy photo by Mass Communication Specialist 1st Class Woody Paschall—CNBC

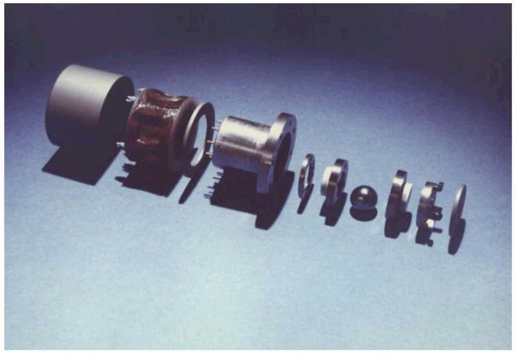
Tactical, MEMs

Analog Devices ADIS16385

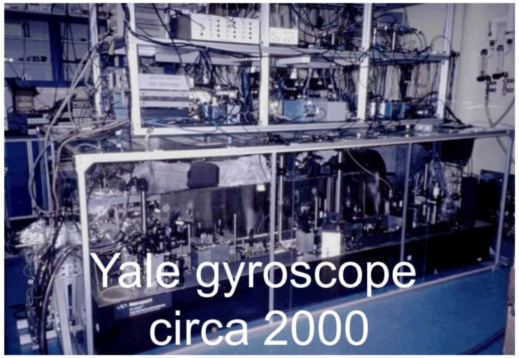
Navigation, HRG

Honeywell HG9900

Strategic, ESG



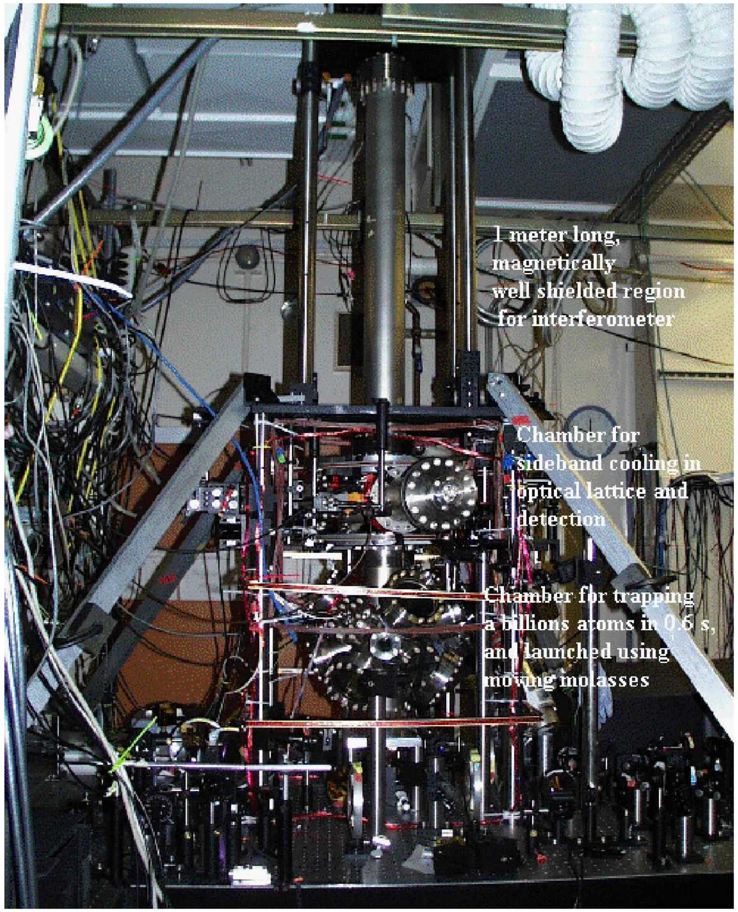
Atomic



Yale gyroscope circa 2000

stability

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

Atom Interferometer Sensors

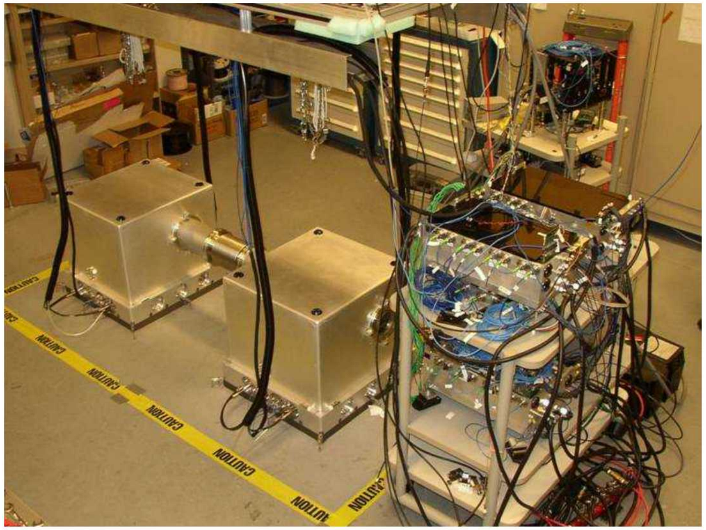
- AI Gravimeter
    - A. Peters *et al,* Metrologia **38**, (2001)
    - Capable of 20 nano-**g** in 1.3 s
    - Recent tower work infers pico-**g** level per shot

10 m tower
Mark Kasevich
Stanford

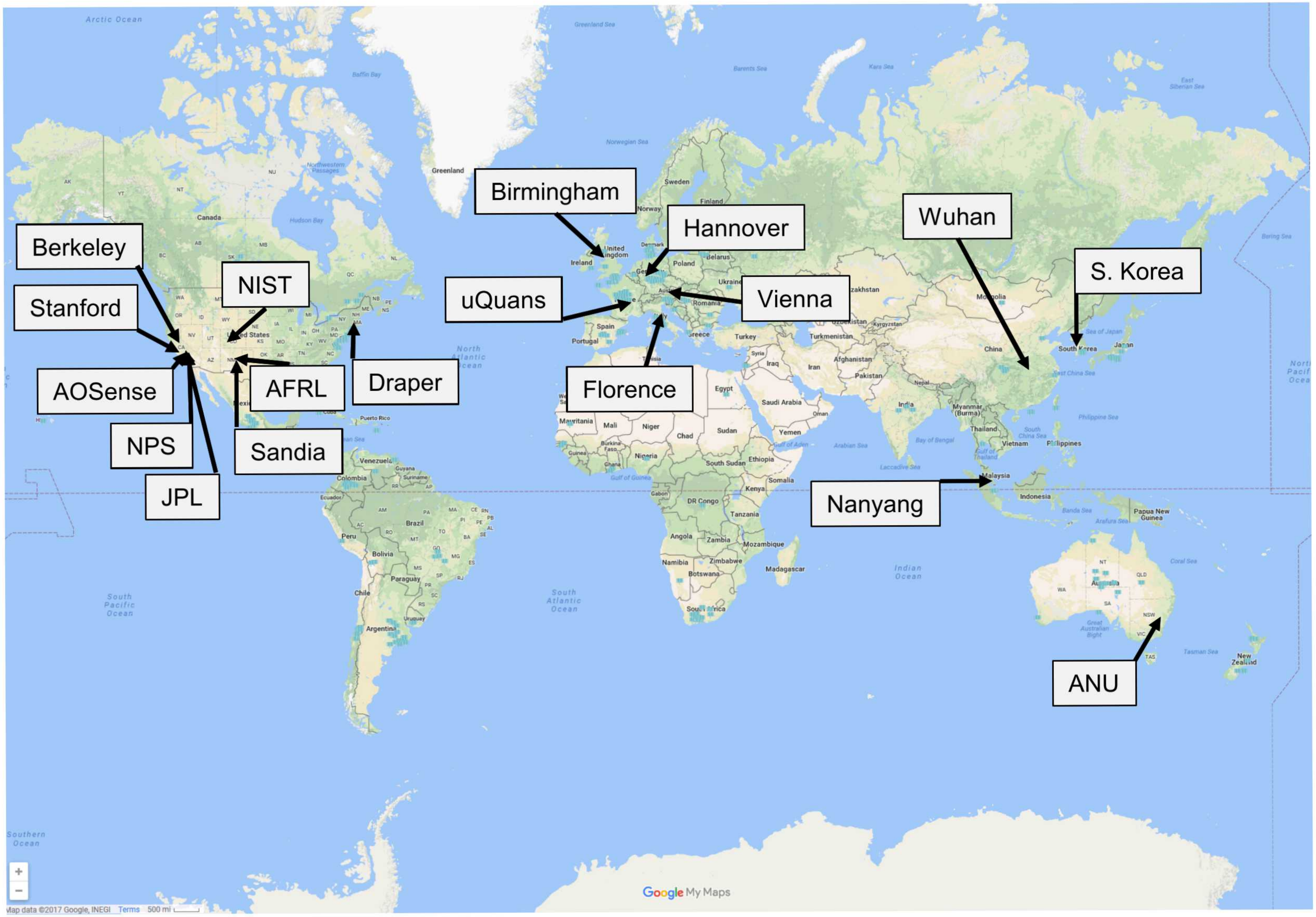
- AI Gyro
    - D. Durfee *et al*, PRL **97**, (2006)
    - Short-term stability ~3μDeg/hr$^{1/2}$
    - High-accuracy navigation grade
        - < 70μDeg/hr bias stability

- 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}

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

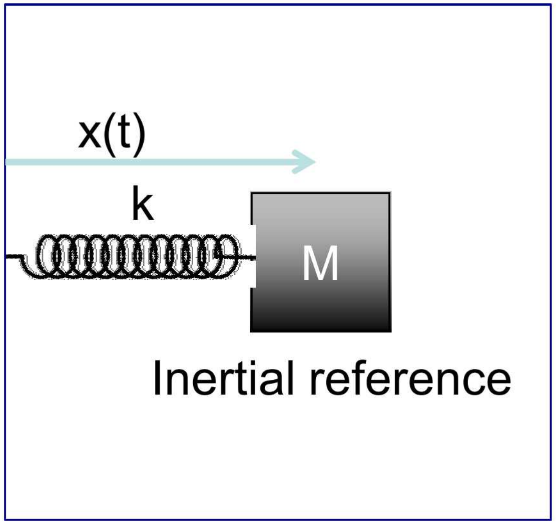


An incomplete map of AI efforts



Inertial measurements

Mass-spring accelerometer



x(t)

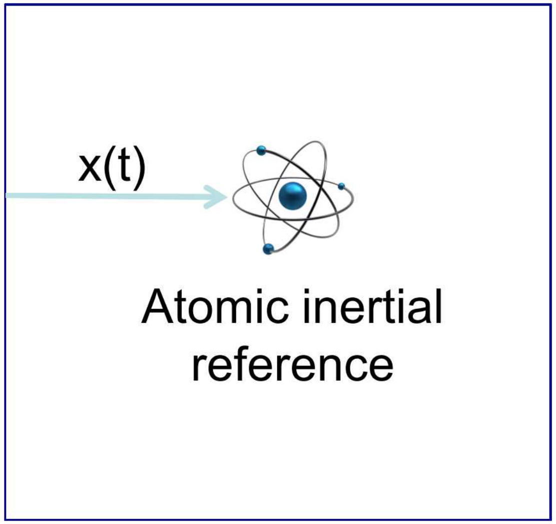
k

M

Inertial reference

platform

Free-fall accelerometer



x(t)

Atomic inertial reference

platform

Atom interferometers

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

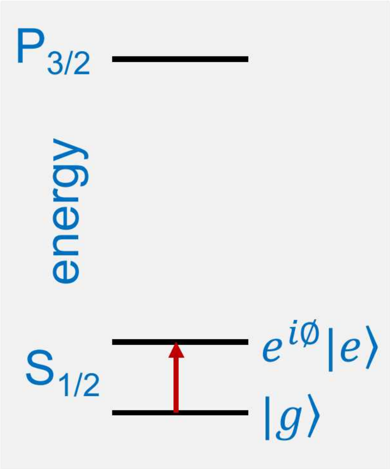
Atom optics, simplified

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

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

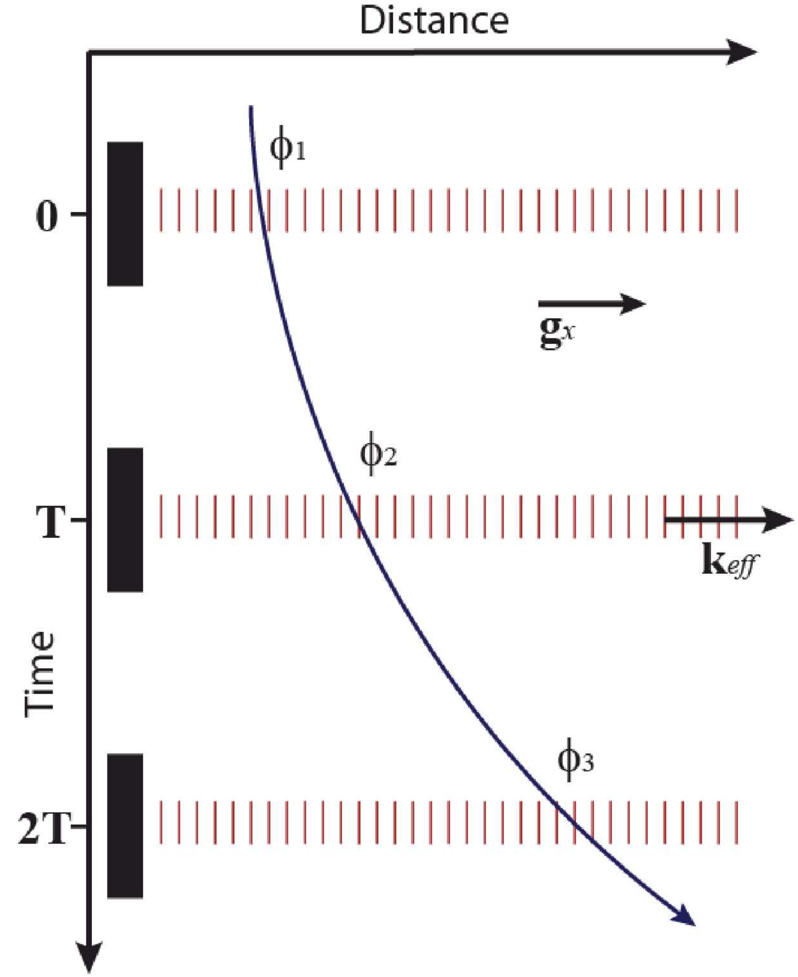
calculate curvature via finite difference method

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



…and then

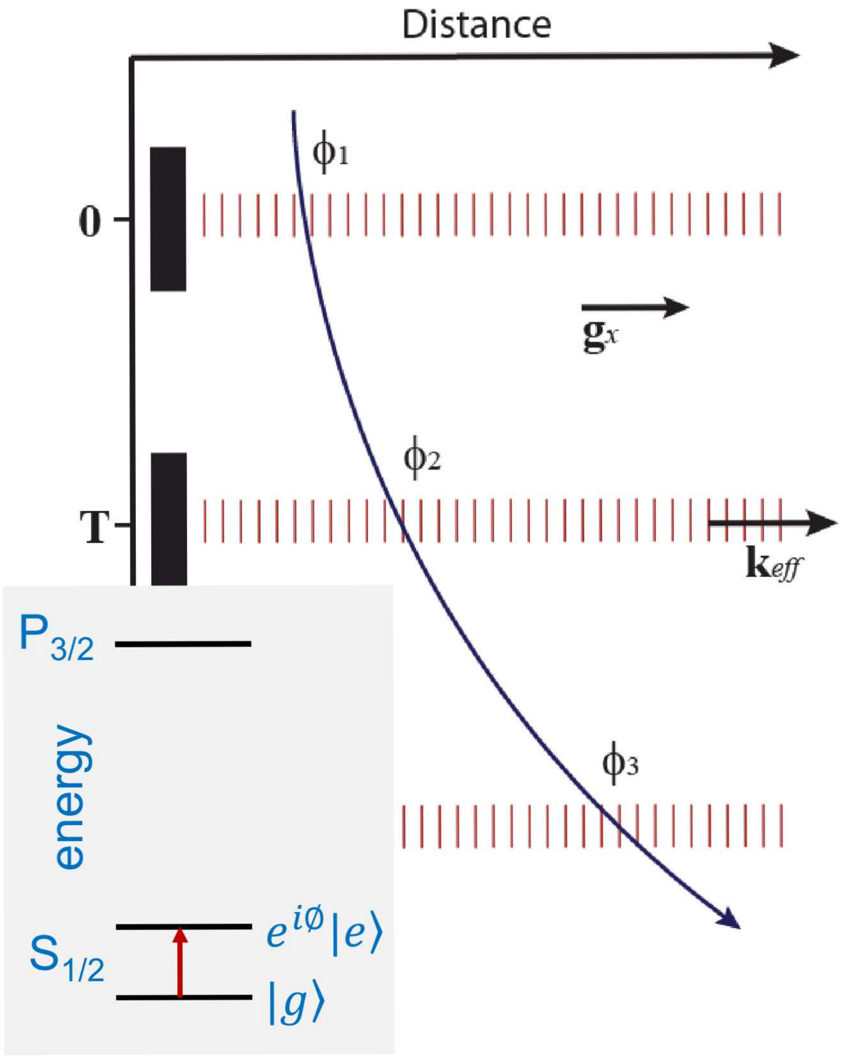
$$g_x = \frac{\Delta\varphi}{k_{eff}T^2}$$



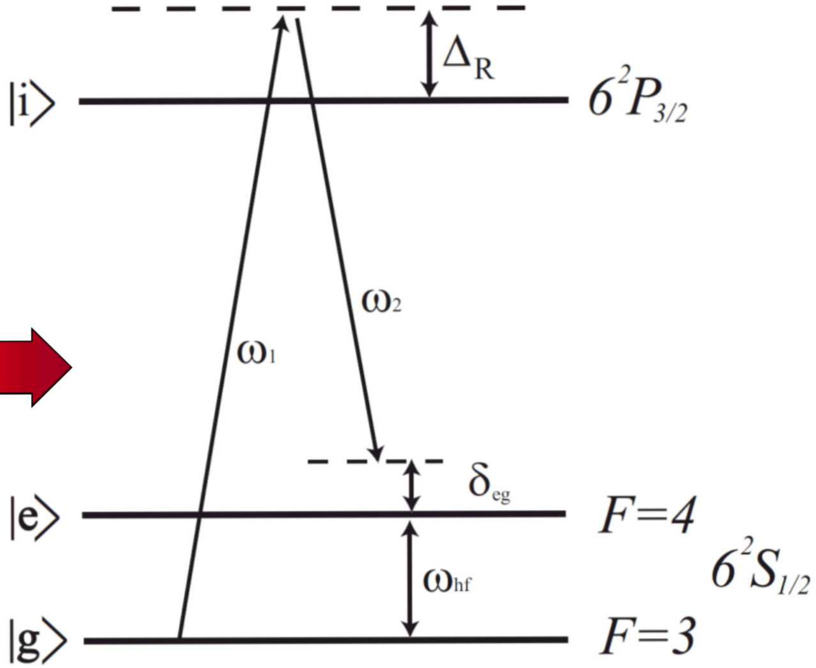
$$P_{\uparrow} = 1/2(1 - cos\Delta\emptyset)$$

…think of $S_{1/2}$ states as pristine oscillator with phase memory

Laser requirements: atom optics



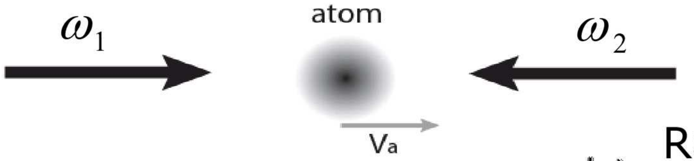
<u>Relevant energy diagram (Cs)</u>



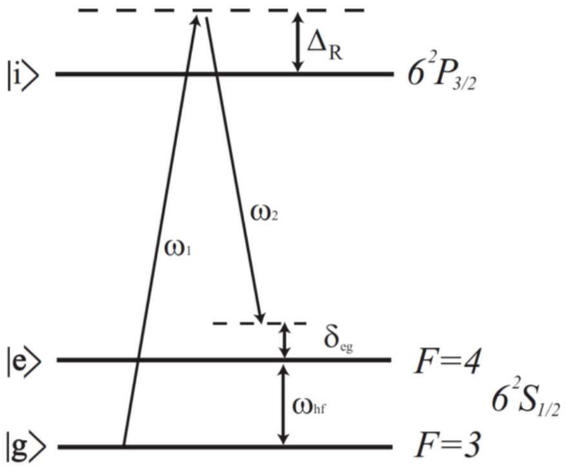
- Phase coherent laser tones separated by 6.8 GHz

Stimulated Raman transition

Laser configuration



Relevant energy diagram (Cs)



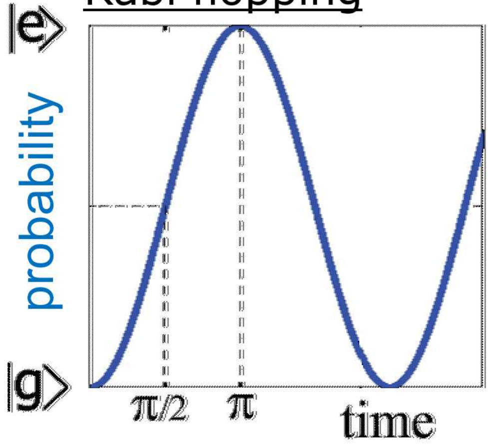
Effective 2-level system

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

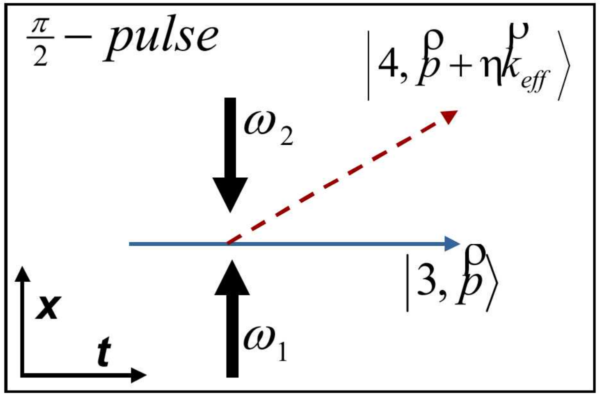
$$\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2 \approx 2\vec{k}_1$$

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

Rabi flopping

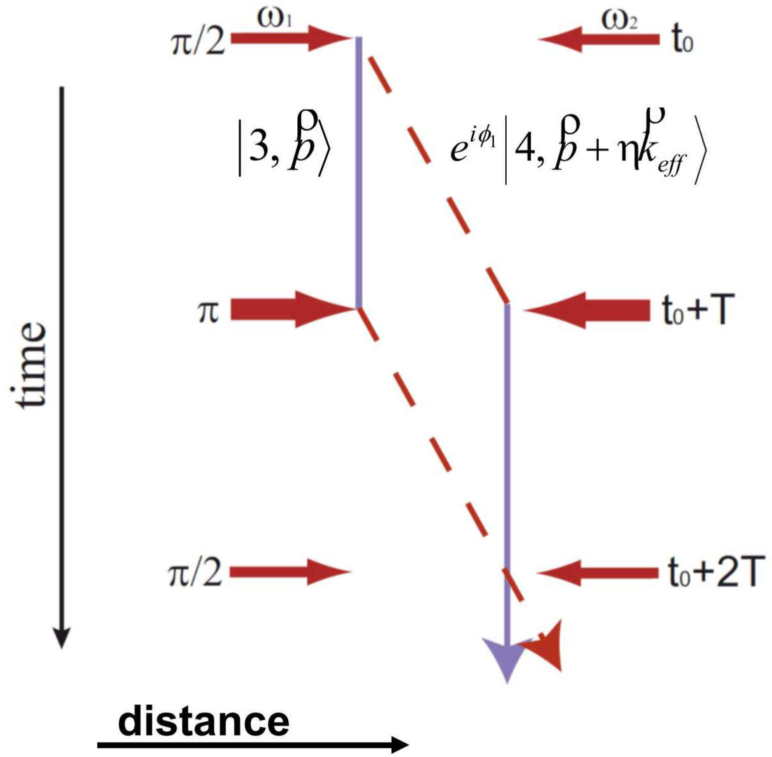


Atom optics beamsplitter



AI phase shift

Interferometer Recoil diagram



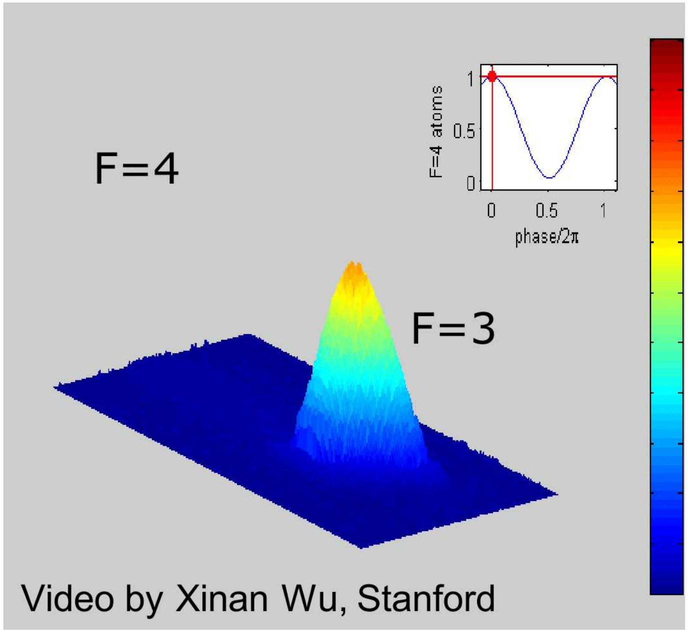
Transition rules

$$\left.\begin{array}{c}
|3,\vec{p}\rangle \rightarrow e^{i\phi}|4,\vec{p}+\hbar\vec{k}_{eff}\rangle \\
|4,\vec{p}+\hbar\vec{k}_{eff}\rangle \rightarrow e^{-i\phi}|3,\vec{p}\rangle \\
\phi = \vec{k}_{eff}\cdot\vec{x}
\end{array}\right\}
\begin{array}{l}
\Delta\phi = \phi_1 - 2\phi_2 + \phi_3 \\
\quad = \vec{k}_{eff}\cdot(\vec{a}T^2 - 2(\vec{v}\times\vec{\Omega})T^2)
\end{array}$$

Interferometer transition probability

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

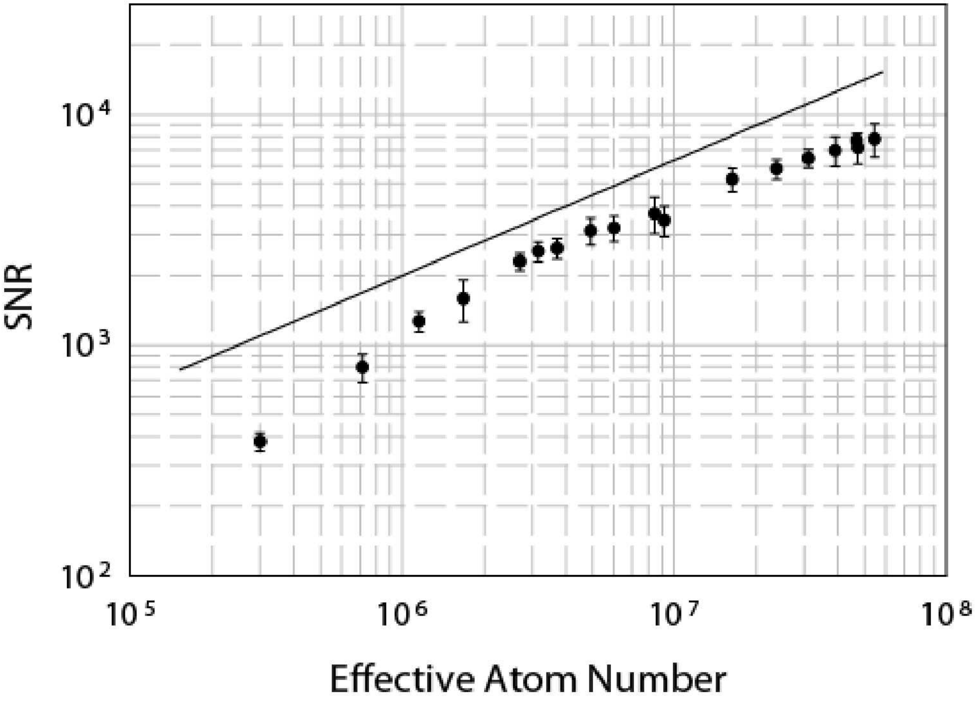
State detection



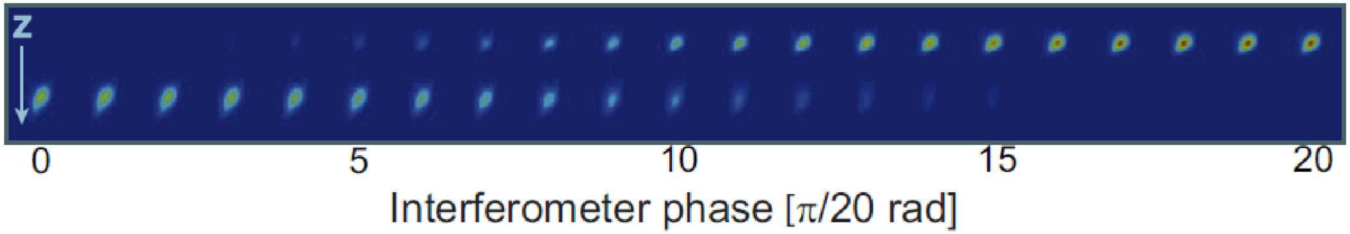
Video by Xinan Wu, Stanford

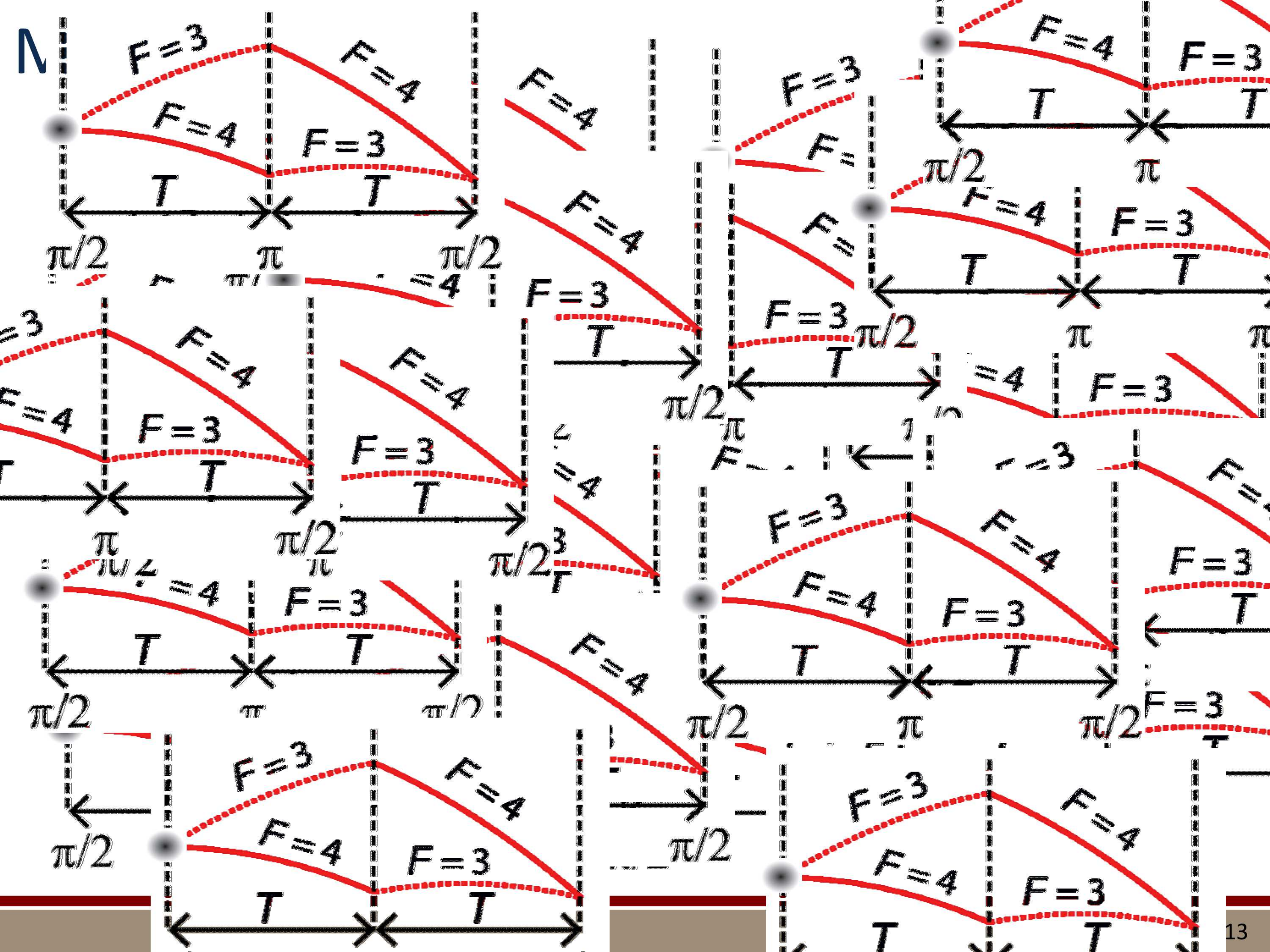
Radiation pressure spatially separates F=3 and F=4 atoms

Biedermann, et al., Opt. Lett. 2007

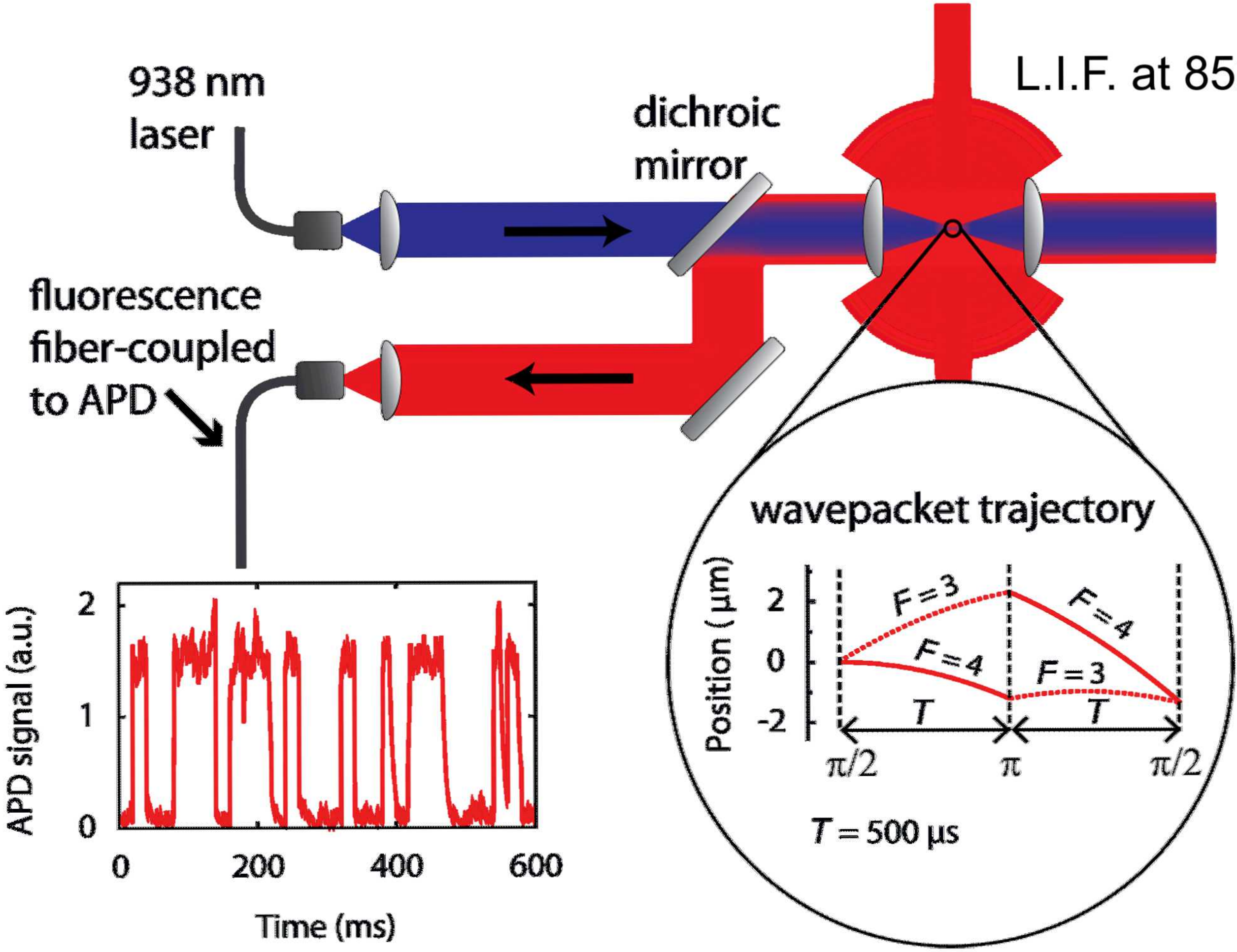


Achieves near atom shot-noise limited performance.



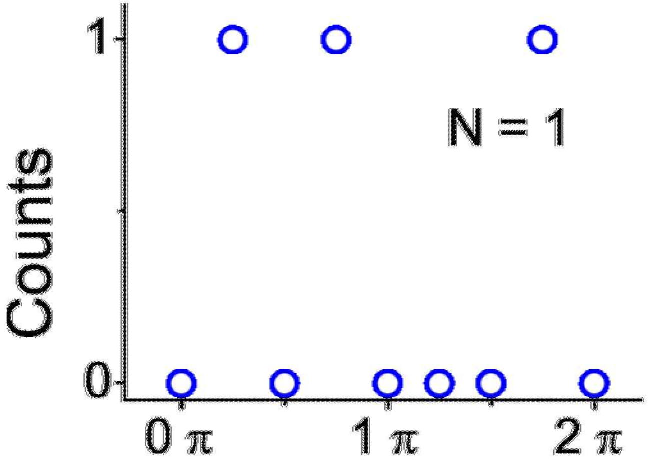

F = 3
F = 4
F = 4
F = 3
T
T
π/2
π
π/2

Free-space matterwave interference with a single atom



L.I.F. at 852 nm

Building fringe one atom at a time



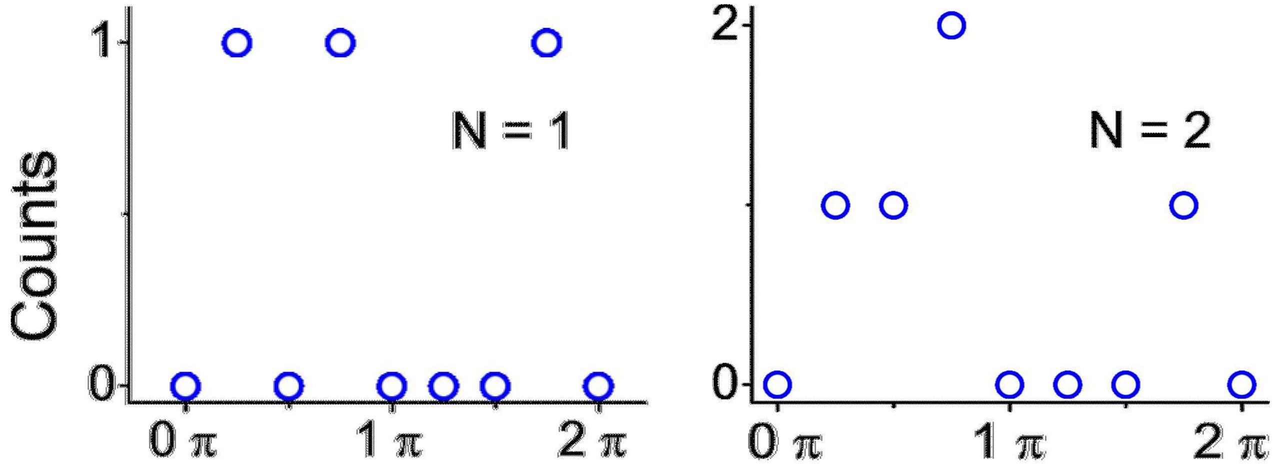
- 1 atom per phase through interferometer.

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

Scan laser phase

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

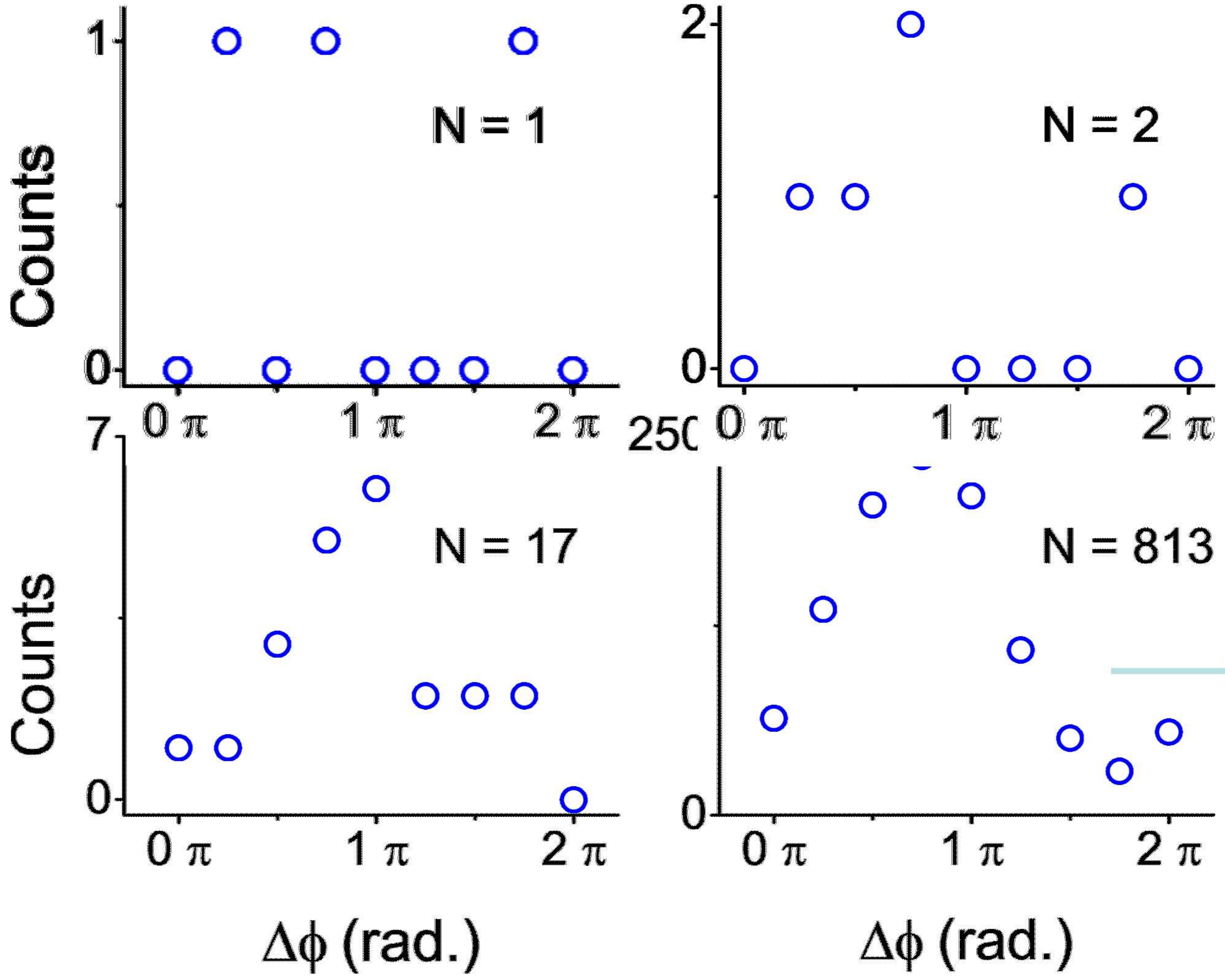
Building fringe one atom at a time



- 2 atoms per phase through interferometer

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

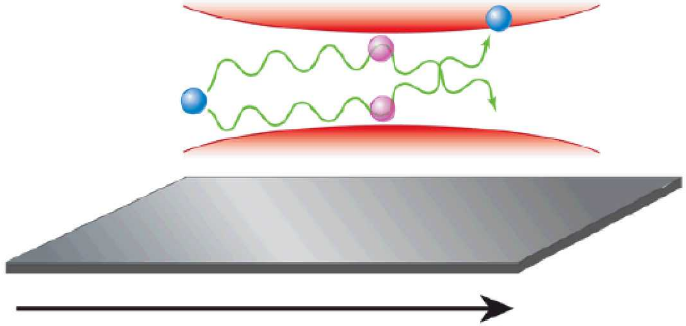
Building fringe one atom at a time



7,317 atoms

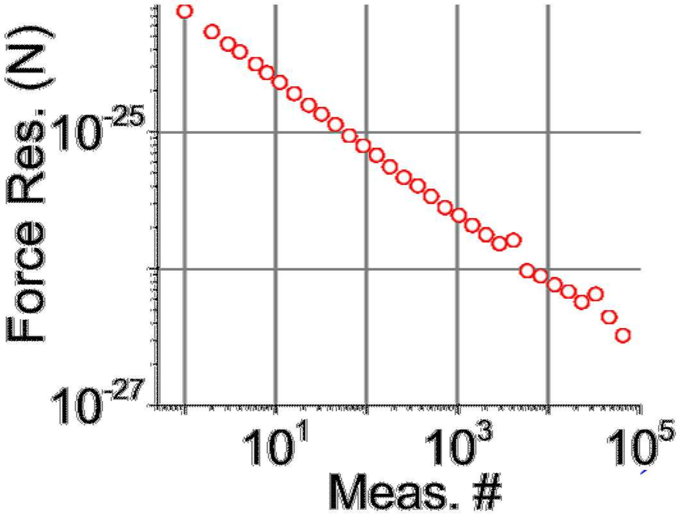
Parazzoli, et al., “Observation of free-space single-atom matterwave interference”, Phys. Rev. Lett. **109**, 230401 (2012)

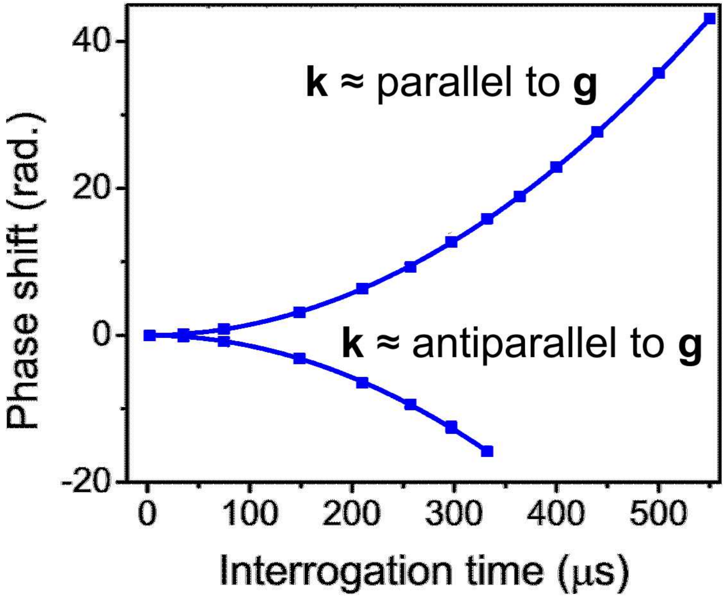
Force resolution of a single atom interferometer



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

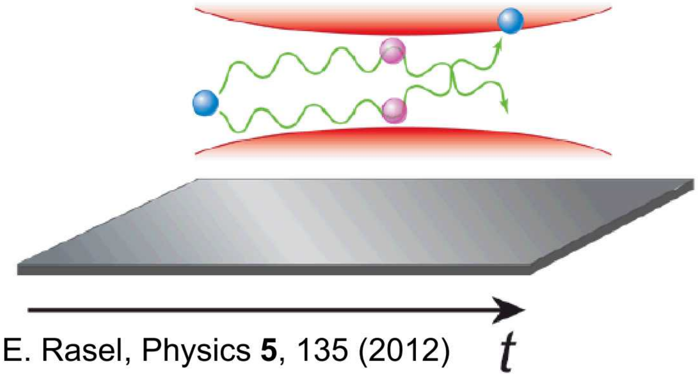
Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)





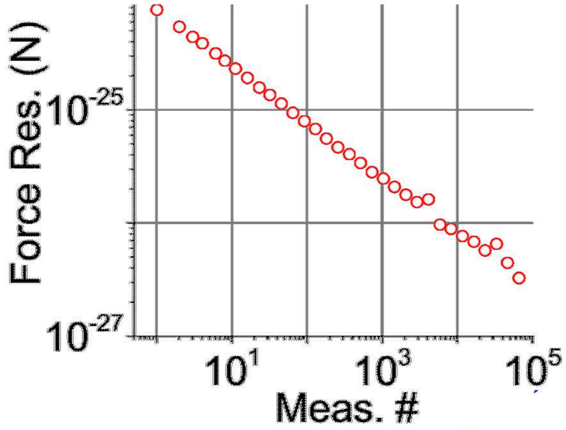
$$\Delta\Phi = \mathbf{k} \bullet \mathbf{a}\, T^2$$

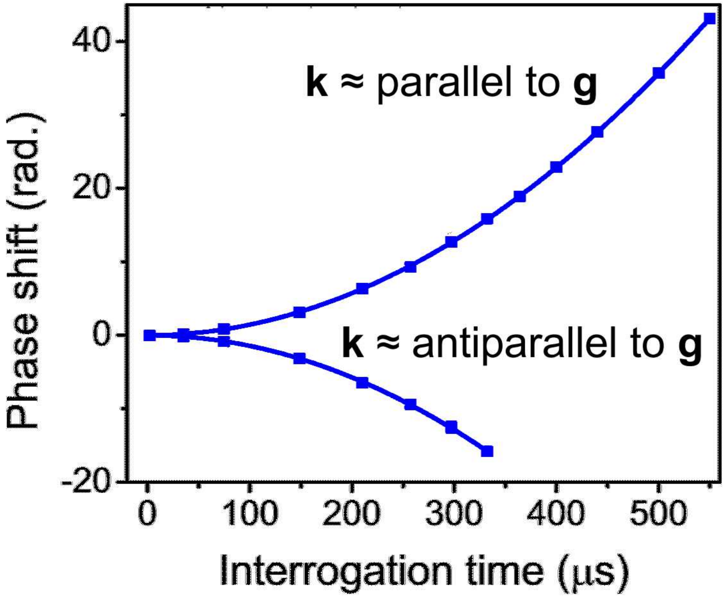
Force resolution of a single atom interferometer

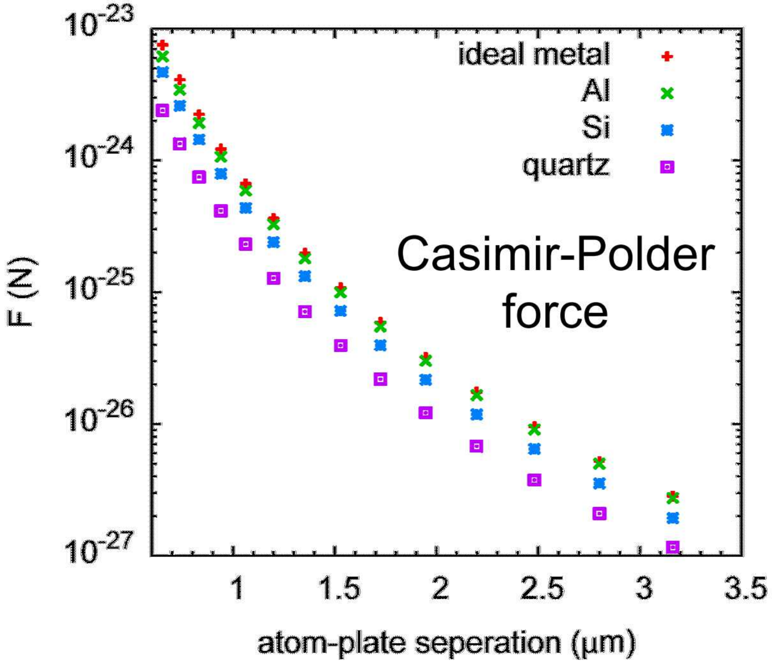


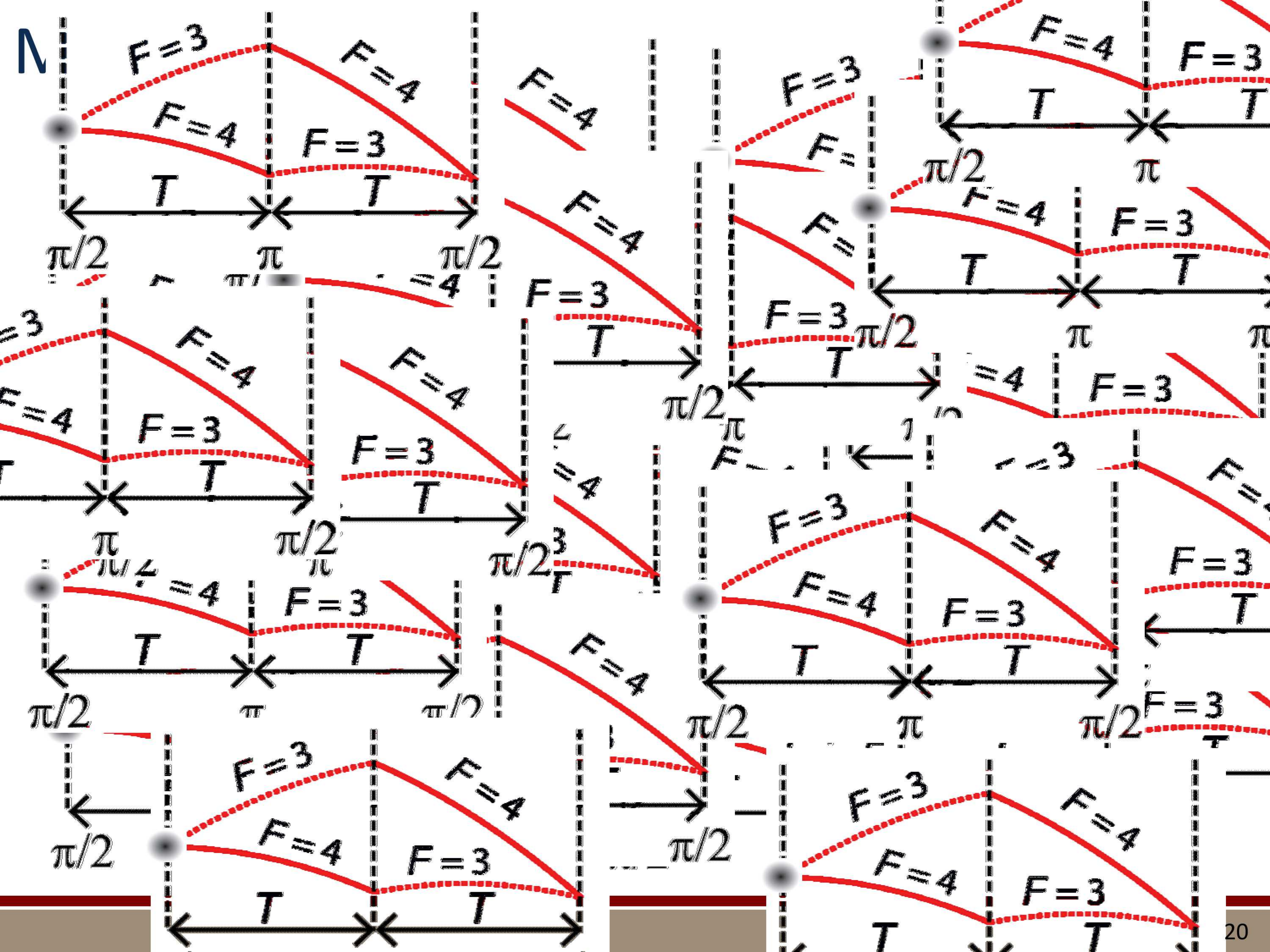
E. Rasel, Physics **5**, 135 (2012)

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

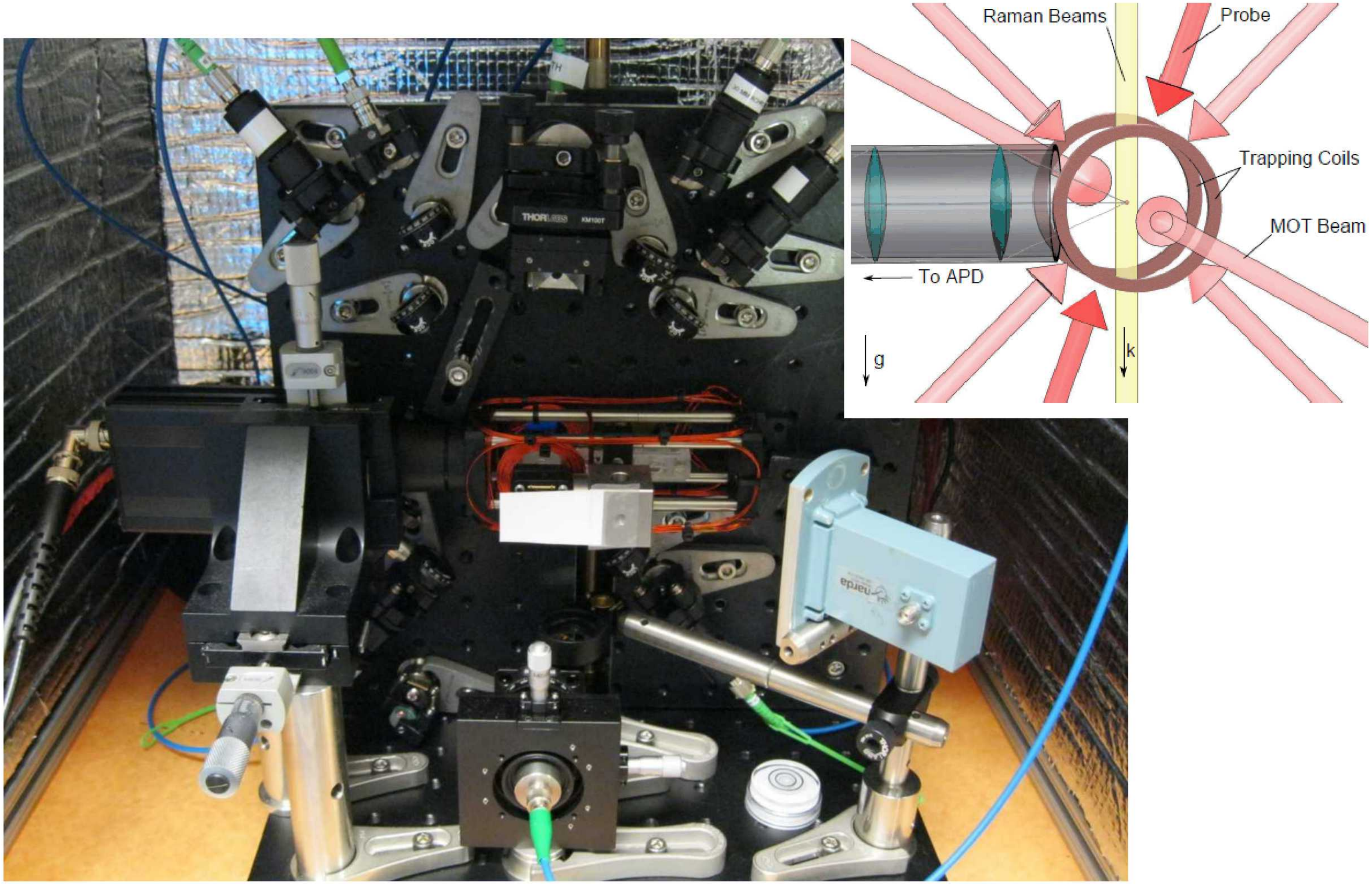







F = 3
F = 4
F = 4
F = 3
T
T
π/2
π
π/2

High-bandwidth interferometer



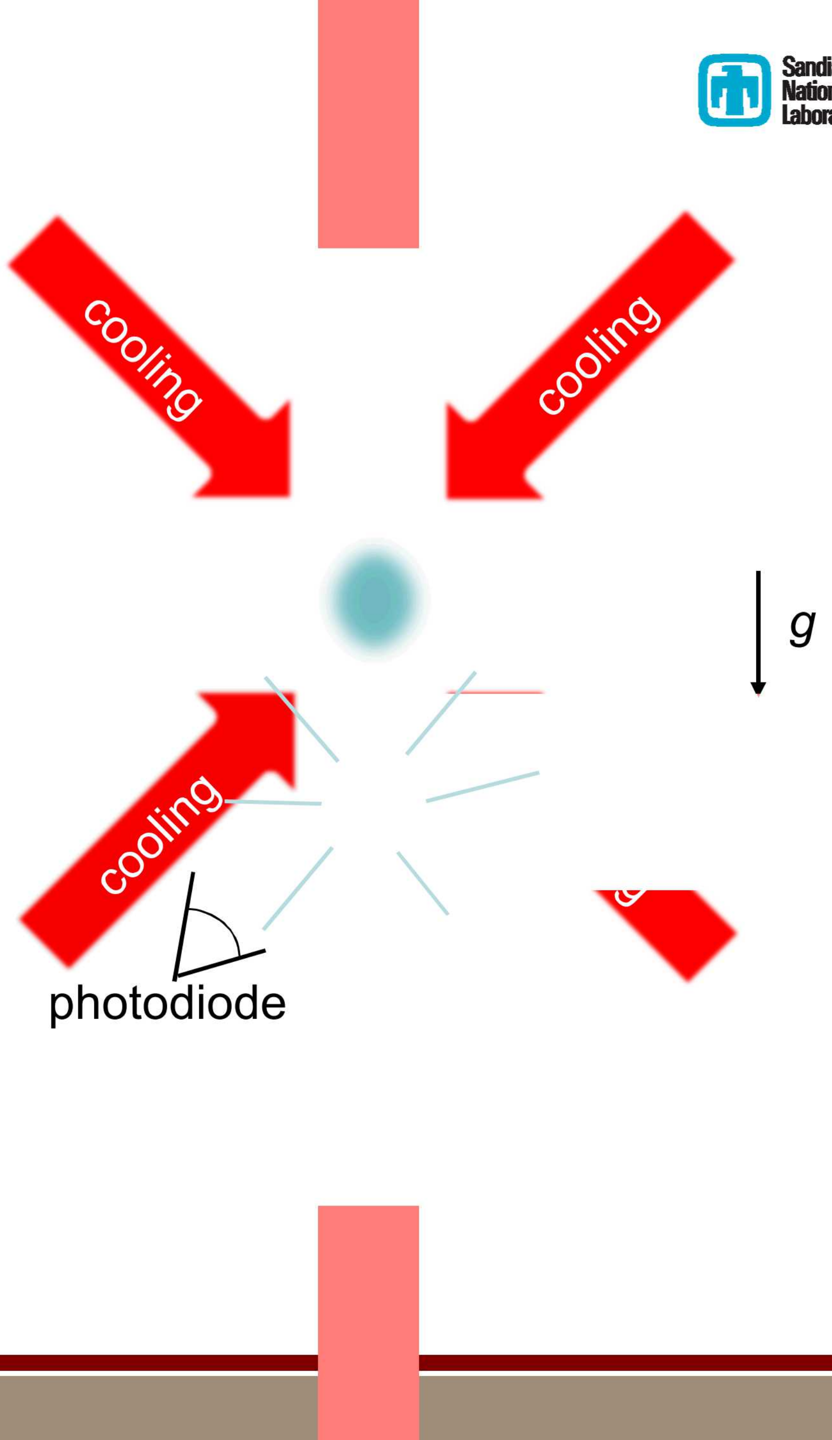
$600\ ng/\sqrt{Hz}$ at 50 Hz

Rakholia, PhD dissertation, UNM

One measurement cycle

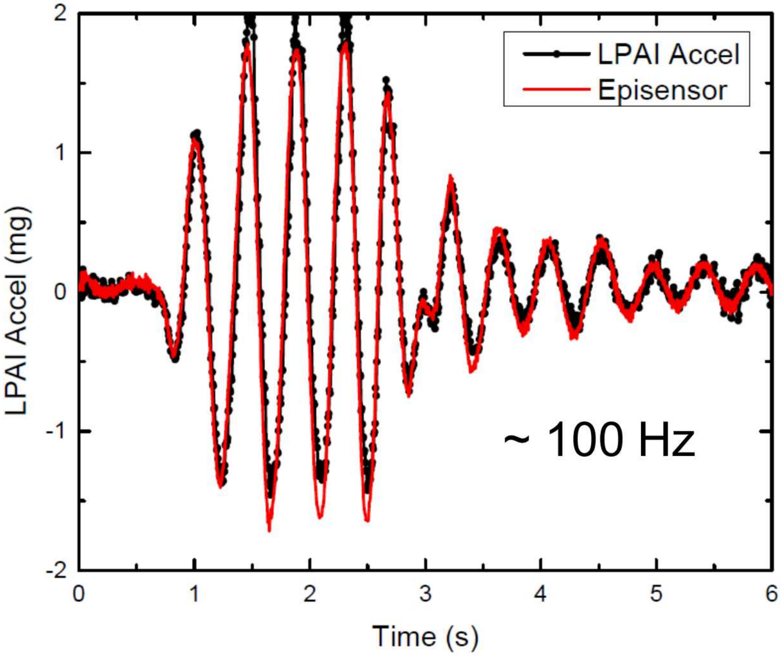
Example, 50 Hz^{-1} cycle:

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

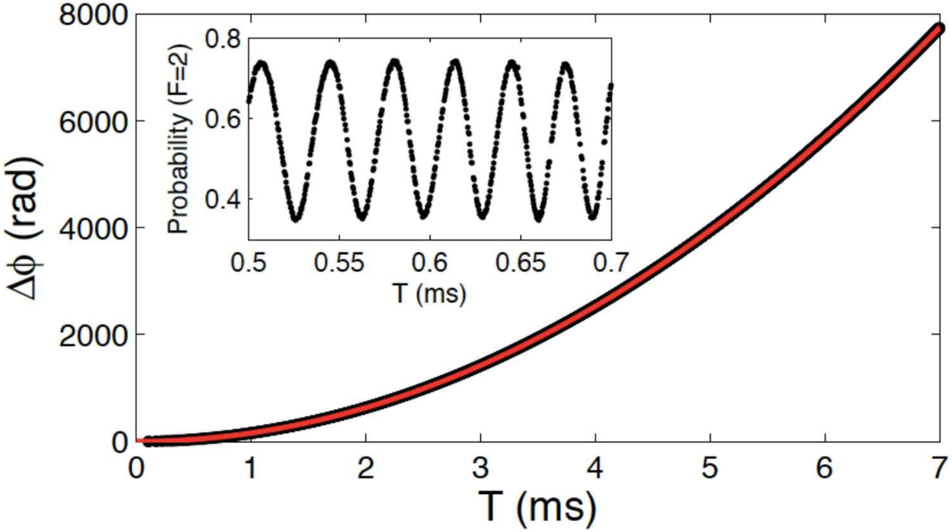


High bandwidth interferometer results

Operating under dynamics



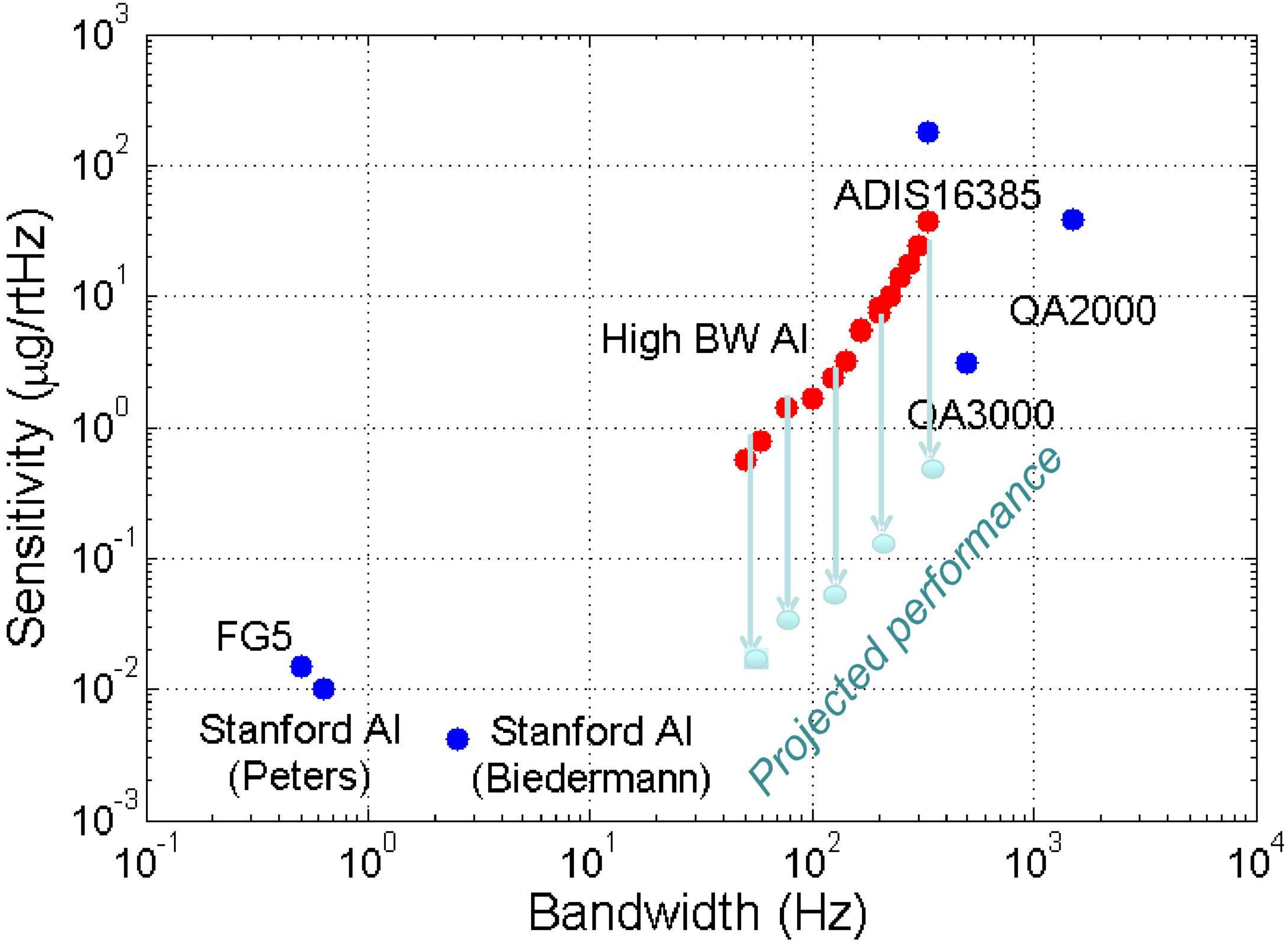
Measurement of *g*



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

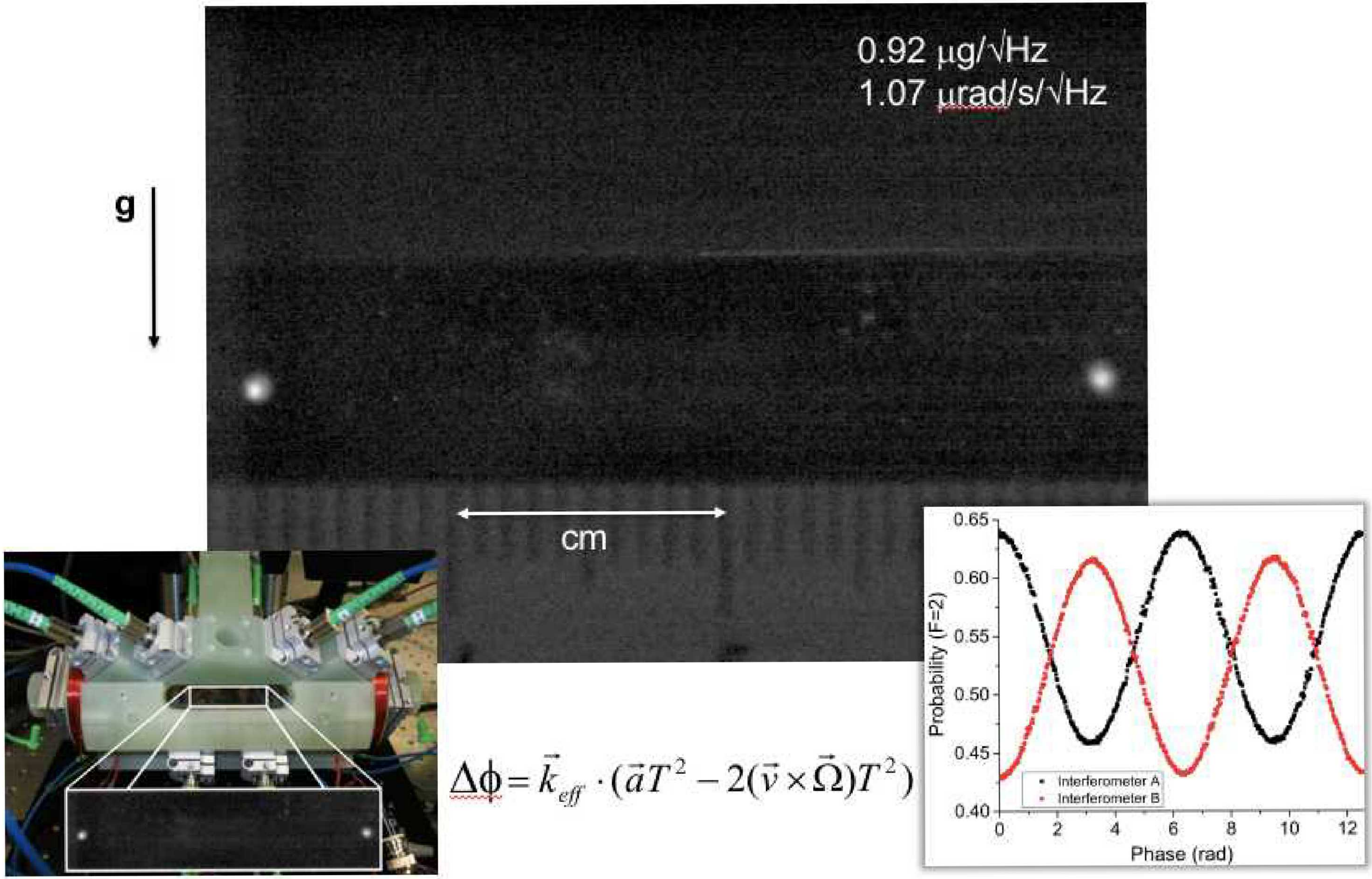
$$P_e(\Delta\phi) = \frac{1}{2}\left(1 - cos(\Delta\phi)\right)$$

Interferometer comparison



H. McGuinness, A. Rakholia, G. Biedermann Appl. Phys. Lett. **100**, 011102 (2012)

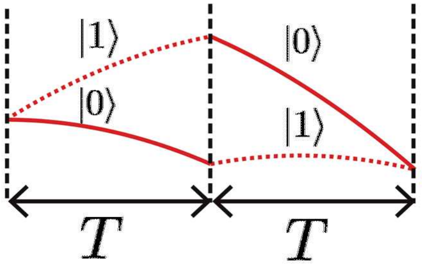
Dueling interferometers



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

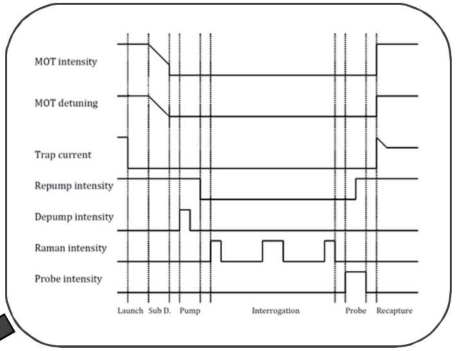
What does it take?

Matterwave trajectory

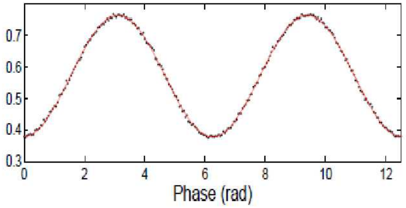


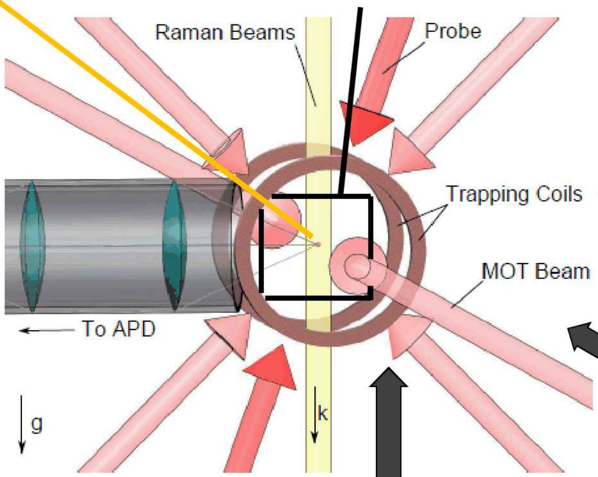
UHV vacuum system

Control electronics

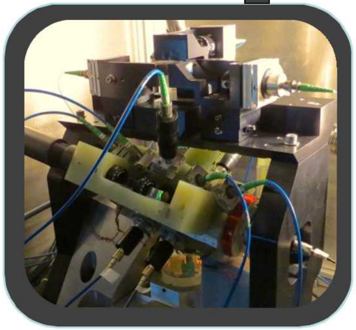


Acceleration →

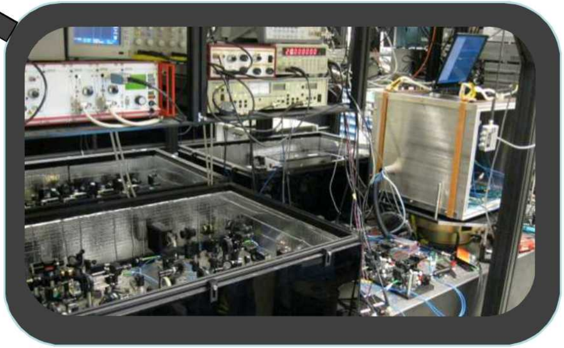




New effort

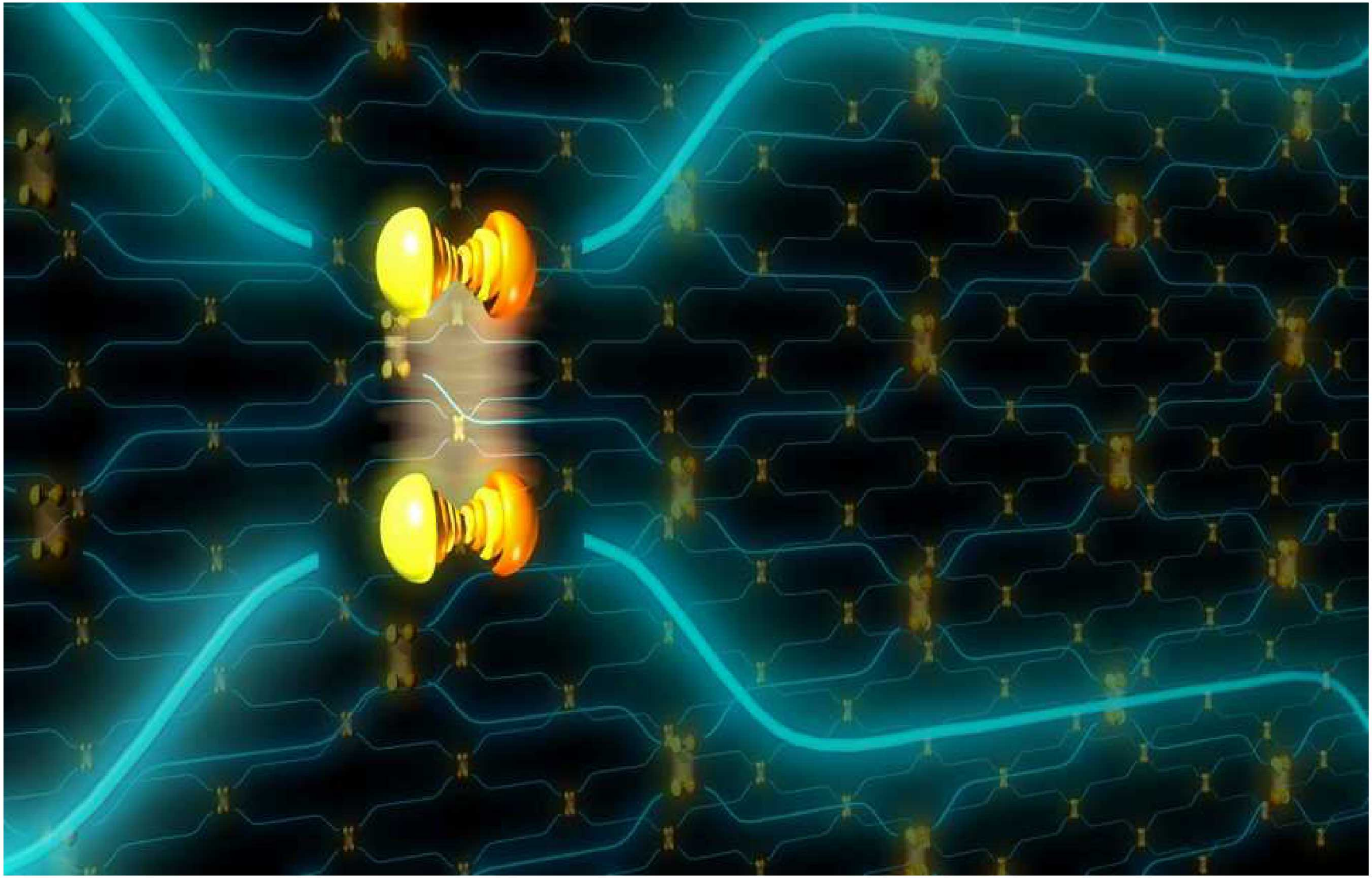


Custom optomechanics



Agile & stable laser system

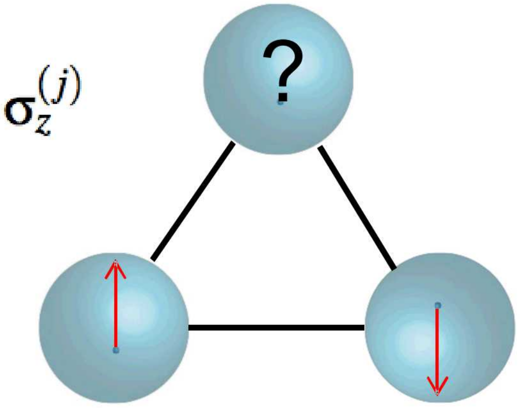
Entangled states of neutral atoms



Applications

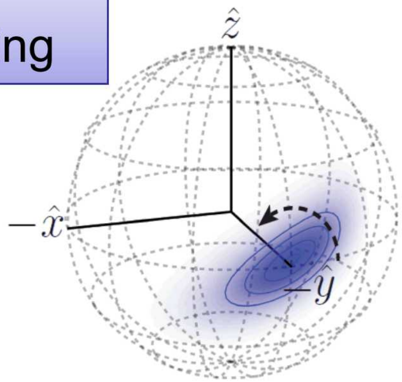
Quantum simulation

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

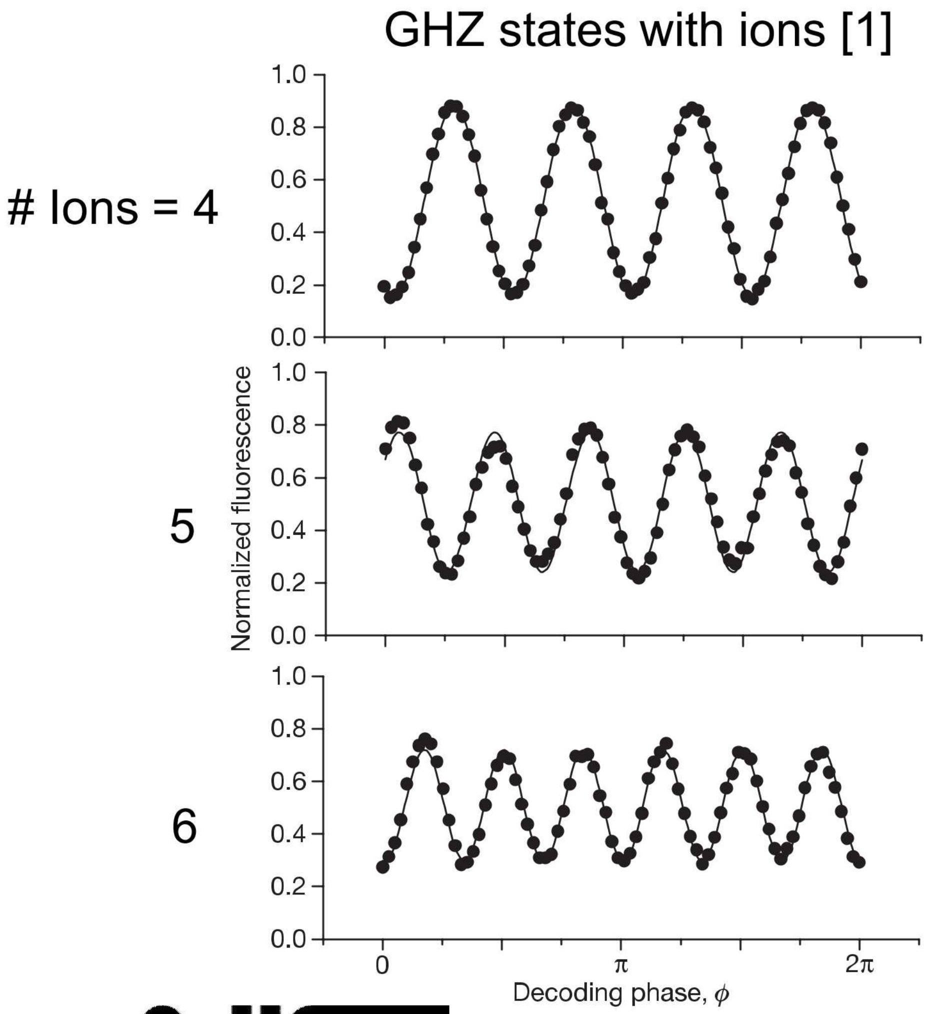


Frustrated magnetism

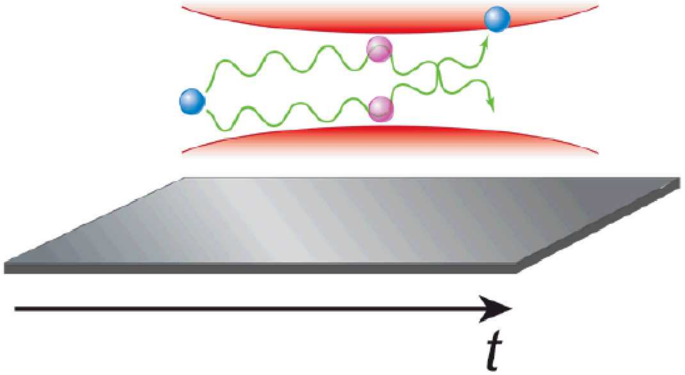
arge-scale/rapid
ntanglement for sensing



Interferometry with GHZ states


GHZ states with ions [1]

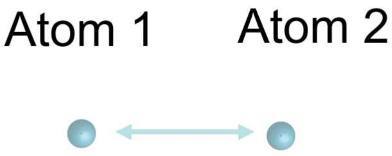
- Sensitivity to a Ramsey interferometer phase shift scales with N


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

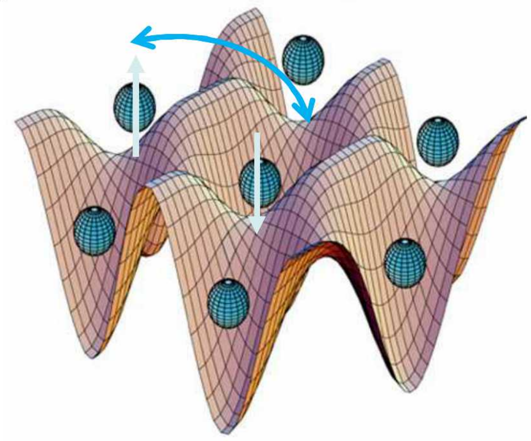
- Apply to single atom interferometers

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

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)

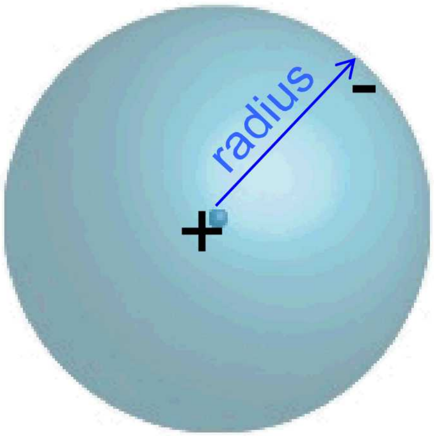
One solution: use Rydberg states

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

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

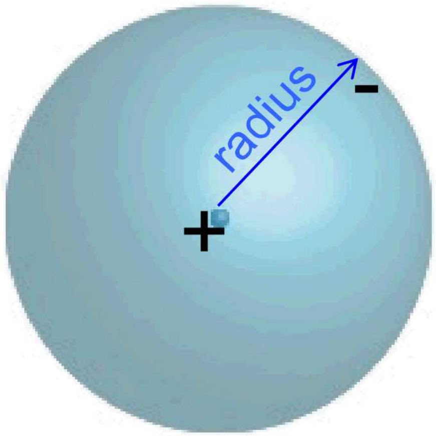
Interaction between *neutral* atoms

Valence electron
in Rydberg state



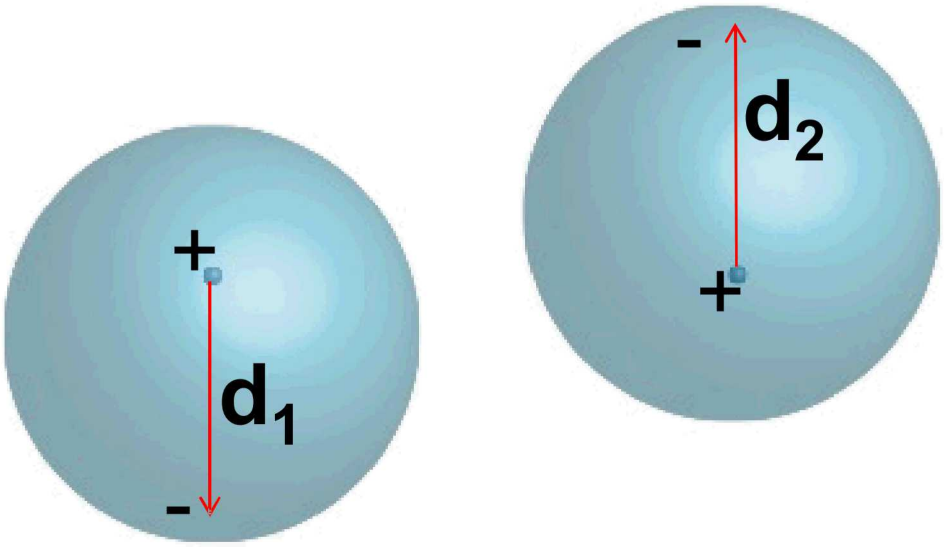
orbital radius α n^2

Valence electron
in Rydberg state



- 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

$\tau \propto n^3$

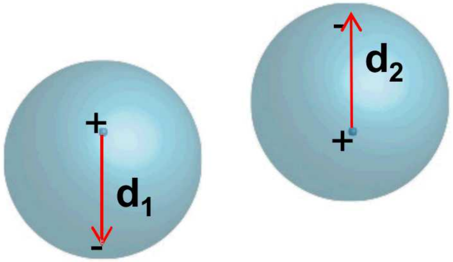
DC polarizability

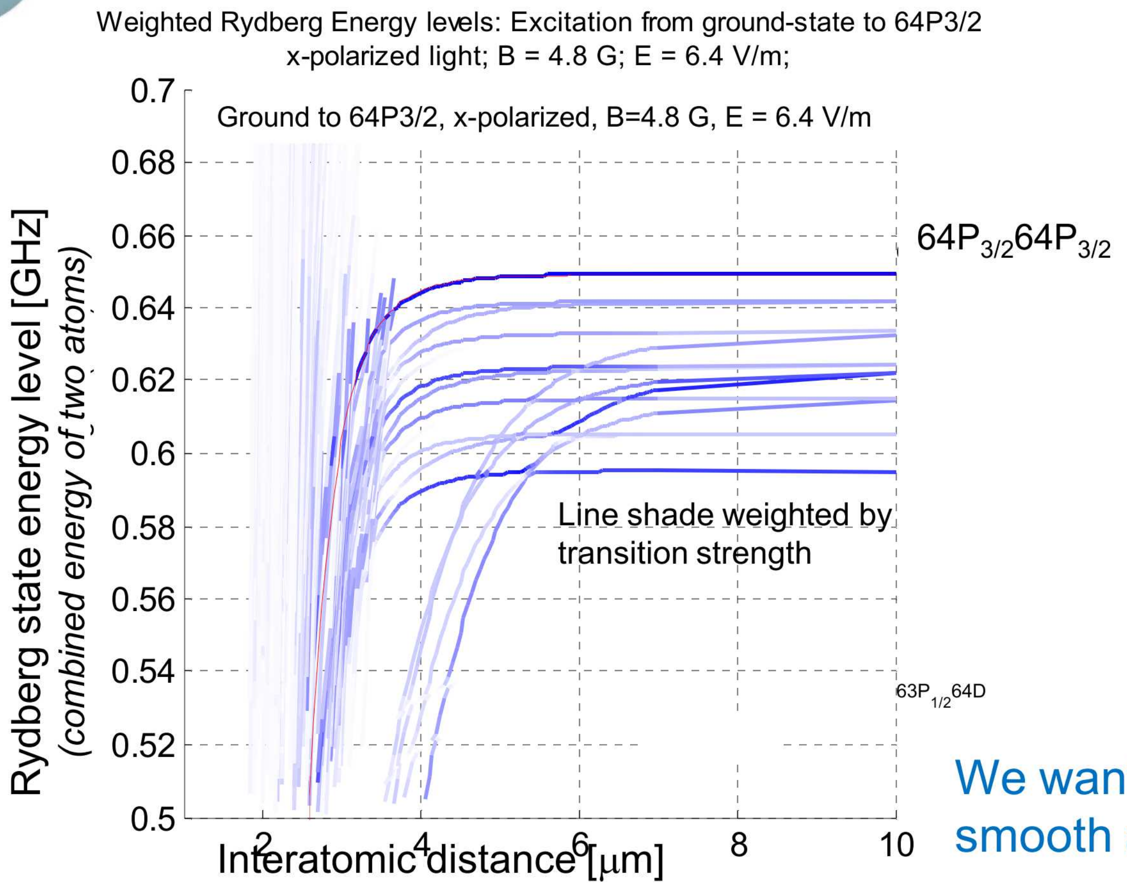
$\alpha(0) \propto n^7$

- 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

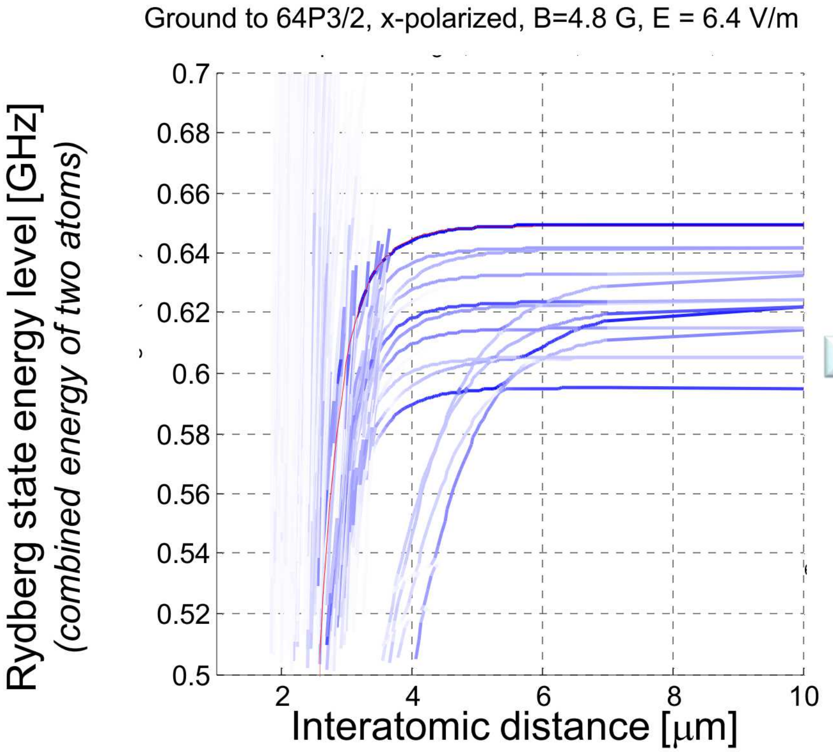


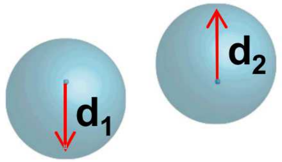


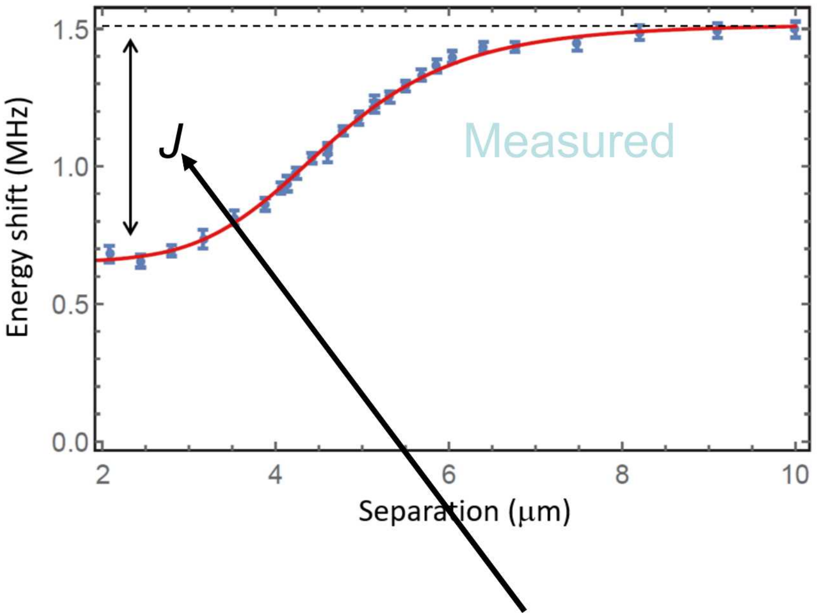
We want something smooth and tunable

Phys. Rev. A 89, 033416 (2014)

Direct Rydberg → Rydberg-Dressed

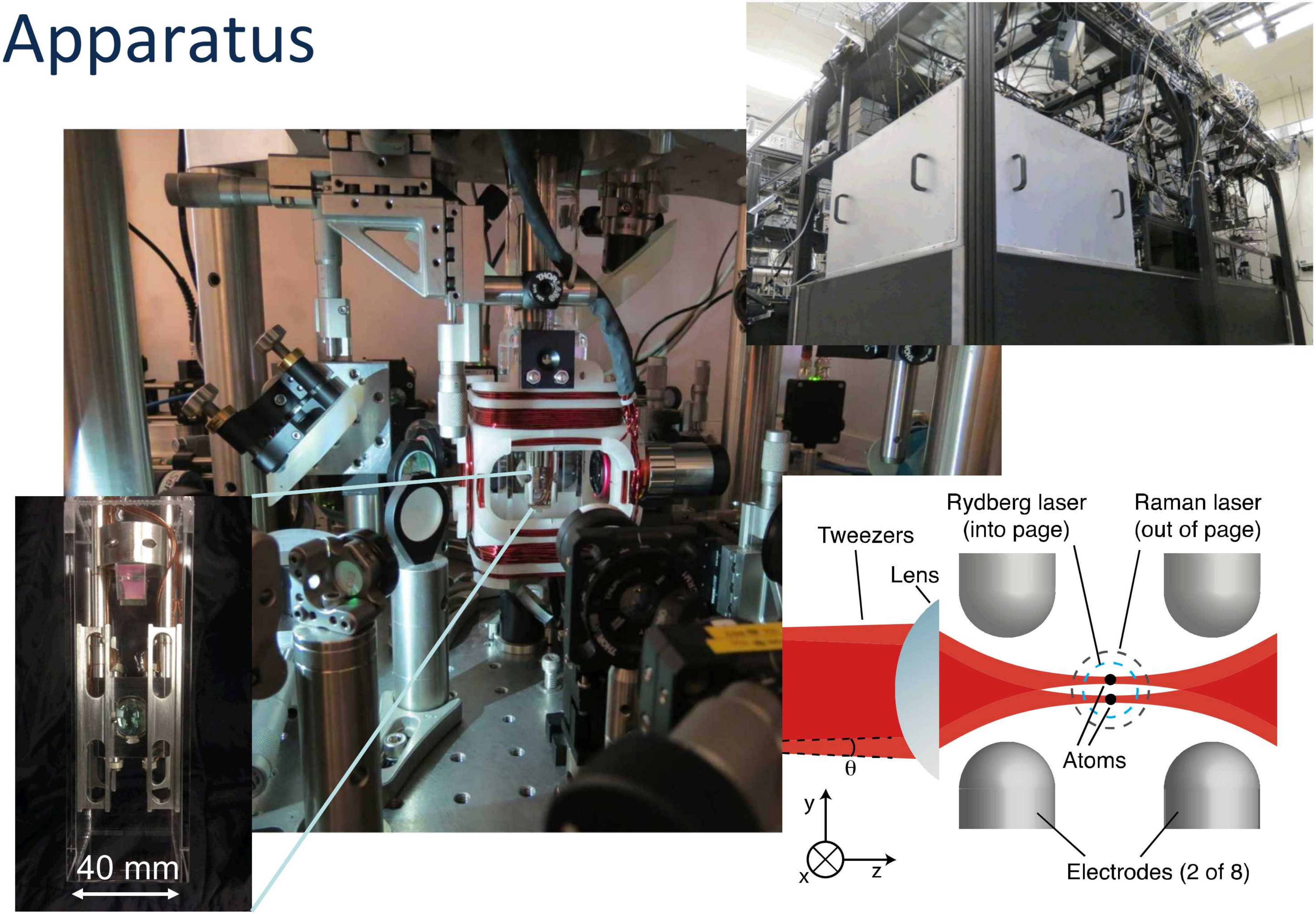

Ground to 64P3/2, x-polarized, B=4.8 G, E = 6.4 V/m





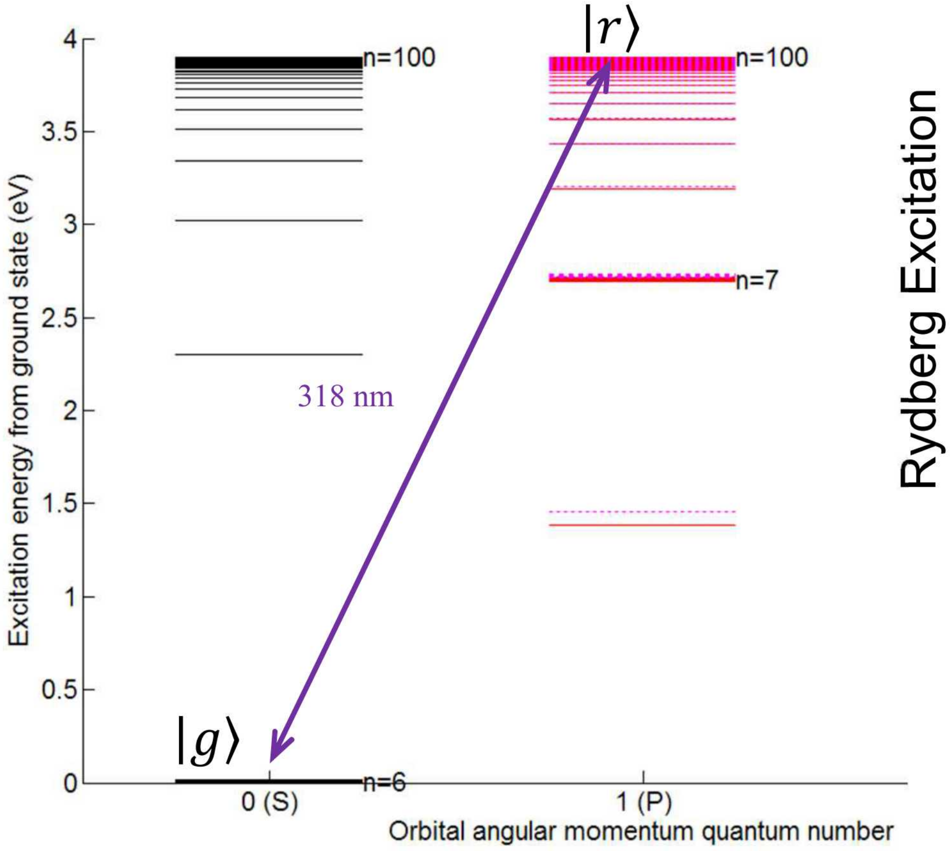
$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

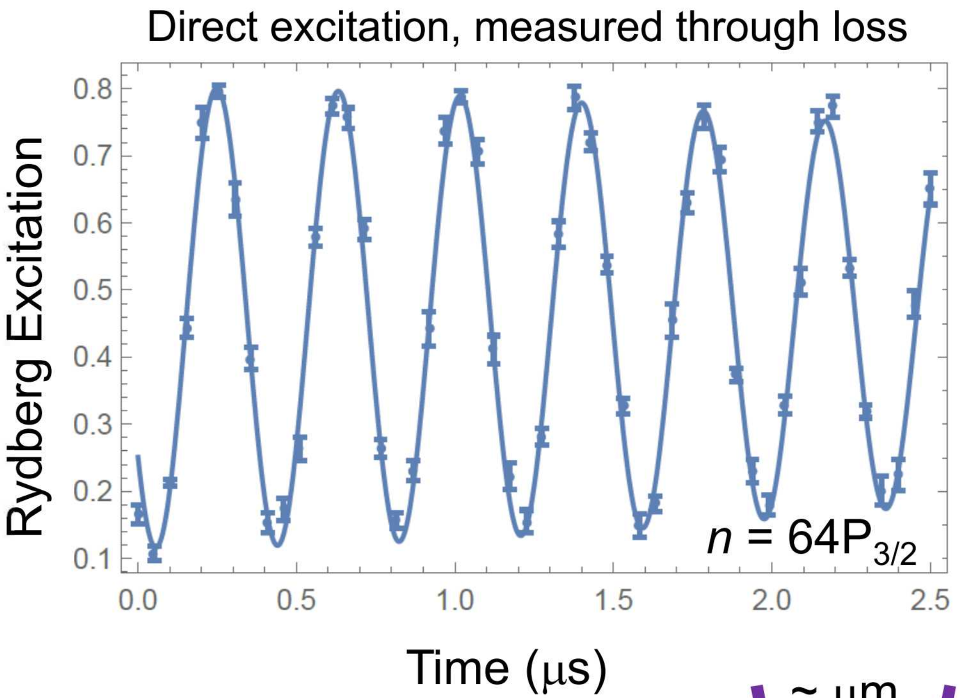
Apparatus

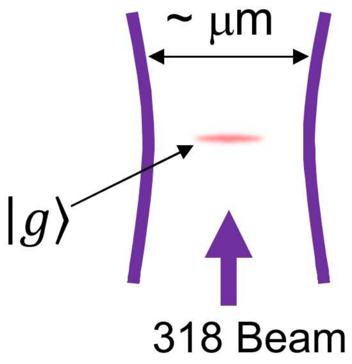


Phys. Rev. A 89, 033416 (2014)

Rydberg Rabi flopping with 318 nm laser

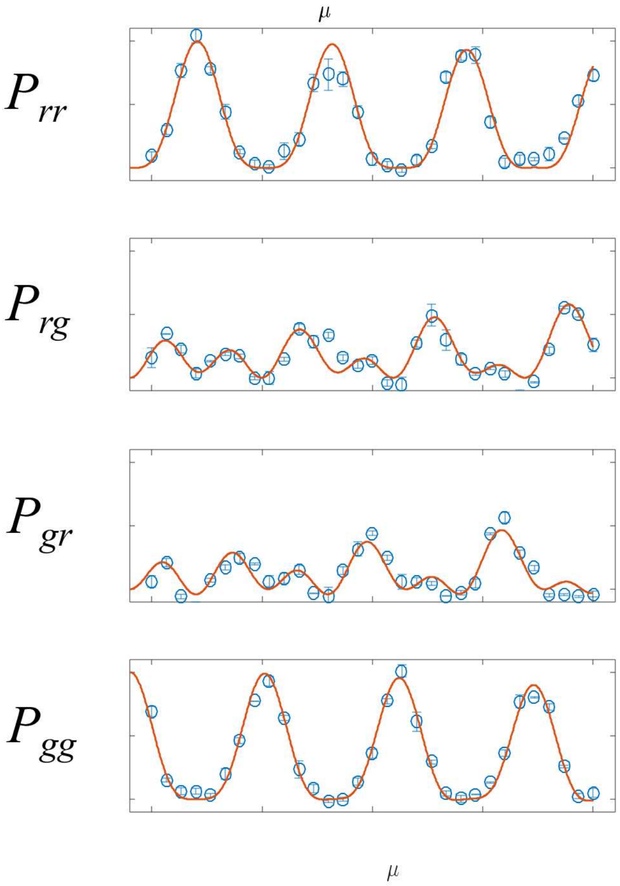


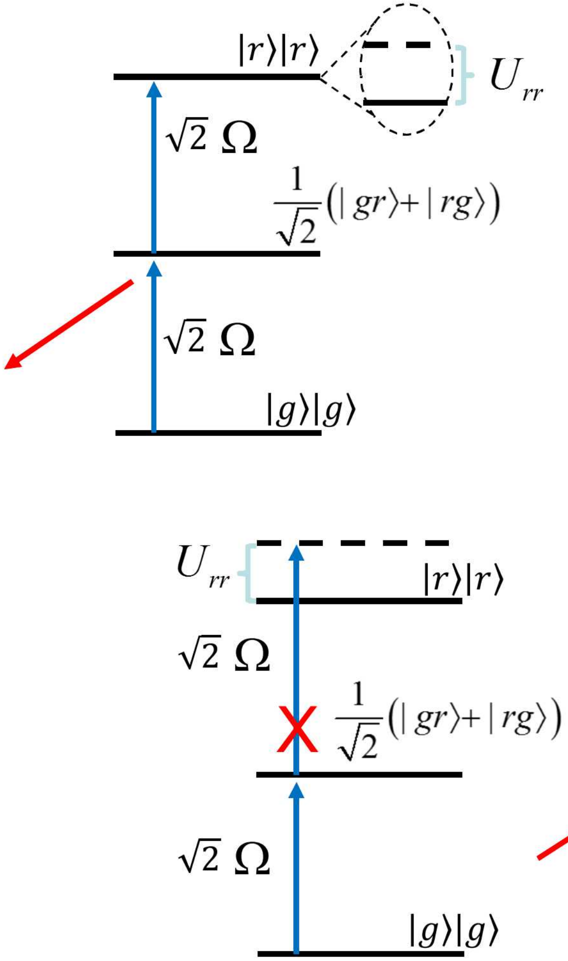




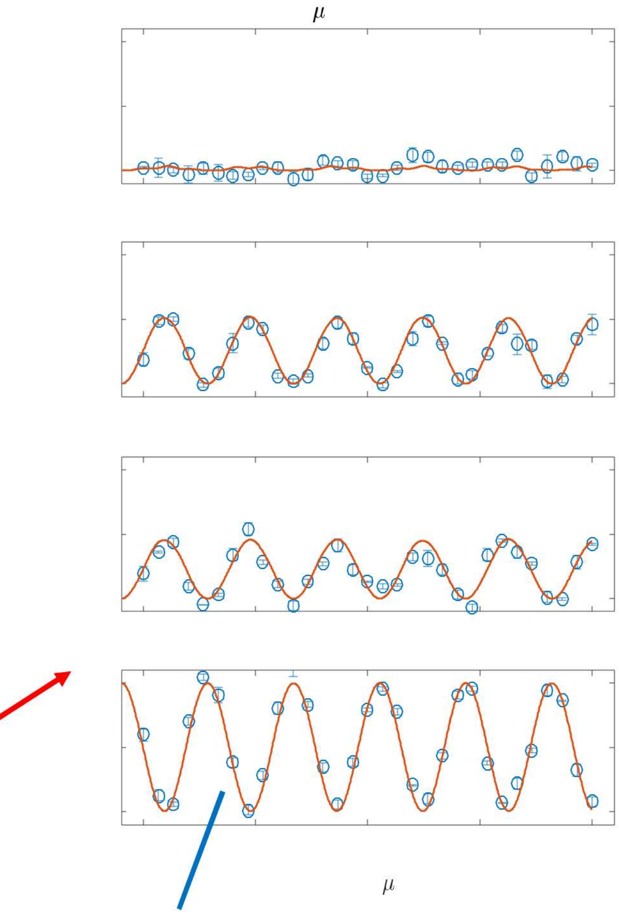
Rydberg blockade

Weak (U_{RR} < 100 kHz)



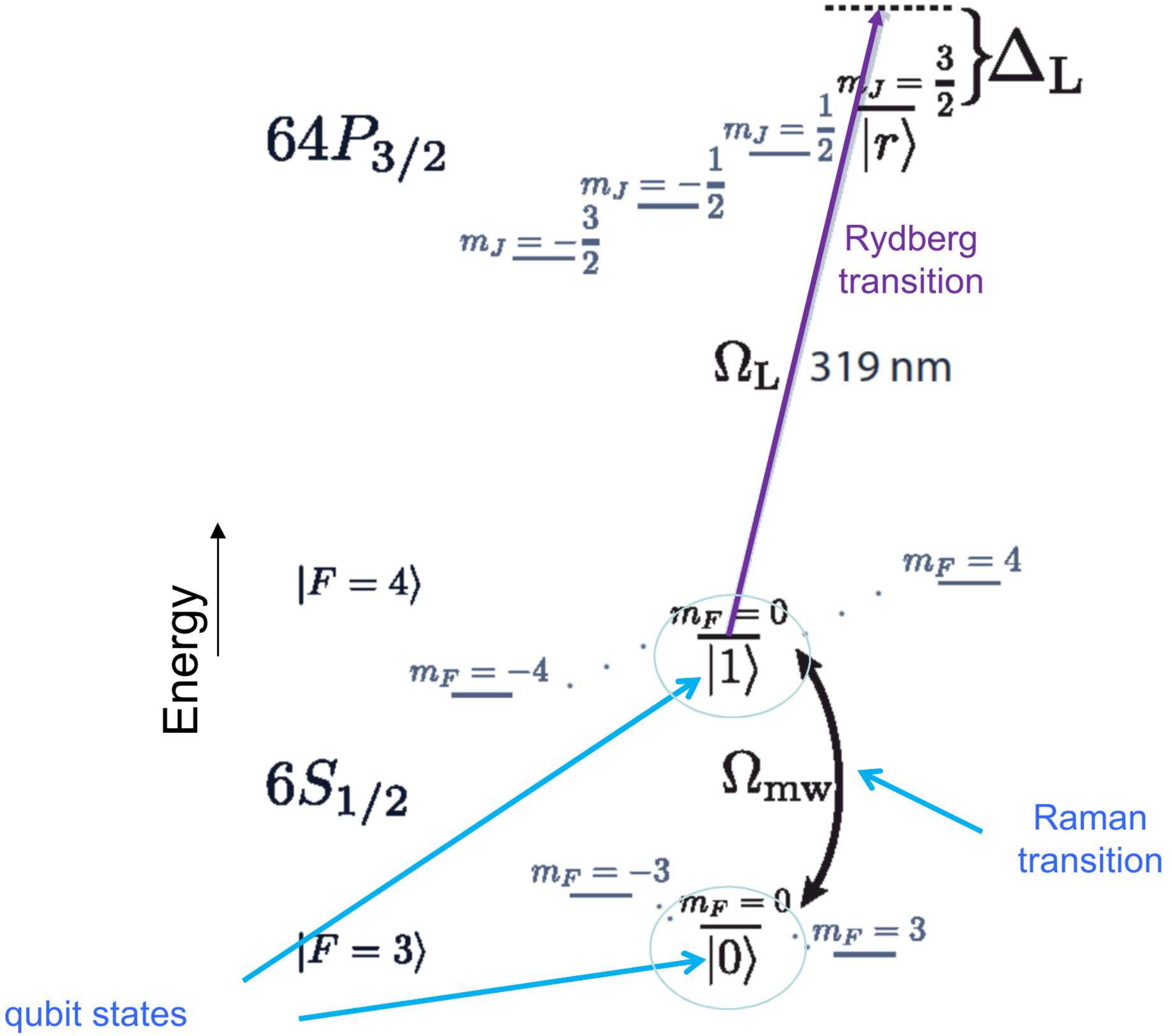


Strong (U_{RR} > 6 MHz)



$\sqrt{2}$ Enhancement

Creating Rydberg-Dressed states

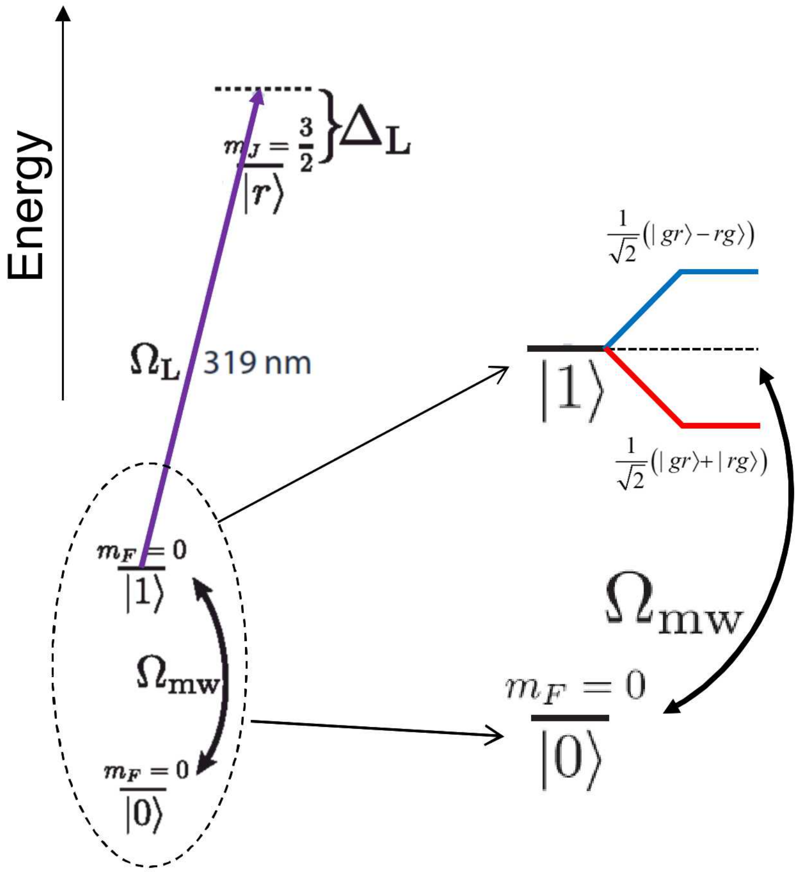


Rydberg transition

Raman transition

qubit states

Creating Rydberg-Dressed states

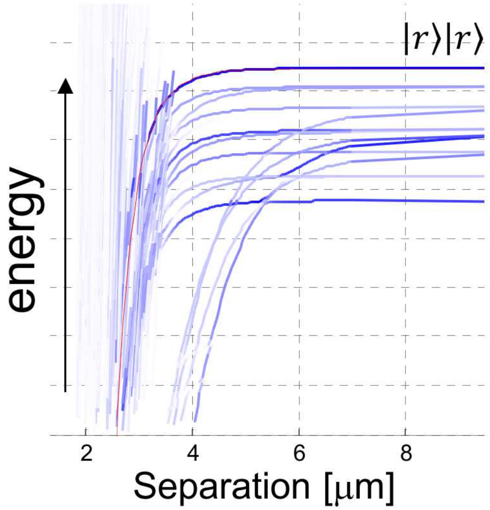


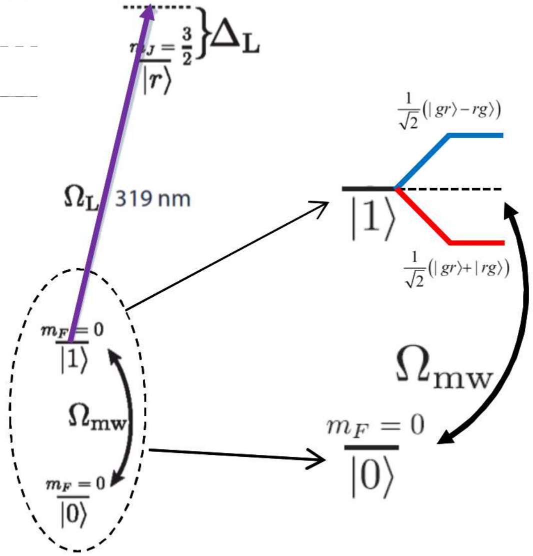
Light-shift Hamiltonian

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

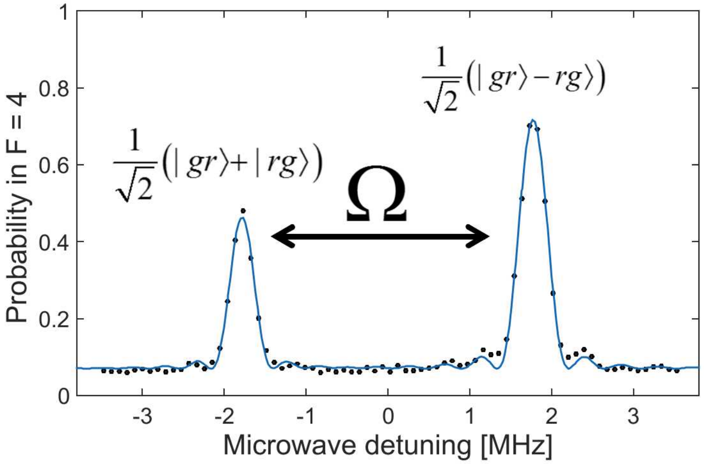
$$\Delta = \frac{\hbar\,\Omega_L^2}{4\,\Delta_L}$$

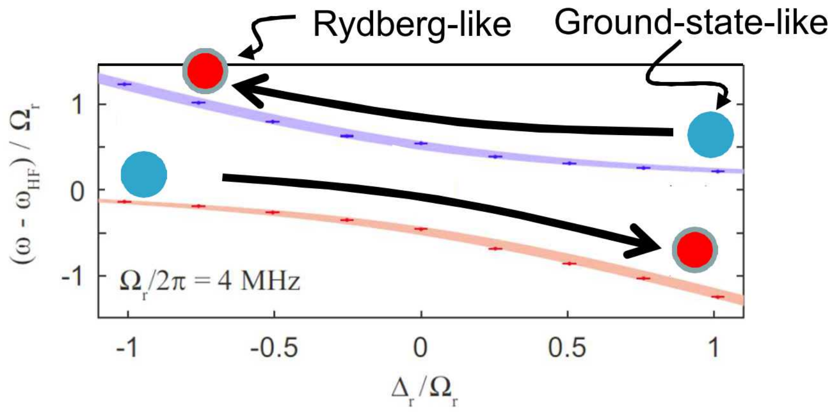
1-atom Rydberg-dressed states



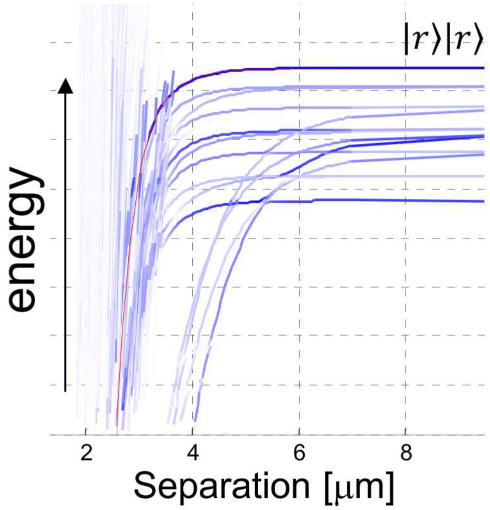


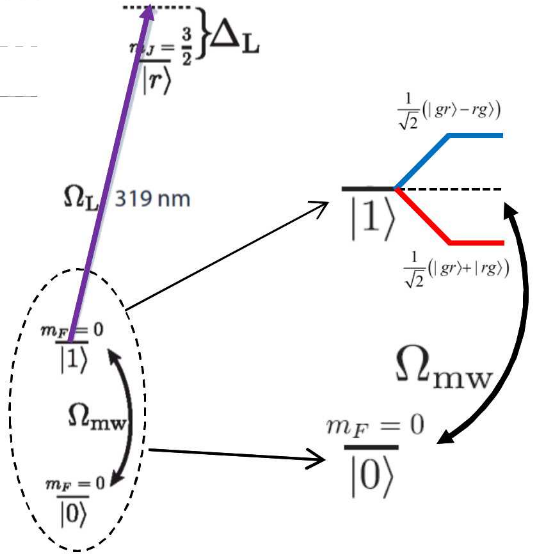
Dressed F=4 state Autler-Townes splitting

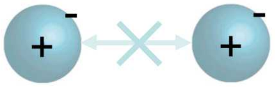


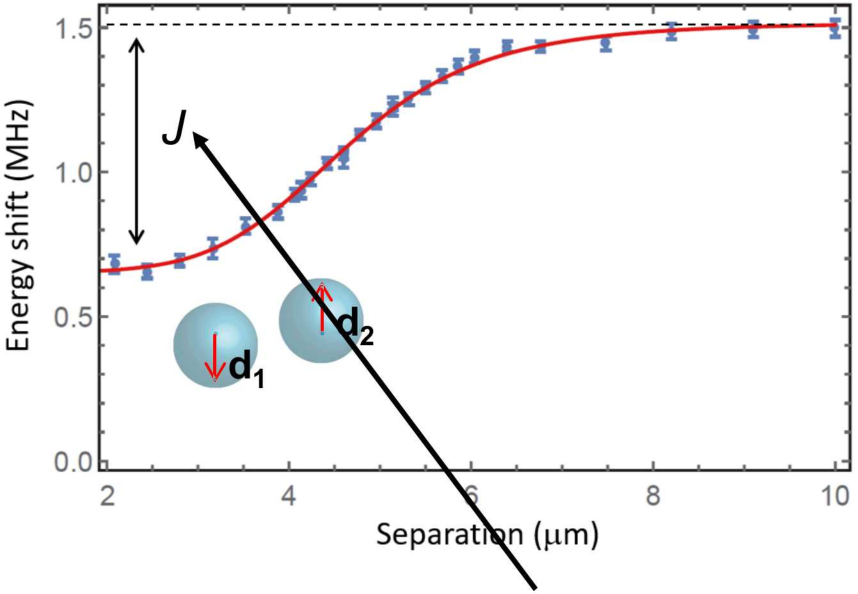


Rydberg-Dressed interaction





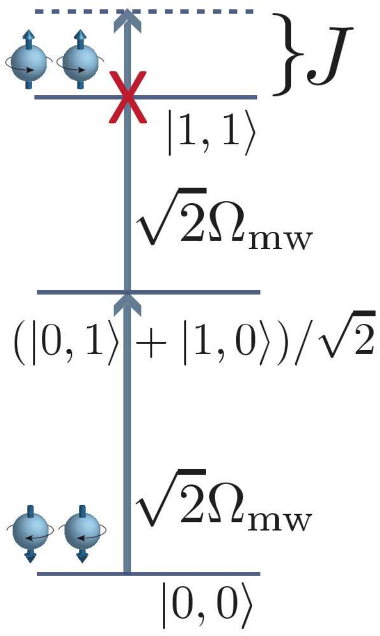


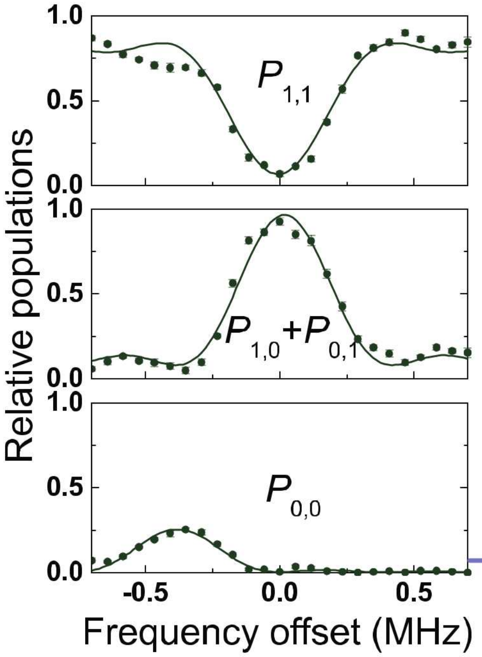


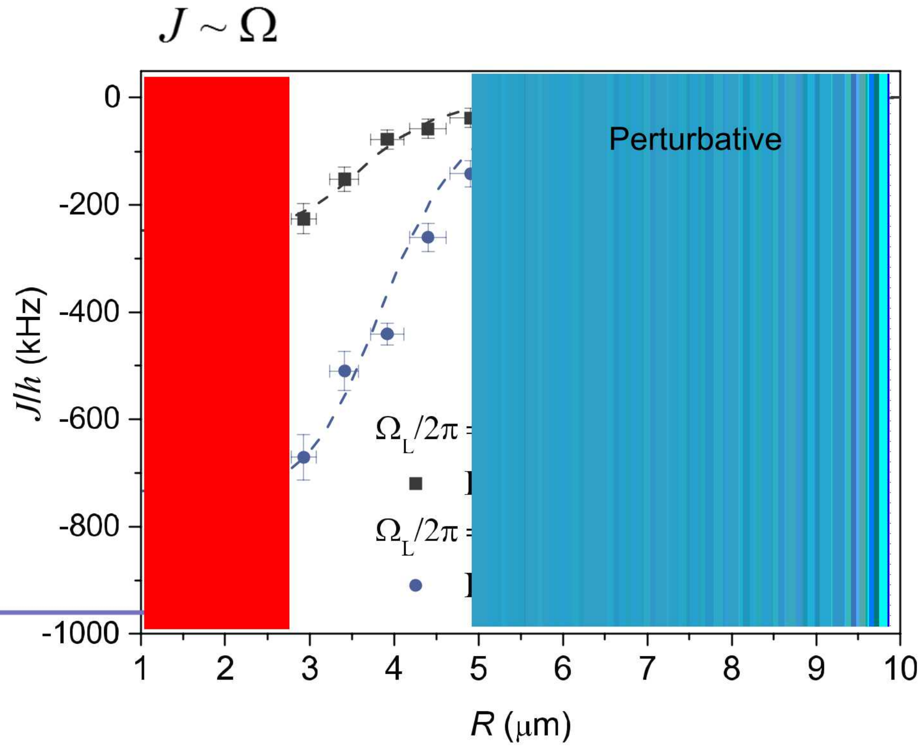
$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

Observing blockade on hyperfine qubit

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



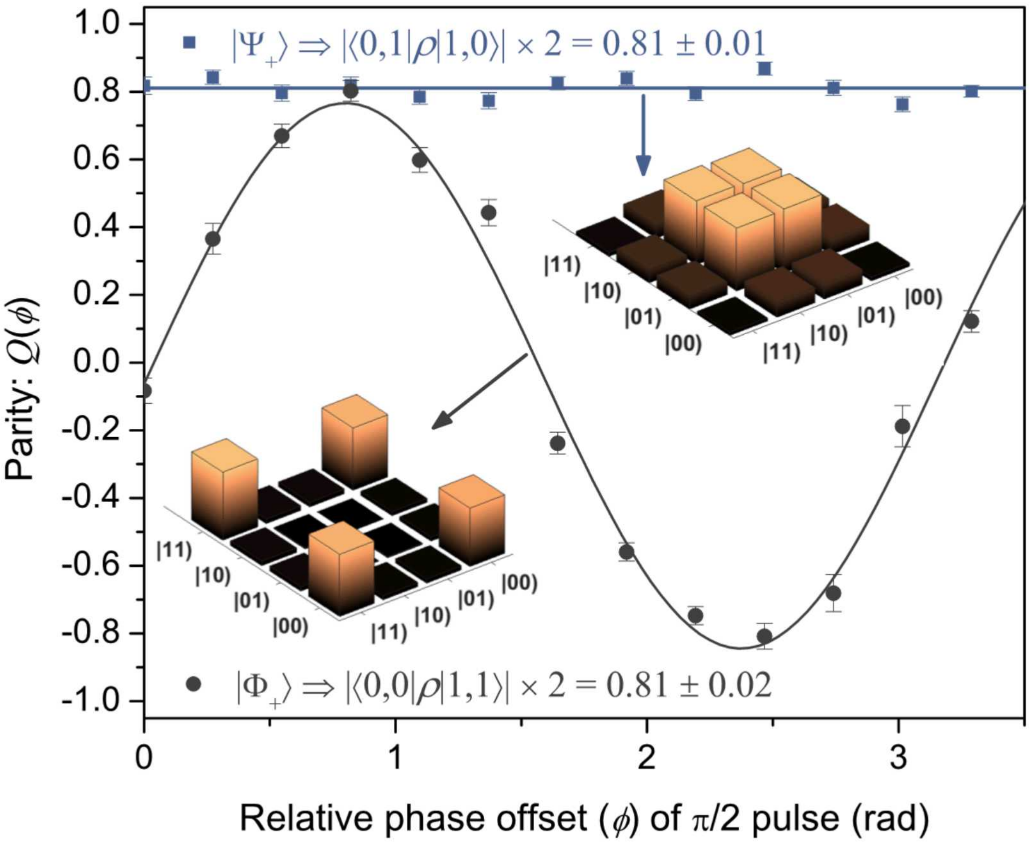


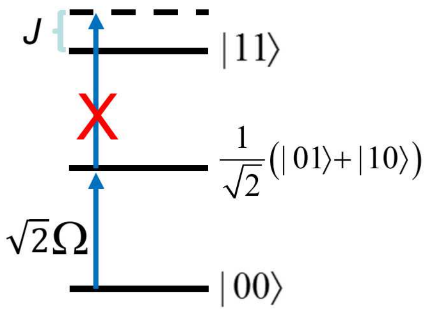


Y.-Y. Jau, et al., G.B., Nature Phys. **12**, 71-74 (2016)

Spin-flip blockade

Verify the entanglement via parity measurements





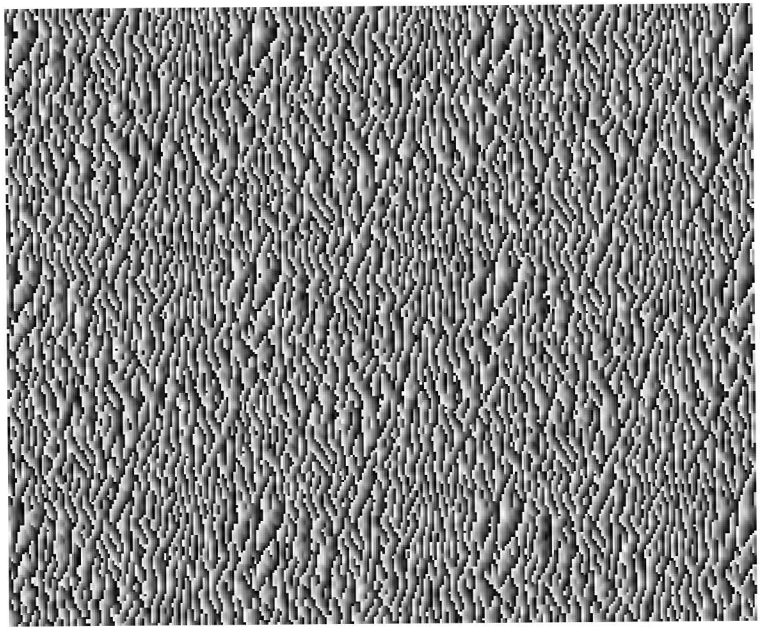
1. Prepare Bell state
2. Apply global $\pi/2$ with given phase
3. Measure parity Q
4. Obtain bound on fidelity =0.81(2)

Y.-Y. Jau, et al., Nature Phys. **12**, 71-74 (2016)

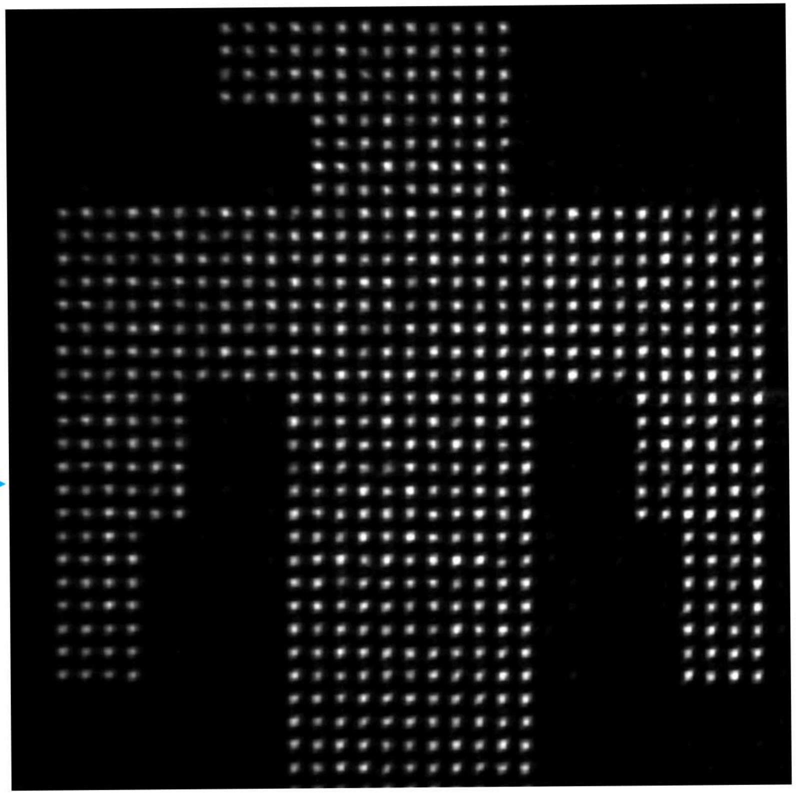
Generation and control of >500 of individual traps

Gerchberg-Saxton algorithm
With GPU compute acceleration
(~50 Hz hologram calculation)

Phase to SLM



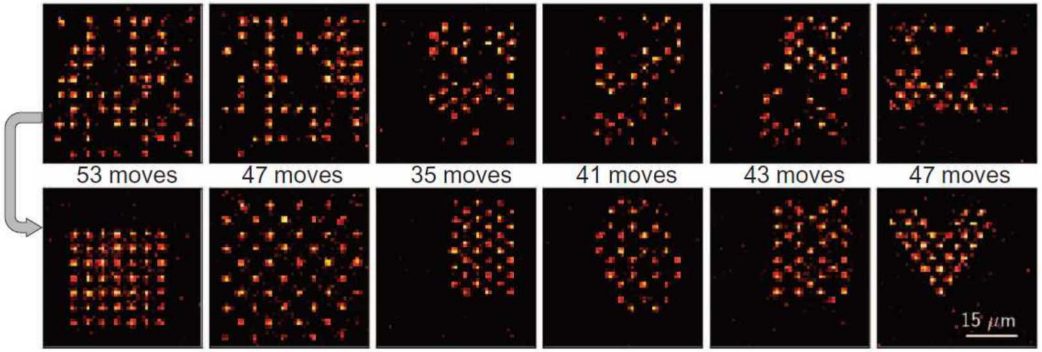
Intensity profile (measured)



Defect-free neutral atom arrays

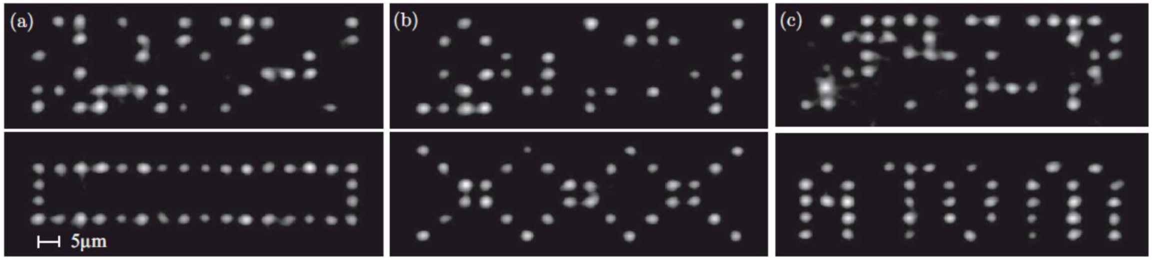
Lukin group, Harvard[1]

Browaeys group, Institut d'Optique (France)[2]



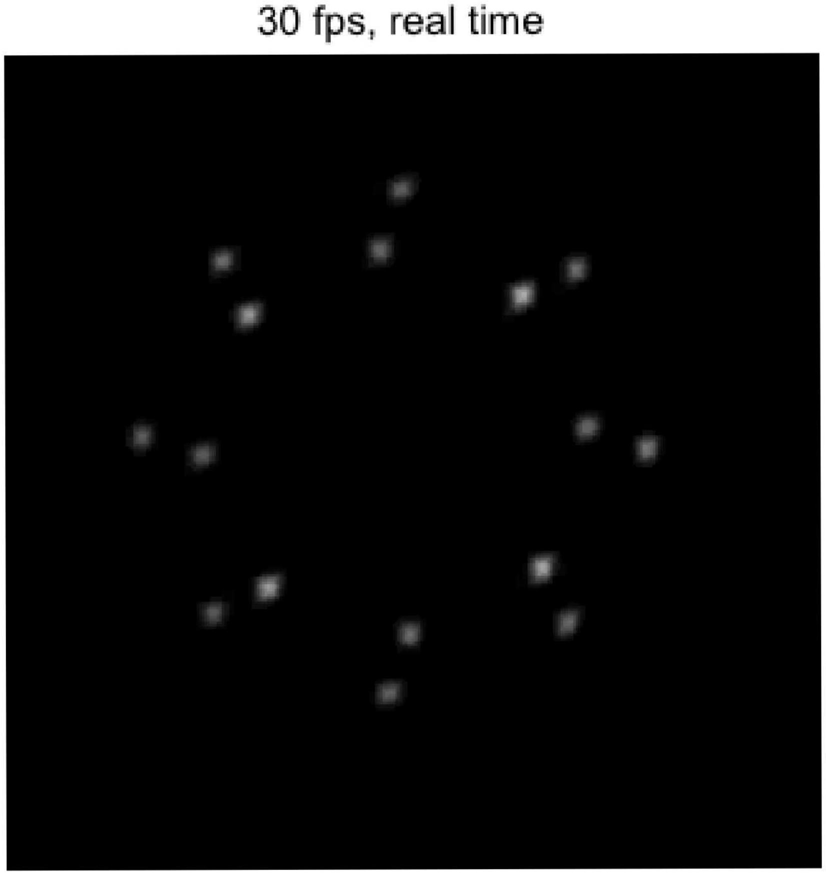
- There has been a revolution in creating defect free, controllable arrays of neutral atoms.
- 1D, 2D & 3D arrays demonstrated.
- This capability makes scaling to a many qubit simulator a possibility.

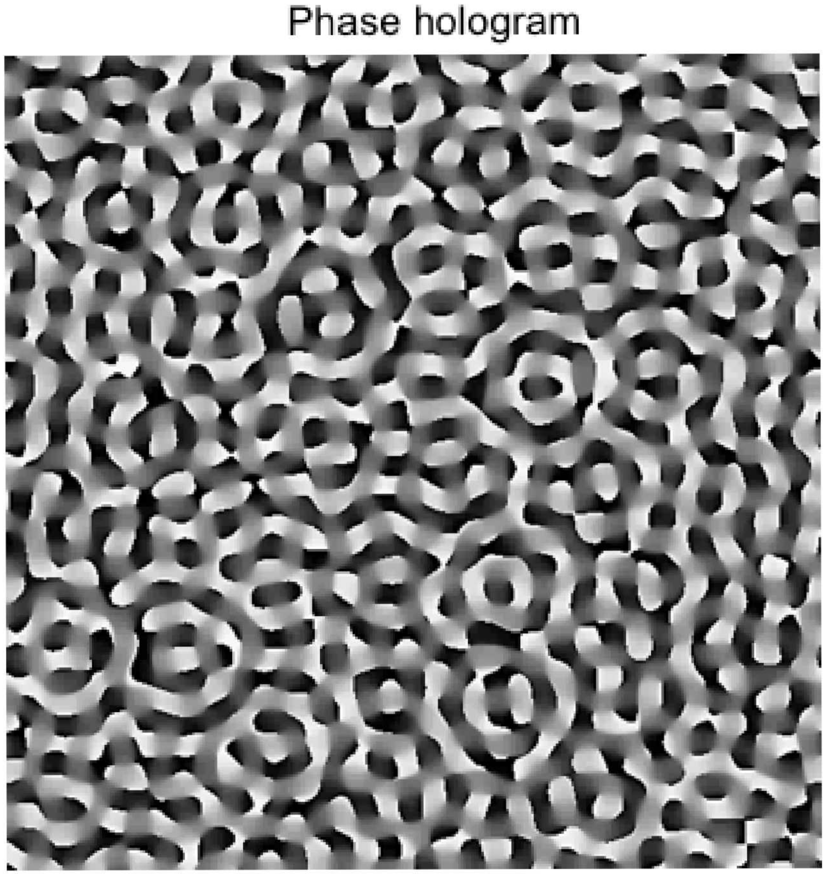
Ahn Group, KAIST (South Korea)[3]

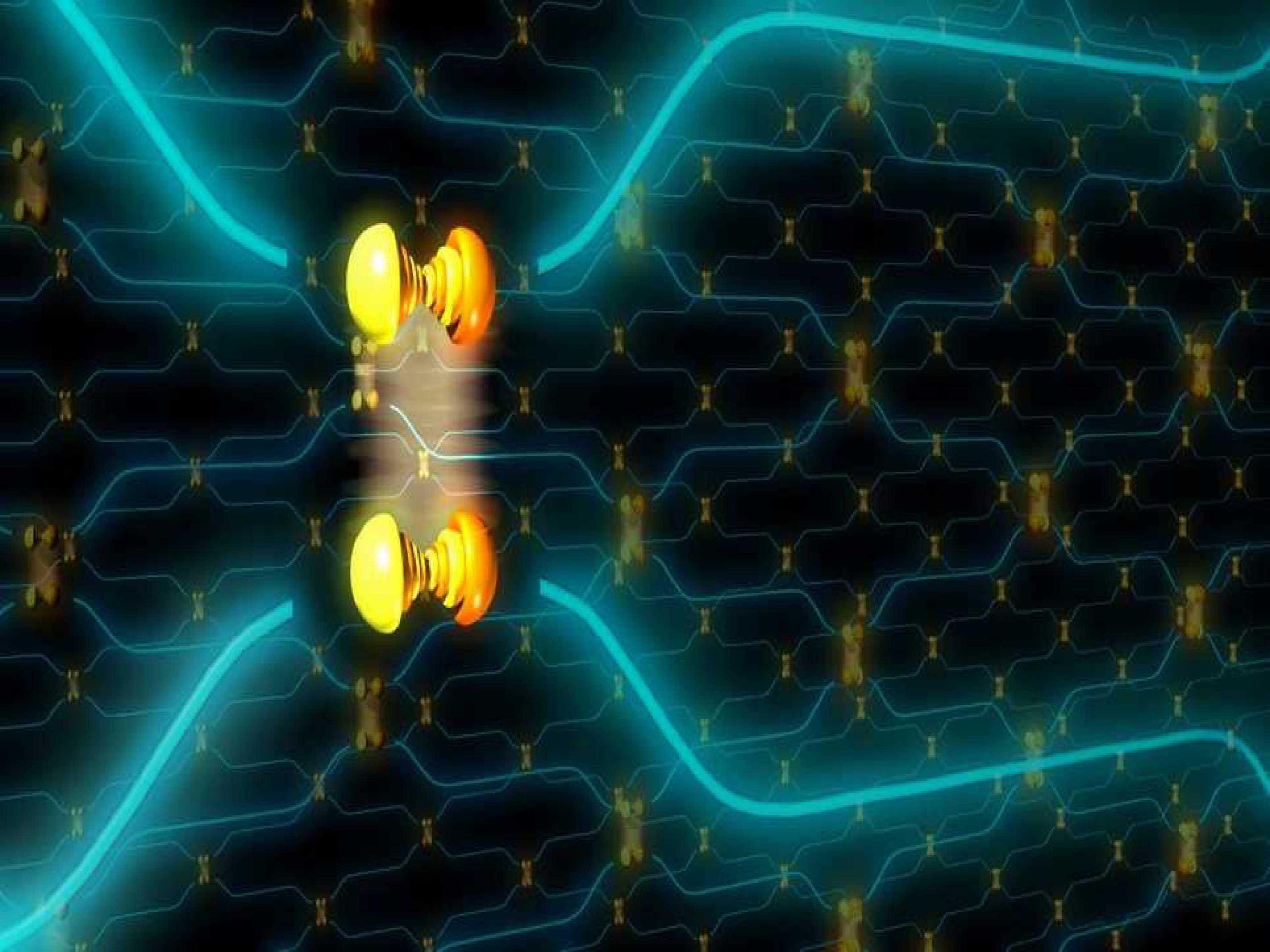


1. M. Endres et al., Science 354, 1024 (2016)
2. D. Barredo et al., Science 354, 1021 (2016)
3. W. Lee et al., Phys. Rev. A **95**, 053424 (2017)

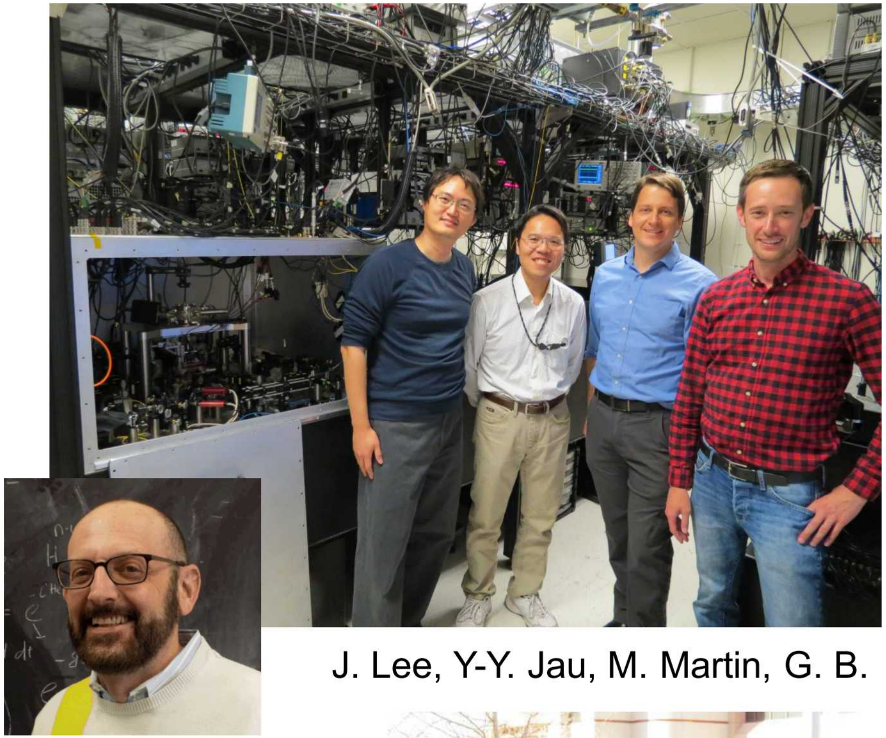
Dynamic control of hologram-generated traps


30 fps, real time


Phase hologram



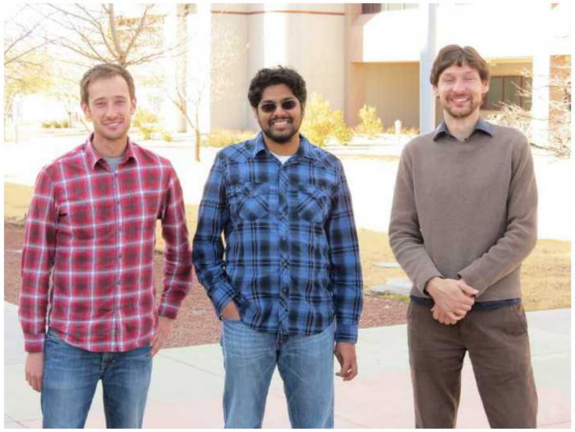
Sandia Team



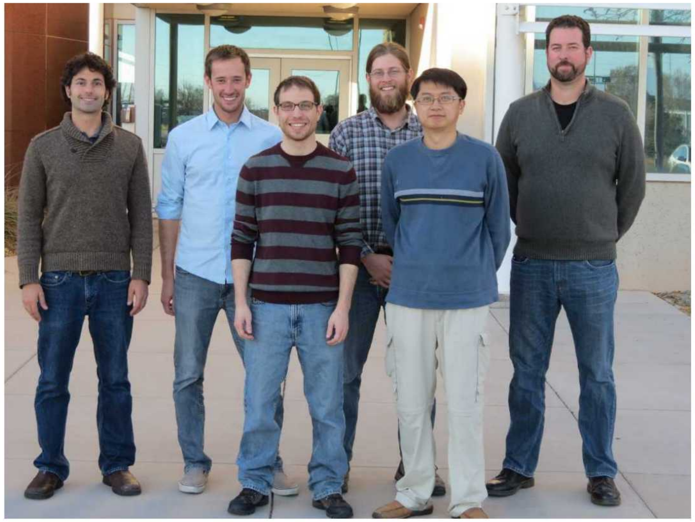
J. Lee, Y-Y. Jau, M. Martin, G. B.

I.Deutsch (UNM)

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



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



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

Postdoc position available. Contact me!