Long Baseline Atom Interferometry: MAGIS-100 [1]

- 3x Sr AI on 100m baseline (gradiometer)
- Single photon transitions: $^{87}\text{Sr} (P_0 \rightarrow 3P_0)$
- Common interferometry laser beam
  - Allows cancellation of common-mode systematics & noise
- Cold atom clouds
  - Freely-falling clocks
  - Inertial references
- Sensitive to signals in $-0.1 \rightarrow 10$ Hz
- Dark Matter (DM): ultralight scalar, B-L vector
- Gravitational Waves: “Mid-Band”
- Tests of quantum mechanics & relativity
- To be constructed at Fermilab (~2026)

Ultralight Scalar Dark Matter Simulation

1. Generate DM waves, each with random $(\vec{t}, \phi)$
2. Sum the waves in each “cycle”
   a. Each “cycle” is a set of waveform points, sampled at nominal atom shot rate
   b. Every cycle separated by ~large time jump
3. Fit each cycle to a sine \( \rightarrow \) extract amplitude & phase to get DM “fingerprint” \( \rightarrow \) accounts for decoherence
   - of wave due to incoherent sum of constituent particles
4. Calculate the gradiometer phase shift, given apparatus and run configuration
5. Apply Gaussian noise to each calculated $\Delta \phi$ to emulate shot noise

\[
\Delta \omega = \sqrt{4\pi G_N (d_{m_\alpha} + \zeta_d)} \int_{t_1}^{t_2} \cos(m_\chi t + \beta) dt
\]

\[
\Phi_d = \Delta \omega \int_{t_1}^{t_2} \left[ \sin(m_\chi t_1 + \beta) - \sin(m_\chi t_2 + \beta) \right] dt
\]

Simulated Campaign Construction

Operational parameters

- LMT: 1000kHz momentum separation
- Flux: $10^8$ atoms/shot ; Shot rate: 10 Hz
- Baseline: 50 m ; Interrogation time: 1.5 sec
- No timing jitter ; Shot-noise limited phase resolution

Phase Analysis. After DM frequency is found, use that to reconstruct the DM wave decoherence “fingerprint”

- In MAGIS’ mass range, DM coherence time ranges from days to years, due to $\sigma(f_0) = 8 \times 10^{-8} f_0$
- Split time series gradiometer phases into uniformly distributed time slices
- For each observation time, assign a phase $\beta_i = 2\pi f_0 t_i$
- Bin wave phases, sum all gradiometer phases in that bin
- Fit binned grad. Phases to sine, extract amplitude and phase to reconstruct DM fingerprint.

References:


Preliminary Results: Impact of Downtime

For a representative mass ($10^{-15}$ eV) Compare each downtime scenario to a no-downtime campaign with the same total number of atoms launched.

Regular maintenance. Scheduled periods of downtime (daily, weekly, monthly) do not significantly degrade DM sensitivity using Compound FFT.

- Reduction in sensitivity scales as expected with reduction in total exposure (number of atoms launched).

Bad atom launches. Experimental fidelity has the most harmful impact on DM sensitivity using Compound FFT analysis.

- A low probability of dropped shots (e.g. 0.02%) can lead to discarding large periods of data (99.5% loss) -- depending on chunk length (1 hour).

Current Status & Next Steps

Developing suite of analysis & signal simulation tools for the MAGIS-100 experiment, aim to make available to LBAI community.

Ongoing investigations & future work:

- Investigating downtime scenarios beyond those presented
  - Noise bursts. Periods of increased noise (e.g., seismics, elevator)
- Expand signal models: B-L vector DM, gravitational waves
- Implement Lomb-Scargle Periodogram [3] in sensitivity calculation to make use of every atom shot
- Codebase optimization

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work is funded in part by the U.S. Department of Energy, Office of Science, High-Energy Physics Program Office as well as the QuantiSED program.