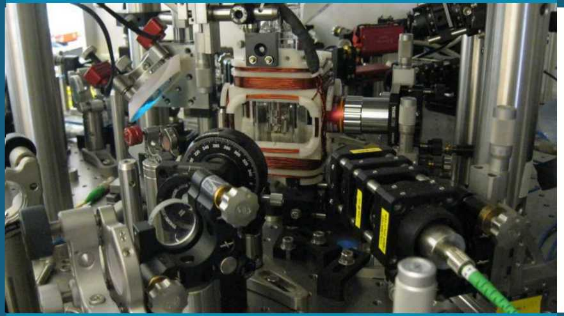
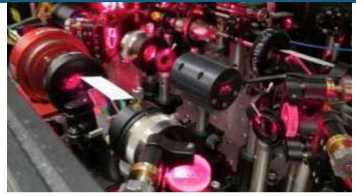
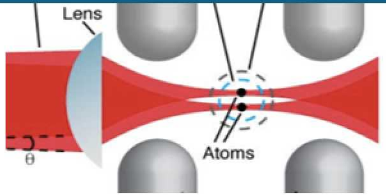
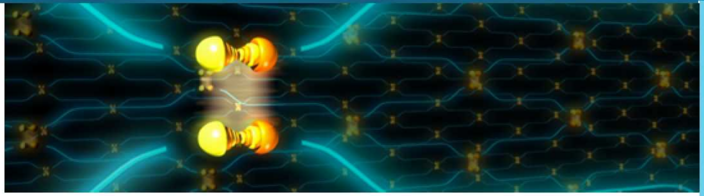
SAND2020-1518C

Entanglement-Enhanced Interferometry with Neutral Atoms





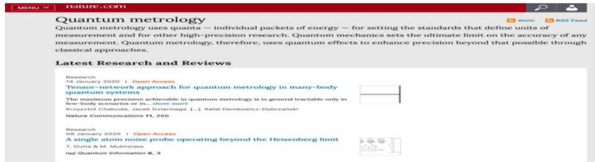


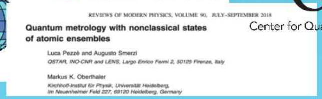


Presented by

Bethany J. Little

Current team: M. N. Chow, L. P. Parazzoli, B. P. Ruzic, C. Brif, G.W. Biedermann





UNM

CQRT Center for Quantum Research and Technology

Quantum Sensors & Metrology

What Makes a Sensor Quantum?[1]

1. Use of a quantum object/system
2. Use of quantum coherence
3. Use of quantum entanglement

Quantum metrology [..] uses quantum effects to enhance precision beyond that possible through classical approaches. [3]

Metrologically useful quantum states have a lot in common with those useful for quantum computing.

- Crucial: tunable interaction between particles[2]
- High fidelity/low error
- Increase N (# of particles)

Some requirements are different

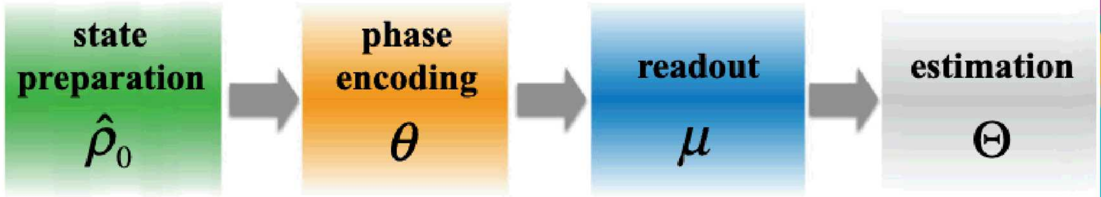
Quantum Metrology with Strongly Interacting Spin Systems

Hengyun Zhou[1,*], Joonhee Choi[1,2,*], Soonwon Choi[3], Renate Landig[1], Alexander M. Douglas[1], Junichi Isoya[4], Fedor Jelezko[5], Shinobu Onoda[6], Hitoshi Sumiya[7], Paola Cappellaro[8], Helena S. Knowles[1], Hongkun Park[1,9] and Mikhail D. Lukin[1,†]

[1] Degen et al.,(2017). *Rev Mod Phys*, *89*(3), 035002; [2] Pezzé, et al. (2018) [3] Nature.com

Parameter Estimation with Quantum States

"The goal of quantitative experiments in physics is to determine a set of parameters to some level of confidence." [1]



Highest confidence corresponds to estimated θ with the smallest uncertainty $\Delta\theta$. (2)

[2]The lower bound:

Quantum Cramér-Rao bound

$$\boxed{\theta_{\mathrm{QCR}} = \frac{1}{\sqrt{F_{\mathrm{Q}}}}}$$

Quantum Fisher information

If $F_Q > N$ (i.e. $\Delta\theta_{QCR} < \Delta\theta_{SQL}$):

- sufficient for entanglement
- necessary and sufficient for *metrologically useful* entangled states.

$F_Q > N$ examples:
Spin-squeezed
GHZ
NOON

In the absence of noise: $\boxed{\Delta\theta_{HL} = 1/N}$ Heisenberg Limit

$$\frac{1}{N} \leq \Delta\theta < \frac{1}{\sqrt{N}}$$

region of metrological advantage

[1] Braunstein, et al. (1996) ; [2] Pezzé, et al. (2018)

1. Inertial Sensing with Neutral Atoms
2. Entangling Neutral Atoms
3. Error Modeling
4. Experiment
5. Conclusion

Inertial Sensing with Neutral Atoms

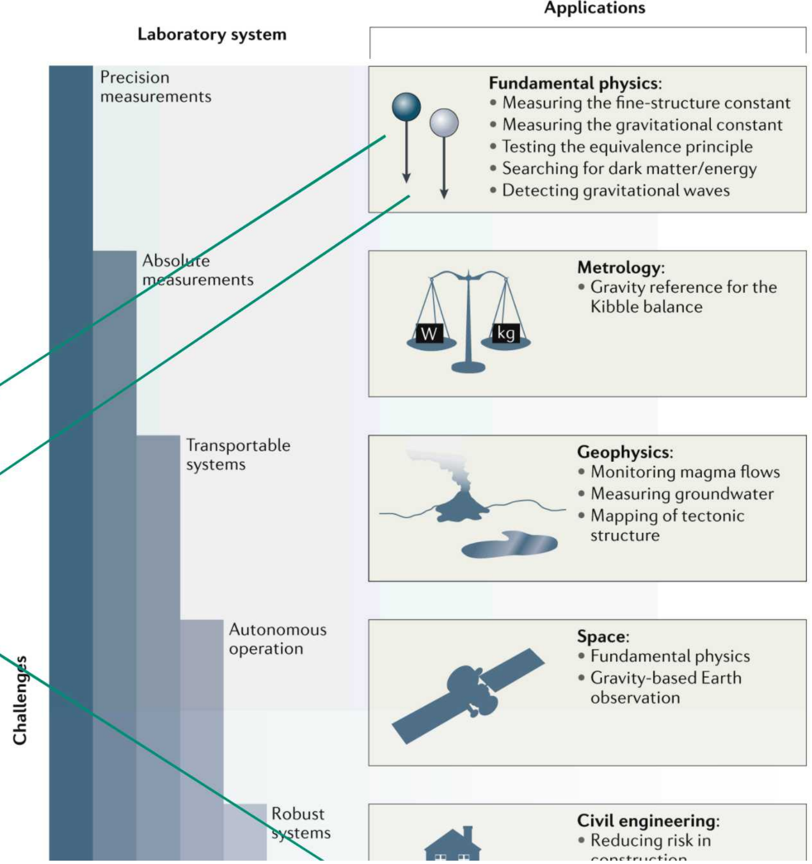
Atom Interferometry

Atom interferometry is a maturing technology with many applications

- Most accurate measurement to date of the fine structure constant, α=1/137.035999046(27)
- Low frequency (0.1-10 Hz) gravitational-wave measurements
- Spring-mass gravimeter takes up to 10 min per measurement point!

“quantum compass”

- Matterwave interferometers are sensitive to
  - Force (acceleration)



Selected for a Viewpoint in *Physics*

PRL 11

Hyb

inte

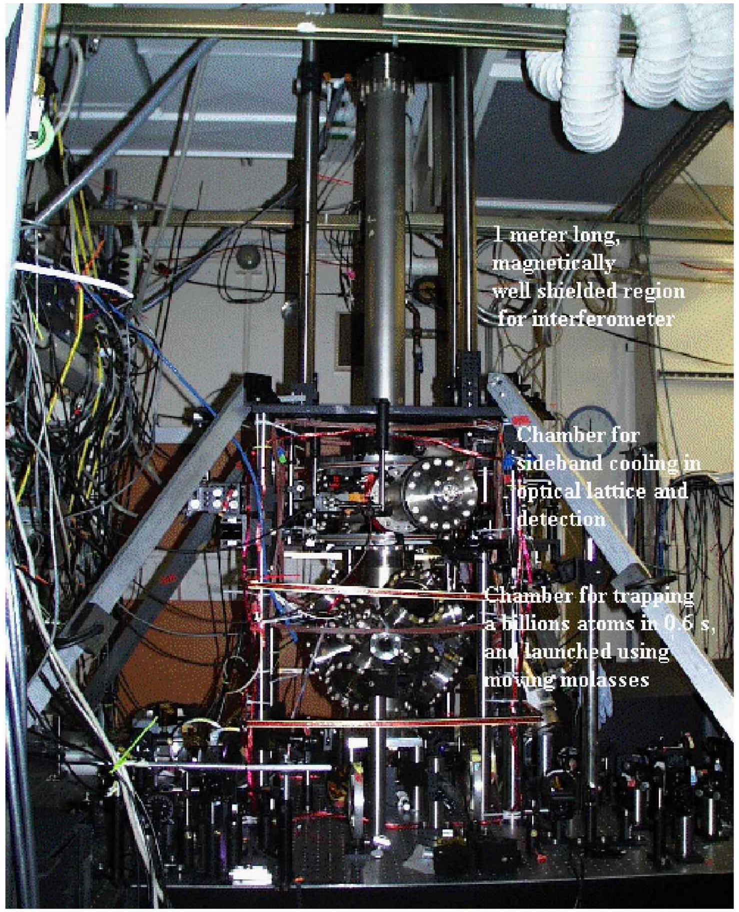
Publi

9 Au

Development of compact cold-atom sensors for inertial navigation

B. Battelier[a,*], B. Barrett[a,b], L. Fouché[a], L. Chichet[a], L. Antoni-Micollier[a], H. Porte
Napolitano[b], J. Lautier[c,†], A. Landragin[c], and P. Bouyer[a]

Atom Interferometry: History



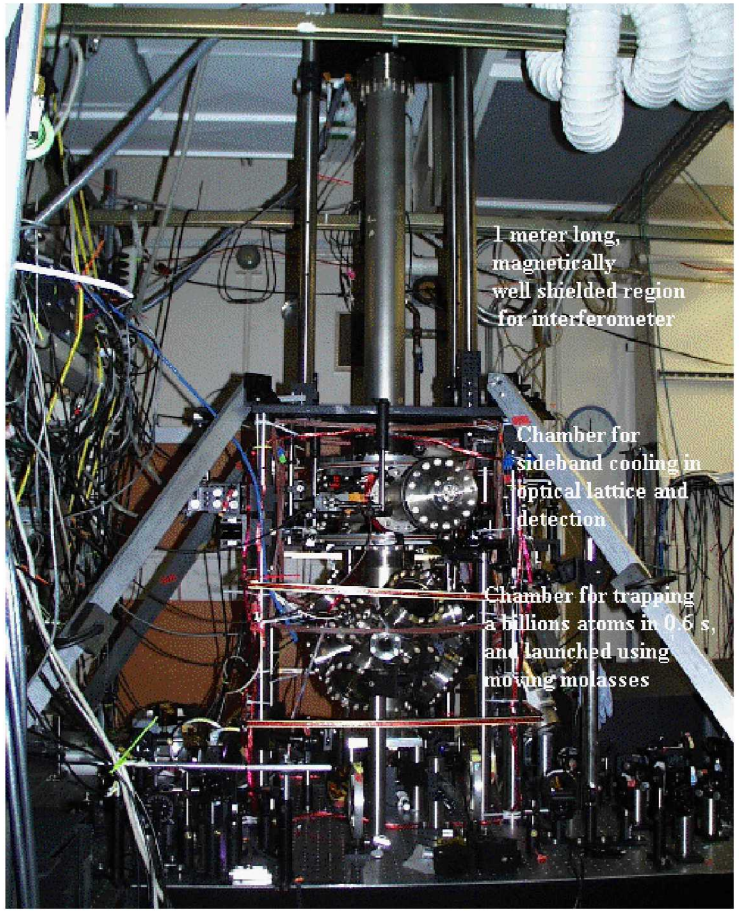
Stanford atom interferometer gravimeter
Steven Chu, 1990's

NIST F-1 atomic fountain clock

Superb gyroscopes and gravity gradiometers demonstrated as well

Kasevich & Chu, PRL 1991

Atom Interferometry: History



Stanford atom interferometer gravimeter
Steven Chu, 1990's

Stanford 10 m tower
Mark Kasevich, 2010's

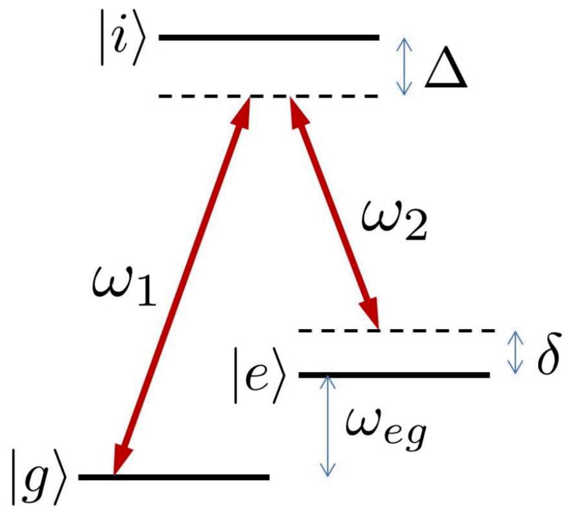
Kasevich & Chu, PRL 1991

(image credit: Kasevich group website)

Atom Interferometry 101

Counter-propagating beams drive Raman transitions

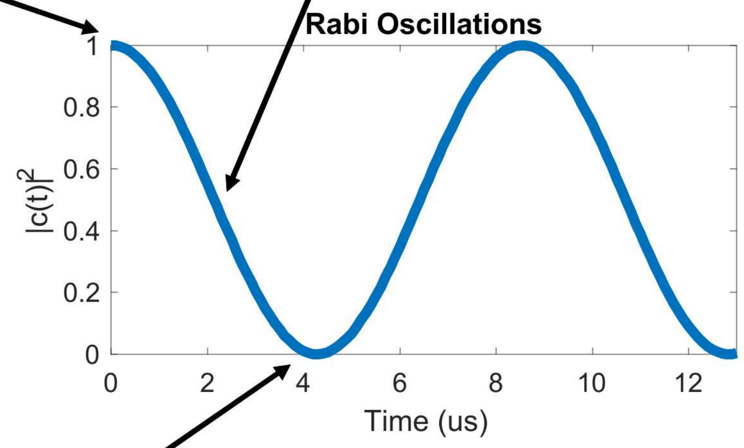
- $\pi/2$ pulse splits the wave function (spatially separated superposition of ground states)
- π pulse sends back



Wavefunction component receives a momentum kick **K** from lasers

$$|\Psi_{\pi/2}\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$

$$|\Psi_0\rangle = |e\rangle$$



$$|\Psi_\pi\rangle = |g\rangle$$

Atom Interferometry 101

Counter-propagating beams drive Raman transitions

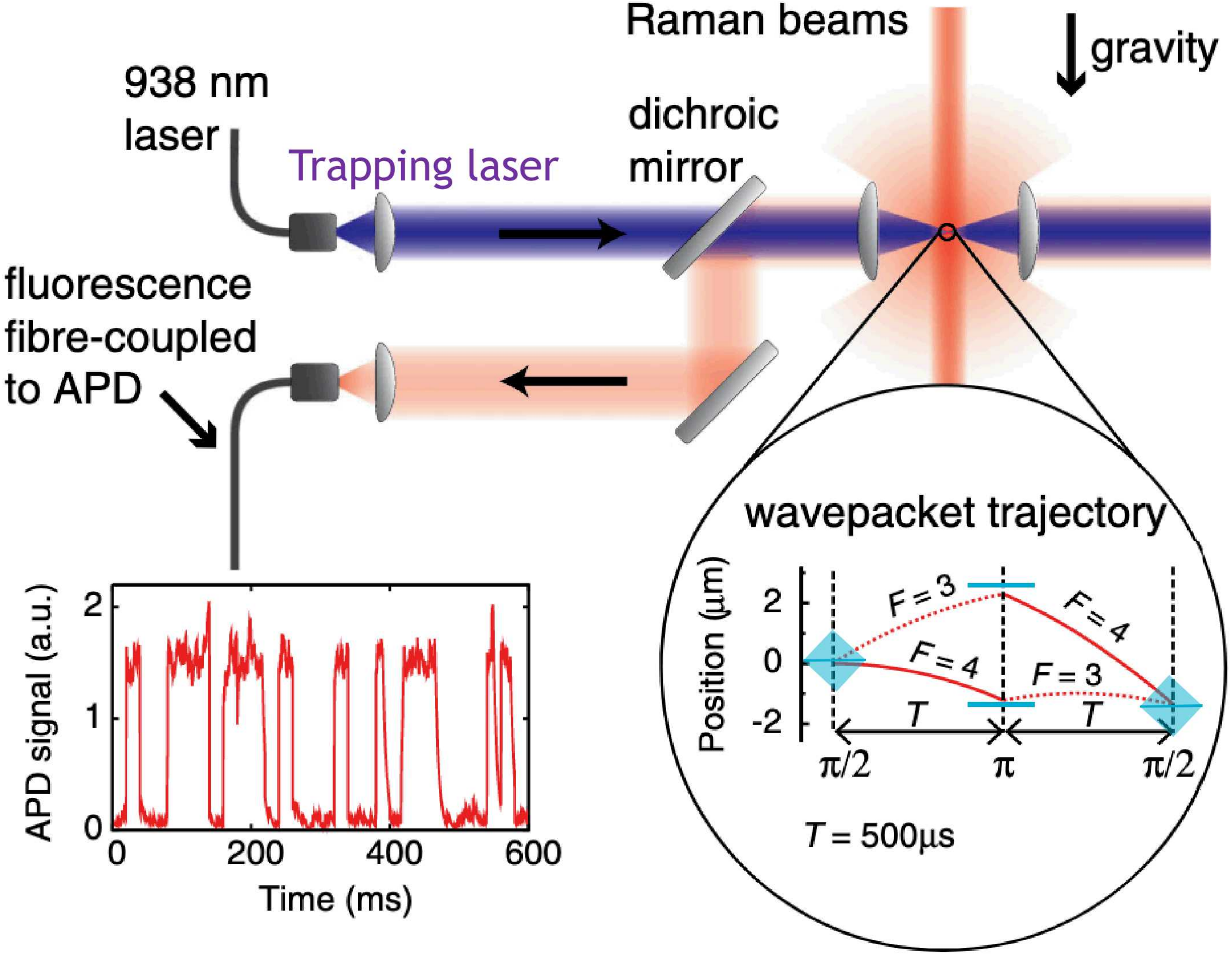
- $\pi/2$ pulse splits the wave function (superposition)
- π pulse sends back
- $\pi/2$ recombines/interferes
- Mach-Zehnder equivalent

The two paths acquire a phase difference

$$\phi = \vec{k} \cdot (\vec{a}T^2 - 2(\vec{\nu} \times \vec{\Omega})T^2)$$

Measure phase by measuring the atomic state:

$$P_{|F=3\rangle} = \frac{1}{2}(1 - \cos\phi)$$



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

Atom Interferometry 101

Counter-propagating beams drive Raman transitions

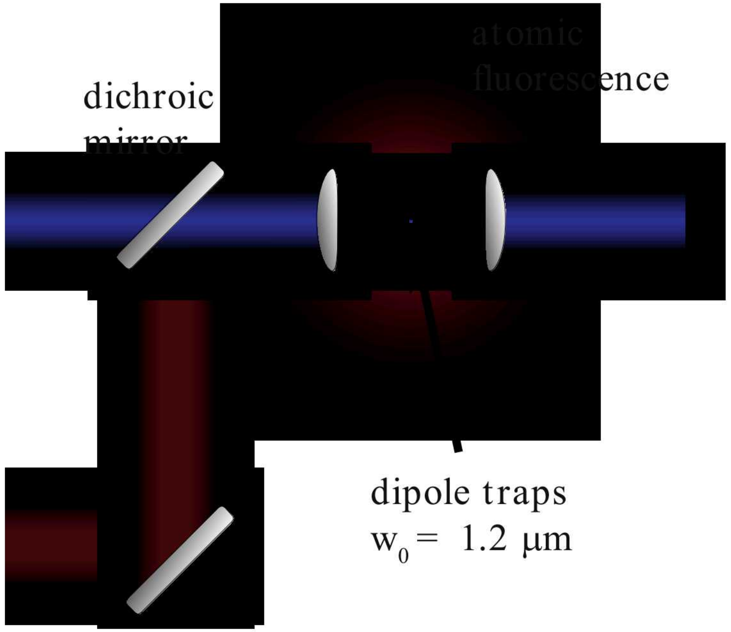
- $\pi/2$ pulse splits the wave function (superposition)
- π pulse sends back
- $\pi/2$ recombines/interferes
- Mach-Zehnder equivalent

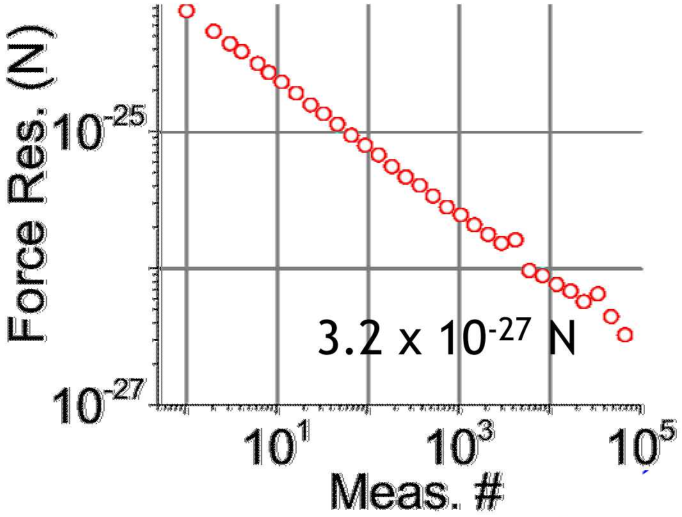
The two paths acquire a phase difference

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

Measure phase by measuring the atomic state:

$$P_{|F=3\rangle} = \frac{1}{2}(1 - \cos\phi)$$





single-atom interferometer

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

Atom Interferometry: Sensitivity

Measurement Limit

$$P_{|F=3\rangle} = \frac{1}{2}(1-\cos\phi)\,; \qquad \phi = \mathbf{K}\cdot\mathbf{a}\,T^2$$

For N atoms, write in terms of parity:

$$\langle\Pi\rangle = \cos^N\phi$$

$$\Pi = \bigotimes_{\alpha=1}^{N}\sigma_z^{(\alpha)} = \bigotimes_{\alpha=1}^{N}(|g\rangle\langle g| - |e\rangle\langle e|)_{(\alpha)}$$

Uncertainty:

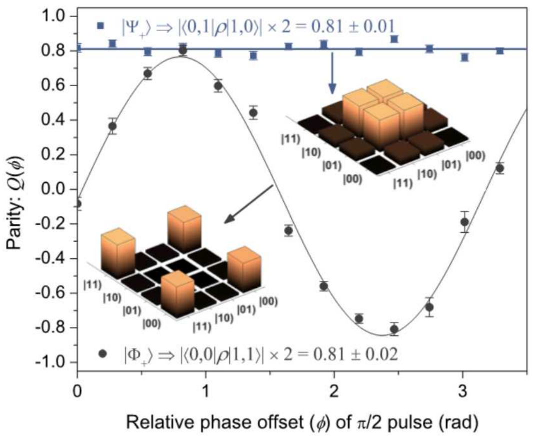
$$\Delta\phi = \frac{\Delta\Pi}{|\partial\langle\Pi\rangle/\partial\phi|}$$

$$\boxed{min\Delta\phi = \frac{1}{\sqrt{N}} \quad \text{Standard Quantum Limit}}$$

Going Beyond the SQL

Metrologically useful quantum states?

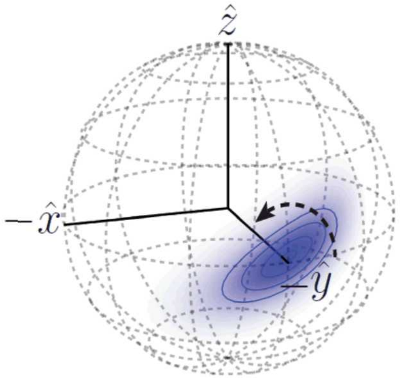
Entangled state[1,2]



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

✗Smaller N
✓High fidelity
✗Fragile, but achievable[1,2]

Spin-squeezed state[3]



✓Large N
✗Low fidelity

? optimal states ?

[1] Y.-Y. Jau, G.B., I.D., *et al.*, Nat Phys. **12** (2016) ; [2] A. Omran, M.D. Lukin *et al.*, Science **365** (2019); *[3] Wineland, et al., PRA 46 (1992)*

Atom Interferometry: Sensitivity

Measurement Limit

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

$$P_{|F=3\rangle} = \frac{1}{2}(1 - cos\phi)\ ;$$

For N atoms, write in terms of parity:

$$\langle\Pi\rangle = \cos^N\phi$$

$$\Pi = \bigotimes_{\alpha=1}^{N}\sigma_z^{(\alpha)} = \bigotimes_{\alpha=1}^{N}(|g\rangle\langle g| - |e\rangle\langle e|)_{(\alpha)}$$

Uncertainty:

$$\Delta\phi = \frac{\Delta\Pi}{|\partial\langle\Pi\rangle/\partial\phi|}$$

$$\boxed{\min_{\phi}\Delta\phi = \frac{1}{\sqrt{N}}}$$

Standard Quantum Limit

N independent atoms

Going Beyond the SQL

Entangled state

$$|\psi\rangle_{in} = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N}|g,\mathbf{p}_\alpha\rangle_\alpha + \bigotimes_{\alpha=1}^{N}|e,\mathbf{p}_\alpha + \hbar\mathbf{K}\rangle_\alpha\right]$$

N entangled atoms in GHZ state

$$\langle\Pi\rangle = \cos(N\phi)$$

$$\boxed{\Delta\phi = \frac{1}{N}}$$

Heisenberg Limit

N entangled atoms

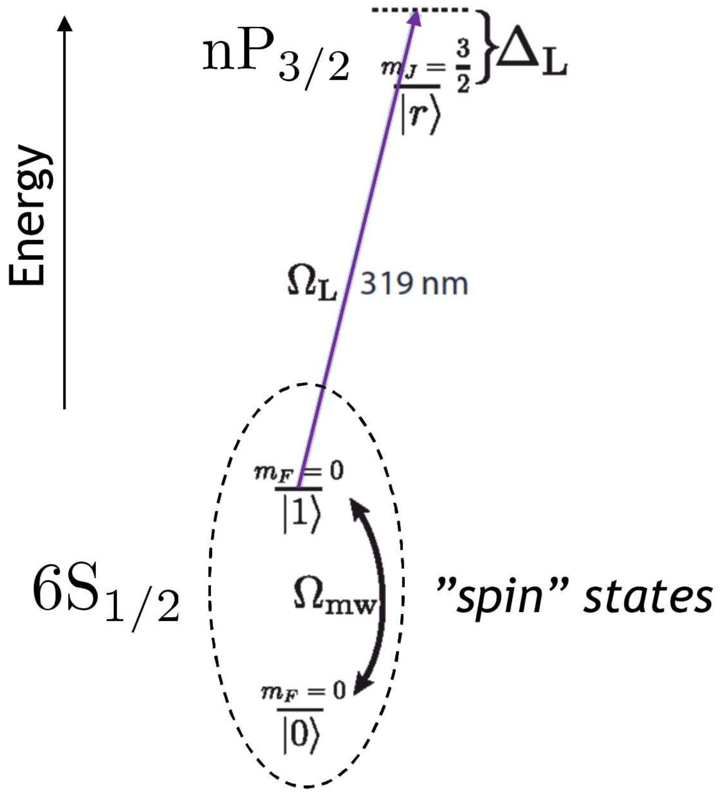
*Next: how to entangle **neutral** atom spins…*

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

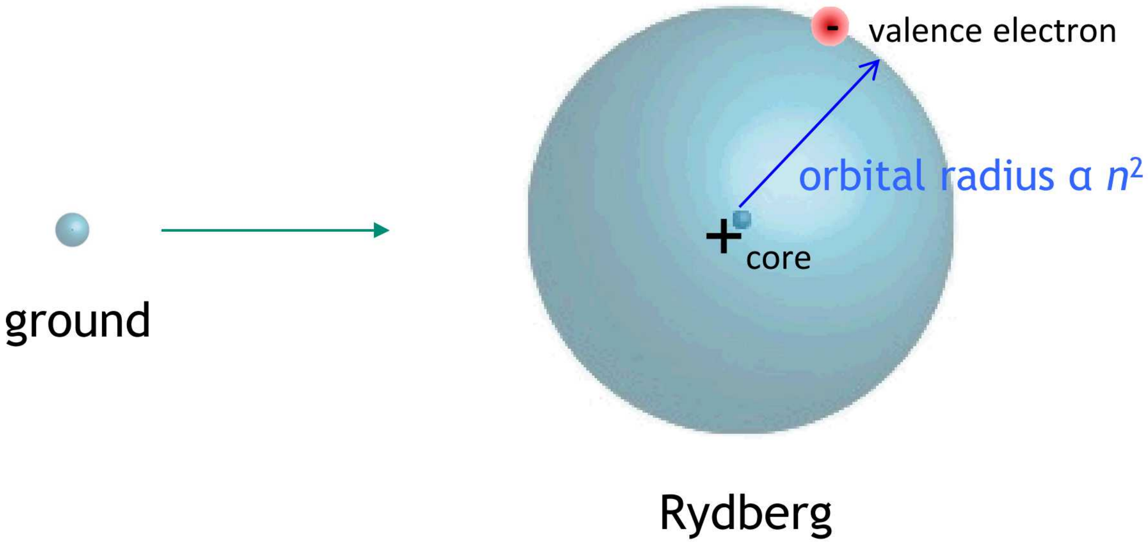
Entangling Neutral Atoms

Entanglement of Neutral Atom Spins

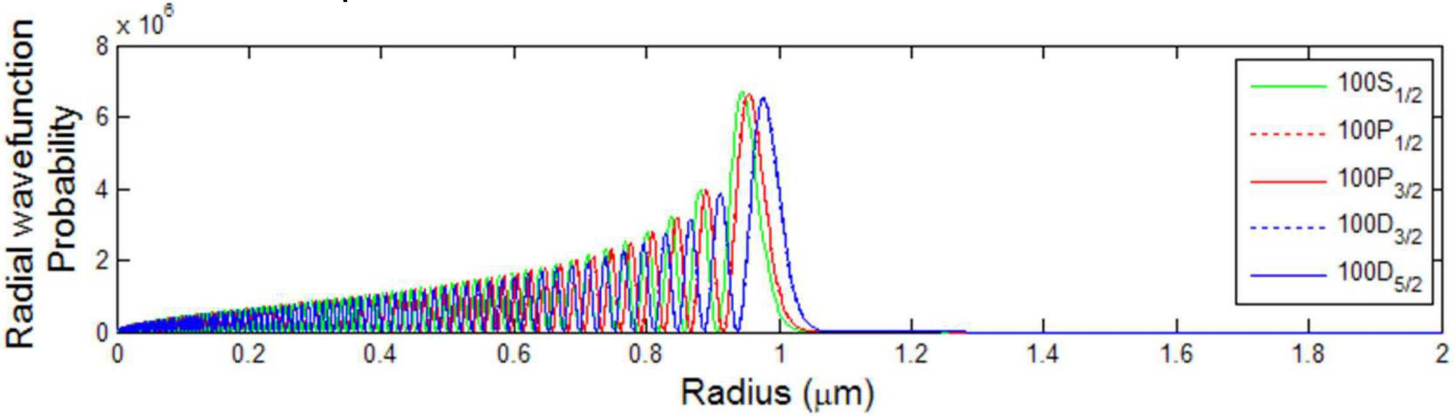
Couple to Rydberg orbitals for interactions



133Cs



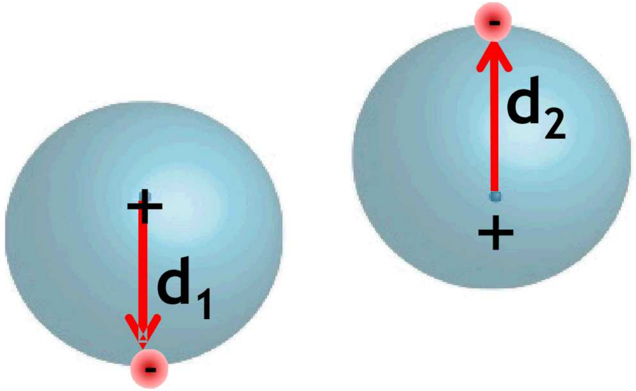
An example of the radial wavefunctions of a Cs atom at n = 100:



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

Entanglement of Neutral Atom Spins

Rydberg Excitation



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 $\propto 1/r^6$

Rydberg Dressing

Small admixture, <1% Rydberg

$$|\psi\rangle = \alpha|g\rangle + \beta|r\rangle$$ [1]

- Retain interaction while preserving longer lifetimes
- Blockade effect in dressed eigenstates
- Expected/Measured lifetime: 120 μs?/??

Entanglement demonstrations

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

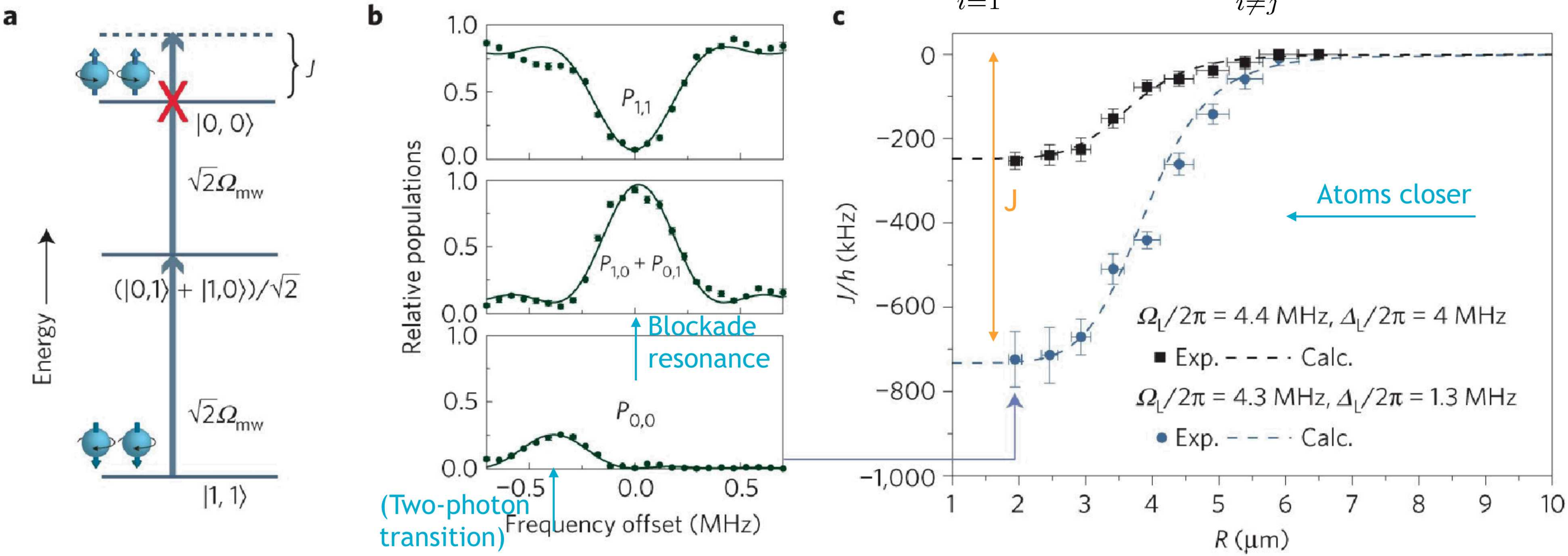
Rydberg Dressing

- Sandia: Y.-Y. Jau, et al., Nat. Phys **12**, 71–74 (2016)
- Mitra, et al., arXiv:1911.04045 (2019)

[1] Johnson and Rolston, Phys Rev A **82** (2010)

Entanglement of Neutral Atom Spins

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



Spin-flip Blockade

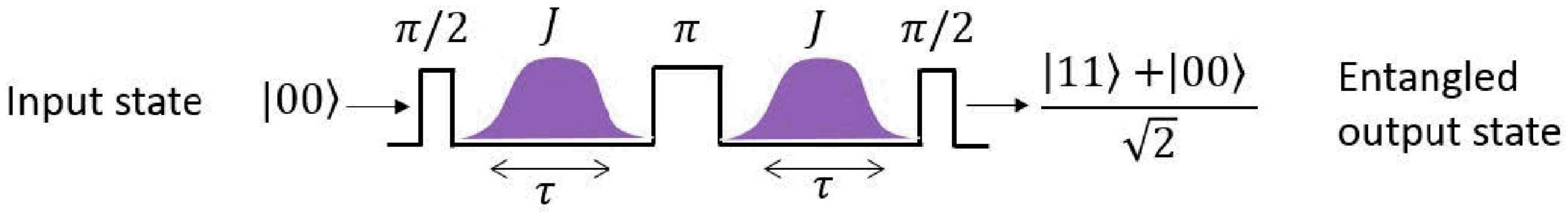
Raman spectroscopy reveals the blockade effect

Interaction as a function of interatomic distance

$$\frac{J}{\hbar} = 2\left(\Omega_{|1,1\rangle \to (|1,0\rangle + |0,1\rangle)/\sqrt{2}} - \Omega_{|1,1\rangle \to |0,0\rangle}\right)$$

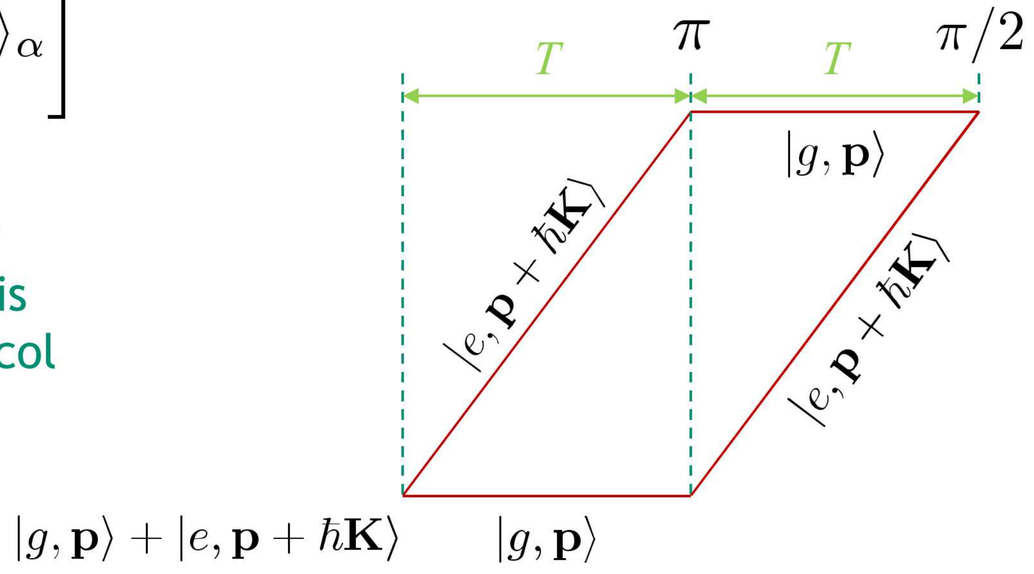
Y.-Y. Jau, …, I.D., **G.B.**, Nature Phys. **12** (2016)

Rydberg Dressing Sequence to Generate a GHZ state



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N}|g,\mathbf{p}_\alpha\rangle_\alpha + \bigotimes_{\alpha=1}^{N}|e,\mathbf{p}_\alpha+\hbar\mathbf{K}\rangle_\alpha\right]$$

Momentum is inherently part of the state after this prep with counter-propagating fields, and is fundamental to our atom interferometer protocol



Progress 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

Single Qubit fidelity	Bell State Fidelity	Year	Reference
0.9983 (14)		2015	T Xia,.. M Saffman, *et al.*
0.9944 (84)		2016	Y. Wang,.. DS Weiss, *et al.*
0.9994		2019	T-Y Wu,.. DS Weiss, *et al.*
	0.86(2)	2019	TM Graham, … M Saffman *et al.*
	0.950(2) [97.4(3)]	2019	H Levine, … VV, HP, MD Lukin *et al.*

Also:

20-atom GHZ state with F>= 0.542(18)
A. Omran *et al.* (2019)

Xu, Victoria, et al. "Probing gravity by holding atoms for 20 seconds." *Science* 366.6466 (2019): 745-749.

New theory work: A. Mitra, ..., I. Deutsch, *et al. Robust Mølmer-Sørensen gate for neutral atoms using rapid adiabatic Rydberg dressing*, arXiv:1911.04045 (2019) → 99.5% gate fidelity predicted

Summary So Far:

AI + Entanglement = Quantum Metrology (Heisenberg Scaling)

- Rydberg Dressing provides entangling mechanism
- GHZ state input to an atom interferometer

Next: What happens to the sensitivity in the presence of realistic conditions?

1. Inertial Sensing with Neutral Atoms
2. Entangling Neutral Atoms
3. Error Modeling
4. Experiment
5. Conclusion

Quantum Metrology in the Real World: Theory

Modeling error for interferometry with entangled atoms

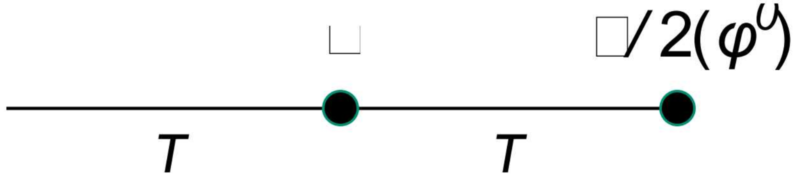
B. P. Ruzic, C. Brif, and G. W. Biedermann, in process, (2020)

Summary: The IDEAL Atom Interferometer

N entangled atoms

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

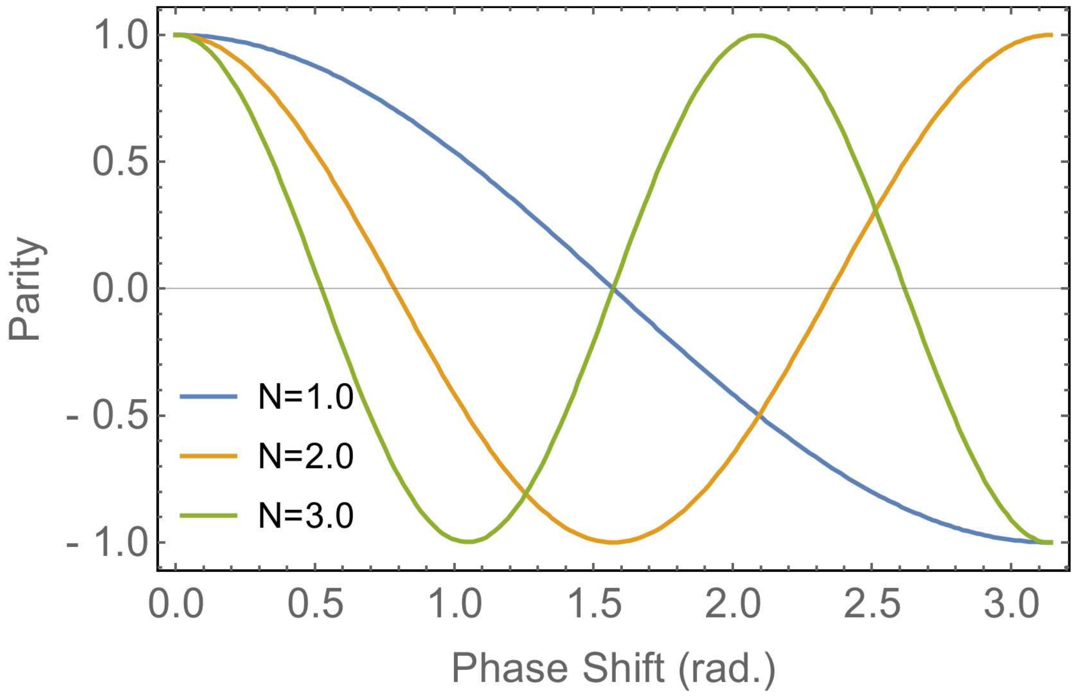
Pulse sequence



Measure Parity

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

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



As N grows:

Parity oscillates faster

$$\langle\Pi\rangle = \cos\Phi_N$$

$$\Phi_N = N K \cdot a T^2 = N\varphi$$

$$\Delta\varphi = \frac{1}{N}$$

Heisenberg Limit

B. P. Ruzic, C. Brif, and G. W. Biedermann, in process, (2020)

Error 1: Imperfect Initial State Preparation

Add a random relative phase and an admixture of a noise state:

$$\rho = (1-p)|\psi\rangle\langle\psi| + p|\zeta\rangle\langle\zeta|$$

phase γ is peaked around zero with standard deviation σ

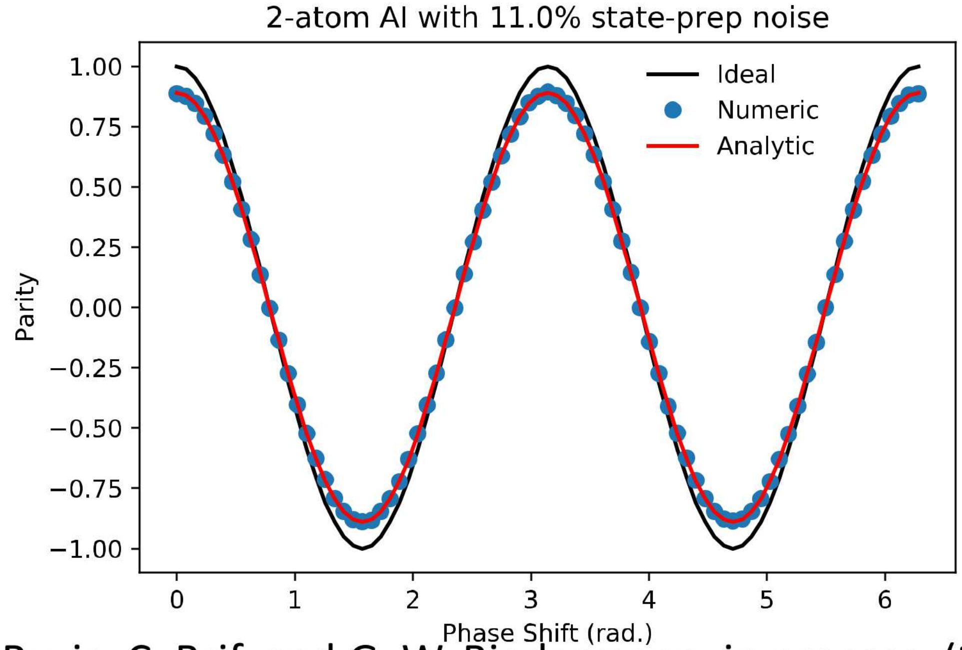
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N}|g,\mathbf{p}_\alpha\rangle_\alpha + e^{i\gamma}\bigotimes_{\alpha=1}^{N}|e,\mathbf{p}_\alpha+\hbar\mathbf{K}\rangle_\alpha\right]$$

random state

$$|\zeta\rangle = \bigotimes_{\alpha=1}^{N}\left[\cos\left(\frac{\vartheta_\alpha}{2}\right)|g,\mathbf{p}_\alpha\rangle_\alpha + e^{i\varphi_\alpha}\sin\left(\frac{\vartheta_\alpha}{2}\right)|e,\mathbf{p}_\alpha+\hbar\mathbf{K}\rangle_\alpha\right]$$

$$\Delta\phi \approx \frac{1}{N(1-p-\sigma^2/2)}$$

If ≪1, deviation from Heisenberg scaling is small



- For two-atom Bell state fidelity of 0.89, $p+\sigma^2/2 \approx 0.11$
- For two-atom Bell state fidelity of 0.95, $p+\sigma^2/2 \approx 0.05$
- Metrological advantage is only linearly sensitive to entanglement imperfection

B. P. Ruzic, C. Brif, and G. W. Biedermann, in process, (2020)

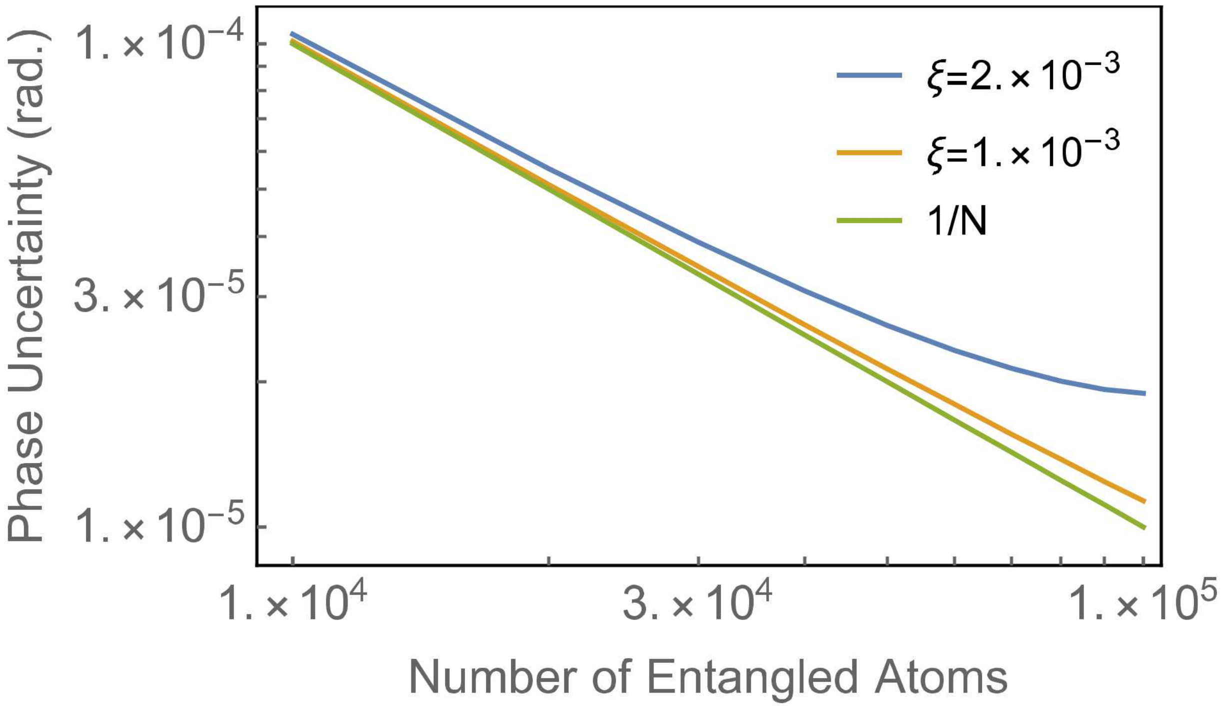
Error 2: Laser Intensity Fluctuations

Raman Laser Intensity Fluctuations lead to random pulse-area errors $A = A_0 + \delta A$

Average over random variable δA with standard deviation $\sigma = \xi A_0$

Phase uncertainty $$\Delta\phi \approx \frac{1}{N(1 - \frac{3\pi^2}{8}N\xi^2)}$$

Error scales with N



In our experiment

$$\xi \approx 10^{-3} \rightarrow 10^{-4}$$

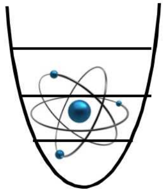
Heisenberg scaling continues to at least

$$N \approx 10^5$$

B. P. Ruzic, C. Brif, and G. W. Biedermann, in process, (2020)

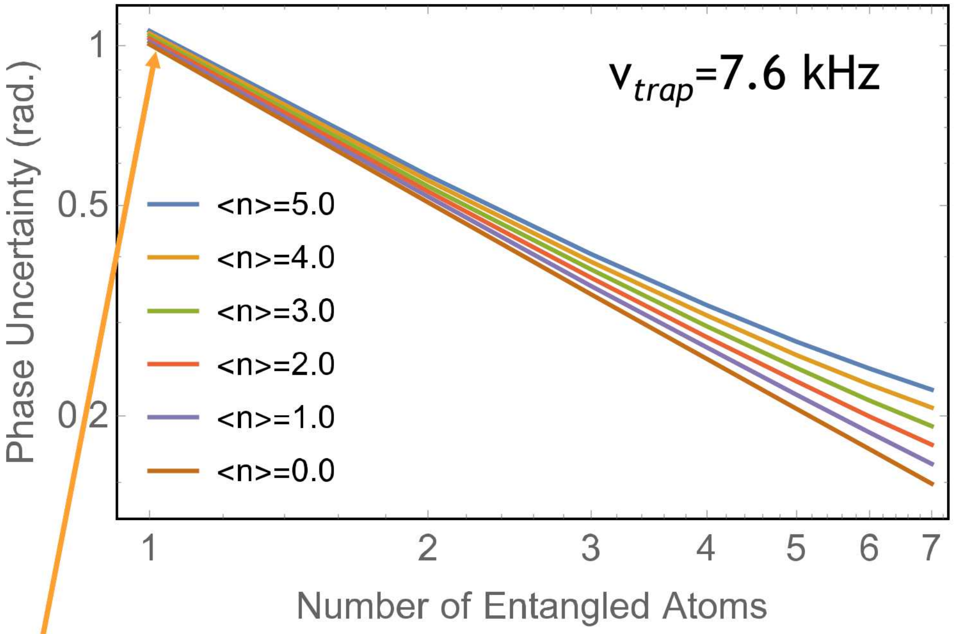
Error 3: Initial Momentum Distribution

Atoms start in optical tweezers $\rho = \rho_{\rm vib} \otimes |\psi_{\rm spin}\rangle\langle\psi_{\rm spin}|$

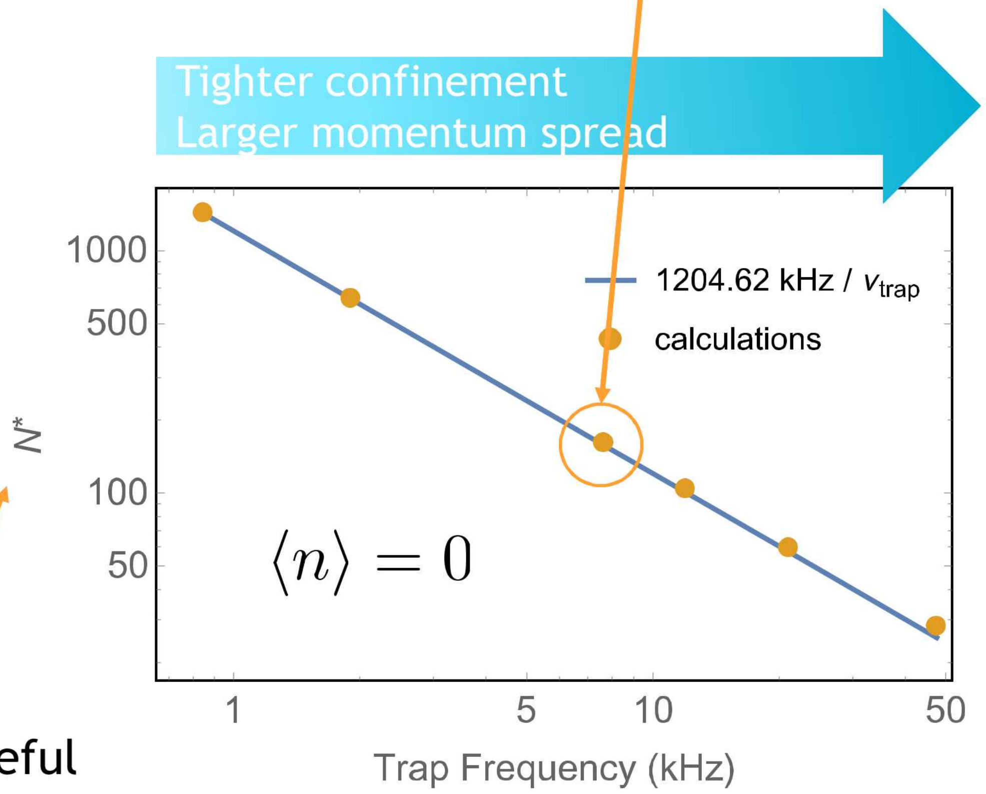


At 7.5 kHz, significant metrological advantage for 150+ atoms

Each run randomly samples a momentum distribution
→ Doppler shift
→ detuning error in pulses



Interferometer with one atom



$\propto$ Temperature

Max. useful number of atoms

B. P. Ruzic, C. Brif, and G. W. Biedermann, in process, (2020)

Error Modeling Summary

Modeled Error Sources:

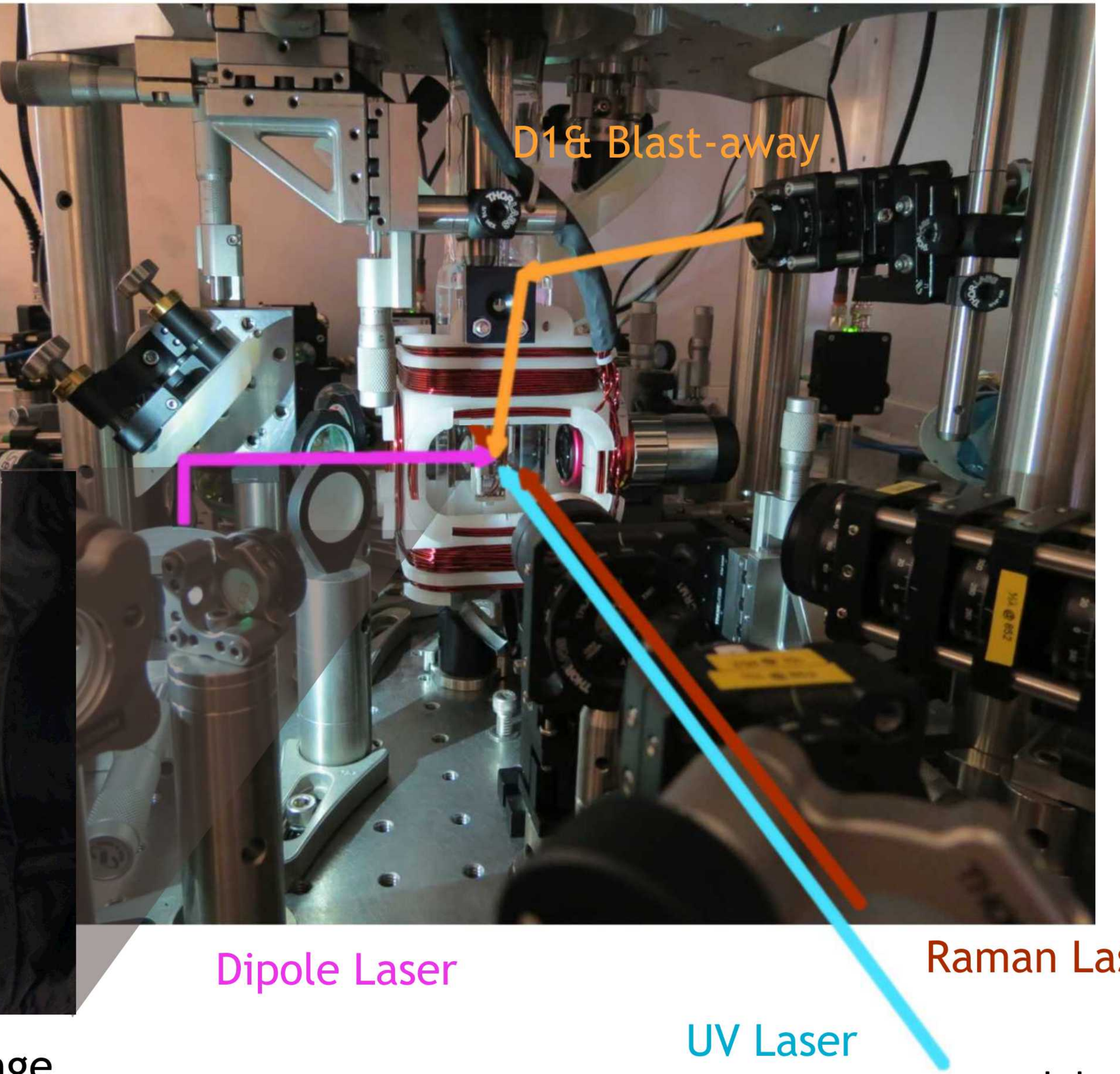
1. Imperfect Initial State Preparation
2. Laser intensity fluctuations
3. Initial momentum distribution (random Doppler shift)

- # 3 is the dominant source of error as the number of entangled atoms is increased
- Even with error, significant metrological advantage expected with hundreds of atoms

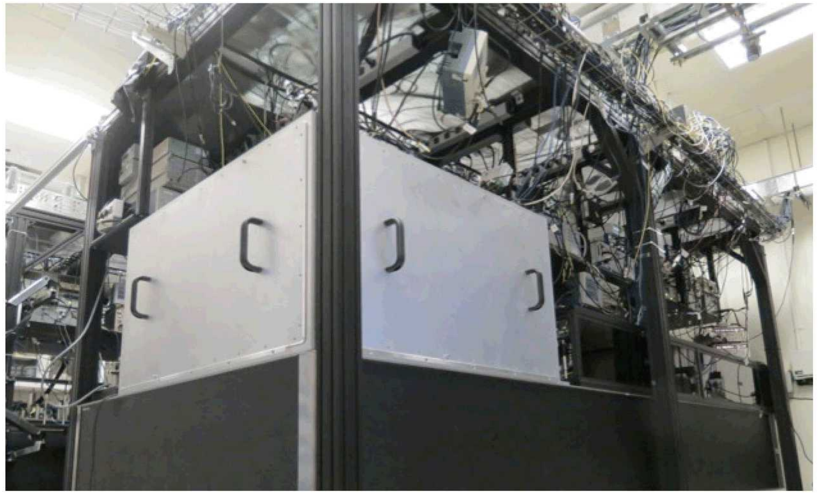
1. Inertial Sensing with Neutral Atoms
2. Entangling Neutral Atoms
3. Error Modeling
4. Experiment
5. Conclusion

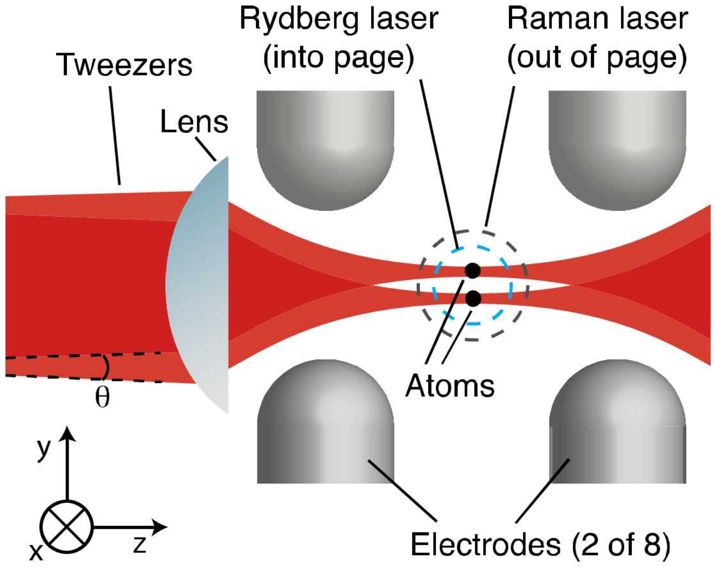
Quantum Metrology in the Real World: Experiment

Experiment Overview



Faraday Cage

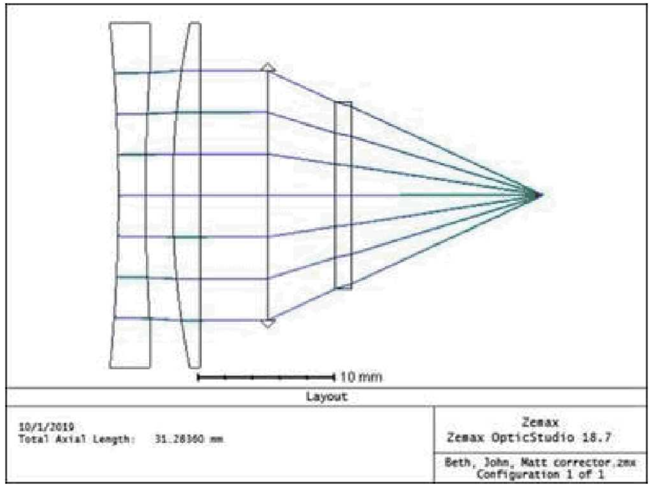




J. Lee, G.B., I.D., *et al.*,Phys. Rev. A. **95**, 041801(R), (2017)

Apparatus Tune-up (/Overhaul)

- New trapping lens (and chamber)
  - More stable
  - Better collection efficiency
  - Worked with Optical Engineer (Bill Sweat) at Sandia National Labs

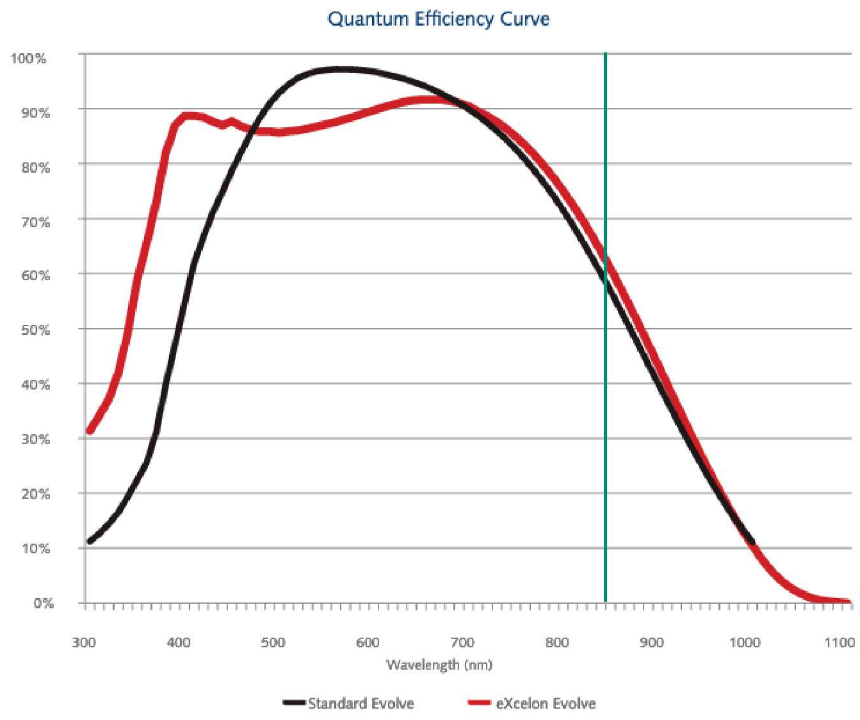


0.45 NA
20.0 mm Working distance
Corrected for chamber glass thickness with additional lenses

Apparatus Tune-up

- New trapping lens (and chamber)
  - More stable
  - Better collection efficiency
  - Worked with Optical Engineer (Bill Sweat) at Sandia National Labs
- New EMCCD
  - Photometrics Evolve 512 Delta
  - Higher quantum efficiency
  - More easily scalable

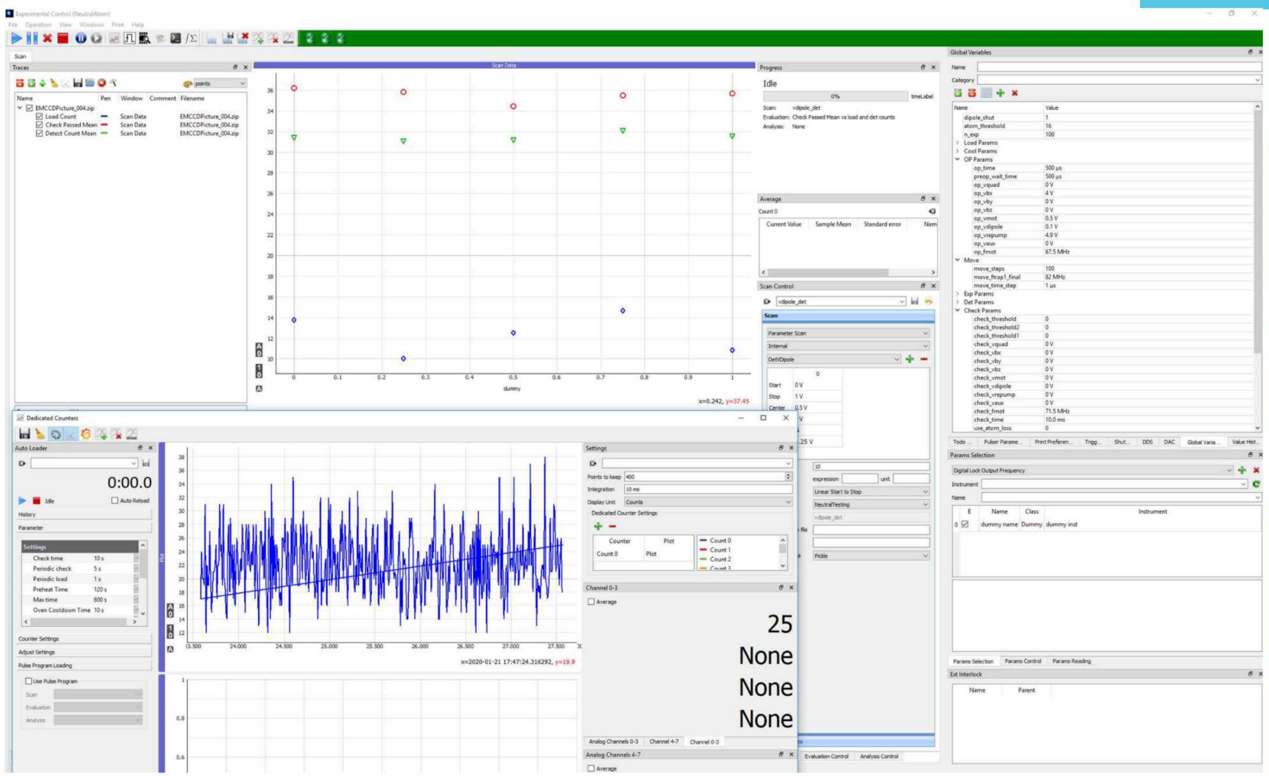
QE>60% at 850 nm

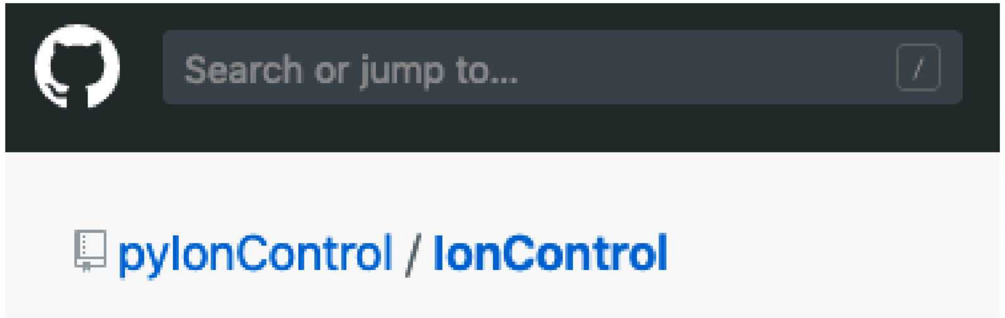


Dark Current ~0.003 e-/pixel/sec

Apparatus Tune-up

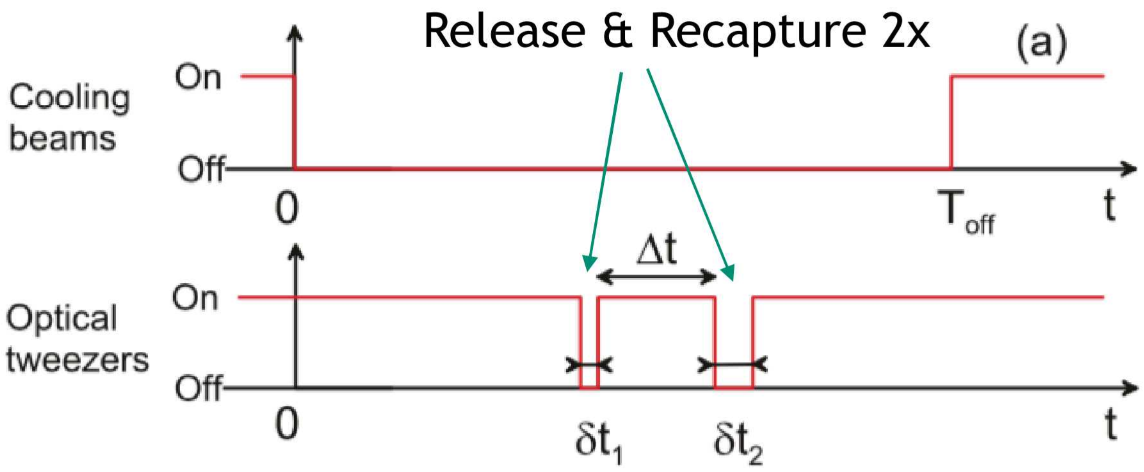
- New trapping lens (and chamber)
  - More stable
  - Better collection efficiency
  - Worked with Optical Engineer (Bill Sweat) at Sandia National Labs
- New EMCCD
  - Photometrics Evolve 512 Delta
  - Higher quantum efficiency
  - More easily scalable
- New Control System
  - Collaboration with ion trapping group at Sandia
  - Capable hardware and software allows better integration and gives more scope for the future



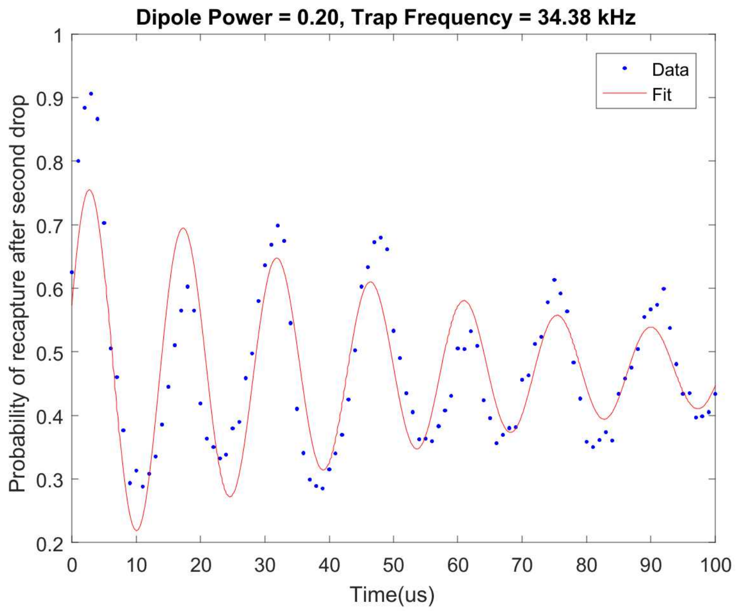


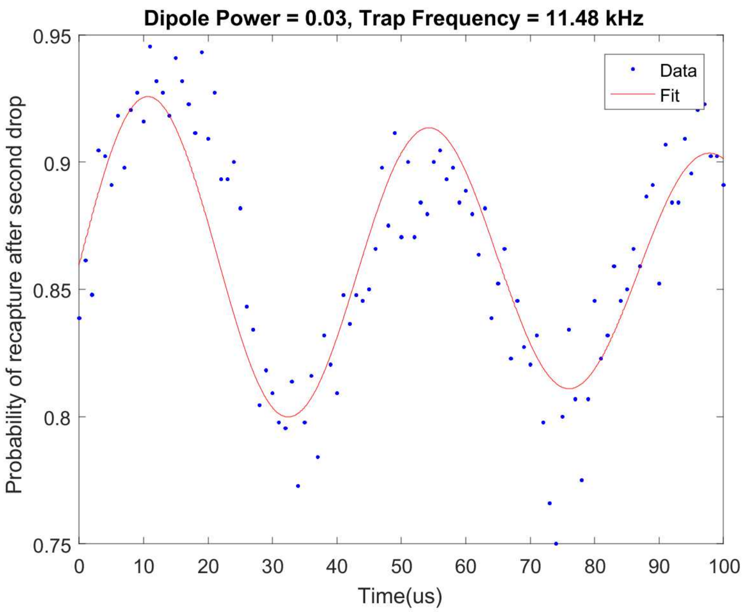
Available on GitHub! (unsupported)

Direct Trap Frequency Measurement



YRP Sortais,… Grangier PRA (2007)





- Trap phase class is selected in δt_1
- Frequency is measured via δt_2
- Probability is maximized when atoms in trap have made one complete cycle

We plan to use a similar technique for delta-kick cooling.

Outlook and Conclusion

Plans for Future Work

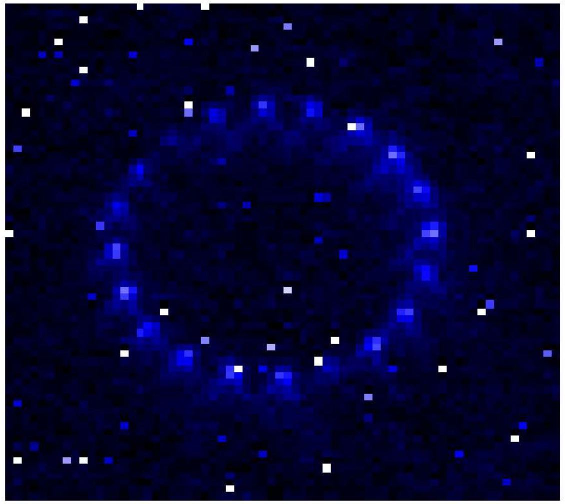
- Demonstrate measurement enhancement with entangled interferometer
- Optimal control with deep learning
  - Sub-doppler cooling
  - Raman beam pulse shaping
  - Optimal entanglement creation
- Explore larger array configuration, building on work already done at Sandia.

Outlook: Large Arrays

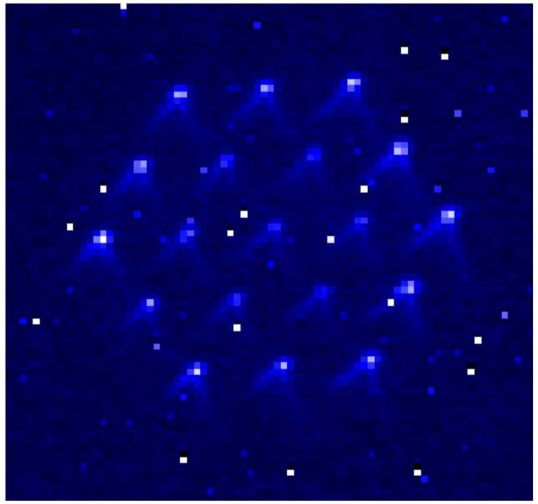
Spatial light modulator allows arbitrary patterns

Large systems > 100

Averaged over many exposures

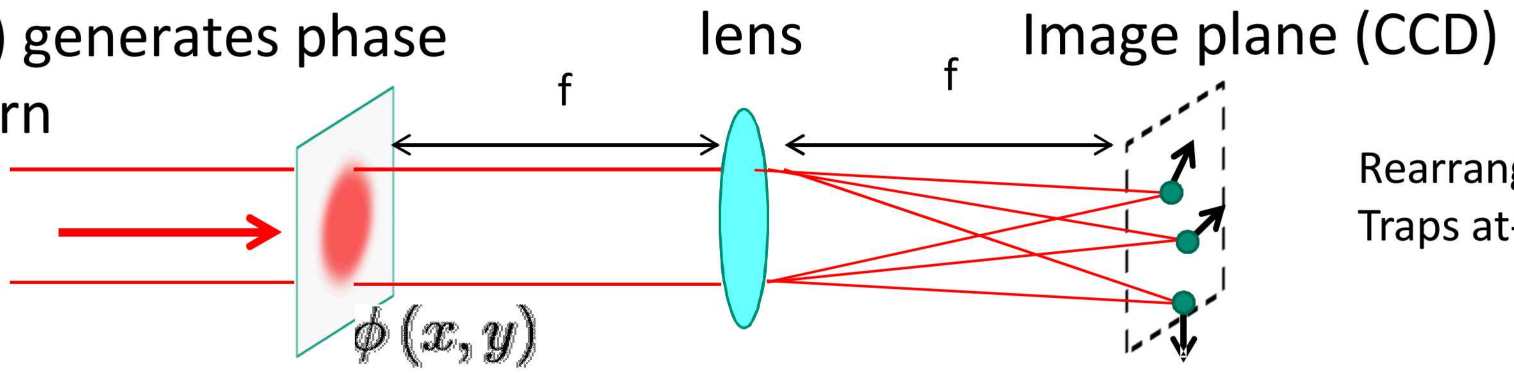


Ring lattice



Triangular lattice

Spatial **L**ight **M**odulator (SLM) generates phase pattern



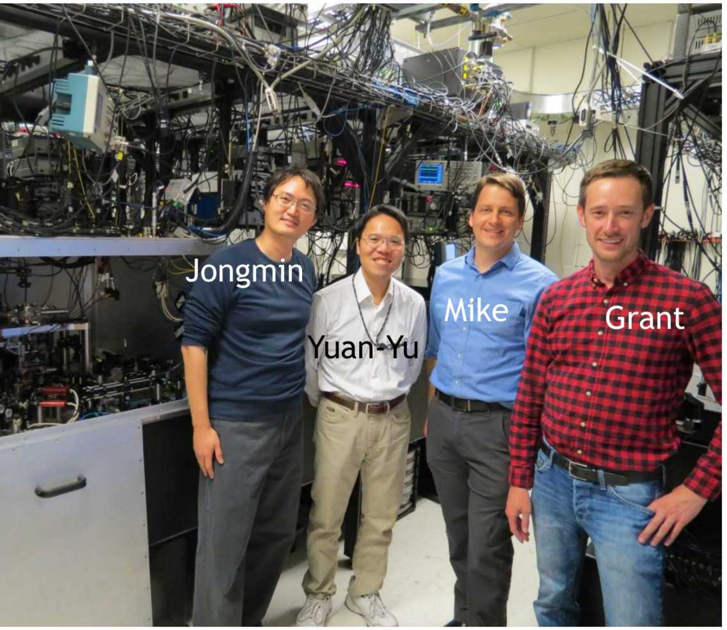
Rearrange Traps at-will

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

Summary

- We have demonstrated entanglement between neutral atoms via Rydberg dressing
- We have demonstrated an atom interferometer with this same platform
- Theory predictions show that there should be a significant metrological advantage to using entangled atoms in an interferometer, even with modeling of significant error
- Significant experimental updates are in progress, and we look forward to sharing the results soon!

Thank You

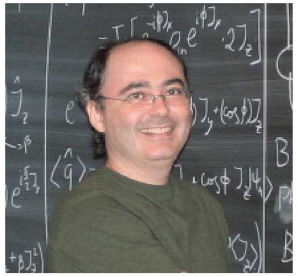


This has been a team effort over many years!

Sandia Experiment:
Bethany Little
Matthew Chow
Paul Parazzoli

Longtime Lead & Continuing Advisor/Collaborator
Grant Biedermann (OU)

Sandia Theory
Brandon Ruzic
Constantin Brif



Constantin

Brandon

Collaborators
Alberto Marino (OU)
Jongmin Lee (SNL)
Yuan-Yu Jau (SNL)
Jonathan Bainbridge (SNL, UNM)
Ivan Deutsch (UNM)
Peter Schwindt (SNL)
Mike Martin (LANL)

John

We welcome discussion & collaboration!

Extra Slides: Error Theory

Increasing the Atom Number

Heisenberg scaling breaks down near

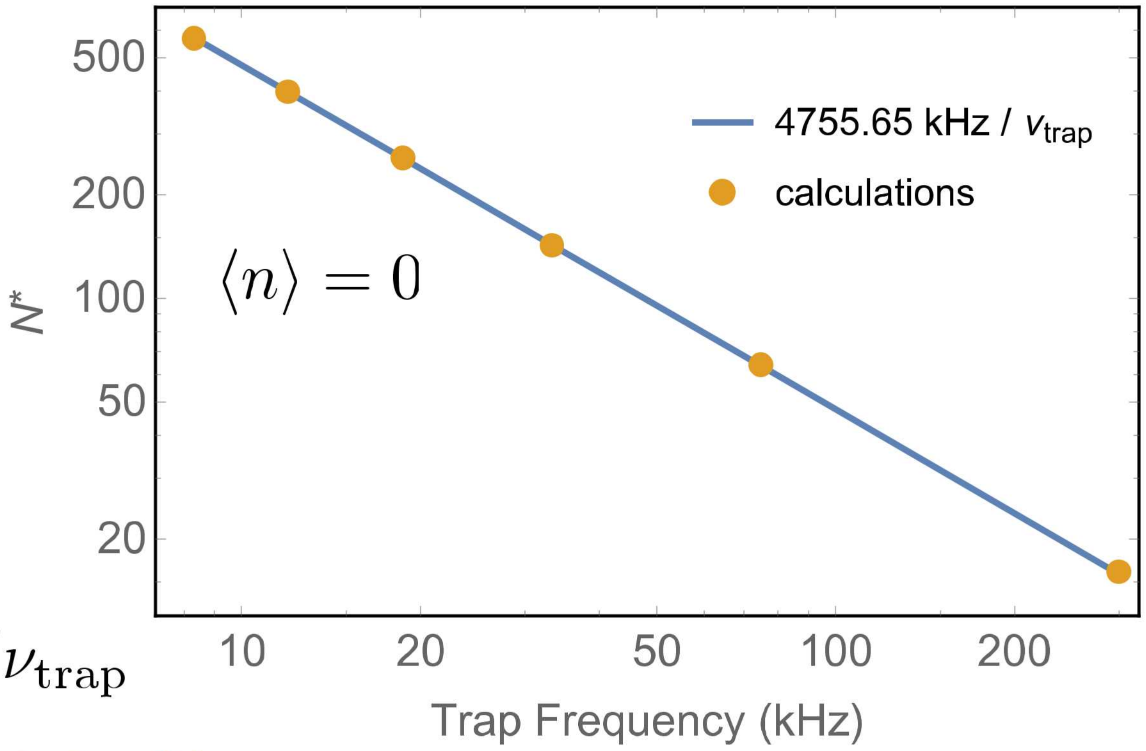
$$N^* \equiv 0.1/\eta$$

Parameter η scales linearly with ν_{trap}

$$\eta \propto \nu_{\mathrm{trap}}$$

Fit to calculations of N^*

$$N^* \approx 4755.86\ \mathrm{kHz}/\nu_{\mathrm{trap}}$$



A trap frequency of 10 kHz is feasible

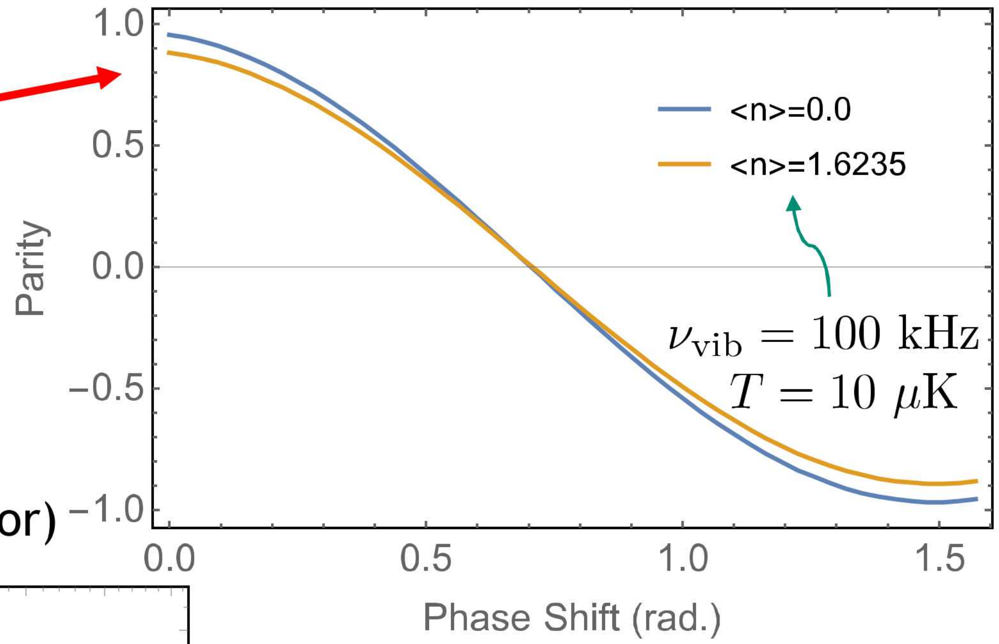
$N^* \approx 476$ at $\langle n \rangle = 0$

Entanglement enhancement starts to slow down at 27 dB beyond SQL

Random Doppler Shift

No analytic result for $\Delta\phi$

requires numerical analysis

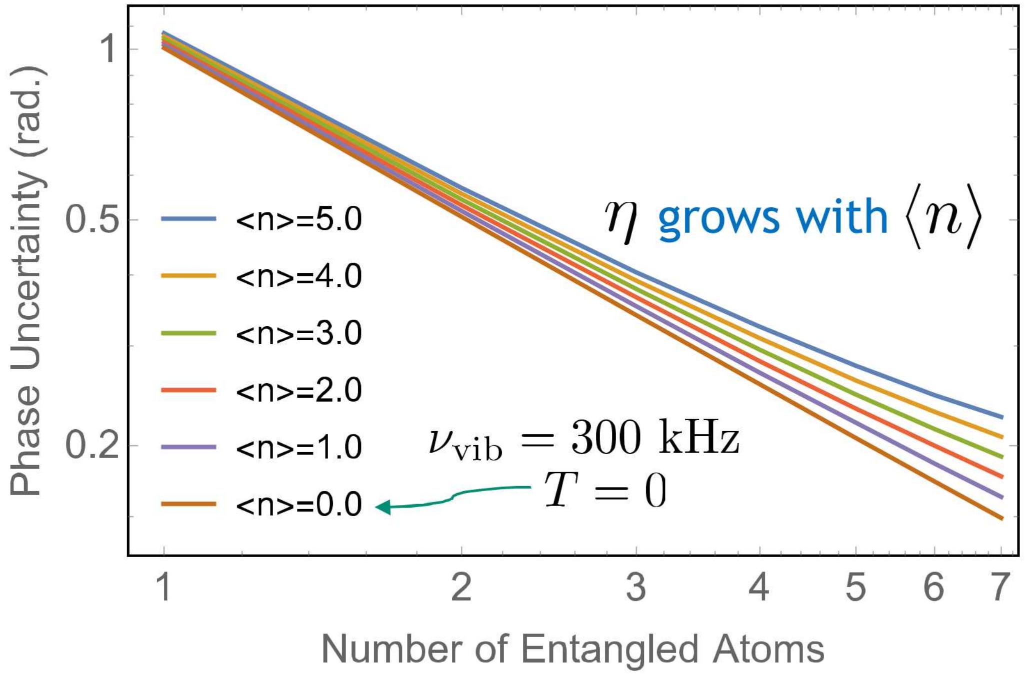


We found

$$\Delta\phi \approx \frac{1}{N(1-\eta N)}$$

when $\eta N \ll 1$

(same form as for laser intensity error)



Deviation from Heisenberg scaling becomes significant around

$$\eta N \approx 0.1 \quad \text{or} \quad N^* \equiv 0.1/\eta$$

Even for $\langle n \rangle = 0$

$\nu_{\text{vib}} = 100\ \text{kHz} \quad N^* \equiv 0.1/\eta \approx 48$

$\nu_{\text{vib}} = 300\ \text{kHz} \quad N^* \equiv 0.1/\eta \approx 16$

Random Doppler Shift

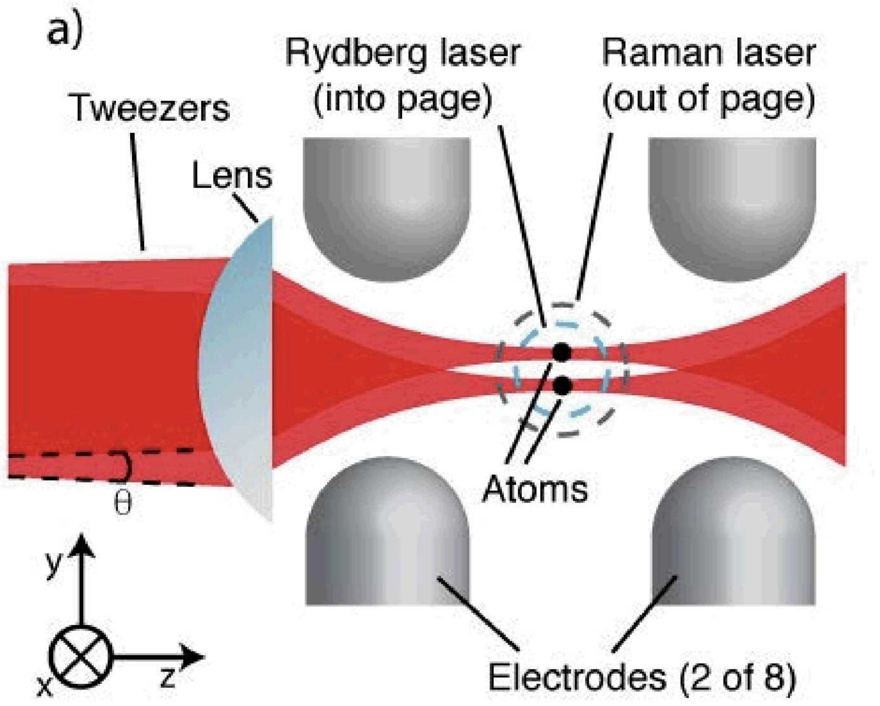
Atoms start in optical tweezers $\rho = \rho_{\text{vib}} \otimes |\psi_{\text{spin}}\rangle \langle\psi_{\text{spin}}|$

Thermal state, described by the average vibrational level

$$\rho_{\text{vib}} = \sum_{n=0}^{\infty} P_n |n\rangle\langle n|$$

$$P_n = \frac{\langle n\rangle^n}{(1+\langle n\rangle)^{n+1}}$$

$$\langle n\rangle = [\exp(\hbar\omega_{\text{vib}}/k_{\text{B}}T) - 1]^{-1}$$



Initial momentum spread

- each run randomly samples a momentum distribution

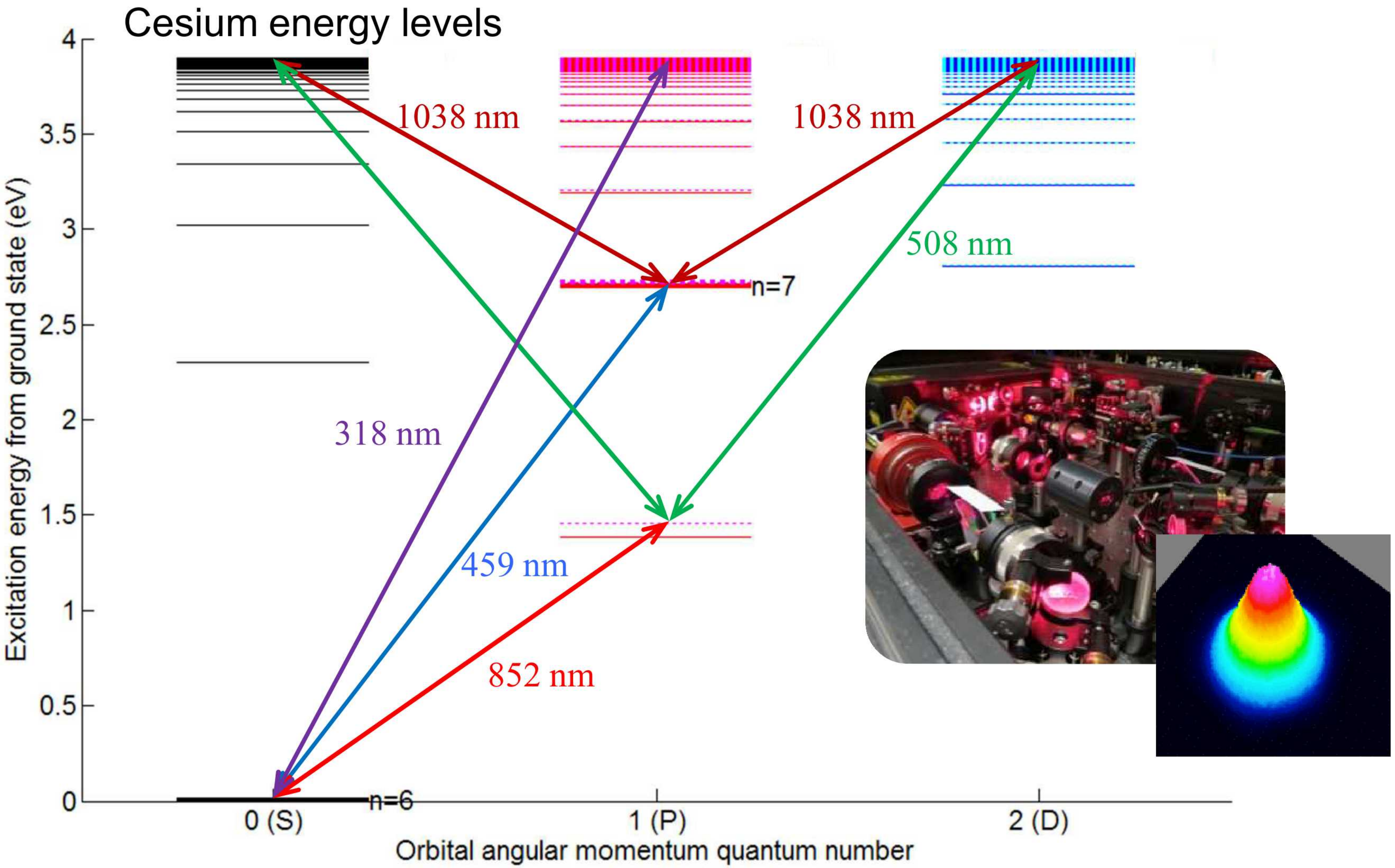
→ doppler shift

→ detuning error in pulses

$$\delta = -\hbar p K/m$$

Extra Slides - Rydberg

Rydberg excitation laser



Phys. Rev. A 89, 033416 (2014)

Extra Slides: Experiment

Single atom control of 2 atoms