Matter wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

PAC Meeting

Jason Hogan

on behalf of the MAGIS collaboration

January 16, 2019
From the July 2018 PAC Report:

The PAC heard a detailed report covering the MAGIS-100 Letter of Intent for the next-generation MAGIS experiment. The hundred-meter MAGIS-100 experiment is an atom interferometric gradiometer that would be housed in the NuMI shaft, containing three atom sources (top, middle, bottom), associated lasers, and a high-vacuum ~100m pipe. The experiment would function as a pathfinder for a km-scale instrument (which could potentially be hosted at SURF in South Dakota) to measure low-frequency gravitational waves, an exciting and unique opportunity made possible by this technology. Additionally, MAGIS-100 will set limits on low-mass dark matter candidates in a class of scenarios predicting oscillations in a background classical field, exotic new forces, and time-dependence of fundamental constants. It will also function as a demonstrator for long-range quantum superpositions setting strict limits on certain models of intrinsic quantum decoherence.

Given the work already carried out at Stanford (MAGIS-10) and the relative maturity of the proposed strontium-based technology which will be fully tested at Stanford before bringing the experiment to Fermilab, MAGIS-100 represents both an exciting science opportunity that leverages quantum science and technology as well as one that poses a low risk for the Laboratory. The PAC finds that the request by MAGIS-100 for engineering and drafting resources to develop a full proposal appears reasonable and strongly supports it. The PAC looks forward to receiving a MAGIS-100 proposal in the near future.

Updates:
• Proposal submitted to the PAC in December 2018
• Grant received from the Gordon and Betty Moore Foundation for MAGIS-100
MAGIS Collaboration

PROPOSAL: P-1101
Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

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\textsuperscript{2}Northern Illinois University; DeKalb, Illinois 60115, USA
\textsuperscript{3}Stanford University; Stanford, California 94305, USA
\textsuperscript{4}University of California at Berkeley; Berkeley, CA 94720, USA
\textsuperscript{5}University of Liverpool; Merseyside, L69 7ZE, UK
\textsuperscript{6}Northwestern University; Evanston, Illinois, USA

Part of the proposed Fermilab Quantum Initiative:
Physics motivation

Dark matter and new forces
- Time-dependent signals caused by ultra-light dark matter candidates (dilaton, ALP, relaxion ...)
- Dark matter that affects fundamental constants: electron mass, fine structure constant
- Time-dependent EP violations from B-L coupled dark matter
- New forces

Advancing quantum science
- Atom de Broglie wavepackets in superposition separated by up to 10 meters
- Durations of many seconds, up to 9 seconds (full height launch)
- Quantum entanglement to reduce sensor noise below the standard quantum limit

Gravitational wave detector development
- Probe for studying cosmology
- Explores range of frequencies not covered by other detectors
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)
Projected sensitivity to dark matter

Sensitivity to ultralight scalar dark matter

Sensitivity to B-L coupled new force

~ 1 year data taking
$10^{15}$ dropped atoms, assuming shot-noise limited phase resolution

Graham et al. PRD 93, 075029 (2016).

Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range (“mid-band”)

Potential for *single baseline* detector (use atoms as phase reference/local clock)

**Mid-band science**
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, ...)

**Mid-band**
- 0.03 Hz to 3 Hz
Quantum science

Realizing macroscopic quantum mechanical superposition states

**Distance:** Wave packets are expected to be separated by distances of up to 10 meters (current state-of-art 0.5 meters)

**Time:** Support record breaking matter wave interferometer durations, up to 9 seconds (current state-of-art 2 seconds)

**Entanglement:** 20 dB spin squeezed Sr atom sources takes advantage of quantum correlations to reduce sensor noise below the standard quantum limit (shot noise)
Detector technology: Atom interferometry and clocks

- Best clocks in the world now lose <1 second in $10^{18}$ seconds
- MAGIS-100 is based on same physics as Sr optical lattice clock
- Atom interferometry provides a pristine inertial reference
- Compare two (or more) atom ensembles separated by a large baseline
- Differential measurement suppresses many sources of common noise and systematic errors

**Atomic clock transition**

**Atom interferometer**

**Gradiometer**
Current generation: Stanford 10-meter scale

Milestones

- Record matter wave interferometer duration (>2 s)
- Record wavepacket separation (>0.5 meter)
- Record effective temperature (< 50 pK)
- First observation of phase shift due to space-time curvature across a single particle’s wavefunction
- Large momentum transfer 90 ħk
- Record accelerometer scale factor
- Dual species ($^{85}$Rb / $^{87}$Rb) gradiometer
- First demonstration of phase shear readout and point source interferometry techniques

10-meter tall Rb atomic fountain

World record wavepacket separation due to multiple laser pulses of momentum

54 cm
Proposed MAGIS-100 at Fermilab

**System Components:**
- 10 times larger than Stanford setup
- Located in MINOS shaft
- 90 meter vacuum tube (vertical)
- Three atoms sources
- Laser system for implementing atom interferometry (hutch at top)
Components and Requirements

6.1 Site
✓ 100 meter shaft of sufficient diameter to install hardware

6.2 Vacuum and Vacuum pipe
✓ 20 cm vertical pipe at 10^{-11} Torr pressure

6.3 Magnetic shielding and magnetic field control
✓ Shield Earth magnetic field to 10 mG (benefits from low susceptibility of Sr)
✓ Uniform horizontal bias field of 1 G

6.4 Atom source
✓ Three cold atom sources
✓ >10^6 atoms/s cooled to 10 nK

6.5 Transfer and Launch
✓ Optical dipole trap and optical lattice acceleration

6.6 Atom optics laser system
✓ >4 W at 698 nm stabilized to <10 Hz linewidth

6.7 Laser wavefront aberrations
✓ Milliradian aberrations, with free-propagation spatial filtering, characterization, and feedback

6.8 Tip-tilt mirrors and rotation compensation
✓ Imprint spatial phase on cloud, suppress Coriolis phase shifts and other systematics

6.9 Controls and monitoring
✓ FPGA timing control

6.10 Cameras and Data Acquisition
✓ Low read noise CCDs (3e rms) with < 10 Hz sample rate

6.11 Computing
✓ 1-2 TB data/day before compression

The proposed experiment meets each of these requirements
Estimated scientific effort

- Steady operations the 10m baseline experiment at Stanford has a scientific staff (students/postdocs/scientists) of **3.3 FTEs**

- The effort in this table is sufficient for operating and analyzing MAGIS-100 24/7 during data runs

- Stanford effort covered by GBMF grant

- Will be requesting support from DOE for Fermilab effort

<table>
<thead>
<tr>
<th>Year</th>
<th>Institution</th>
<th>Scientists</th>
<th>Postdocs</th>
<th>Students</th>
<th>TOTAL FTEs</th>
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<th>Scientists</th>
<th>Postdocs</th>
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<tr>
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<th>Students</th>
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<tbody>
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<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
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<td>1</td>
<td>0</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Liverpool</td>
<td>0.5</td>
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<td>2</td>
<td>3.5</td>
</tr>
<tr>
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<td>NIU</td>
<td>0.7</td>
<td>1</td>
<td>2</td>
<td>3.7</td>
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<tr>
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<td>1</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Stanford</td>
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<td>1</td>
<td>4</td>
<td>5.5</td>
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<td><strong>5.0</strong></td>
<td><strong>9.5</strong></td>
<td><strong>18.4</strong></td>
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MAGIS-100 is a 5 year project; above shows FTEs for 3 year construction phase
New funding received from GBMF
$9.8M, 5 years, start date Jan 2019

MAGIS-100 at Fermilab ($3.39M)

• 100 meter vacuum tube (Fermilab design contribution)
• Three atomic sources (Stanford design contribution)
• Atom interferometry laser system (Northwestern design contribution)

Atom interferometry sensor development at Stanford ($6.41M)

<table>
<thead>
<tr>
<th>Sensor technology</th>
<th>State of the art</th>
<th>Goal</th>
<th>GW sensitivity improvement</th>
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<tbody>
<tr>
<td>LMT atom optics</td>
<td>$n = 10^2$</td>
<td>$n = 10^3$</td>
<td>10</td>
</tr>
<tr>
<td>Spin squeezing</td>
<td>20 dB (Rb), 0 dB (Sr)</td>
<td>20 dB (Sr)</td>
<td>10</td>
</tr>
<tr>
<td>Atom flux</td>
<td>$\sim 10^6$ atoms/s</td>
<td>$10^8$ atoms/s</td>
<td>10</td>
</tr>
</tbody>
</table>

Hogan
Kasevich
Hogan
Sensitivity development plan (part of GBMF grant)

Phase noise improvements:
- 10x from higher flux
- 10x from squeezing

Atom source scaling: $\sim \sqrt{n}/2$

<table>
<thead>
<tr>
<th></th>
<th>MAGIS-100 (current)</th>
<th>MAGIS-100 (5 year)</th>
<th>MAGIS-km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>100 m</td>
<td>100 m</td>
<td>2 km</td>
</tr>
<tr>
<td>Phase noise</td>
<td>$10^{-3}/\sqrt{\text{Hz}}$</td>
<td>$10^{-5}/\sqrt{\text{Hz}}$</td>
<td>$0.3 \times 10^{-5}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>LMT</td>
<td>100</td>
<td>4e4</td>
<td>4e4</td>
</tr>
<tr>
<td>Atom sources</td>
<td>3</td>
<td>3</td>
<td>30</td>
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</table>

MAGIS-km additional factor of 3x improvement in phase noise from flux + quantum entanglement (spin squeezing)
## Preliminary Project Milestones and Budget

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Location</th>
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<tbody>
<tr>
<td>Atom source design and procurement</td>
<td>Adapt existing designs and add environmental protection and other hardware needed to integrate into MAGIS-100.</td>
<td>Stanford</td>
</tr>
<tr>
<td>Laser system design and procurement</td>
<td>Design high-power atom optics laser system based on coherently combined Tisapphire lasers. Procure necessary equipment.</td>
<td>Stanford</td>
</tr>
<tr>
<td>Preliminary site engineering</td>
<td>Study vibration environment, magnetic field environment, and temperature environment. Begin engineering for vibration isolation (if necessary), magnetic shielding and active magnetic field compensation, and temperature control.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>100 m vacuum vessel design and procurement</td>
<td>Design system of vacuum pumps, viewports, and atom source connection nodes. Procure necessary equipment.</td>
<td>Stanford/FNAL</td>
</tr>
<tr>
<td>Build 100 m vacuum segments</td>
<td>Install viewports and connection nodes.</td>
<td>Stanford</td>
</tr>
<tr>
<td>Complete site design</td>
<td>Finalize vibration, magnetic, and temperature engineering.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Atom source qualification</td>
<td>Build atom sources. Verify that necessary atom flux is delivered.</td>
<td>Stanford</td>
</tr>
<tr>
<td>Laser system qualification</td>
<td>Build laser system. Verify that power delivered, frequency and amplitude agility, and phase noise meet specifications.</td>
<td>Stanford</td>
</tr>
<tr>
<td>Detector commissioning</td>
<td>Install 100 m vacuum vessel, magnetic shield, atom sources, and laser system. Test lattice shuttling of atoms from atom sources into 100 m vacuum tube, dropping of atoms, lattice launching of atoms, and atom optics laser pulses.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Atom interferometry in 100 meter vacuum</td>
<td>Run atom interferometers using each of the three atom sources. Implement LMT atom optics in interferometers.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Gradiometer with two sources</td>
<td>Long baseline gradiometer. Study noise sources.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Science data runs</td>
<td>Long science data runs with two-source gradiometer (gravitational wave detector prototype).</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Gradiometer with three sources</td>
<td>Incorporate third source into long baseline gradiometer.</td>
<td>Fermilab</td>
</tr>
<tr>
<td>Study GGN suppression</td>
<td>Use three-source gradiometer to study gravity gradient noise (GGN) impact and mitigation strategies. Additional long science data runs.</td>
<td>Fermilab</td>
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### Estimated DOE Request

<table>
<thead>
<tr>
<th>M&amp;S + technical effort</th>
<th><strong>Sub-Total</strong></th>
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</thead>
<tbody>
<tr>
<td>Fabricate Atom Sources (Stanford)</td>
<td>1,869,000</td>
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<tr>
<td>Vacuum Tube Procurement (Stanford)</td>
<td>931,060</td>
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<tr>
<td>Interferometer Laser (Stanford)</td>
<td>593,200</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>3,393,260</strong></td>
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### Moore Funding

<table>
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<th>Estimated DOE Request</th>
<th>Direct Cost ($)</th>
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<tr>
<td>Interferometer Shaft Support Structure</td>
<td>99,000</td>
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<tr>
<td>Laser hut and support platform</td>
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<tr>
<td>Engineering (FNAL)</td>
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<tr>
<td>Drafting and Technical</td>
<td>304,000</td>
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<tr>
<td>Installation Equipment</td>
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<tr>
<td>Installation</td>
<td>51,000</td>
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<tr>
<td>Operation and Materials</td>
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<tr>
<td><strong>Sub-Total</strong></td>
<td><strong>919,000</strong></td>
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**TOTALS**

| **DIRECT**                             | **4,312,260**  |
| **INDIRECT**                           | **691,000**    |
| **FULLY BURDENED**                     | **5,003,260**  |

Proposal Table 4 (page 41)
Stanford MAGIS prototype

Sr gradiometer CAD (atom source detail)

Two assembled Sr atom sources

Trapped Sr atom cloud (Blue MOT)

Atom optics laser (M Squared SolsTiS)
a) Is the science in the proposal interesting and/or compelling?  
“...MAGIS-100 represents both an exciting science opportunity that leverages quantum science and technology as well as one that poses a low risk for the Laboratory” – PAC Report, July 2018

b) Is the technique proposed appropriate for, and likely to be capable of, reaching the physics goals of the experiment?  
Yes, the community has endorsed this approach (e.g., BRN process). The first set of science goals (DM, quantum) use proven technology. Additional science (GW, DM) will depend on the outcome of parallel R&D program (already funded by GBMF).
c) What is the competition for reaching the physics goals of the proposed experiment? Does the proposed experiment have particular advantages or disadvantages relative to the competition?

See next

d) What is needed to make such an experiment successful?

DOE support for Fermilab components of program (Effort + M&S)

- Will submit to next quantum science call (expected shortly)

Aggressive hiring (postdocs, students) to maintain GBMF grant schedule.
In our frequency range, in our time frame
• Clocks: Compare two species (some overlap at lowest frequencies, less sensitive to $d_{me}$)
• Eöt-Wash: Torsion pendulum experiments (overlap at low frequency, less sensitivity in our time frame)
• MIGA: Terrestrial atom interferometer detector in France (complementary technique with different systematics; e.g., susceptible to laser noise, needs two baselines)
• AION: MAGIS-like proposal based in the UK (needs 10 m prototype first)

Not in our frequency range, not in our time frame
• LIGO/LISA/ET (complementary; targeting different frequencies ranges)
• DECIGO, LISA variants in mid-band (space-based, 2030s)
• Axion searches with NMR/lumped circuit/microwave cavities (complementary, higher frequencies)
We request the PAC to recommend Stage 1 approval for MAGIS-100, so that the collaboration can make the best case possible to the DOE for funding in the upcoming quantum science funding opportunity.
Backup
<table>
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<th>Direct Costs</th>
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<td>4,503,459</td>
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<td>Travel</td>
<td>23,905</td>
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<td>M&amp;S for R&amp;D</td>
<td>374,000</td>
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<tr>
<td>M&amp;S for MAGIS-100</td>
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<tr>
<td>Equipment for R&amp;D</td>
<td>1,124,000</td>
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<td>Equipment for MAGIS-100</td>
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<td><strong>Total Direct</strong></td>
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<tr>
<td>Indirect</td>
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<td><strong>TOTAL ($)</strong></td>
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Table 6: Summary of Funding from the Moore Foundation.

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<td>M&amp;S for MAGIS-100</td>
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<tr>
<td>Equipment for MAGIS-100</td>
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<tr>
<td><strong>Total ($)</strong></td>
<td><strong>3,393,260</strong></td>
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## MAGIS-100 assembly milestones

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<tr>
<th>Year</th>
<th>Stanford</th>
<th>Fermilab</th>
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<tr>
<td>1</td>
<td><strong>Q1</strong></td>
<td>Complete prelim. engineering</td>
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<tr>
<td></td>
<td><strong>Q2</strong></td>
<td>Atom sources &amp; lasers procured</td>
</tr>
<tr>
<td></td>
<td><strong>Q3</strong></td>
<td>Vac. vessel &amp; shielding procured</td>
</tr>
<tr>
<td></td>
<td><strong>Q4</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Q1</strong></td>
<td>Delivery of interferometer vac. vessel</td>
</tr>
<tr>
<td></td>
<td><strong>Q2</strong></td>
<td>Atom sources &amp; lasers delivered</td>
</tr>
<tr>
<td></td>
<td><strong>Q3</strong></td>
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<tr>
<td></td>
<td><strong>Q4</strong></td>
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</tr>
<tr>
<td>3</td>
<td><strong>Q1</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Q2</strong></td>
<td>Begin commissioning. First quantum physics results</td>
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<td></td>
<td><strong>Q3</strong></td>
<td>First Dark Matter results</td>
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<td><strong>Q4</strong></td>
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## MAGIS-100 run time

<table>
<thead>
<tr>
<th>Science Topic</th>
<th>Required number of atoms</th>
<th>Atoms/sec when taking science data</th>
<th>Fraction of calendar taking science data</th>
<th>Estimated run time (years)</th>
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<td>Commissioning</td>
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<tr>
<td>Phase 2: Dark Sector Campaign</td>
<td>$10^{15}$</td>
<td>$10^8$</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Phase 3: Mid-band development</td>
<td>$10^{15}$</td>
<td>$10^8$</td>
<td>0.3</td>
<td>1</td>
</tr>
</tbody>
</table>
Preliminary seismic data at MINOS shaft

- REF TEK 151B-120 Observer
- 20 samples/s
- 10 days sample period
- Mean (red), median (green)
Systematic Errors

• Leading systematic errors and associated initial requirements for MAGIS-100

  – Wavefront aberrations: $\lambda/100$ optics

  – Pointing jitter: control or monitoring at the level of $1 \text{nrad}/\text{Hz}^{(1/2)}$ in relevant frequency band (can use split photodetectors to measure)

  – AC Stark shifts: $0.1\% /\text{Hz}^{(1/2)}$ laser intensity stabilization

  – Initial kinematic jitter: measure atom kinematics on each shot at the level of 1 micron (achievable with CCD cameras for spatial resolution)
Ultralight dilaton DM acts as a background field (e.g., mass $\sim 10^{-15} \text{ eV}$)

$$\mathcal{L} = + \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^2 \phi^2 - \sqrt{4\pi G_N} \phi \left[ d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right] + \ldots$$

 electron coupling

 photon coupling

 e.g., QCD

 DM scalar field

 $$\phi(t, x) = \phi_0 \cos \left[ m_{\phi}(t - v \cdot x) + \beta \right] + \mathcal{O} \left( |v|^2 \right)$$

 $$\phi_0 \propto \sqrt{\rho_{\text{DM}}}$$

 DM mass density

 DM coupling causes time-varying atomic energy levels:
Atomic sensors for gravitational wave detection

Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range (“mid-band”)

Potential for *single baseline* detector (use atoms as phase reference/local clock)

**Mid-band**

0.03 Hz to 3 Hz

**Mid-band science**

- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, ...)

**Satellite proposal using optical lattice clocks + drag free inertial reference** (Kolkowitz et al., *PRD* 2016)

**MAGIS**: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich)

**MIGA**: Terrestrial detector using atom interferometer + optical cavity (Bouyer, France)
Sky position determination

Sky localization precision:

$$\sqrt{\Omega_s} \sim \left( \text{SNR} \cdot \frac{R}{\lambda} \right)^{-1}$$

**Mid-band advantages**
- Small wavelength $\lambda$
- Long source lifetime (~months) maximizes effective $R$

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\sqrt{\Omega_s}$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>0.16</td>
</tr>
<tr>
<td>GW151226</td>
<td>0.20</td>
</tr>
<tr>
<td>NS-NS (140 Mpc)</td>
<td>0.19</td>
</tr>
</tbody>
</table>
**MAGIS-100: GW detector prototype at Fermilab**

**Matter wave Atomic Gradiometer Interferometric Sensor**
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves

**Mid-band science**
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- BH, NS, WD binaries
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

**Timeline**
- 2019 – 2023: MAGIS-100 at Fermilab (100-meter prototype detector)
- 2023 – 2028: Kilometer-scale GW detector (e.g., SURF Homestake site) [Proposed]
Gradiometer
Atom Source
Detector operation modes

(a) Max drop

(b) Max baseline

(c) GG rejection
Atom interference

Light interferometer

Atom interferometer

http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html
Atom optics using light

Light absorption:

$\hbar k \quad \rightarrow \quad \begin{array}{c} \vdots \\ \vdots \end{array} \quad \rightarrow \quad \begin{array}{c} \vdots \\ \vdots \end{array}$

$\hbar k$

$\nu = \frac{\hbar k}{m}$

Stimulated emission:

$\hbar k \quad \rightarrow \quad \begin{array}{c} \vdots \\ \vdots \end{array} \quad \rightarrow \quad \begin{array}{c} \vdots \\ \vdots \end{array}$

$\hbar k$
Light Pulse Atom Interferometry

Images of atom port populations vs phase

Science signal (CCD images):

Data from world record atom interferometer duration (>2 seconds) at Stanford

Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer

90 photons worth of momentum

World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., Nature 2015
Current generation: Stanford 10-meter scale

- Atom Optics & Lattice Beam
- Delivery Enclosure
- Upper Detection Region
- 3 Layer Magnetic Shield (<1 mG on axis)
- Lower Detection Region
- 2D MOT Loading 3D
- Rotation Compensation System
Gradiometer Demonstration (Rb)

Gradiometer interference fringes

Gradiometer response to 84 kg lead test mass

Asenbaum et al., PRL 118, 183602 (2017)
Advanced atom optics

Large momentum transfer atom optics

Resonant interferometer sequence