



MAGIS-100 at FNAL

A 100 meter atom interferometer

Rob Plunkett

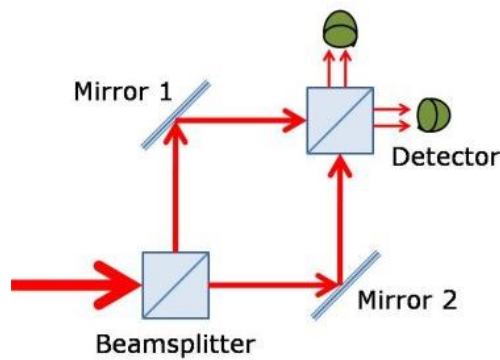
Fermi National Accelerator Laboratory

SIST/GEM Summer Lectures 2022

June 21 , 2022

Brief Introduction to Atom Interferometry

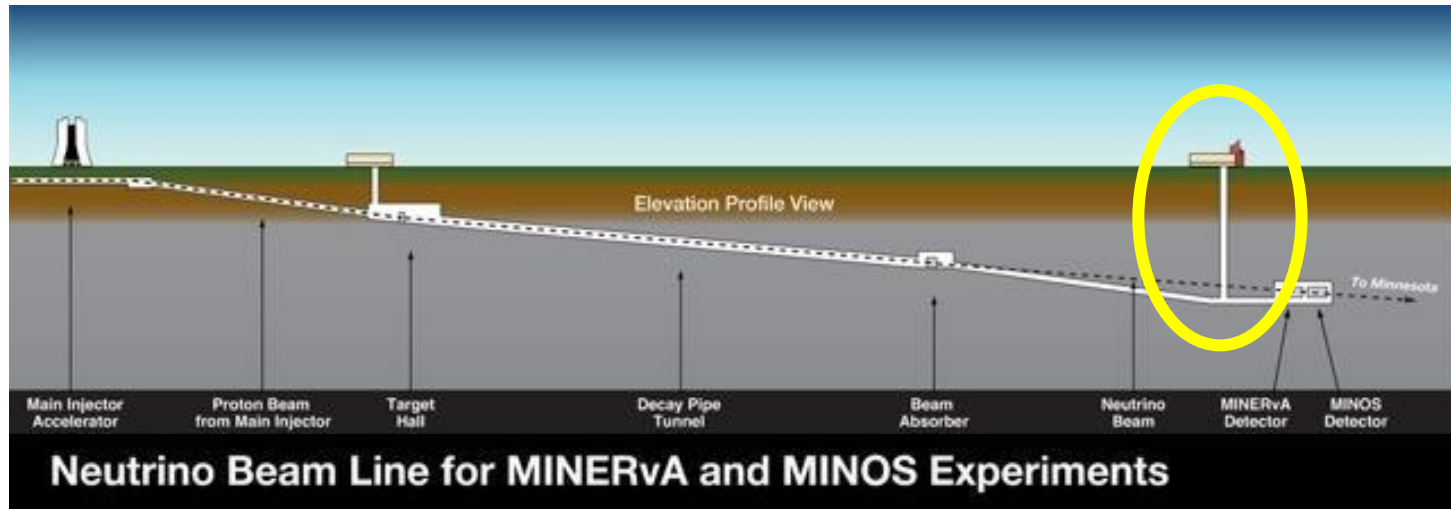
- Use cold atoms to detect phase shifts from split paths.
- Analogous to Mach-Zender Interferometry with light.



Existing 10 m
Interferometer
at Stanford

- Sensitivities for many fundamental physics applications scale with length of the baseline.
- Current baselines about 10 m
- Will extend this to ~100 m, increasing sensitivity.

MAGIS-100: Bringing Large Scale Interferometry to Fermilab



- Use existing 100 m shaft from NuMI/MINOS program
- Equipped surface building because underground experiments still active
- Serves both to study fundamental physics and as prototype for longer baseline (km scale) in future

MAGIS-100 Collaboration



STANFORD



Northwestern
University



UNIVERSITY OF
LIVERPOOL



Northern Illinois
University



JOHNS HOPKINS
UNIVERSITY



UNIVERSITY OF
CAMBRIDGE



THE UNIVERSITY OF
CHICAGO

GORDON AND BETTY
MOORE
FOUNDATION

GBMF7945

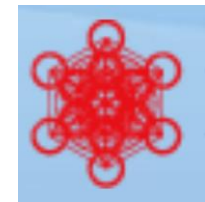


QuantiSED 2019



UK STFC

Science and
Technology
Facilities Council



Kavli Foundation

Two State Systems

- One of most important examples in Quantum Mechanics
- Applications: Lasers, MRI, Neutrino Oscillations.
- In atomic physics:

Ammonia Molecule

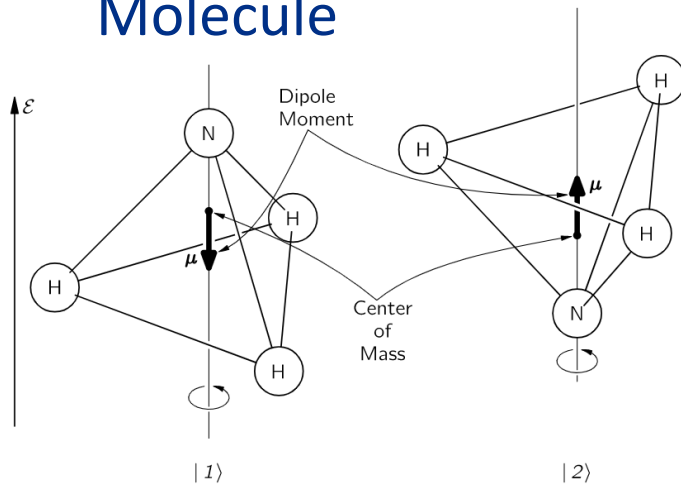



Fig. 9-1. A physical model of two base states for the ammonia molecule. These states have the electric dipole moments μ .

$$i\hbar \frac{dC_1}{dt} = H_{11}C_1 + H_{12}C_2,$$

$$i\hbar \frac{dC_2}{dt} = H_{21}C_1 + H_{22}C_2.$$


Electric Field E
causes energy
difference $\sim 2\mu E$

Governing Equations
 Ref: Feynman vol. 3,
 Lecture 9

Rabi Frequency

- In a sinusoidal field, the system will oscillate between the two states.
- The RABI FREQUENCY provides a measure of the strength of the interaction.

Here, the interaction strength is μE .

This is $1/\Omega$ Rabi

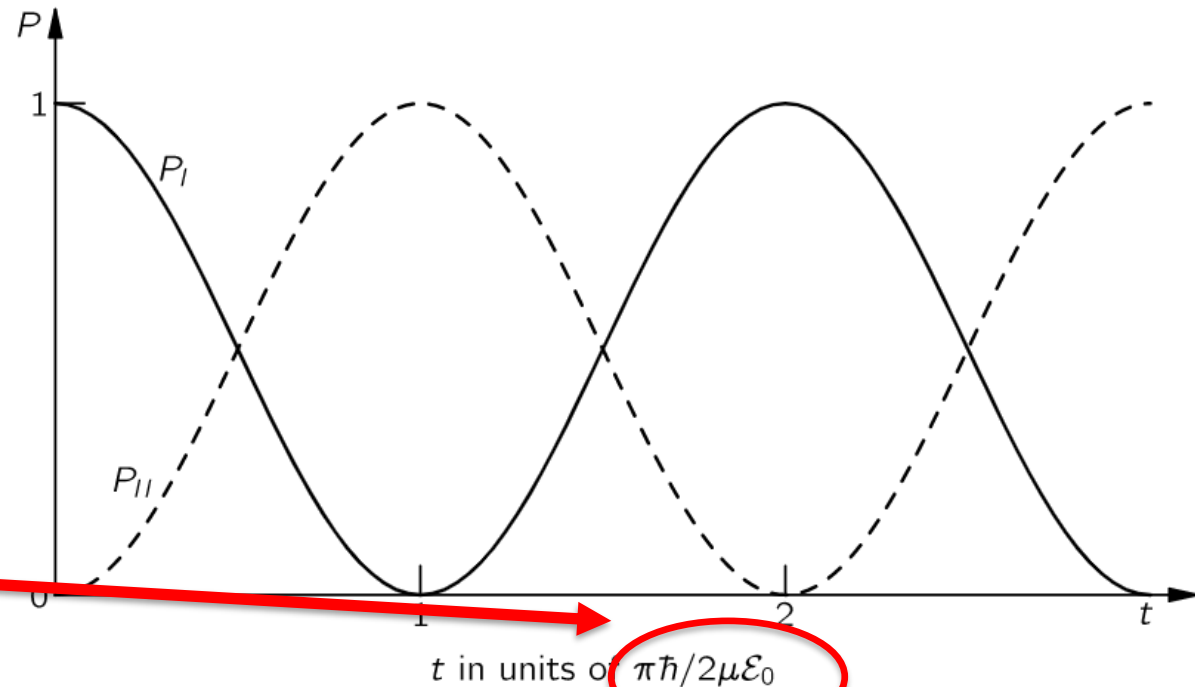
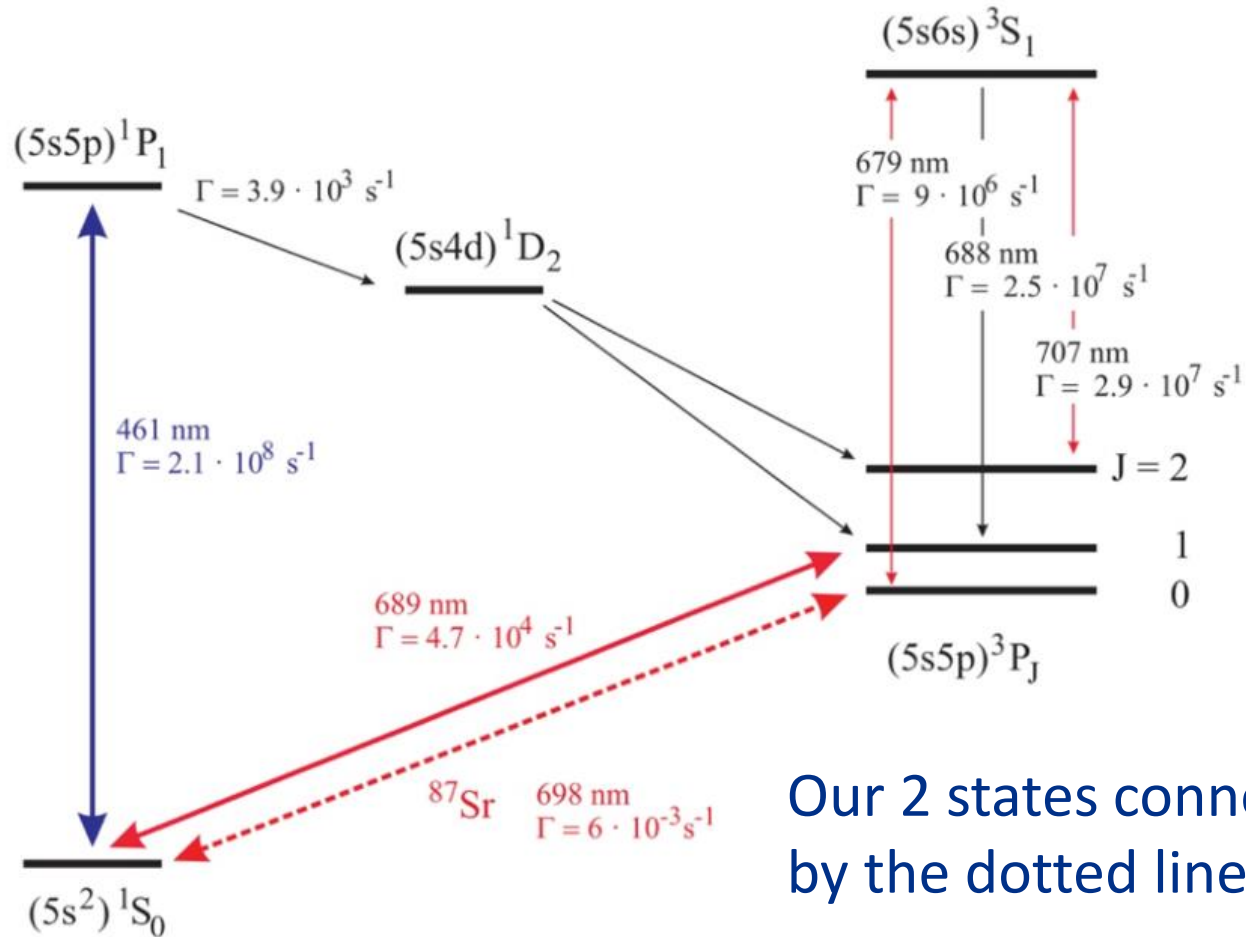


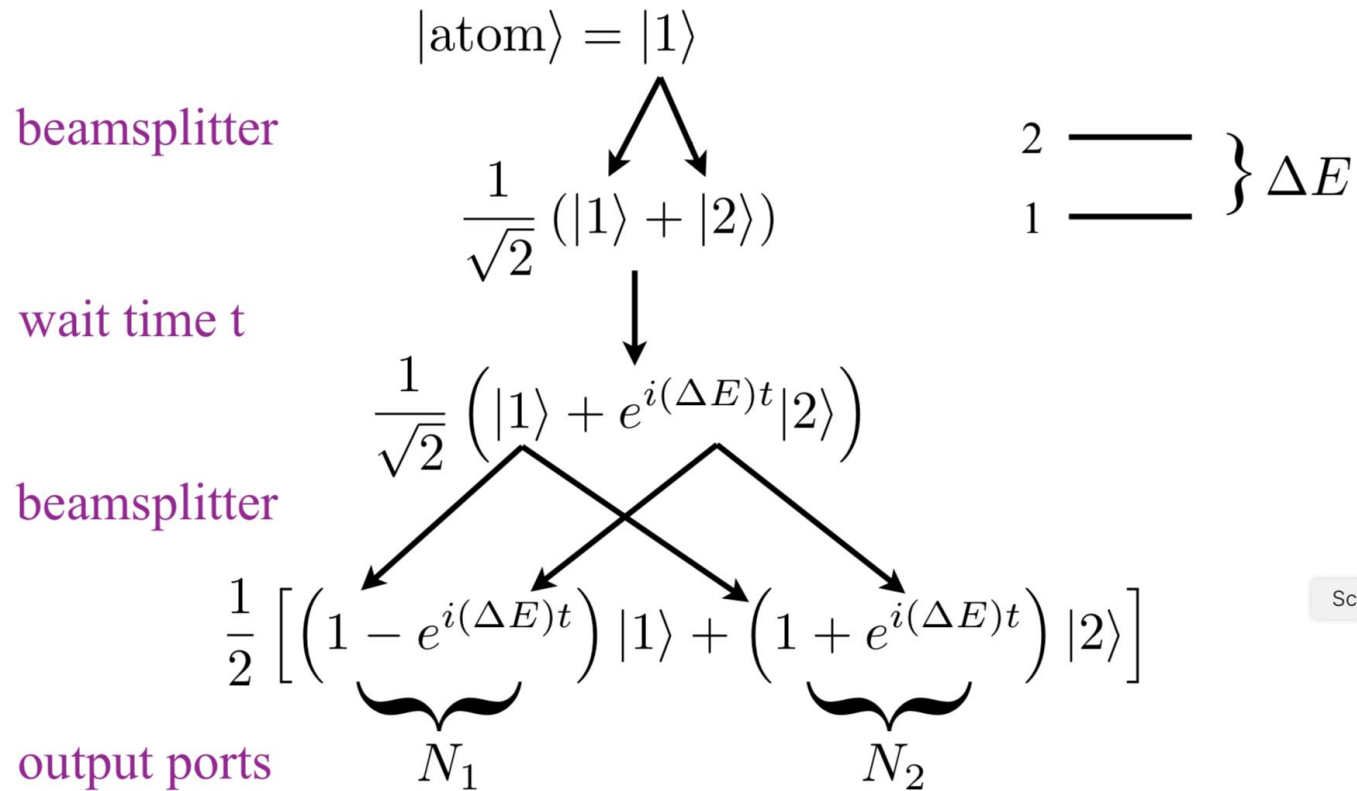
Fig. 9-5. Probabilities for the two states of the ammonia molecule in a sinusoidal electric field.

Strontium Spectrum



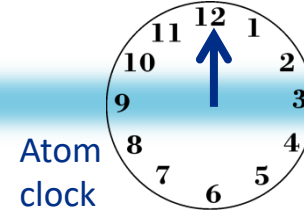
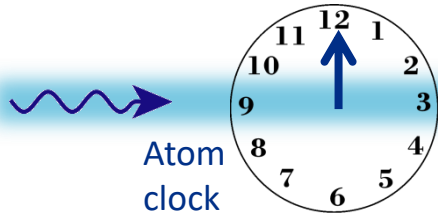
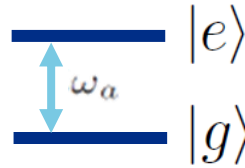
Our 2 states connected by the dotted line.

Pulsed Atomic Clock



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

Concept: Two Atomic Clocks



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

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)

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

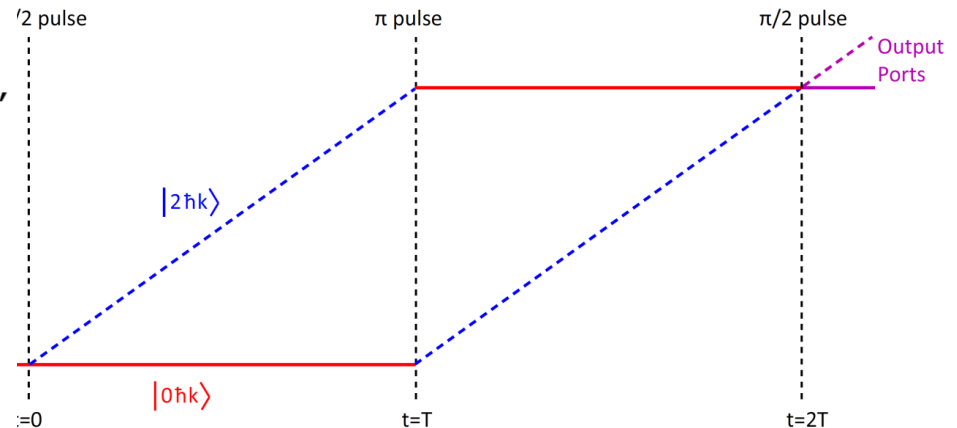
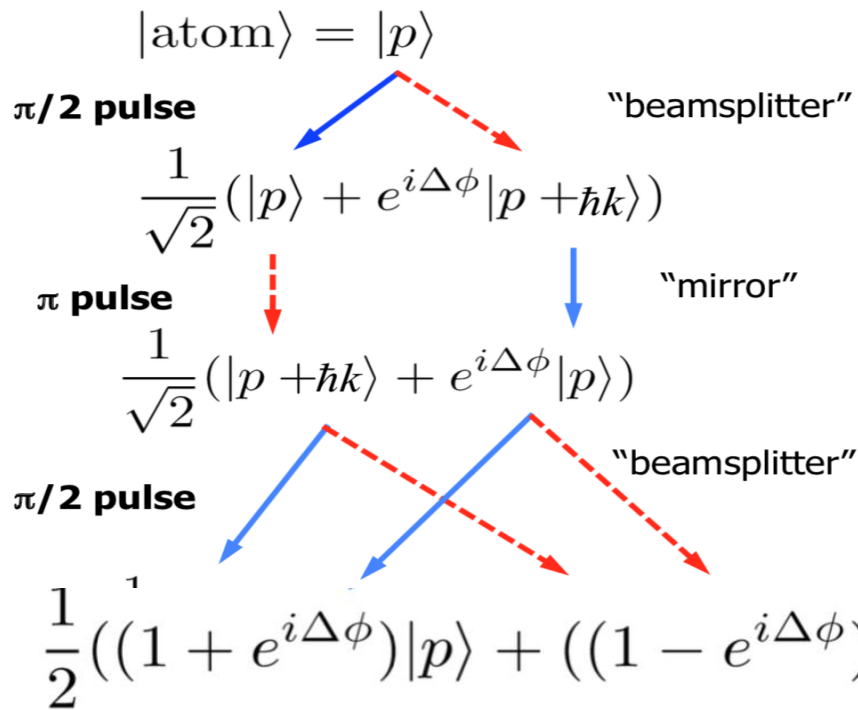
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T}$$

Time



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)



Effects scale like AREA, so

Long T good

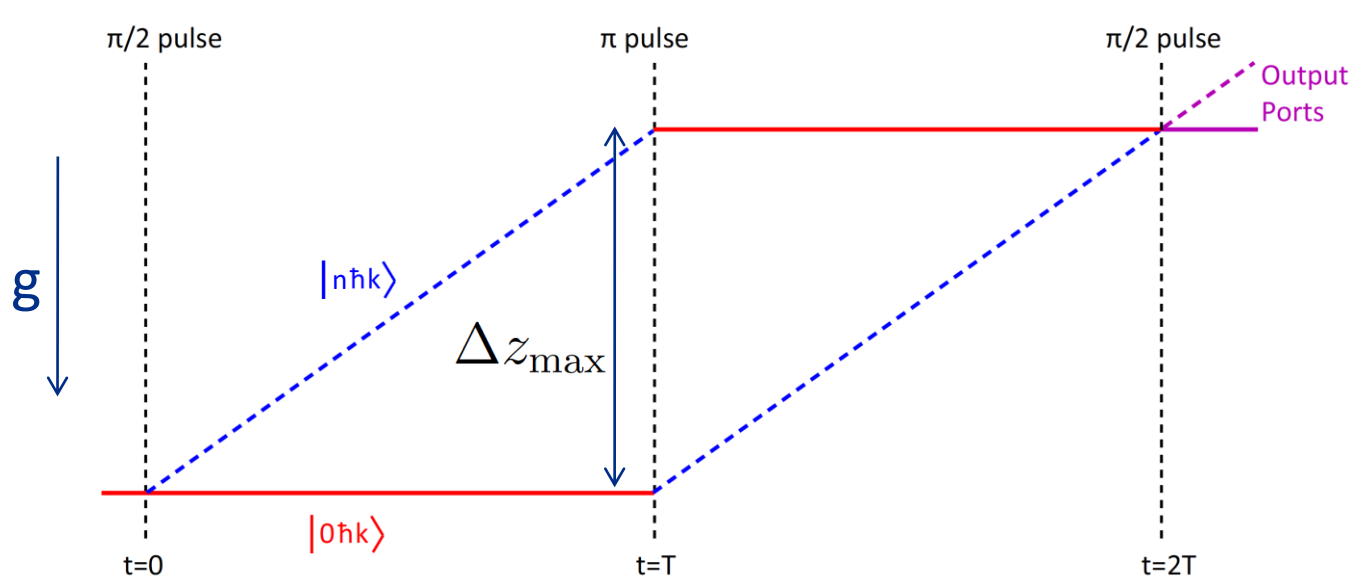
High Momentum Good

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

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

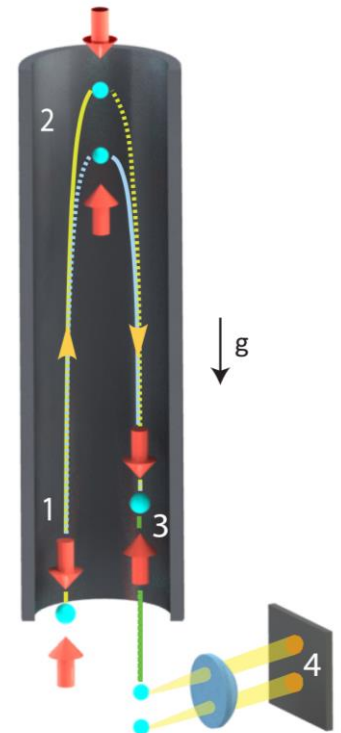
Interferometer Phase Shift

- Back-of-the-envelope phase shift calculation (not fully rigorous, but gives the right answer): look at gravitational potential energy difference between two paths



$$P_1 = \frac{1}{2} + \frac{1}{2}C \cos(\Delta\phi)$$

$$P_2 = \frac{1}{2} - \frac{1}{2}C \cos(\Delta\phi)$$



Acceleration sensitivity (consideration sensitivity to g as illustrative example)

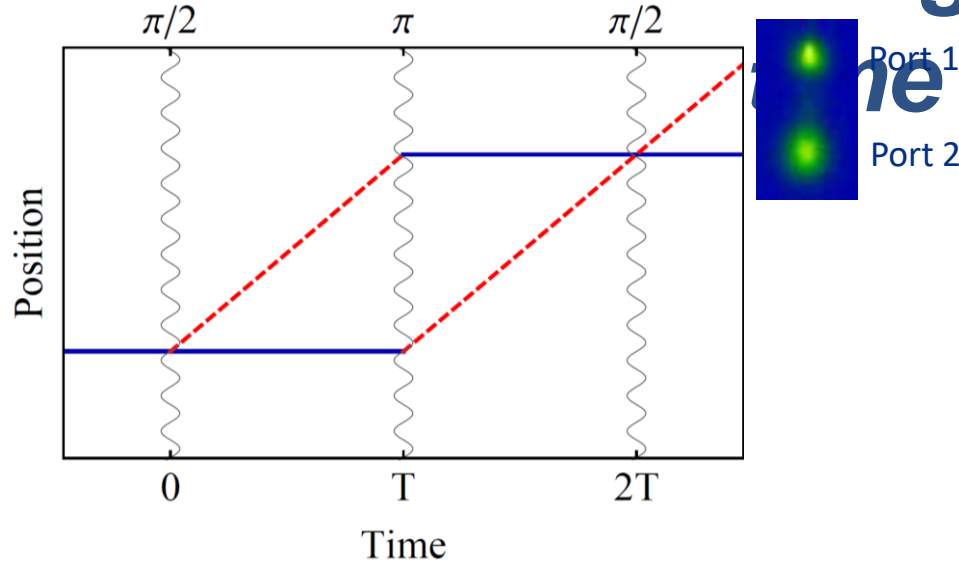
$$\Delta\phi = -\frac{m}{\hbar}g\Delta z_{\max}T$$

$$\Delta\phi = -nkgT^2$$

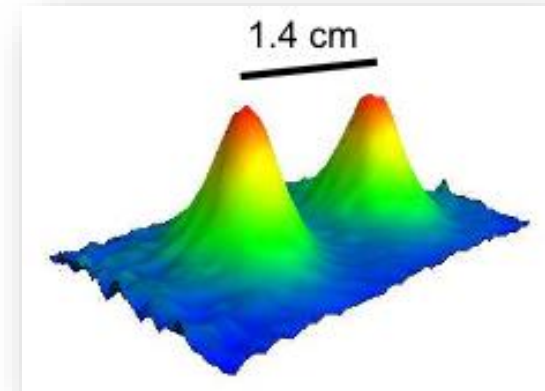
$$\Delta z_{\max} = \frac{n\hbar k}{m}T$$

For $n=100$, 461 nm light (for Sr atoms), $T = 1$ s, phase shift from g is 10^{10} radians

Interference at long interrogation

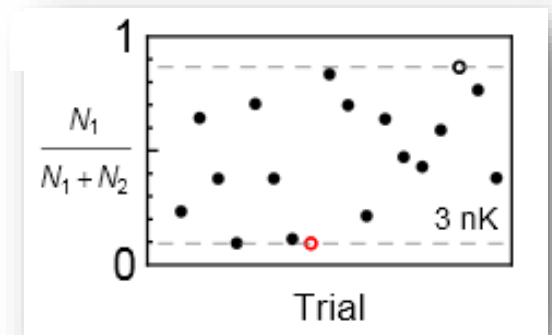
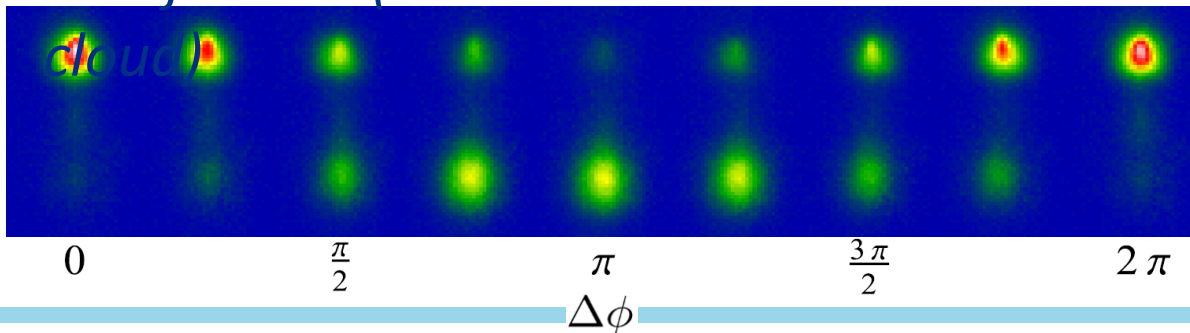


$2T = 2.3$ seconds
 1.4 cm wavepacket separation

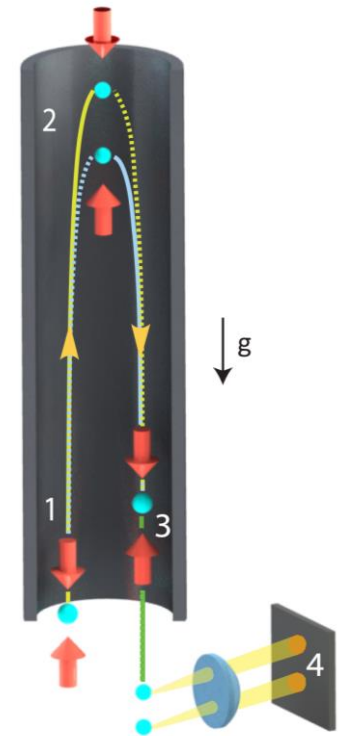
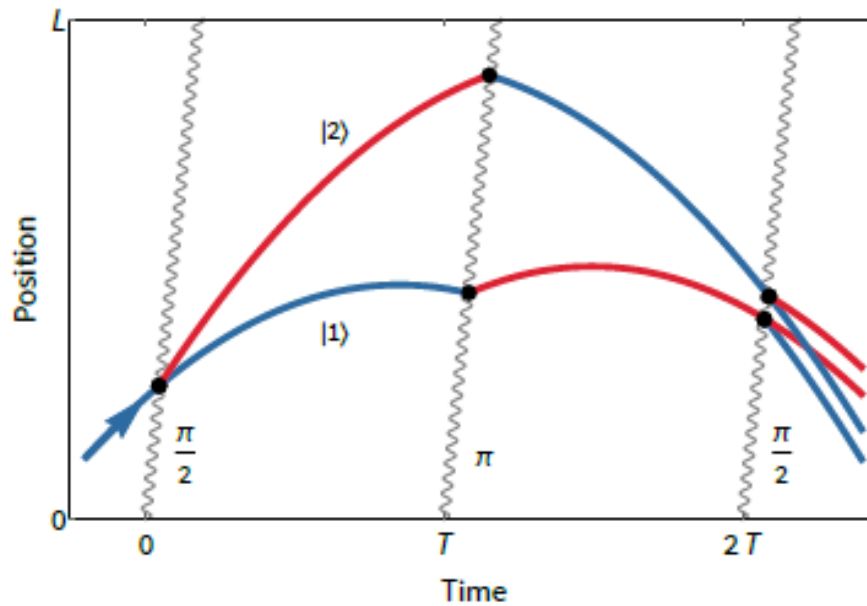


Wavepacket separation at apex (this data 50 nK)

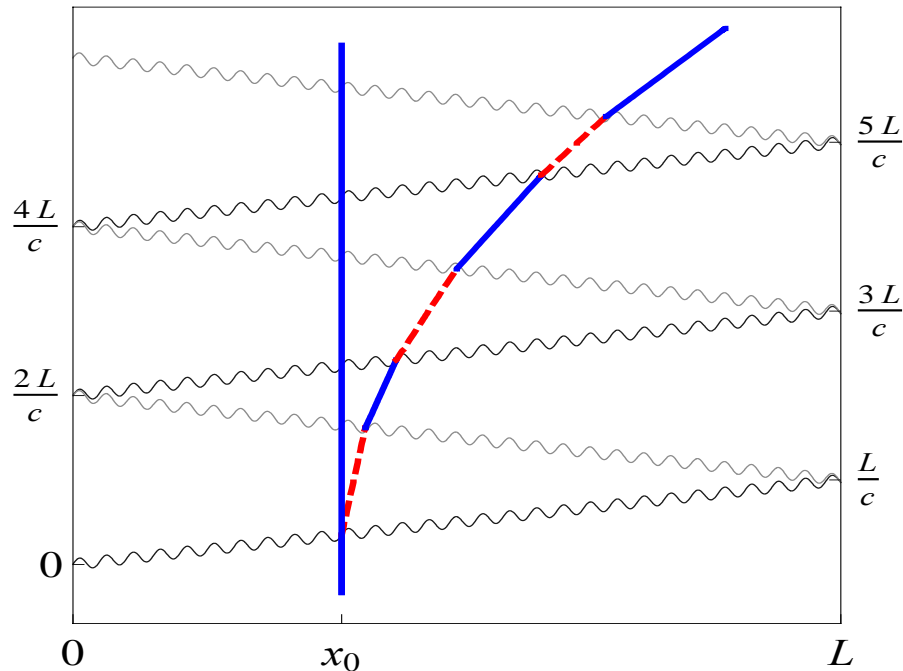
Interference (3 nK)



Fountain Interferometer

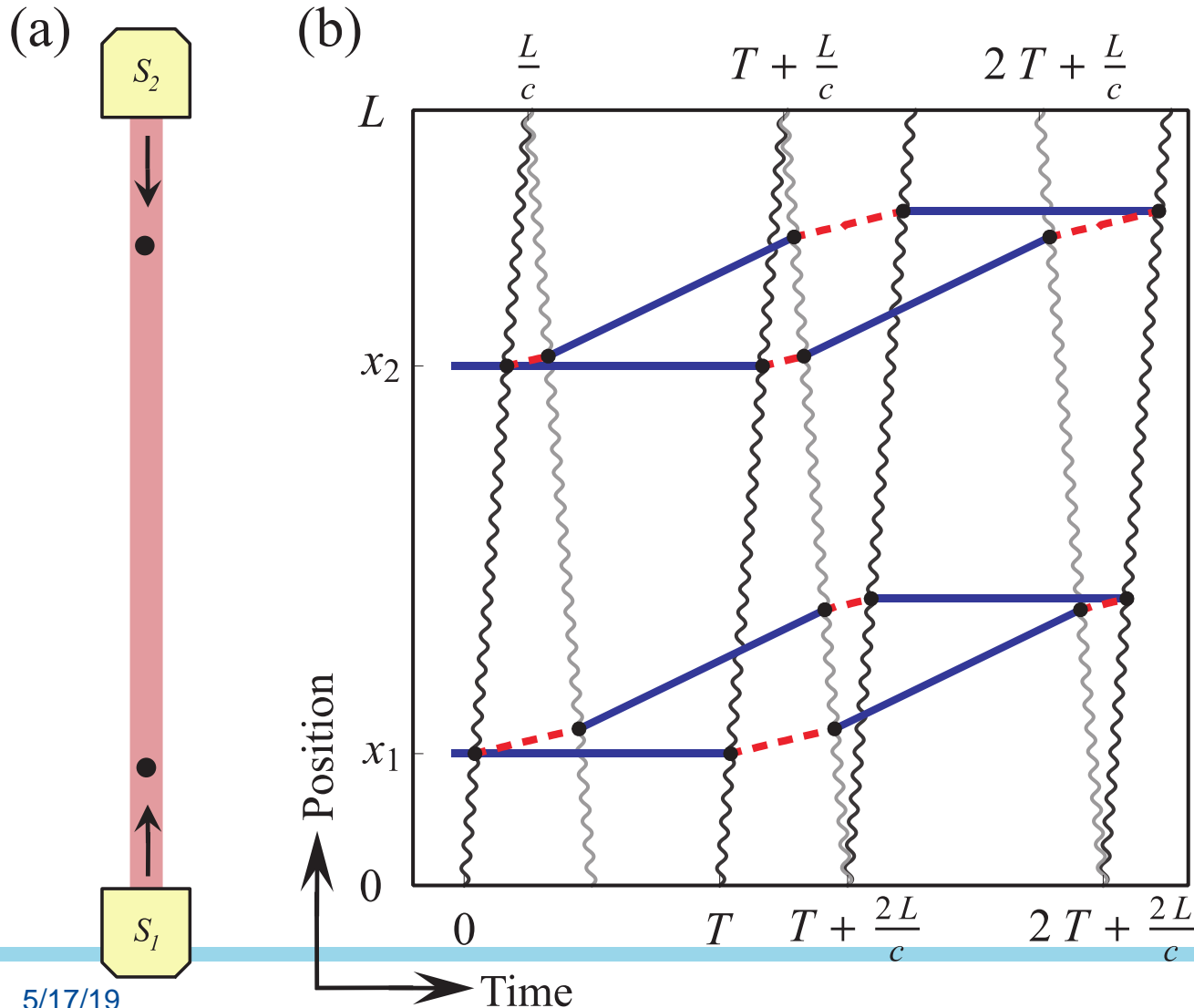


Large Momentum Transfer (LMT) Beamsplitter



- Increase interferometer area by making a higher momentum arm.
- Multiple small kicks from repeated excitations and de-excitation of clock transition.
- Technique can be used for hundreds of pulses
- Active development at Stanford.

Gradiometer to reduce systematics



Science of Interferometry at Large Scales

- Quantum Science
- Ultra Light Scalar Dark Matter
- B-L Dark Forces
- Gravitational Wave Demonstrator

Quantum Science with MAGIS-100

- 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

Ultralight scalar dark matter

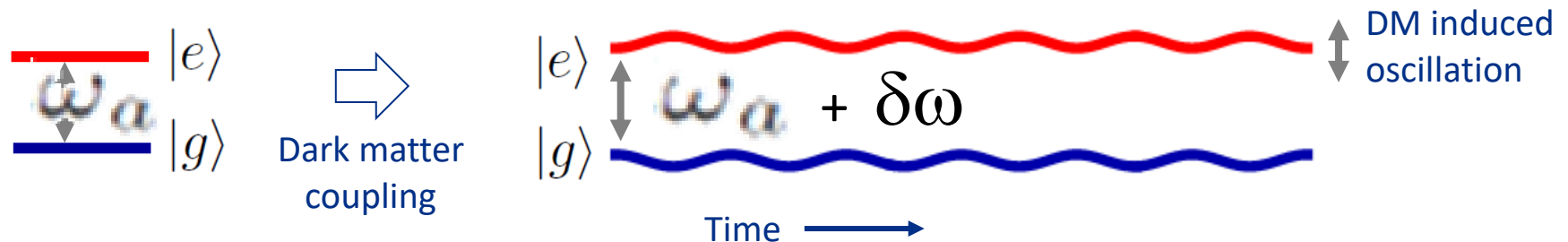
Ultralight dilaton DM acts as a background field (e.g., mass $\sim 10^{-15}$ eV)

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

↓ DM scalar field

$$\phi(t, \mathbf{x}) = \phi_0 \cos [m_\phi (t - \mathbf{v} \cdot \mathbf{x}) + \beta] + \mathcal{O}(|\mathbf{v}|^2) \quad \phi_0 \propto \sqrt{\rho_{\text{DM}}} \quad \text{DM mass density}$$

DM coupling causes time-varying atomic energy levels:



Light Dark Matter Landscape

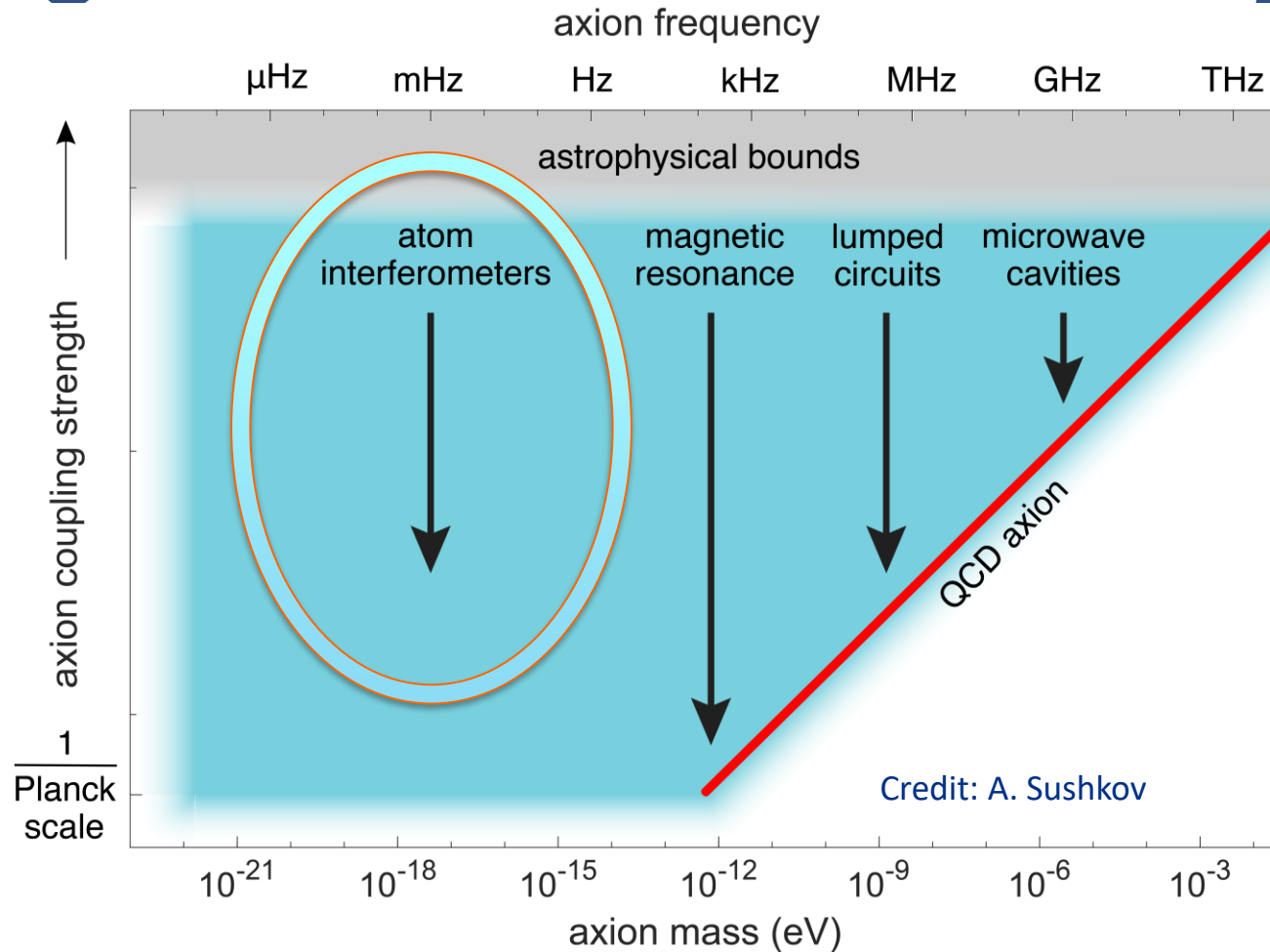
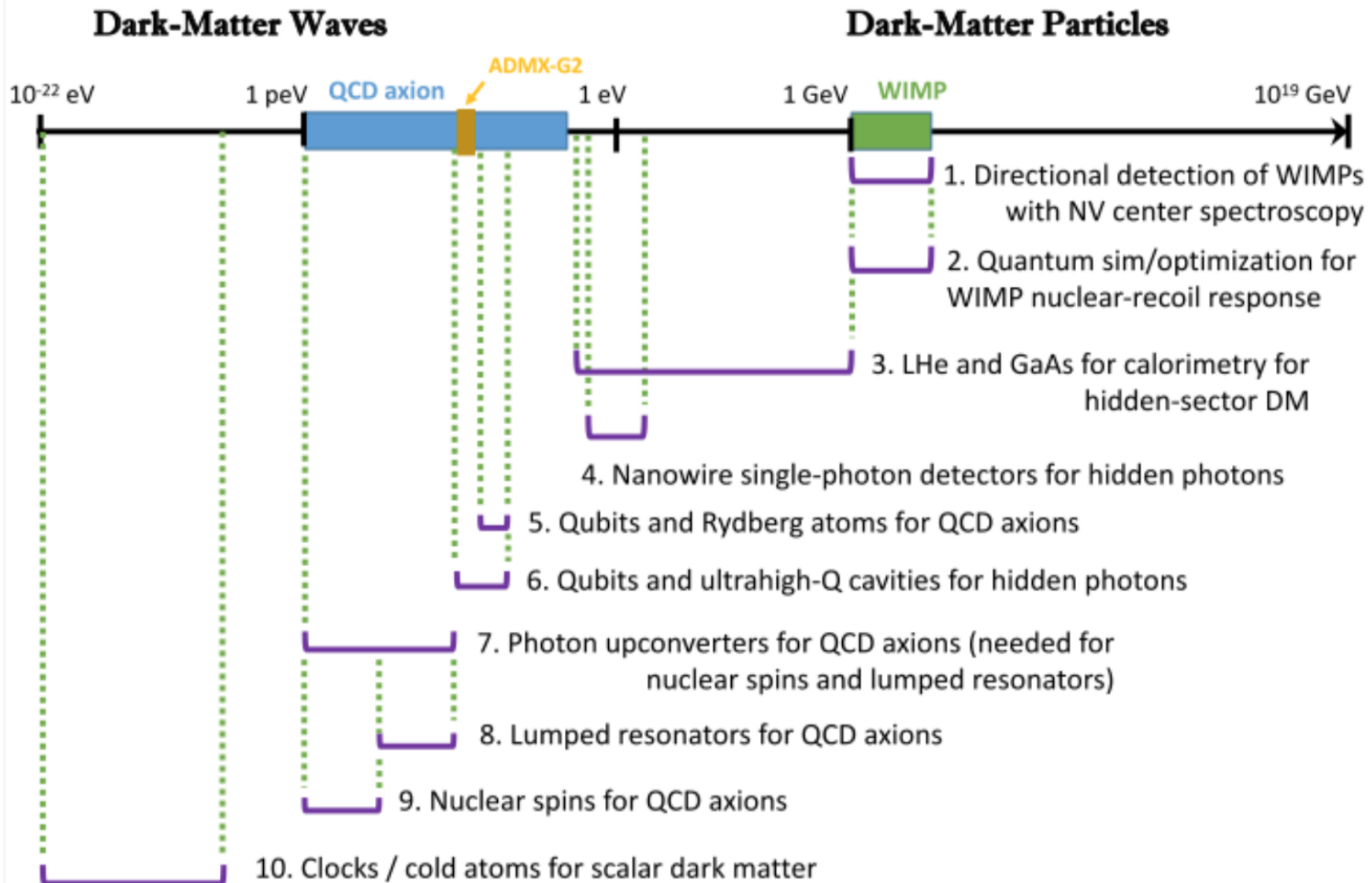


Figure from DOE Dark Matter Research Needs Report, 2018

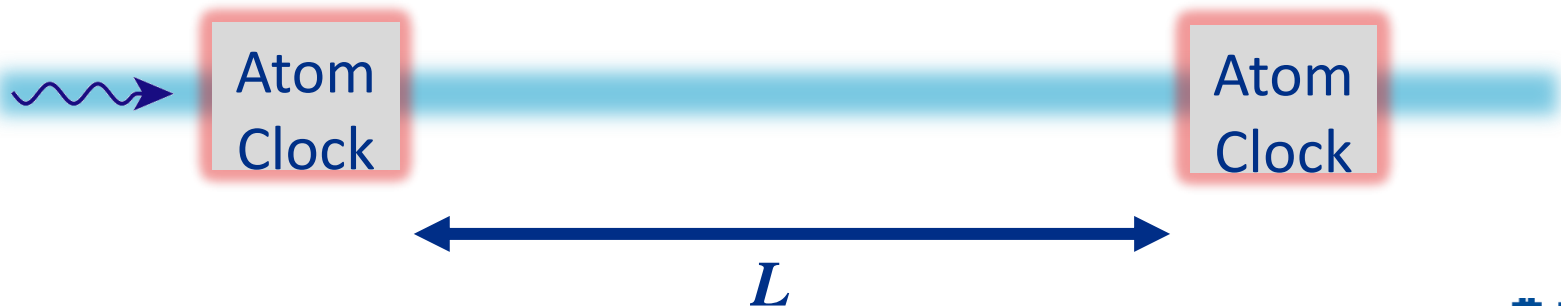
Broader View of Landscape

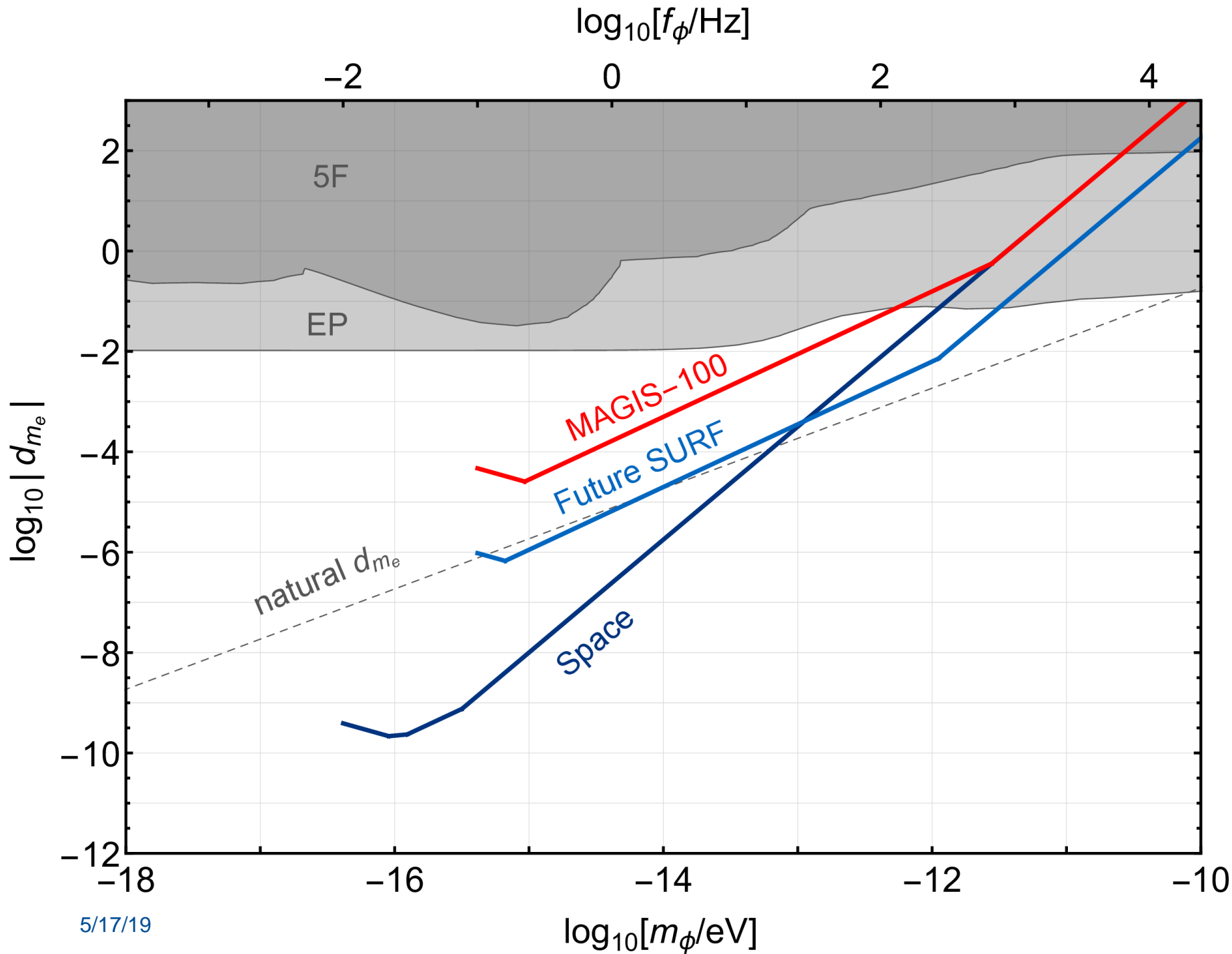


Measurement Concept

Essential Features

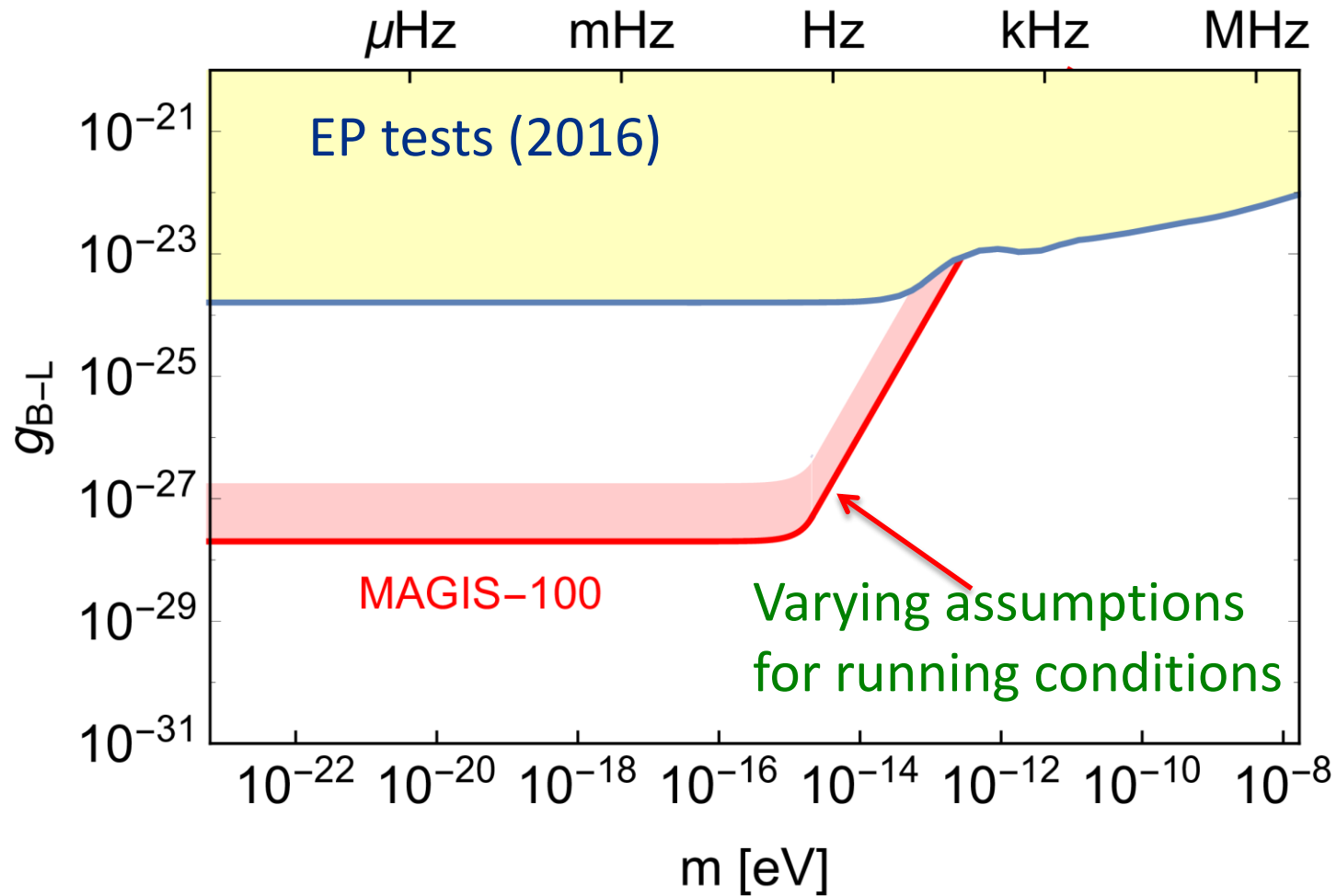
1. Light propagates across the baseline at a constant speed
2. Clocks read transit time signal over baseline
3. DM changes number of clock ticks associated with transit by modifying clock ticking rate
4. Many pulses sent across baseline (large momentum transfer) to coherently enhance signal





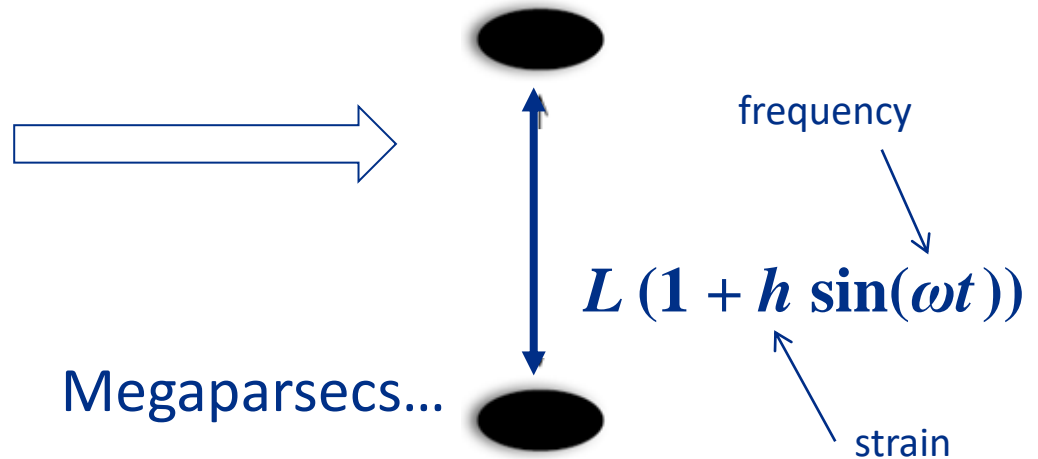
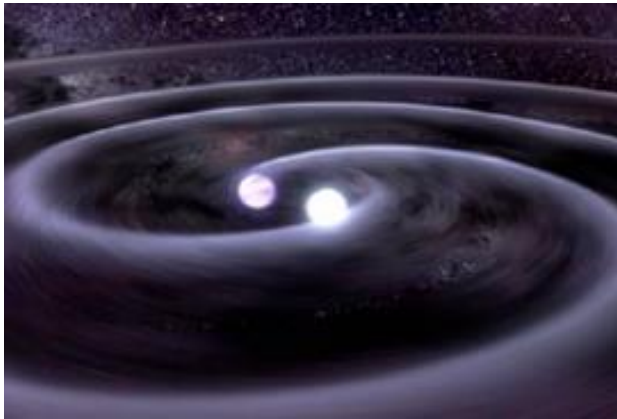
B-L Dark Forces

- In addition to scalar dark matter, other types of interactions can be looked for.
- One example is a new vector boson coupling to B-L
- If dark matter, will have time dependence.
- If new force sourced by earth, force is static.
- MAGIS-100 will search for this with atom source with dual isotope capability.
- Competitive or better than, and extremely complementary to, other efforts, e.g. upgraded torsion pendula.



Expected MAGIS-100 B-L dark matter sensitivity

Gravitational Wave Detection



New carrier for astronomy: Generated by moving mass instead of electric charge

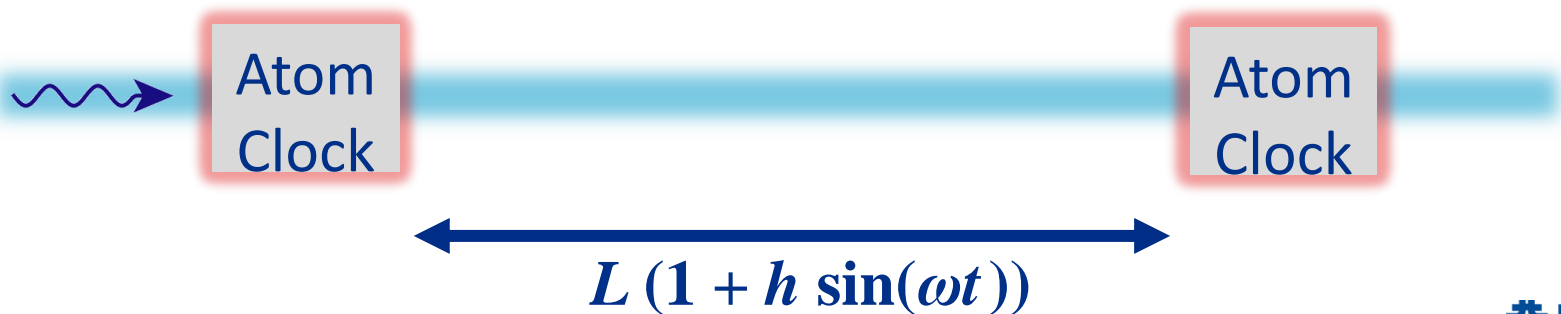
Tests of gravity: Extreme systems (e.g., black hole binaries) test general relativity

Cosmology: Can see to the earliest times in the universe

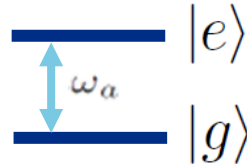
Measurement Concept

Essential Features

1. Light propagates across the baseline at a constant speed
2. Clock atoms read transit time signal over baseline
3. GW changes number of clock ticks associated with transit by modifying light travel time across baseline
4. Many pulses sent across baseline (large momentum transfer) to coherently enhance signal



Two Atomic Clocks



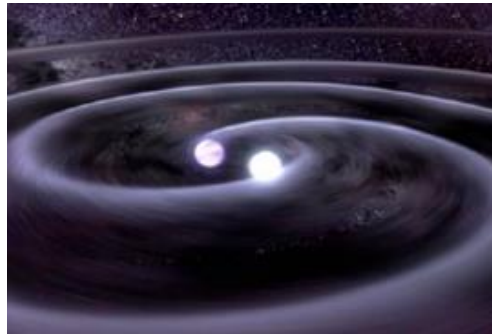
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle$$

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

GW changes baseline, and therefore light travel time, between pulses (signal maximized when GW period on scale of time between pulses)

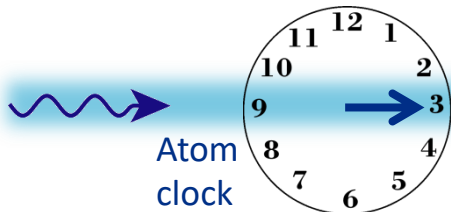
$$\Delta T \sim hL/c$$

Time

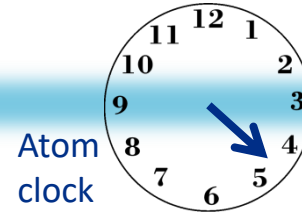


$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T}$$

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



Atom clock



Atom clock

Mid-band Science

Mid-band discovery potential

Historically every new band/modality has led to discovery
Observe LIGO sources when they are younger

Optimal for sky localization

Predict *when* and *where* events will occur (before they reach LIGO band)
Observe run-up to coalescence using electromagnetic telescopes

Astrophysics and Cosmology

White dwarf binaries (Type IA supernovae), black hole binaries, and neutron star binaries

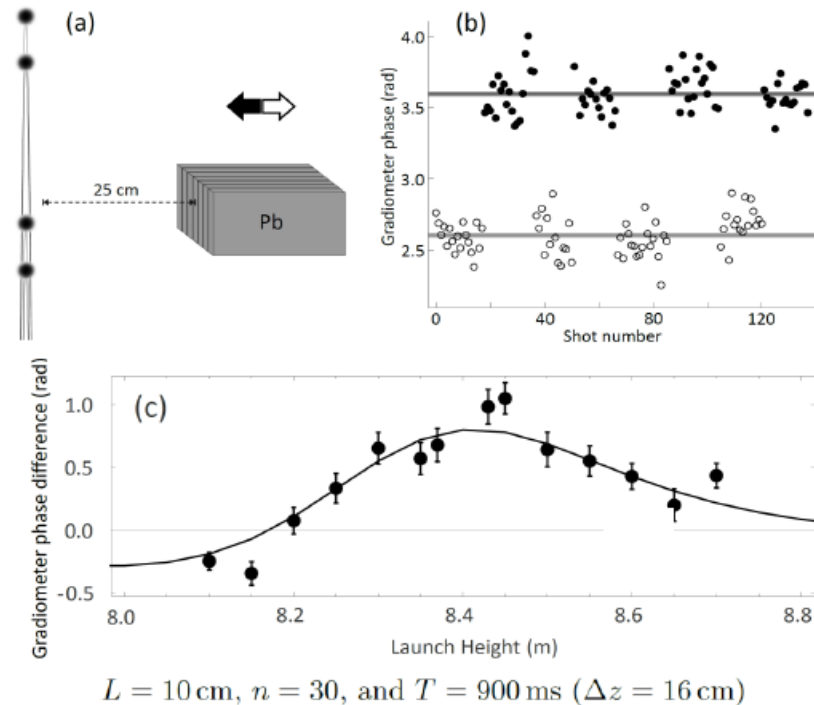
Early universe stochastic sources? (cosmic GW background)

- e.g., from inflation

- operating in mid-band instead of lower frequencies may be advantageous for avoiding background noise from white dwarf sources

Gravity Demonstration

Gradiometer response to 84 kg lead test mass



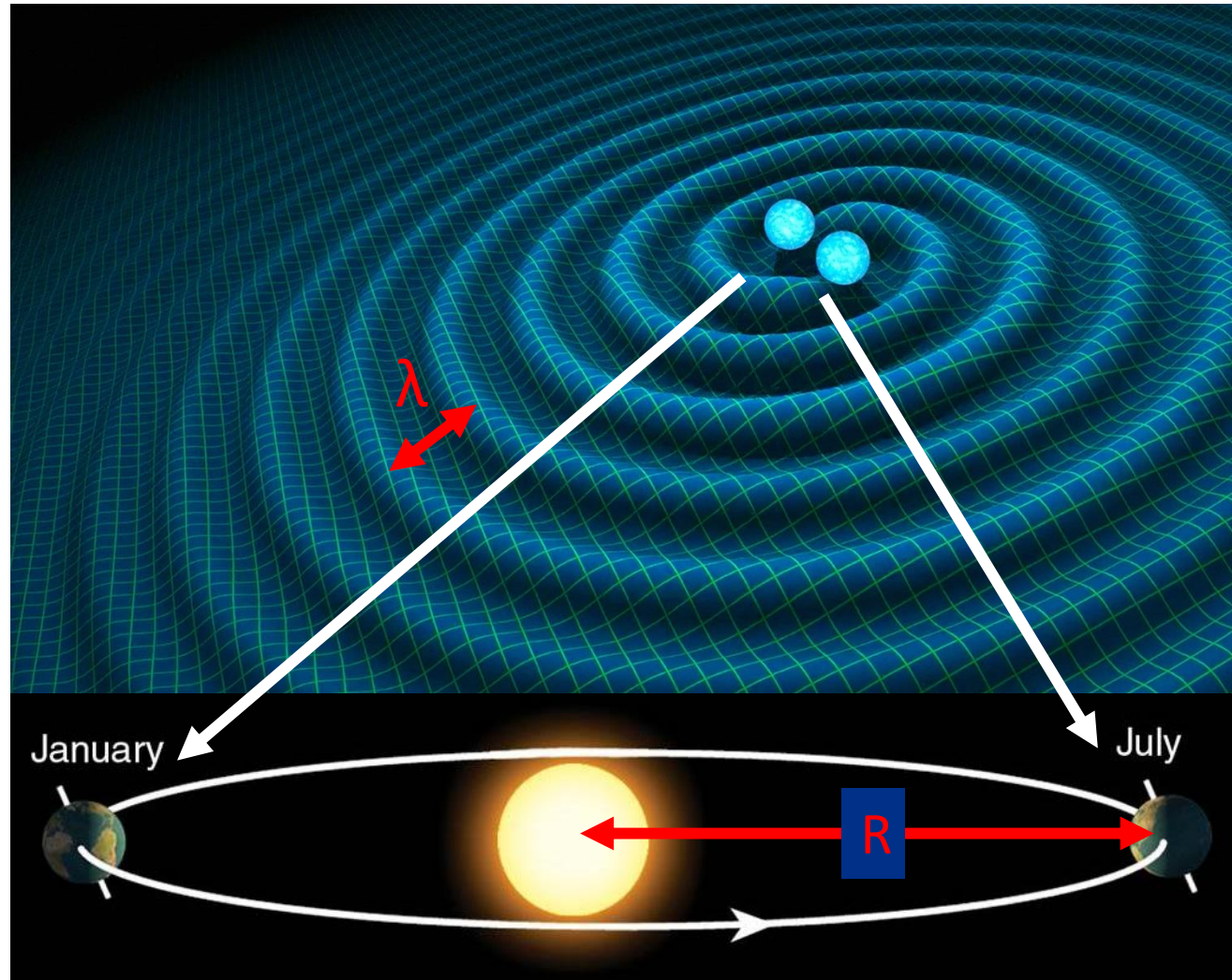
Sky position determination

Sky localization
precision:

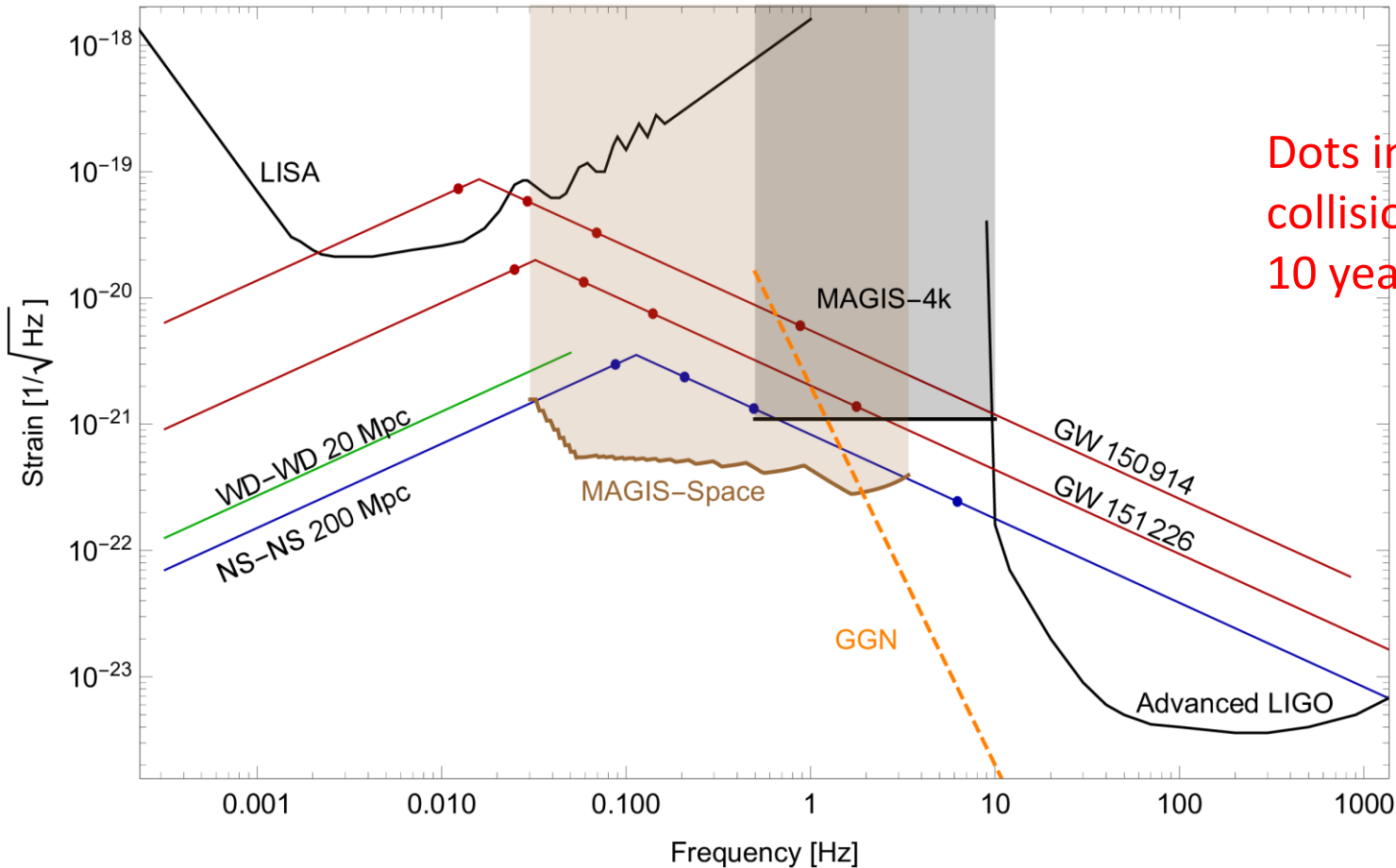
$$\sqrt{\Omega_s} \sim \left(\text{SNR} \cdot \frac{R}{\lambda} \right)^{-1}$$

Mid-band advantages

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



Long Range Program Sensitivity

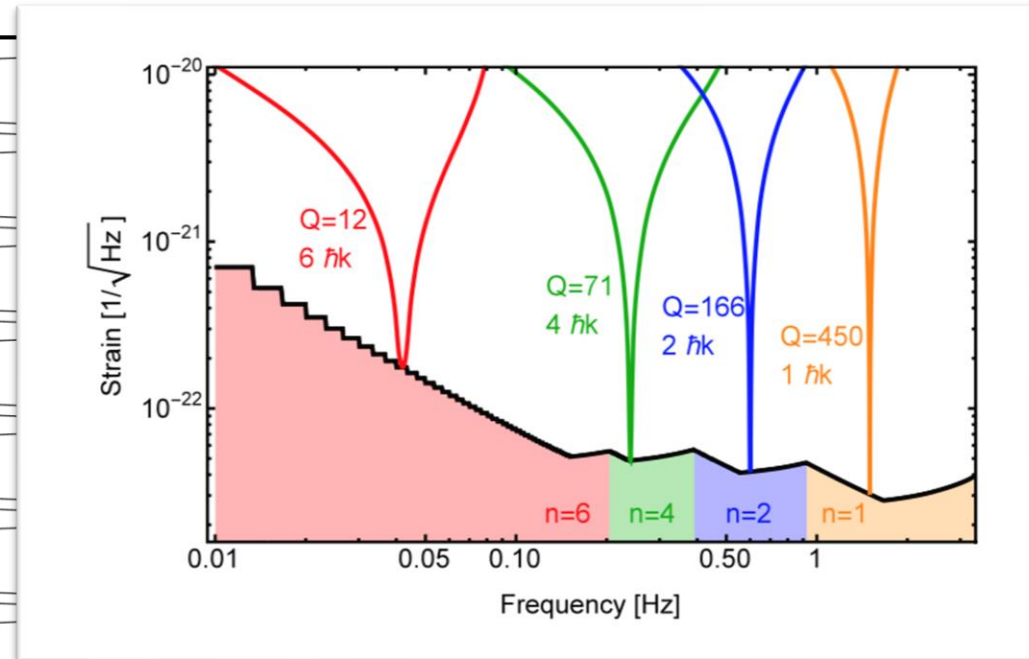
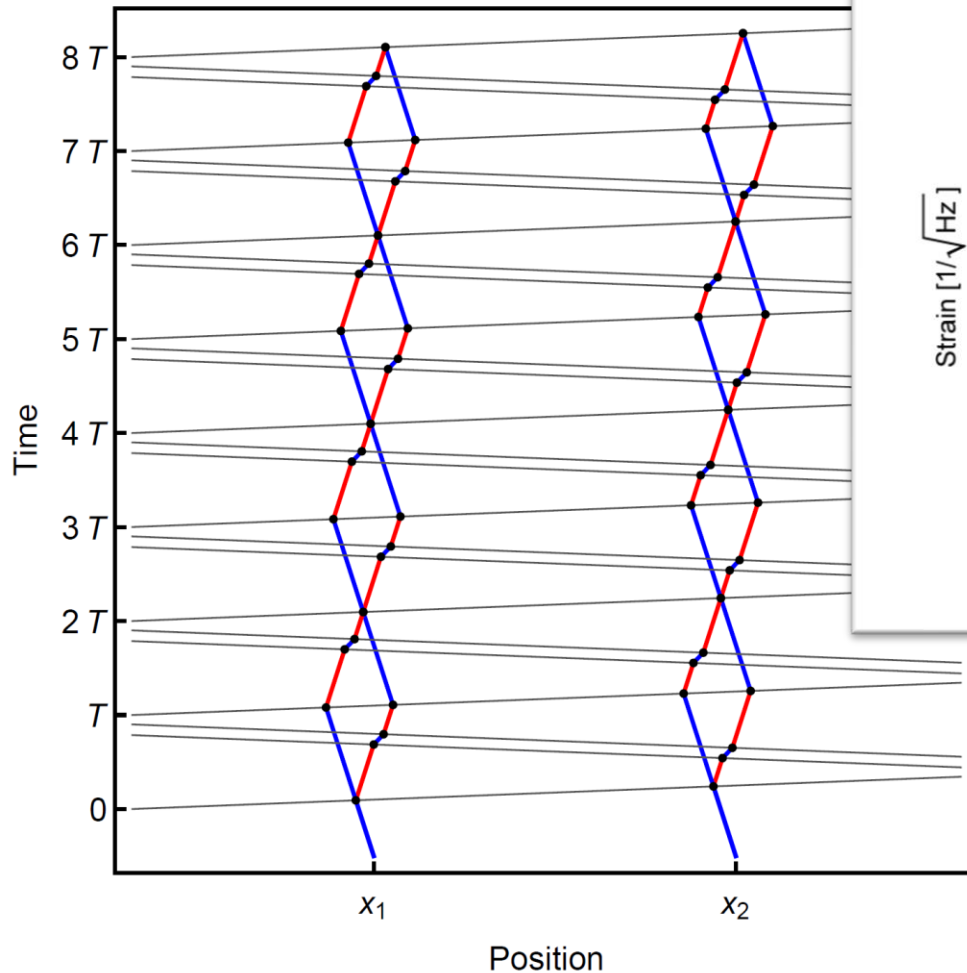


Dots indicate time-to-collision ranging from 10 years to 0.01 year.

Full Scale future MAGIS detector fills frequency sensitivity gap in ~ 1 Hz range. MAGIS-100 will give limits in this range several orders of magnitude beyond existing (but no known sources of such strength.)

Resonant Pulse Sequences

Resonant sequence ($Q = 4$)



Multiple Interferometer sequences (Q) act as band pass filter.

Graham, *et al.*, PRD (2016)

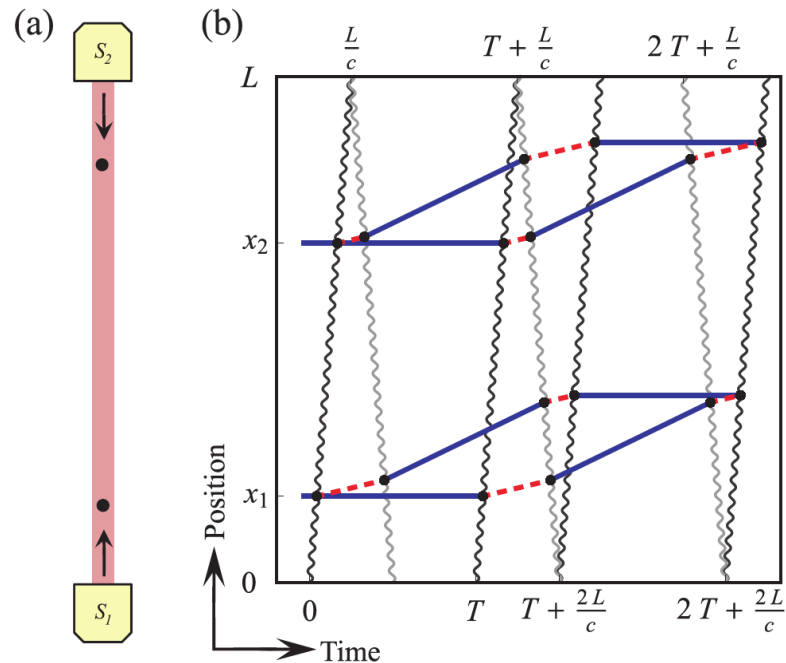
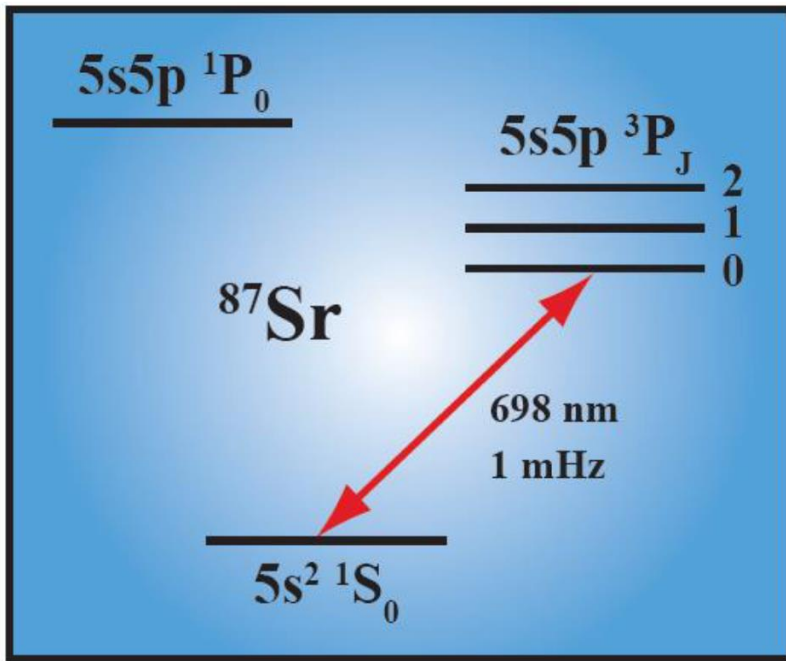
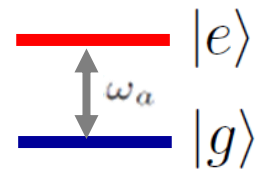


Advantages of Sr for MAGIS-100

- Narrow excited state has long lifetime (~ 150 s).
- Resonant single laser beam excitations can be used while avoiding spontaneous emission, which would cause particle loss.
- The long-lived metastable state could in principle allow interrogation times up to 100 seconds,
- Achieving a long-lived state with one laser photon (and one laser) reduces laser phase noise – good for gradiometer measurements.
- Sr has greatly reduced sensitivity to external magnetic fields (factor of 1000).

Note: Significant laser power needed to rapidly populate 689 nm state.

Hybrid Clock/Accelerometer



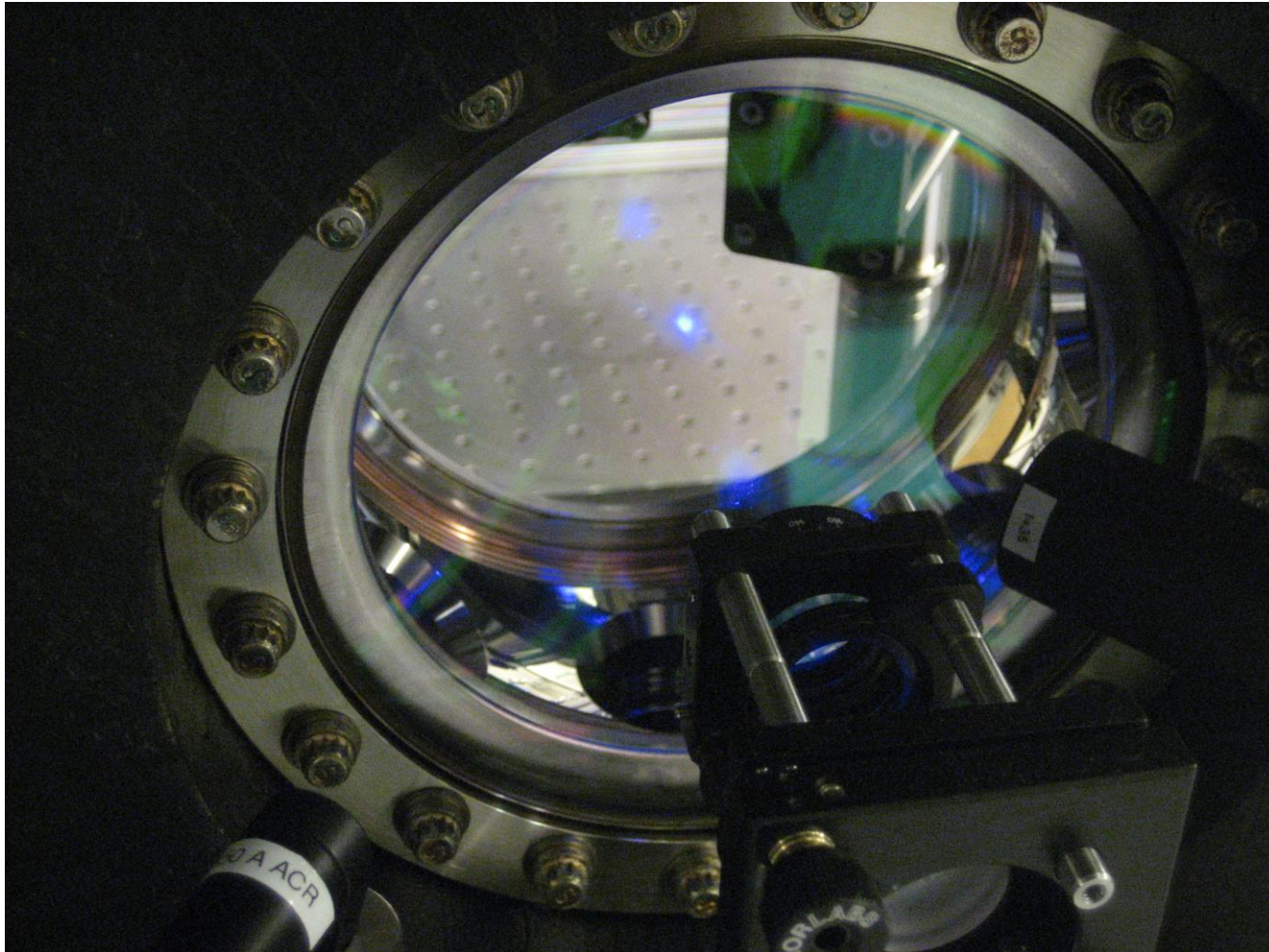
Sr has a narrow optical clock transition with a long-lived excited state that atoms can populate for >100 s without decaying.

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

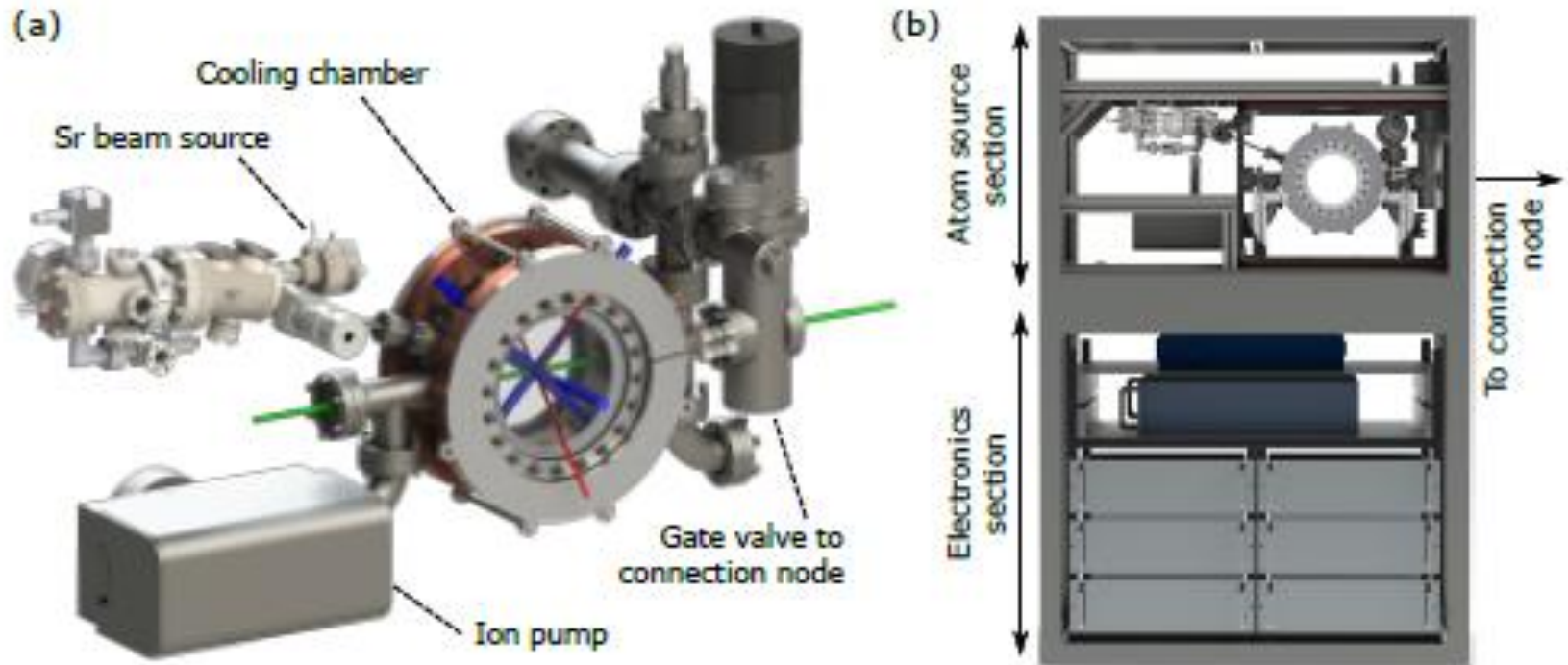
- Beamsplitter—Mirror—Beamsplitter sequence makes interferometer insensitive to initial atom position and velocity

- Only sensitive to relative *acceleration* of baseline between two clocks/interferometers

Cloud of Cooled Sr Atoms (Stanford)

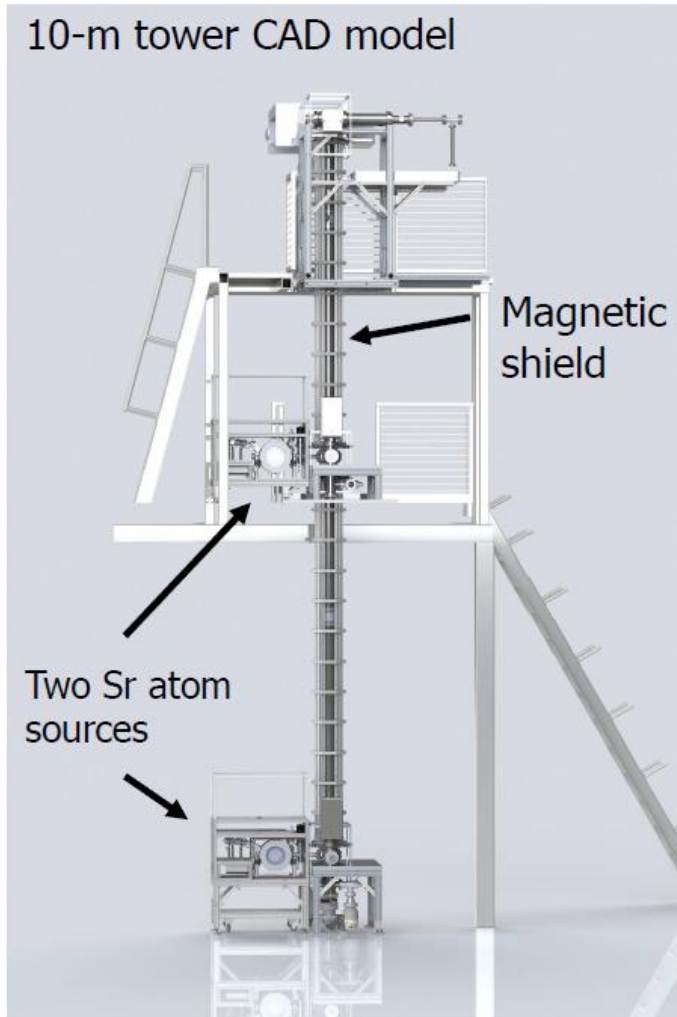


Modular Atom Sources



10-meter Sr prototype design

10-m tower CAD model



Two assembled Sr atom sources



*2D transverse octagonal shield simulation,
with coils for transverse bias field*

Prototype assembly
to occurring NOW

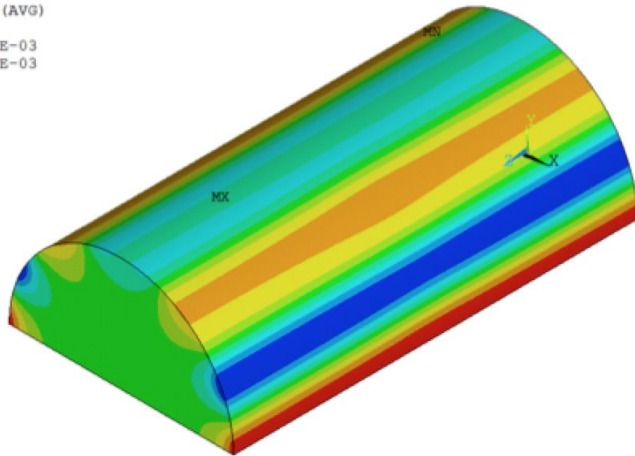
Collaboration on Magnetic Shield Design

Continuous Shield – no circumferential air gaps

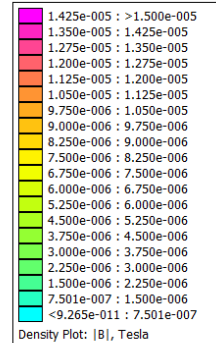
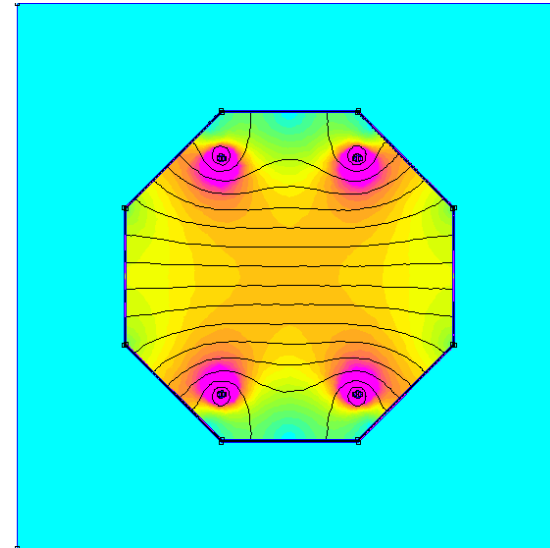
```
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BSUM (AVG)
RSYS=0
SMN =.893E-03
SMX =.977E-03
```

Volume weighted B_mod = 0.936e-3 G

ANSYS
R19.2
DEC 14 2018
06:26:48



Continuous shield, fine mesh

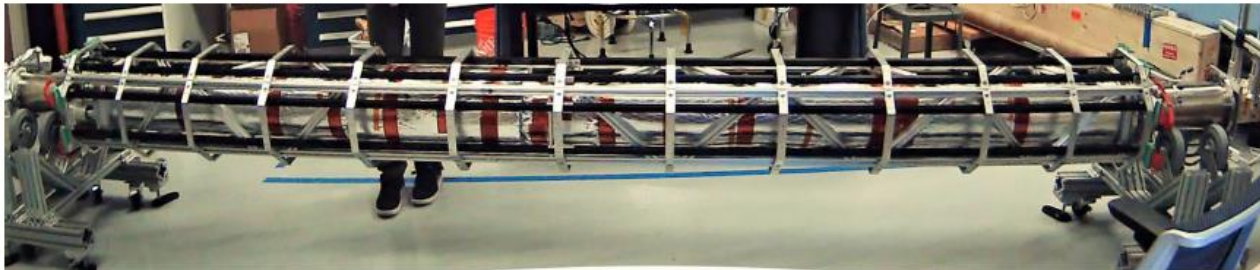


3D simulations have been done at Fermilab with ANSYS.

Stanford has done 2D simulation (cross-sectional view) of bias magnetic field inside an octagonal shield

Prototype Module with Magnetic Shield at Stanford

Assembled prototype MAGIS module with horizontal bias coils and magnetic shield

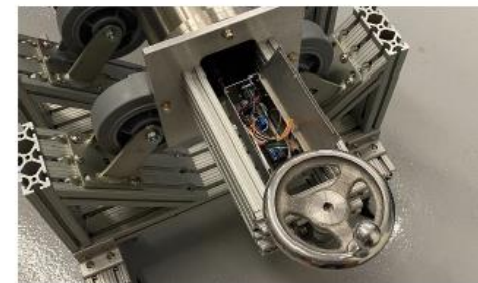
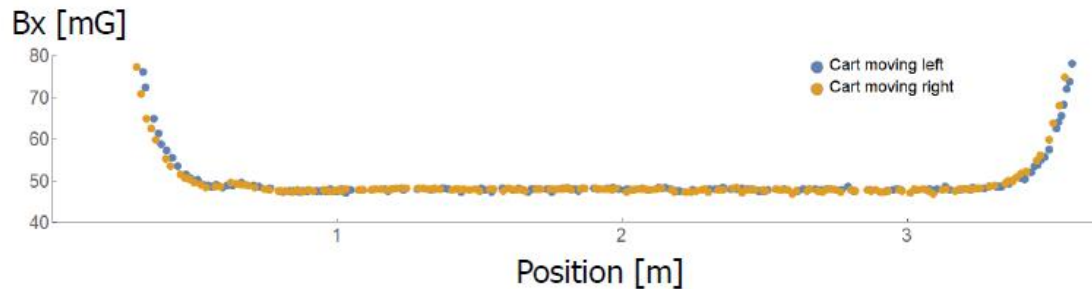


Before shield



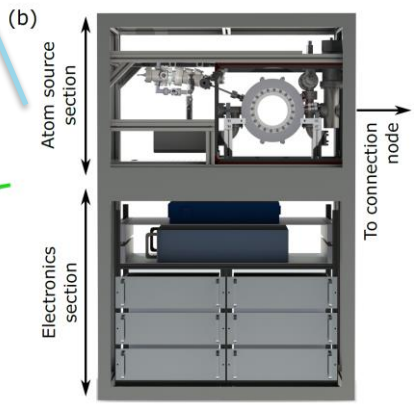
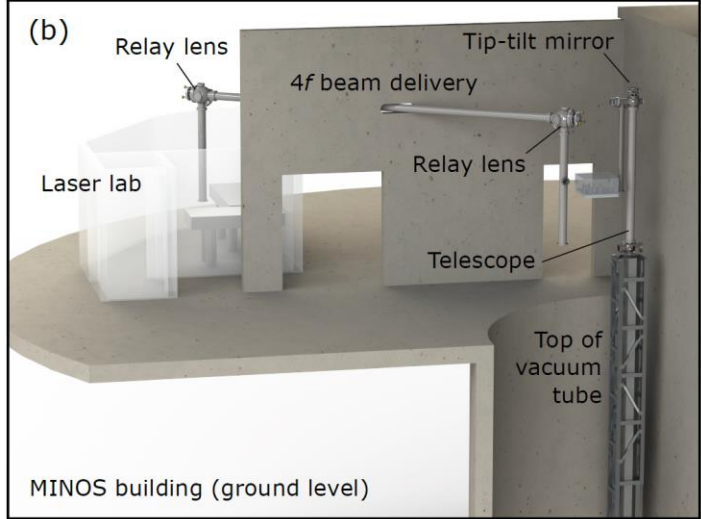
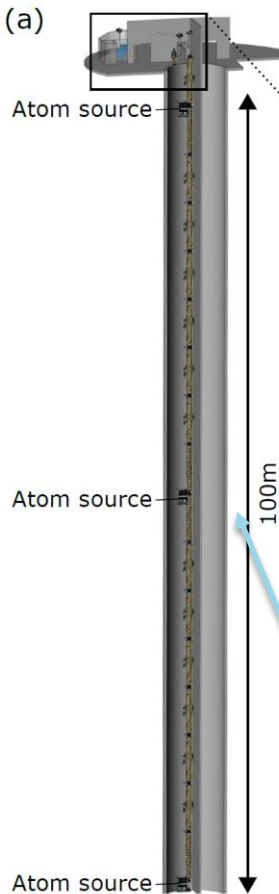
With shield

After degauss, magnetic shield meets specifications:

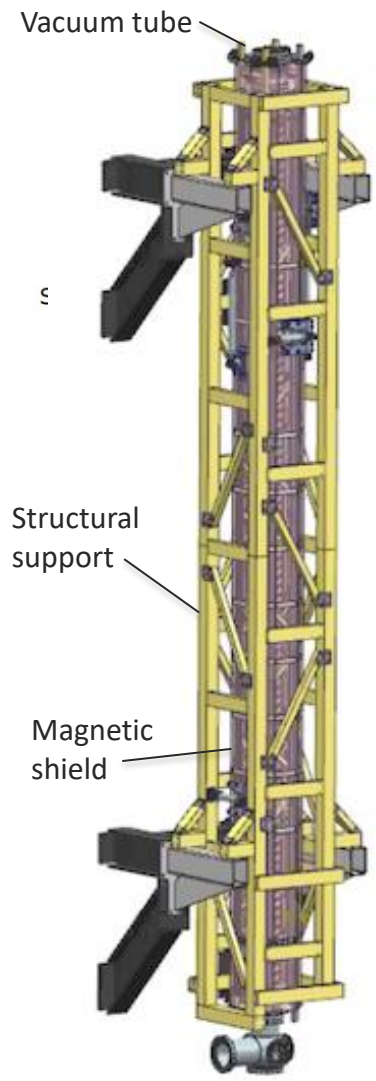


Magnetometer shuttle on suspension wires

Experiment Layout at Fermilab: Shaft, and Surface



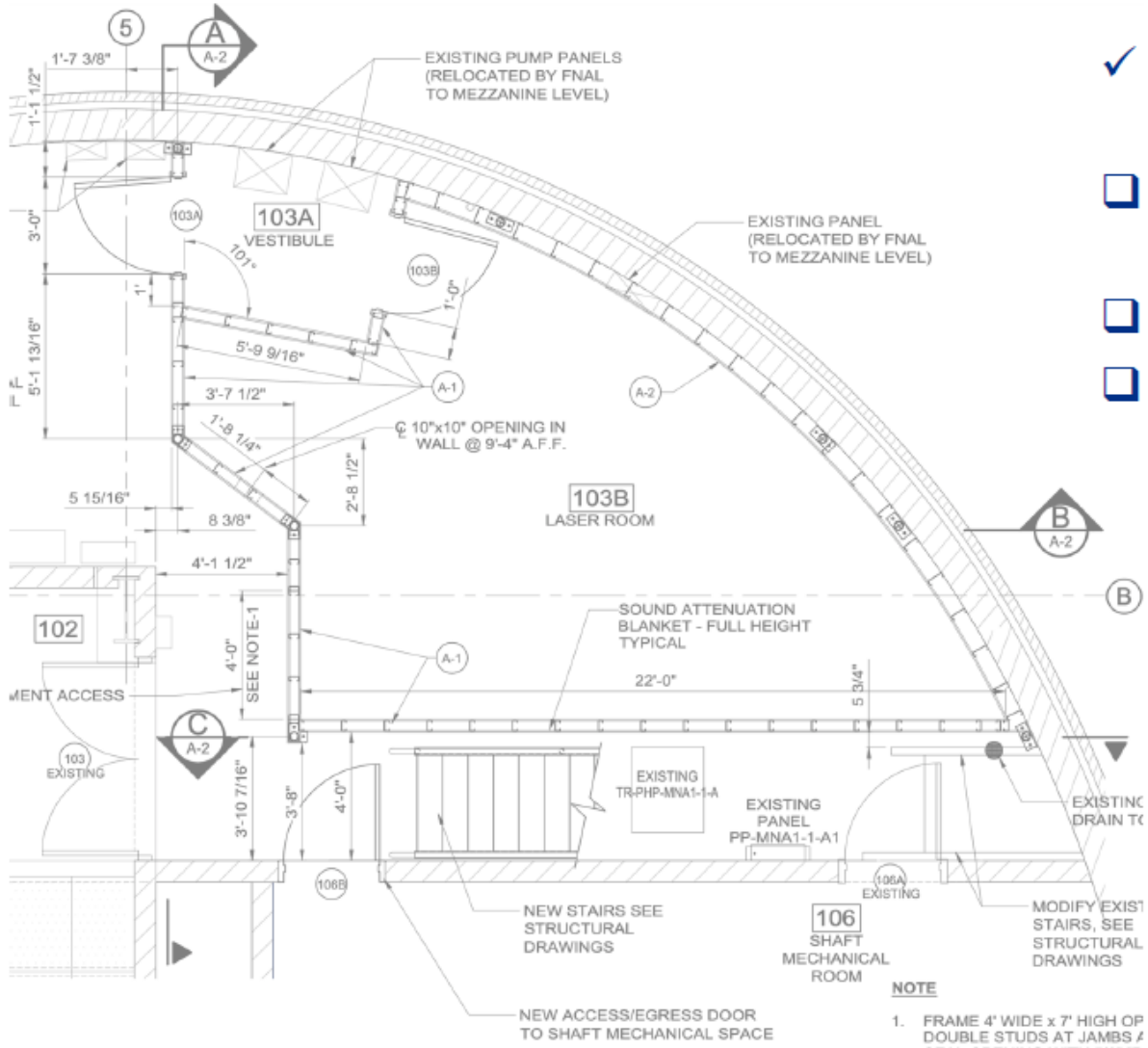
Atom Source x 3



Modular Section x 17

Laser Lab Construction

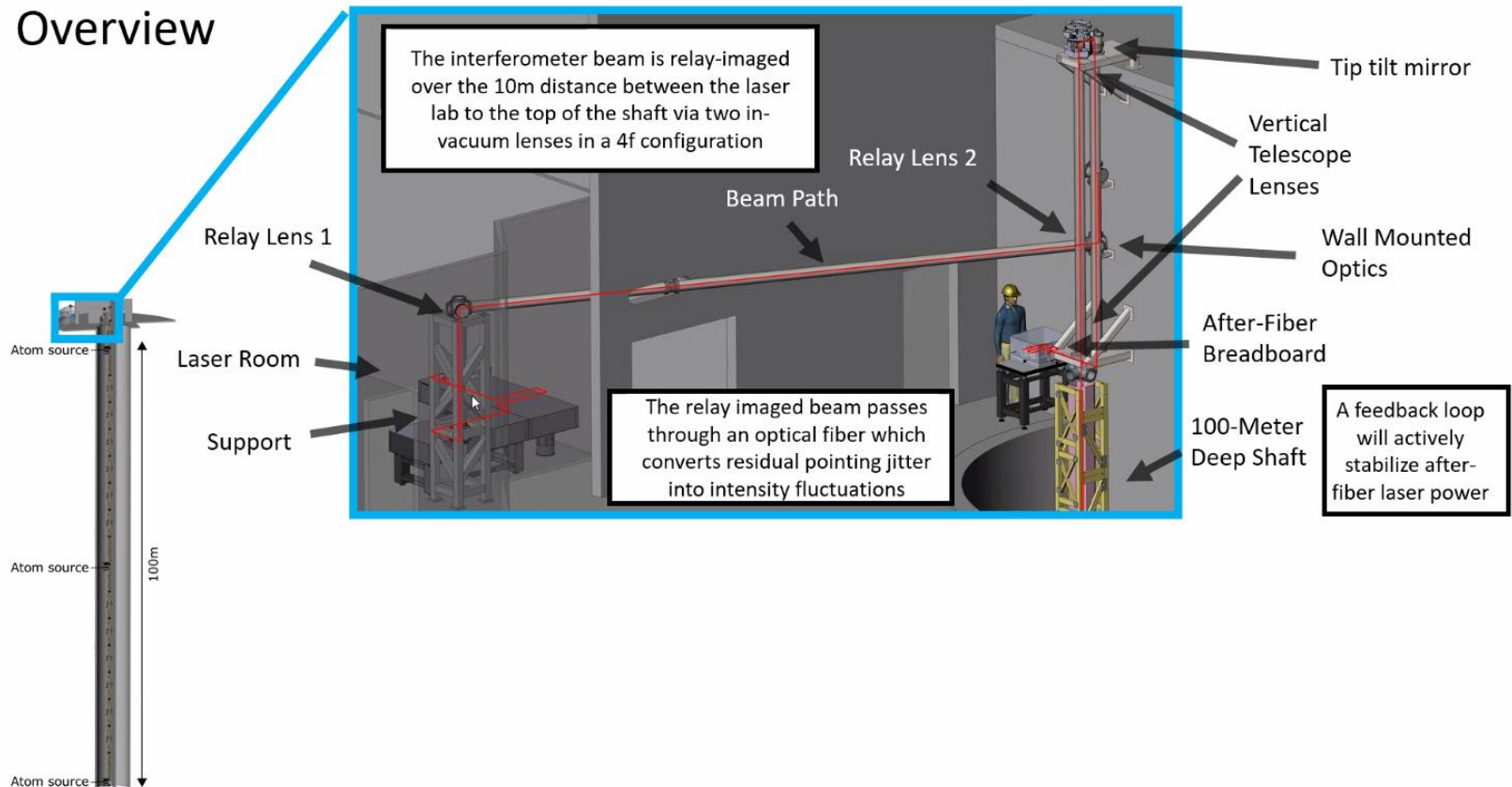
- ✓ Construction drawing package complete
- ✓ Final Review findings addressed
- Corrected drawing package generated
- Final Approval
- Procurement



PLAN AT T/F.F. EL. 748'-6"

Beam Transfer Design

Overview



Camera Readout

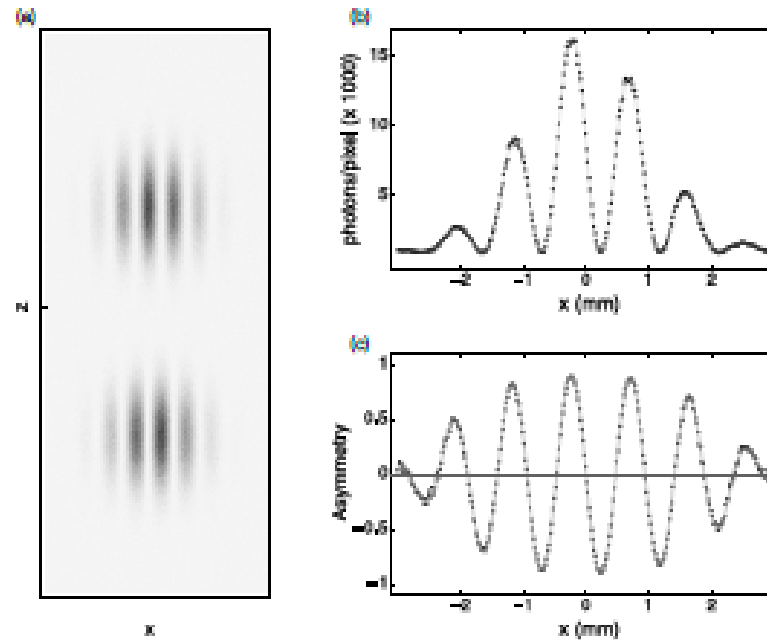
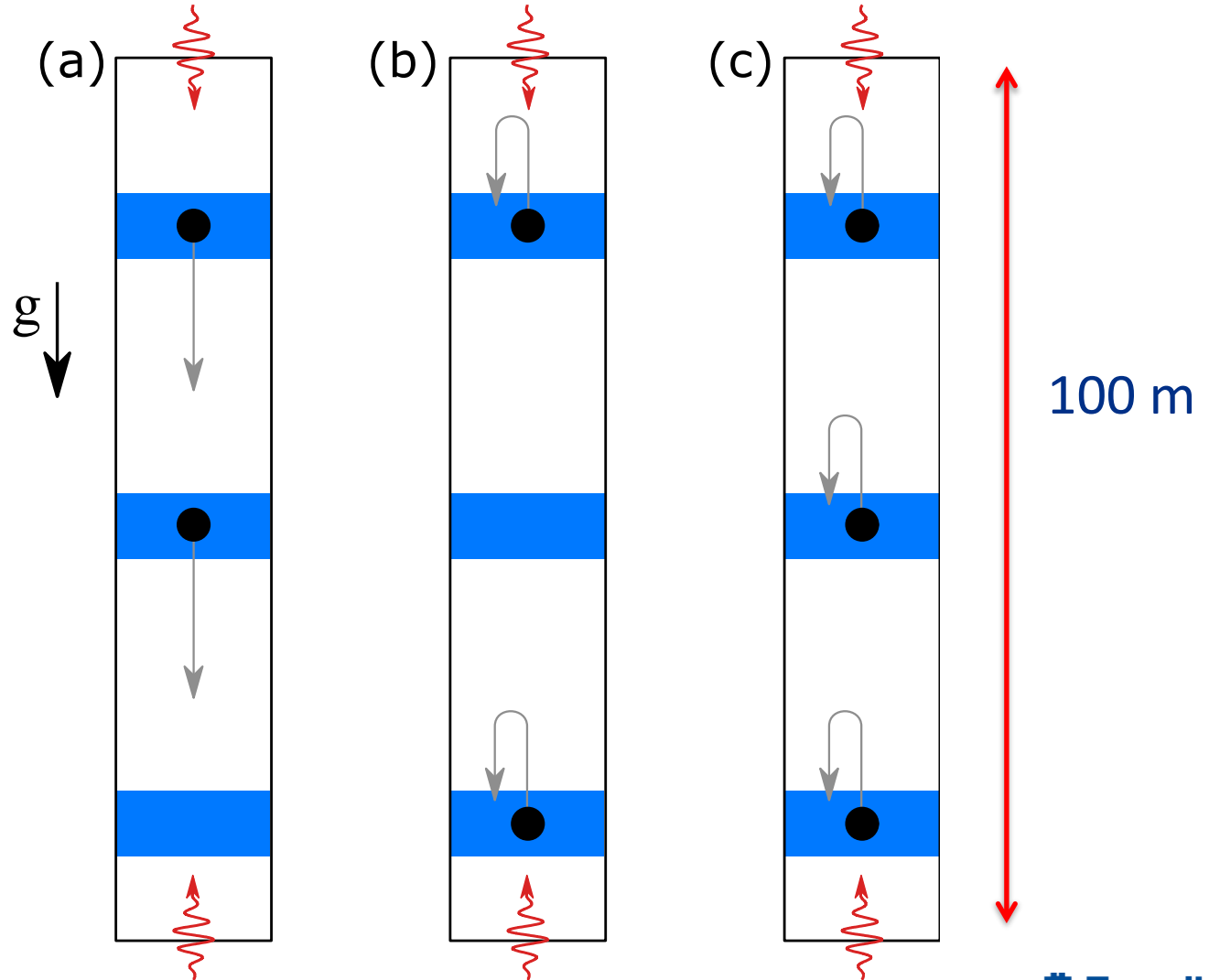


Figure 13. Simulated image of an atom interference pattern in the detection region at the end of a MAGIS-100 interferometer. (a) The simulated image shows the two detected sub-populations corresponding to the two output ports of the interferometer. The fringes are the result of the phase shear readout 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.

MAGIS-100 Modes



Location – MINOS building



Ground level of MINOS building.

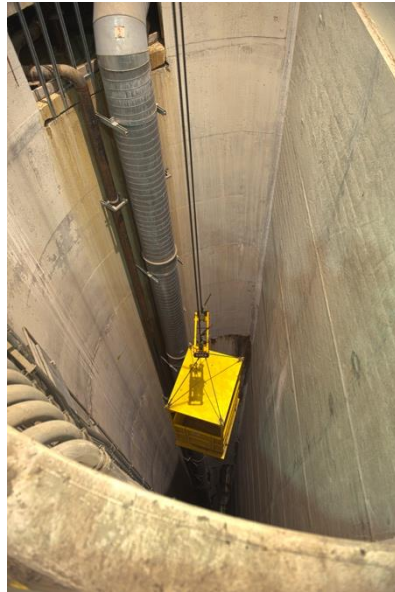
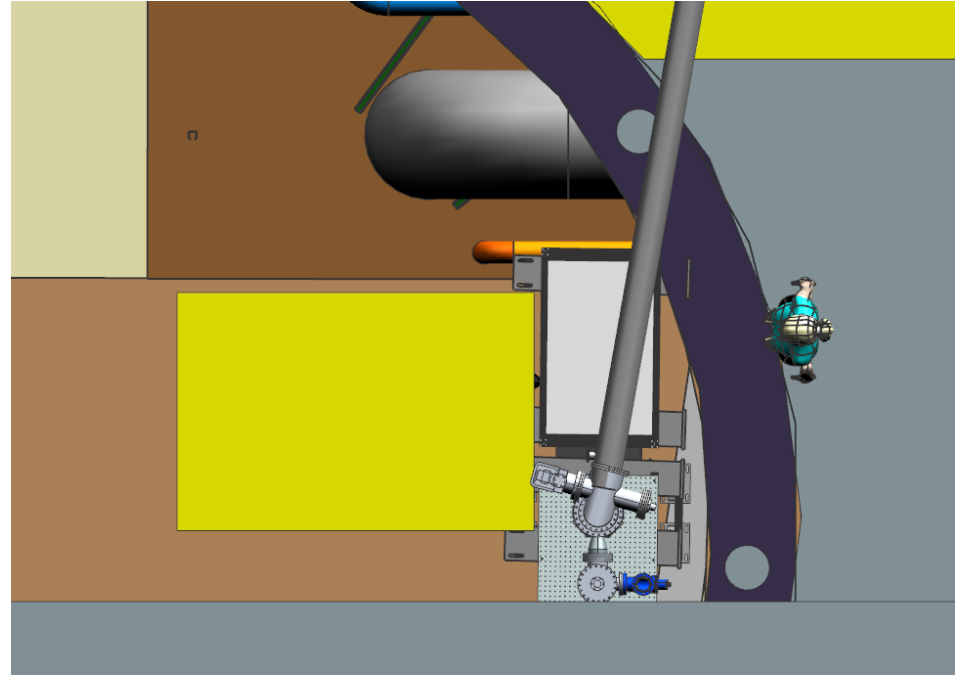
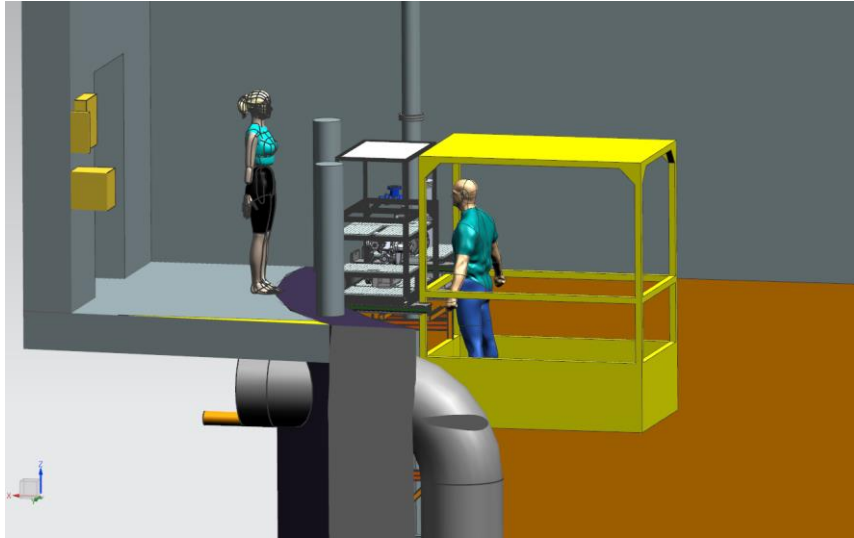


Location – Shaft in MINOS building

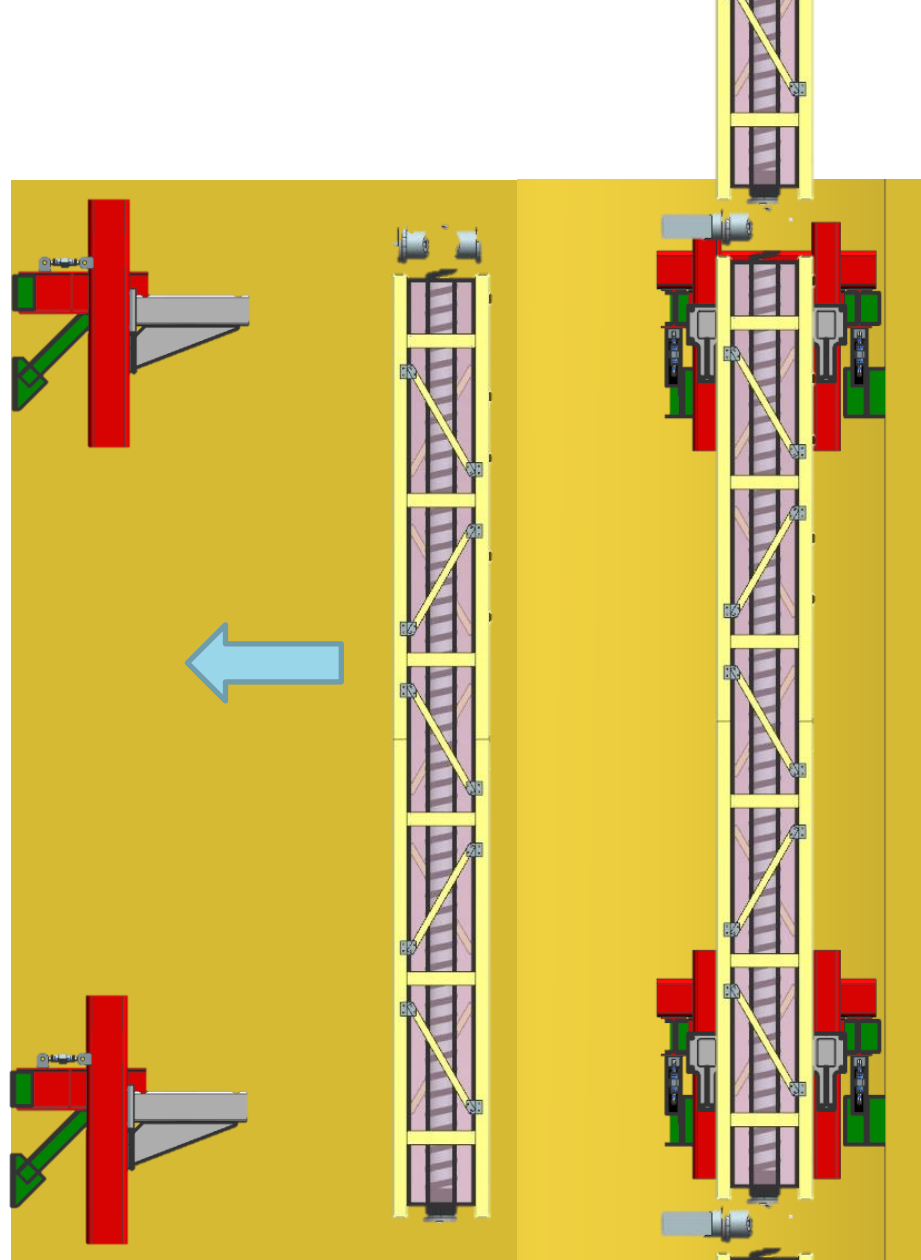
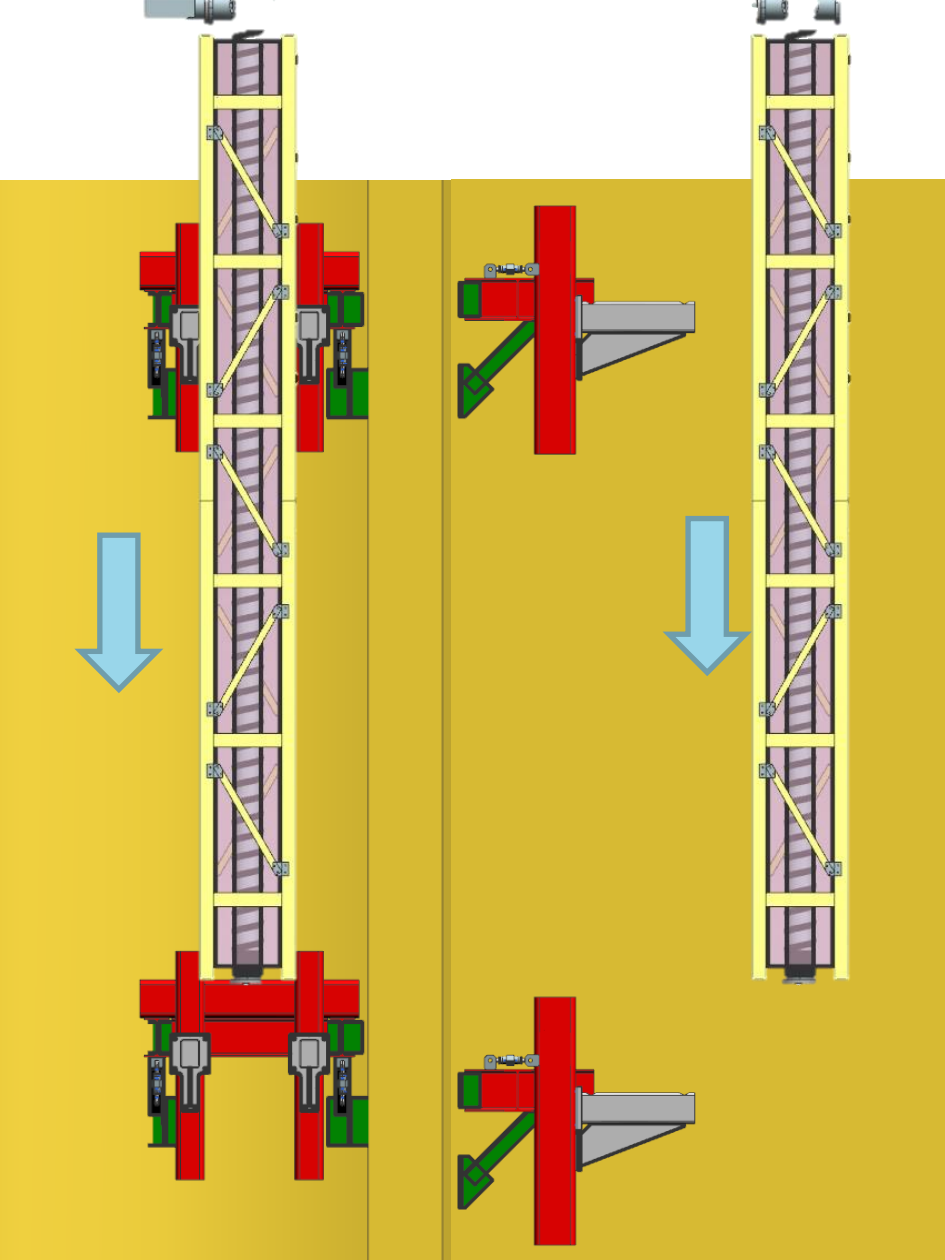


Top and bottom of ~100m shaft.

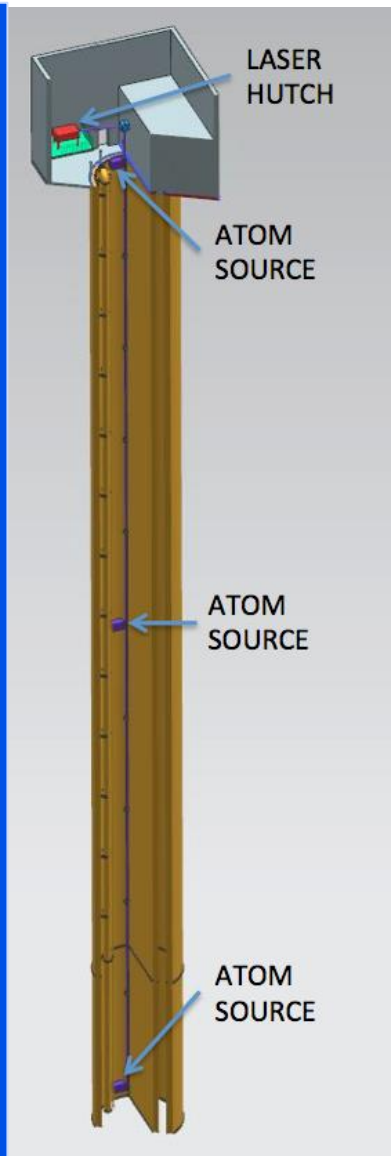
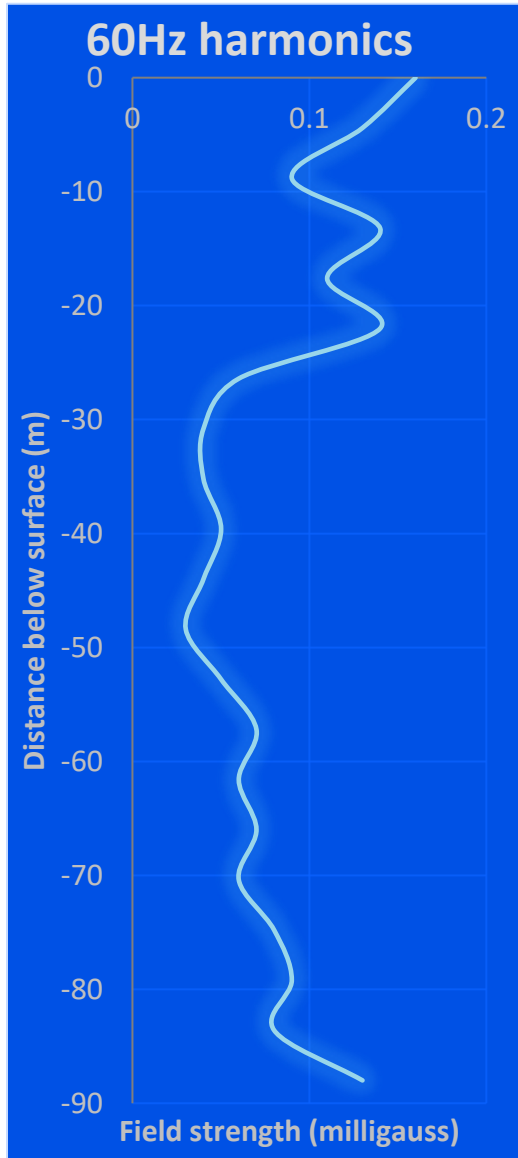
Technical: Installation Plan



Accessibility from personnel basket.



Magnetic Monitoring



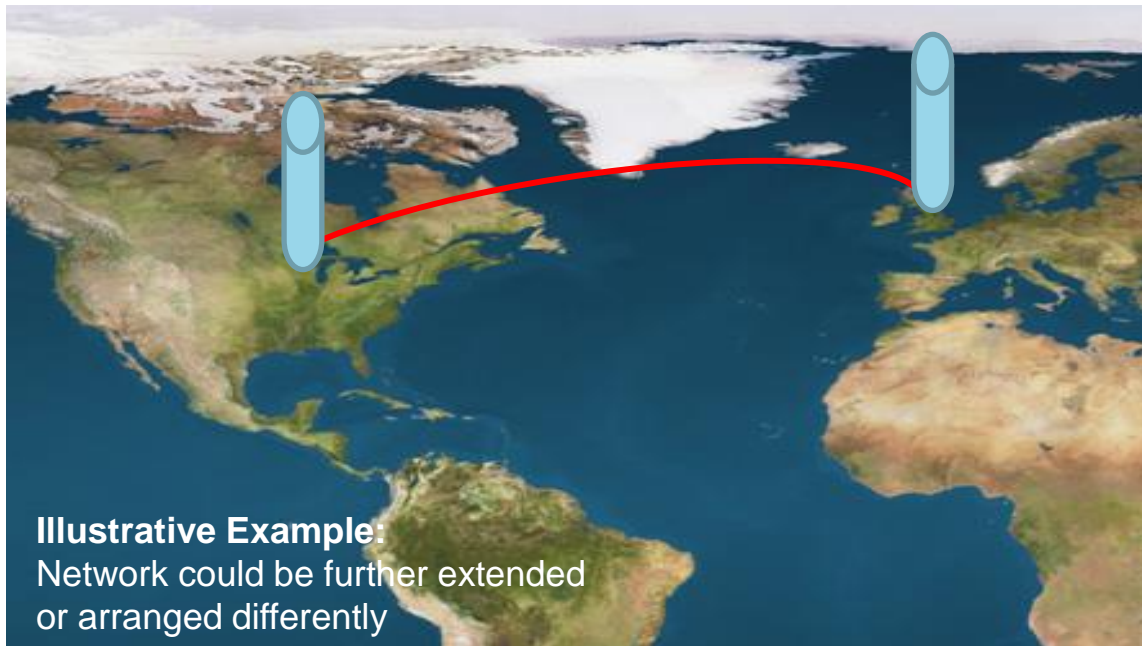
- Strongest time-varying magnetic fields in shaft are 60Hz harmonics from power feed to underground areas
- Time-varying fields could be a source of experimental background for MAGIS
- Continuous logging of fields with Bartington Mag690 fluxgate magnetometers (also used by Muon g-2)



Development of MAGIS Program in Short and Long Term

- Short term R&D concurrent with first deployment of detector
- Includes
 - Develop advanced LMT technology
 - Increase steady-state source flux
 - Spin-squeezed sources to further increase intensity (statistics!)
 - Resonant interferometry
- Need to aim development for longer 1.5 -4 km deployment
 - Modular construction
 - Large scale integration and operation
 - Identify any design problems early
 - Increased laser power
 - Additional mitigation of systematics:
 - Wavefront transverse phase variation
 - Laser Pointing
 - Coriolis compensation.
- MAGIS-100 provides essential input in all these areas.

UK AION Ultimate Goal: Establish International Network



Programme would reach its ultimate sensitivity by operating two detectors in tandem

- A UK Effort 'AION' to network with MAGIS is in preparation
- Develop a LIGO/VIRGO style collaboration
- Rejection of non-common mode backgrounds
 - unequivocal proof of any observation

UK International Collaboration

- AION greatly benefits from close collaboration on an international level with MAGIS-100
 - goal of an eventual km-scale atom interferometer on comparable timescales
- operating two detectors, one in the UK and one in the US in tandem enables new physics opportunities
- MAGIS experiment and Fermilab endorsed collaboration with AION
- US-UK collaboration serves as a testbed for full-scale terrestrial (kilometer-scale) and satellite-based (thousands of kilometres scale) detectors and builds the framework for global scientific endeavor

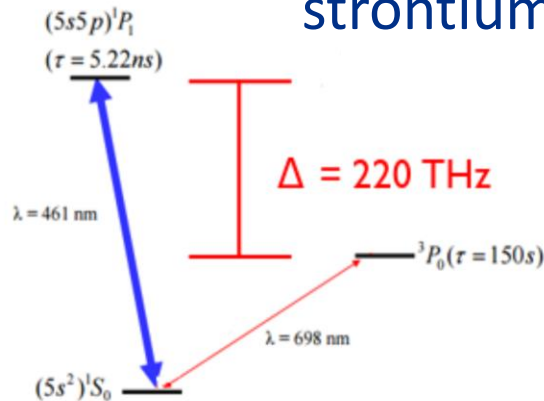
Conclusions

- MAGIS-100 extends the capabilities of Atom Interferometry - a lot.
- A vital component of the new science of low-mass dark matter searches.
- Will give us the means to build even bigger and explore the gravitational wave universe.
- Cries out for international networking – and it's happening!

BACKUP

Example: Extreme LMT with clock atoms

Clock atoms (e.g. strontium)



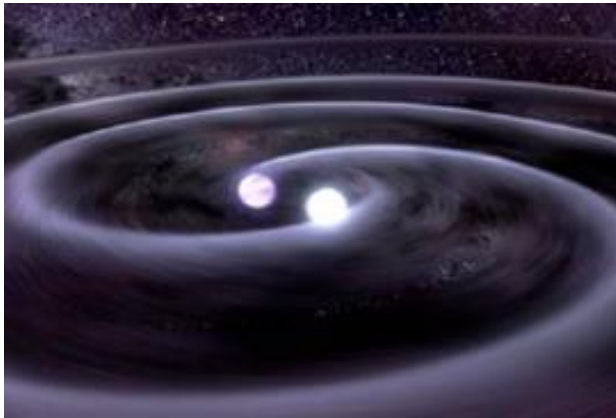
Single photon transition for atom optics

Spontaneous emission naturally highly suppressed (150 s lifetime clock state, other levels far detuned)

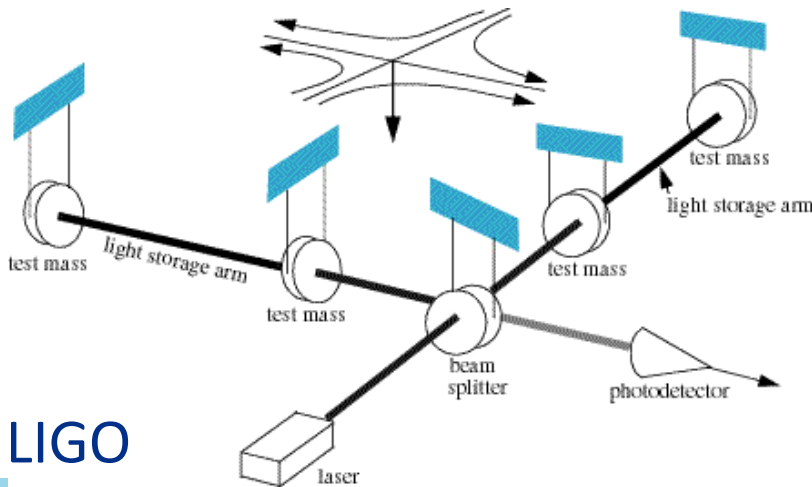
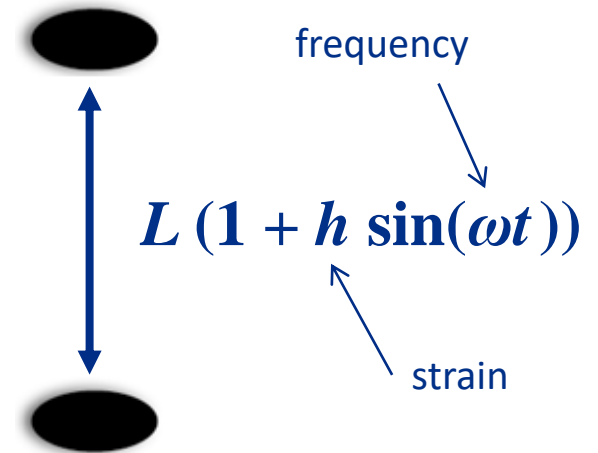
Current state of the art: ~100 pulses

Possibility to support $> 10^6$ pulses

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



Megaparsecs...

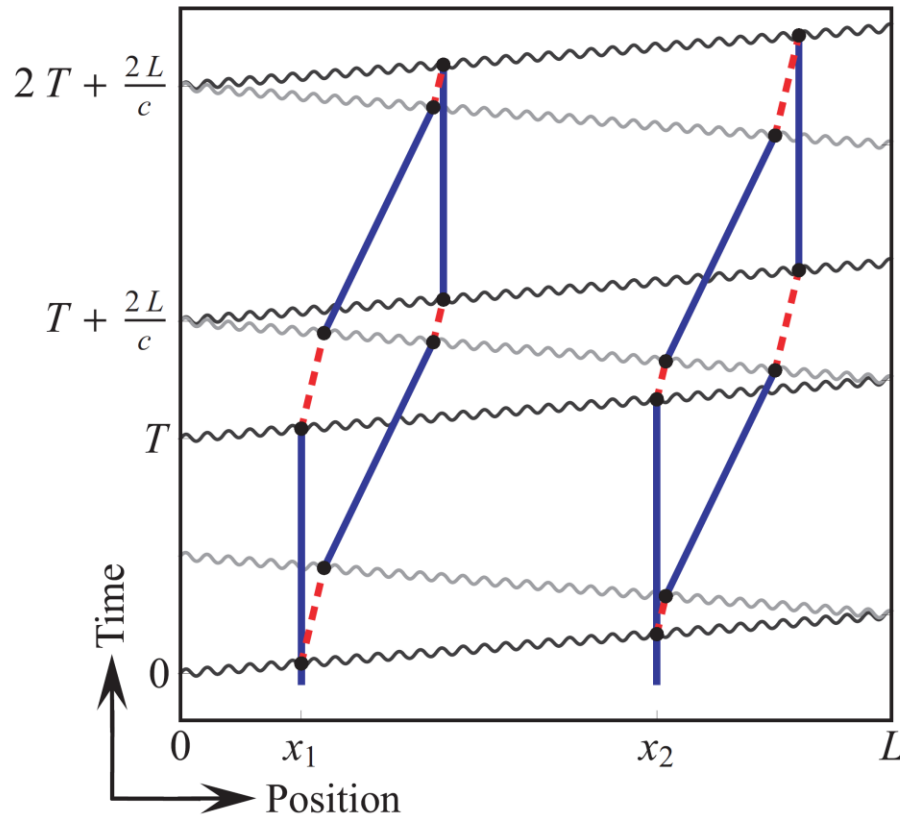
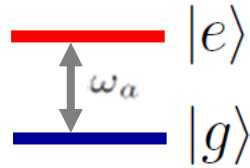


LIGO and other optical interferometers **use two baselines**

In principle, **only one is required**

LIGO

Gradiometer Using Different Internal Clock States



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

Excited state phase evolution:

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

Two ways for phase to vary:

$$\delta\omega_A \quad \text{Dark matter}$$

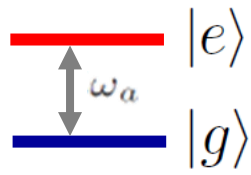
$$\delta L = hL \quad \text{Gravitational wave}$$

DM causes time-variation of transition frequency

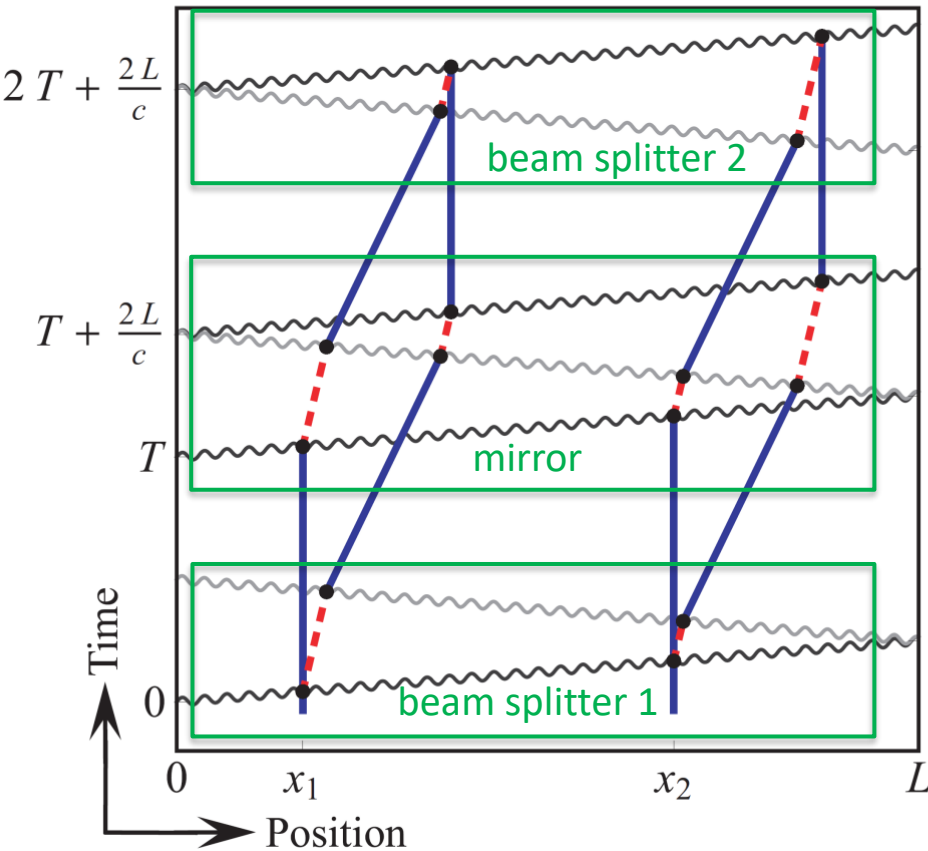
Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

Gradiometer DM Signal (same as GW configuration)



Phase shift of an interferometer determined by difference in times spent in excited clock state for arm 1 vs arm 2



Look at difference in phase shifts for two interferometers separated by baseline $\sim L$ (gradiometer phase shift)

Magnitude of contribution to gradiometer phase shift from each interferometer zone: $\Delta\phi \sim \omega_A (2L/c)$

For constant (or linearly drifting) L and transition frequency, gradiometer phase shift cancels between all three zones

To have a nonzero gradiometer phase shift, need transition frequency or L to vary on the time scale of time T between each zone

Two ways to get a signal:

$\delta\omega_A$ *Dark matter*

$\delta L = hL$ *Gravitational wave*

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

Large Spacetime Area Interferometers

- Inertial sensitivity proportional to enclosed spacetime area

$$\Delta\phi = -\frac{m}{\hbar}g\underline{\Delta z_{\max}T} \quad \Delta z_{\max} = \frac{n\hbar k}{m}T \quad \Delta\phi = -nkgT^2$$

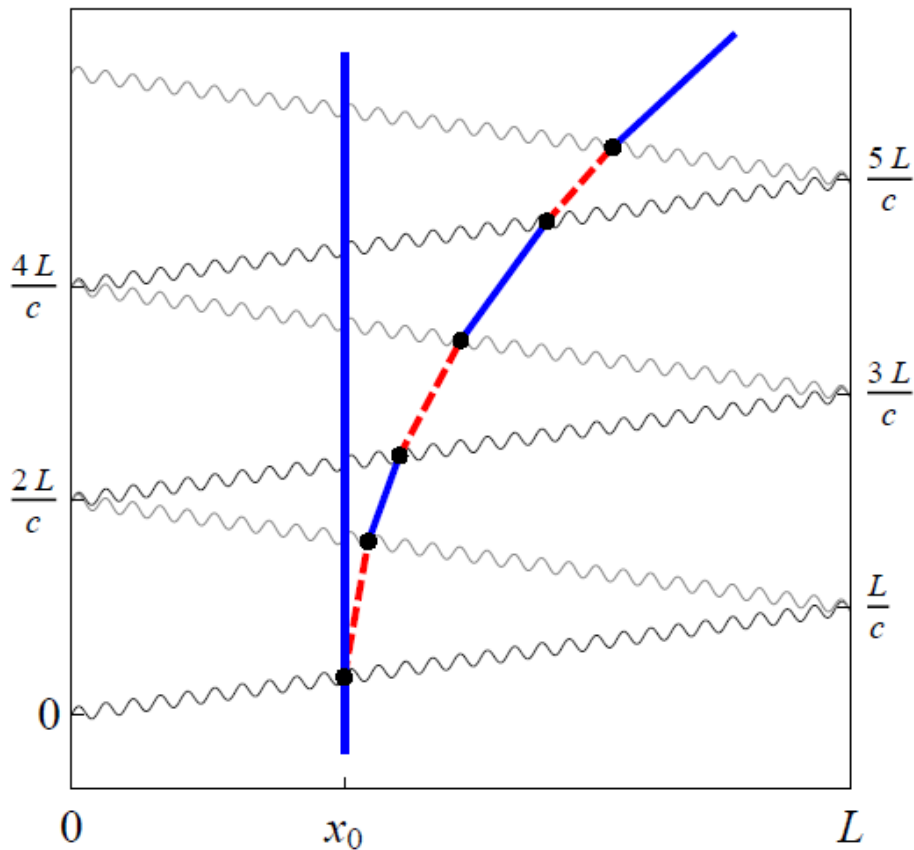
1. Increase momentum splitting $n\hbar k$ between the two interferometer arms.
1. Make a tall atomic fountain to increase the free fall distance $\sim gT^2$.
2. Do both at the same time. Typical operating conditions: arm splitting >10 cm, $T \sim 1$ s

TK, P. Asenbaum, C. Overstreet, C. Donnelly, S. Dickerson, A. Sugarbaker, J. Hogan, and M. Kasevich, Nature 2015
P. Asenbaum, C. Overstreet, TK, D. Brown, J. Hogan, and M. Kasevich, PRL 2017

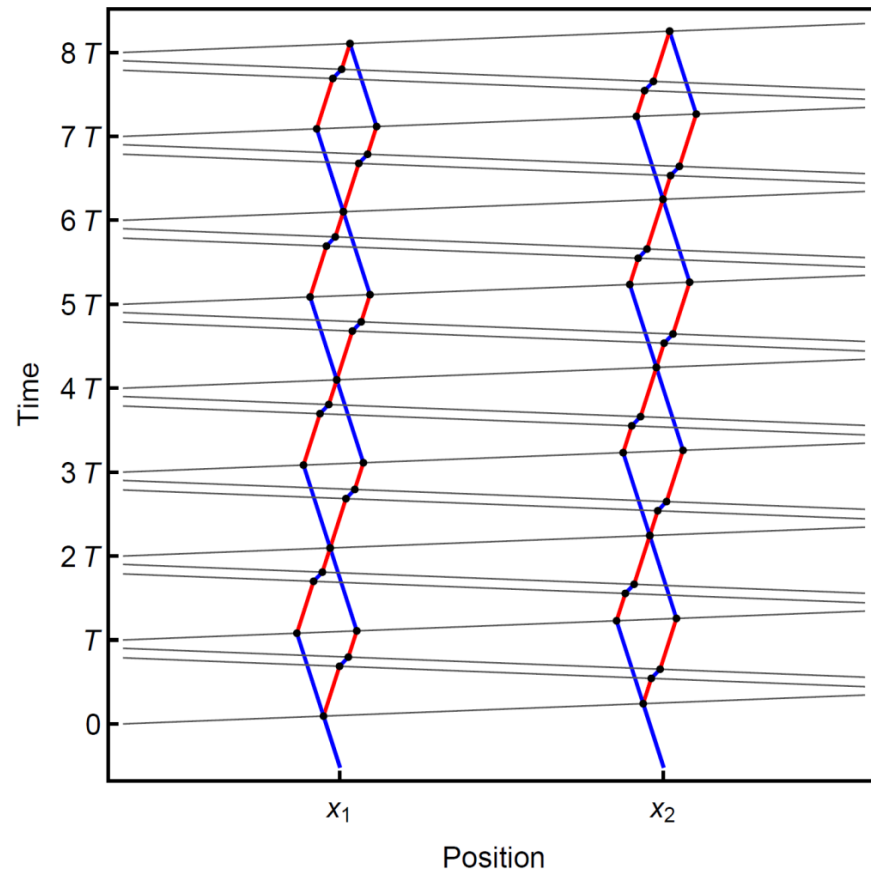
LMT and Resonant Pulse Sequences

Sequential single-photon transitions remain laser noise immune

LMT beamsplitter (N = 3)



Resonant sequence (Q = 4)



Graham, *et al.*, PRL (2013)

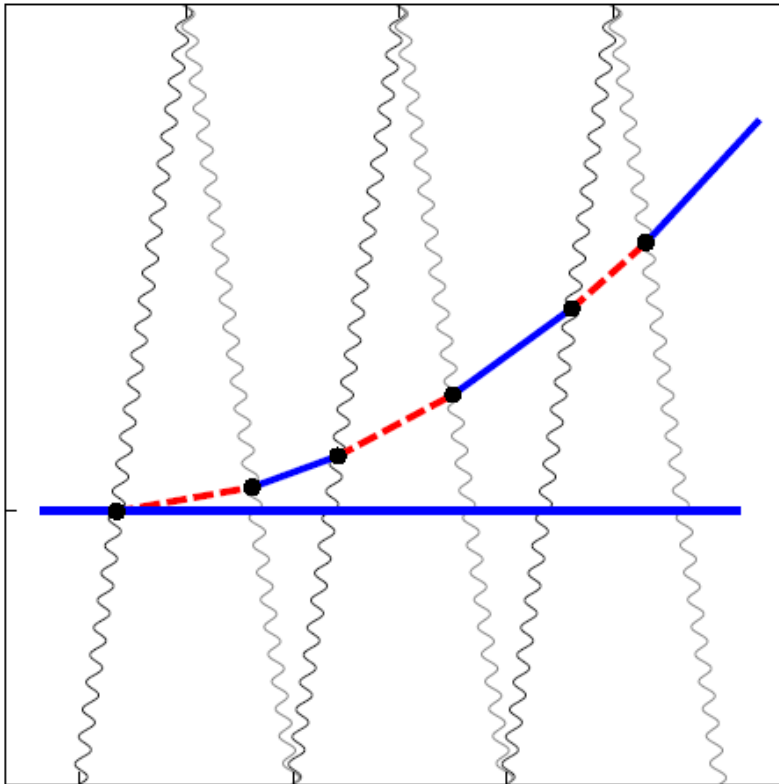
Graham, *et al.*, PRD (2016)



Large Momentum Transfer (LMT) Pulse Sequences

Sequential single-photon transitions remain laser noise immune

LMT beamsplitter



- Additional laser pulses exchanged across baseline, further accelerate one of the interferometer arms (detuned from second arm due to Doppler shift)
- Additional pulses coherently enhance differential clock signal: total amount of time spent in excited state during beam splitter decreases as x increases from 0 to L (giving differential signal) and is proportional to number of pulses
- Magnitude of contribution to differential phase shift from each interferometer zone for beam splitters with $2n$ pulses:

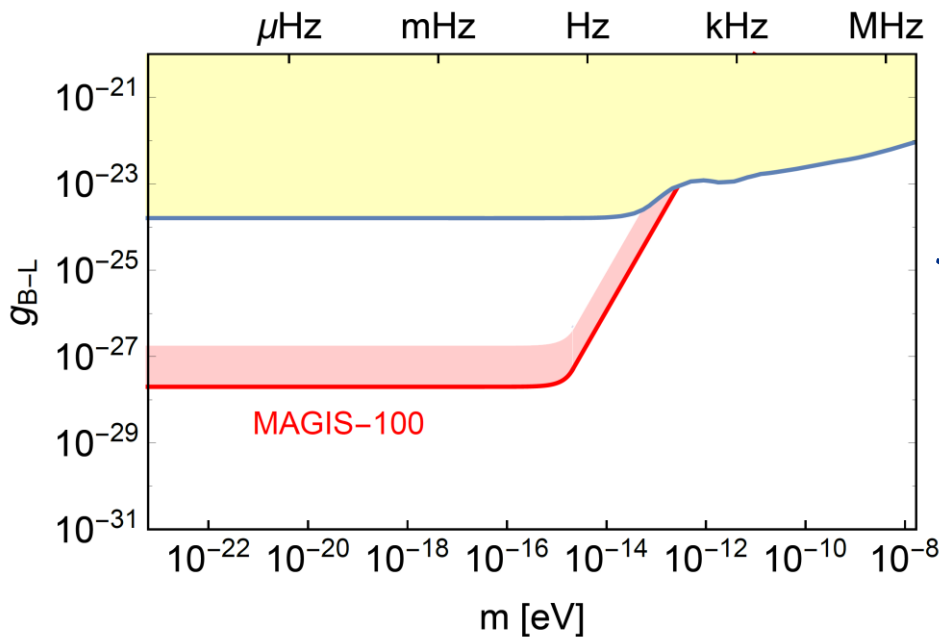
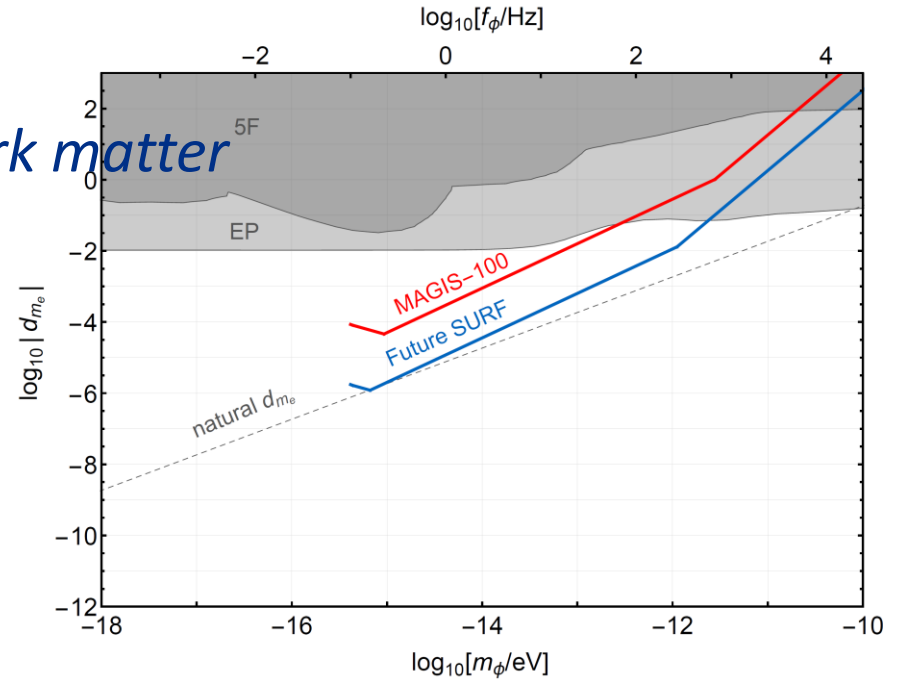
$$\Delta\phi \sim 2n\omega_A (L/c)$$

Graham, *et al.*, PRL (2013)

Projected sensitivity to dark matter

for MA

Sensitivity to ultralight scalar dark matter

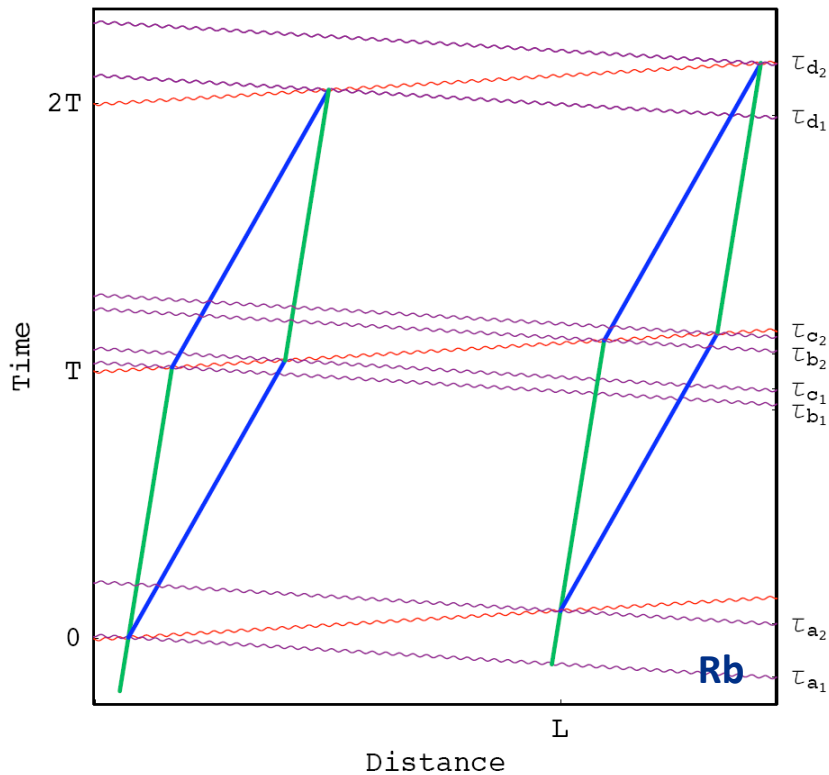


Sensitivity to B-L coupled new force

~ 1 year data taking
Assuming shot-noise limited
phase resolution

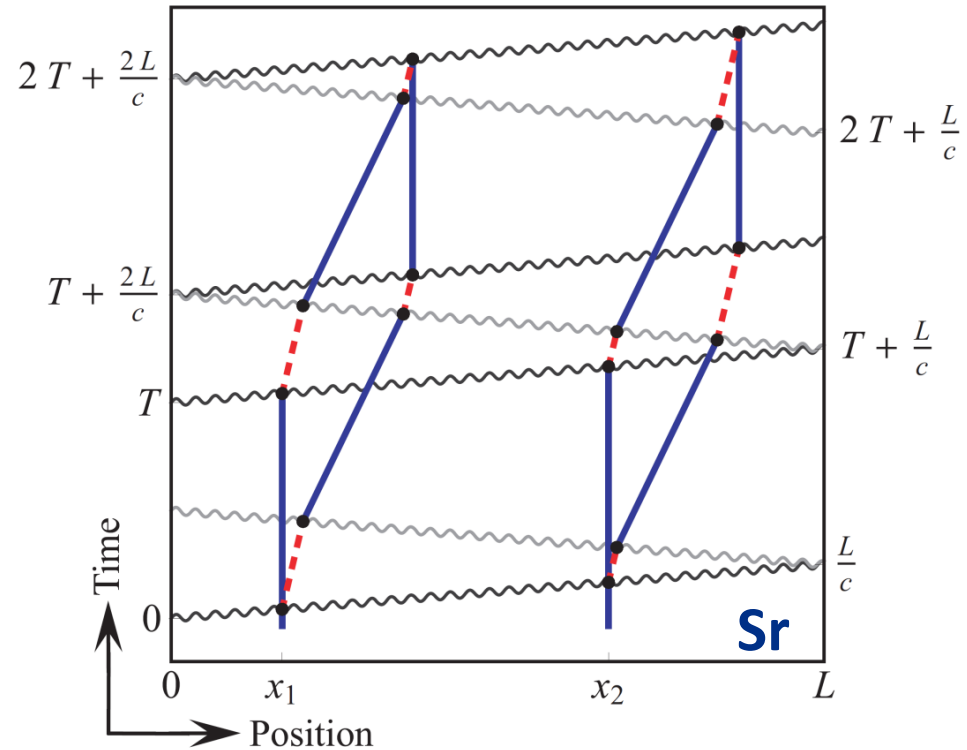
Two-photon vs. single photon AI

2-photon transitions



Laser phase **not** common

1-photon transitions



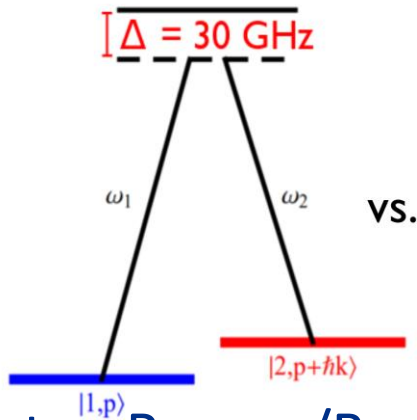
Laser noise suppressed

Graham, et al., PRD 78, 042003, (2008).

Yu, et al., GRG 43, 1943, (2011).

Extreme LMT with clock atoms

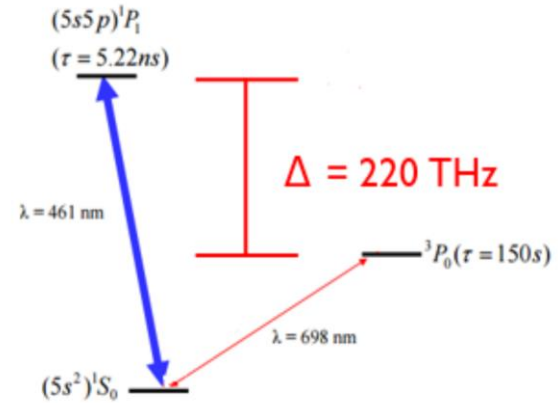
Alkali atoms (e.g. rubidium)



Two photon Raman/Bragg transitions for atom optics

Requires large detuning, high power to suppress spontaneous emission

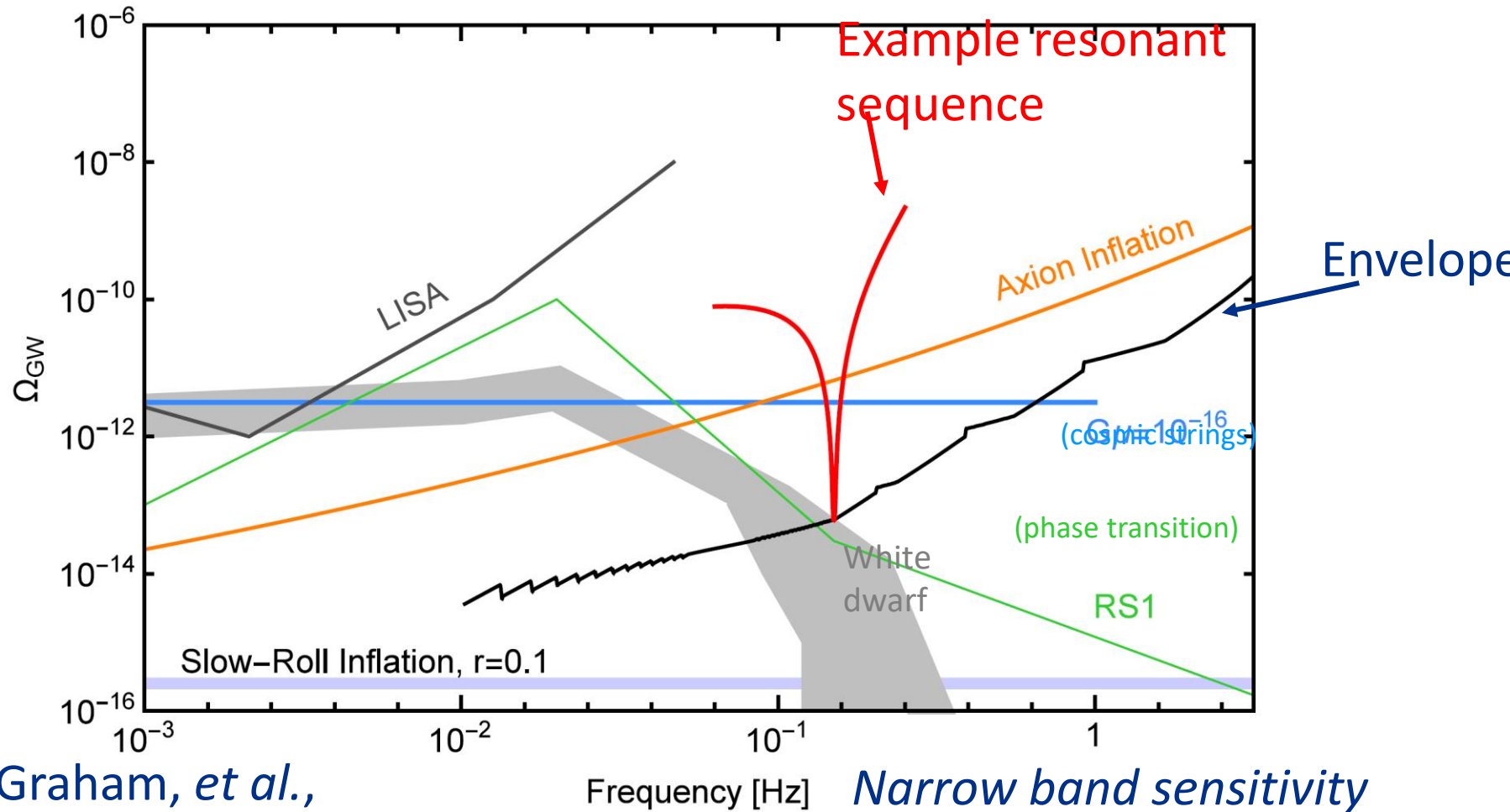
Clock atoms (e.g. strontium)



Single photon transition for atom optics

Spontaneous emission naturally highly suppressed (150 s lifetime clock state, other levels far detuned)

Bounds on stochastic GW sources



Graham, *et al.*,
arXiv:1606.01860
(2016)

*Narrow band sensitivity
possible in 1 year*

Sequential Bragg Atom Optics

