University of BRISTOL

# Controlling ultracold atoms in optical lattices: theory and practice …but mostly practice

Dr Carrie Weidner

Quantum Engineering Technology Labs

9 September 2024



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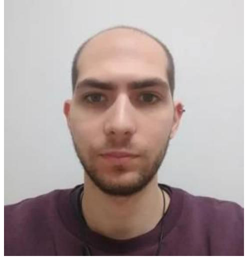

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## *To learn more: www.bristol.ac.uk/qet-labs/research/*

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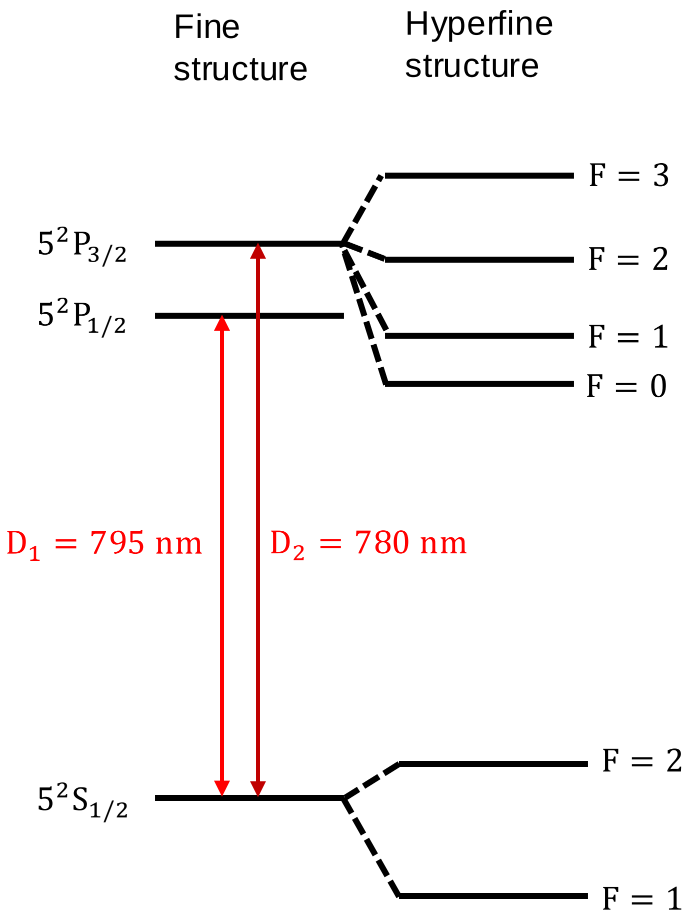
# Things I do that I won’t talk about

- Using hot atom vapour to generate squeezed light and sense magnetic fields
- Quantum simulation and quantum gas microscopy – looking at the world one atom at a time
- Robust quantum control
- Quantum memories, atoms and integrated photonics, and other fun with my QET Labs friends
- Quantum physics education research

# Part 0: The preliminaries

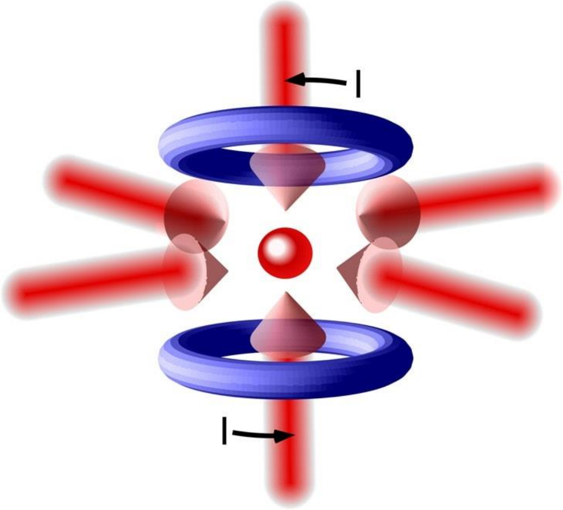
# What's in an atom?

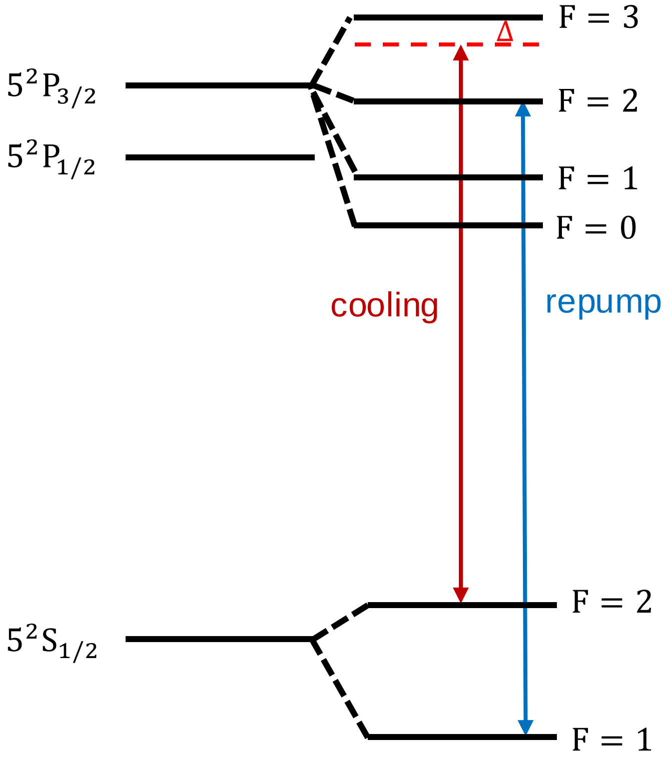
- Alkali metal atoms like Rb-87 (my favorite atom) have one electron in an un-filled orbital
- What is the energy level structure of this single electron?
- Remember spectroscopic notation: $N^{2S+1}L_J$



# Cooling alkali metal atoms with lasers and magnetic fields

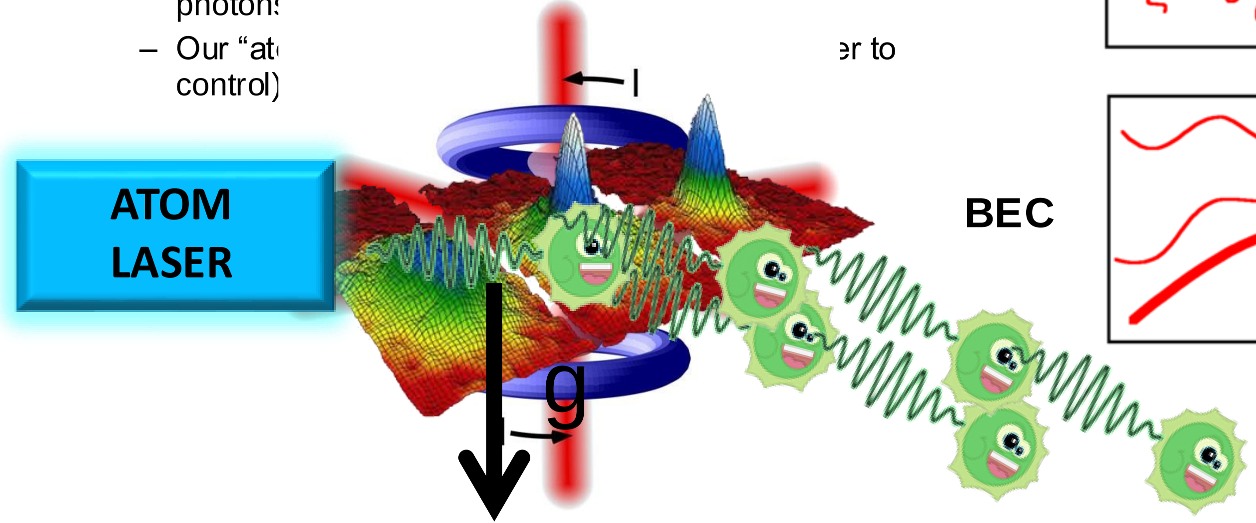
- Atoms are cooled to ≈ 125 μK in magneto-optical traps (MOTs), ≈ 6 μK via further Sisyphus cooling

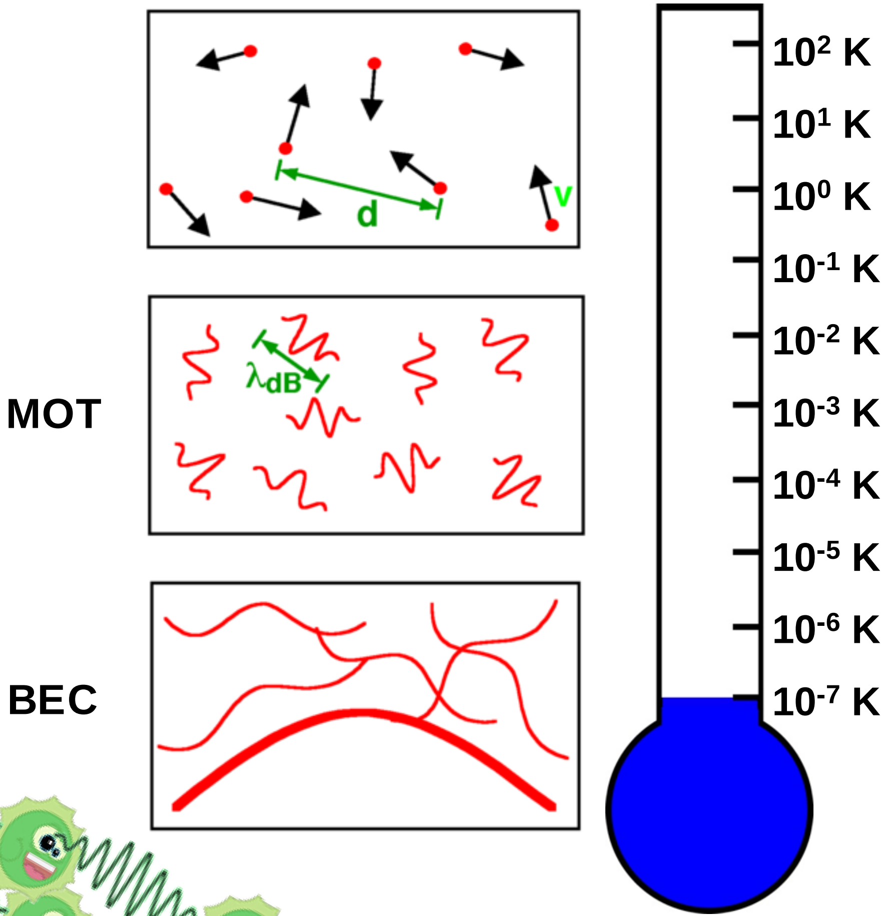


# Further cooling of a (bosonic) atom

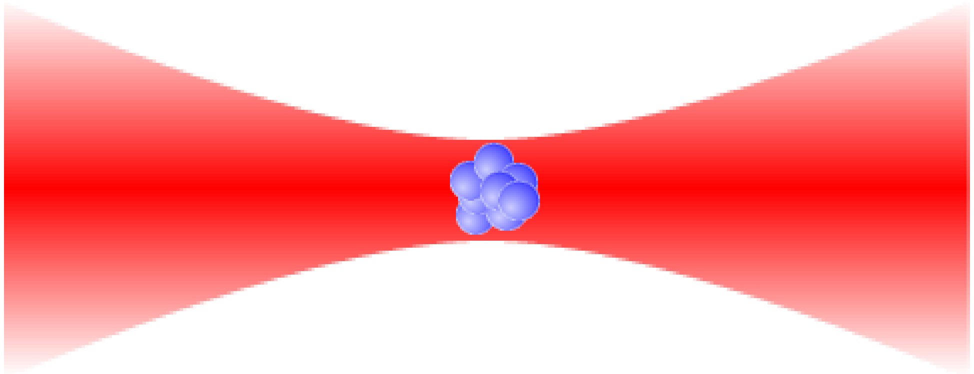
- If you get bosonic atoms cold enough (≈100 nK), their deBroglie wavelength is on the order of the inter-particle spacing
  - This is known as a Bose-Einstein condensate, or BEC.
  - The atoms become mutually coherent, like the photons
  - Our “at… er to control)



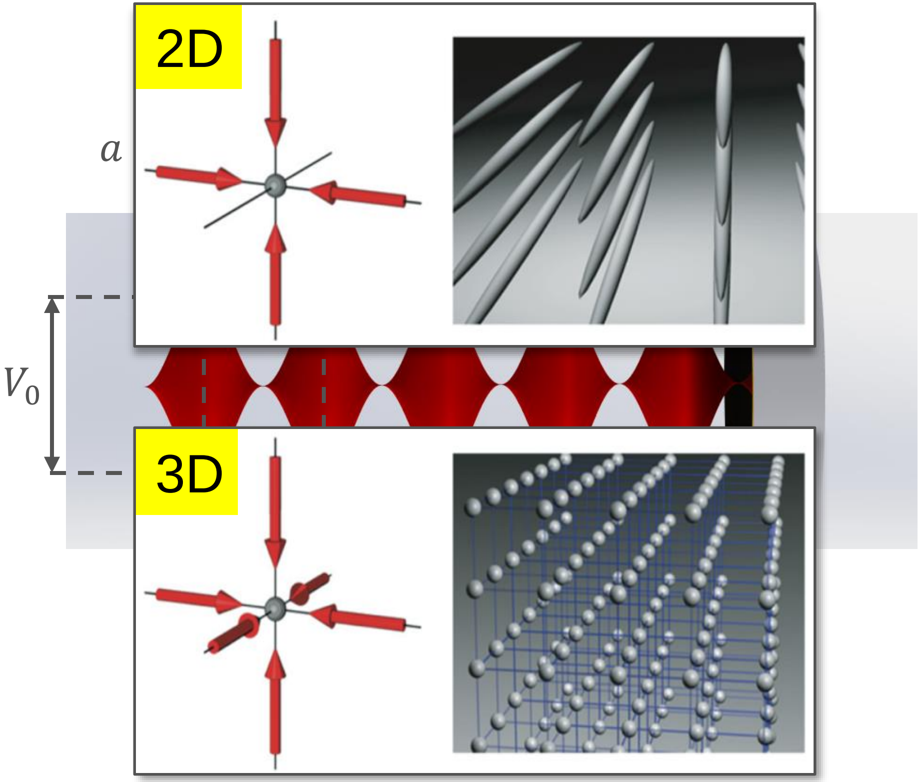
# Trapping atoms with light

- Light induces a dipole moment in an atom
- This gives rise to a potential proportional to the light intensity
- For red-detuned light ($\Delta = \omega_{light} - \omega_{atom} < 0$) this potential is attractive, and the atoms move towards the intensity maxima.
- Depth
$$U \propto I(\vec{r})/\Delta$$
- Scattering rate
$$\Gamma_{sc} \propto I(\vec{r})/\Delta^2$$
- We want a lot of power from a laser far-detuned from resonance!



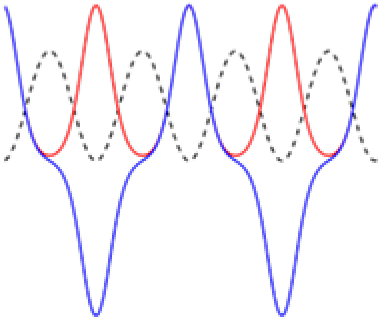
# The optical lattice: an egg carton for atoms

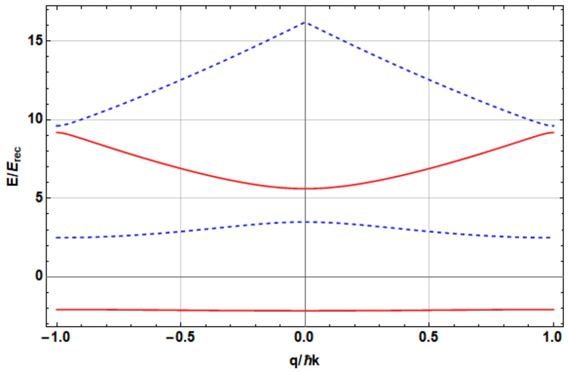
- Reflect a dipole laser back on itself to create a sinusoidally-varying potential
  $$V(x) = V_0 \cos(2k_L x)$$
- Depth typically expressed in recoils
  $$V_0 = sE_R = s\frac{\hbar^2 k_L^2}{2m}$$
- Can work in (up to) three dimensions!

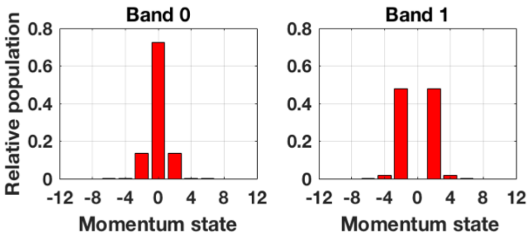


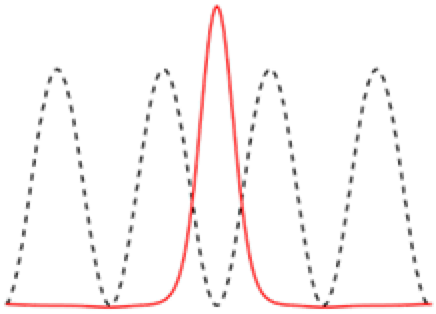
# How do we describe the atom wavefunction in a lattice?

- Two (equivalent) bases are commonly used
- Bloch functions
  - Atoms delocalized in position, localized in momentum space
  - Gives rise to band structure within a Brillouin zone
- Wannier functions
  - Atoms localized in position space (to a single lattice site), delocalized in momentum space
  - Composed of sums of Bloch functions in a given band
- Localized or delocalized? It depends on the lattice depth (and the problem).
  - Deeper lattices: more localized atoms





# Part 1: Inertial sensing with ultracold atoms trapped in phase-modulated optical lattices [PRL **120**, 263201, (2018)]

**Experimental Demonstration of Shaken-Lattice Interferometry**

C. A. Weidner and Dana Z. Anderson*
*Department of Physics and JILA, University of Colorado, Boulder, Colorado 80309-0440, USA*

(Received 28 January 2018; published 27 June 2018)

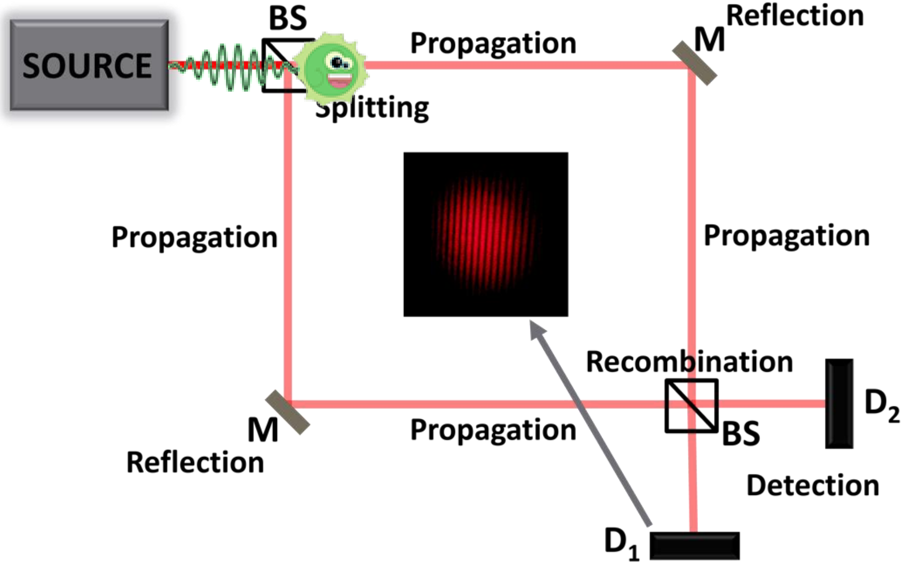
# Shaken lattice interferometry: building a sensor with atoms in optical lattices

The recipe:

- Take your favourite atom, and make it very cold
- Load it into the ground state of a **shallow** optical lattice potential
- Modulate the lattice to implement the atom-optical elements of an interferometer

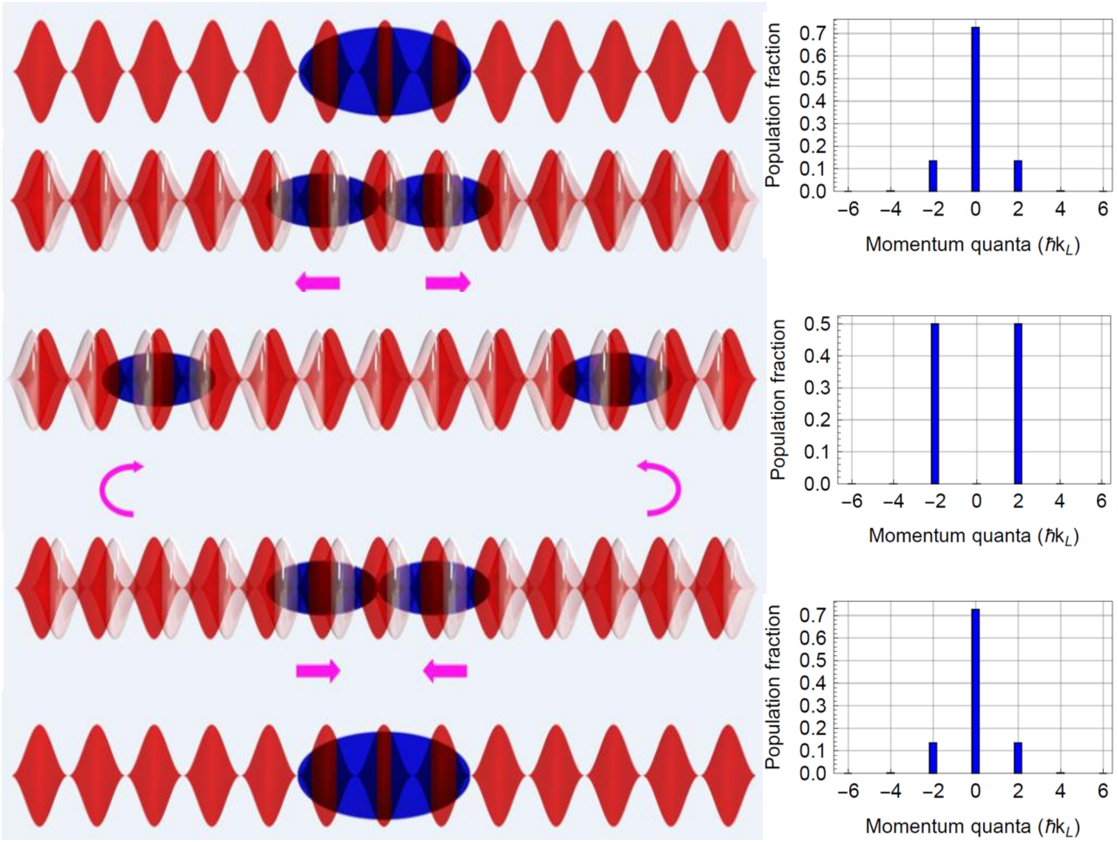
$$V(x,t) = V_0 \cos\big(2kx + \phi(t)\big)$$

What we control!



# Building a shaken lattice interferometer

- Work in the Bloch basis: atoms delocalized in position, localized in momentum
- Starting with atoms in the ground state of the lattice potential, we implement:
  - Splitting
  - Propagation
  - Reflection
  - Reverse propagation
  - Recombination back into the ground state
- The best shaking function $\phi(t)$ is determined via optimal control



# Building a shaken lattice interferometer

- Measurement: relative population in the atoms' momentum states
  - Define a vector $\vec{P}$ with elements $\{P_n\}$ containing the relative population in the $2n\hbar k$ state
  - We do not have access to phase information!
- Once the shaking function is known, it is fixed.
  - Can then calibrate the system's response to a signal (acceleration $a$)
  - Scale sensitivity by changing the total interrogation (shaking) time $T$

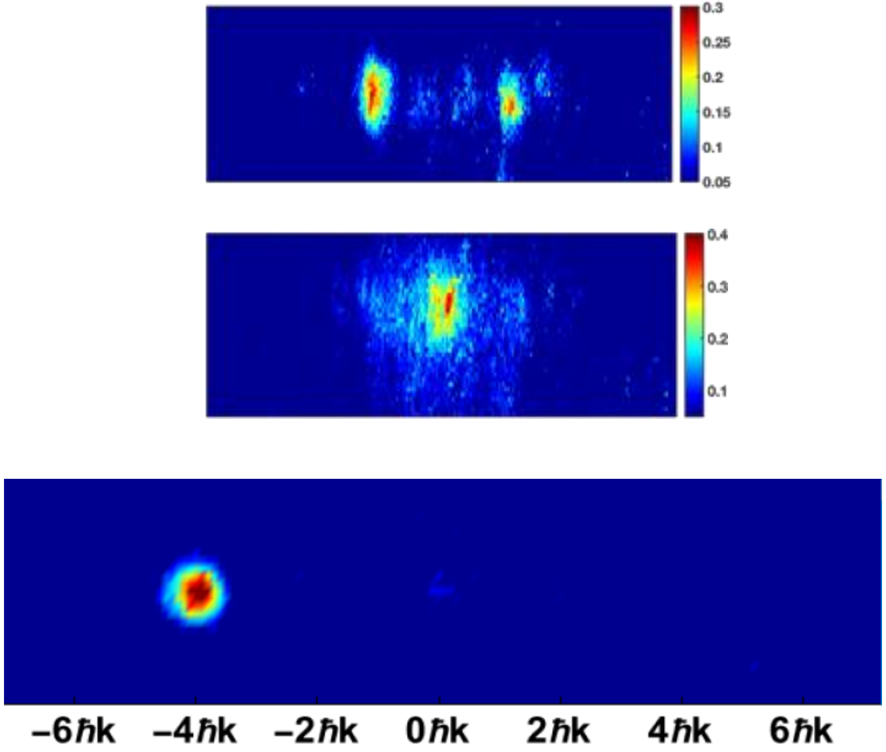



Image credit C. LeDesma et al. arXiv:2305.17603, (2023).

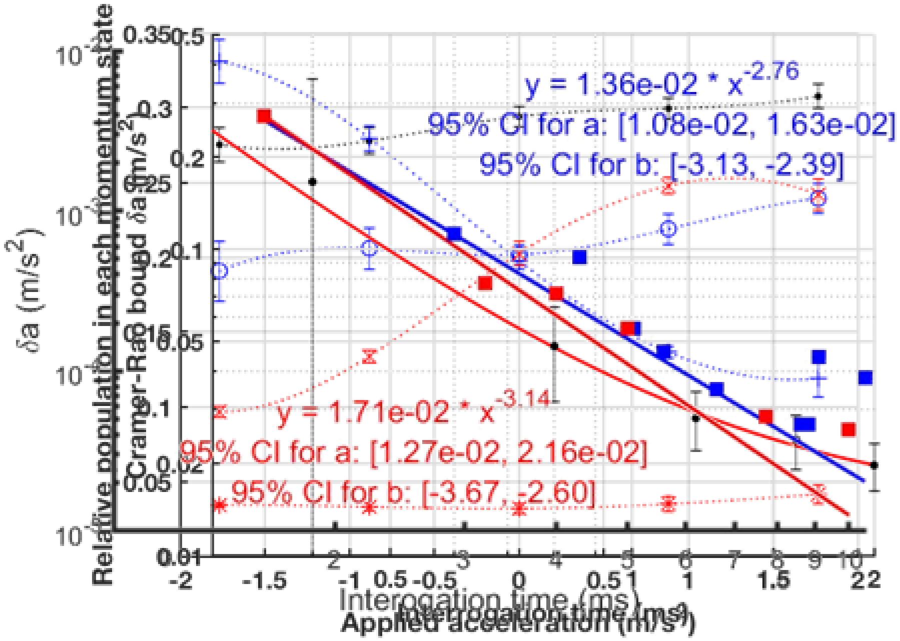
# But is it a sensor? Adding a signal

- We determine a signal by measuring how the atom momentum populations change with the applied signal
- The magnitude and direction of a signal is easily determined here, due to symmetry breaking as the lattice begins to shake
- Use the classical Fisher information $F_c$ to define a minimum detectable acceleration $\delta a = 1/\sqrt{F_c}$ given the momentum population vectors $\vec{P}$ that we measure.
- CFI:

$$F_C(a) = N_{at} \sum_{n=-N}^{N} \frac{\left(\partial P_{a,n}/\partial a\right)^2}{P_{a,n}}$$

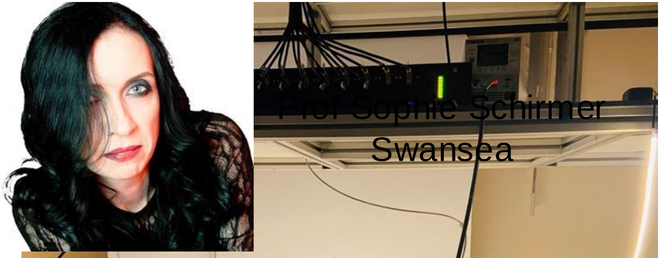
- Use this to find how $\delta a$ scales with $T$
- Simulations (experiments) give $n = 2.21 \pm 0.31$ $(1.96 \pm 0.13)$ consistent with typical atom interferometers where $n = 2$.

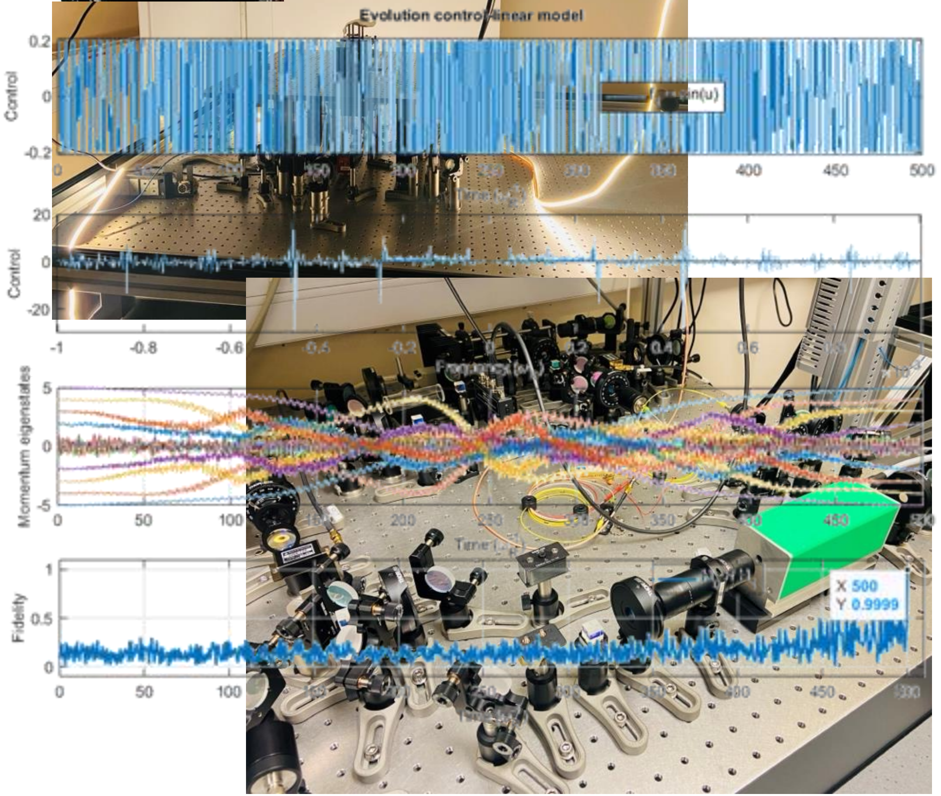
PRELIMINARY DATA!!!!



# So what’s next?

- Build a 3D lattice system in Bristol
- Demonstrate a multi-axis inertial sensor (3 axes of acceleration, 3 axes of rotation)
- Open question #1: What is the best scaling with $T$ that we can get?
- Open question #2: How robust is this method in the real world?
- Open question #3: What are the fundamental limitations of shaken lattice interferometry?



# Part 2: Generating interesting quantum states with ultracold atoms trapped in a deep optical lattice [*APL Quantum* **1**, 026109 (2024)]

## Deterministic generation of highly squeezed GKP states in ultracold atoms

Cite as: APL Quantum 1, 026109 (2024); doi: 10.1063/5.0197119
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[2] Quantum Engineering Technology Laboratories, H. H. Wills Physics Laboratory and Department of Electrical, Electronic, and Mechanical Engineering, University of Bristol, Bristol BS8 1FD, United Kingdom

# What makes a quantum state interesting…or even quantum?

- Remember our friend the Wigner function:

$$\mathcal{W}(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} dy\,\psi^*(x+y)\psi(x-y)e^{2ipy/\hbar}$$

- Wigner negativity gives rise to uniquely quantum states (“non-Gaussian states”)

PRX QUANTUM **2,** 030204 (2021)

Tutorial

**Non-Gaussian Quantum States and Where to Find Them**

Mattia Walschaers*

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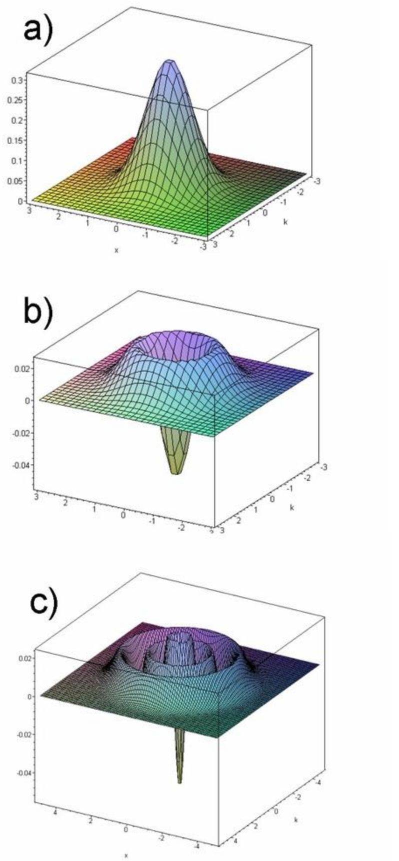
(Received 2 May 2021; published 28 September 2021)

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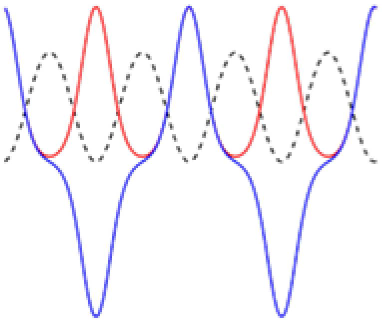
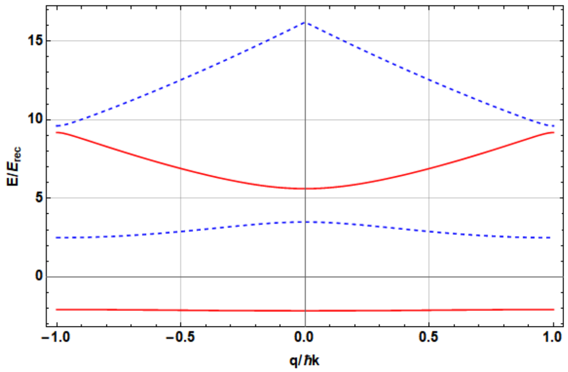
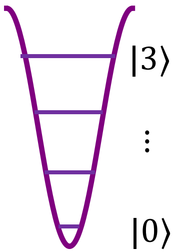
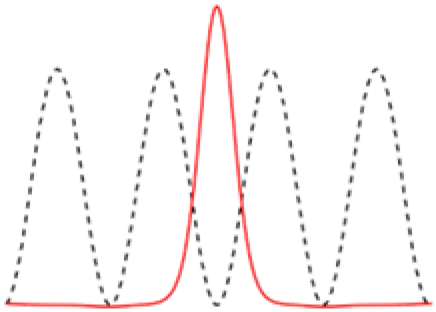
# How do we describe the atom wavefunction in a lattice?

- Two (equivalent) bases are commonly used
- Bloch functions
  - Atoms delocalized in position, localized in momentum space
  - Gives rise to band structure within a Brillouin zone
- Wannier functions
  - Atoms localized in position space (to a single lattice site), delocalized in momentum space
  - Composed of sums of Bloch functions in a given band
- Localized or delocalized? It depends on the lattice depth (and the problem).
  - Deeper lattices: more localized atoms
  - Very deep lattices have discrete vibrational levels within a single lattice site, label these with $|n\rangle$





# The GKP state

- The GKP state is a means of encoding a qubit in an oscillator (or anything that admits a Fock space)

$$|\mu = 0,1\rangle \propto \sum_n |2n+\mu\rangle$$

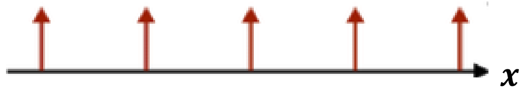
- Excellent for error correction, the pathway to fault tolerance
- We are forced by physics to only make approximate GKP states ("finite-squeezed" states)

$$|\mu_\beta\rangle \propto \exp(-\beta E_n)|\mu\rangle$$

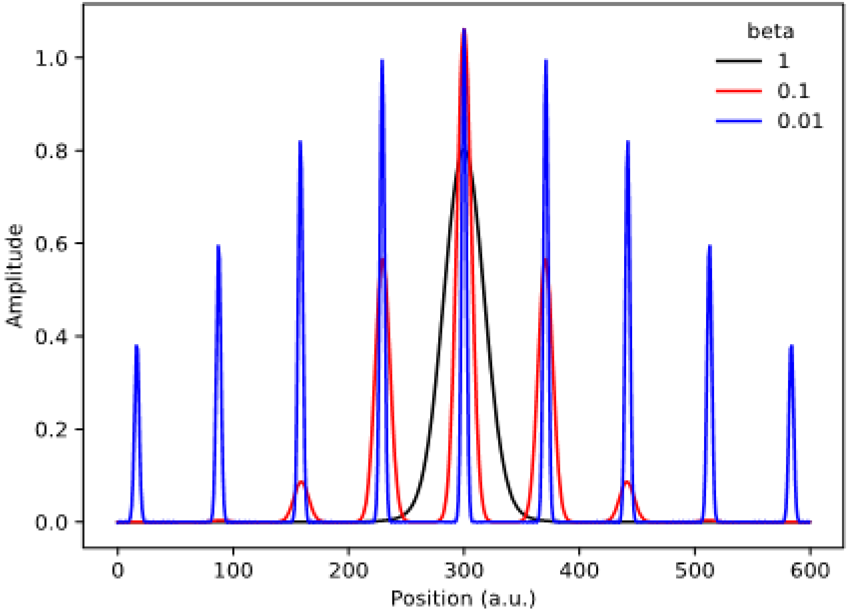
PHYSICAL REVIEW A, VOLUME 64, 012310

**Encoding a qubit in an oscillator**

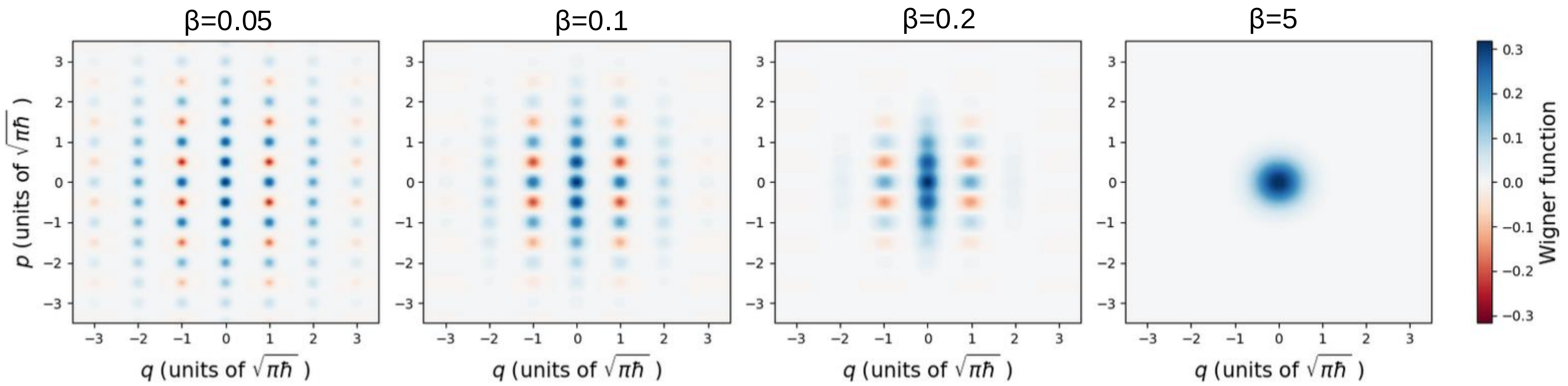
Daniel Gottesman,[1,2,*] Alexei Kitaev,[1,†] and John Preskill[3,‡]
[1]Microsoft Corporation, One Microsoft Way, Redmond, Washington 98052
[2]Computer Science Division, EECS, University of California, Berkeley, California 94720
[3]Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125
(Received 9 August 2000; published 11 June 2001)




Ideal GKP state Dirac comb



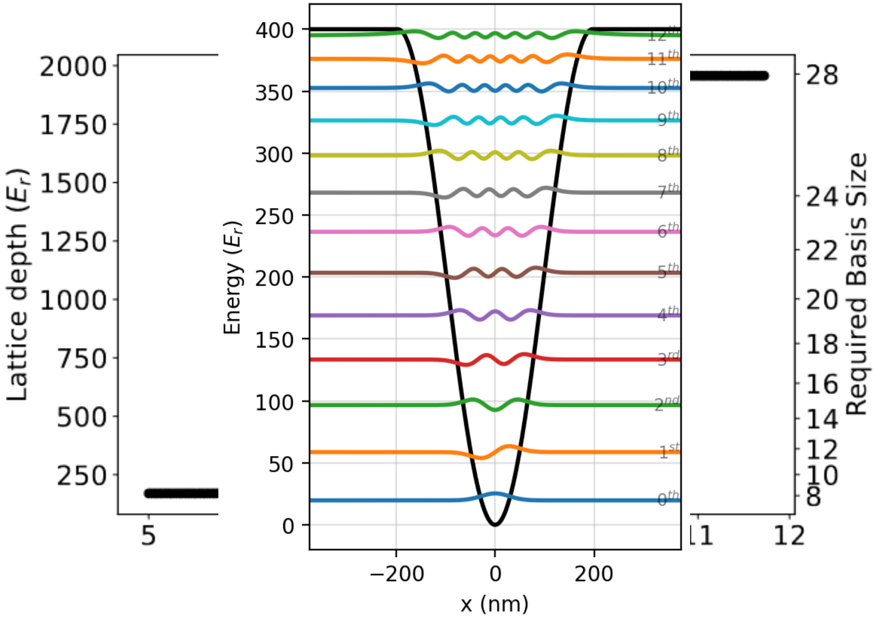
# The Wigner function of the imperfect GKP state




Images credit: https://strawberryfields.ai/photonics/demos/run_GKP_bosonic.html

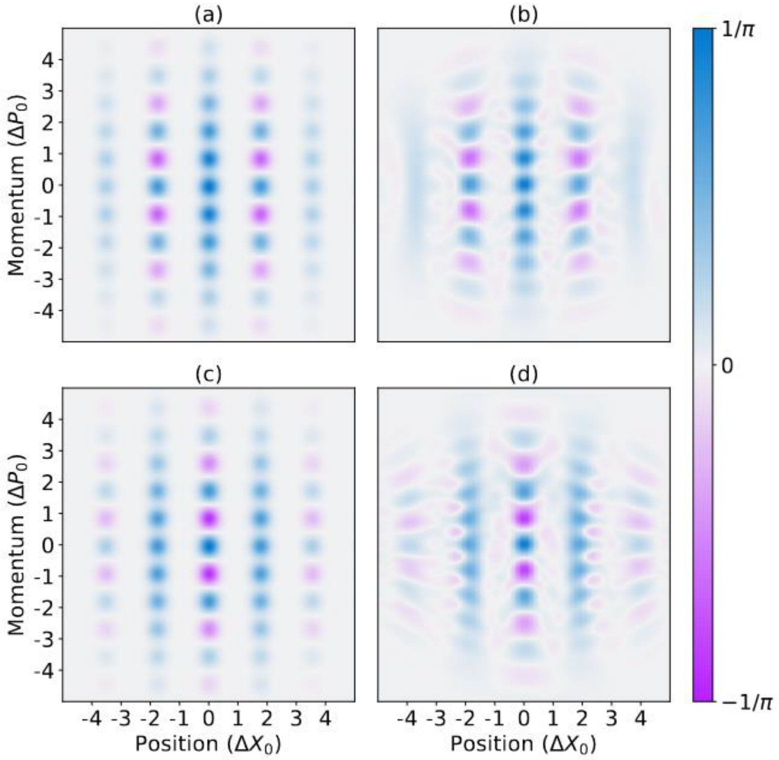
# Making GKP states with atoms in lattices

- Higher lattice depth = more Fock states = more squeezing
- In a $1500E_R$ lattice potential, we admit 24 bound Fock states in a single site, corresponding to 10dB squeezing.



# Making GKP states with atoms in lattices

- Higher lattice depth = more Fock states = more squeezing
- In a $1500E_R$ lattice potential, we admit 24 bound Fock states in a single site, corresponding to 10dB squeezing.
- Using gradient-based optimal control methods, generated this 10dB squeezed GKP state with fidelity $> 0.99$ in about 141 (158) μs for the $|GKP\ 0\rangle$ ($|GKP\ 1\rangle$) state.



# Some experimental considerations

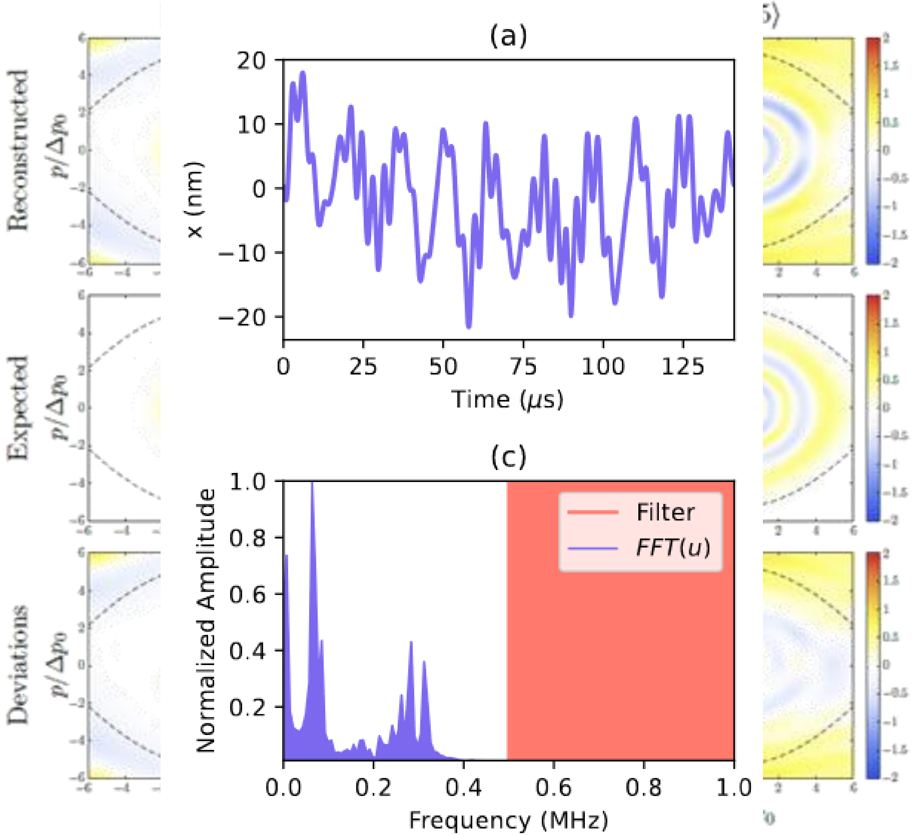
- Our protocols are experimentally viable with respect to laser power, wavelength, etc.
- Make use of a recent proposal to directly measure the Wigner function of atoms
- In the worst-case scenario, state generation takes $\approx 3\%$ of the atom lifetime in the lattice, measurement protocol is $\approx 10\%$ of the lifetime.

**IOP** Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **55** (2022) 194004 (10pp) https://doi.org/10.1088/1361-6455/ac8bb8

## Direct measurement of the Wigner function of atoms in an optical trap

Falk-Richard Winkelmann[1], Carrie A Weidner[2], Gautam Ramola[1], Wolfgang Alt[1], Dieter Meschede[1] and Andrea Alberti[1,*]



# So what’s next (GKP edition)

- We should be able to do the experiment in the same system as the shaken lattice interferometry system (with some minor laser-based modifications)
- Open question #1: Are these shaking protocols robust?

PHYSICAL REVIEW A **107**, 032606 (2023)

**Statistically characterizing robustness and fidelity of quantum controls and quantum control algorithms**

Irtaza Khalid,[1,*] Carrie A. Weidner,[2,†] Edmond A. Jonckheere,[3,‡] Sophie G. Shermer,[4,§] and Frank C. Langbein[1,||]

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[4]*Department of Physics, Swansea University, Swansea SA2 8PP, United Kingdom*

(Received 18 July 2022; revised 4 November 2022; accepted 2 March 2023; published 14 March 2023)

# So what’s next (GKP edition)

- We should be able to do the experiment in the same system as the shaken lattice interferometry system (with some minor laser-based modifications)
- Open question #1: Are these shaking protocols robust?
- Open question #2: Can we do any entangling gates?

PHYSICAL REVIEW A **100**, 052314 (2019)

**Time-optimal control of collisional $\sqrt{\text{SWAP}}$ gates in ultracold atomic systems**

Jesper Hasseriis Mohr Jensen,* Jens Jakob Sørensen, Klaus Mølmer, and Jacob Friis Sherson†
*Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark*

(Received 19 July 2019; revised manuscript received 27 September 2019; published 12 November 2019)

# So what’s next (GKP edition)

- We should be able to do the experiment in the same system as the shaken lattice interferometry system (with some minor laser-based modifications)
- Open question #1: Are these shaking protocols robust?
- Open question #2: Can we do any entangling gates?
- Open question #3: Is momentum-space encoding a better route?

PRX QUANTUM **2,** 040303 (2021)

**Quantum State Control of a Bose-Einstein Condensate in an Optical Lattice**

N. Dupont,[1] G. Chatelain,[1] L. Gabardos,[1] M. Arnal,[1] J. Billy,[1] B. Peaudecerf,[1] D. Sugny,[2] and D. Guéry-Odelin[1,*]

[1] *Laboratoire Collisions Agrégats Réactivité, UMR 5589, FERMI, UT3, Université de Toulouse, CNRS, 118 Route de Narbonne, Toulouse CEDEX 09 31062, France*

[2] *Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR 6303, 9 Avenue A. Savary, BP 47 870, Dijon Cedex F-21078, France*

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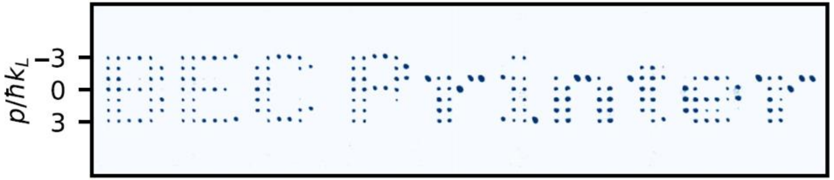

# So what’s next (GKP edition)

- We should be able to do the experiment in the same system as the shaken lattice interferometry system (with some minor laser-based modifications)
- Open question #1: Are these shaking protocols robust?
- Open question #2: Can we do any entangling gates?
- Open question #3: Is momentum-space encoding a better route?
- Open question #4: Is this even useful for anything?

# The GECKO Group [Generally Experimental Control for Kwantum Optimization]

University of BRISTOL

Thanks to:
--Prof. Dana Z. Anderson (JILA, CU Boulder)
--My collaborators at IAP in Bonn (D. Meschede, A. Alberti, F.-R. Winkelmann)
--The GECKO group (Generally Experimental Control and Kwantum Optimization) in Bristol (for this work: H.C.P. Kendell, V. Bharti, D. Chakraborty and G. Ferranti)

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# Thank you for listening!

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