Research Spotlight Forum

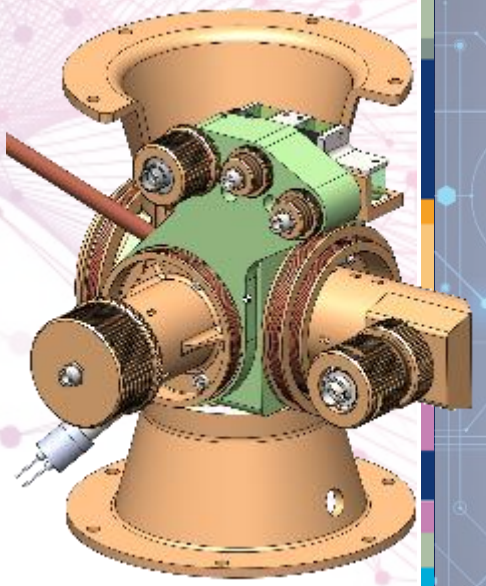
6.4.19 Quantum Information Sciences

Quantum (Atomic) Sensing at Sandia

Shanalyn Kemme

Manager, Org 05228

Atomic Optical Sensing



pability Overview

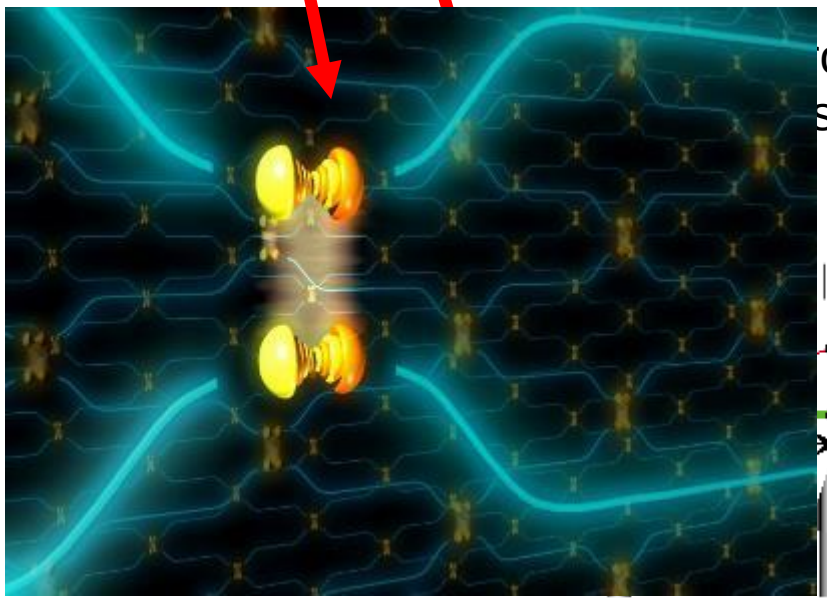
Sandia National Laboratories | Georgia Institute of Technology | Illinois | Purdue University | The University of Texas at Austin | The University of New Mexico | New Mexico State University | New Mexico Tech

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2019-6375 PE

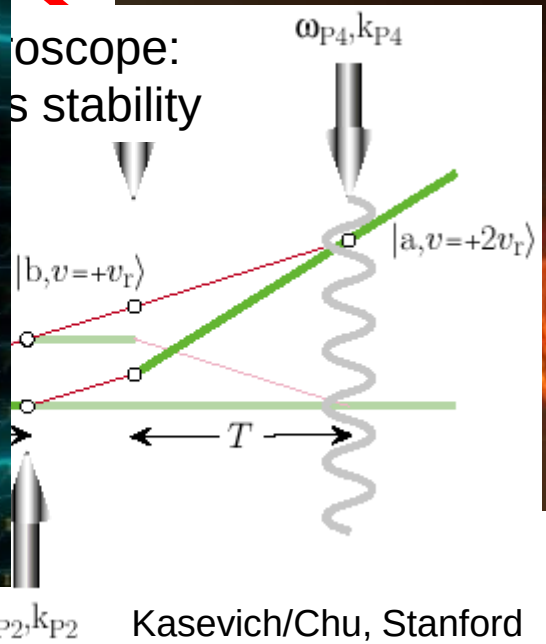
U.S. Department of Energy | NNSA

Applications of Neutral Atoms

- Atomic clocks
- Magnetometers
- Inertial sensors
- Q-bits for quantum information processing



oscope:
s stability

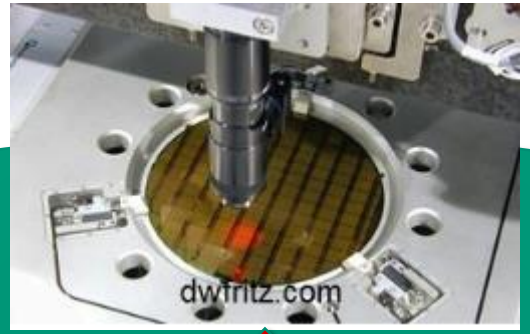


Kasevich/Chu, Stanford

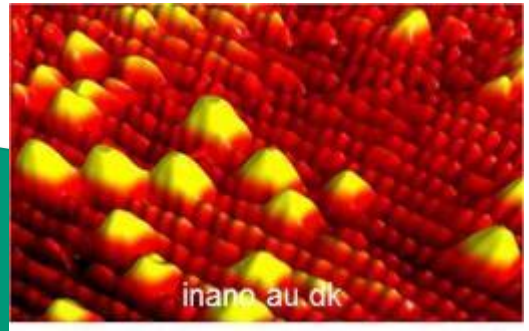
Potential Application Impact

Timing

Non Destructive Evaluation



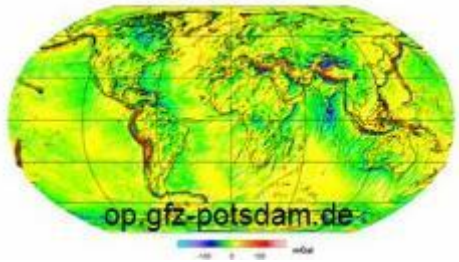
Surface Science



Medical Imaging

QUANTUM SENSORS

Navigation



Gravimetry

Trace Chemical Detection

Outline

Atomic sensors

- Trapped Ion Atomic Clocks (Peter Schwindt)
- Optically Pumped Magnetometers (Peter Schwindt)
- Atom Interferometers (Grant Biedermann)
- Electric Field Sensors (Yuan-Yu Jau)
- Neutral Atom Quantum Computing (Grant Biedermann)

Atomic Clocks at Sandia

Microwave atomic clocks

DARPA funded efforts

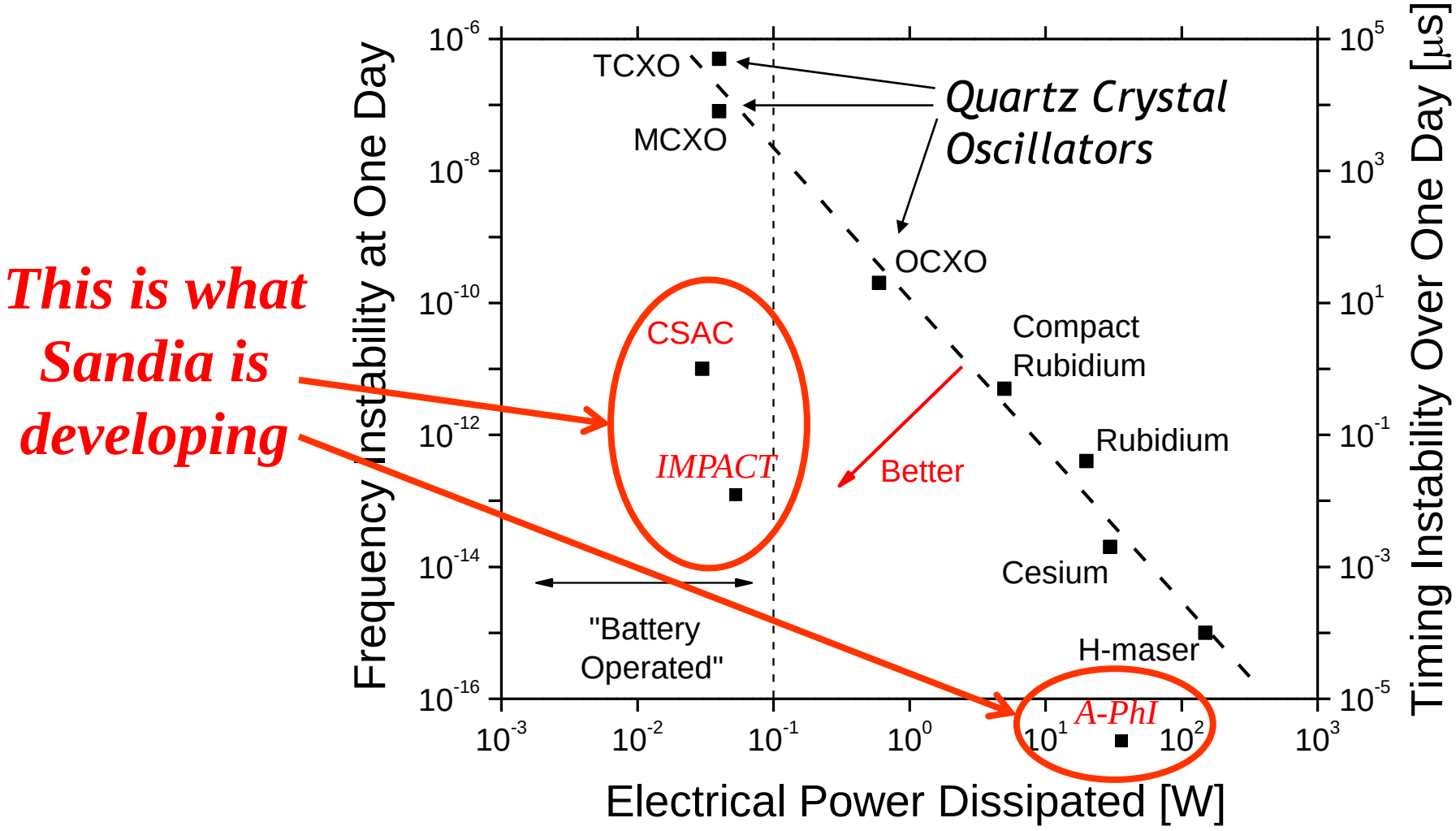
- Chip Scale Atomic Clocks (CSAC)
  - Developed vertical cavity surface emitting lasers (VCSELs)
- Trapped Yb ion atomic clocks
  - Integrated Micro Primary Atomic Clock Technology (IMPACT)
  - Atomic Clocks with Enhanced Stability (ACES)

Optical atomic clocks

Yb ion optical clocks

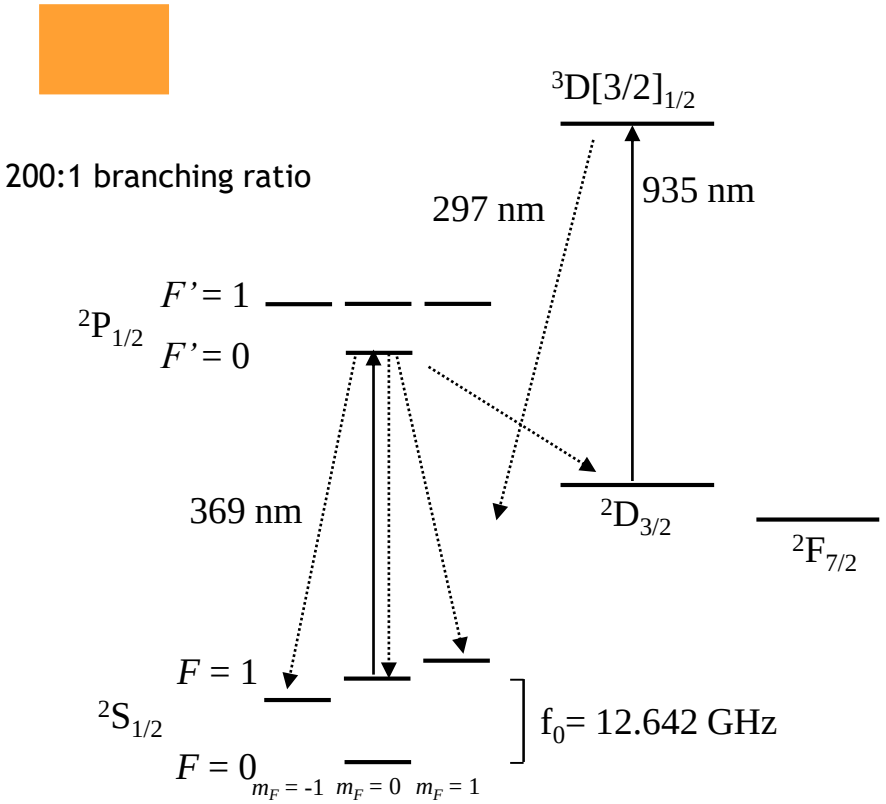
- Internally funded: Laboratory Directed Research and Development (LDRD)
- DARPA funded: Atomic-Photonic Integration (A-PhI)

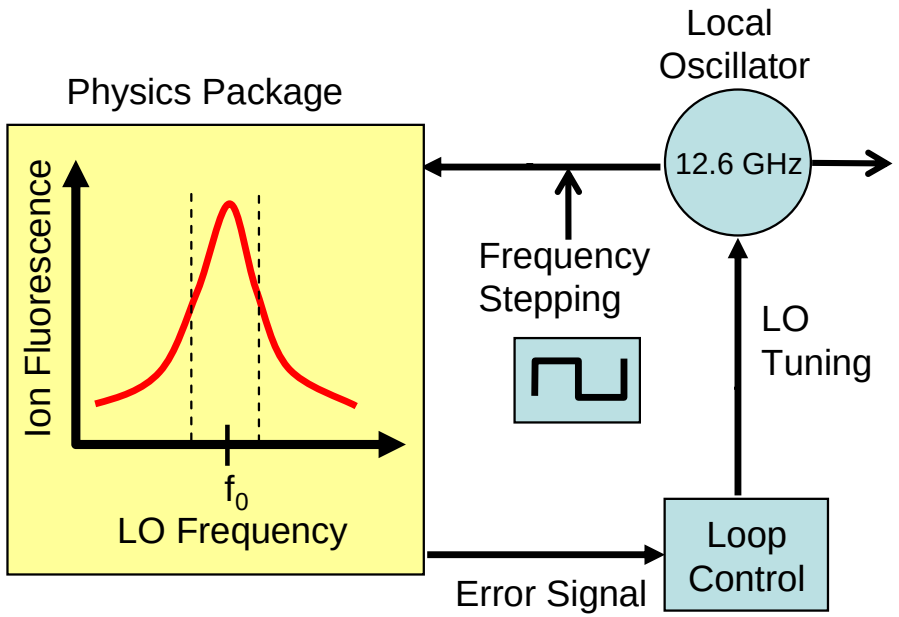
Atomic Clocks - Commercial

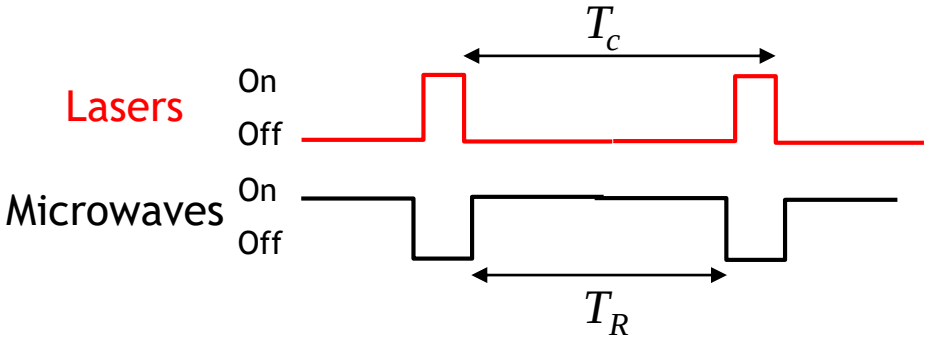


Adapted from figure by M. Garvey, Symmetricom

Atomic Frequency Reference with $^{171}Yb^{+}$







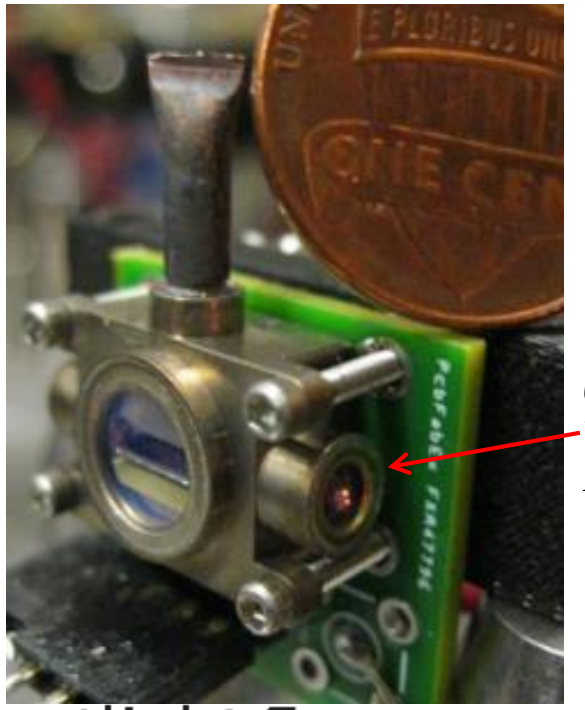
IMPACT Phase III Atomic Clock Operation

Demonstrated potential of clock based on trapped Ytterbium ions, $^{171}Yb^{+}$.

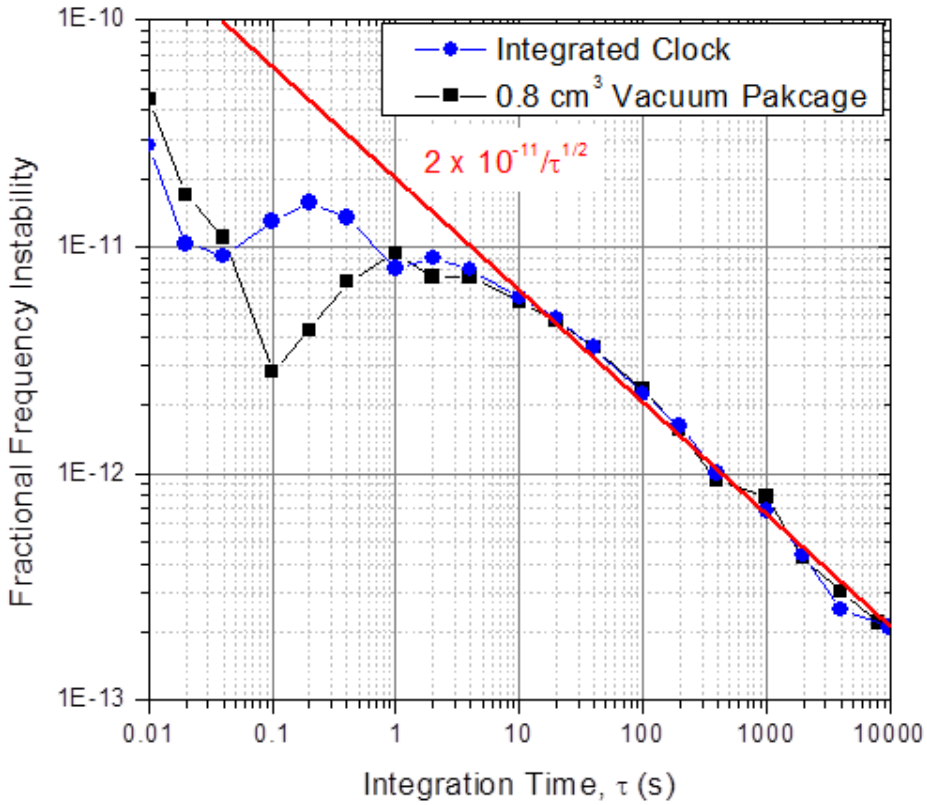
Full clock system operated at NIST for 49 days

Miniaturized vacuum package, 0.8 cm^3

- Integrated RF Paul trap
- MEMS Yb sources
- Demonstrated $2 \times 10^{-11}/\tau^{1/2}$ instability



0.8 cm^3 Vacuum Package



Enabling New Capabilities

- *GPS denied environments*
- *Rapid GPS acquisition*
- *Miniaturized platforms*

Applications

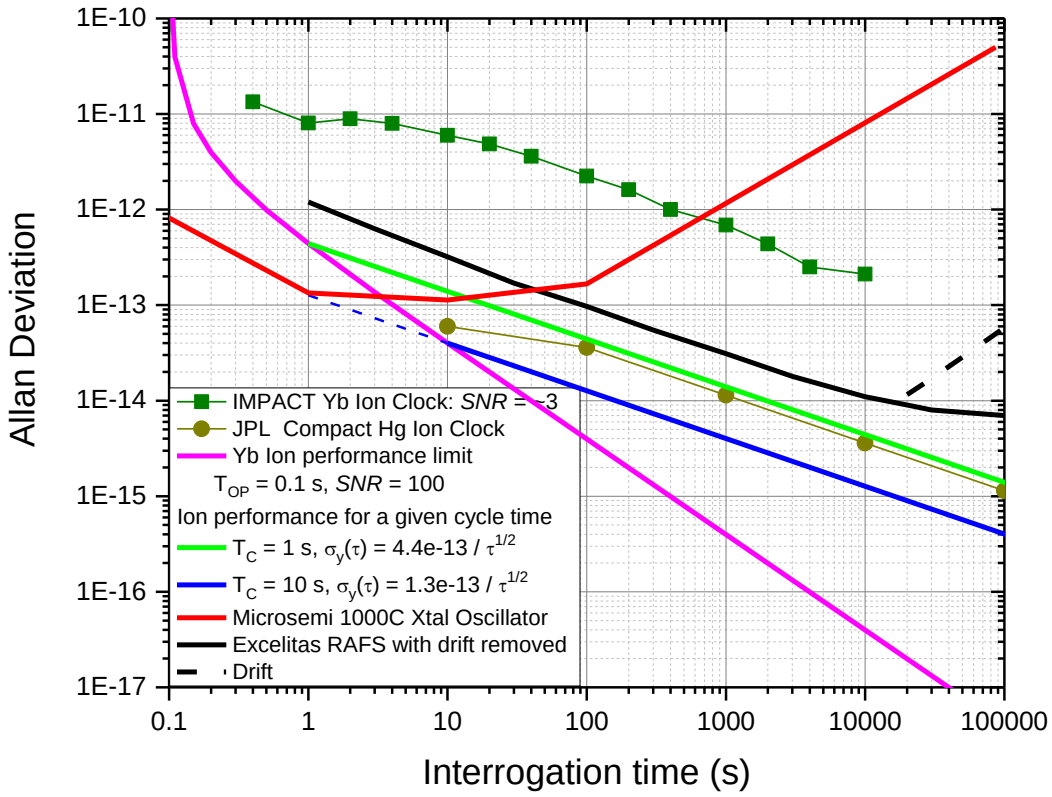
Trapped ions inherently insensitive to acceleration

Excellent timing for:

- Rapid GPS acquisition, and GPS denied navigation and timing
- Nano/pico (cube) satellites
- Pulsed radio and spread spectrum communications

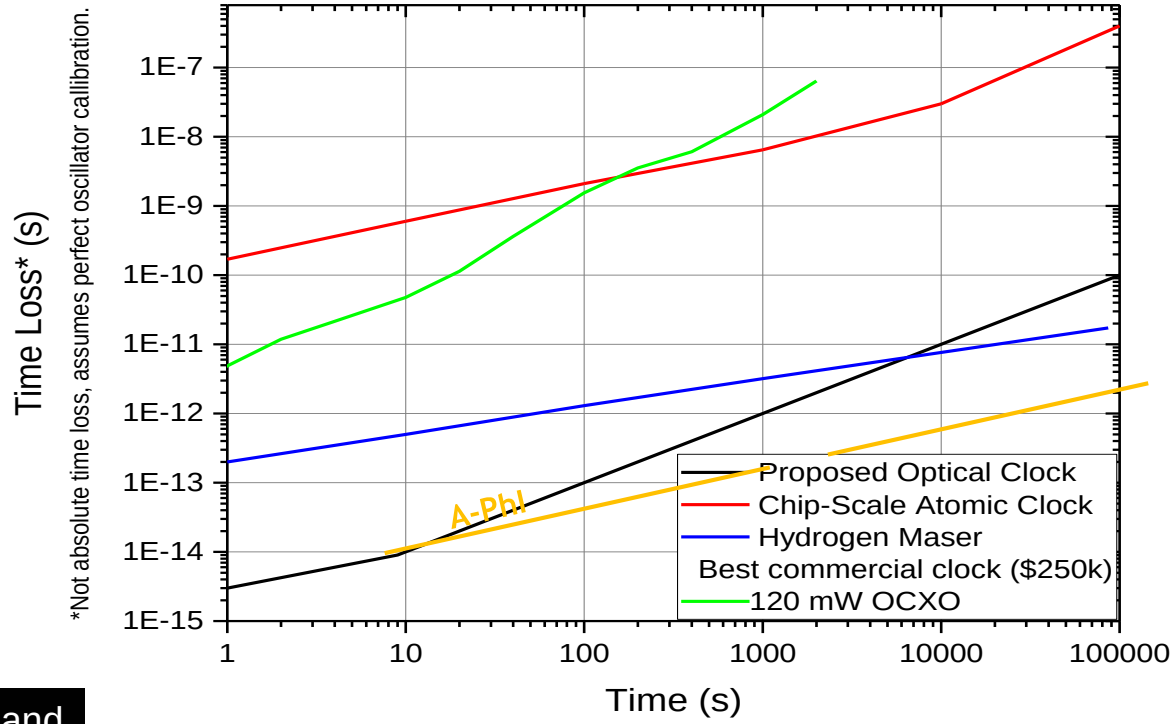
Potential low power GPS Rb replacement

- Trapped ions have reduced drift



Optical Clock Applications

Toward GPS-denied navigation solutions, particularly in the areas of Surveillance & Reconnaissance, hypersonic vehicles, and autonomous aircraft



Oscillator	Size	Power	Time Loss/Day (relative)	Cost
Miniature Optical Clock	5 L	10 W	0.08 ns/day	???
Chip-scale atomic clock	16 mL	120 mW	300 ns/day	~$2,000
Hydrogen Maser	370 L	75 W	.015 ns/day	$250,000
Low-power OCXO	2 mL	120 mW	10,000 ns/day	~$400

Optically Pumped Magnetometers (OPMs) at Sandia

OPMs for magnetoencephalography (MEG)

- National Institutes of Health

OPMs for the detection of status of capacitive discharges units (CDUs)

Development of a OPM gradiometer

- DARPA: Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT)

Nitrogen-vacancy centers is diamond (Pauli Kehayias)

- High spatial resolution magnetometry

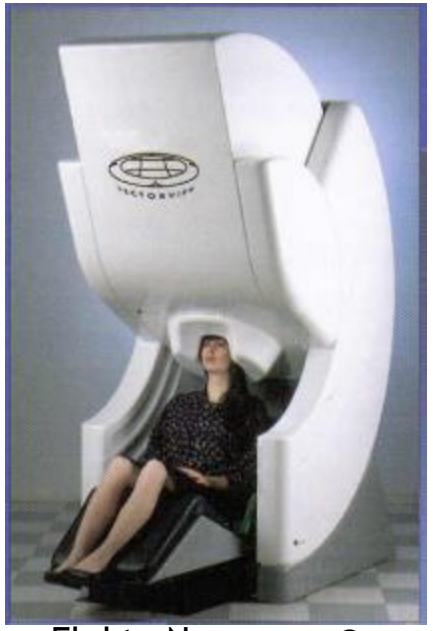
Current Technology

Superconducting Quantum Interference Devices (SQUIDs)

- Mature technology
  - Highly sensitive, 2-3 fT / $Hz^{1/2}$
  - Whole head coverage (> 300 channels)
- Disadvantages
  - Require cryogenic cooling
  - Large and power hungry
  - $$$ → ~150systems worldwide
  - Fixed head size

Optically Pumped Magnetometer Potential

- Record sensitivity of 160 aT / $Hz^{1/2}$ (Romalis, Princeton)
  arXiv:0910.2206v1 [physics.atom-ph] 12 Oct 2009
- Vast improvement in size and portability.
- Sensor closer to the source

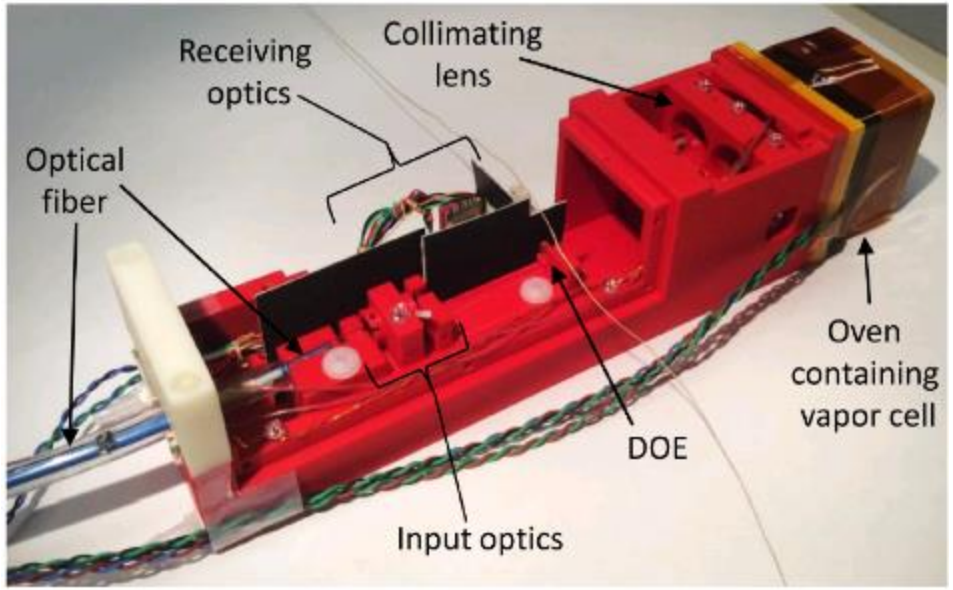


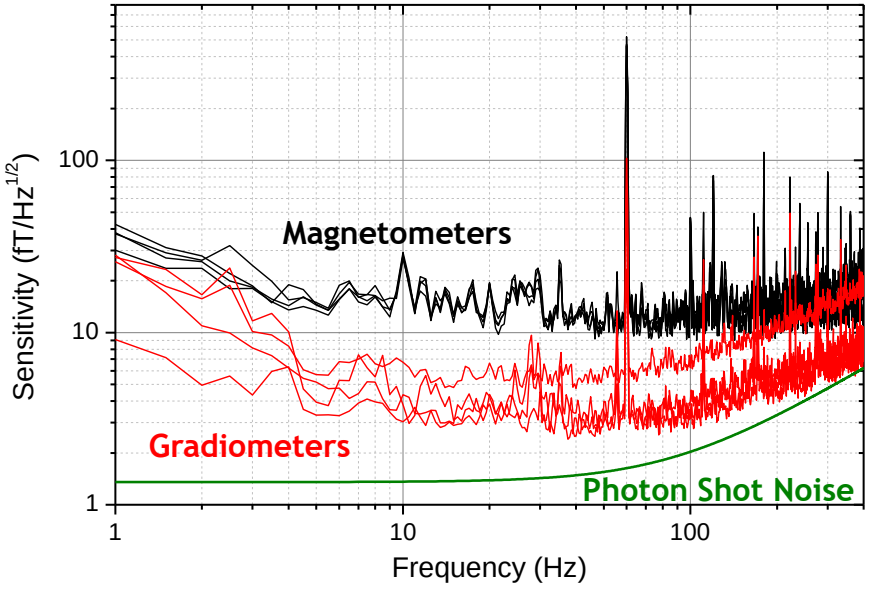
Elekta Neuromag®.

(Million-dollar shielded room sold separately)

University College London, University of Nottingham, QuSpin

4-Channel Sensor Performance





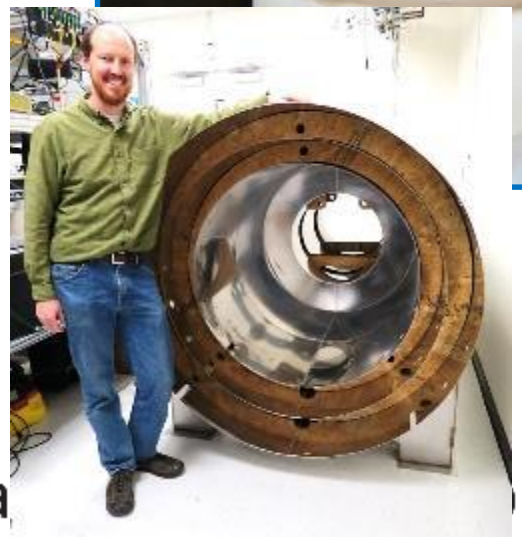
	Ch 1	Ch 2	Ch 3	Ch 4
DC Slope	0.158 V/nT	0.14 V/nT	0.158 V/nT	0.228 V/nT
3 dB Bandwidth	83 Hz	85 Hz	87 Hz	86 Hz

A. P. Colombo *et al.*, "Four-channel optically pumped atomic magnetometer for magnetoencephalography," *Optics Express*, vol. 24, no. 14, pp. 15403-15416, 2016.

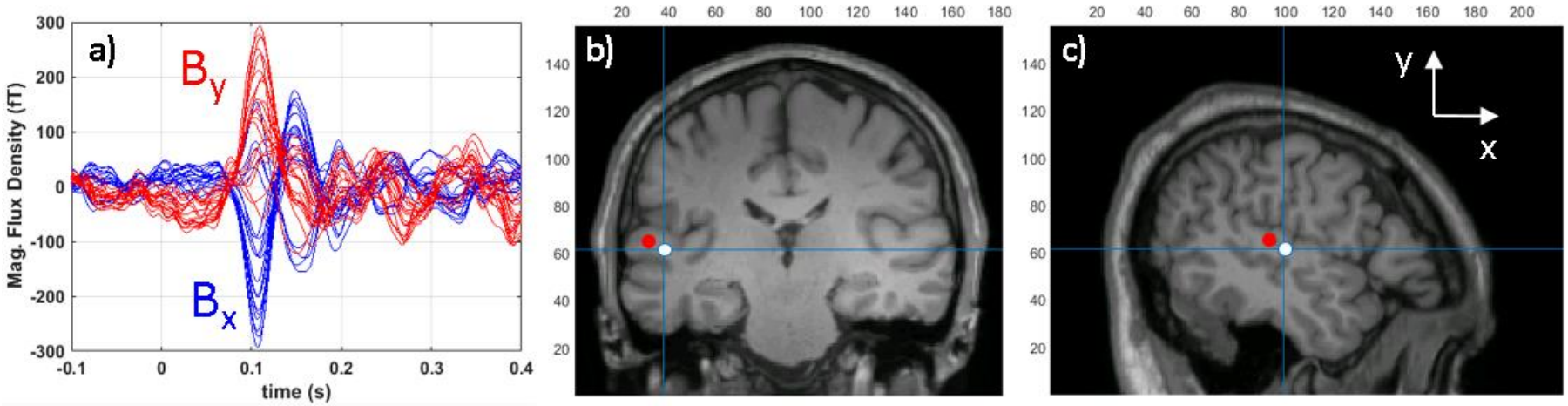
The 20-Channel Array

5-sensor, 20-channel array

Partially covers the left hemisphere



Auditory Evoked Magnetic Fields: Localization



- Auditory stimulation
  - 1000 Hz tone, every 1 to 1.5 s
  - 456 trials
- White dot: OPM location
- Red dot: SQUID MEG location

Comparison of the AEF source localization error		
	Position Error	Moment Angle Error
SUBJ1	2.4 cm	19 °
SUBJ2	0.5 cm *	15 °
SUBJ3	1.0 cm	15 ° (+180 °)
* Poor MRI coregistration.		

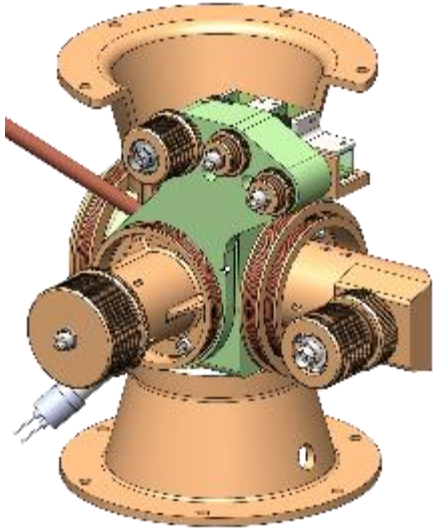
Project Overview

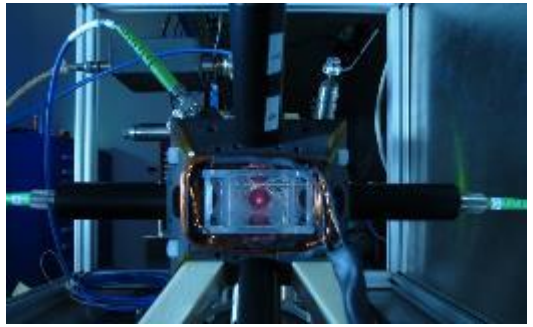
Grant Biedermann, PI

Strategic Inertial Guidance

ΣΙΓΜΑ

with MAtterwaves





Atom interferometer performance comparison

	Navigation Grade (HG9900)	**Atom Interferometry (Lab demonstration)**
Accel Bias (1σ) [ug]	< 25	$< 10^{-4}$
Accel SF (1σ) [PPM]	< 100	$< 10^{-4}$
Accel Random Walk [μg/root-Hertz]	not reported, QA ~ 10	10^{-5}
Gyro Bias (1σ) [deg/hr]	< 0.003	$< 7 \times 10^{-5}$
Gyro SF [PPM]	< 5	< 5
Gyro Random Walk (1σ) [deg / root-hour]	< 0.002	2×10^{-6}

The message

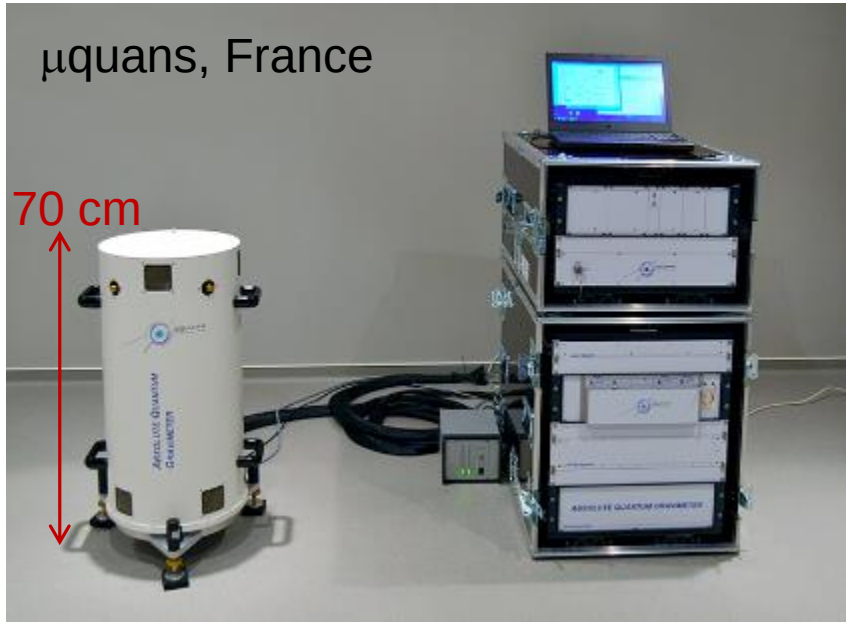
- Atom interferometers operate spectacularly well in laboratory environments
- Fielding is challenging in a compact form and in all but the most benign environments
- This stems from system reliability issues, system size, and dynamic range

Guiding principle of SIGMA

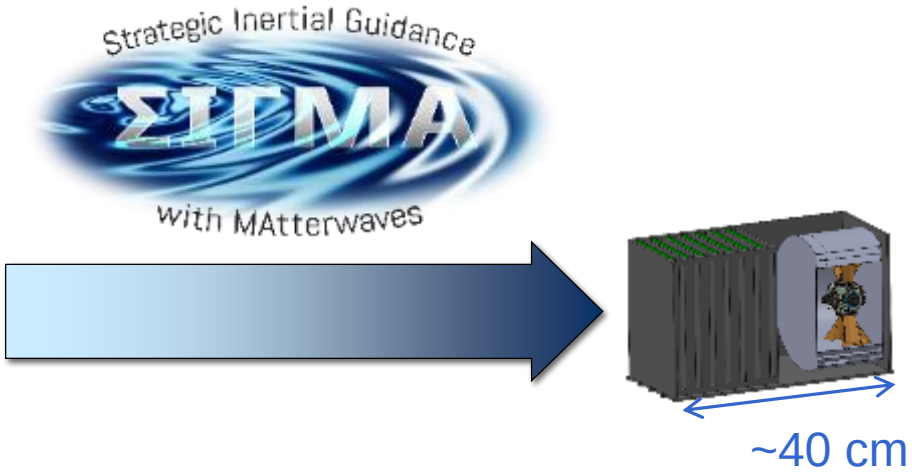
Target a **rugged** demonstrator requiring revolutionary system advances

Strategic Inertial Guidance
ΣΙΓΜΑ
with MAtterwaves

SIGMA vision: *more specifically*



100 kg, 300 W, 50 ng/√Hz, $500k



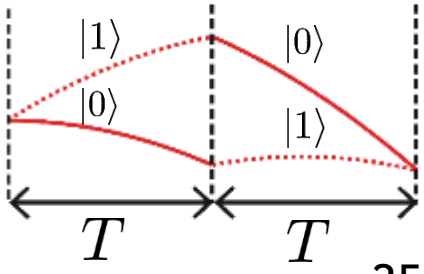
	AI COTS	SIGMA prototype	SIGMA future
Volume [liters]	3,000	5	<0.3

Enable sub-100 *ng* performance in 1000x smaller package

What will it take?

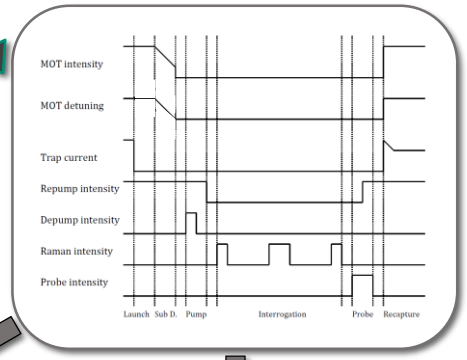
UHV vacuum system

Atom interferometer physics



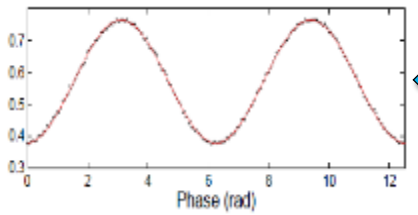
Dynamic range servo

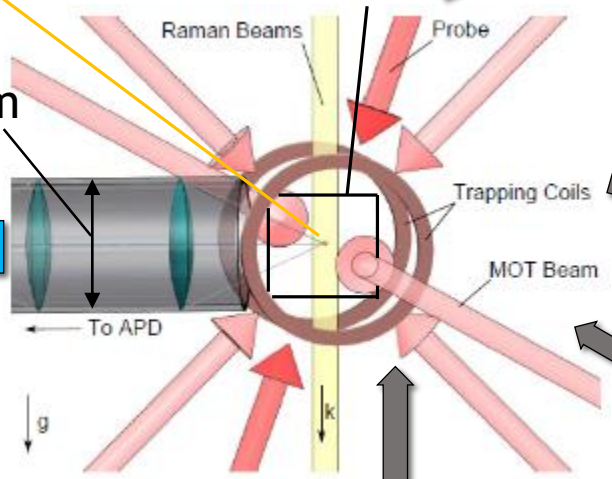
Control electronics

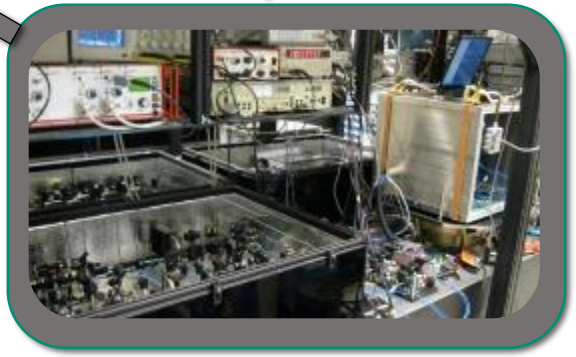


25 mm

Acceleration →







Agile & stable laser system

Custom optomechanics

H. J. McGuinness, et al., Appl Phys Lett **100**, 011106 (2012).

Advanced sensing—entanglement

Constantin Brif, 8759

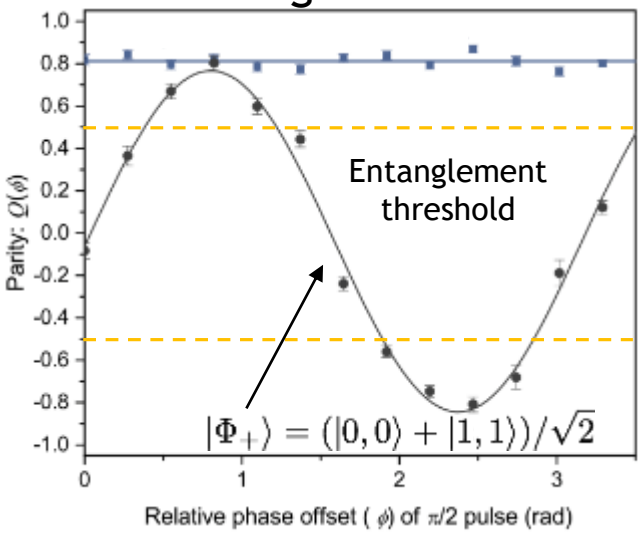
- For N independent atoms, phase uncertainty = **standard quantum limit** (SQL):

$$\Delta\phi \geq \Delta\phi_{\mathrm{SQL}} = 1/\sqrt{N}$$

- AI precision can surpass the SQL using an **entangled state**:

$$\Delta\phi < \frac{1}{\sqrt{N}}$$

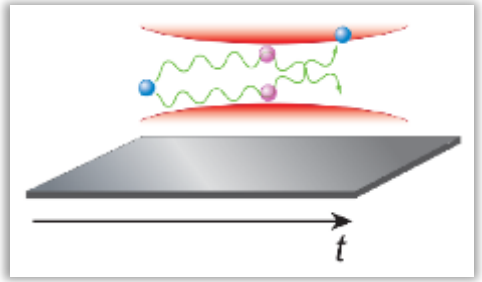
2 entangled Cs atoms



SNL results: Nat. Phys. 2016

Challenge

First ever demonstration of entanglement-enabled gain in an inertially-sensitive atom interferometer



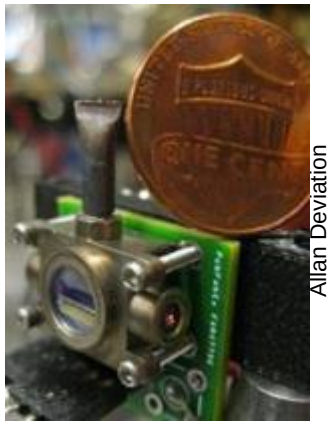
SNL-demonstrated gravimeter in this system, *PRL* (2012)

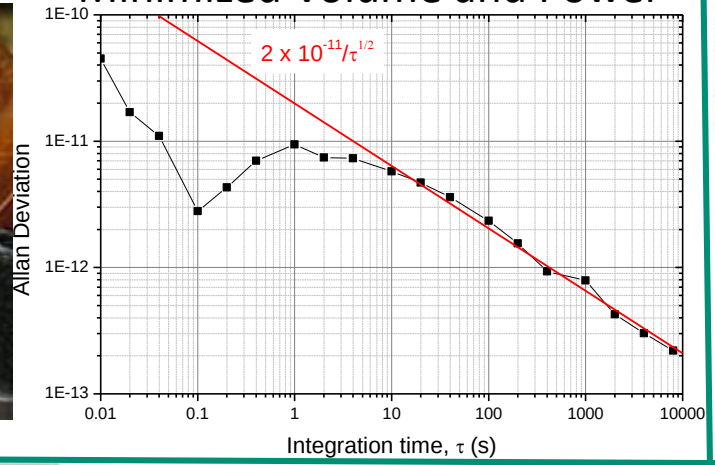
Atomic Sensing

ATOMIC CLOCKS

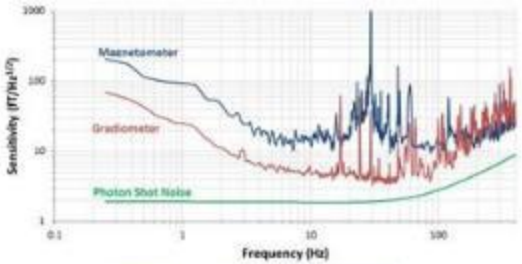
Maximized Precision and Stability

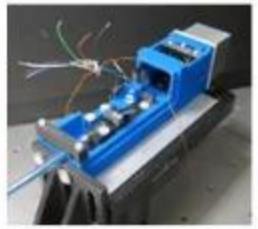
Minimized Volume and Power

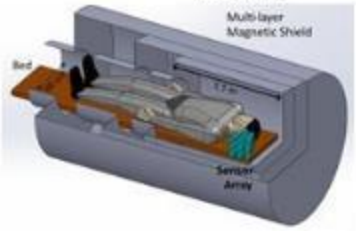




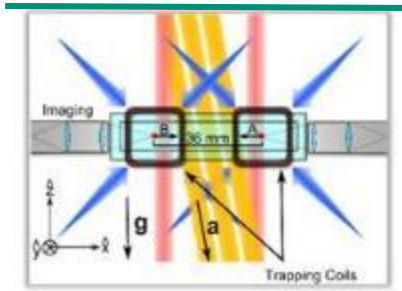
ATOMIC MAGNETOMETRY FOR MAGNETOENCEPHALOGRAPHY

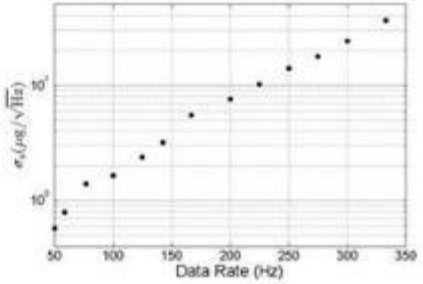


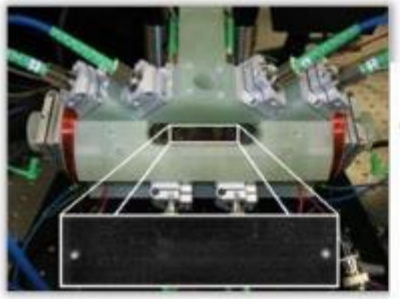


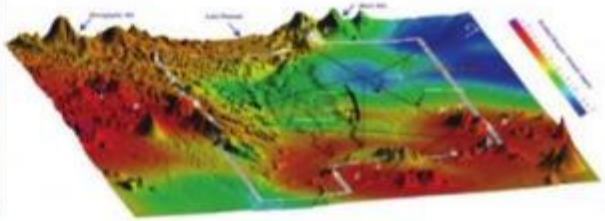


ATOM INTERFEROMETRY



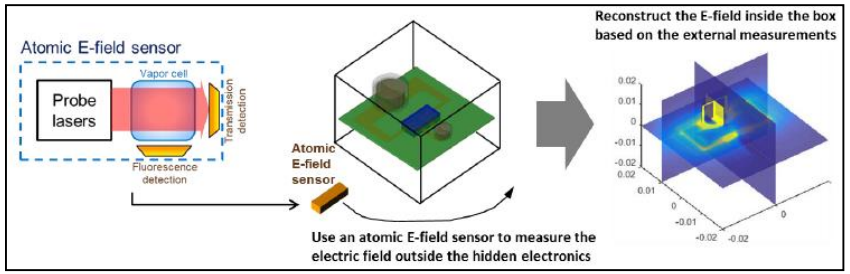


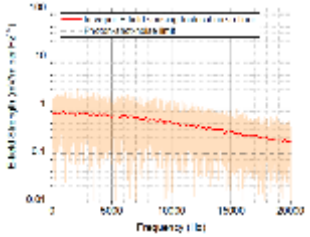




FIELD SENSING

Rydberg atom based electric field sensing





Demonstrated in-vapor E-field sensitivity better than 1 mV/(m·Hz$^{1/2}$)