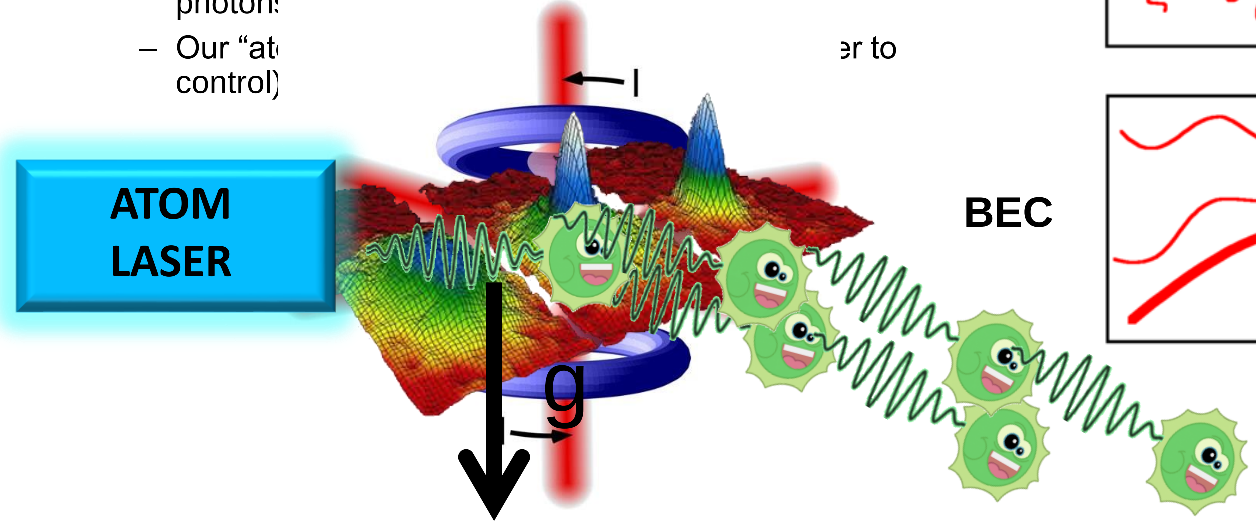
Quantum sensing with ultracold atoms in phase modulated optical lattices

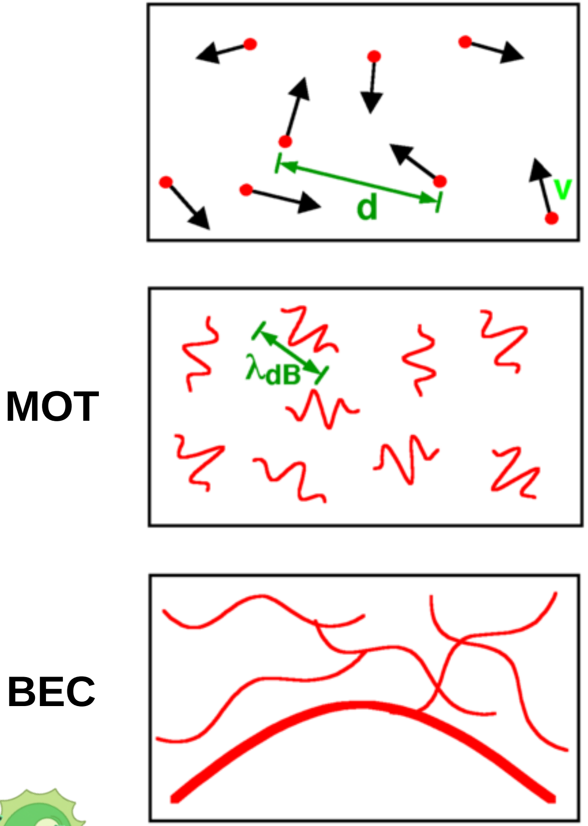
Dr Carrie Weidner
Quantum Engineering Technology Labs
University of Bristol
3 April 2024

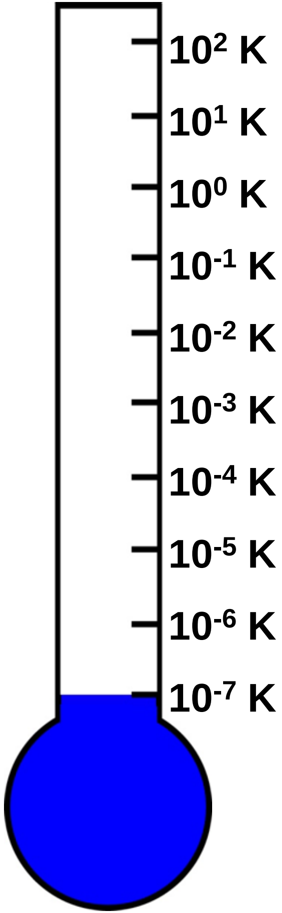
The preliminaries

Making bosonic atoms very cold

- 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 photon
  - Our “at … er to control)

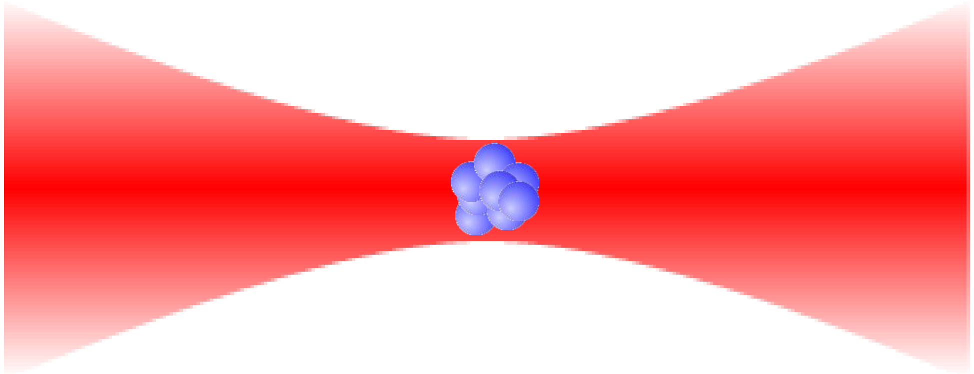






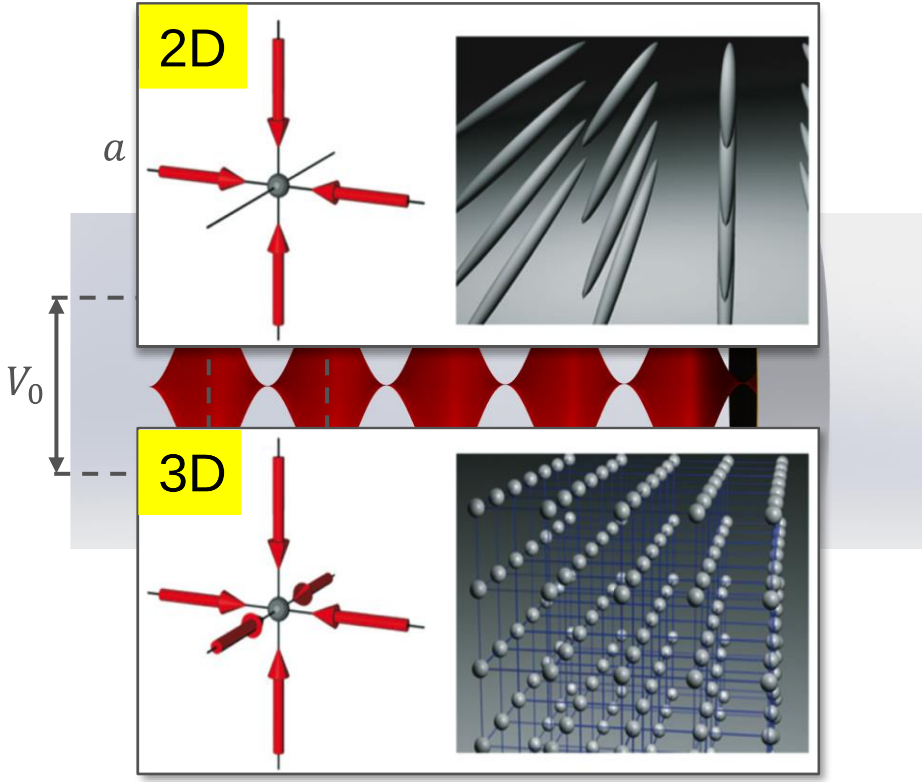
Trapping atoms with light

- Light induces a dipole moment in an atom
$$\vec{d} = \alpha\vec{E}$$
- This gives rise to a force and potential
$$\vec{F} = -\nabla U \propto -\alpha(\omega)I(\vec{r})$$
- 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!



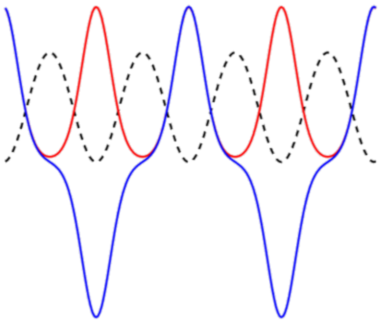
The optical lattice: an egg carton for atoms

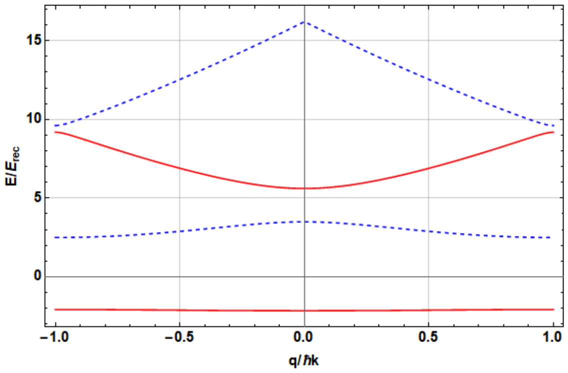
- Reflect a dipole laser back on itself to create a sinusoidally-varying potential
  $$V(x) = V_0 \cos(2k_L x)$$
- Depth typically expressed in recoils
  $$V_0 = sE_R = s\frac{\hbar^2 k_L^2}{2m}$$
- Can work in (up to) three dimensions!

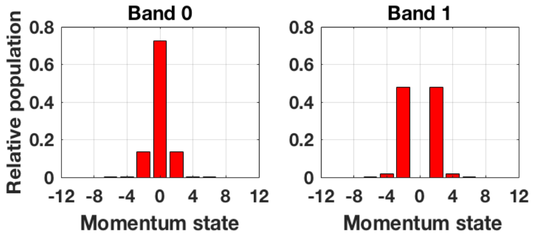


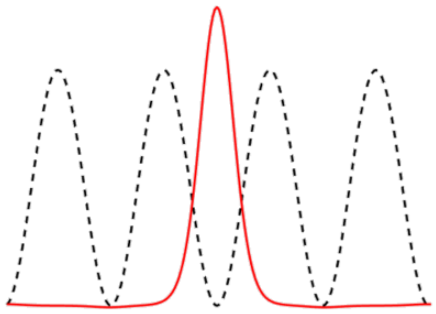
How do we describe the atom wavefunction in a lattice?

- 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
  - SLI uses shallow lattices—**we control the momentum states of the atoms!**









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)

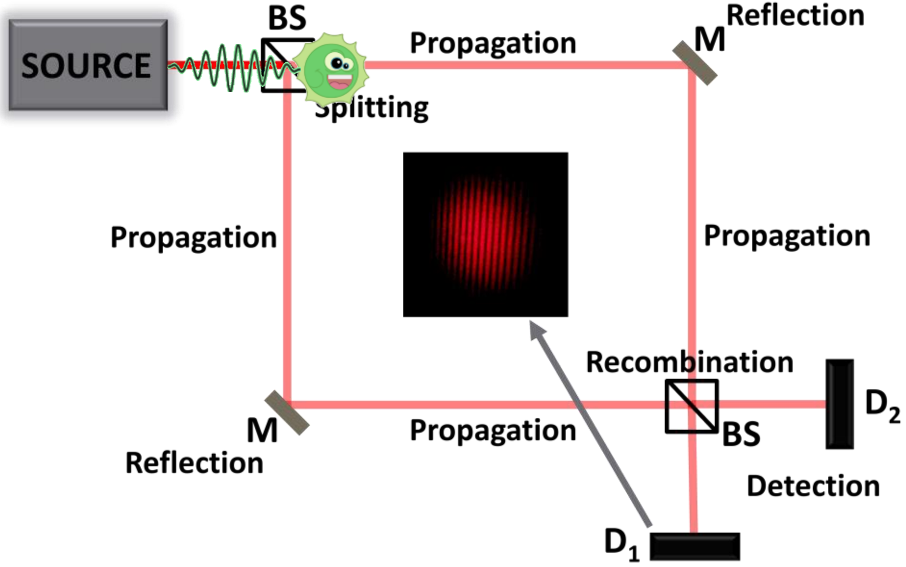
Shaken lattice interferometry: building a sensor with atoms in optical lattices

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

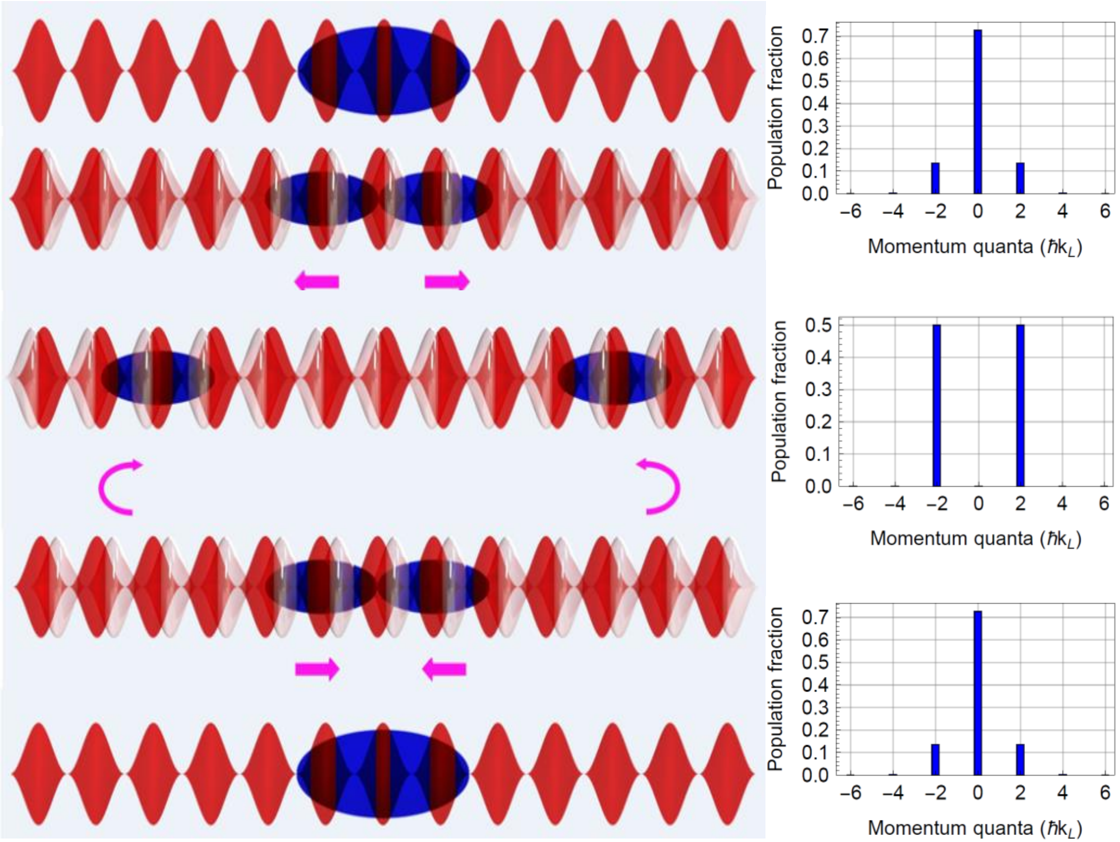
$$V(x,t) = V_0 \cos\left(2kx + \phi(t)\right)$$

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

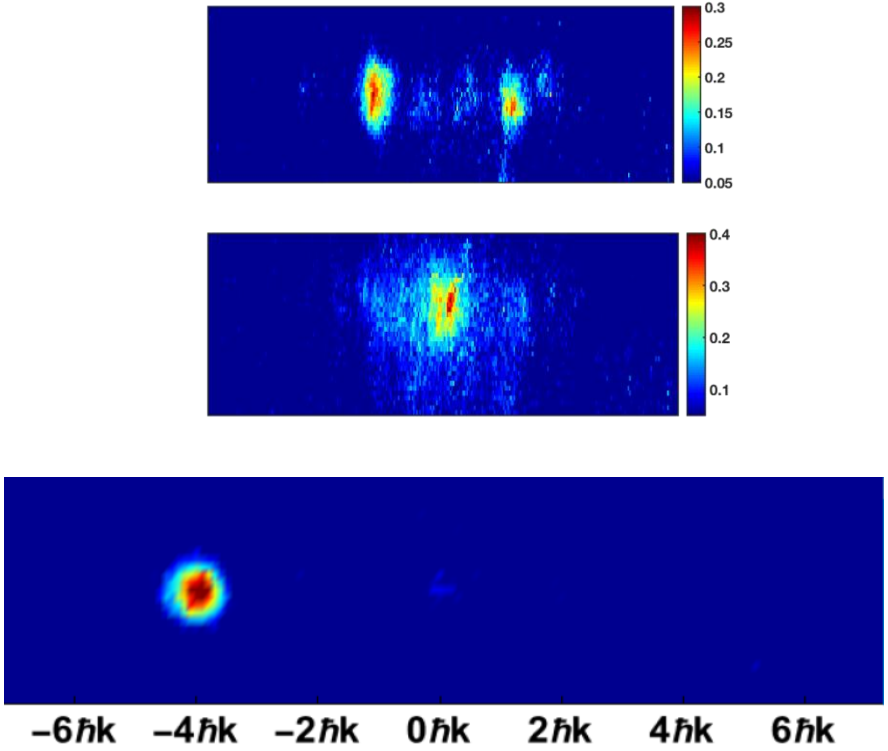


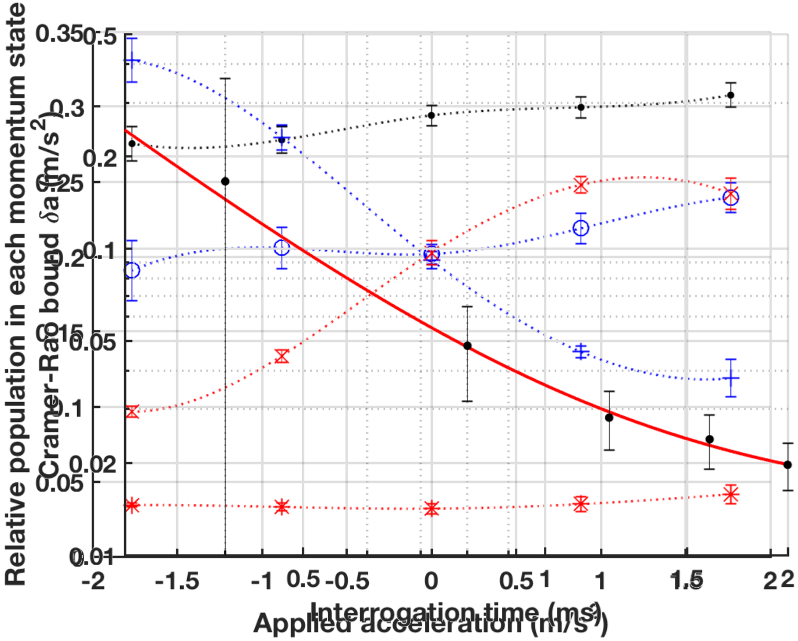
Image credit C. LeDesma et al. arXiv:2305.17603, (2023).

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:

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

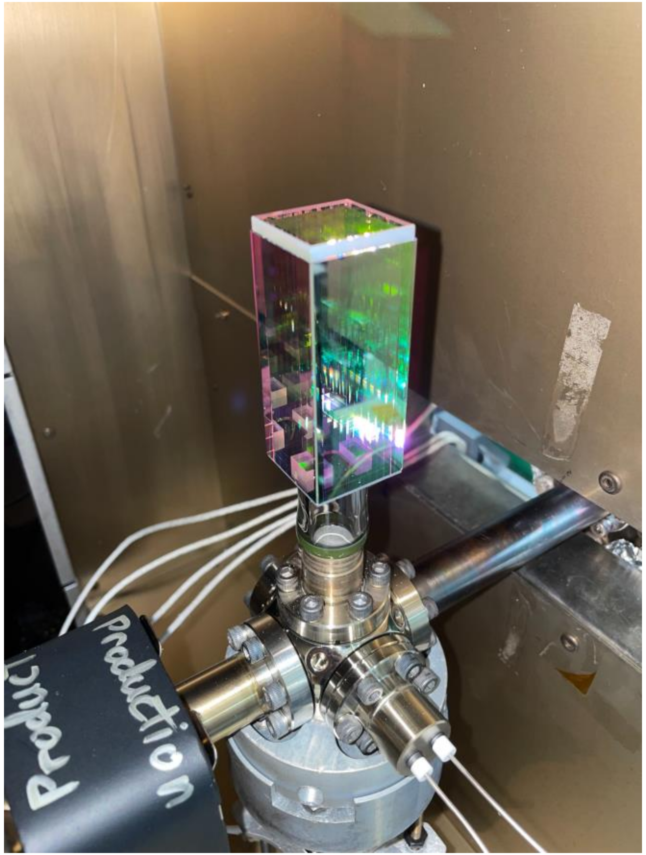
- Use this to find how δa scales with T
- Simulations (experiments) give $n = 2.21 \pm 0.31\ (1.96 \pm 0.13)$ consistent with typical atom interferometers where $n = 2$.



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)

Infleqtion



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?

New Journal of Physics
The open access journal at the forefront of physics
Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

PAPER

Simplified landscapes for optimization of shaken lattice interferometry

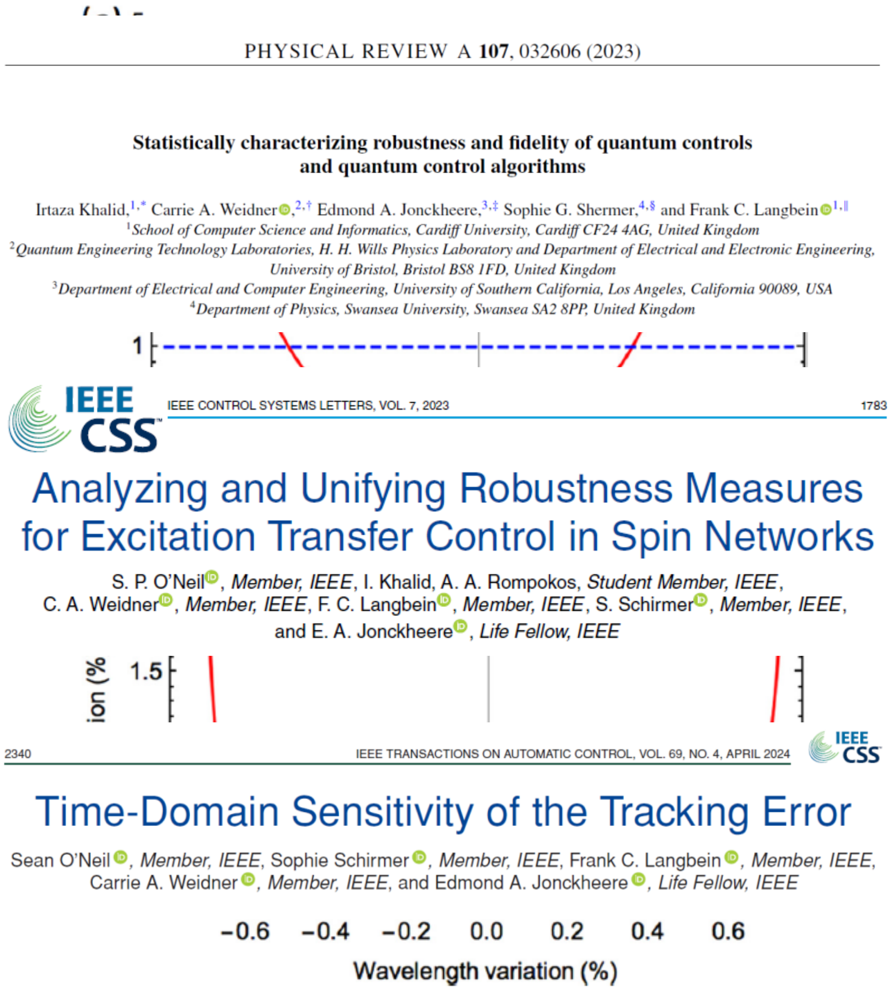
C A Weidner and D Z Anderson[1]

Abstract

Motivated by recent results using shaken optical lattices to perform atom interferometry, we explore the splitting of an atom cloud trapped in a phase-modulated ('shaken') optical lattice. Using a simple analytic model we are able to show that we can obtain the simplest case of $\pm 2\hbar k_L$ splitting via single-frequency shaking. This is confirmed both via simulation and experiment. Furthermore, we are able to split with a relative phase θ between the two split arms of 0 or π depending on our shaking frequency. Addressing higher-order splitting, we determine that $\pm 6\hbar k_L$ splitting is sufficient to be able to accelerate the atoms in counterpropagating lattices. Finally, we show that we can use a genetic algorithm to optimize $\pm 4\hbar k_L$ and $\pm 6\hbar k_L$ splitting to within $\approx$0.1% by restricting our optimization to the resonance frequencies corresponding to single- and two-photon transitions between Bloch bands. As a proof-of-principle, an experimental demonstration of simplified optimization of $4\hbar k_L$ splitting is presented.

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?


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,∥]

[1]*School of Computer Science and Informatics, Cardiff University, Cardiff CF24 4AG, United Kingdom*
[2]*Quantum Engineering Technology Laboratories, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1FD, United Kingdom*
[3]*Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, California 90089, USA*
[4]*Department of Physics, Swansea University, Swansea SA2 8PP, United Kingdom*

IEEE CSS — IEEE CONTROL SYSTEMS LETTERS, VOL. 7, 2023 — 1783

Analyzing and Unifying Robustness Measures for Excitation Transfer Control in Spin Networks

S. P. O’Neil, *Member, IEEE*, I. Khalid, A. A. Rompokos, *Student Member, IEEE*, C. A. Weidner, *Member, IEEE*, F. C. Langbein, *Member, IEEE*, S. Schirmer, *Member, IEEE*, and E. A. Jonckheere, *Life Fellow, IEEE*

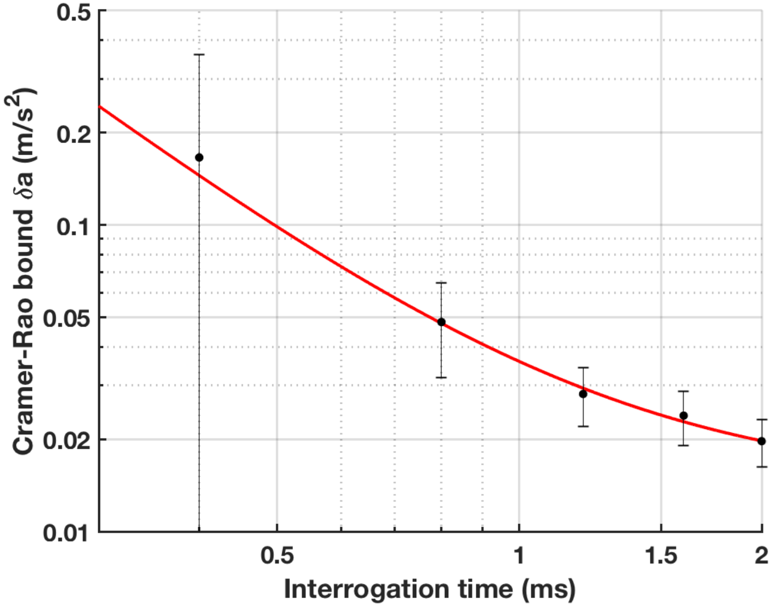
2340 — IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 69, NO. 4, APRIL 2024 — IEEE CSS

Time-Domain Sensitivity of the Tracking Error

Sean O’Neil, *Member, IEEE*, Sophie Schirmer, *Member, IEEE*, Frank C. Langbein, *Member, IEEE*, Carrie A. Weidner, *Member, IEEE*, and Edmond A. Jonckheere, *Life Fellow, IEEE*

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?



University of BRISTOL

Thanks to:
--The Bristol team: Dr. Vineet Bharti (experiment), Dr. Dhritiman Chakraborty (theory), Harry Kendell (both experiment and theory)
--Collaborators Prof. Sophie Schirmer (Swansea), Prof. Frank Langbein (Cardiff), Prof. Edmond Jonckheere and Sean O'Neil (USC)

Thank you for listening!

bristol.ac.uk