Advances in Atom Based Sensors for PNT

Dana Z. Anderson
Founder & Chief Strategy Officer
Infleqtion
dana@infleqtion.com

Tough Act to Follow

- Datasheet from high-performance inertial measurement unit (IMU)
  - measures 6 axes
    - 3 acceleration
    - 3 rotation (fiber optic gyro, FOG)
- Reference: earth rate = 15°/hr
- Gyro
  - Sensitivity: ~10^{-5} earth rate
  - Dynamic range ~2×10^8
- IMU
  - Tolerate 60 g accelerations
  - 10 year life.
  - Volume 1 ft^3

PERFORMANCE

GYRO PERFORMANCE

Bias Stability (1σ)	0.0001 °/hr.
Angle Random Walk (EOL)	0.0005 °/√hr.
Scale Factor Stability	± 2 ppm
Scale Factor Linearity	10 ppm
Angular Rate Range	> 45 °/sec
Acceleration Range	± 8 °/sec²

ACCELEROMETER PERFORMANCE

Range (g's)	60 g
Bias (milli g's)	2 µg
Scale Factor Stability	300 ppm

SYSTEM PERFORMANCE

Bandwidth	> 500 Hz
Operating Life	10 yrs.(1,400

CHARACTERISTICS

Interface	Custom serial

PHYSICAL

Weight	18 lb., 8.165 k
Dimensions	11.9 in. L x 11. 30.23 cm L x 2
Power	10 W @ 28 VD

ertial Measurement Unit

The CIRUS-A IMU's performance enhances all EO/IR platforms ability to identify and defeat threats from the air and on the ground.

L-3 Space & Navigation
450 Clark Drive
Budd Lake, NJ 07828

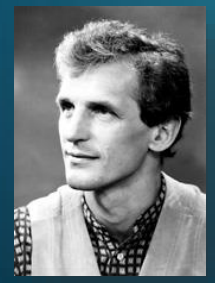
Quantum Matter — *Ultracold Atoms*

2001
For the achievement of Bose-Einstein Condensation

- Laser cooling is the starting point for much of atom-based quantum technology.
- *No cryogenics, no liquid anything*
- *Cold, very cold, and ultracold*
  - when temperature is no longer meaningful.
  - behavior must be described by the laws of quantum mechanics.
- There are many forms of ultracold matter
  - Bose-Einstein condensate (BEC) is one of them.
  - Fermi gases.
  - Atoms in optical lattices.
  - Quantum computer qubits of atoms or ions.

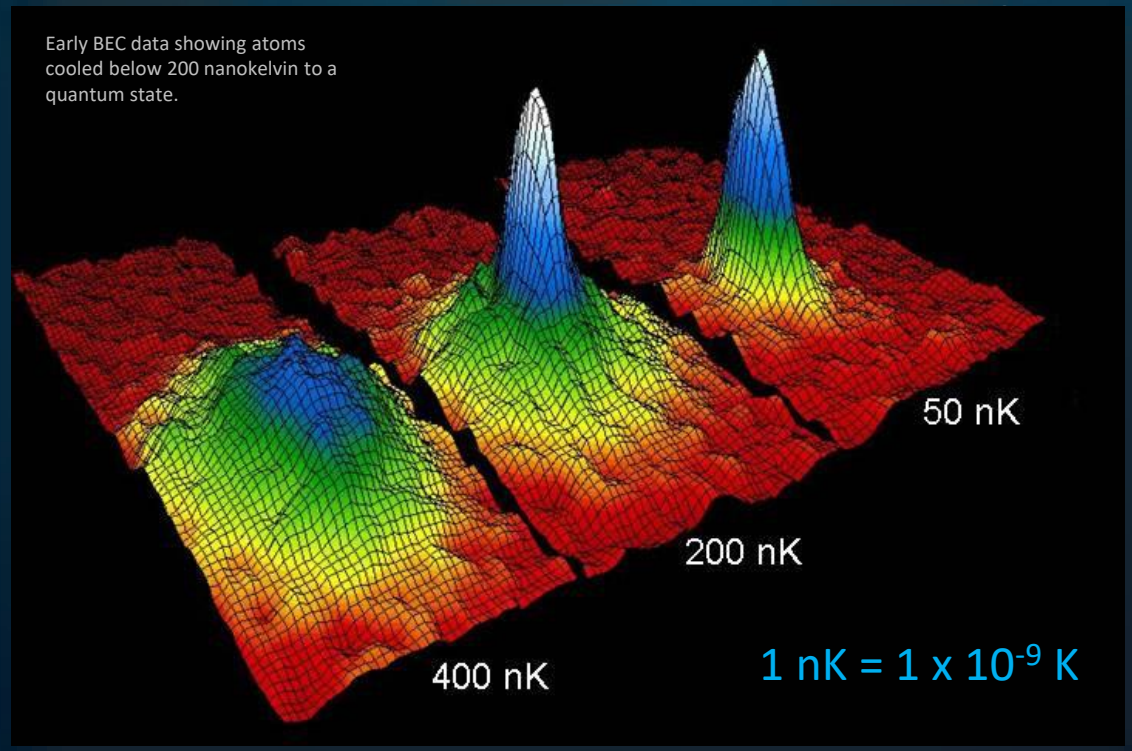
1995: The Atom Analog of the Laser enables quantum state "manufacture"

Eric Cornell
NIST/Univ. of Colorado



Wolfgang Ketterle
MIT

Carl Wieman
Univ. of Colorad



Quantum Timekeepers: A Million Times Better Performance

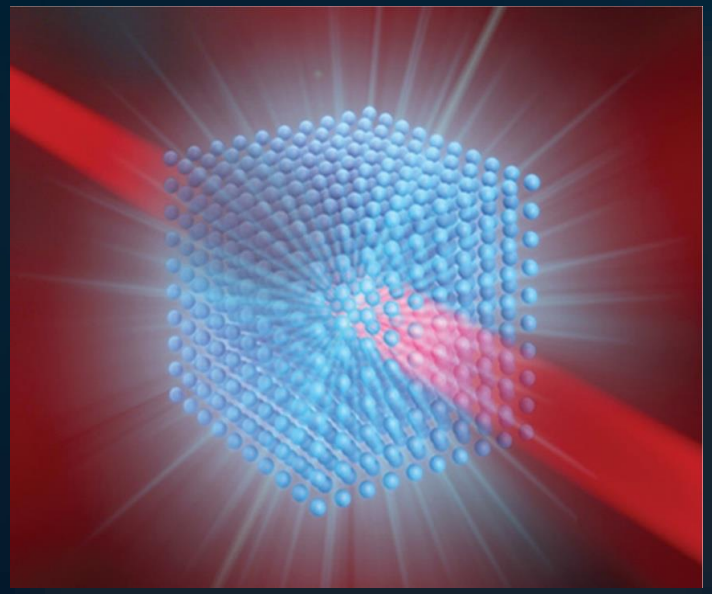
The Optical Lattice Atomic Clocks

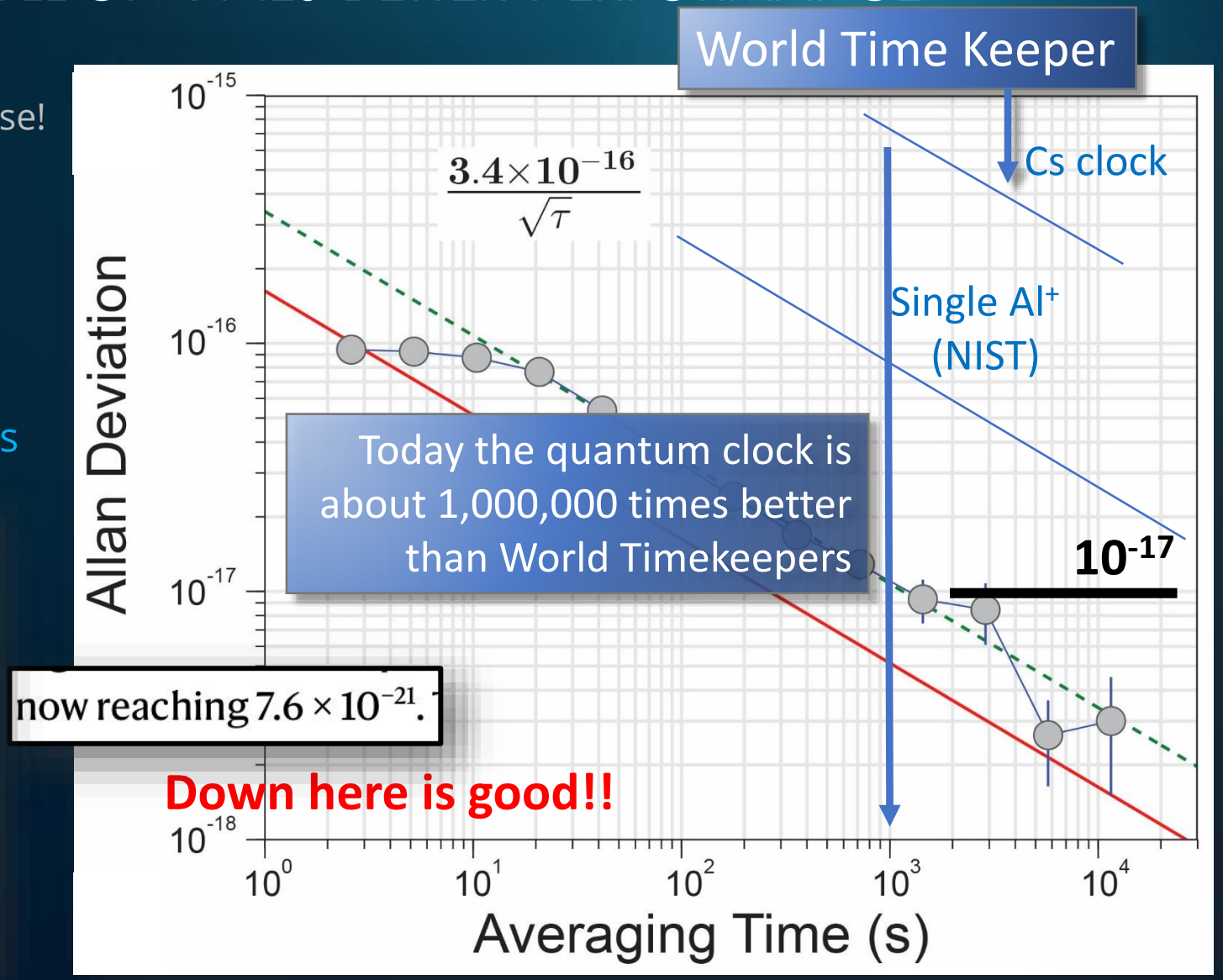
- Loses 1 sec accuracy in the age of the universe!
- Ticks at a different rate when lifted by 3 mm because of earth's gravity.

Optical *Lattice Clock Technology*

- 3D lattice made by 3 sets of interfering laser beams.

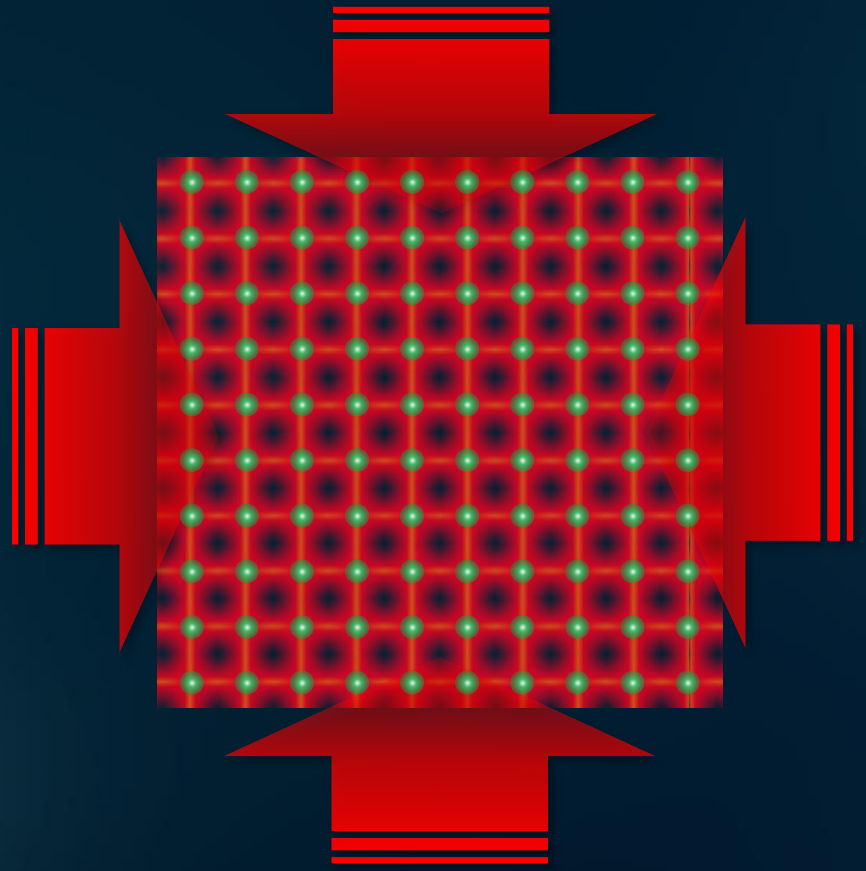
Performance advantage applies to sensors as well.



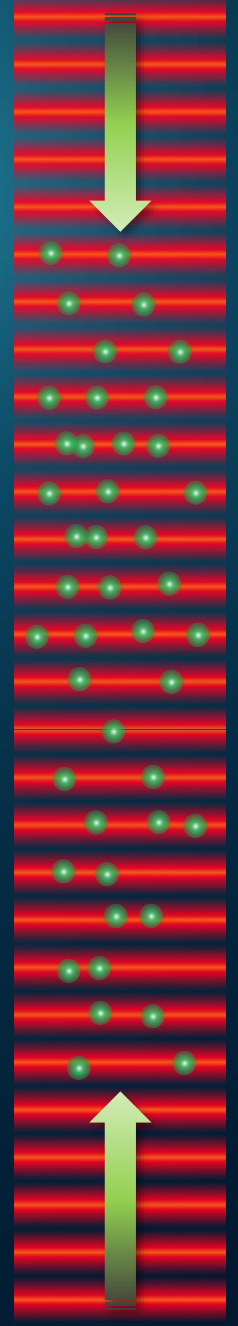


Holding Atoms Up Against Gravity & Other Forces

and other compelling stories



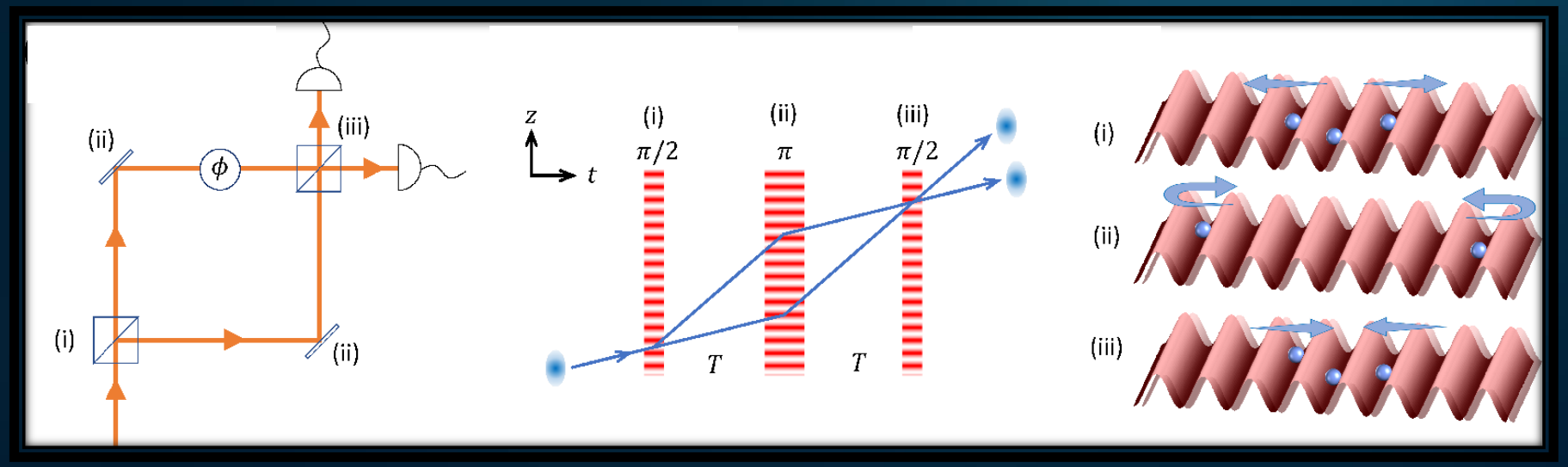
- A pair of oppositely directed laser beams will form an interference pattern.
- Detuned to the red of atomic resonance, atoms will be *trapped* in the high intensity regions, holding them up against gravity.
- Optical Lattices
  - Can make 2-D and 3-D (and more complicated) arrays.
  - Trap and manipulate atoms with 10's to 100's of g's.



Machine Learning for Inertial Sensing using Interferometry

The “expert’s” view: Interferometry takes place in 5 steps of 4 types

1. Split
2. Propagate
3. Reflect
4. Propagate
5. Combine



Mach-Zehnder Bragg Interferometer Shaken Lattice

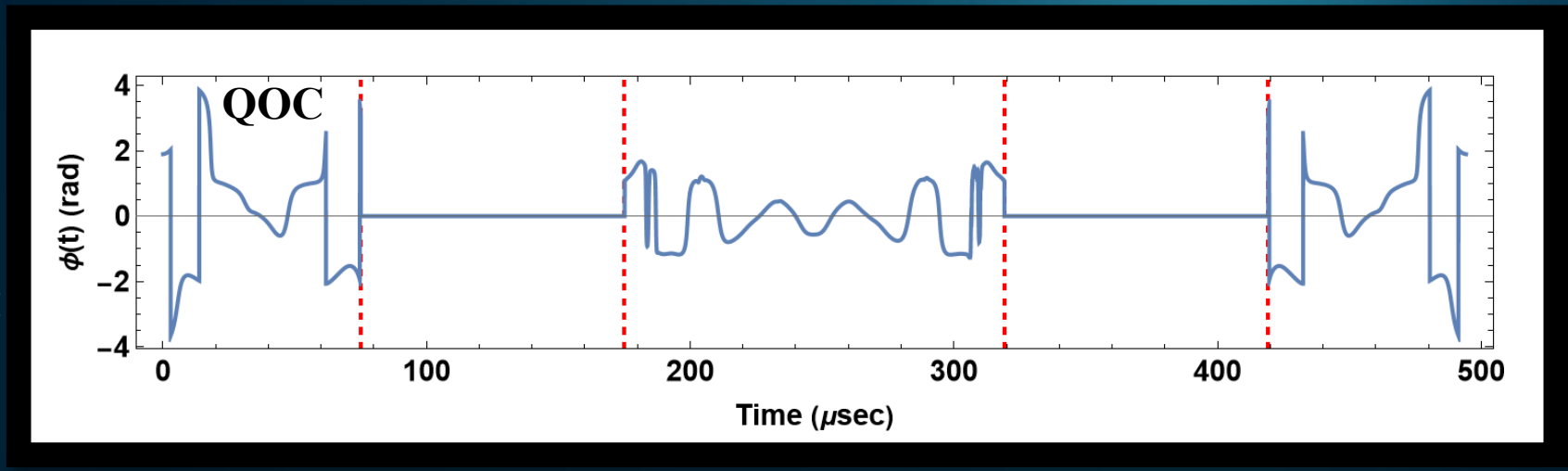
Quantum Machine Learning to Sense Acceleration

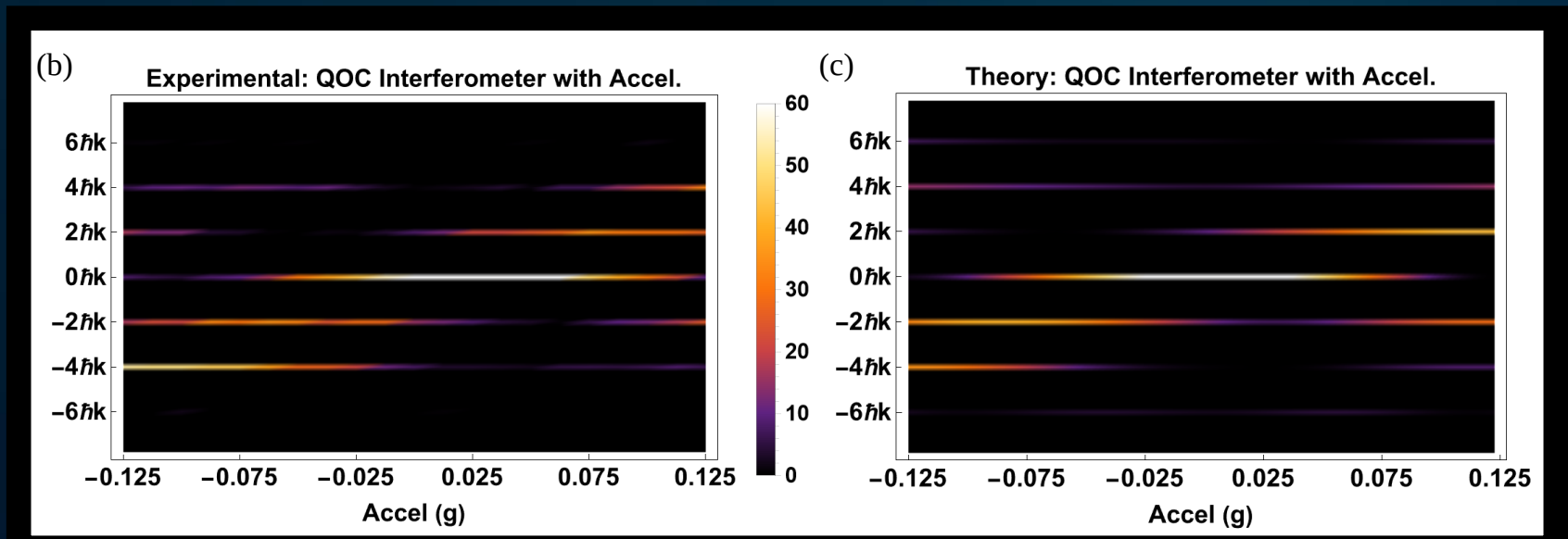
Teaching a lattice to sense acceleration through shaking.

Acceleration measurement: Learning simulation and experiment in good agreement.

Fingerprint: any given acceleration corresponds to a unique signal distribution.

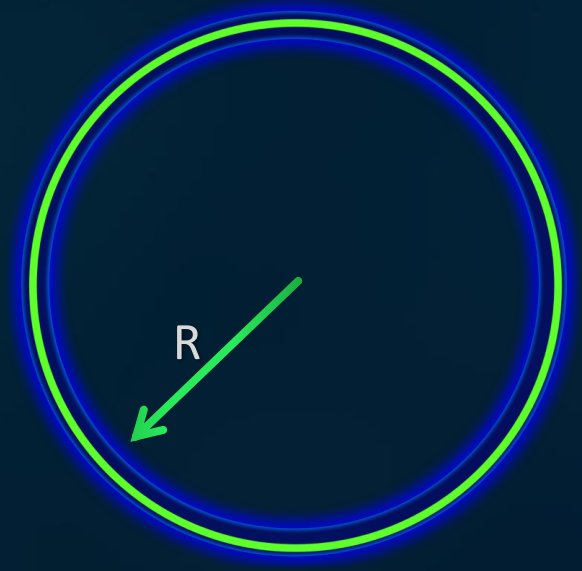
This is a *very* small interferometer. Just a few microns.





What Does it Take to Achieve High Performance?

Take the gyro for example:



Circular path

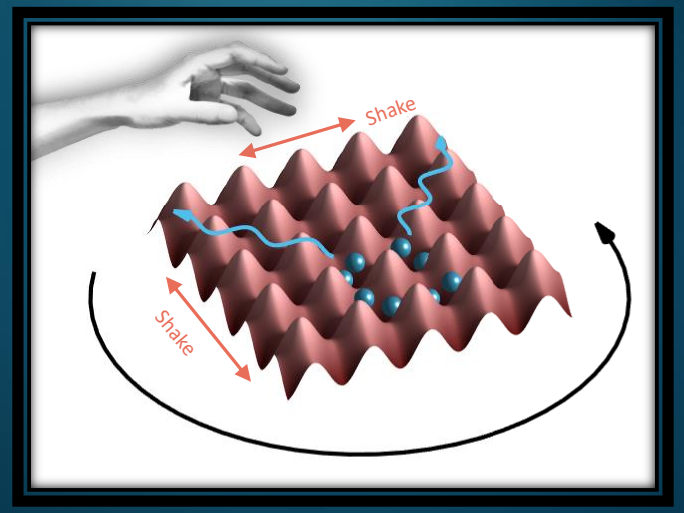
Strategic grade

R = 0.5 mm
N = 1000 atoms/s
τ = 1 s
v = 1 m/s

Machine Learning & Quantum Sensing

- Atoms in an optical lattice are “trained” to carry out atom interferometry.
- Machine learning applied to quantum systems
  - Optimal control
  - Reinforcement learning

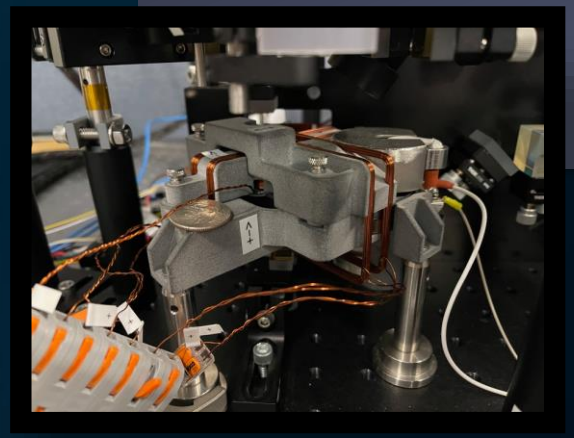
- Lattice forces 10’s to hundreds of g’s
  - Able to operate in a harsh dynamical environment
  - Still take advantage of sensitivity of atoms to external influences.
- Better than strategic grade positioning and navigation performance in a mm-scale sensor device
- Better than 1000x reduction in core sensor volume



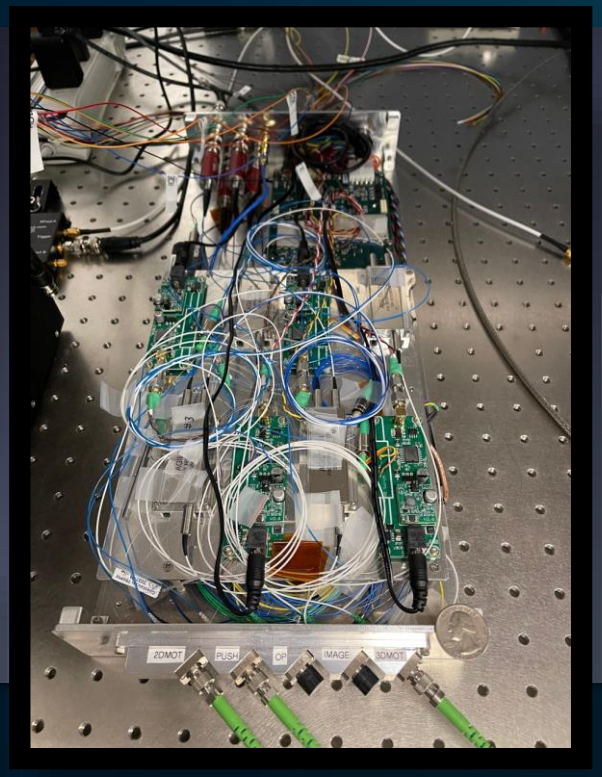
Litton aircraft (now Northrop-Grumman) navigation quality “Zeelag” laser gyro, 7 cm(?) per side
-related to Dana’s PhD work

Honey, I Shrunk the Quantum Matter Machine

Integrated UHV vacuum cell



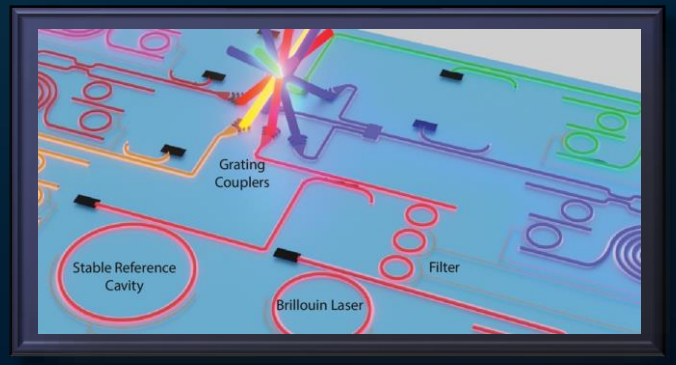
Packaged Vacuum & Optics



Laser System

Today's atomic quantum technology is on its way to fitting in about 5 CD/DVD home players.

Tomorrow's *miniature* atom-based PNT technology will depend on the development of photonic integrated circuits.



Thank You!