New Ideas for Low-Frequency Gravitational Wave Detection with Quantum Sensors (MAGIS/AION)

SQMS Quantum for Science Workshop, March 2024

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Overview

- Brief introduction to atom interferometry

- Long-baseline atom interferometers for gravitational wave (GW) detection
  - Global landscape of long-baseline atom interferometers
  - MAGIS-100 atom interferometer at Fermilab

- Recent experiments on enhancing atom interferometers using quantum optimal control (work supported by SQMS)

See also talk by Oliver Buchmueller

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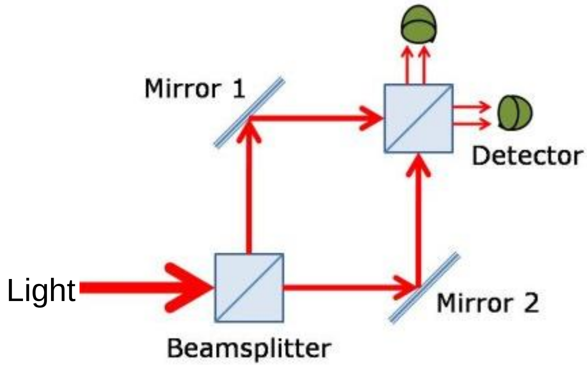
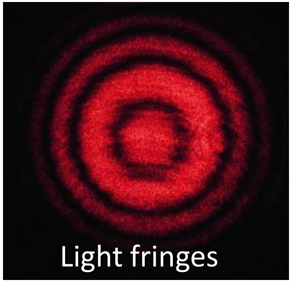
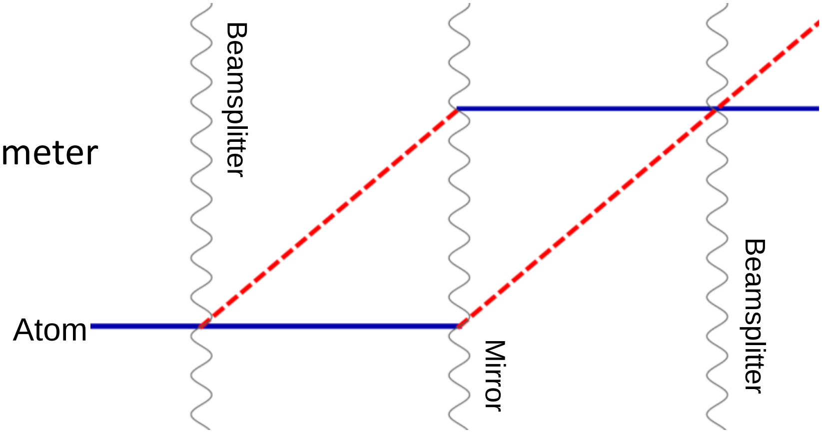
Atom interference

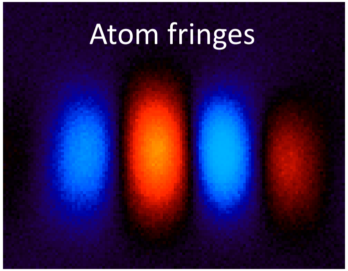
Light interferometer





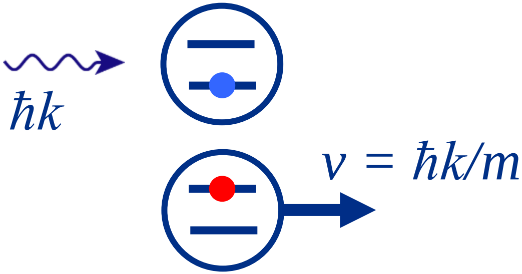
Atom interferometer



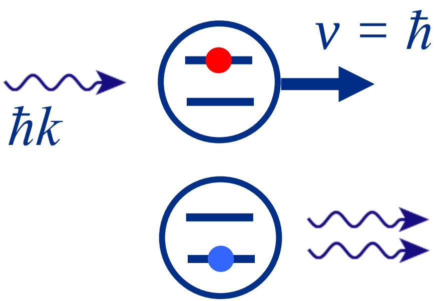


Atom optics using light

(1) Light absorption (transition from ground to excited state):



(2) Stimulated emission (transition from excited to ground state):



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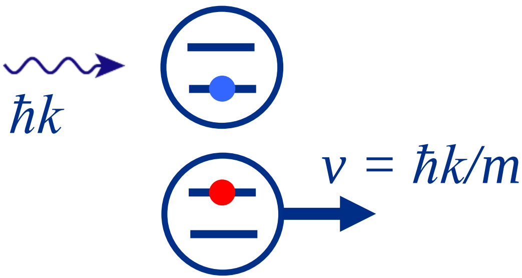
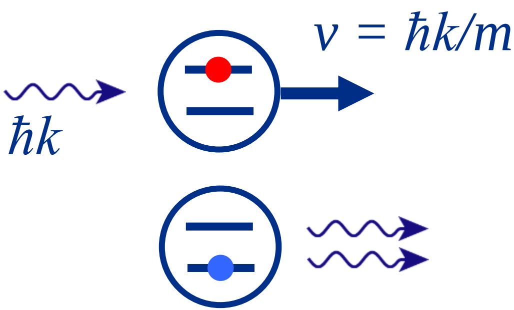
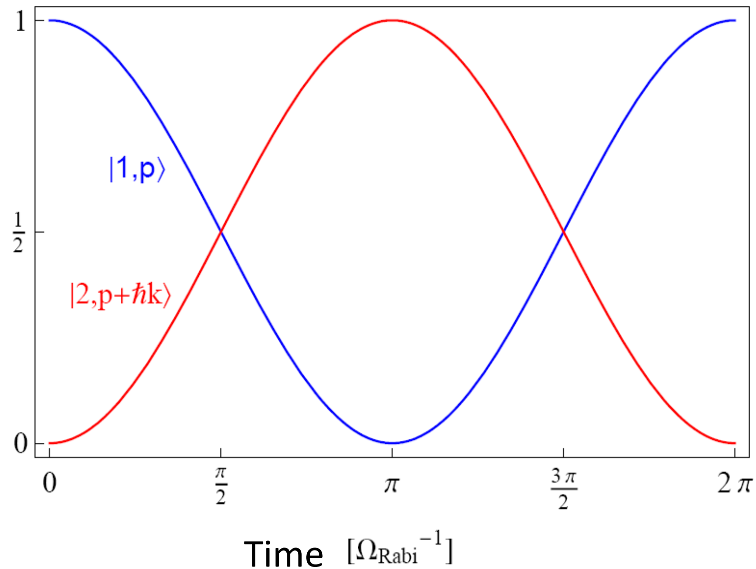


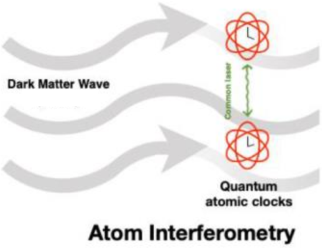
(2) Stimulated emission:



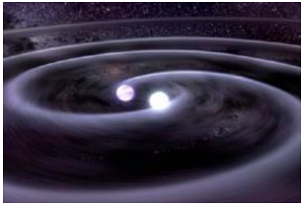
Rabi oscillations



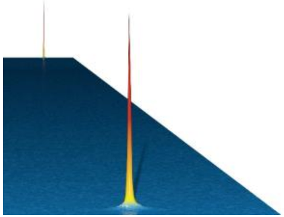
Long-Baseline Atom Interferometeters: Science Motivation



- Search for wavelike dark matter
  - Oscillating atomic transition frequencies
  - Oscillating species-dependent accelerations
  - Spin precession



- Gravitational wave detection in new, mid-band frequency range (0.03 – 3 Hz)
  - Complementary to program of laser interferometer detectors such as LIGO and LISA
  - Promising to detect GWs generated during the early Universe, probe of high energy physics
  - Provide forewarning to electromagnetic telescopes in advance of merger



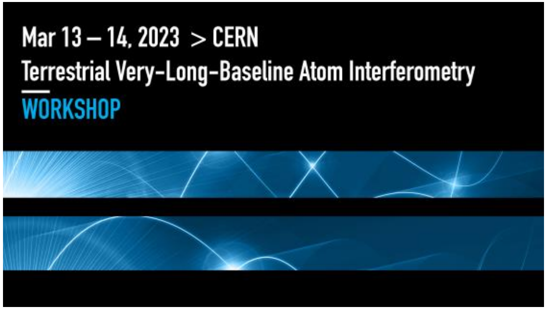
- Fundamental tests of quantum mechanics at macroscopic scales
  - Delocalizations >1 m for multiple seconds
  - Test fundamental decoherence mechanisms, non-linear quantum mechanics

Graham et al., PRD 93, 075029 (2016); Arvanitaki et al., PRD 97, 075020 (2018); Graham et al., PRD 97, 055006 (2018)

Global Efforts in Long-Baseline Atom Interferometry

- Growing global community in this area

- Example: CERN Very-Long-Baseline Terrestrial Atom Interferometry Workshop, March 13-14 (2023): ~200 registered participants. https://indico.cern.ch/event/1208783/



MAGIS-100 in US (Abe et al., QST 6, 044003 (2021))

AION in UK (Badurina et al., J. of Cosmology and Astrophysics 05 (2020) 011)

MIGA in France (Canuel et al., Scientific Reports 8, 14064 (2018))

ZAIGA in China (Zhan et al., International Journal of Modern Physics D 29, 1940005 (2020))

VLBAI in Germany (Hartwig et al., New Journal of Physics 17, 035011 (2015))

- Community is also studying prospects for future space-based detectors (Abou El-Neaj et al., EPJ Quantum Technology 7, 6 (2020)); synergies with related proposals using optical lattice clocks in space (Kolkowitz et al., PRD 94, 124043 (2016))

Workshop summary: Abend et al., arXiv:2310.08183 (2023), in press AVS Quantum Science

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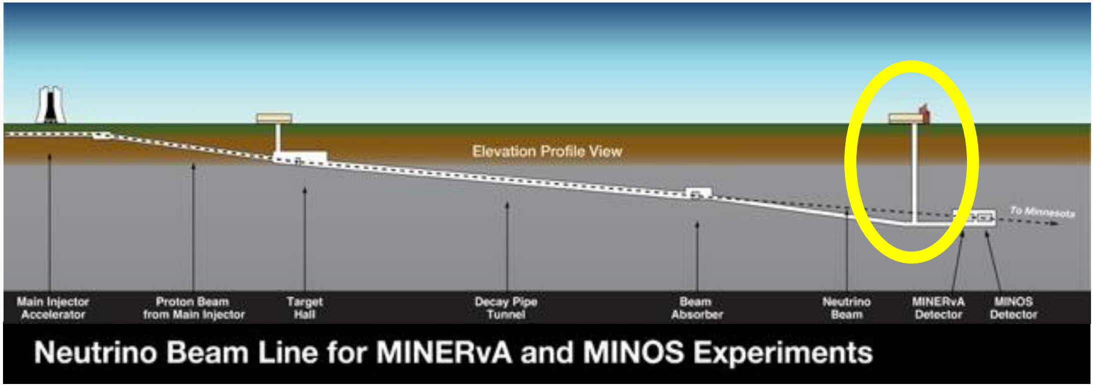
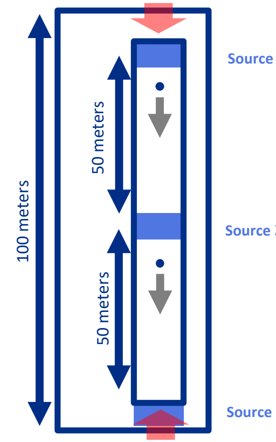
MAGIS-100 detector at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor





- 100-meter-tall atom interferometry apparatus
- Quantum mechanics at very large scales
- Search for dark matter
- Prototype for a new type of gravitational wave detector

Fermilab · Northwestern University · ODU · Jefferson Lab · Northern Illinois University · Johns Hopkins University · University of Cambridge · SLAC · University of Liverpool

Abe et al., Quantum Science and Technology 6, 044003 (2021)

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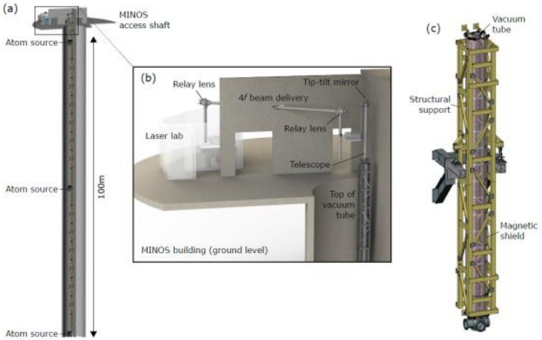
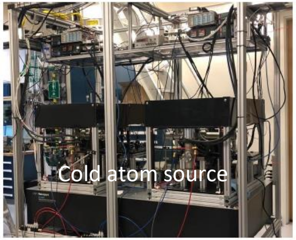
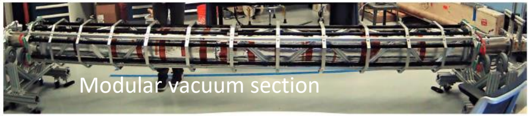
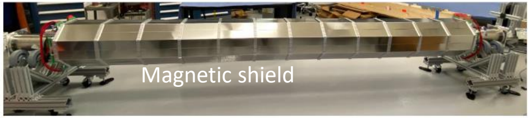
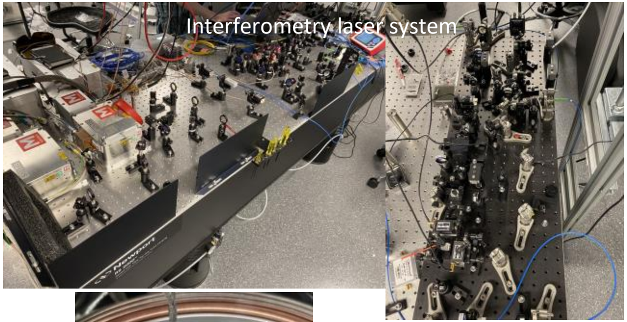
MAGIS-100 Experiment











- 17 modules, each with magnetic shielding, vacuum pipe, current-carrying wires for generating bias magnetic field

- Laser lab at top of shaft (currently undergoing construction)

- Three Sr atom sources over 100 m baseline, local optical lattices can launch atoms from each source

- High-power laser system with agile frequency control, spatially filtered beam mode, and precisely controlled pointing via tip-tilt mirrors

- Construction and testing of subsystems underway

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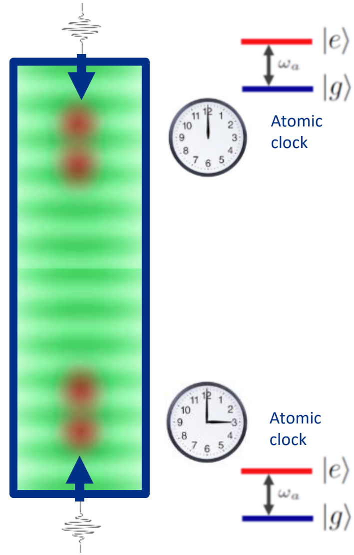
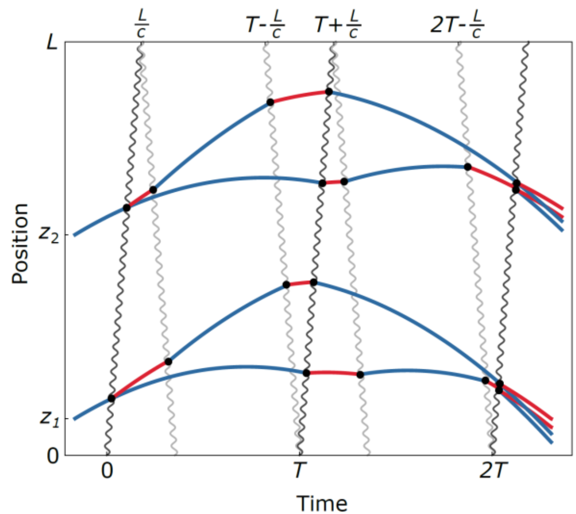
Measurement Concept

Freely-falling atoms on each end serve as **inertial references**

Atoms act as **clocks** to measure light travel time across baseline: “active proof mass”

Multiple pulses across baseline coherently enhance signal





Differential phase evolution:

$$\Delta\phi \sim \omega_A \left(2L/c\right)$$

Two ways for phase to vary:

$\delta\omega_A$ *Dark matter*

$\delta L = hL$ *Gravitational wave*

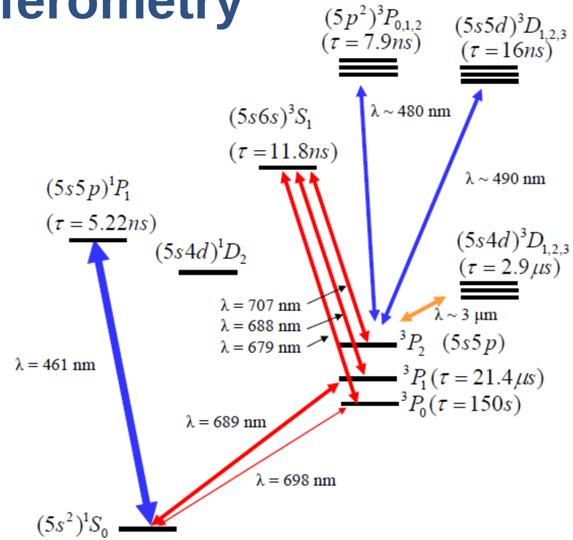
Yu and Tinto, GRG 43, 1943 (2011); Graham et al., PRL 110, 171102 (2013); Arvanitaki et al., PRD 97, 075020 (2018); Norcia et al., PRA 96, 042118 (2017)

Strontium clock atom interferometry

Sr has a narrow "optical clock" transition at 698 nm with a long-lived excited state (natural lifetime >100 s)

Atom optics based on absorption/stimulated emission of photons on this 698 nm line

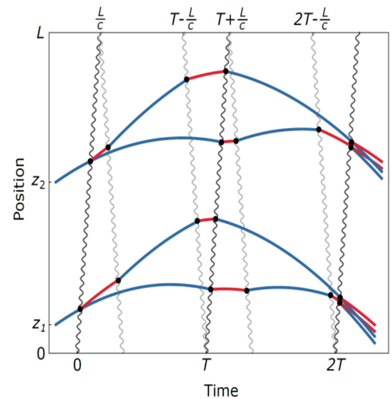
Can also use 689 nm line, higher Rabi frequency but shorter excited state lifetime



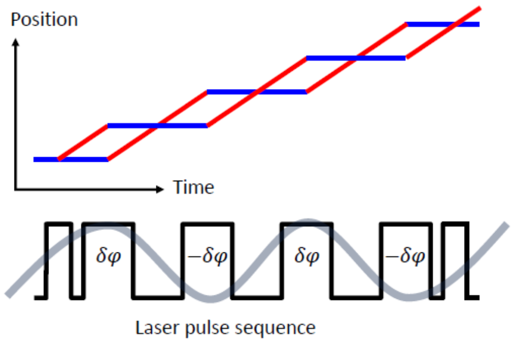
<u>Hybrid clock/atom interferometer</u>

Long-lived superposition of internal states with large energy difference: clocklike features

Atom wavefunction spatially splits due to photon momentum recoils: atom interferometer features



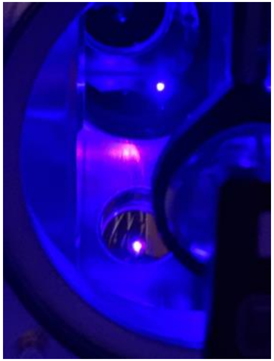
Resonant Atom Interferometry



- Proposed for multiple types of dark matter, gravitational wave, and dark energy searches in terrestrial and space experiments

- Multiple interferometer loops (N loops) can amplify signal by a factor of 2N at the resonance frequency

- Analogy to lock-in detection and dynamical decoupling



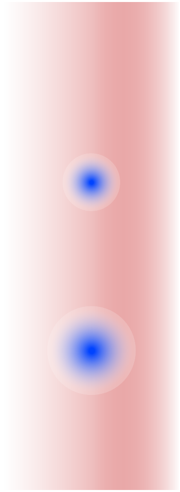
Implement using MAGIS laser system with Sr-88 atom interferometer at Northwestern, using single-photon transitions on 689 nm line

Graham, *et al.*, PRD 94, 104022 (2016); Coslovsky et al., Slow Light, Fast Light and OptoAtomic Prevision Metrology X (2017); Jaffe et al. PRL 121, 040402 (2018); Kim et al., arXiv:2201.11888 (2022); Chiow and Yu, PRD 97, 044403 (2018)

Challenges

Hard to make a good atom mirror! Mirror pulse fidelity never perfect due to experimental tradeoffs and imperfections

- Finite atom cloud temperature and size, laser intensity inhomogeneity across atom cloud, etc…



Perform experiments with constraints on atom mirrors representative of expectations for MAGIS-100

How many loops can we do?

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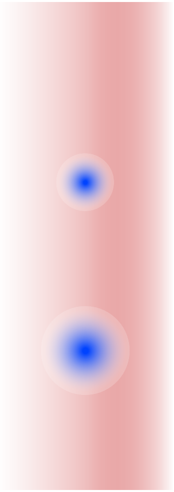

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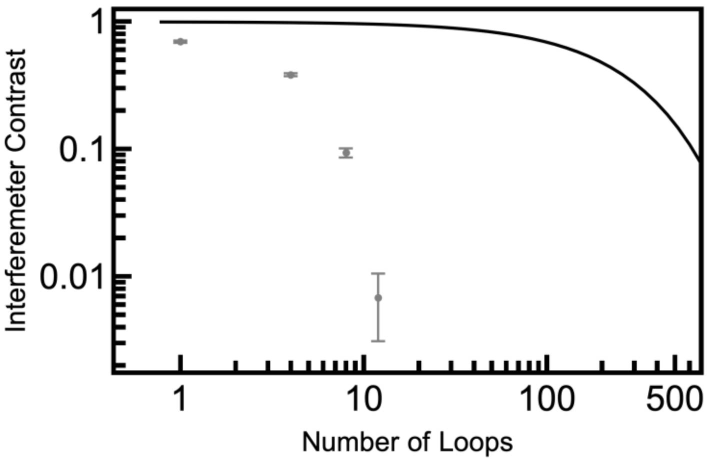

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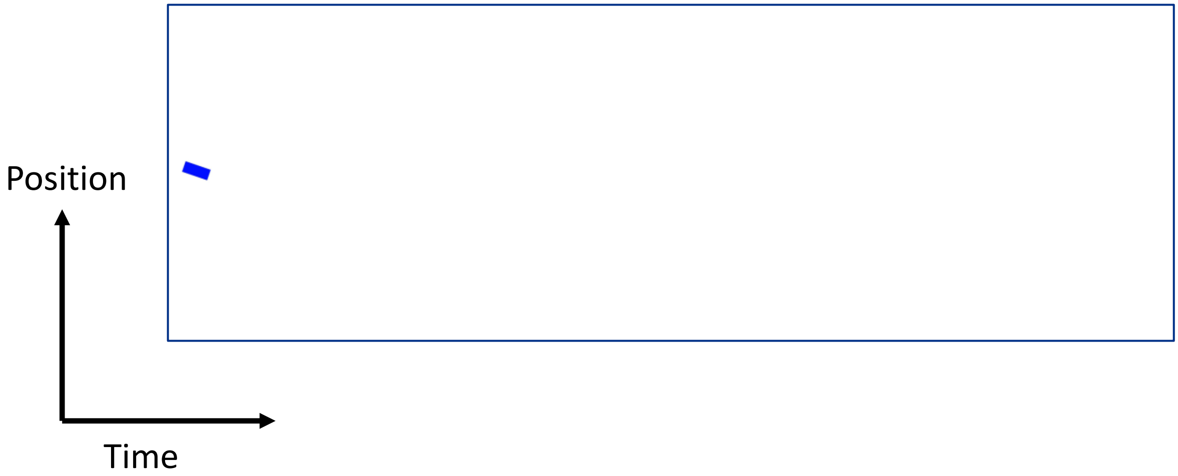
The Ideal (Unrealistic) Case

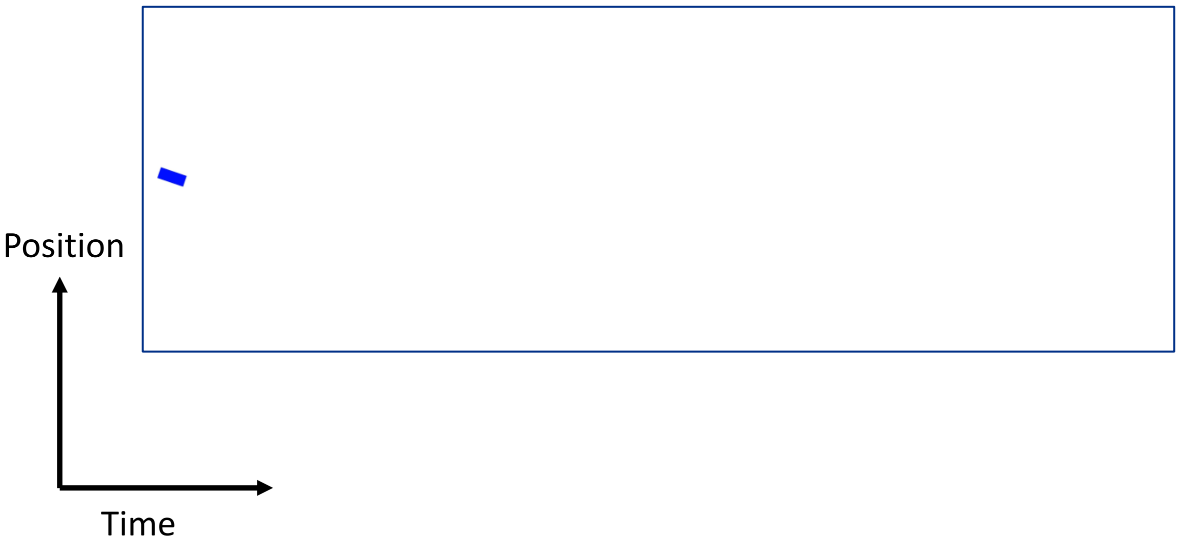
Perfect atom mirrors



The Realistic Case

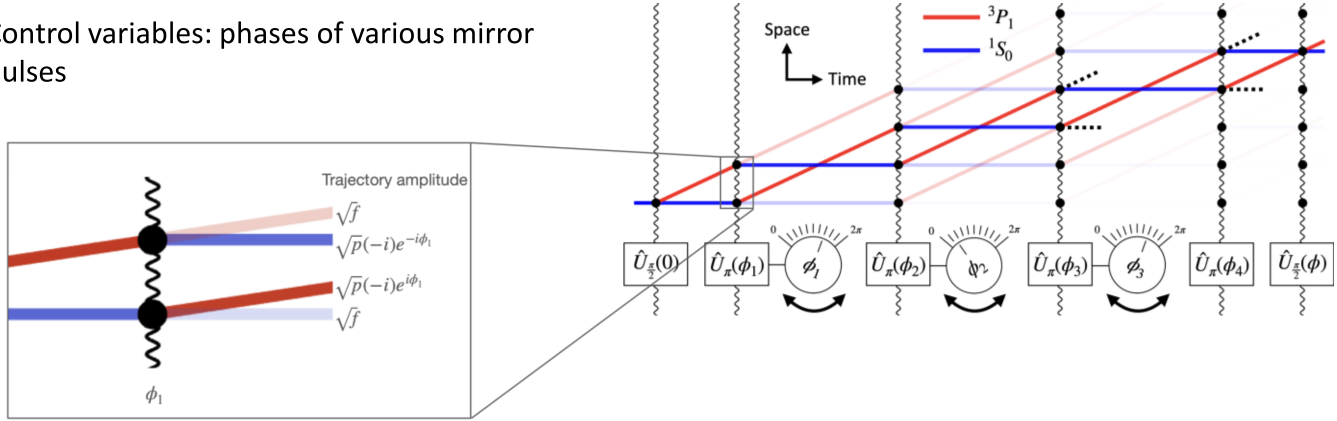
Imperfect atom mirrors

Atoms branch off into stray trajectories, which can interfere with each other (multipath interference)



Overcoming the Challenge: Applying Quantum Optimal Control to Multipath Interference

Control variables: phases of various mirror pulses



Open-loop approach: numerical algorithm to minimize a specified cost function based on simulations of experiment

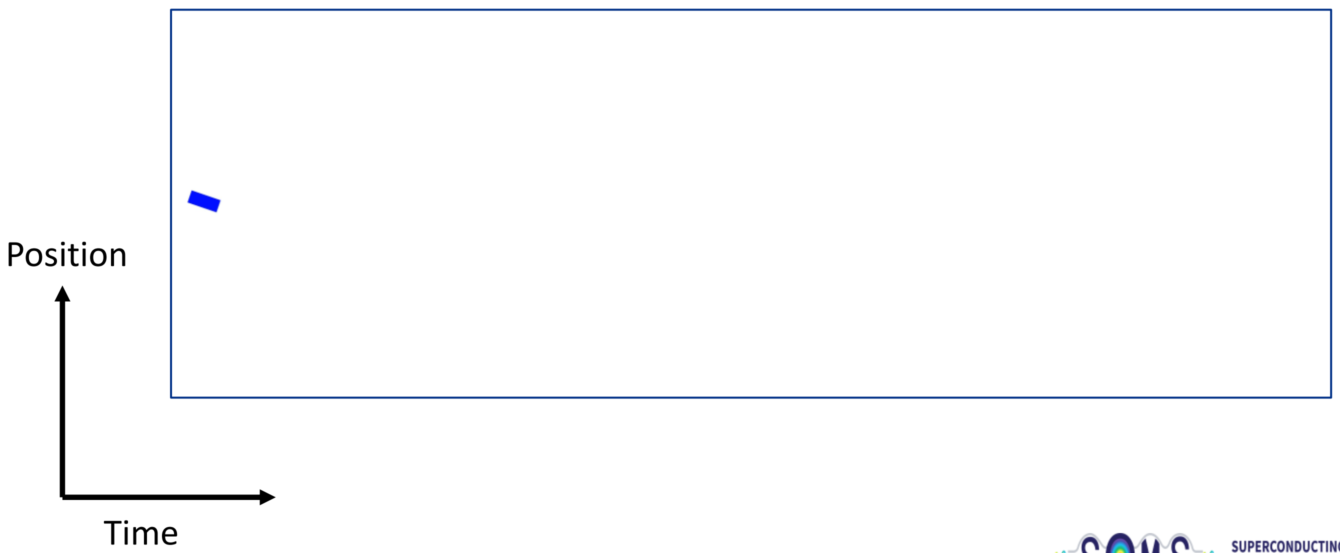
Closed-loop approach: use input from experimental data

Our Solution

Choose cost function to:

-maximize probability that stray paths constructively recombine into "central family" of trajectories that overlap with ideal paths

-suppress spreading of atom trajectories through destructive interference



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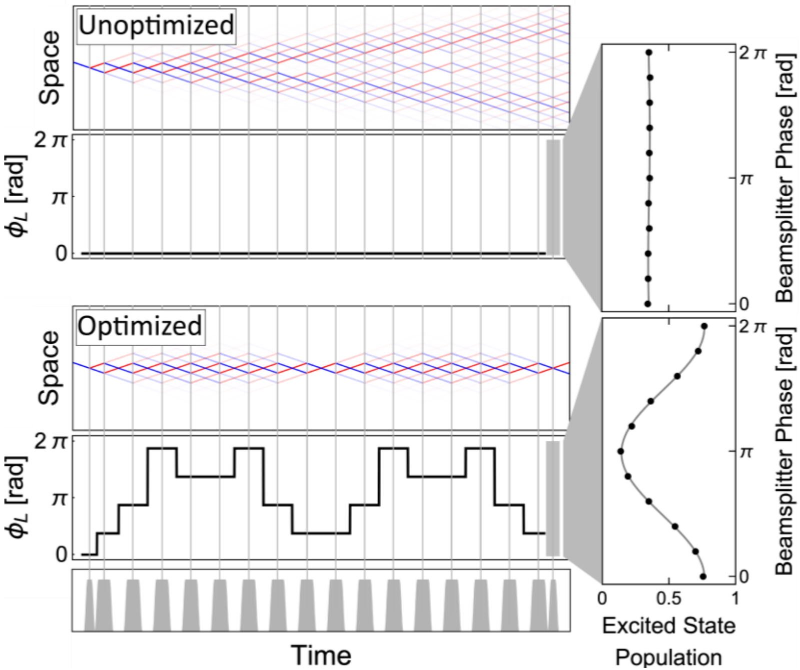
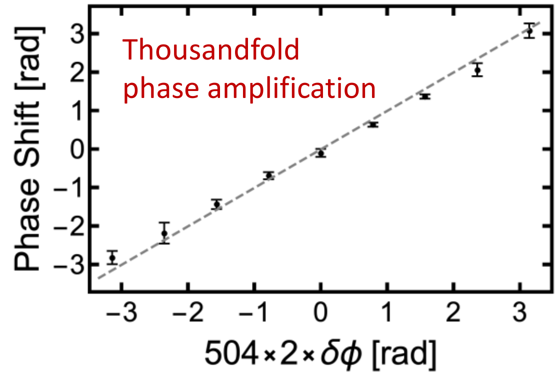
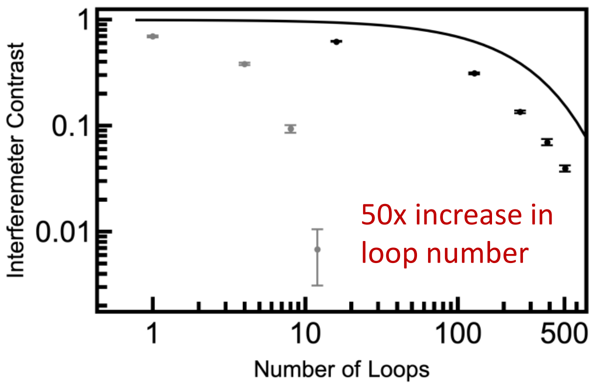
Improvement from Optimization

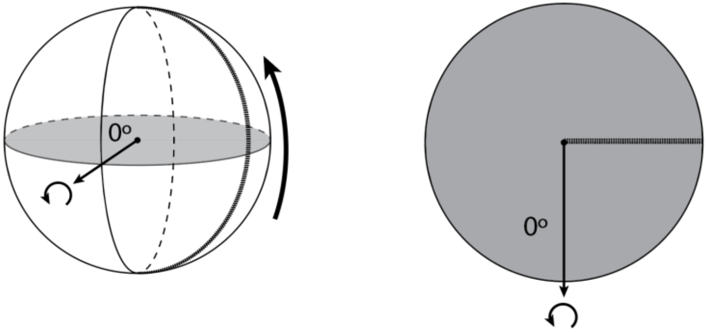






Contrast remains within order 1 factor of fundamental spontaneous emission contrast limit up to ~500 loops

Aggregate Spontaneous Emission Phase



Atoms can spontaneously decay to ground state midway through a mirror pulse

Remainder of mirror pulse can once again put the atom in superposition

Can there be a nonzero average interference pattern generated by atoms that underwent spontaneous emission at different points in time?

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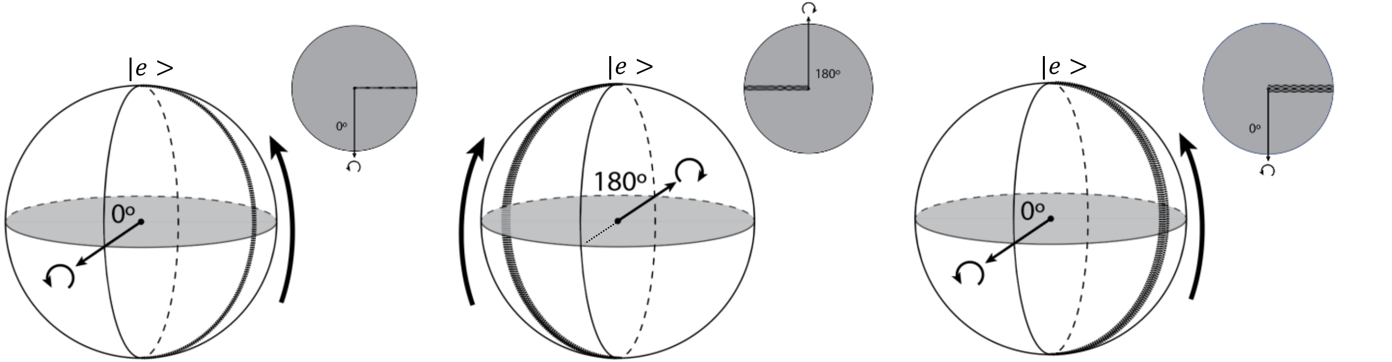

Yes, for some pulse sequences these atoms build up with a certain average “aggregate phase”, generating interference fringe with high contrast but insensitive to desired signal

If pulse sequence not chosen careful, this unwanted interference fringe can dominate over the signal we want to measure

Constrain optimization to avoid pulse sequences where this happens

Conclusion

- Long-baseline atom interferometry promising for gravitational wave detection, dark matter searches, gravitational wave detection, and foundational quantum science

- Rapidly growing global community in this area

- Quantum optimal control has the potential to be an essential tool for allowing these interferometers to reach their full potential in the face of challenging experimental constraints

- We have also implemented closed-loop control, converges to similar result as open-loop

Acknowledgements

MAGIS Collaborators

Jason Hogan (Spokesperson) (Stanford)
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John March-Russell (Oxford)
Ian Shipsey (Oxford)
Jeremiah Mitchell (Cambridge)
Val Gibson (Cambridge)
Ariel Schwartzman (SLAC)
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Northwestern Team

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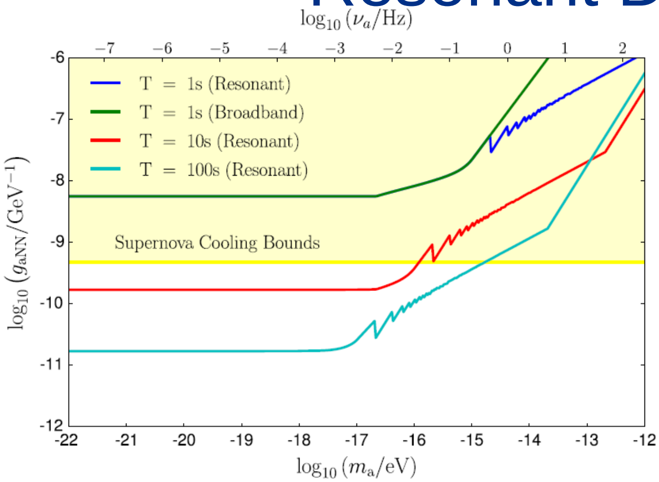
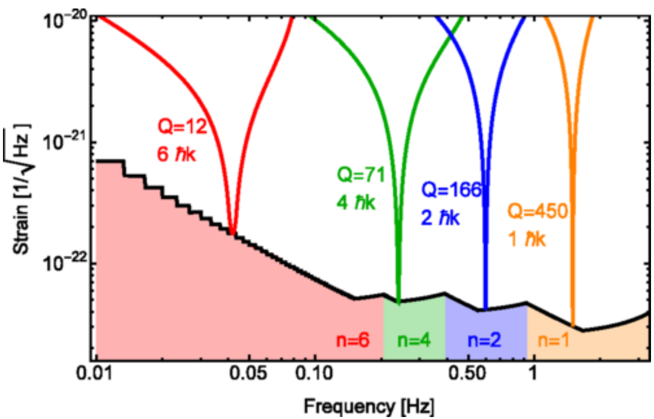
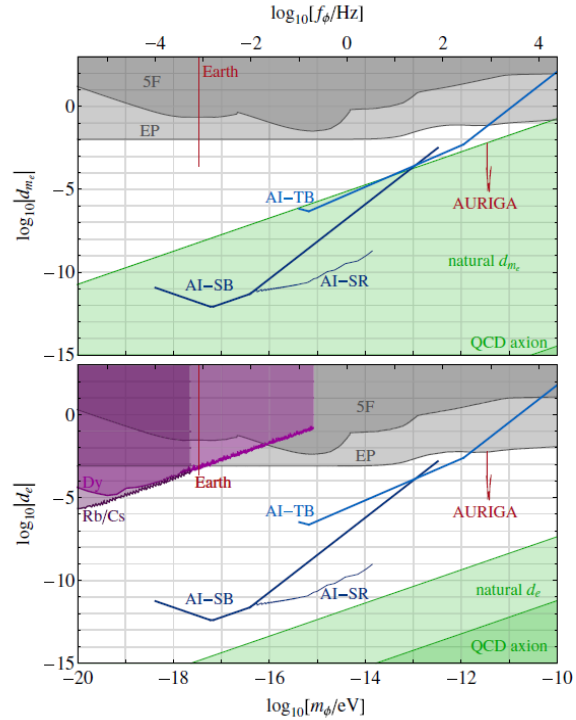
Hardeep Singh (PhD student)
Jay Jachinowski (undergrad)
Garrett Louie (undergrad)

Resonant DM and GW







Graham et al., PRD 93, 075029 (2016); Arvanitaki et al., PRD 97, 075020 (2018); Graham et al., PRD 97, 055006 (2018)

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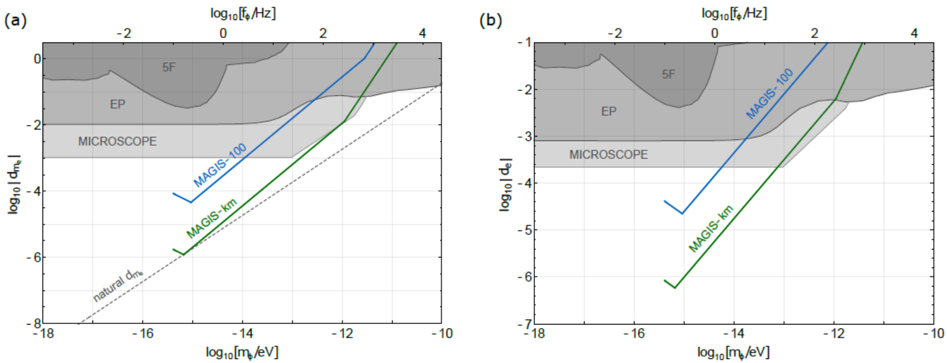
MAGIS-100 Dark Matter Searches

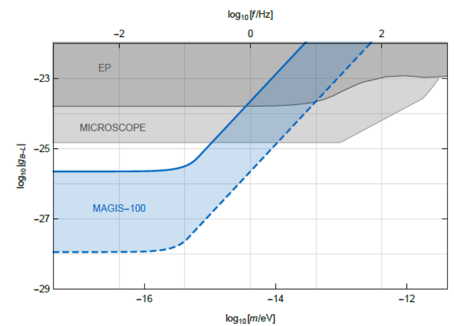
Example: coupling to electron mass or fine structure constant

Bound assumptions: 50 m launch, 1000 $\hbar k$ atom optics, 10^8 atoms/s flux, shot noise limited, 1 year of data



Example: vector DM coupling to B-L

Bound assumptions: 50 m launch, 100 $\hbar k$ atom optics, 10^6 atoms/s flux, shot noise limited, 1 year of data (solid curve); 100 m launch, 1000 $\hbar k$ atom optics, 10^8 atoms/s flux, shot noise limited, 1 year of data (dashed curve);



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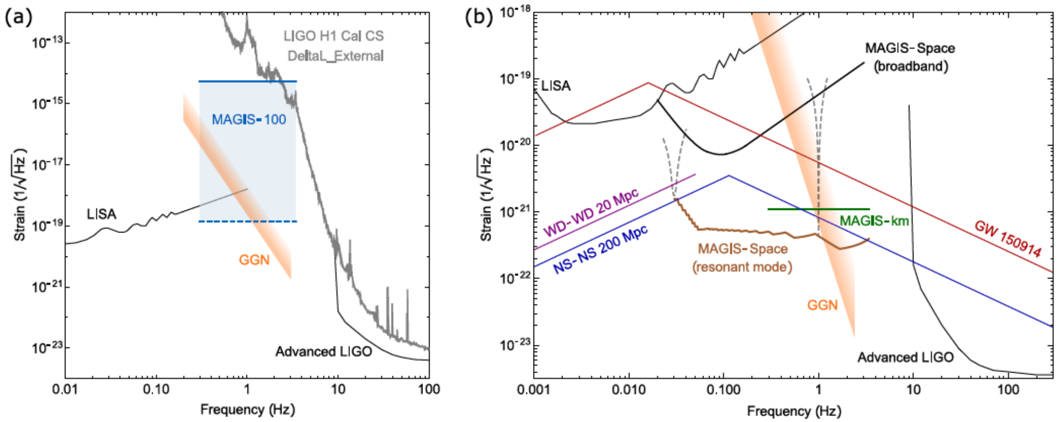
Mid-band Gravitational Wave Detection



-Path to continued improvement through R&D efforts, which we are pursuing (MAGIS-100 serving as testbed)

-Potential for future km-scale terrestrial detector and satellite-based detector

-GGN (gravity gradient noise) important at lower frequencies for terrestrial detectors: seismic waves disturb local mass distribution, cause oscillating gravity gradient that is a noise background