Title: Atom interferometry, atomic clocks

Speakers: Jason Hogan

Collection: School on Table-Top Experiments for Fundamental Physics

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Atom interferometry, atomic clocks

School on Table-Top Experiments for Fundamental Physics

Perimeter Institute

Jason Hogan
Stanford University
September 20, 2022

Outline

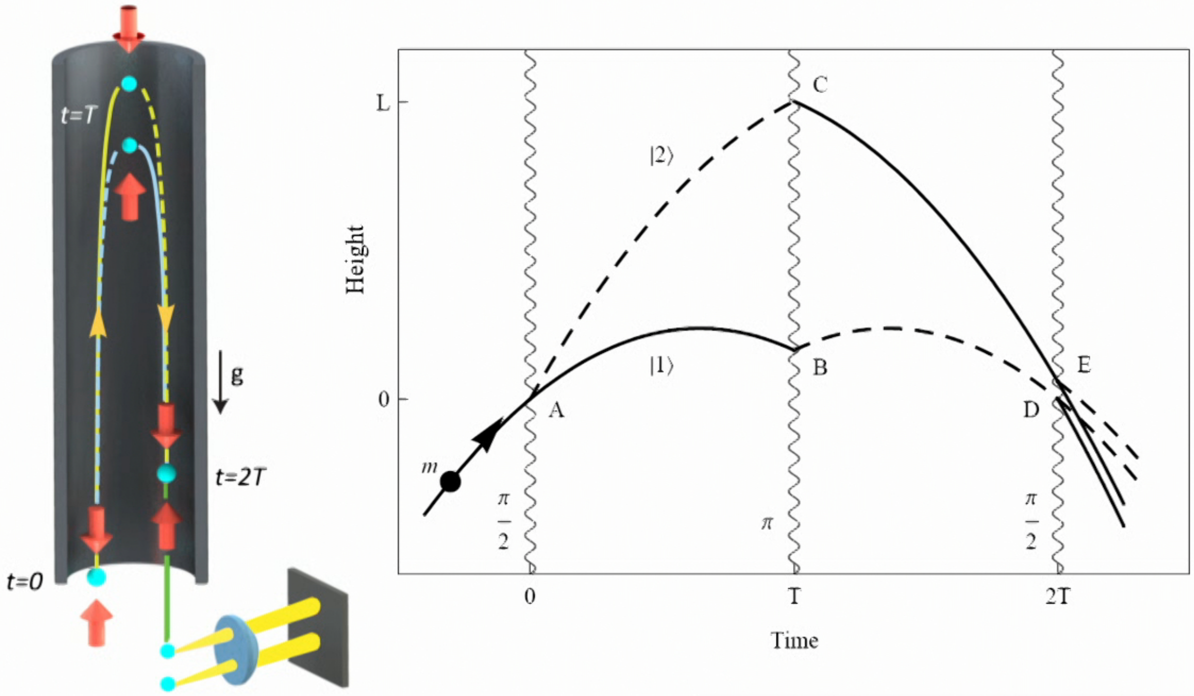
Lecture 1

- General introduction and motivation
- Atom interferometer phase response theory
- Example applications: Spacetime curvature, EP tests, gravitational Aharonov-Bohm, atom charge neutrality

Lecture 2

- Gravitational wave detection
- Clock atom interferometry and MAGIS
- MAGIS-100: design, systematic error mitigation, and construction
- Advanced atom optics (large momentum transfer techniques)

Light pulse atom interferometer



$$\Delta\phi = k_{\text{eff}} g T^2$$

Proportional to spacetime area enclosed.

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\text{eff}} g T^2}$$

Sensitivity

$$\delta\phi \sim \frac{1}{\sqrt{N}}$$

Shot noise

T : Long duration

k_{eff} : Large wavepacket separation

$\delta\phi$: High flux, spin squeezing

Aharonov-Bohm effect

- Aharonov-Bohm effect is a phase shift in an interferometer arising from (an integral over) the potential, rather than a local derivative of the potential
- Phase shift even if particle's path is "force free"
- Some applications w/atoms: Gravitational AB effect, test of charge neutrality

Electromagnetic realizations: "vector AB" and "scalar AB":

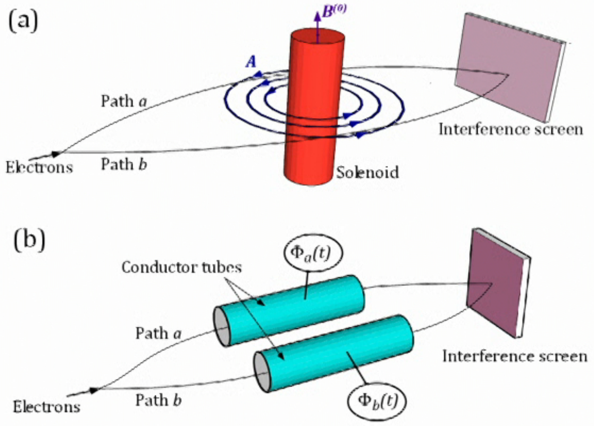


Image: Saldanha, Pablo L. Braz.J.Phys. 46 (2016) no.3, 316-320 arXiv:1509.02346

$$\Delta\phi_{\text{vec}} = q\oint \mathbf{A}\cdot d\mathbf{r} = q\iint \nabla\times\mathbf{A}\cdot d\mathbf{a} = q\iint \mathbf{B}\cdot d\mathbf{a}$$

Enclosed flux of **B**

$$\Delta\phi_{\text{scalar}} = q\oint \phi\, dt = q\iint \nabla\phi\cdot d\mathbf{x}\, dt$$

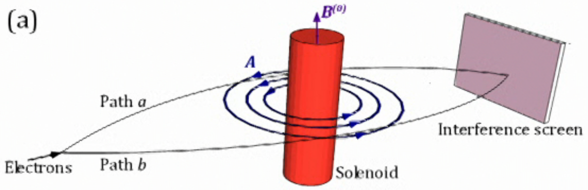
Enclosed flux of **E**

Lorentz invariant expression:

$$\Delta\phi_{\text{AB}} = q\oint A^{\mu} dx_{\mu} = \frac{q}{2}\int_{\Sigma} F^{\mu\nu}\, dx_{\mu}\wedge dx_{\nu}$$

Potentials vs fields?

$$\Delta\phi_{\mathrm{vec}} = q \oint \mathbf{A} \cdot \mathbf{dr}$$



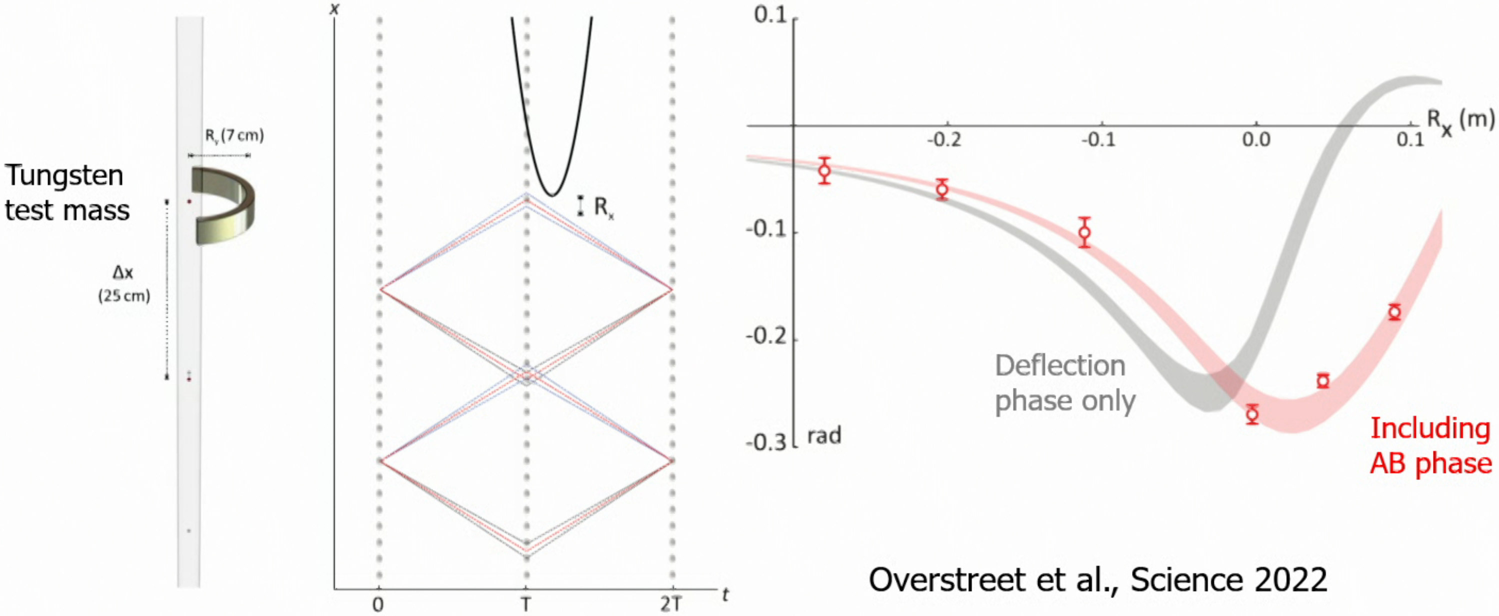
- Sometimes claimed that AB effect indicates that potentials are “more physical” than fields in quantum mechanics.
- But potentials alone are not gauge invariant… (loop integral of potential is)
- Implication: QM depends on more general closed loop integrals of the potentials, instead of just local circulation density (curl) as in classical physics:

$$(\nabla \times \mathbf{A}) \cdot \hat{\mathbf{n}} = \lim_{S \to 0} \left(\frac{1}{S} \oint_{\partial S} \mathbf{A} \cdot \mathbf{dr} \right)$$

- Classical physics only depends on local (infinitesimal) closed loop integral of potentials.
- In QM, finite closed loop integrals can also contribute (wavefunction is delocalized).

Gravitational Aharonov-Bohm

First observation of gravitational scalar AB effect (10 m Rb atom interferometer, Kasevich)

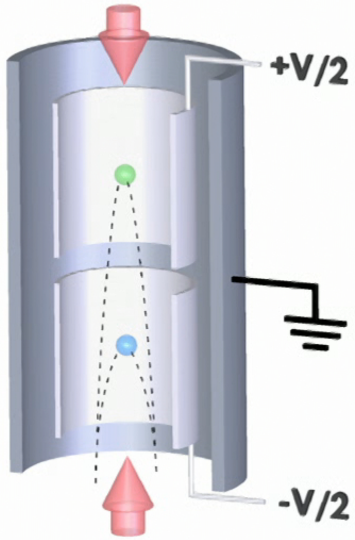


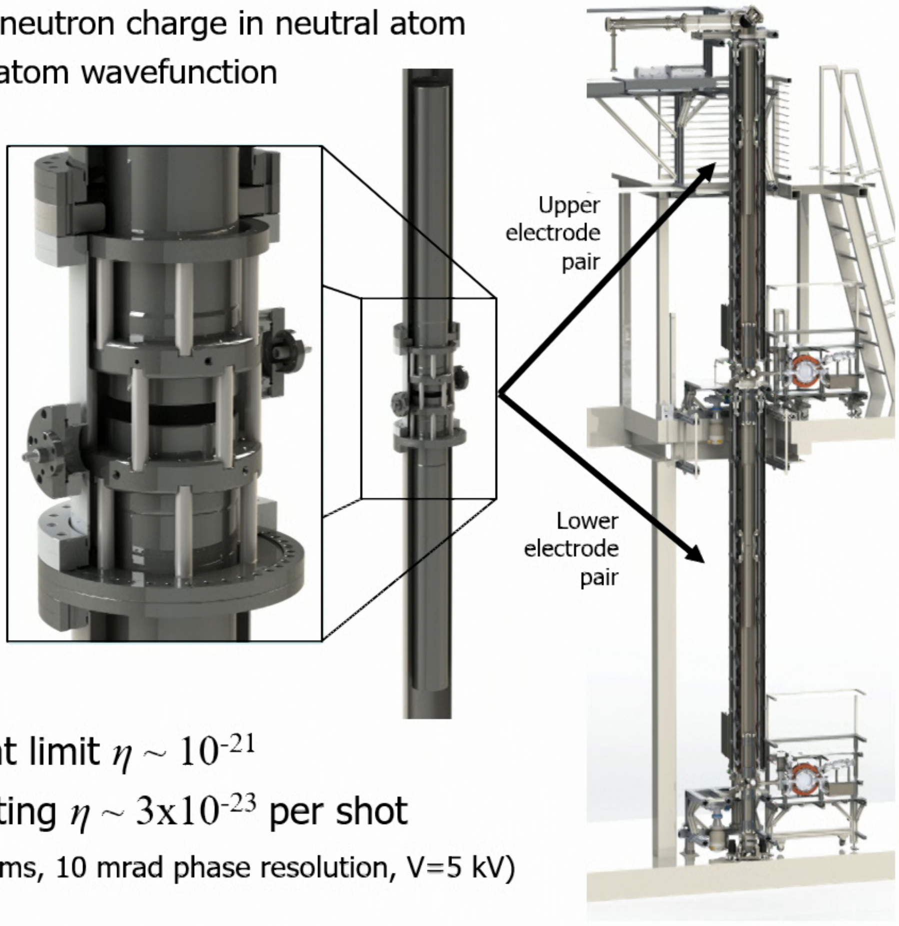
Overstreet et al., Science 2022

- Not force free: test mass causes both deflection and AB phase
- Measure deflection phase separately with small, localized interferometers on each arm
- Gravitational AB provides "indirect evidence that gravity has quantum features" (Overstreet et al., arXiv:2209.02214)

Testing atom charge neutrality with AB effect

- Test proton vs electron as well as neutron charge in neutral atom
- Use LMT atom optics to separate atom wavefunction





New Stanford Sr tower

charge per nucleon

nucleons

$$\Delta\phi = \eta A e \int \frac{V}{\hbar} dt$$

Current limit $\eta \sim 10^{-21}$

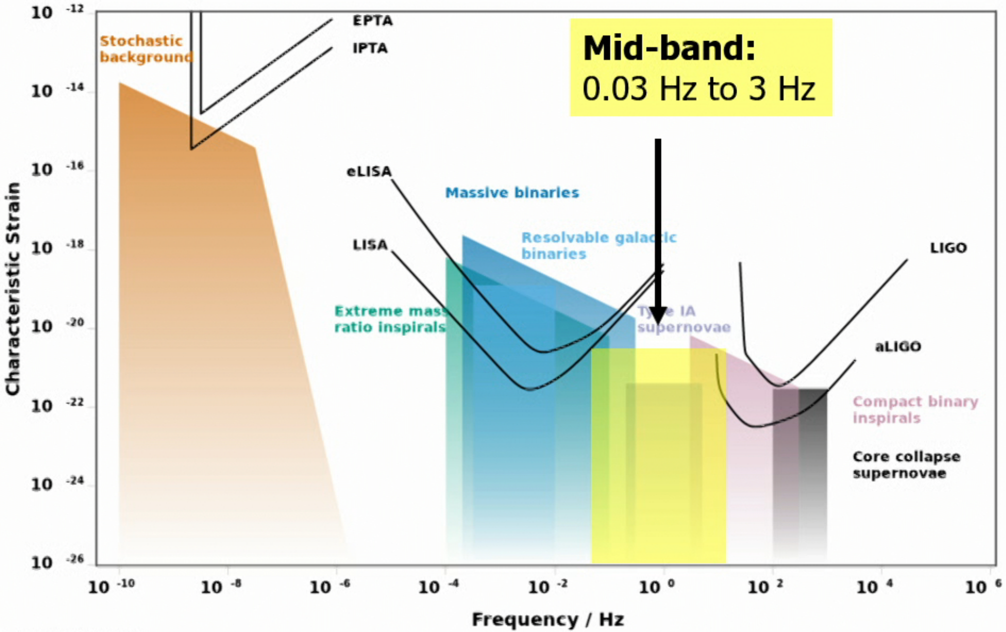
Projecting $\eta \sim 3\text{x}10^{-23}$ per shot

(T=100 ms, 10 mrad phase resolution, V=5 kV)

See Ben Garber's poster on "QMATCH" experiment

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")



Mid-band science

- LIGO sources before they reach LIGO band
- Sky localization: predict when and where events will occur (multi-messenger astronomy)
- Cosmological sources
- Wave-like dark matter (dilaton, ALP, …)

Sky position determination

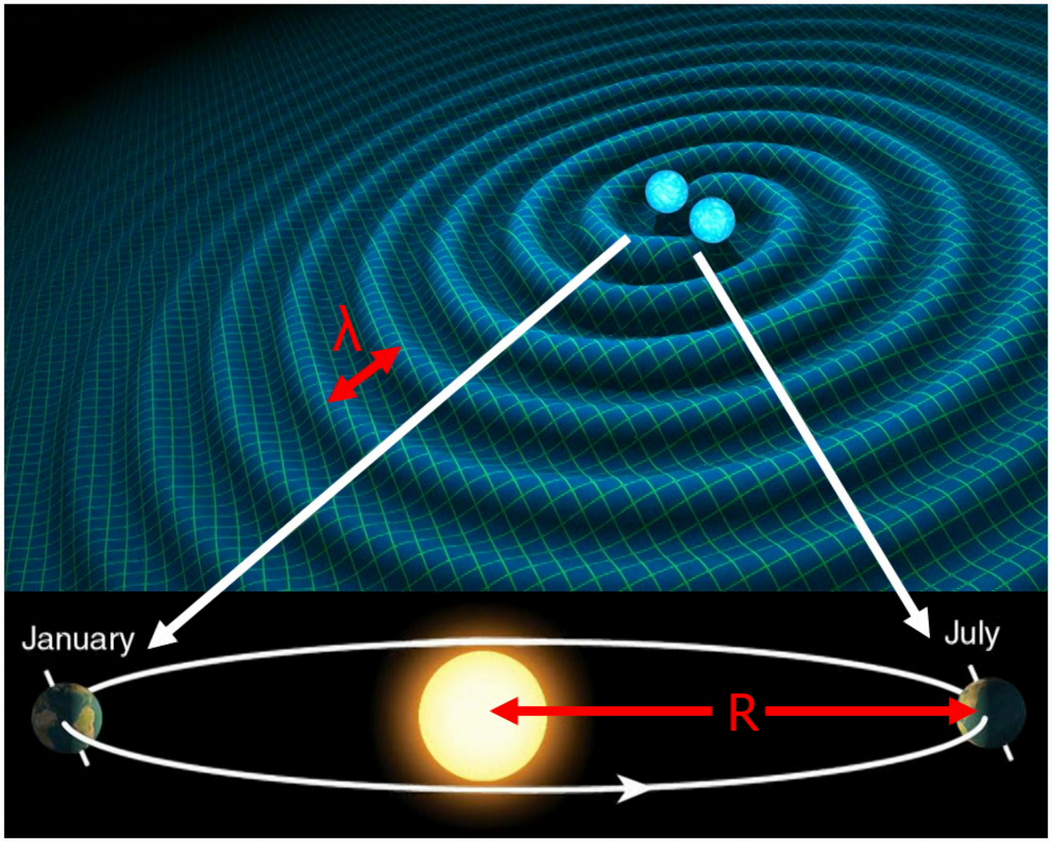
Sky localization precision:

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

Mid-band advantages

- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

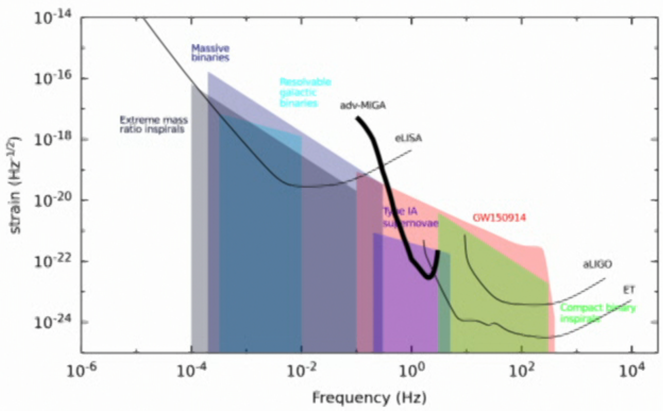


Graham et al., **PRD** 024052 (2018).

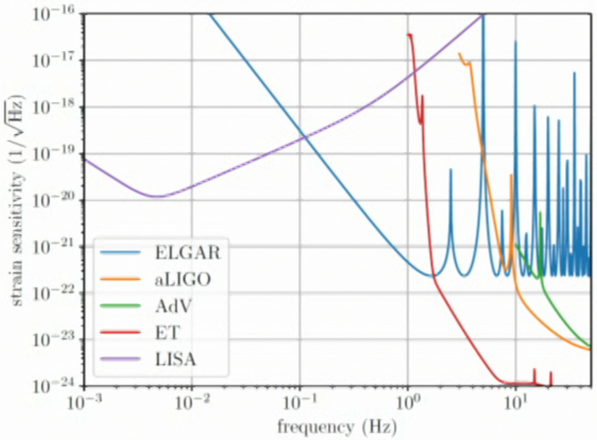
Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

International efforts in atomic sensors for mid-band GW

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)

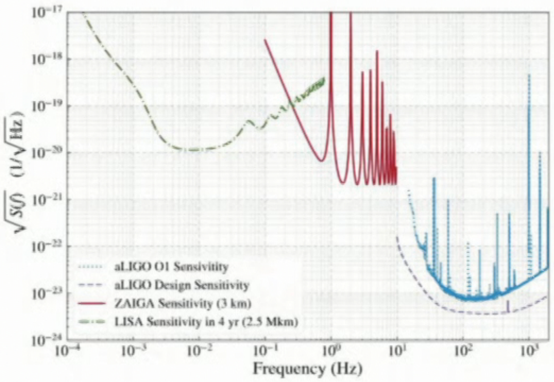


ELGAR: European Laboratory for Gravitation and Atom-interferometric Research



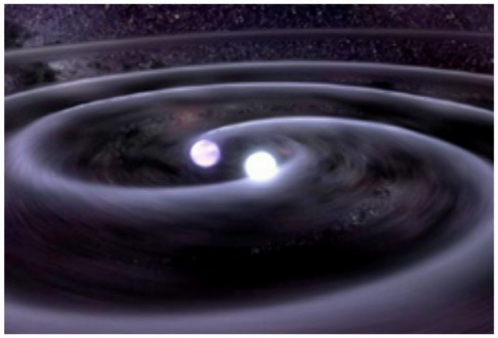
AION: Atom Interferometer Observatory and Network (UK)

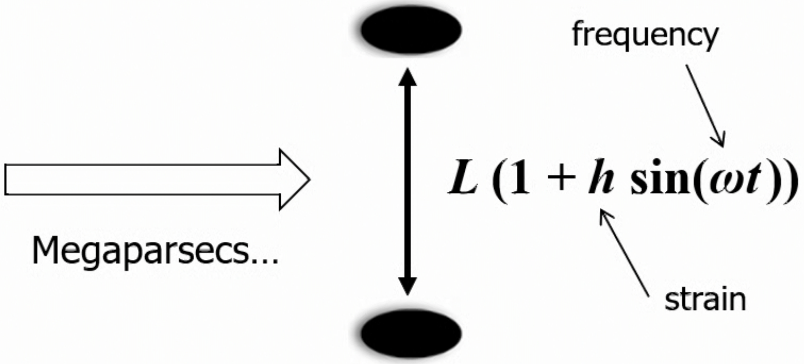
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)

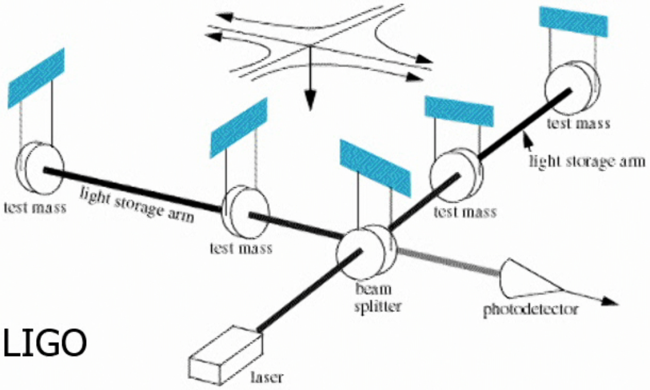


Gravitational Wave Detection

$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)))dx^2 - (1 - h\sin(\omega(t-z)))dy^2 - dz^2$$







LIGO

- LIGO and other optical interferometers **use two baselines**
- In principle, **only one is required**
- Second baseline needed to reject laser technical noise

MAGIS concept

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

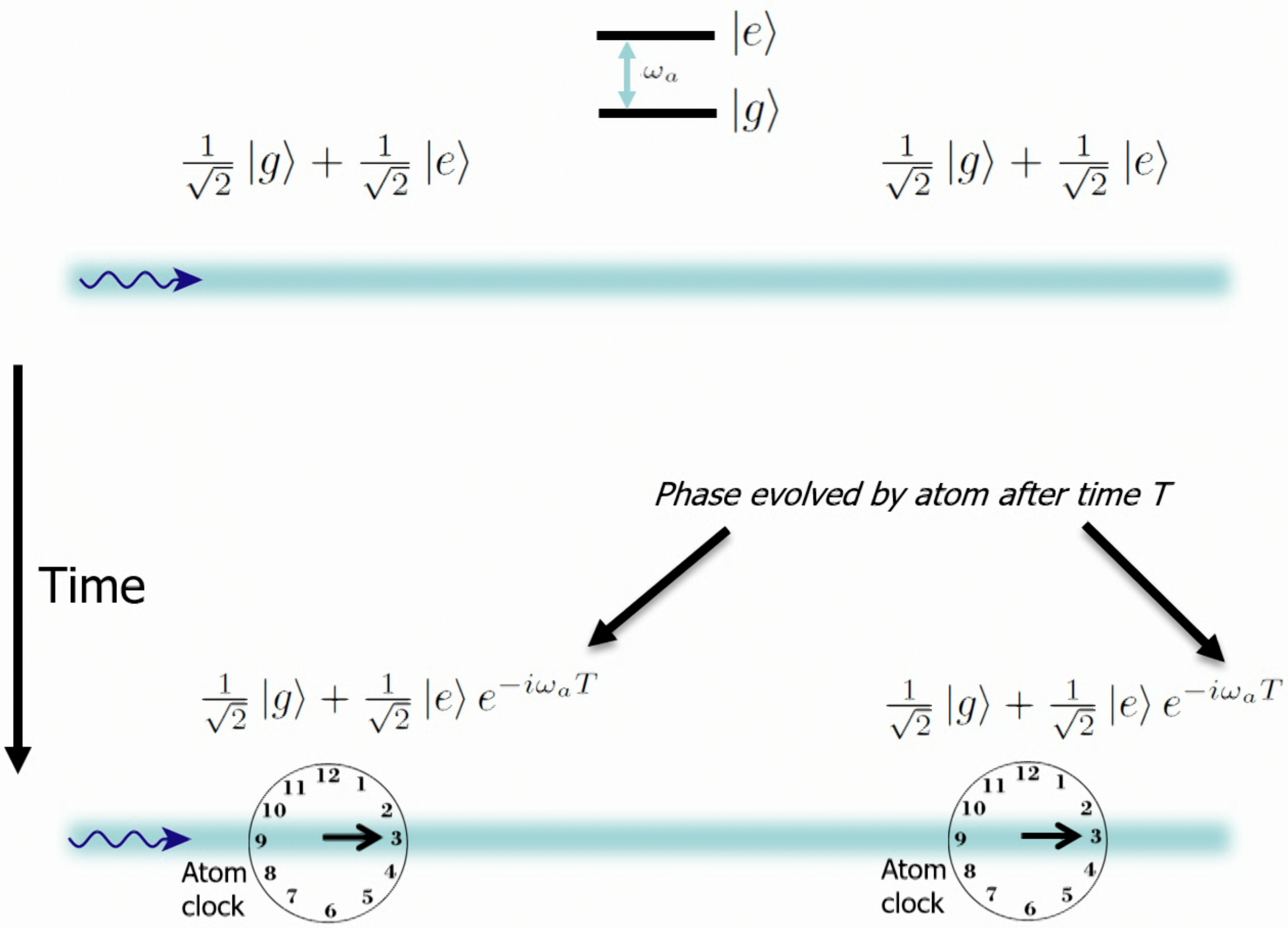
Passing gravitational waves cause a small modulation in the distance between objects. Detecting this modulation requires two ingredients:

1. **Inertial references**
    - Freely-falling objects, separated by some baseline
    - Must be insensitive to perturbations from non-gravitational forces
2. **Clock**
    - Used to monitor the separation between the inertial references
    - Typically measures the time for light to cross the baseline, via comparison to a precise phase reference (e.g. a clock).

In MAGIS, atoms play both roles.

Atom as "active" proof mass: Atomic coherence records laser phase, avoiding the need of a reference baseline – **single baseline** gravitational wave detector.

Simple Example: Two Atomic Clocks



$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

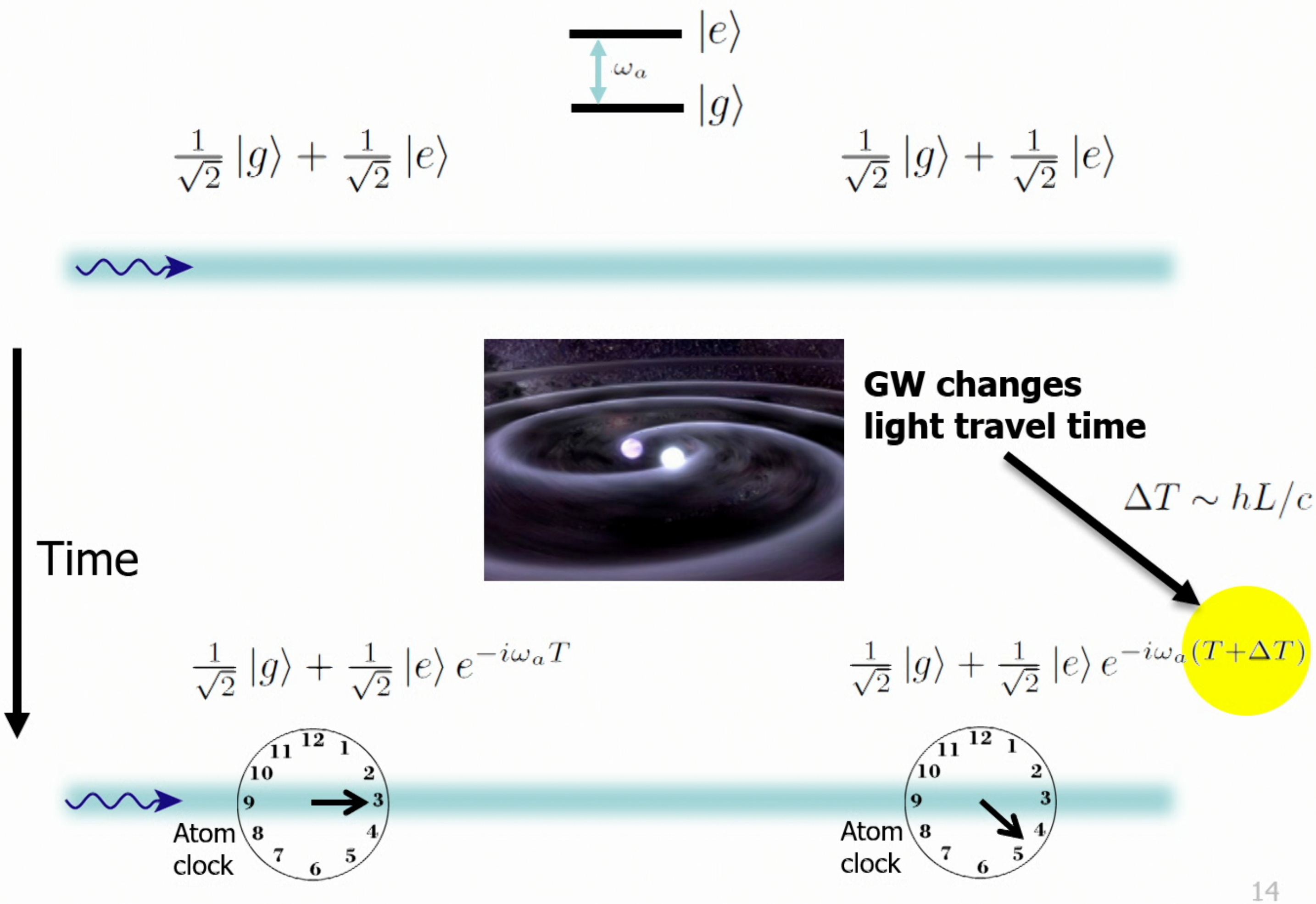
$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

Phase evolved by atom after time T

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

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

Simple Example: Two Atomic Clocks



$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle \qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle$$

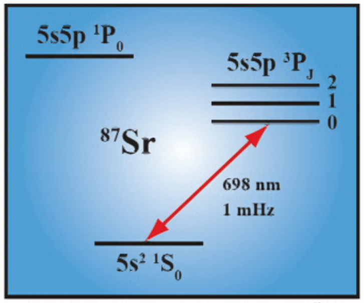
GW changes light travel time

$\Delta T \sim hL/c$

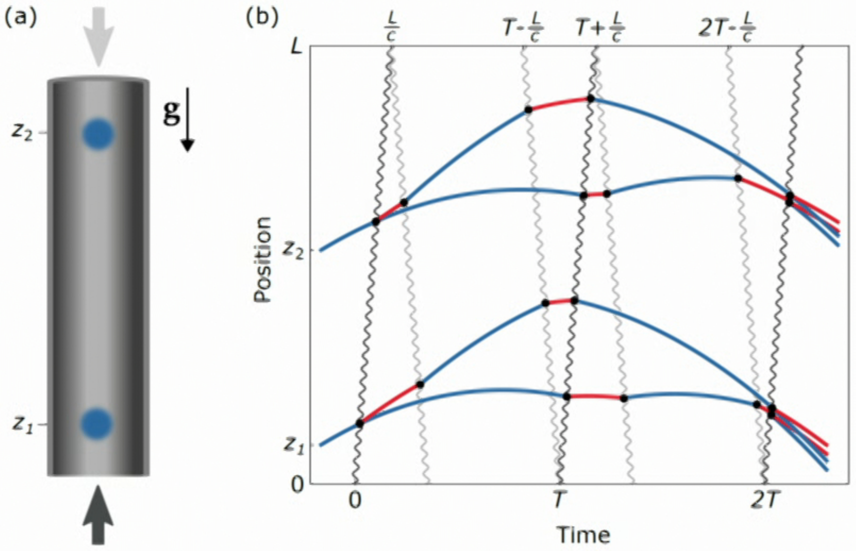
$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\,e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\,e^{-i\omega_a(T+\Delta T)}$$

Clock atom interferometry

New kind of atom interferometry using **single-photon transitions** between long-lived **clock states**



Clock transition in candidate atom ^{87}Sr



Excited state phase evolution:

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

(variations over time T)

Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

Ultralight (wave-like) dark matter

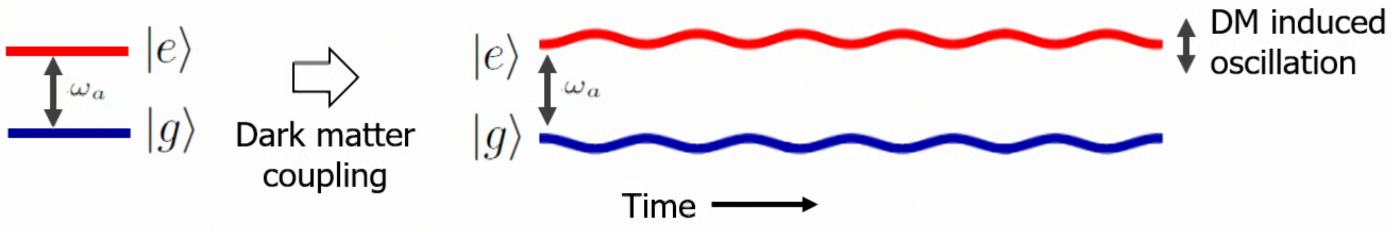
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

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

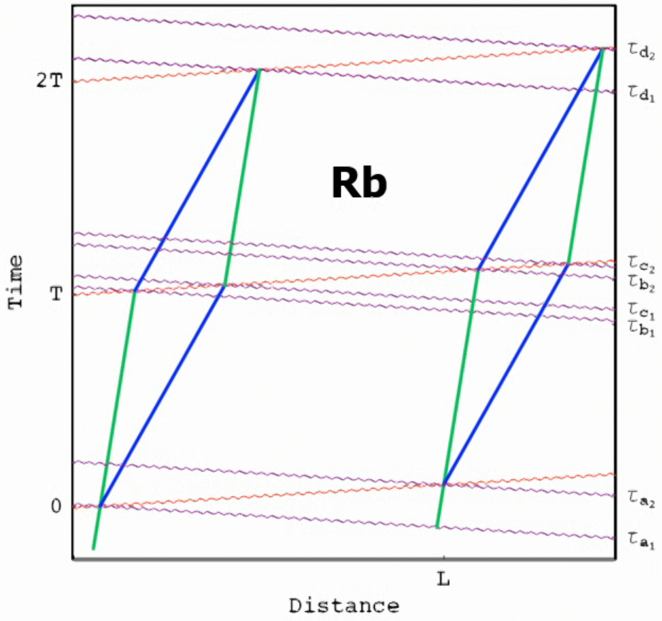
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:



Two-photon vs. single photon transitions

2-photon transitions (Raman/Bragg)

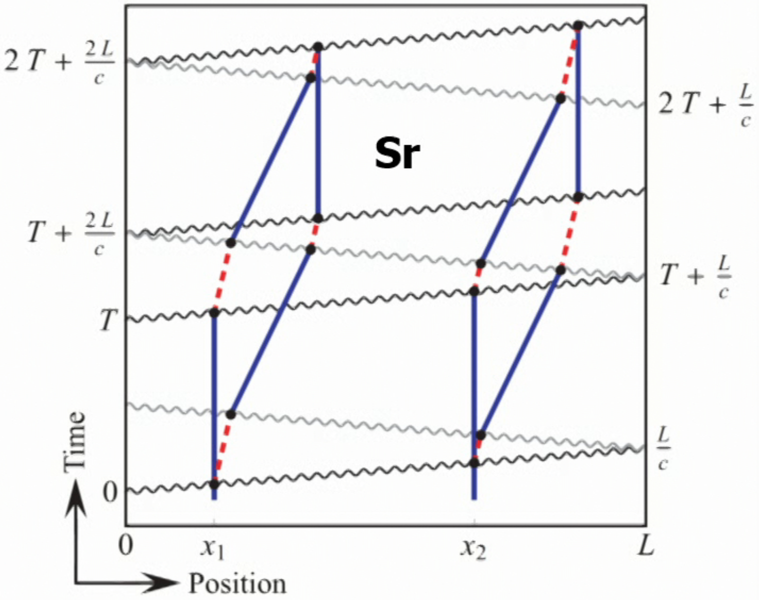


- Sensitive to laser wavelength

$$\frac{\delta\omega}{\omega} \ll h \sim 10^{-20}$$

- Requires multiple baselines

1-photon transitions

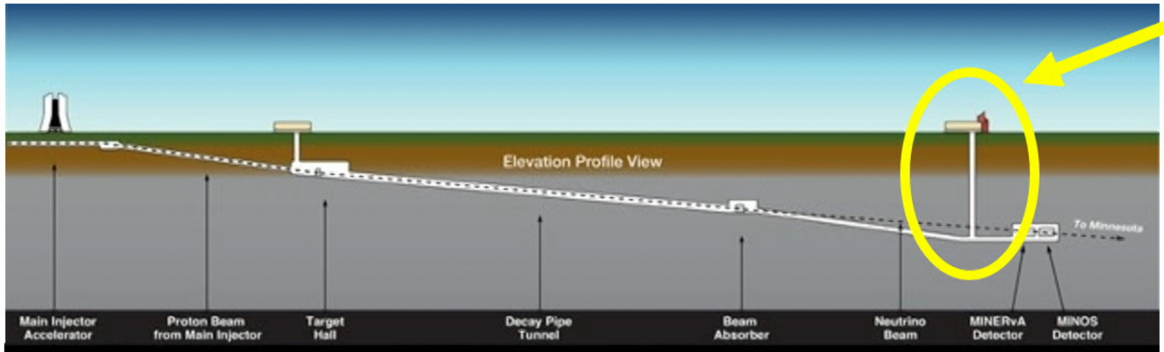


- Sensitive to atomic splitting
- **Single baseline operation**

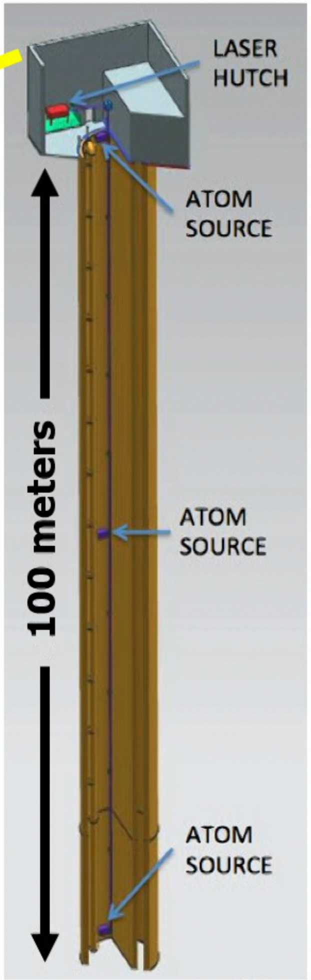
Graham et al., PRD 78, 042003, (2008).
Yu et al., GRG 43, 1943, (2011).

MAGIS-100: Detector prototype at Fermilab

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



Neutrino Beam Line for MINERvA and MINOS Experiments

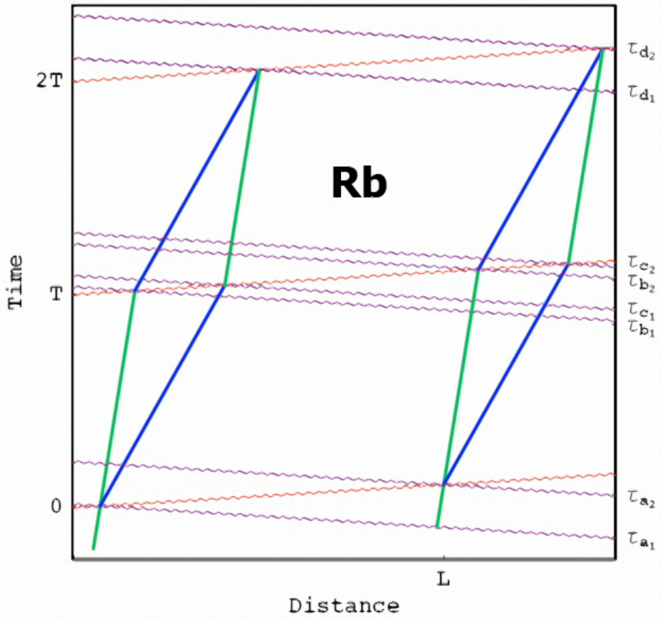


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

Stanford · Johns Hopkins University · Northwestern University · Fermilab · SLAC · The University of Chicago · University of Cambridge · Northern Illinois University · University of Oxford · University of Liverpool

Two-photon vs. single photon transitions

2-photon transitions (Raman/Bragg)



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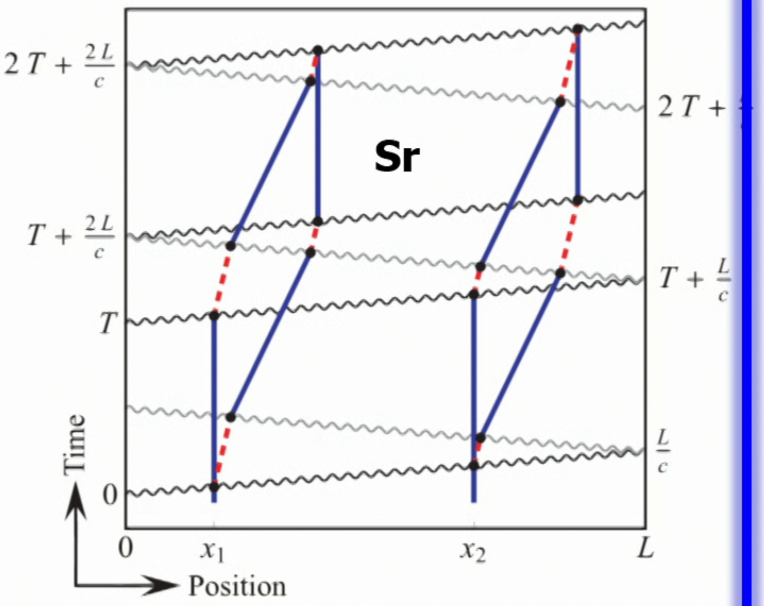
1-photon transitions

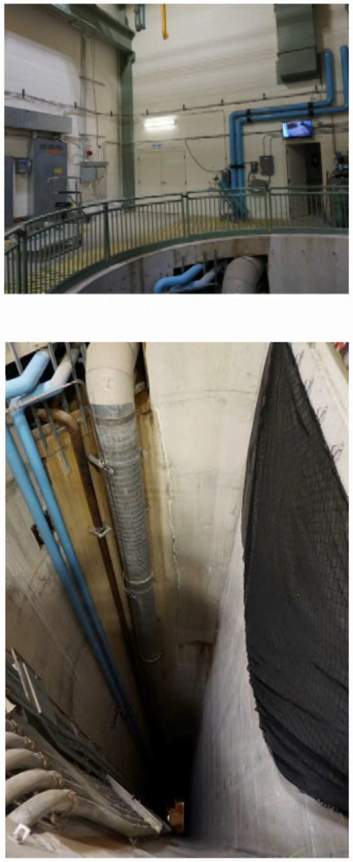


- Sensitive to atomic splitting
- **Single baseline operation**

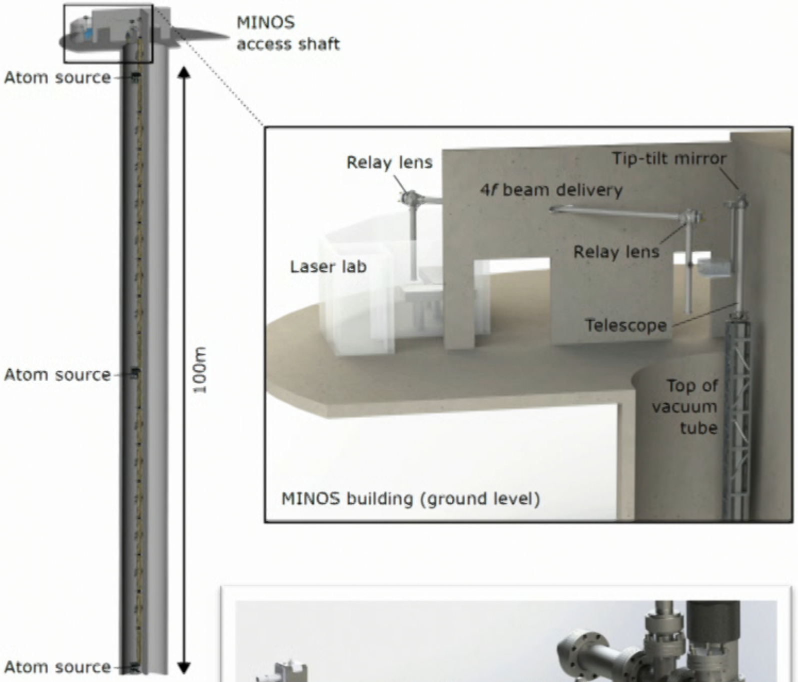
MAGIS

Graham et al., PRD 78, 042003, (2008).
Yu et al., GRG 43, 1943, (2011).

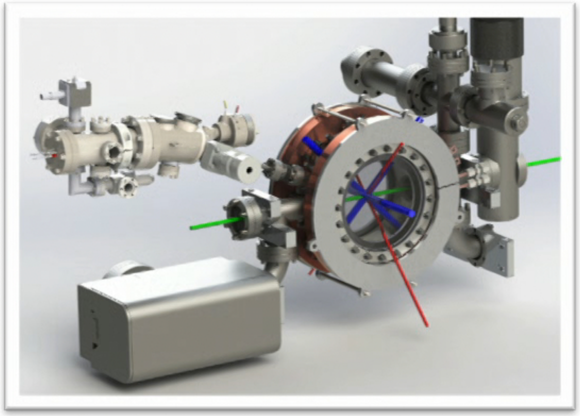
MAGIS-100 design

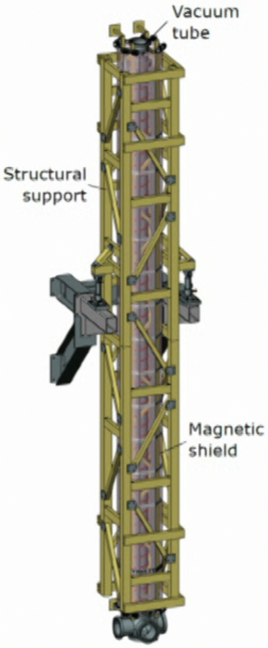


MINOS access shaft

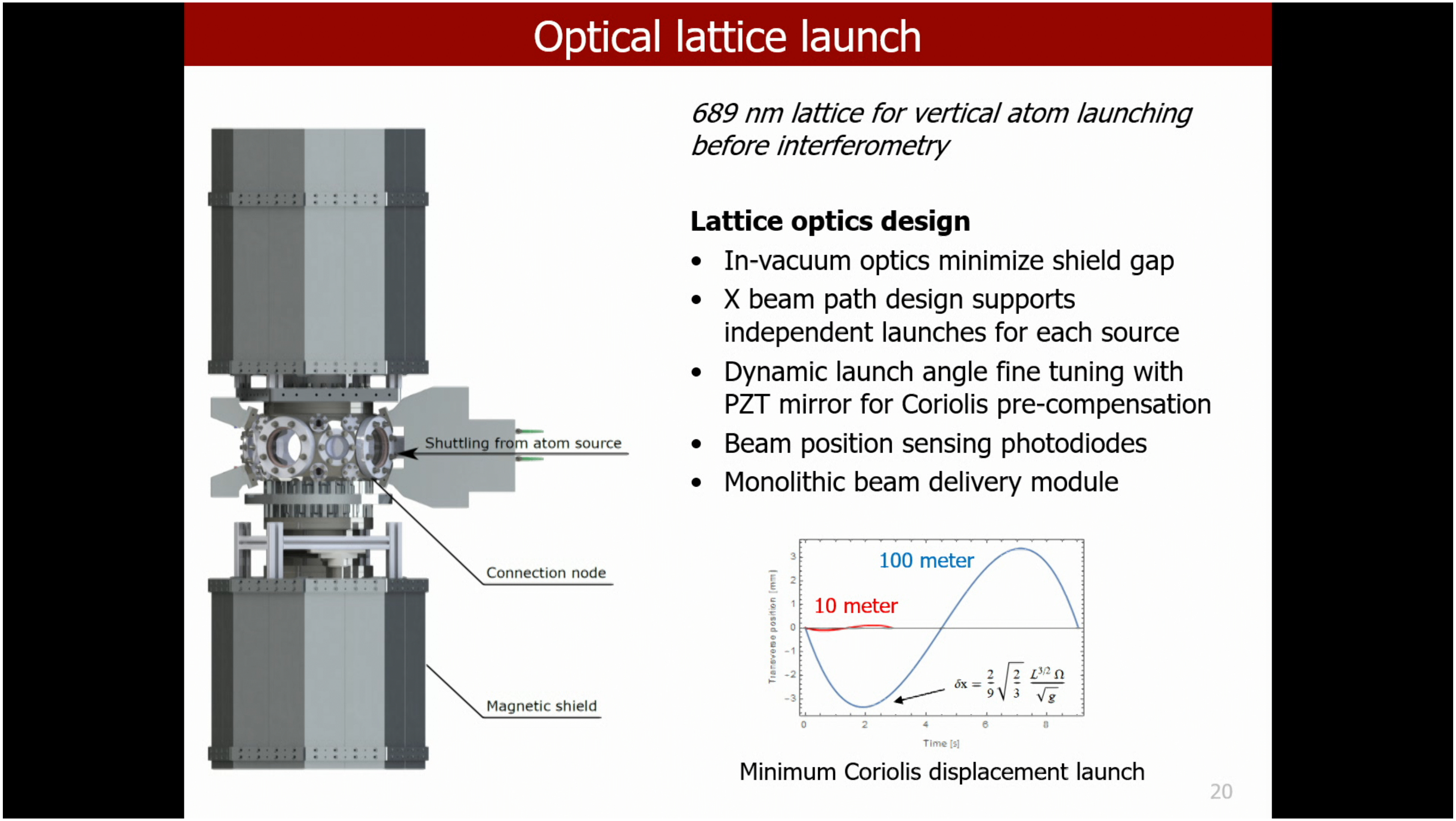


Sr atom sources





Modular section of 100 meter science region



Optical lattice launch

689 nm lattice for vertical atom launching before interferometry

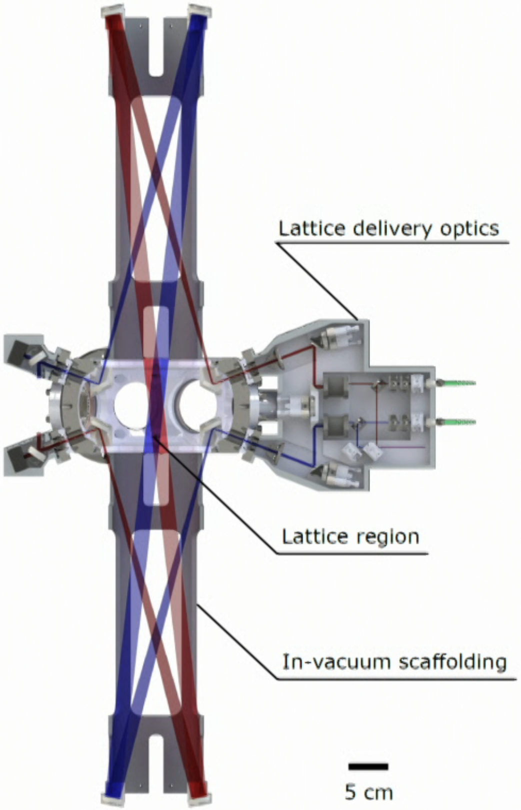
Lattice optics design

- In-vacuum optics minimize shield gap
- X beam path design supports independent launches for each source
- Dynamic launch angle fine tuning with PZT mirror for Coriolis pre-compensation
- Beam position sensing photodiodes
- Monolithic beam delivery module

$$\delta x = \frac{2}{9}\sqrt{\frac{2}{3}}\,\frac{L^{3/2}\,\Omega}{\sqrt{g}}$$

Minimum Coriolis displacement launch

Optical lattice launch



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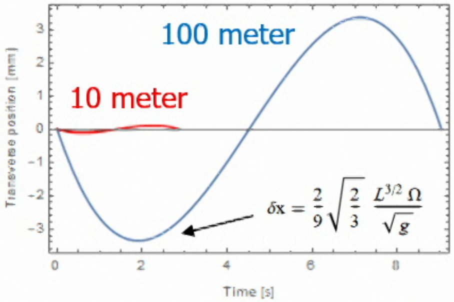
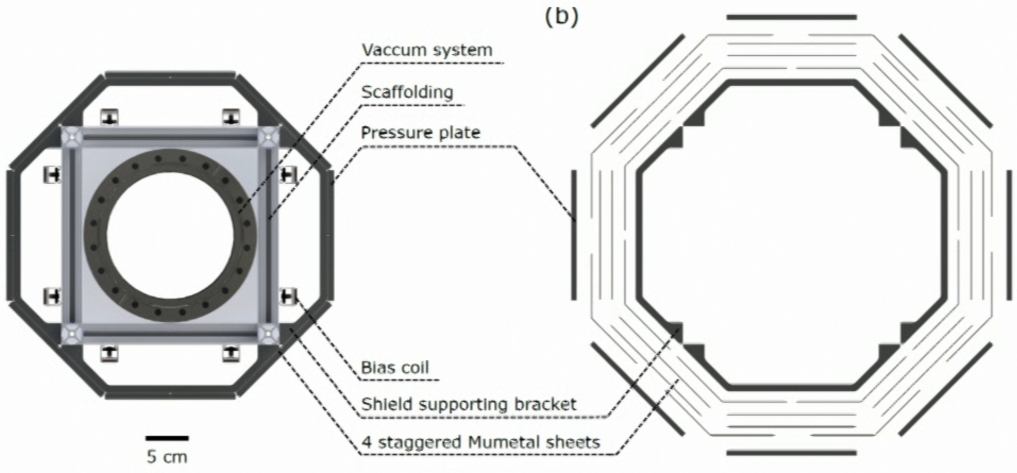
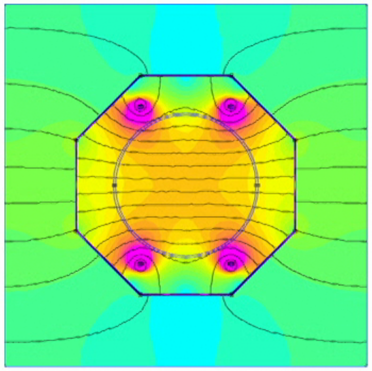


Minimum Coriolis displacement launch

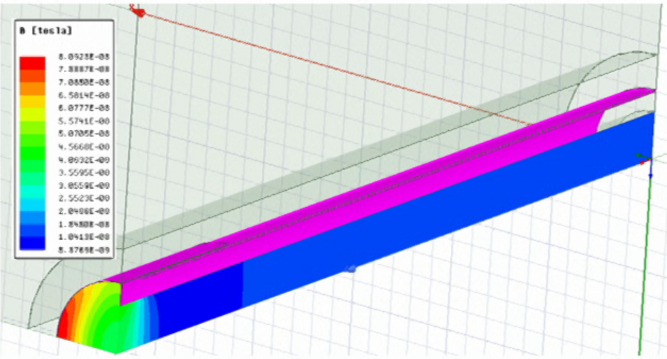
MAGIS-100 magnetic shield



- Octagon shield
- 4 sheet, overlapping design
- Adapted from proven Hannover design
- Internal bias coils

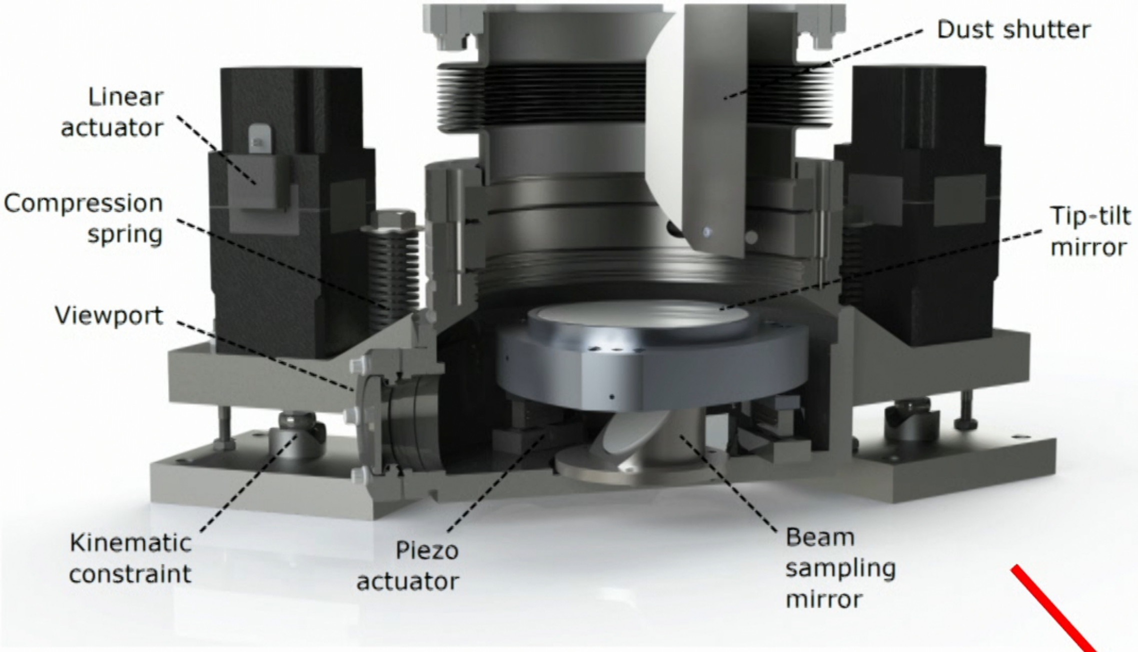


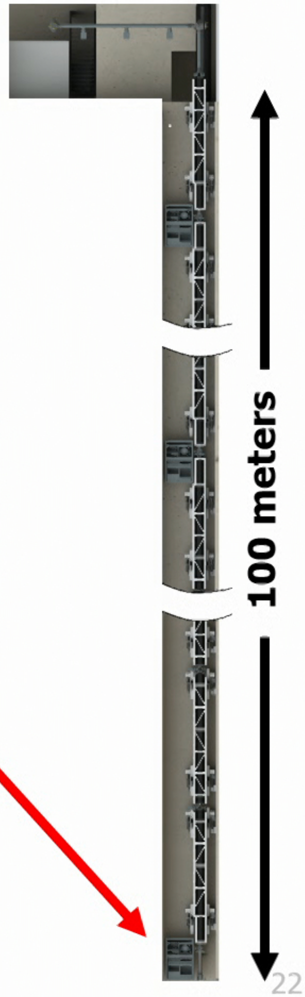
Shield + bias field simulation



3D horizontal field simulation

MAGIS-100 tip-tilt mirror for rotation compensation

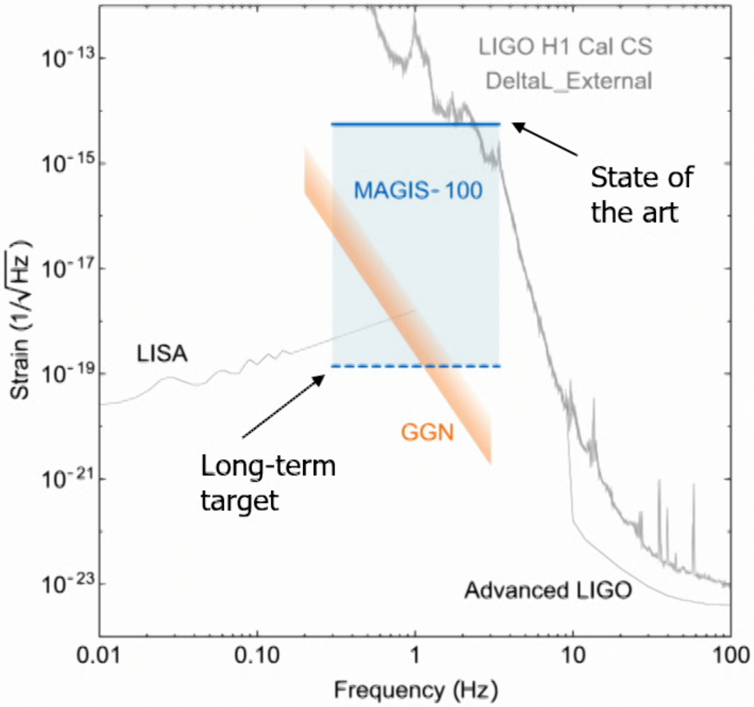




- Mirror at bottom to reflect interferometry laser light
- 3-axis piezo actuators for fine control
- Suppress Coriolis phase shifts by counter-rotating
- Coarse alignment with linear actuators

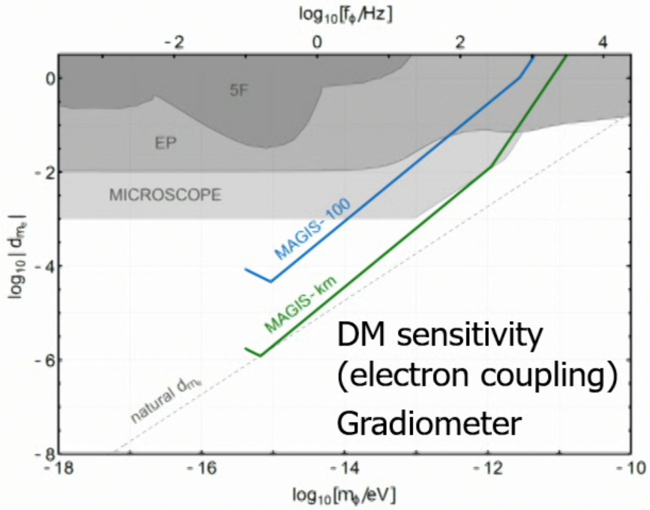
MAGIS-100 projected sensitivity

Gravitational wave sensitivity



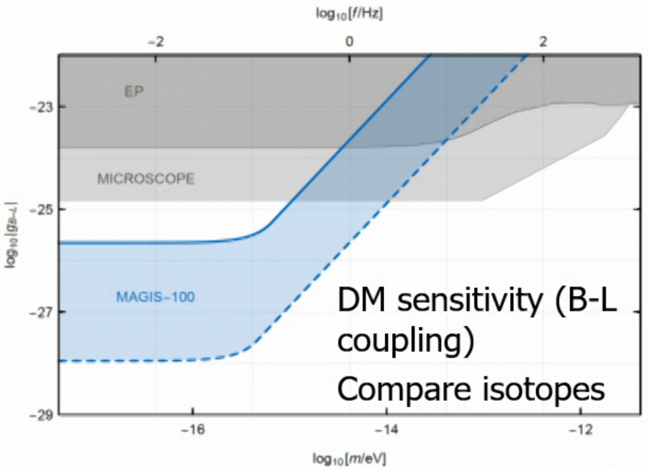
State of the art

Long-term target



DM sensitivity (electron coupling)

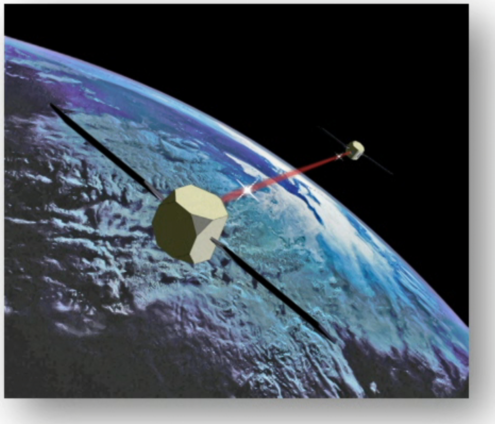
Gradiometer



DM sensitivity (B-L coupling)

Compare isotopes

MAGIS-style satellite detector



Satellite detector concept

- Two spacecraft, MEO orbit
- Atom source in each
- Heterodyne laser link
- Resonant/LMT sequences

Example design

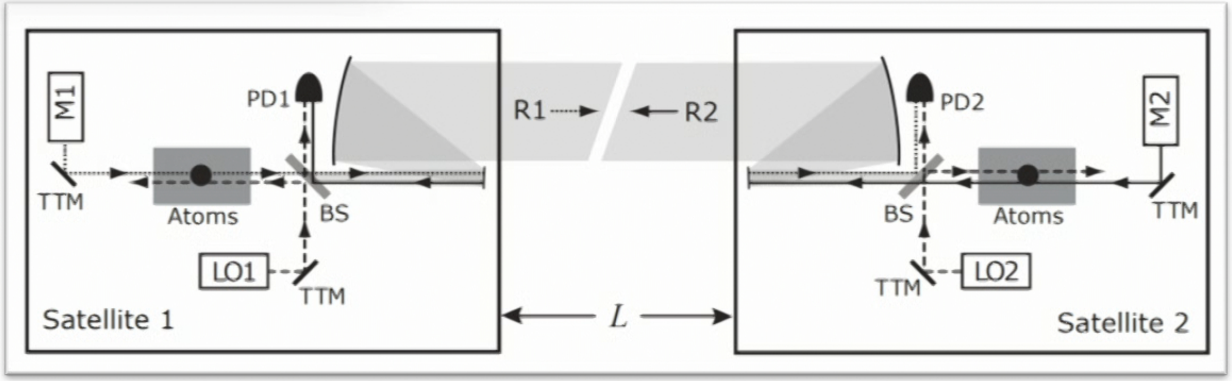
$$L = 4 \times 10^7 \text{ meters}$$

$$10^{-4} \text{ rad}/\sqrt{\text{Hz}}$$

$$\frac{n\hbar k}{m} T < 1 \text{ m}$$

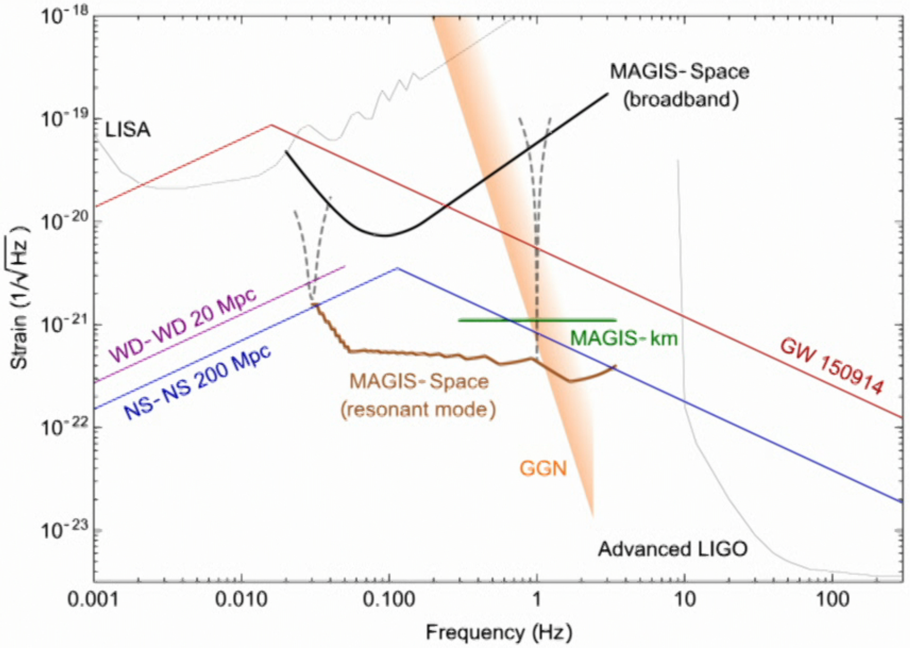
$$2TQ < 300 \text{ s}$$

$$n_p < 10^3$$

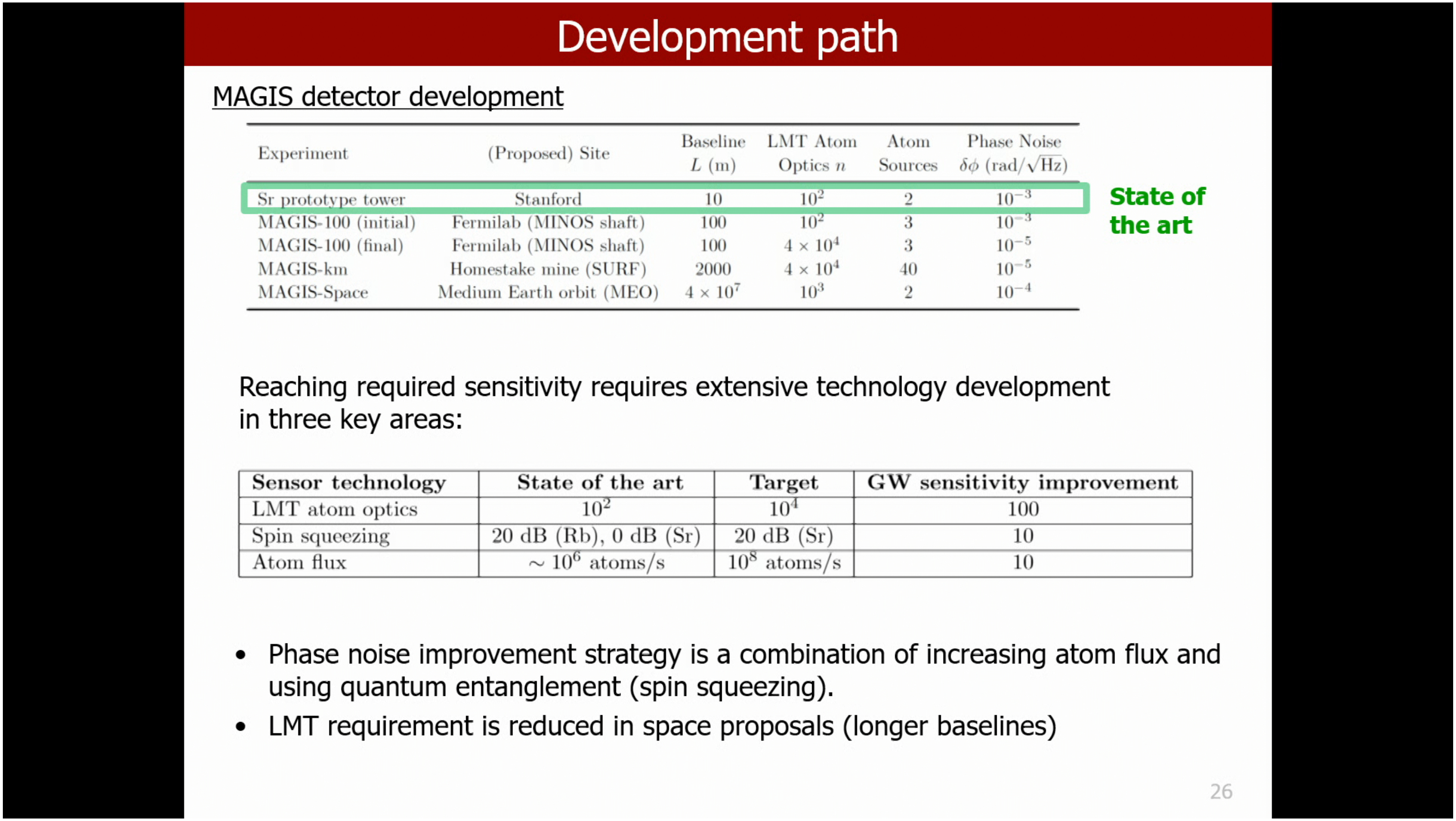


- Heterodyne link concept analogous to LISA (synthesize ranging between two test masses)
- Decouples atom-laser interaction strength from baseline length (diffraction limit)

Full scale MAGIS projected GW sensitivity



- Mid-band GW sources detectable from ground and space
- Gravity gradient noise (GGN) likely limits any terrestrial detector at low frequencies
- Longer baselines available in space reduce requirements (e.g., LMT), but can impact frequency response at high frequencies
- Flexible detection strategies possible (broadband vs resonant) with different tradeoffs in sensitivity/bandwidth



Development path

MAGIS detector development

Experiment	(Proposed) Site	Baseline L (m)	LMT Atom Optics n	Atom Sources	Phase Noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7	10^3	2	10^{-4}

State of the art

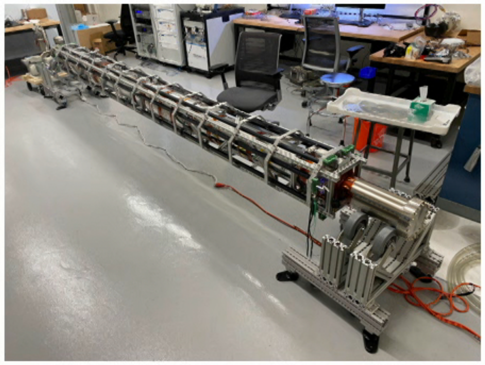
Reaching required sensitivity requires extensive technology development in three key areas:

Sensor technology	State of the art	Target	GW sensitivity improvement
LMT atom optics	10^2	10^4	100
Spin squeezing	20 dB (Rb), 0 dB (Sr)	20 dB (Sr)	10
Atom flux	$\sim 10^6$ atoms/s	10^8 atoms/s	10

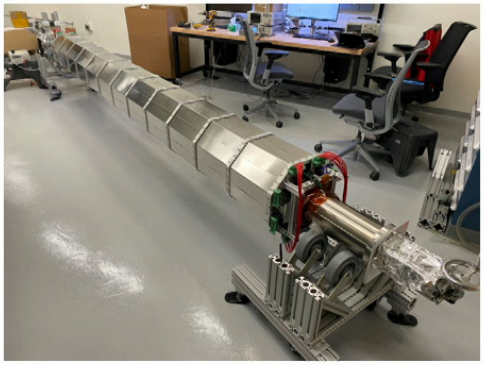
- Phase noise improvement strategy is a combination of increasing atom flux and using quantum entanglement (spin squeezing).
- LMT requirement is reduced in space proposals (longer baselines)

MAGIS-100 development at Stanford

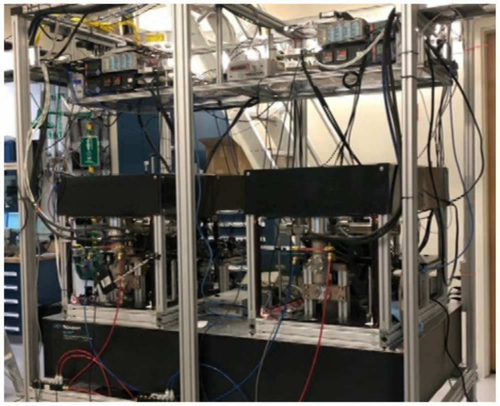
10-m Sr tower CAD model



Vacuum and bias coils
for prototype module



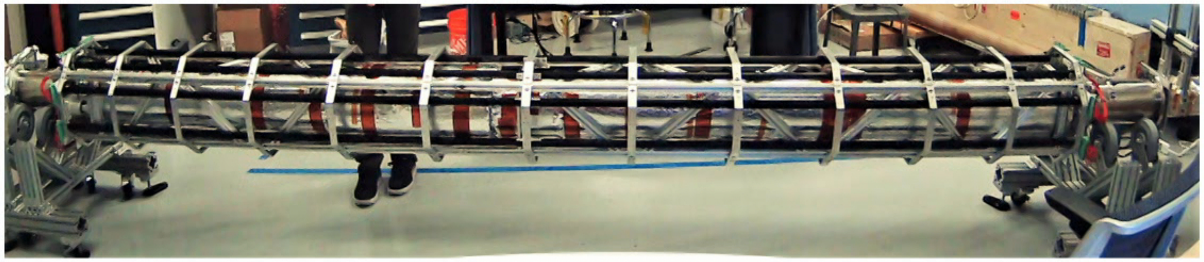
Magnetic shield
assembled and tested



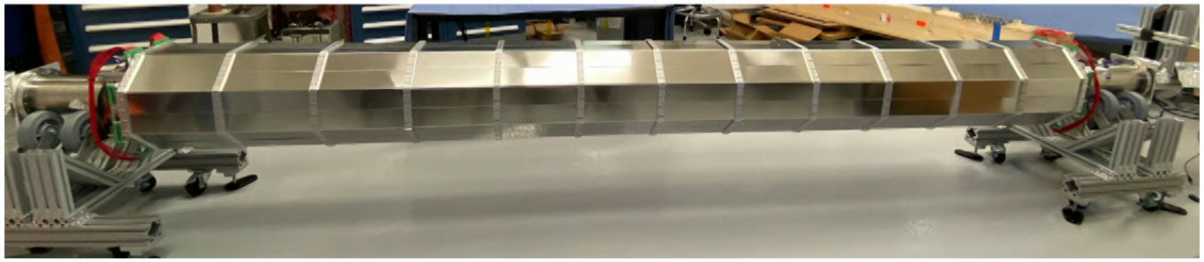
Two prototype
Sr atom sources

Magnetic shield assembly and test

Assembled prototype MAGIS module with horizontal bias coils and magnetic shield

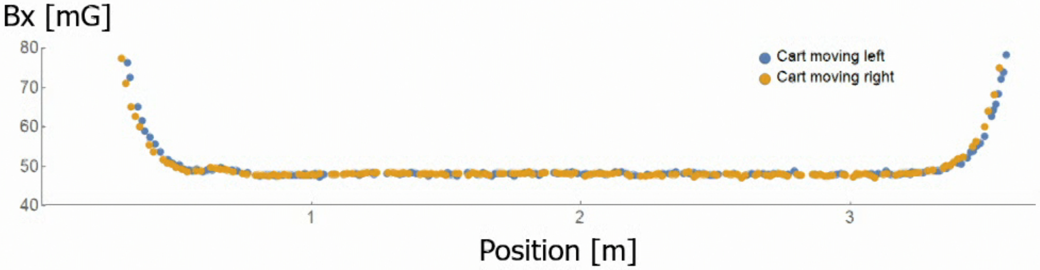


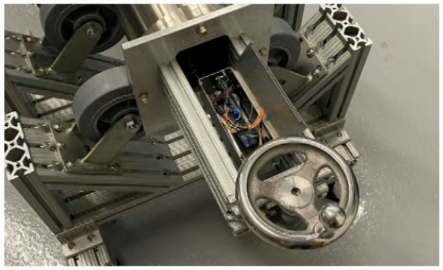
Before shield



With shield

After degauss, magnetic shield meets specifications:





Magnetometer shuttle on suspension wires