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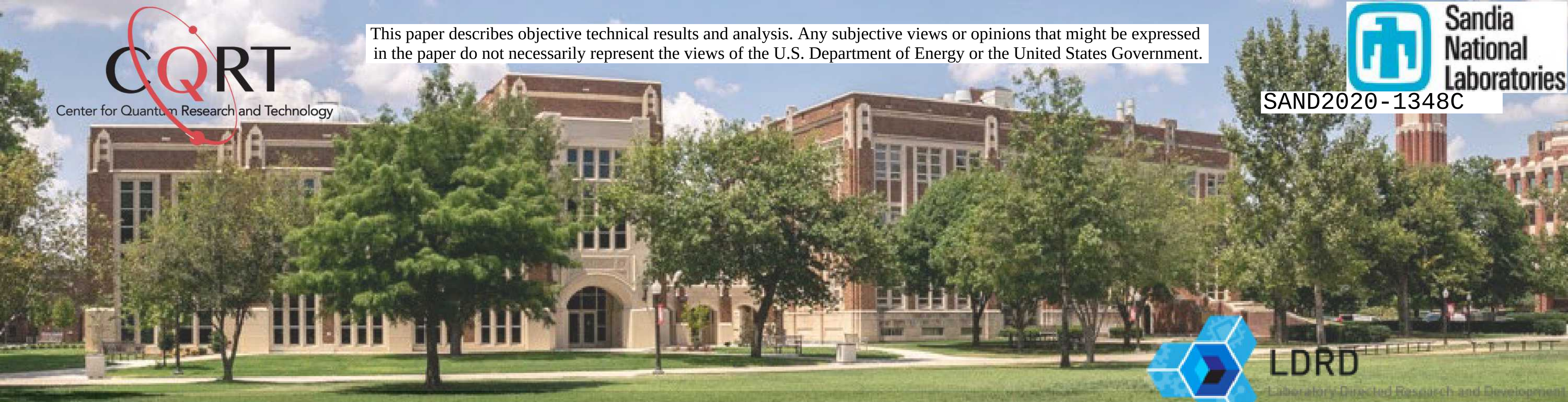
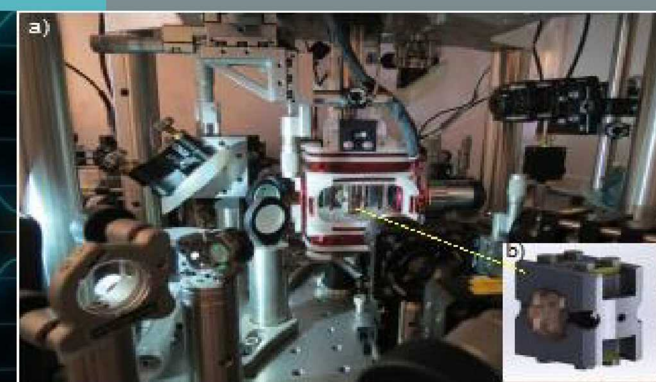


Growing complexity in quantum metrology with neutral atom spins

Grant Biedermann
University of Oklahoma

Jongmin Lee: Sandia National Laboratories

Team: L.P. Parazzoli, B. Little, M. Chow, J. Lee, P. Schwindt, C. Brif, B. Ruzic, W. Kendal, A. Orozco



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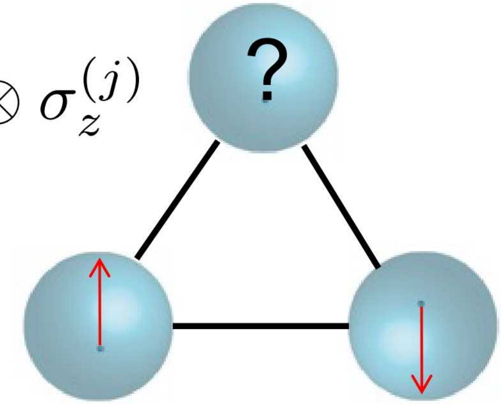
Future applications of *Neutral Atom* quantum information systems

Quantum simulation

$$H = \sum_{i=1}^{N} h_x^{(i)} \sigma_x^{(i)} + \ldots + \sum_{i \neq j}^{N} J_{i,j} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

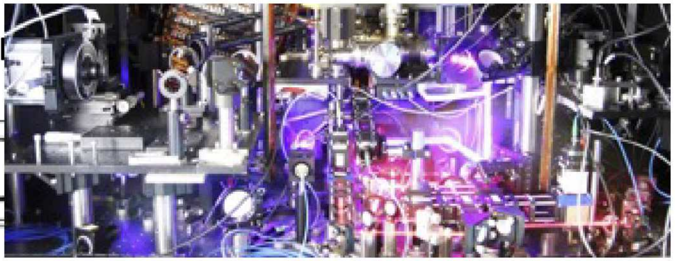


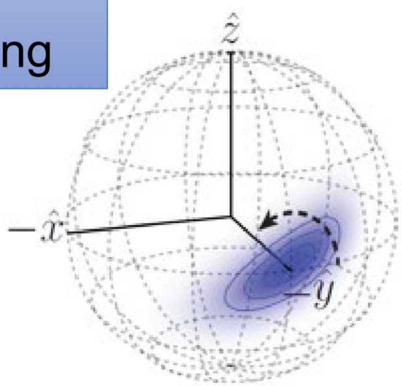
Frustrated magnetism

Large-scale/rapid entanglement for sensing

Sr lattice clock, Ye lab JILA

Quantum Fourier tra





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

2015 Guinness book

AI phase shift: a simple perspective

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

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

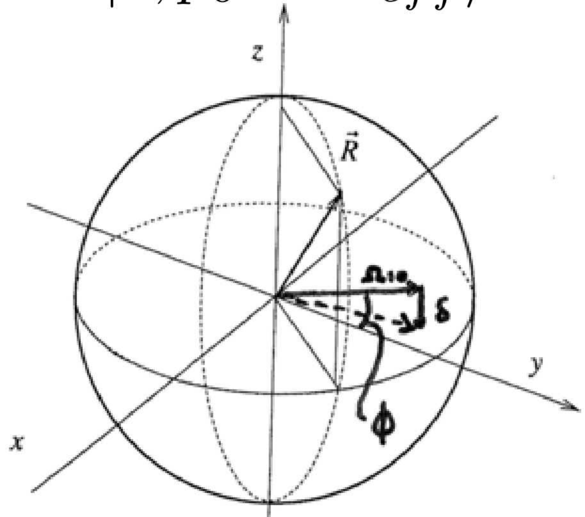
calculate curvature via finite difference method

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

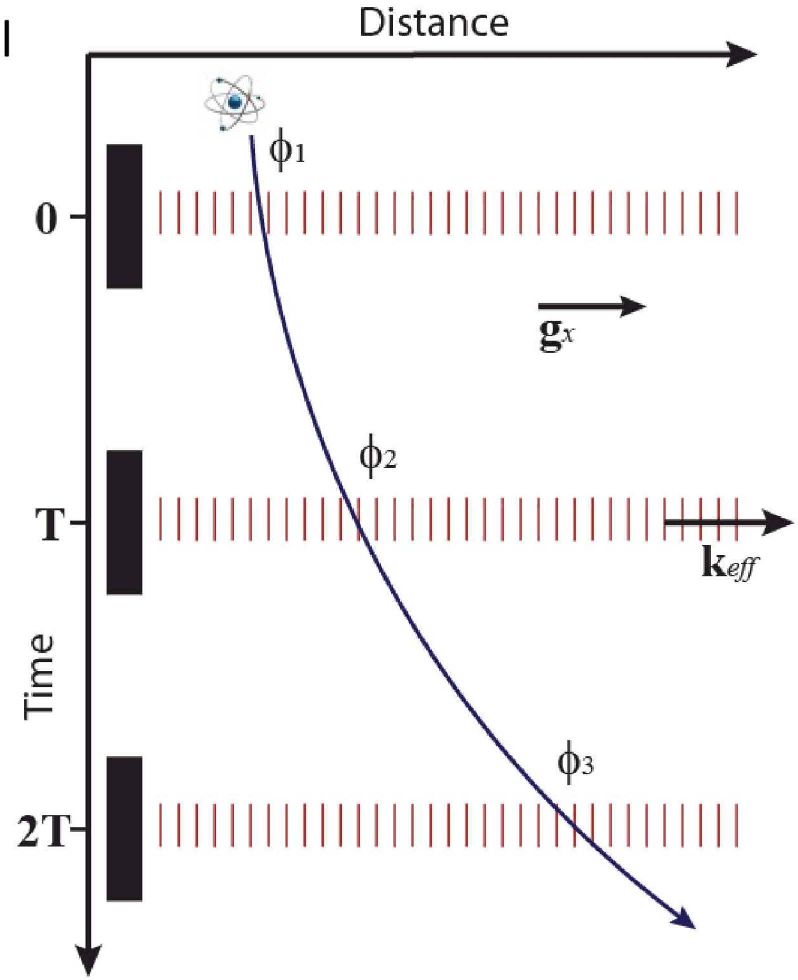
…and then

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

$$|1, \vec{p}_0 + \hbar\vec{k}_{eff}\rangle$$



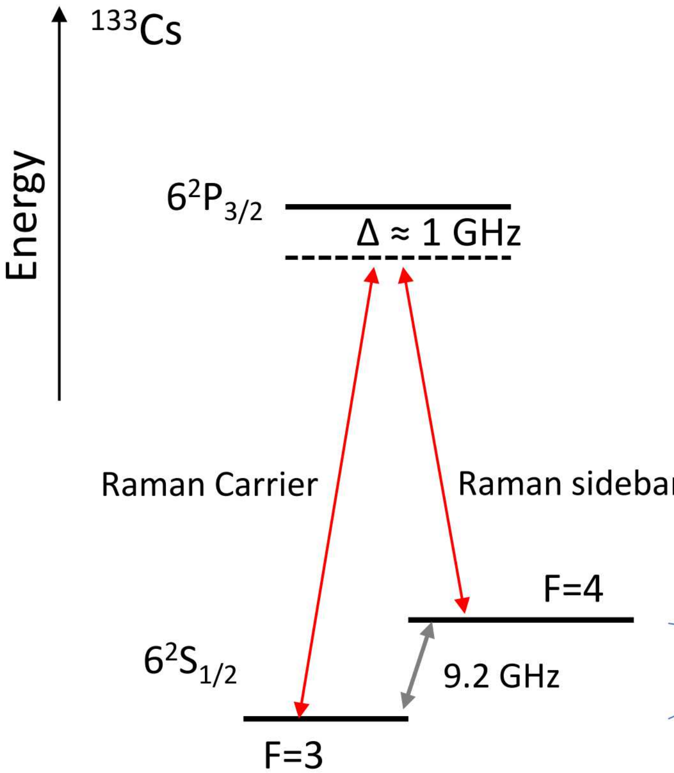
$$|0, \vec{p}_0\rangle$$

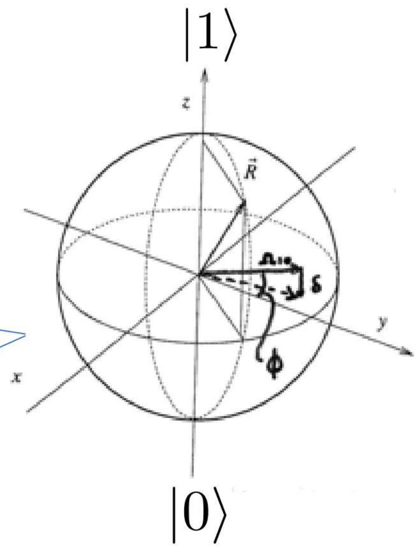


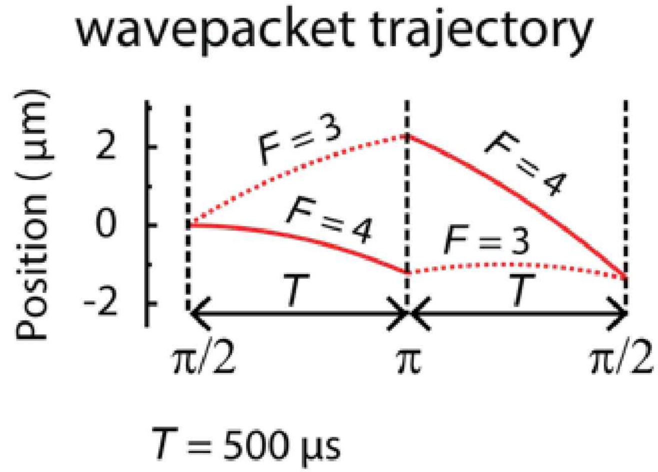
$$P_{|1\rangle} = \frac{1}{2}(1 - \cos(\Delta\phi + \phi_0))$$

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

Photon recoil beam splitter

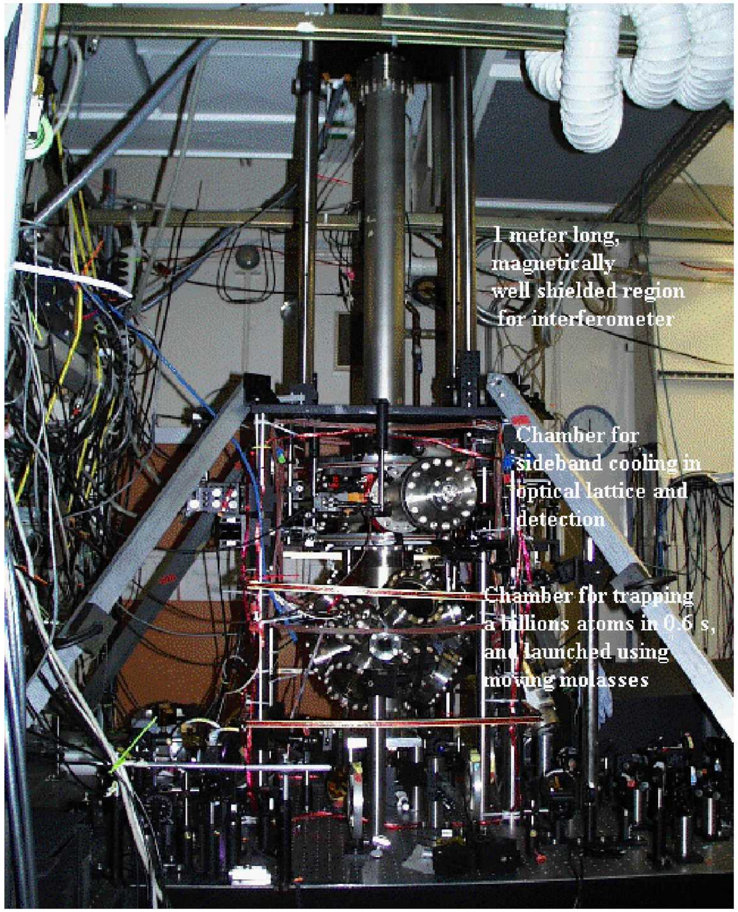






Store "spin" information in ground states

Light-pulse atom interferometers



Stanford atom interferometer gravimeter
Steven Chu, 1990's

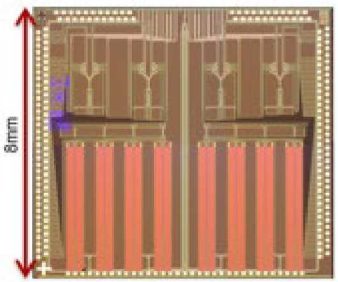
NIST F-1 atomic fountain clock
(credit: NIST website)

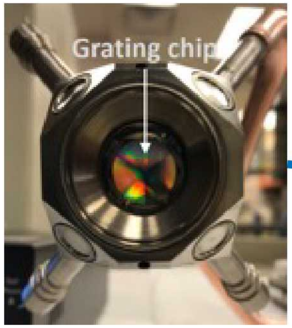
Superb gyroscopes and gravity gradiometers demonstrated as well

SNL Atom Interferometer Development

Sandia National Laboratories

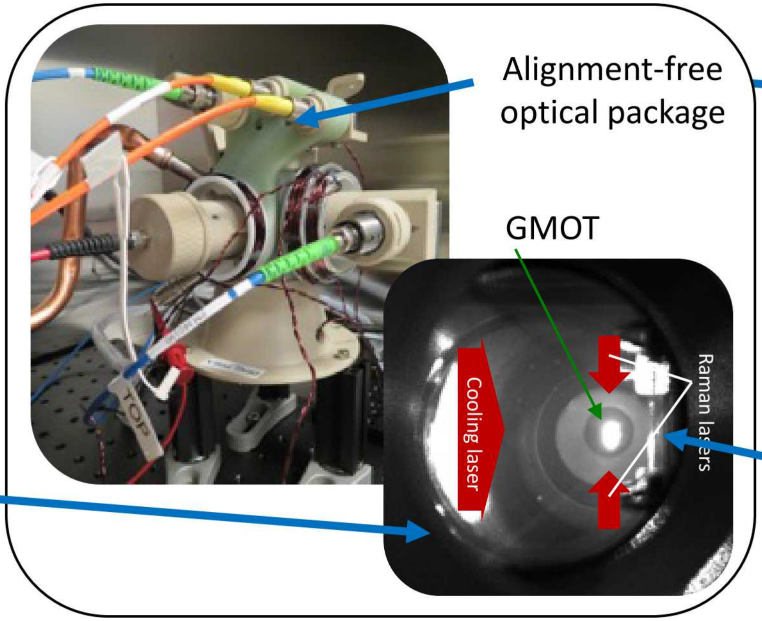
Integrated Photonics

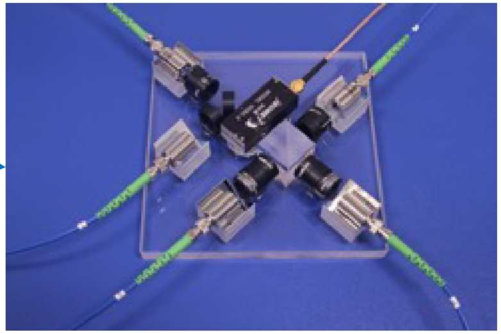


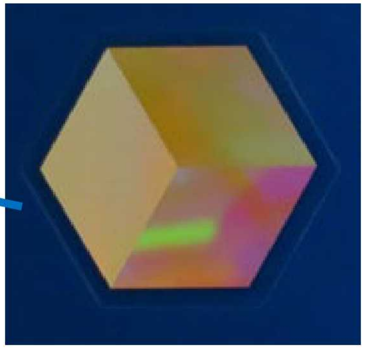


Custom vacuum chamber

Cold Atom Sensor Head with Grating-mirror MOT and Alignment-Free Optical Package





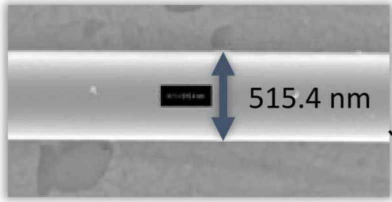


Sandia-fabricated Grating-mirror chip

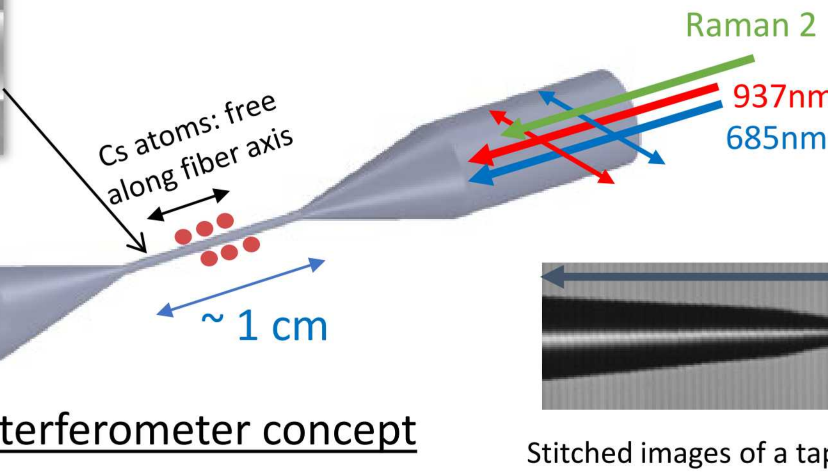
Contact: Jongmin Lee
Peter Schwindt

SNL Guided Atom Interferometer

Sandia National Laboratories

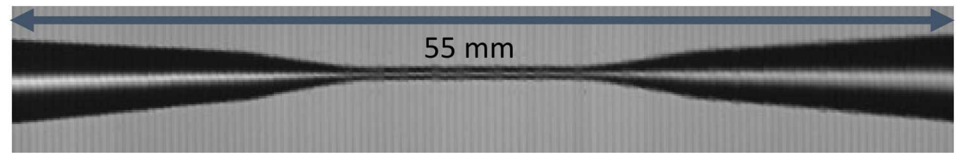


SEM image of nanofiber

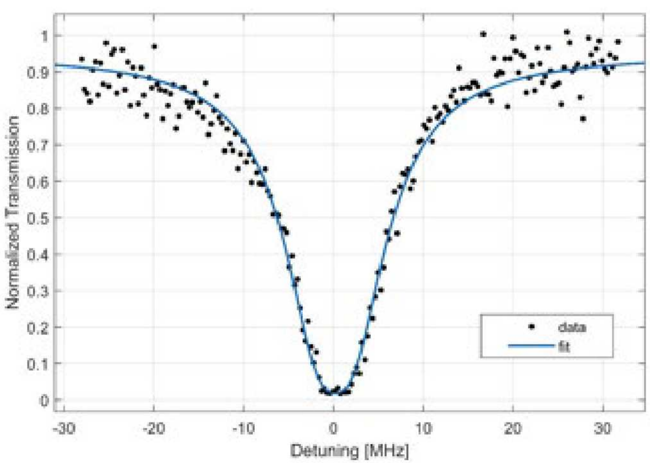


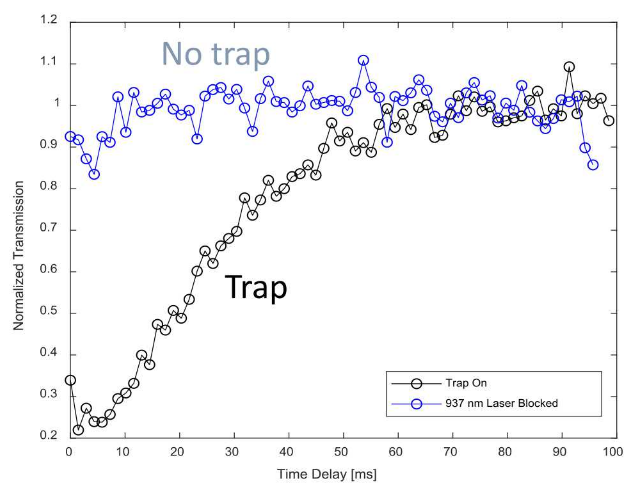
Interferometer concept

Contact: Jongmin Lee
Adrian Orozco
Will Kendal

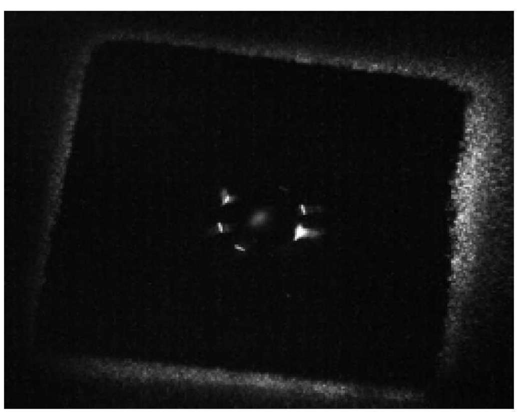


Stitched images of a tapered optical fiber demonstrating algorithmic pulling



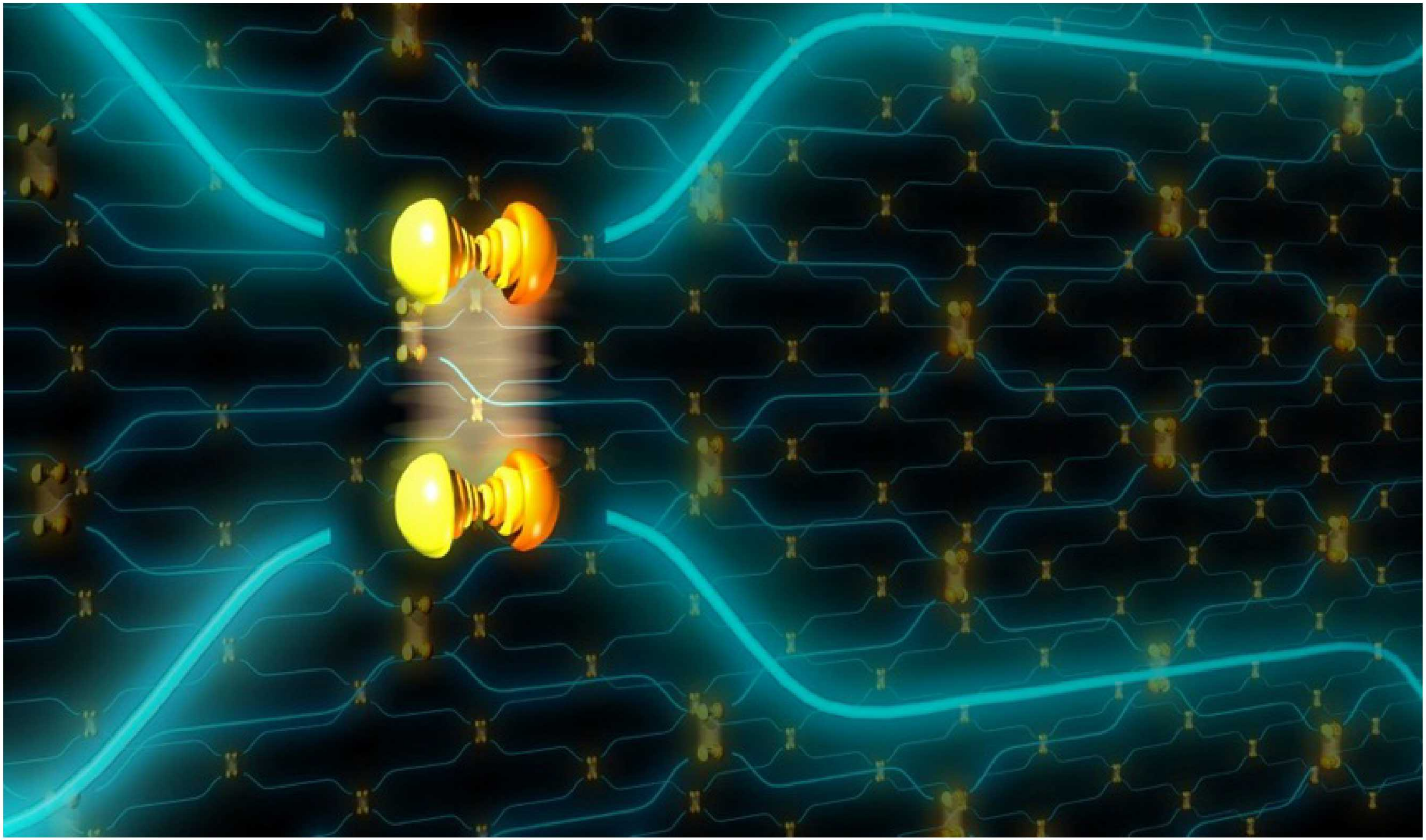


New direction: microfabricated waveguides



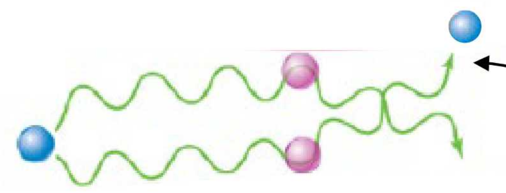
- OD_N = 3.95, OD_1 = 0.078; absorption measurement with nanofiber probe
- Trapped atom number = 50; Trap lifetime = 30ms

Interferometry with entangled spins



Quantum metrology of inertial forces with neutral atom spins

Matterwave interferometer



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

$$\langle \Pi \rangle = cos\theta$$

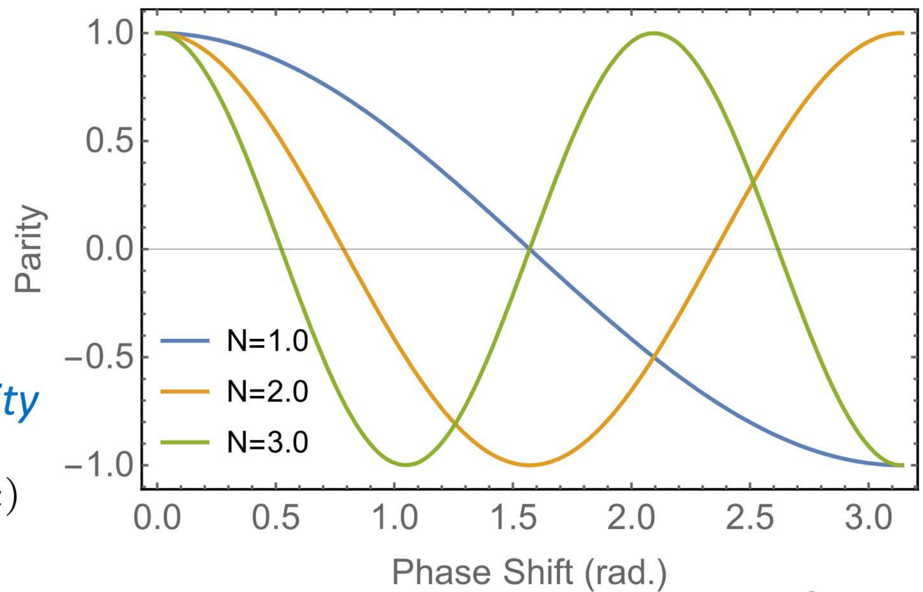
θ proportional to gravity

GHZ state

$$|\psi\rangle = |0\rangle^{\otimes N} + e^{iN\phi}|1\rangle^{\otimes N}$$

$$\langle \Pi \rangle = cos N\theta$$

For 2 atoms $\langle \Pi \rangle = P_{ee} + P_{gg} - P_{eg} - P_{ge}$

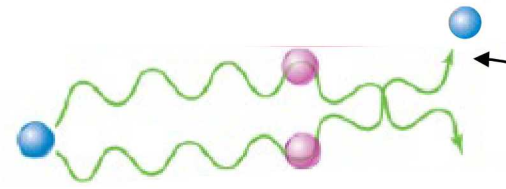


Measure Parity

$$\Pi = \bigotimes_{\alpha=1}^{N} \sigma_z^{(\alpha)}$$

Quantum metrology of inertial forces with neutral atom spins

Matterwave interferometer



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

$$\langle \Pi \rangle = cos\theta$$

θ proportional to gravity

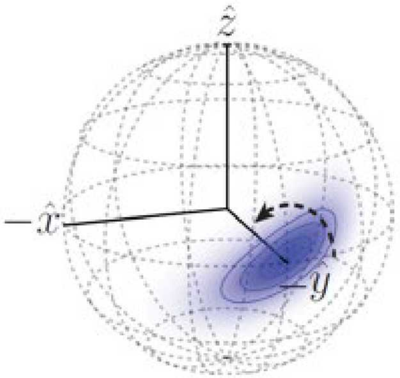
<u>GHZ state</u>

$$|\psi\rangle = |0\rangle^{\otimes N} + e^{iN\phi}|1\rangle^{\otimes N}$$

$$\langle \Pi \rangle = cosN\theta$$

? optimal states ?

F Fröwis *et al* 2014 *New J. Phys.* **16** 083010



Spin-squeezed state

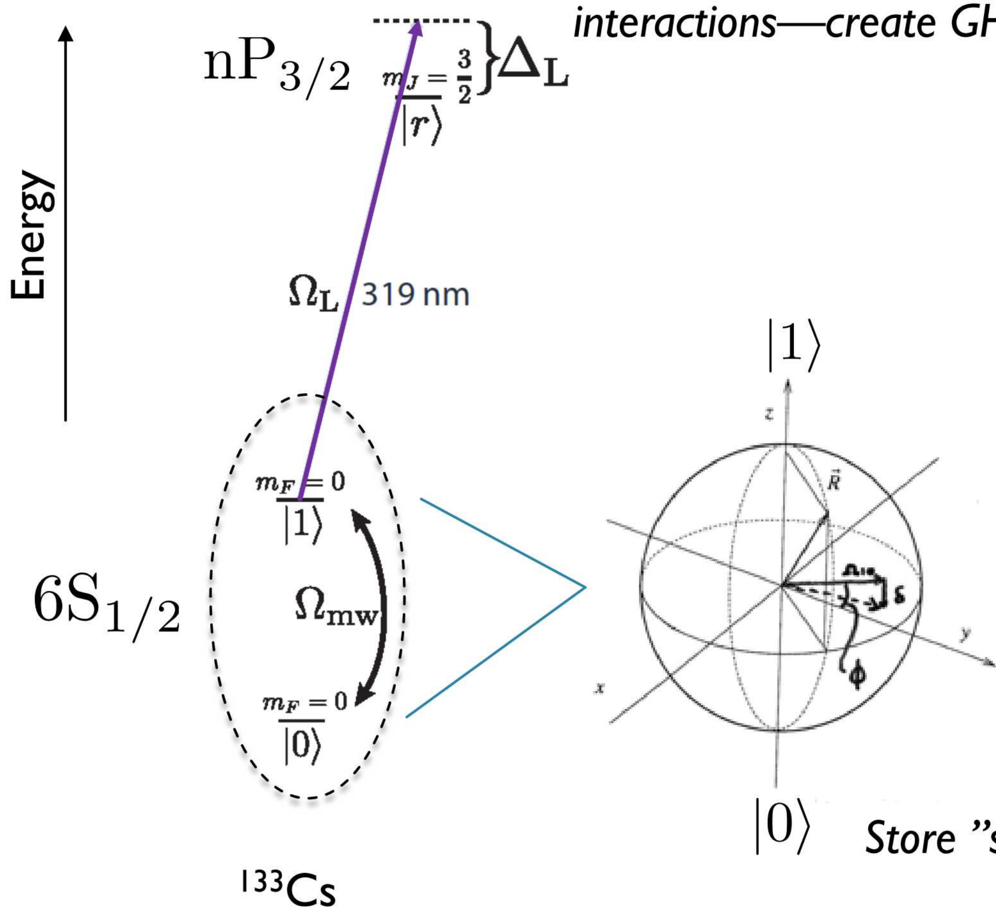
Wineland, et al., PRA 46 (1992)

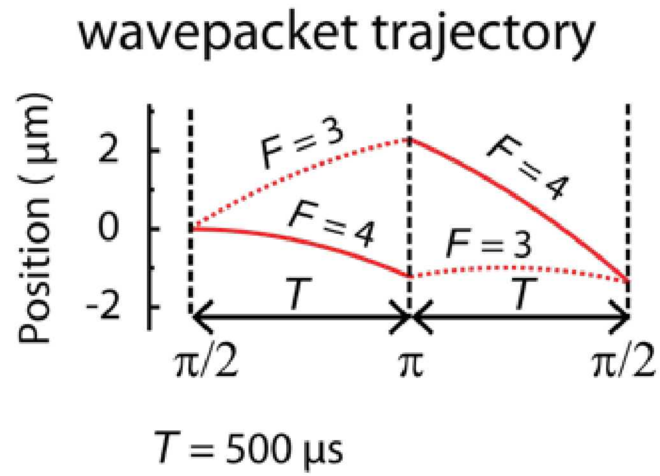
FRAGILE!

ROBUST!

Neutral atom spins

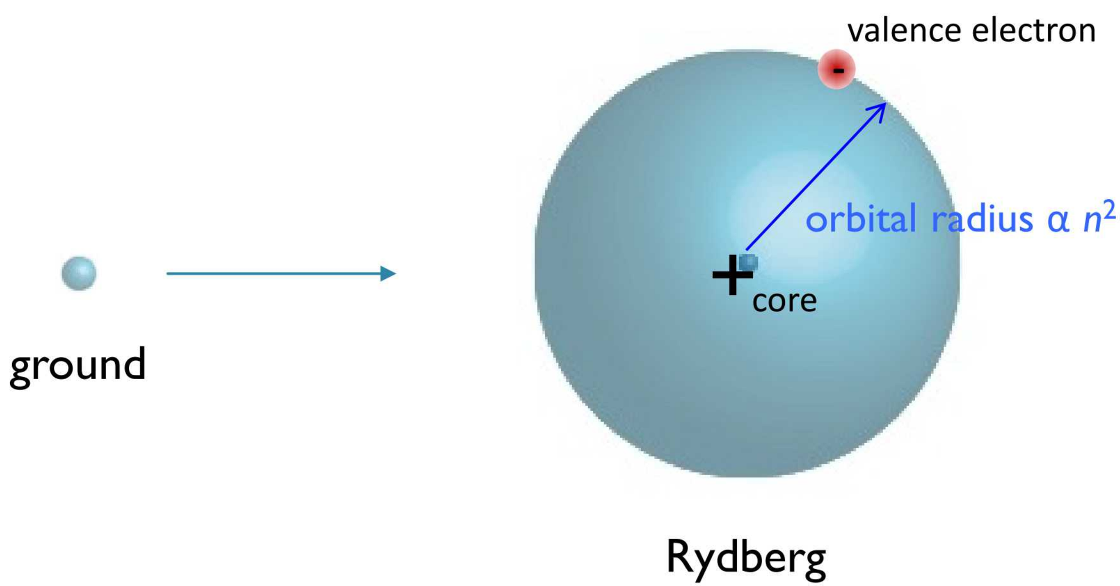
Couple to Rydberg orbitals for entangling interactions—create GHZ state



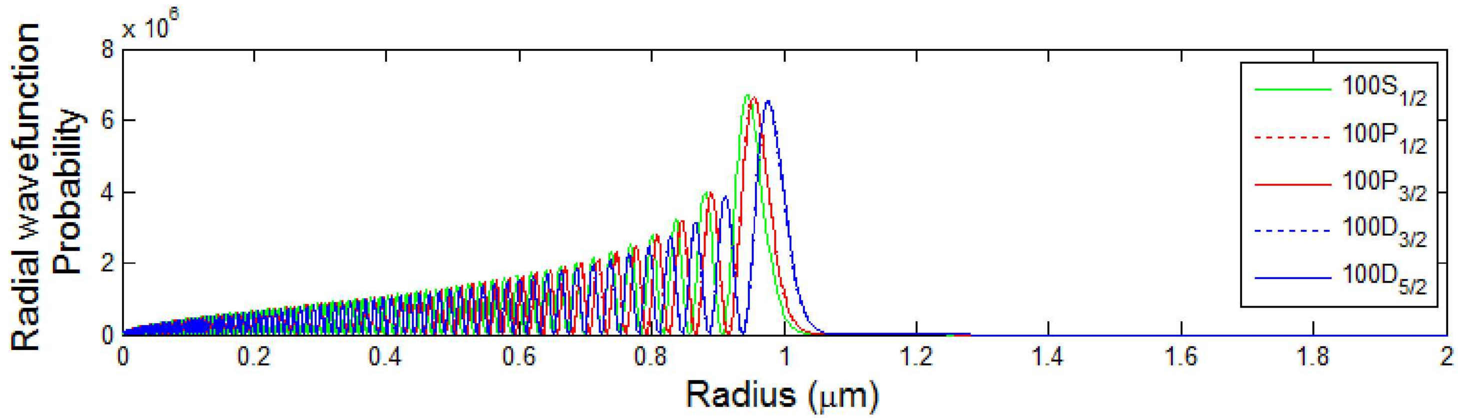


Store "spin" information in ground states

Rydberg orbitals

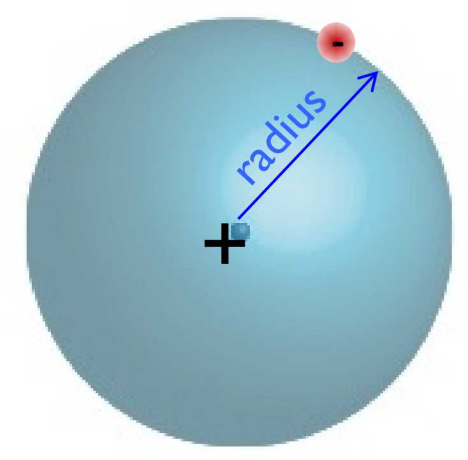


An example of the radial wavefunctions of a Cs atom at n = 100:



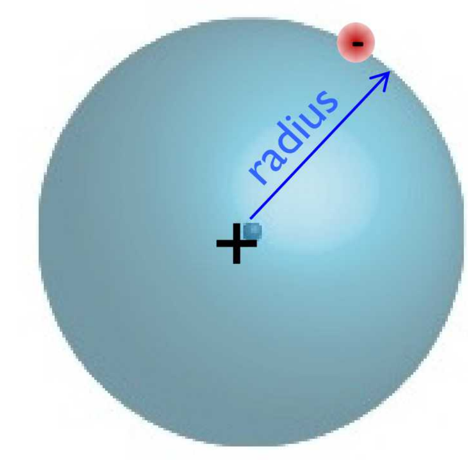
Interaction between *neutral* atoms

Valence electron in Rydberg state



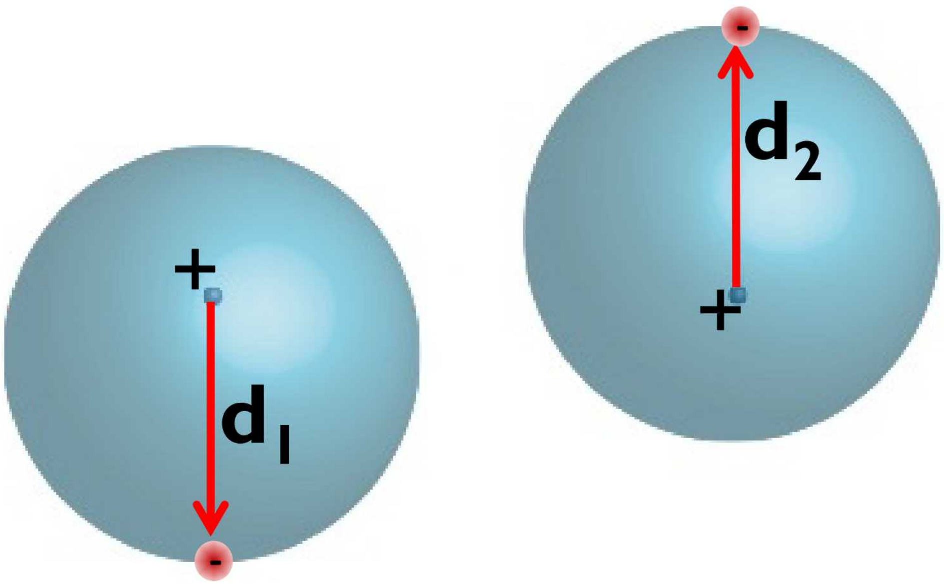
orbital radius α n^2

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

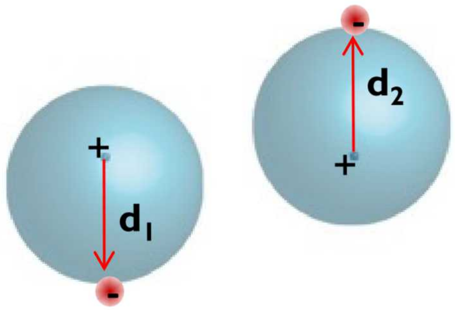
$$\alpha(0) \propto n^7$$

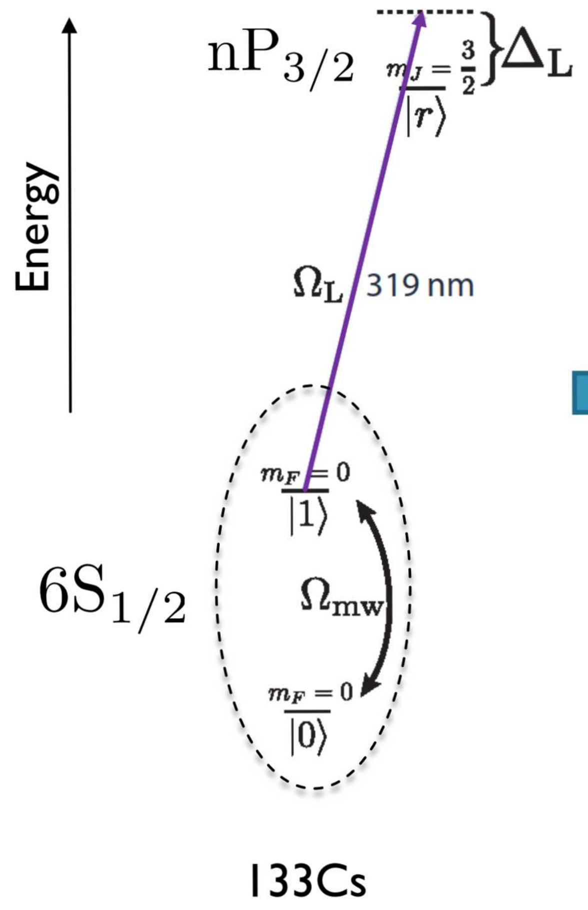
- Even the presence of another atom can cause a massive response >> 10 MHz
- Induced Electric Dipole-Dipole Interaction $\propto 1/r^6$

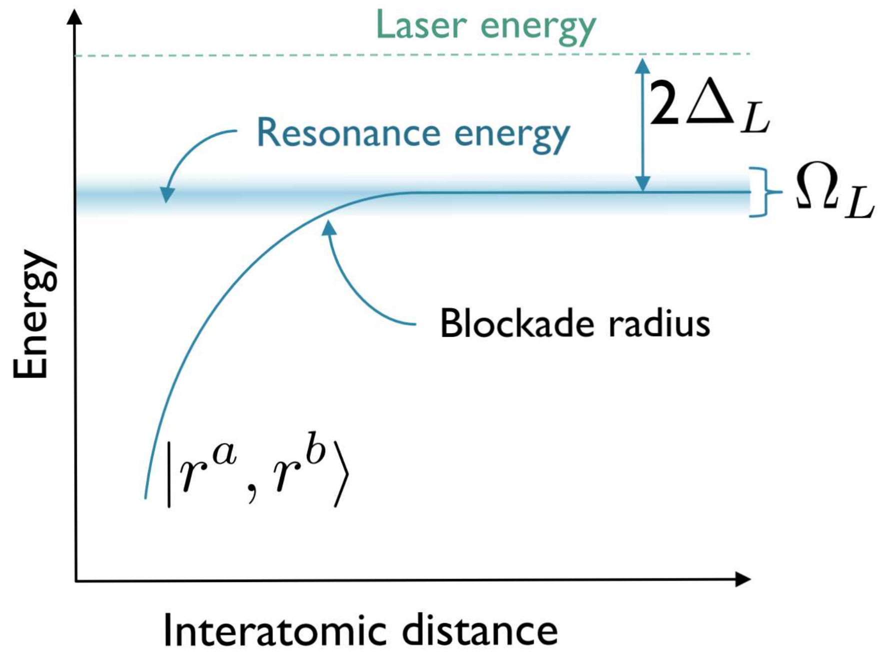
Entanglement demonstrations

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

Rydberg blockade



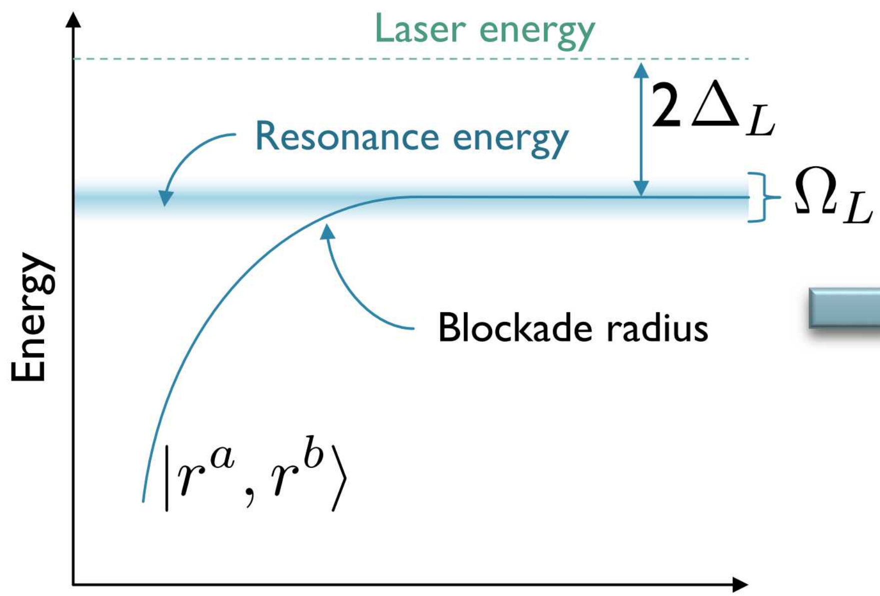




Single atom

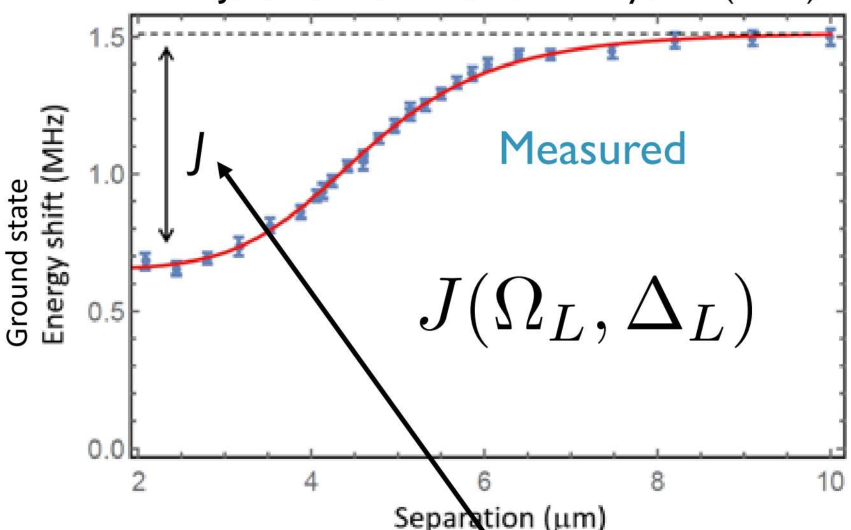
2 atoms

Direct Rydberg → Rydberg-Dressed



Rydberg-Dressed Interaction

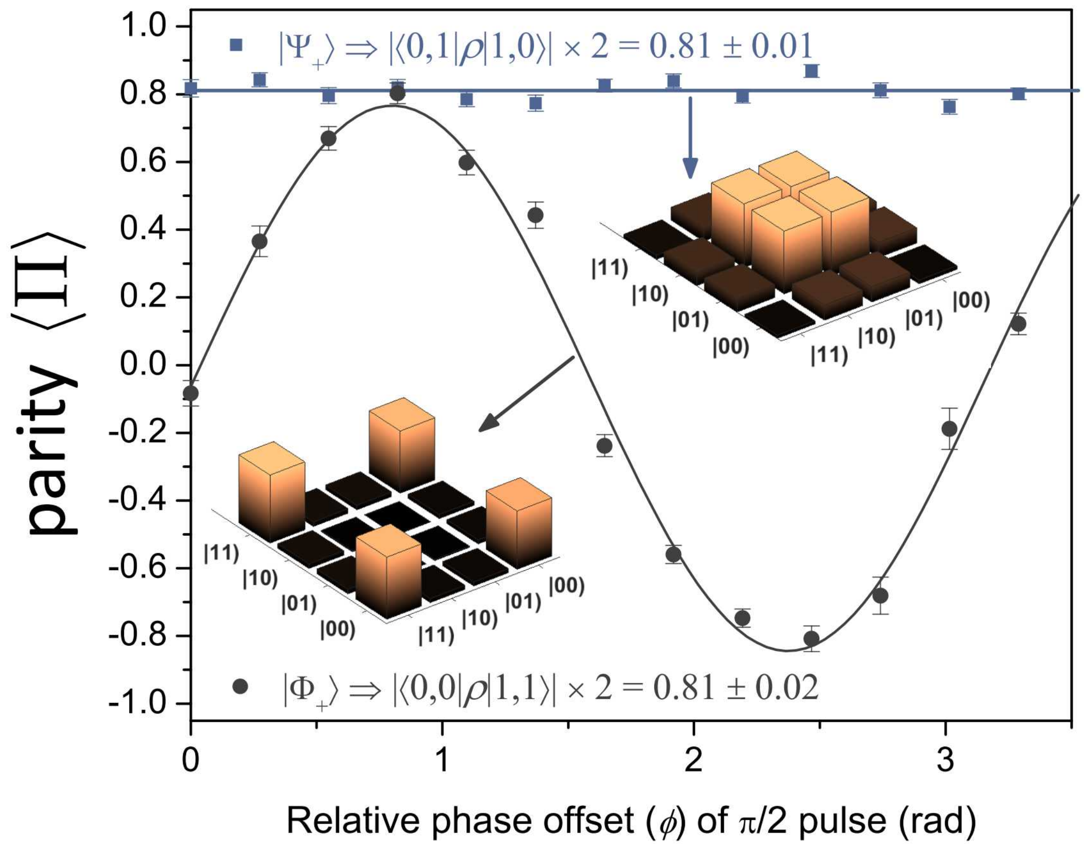
Y.-Y. Jau, …, I.D., **G.B.**, Nature Phys. **12** (2016)



$$H = \sum_{i=1}^{N} h_x^{(i)} \sigma_x^{(i)} + \dots + \sum_{i \neq j}^{N} J_{i,j} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

Spin-flip blockade

Verify the entanglement via parity measurements

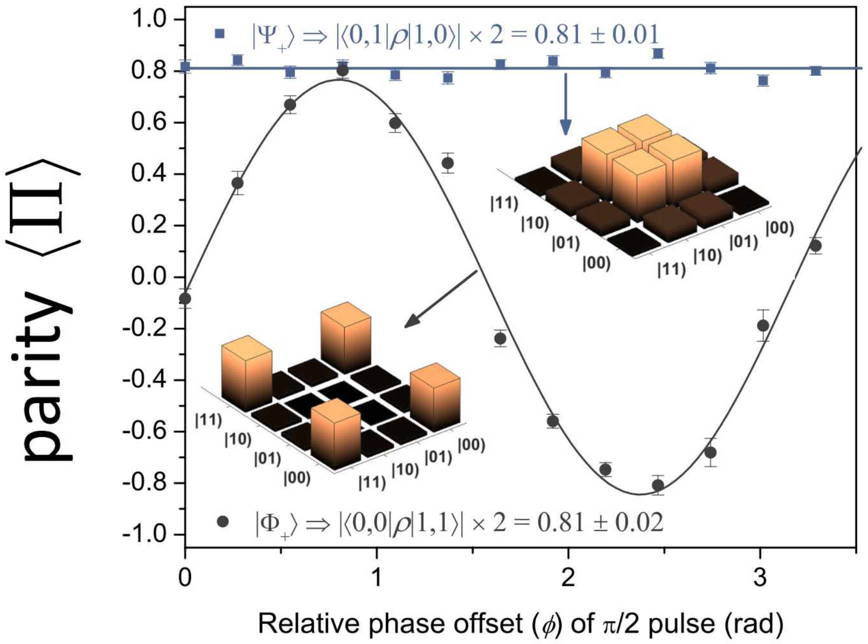


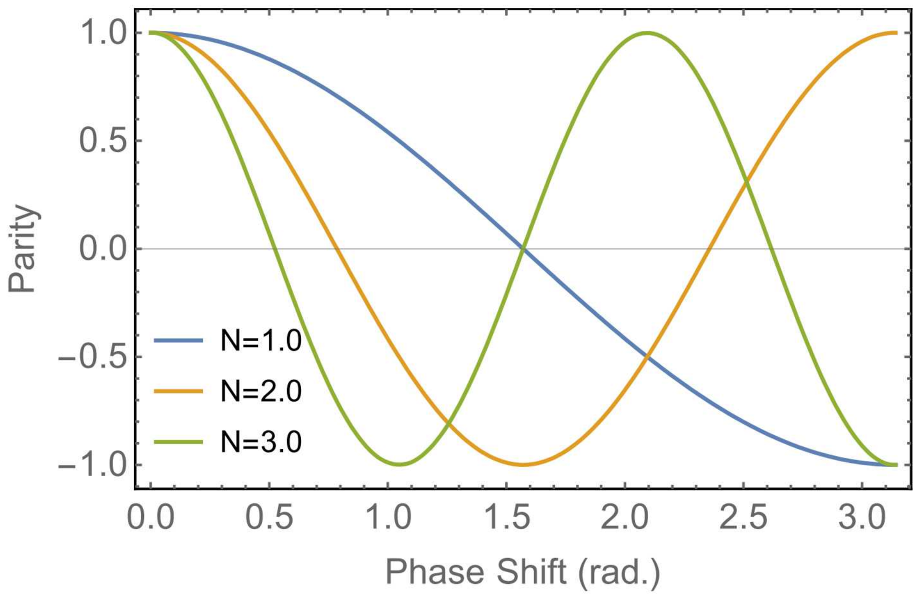
For 2 atoms

$$\langle \Pi \rangle = P_{ee} + P_{gg} - P_{eg} - P_{ge}$$

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

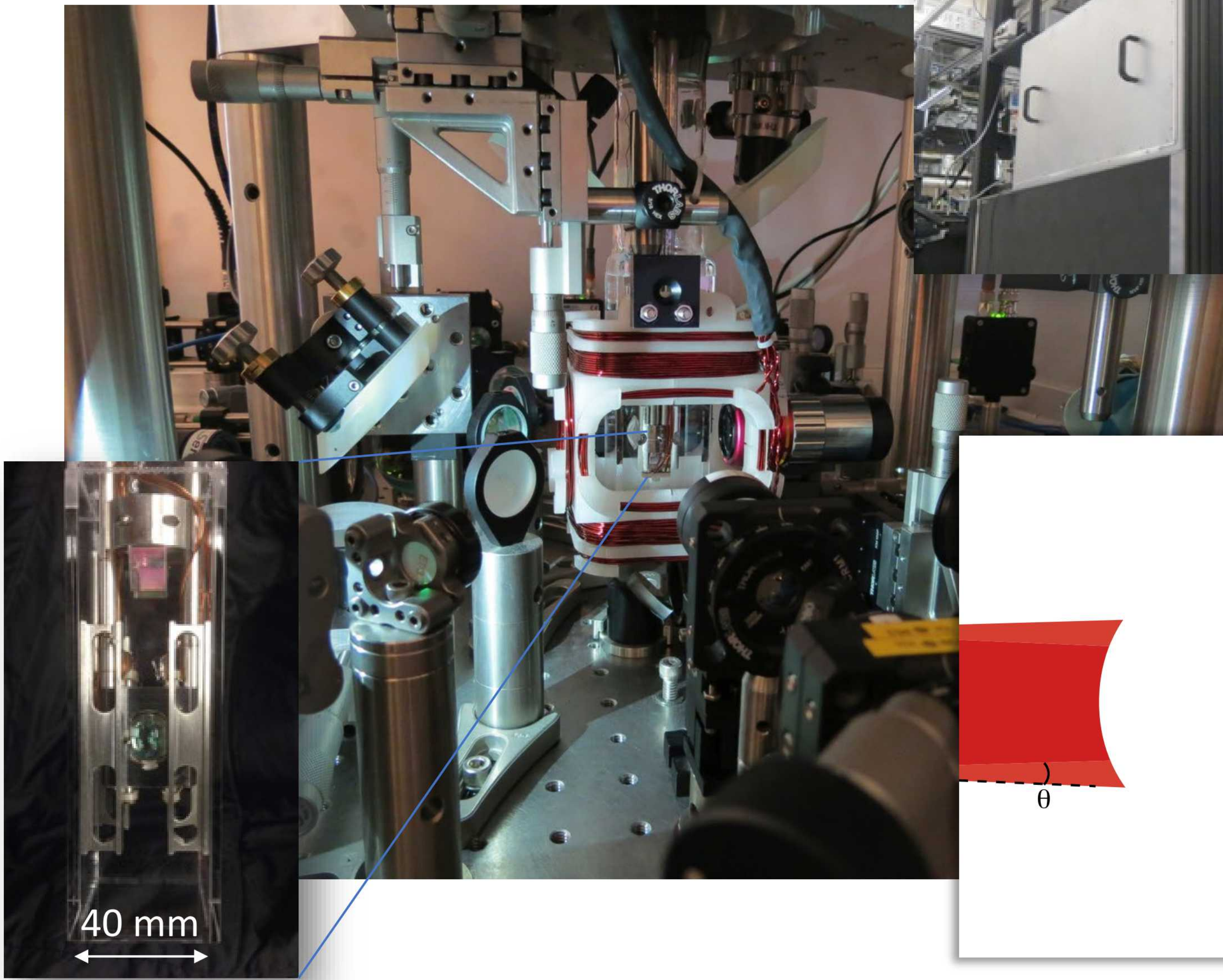
Spin-flip blockade

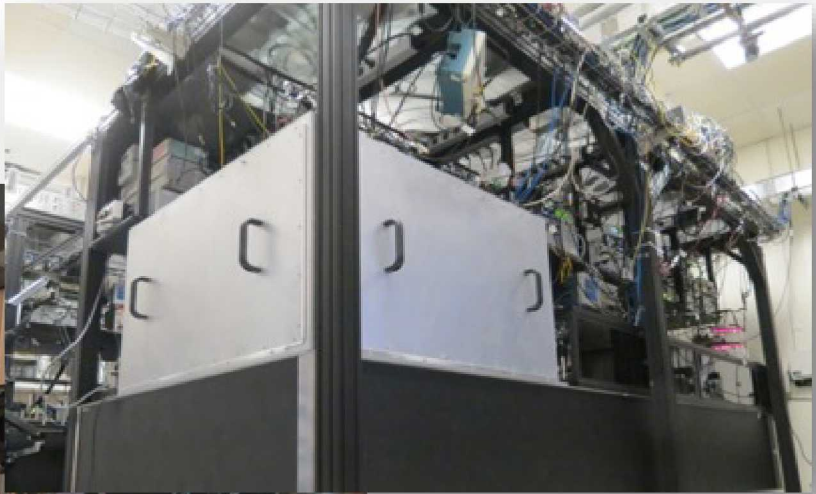


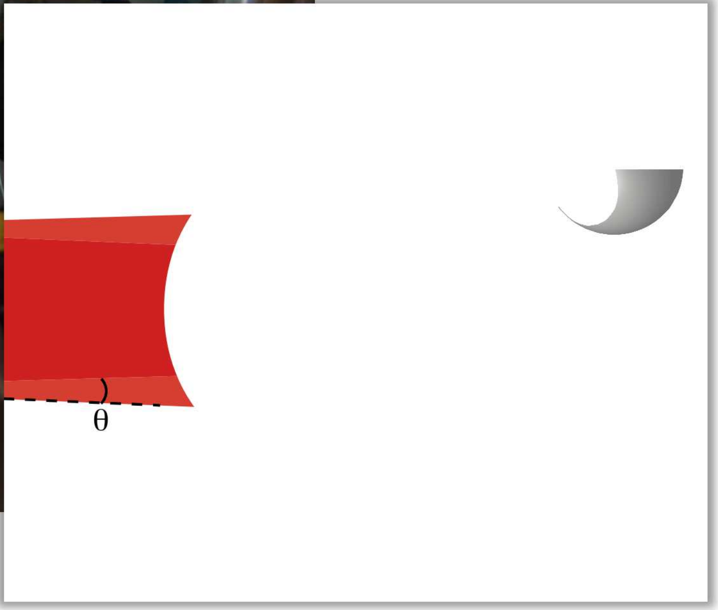


Y.-Y. Jau, G.B., I.D., et al., Nature Phys. **12**, 71-74 (2016)

Experiment hardware





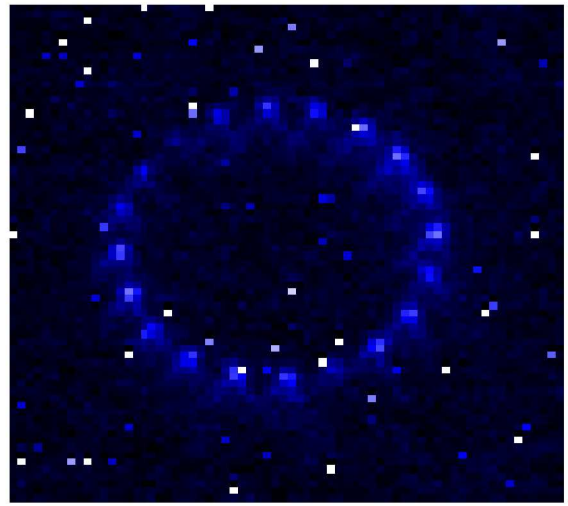


J. Lee, G.B., I.D., *et al.*,Phys. Rev. A. **95**, 041801(R), (2017)

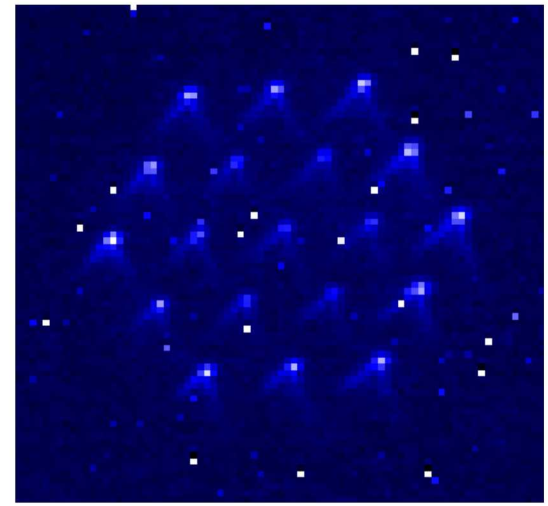
Outlook: large arrays

- Spatial light modulator allows arbitrary patterns
- Large systems > 100

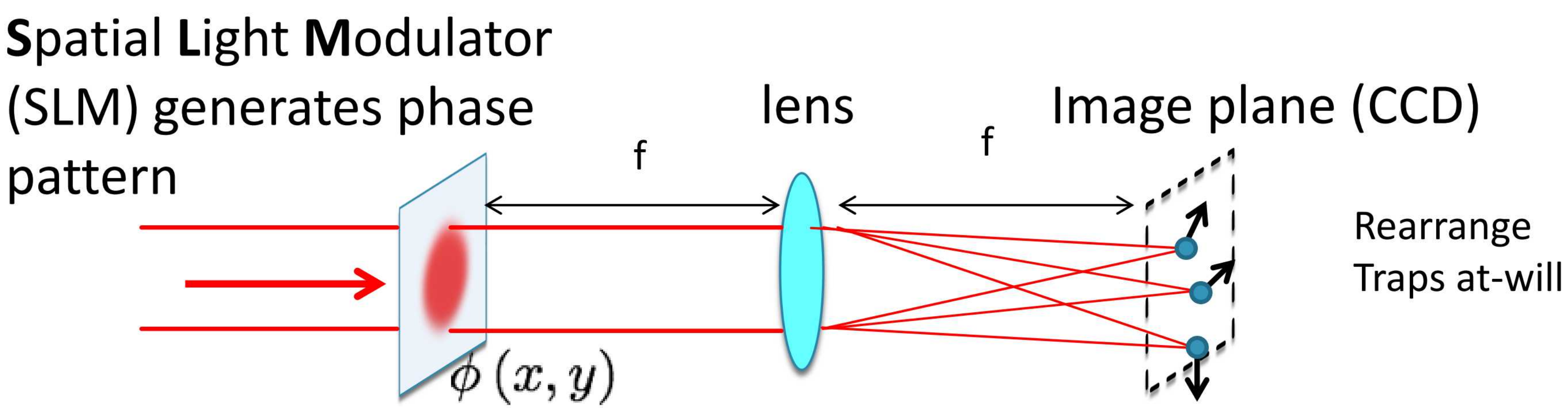
Averaged over many exposures



Ring lattice



Triangular lattice

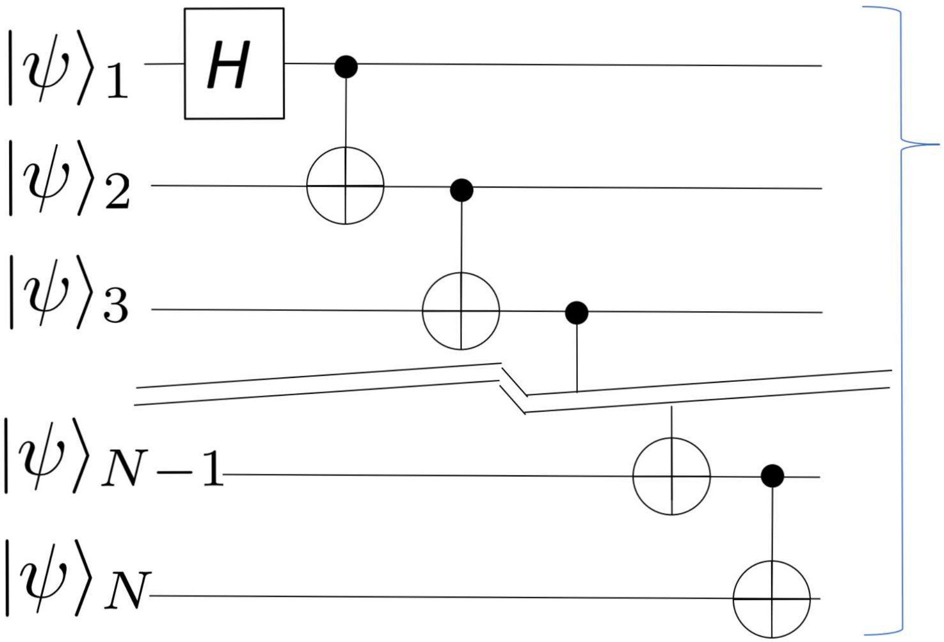


Data and image credit: Michael Martin, Sandia (now at LANL)

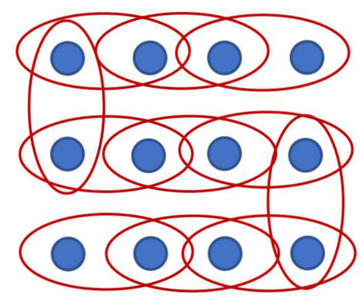
Path to complex quantum systems

Generating an entangled state of N atoms

<u>Sequential gate approach</u>



$$|\psi\rangle = |0\rangle^{\otimes N} + e^{iN\phi}|1\rangle^{\otimes N}$$



Array of atoms

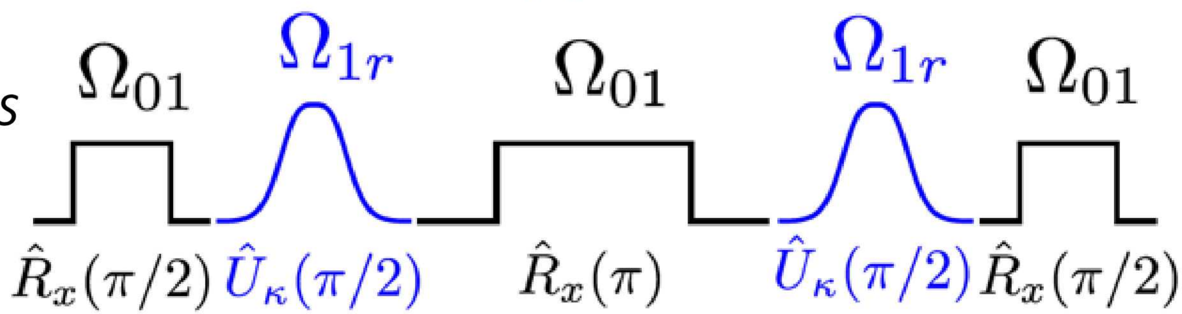
Progress in entangling neutral atoms

Atom	Method	Bell fidelity	Post selected fidelity	Year and reference
^{87}Rb	Blockade, simultaneous addressing	(0.46)	0.75	2009 [35]
^{87}Rb	Blockade, separate addressing	(0.48)	0.58	2009 [33]
^{87}Rb	Blockade, separate addressing	0.58	0.71	2010 [34]
Cs	Blockade, separate addressing	0.73	0.79	2015 [10]
Cs	Dressing, simultaneous addressing	0.60	0.81	2015 [11]
^{87}Rb	Local spin exchange	(0.44)	0.63	2015 [31]

M. Saffman, J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 202001

Now 89% to 97%
(see new results from Harvard and Wisconsin)

Dressed-Rydberg approach ENABLES this protocol

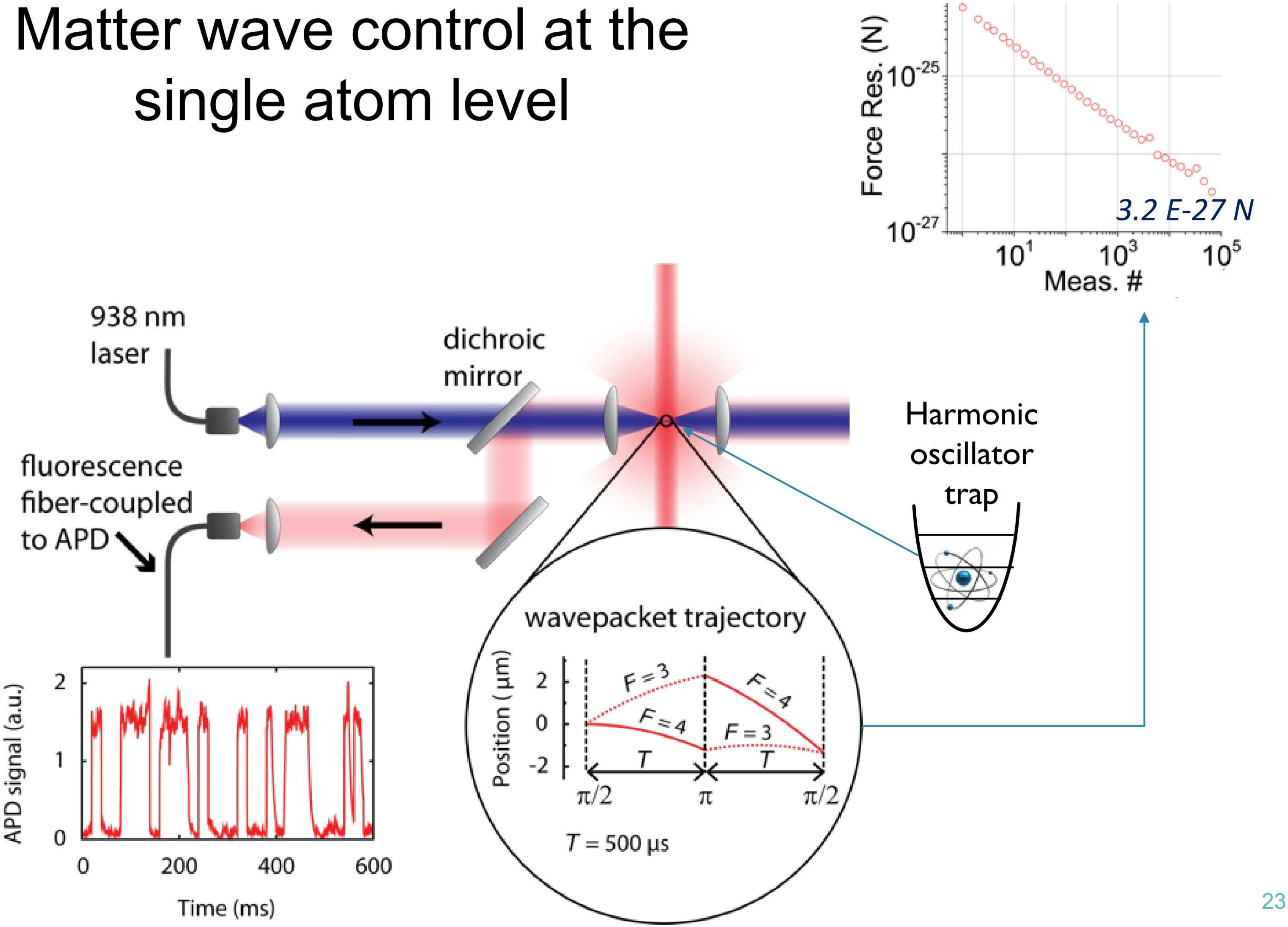


→ 99.5%

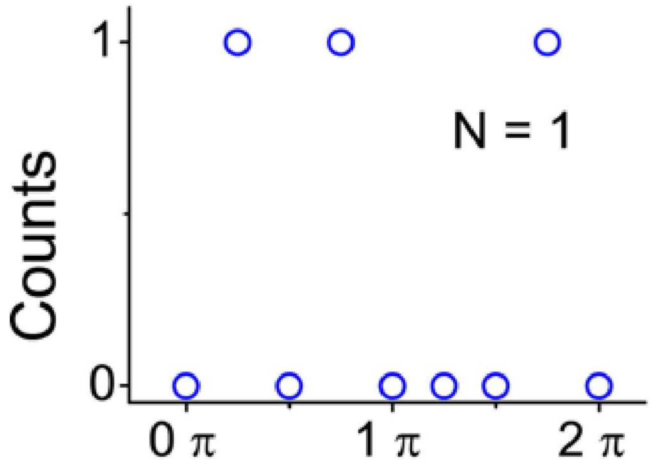
See our new theory work: A. Mitra, …, G.B., I. Deutsch, *Robust Mølmer-Sørensen gate for neutral atoms using rapid adiabatic Rydberg dressing*, arXiv:1911.04045 (2019)

Parazzoli,…,**G.B.**, Phys. Rev. Lett. **109**, 230401 (2012)

Matter wave control at the single atom level



Building fringe one atom at a time

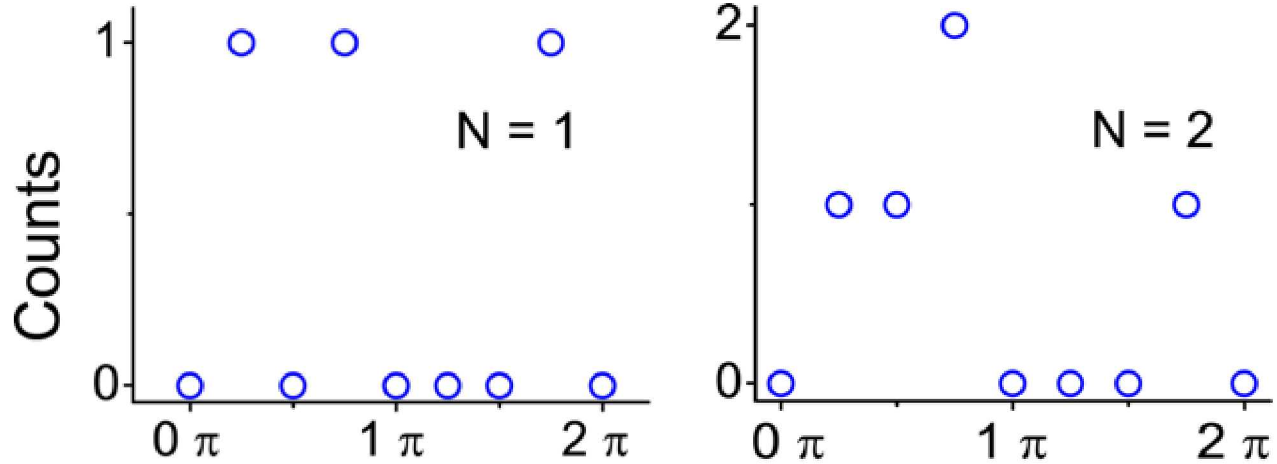


Scan laser phase

- 1 atom per phase through interferometer.

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

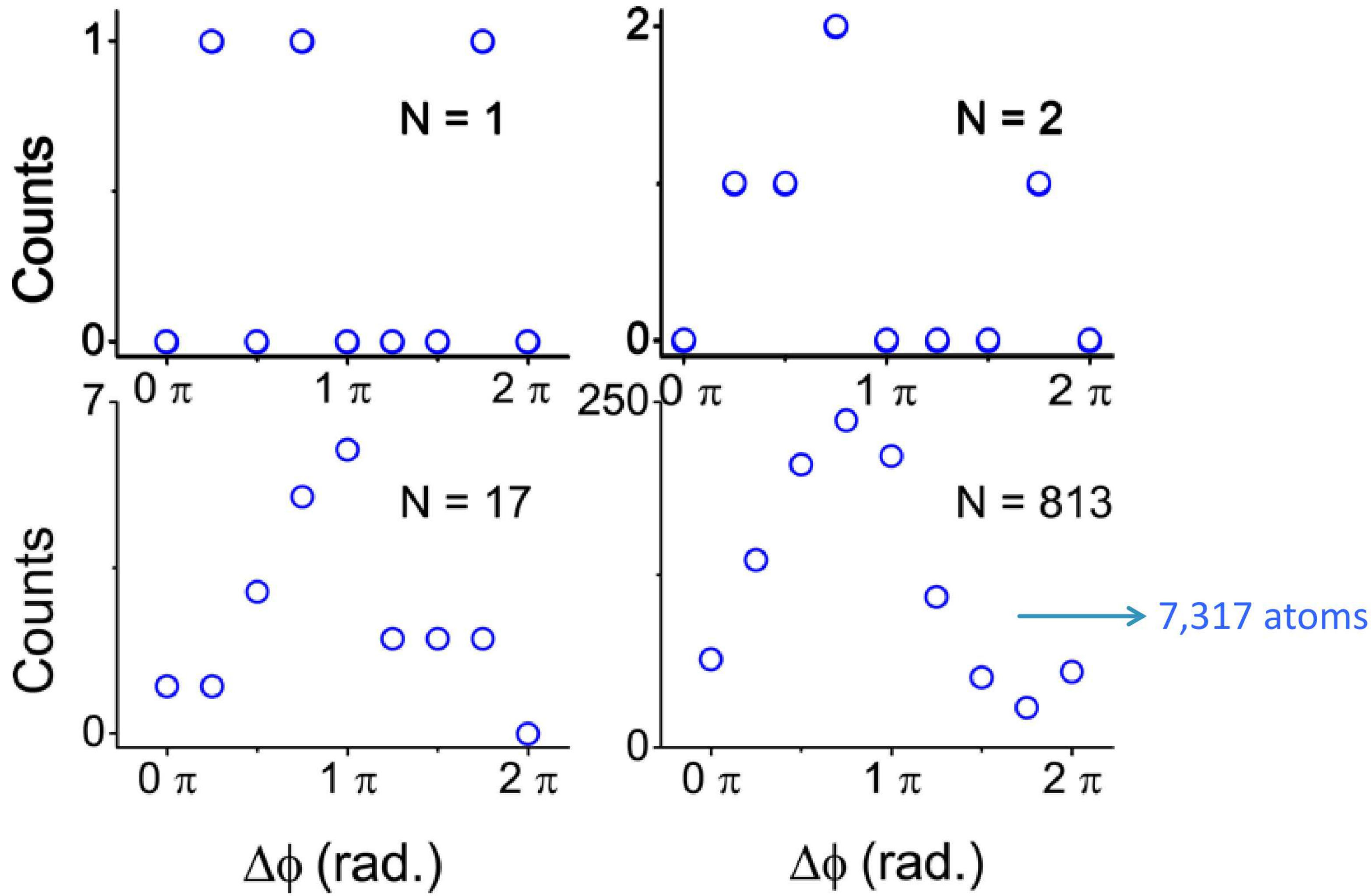
Building fringe one atom at a time



- 2 atoms per phase through interferometer.

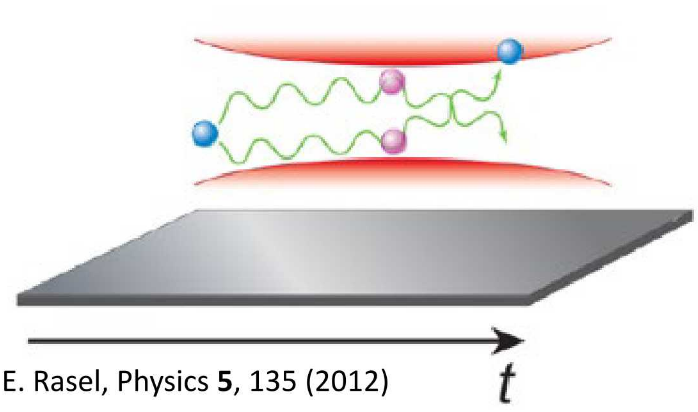
Parazzoli, et al., "Observation of free-space single-atom matterwave interference", Phys. Rev. Lett. **109**, 230401 (2012)

Building fringe one atom at a time



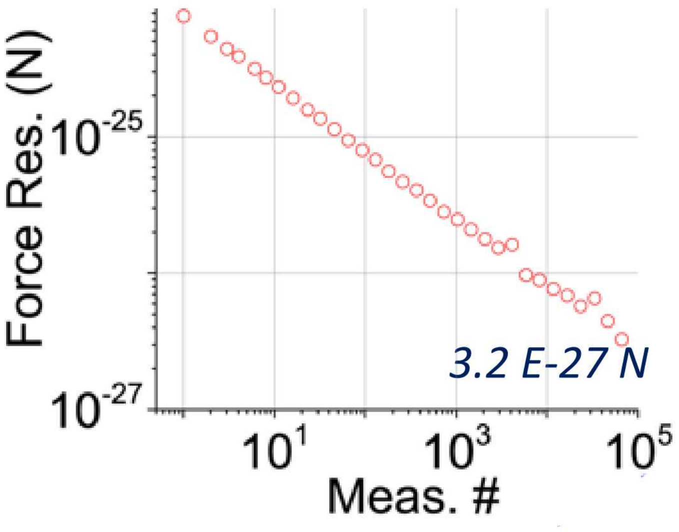
Parazzoli, et al., "Observation of free-space single-atom matterwave interference", Phys. Rev. Lett. **109**, 230401 (2012)

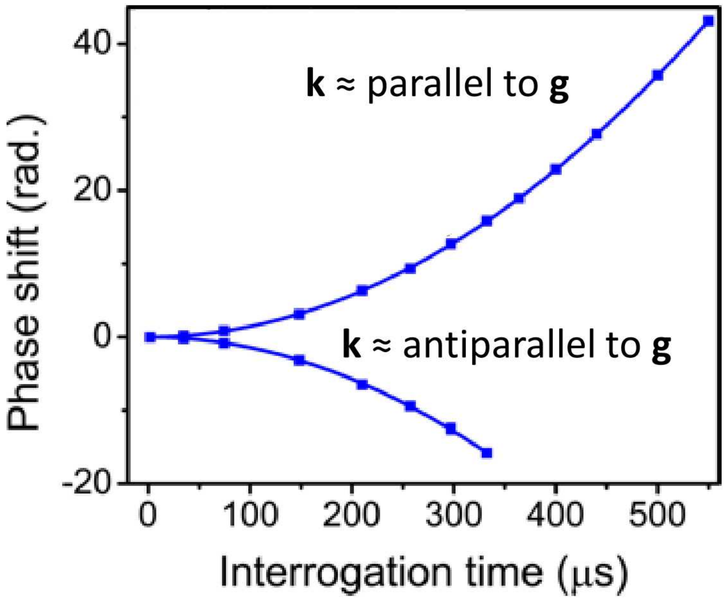
Force resolution of a single atom interferometer



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

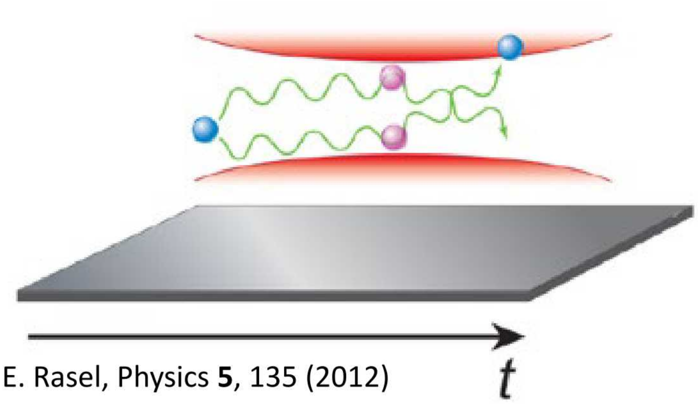
Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)



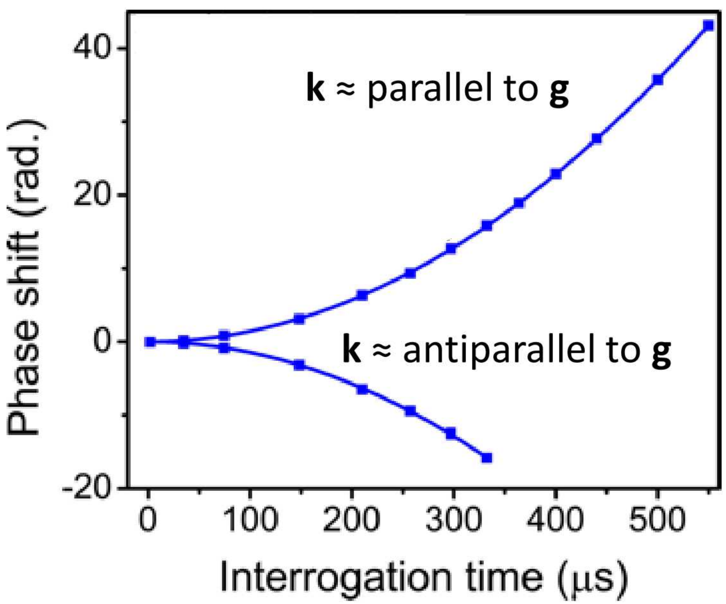


$$\Delta\phi = \vec{k}_{eff} \cdot \vec{g}\, T^2$$

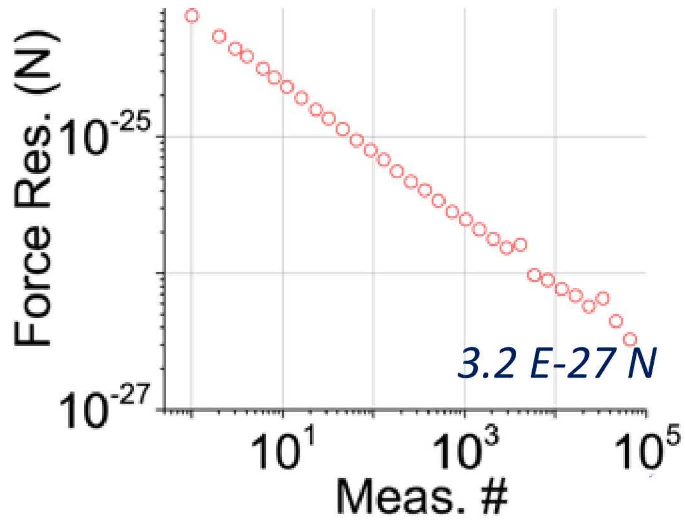
Force resolution of a single atom interferometer



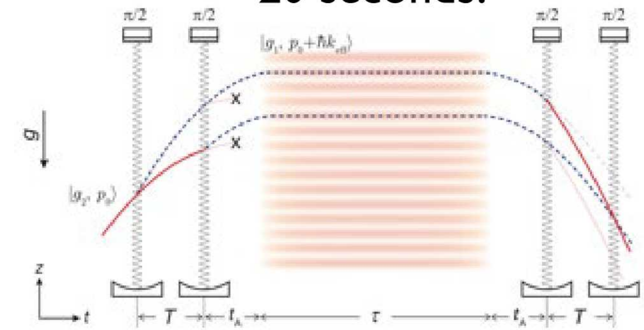
E. Rasel, Physics **5**, 135 (2012)



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



20 seconds!



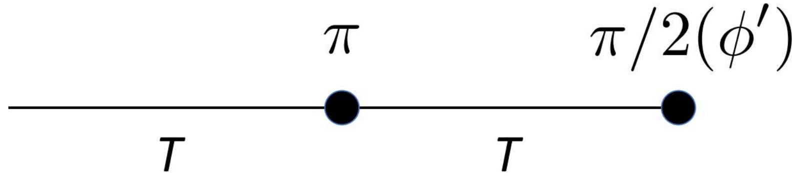
V. Xu, et al., *Science* 2019

The Ideal Atom Interferometer

N entangled atoms

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

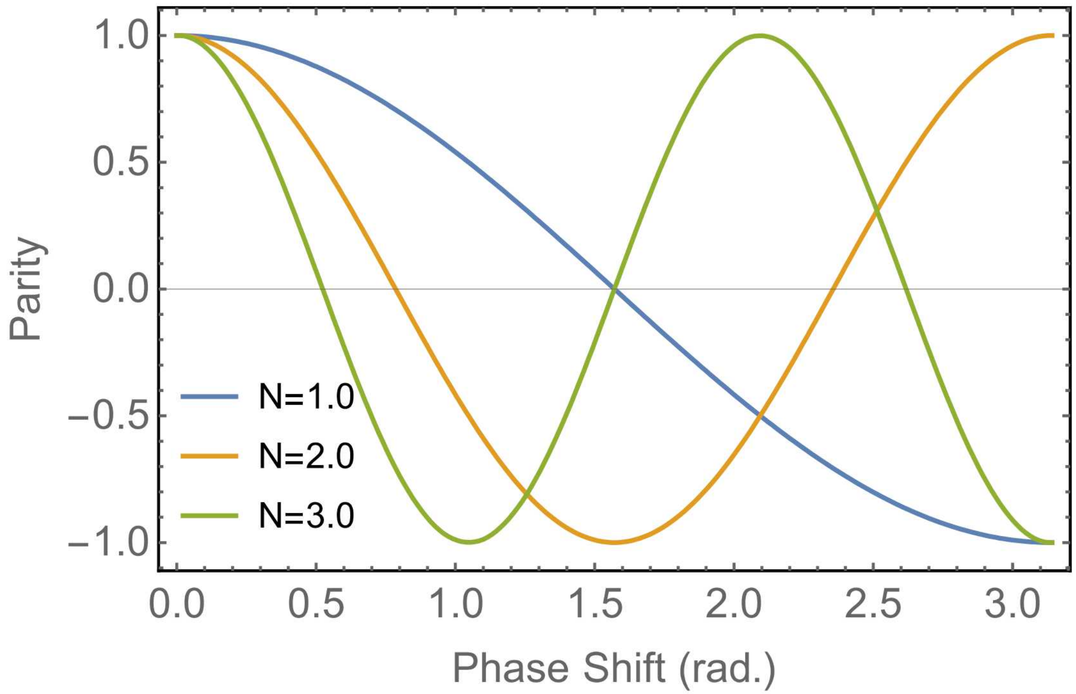
Pulse sequence



Measure Parity

$$\Pi = \bigotimes_{\alpha=1}^{N} \sigma_z^{(\alpha)}$$

For 2 atoms $\langle \Pi \rangle = P_{ee} + P_{gg} - P_{eg} - P_{ge}$



As N grows:

Parity oscillates faster

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

$$\Theta_N = N\mathbf{K} \cdot \mathbf{a}T^2$$

$$= N\phi$$

Theory by Constantin Brif

&

Brandon Ruzic

Sandia National Laboratories

Imperfect Initial State Preparation

Random initial state fraction

Uncertainty in initial phase

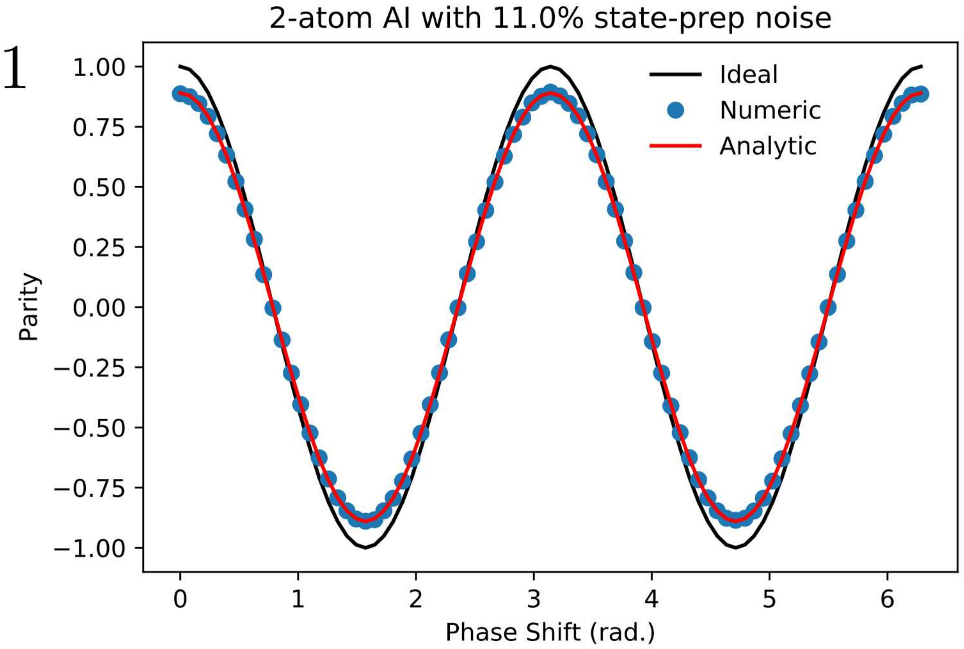
Analytic result when $p + \sigma^2/2 \ll 1$

$$\langle \Pi \rangle \approx (1 - p - \sigma^2/2) \cos \Theta_N$$

$$\Theta_N = N\mathbf{K} \cdot \mathbf{a}T^2 = N\phi$$

Visibility is reduced

$p + \sigma^2/2 \approx 0.11$ for two atoms

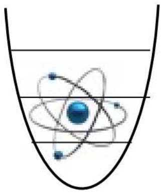


Metrological advantage is only linearly sensitive to entanglement imperfection

Random Doppler Shift

Atoms start in optical tweezers

$$\rho = \rho_{\mathrm{vib}} \otimes |\psi_{\mathrm{spin}}\rangle \langle\psi_{\mathrm{spin}}|$$



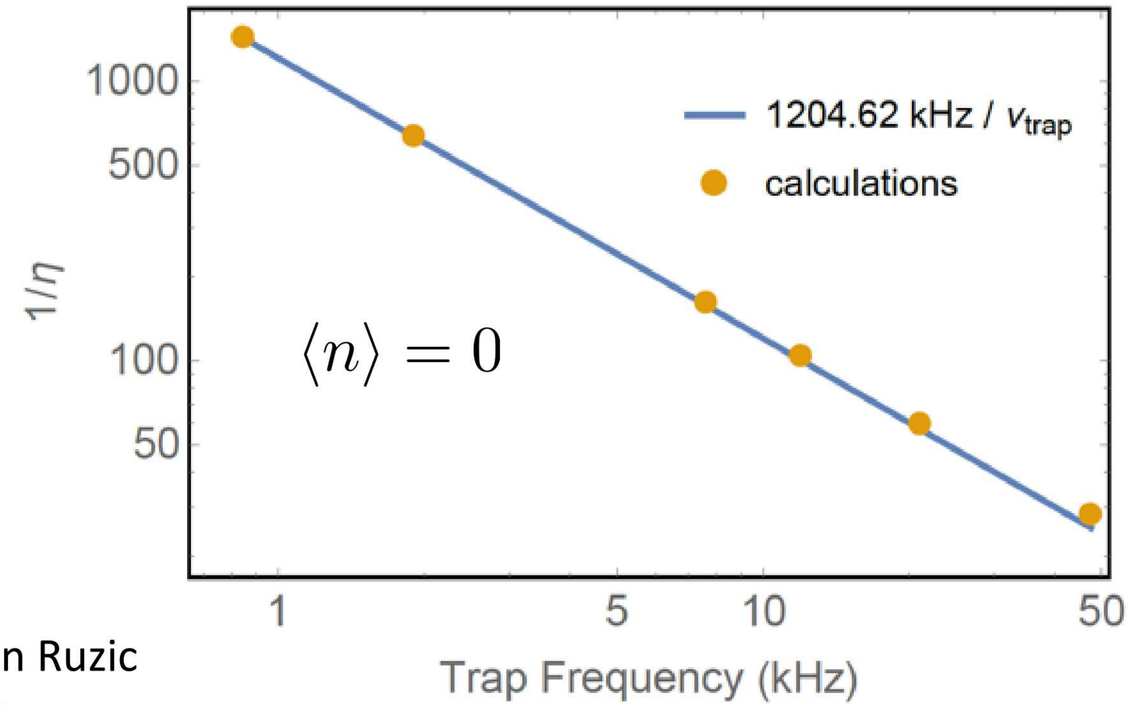
Initial momentum spread

- Each run randomly samples a momentum distribution

→ doppler shift

→ detuning error in pulses

Max. useful number of atoms →



$\propto$ Temperature

Theory by Constantin Brif & Brandon Ruzic

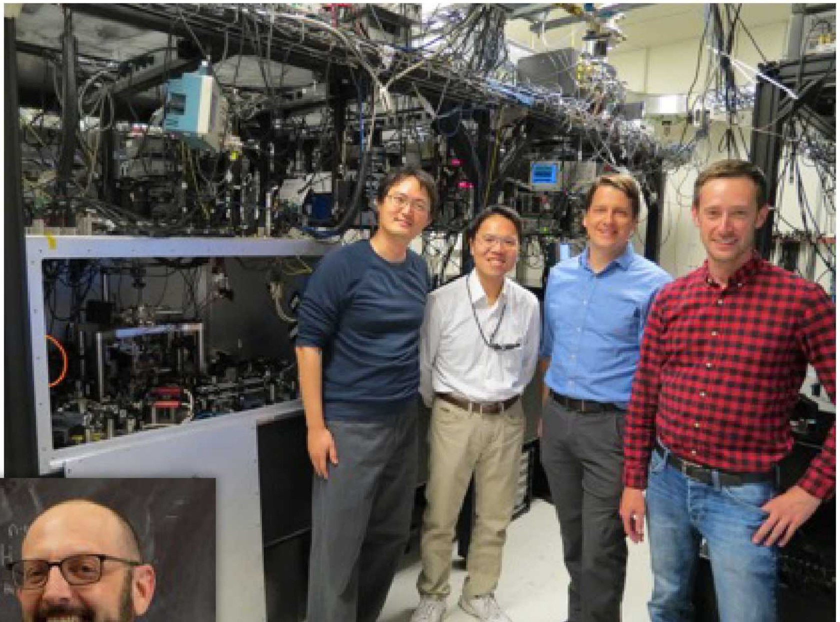
Sandia National Laboratories

Summary

- Sandia is a significant player in the development of atom interferometer technique and instrumentation
- Entangled atom interferometer for > 1000 atoms appears feasible with our current approach
- Doppler broadening is the dominant limitation
- Phase resolution performance of GHZ state with 100 atoms is already comparable to typical LPAI results (10 mrad/shot)

Sandia-OU-UNM Team

LDRD
Laboratory Directed Research and Development

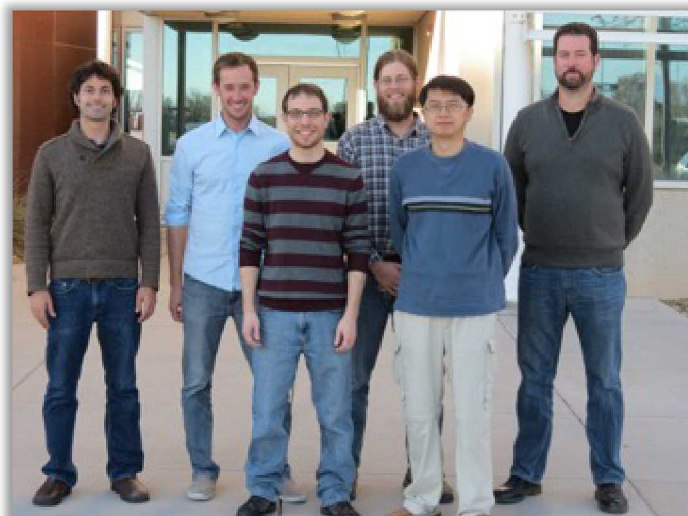


J. Lee, Y-Y. Jau, M. Martin, G.B.

I.Deutsch (UNM)

Not pictured

- Adrian Orozco
- Will Kendal
- Constantin Brif
- Brandon Ruzic
- Peter Schwindt
- Bethany Little
- Matthew Chow
- Anupam Mitra



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