SAND2019-6375PE

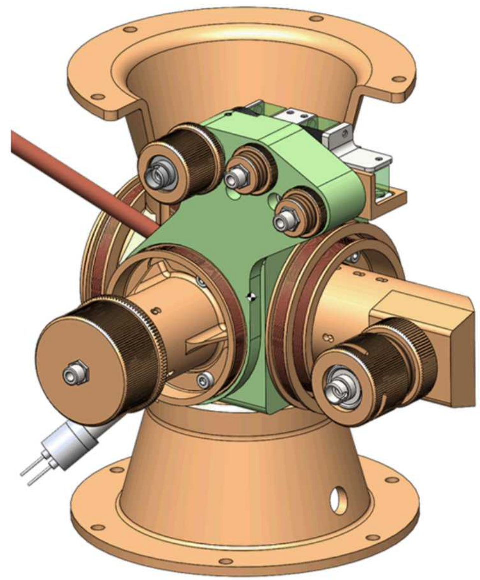
Strategic Inertial Guidance ΣΙΓΜΑ with MAtterwaves

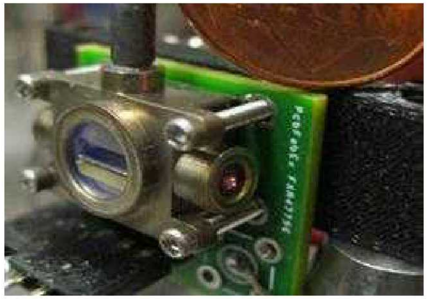
Quantum (Atomic) Sensing at Sandia

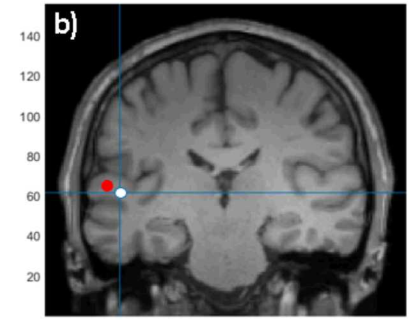
Shanalyn Kemme

Manager, Org 05228

Atomic Optical Sensing







U.S. DEPARTMENT OF ENERGY

NNSA

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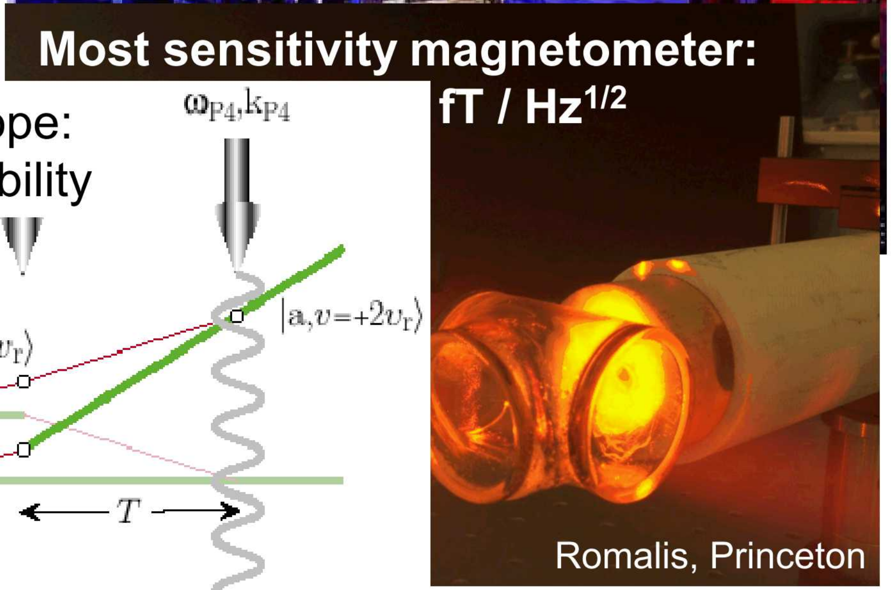
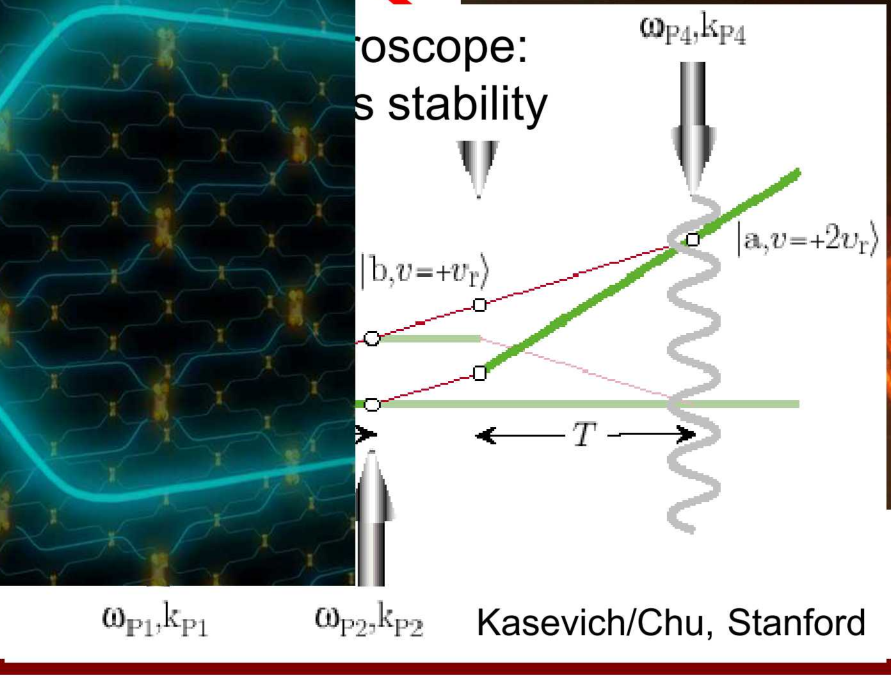
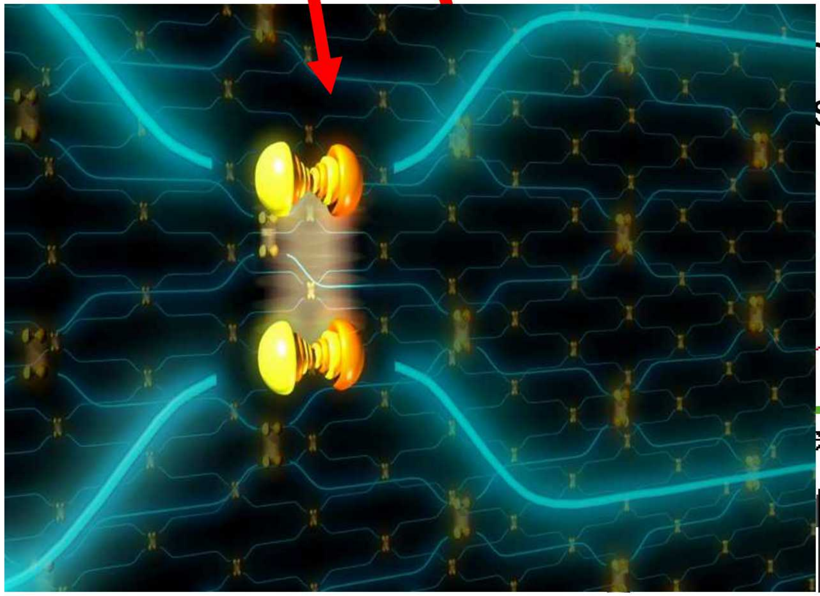
Applications of Neutral Atoms

- Applications of neutral atoms
  - Atomic clocks
  - Magnetometers
  - Inertial sensors
  - Q-bits for quantum information processing





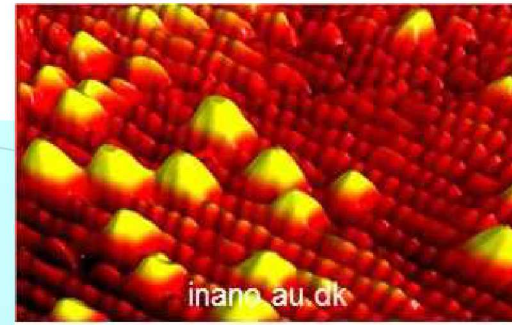


Potential Application Impact

Timing

Non Destructive Evaluation

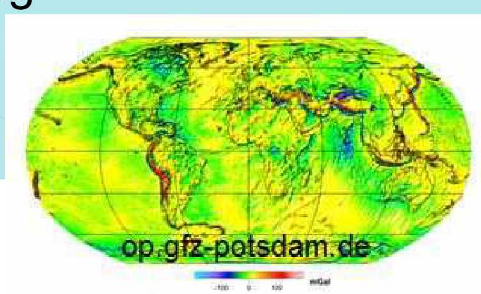
Surface Science



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

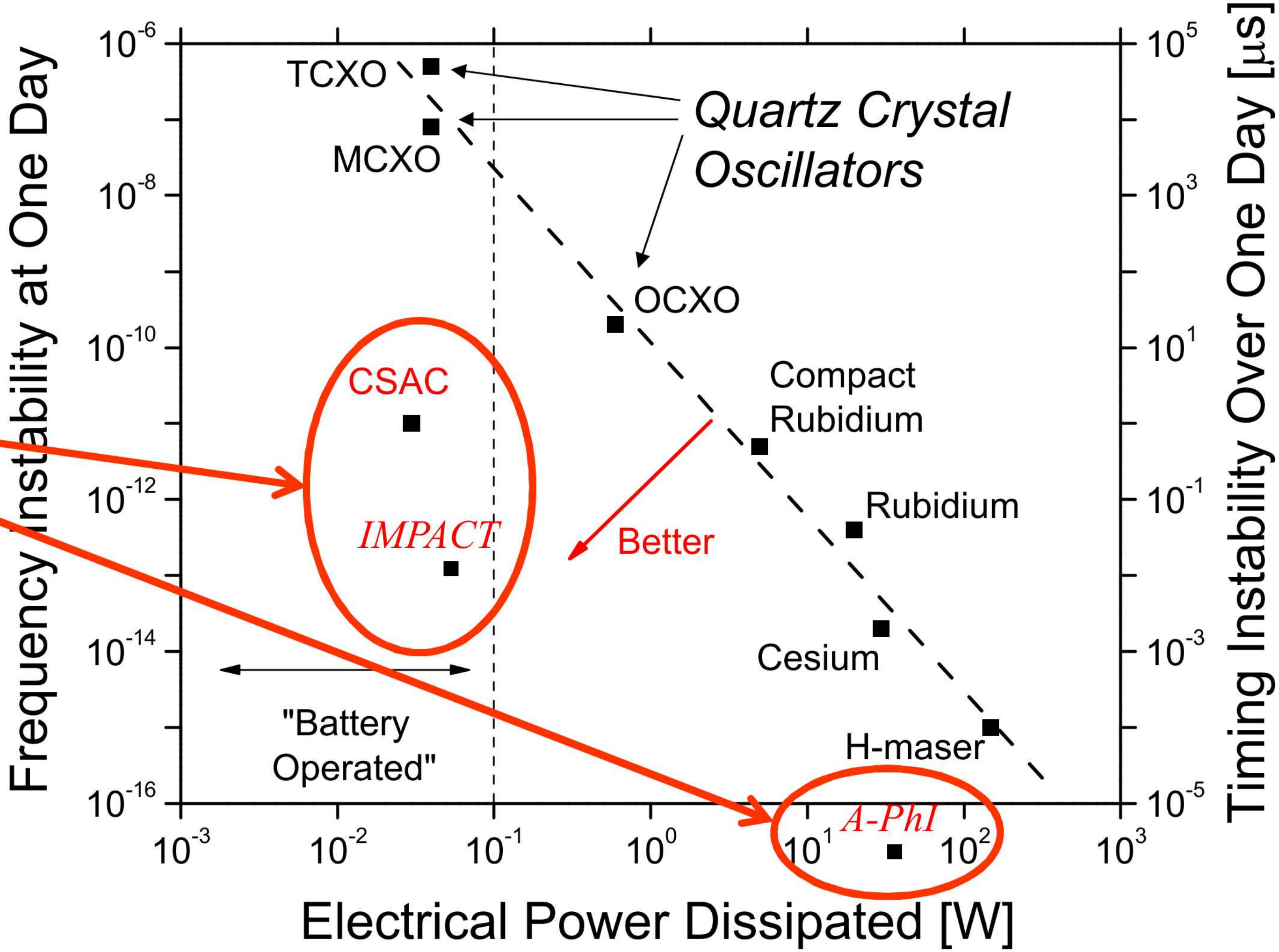
- DARPA funded efforts
  - Chip Scale Atomic Clocks (CSAC)
    - Developed vertical cavity surface emitting lasers (VCSELs)
  - Trapped Yb ion atomic clocks
    - Integrated Micro Primary Atomic Clock Technology (IMPACT)
    - Atomic Clocks with Enhanced Stability (ACES)

Optical atomic clocks

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

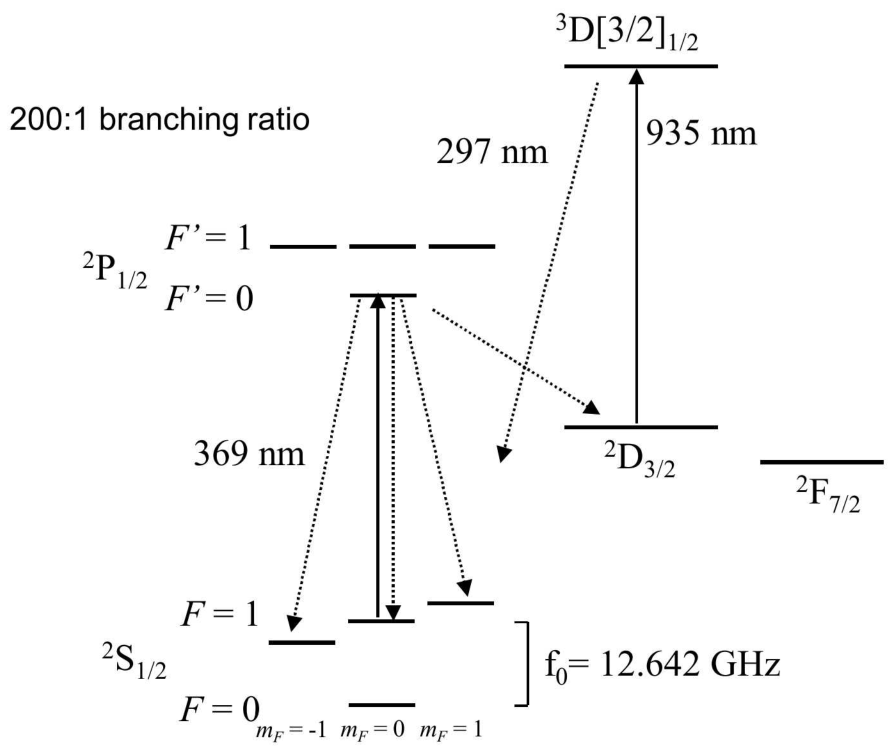
Atomic Clocks - Commercial

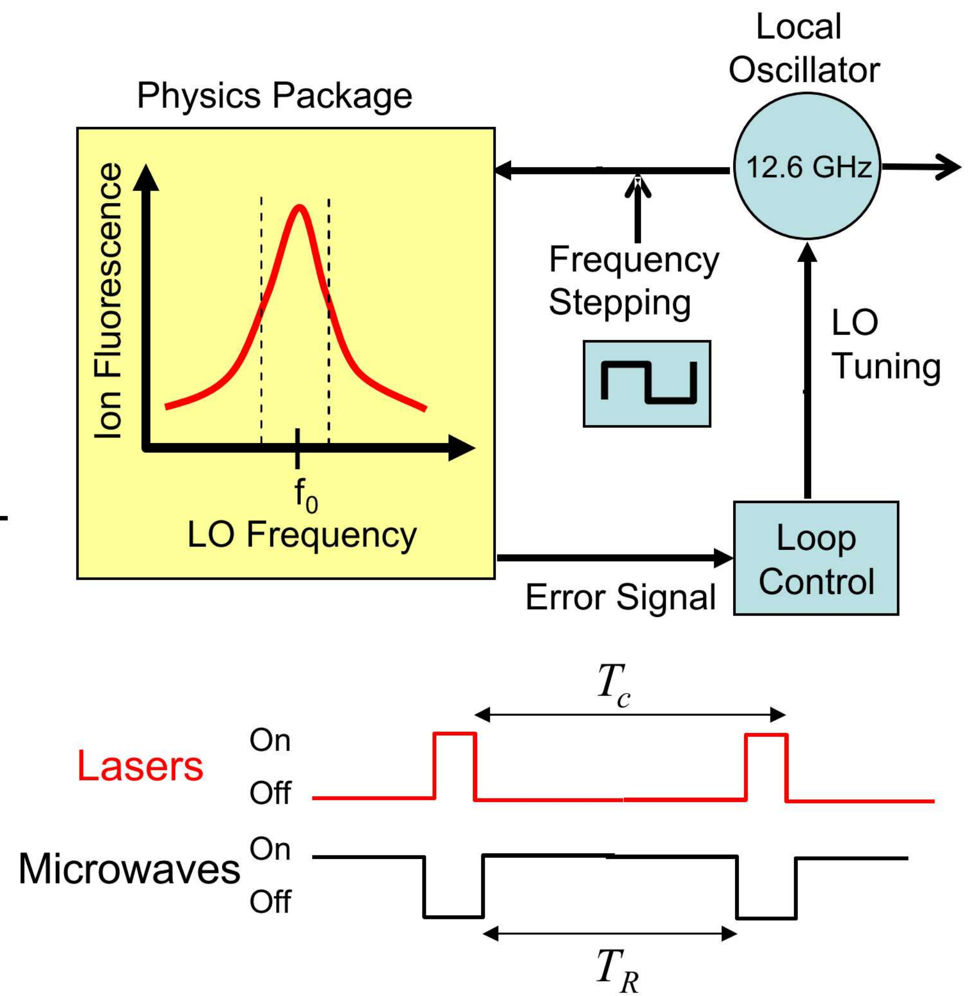
This is what Sandia is developing



Adapted from figure by M. Garvey, Symmetricom

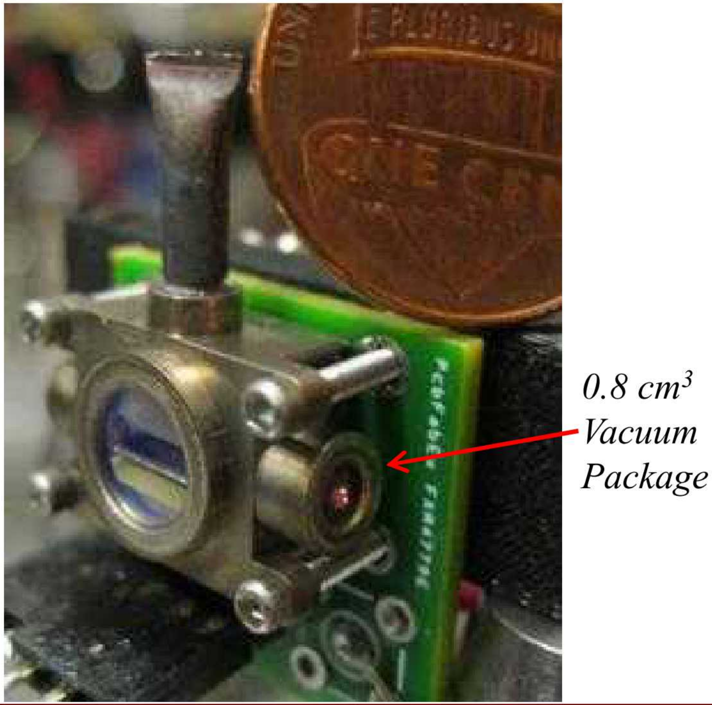
Atomic Frequency Reference with $^{171}Yb^+$

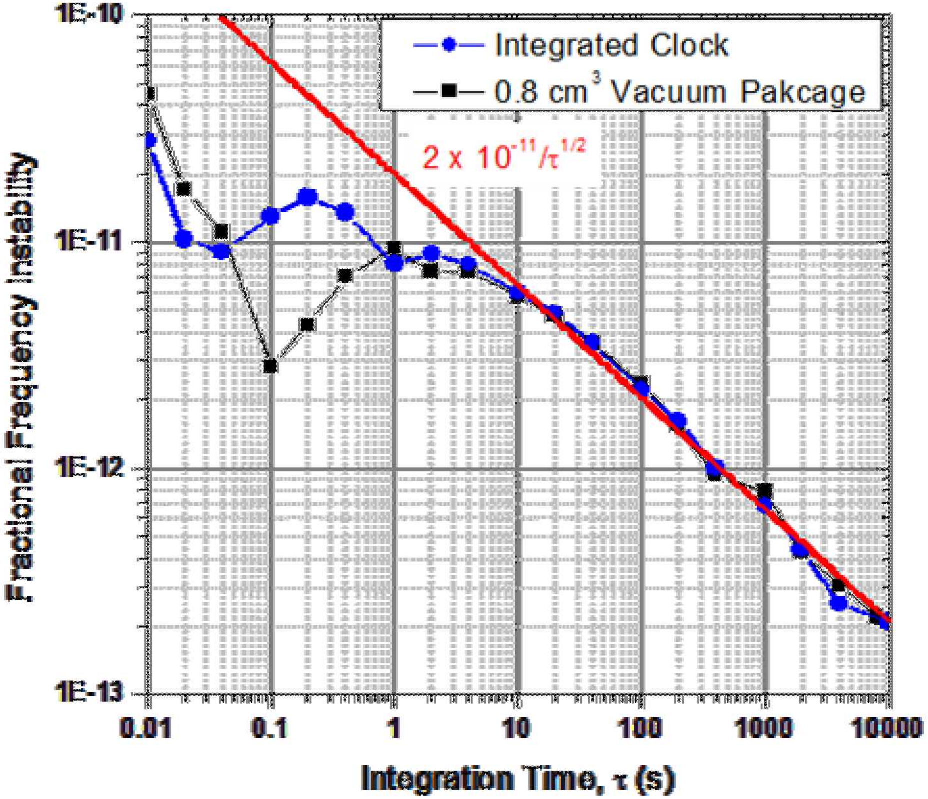




IMPACT Phase III Atomic Clock Operation

- 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

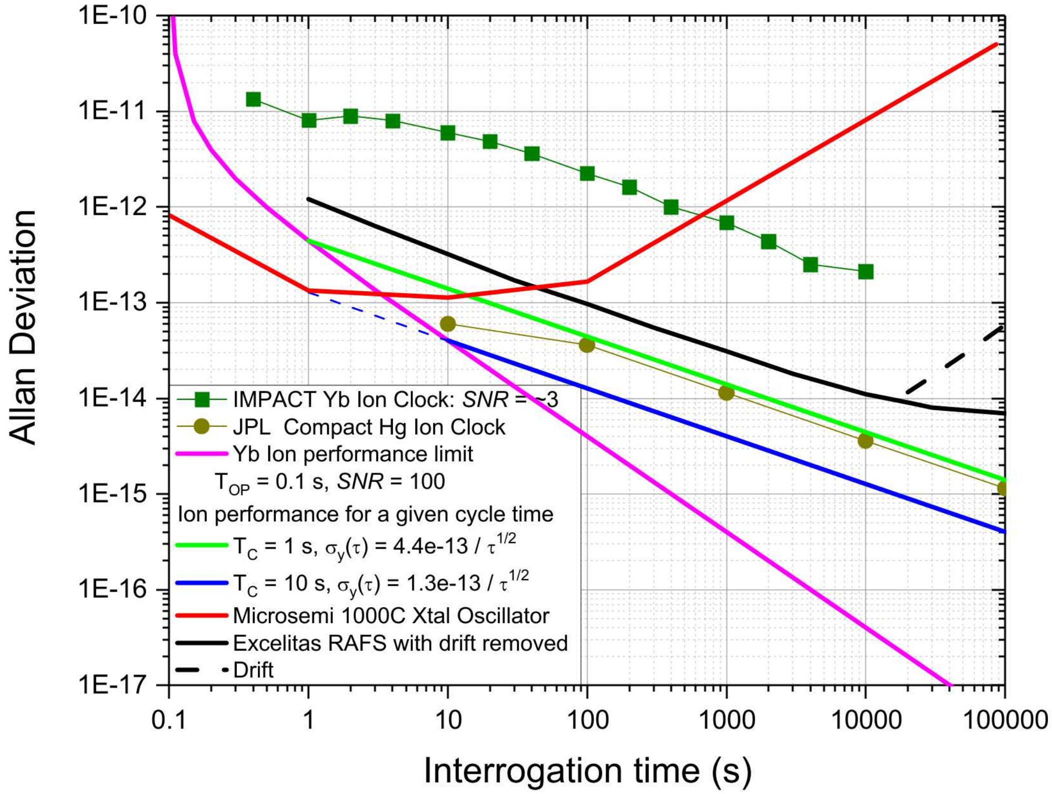




Enabling New Capabilities
- *GPS denied environments*
- *Rapid GPS acquisition*
- *Miniaturized platforms*

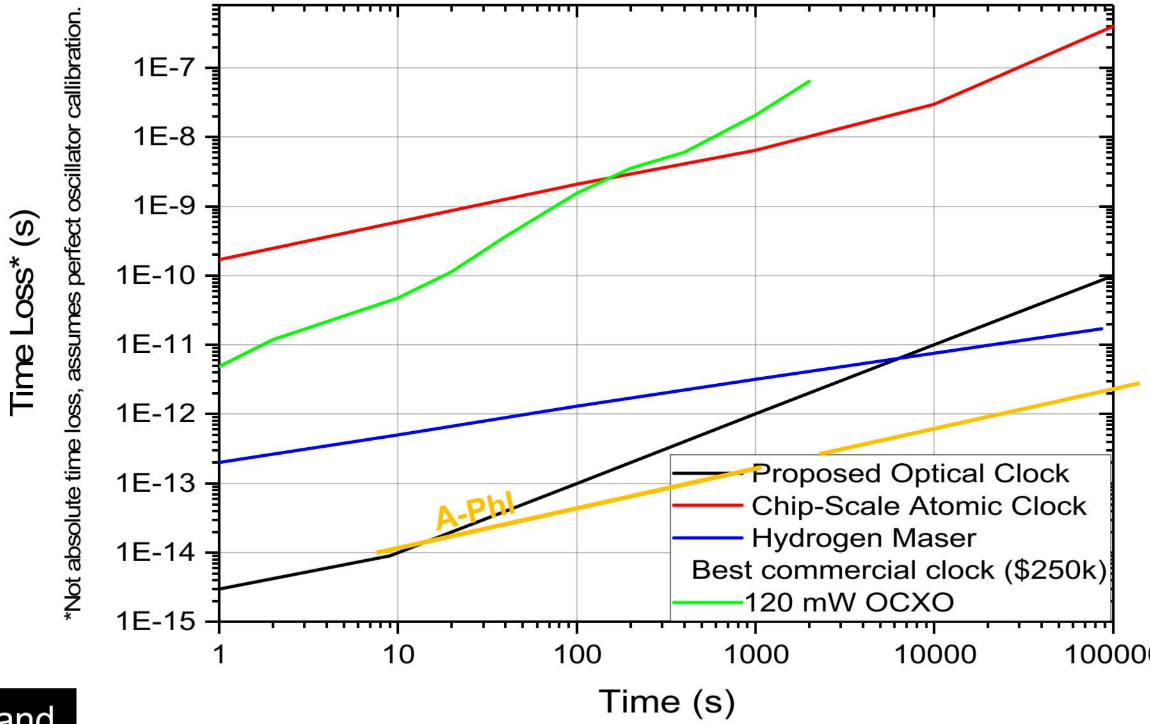
Applications

- 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

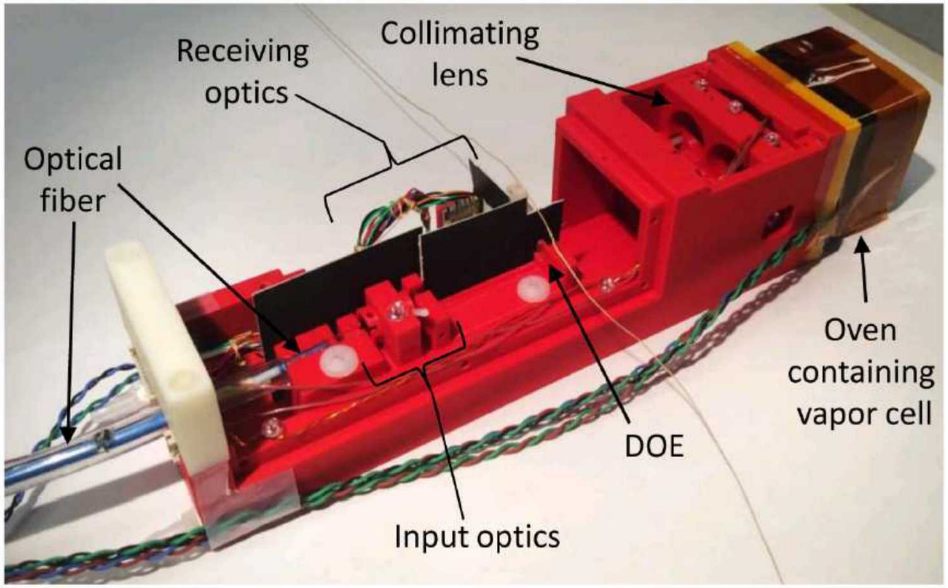
Elekta Neuromag®.
(Million-dollar shielded room sold separately)

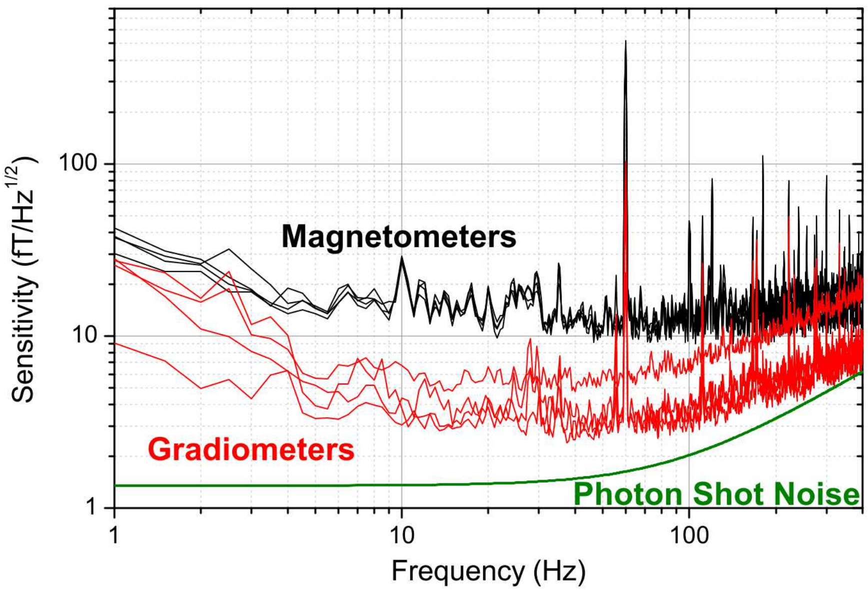
University College London, University of Nottingham, QuSpin

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

4-Channel Sensor Performance





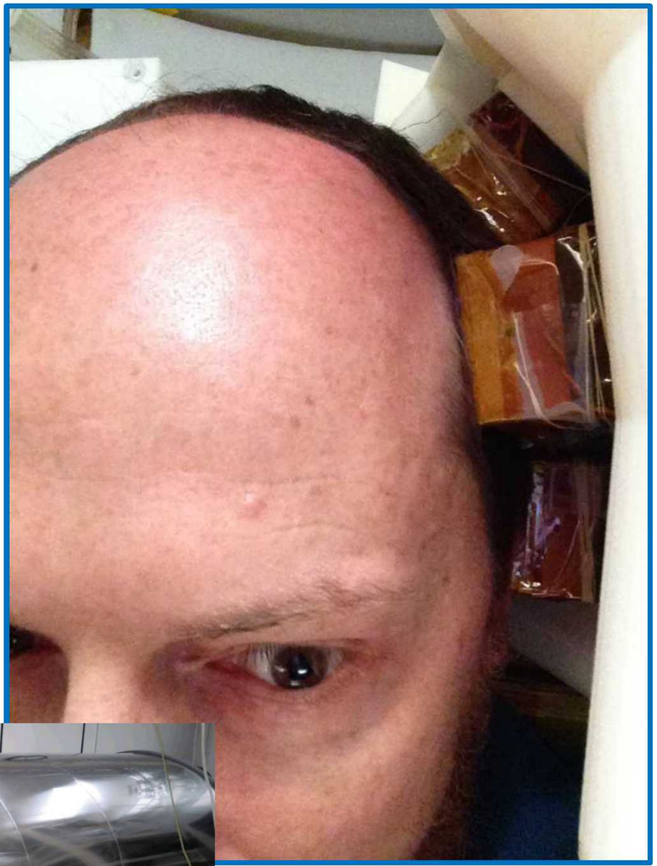
	Ch 1	Ch 2	Ch 3	Ch 4
DC Slope	0.158 V/nT	0.14 V/nT	0.158 V/nT	0.228 V/nT
3 dB Bandwidth	83 Hz	85 Hz	87 Hz	86 Hz

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

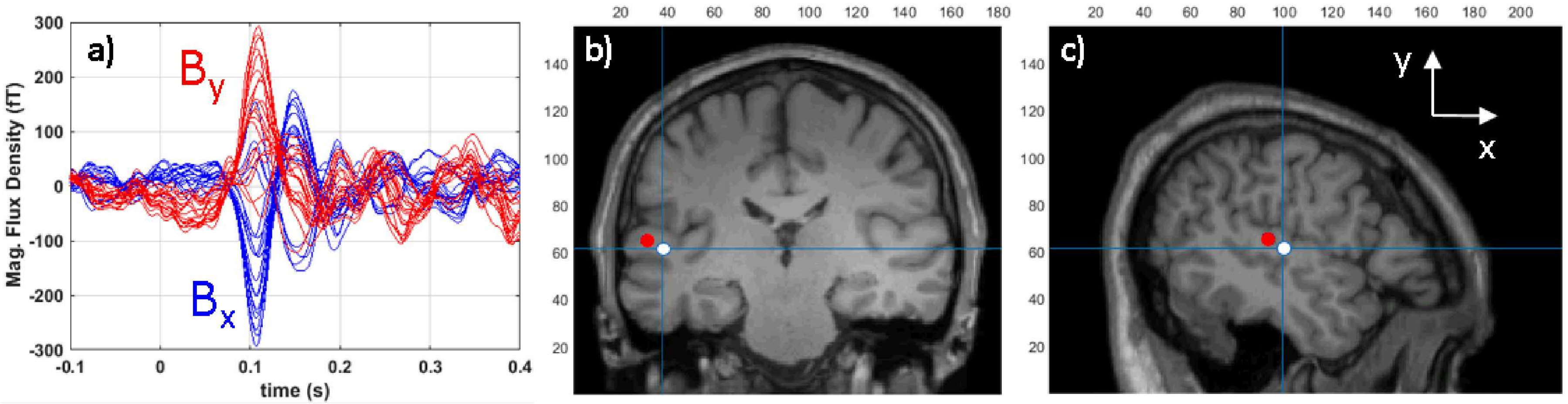
The 20-Channel Array

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 °)

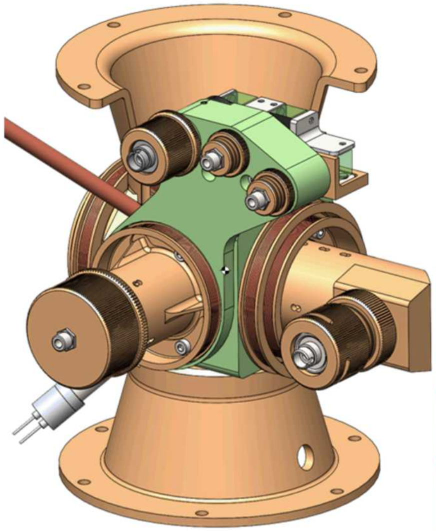
*** Poor MRI coregistration.**

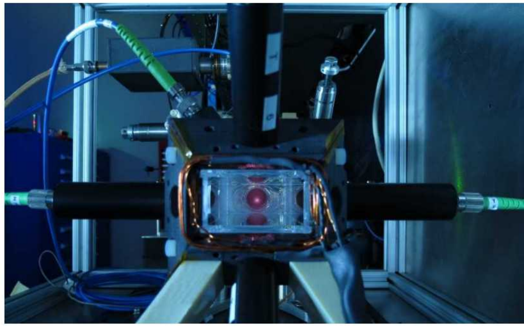
Strategic Inertial Guidance with MAtterwaves

ΣΙΓΜΑ

Project overview

Grant Biedermann, PI





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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}

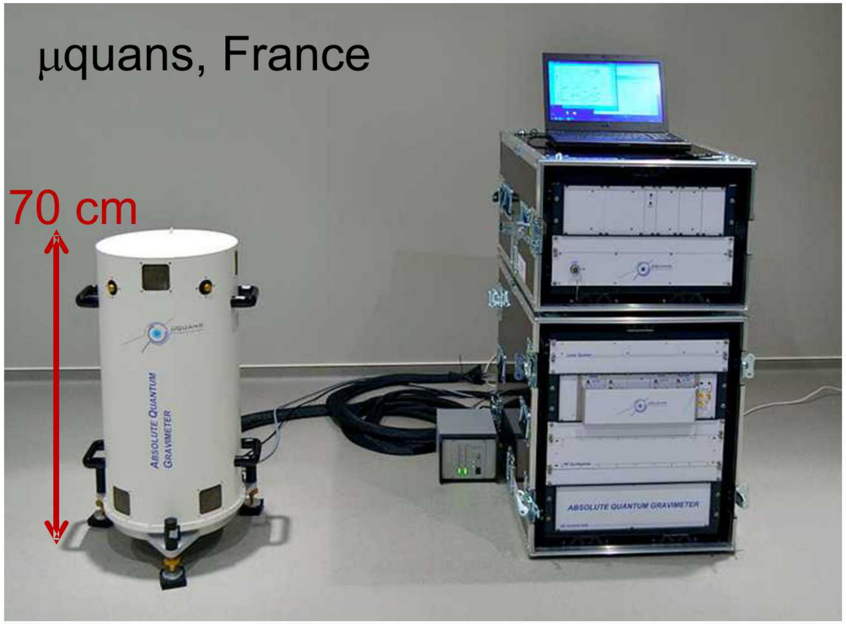
The message

- 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

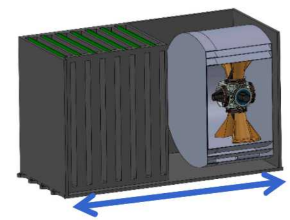
Strategic Inertial Guidance
ΣΙΓΜΑ
with MAtterwaves

SIGMA vision: *more specifically*



100 kg, 300 W, 50 n*g*/√Hz, $500k

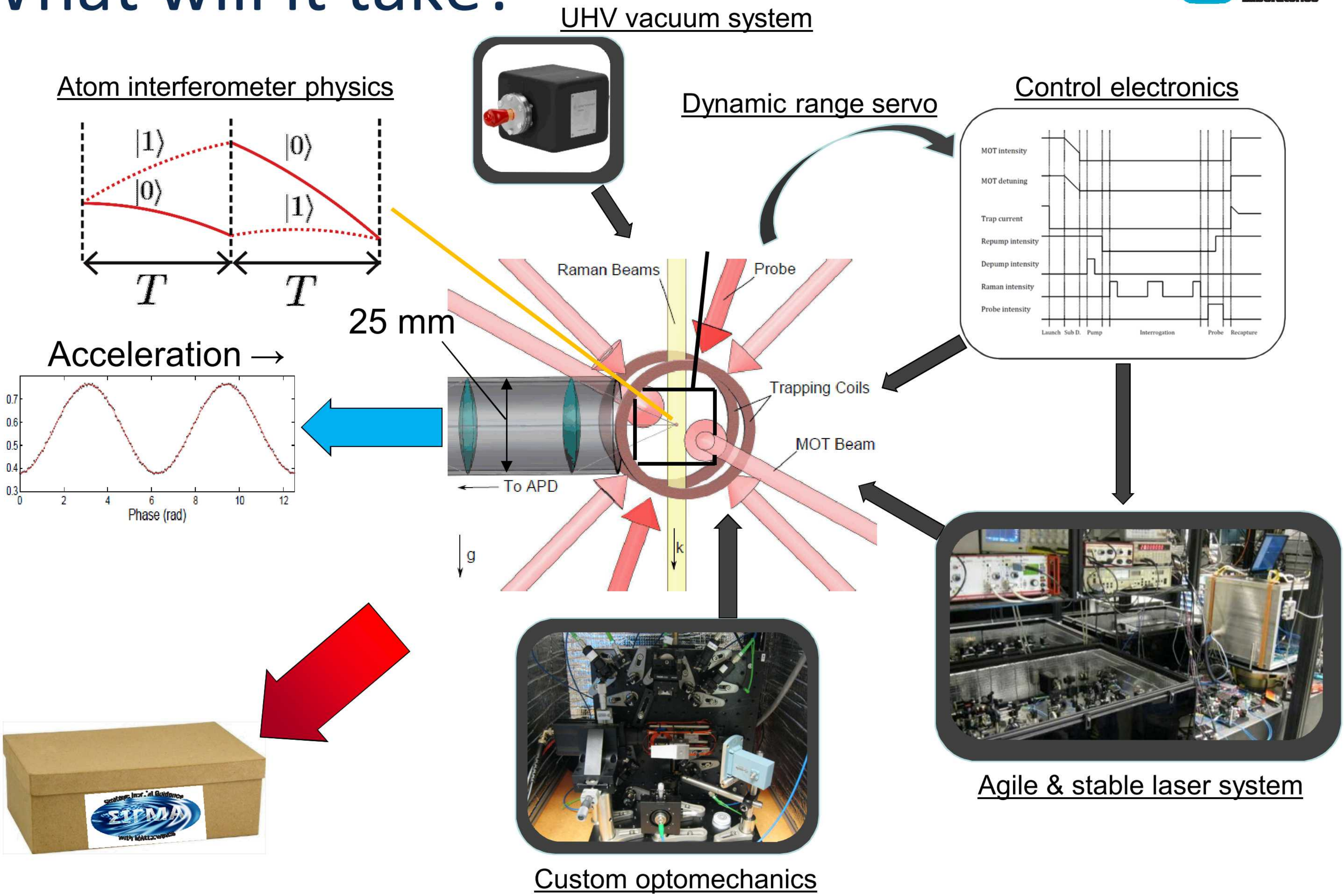
Strategic Inertial Guidance with MAtterwaves
ΣΙΓΜΑ



	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?



Advanced sensing—entanglement

Constantin Brif, 8759

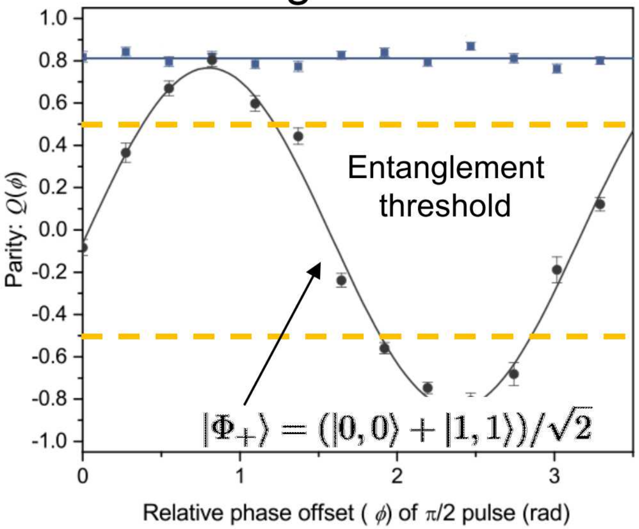
- For N independent atoms, phase uncertainty = **standard quantum limit** (SQL):

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

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

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

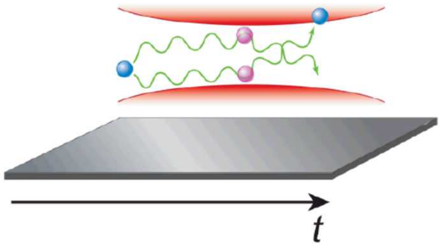
2 entangled Cs atoms



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)

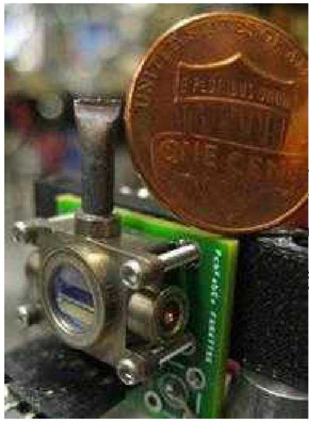
Atomic Sensing

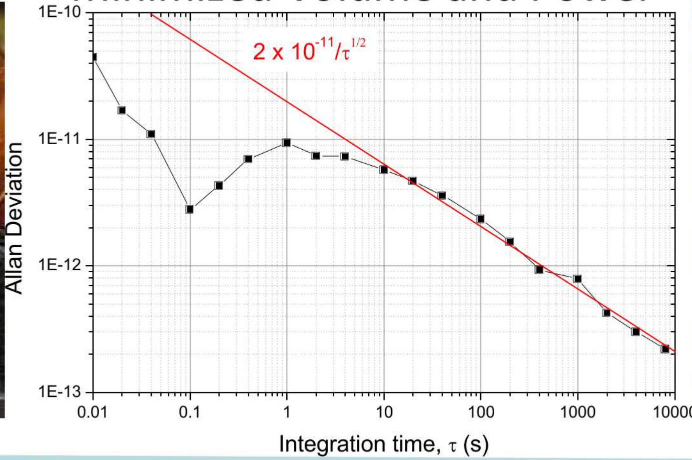
Sandia National Laboratories

ATOMIC CLOCKS

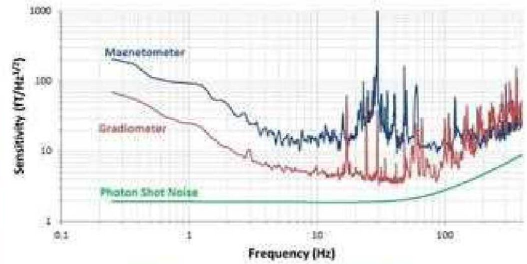
Maximized Precision and Stability

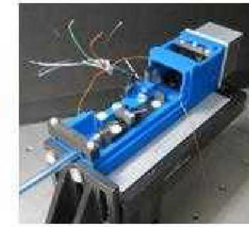
Minimized Volume and Power

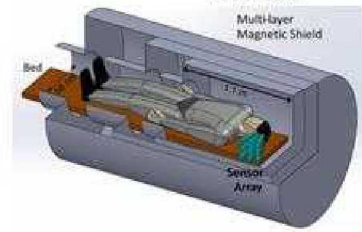


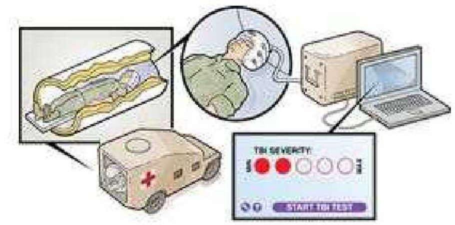


ATOMIC MAGNETOMETRY FOR MAGNETOENCEPHALOGRAPHY

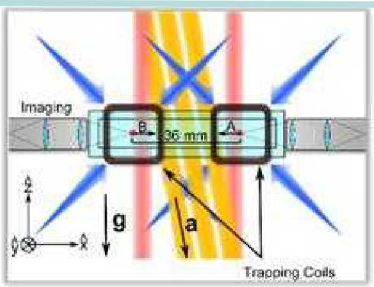


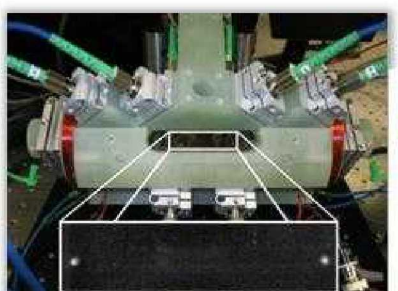


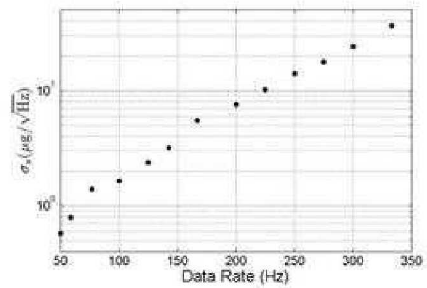


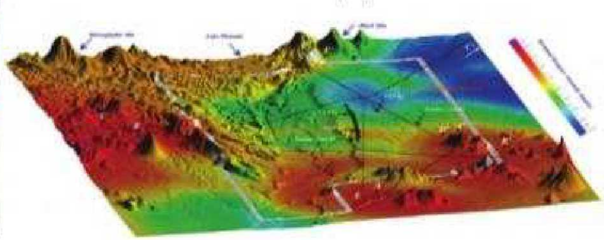


ATOM INTERFEROMETRY



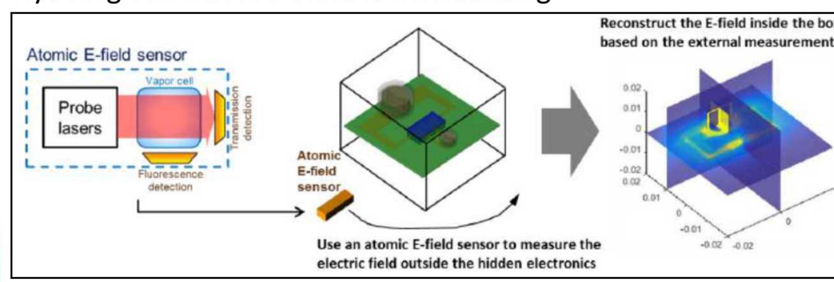


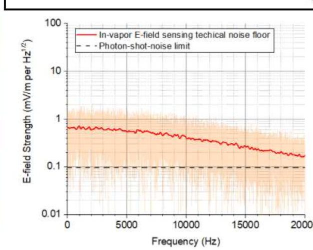




FIELD SENSING

Rydberg atom based electric field sensing





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