Quantum Sensing and Information Processing

Lecture 1: Introduction and Overview

Randy S Roberts
Jonathan L DuBois
Steve B Libby

May 7th, 2019

LLNL-PRES-774185

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Lawrence Livermore National Laboratory

Quantum Sensing and Information Processing Lecture Series

- Quantum information and sensing technologies are entering a period of growth
- This series of lectures is designed to provide an introduction to a range of topics in quantum information and sensing
- Detailed knowledge of quantum mechanics is not required for these lectures. Necessary background will be provided as needed.

Lecture series sponsored by the Engineering Directorate and the Center for Advanced Signal and Image Sciences (CASIS)

Lecture Topics

- Introduction and Overview
- Quantum Devices — Focus on LLNL Research
- Control of Quantum Devices
- Application: Sensing with Quantum Devices
- Error Modelling
- Application: Quantum Computation
- Application: Quantum Computing Algorithms
- Application: Quantum Communications

Schedule

- Approximately two lectures per month, ending in September
- Date/time/venue on CASIS Website and Newsline
- Lecture slides and video posted on the CASIS website:

https://casis-dev.llnl.gov/seminars/quantum_information

Next Lecture:
Thursday, May 30th at 2:00
B453 Auditorium (Armadillo Room)

CASIS Workshop, Wednesday, May 15th LVOC

Center for Advanced Signal and Image Sciences Workshop

CYBER ATTACKS ON INTERNET OF THINGS SENSOR SYSTEMS FOR INFERENCE

15 MAY 2019

The internet of things (IoT) improves pervasive sensing and control capabilities by connecting digital communication, signal processing, and massively deployed sensors. But low-cost, spatially distributed IoT sensor nodes with limited hardware and battery power, combined with the low latency needed to avoid unstable control loops, presents severe security challenges. By modifying data communications among IoT sensors, attackers can compromise any algorithm using the data for inference.

Professor Blum describes tight bounds on algorithms that estimate a parameter derived from the attacked data and communications, under any statistical model. The results hold regardless of the estimation algorithm adopted. Attacks that make the target data useless for reducing these bounds and applications to IEEE 1588 for clock synchronization are discussed.

Lawrence Livermore National Laboratory, HPC Innovation Center (HPCIC)
Workshop begins at 9:00 am— Keynote address at 1:00 pm

Rick S. Blum has taught at Lehigh University since 1991, researching signal processing for cybersecurity, smart grids, communications, sensor networking, and radar and sensor processing. An IEEE Third Millennium medal winner, SPS Distinguished Lecturer, and IEEE fellow with several patents, he has edited IEEE Transactions on Signal Processing, IEEE Communications Letters, and select IEEE journals, while serving on three technical committees: the Sensor Array (SPS), Multichannel and Signal Processing for Communications (SPS), and Communications Theory (CS). He holds a B.S.E.E. from Penn State (1984) and M.S. and Ph.D in EE from University of Pennsylvania (1991).

For information and to register, go to **https://casis.llnl.gov/**

ENGINEERING

For technical information:
David Chambers, (925) 423-8893, chambers2@llnl.gov

For registration and general information:
Vera Sanchez, (925) 422-3355, sanchez5@llnl.gov

Sponsored by the LLNL Engineering Directorate and the Center for Advanced Signal and Image Sciences (CASIS)

Joint technical meeting with, and refreshments provided by, the Oakland-East Bay Chapter of the IEEE Signal Processing Society

CASIS LLNL

IEEE Advancing Technology for Humanity

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LLNL-BR-769869

Presentations on:

- Machine learning
- Graph theory
- Applications of signal processing
- Geophysical signal processing
- Non-Destructive Evaluation
- Signal, Imagery and Systems

Register at:

https://casis.llnl.gov/casis-2019

Quantum Information Processing

Jonathan L. DuBois
dubois9@llnl.gov
Quantum Coherent Device Physics Group Leader
Physics Division

May 7, 2019

Lawrence Livermore National Laboratory

LLNL-PRES-774185

What's the big deal about Quantum Information and Sensing?

- What is quantum computing?
- Computational speedup:
    - Factoring large numbers with Shor's algorithm
    - Quantum Simulation

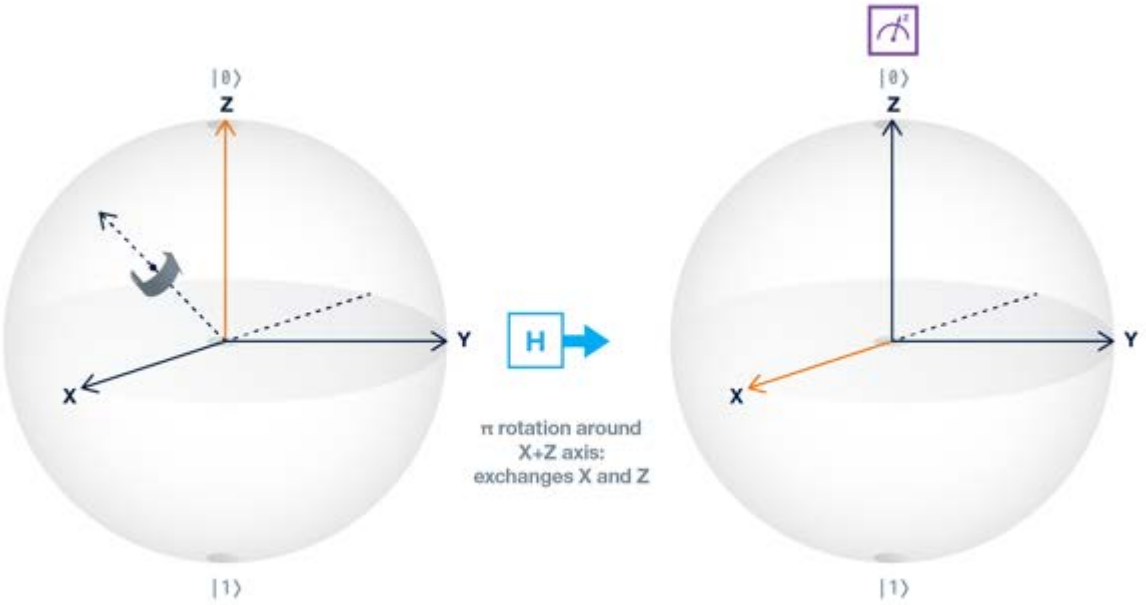
- National Quantum Initiative Act
- DOE/NNSA's interest
- LLNL's Strategy and LDRD investments

- Position, Navigation and Timing—how much better can it be over conventional approaches

What is quantum computing?

Classical states: 0 or 1 i.e. TRUE or FALSE

Quantum states: $\alpha|0\rangle + \beta|1\rangle$ $\alpha^2 + \beta^2 = 1$

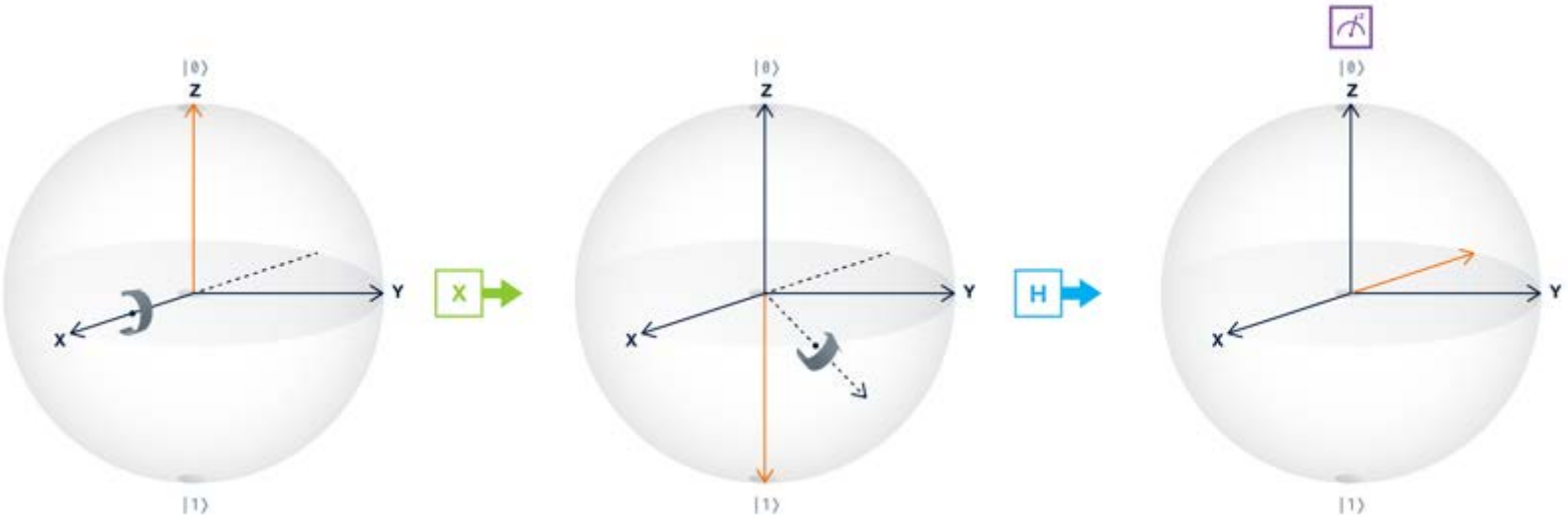


$$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle),$$

TRUE *and* FALSE

What is quantum computing?

Quantum gates: move states



Single qubit gates can be thought of as rotations around different axes

Adding more qubits

$$c_0|00\rangle + c_1|01\rangle + c_2|10\rangle + c_3|11\rangle$$

$$\sum_i c_i^2 = 1$$

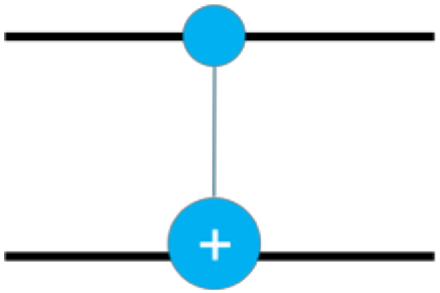
Allowed states aren't easy to visualize: They live on a 4D hypersphere.

Every additional qubit added doubles the size of the allowed states

N qubits = 2^N degrees of freedom

Adding more qubits

Two qubit quantum gates: move two qubit quantum states



Starting state		Ending State
|00>	→	|00>
|10>	→	|10>
|01>	→	|11>
|11>	→	|01>

A small set of single qubit gates combined with this two qubit CNOT gate form a complete set.

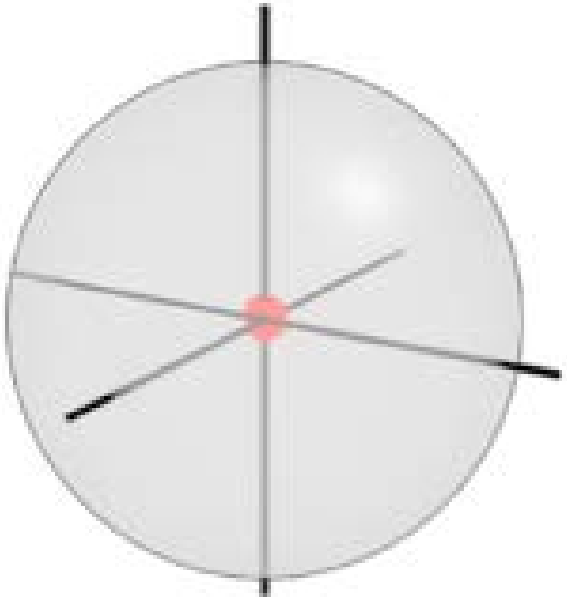
By combining sequences of these gates, every possible quantum state can be transformed into every other possible state

What can (and does) go wrong?

"Dephasing"

Control errors and interactions with the environment add random perturbations to the state.

"Decoherence"



Quantum coherence is lost by 'measurement' from environment
TRUE and FALSE becomes
TRUE or FALSE

Quantum Computing speedups

Representing n qubits ->2^n dimensional vector

- Quantum Fourier Transform on full quantum state

  $O(n \log n)$ Quantum operations

- Classical Fast Fourier Transform on same 2^n dimensional vector

  $O(2^n \log\ n)$ Classical operations

This is the basis of Shor's algorithm for integer factorization

Simulating quantum dynamics with quantum computers

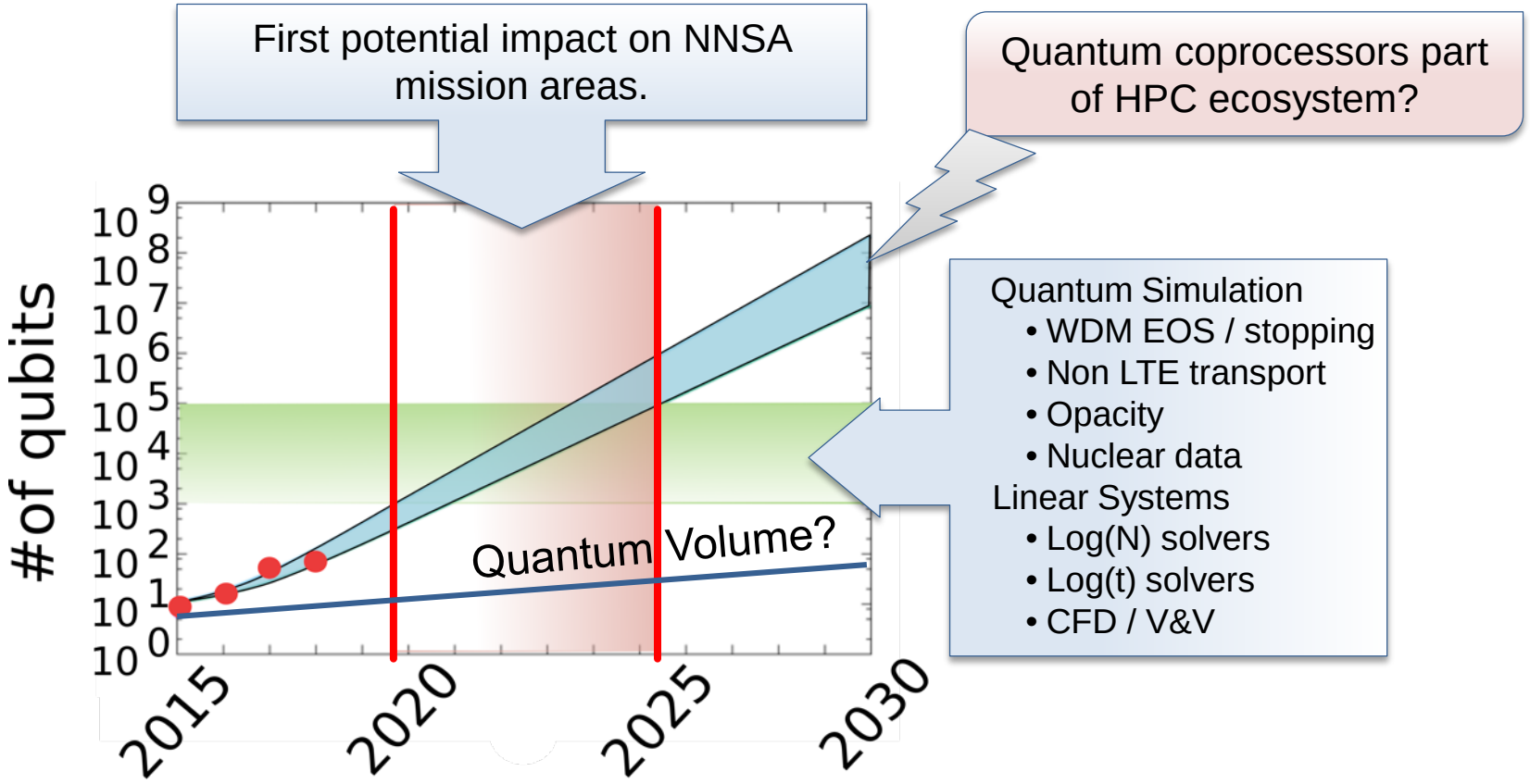
Quantum dynamics for n “particles” controlled by dim[H] ~ Exp(n)

Classical simulation: Cost: ~(dim[H])(# time steps)

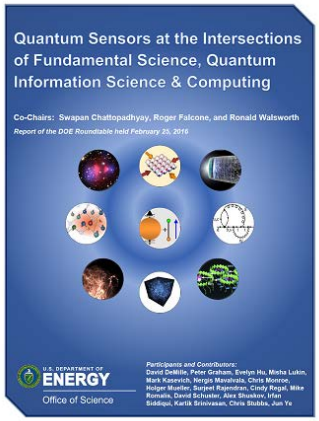
Quantum simulation: Cost: ~(log (dim[H]))(# time steps)

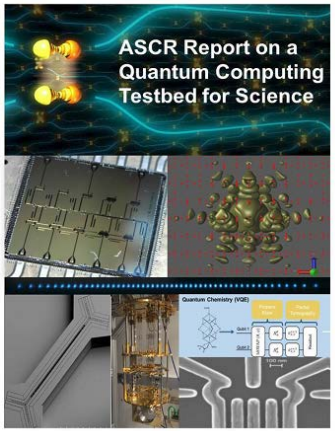
Also implies potential *exponential* speedup for other linear systems

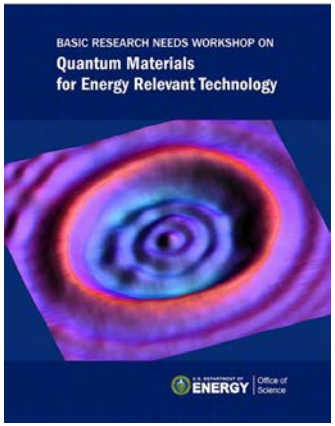
Quantum computing timeline and impacts

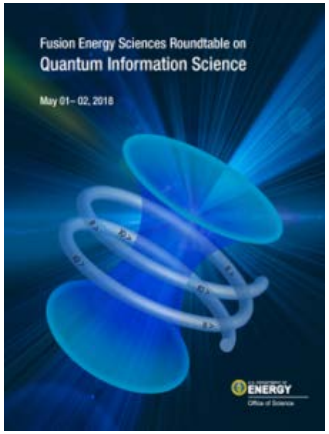


DOE / national investment in quantum









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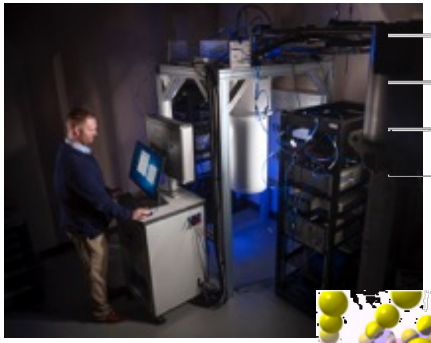
National Quantum Initiative

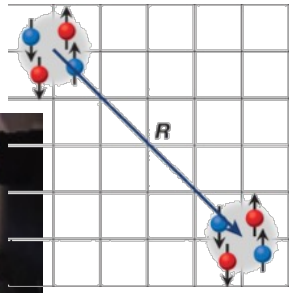
DOE is directed to undertake a QIS research program and provide *"research experiences and training"* for undergraduate and graduate students. The act lists seven areas of specific interest for training: quantum information theory, quantum physics, quantum computational science, applied mathematics and algorithm development, quantum networking, quantum sensing and detection, and materials science and engineering.

The act directs DOE to establish between two and five competitively awarded "National Quantum Information Science Research Centers." Each is to be allocated up to $25 million annually through fiscal year 2023

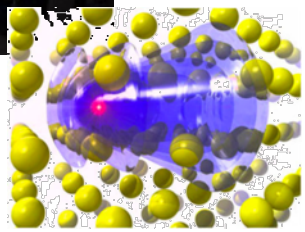
Quantum Computing & Sensing @ LLNL: where we are today?



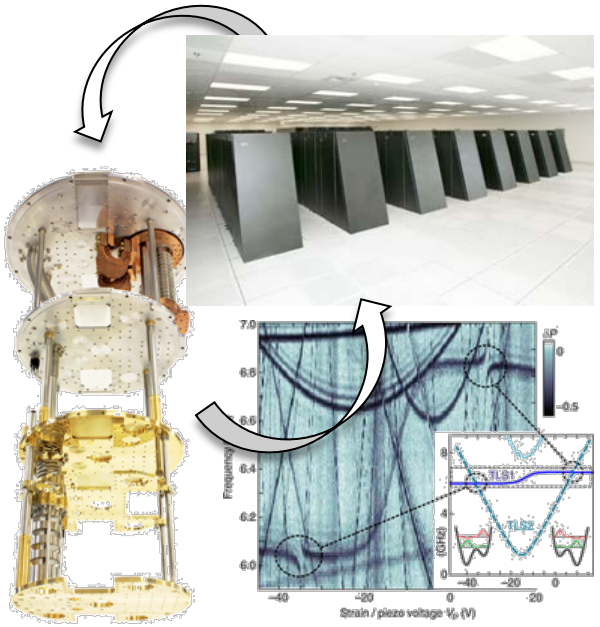
LLNL developed ~20 qubit quantum simulation testbed

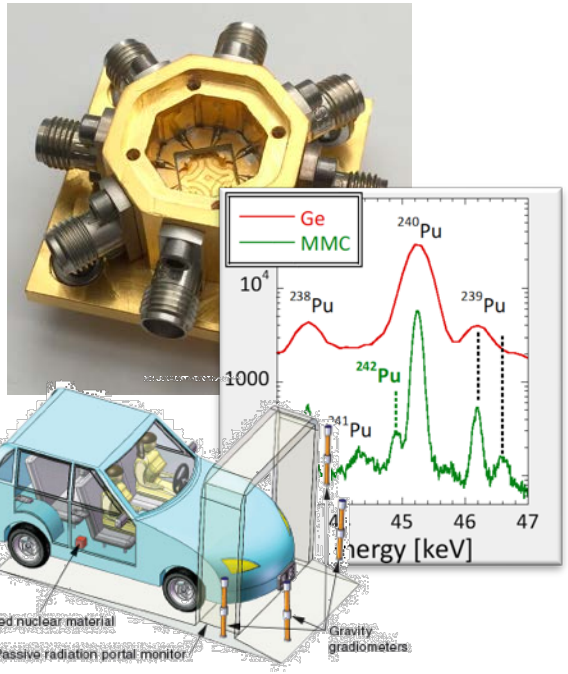


Nucleon dynamics



HED energy transfer

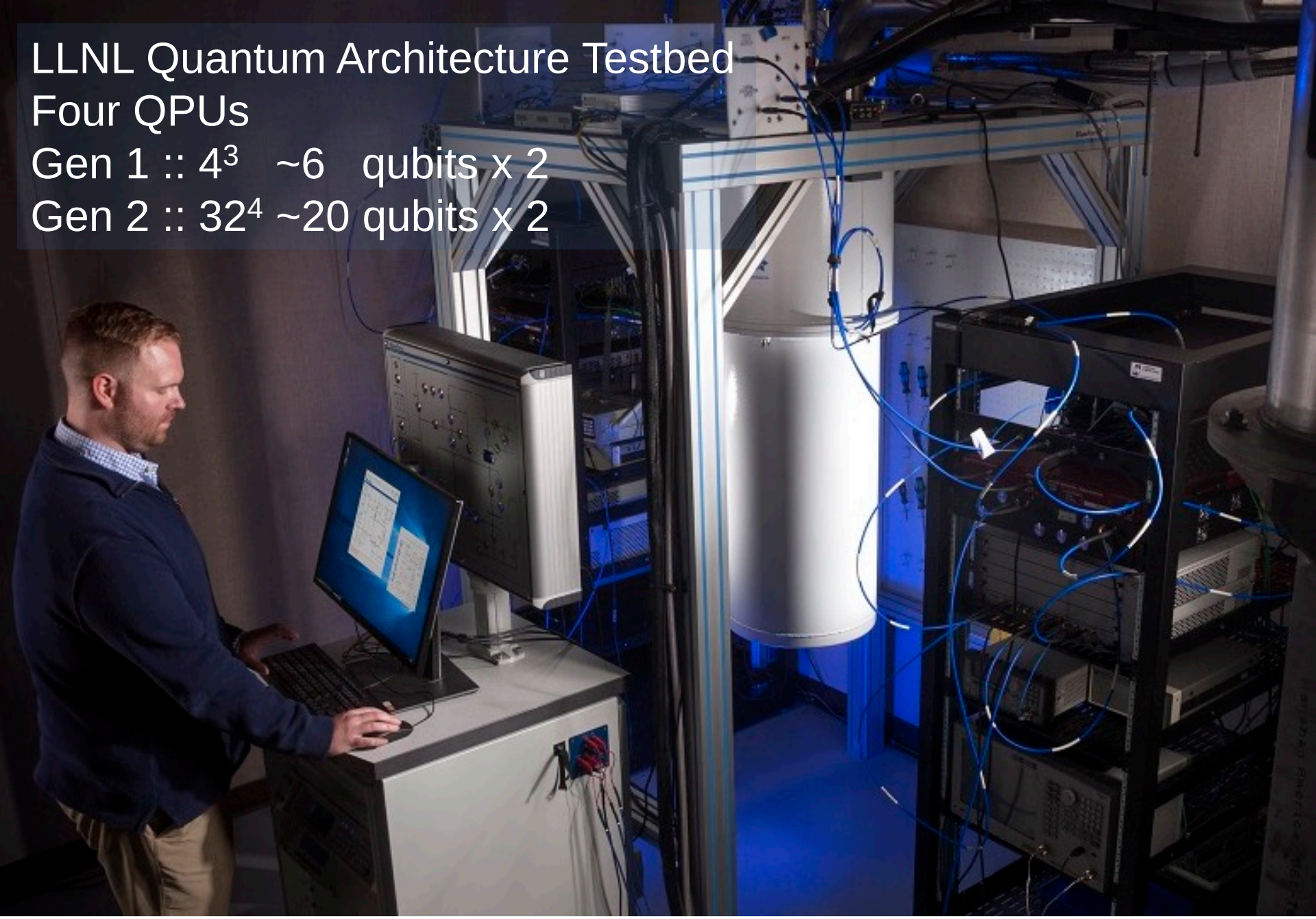




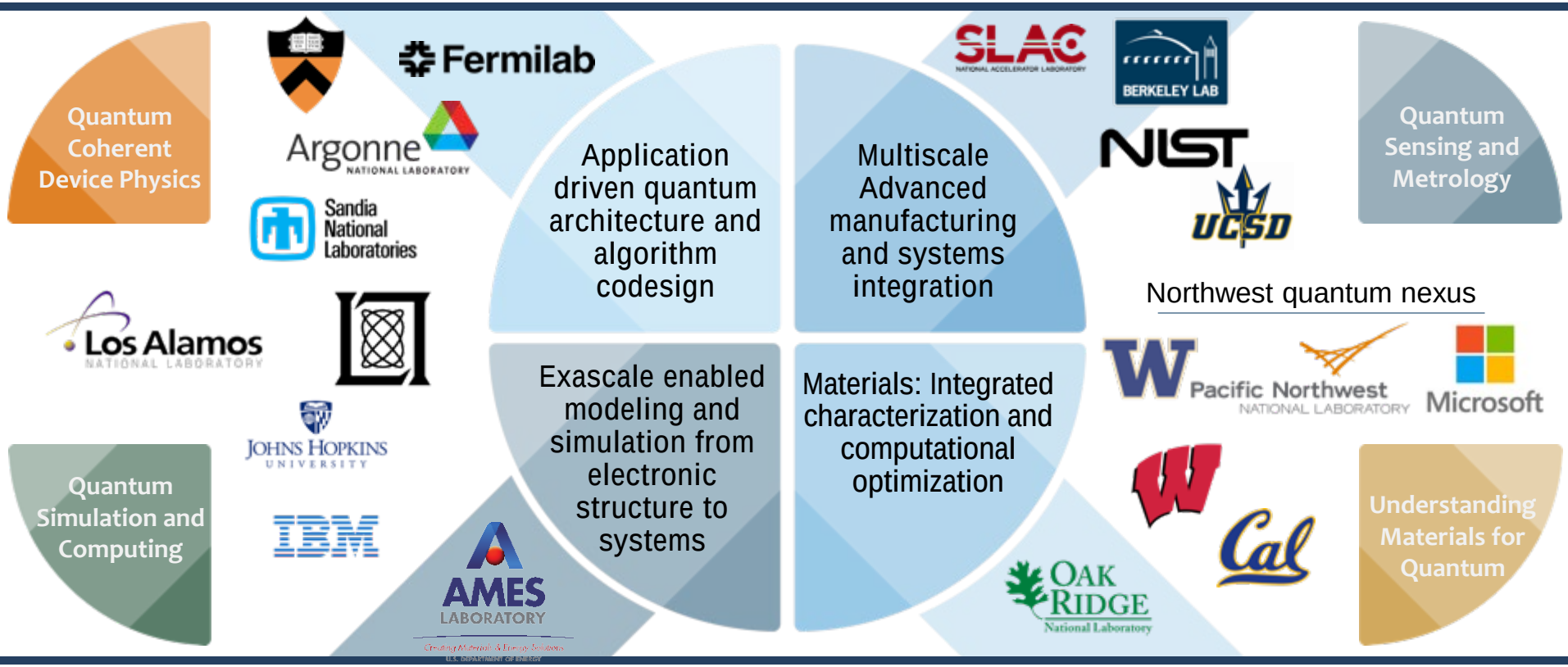
Quantum computing hardware co-design for near term applications in science and DOE/NNSA mission space.

Application of expertise in quantum simulation and HPC enabled computational materials design to improve device performance.

Design, development and testing of quantum sensing platforms for scientific, defense and national security applications.


LLNL Quantum Architecture Testbed
Four QPUs
Gen 1 :: 4^3 ~6 qubits x 2
Gen 2 :: 32^4 ~20 qubits x 2

LLNL: A partner for quantum science at scale



Quantum Sensing

Stephen B. Libby
libby1@llnl.gov
Theory and Modeling Group Leader
Physics Division

May 7, 2019

Lawrence Livermore National Laboratory

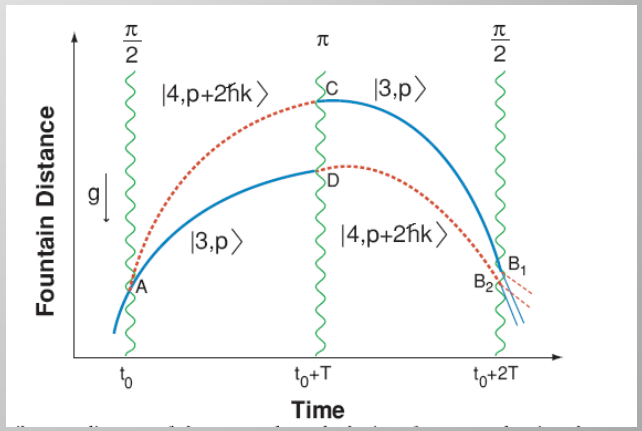
LLNL-PRES-774185

Quantum Coherent Control is Driving Significant Advances in Precision Sensing & Measurement

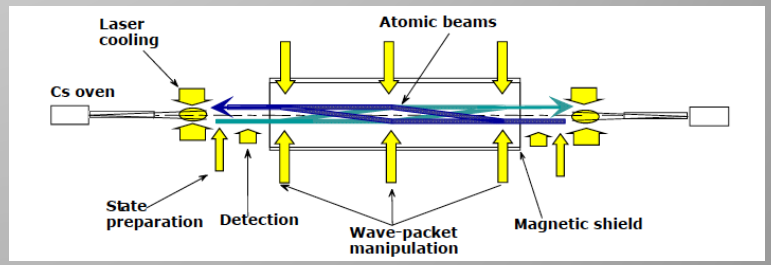
- Quantum Sensor advantages: great precision, environmental control and isolation, intrinsic 'self-calibration,' 'instant on,' no significant baseline drift – natural for fast, real time applications.

- Synergistic with quantum computing. Exploit multi-qubit gates protocols (Hadamard/Pauli vs. $\pi/2$ & π pulses)

- Applications: atomic clocks, field and force sensors (e.g., gravity, inertial navigation, magnetism), metrology, fundamental science (e.g. axions, dark matter, gravitational waves,…)



- Atomic fountain and Sagnac interferometry (exploits quantum correlated internal atomic and momentum states).
  - *Gravity gradiometry* (mass 'tomography')
    - Hidden mass detection at close range (portal scan & emergency response) – (current LLNL/AOSense)
    - Further applications: tunnel/underground structure detection, city scan, treaty verification, naval.
  - *Inertial motion sensors* – beyond GPS – dead reckoning navigation (current AOSense/LLNL)



Quantum Sensors*

TABLE I. Experimental implementations of quantum sensors.

Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency	Initalization	Readout	Type[a]
Neutral atoms						
Atomic vapor	Atomic spin	Magnetic field, rotation, time/frequency	dc-GHz	Optical	Optical	II, III
Cold clouds	Atomic spin	Magnetic field, acceleration, time/frequency	dc-GHz	Optical	Optical	II, III
Trapped ion(s)						
	Long-lived electronic state	Time/frequency	THz	Optical	Optical	II, III
		Rotation		Optical	Optical	II
	Vibrational mode	Electric field, force	MHz	Optical	Optical	II
Rydberg atoms						
	Rydberg states	Electric field	dc, GHz	Optical	Optical	II, III
Solid-state spins (ensembles)						
NMR sensors	Nuclear spins	Magnetic field	dc	Thermal	Pick-up coil	II
NV^b center ensembles	Electron spins	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz	Optical	Optical	II
Solid-state spins (single spins)						
P donor in Si	Electron spin	Magnetic field	dc-GHz	Thermal	Electrical	II
Semiconductor quantum dots	Electron spin	Magnetic field, electric field	dc-GHz	Electrical, optical	Electrical, optical	I, II
Single NV^b center	Electron spin	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz	Optical	Optical	II
Superconducting circuits						
SQUID[c]	Supercurrent	Magnetic field	dc-GHz	Thermal	Electrical	I, II
Flux qubit	Circulating currents	Magnetic field	dc-GHz	Thermal	Electrical	II
Charge qubit	Charge eigenstates	Electric field	dc-GHz	Thermal	Electrical	II
Elementary particles						
Muon	Muonic spin	Magnetic field	dc	Radioactive decay	Radioactive decay	II
Neutron	Nuclear spin	Magnetic field, phonon density, gravity	dc	Bragg scattering	Bragg scattering	II
Other sensors						
SET[d]	Charge eigenstates	Electric field	dc-MHz	Thermal	Electrical	I
Optomechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz	Thermal	Optical	I
Interferometer	Photons, (atoms, molecules)	Displacement, refractive index	...			II, III

[a]Sensor type refers to the three definitions of quantum sensing in Sec. II.A.
[b]*NV*: nitrogen vacancy.
[c]SQUID: superconducting quantum interference device.
[d]SET: single electron transistor.

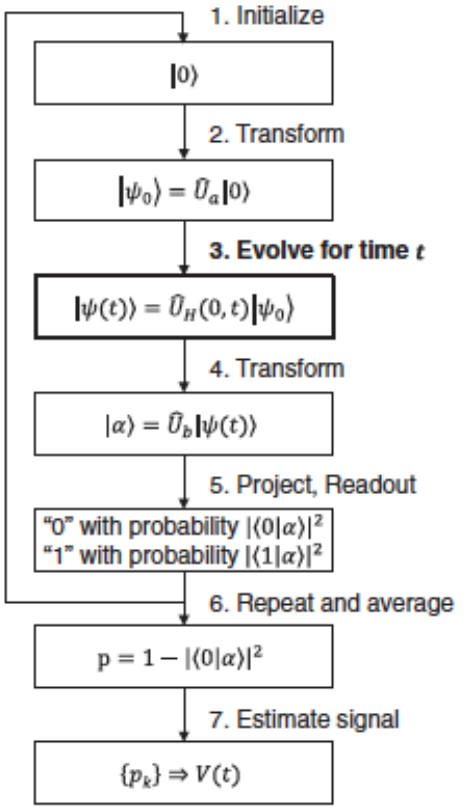
- Type I exploits quantum object (e.g. few state system with gaps).
- Type II exploits quantum phase coherence.
- Type III exploits 'true' quantum characteristics – entanglement/squeezing (non-classical correlations)

$$\psi = [2\cosh(2\theta)]^{-1/2} \times (e^{-\theta}|2\rangle_a|2\rangle_b + e^{i\phi}e^{\theta}|1\rangle_a|1\rangle_b)$$

- Atomic Clock – environment insensitive transition – lock local oscillator. (e.g. hyperfine $F = 4, m = 0\rangle$ to $F = 3, m = 0\rangle$)
- Field and force sensors – 'clock' operated on a sensitive transition.

* *Quantum sensing*, C. L. Degen, F. Reinhard, P. Cappellaro, RMP, 89, (2017), 035002.

Quantum Sensing: Detection, Interferometry, Noise*



Basic steps in the quantum sensing process

$$\hat{H}(t) = \hat{H}_0 + \hat{H}_V(t) + \hat{H}_{\text{control}}(t)$$

Ramsey Interferometry

$$|\psi_0\rangle = |+\rangle \equiv \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \Rightarrow |\psi(t)\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{-i\omega_0 t}|1\rangle) \Rightarrow |\alpha\rangle = \tfrac{1}{2}(1 + e^{-i\omega_0 t})|0\rangle + \tfrac{1}{2}(1 - e^{-i\omega_0 t})|1\rangle$$

$$\begin{aligned} p &= 1 - |\langle 0|\alpha\rangle|^2 \\ &= \sin^2(\omega_0 t/2) = \tfrac{1}{2}[1 - \cos(\omega_0 t)] \end{aligned}$$

Quantum Projection Noise Limited Sensitivity

$$\delta F_{\min} = \frac{h\delta\varphi}{\mu T} \qquad \delta F_{\min} = \frac{h\delta\varphi}{\mu T_2}\sqrt{\frac{T_2}{T}} = \frac{h}{\mu\sqrt{T_2 T N}}$$

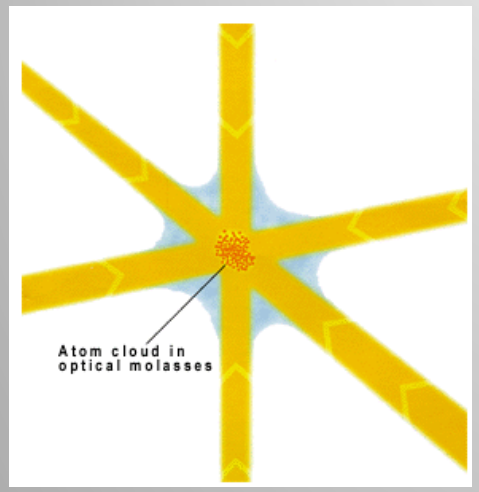
*_Quantum sensing_, C. L. Degen, F. Reinhard, P. Cappellaro, RMP, 89, 035002, (2017).

Atomic Sensors – a review, J. Kitching, S. Knappe, E. A. Donley, IEEE Sensors, 11, 9, 1749, (2011).

Squeezed atomic states and projection noise in spectroscopy, D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen, Phys. Rev. A, vol. 50, pp. 67–88, (1994).

Laser Cooled Atoms and Quantum Coherence Give Rise to Sensitive Interferometers*

Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.



Laser cooling: Laser light is used to cool atomic vapors to temperatures of ~10^{-6} deg K.

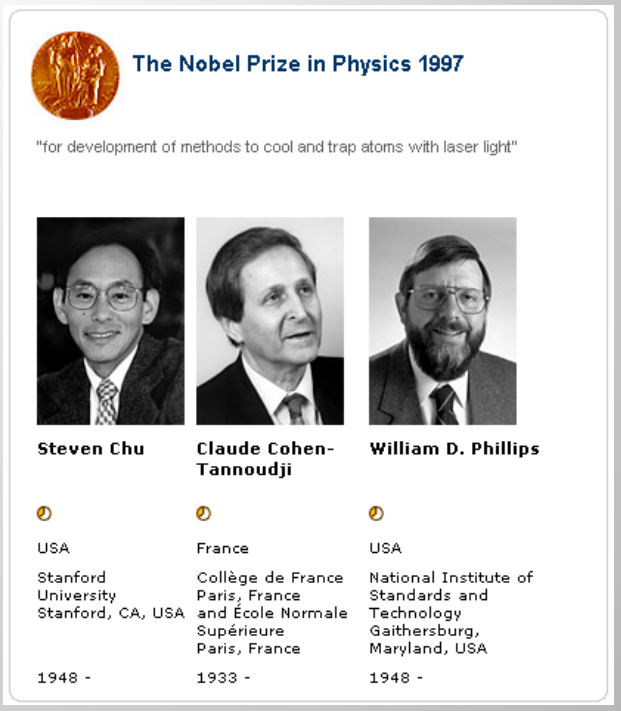


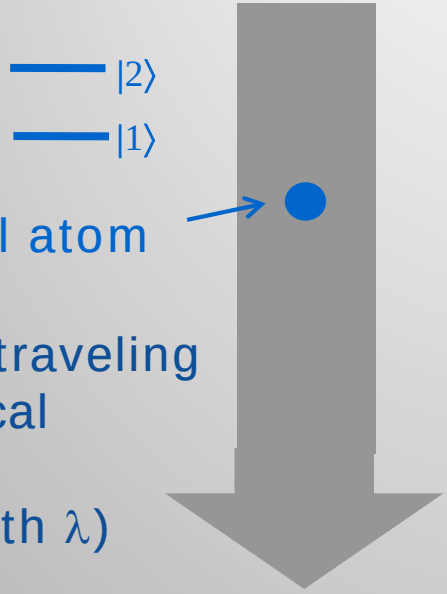
Image source:www.nobel.se/physics

Laser Cooled Atoms Enable Sensitive Inertial Sensors – at 10^{-6} K, cesium de Broglie wavelength is ~ $h/(MkT)^{1/2}$ ~ .1 μm. (compare 1970's neutrons - $h/(mkT)^{1/2}$ ~1.445 Å)

- *M. A. Kasevich and S. Chu, Phys. Rev. Lett. 67, 181, (1991) & Appl. Phys. B 54, 321, (1992)
- B. Young, M. Kasevich, and S. Chu, in Atom Interferometry, Academic Press, (1997)

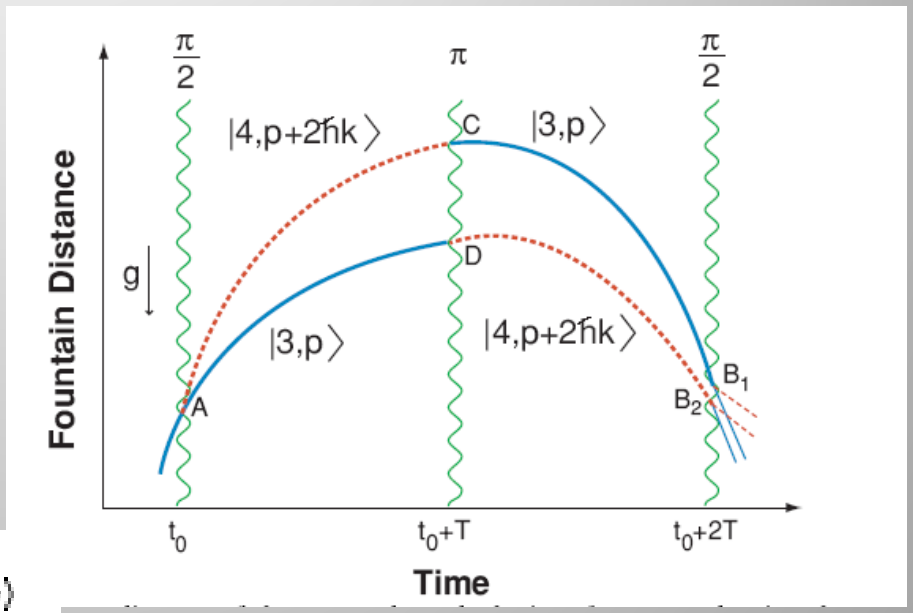
(Light-pulse) atom interferometry builds on laser cooled atoms ($T \leq 10^{-6}$ K)

Resonant optical interaction



Recoil diagram

- Momentum conservation between atom and laser light field (recoil) leads to spatial separation of atomic wavepackets.



$$|\psi(t)\rangle = \cos\left(\frac{\Omega t}{2}\right)|1,\mathbf{p}\rangle + e^{-i\frac{\pi}{2}}e^{i\phi_L}\sin\left(\frac{\Omega t}{2}\right)|2,\mathbf{p}+\hbar\mathbf{k}_{\text{eff}}\rangle$$

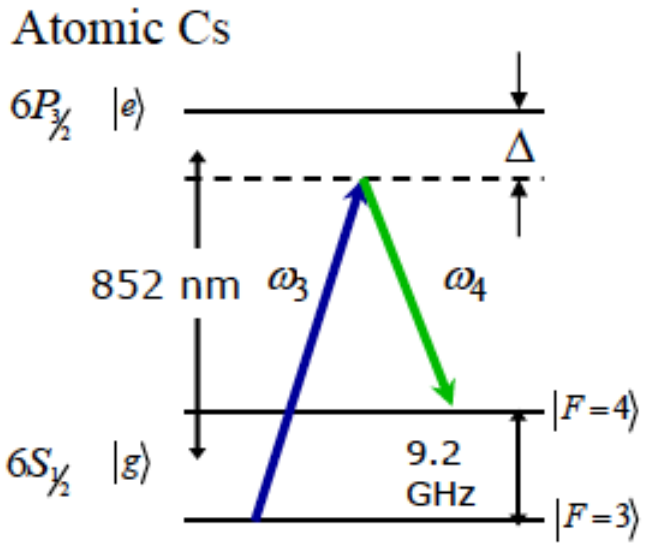
- 780 nm laser stabilized to < 1 kHz can measure the atom's position ~ 1:10^{12} .

Atomic deflection due to 25 kg mass at a distance of 1 meter over Δt ~ .25 sec is ~.5 Å.

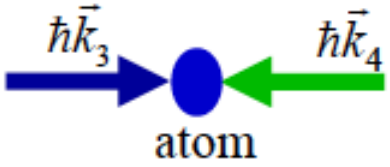
- Semi-classical phase shift ~ $n\hbar k\delta g T^2$ High momentum transfer n >> 2.

Stimulated Raman transitions – Rabi oscillations between hyperfine states

Level scheme



Excitation Geometry



Doppler sensitive configuration

- k_3, k_4 counter-propagate

Ground states

- Avoid spontaneous emission
- Excitation between magnetic field insensitive sublevels

Large detuning D

- Effective 2-level system

  $F=3, m_f=0 \leftrightarrow F=4, m_f=0$

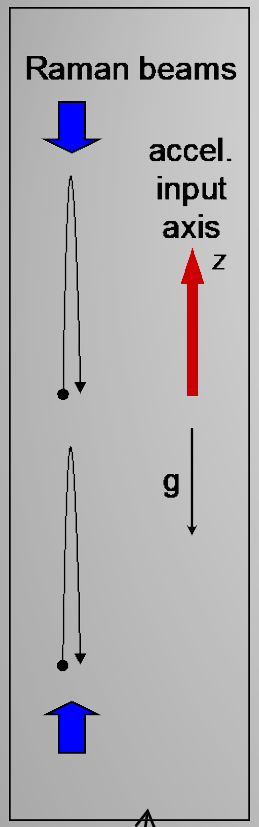
- Effective traveling wave excitation

  $k_{eff} = k_3 - k_4 \sim 2k_3$

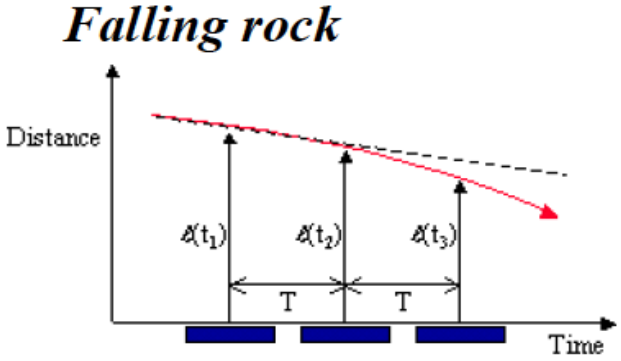
- Effective transition frequency

  $\Delta\omega_{eff} = \omega_3 - \omega_4$

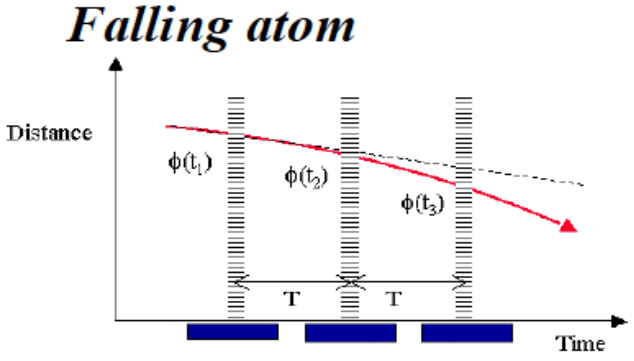
How does 'Quantum Optic' Atom Interferometery Work - II?



Paired atom fountains 'interrogated' by common Raman lasers – PINS gradiometer



- Measure three distances: $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$
- Acceleration: $a \sim [\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$



- Laser phases at atoms: $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$
- Atomic physics $\Rightarrow$ $a \sim [\phi(t_1) - 2\phi(t_2) + \phi(t_3)]$

Cold cesium atoms at ~ 1 μK (v ~ 1 cm/sec) are prepared in a magneto-optical trap in the F=3 state. The atoms are launched upward by moving optical molasses at v ~ 3 m/sec.

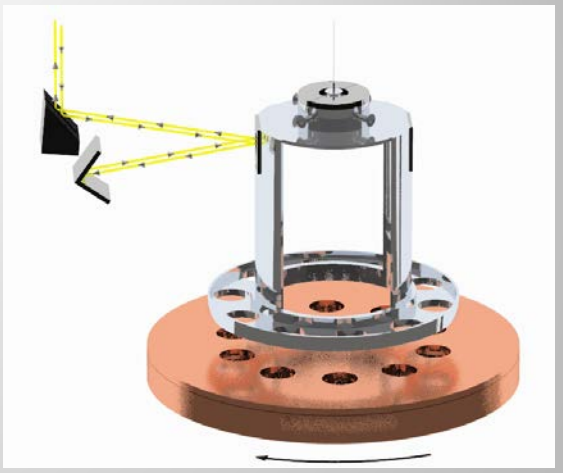
The two photon Raman method coherently splits and later recombines the cold cesium atoms in a quantum mechanical analog of a classical Mach-Zehnder interferometer.

780 nm laser stabilized to < 1 kHz can measure the atom's position ~ 1:10^{12}.

Atomic deflection due to 25 kg mass at a distance of 1 meter over Δt ~ .25 sec is ~.5 Å.

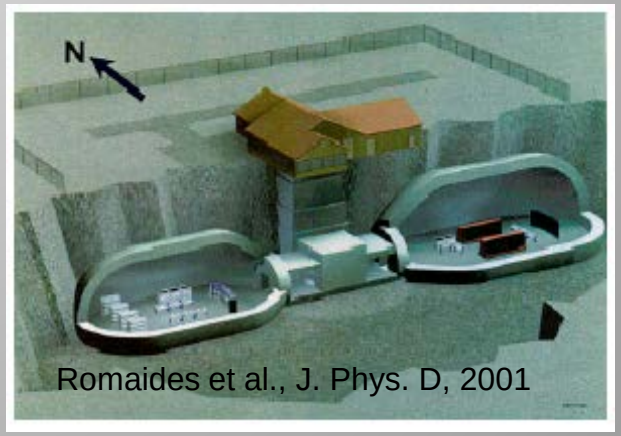
Gravity measurements have been around for a long time (e.g. in fundamental physics, geodesy). What's new now? Cold atom vs. mechanical gravity sensors.

- Gravity measurements date back to Bouger, Cavendish (18th century), and Eötvös (19th century).
- Applications ranged from geodesy, to fundamental physics (e.g. Eötvös tests of the principle of equivalence 1896 – 1909 & current 'Eöt-Wash group).
- The Eötvös torsion pendulum was instrumental in the discovery of the oil fields in Texas (1920's).
- Gravimetry and Gradiometry has been occasionally proposed for security applications including treaty verification, underground structure discovery, transport scanning:
  - J. A. Parmentola, The Gravity Gradiometer as a Verification Tool, Sci Global Security, 2, 43-57 (1990).
  - S. D. Gray, et. al., "Estimating the Weight of Very Heavy Objects with a Gravity Gradiometer" J. Phys. D, 28, 2378, (1995).
  - A. J. Romaides et. al., "A Comparison of Gravimetric Techniques for Measuring Subsurface Void Signals," J. Phys. D 34, 433-443, (2001).
  - B. Kirkendall, Y. Li, and D. Oldenburg, "Imaging Cargo Containers Using Gravity Gravity Gradiometry" IEEE Trans. GeoSci, 45, 1786-1797, (2007).
- Generically, mechanical gravity instruments suffer from calibration and environmental/baseline drifts in short time scale/mobile operations.
- Cold atom based sensors – no calibration, stable!



Eöt-Wash torsion pendulum experiment

C. D. Hoyle et. al., Phys. Rev. D 70, 042004, (2004)
D. J. Kapner et. al., Phys. Rev. Lett 98, 021101 (2007).

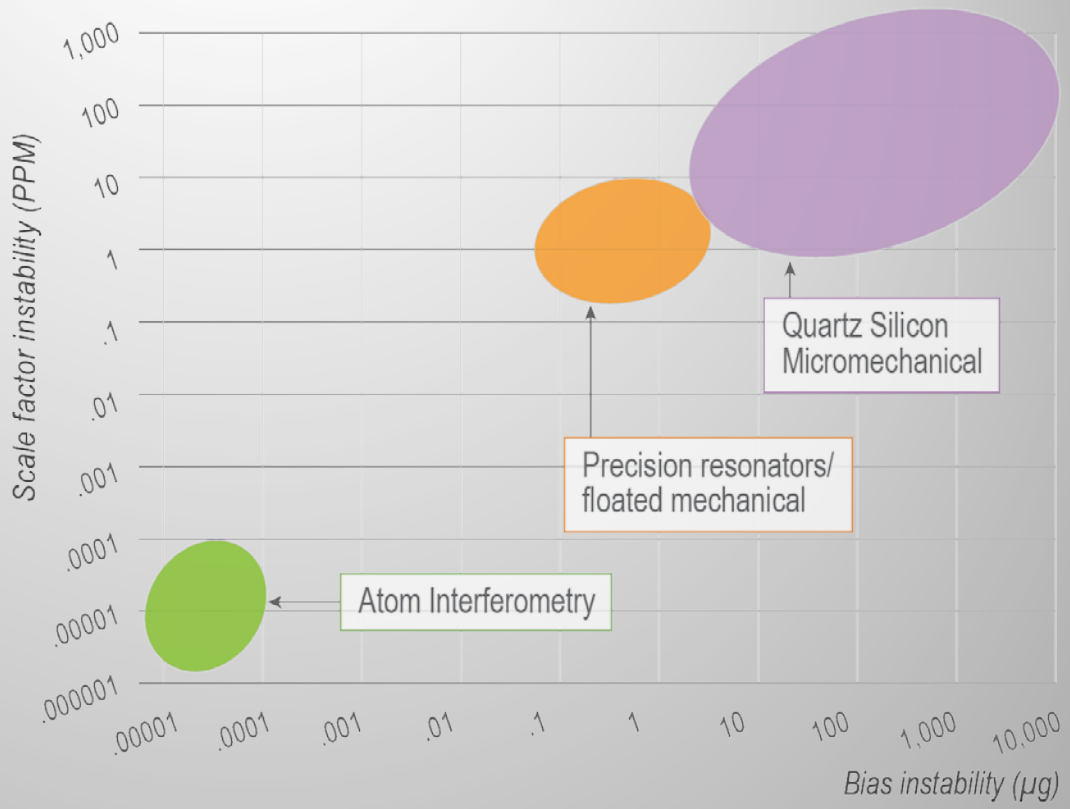


Romaides et al., J. Phys. D, 2001

Cold-Atom interferometry gravity sensors demonstrate off-the-chart performance

AI sensor performance in open literature:

- Bias stability: <<10^{-10} g
- Noise: < 4×10^{-9} g/Hz$^{1/2}$
- Scale Factor: < 10^{-10}



Bias – DC offset under zero applied acceleration

Scale factor – sensitivity relating applied acceleration to sensor output

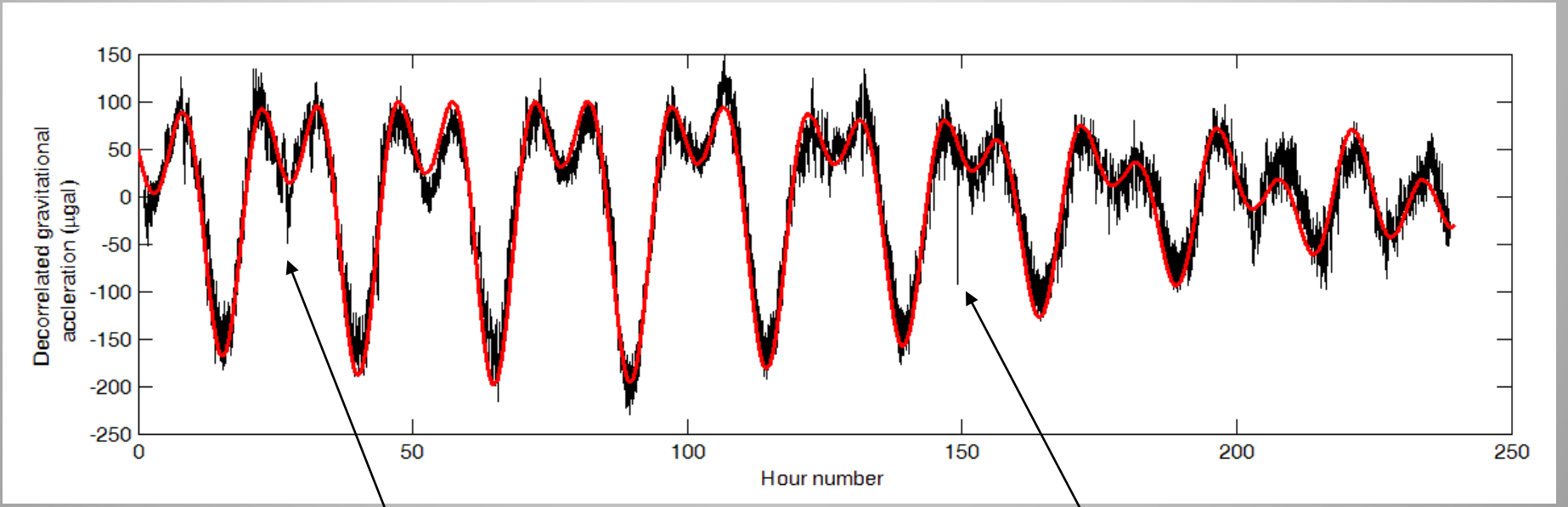
Quantum projection noise limited performance (present) depends on *D, T,* number of atoms *N*, photon recoil k_{eff}, interference fringe contrast η:

$$\Delta T_{zz} \approx \frac{1}{\eta\sqrt{N}\, D\, k_{eff} T^2}$$

Squeezed state detection ~ $1/N^q$ $(.5 < q < 1)$. Uncertainty limit ~ 1/N

When operated as a **gravimeter**, we precisely track the Earth's tides: Results agree in detail with geological models (with ocean damping)

- Individual interferometer is sensitive to acceleration. Red is a tidal model, black is data (offset and slope free parameters). Noise is due to vibrations. (noise equivalent in 'gravimeter mode' required for our apps is ~ 10^{-1} μgal/√Hz).

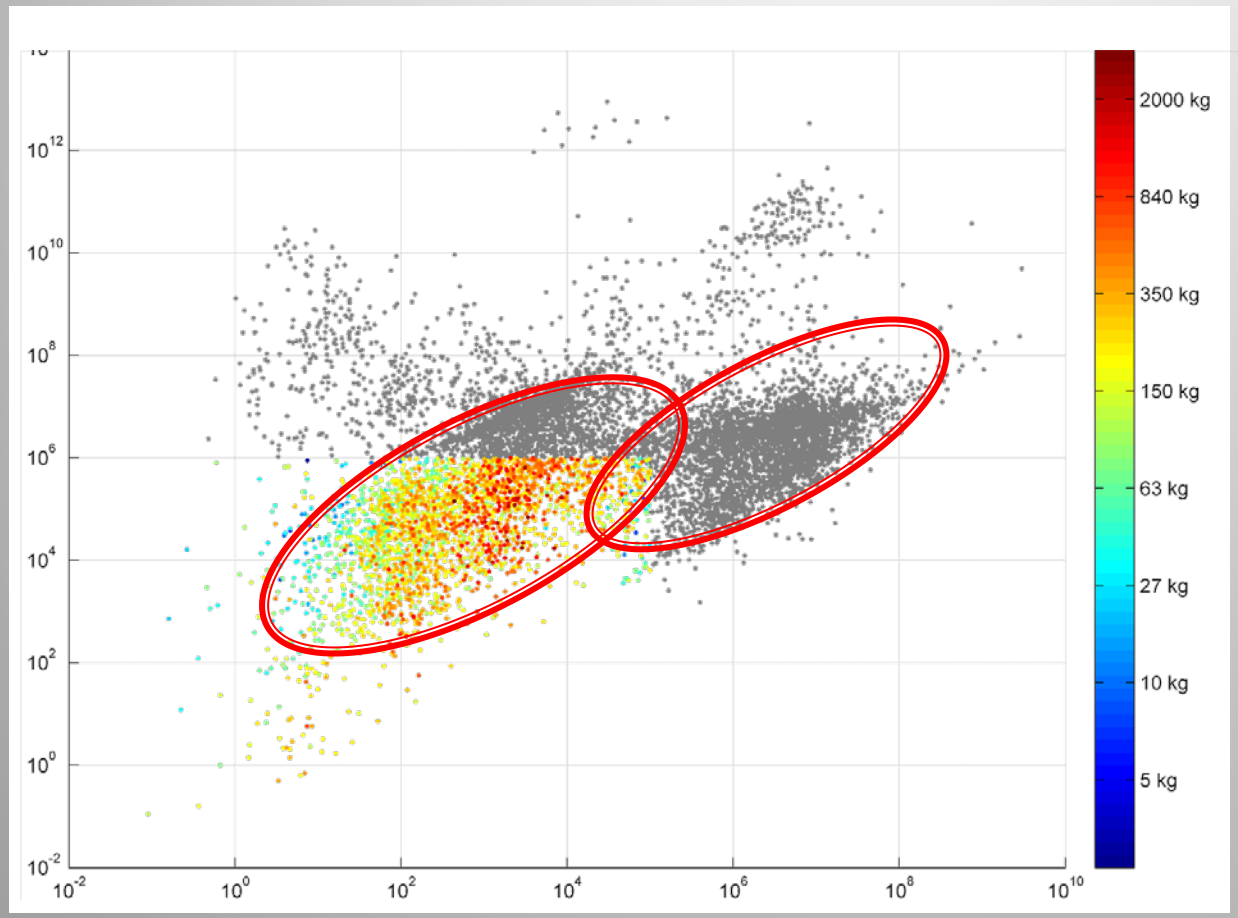


This vibration noise at ~ 50 μgal/(Hz)$^{1/2}$ is large compared to that required for security applications (0.1 μgal), underscoring why operation as a gradiometer essential.

Honduras earthquake 28/5/2009

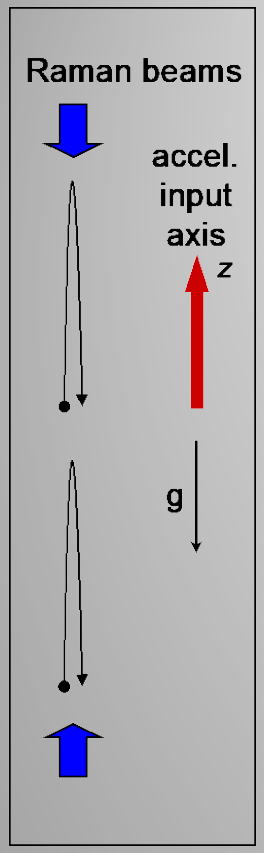
The rapid, passive detection of threats with weak radiation signatures is a major challenge

Data from LLNL unclassified fissile models (spanning set)



- Apply real time atom interferometry to do accurate gravitational 'tomography.'
- Real-time tomography requires - .1 Eotvos/Hz$^{.5}$
- 'High momentum transfer.'
- Mass distributions are naturally complementary to radiation sensing
- Sensor fusion

Two Photon Raman Atomic Fountain Interferometer – Semi-classical Gravitational Phase Shift Analysis & Gradiometer Response



Paired atom fountains 'interrogated' by common Raman lasers

$$\phi_{tm} = \vec{k}_{eff}\delta\vec{\phi},$$
$$\delta\vec{\phi} = \delta\vec{x}(t_1+2T) - 2\delta\vec{x}(t_1+T) + \delta\vec{x}(t_1)$$

$$\delta\vec{x}(t) = \int_0^t dt'\,(t-t')\,\delta\vec{g}\left[\vec{x}_0(t')\right]$$

$$r(x) = \frac{\delta\phi_z^{(2)} - \delta\phi_z^{(1)}}{T^2(z_{02}-z_{01})}$$

Ideal GG Sensitivity ~ $1/(kLT^2R^{.5}$ SNR)

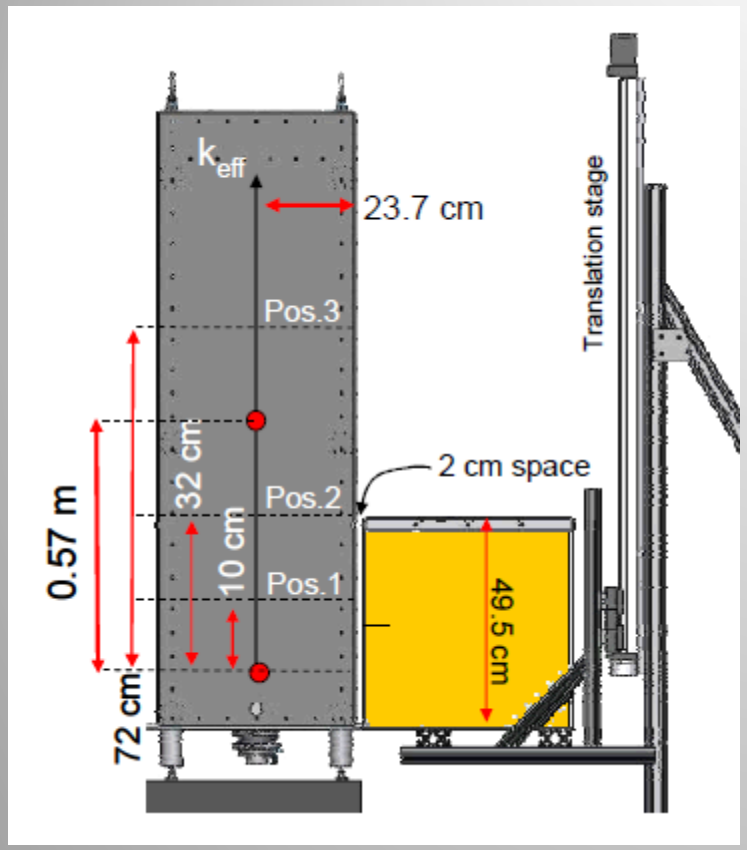
R = atom cloud launch rate
SNR = signal to noise ratio

Gravity gradient of 25 kg sphere at 1 meter is 3.4 10^{-9} s^{-2}.

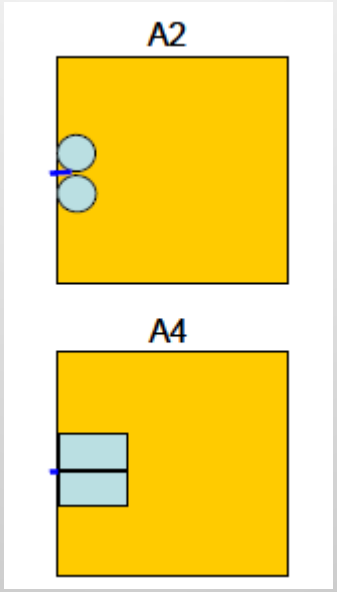
GG directly above 1.5 x 1.5 m^2 tunnel buried 30 m ~ .8 10^{-9} s^{-2}

- Cooled, (initially F=3) cloud of ~ 10^8 alkali atoms. Unperturbed launch trajectory: v_0~ 2- 3 m/sec. t_1= 45 ms. T~ 250 ms. z_{02}-z_{01} ~ .5 m
- Raman laser wavevector k_{eff} ~ 10^7 m^{-1}.
- Semiclassical treatment: Mach-Zehnder steps are in 'sudden' approximation. O(T^2) phase shift is solely due to light-atom interaction (k.δx) (higher order has Coriolis cross couplings, etc.)
- Quantum corrections computed.
- Individual interferometer gross phase ~ k_{eff} gT^2 ~ 10^8 radians (due mainly to the earth).
- Interferometer differences $\delta\varphi^{(1)}$-$\delta\varphi^{(2)}$: 1 to 10^{-4} rad. (10^{-3} rad ~ 2 10^{-9} /sec^2). Shot noise limited.
- Gravity gradient is T_{zz} = ($\mathbf{g_1}$-$\mathbf{g_2}$)/L. 1 **Eötvös** is 10^{-9} s^{-2} . Gravity gradient of Earth at Earth surface is 3 10^{-6} s^{-2}.

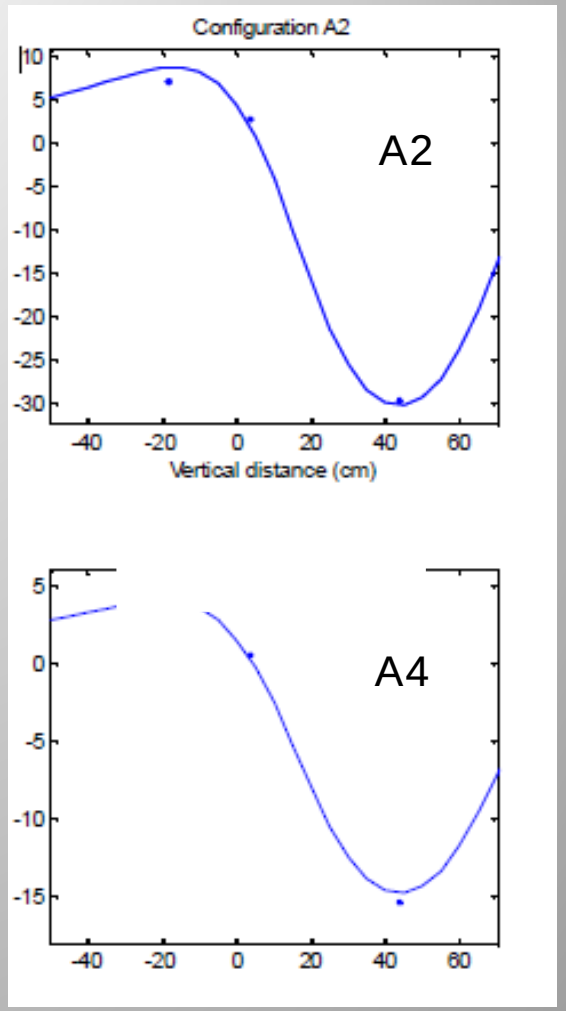
Gravity gradiometer – the beginnings of mass tomography (2010)* LLNL/AOSense collaboration



Sample mass configurations:

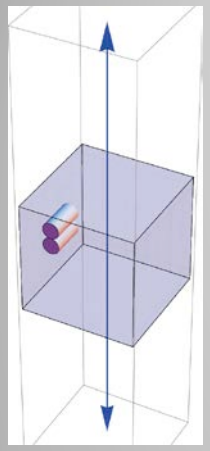


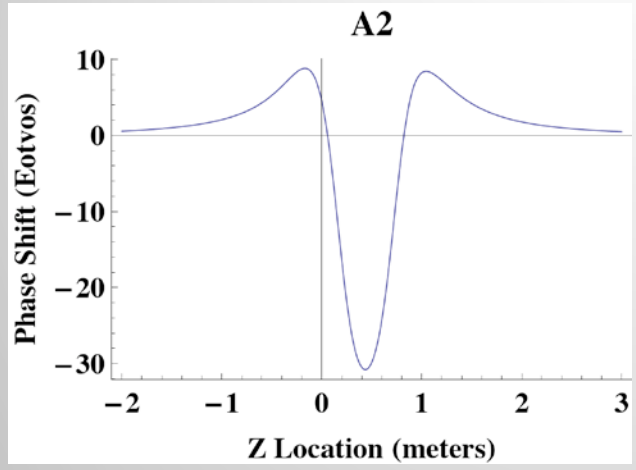
Data:

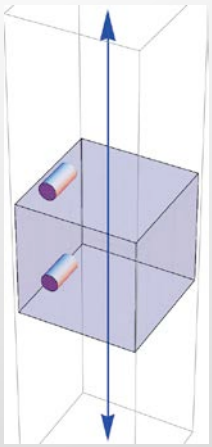


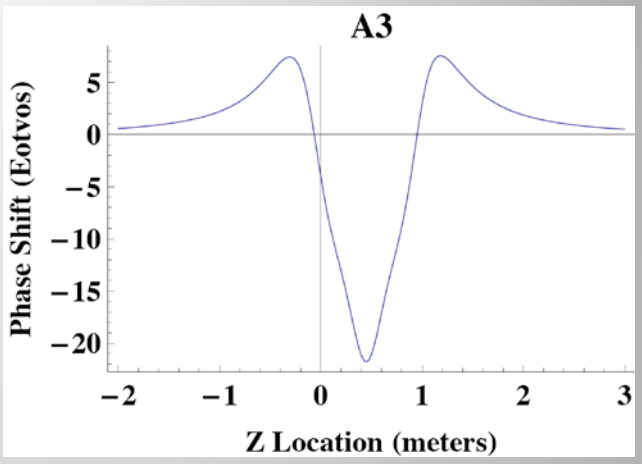
*"*Feasibility Study of a Passive, Stand-off Detector of High-Density Masses with a Gravity Gradiometer Based on Atomic Interferometry*," S. B. Libby, P.I., LLNL LDRD, FY 2010.

The time-averaged data matched the predicted responses very well

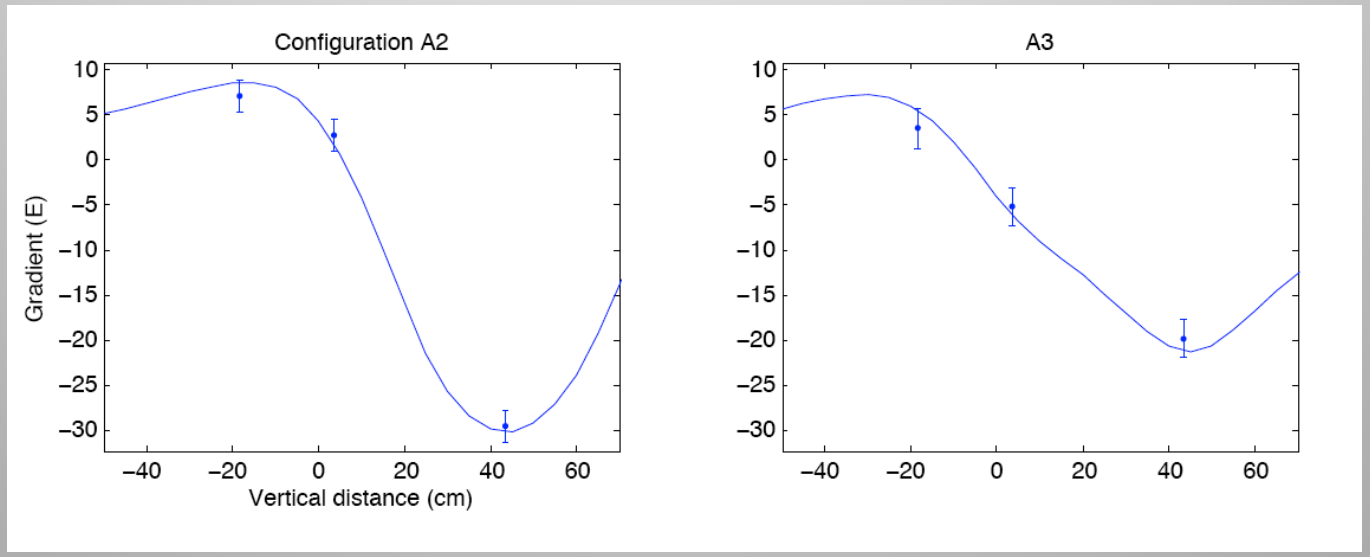








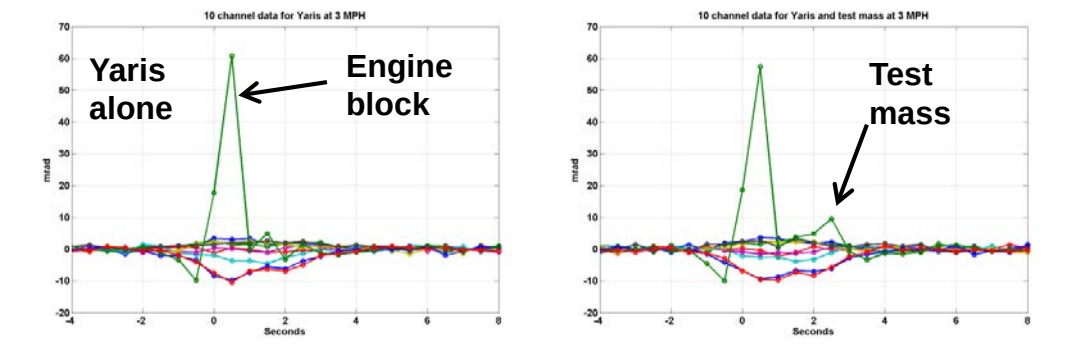
Gravity Gradient (Eötvös)

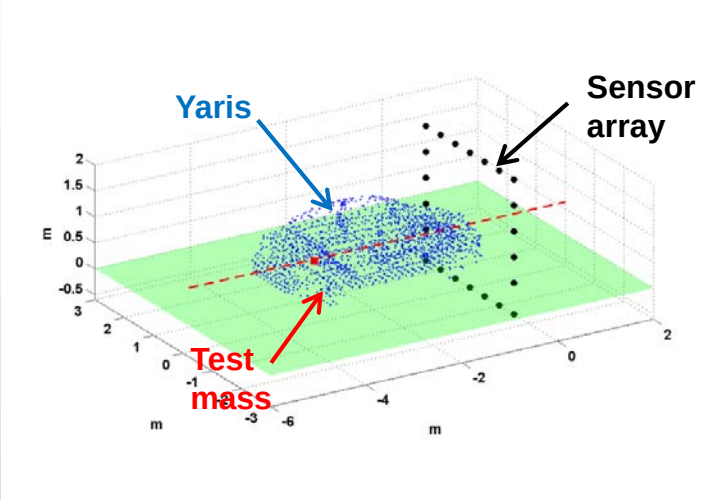


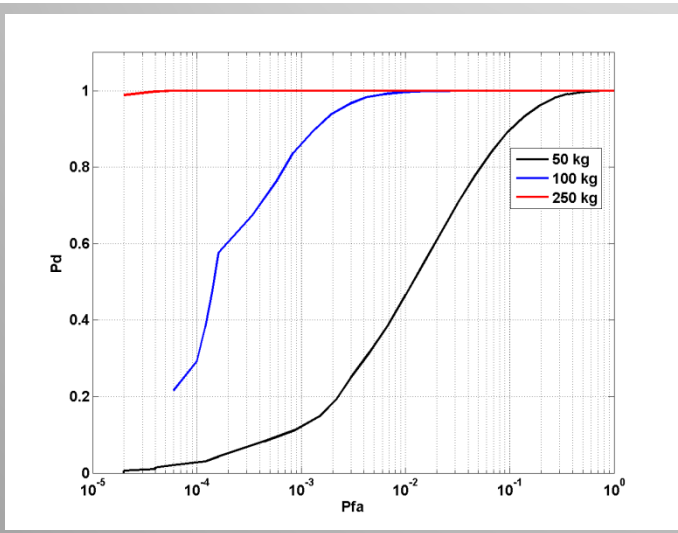
Z axis: box center position in cm

Probabilistic detection statistics demonstrates high density threat detection

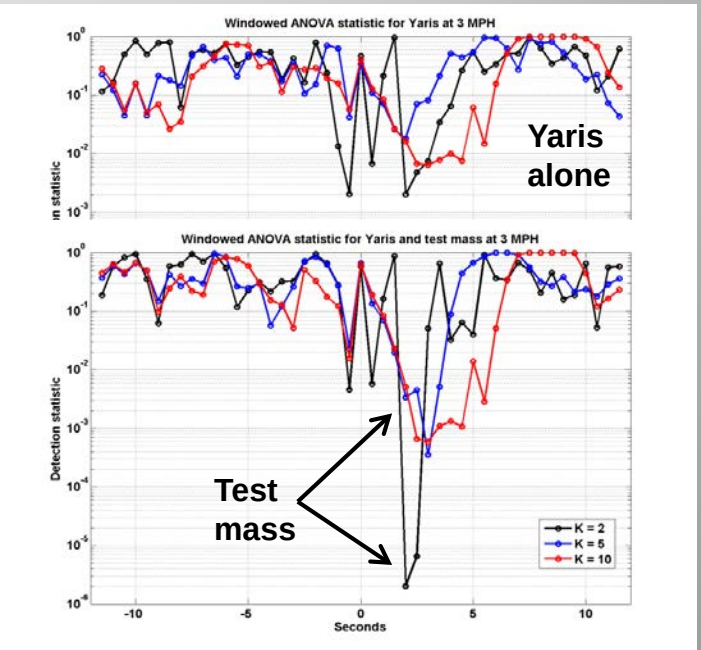
- We developed a signal processing system for ‘gradiometer’ portal data using multiple sensors and ‘windowed analysis of variance.’







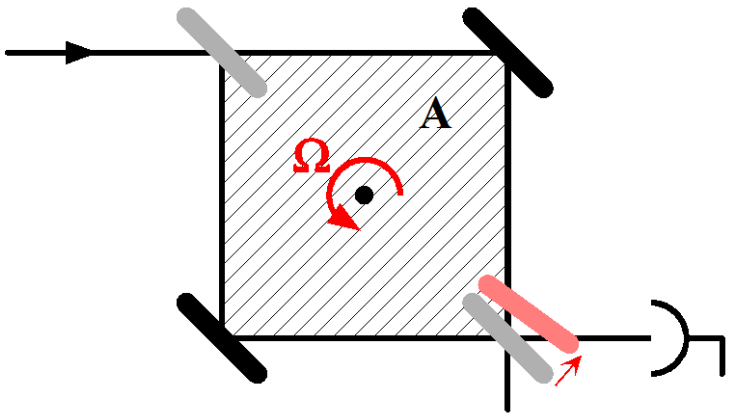
ROCs for portal sensor window, different test masses.

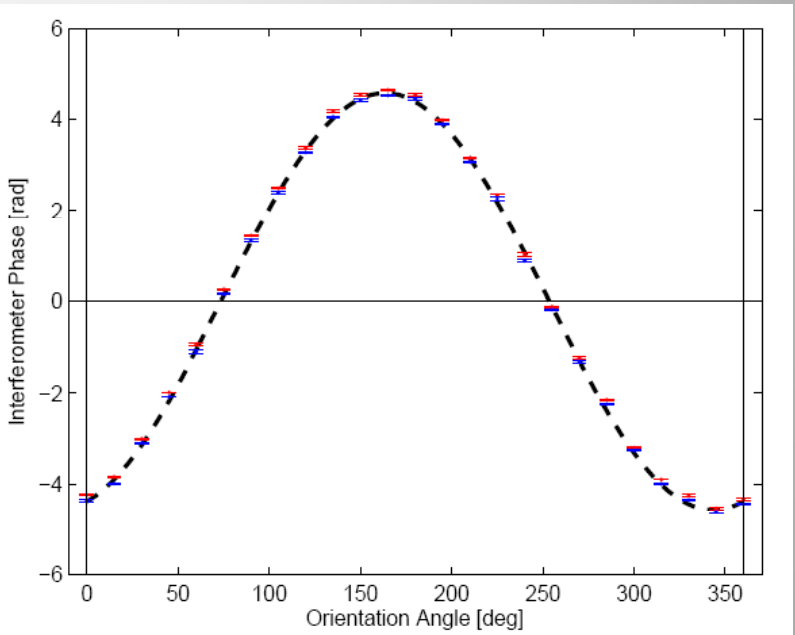


Sagnac gyroscope atom interferometer configuration: navigation beyond GPS

Rotations

Sagnac effect for de Broglie waves





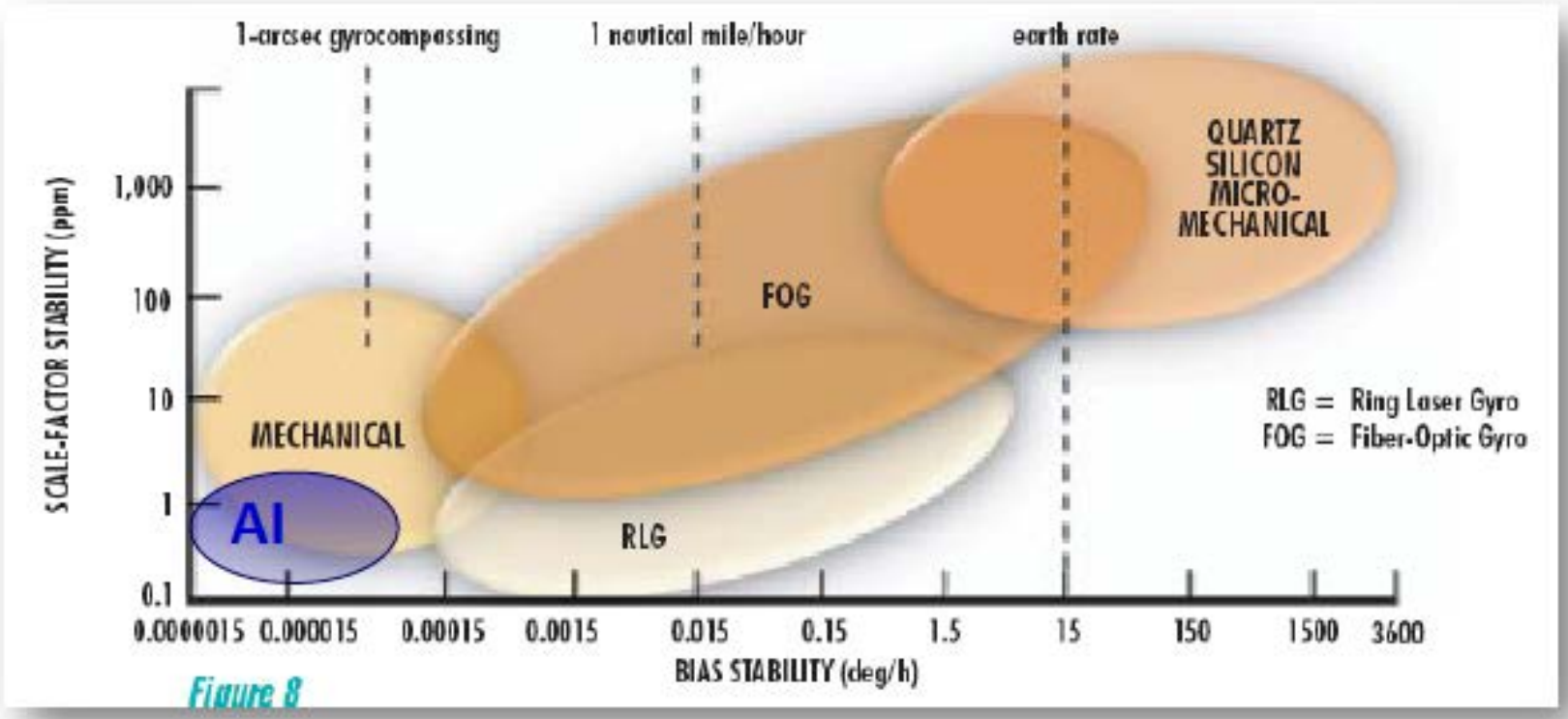
Gyroscope output vs.orientation.

$$\Omega_E = 7.29 \times 10^{-5} \text{ rad s}^{-1}$$

$$\Delta\Phi = \frac{4\pi\Omega \cdot A}{\lambda v}.\ mc^2/\hbar\omega = 6 \times 10^{10}$$

Quantum shot noise floor - 200 μdeg/hr$^{1/2}$
Initial rotation sensitivity - 6 x 10^{-10} rad s^{-1}
T. Gustavson Stanford thesis 2000.

Light-pulse AI gyroscope performance – a revolution in navigation



Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

Quantum Sensors Applications

- *Atomic Clocks*
  - Al^+ , Yb, Sr, clock comparisons
- *Atomic fountain gravity gradiometry* (mass 'tomography')

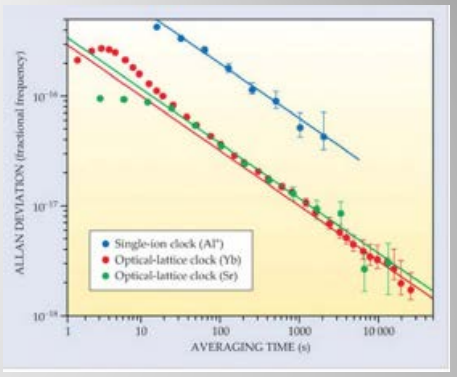
  Hidden mass detection at close range (portal scan & emergency response) – (current LLNL/AOSense)

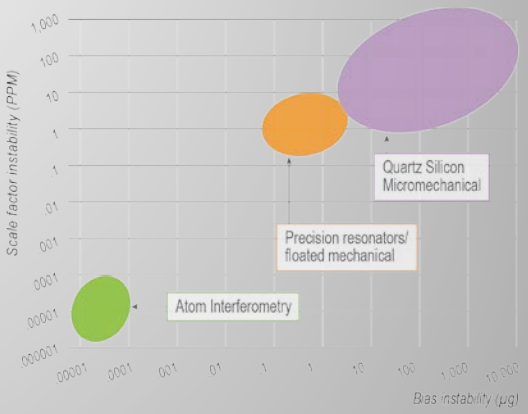
  Potential further applications: tunnel/underground structure detection, city building scan, treaty verification, …

  Closely connected to fundamental physics experiments:
  - Measure "G" to $1/10^6$
  - Space based sensors with ~ 10^{-5} E sensitivity – GRACE mission follow-on.
  - Gravitational wave detection in the .1 – 10 Hz regime
  - 'high momentum transfer'
- *Inertial motion sensors* – beyond GPS – dead reckoning navigation (current AOSense/LLNL)

  Navy and Air Force navigation

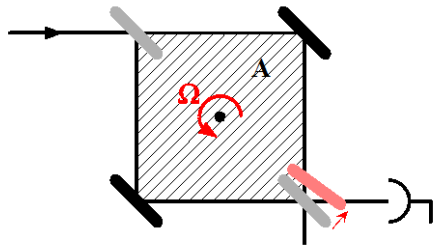
  High precision navigation solution – Machine learning improved Kalman filter.





Rotations

Sagnac effect for de Broglie waves



The LLNL/AOSense Cold Atom Gravity & Gyro Sensor Team

LLNL:

- Stephen Libby
- David Chambers
- Hema Chandrasekharan
- Vijay Sonnad
- Steven Kreek
- Karl Nelson
- Mark Cunningham
- Lance Bentley Tammero
- Kristin Lennox
- Steven Bond
- Jake Trueblood
- John Taylor, Pete Davis, Stan Edson, Pete Fitsos
- Kyle Brady (UC Berkeley – summer student 2010)
- Rees McNally (U. Colorado – summer student 2013)
- Ming-Yee Tsang (Princeton – summer student 2014)
- Samuel Stone (Cal State Chico – summer student 2017)

AOSense, Inc.:

- Brenton Young
- Miro Shverdin
- Mike Matthews
- Matt Cashen
- Jamil Abo-Shaeer
- Alan Zorn
- Adam Black
- Boris Dubetsky
- Mark Kasevich
- Tom Loftus

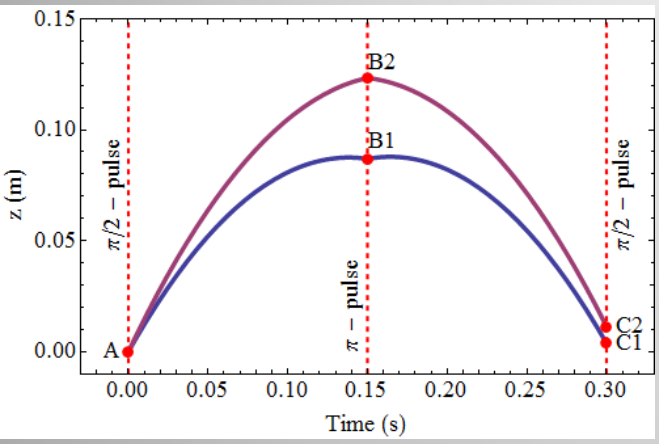
Quantum Sensing – next topics

- Gravity tomography
- More on gyros/navigation
- More on the ADMX (dark matter axion experiment) - squeezed state detection.
- Classical vs. quantum detection theory – signal analysis
- How quantum sensing impacts quantum computing (e.g. accurate phase detection/estimation).
- Beyond the ‘standard quantum limit’ (quantum projection noise) – optimized detection.
- Quantum ‘illumination’ – exploiting residual entanglement for sensing in a lossy and noisy environment – target detection

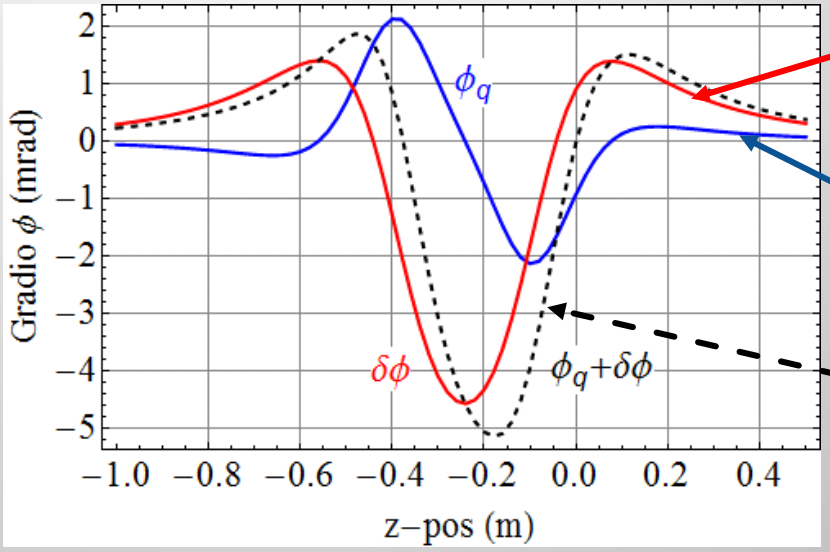
Back-up Slides

Quantum corrections* are significant in LMT k_{eff}~ 50 k_{Raman} cold atom interferometers

Wavepacket motion



Interferometer Phase – 50 k case



Phase w/o quantum correction

Quantum correction

Total phase

$$\phi_q(\boldsymbol{x},\boldsymbol{p}) = \frac{N\hbar k_{eff}}{2M}\boldsymbol{n_k}\cdot[t_1(t_1\boldsymbol{\omega}_{20}-\tau_3\boldsymbol{\omega}_{30})+2(\tau_2\boldsymbol{\omega}_{31}-t_1\boldsymbol{\omega}_{21})-\boldsymbol{\omega}_{32}+\boldsymbol{\omega}_{22}]$$

$$\boldsymbol{\omega}_{ij} \equiv \int_{\tau_{i-1}}^{\tau_i} t^j\left(\boldsymbol{n_k}\cdot\partial_{\boldsymbol{R}^{(0)}(\boldsymbol{x},\boldsymbol{p},t)}\right)\delta\boldsymbol{g}\left(\boldsymbol{R}^{(0)}(\boldsymbol{x},\boldsymbol{p},t)\right)dt, \text{ where}$$

$$\tau = \{t_1, t_1+T, t_1+2T\}.$$

- Large separation between the two paths accumulate significant quantum correction to semi-classical form for interferometer phase. Quantum corrections are computed via Wigner distributions or path Integrals.
- B. Dubetsky, S. B. Libby, and P. Berman, *Atom Interferometry in the Presence*…Atoms 2016, 4, 14.
- J. M. Hogan, D. M. S. Johnson, & M. A. Kasevich, *Light Pulse Atom Interferometry*, ArXiv 0806.3261.