Probes of New Physics with MAGIS-100

Snowmass Contribution #57

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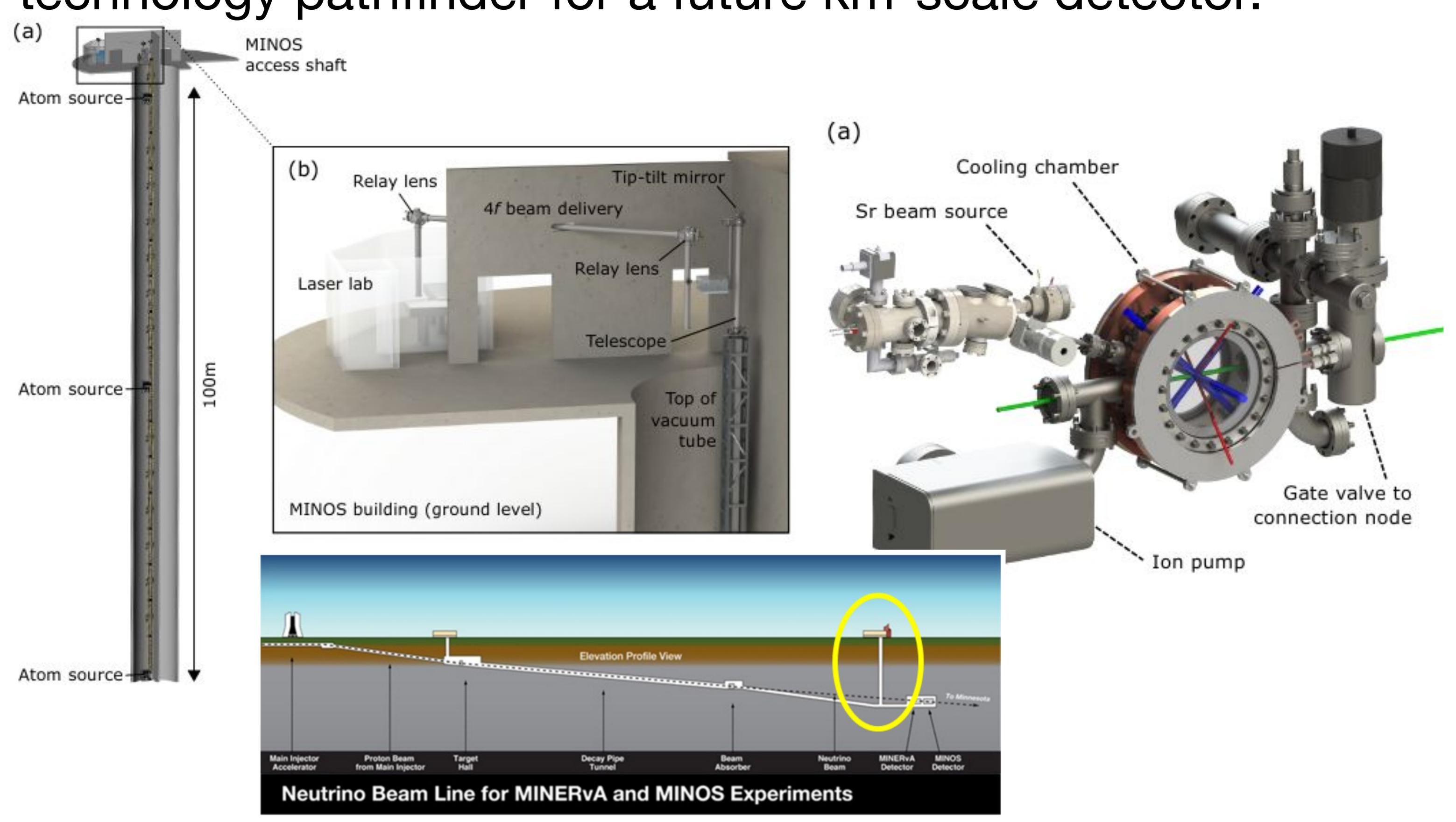
The MAGIS-100 Experiment

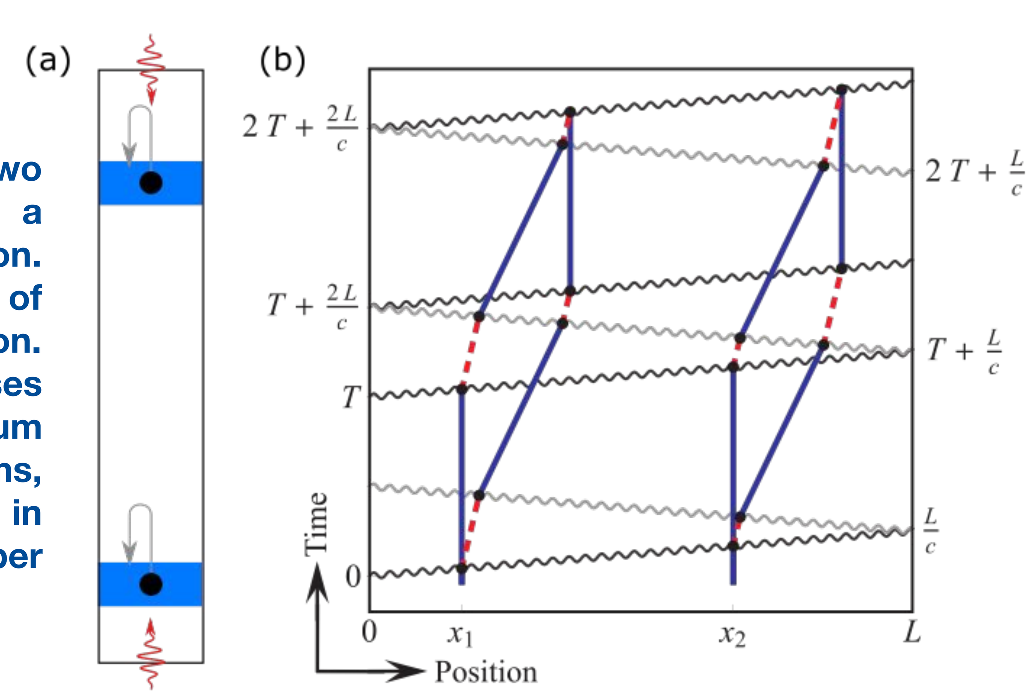
The Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) is an ultracold atom interferometry experiment for detection of ultralight dark matter, gravitational waves, and new forces. It features 3 coupled Sr atom interferometers along a 100m vertical baseline. Beyond the tests of fundamental and cosmic physics, MAGIS-100 serves as a technology pathfinder for a future km-scale detector.



(Upper left) A rendering of the MAGIS-design showing the three locations of the atom interferometers with an inlay showing the laser delivery system. (Upper right) A rendering of the design of the ultracold Sr atom sources to be used in the experiment. (Lower) MAGIS-100 will be constructed in the existing 100m NuMI access shaft at Fermilab near Chicago, USA. Images from [1].

Light-Pulse Atom Interferometry

Coupled laser pulses place the atoms in a superposition of internal states and separate their momenta, sending them along different trajectories. Between laser pulses, the atoms are in free-fall allowing them to serve as inertial references, as well as extremely precise atomic clocks. The pulses for each interferometer are derived from the same laser, which enables a reduction in correlated noise and systematics.

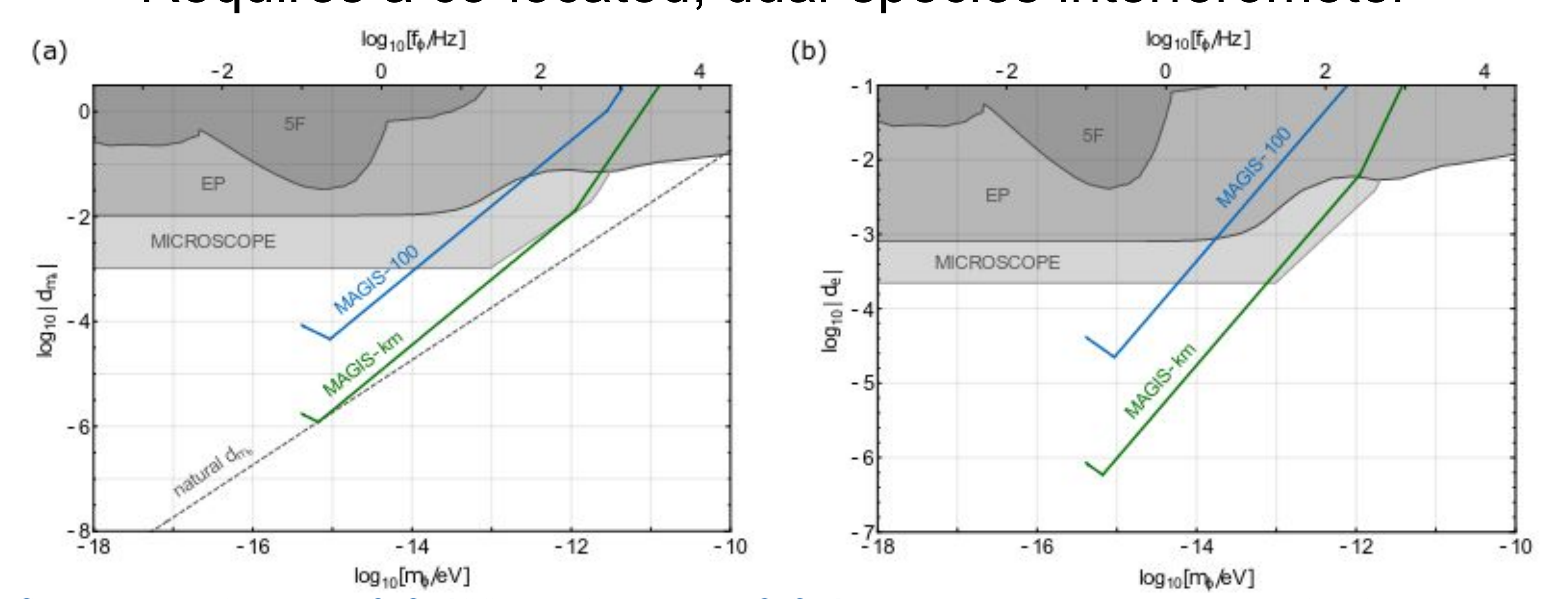


(Left) A schematic of two coupled interferometers in a gradiometer configuration. (Right) A spacetime diagram of the gradiometer configuration. Repeated mirror (π) pulses increase the momentum separation of the two arms, resulting in an increase in sensitivity linear in the number of pulses. Image from [2].

MAGIS-100 is sensitive to shifts in atomic energy levels, differential accelerations, and modulation of length scales via the light travel time, which all manifest as a phase shift between the coupled interferometers.

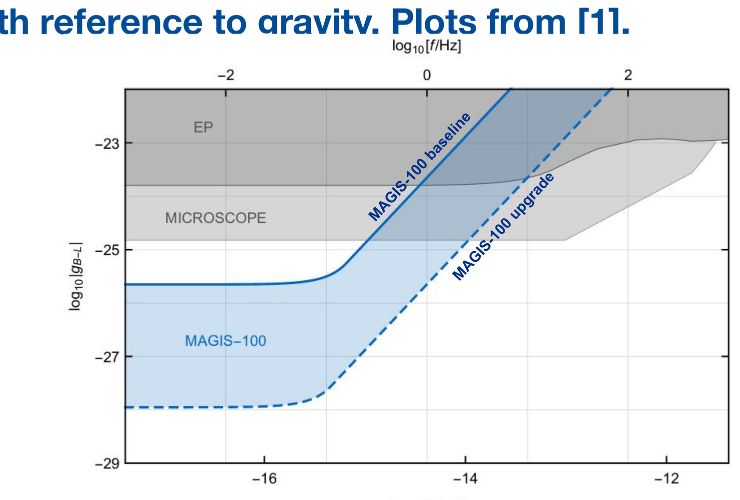
Dark Matter & New Forces

- Bosonic DM fields oscillate at a frequency determined by the particles mass.
- Scalars that couple to the photon and electron fields induce time-dependent fluctuations in the energy levels of atoms in the interferometer.
- Vector particles produce time-varying accelerations of different magnitude for different isotopes.
  - Modifies the Hamiltonian → appears in phase shift
  - Requires a co-located, dual-species interferometer



Sensitivity of the MAGIS-100 and future MAGIS-1K experiments to a scalar DM field that couples to electrons (left) and photons (right). This coupling induces an oscillation in the values of the electron mass and the fine structure constant, respectively, leading to time-varying energy levels of atoms in the interferometers. For masses below 10^{-15} eV, the MAGIS concept is uniquely posed to probe couplings over 1000x weaker than gravity. The coupling strengths are defined with reference to gravity. Plots from [1].

Sensitivity of the MAGIS-100 experiment to a new gauge boson that couples to B-L (neutron content). If this boson is the dark matter, it produces an oscillatory signal, while if sourced from the earth, it is a static effect. The blue shaded region indicates the span of the MAGIS reach from initial performance to the target parameters. Plot from [1,3].



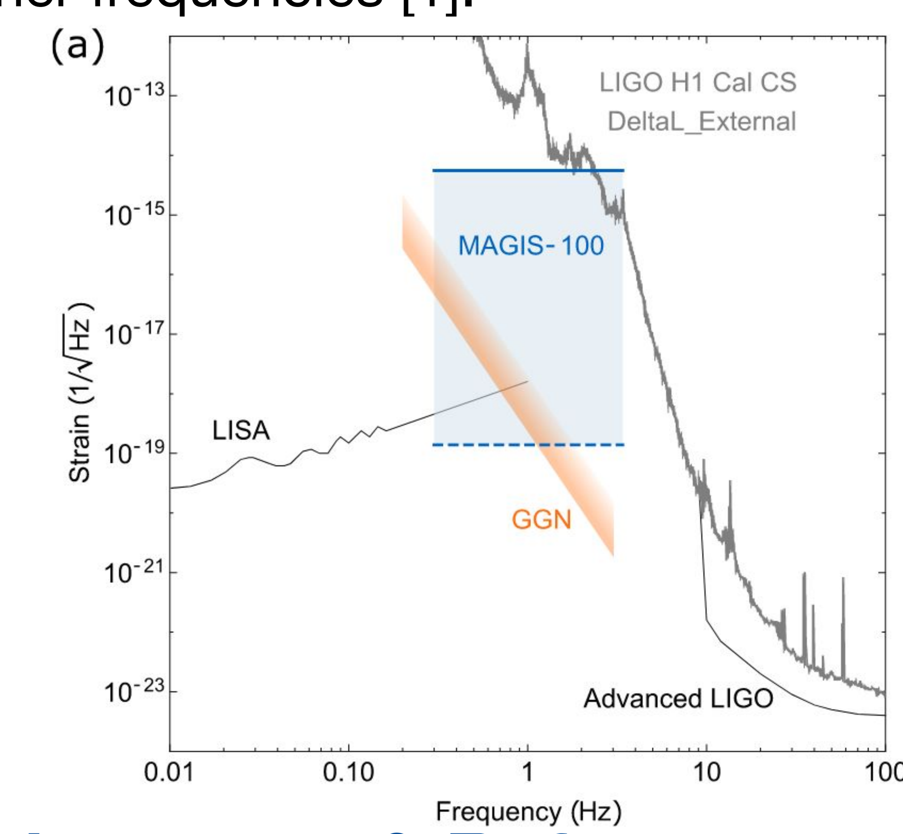
Quantum Mechanics: Tests & Applications

- Optimal quantum control sequences (QIS)
- Quantum superposition over unprecedented scales
  - Wavepacket separation (~10 m)
  - Coherence time (~9 sec)
- Non-linear corrections to Schrödinger's Eqn
- Investigating the use of spin-squeezed atom ensembles to surpass the standard quantum limit

Gravitational Waves

- Time-dependent strain modulates light travel time across interferometer baseline which is resolved in the differential phase measurement.
- MAGIS-100 will encounter a fundamental strain sensitivity limit due to gravitational gradient noise [4].
- Sensitive to the "mid-band" frequency range where interesting cosmological (*e.g.*, inflation, reheating) sources may be found. Strain sensitivity of MAGIS probes theoretical sources of GW, and can see binary NS and BH systems earlier than LIGO, before they evolve to higher frequencies [1].

MAGIS-100's sensitivity to gravitational waves, which spans the "mid-band" frequency region between LIGO and LISA. Known sources of GWs in this region include theoretical cosmological phenomena, and neutron star (NS) binaries, as well as black hole binaries with M~$\mathcal{O}$(10)$M_\odot$, earlier in their mergers than LIGO. The orange region indicates the fundamental sensitivity limit from seismic (gravitational gradient) noise. Plot from [1].



Outlook, Acknowledgements & References

- Construction begins Fall 2022, commissioning follows in Spring 2024. First science results in late 2024. Two years of science data to follow.
- MAGIS-100 uses quantum superposition at unprecedented scales to probe scalar and vector DM candidates down to 10^{-15} eV and 10^{-18} eV, as well as mid-band gravitational waves.
- To reach desired sensitivity, MAGIS will advance the state of the art in atom interferometry and quantum manipulation.

On behalf of the MAGIS-100 Collaboration.

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[1] *Abe et al., Quantum Sci. Technol. 6, 044003 (2021)*
[2] *Graham et al., PRL 110, 171102 (2013).*
[3] *Graham et al., Phys. Rev. D 93, 075029 (2016)*
[4] *J. Mitchell et al 2022 JINST 17 P01007*