MAGIS-100

Jon Coleman On behalf of the MAGIS collaboration

Workshop on Atomic Experiments for Dark Matter and Gravity Exploration

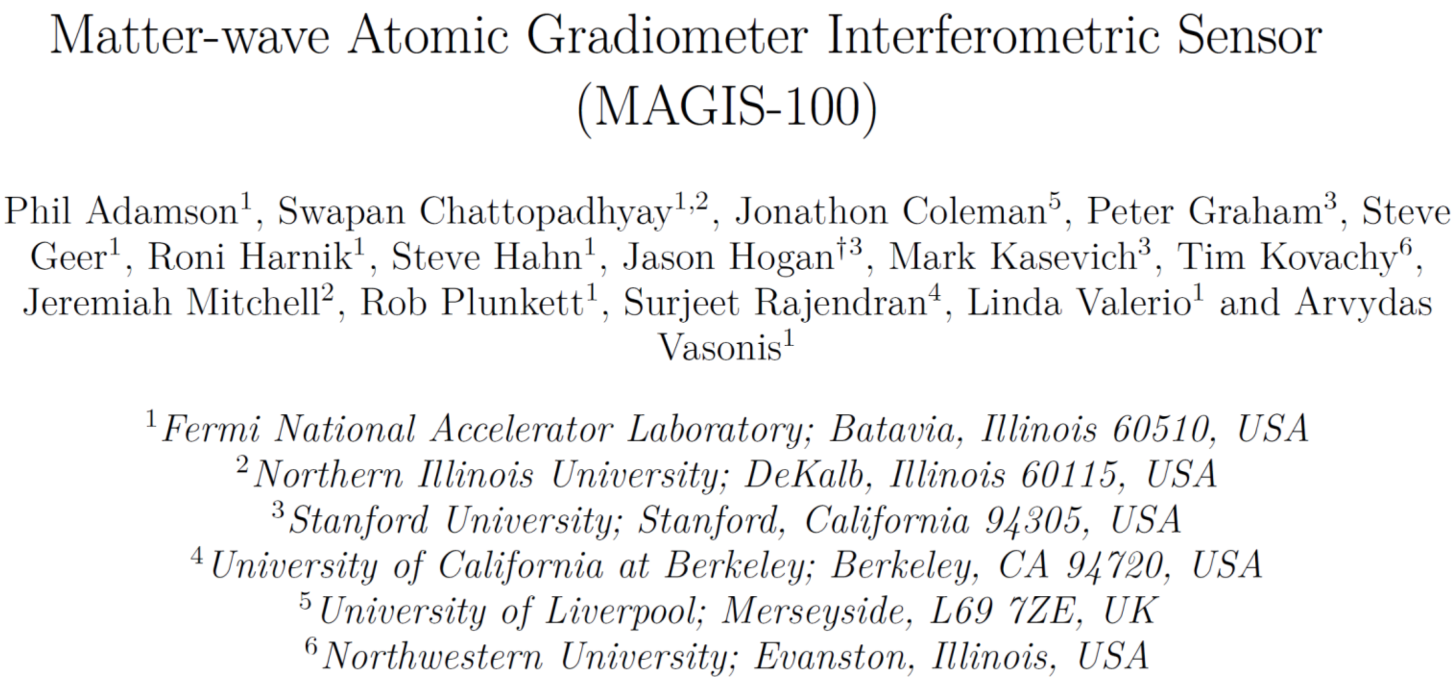
22-23 July 2019

CERN

UNIVERSITY OF LIVERPOOL

THE ROYAL SOCIETY

MAGIS Collaboration



Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Phil Adamson[1], Swapan Chattopadhyay[1,2], Jonathon Coleman[5], Peter Graham[3], Steve Geer[1], Roni Harnik[1], Steve Hahn[1], Jason Hogan[†3], Mark Kasevich[3], Tim Kovachy[6], Jeremiah Mitchell[2], Rob Plunkett[1], Surjeet Rajendran[4], Linda Valerio[1] and Arvydas Vasonis[1]

[1] *Fermi National Accelerator Laboratory; Batavia, Illinois 60510, USA*
[2] *Northern Illinois University; DeKalb, Illinois 60115, USA*
[3] *Stanford University; Stanford, California 94305, USA*
[4] *University of California at Berkeley; Berkeley, CA 94720, USA*
[5] *University of Liverpool; Merseyside, L69 7ZE, UK*
[6] *Northwestern University; Evanston, Illinois, USA*

Science Case – See Fermilab LoI

A new ‘telescope’ for Unexplored Phase Space

“Ultralight” dark matter (e.g., axions, dilatons, etc.)

- Mass ~10^{-15} eV
- Would act like a **classical field**

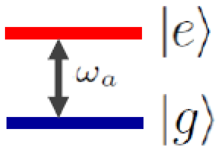
Gravitational waves in the mid-band

Tests of quantum mechanics at long time / length scales

Equivalence principle tests (spin dependent gravity)

Lorentz invariance tests

Clock Gradiometer Concept

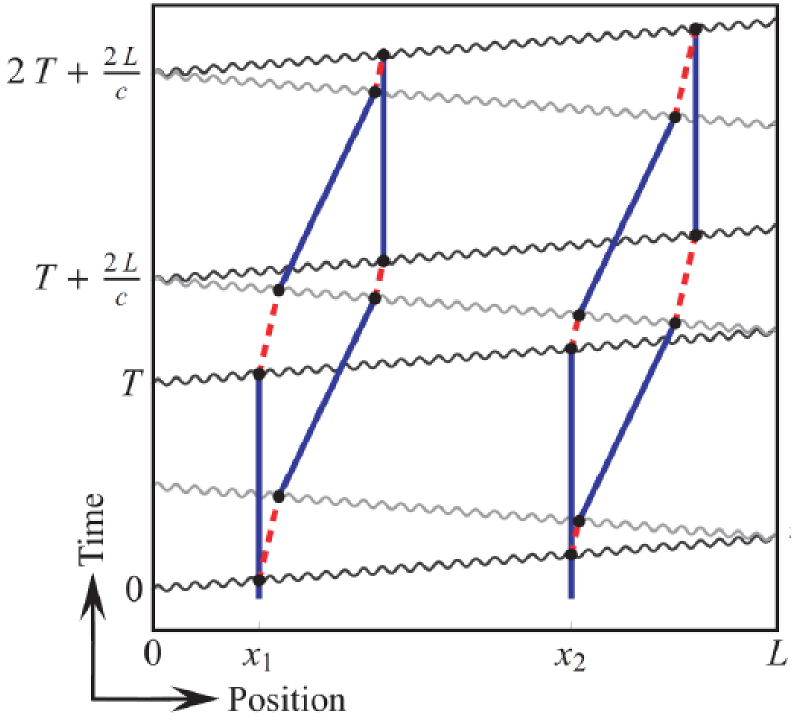


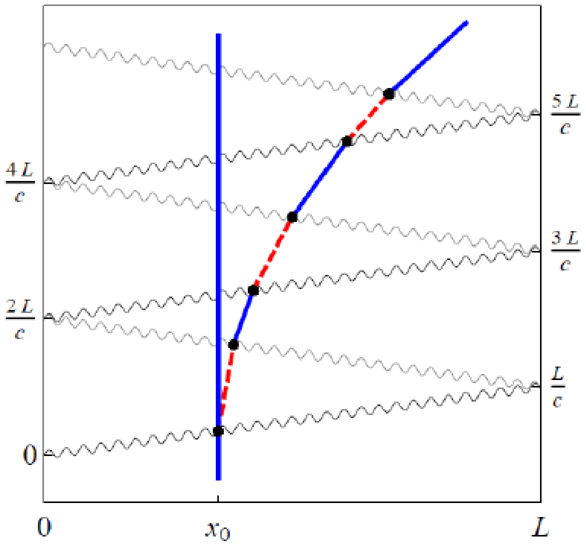
Excited state phase evolution:

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

Two ways for phase to vary:

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





LMT beamsplitter (6 ħk)

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

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

Multiple ways to detect ultralight DM (axions, dilatons, moduli, etc)

1. Effects fundamental constants such as the electron mass or fine structure constant will change the energy levels of the quantum states used in the interferometer

2. Causes accelerations: can be searched for by comparing the accelerometer signals from two simultaneous quantum interferometers run with different Sr isotopes

3. Effects precession of nuclear spins, such as general axions. Searched for by comparing simultaneous, co-located interferometers with the Sr atoms in different quantum states with differing nuclear spins

Ultralight scalar dark matter

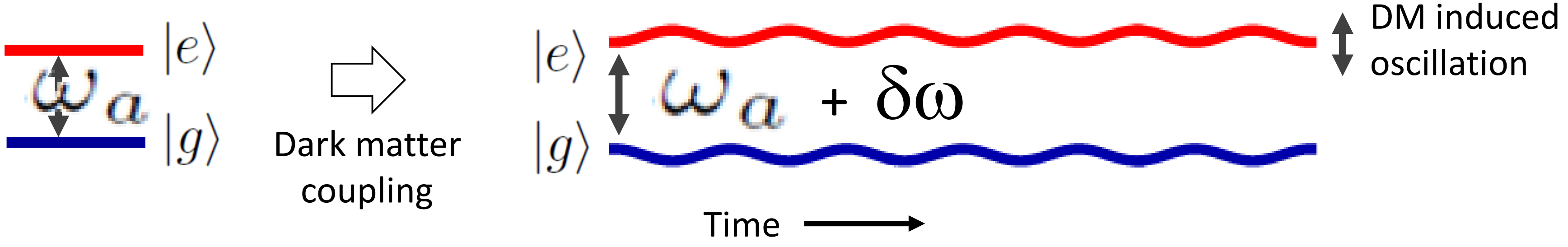
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

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

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

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

DM coupling causes time-varying atomic energy levels:



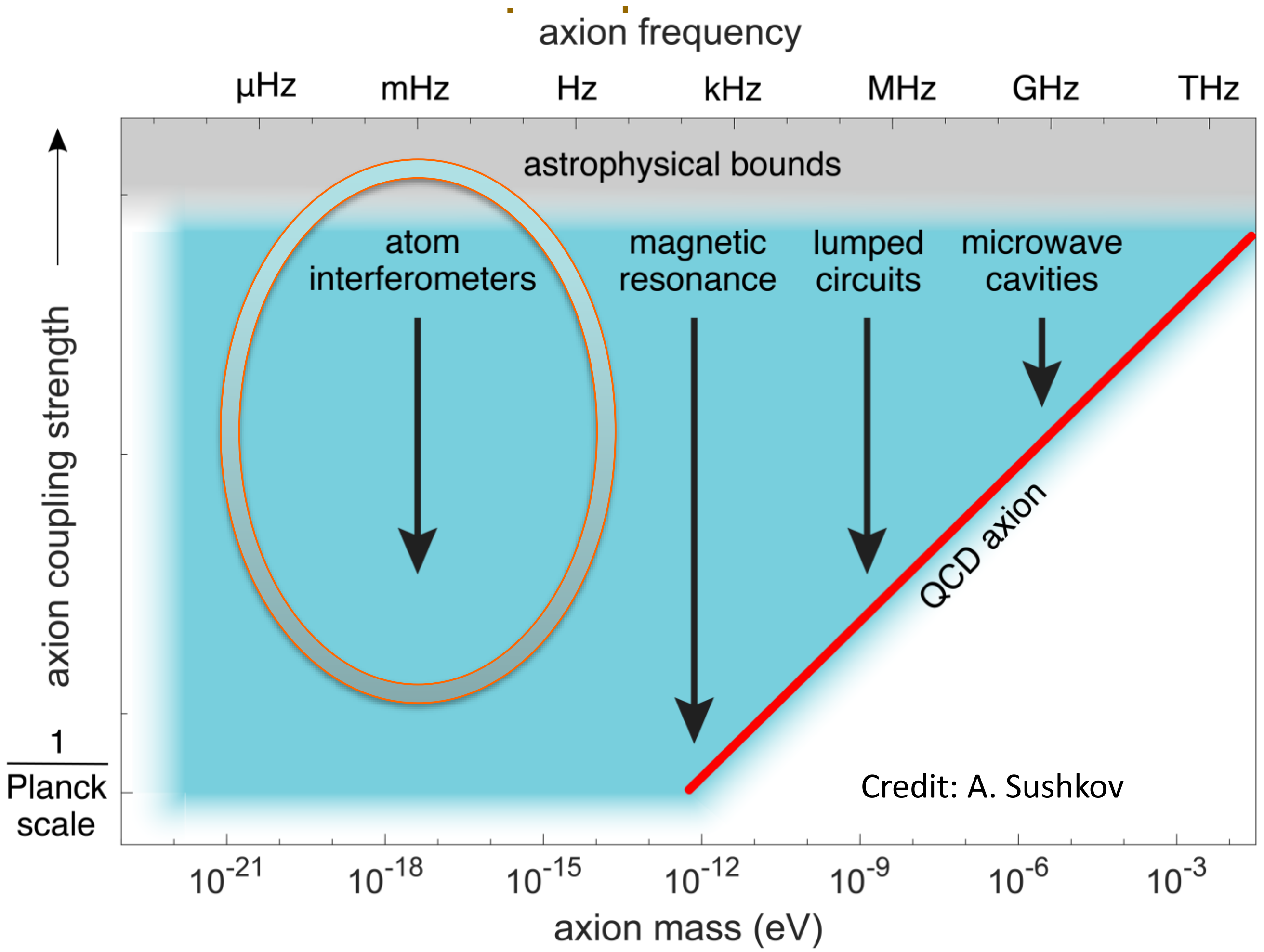
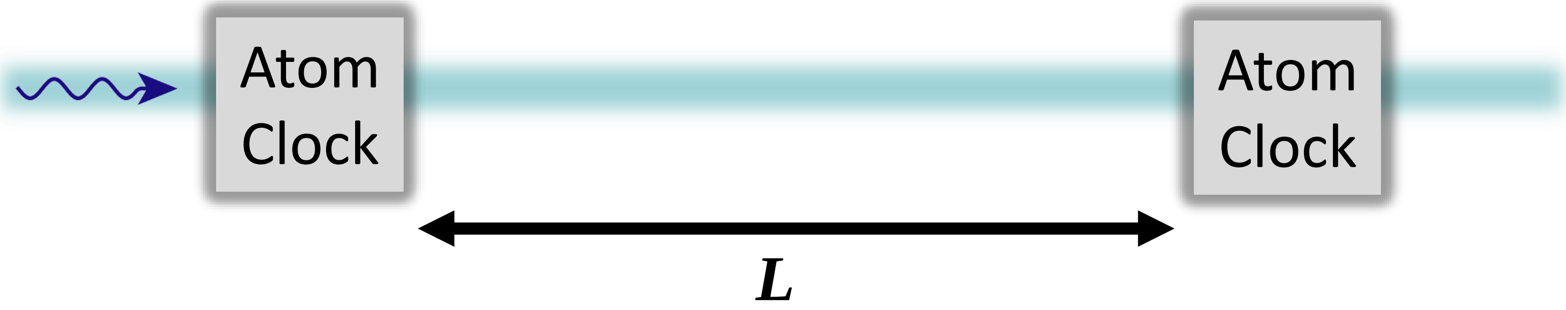
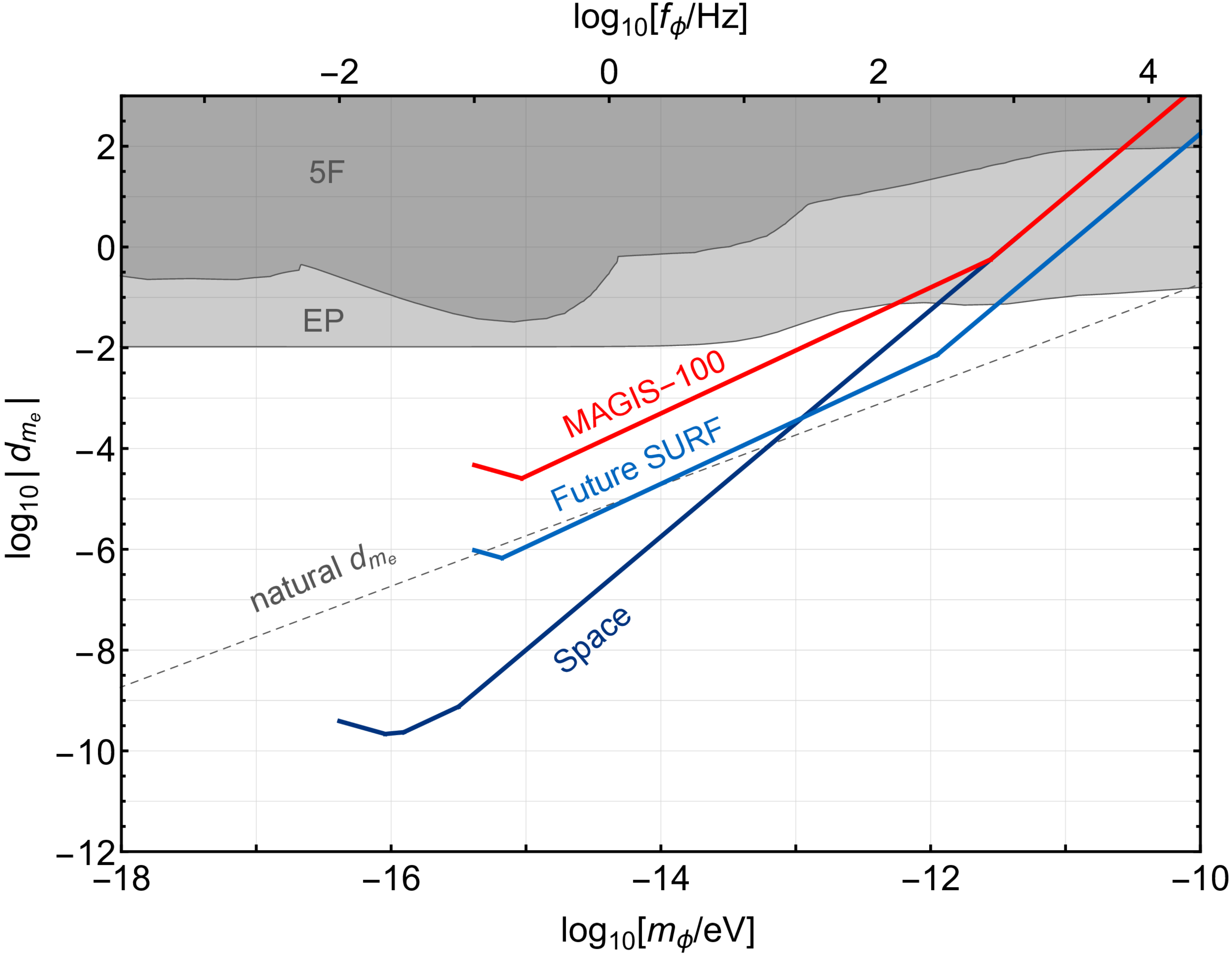


Figure from DOE Dark Matter Research Needs Report, 2018

Measurement Concept

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





$\log_{10}[f_\phi/\text{Hz}]$
−2
0
2
4
2
0
−2
−4
−6
−8
−10
−12
$\log_{10}|d_{m_e}|$
5F
EP
MAGIS–100
Future SURF
Space
natural d_{m_e}
−18
−16
−14
−12
−10
$\log_{10}[m_\phi/\text{eV}]$

B-L Dark Forces

In addition to scalar dark matter, other types of interactions can be looked for.

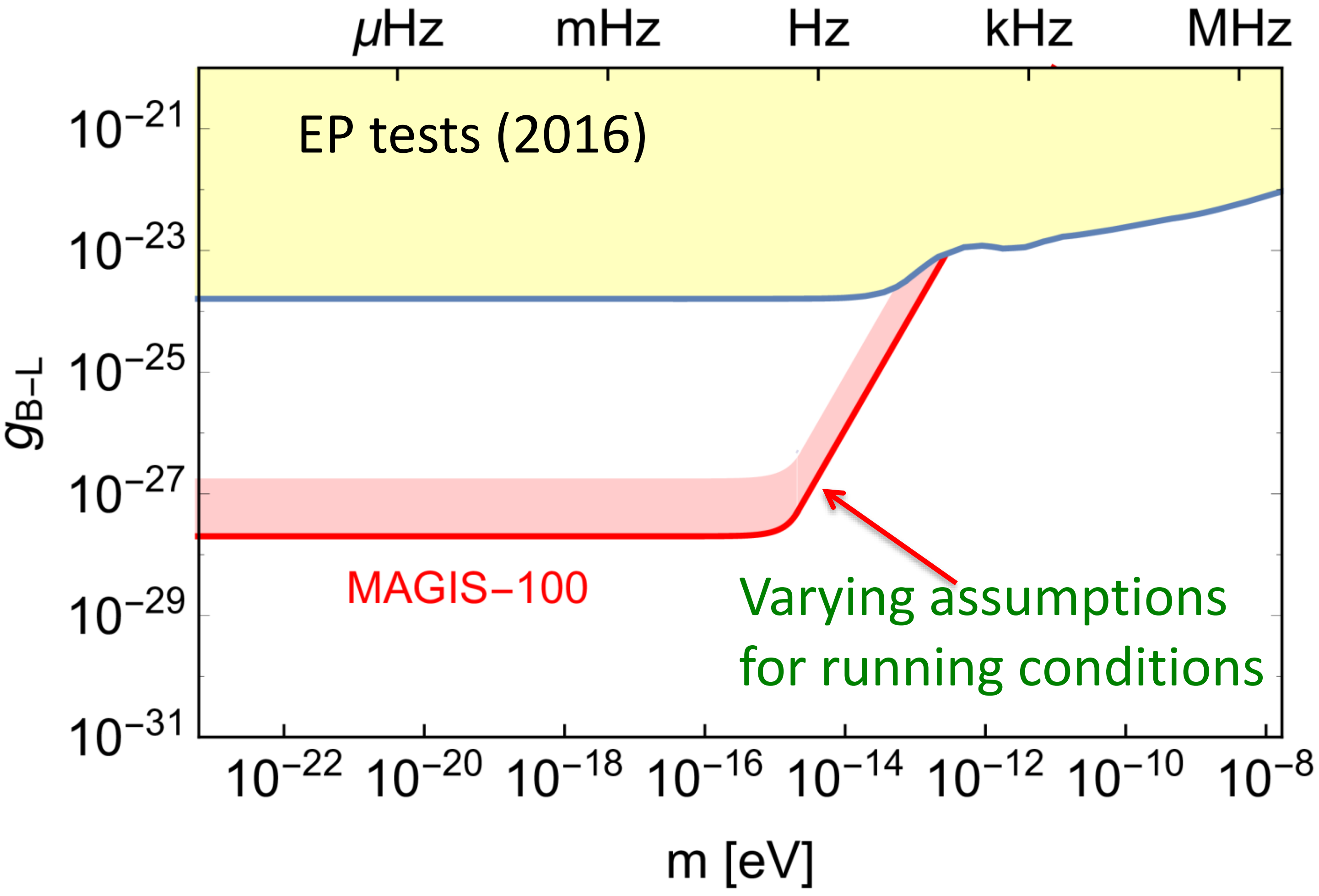
One example is a new vector boson coupling to B-L

If dark matter, will have time dependence.

If new force sourced by earth, force is static.

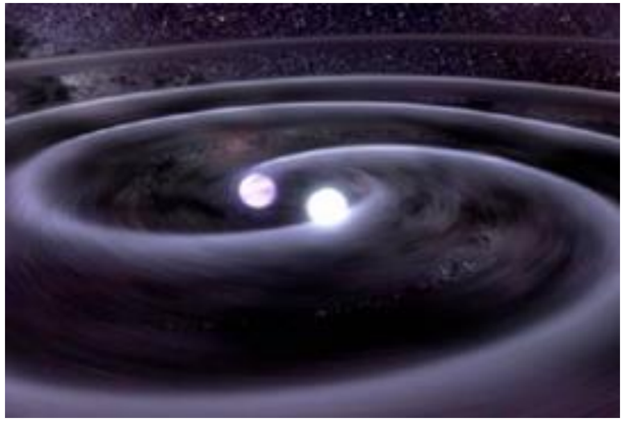
MAGIS-100 will search for this with atom source with dual isotope capability.

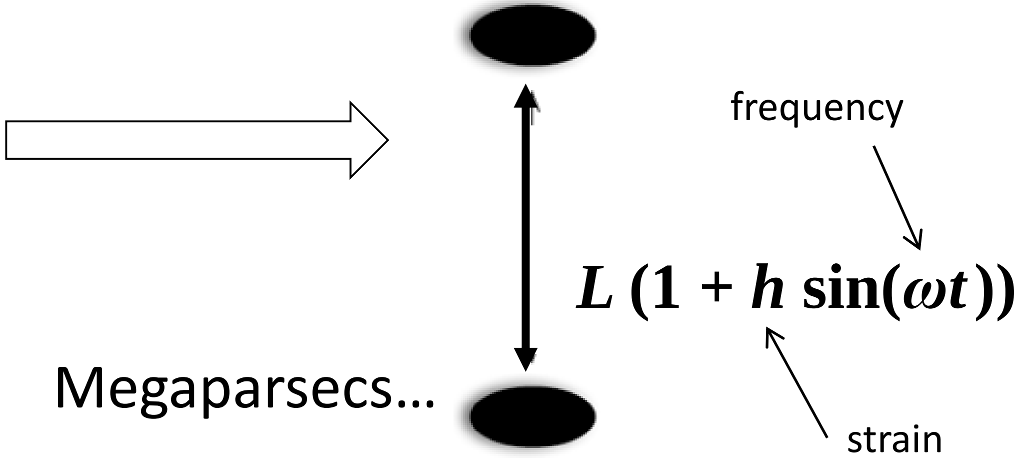
Competitive or better than, and extremely complementary to, other efforts, e.g. upgraded torsion pendula.



Expected MAGIS-100 B-L dark matter sensitivity

Gravitational Wave Detection





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

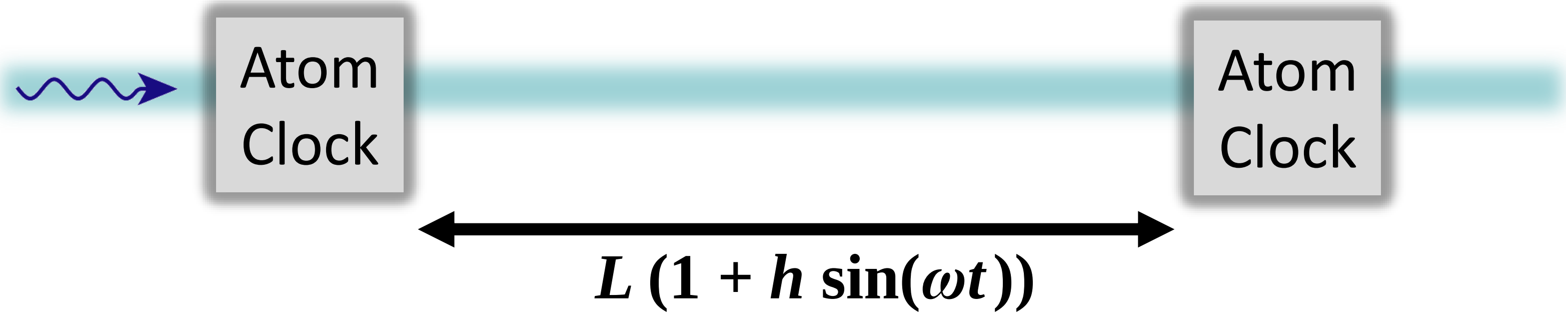
New carrier for astronomy: Generated by moving mass instead of electric charge

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

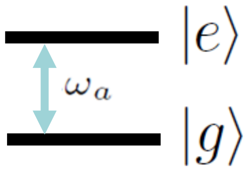
Cosmology: Can see to the earliest times in the universe

Measurement Concept

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



$$|e\rangle$$

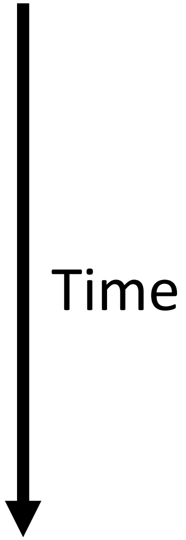
$$\omega_a$$

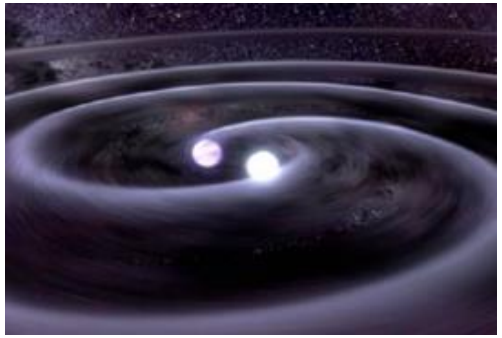
$$|g\rangle$$

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

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

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





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

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)

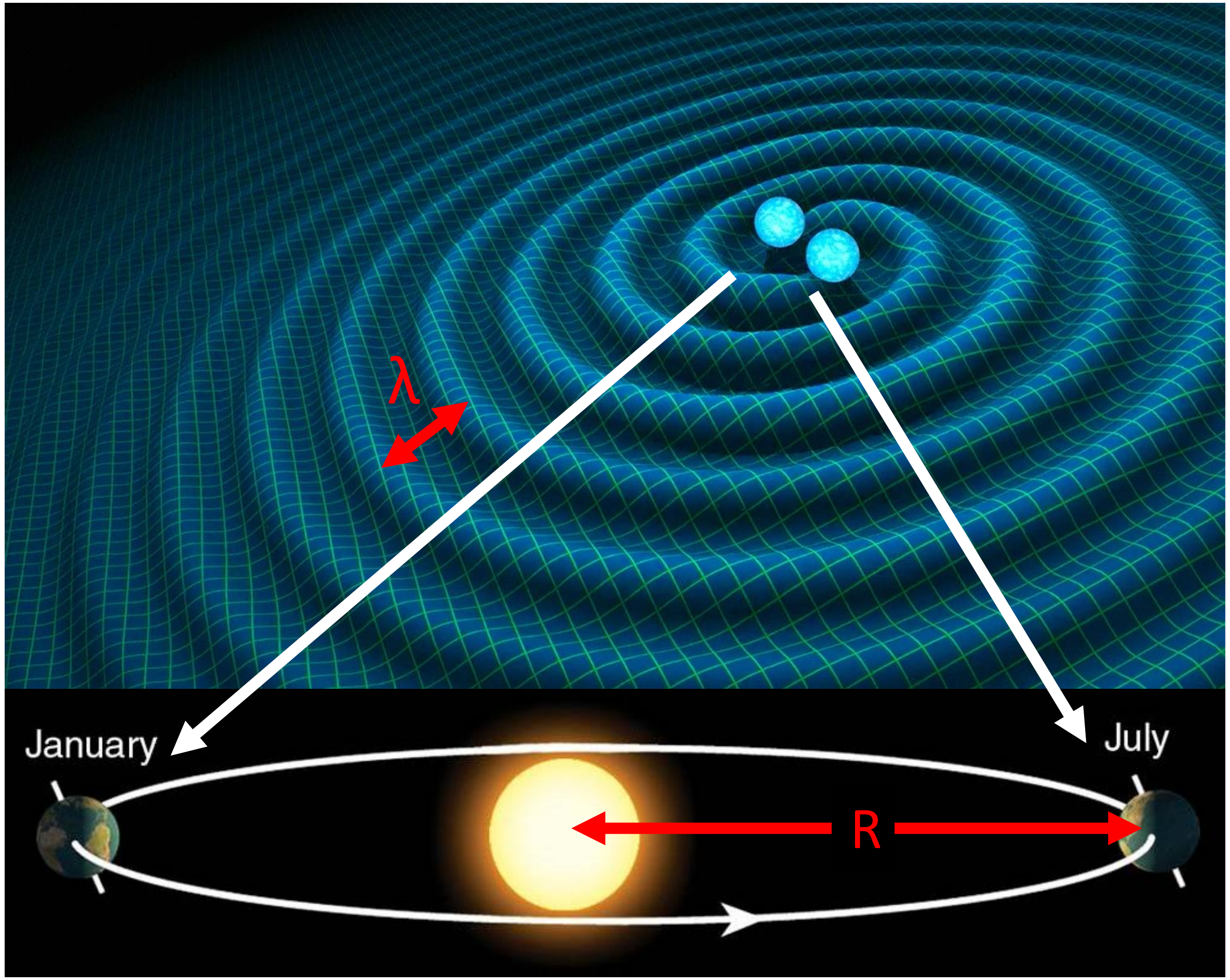
- e.g., from inflation
- operating in mid-band instead of lower frequencies may be advantageous for avoiding background noise from white dwarf sources

Sky position determination

Sky localization precision:

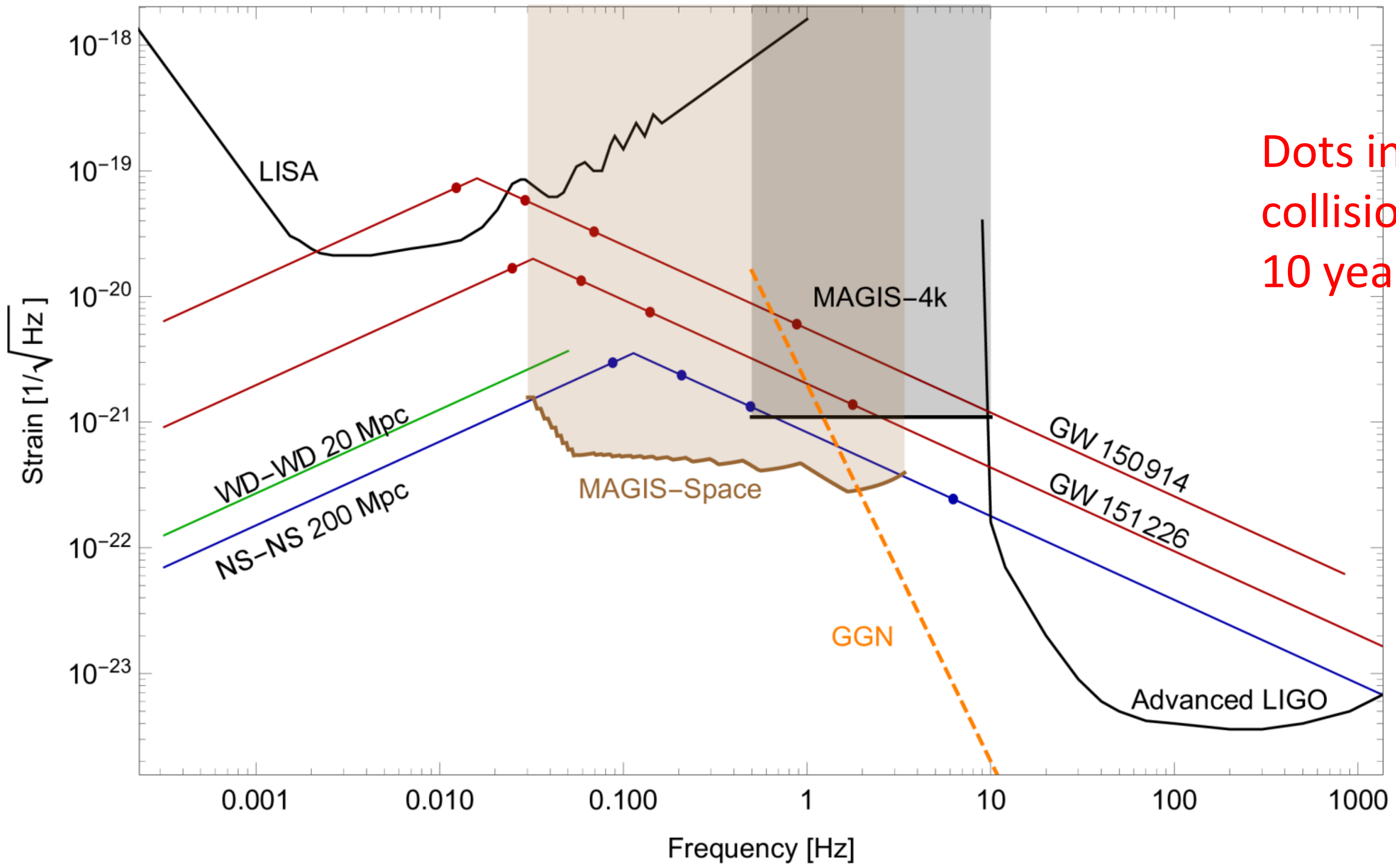
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

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



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

Long Range Program Sensitivity

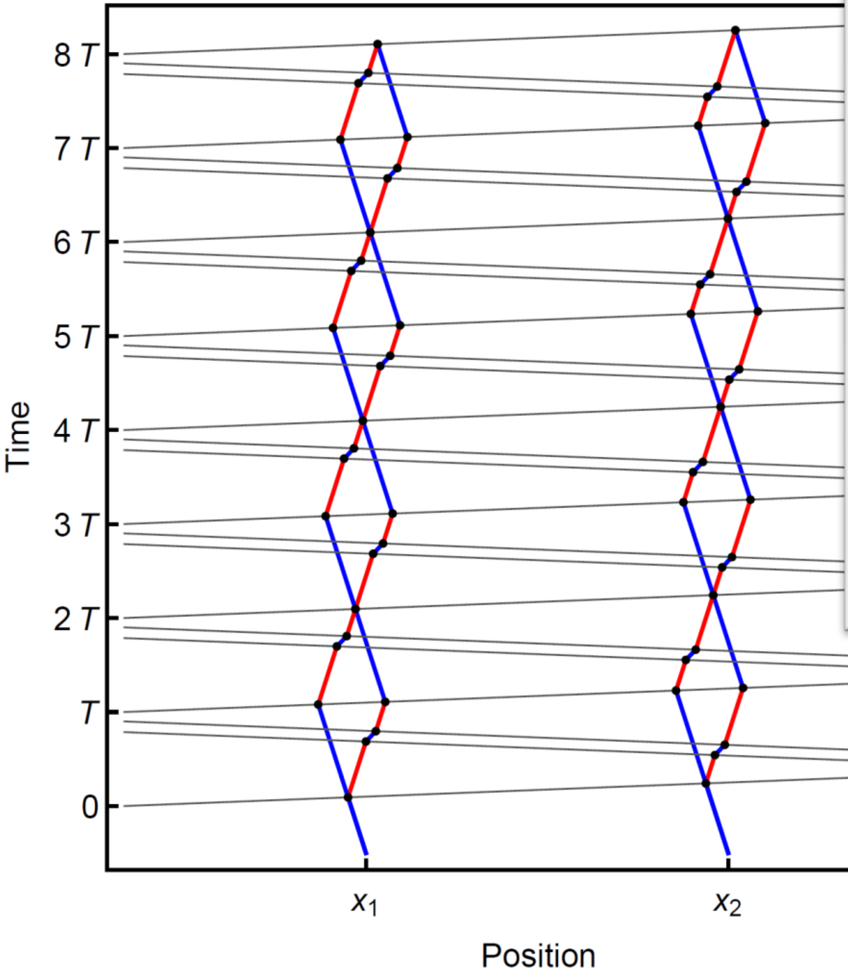


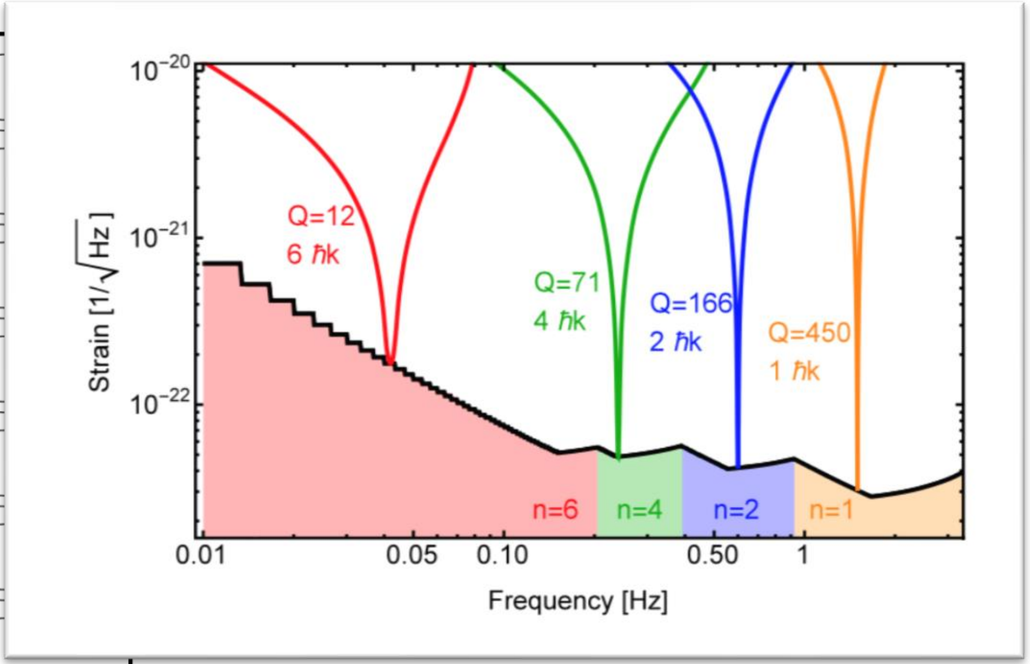
Dots indicate time-to-collision ranging from 10 years to 0.01 year.

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)

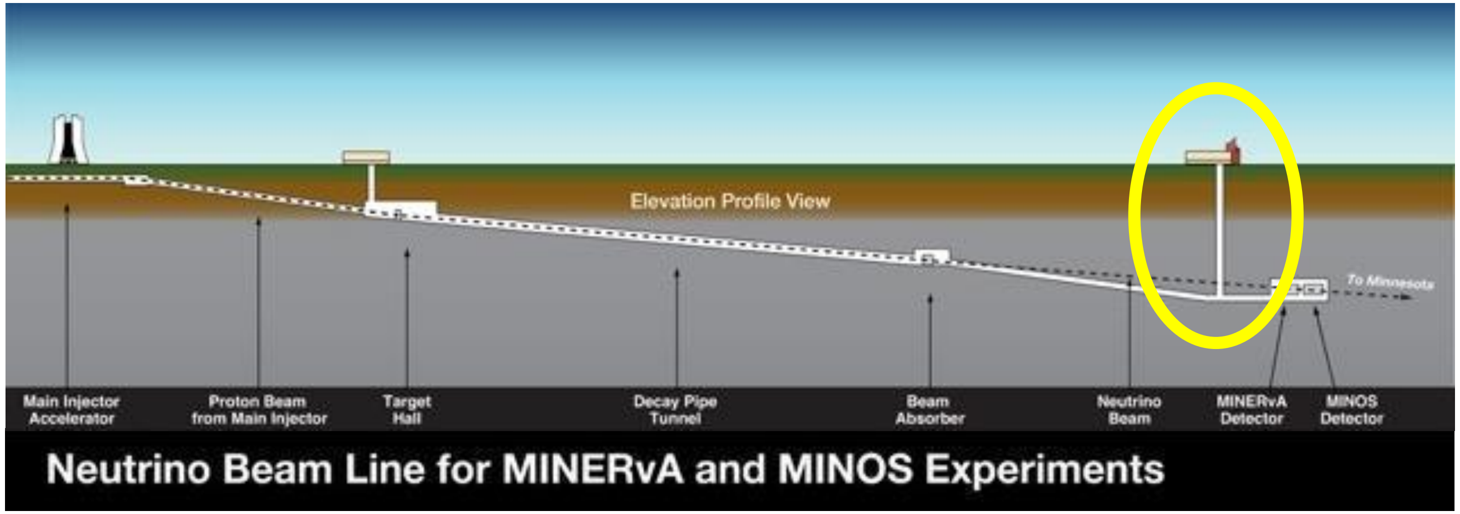




Multiple Interferometer sequences (Q) act as band pass filter.

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

MAGIS-100: Bringing Large Scale Interferometry to Fermilab

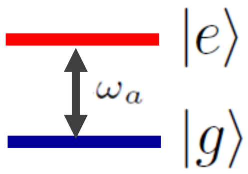


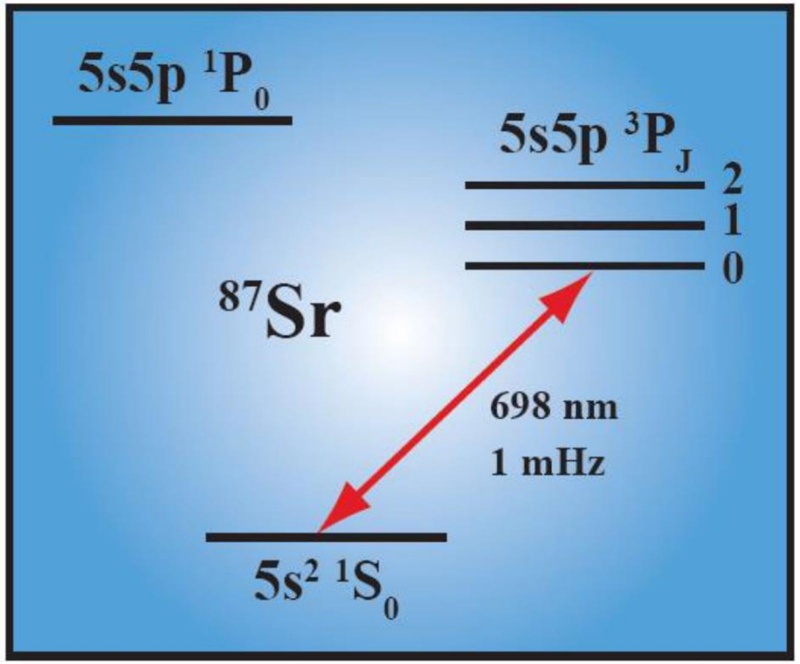
Use existing 100 m shaft from NuMI/MINOS program

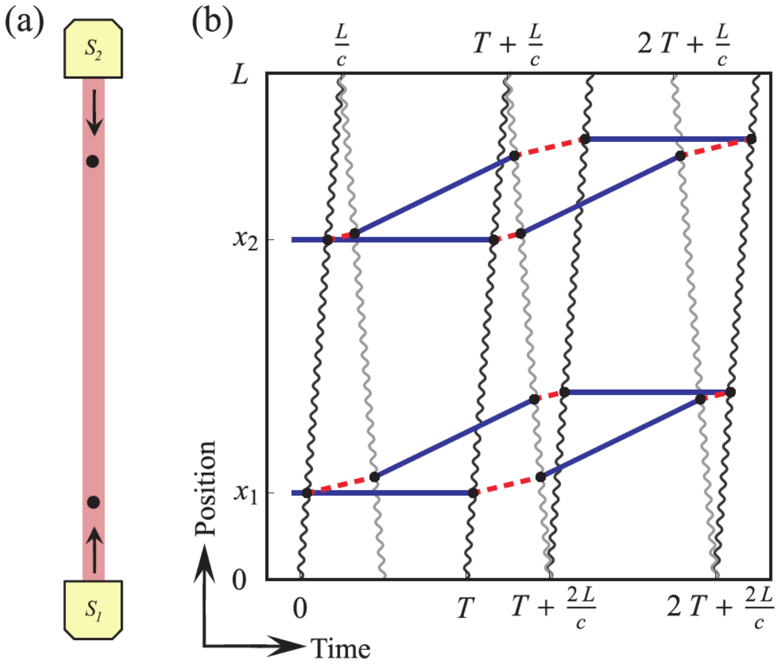
Equipped surface building because underground experiments still active

Serves both to study fundamental physics and as prototype for longer baseline (km scale) in future

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

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.

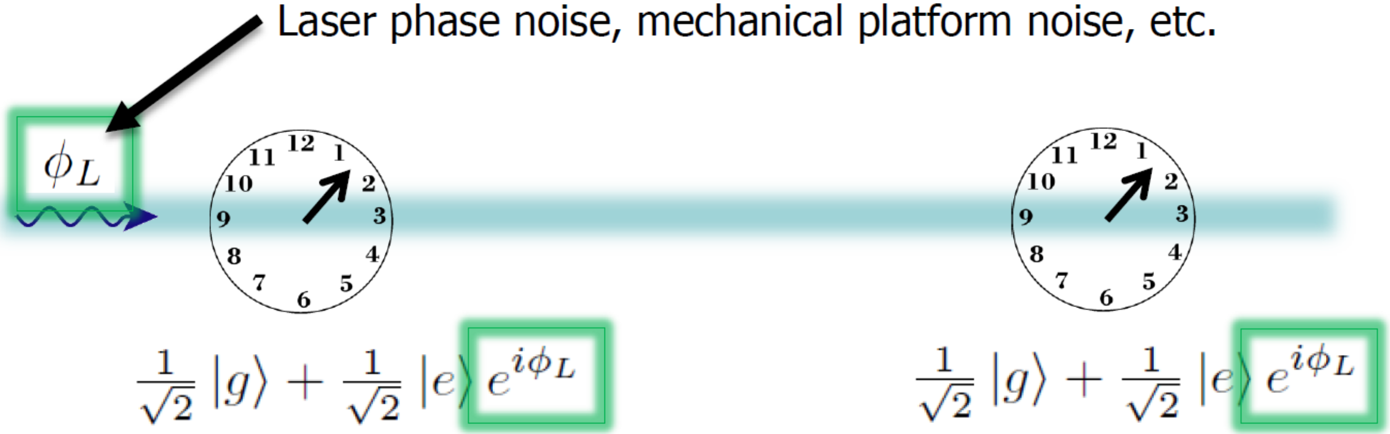
Achieving a long-lived state with one laser photon (and one laser) reduces laser phase noise – good for gradiometer measurements.

Sr has greatly reduced sensitivity to external magnetic fields (factor of 1000).

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

Common-Mode Laser Noise Suppression

Phase of the laser is imprinted onto the phase of the atom



Laser phase noise, mechanical platform noise, etc.

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \boxed{e^{i\phi_L}}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \boxed{e^{i\phi_L}}$$

Two interferometers interact with common laser pulses: laser noise (e.g., from vibrations in the optical path) suppressed as a common mode

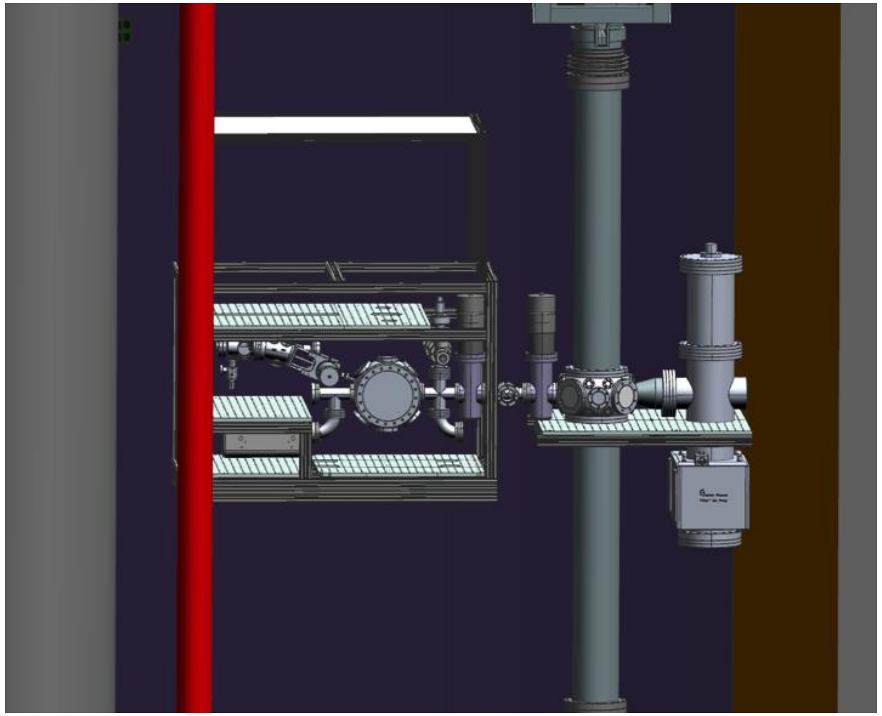
Location – MINOS building

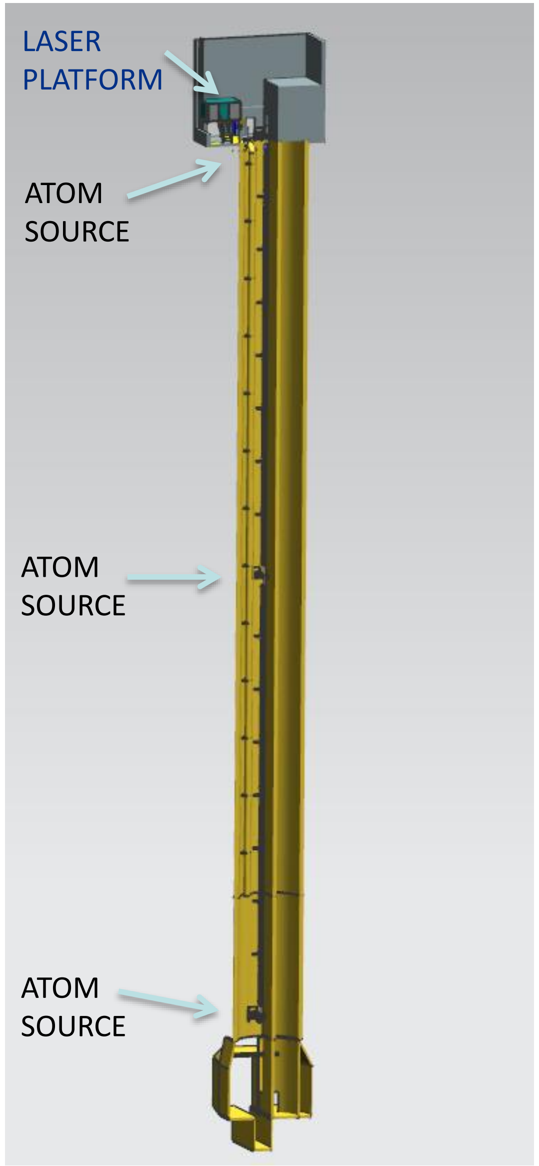
Ground level of MINOS building.

Location – Shaft in MINOS building

Top and bottom of ~100m shaft.

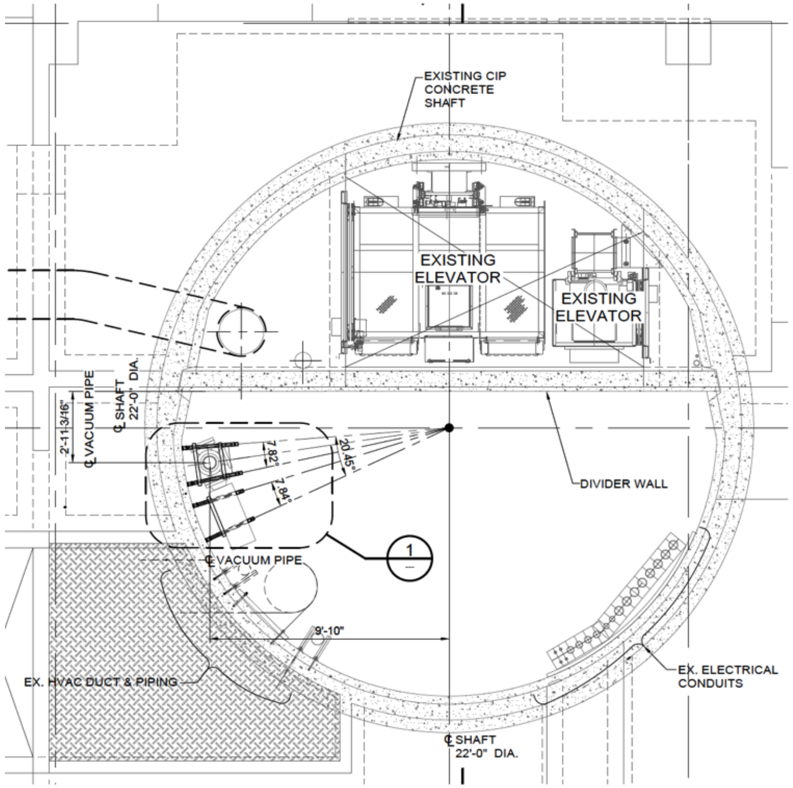
Technical: Layout 3D model

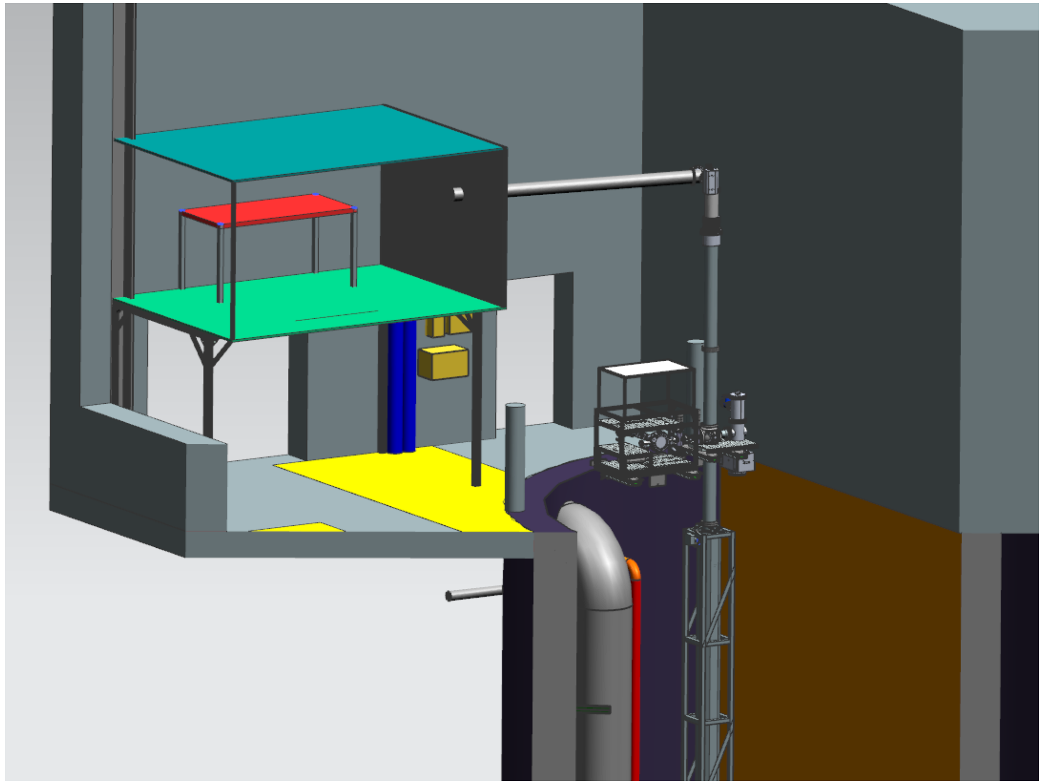




atom source details with overall layout.
Atom sources mounted to 2m sections with in-vacuum optics.

Preliminary designs – 3D model

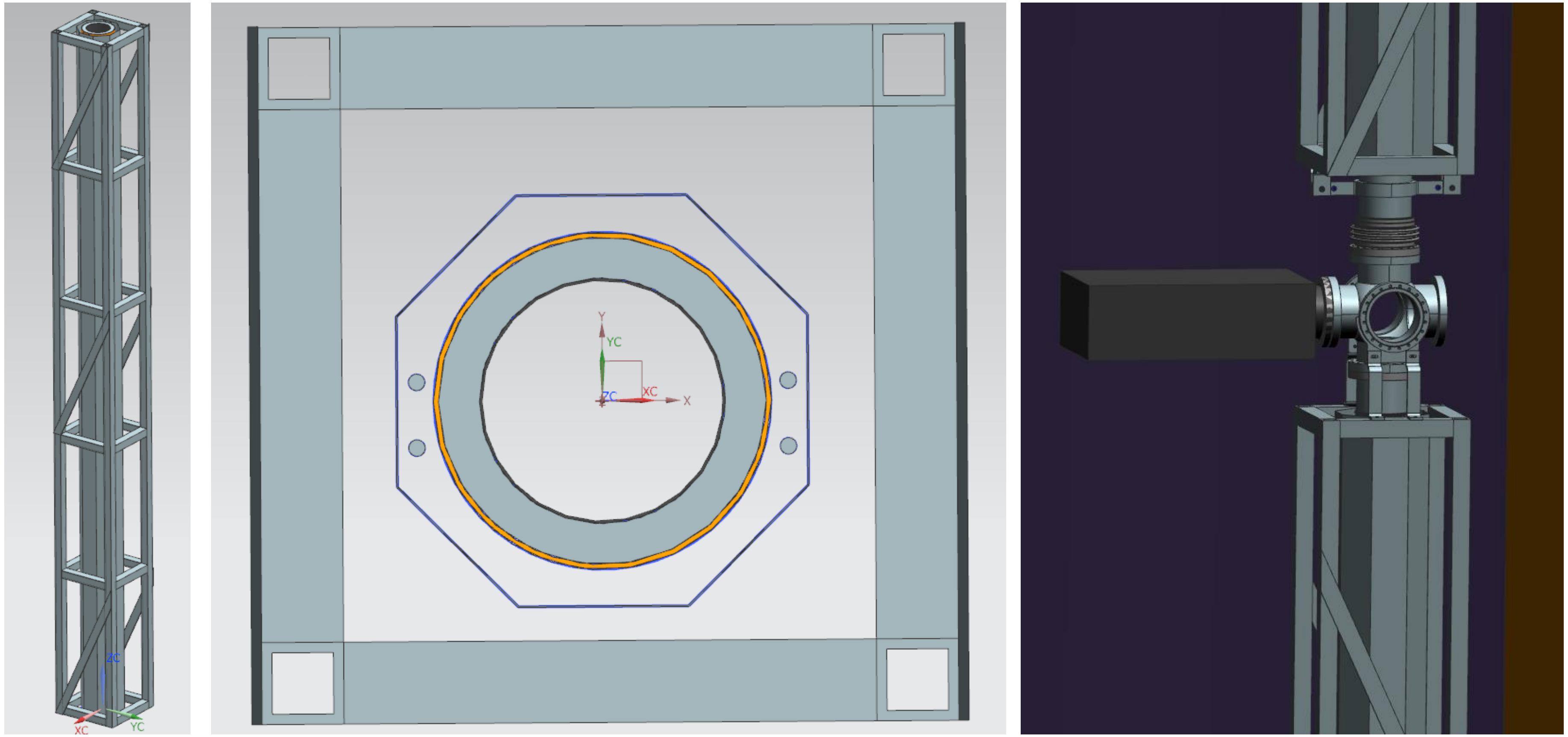




Civil engineering drawing of shaft and proposed location of mounting brackets.

Cutaway view of laser platform and top of shaft.

Preliminary designs – 3D model

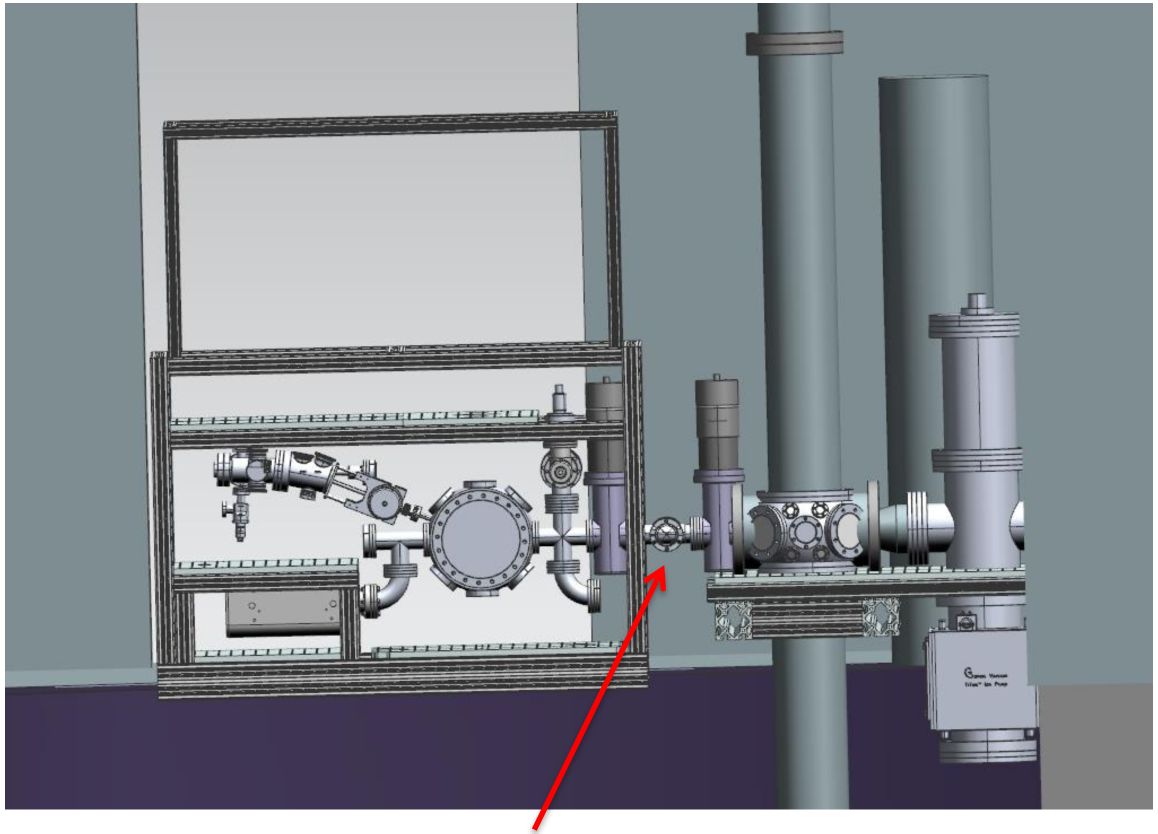


Modular assembly concept uses support frames.

Cross section shows 6” dia. vacuum tube, heating/insulation system, bias field wires, octagonal mu metal shield, and support frame.

Vacuum pumps and viewports will be placed between (~5.7m) tube sections.

Conceptual Plan for Transition Regions

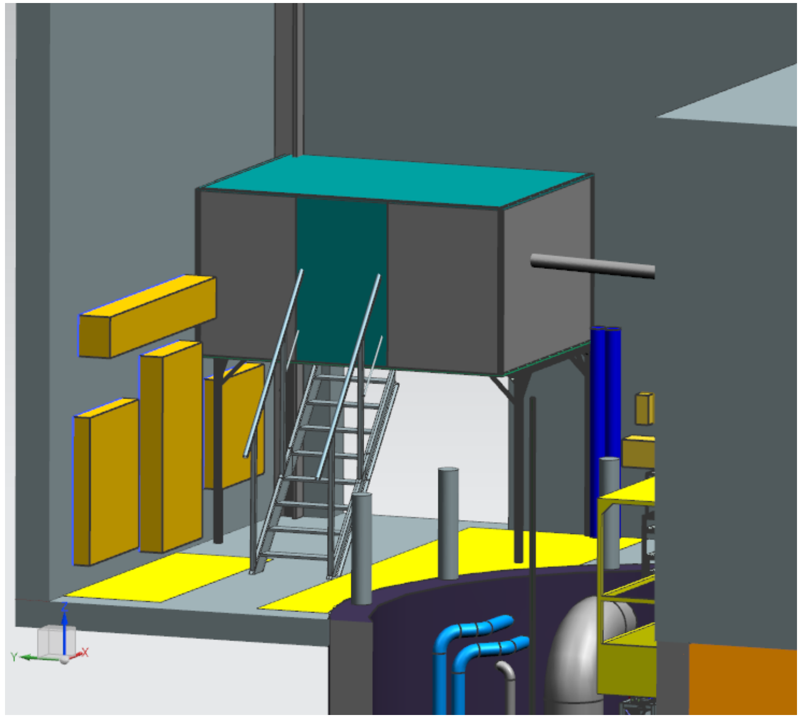


In tube beam optics in transition region allow establishment of launch lattice

“Airlock” region between each atom source and the main tube will allow vacuum to be established independently.

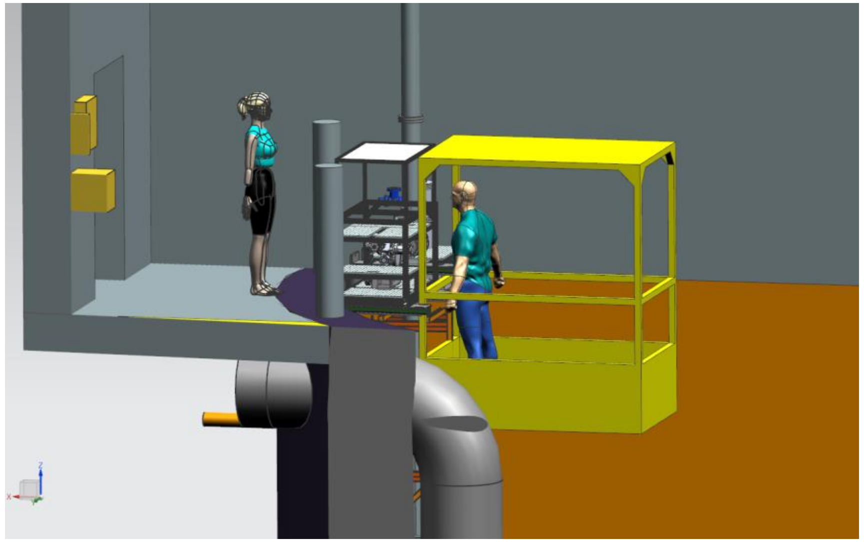
Component locations still being optimized.

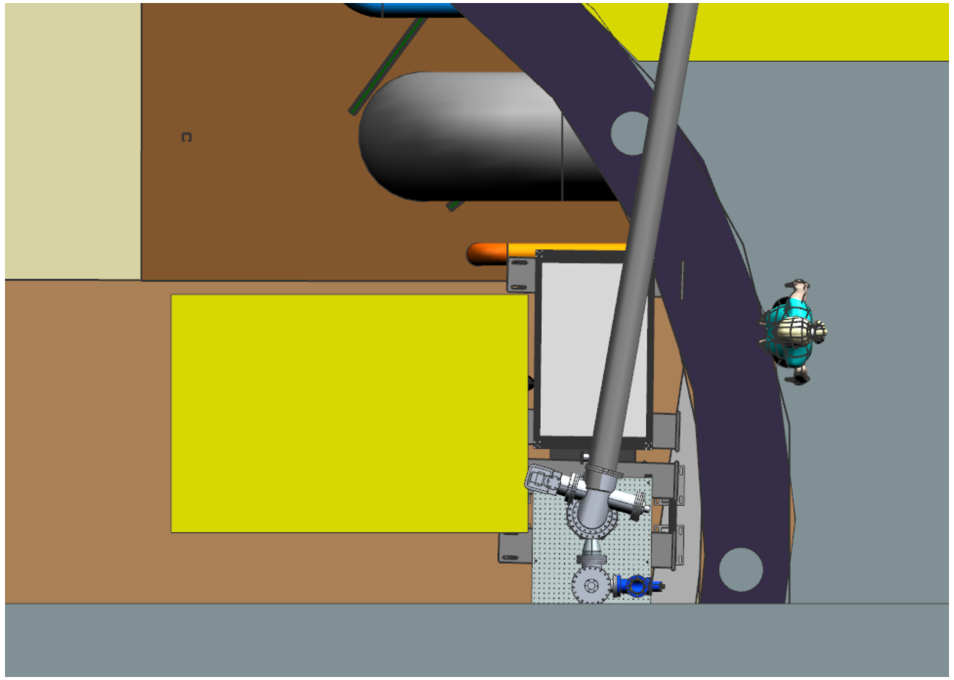
Laser room proposal

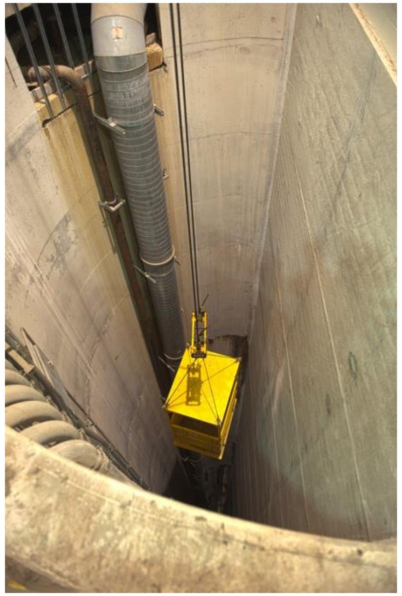


Raised, light-tight, climate-controlled laser room is expected to be similar to other laser rooms built at Fermilab. PIP-II laser room photos shown.

Technical: Beginnings of Installation Plan







Accessibility from personnel basket.

Need additional winch or small mobile gantry to lower sections into place.

Development of MAGIS Program in Short and Long Term

Short term R&D at Stanford concurrent with first deployment of detector

Includes:

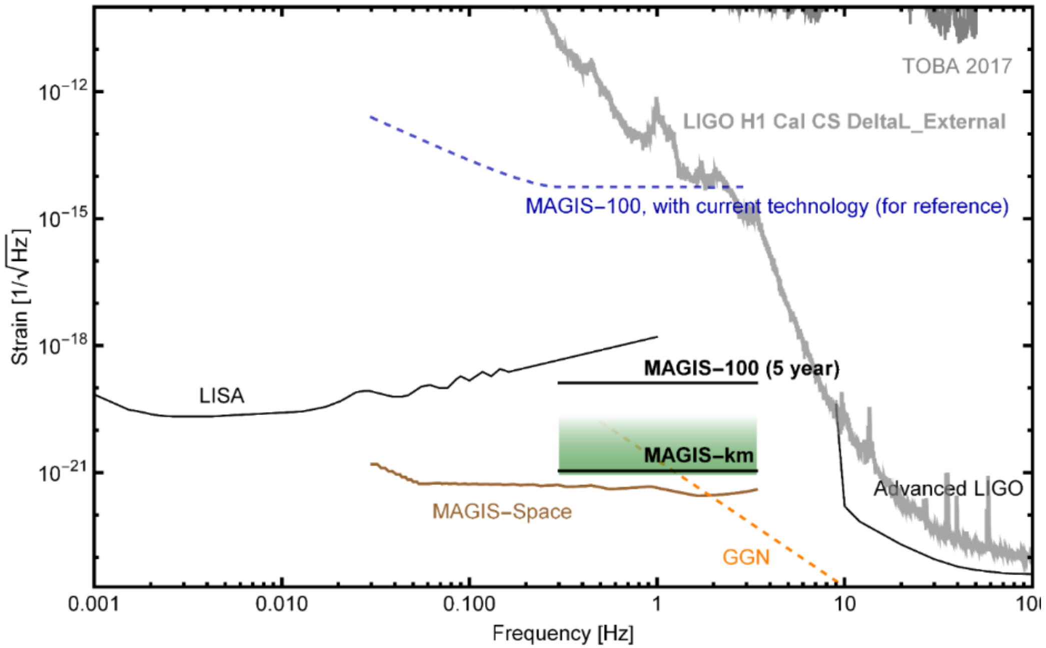
- Develop advanced LMT technology
- Increase steady-state source flux
- Spin-squeezed sources to further increase intensity (statistics!)
- Resonant interferometry

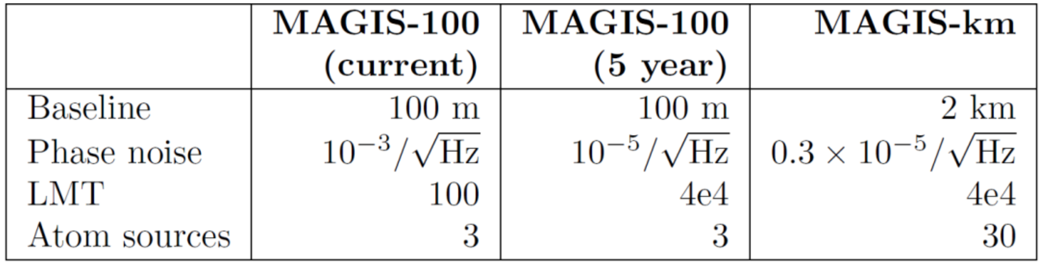
Need to aim development for longer 1.5 - 4 km deployment:

- 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.

GW Sensitivity development plan





	MAGIS-100 (current)	**MAGIS-100 (5 year)**	**MAGIS-km**
Baseline	100 m	100 m	2 km
Phase noise	$10^{-3}/\sqrt{\text{Hz}}$	$10^{-5}/\sqrt{\text{Hz}}$	$0.3 \times 10^{-5}/\sqrt{\text{Hz}}$
LMT	100	4e4	4e4
Atom sources	3	3	30

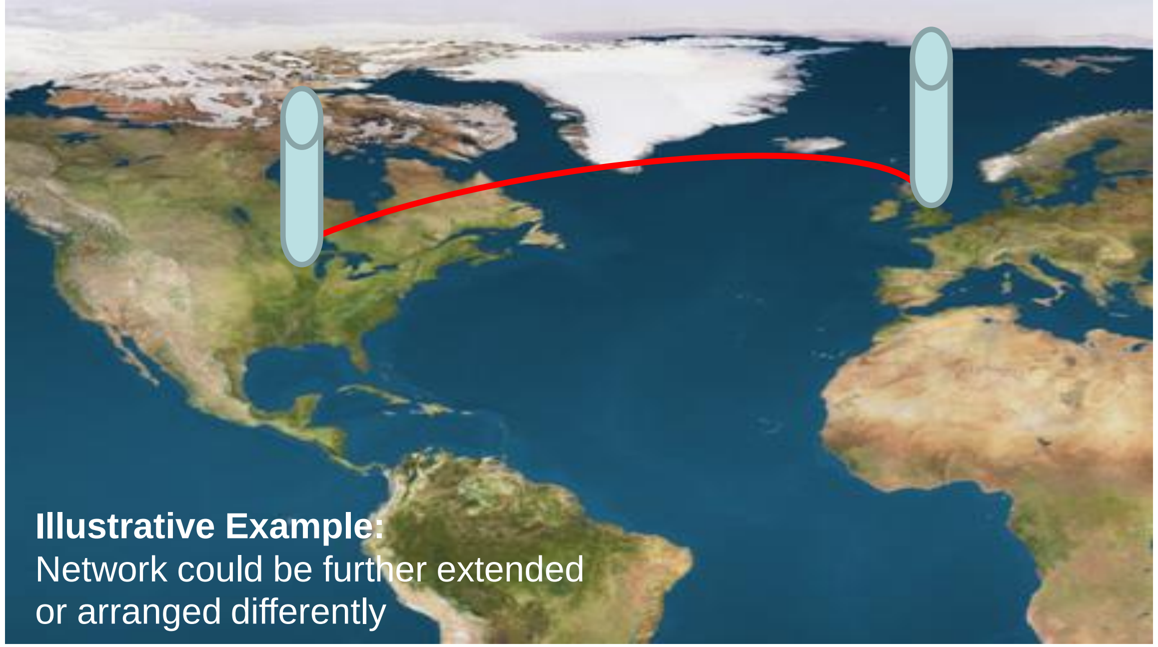
Phase noise improvements:

10x from higher flux
10x from squeezing

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

MAGIS-km additional factor of 3x improvement in phase noise from flux + quantum entanglement (spin squeezing)

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

See AION presentation
by Oliver Buchmueller

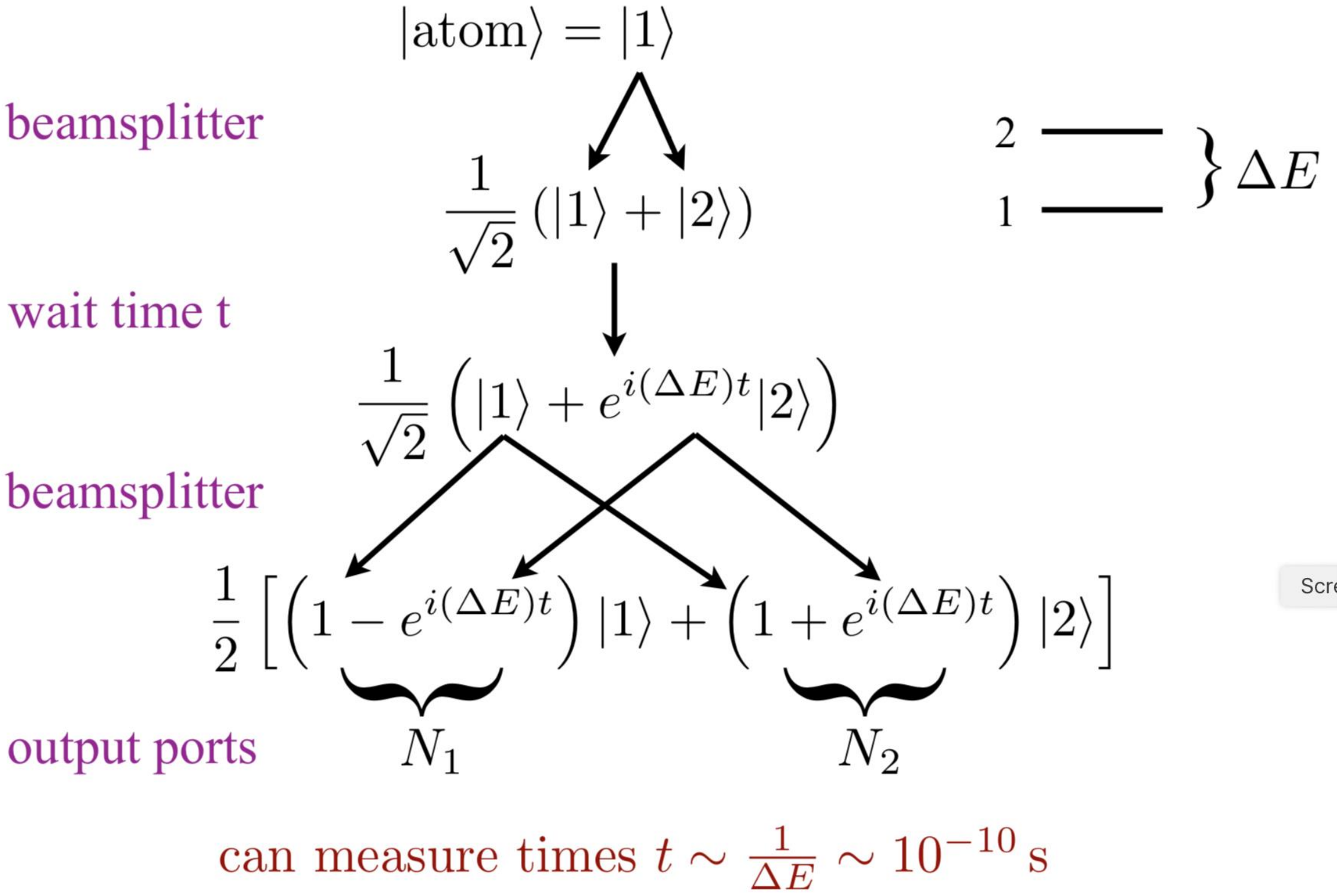
Summary

- MAGIS-100 is a new experiment at Fermilab
  - potential to scale much larger to SURF
- Using Atom Interferometry as a macroscopic quantum probe of the ‘early universe’ through:
  - gravitational waves
  - and the ‘dark sector
- Proposal currently given stage-1 approval by the Fermilab PAC
- MAGIS-100 has been funded through the Gordon and Betty Moore Foundation
- QIS application with DOE pending

- AION initiative to network with MAGiS

GORDON AND BETTY
MOORE
FOUNDATION

Pulsed Atomic Clock



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

beamsplitter

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

$\}\,\Delta E$

wait time t

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

beamsplitter

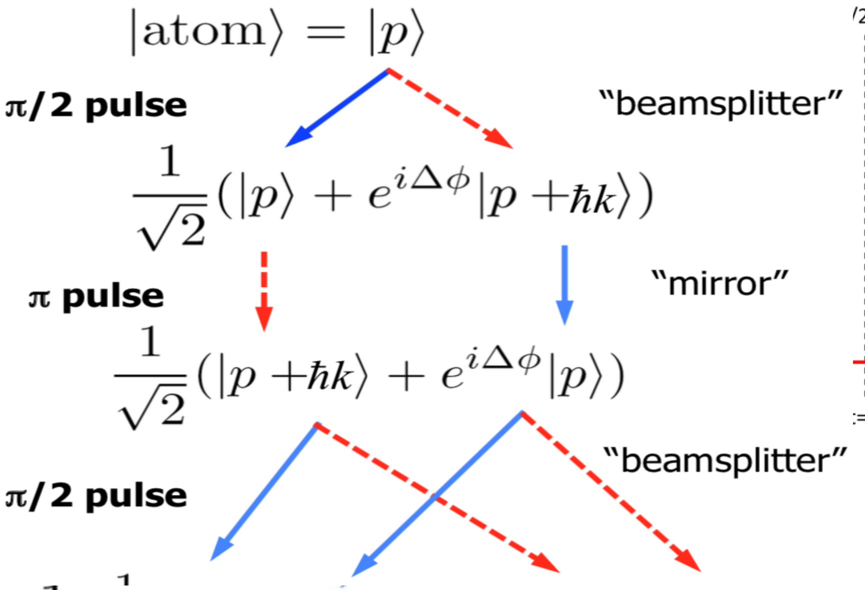
$\frac{1}{2}\left[\underbrace{\left(1 - e^{i(\Delta E)t}\right)}_{N_1}|1\rangle + \underbrace{\left(1 + e^{i(\Delta E)t}\right)}_{N_2}|2\rangle\right]$

output ports

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

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"

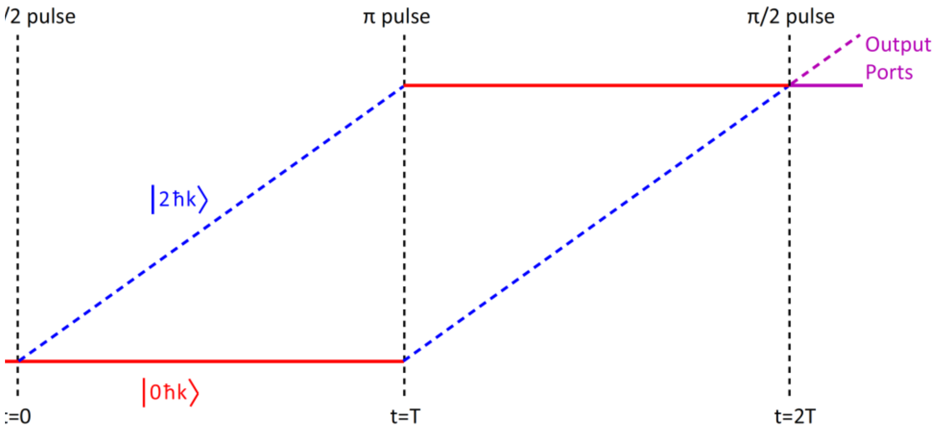
$$\frac{1}{\sqrt{2}}(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

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

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