# Searches for Ultralight Dark Matter and New Forces with MAGIS-100


Dylan J Temples *on behalf of the MAGIS-100 Collaboration*


21 July 2022


FERMILAB-SLIDES-22-077-QIS


MAGIS-100

U.S. DEPARTMENT OF ENERGY | Office of Science

Gordon and Betty MOORE FOUNDATION

UKRI Science and Technology Facilities Council

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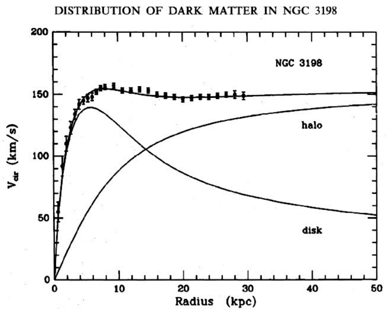
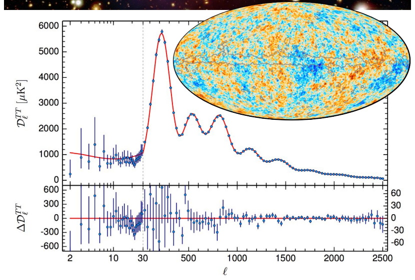
# Ultralight Dark Matter



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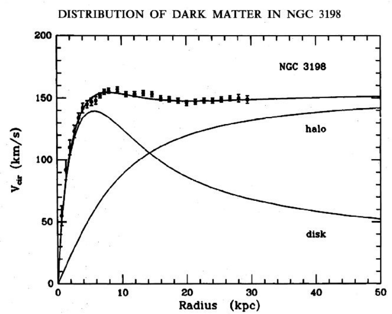


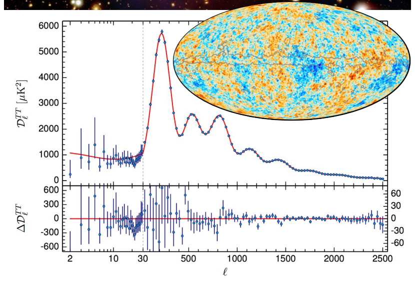


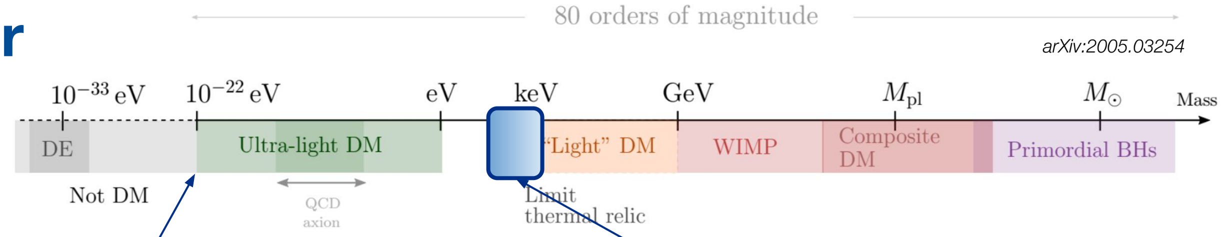


*arXiv:2005.03254*

Compton wavelength larger than dwarf spheroidal galaxy

Lower limit for fermionic DM
Tremaine-Gunn Bound

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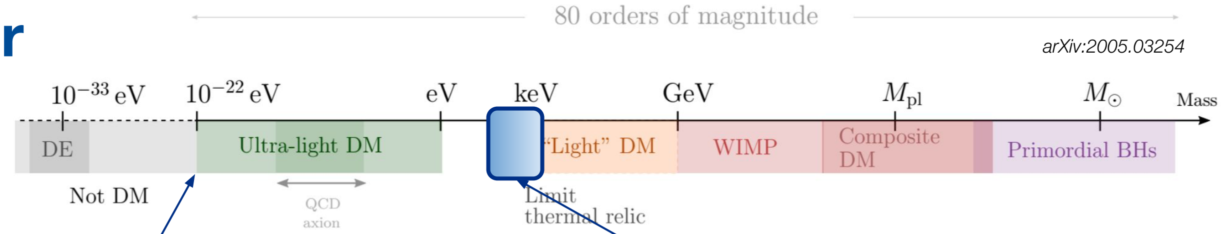


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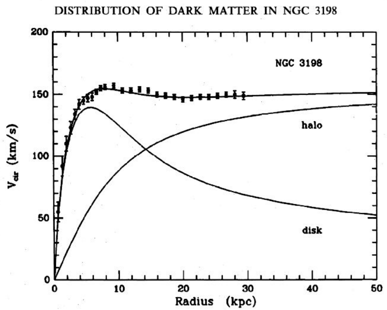


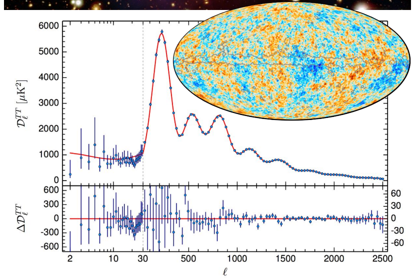


GeV+ scale (WIMP-like) - Extensive searches, decades of null results, $10^7$x increase in sensitivity



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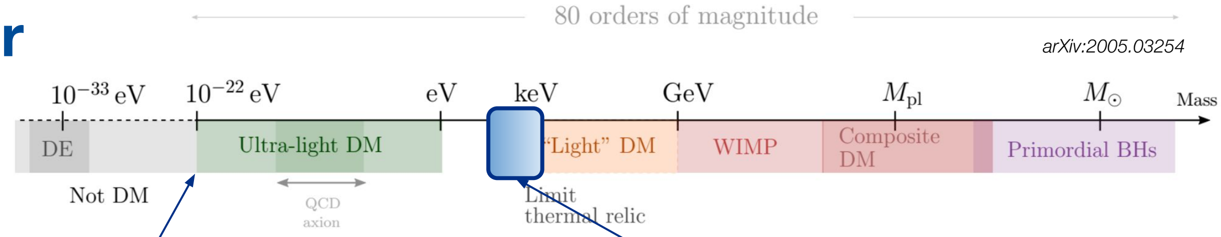


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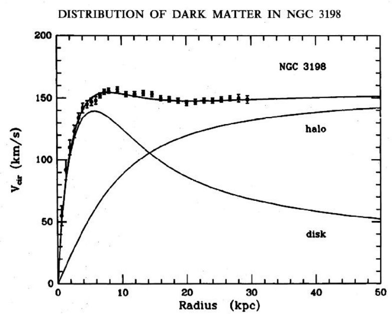


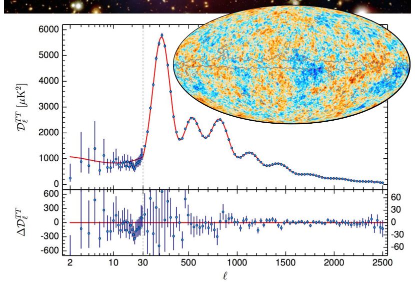

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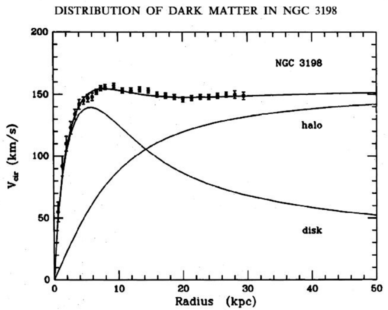


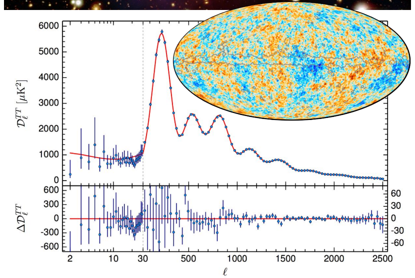

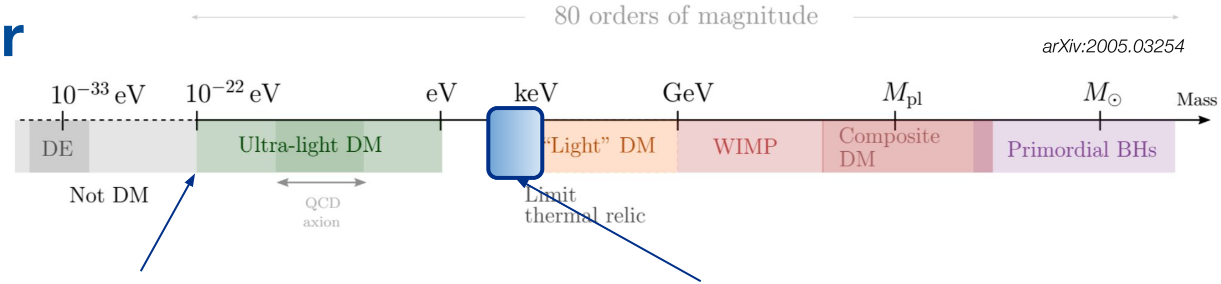


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**Ultralight DM** (m << eV) - want to explore down to $10^{-22}$ eV

- Axions - Current exploration focused in $10^{-5}$ -- $10^{-7}$ eV range
- Other candidates: hidden photons, dilaton, relaxion
- Landscape $<10^{-10}$ eV wide open - current constraints from EP-violation and 5th force searches

# Ultralight Dark Matter Properties

- Bosonic: scalar, pseudoscalar, and vector couplings
- DM density in galaxies → high occupation number in each coherence volume
- Classical oscillating field

$$\phi(t) \approx \phi_0 \cos(m_\phi t) \qquad \text{where} \qquad \phi_0 = \sqrt{2\rho_{\mathrm{DM}}}/m_\phi$$

  - Characteristic coherence time & length

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- *Cause precession of nuclear* or electron *spins*
- Generate currents in electromagnetic systems
- Produce photons
- *Induce equivalence-principle-violating accelerations*
- *Modulate the values of the fundamental "constants" of nature*

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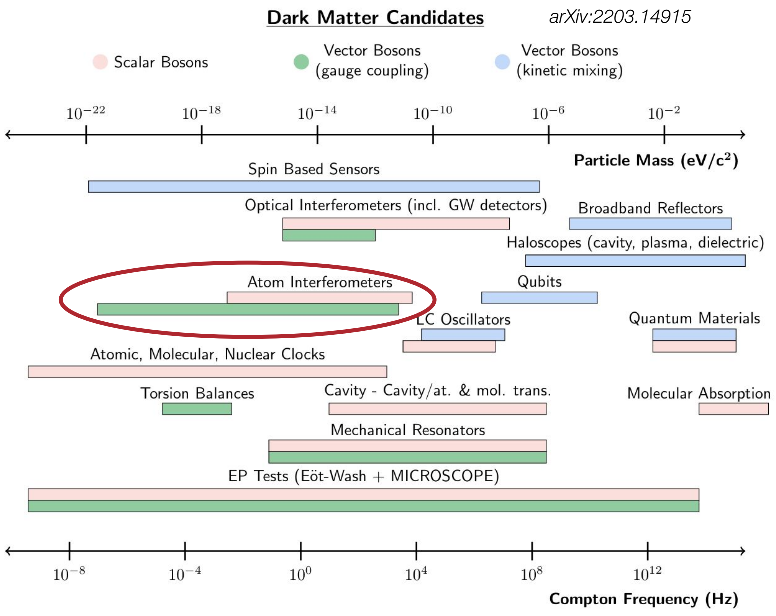


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→ Use precision atomic clocks and inertial references to measure these effects

# The MAGIS-100 Experiment

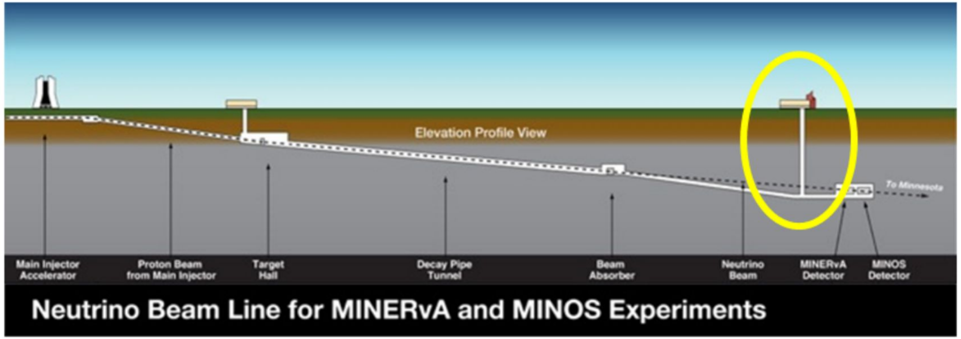
**Matter-wave Atomic Gradiometer Interferometric Sensor**

- 3x Sr atom interferometers
- 90 meter vertical baseline

Collaboration: AMO + HEP

- 10 institutions (US & UK)
- ~70 scientists & engineers

arxiv:1812.00482



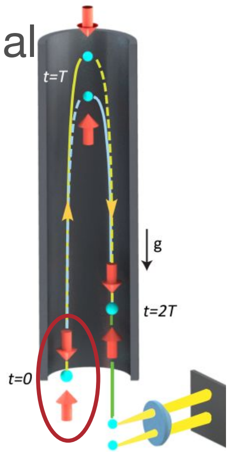

To be constructed at Fermilab in the MINOS access shaft to the NuMI tunnel

Based on 10-m prototype atomic fountain at Stanford

STANFORD · JOHNS HOPKINS UNIVERSITY · Northwestern University · Fermilab · SLAC · THE UNIVERSITY OF CHICAGO · UNIVERSITY OF CAMBRIDGE · Northern Illinois University · UNIVERSITY OF OXFORD · UNIVERSITY OF LIVERPOOL

# Light-Pulse Atom Interferometry

- Beamsplitter pulse (π/2) → equal superposition of |1⟩and |2⟩
- |2⟩gets momentum kick from absorbing photon




## Mach-Zehnder deBroglie Wave Interferometry

Abe et al, Quantum Sci. Technol. 6, 044003 (2021) [arxiv:2104.02835]
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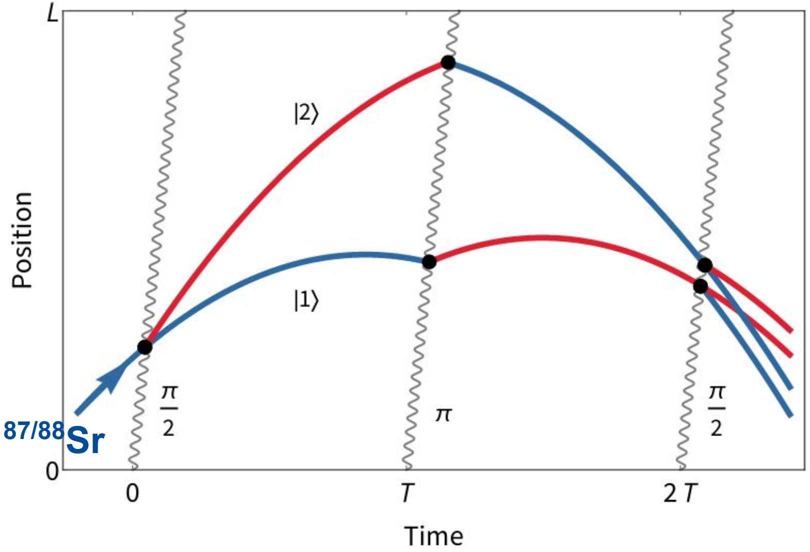

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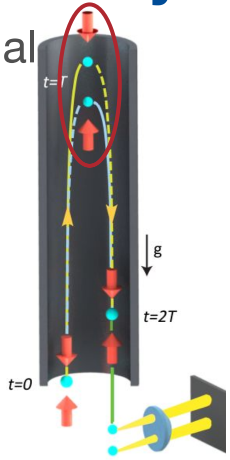
- Excited state accumulates phase relative to ground state

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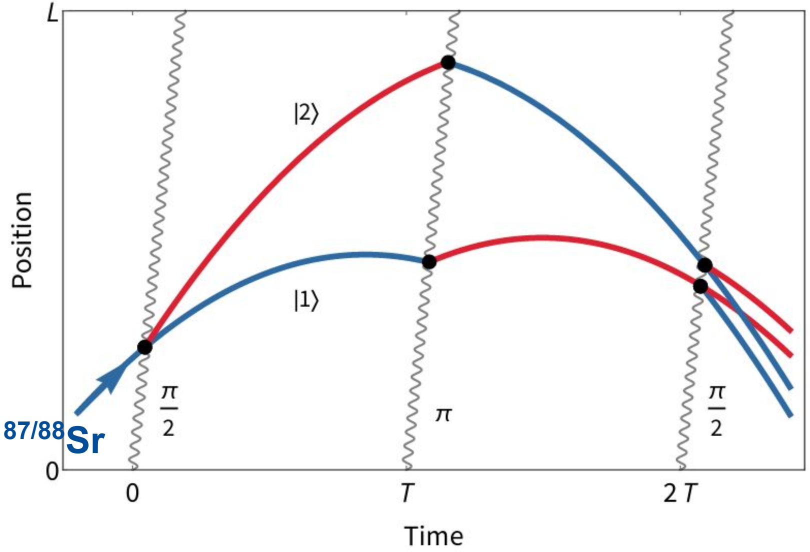



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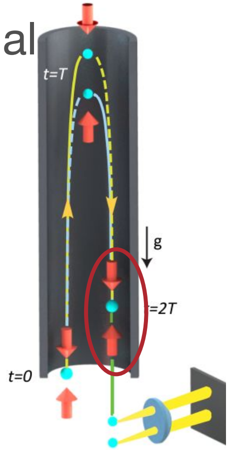


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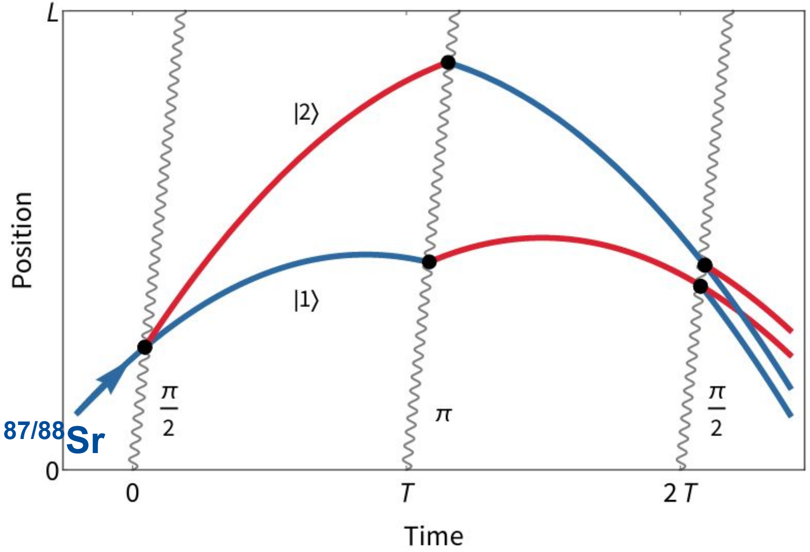




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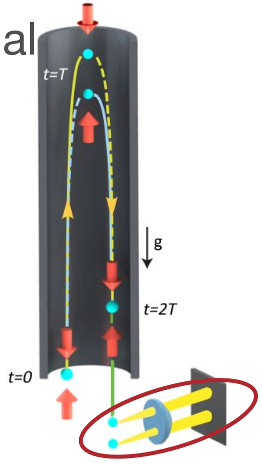
- Two atom clouds ("ports") are imaged and fit to determine δΦ

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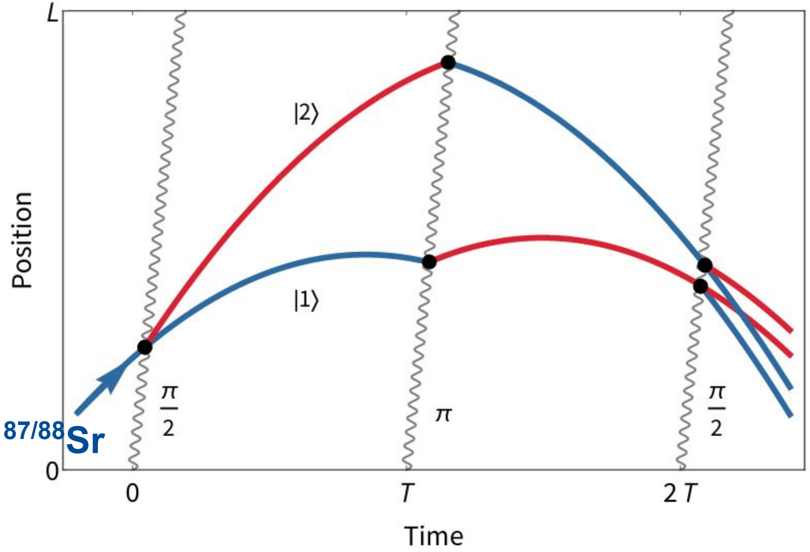


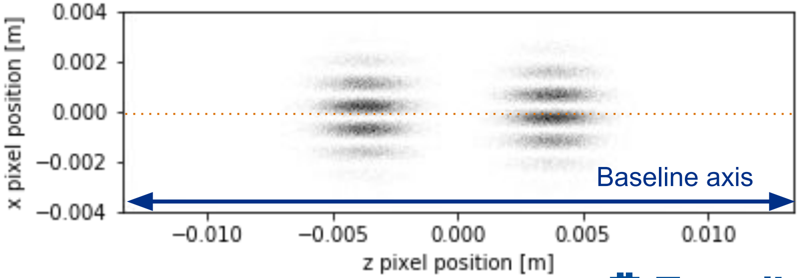

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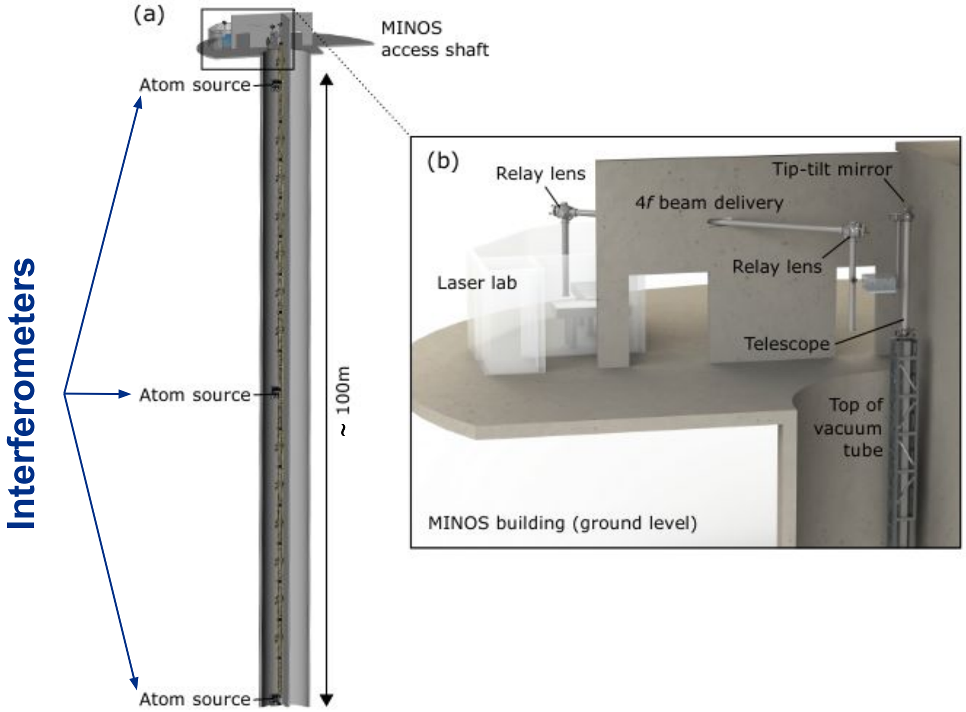


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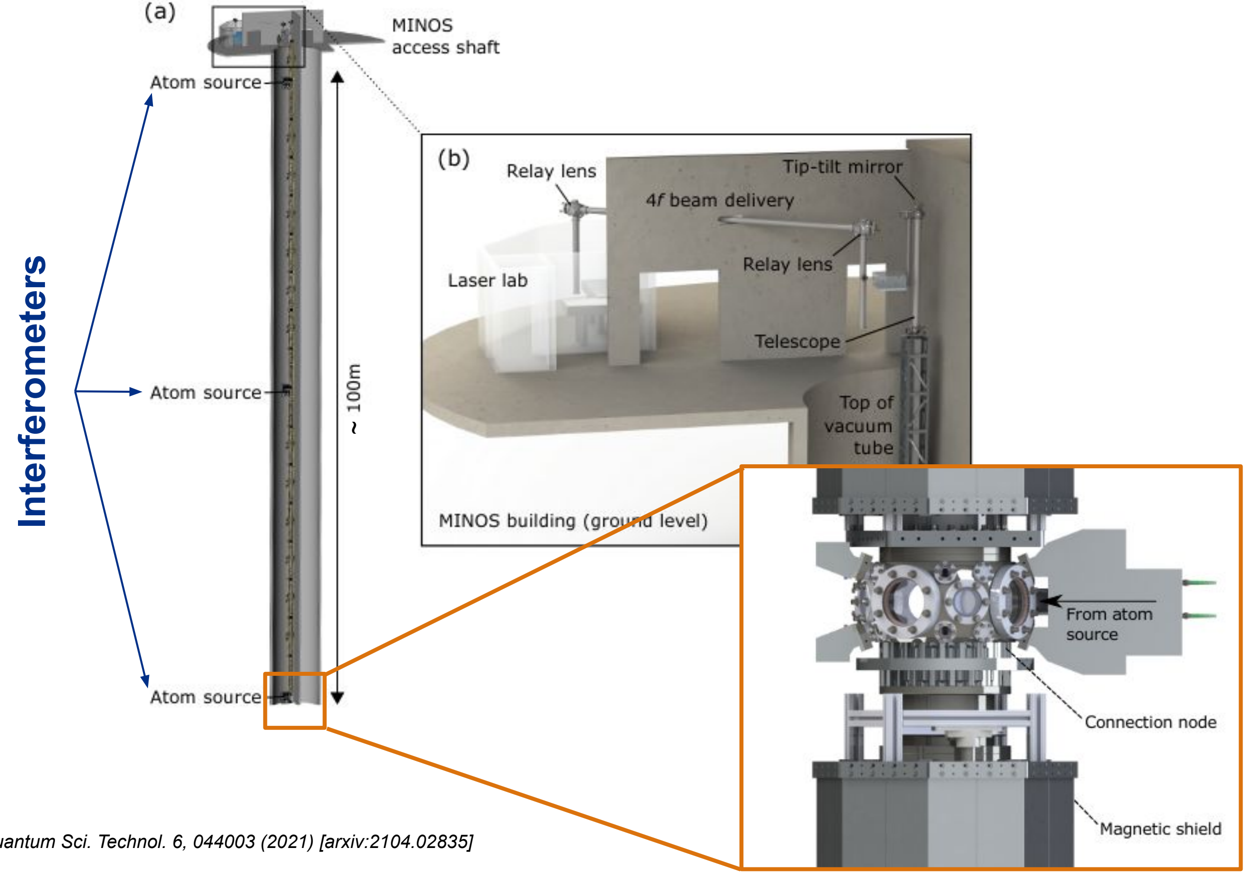


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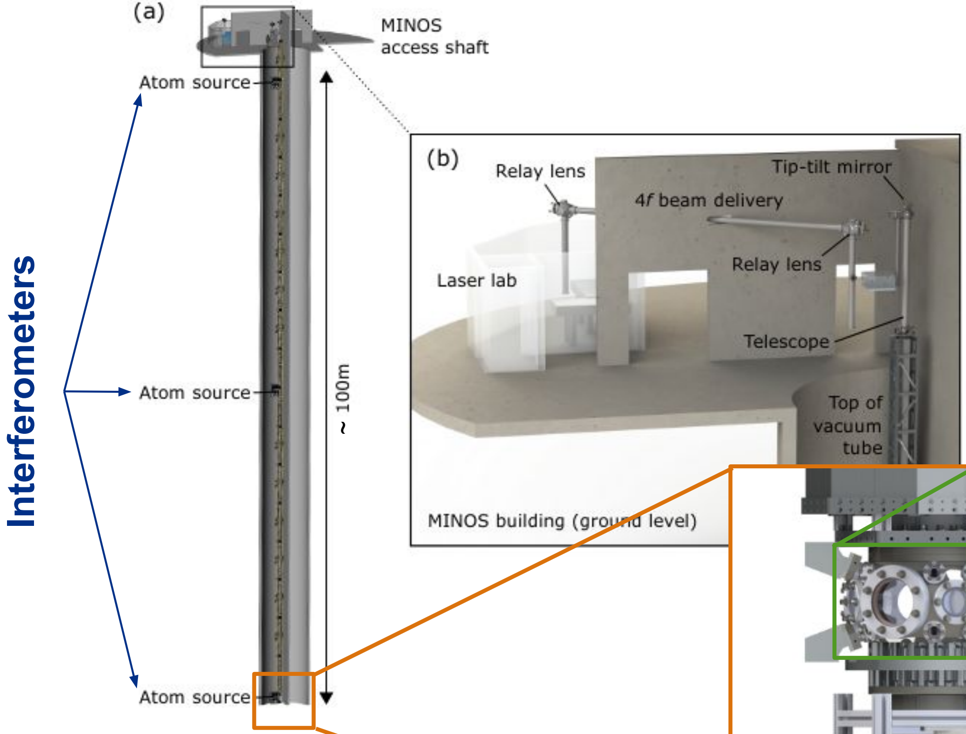
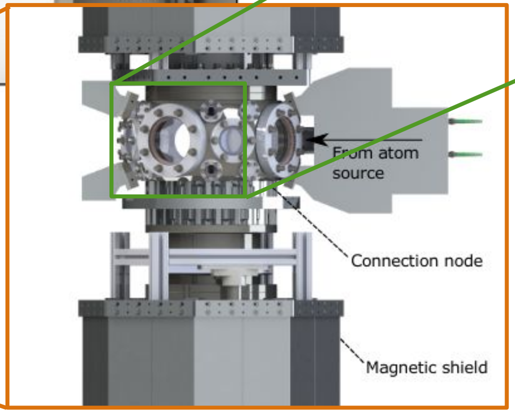
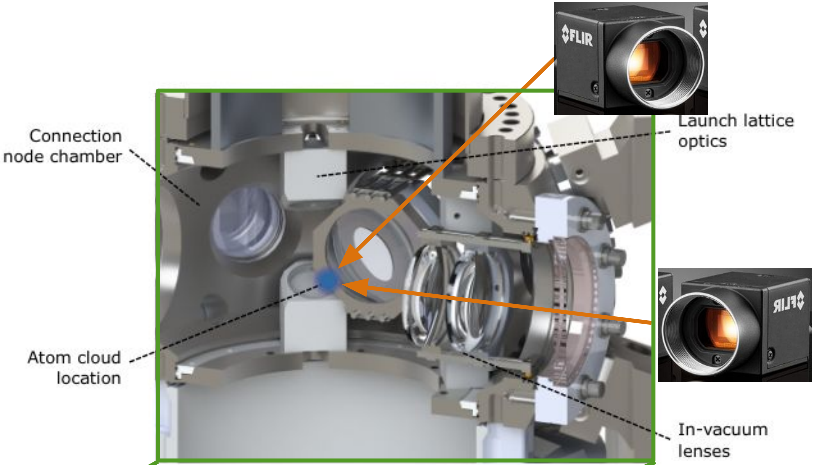
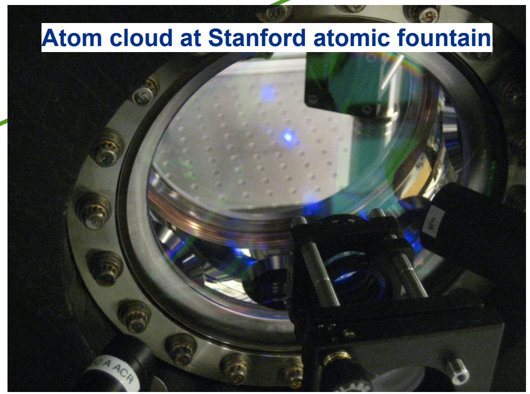
# The MAGIS-100 Apparatus

**Interferometers**

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# Signals in MAGIS-100

MAGIS-100 is sensitive to time-varying signals in the 0.1--10 Hz frequency range

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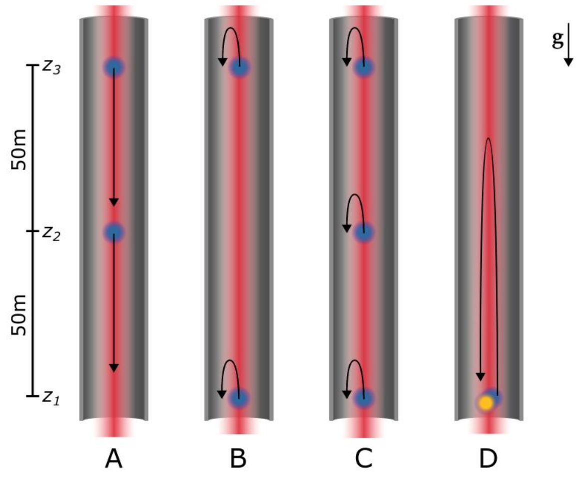
- Modulation of light travel time (via differing path lengths in interferometer) A/B/C
- Fluctuating fundamental constants: $\alpha$, $m_e$ (via shifts in atomic energy levels) A/B/C
- Precession of spins (via comparison of states with differing nuclear spin) A/B/C
- Acceleration of test masses (via differential response for two isotopes) D

**4 operational configurations**

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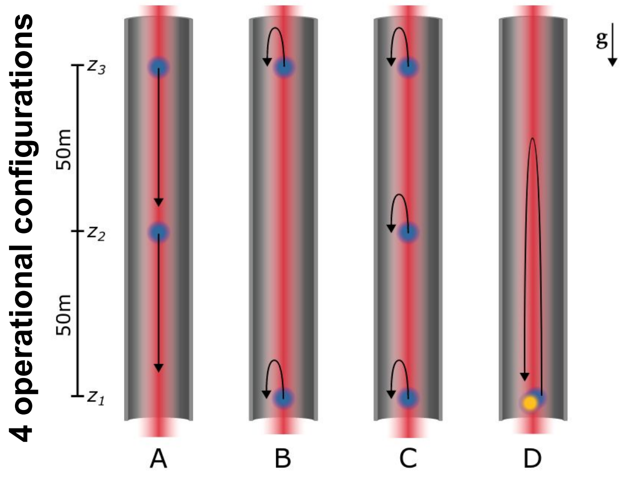


**All result in a time-dependent phase shift between the interferometers**

Phase resolution ~ $10^{-3}$ rad/Hz$^{1/2}$
Strain sensitivity ~$10^{-19}$ Hz$^{-1/2}$

*Quantum Sci. Technol. 6, 044003 (2021) [arxiv:2104.02835]*

# Phase Evolution

After the interferometer spends time T in the excited state:

$$\frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle e^{-i\omega_A T}$$

- $\omega_A$: energy difference between $|1\rangle$, $|2\rangle$
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Excited state phase difference between interferometer arms:

$$\Delta\phi = \omega_A(2L/c)$$

1. Modulation in atomic energy levels

$$\omega_A \to \omega_A + \delta\omega_A(t)$$

   a. e.g., ultralight scalar

2. Modulation in light travel time

$$L \to L + \delta L(t) = L(1 + h(t))$$

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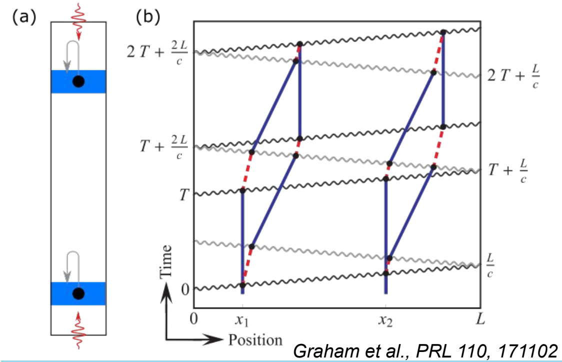
Interferometers along baseline L are coupled via light travel time of laser




Graham et al., PRL 110, 171102 (2013).

Differential measurement suppresses many sources of common noise and systematic errors

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# Ultralight Scalar Bosons

Linear couplings to photons and electrons

$$\mathcal{L} \supset \sqrt{4\pi G_N}\phi\left(\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e}m_e\bar{\psi}\psi\right)$$

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Generates time-dependent terms in electron mass and fine-structure constant

$$m_e(t,x) = m_{e0}\left(1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,x)\right)$$

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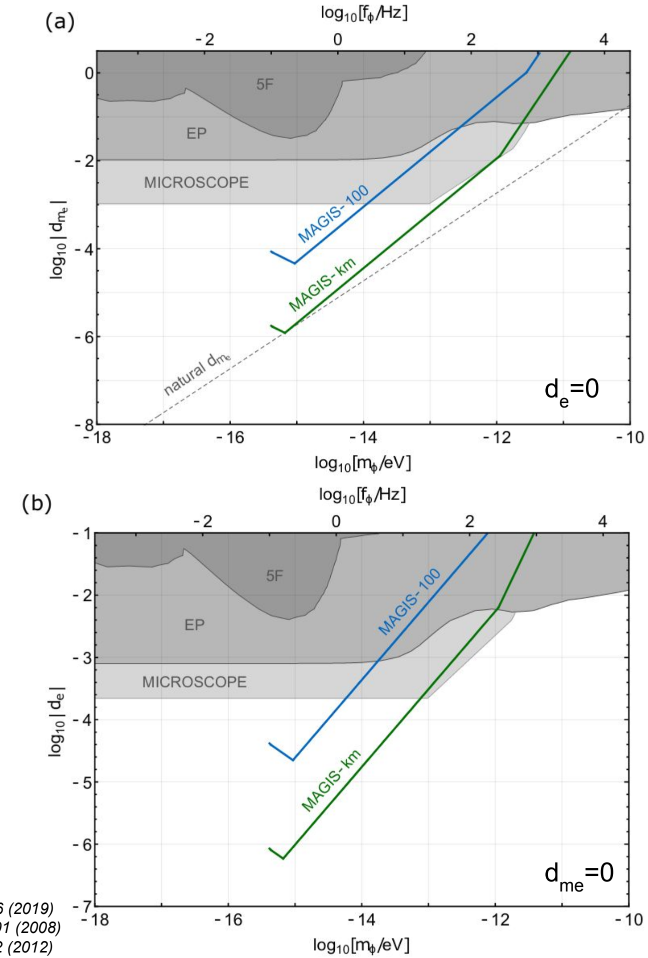
Leading to oscillating energy splittings in atomic states with amplitude

$$\Delta\omega_A = \omega_A\sqrt{4\pi G_N}\phi_0\left(d_{m_e} + \xi d_e\right)$$

$$\text{where} \quad \phi_0 = \sqrt{2\rho_{\mathrm{DM}}}/m_\phi$$




**Current bounds:**
*Touboul et al, Class. Quantum Grav.* ***36*** *225006 (2019)*
*Schlamminge et al, Phys. Rev. Lett. 100, 041101 (2008)*
*Wagner et al, Class. Quantum Grav. 29 184002 (2012)*
*Adelberger et al, Annu. Rev.Nucl. Part. Sci. 53, 77 (2003)*

*Arvanitaki et al, Phys. Rev. D 97, 075020 (2018)*
*Abe et al, Quantum Sci. Technol. 6, 044003 (2021)*

**See also:**
R. James talk "Directional dark matter searches with levitated optomechanics"

# Ultralight Vector Bosons

Consider a massive vector $A^\mu$ coupled to a $U(1)_{B-L}$ charge (neutron content)

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This exerts a differential force on isotopes of the same element

$$\mathbf{F} = m_A g_{B-L} Q_{U(1)_{B-L}} \sum_i A_i \mathbf{e}_i \sin\left(m_A t - m_A v_{\mathrm{DM}} \hat{\mathbf{k}}_i \cdot \mathbf{x} + \phi_i\right)$$

→ Equivalence principle violating force

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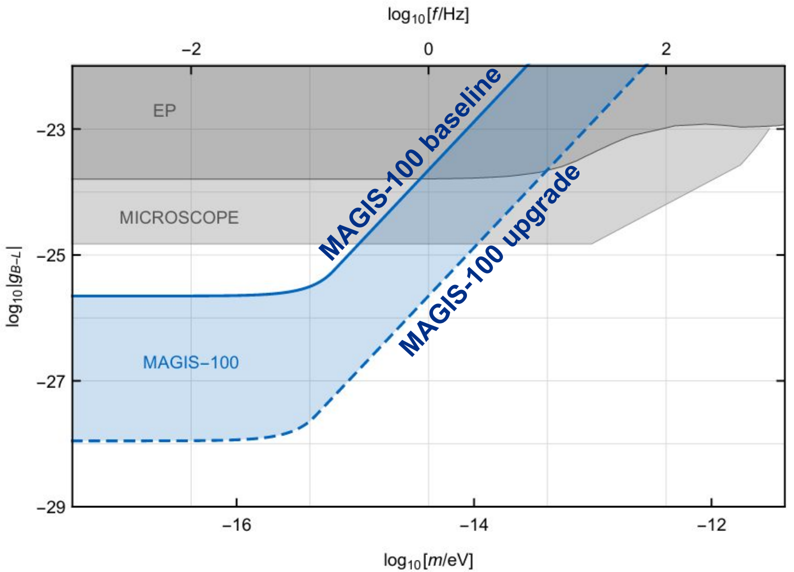
→ Equivalence principle violating force

Leading to a time-varying differential acceleration (if it's DM, static otherwise)

Requires operation of dual-species colocated interferometer ($^{87/88}$Sr)

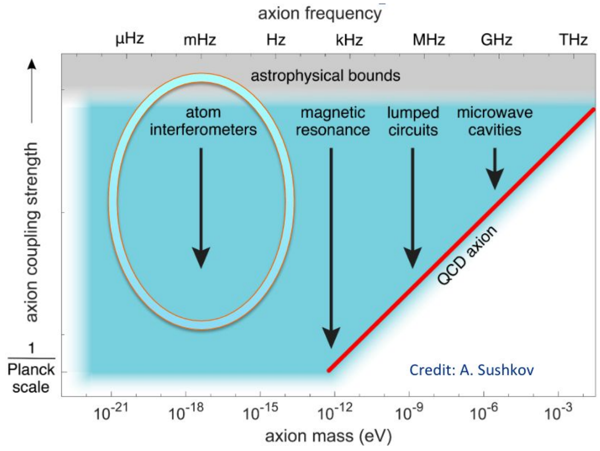
*Abe et al, Quantum Sci. Technol. 6, 044003 (2021)*




Theoretical calculations from *Graham et al, Phys. Rev. D 93, 075029 (2016)*

Detailed signal & readout simulation with target MAGIS parameters underway

# Axion Like Particles




*2018 DOE Dark Matter Research Needs report*

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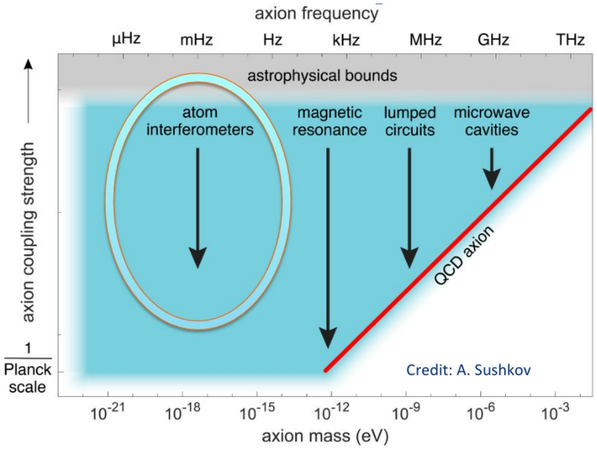
Work by **Sam Hindley** (Liverpool)

Axion field couples to atoms via interaction with spins

→ time-oscillating “dark magnetic fiel

$$\mathcal{L} \supset g_{aNN} \partial_\mu a \bar{\psi} \gamma^5 \gamma^\mu$$

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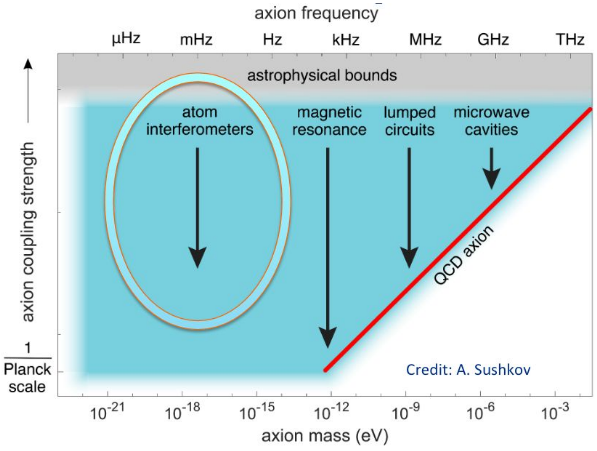
- Axion telescopes & resonant cavities ~ $g_{a\gamma\gamma}^{2}$
- Light shining through walls ~ $g_{a\gamma\gamma}^{4}$

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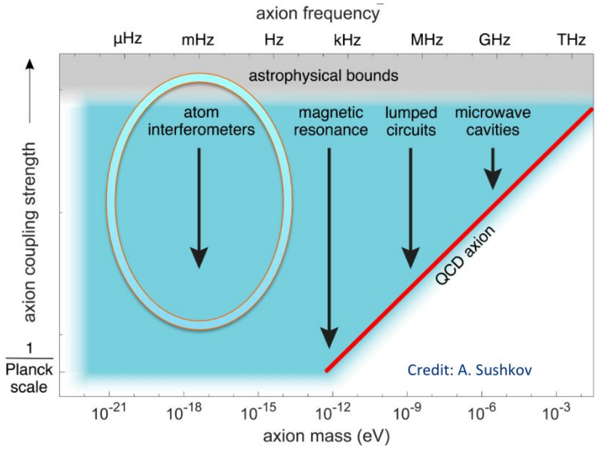
- Larmor precession, modifications to Hamiltonian under which the spins evolve in time.
- Frequency, direction set by properties of the axion field.
- Measured by interference of atom cloud that has evolved in a superposition of different spin-states.




*2018 DOE Dark Matter Research Needs report*



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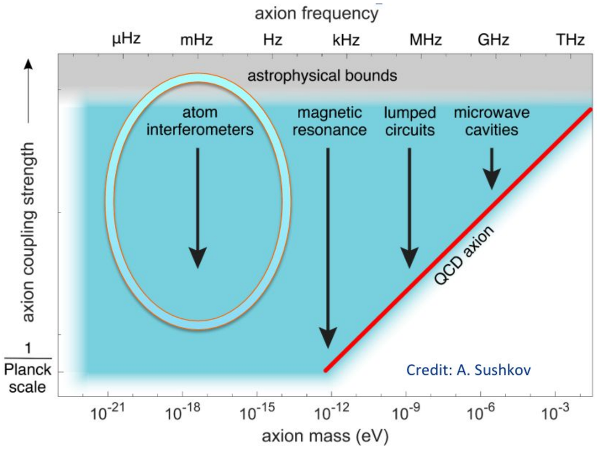


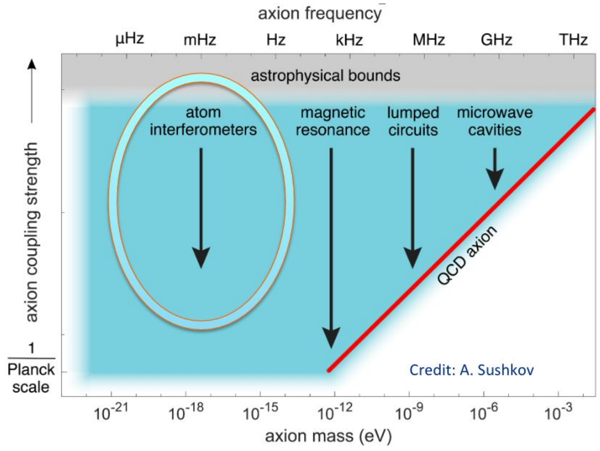

*2018 DOE Dark Matter Research Needs report*

**Spin interferometry never before realized in laboratory!**

# Axion Like Particles

Work by **Sam Hindley** (Liverpool)

Must prepare ensembles of the same isotope in differing spin states: Sr $^1S_0$-$^3P_0$ optical clock transition




*2018 DOE Dark Matter Research Needs report*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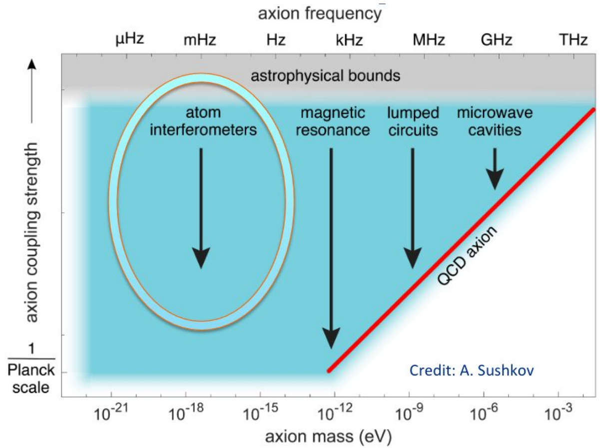
- No benefit from free-fall over long distances




*2018 DOE Dark Matter Research Needs report*

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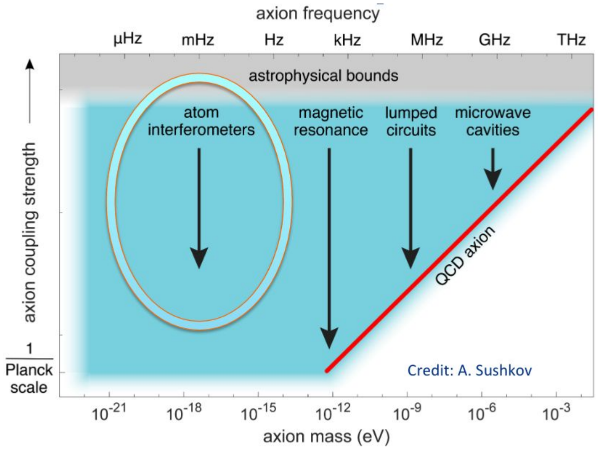
Need to "bounce" atoms in a region of enhanced magnetic shielding (x$10^{3.5}$ over planned) to achieve necessary interrogation times

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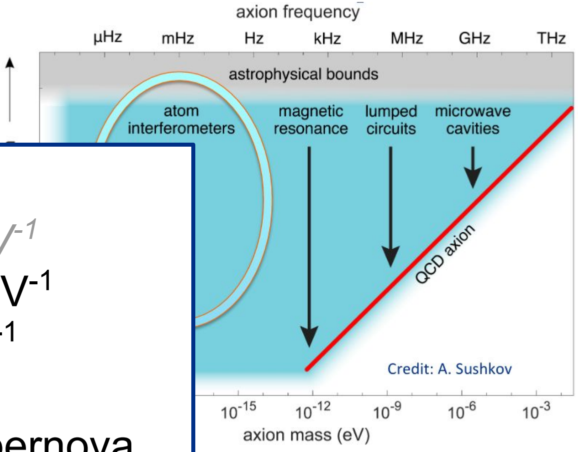



*ark Matter Research Needs report*

<u>Preliminary sensitivities</u> for $m_a < 10^{-14}$ eV

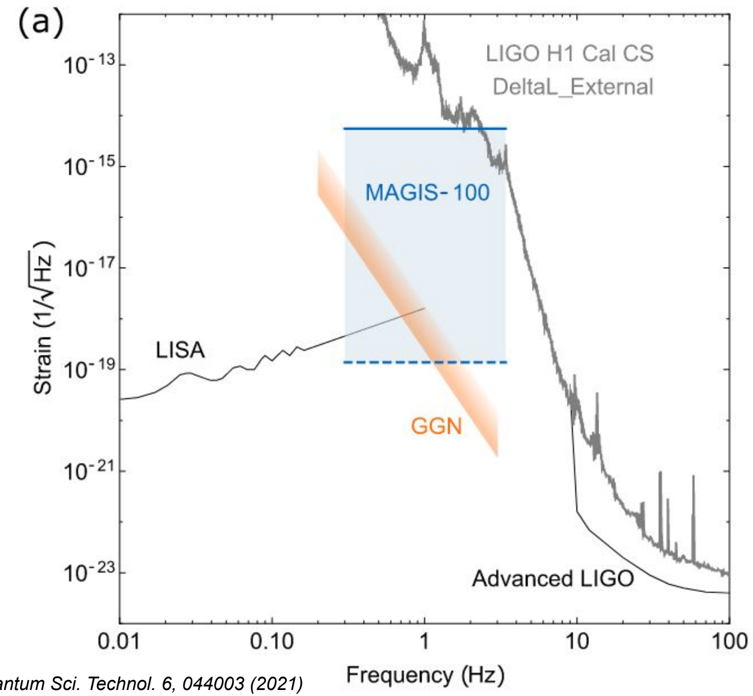
| | |
|---|---|
| Current: | *$g_{aNN} > 1.5 \times 10^{-9}$ GeV$^{-1}$* |
| MAGIS prelim. goals: | $g_{aNN} > 2.5 \times 10^{-10}$ GeV$^{-1}$ |
| Future: | $g_{aNN} > 5 \times 10^{-13}$ GeV$^{-1}$ |

Note: only bound in this mass region from Supernova cooling ($g_{aNN} < 6 \times 10^{-10}$ GeV$^{-1}$) *[Raffelt, Phys Rep 198, 001113 (1990)]*

**More studies ongoing!**

# Other MAGIS Science

## “Mid-Band” Gravitational Waves




*Quantum Sci. Technol. 6, 044003 (2021)*

## Precision Tests of Quantum Mechanics

- Demonstrate superposition across unprecedented length scales
  - Wavepacket separation (~10 m)
  - Coherence time (~9 sec)
- Investigate optimal quantum control sequences (QIS)
- Probe non-linear corrections to Schrödinger’s Equation
- Utilize spin-squeezed atom ensembles to surpass the standard quantum limit

# Systematics & Backgrounds

| Source | Magnitude of phase noise | *Spectral densities in 0.1 -- 3 Hz range |
|---|---|---|
| Magnetic fields | $10^{-3}$ rad $Hz^{-1/2}$ | *Dickerson, et al. Rev. Sci. Instrum. 83, 065108 (2012)* |
| Laser wavefront aberrations | $10^{-4}$ rad $Hz^{-1/2}$ | *Schkolnik, et al. Appl. Phys. B 120, 311–316 (2015)* |
| Laser pointing jitter | $10^{-4}$ rad $Hz^{-1/2}$ | *Hogan et al. Gen. Relativ. Gravit. 43, 1953–2009 (2011)* |
| AC Stark shifts | $10^{-4}$ rad $Hz^{-1/2}$ | *Kovachy, et al. Nature 528, 530–533 (2015)* |

Sub-dominant sources: laser phase noise, seismic vibrations, Coriolis & Earth effects, mean field shifts, blackbody radiation shifts.

All sources are well understood and can be controlled within the requirements of MAGIS-100.

For complete discussion, see *Quantum Sci. Technol. 6, 044003 (2021) 2104.02835*

# Project Status

| Parameter | Target Value | Primary Driving Factors |
|---|---|---|
| LMT atom optics | $n = 100$ | Increase sensitivity to science signals |
| Phase resolution | $10^{-3}$ rad/$\sqrt{\text{Hz}}$ | Increase sensitivity to science signals |
| Frequency noise/drift | $< 10$ Hz | Increase pulse transfer efficiency (Section 4.3) |
| Per shot position uncertainty | 10 $\mu$m/$\sqrt{\text{Hz}}$ | Coupling to wavefront aberrations (Section 5.2) |
| Per shot velocity uncertainty | 10 $\mu$m/s/$\sqrt{\text{Hz}}$ | |
| Laser wavefront variation | 5 mrad* | Coupling to cloud kinematic and laser pointing jitter (Section 5.2 and Section 5.4) |
| Laser intensity stabilization | 0.1%/$\sqrt{\text{Hz}}$ | AC Stark shifts (Section 5.5) |
| Laser pointing stability | 30 nrad/$\sqrt{\text{Hz}}$ | Coupling to wavefront aberrations (Section 5.4) |
| Magnetic field uniformity | 1 mG (rms) | Clock frequency shifts |

*at transverse length scales $\lesssim 3$ mm



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# Project Status

- In final design stages
- Construction this Fall
- Commissioning Spring 2024
- Science run ~late 2024
- Two years of science data
- MAGIS-100 is a pathfinder for MAGIS-1K and MAGIS-space

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**Global atom interferometry network**

| | | | |
|---|---|---|---|
| 1. | MAGIS-100 | 100m | Chicago, USA |
| 2. | MIGA | 200m | Rustrel, France |
| 3. | ZAIGA | 300m | Zhaoshan, China |
| 4. | AION | 100m | UK |
| 5. | ELGAR | 3200m | France/Italy |

# Conclusions

MAGIS-100

- Exhaustive DM searches must be conducted to the lower limit of the ultralight regime
- MAGIS-100 uses quantum superposition at unprecedented scales to probe scalar and vector DM candidates down to and beyond $10^{-15}$ eV and $10^{-17}$ eV
- To reach required sensitivity, MAGIS will advance the state of the art in atom interferometry and quantum manipulation
- Construction soon to be underway - first science data in 2024!

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U.S. DEPARTMENT OF ENERGY | Office of Science

UKRI Science and Technology Facilities Council

Gordon and Betty MOORE FOUNDATION

THE KAVLI FOUNDATION

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# Backup & Notes

# Outline

- Ultralight DM motivation
- MAGIS-100  & light-pulse atom interferometry
- DM model sensitivity
- Project status

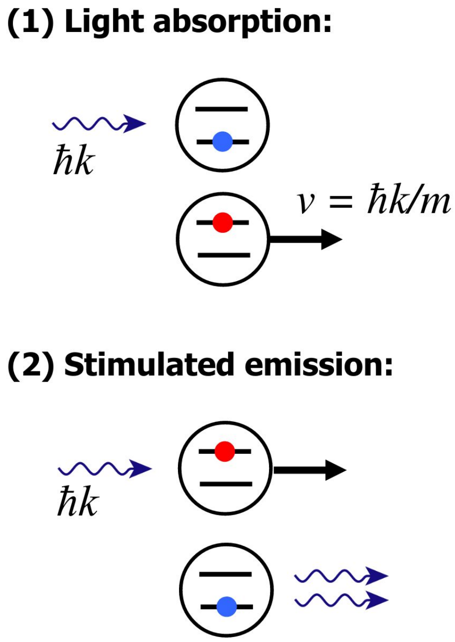
# Abstract

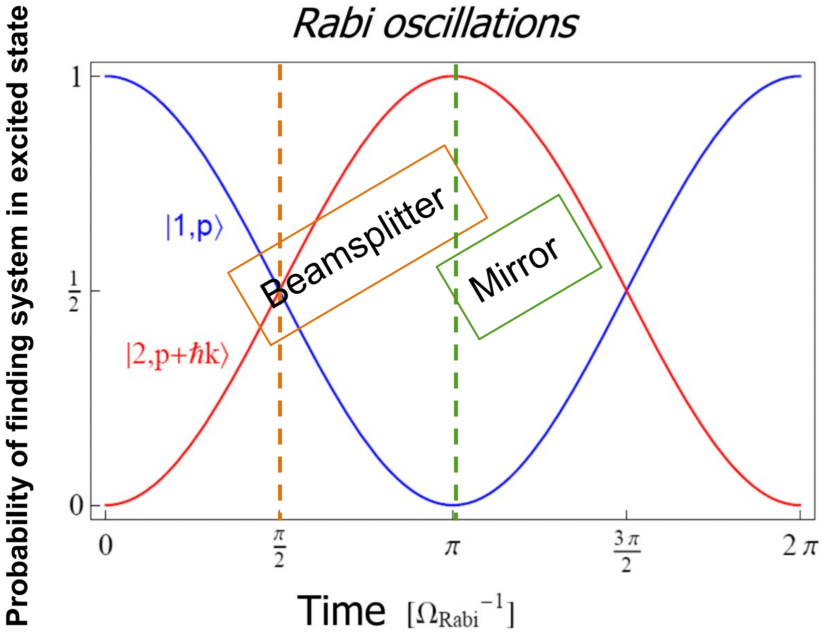
Searches for dark matter (DM), using a vast array of different technologies that cover a wide range of DM masses, have consistently returned null results. While most experiments have probed WIMP-like dark matter above a few GeV in mass, models of light (< 1 meV) bosonic dark matter are compelling and large swaths of parameter space remain unexplored. One such model, an ultralight scalar particle that couples to fundamental constants (e.g. electron mass, fine structure constant) will induce time-dependent fluctuations in the energy levels of atoms, which can be detected using precision quantum-mechanical sensors. The Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100), soon to be constructed at Fermilab, will search for various ultralight DM models and new forces using three coupled light-pulsed atom interferometers across a 100-meter baseline. The experiment offers sensitivity to bosonic DM candidates in the mass range of $10^{-22}$–$10^{-15}$ eV, a region of parameter space that is relatively unconstrained. This detector builds on expertise from the 10-meter prototype at Stanford and capitalizes on the latest advancement in atomic clock technology, and will serve as a pathfinder for a future kilometer-scale sensor. In this talk, I summarize the planned scientific program for the experiment and present projected sensitivities of searches for dark matter and new forces.

# Rabi Oscillations

Sinusoidally driven system will oscillate between two states |1⟩and |2⟩

The Rabi Frequency provides a measure of the strength of the interaction



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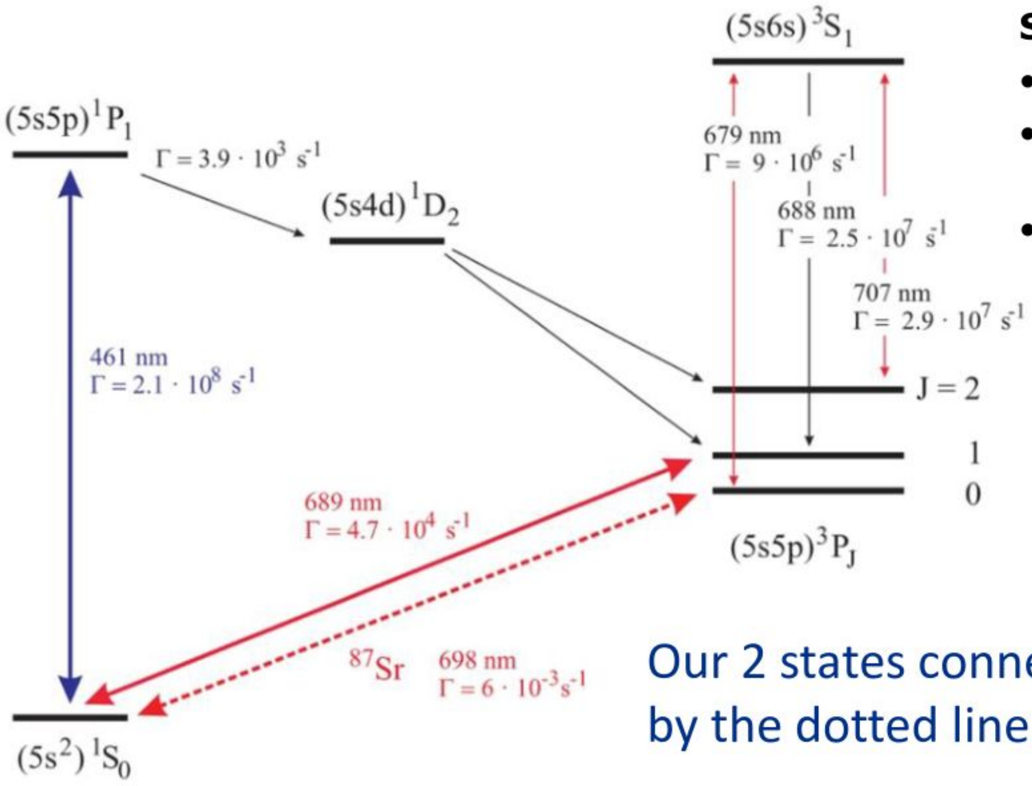
# Strontium Clock States




Our 2 states connected by the dotted line.

**Single photon clock transitions**

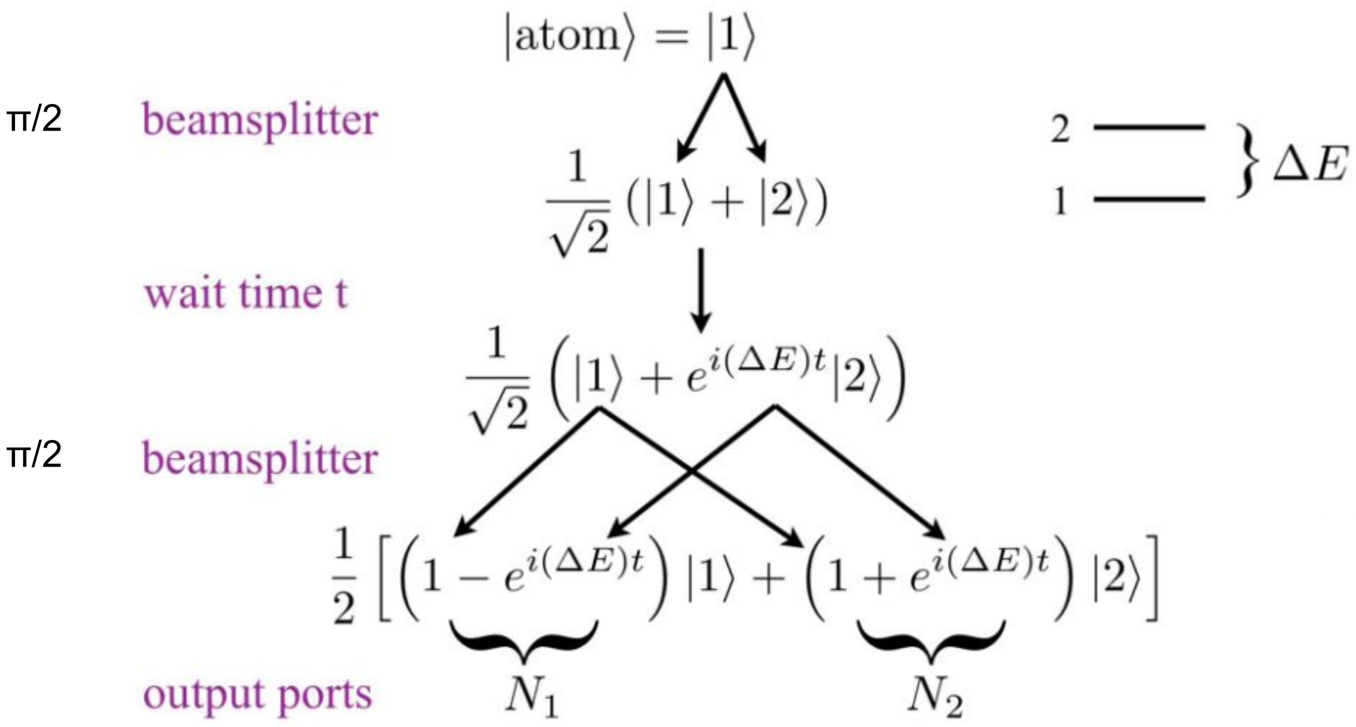
- Requires long-lived excited state
- Reduced spontaneous emission (other levels far detuned)
- Possibility to support > $10^6$ pulses

Use **689 nm transition** for initial demonstration of LMT clock atom interferometry

689 transition features:

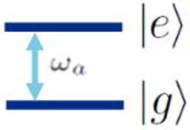
- 1-photon AI possible
- 22 μs lifetime
- High Rabi frequency possible

# Light-Pulse Atomic Clock




can measure times $t \sim \frac{1}{\Delta E} \sim 10^{-10}$ s

# Coupled Atomic Clocks





Time

1. Laser pulses creates superposition of clock states, "starts clock ticking"
2. Second pulse represents end of measurement, phase reflects amount clock ticked during measurement time

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

*Phase evolved by atom after time T (second clock starts slightly later, by amount L/c for baseline length L, than first because of light travel time, but also ends time L/c later)*

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

GW changes baseline, and therefore light travel time, between pulses (signal maximized when GW period on scale of time between pulses)
$T \to T + \Delta T$
with $\Delta T \sim Lh/c$

# Coupled Atomic Clocks

1. Light propagates across the baseline at a constant speed
2. Clocks read transit time signal over baseline
3. Something changed the number of clock ticks associated with light transit
    a. DM modifies clock ticking rate
    b. GW modifies light travel time across baseline
4. Many pulses sent across baseline (large momentum transfer) to coherently enhance signal
5. Differential phase shift between two or more interferometers separated in space

# Atom Interferometry

Laser pulses act as beam splitters and mirrors for atomic wavefunction

Highly sensitive to accelerations (or to time-variations of atomic energy levels)

$$|\mathrm{atom}\rangle = |p\rangle$$

**π/2 pulse** "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p+\hbar k\rangle)$$

**π pulse** "mirror"

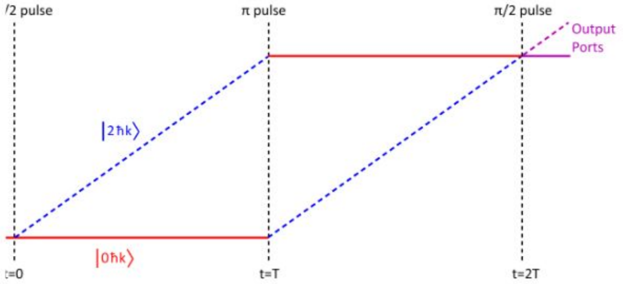
$$\frac{1}{\sqrt{2}}(|p+\hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

**π/2 pulse** "beamsplitter"

$$\frac{1}{2}((1+e^{i\Delta\phi})|p\rangle + ((1-e^{i\Delta\phi}))|p+\hbar k\rangle)$$

$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |p+\hbar k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$



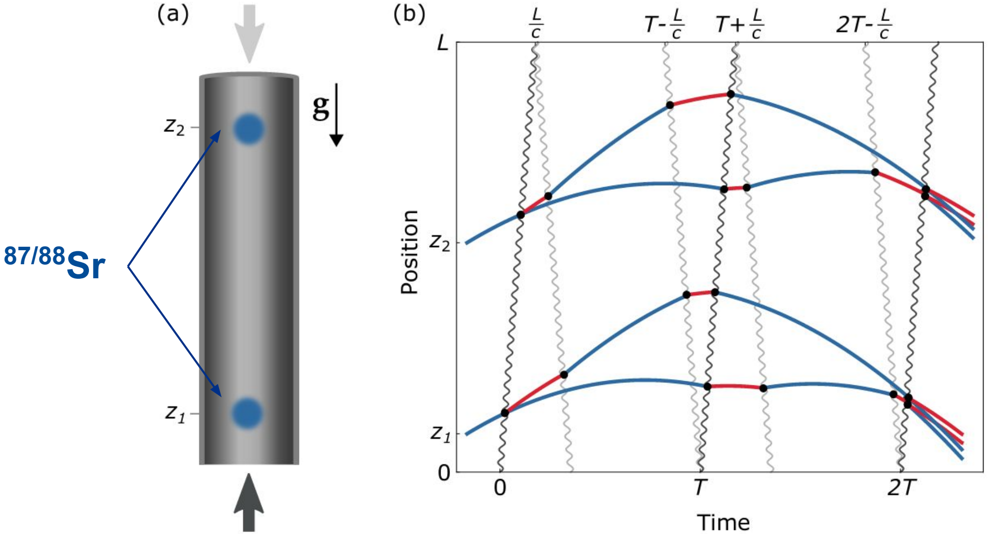

Effects scale like AREA, so

Long T good

High Momentum Good

# Light-Pulse Atom Interferometry

Abe et al. Quantum Sci. Technol. 6, 044003 (2021) [arxiv:2104.02835]
Rudolph et al. Phys. Rev. Lett. 124, 083604 (2020) [arxiv:1910.05459]
Kovachy et al. Nature volume 528, pages 530–533 (2015)




**Large momentum transfer** laser pulses applied to further separate wave packets' momenta → sensitivity scales linearly with momentum separation

LMT atom optics of order $n$ refers to an $n\hbar k$ momentum splitting between the two arms of the atom interferometer (corresponding to $n$ photon recoil kicks)

Can tune the light to interact with only one arm due to Doppler shift



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# Fitting for Phase: Single Interferometer

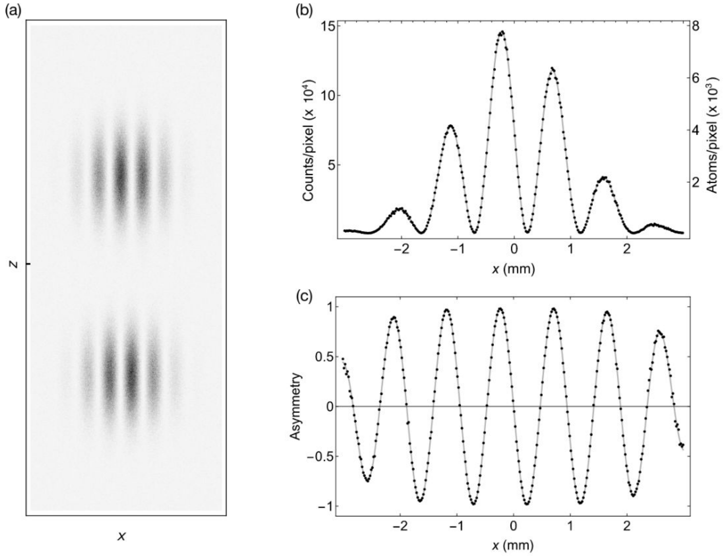
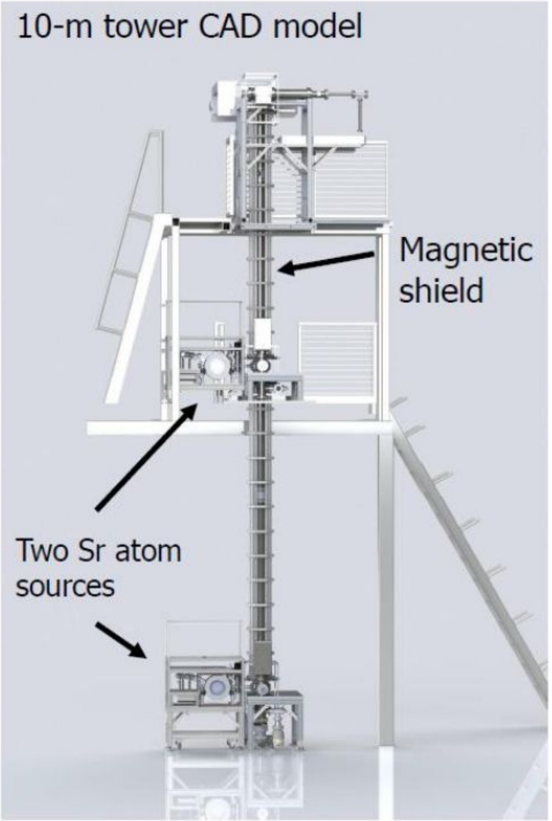
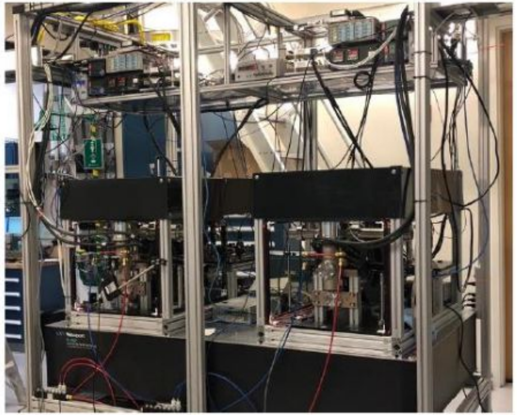


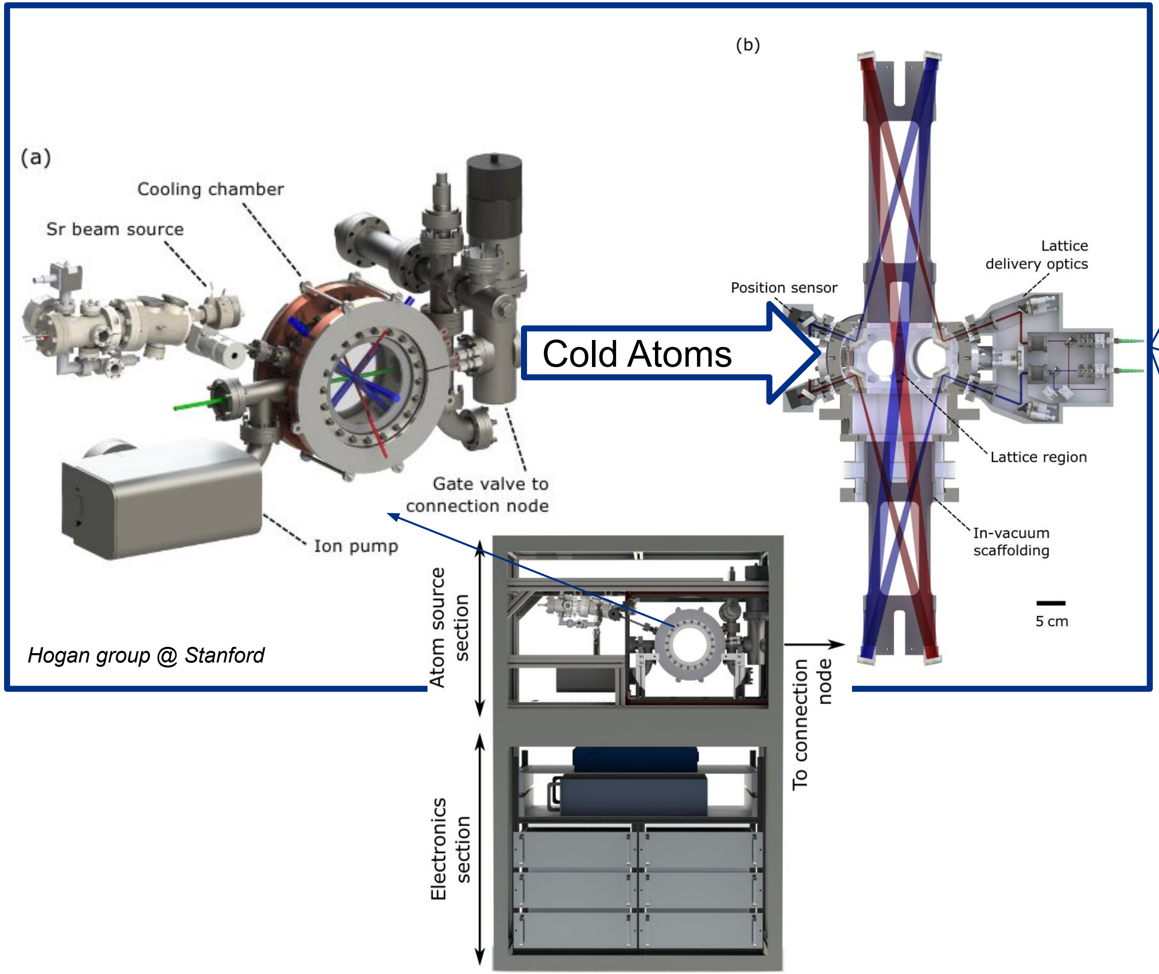

**Figure 13.** Simulated image of an atom interference pattern in the detection region at the end of a MAGIS-100 interferometer. (a) The simulated image shows the two detected sub-populations corresponding to the two output ports of the interferometer. The fringes are the result of the phase shear readout technique. (b) The $x$-projection of the upper-half of the pixel plane which contains the image associated with the upper of the two output ports. (c) The two-port asymmetry constructed from the $x$-projections of the two ports. The curves in (b) and (c) panels result from fitting the simulated data to obtain the phase associated with the interference pattern.

# The Stanford 10-meter Atomic Fountain

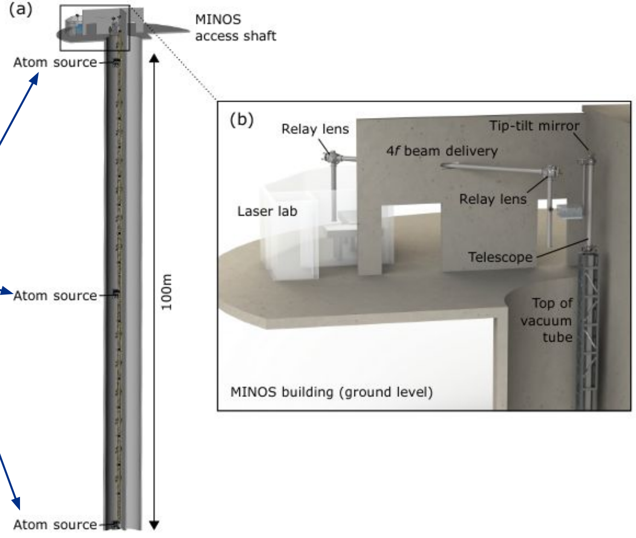


*Quantum Sci. Technol. 6, 044003 (2021) [arxiv:2104.02835]*




*Hogan group @ Stanford*



# Magnetic Fields

**The clock energy levels of Sr shift in response to magnetic fields.**

→ Time varying magnetic fields can mimic DM or GW signals

→ Largest effect on phase response - most important to minimize & track

Detector enclosed in mu-metal magnetic shielding along entire baseline

Bias field applied to compensate for (transverse) residual static component

Problematic frequencies: DC - 10 Hz

Sensor requirements:

- < 0.1 mG resolution
- > ±1 G dynamic range
- > 10 Hz sampling rate

Applied bias field → $B_0$; Time-varying component → $\delta B$; Time from BS to M pulse → $T$

$$\delta\phi_{\mathrm{mag}} \sim \left(1 \times 10^{-3}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}\right)\left(\frac{B_0}{1\ \mathrm{G}}\right)\left(\frac{\delta B}{1\ \mathrm{mG}/\sqrt{\mathrm{Hz}}}\right)\left(\frac{T}{1\ \mathrm{s}}\right)$$

# Vibrations

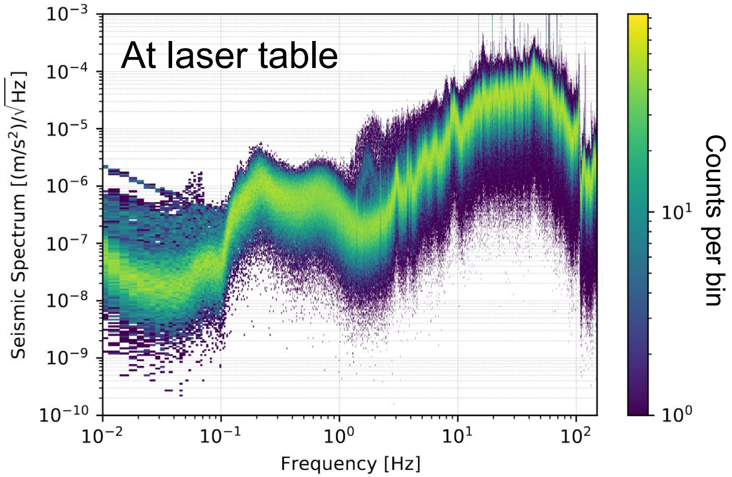
**Ground vibrations imprint phase noise on the interferometry laser pulses due to vibrations of the critical beam delivery and steering optics.**

# LMT pulses — Velocity difference between atom clouds — Time from BS to M pulse — Amplitude spectral density

$$\delta\phi_{\text{vibration}} \sim \left(10^{-8}\ \text{rad}/\sqrt{\text{Hz}}\right)\left(\frac{n}{100}\right)\left(\frac{\Delta v}{100\ \mu\text{m/s}}\right)\left(\frac{T}{1\ \text{s}}\right)\left(\frac{\delta a}{10^{-4}\text{m/s}^2/\sqrt{\text{Hz}}}\right)$$

Track vibrations with:

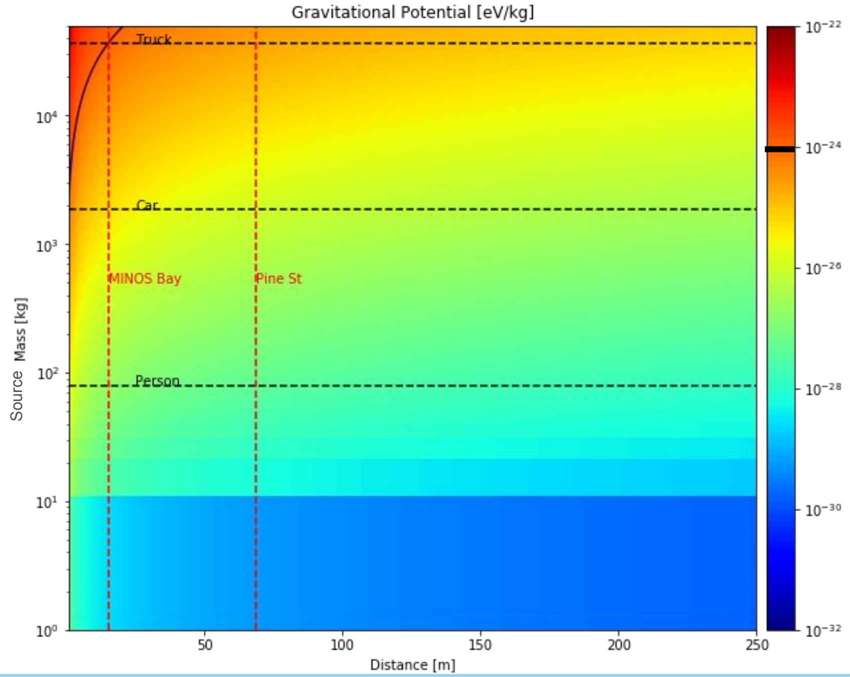
- 2x Seismometer: **Trimble 151B**
  - Located on surface
- Accelerometers: Nanometrics Titan (DC – 430 Hz)
  - Variable range: ±0.25 g to ±4 g
  - One at each atom source




*J. Mitchell et al 2022 JINST **17** P01007 [arxiv:2202.04763]*

# Gravitational Disturbances: Motion of massive objects

- Vehicles on Pine St
- People, machinery in MINOS high bay or parking lot


What do we care about?

1. Things heavier than fully-loaded semi truck at a distance of Pine St
2. Things heavier than a car inside the MINOS surface building

How to track this:

- Webcam with motion trigger
- ML algorithm to guess the mass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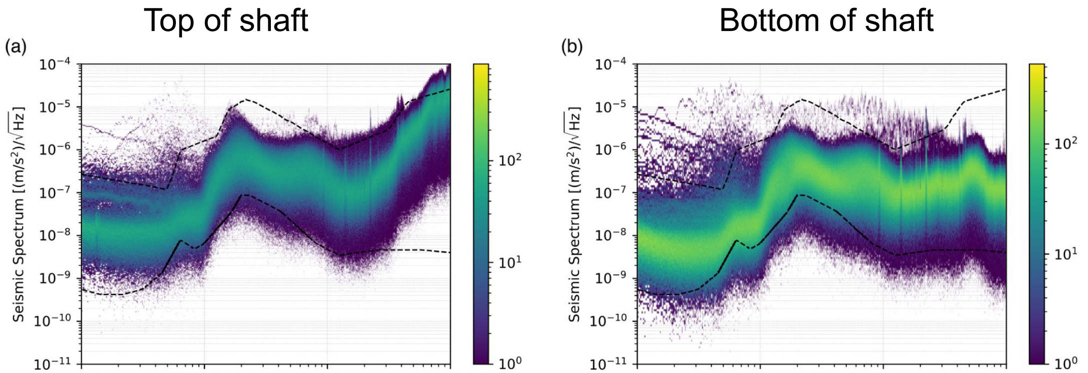
# Gravitational Disturbances: Gravity Gradient Noise

Fluctuation of the local gravitational potential sourced by mass density fluctuations of the ground




*J. Mitchell et al 2022 JINST* ***17*** *P01007 [arxiv:2202.04763]*