Quantum Network of Magnetometers

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Coordinating Panel for Advanced Detectors (CPAD) Workshop
11/30/2022, Stony Brook, NY

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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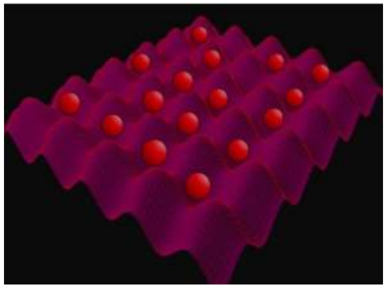
Atomic sensors

Atomic clocks

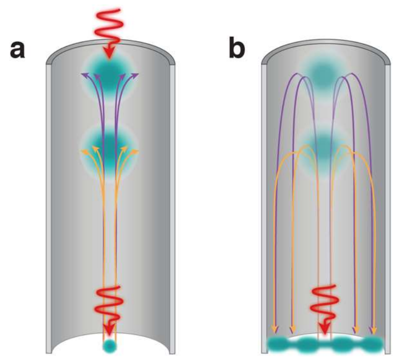


J. Ye Group website

Time keeping for:

- Define unit of time: second
- Communication and GPS positioning
- Many-body physics
- Search for dark matter

Atom interferometers

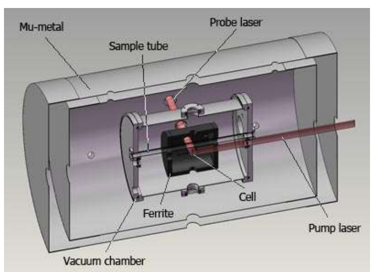


APS/Carin Cain

Free-space inertial sensors:

- Gravity sensors (gravity field monitoring)
- Inertial measurements for navigation
- Precision measurements (EP, GW detection)

Optical magnetometers



Romalis Group Webpage

- Biological and medical sensing
- New interest for fundamental research (HEP)
- Room temperature operation!

GNOME Collaboration

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Atomic clocks

Resolving the gravitational redshift across a millimetre-scale atomic sample

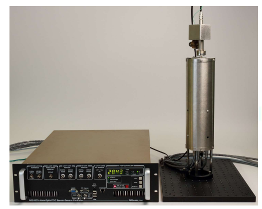
Tobias Bothwell, Colin J. Kennedy, Alexander Aeppli, Dhruv Kedar, John M. Robinson, Eric Oelker, Alexander Staron & Jun Ye

Nature 602, 420–424 (2022) | Cite this article

Abstract

Einstein's theory of general relativity states that clocks at different gravitational potentials tick at different rates relative to lab coordinates—an effect known as the gravitational redshift[1]. As fundamental probes of space and time, atomic clocks have long served to test this prediction at distance scales from 30 centimetres to thousands of kilometres[2,3,4]. Ultimately, clocks will enable the study of the union of general relativity and quantum mechanics once they become sensitive to the finite wavefunction of quantum objects oscillating in curved space-time. Towards this regime, we measure a linear frequency gradient consistent with the gravitational redshift within a single millimetre-scale sample of ultracold strontium. Our result is enabled by improving the fractional frequency measurement uncertainty by more than a factor of 10, now reaching 7.6×10^{-21}. This heralds a new regime of clock operation necessitating intra-sample corrections for gravitational perturbations.

$2\text{x}10^{-12}$ @1s



Atom interferometers

PHYSICAL REVIEW LETTERS **125**, 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are suppressed by calibrating the angles and frequencies of the interferometry beams. We find an Eötvös parameter of $\eta = [1.6 \pm 1.8(\text{stat}) \pm 3.4(\text{syst})] \times 10^{-12}$, consistent with zero violation of the equivalence principle. With a resolution of up to 1.4×10^{-11} g per shot, we demonstrate a sensitivity to η of $5.4 \times 10^{-11}/\sqrt{\text{Hz}}$.

DOI: 10.1103/PhysRevLett.125.191101

Optical magnetometers

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. **58** (2013) 8153–8161 doi:10.1088/0031-9155/58/22/8153

A compact, high performance atomic magnetometer for biomedical applications

Vishal K Shah[1] **and Ronald T Wakai**[2]

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Online at stacks.iop.org/PMB/58/8153

Abstract
We present a highly sensitive room-temperature atomic magnetometer (AM), designed for use in biomedical applications. The magnetometer sensor head is only 2 × 2 × 5 cm^3 and is constructed using readily available, low-cost optical components. The magnetic field resolution of the AM is <10 fT Hz$^{-1/2}$, which is comparable to cryogenically cooled superconducting quantum interference device (SQUID) magnetometers. We present side-by-side comparisons between our AM and a SQUID magnetometer, and show that equally high quality magnetoencephalography and magnetocardiography recordings can be obtained using our AM.

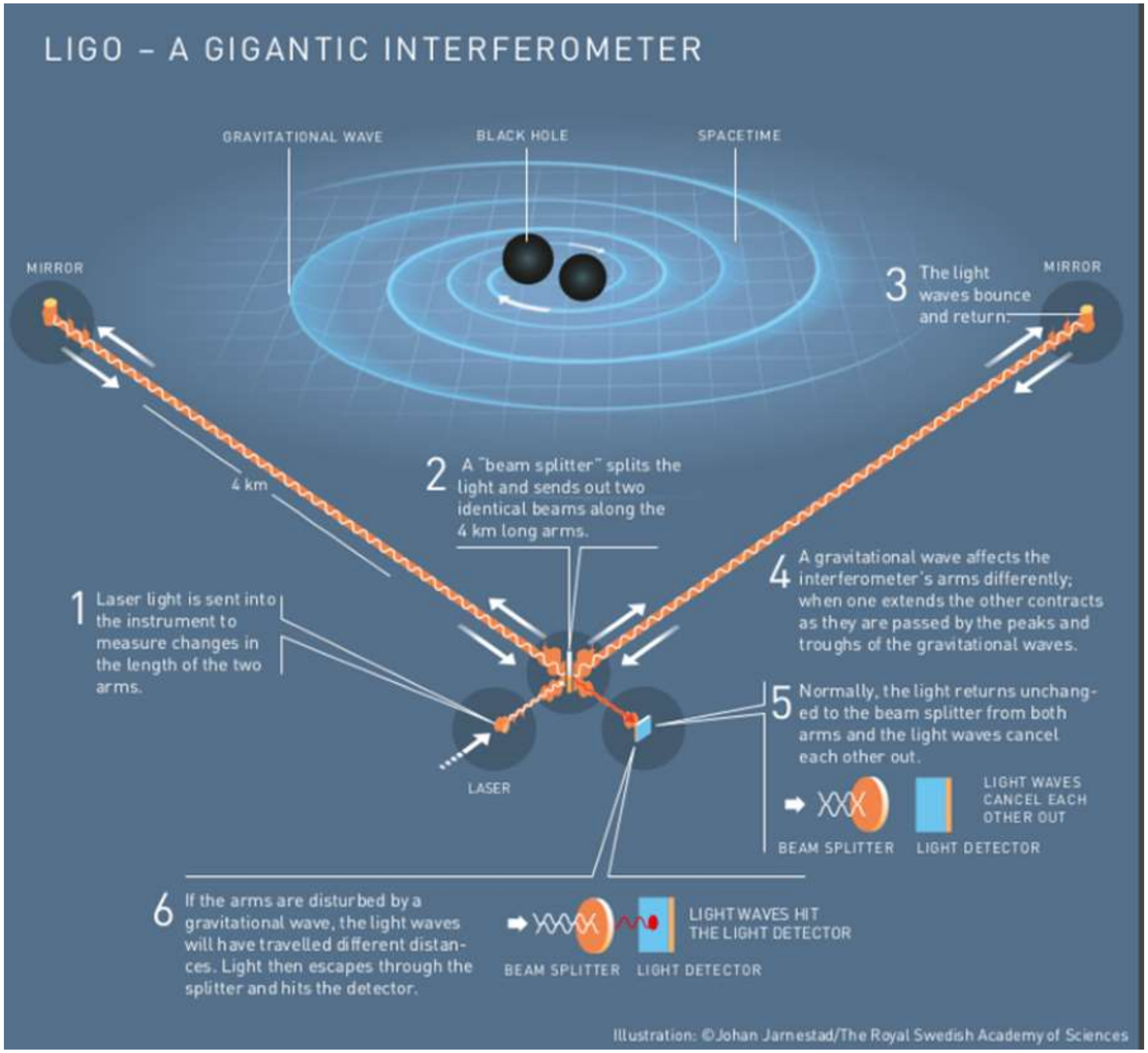
(Some figures may appear in colour only in the online journal)

$$\Delta\phi \sim \frac{1}{\sqrt{N}\,T^{\alpha}}$$

Quantum advantage has been demonstrated by the LIGO collaboration (optical interferometer) in 2019.

It increased the detection rate by up to 50%!

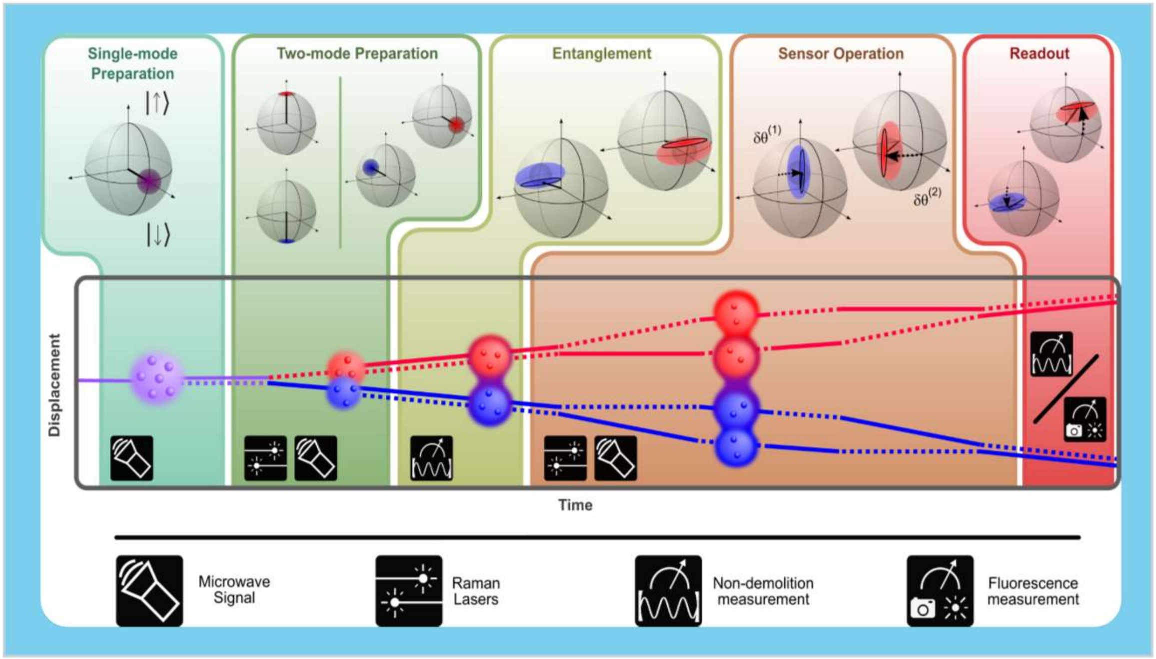
Non-classical (squeezed) light as input.
Has quantum advantage been used in atomic sensors?

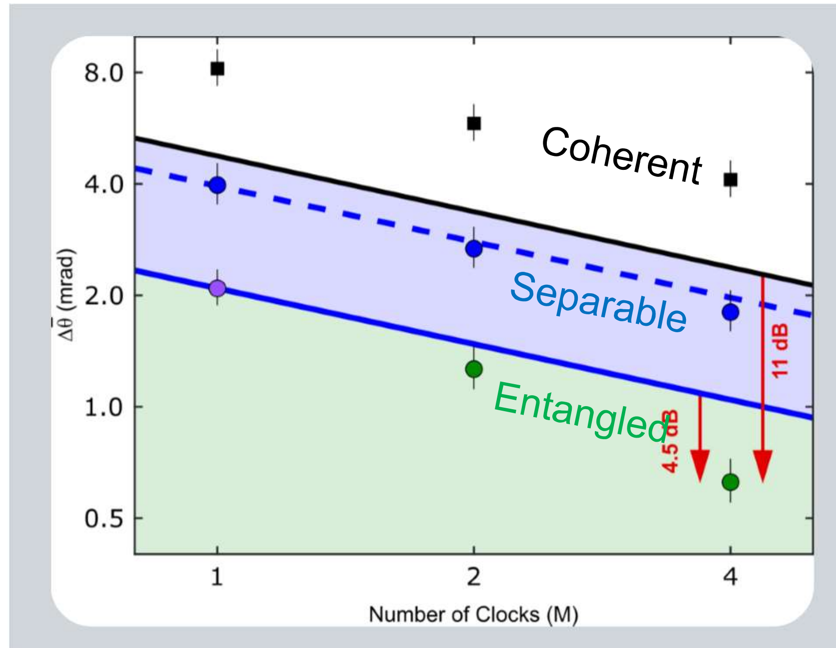


Article | Published: 23 November 2022

Distributed quantum sensing with mode-entangled spin-squeezed atomic states

Benjamin K. Malia, Yunfan Wu, Julián Martínez-Rincón & Mark A. Kasevich





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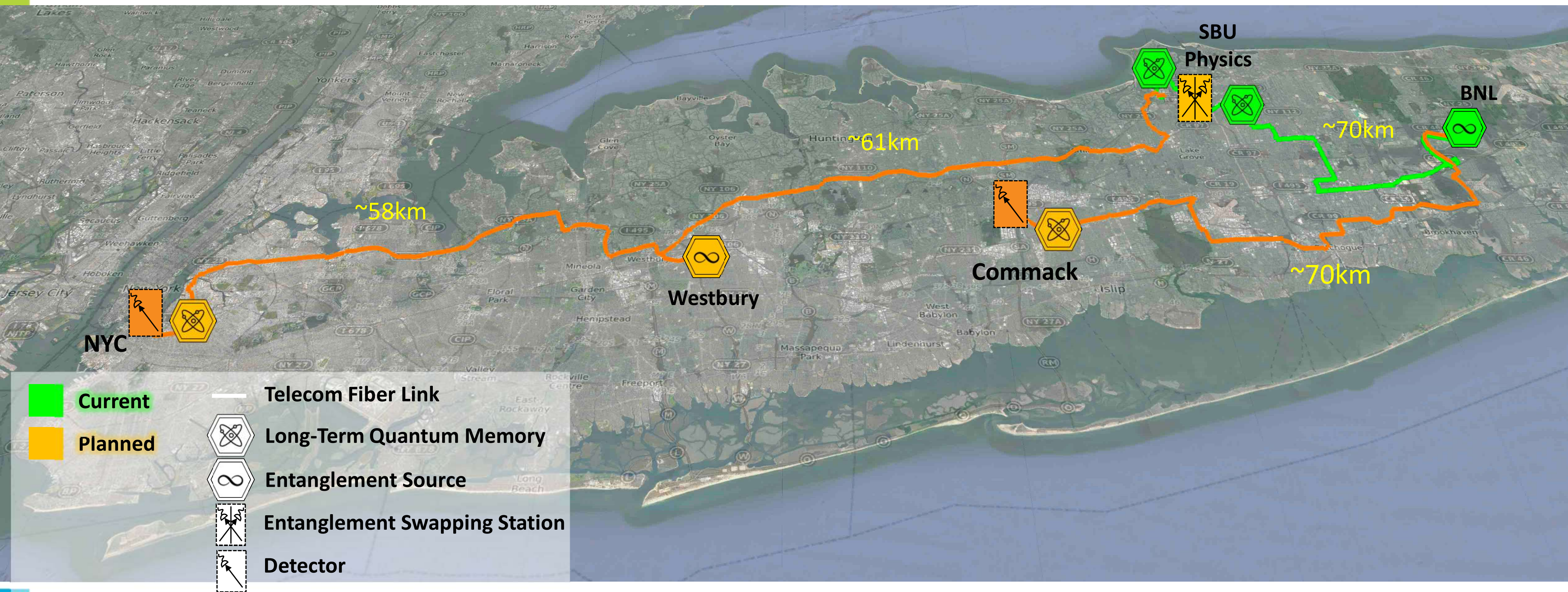
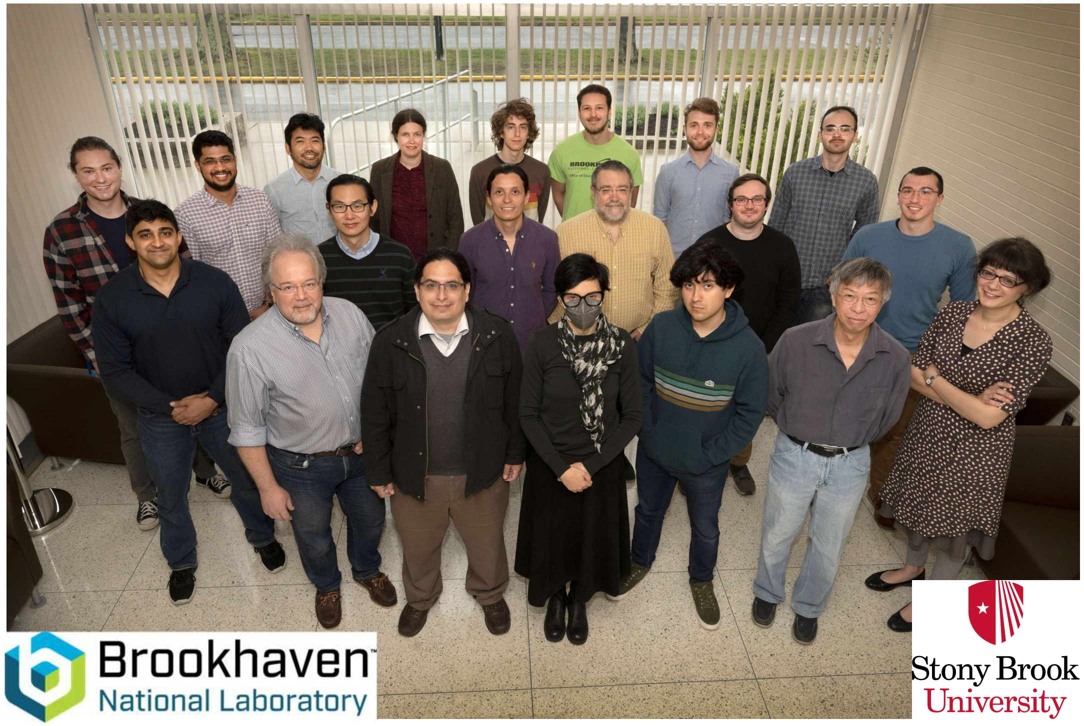
LIQuIDNet: Long Island Quantum Information Distribution Network



arxiv:2101.12742 (New version coming soon)



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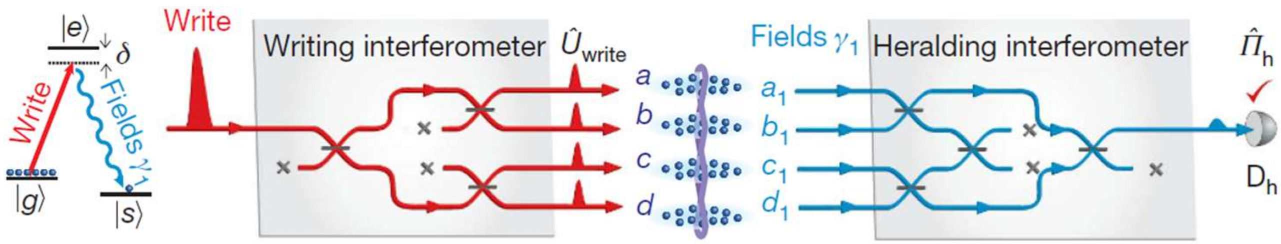
Guodong Cui
Samet Demircan
Sonali Gera
Siddharth Sehgal
Chase Wallace
Will Bidle

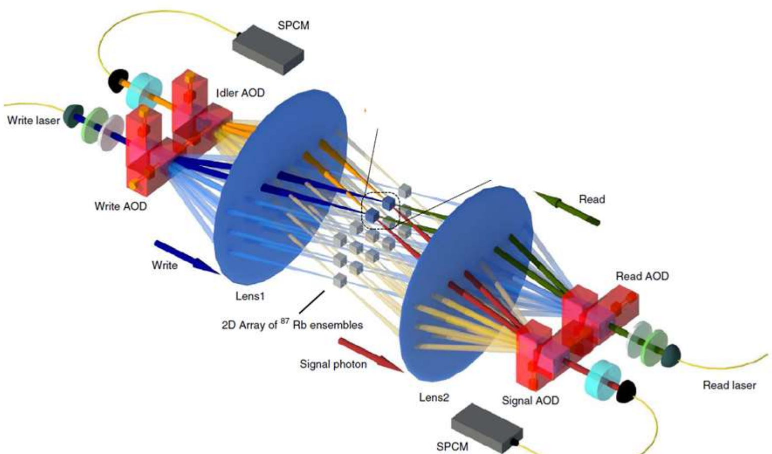
First clear path:
Entangled Multiplexed Magnetometer

Pioneering work by J. Kimble:

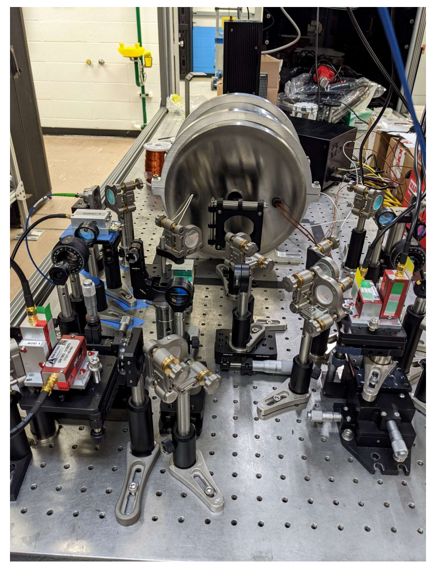


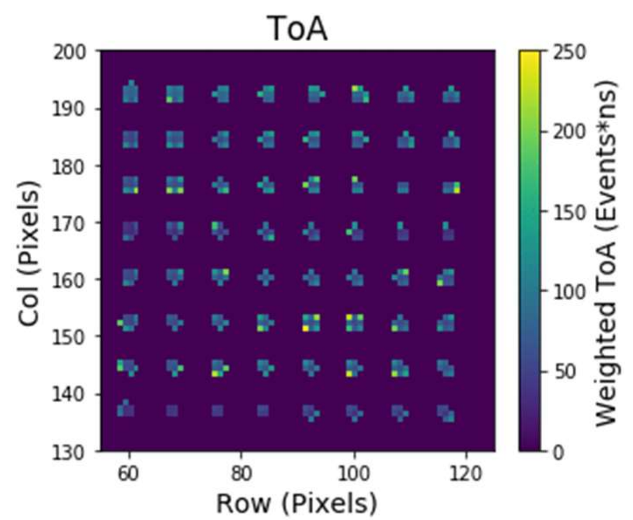
$$|W\rangle_\gamma = \frac{1}{2}\left[\left(|1000\rangle + e^{i\phi'_1}|0100\rangle\right) + e^{i\phi'_2}\left(|0010\rangle + e^{i\phi'_3}|0001\rangle\right)\right]$$

K.S. Choi et. al. *Entanglement of spin waves among four quantum memories,* Nature 468 18 412-416 (2010).



Y.-F. Pu, et. al. *Experimental realization of a multiplexed q. memory with 225 individually accessible memory cells,* Nature Communications 15359 (2017).





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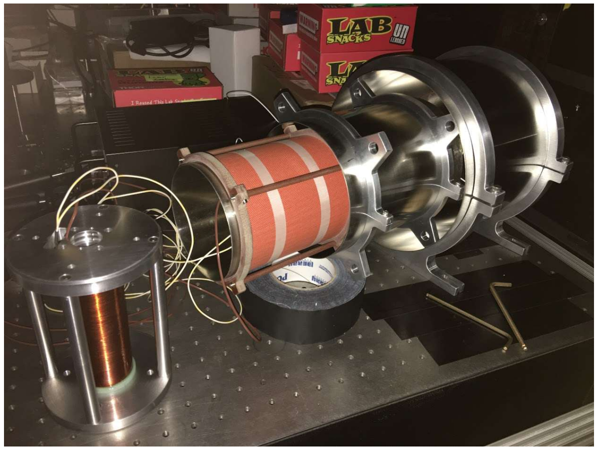
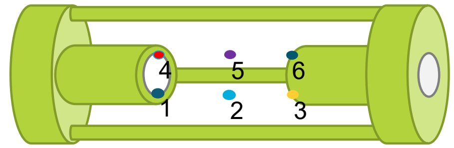
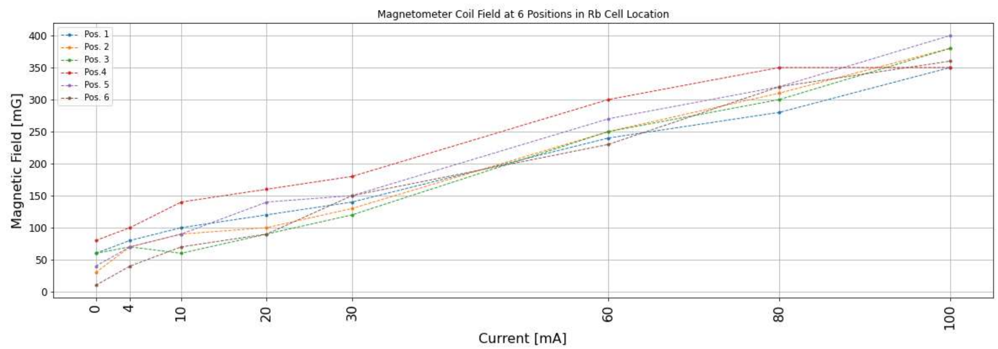
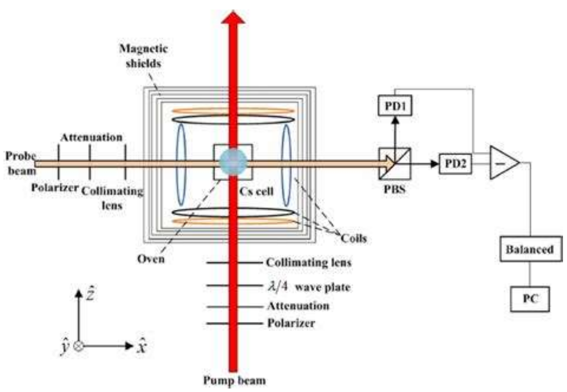
First step: tailoring the memory to be a magnetometer



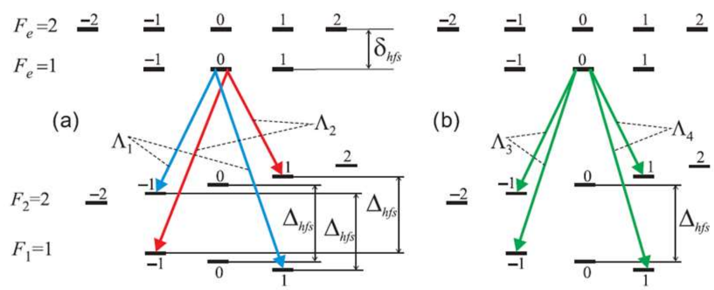


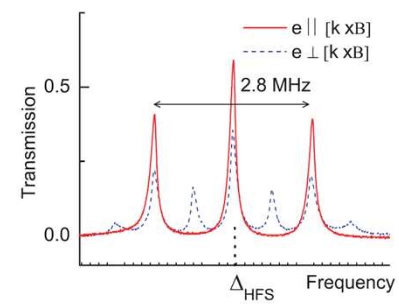


Standard Optical Magnetometer:



EIT Magnetometer:





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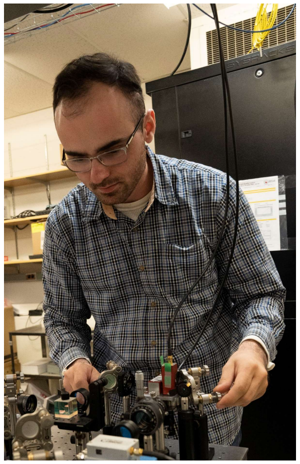
V. I. Yudin, et. al. *Vector magnetometry based on EIT in linearly polarized light,* Phys. Rev. A 82 033807 (2010).



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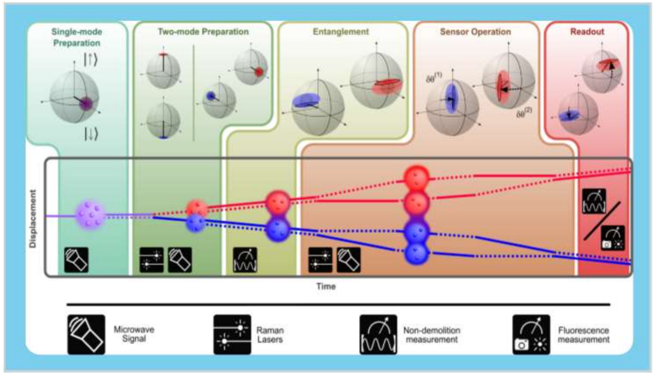
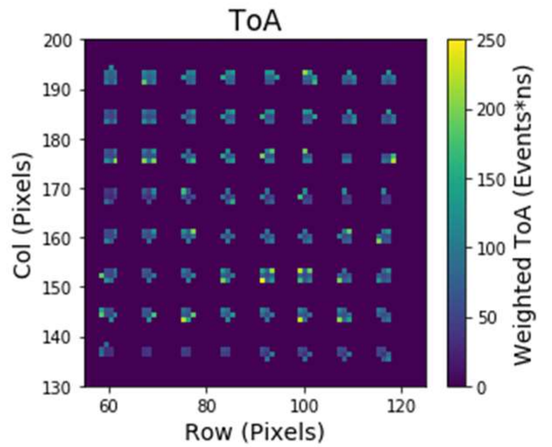
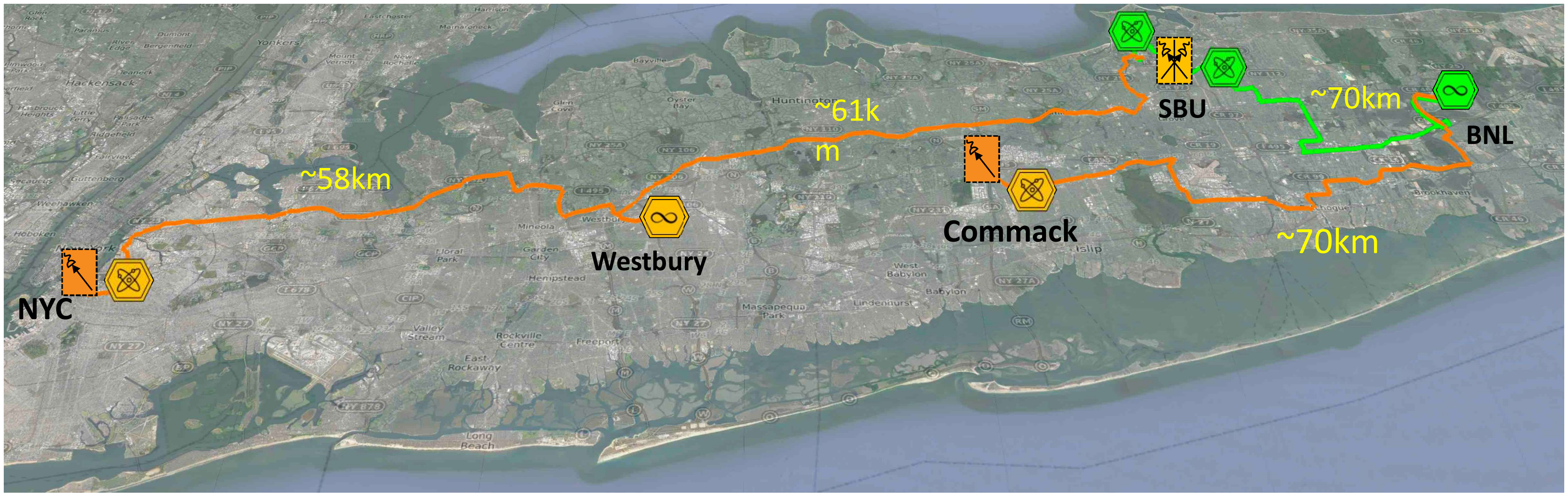


Thank you!





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