MAGIS-100 at FNAL

A 100 meter atom interferometer

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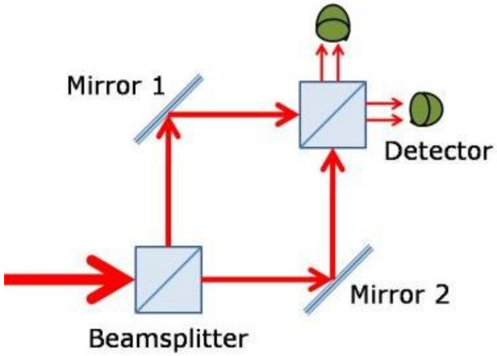
Brief Introduction to Atom Interferometry

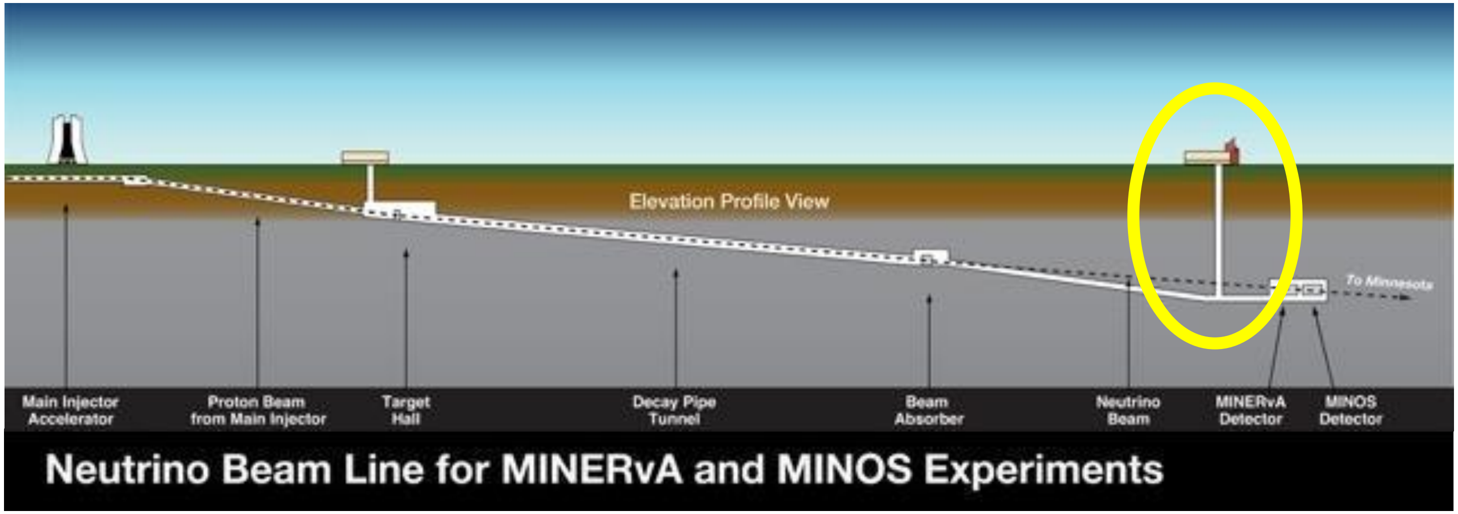
- Use cold atoms to detect phase shifts from split paths.
- Analogous to Mach-Zender Interferometry with light.



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

Fermilab

Northwestern University

UNIVERSITY OF LIVERPOOL

Northern Illinois University

JOHNS HOPKINS UNIVERSITY

SLAC

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF CHICAGO

OLD DOMINION UNIVERSITY

GORDON AND BETTY MOORE FOUNDATION

GBMF7945

DOE QuantiSED

UKRI Science and Technology Facilities Council

UK STFC

Kavli Foundation

Two State Systems

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

Ammonia Molecule

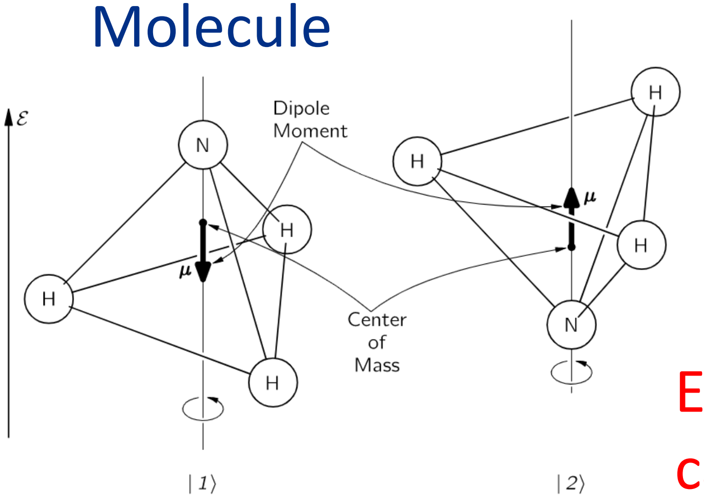


Fig. 9–1. A physical model of two base states for the ammonia molecule. These states have the electric dipole moments $\boldsymbol{\mu}$.

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

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

Governing Equations
Ref: Feynman vol. 3, Lecture 9

Electric Field E causes energy difference ~ 2μE

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/Ω Rabi

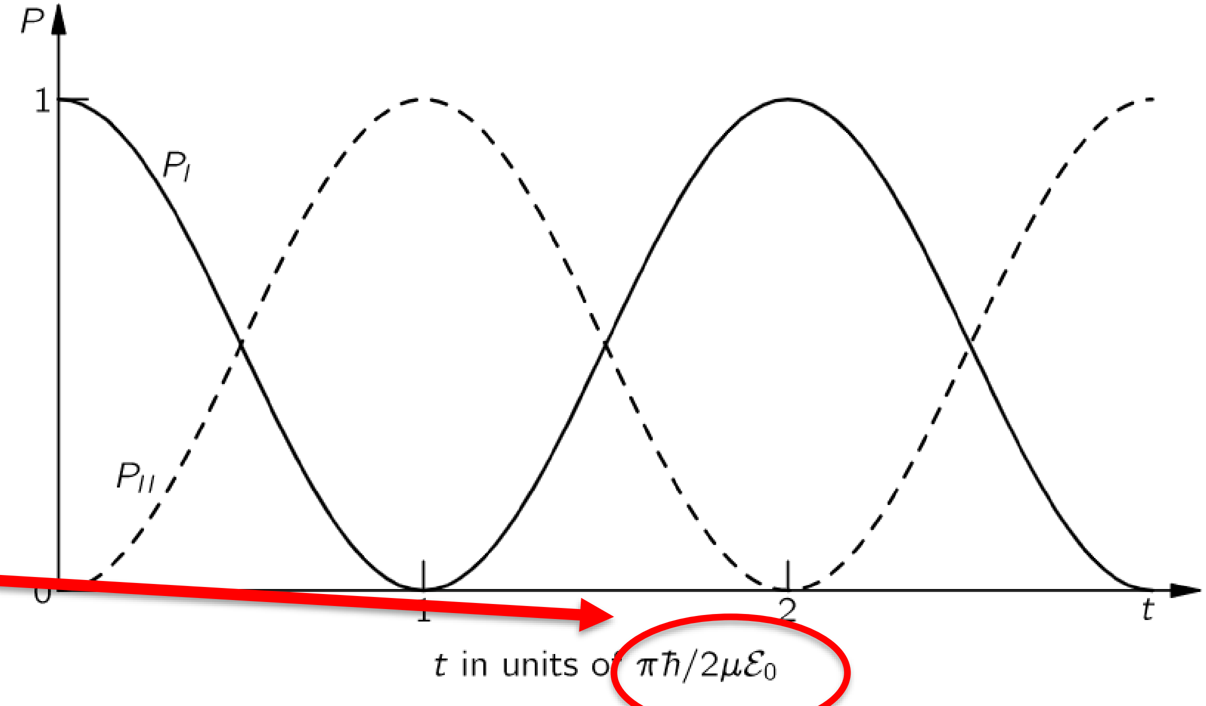
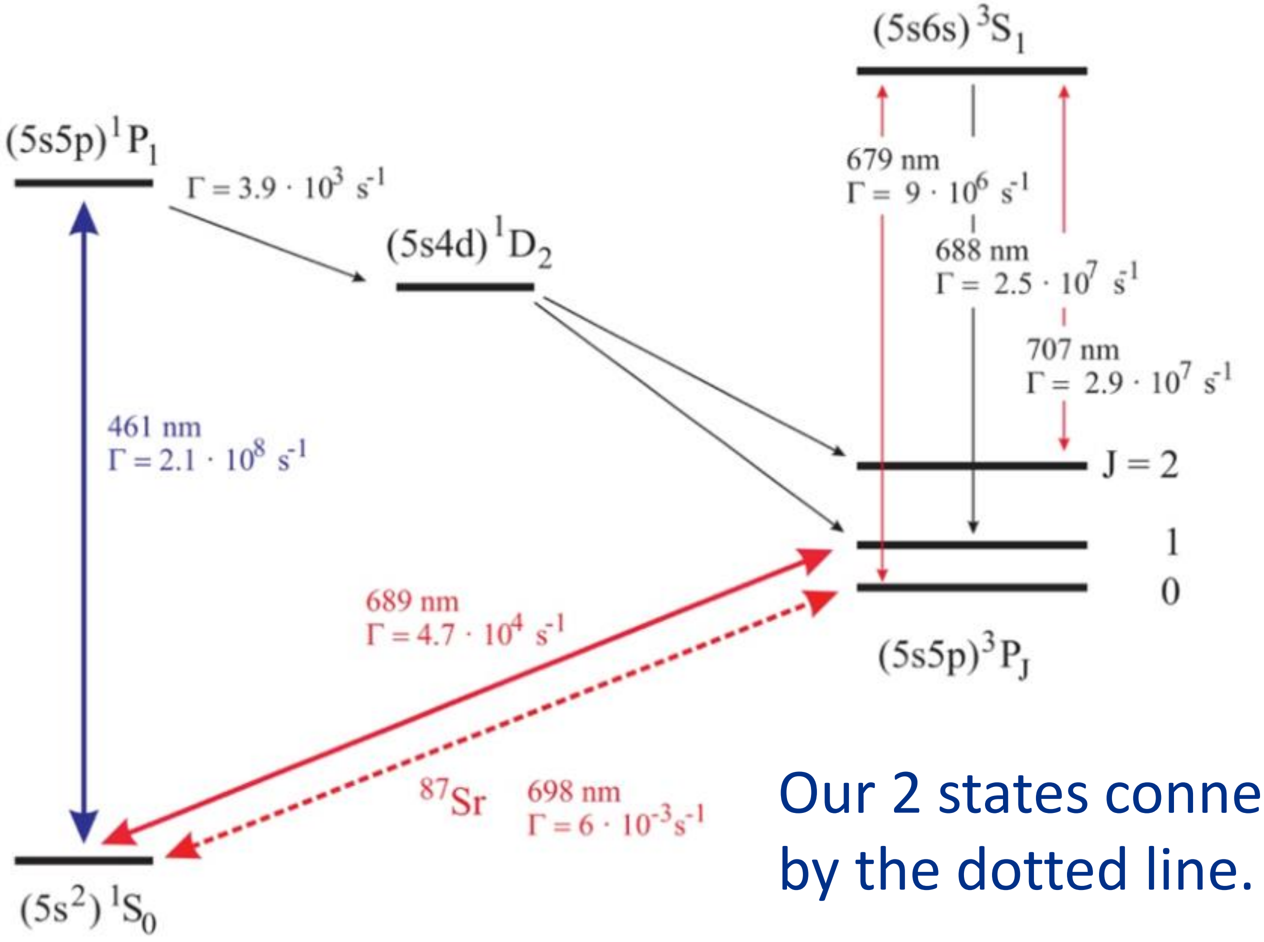


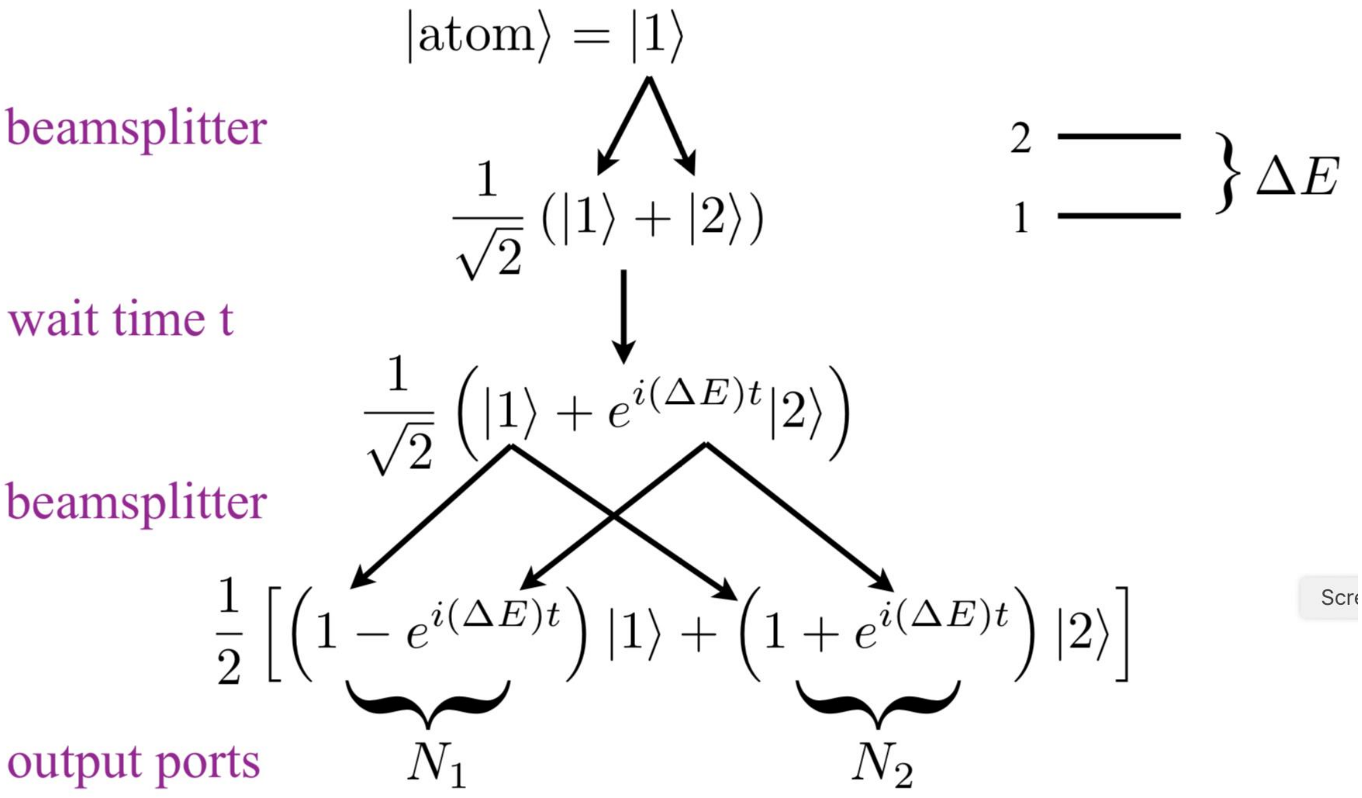
Fig. 9–5. Probabilities for the two states of the ammonia molecule in a sinusoidal electric field.

Strontium Spectrum



Our 2 states connected by the dotted line.

Pulsed Atomic Clock



$$|\text{atom}\rangle = |1\rangle$$

beamsplitter

$$\frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$

wait time t

$$\frac{1}{\sqrt{2}}\left(|1\rangle + e^{i(\Delta E)t}|2\rangle\right)$$

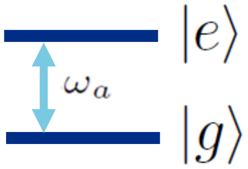
beamsplitter

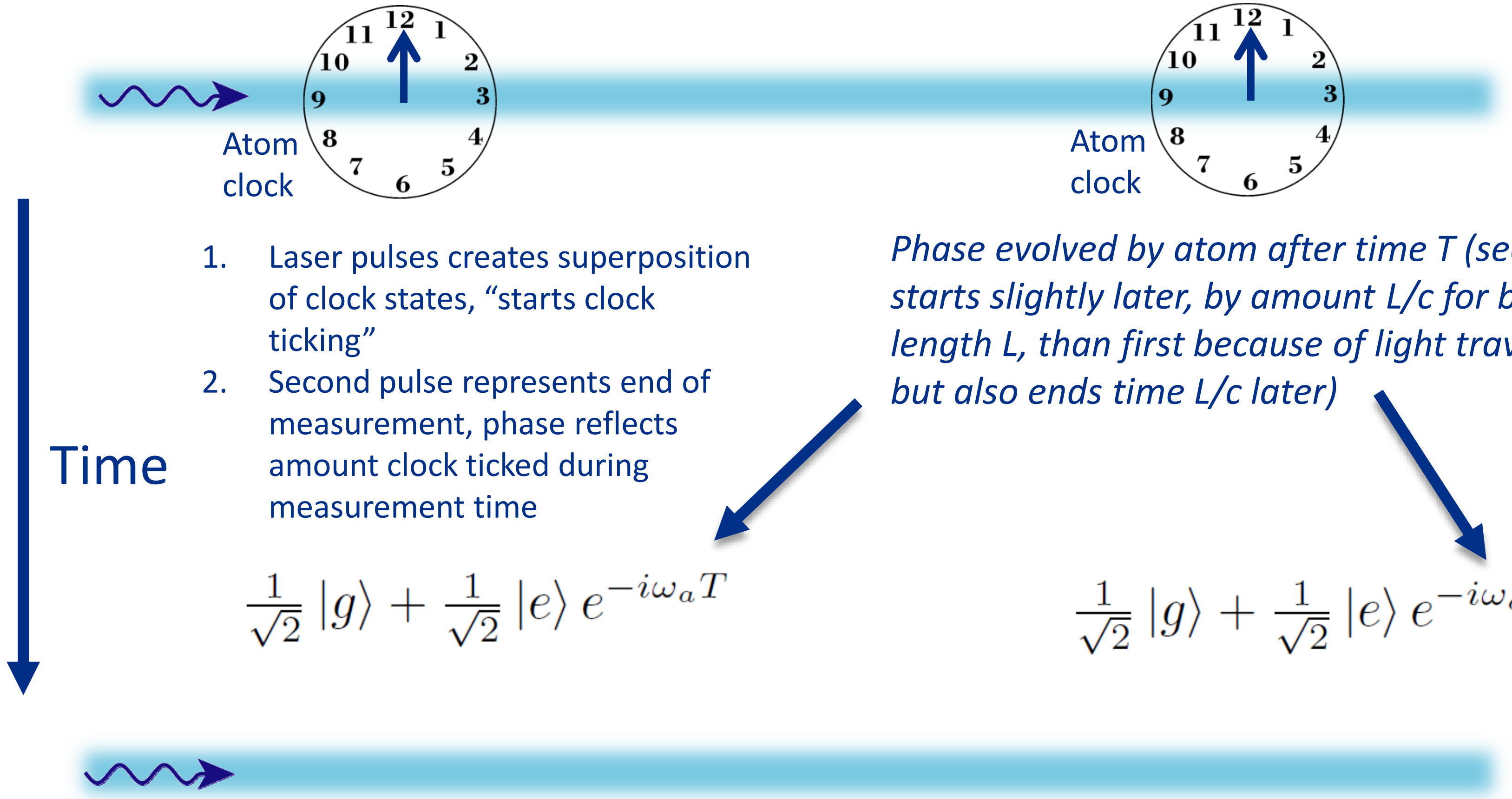
$$\frac{1}{2}\left[\underbrace{\left(1 - e^{i(\Delta E)t}\right)}_{N_1}|1\rangle + \underbrace{\left(1 + e^{i(\Delta E)t}\right)}_{N_2}|2\rangle\right]$$

output ports

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

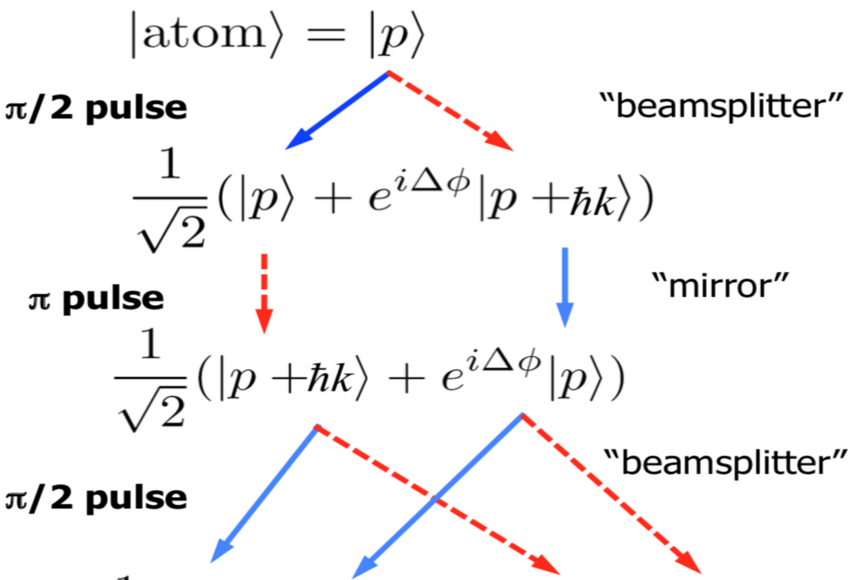
Phase evolved by atom after time T (second clock starts slightly later, by amount L/c for baseline length L, than first because of light travel time, but also ends time L/c later)

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

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

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"

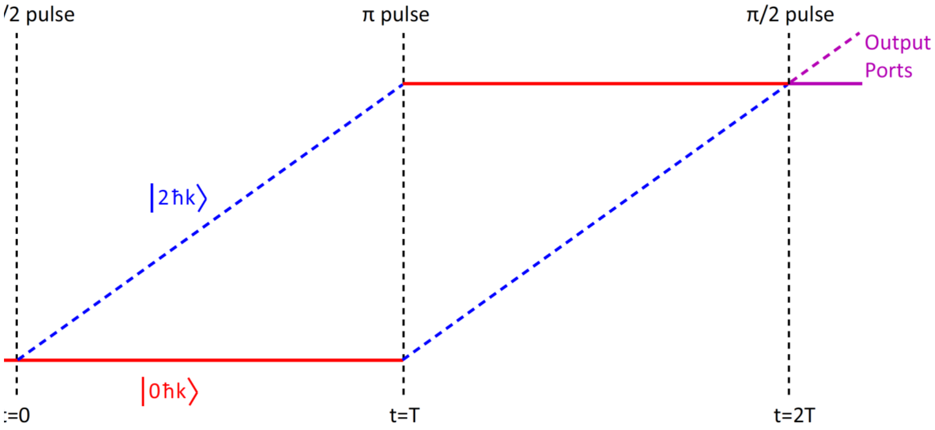
$$\frac{1}{\sqrt{2}}(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

π/2 pulse "beamsplitter"

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

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

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



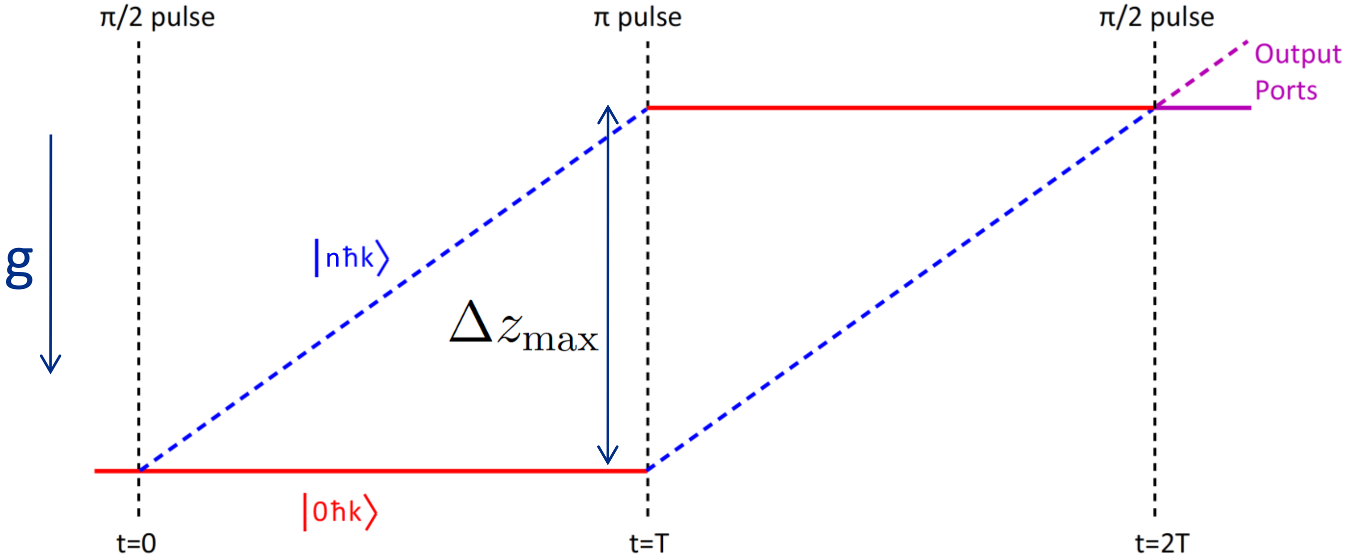
Effects scale like AREA, so

Long T good

High Momentum Good

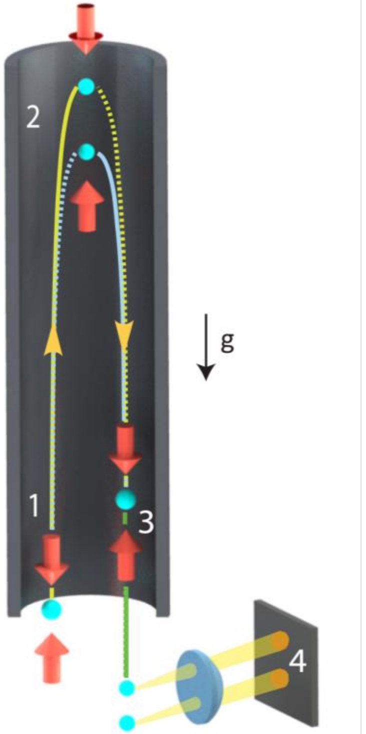
Interferometer Phase Shift

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



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

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



Acceleration sensitivity (consideration sensitivity to g as illustrative example)

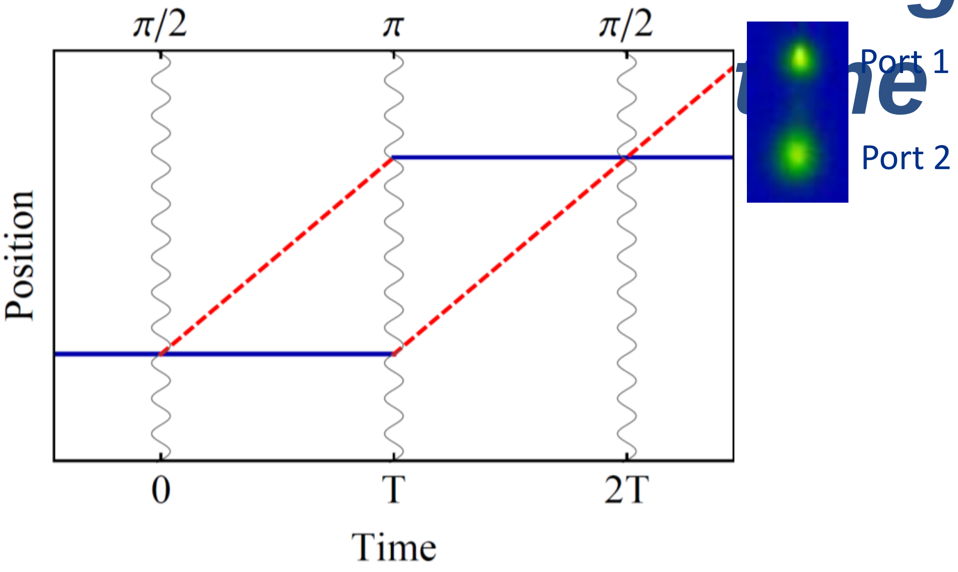
$$\Delta\phi = -\frac{m}{\hbar} g \Delta z_{\max} T$$

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

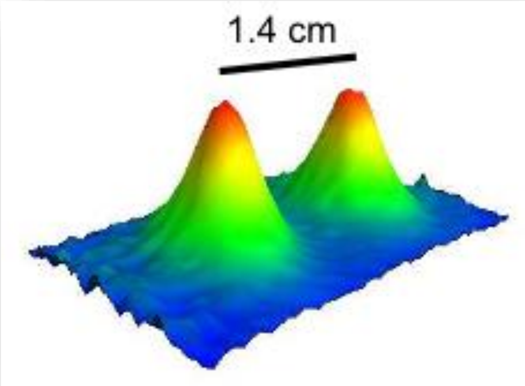
$$\boxed{\Delta\phi = -nkgT^2}$$

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

Interference at long interrogation time

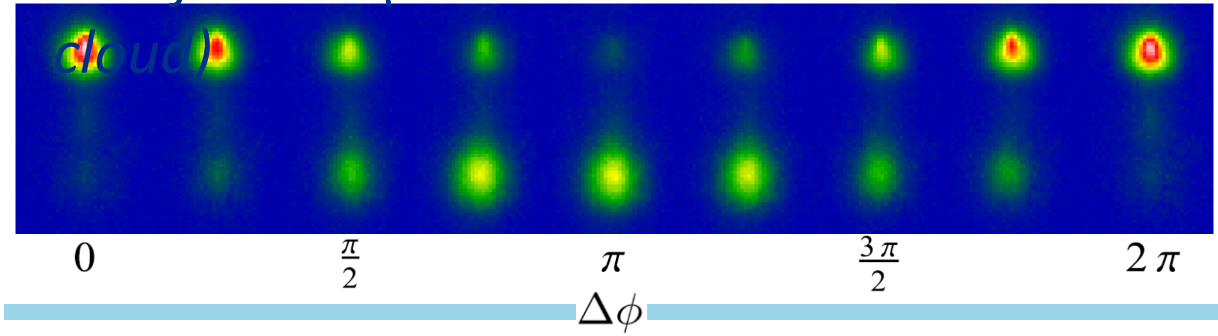


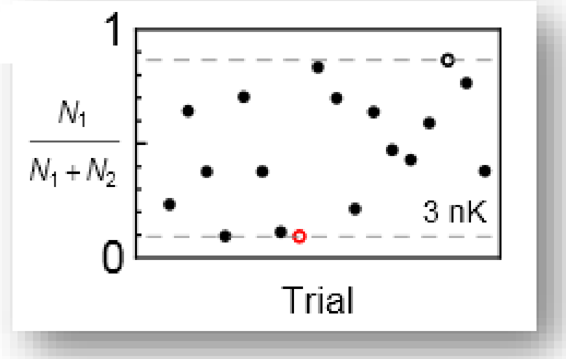
2T = 2.3 seconds
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

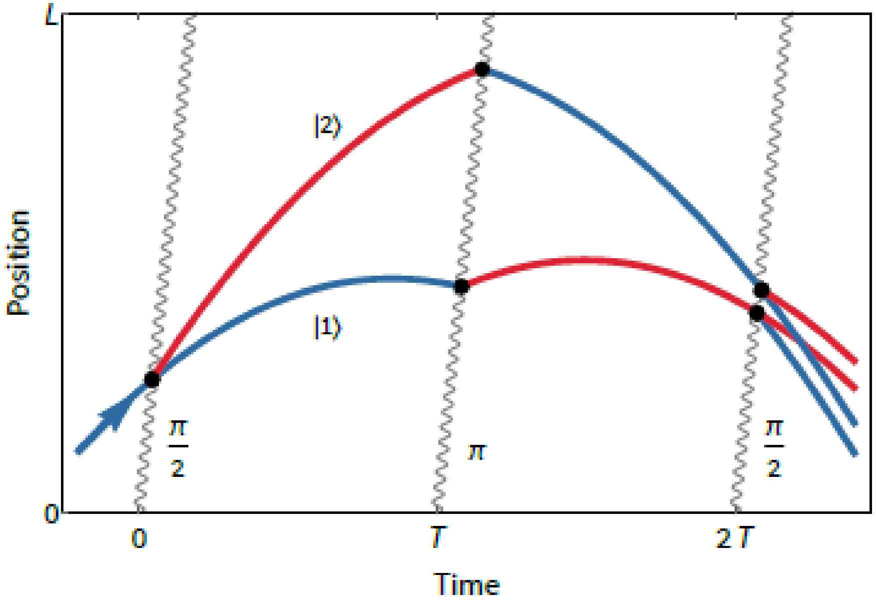
Interference (3 nK cloud)

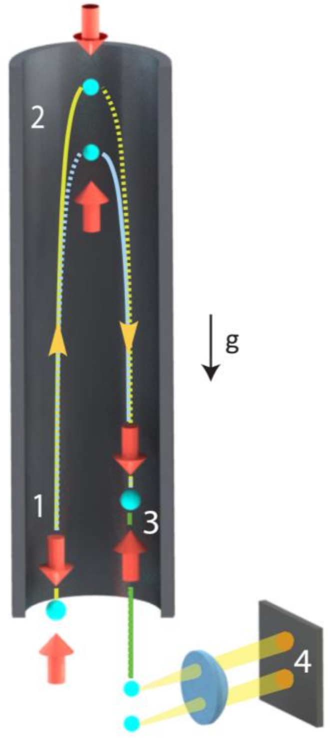




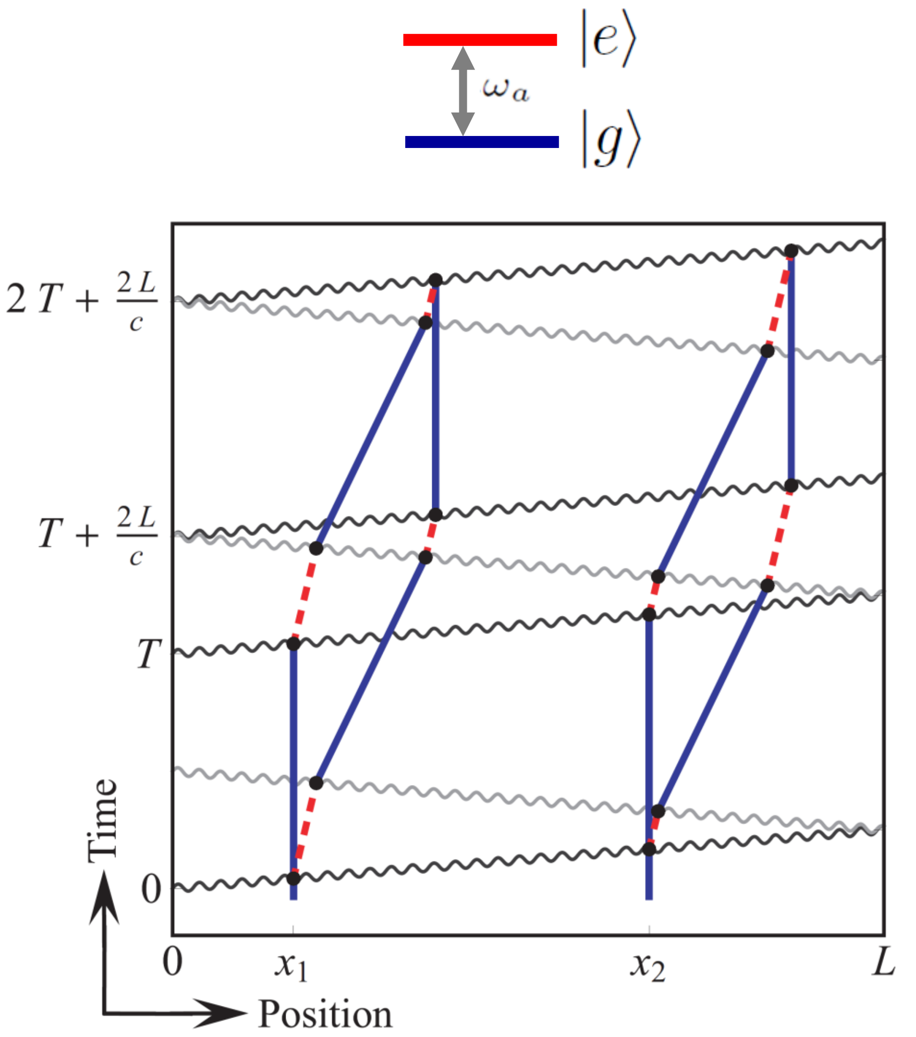
Dickerson, et al., PRL **111**, 083001 (2013).

Fountain Interferometer





Gradiometer Using Different Internal Clock States



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

Excited state phase evolution:

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

Two ways for phase to vary:

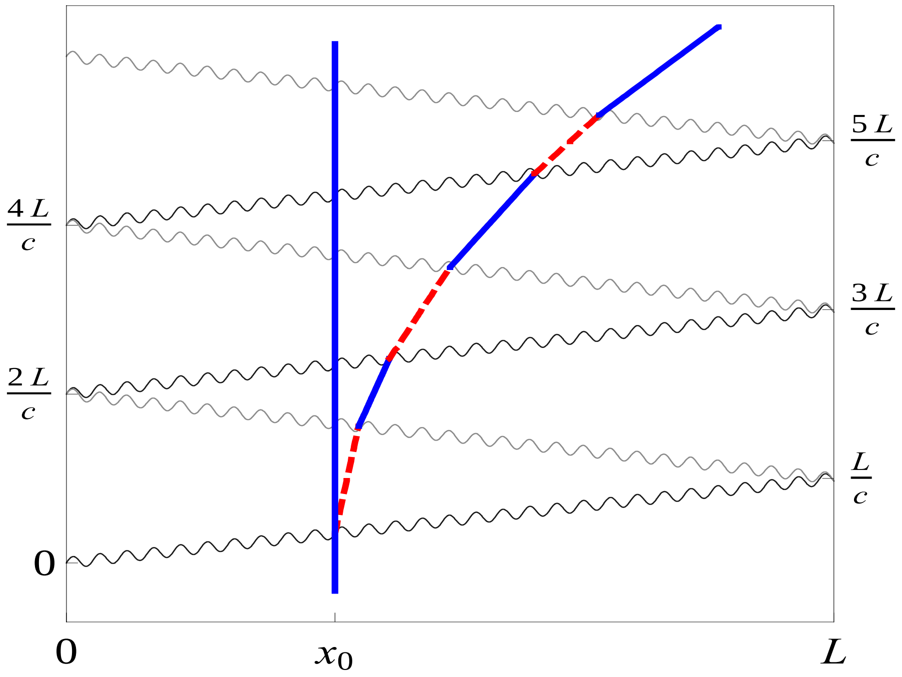
$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

DM causes time-variation of transition frequency

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

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.

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 DM is almost a classical field (e.g., mass ~10^{-15} eV)

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

DM scalar field

Electron coupling

Photon coupling

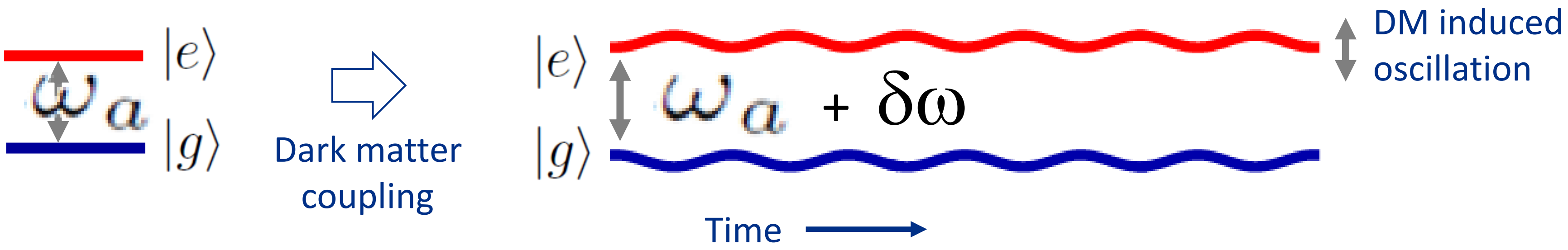
e.g., QCD

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

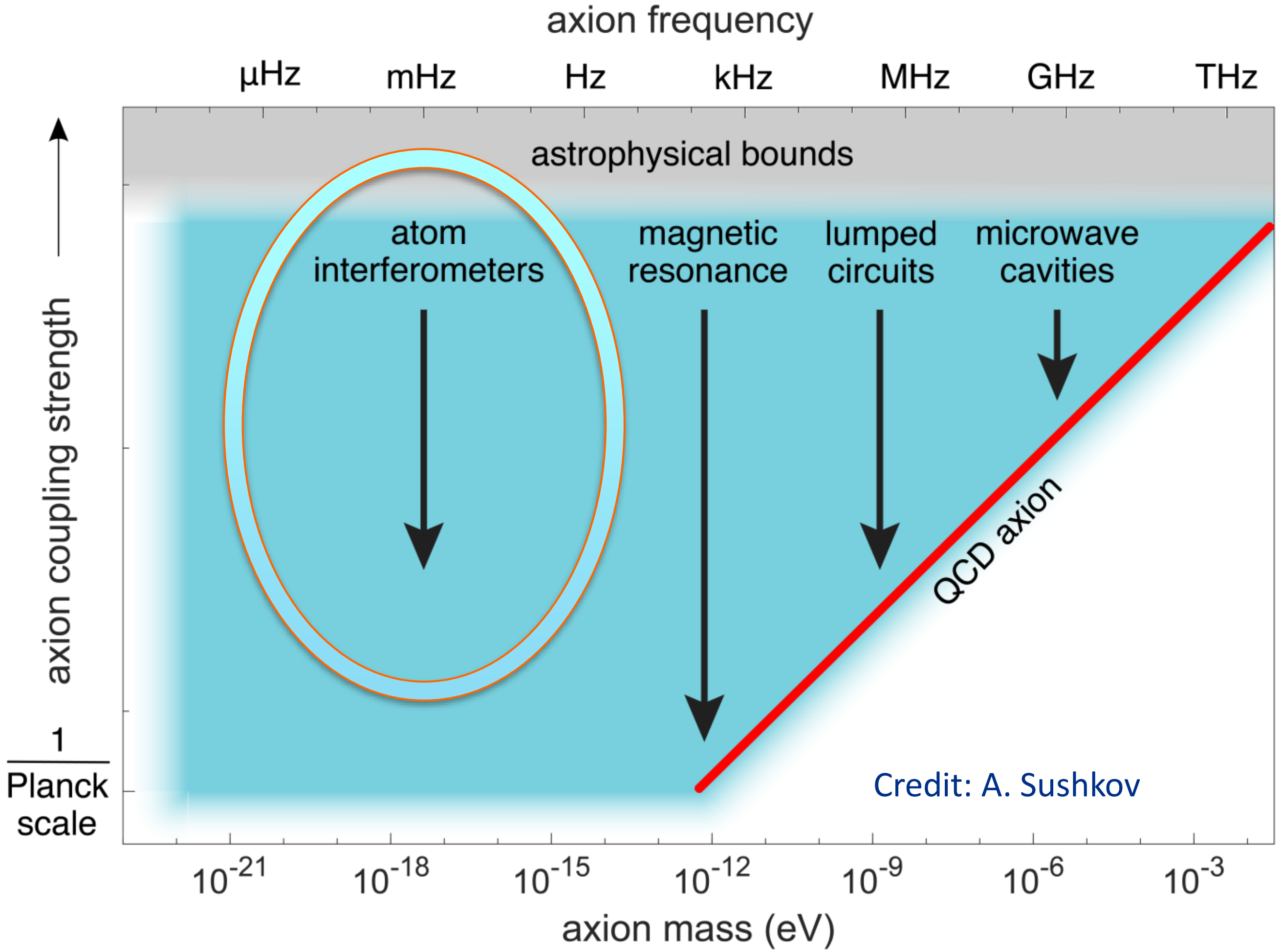
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$

DM mass density

DM coupling causes time-varying atomic energy levels:



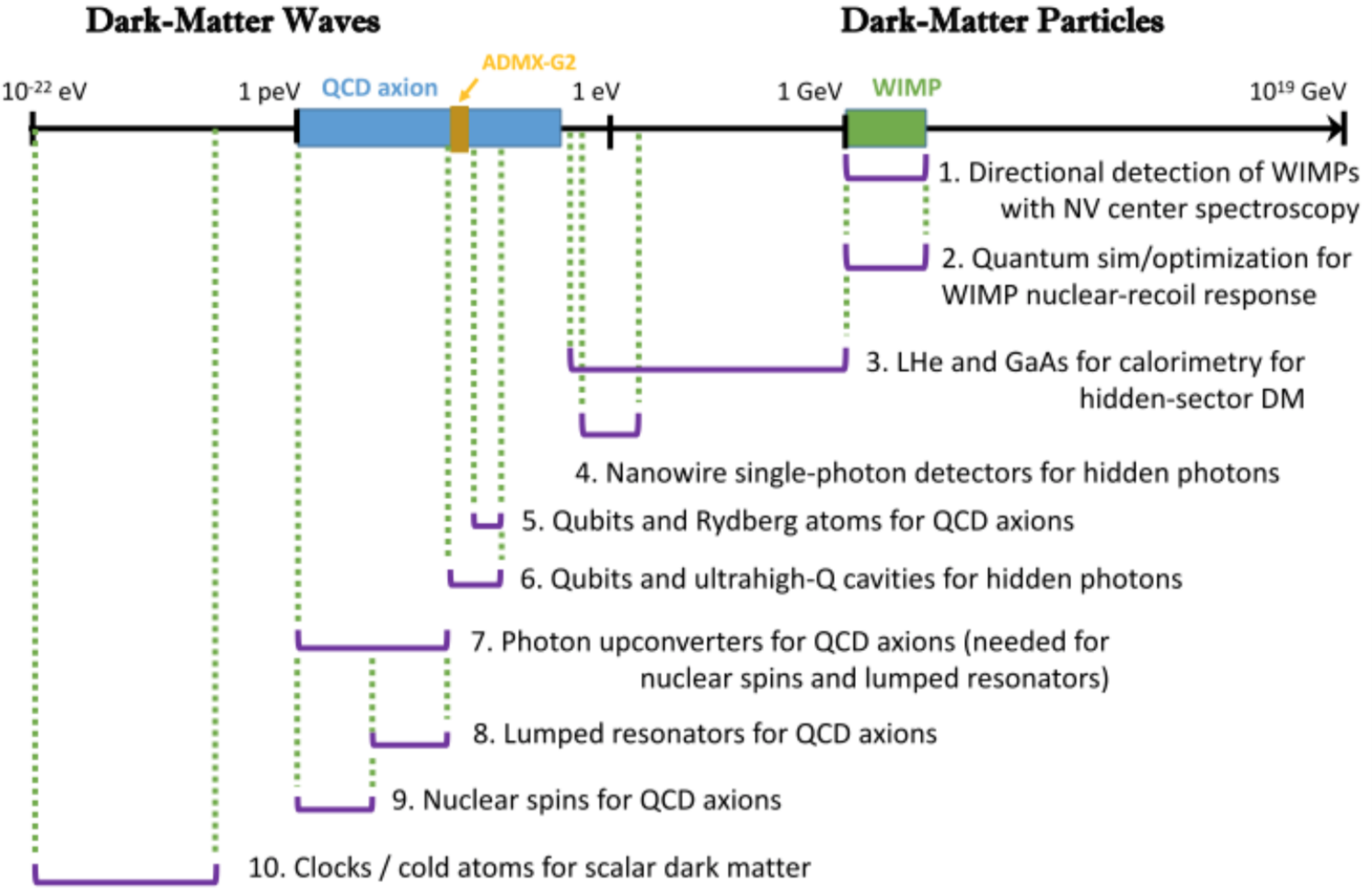
Light Dark Matter Landscape



Credit: A. Sushkov

Figure from DOE Dark Matter Research Needs Report, 2018

Dark Matter Landscape



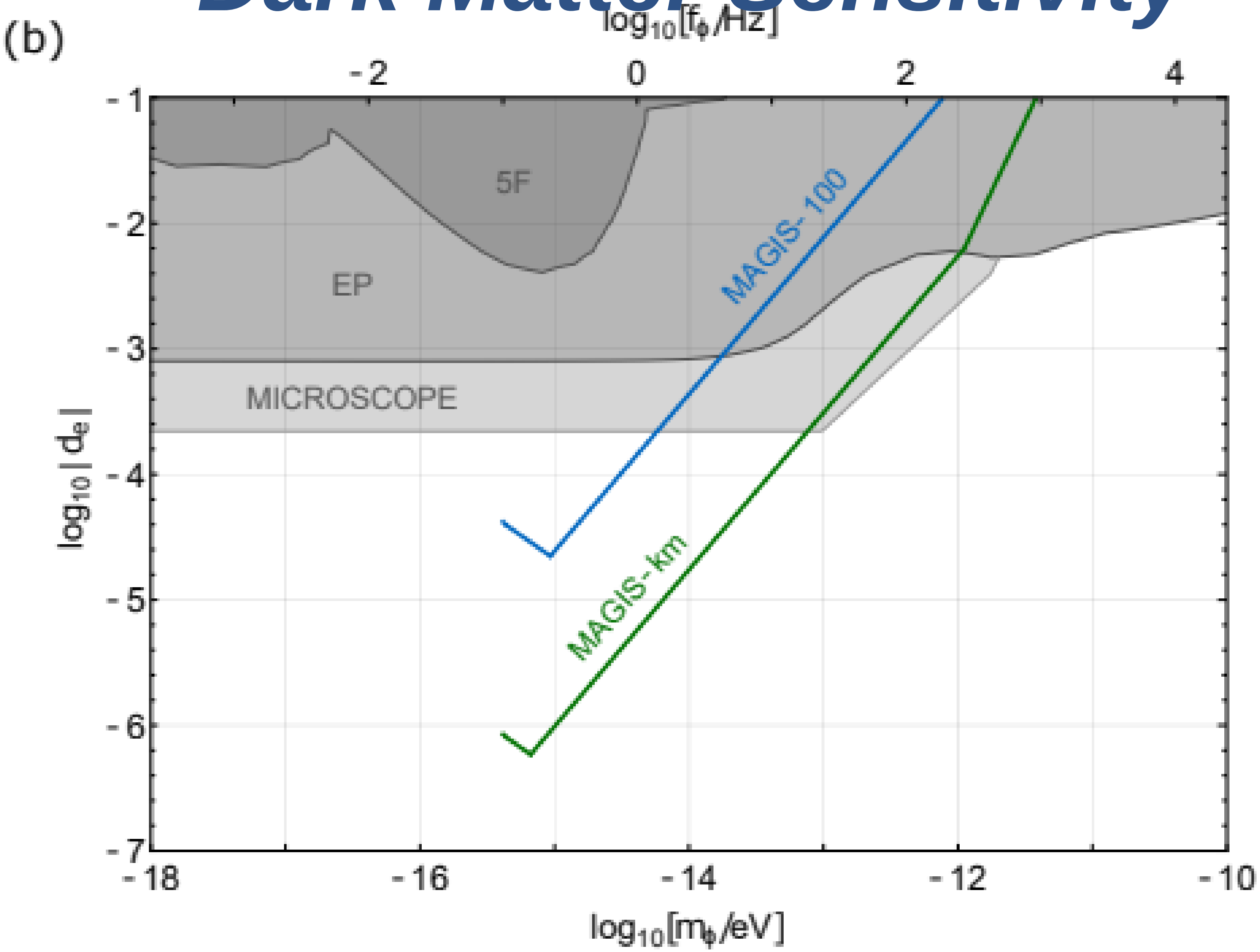
1. Directional detection of WIMPs with NV center spectroscopy
2. Quantum sim/optimization for WIMP nuclear-recoil response
3. LHe and GaAs for calorimetry for hidden-sector DM
4. Nanowire single-photon detectors for hidden photons
5. Qubits and Rydberg atoms for QCD axions
6. Qubits and ultrahigh-Q cavities for hidden photons
7. Photon upconverters for QCD axions (needed for nuclear spins and lumped resonators)
8. Lumped resonators for QCD axions
9. Nuclear spins for QCD axions
10. Clocks / cold atoms for scalar dark matter

DM 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

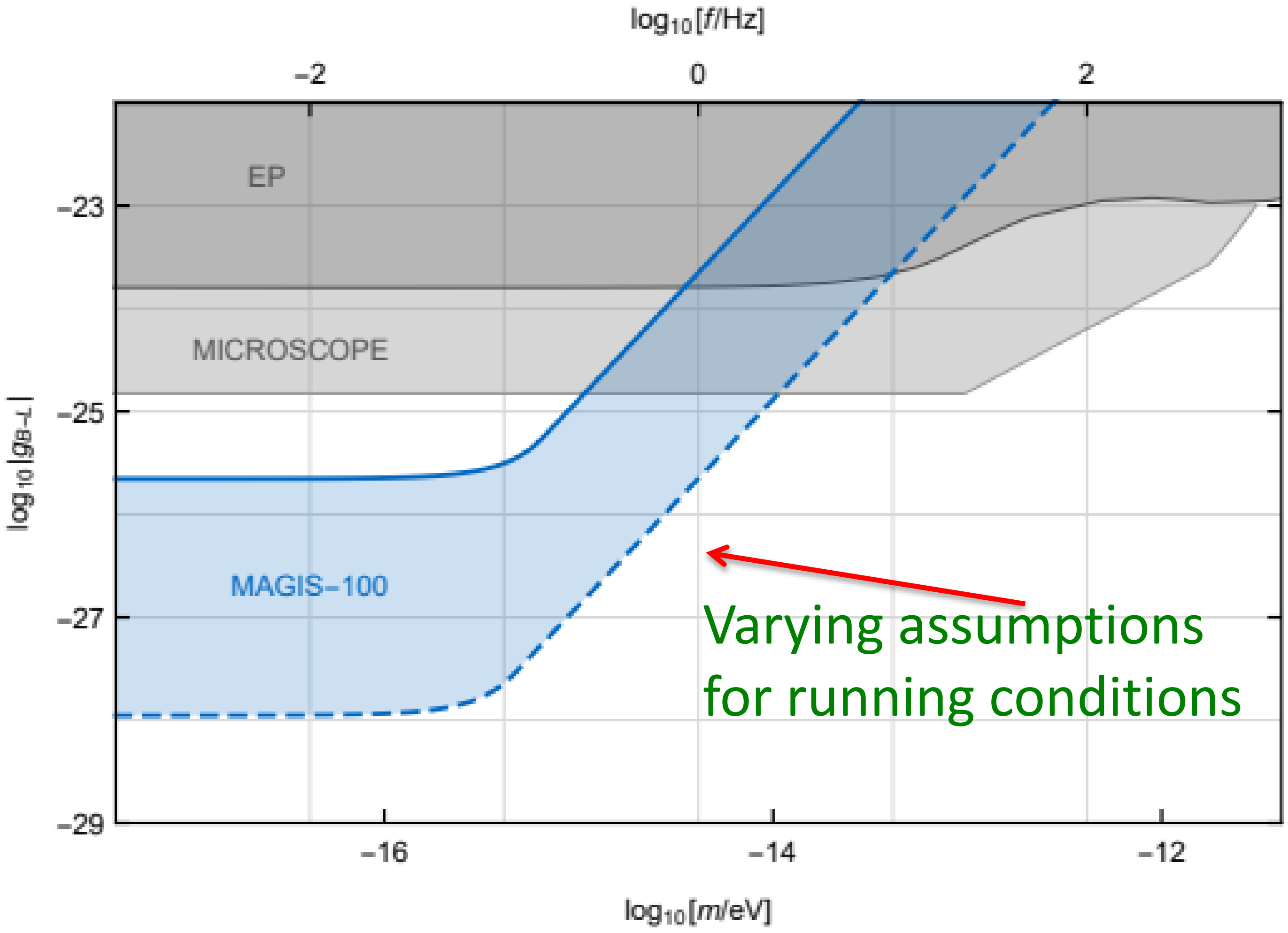
Dark Matter Sensitivity



B-L Dark Forces

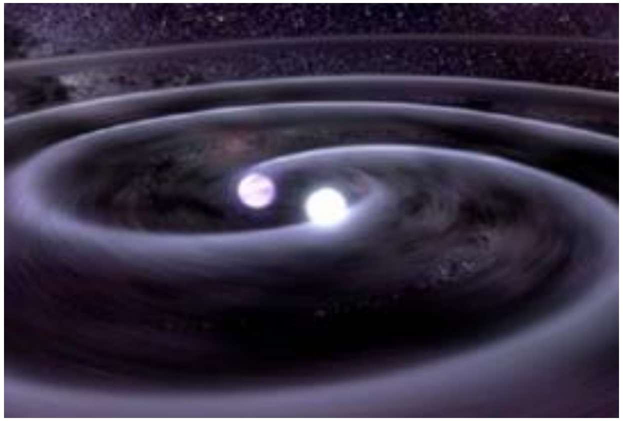
- In addition to scalar dark matter, other types of interactions can be looked for.
- One example is a new vector boson coupling to B-L (protons vs neutrons)
- If dark matter, will have time dependence.
- If new force sourced by earth, force is static.
- MAGIS-100 will search for this with atom source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

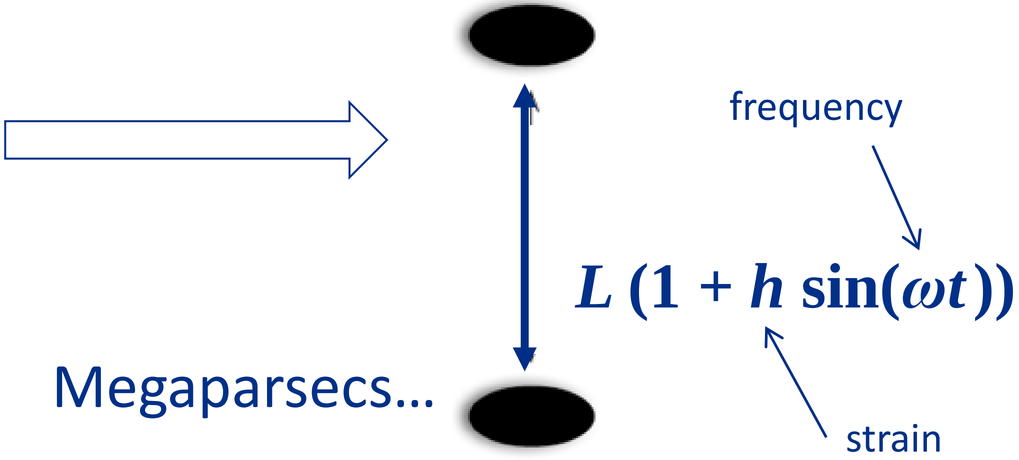
B-L New Forces Sensitivity



Varying assumptions for running conditions

Gravitational Wave Detection





frequency

$$L\,(1 + h\sin(\omega t))$$

Megaparsecs…

strain

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

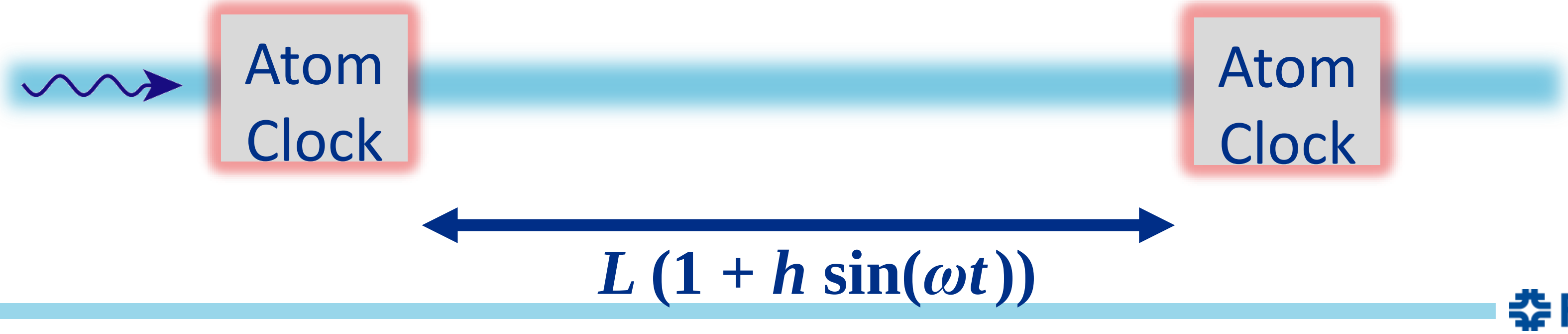
Tests of gravity: Extreme systems (e.g., black hole binaries) test general relativity

Cosmology: Can see to the earliest times in the universe

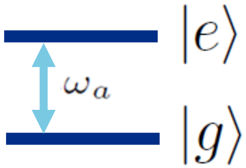
Measurement Concept

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

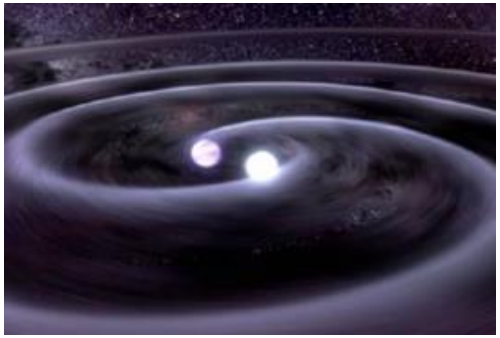


Two Atomic Clocks



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

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

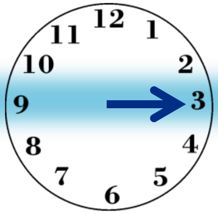


Time

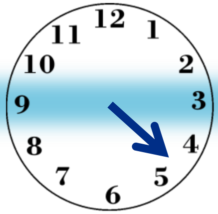
$\Delta T \sim hL/c$

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

Atom clock

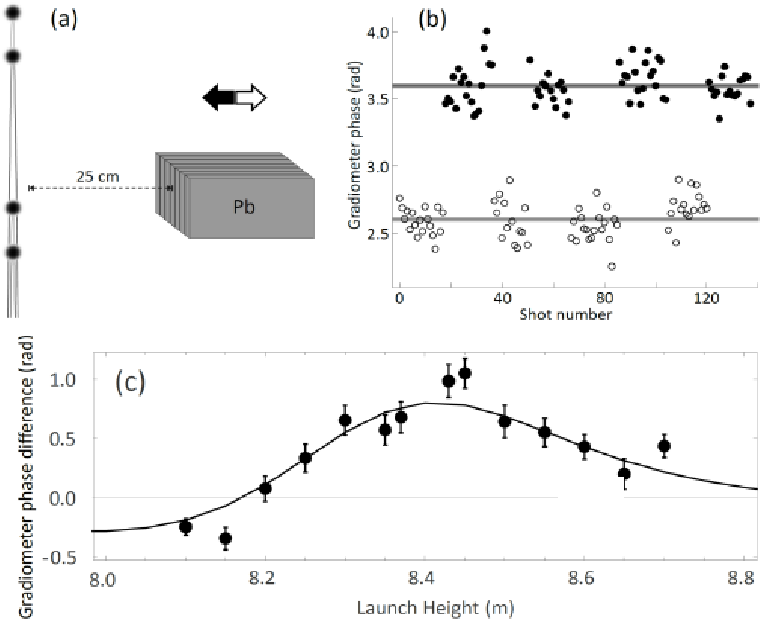


Atom clock



Gravity Demonstration

Gradiometer response to 84 kg lead test mass



$L = 10\,\mathrm{cm}$, $n = 30$, and $T = 900\,\mathrm{ms}$ $(\Delta z = 16\,\mathrm{cm})$

Asenbaum et al., PRL **118**, 183602 (2017)

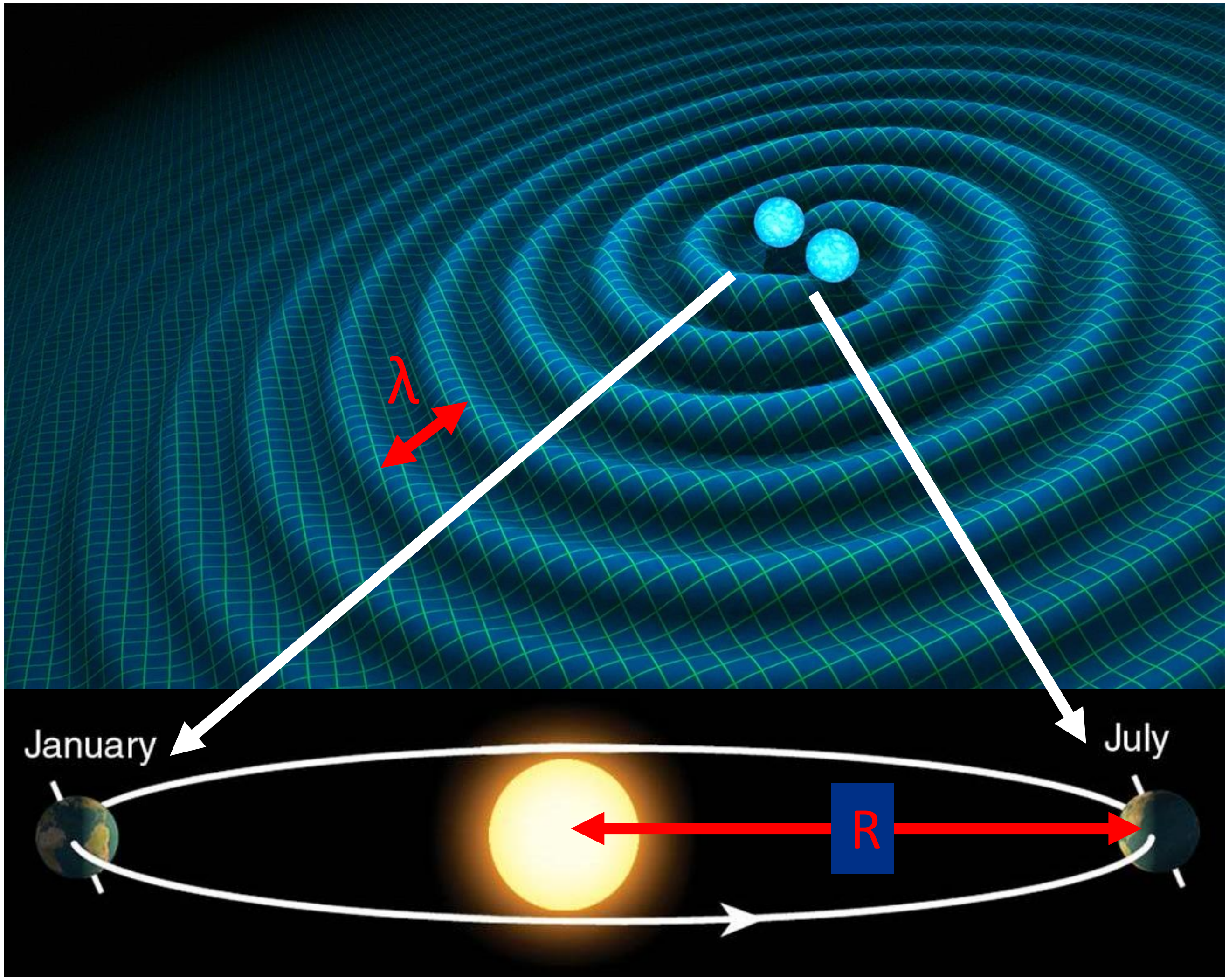
Sky position determination

Sky localization precision:

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

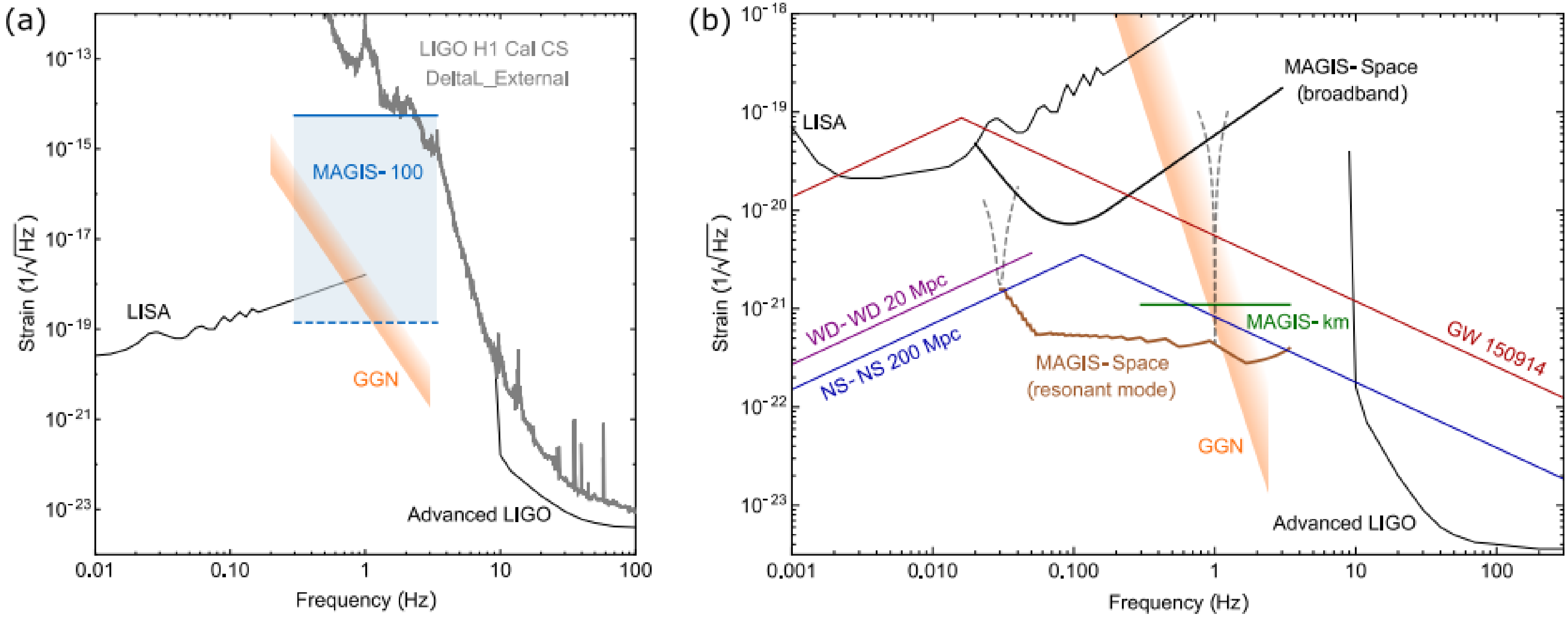
Mid-band advantages

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



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

GW Sensitivity in Near and Long Term



Full Scale future MAGIS detector fills frequency sensitivity gap in ~1 Hz range.
MAGIS-100 will probe this range several orders of magnitude beyond existing limits.

Mid-band Science

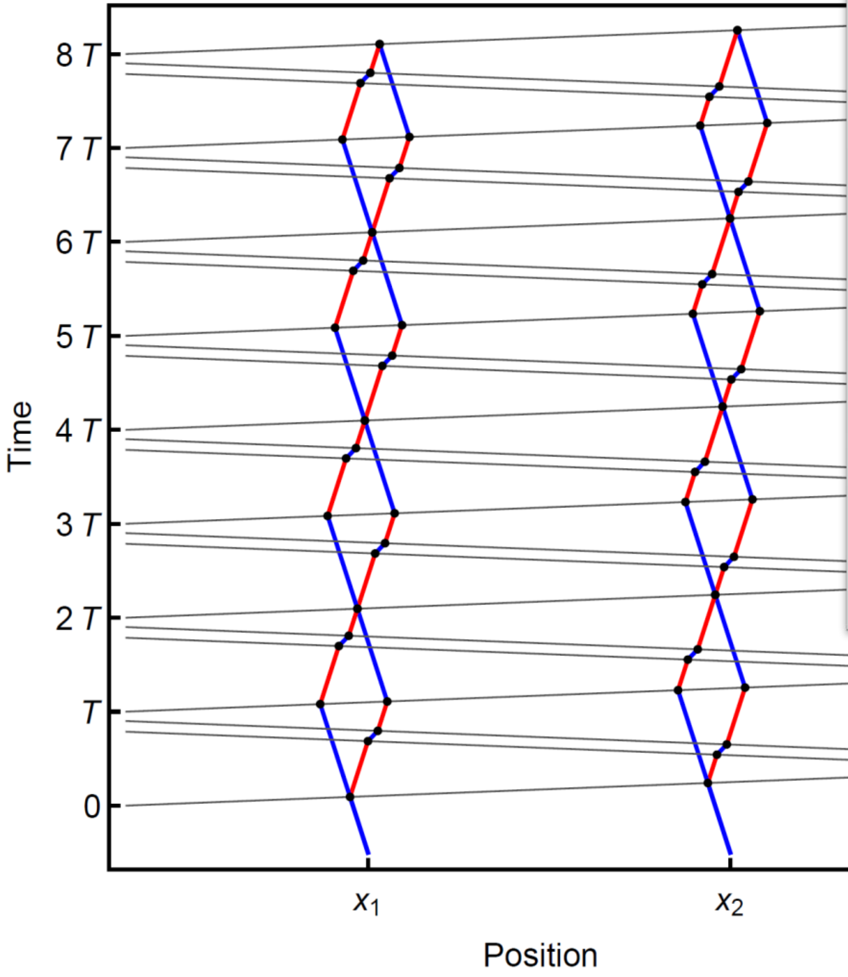
Mid-band discovery potential
Historically every new band/modality has led to discovery
Observe LIGO sources when they are younger

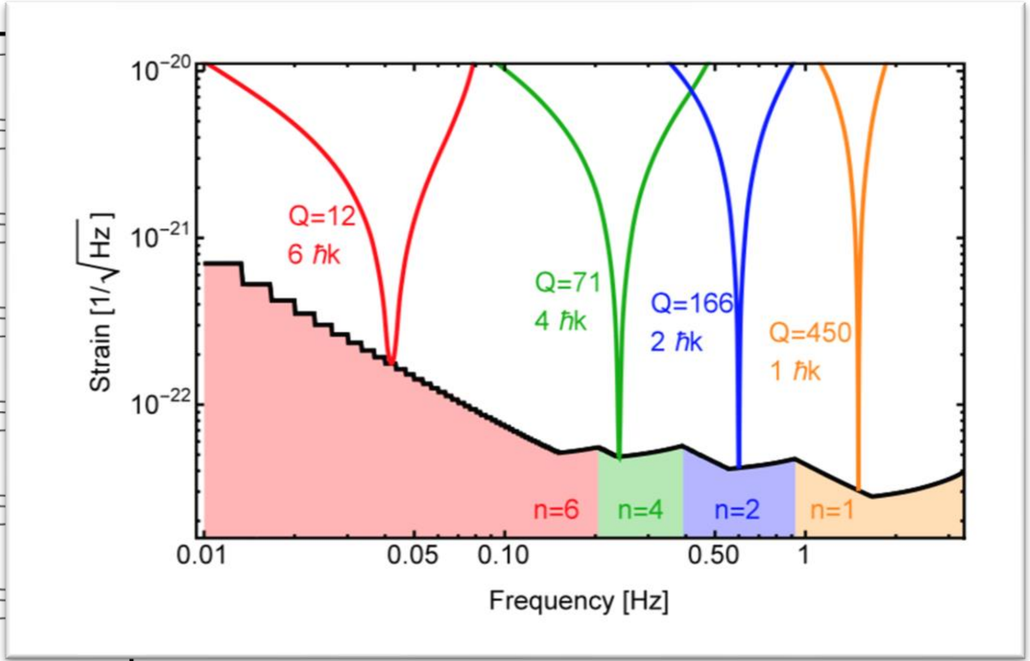
Optimal for sky localization
Predict *when* and *where* events will occur (before they reach LIGO band)
Observe run-up to coalescence using electromagnetic telescopes

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

Resonant Pulse Sequences

Resonant sequence (Q = 4)

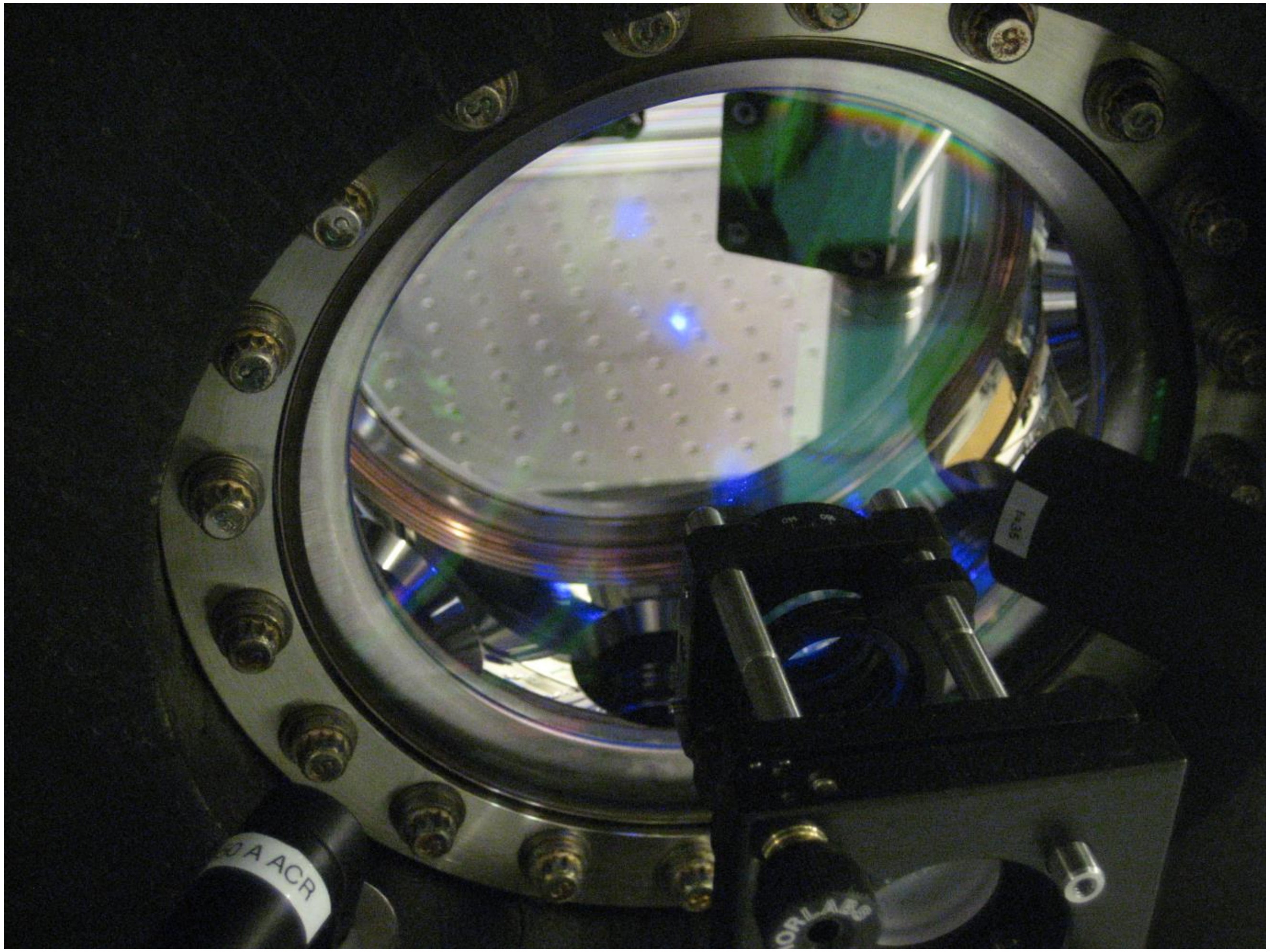




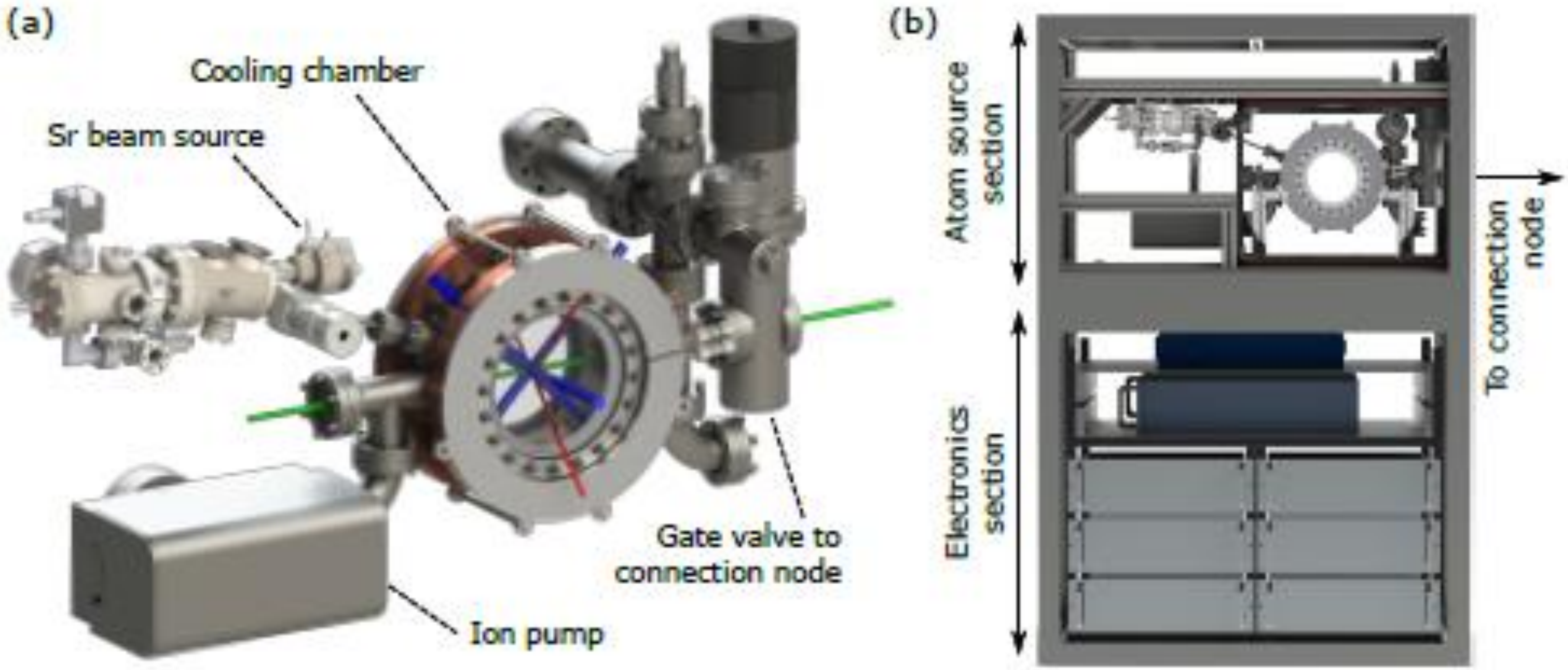
Multiple Interferometer sequences (Q) act as band pass filter.

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

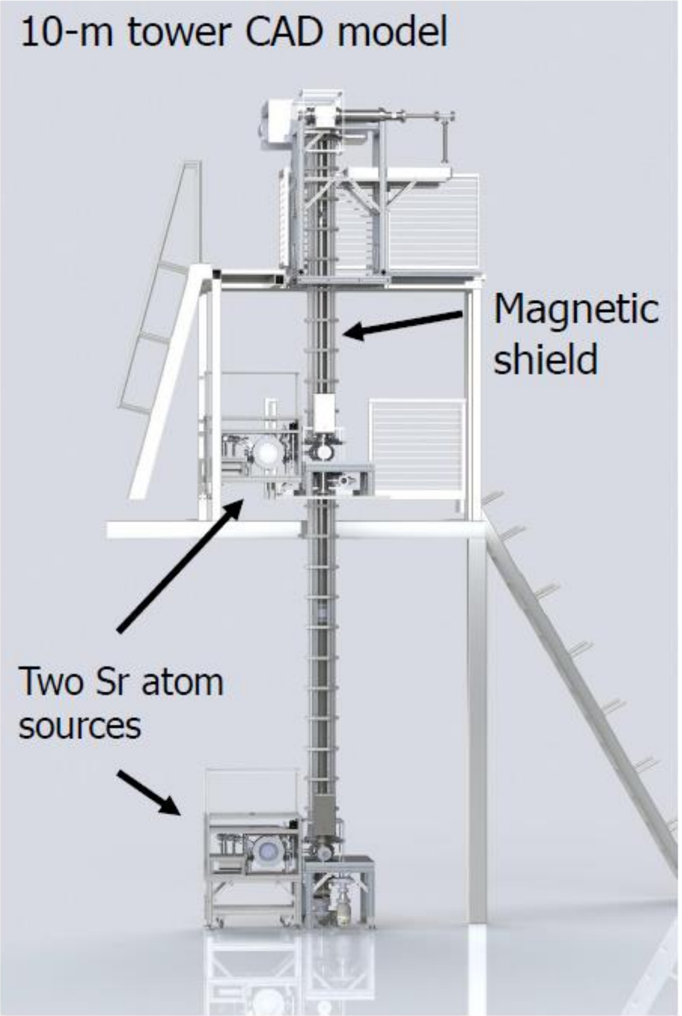
Cloud of Cooled Sr Atoms (Stanford)



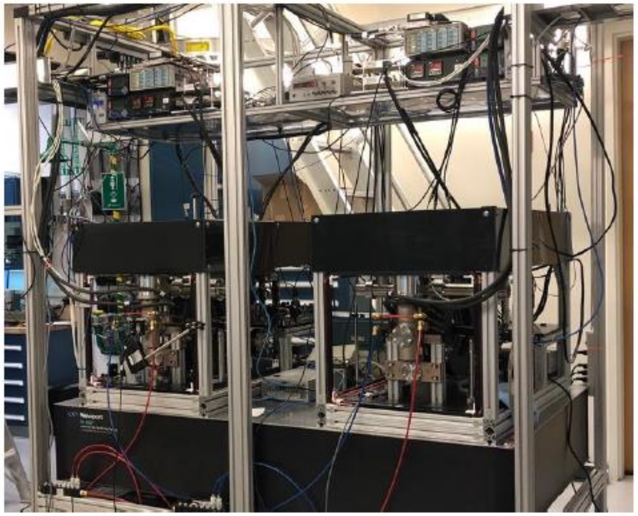
Modular Atom Sources



10-meter Sr prototype design



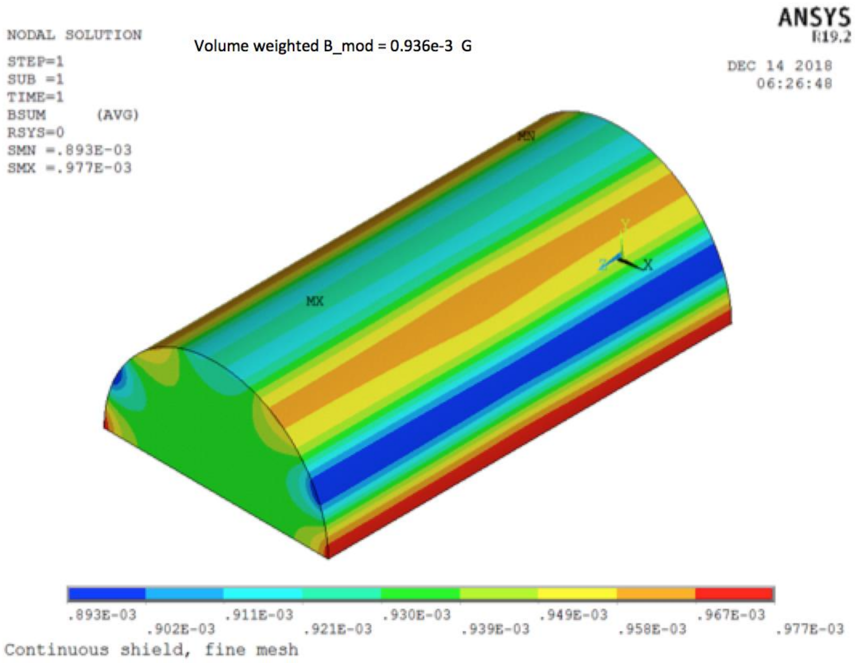
Two assembled Sr atom sources



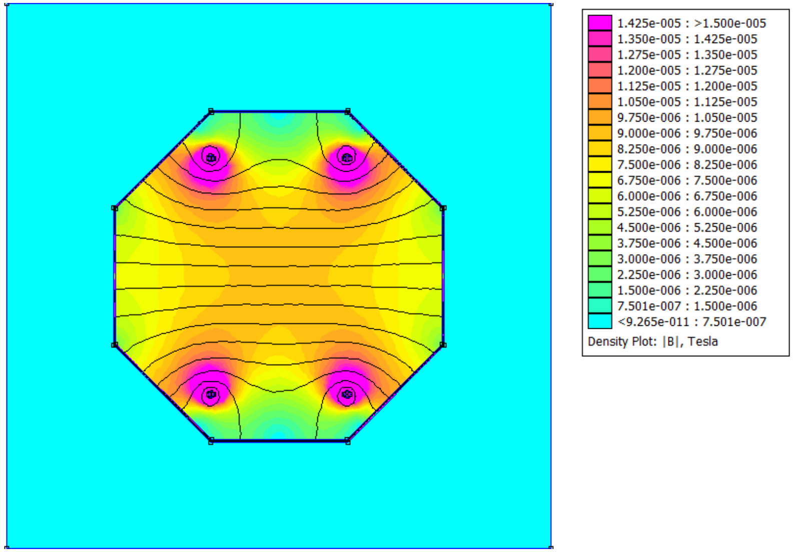
Prototype being erected NOW

Magnetic Shield Design

Continuous Shield – no circumferential air gaps



Volume weighted B_mod = 0.936e-3 G

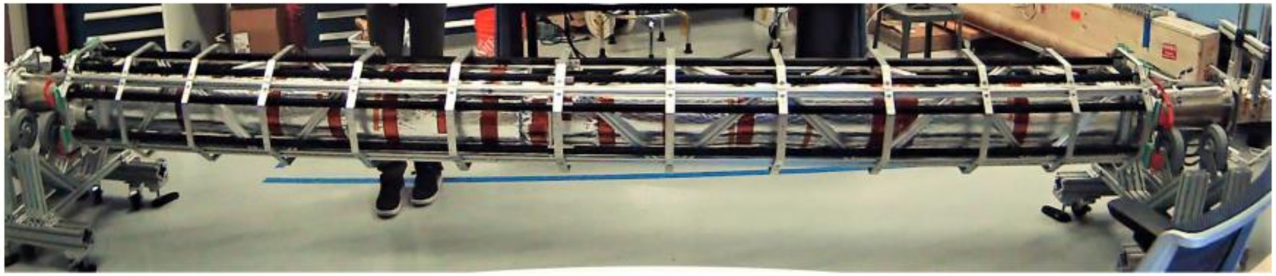


3D simulations have been done at Fermilab with ANSYS.

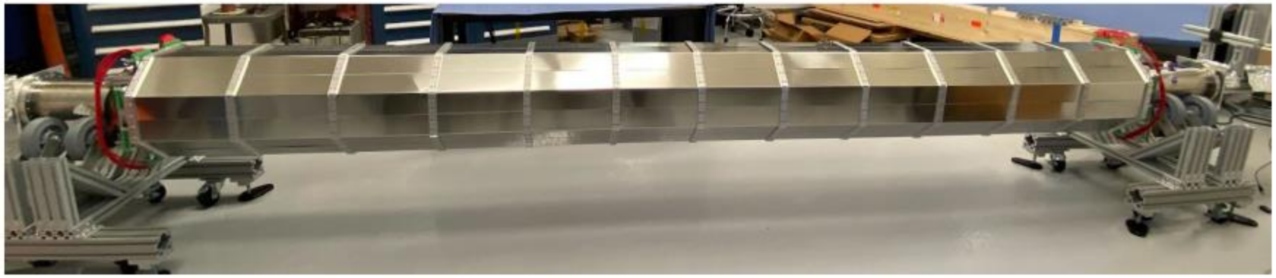
Stanford has done 2D simulation (cross-sectional view) of bias magnetic field inside an octagonal shield

Prototype Module with Magnetic Shield at Stanford

Assembled prototype MAGIS module with horizontal bias coils and magnetic shield

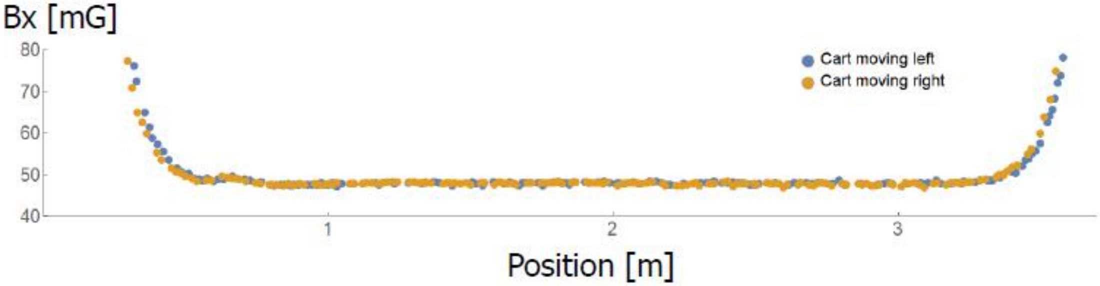


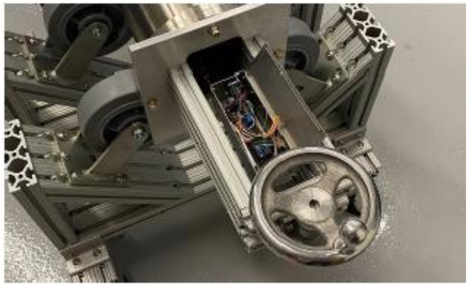
Before shield



With shield

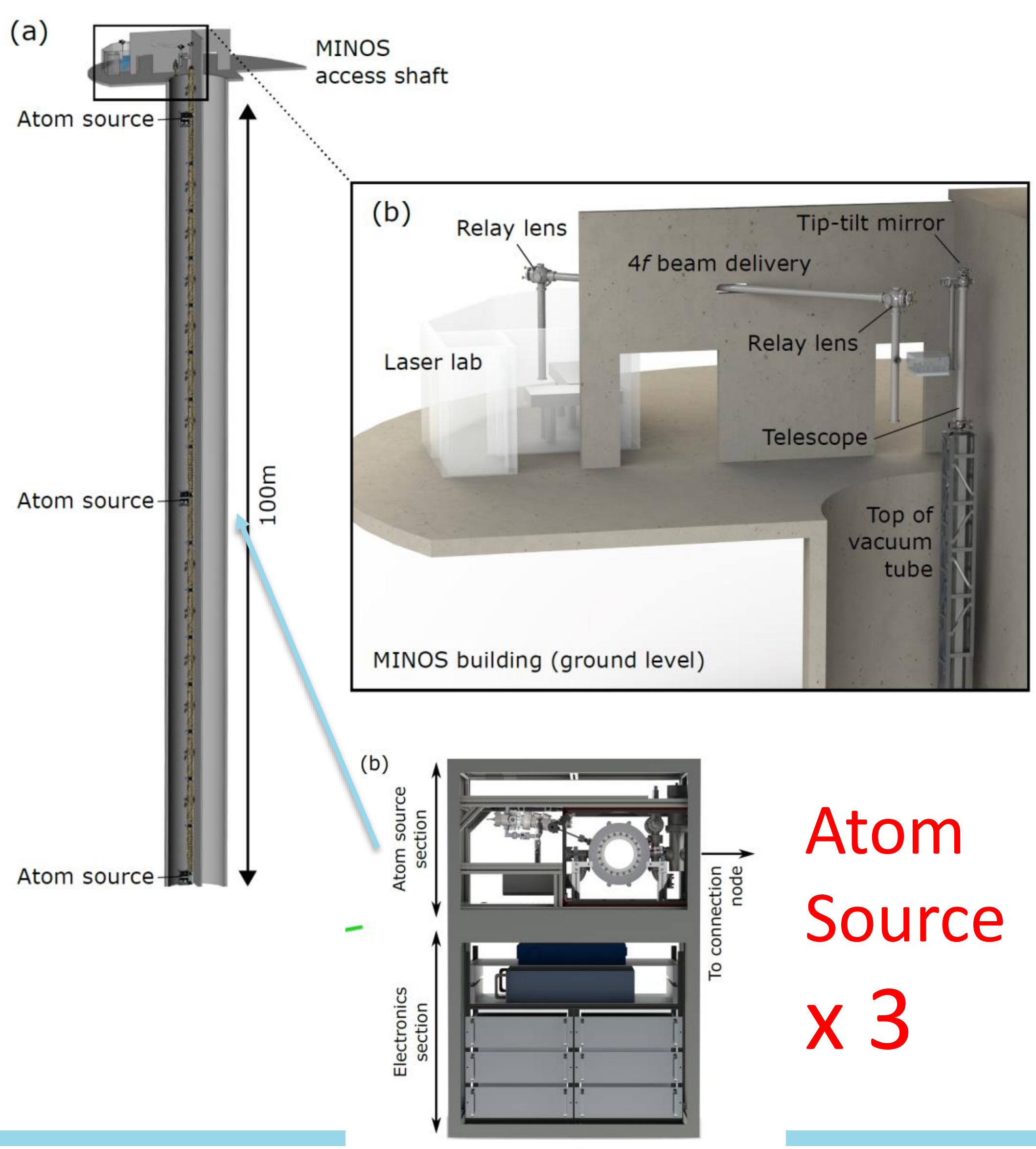
After degauss, magnetic shield meets specifications:



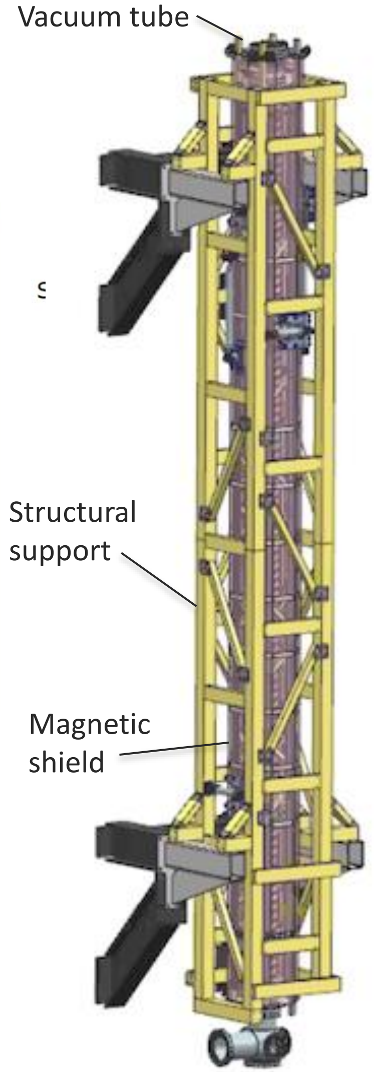


Magnetometer shuttle on suspension wires

Experiment Layout at Fermilab: Shaft, and Surface

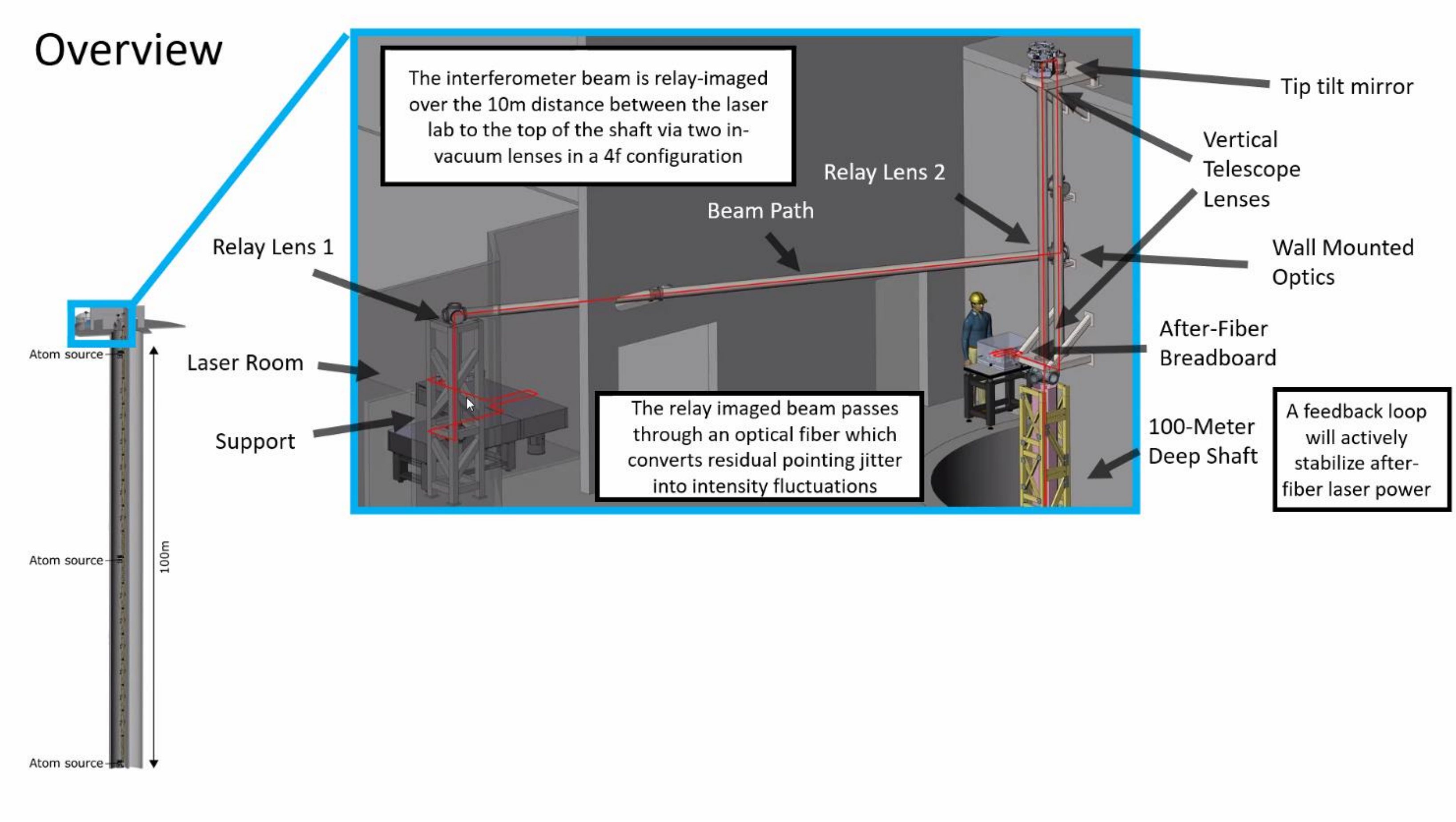


Atom Source x 3



Modular Section x 17

Beam Transfer Design



The interferometer beam is relay-imaged over the 10m distance between the laser lab to the top of the shaft via two in-vacuum lenses in a 4f configuration

The relay imaged beam passes through an optical fiber which converts residual pointing jitter into intensity fluctuations

A feedback loop will actively stabilize after-fiber laser power

Laser Lab Construction

Final outfitting stage

Camera Readout

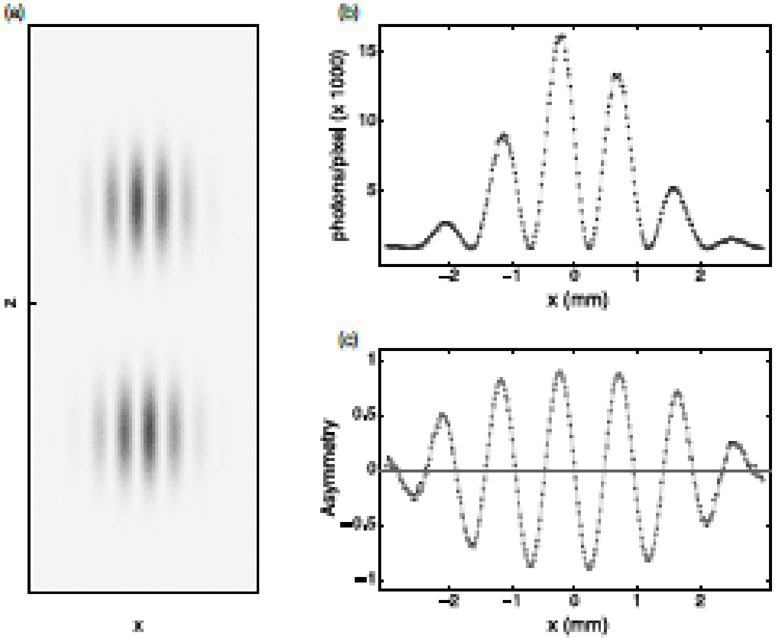
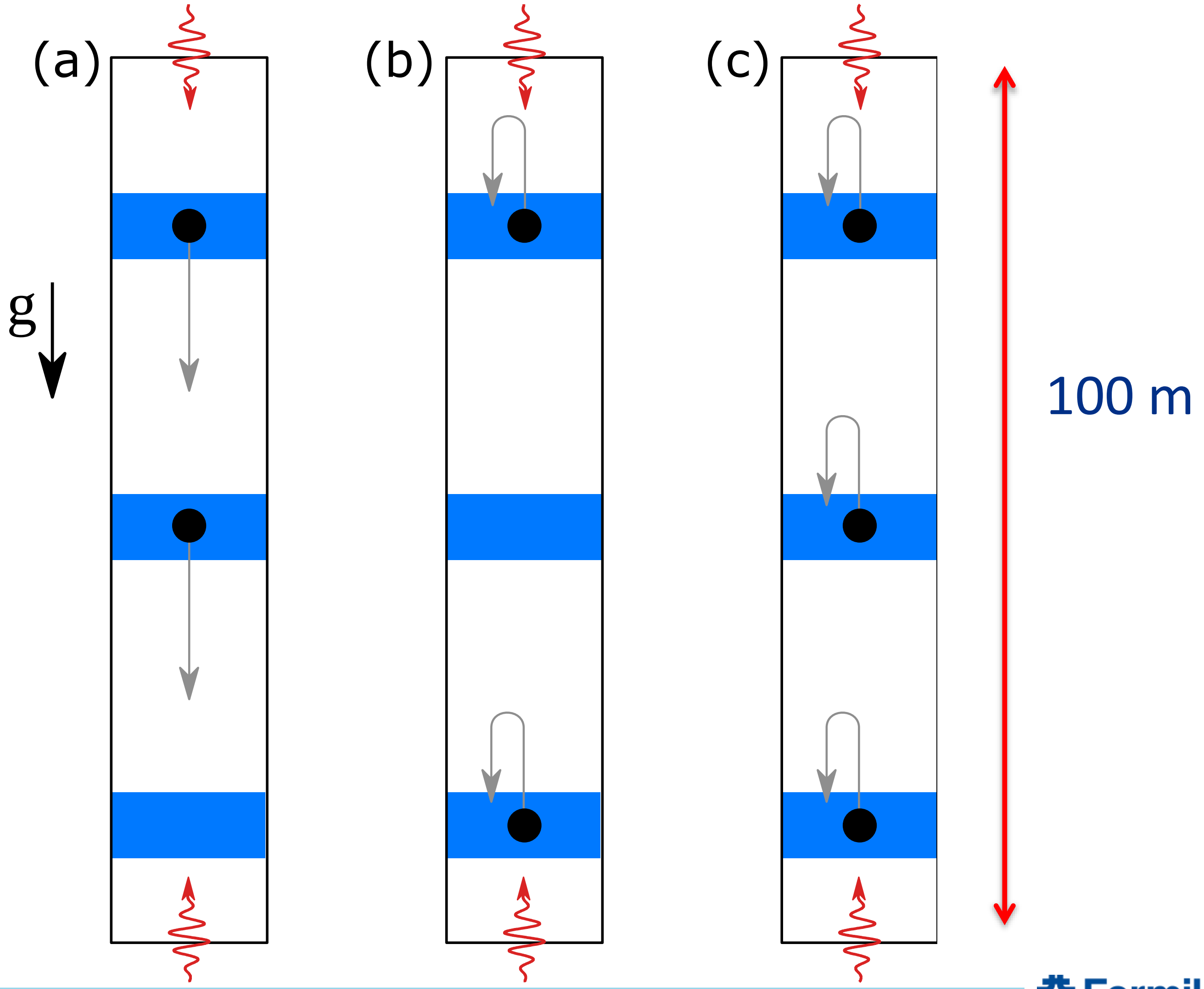


Figure 13. Simulated image of an atom interference pattern in the detection region at the end of a MAGIS-100 interferometer. (a) The simulated image shows the two detected sub-populations corresponding to the two output ports of the interferometer. The fringes are the result of the phase shear readout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



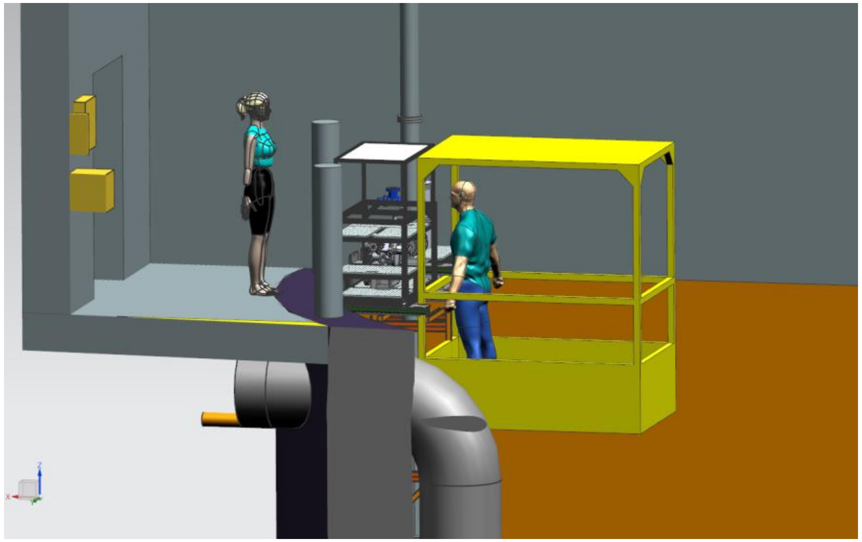
Location – MINOS building

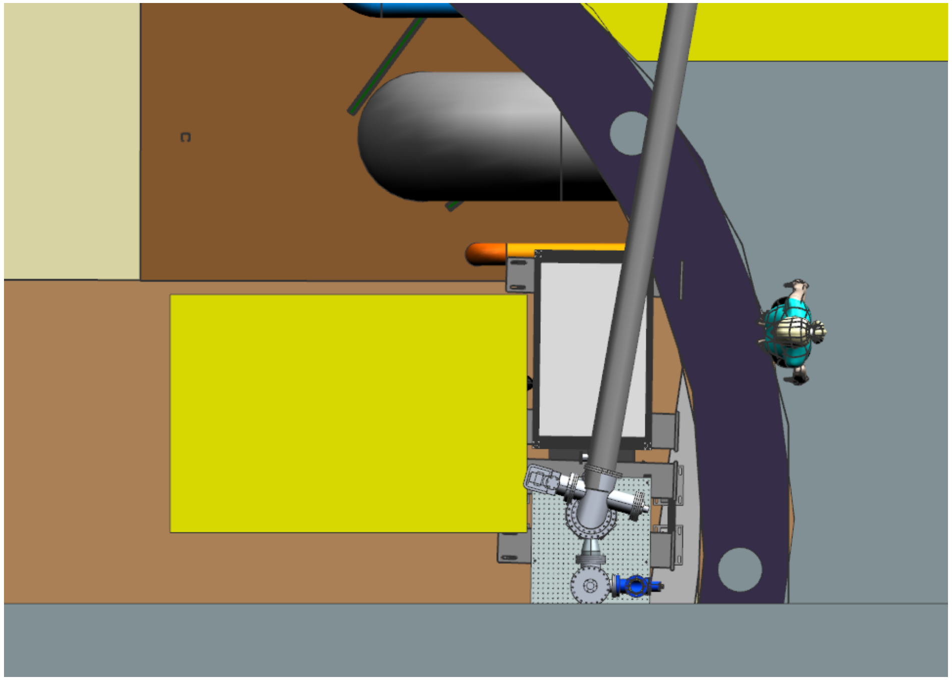
Ground level of MINOS building.

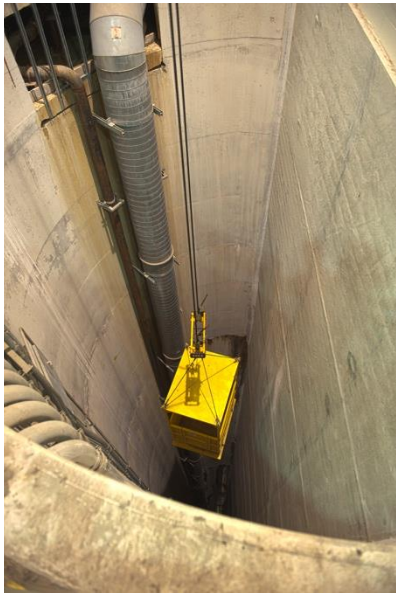
Location – Shaft in MINOS building

Top and bottom of ~100m shaft.

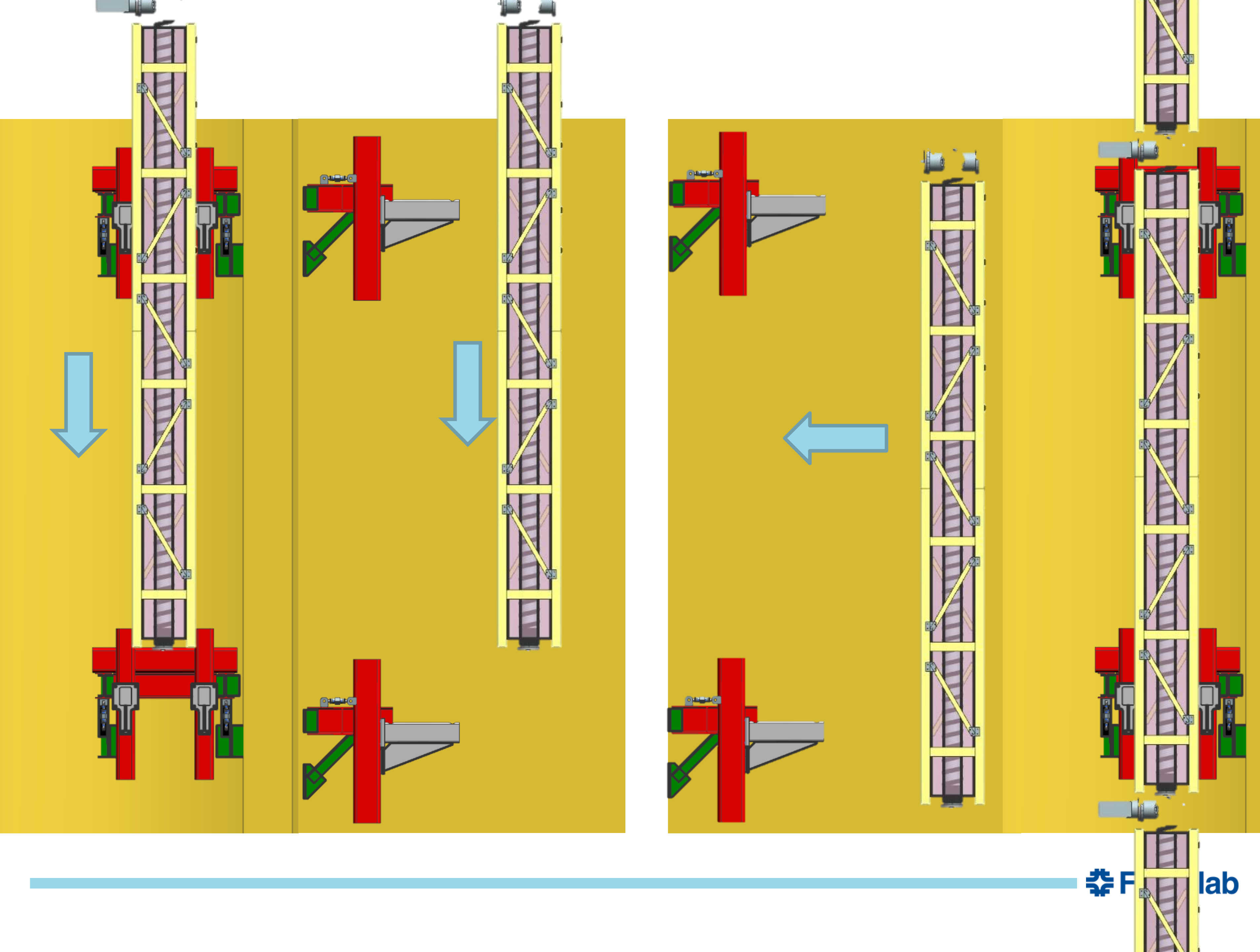
Technical: Installation Plan







Accessibility from personnel basket.



UK AION Ultimate Goal: Establish International Network

Illustrative Example:
Network could be further extended
or arranged differently

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.

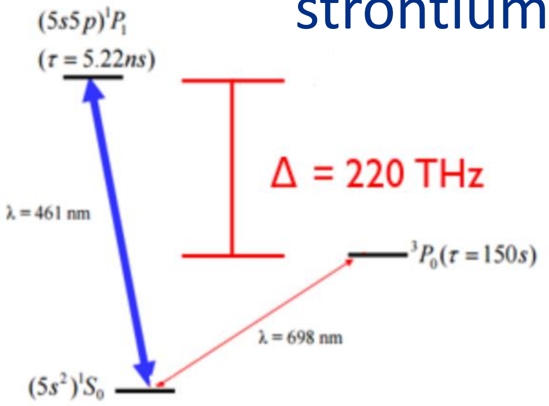
- Will give us the means to build even bigger and explore the gravitational wave universe.

- Cries out for international networking – and it’s happening!

BACKUP

Example: Extreme LMT with clock atoms

Clock atoms (e.g. strontium)



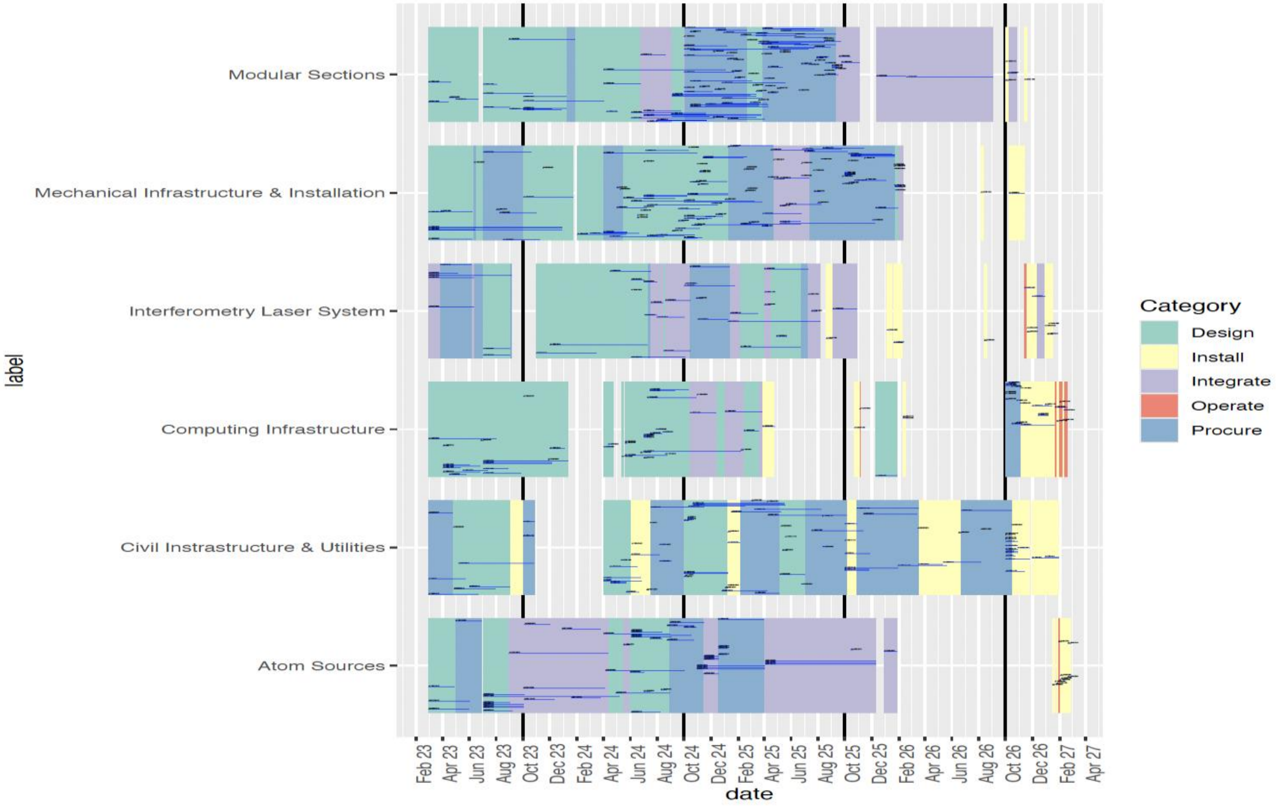
Single photon transition for atom optics

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

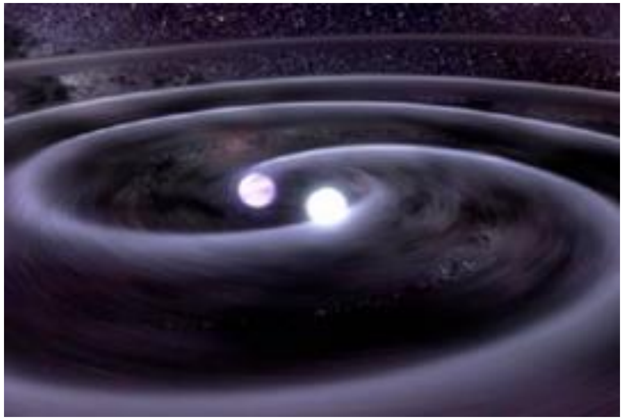
MAGIS-100 Recent Construction Schedule

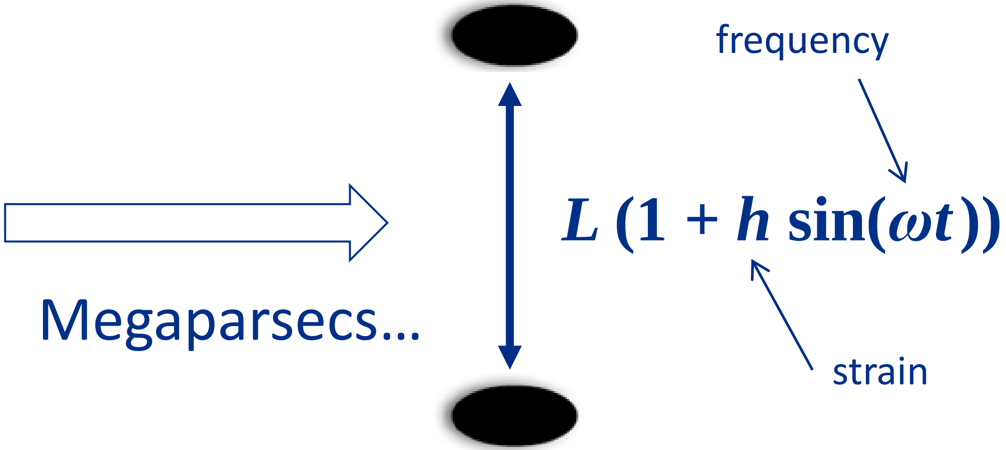


Development of MAGIS Program in Short and Long Term

- 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 interfereometry
- 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.

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



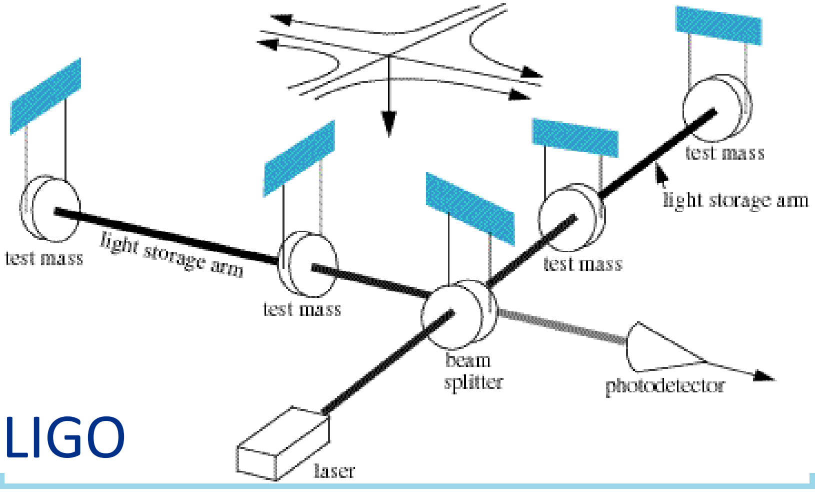


Megaparsecs…

$L\,(1 + h\,\sin(\omega t))$

frequency

strain



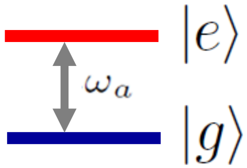
LIGO

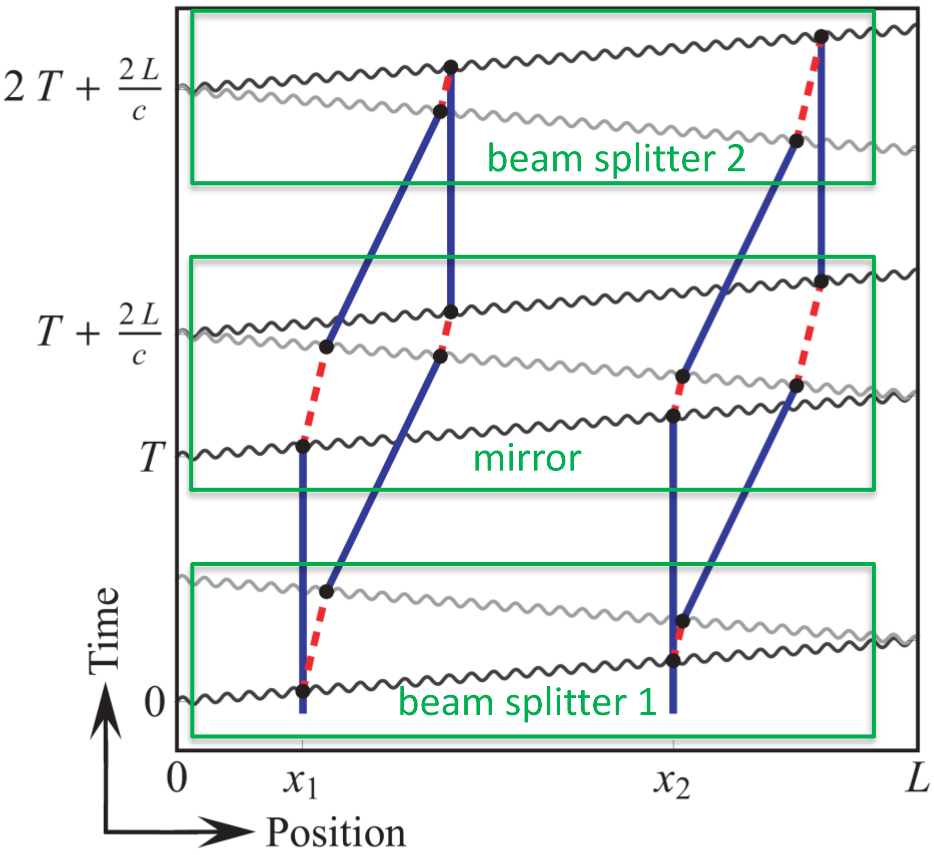
LIGO and other optical interferometers **use two baselines**

In principle, **only one is required**

Second baseline needed to

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 ~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

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

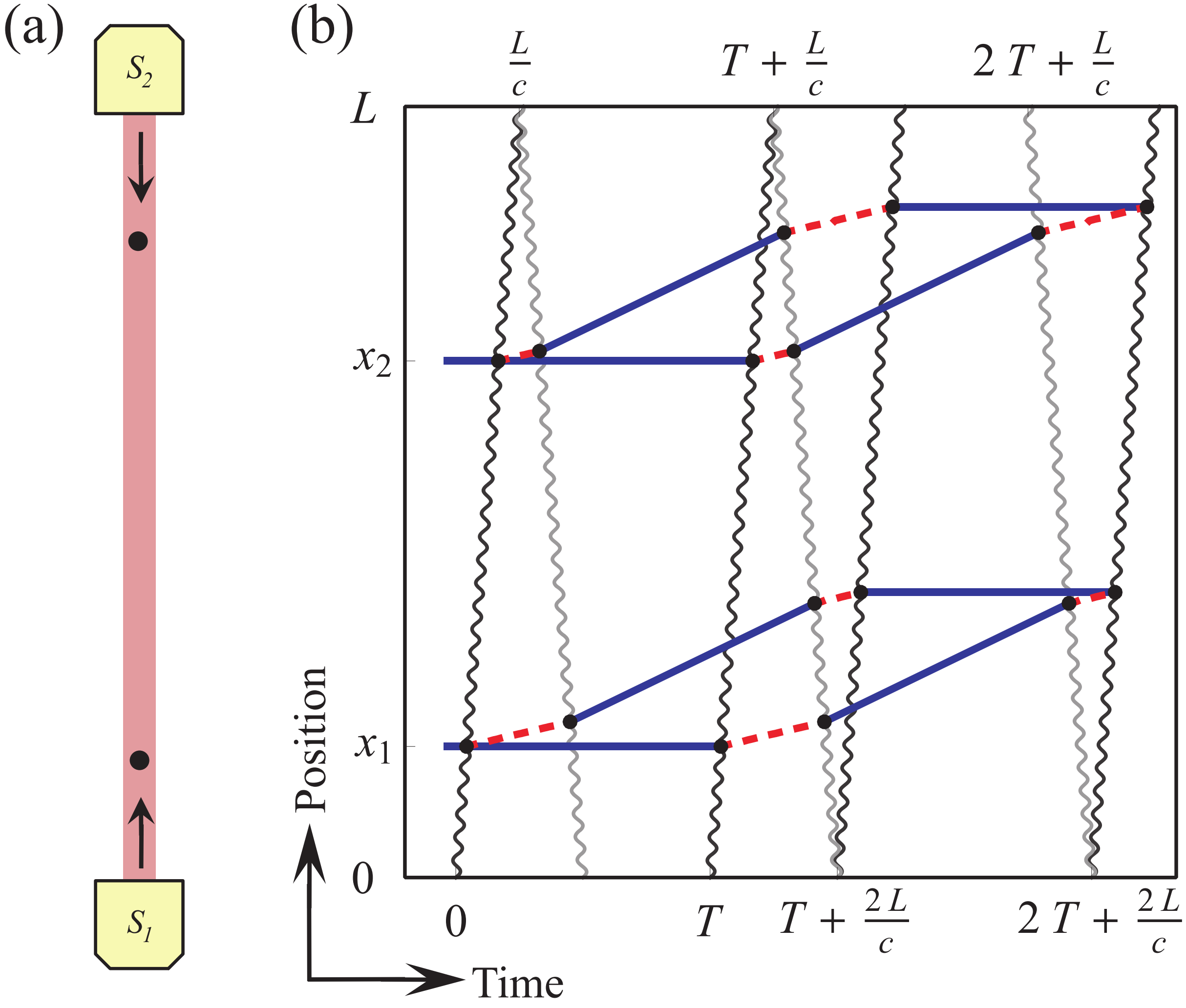
1\. Increase momentum splitting $n\hbar k$ between the two interferometer arms.

1\. Make a tall atomic fountain to increase the free fall distance ~gT^2.

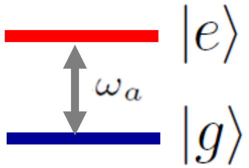
2\. Do both at the same time. Typical operating conditions: arm splitting >10 cm, T ~ 1 s

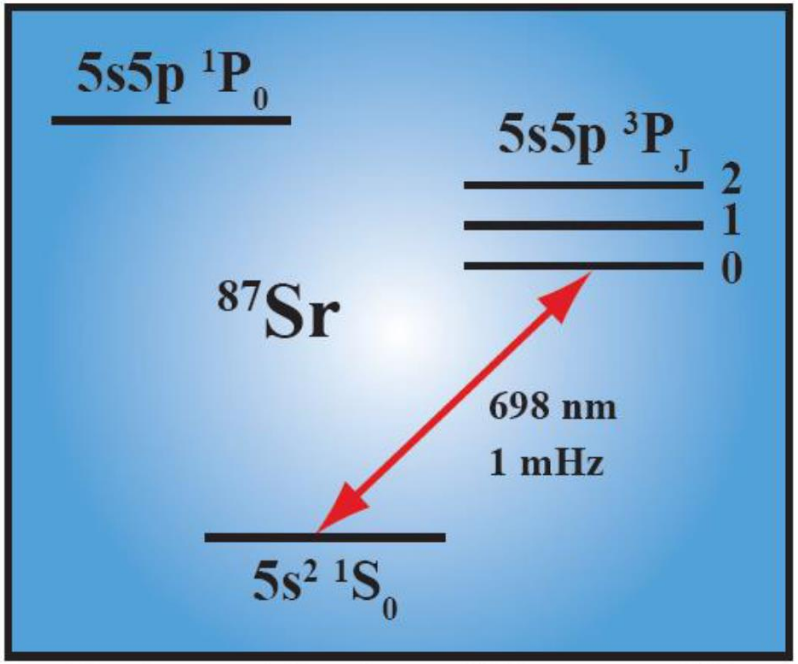
TK, P. Asenbaum, C. Overstreet, C. Donnelly, S. Dickerson, A. Sugarbaker, J. Hogan, and M. Kasevich, Nature 2015
P. Asenbaum, C. Overstreet, TK, D. Brown, J. Hogan, and M. Kasevich, PRL 2017

Gradiometer to reduce systematics



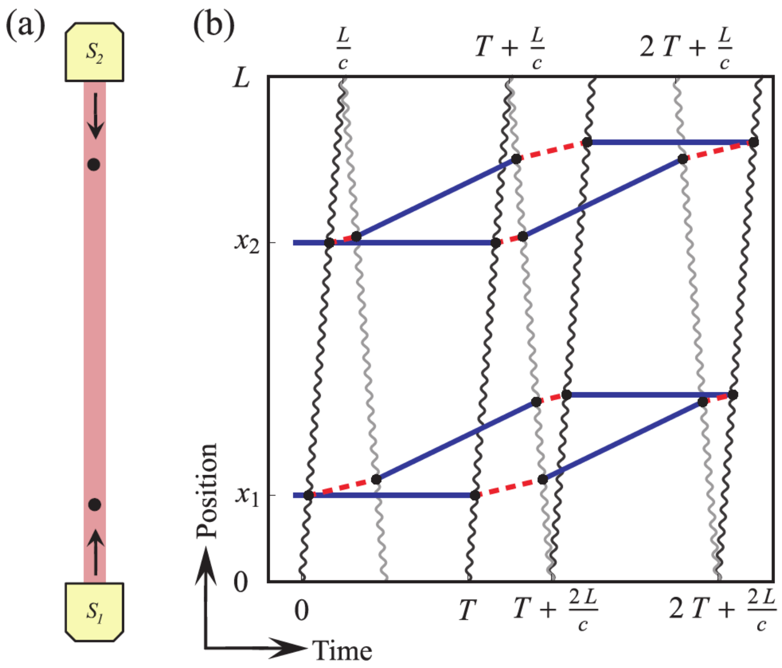
Hybrid Clock/Accelerometer





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)



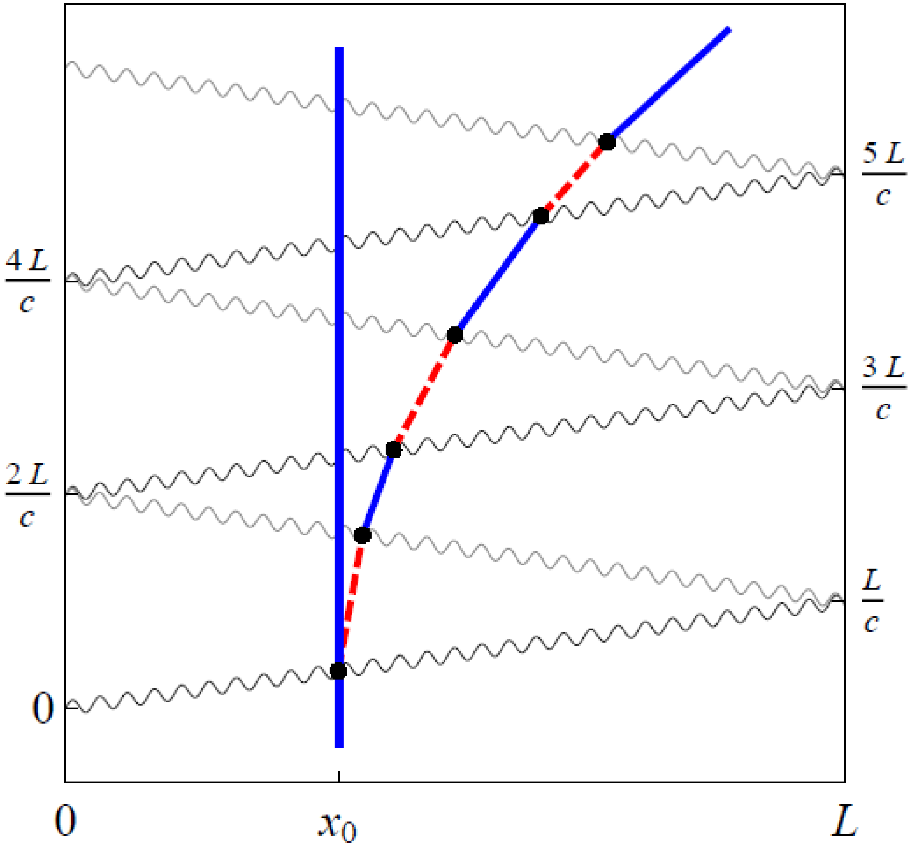
- Beamsplitter—Mirror—Beamsplitter sequence makes interferometer insensitive to initial atom position and velocity

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

LMT and Resonant Pulse Sequences

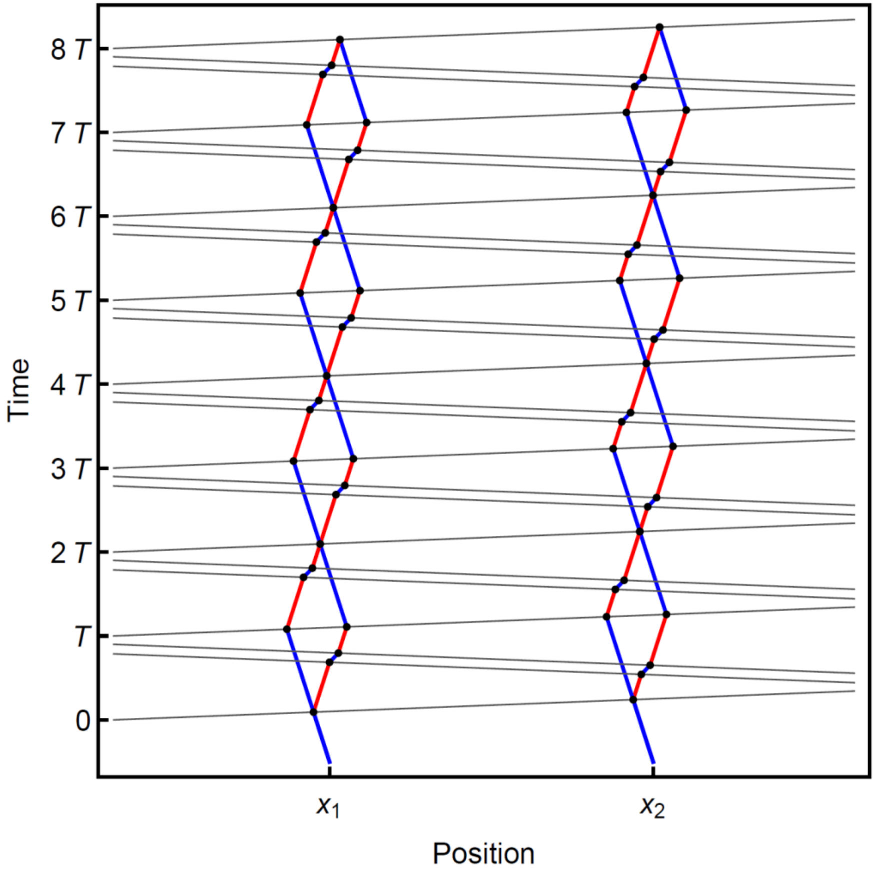
Sequential single-photon transitions remain laser noise immune

LMT beamsplitter (N = 3)



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

Resonant sequence (Q = 4)

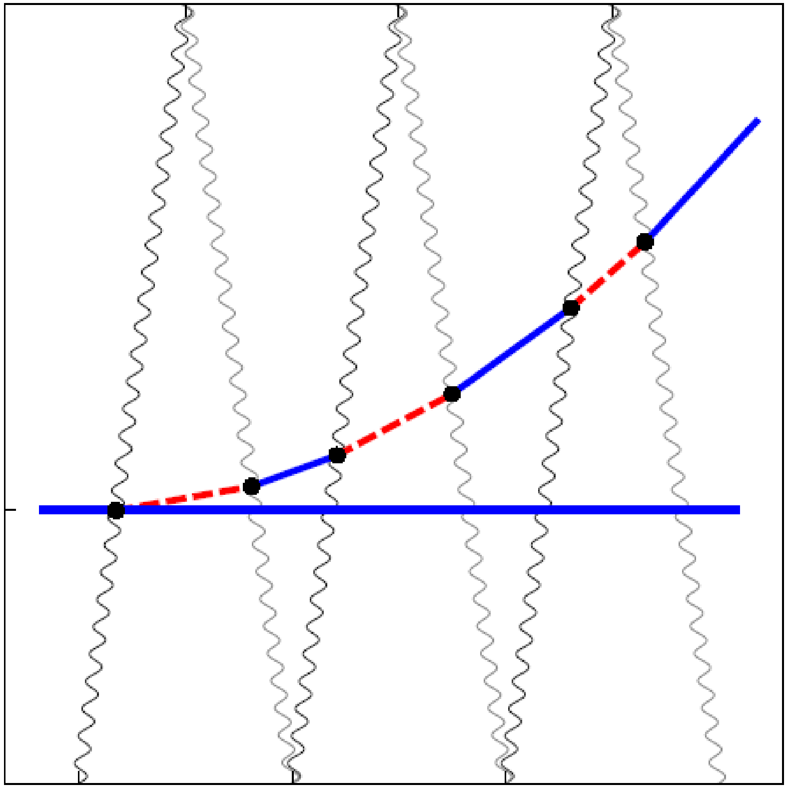


Graham, *et al.*, PRD (2016)

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: <u>total amount of time spent in excited state during beam splitter decreases as x increases from 0 to L (giving differential signal)</u> **<u>and is proportional to number of pulses</u>**

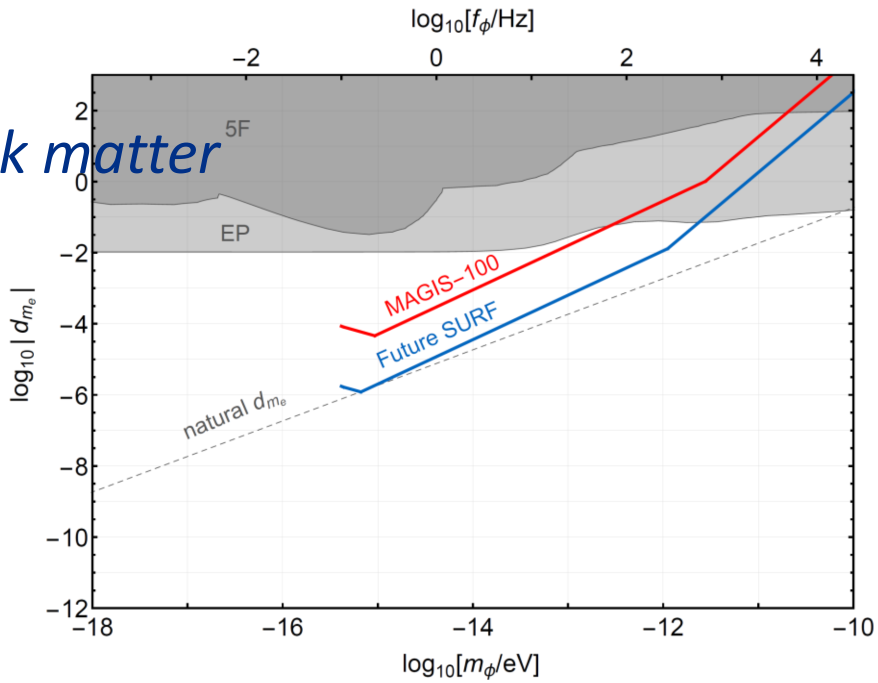
- Magnitude of contribution to differential phase shift from each interferometer zone for beam splitters with 2n pulses:

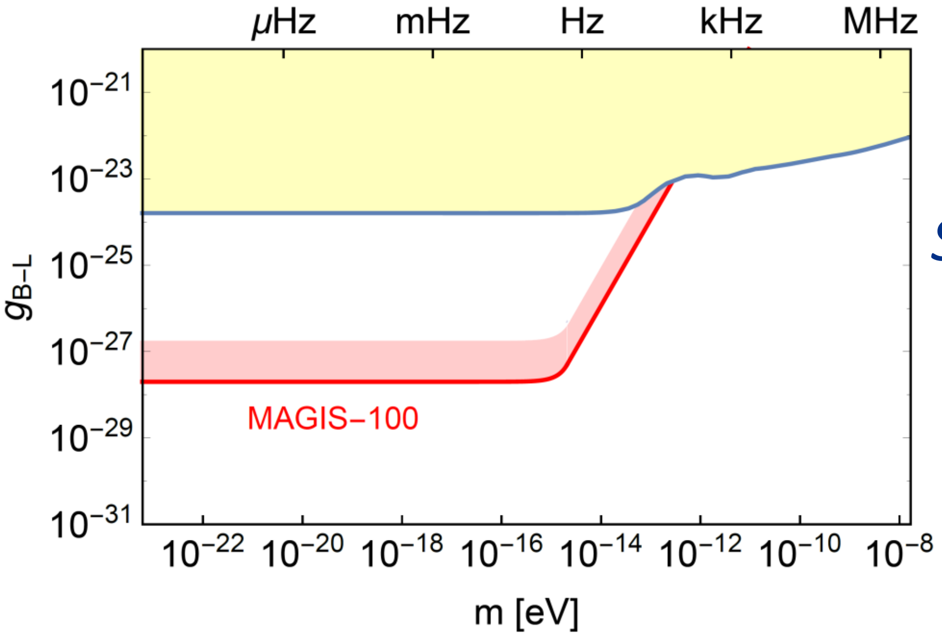
$$\Delta\phi \sim 2n\omega_A\left(L/c\right)$$

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

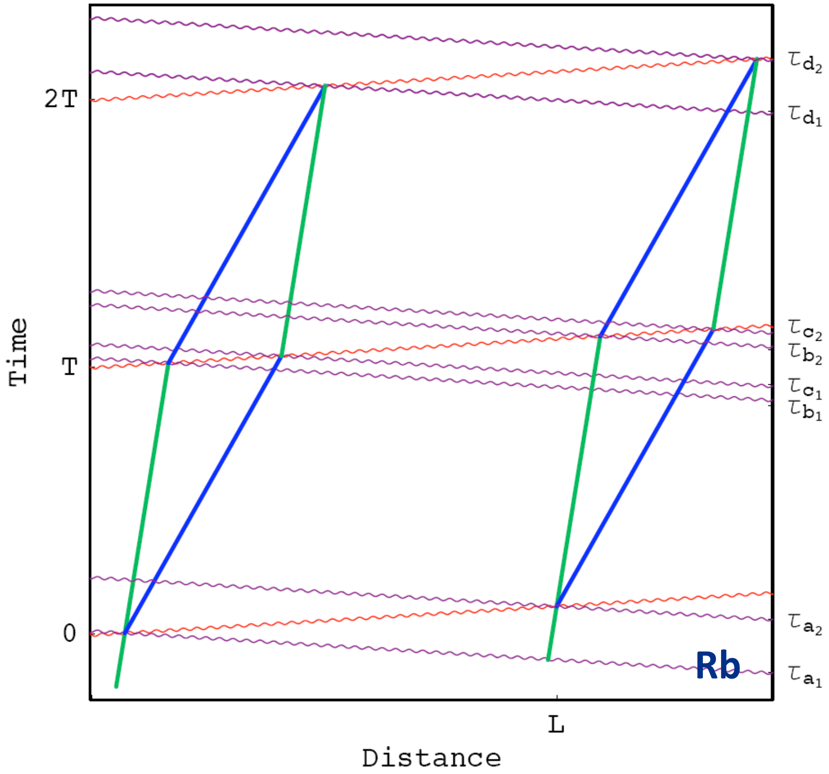
~ 1 year data taking
Assuming shot-noise limited phase resolution

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

Arvanitaki et al., PRD **97**, 075020 (2018).

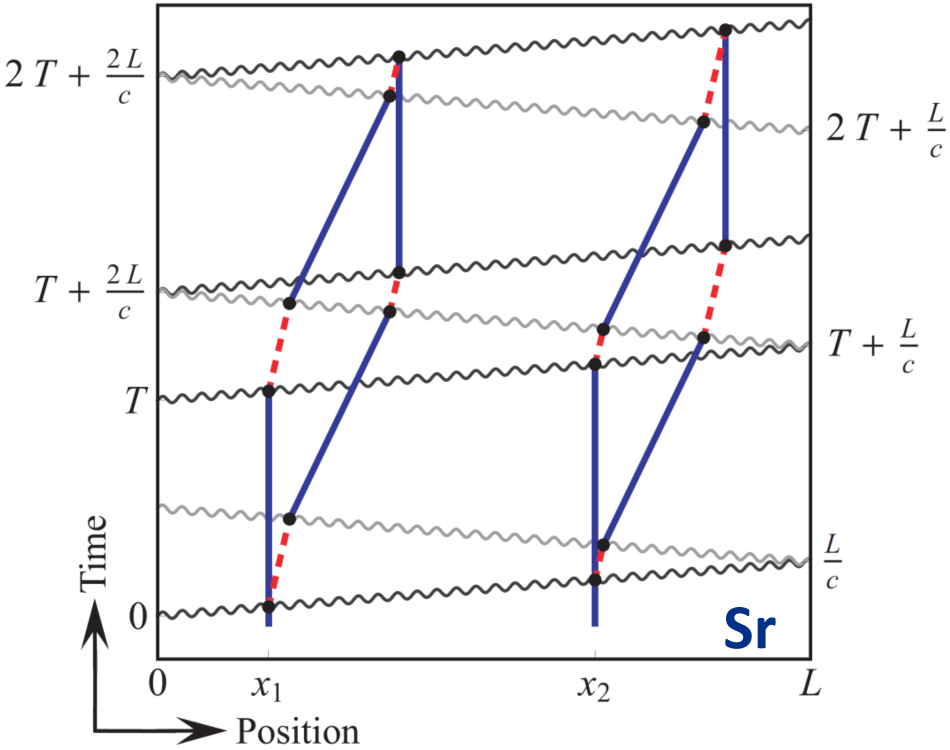
Two-photon vs. single photon AI

2-photon transitions



Laser phase **not** common

1-photon transitions

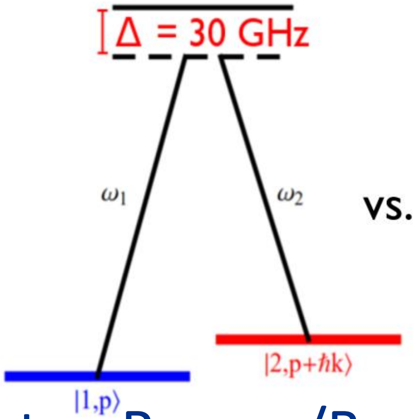


Laser noise suppressed

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

Extreme LMT with clock atoms

Alkali atoms (e.g. rubidium)

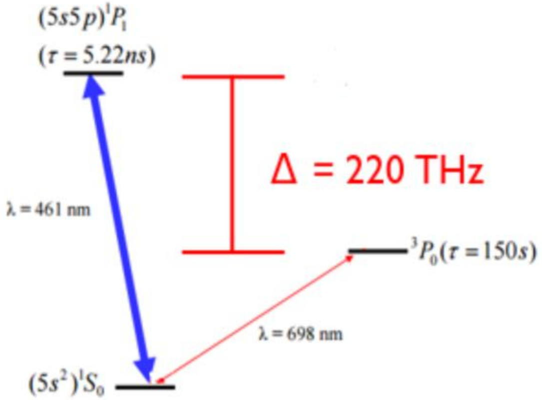


Two photon Raman/Bragg transitions for atom optics

Requires large detuning, high power to suppress spontaneous emission

Current state of the art: ~100

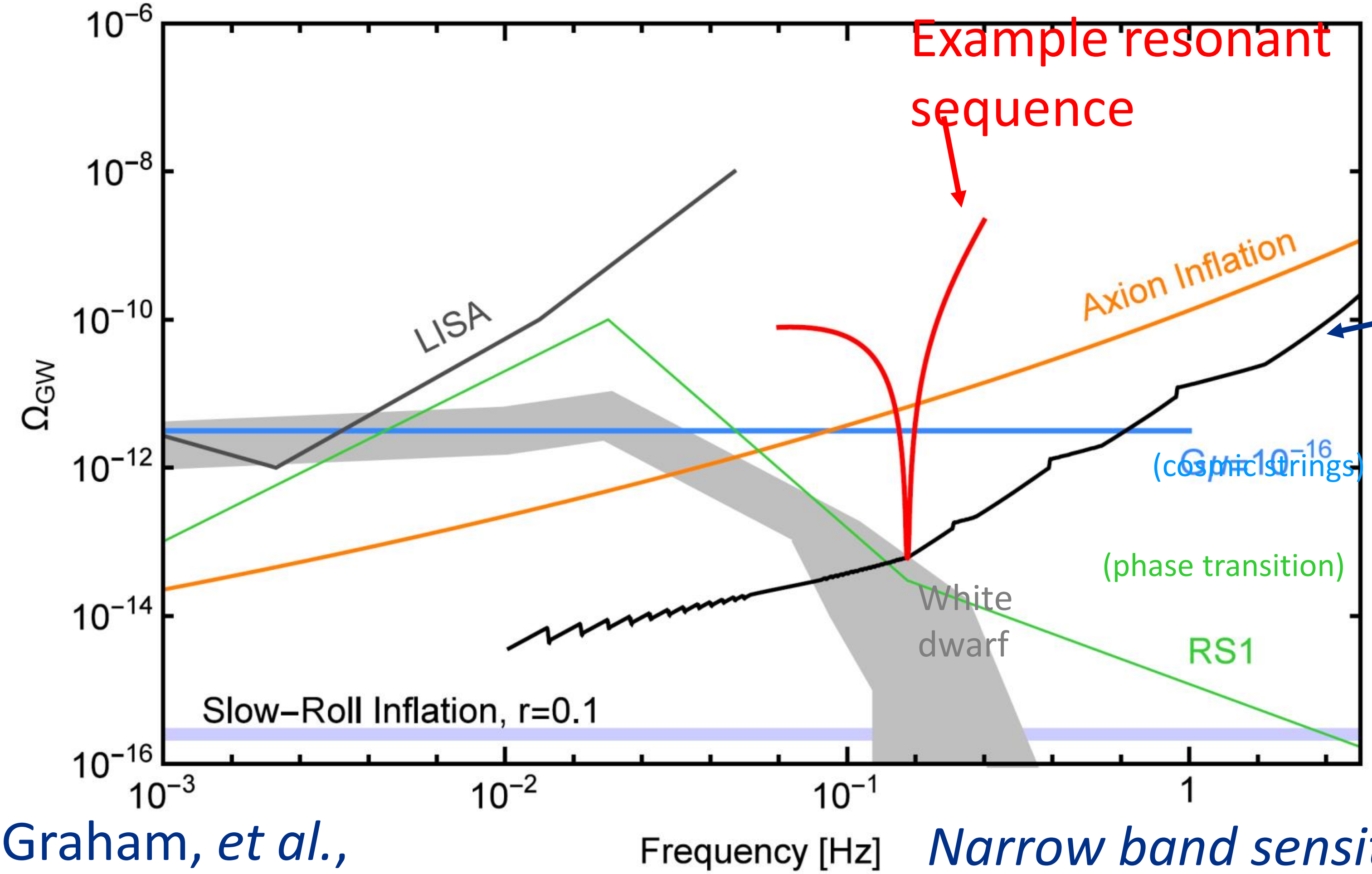
Clock atoms (e.g. strontium)



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



Example resonant sequence

Envelope

(cosmic strings)

(phase transition)

White dwarf

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

Narrow band sensitivity possible in 1 year

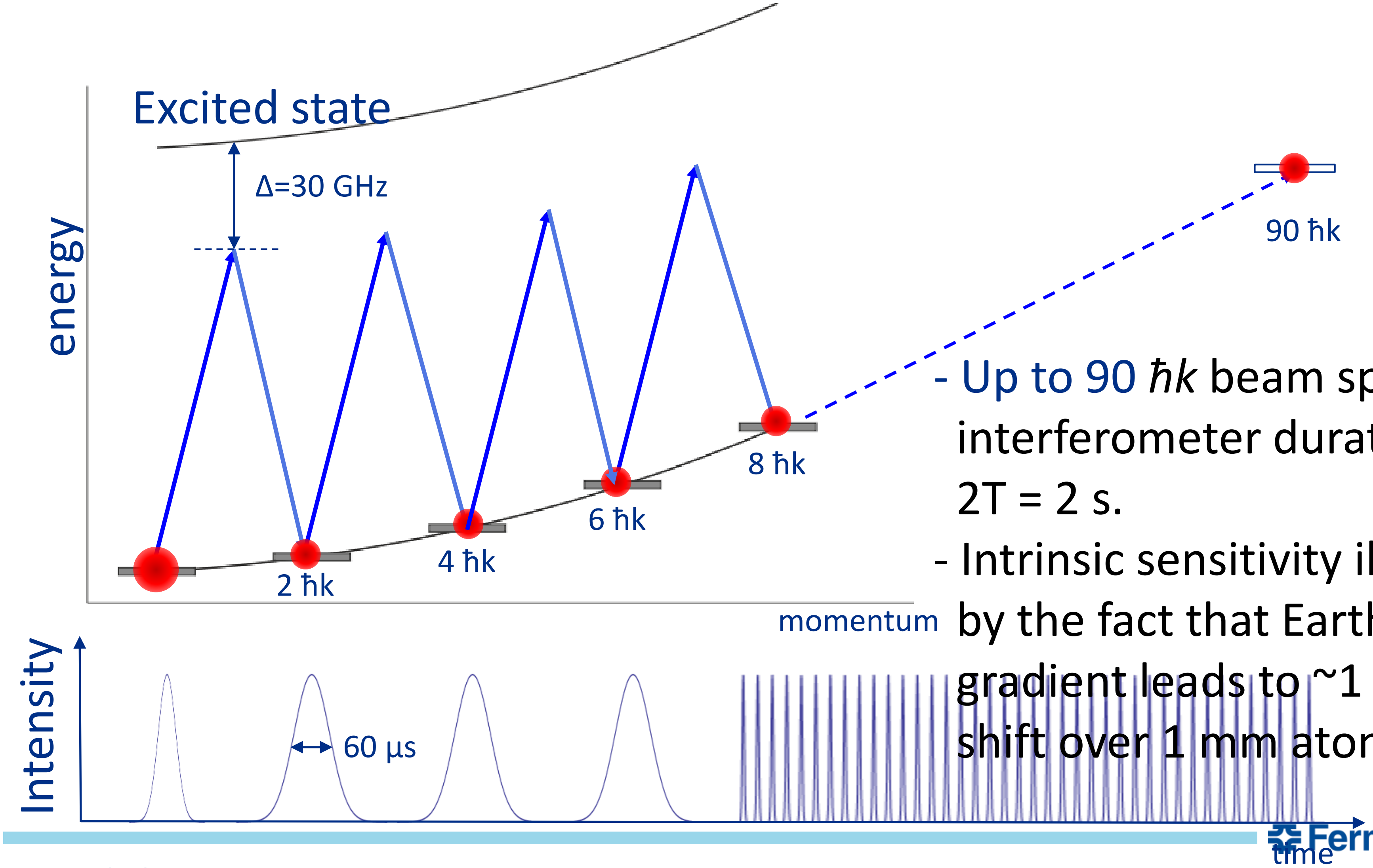
Advantages of Strontium

- 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.

Sequential Bragg Atom Optics



- Up to 90 $\hbar k$ beam splitters
  interferometer duration
  2T = 2 s.
- Intrinsic sensitivity illustra
  by the fact that Earth grav
  gradient leads to ~1 rad ph
  shift over 1 mm atom clou