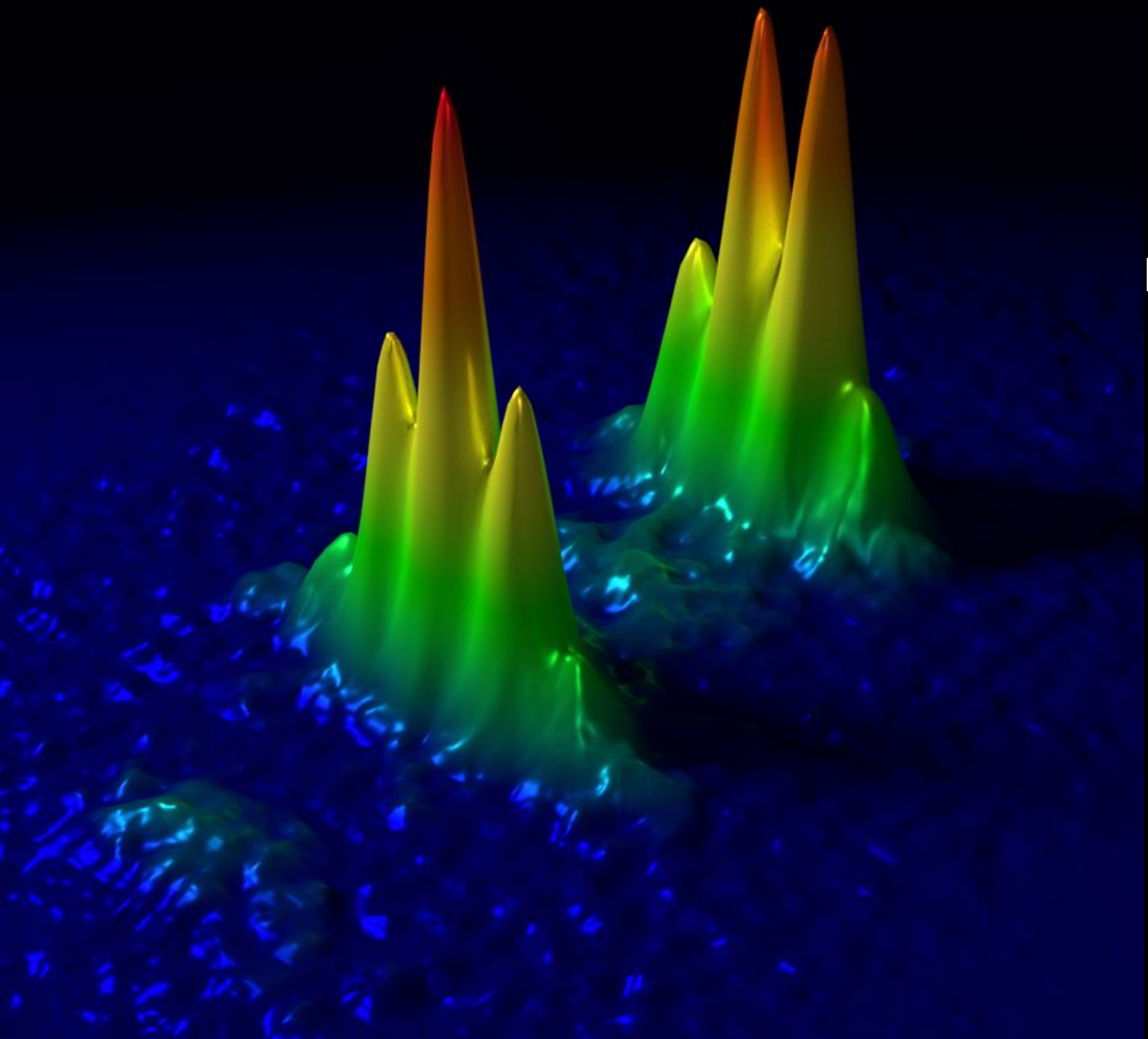
The MAGIS-100 Project in the US



First AION Workshop

Imperial College London

Jason Hogan
Stanford University
March 25, 2019

MAGIS Collaboration

PROPOSAL: P-1101

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*

STANFORD

UNIVERSITY OF CALIFORNIA BERKELEY

Northwestern University

NIU Northern Illinois University

UNIVERSITY OF LIVERPOOL

Fermilab

Part of the proposed Fermilab Quantum Initiative:
http://www.fnal.gov/pub/science/particle-detectors-computing/quantum.html#magis

Physics motivation

Dark matter and new forces

- Time-dependent signals caused by ultra-light dark matter candidates (dilaton, ALP, relaxion …)
- Dark matter that affects fundamental constants: electron mass, fine structure constant
- Time-dependent EP violations from B-L coupled dark matter
- New forces

Advancing quantum science

- 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

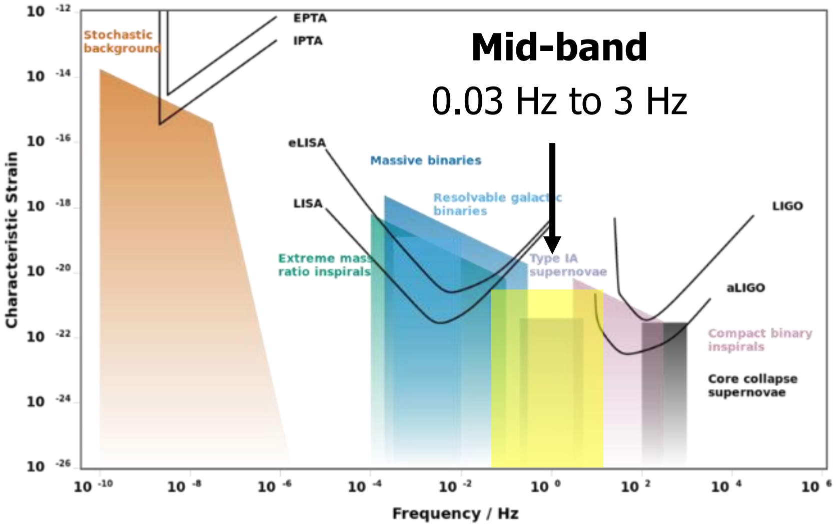
Gravitational wave detector development

- Probe for studying cosmology
- Explores range of frequencies not covered by other detectors
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)

Atomic sensors for gravitational wave detection

Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range (“mid-band”)

Potential for *single baseline* detector (use atoms as phase reference/local clock)

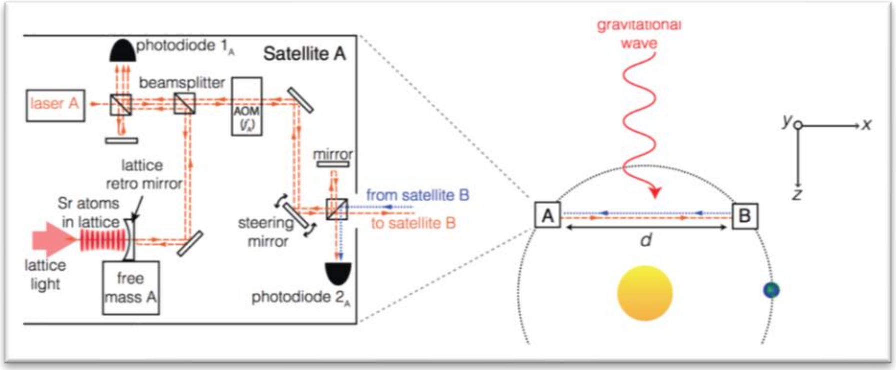


Mid-band

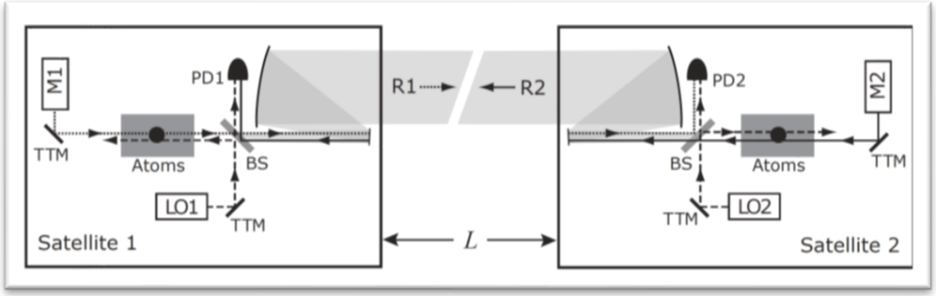
0.03 Hz to 3 Hz

Mid-band science

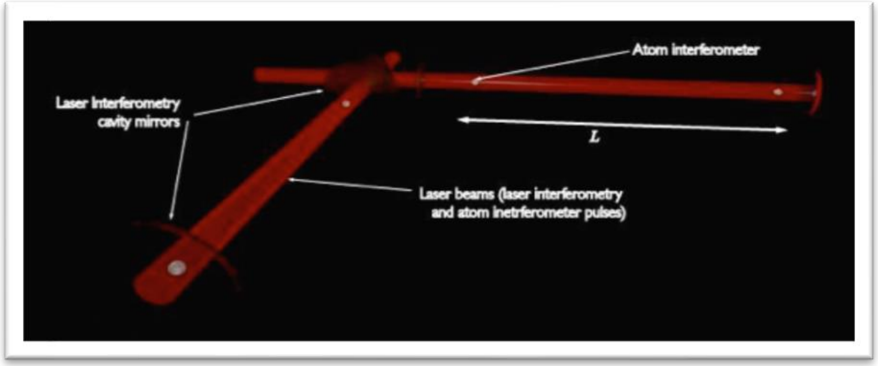
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)



Satellite proposal using optical lattice clocks + drag free inertial reference (Kolkowitz et al., **PRD** 2016)



MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich)



MIGA: Terrestrial detector using atom interferometer + optical cavity (Bouyer, France)

Sky position determination

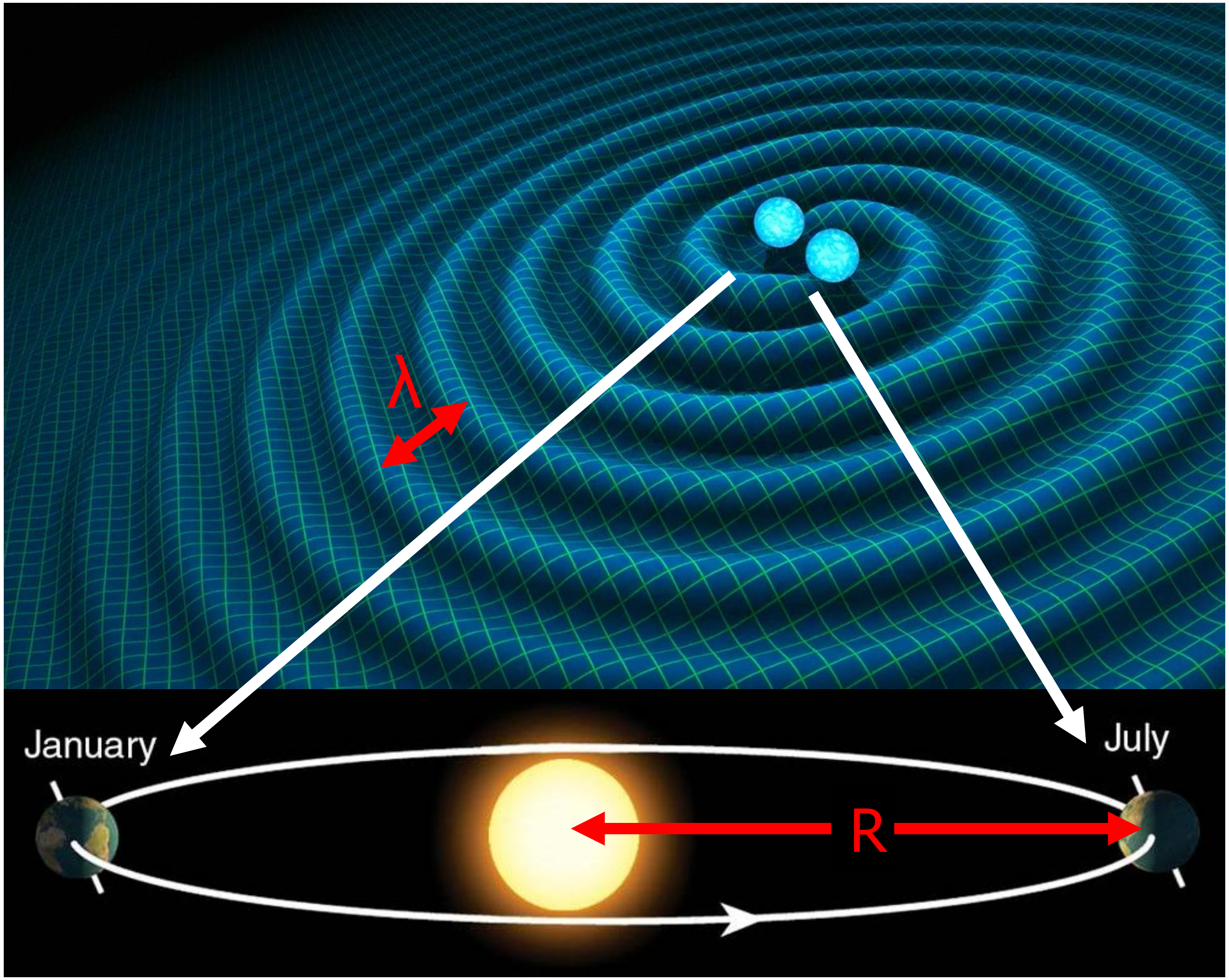
Sky localization precision:

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

Mid-band advantages

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

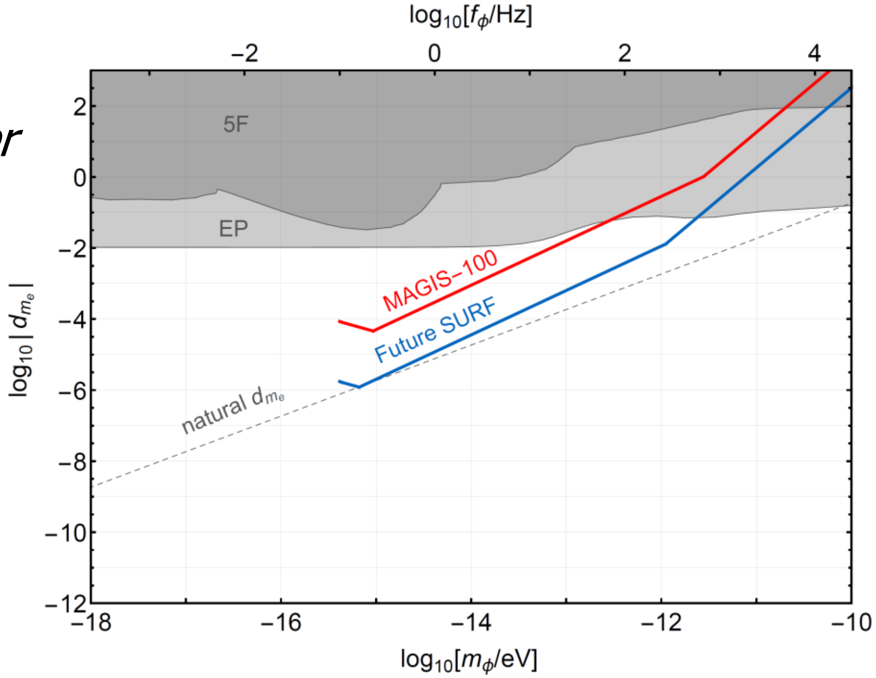
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

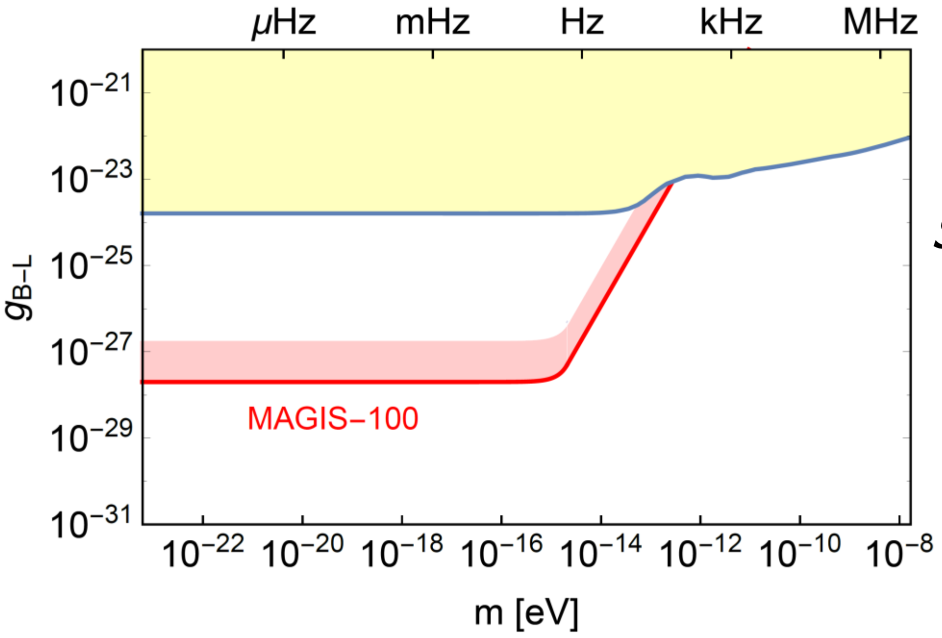


Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

Projected sensitivity to dark matter

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).

Quantum science

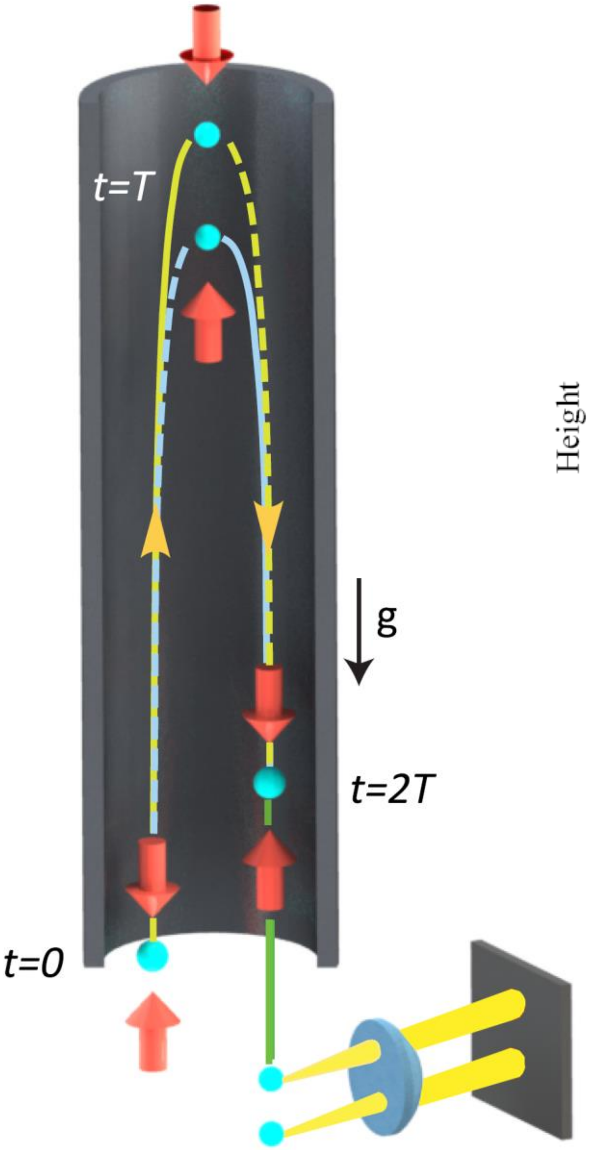
Realizing macroscopic quantum mechanical superposition states

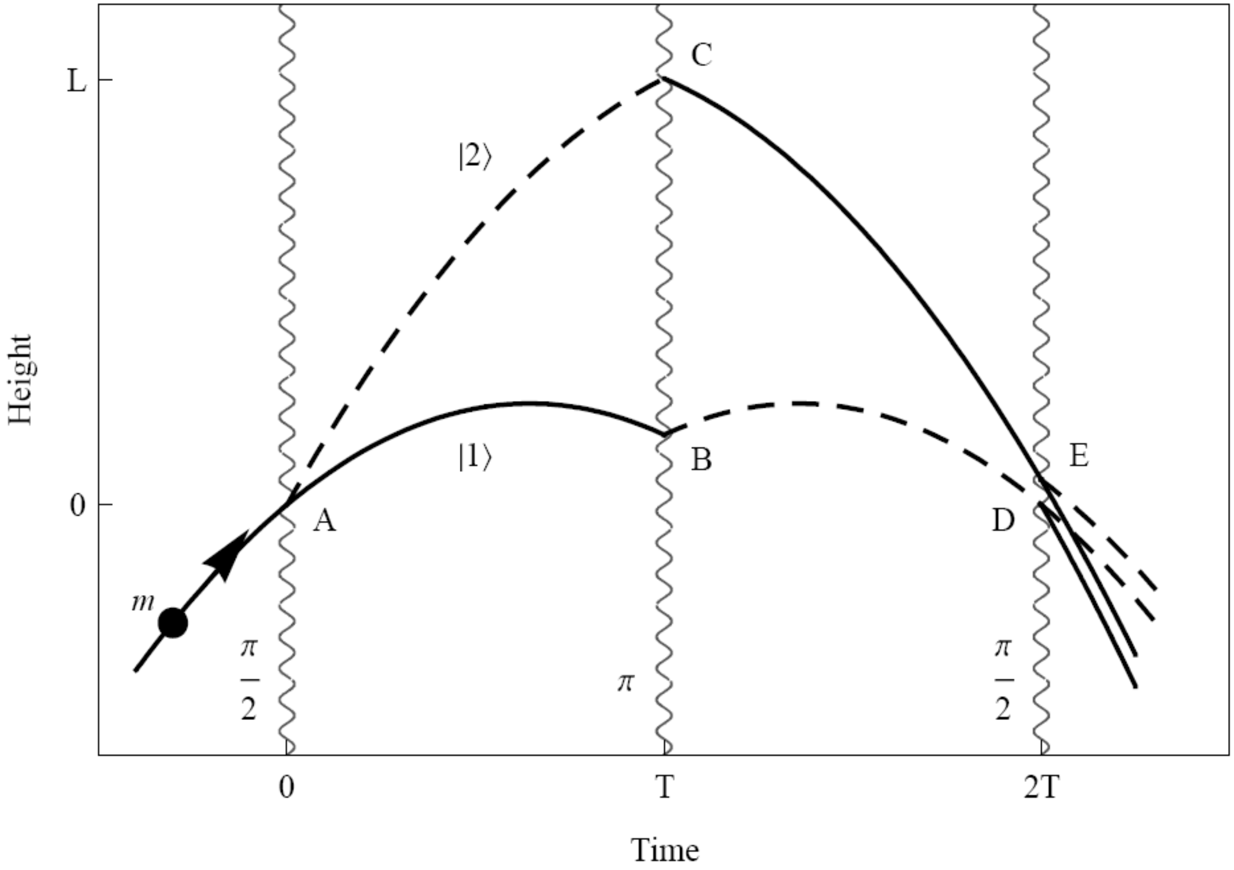
Distance: Wave packets are expected to be separated by distances of up to 10 meters (current state-of-art 0.5 meters)

Time: Support record breaking matter wave interferometer durations, up to 9 seconds (current state-of-art 2 seconds)

Entanglement: 20 dB spin squeezed Sr atom sources takes advantage of quantum correlations to reduce sensor noise below the standard quantum limit (shot noise)

Light Pulse Atom Interferometry





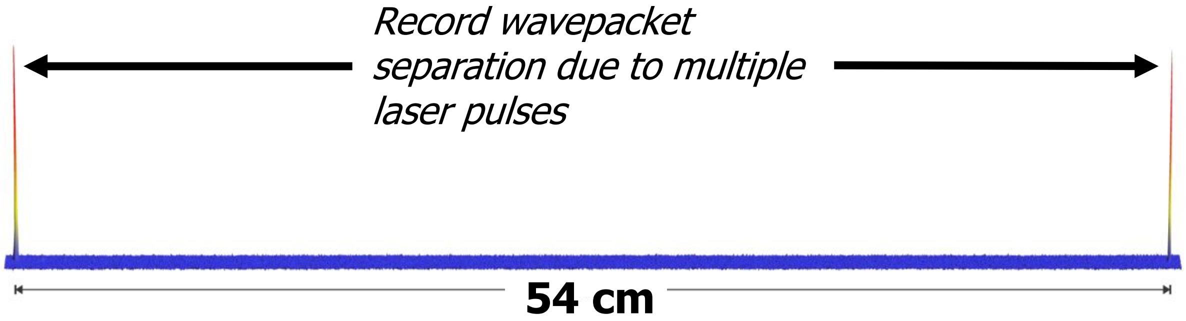
- Long duration
- Large wavepacket separation

Current generation: Stanford 10-meter fountain

10-meter tall Rb atomic fountain

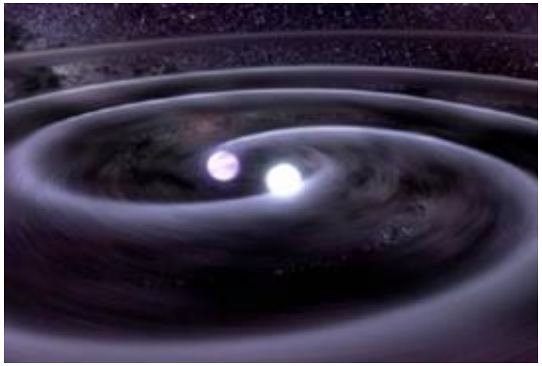
Milestones

- Record matter wave interferometer duration (>2 s)
- Record wavepacket separation (>0.5 meter)
- Record effective temperature (< 50 pK)
- First observation of phase shift due to space-time curvature across a single particle's wavefunction
- Large momentum transfer 90 ħk
- Record accelerometer scale factor
- Dual species (^{85}Rb / ^{87}Rb) gradiometer
- First demonstration of phase shear readout and point source interferometry techniques



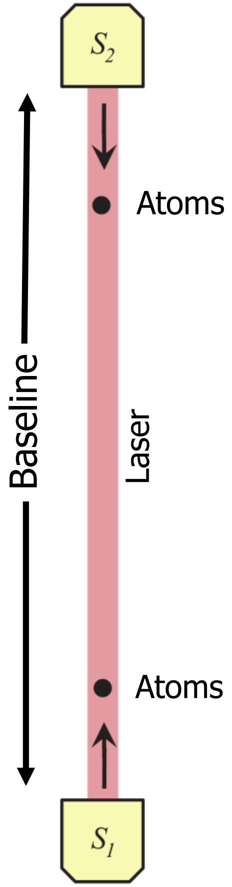
Record wavepacket separation due to multiple laser pulses

Gradiometer detector concept



GW source (e.g., black hole binary inspiral)

Gradiometer

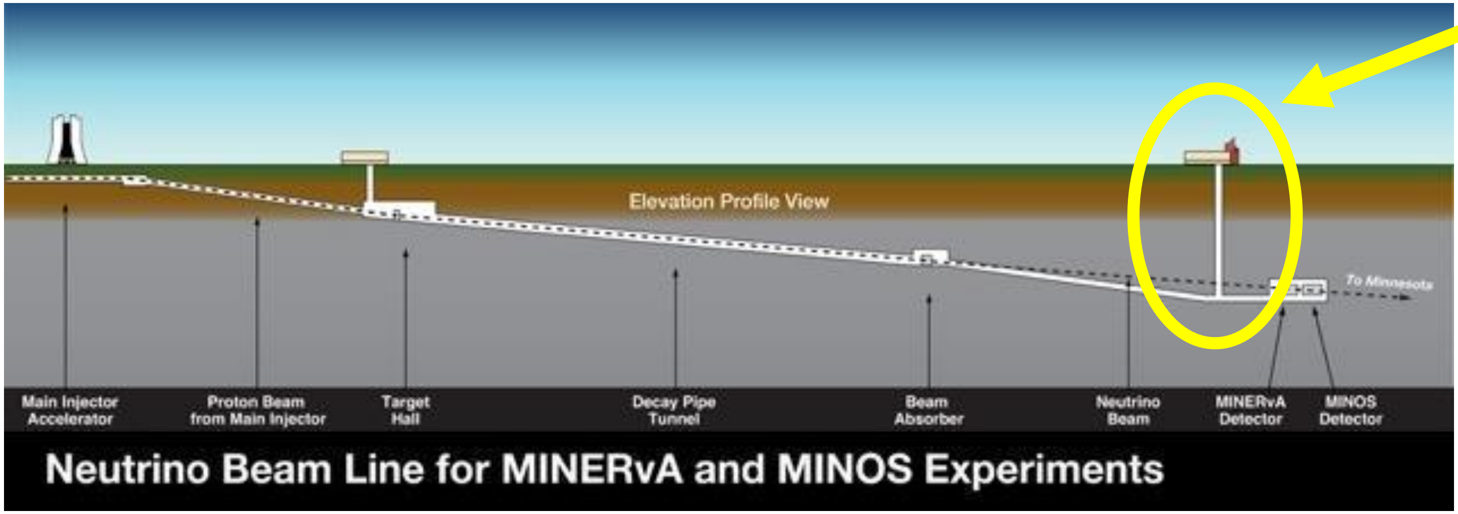


- Compare two (or more) atom ensembles separated by a **large baseline**
- Science signal is **differential phase** between interferometers
- Differential measurement suppresses many sources of common noise and systematic errors

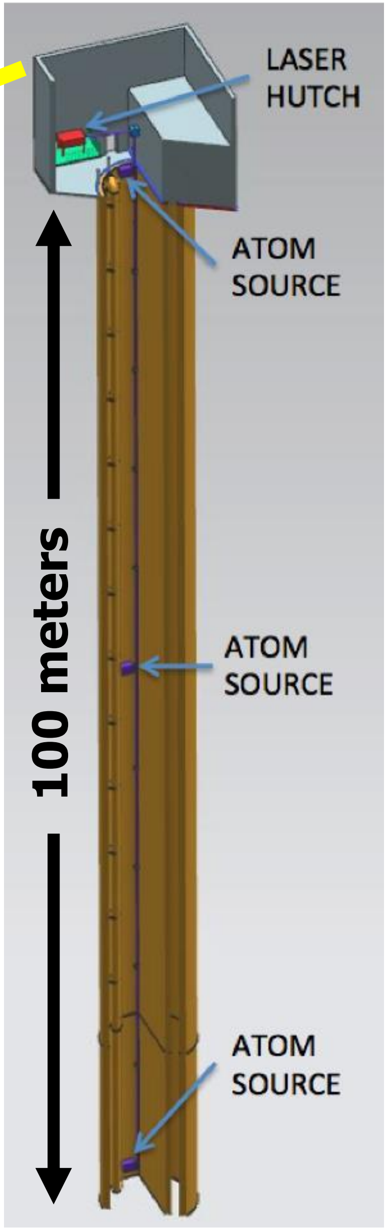
Science signal strength is proportional to baseline length (DM, GWs).

MAGIS-100: GW detector prototype at Fermilab

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



Neutrino Beam Line for MINERvA and MINOS Experiments



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

STANFORD
Fermilab
BERKELEY
UNIVERSITY OF LIVERPOOL
Northwestern University
Northern Illinois University

Gordon and Betty Moore Foundation grant

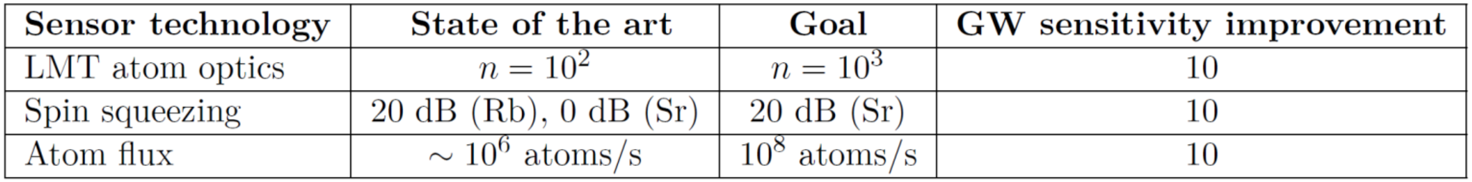
GORDON AND BETTY
MOORE
FOUNDATION

- New funding received from GBMF
- \$9.8M, 5 years, start date Jan 2019

MAGIS-100 at Fermilab

- 100 meter vacuum tube (Fermilab design contribution)
- Three atomic sources (Stanford design contribution)
- Atom interferometry laser system (Northwestern design contribution)

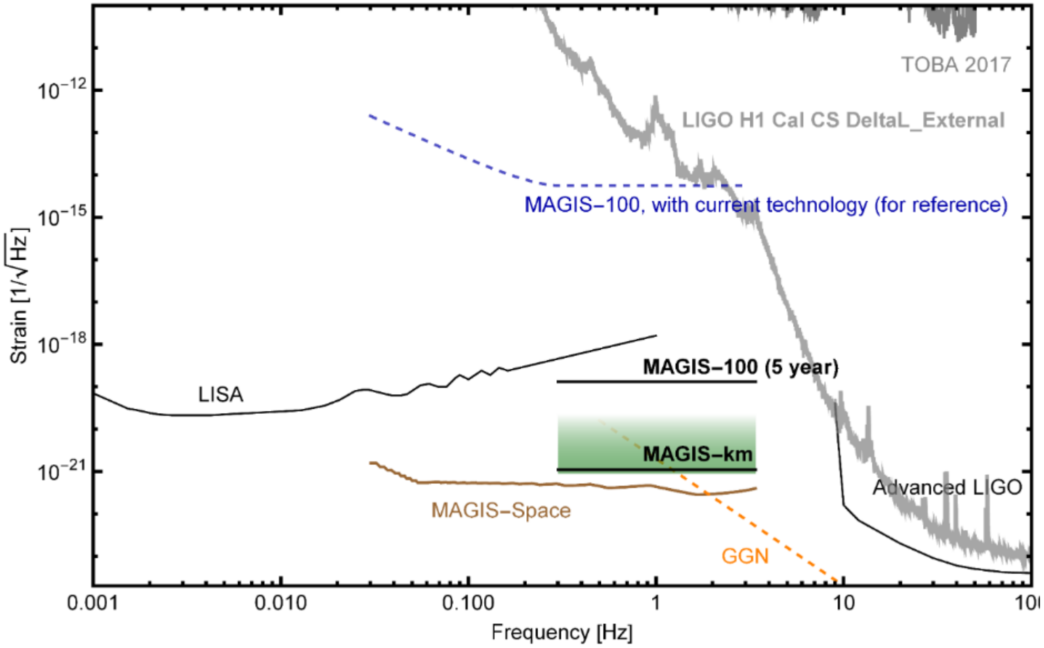
Atom interferometry sensor development at Stanford



Sensor technology	State of the art	Goal	GW sensitivity improvement
LMT atom optics	$n = 10^2$	$n = 10^3$	10
Spin squeezing	20 dB (Rb), 0 dB (Sr)	20 dB (Sr)	10
Atom flux	$\sim 10^6$ atoms/s	10^8 atoms/s	10

Hogan
Kasevich
Hogan

GW Sensitivity development plan (part of GBMF grant)



Phase noise improvements:

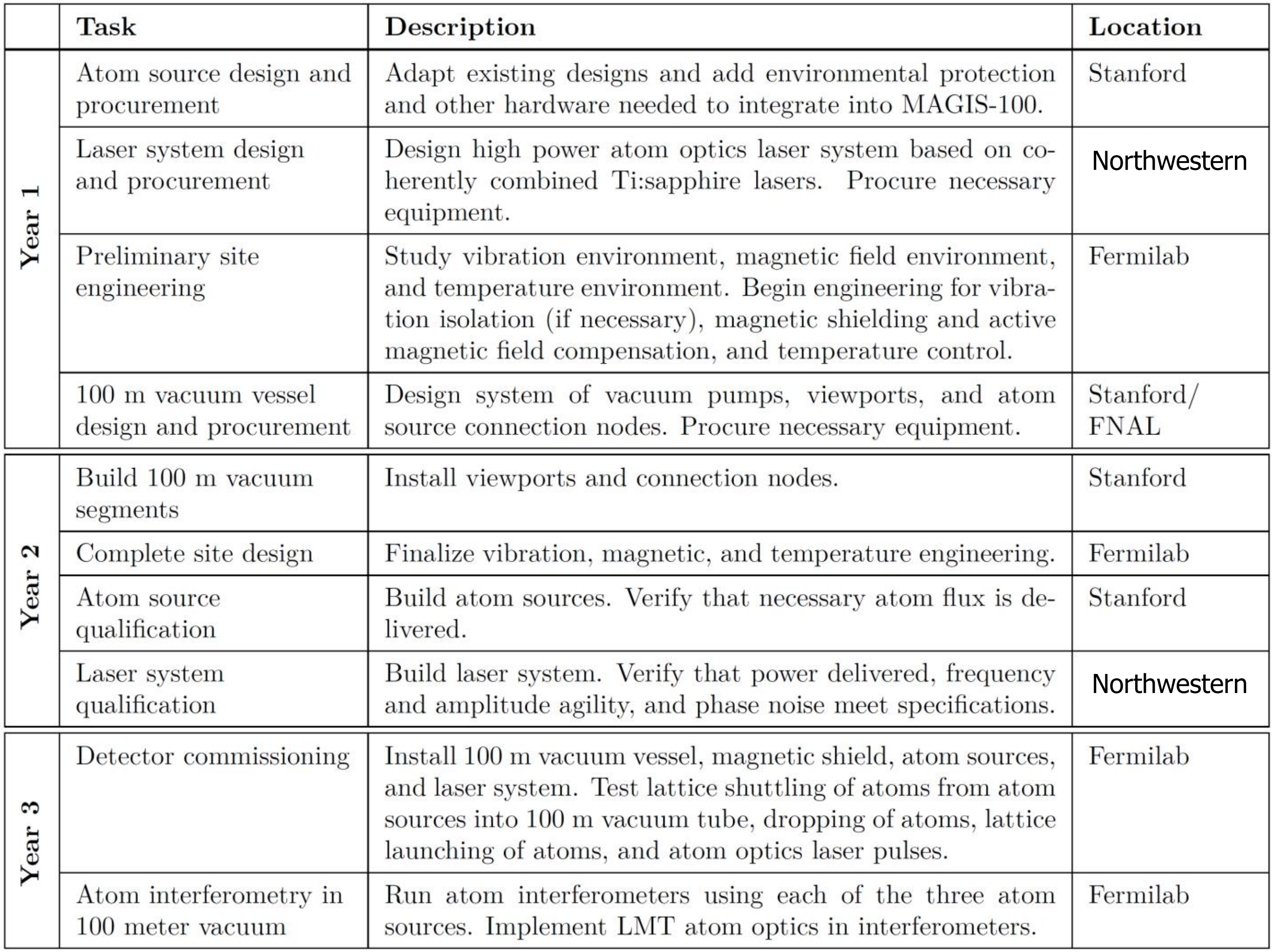
- 10x from higher flux
- 10x from squeezing

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

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

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

MAGIS-100 timeline: Design phase



	Task	Description	Location	Target Completion
Year 1	Atom source design and procurement	Adapt existing designs and add environmental protection and other hardware needed to integrate into MAGIS-100.	Stanford	Dec 2019
	Laser system design and procurement	Design high power atom optics laser system based on coherently combined Ti:sapphire lasers. Procure necessary equipment.	Northwestern	Summer 2019
	Preliminary site engineering	Study vibration environment, magnetic field environment, and temperature environment. Begin engineering for vibration isolation (if necessary), magnetic shielding and active magnetic field compensation, and temperature control.	Fermilab	Fall 2019
	100 m vacuum vessel design and procurement	Design system of vacuum pumps, viewports, and atom source connection nodes. Procure necessary equipment.	Stanford/ FNAL	Dec 2019
Year 2	Build 100 m vacuum segments	Install viewports and connection nodes.	Stanford	Summer 2020
	Complete site design	Finalize vibration, magnetic, and temperature engineering.	Fermilab	Fall 2020
	Atom source qualification	Build atom sources. Verify that necessary atom flux is delivered.	Stanford	Dec 2020
	Laser system qualification	Build laser system. Verify that power delivered, frequency and amplitude agility, and phase noise meet specifications.	Northwestern	Fall 2020
Year 3	Detector commissioning	Install 100 m vacuum vessel, magnetic shield, atom sources, and laser system. Test lattice shuttling of atoms from atom sources into 100 m vacuum tube, dropping of atoms, lattice launching of atoms, and atom optics laser pulses.	Fermilab	Summer 2021
	Atom interferometry in 100 meter vacuum	Run atom interferometers using each of the three atom sources. Implement LMT atom optics in interferometers.	Fermilab	Dec 2021

Years 4 and 5 for science data taking and analysis

MAGIS-100 Location: MINOS building

Ground level of MINOS building

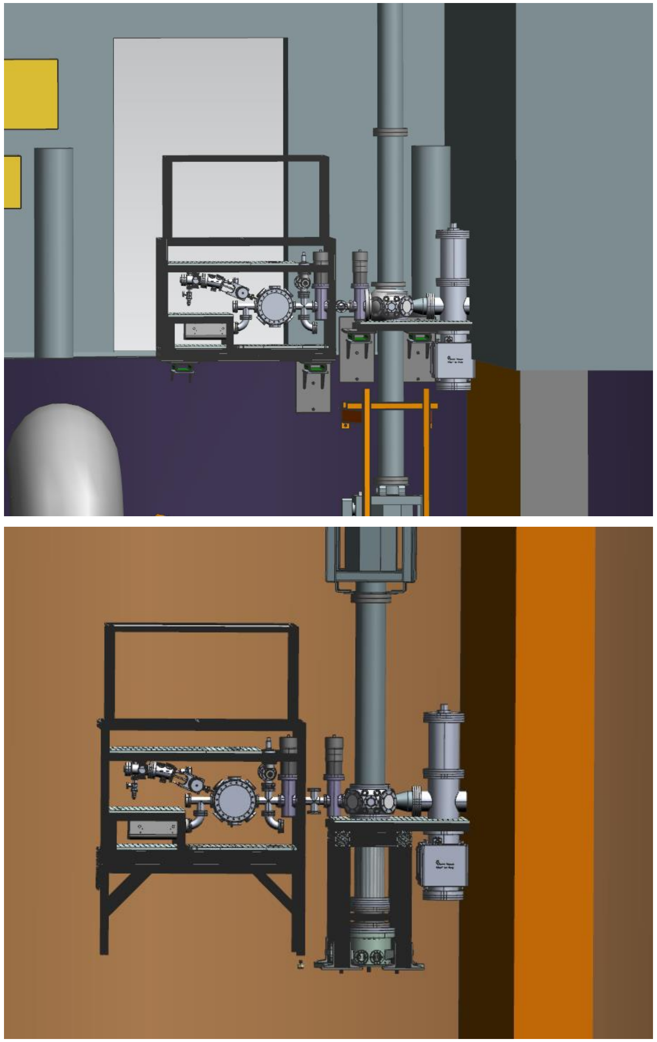
From: L. Valerio (Fermilab), MAGIS Project Engineer

MAGIS-100 Location: Shaft in MINOS building

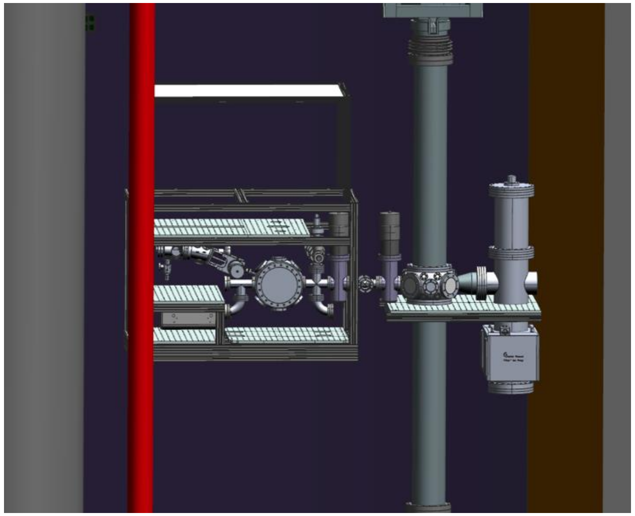
Top and bottom of ~100m shaft.

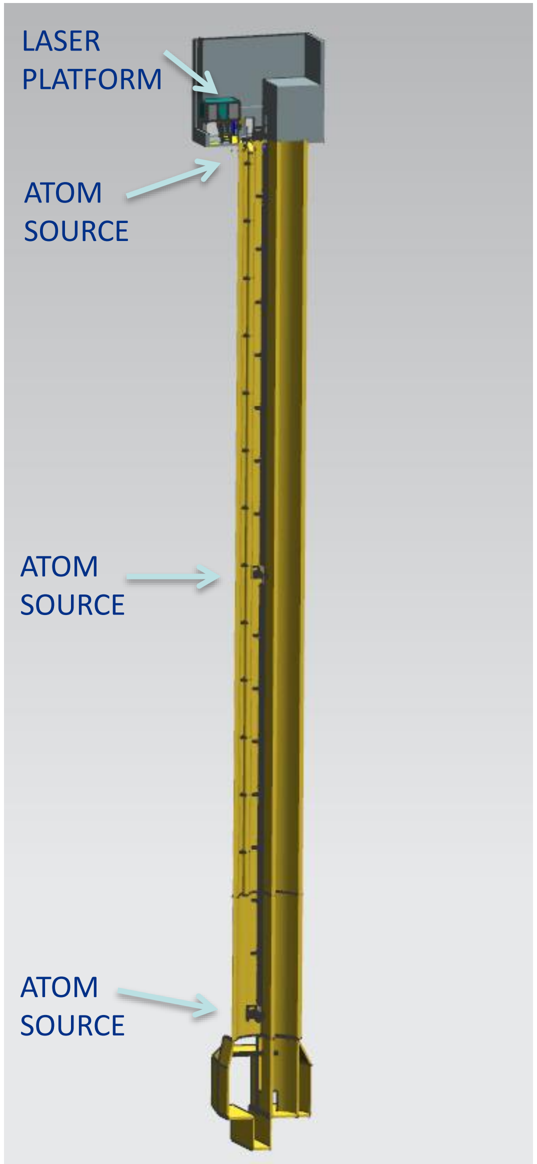
From: L. Valerio (Fermilab), MAGIS Project Engineer

Preliminary designs – 3D model



Top, middle, and bottom atom source details

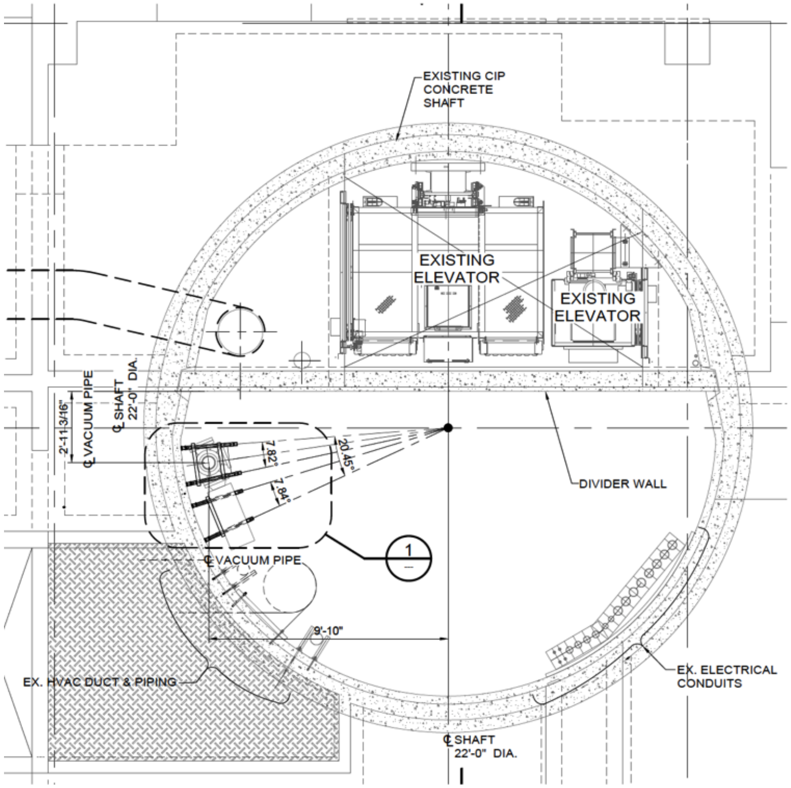


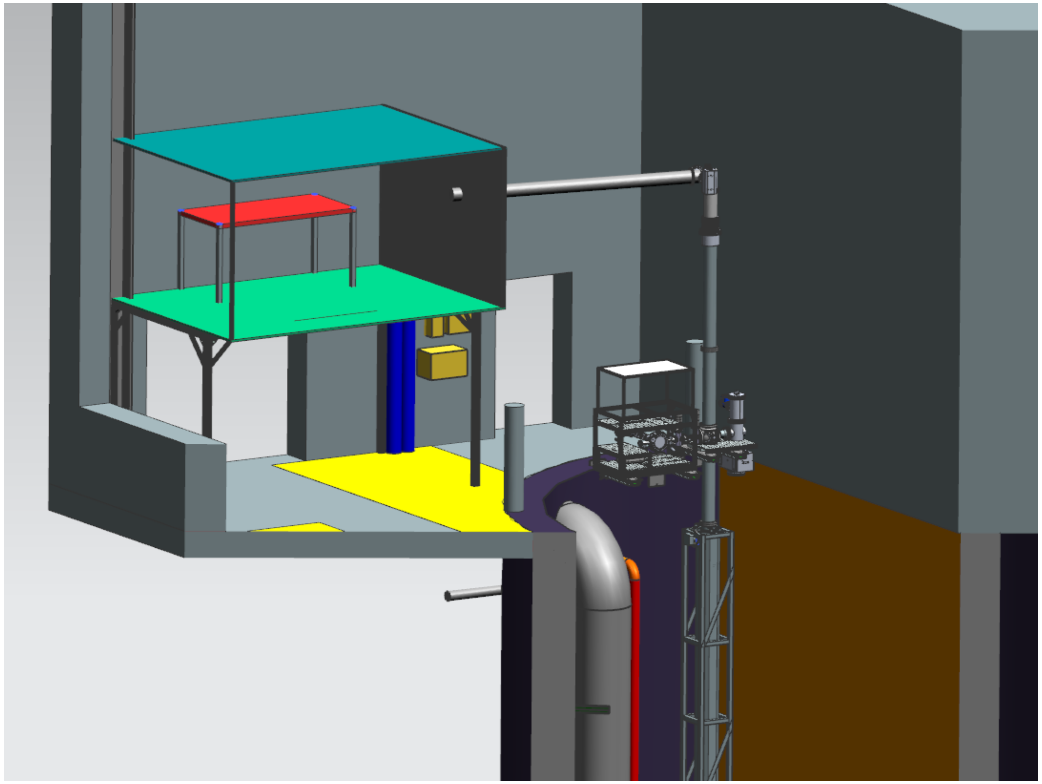


Atom sources mounted to 2m sections with in-vacuum optics for atom launch.

From: L. Valerio (Fermilab), MAGIS Project Engineer

Preliminary designs – 3D model



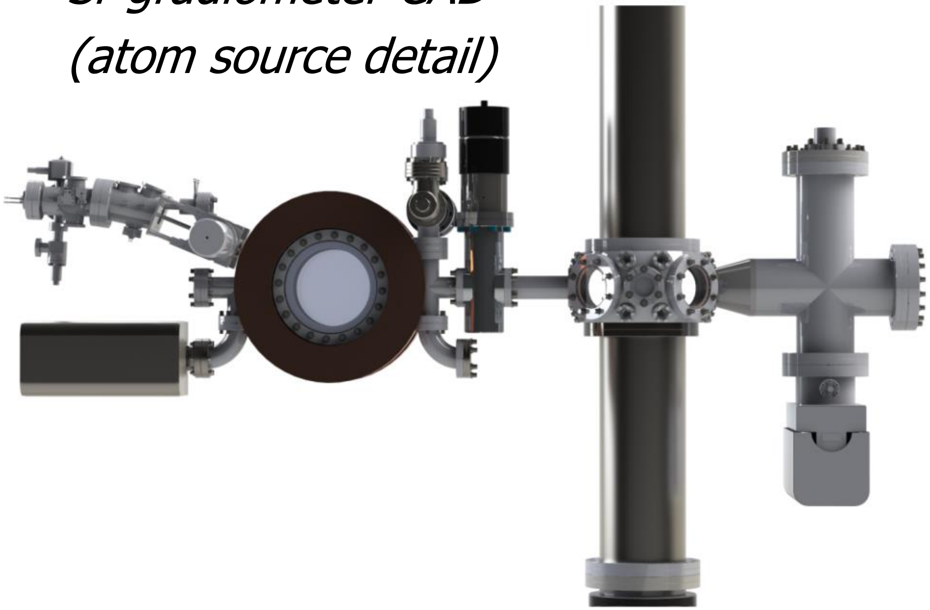


Civil engineering drawing of shaft and proposed location of mounting brackets.
Cutaway view of laser platform and top of shaft.

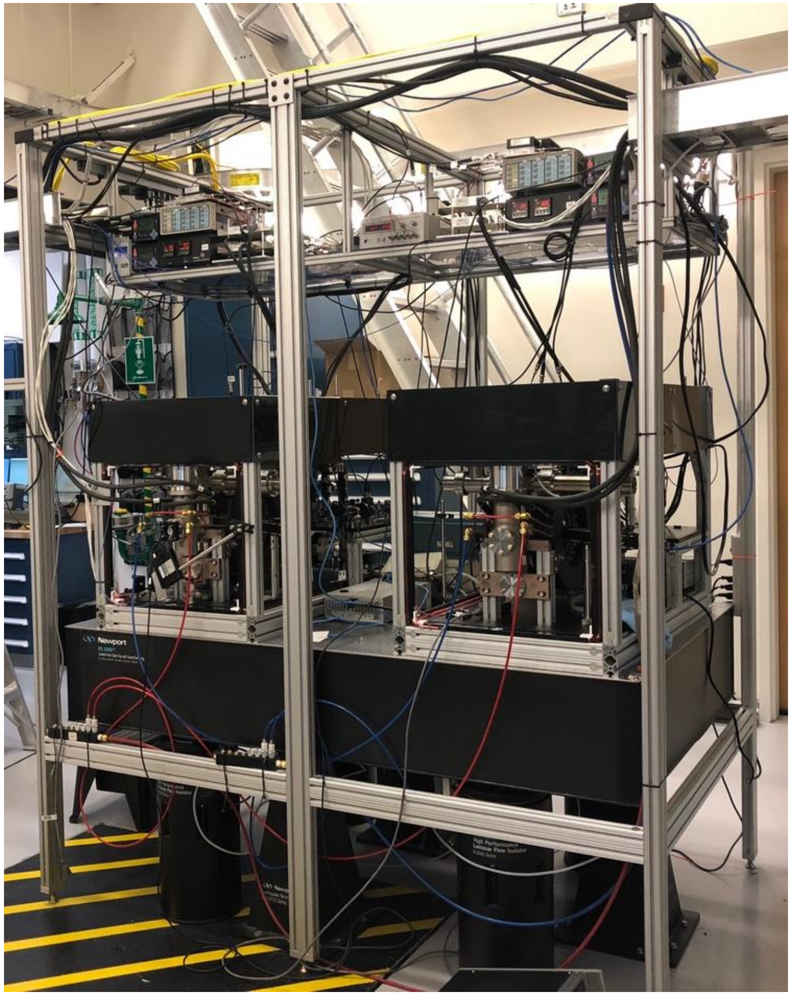
From: L. Valerio (Fermilab), MAGIS Project Engineer

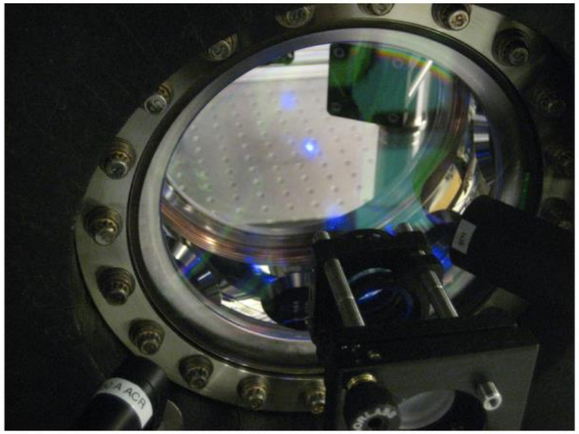
Stanford Sr 10-meter prototype

Sr gradiometer CAD
(atom source detail)



Two assembled Sr atom sources

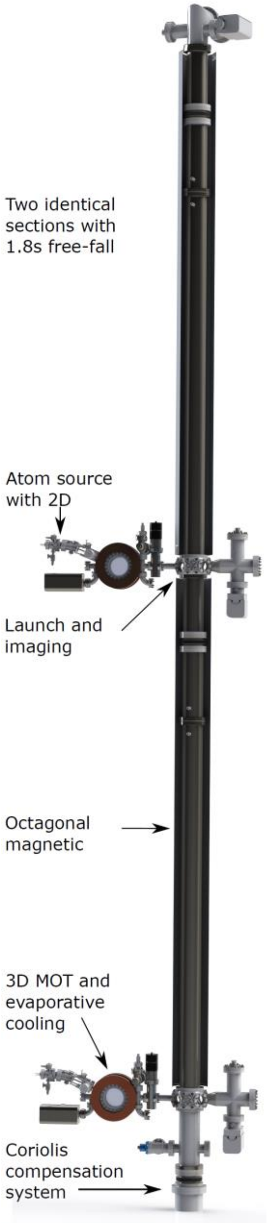




Trapped Sr atom cloud
(Blue MOT)

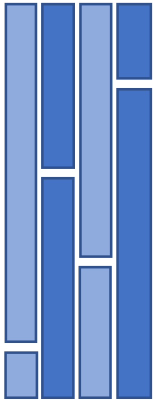
10-meter Sr prototype design

Vacuum system CAD



Magnetic shield design and simulations

Example multi-layer design

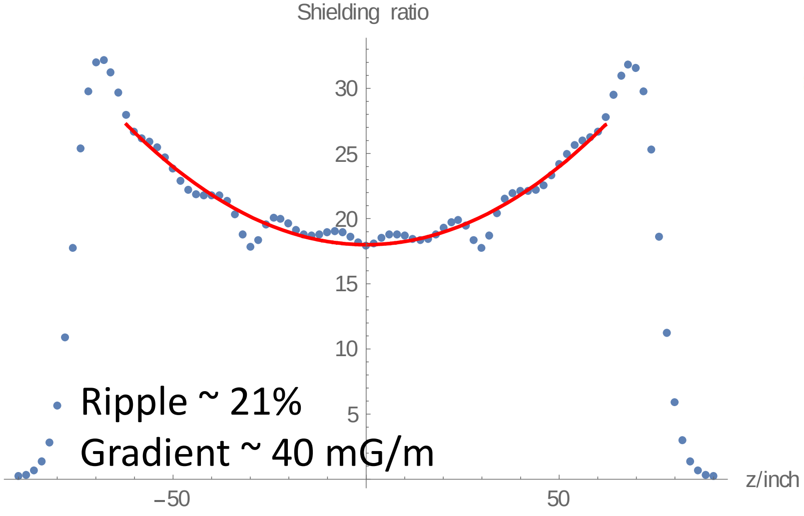


staggered layer design

Layer thickness 0.02 inch

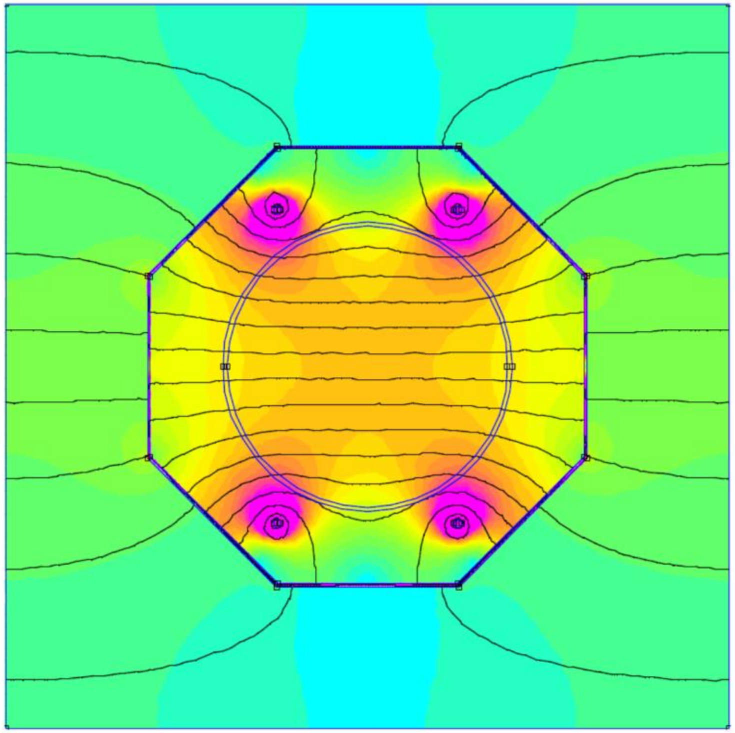
Conservative 100 μm gaps

2D FEM shielding results



- Ripple ~ 21%
- Gradient ~ 40 mG/m

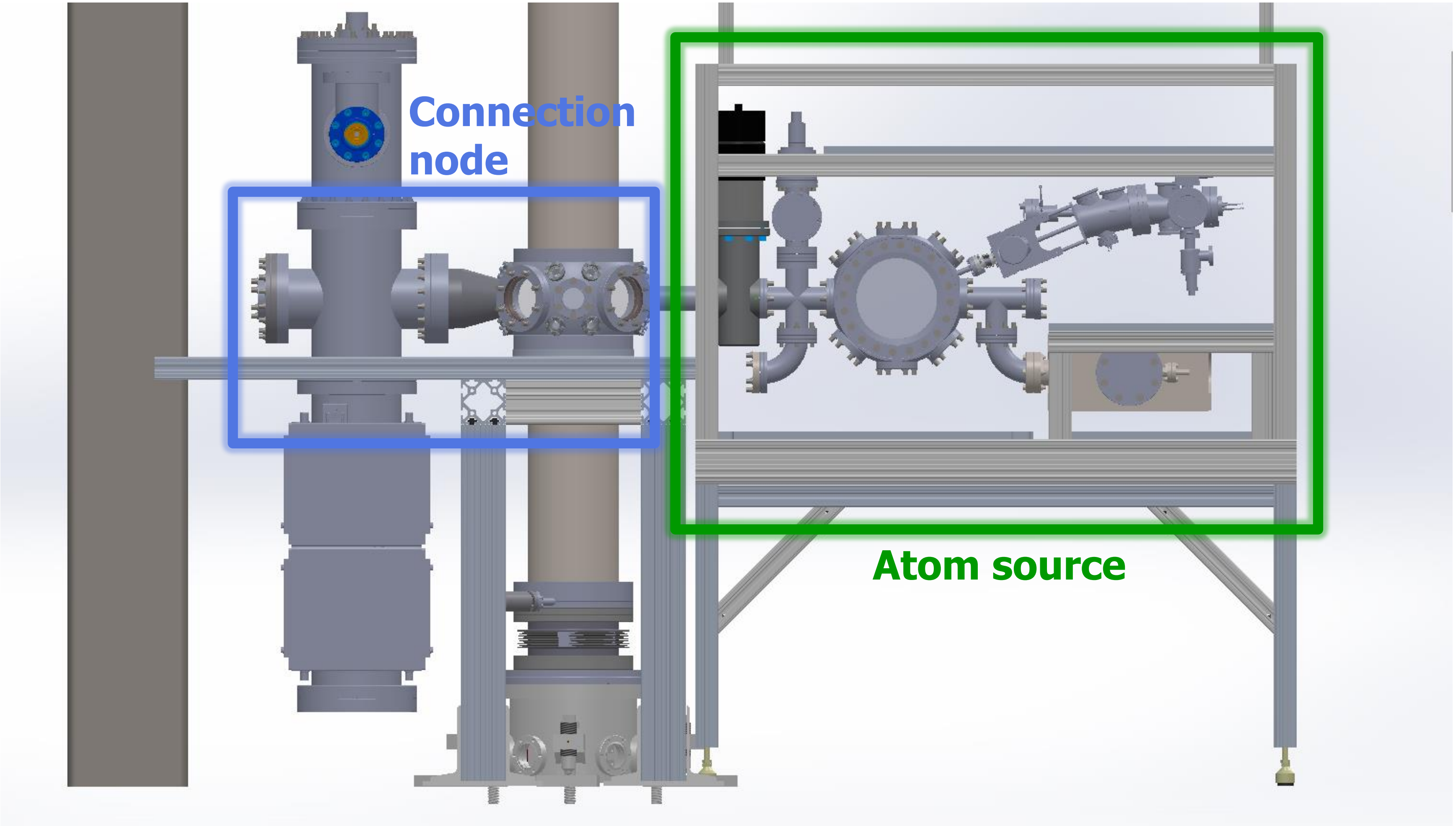
Bias magnetic field simulation



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

Assembly to occur in summer/fall 2019

10-m prototype: Atom source connection

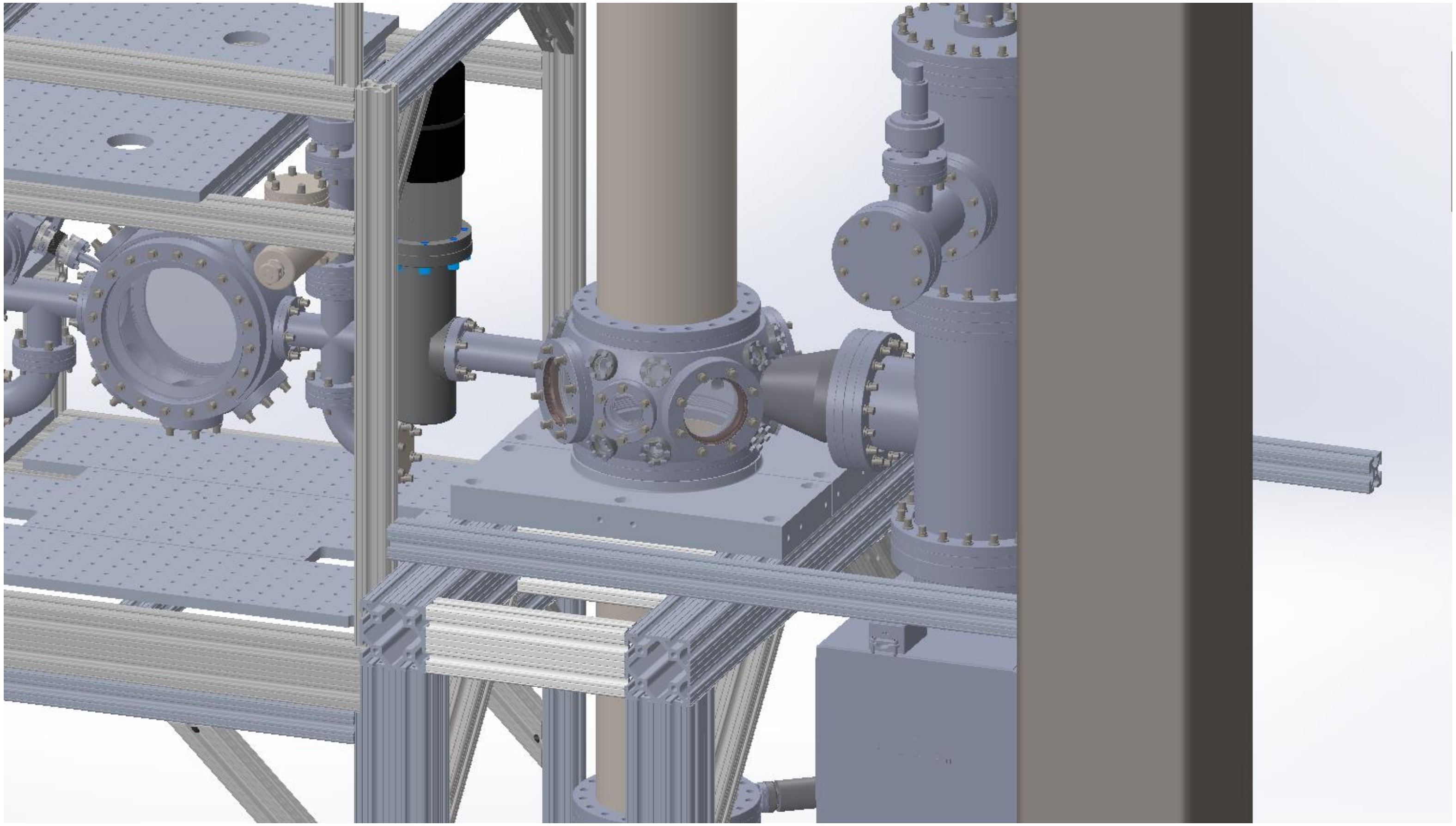


CAD model of lower atom source in Sr 10-m prototype.

Atom source connection node

Functions

- Atom detection: imaging from two directions
- Lattice shuttle, lattice launch
- Vacuum pumping



10-m prototype CAD

MAGIS-100 atom sources sub-systems

Design based on existing Sr atom sources

3x Sr atom sources targeting 1e6 atoms/s, nK temperature

System level component list (sub-systems)

- Commercial Sr beam (oven, Zeeman slower, 2D MOT) **Fall 2019**
- 3D cooling vacuum chamber, pumps **Spring 2020**
- Magnetic coils (quadrupole for MOT, bias coil set) **Spring 2020**
- Laser frequency locks: 461 nm, 689 nm (narrow), 679 nm, 707 nm **Summer 2020**
- Laser frequency control (AOMs, fiber EOMs) **Summer 2020**
- RF electronics for laser frequency control **Summer 2020**
- Power electronics (magnetic coils, DC power rails) **Summer 2020**
- Timing control electronics **Summer 2020**
- Laser delivery optics frame **Fall 2020**
- 1064 nm dipole trap (matter wave lensing, evaporation, shuttle) **Fall 2020**
- Detection/diagnostics imaging system **Fall 2020**
- Remote monitoring and tweak-up system **Winter 2020**
- Environmental isolation and control (temperature, water infiltration, laser safety) **Winter 2020**

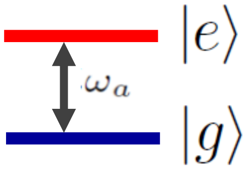
Atom optics

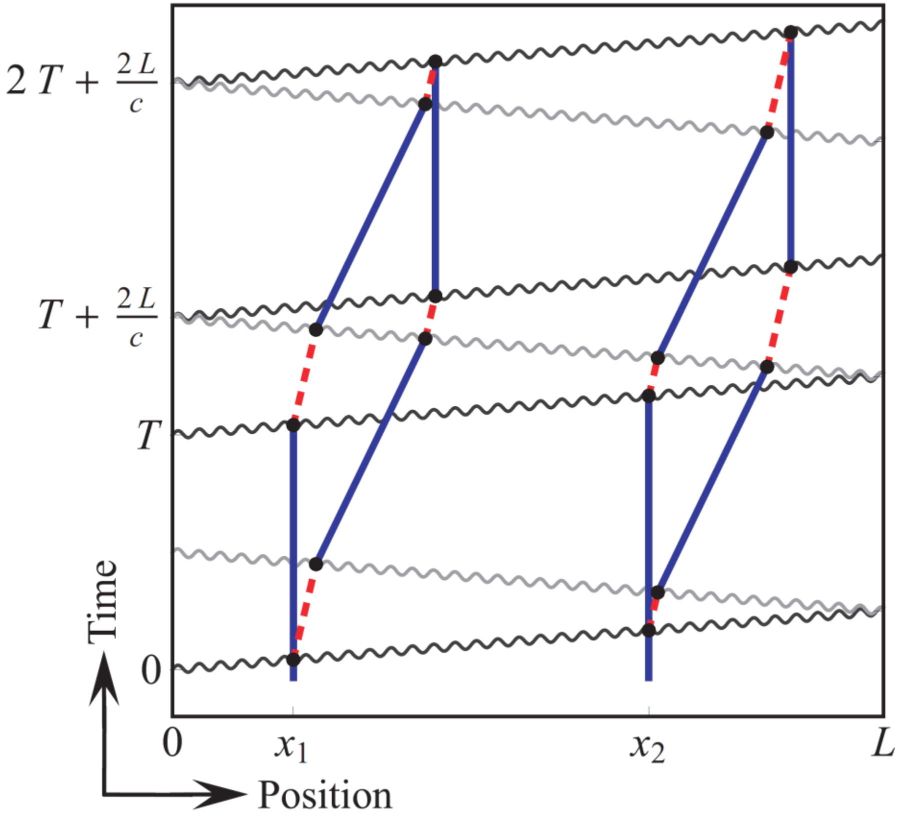
<u>Two detection modes:</u>

- Single photon transitions on clock transition
  - Long-baseline gradiometer configuration
  - Gravitational wave detection
  - Scalar dark matter search

- Two-photon Bragg transitions
  - Compare two co-located isotopes
  - Time-varying Equivalence Principle violating new forces
  - B-L vector coupled dark matter search

Clock gradiometer using single photon transitions





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*

Each interferometer measures the change over time T

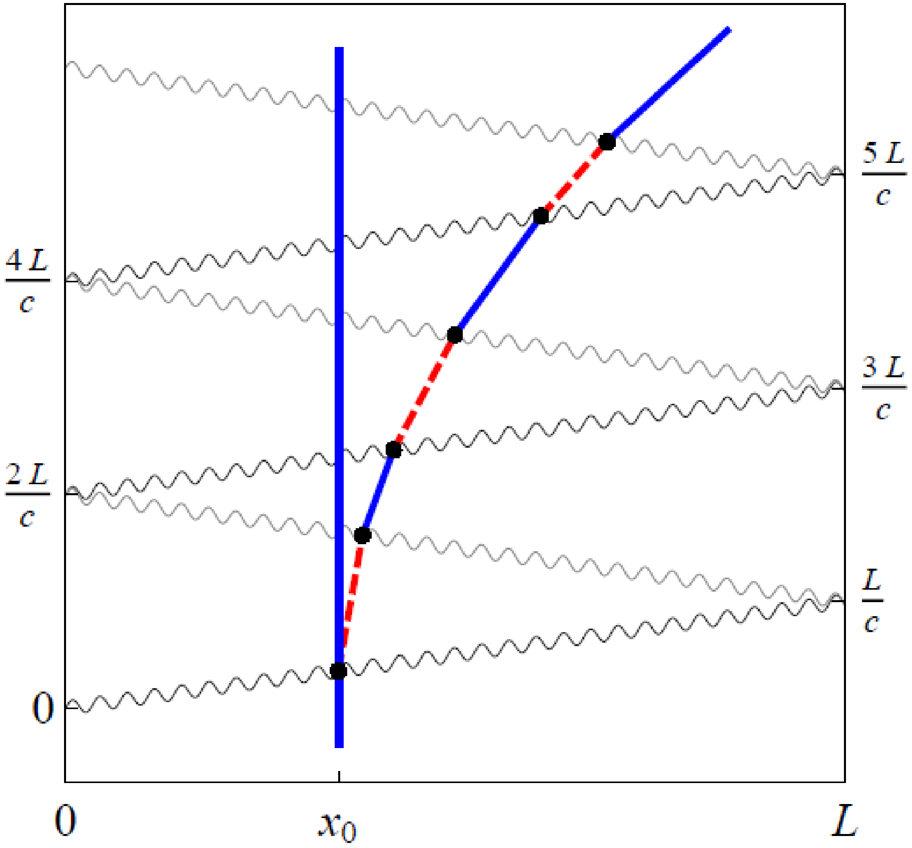
Laser noise is common-mode suppressed in the gradiometer

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

LMT and Resonant Pulse Sequences

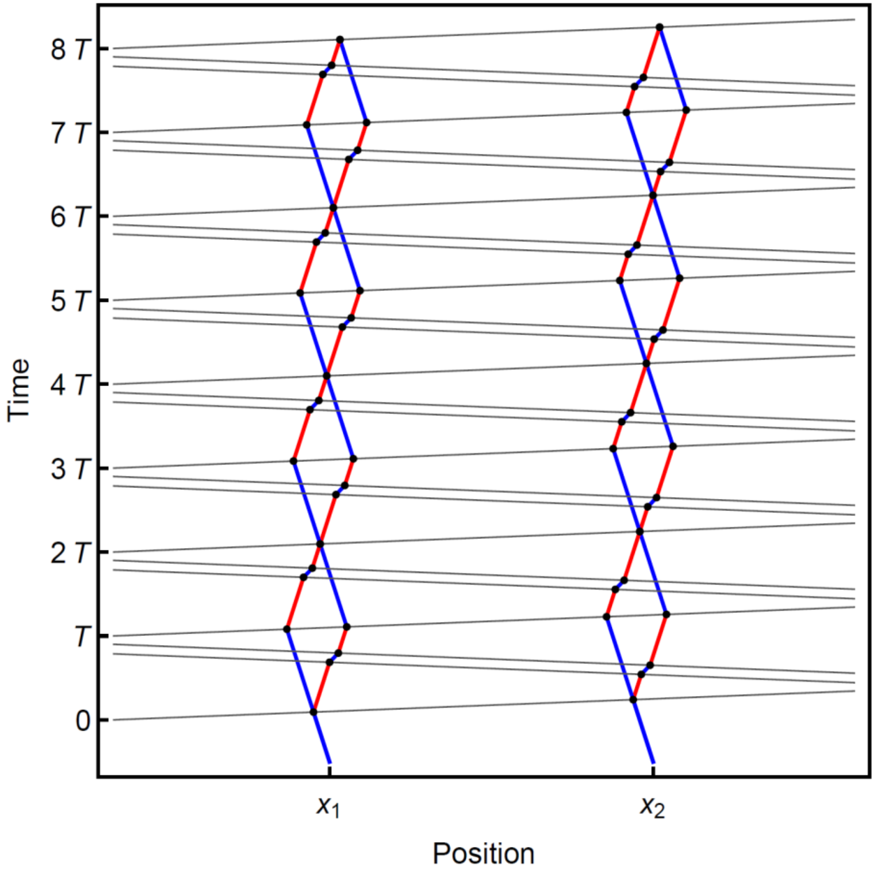
Sequential single-photon transitions remain laser noise immune

LMT beamsplitter (N = 3)



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

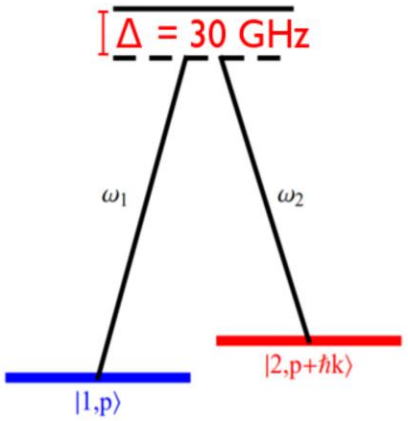
Resonant sequence (Q = 4)



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

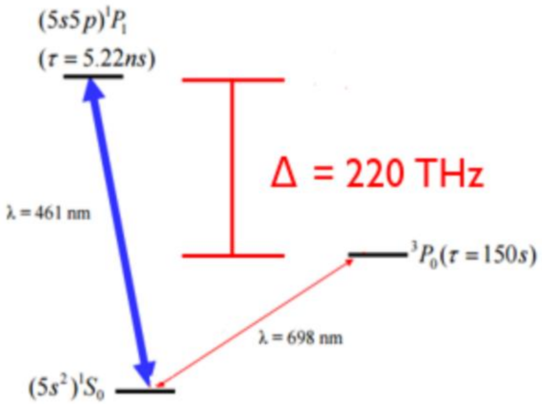
Extreme LMT with clock atoms

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 pulses

Clock atoms (e.g. strontium)



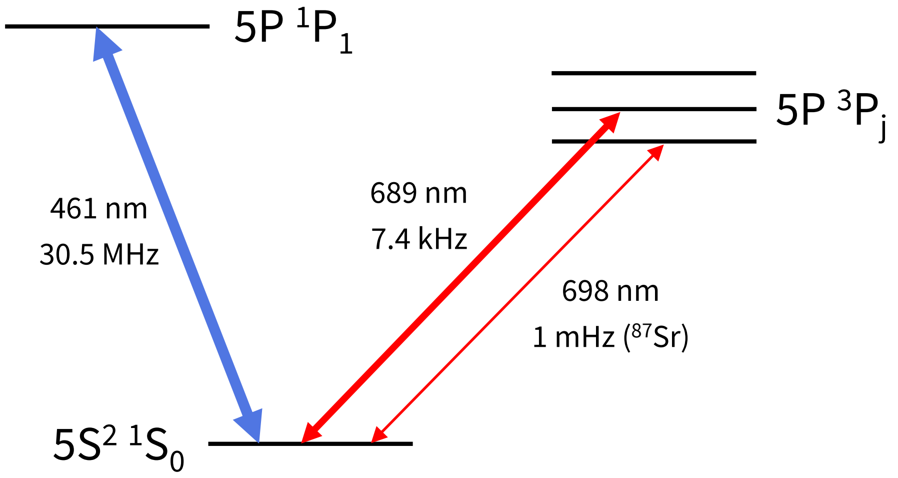
- Single photon transition for atom optics
- Spontaneous emission naturally highly suppressed (150 s lifetime clock state, other levels far detuned)
- Possibility to support > 10^6 pulses

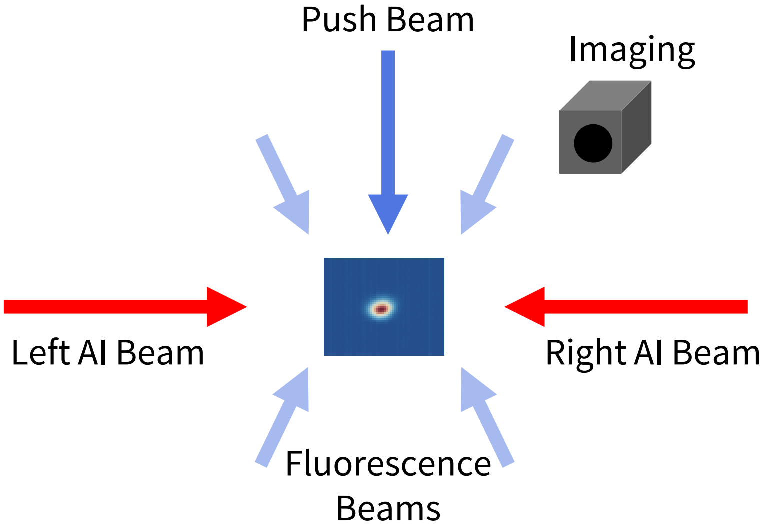
Clock atom interferometry demonstration

- Goal: 698 nm clock transition in ^{87}Sr
- Use 689 nm transition in ^{88}Sr for **initial demonstration** of LMT clock AI

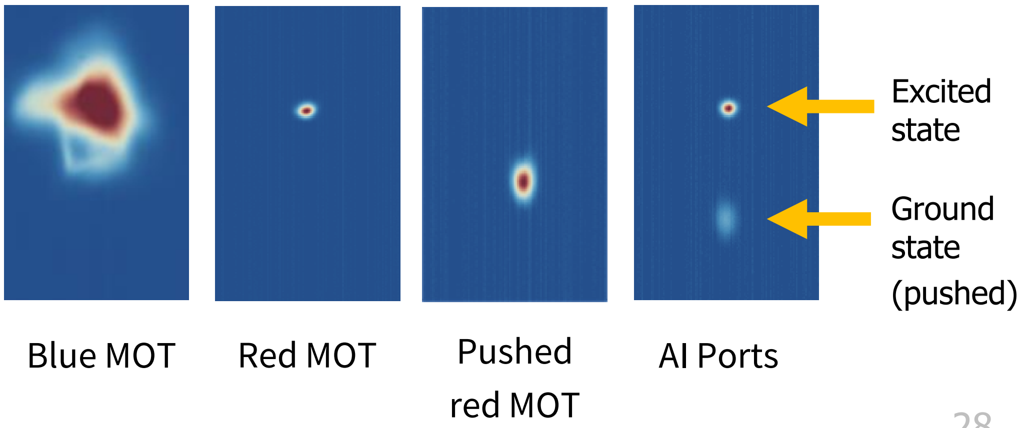
<u>689 nm transition features:</u>

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



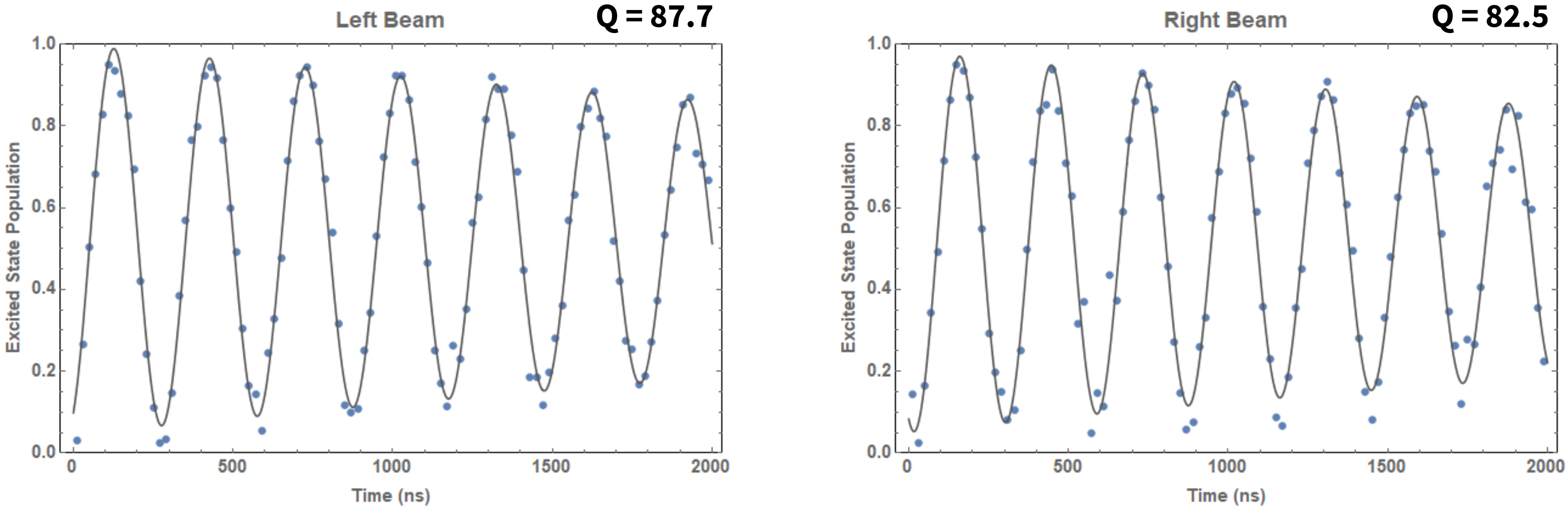


Experimental sequence and detection protocol



Rabi oscillations

Rabi oscillations on the 689 nm transition

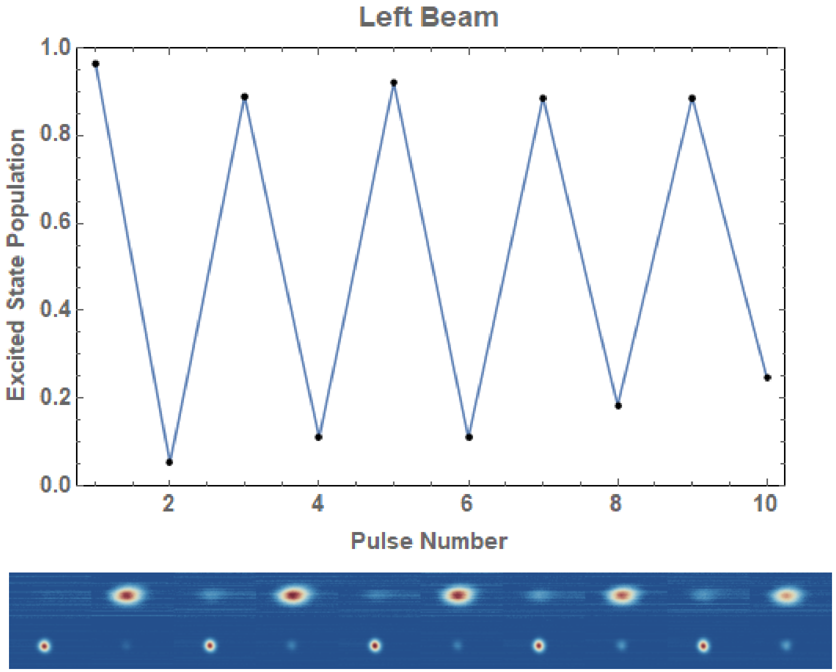


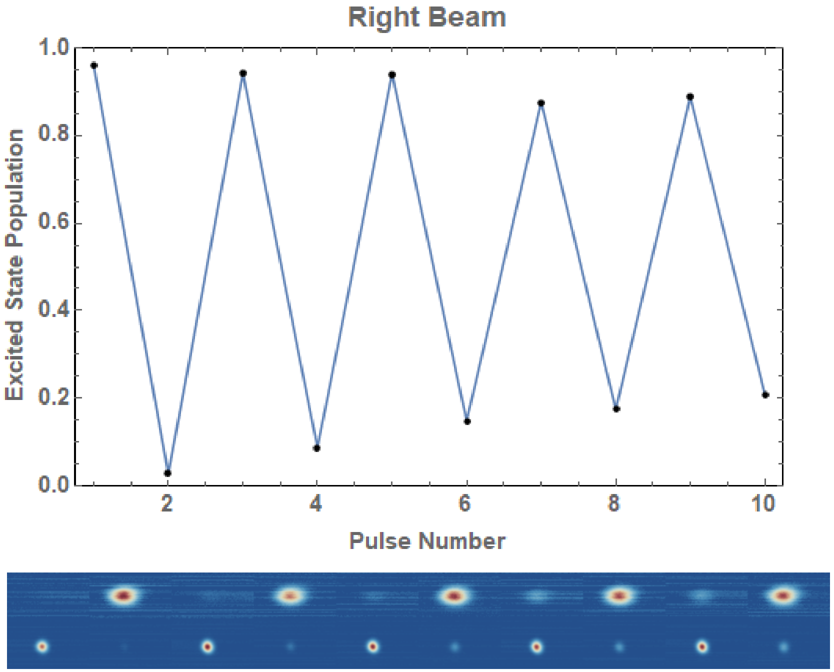
- High Q, high Rabi frequency (MHz), 150 ns π-time, good contrast
- Residual decay explained by finite beam sizes
- Trade-off between Rabi frequency and Q

Measured inhomogeneous loss could support 1000 ħk atom optics (>95% efficiency)

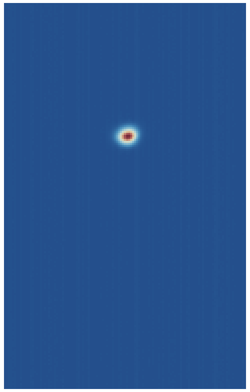
LMT beam splitter demonstration

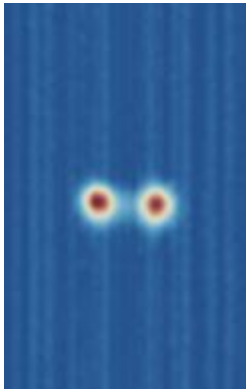
Sequential π-pulses show similar efficiency





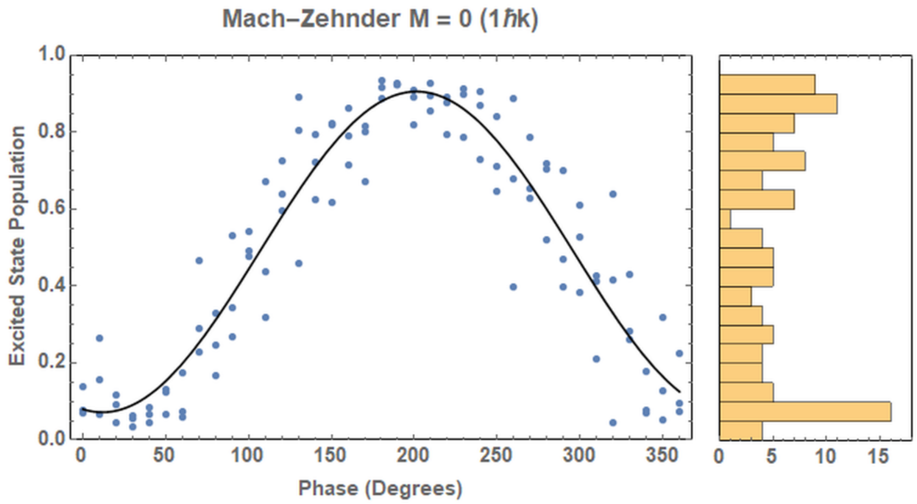
Beam splitter (π/2)
+ 20 alternating π pulses





41ħk Beam Splitter
(after TOF)

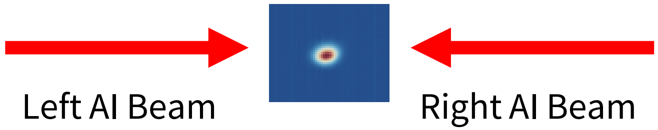
Mach-Zehnder Interferometer (Preliminary!)



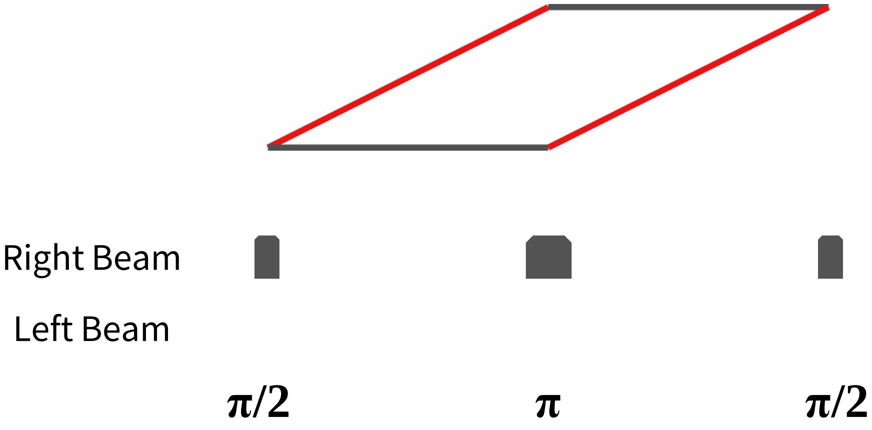
M = 0 (1ħk)

Contrast = 0.9

Visibility = 0.83


Left AI Beam

Right AI Beam

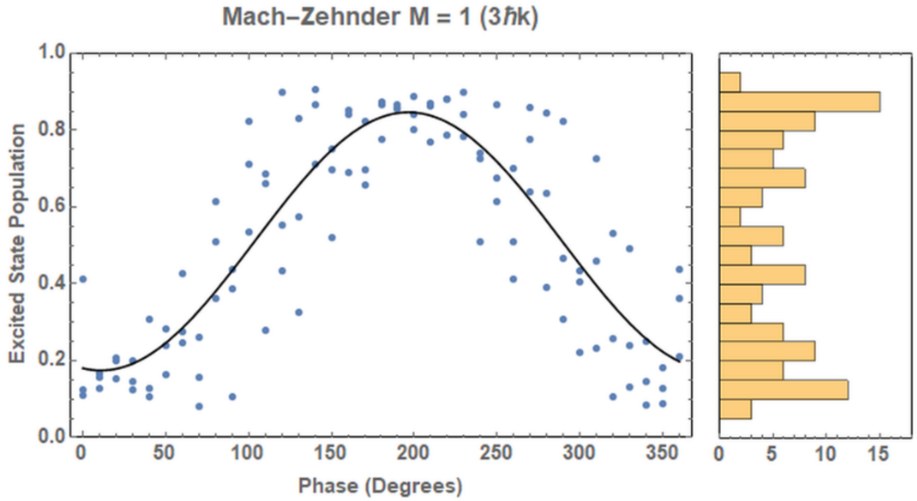

Right Beam

Left Beam

$\pi/2$ π $\pi/2$

This sequence first demonstrated (on 698 nm transition) in:
L. Hu, N. Poli, L. Salvi, and G. M. Tino, PRL 119, 263601 (2017).

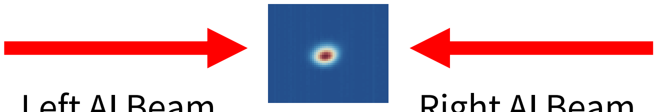
Mach-Zehnder & LMT (Preliminary!)

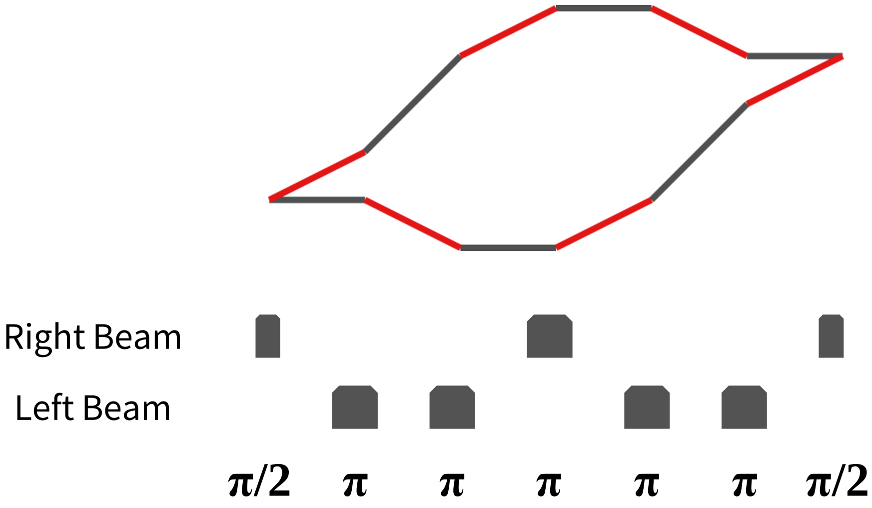


M = 1 (3ℏk)

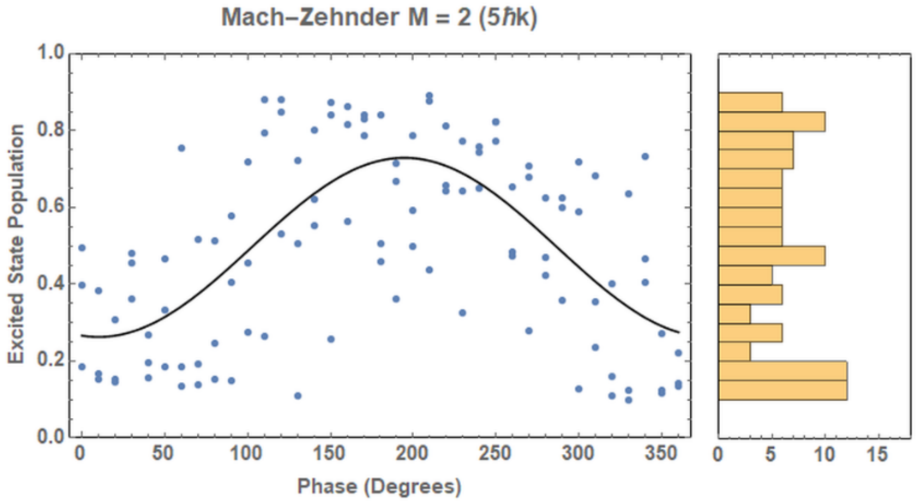
Contrast = 0.83

Visibility = 0.67



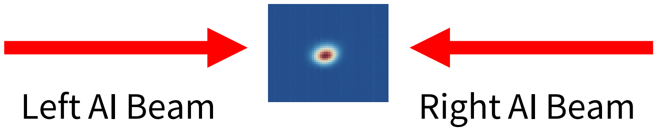


Mach-Zehnder & LMT (Preliminary!)



Contrast = 0.79

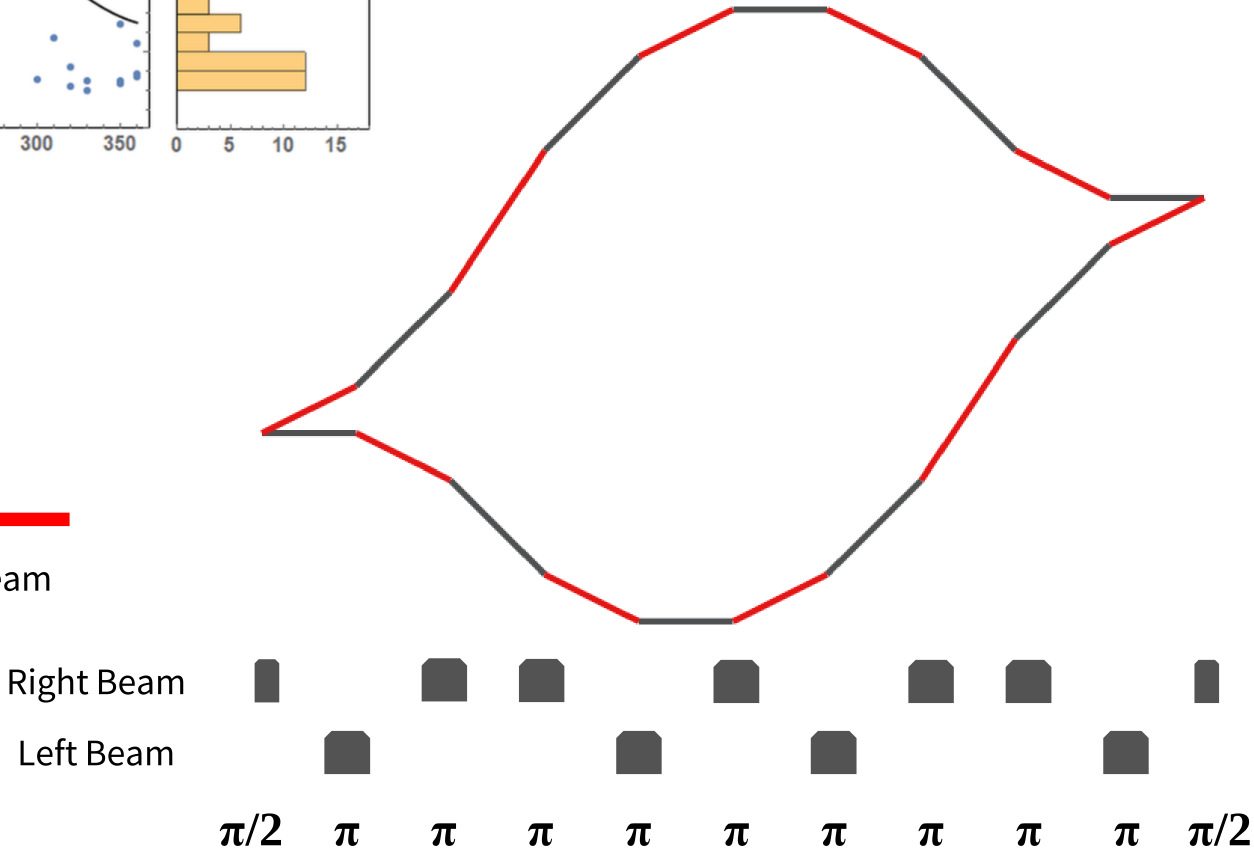
Visibility = 0.47



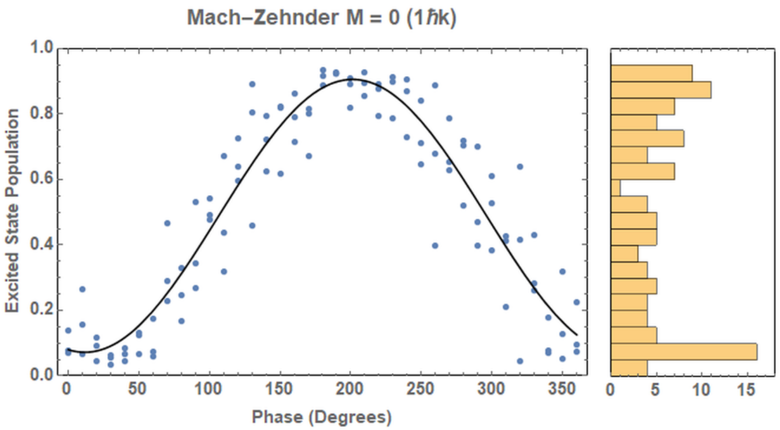
Left AI Beam

Right AI Beam

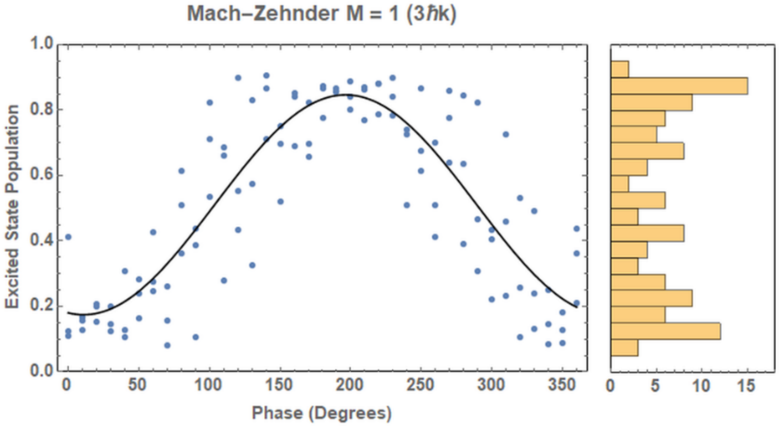
M = 2 (5ħk)

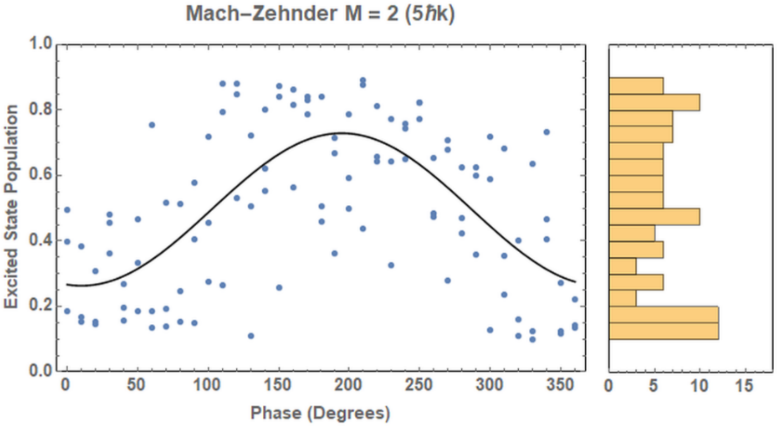


Mach-Zehnder & LMT (Preliminary!)



M	N π	ħk	Visibility	Contrast
0	1	1	0.83	0.90
1	5	3	0.67	0.83
2	9	5	0.47	0.79





Consistent high contrast; reduction of visibility as expected due to phase noise.

Next steps: Extend to higher LMT and implement gradiometer sequences.

Collaborators

Sr Atom Interferometry
Jan Rudolph
TJ Wilkason
Hunter Swan
Yijun Jiang
Ben Garber
Connor Holland

Rb Atom Interferometry
Mark Kasevich
Tim Kovachy
Chris Overstreet
Peter Asenbaum
Remy Notermans

Theory
Peter Graham
Roger Romani
Savas Dimopoulos
Surjeet Rajendran
Asimina Arvanitaki
Ken Van Tilburg

MAGIS-100:
Joseph Lykken (Fermilab)
Robert Plunkett (Fermilab)
Swapan Chattopadhyay (Fermilab/NIU)
Jeremiah Mitchell (Fermilab)
Roni Harnik (Fermilab)
Phil Adamson (Fermilab)
Steve Geer (Fermilab)
Jonathon Coleman (Liverpool)
Tim Kovachy (Northwestern)

GORDON AND BETTY MOORE FOUNDATION
GBMF7945

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA
DE-SC0019174

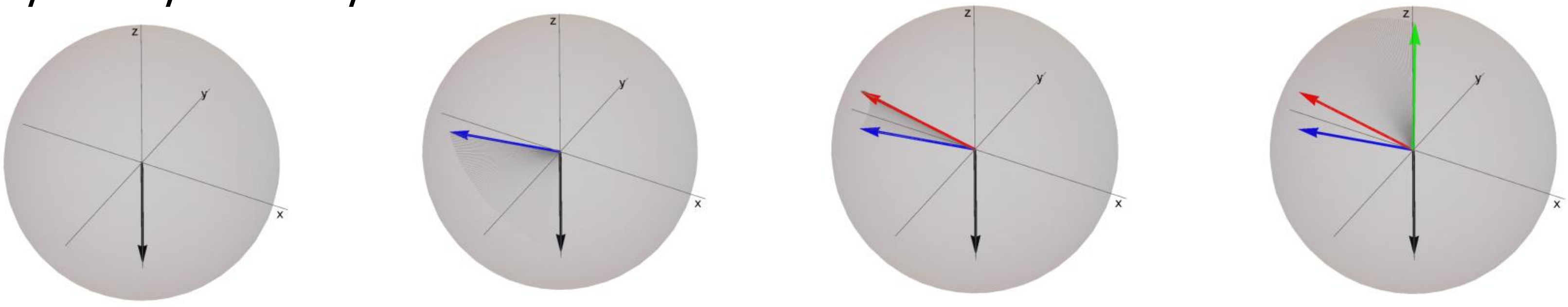
Office of Naval Research Science & Technology
N00014-17-1-2247

Backup

Technical noise suppression

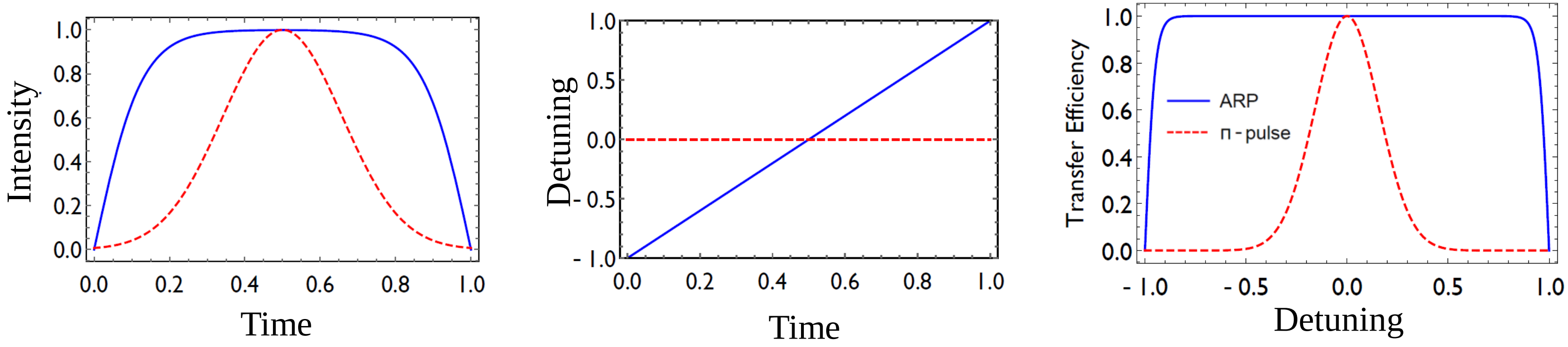
- Practical limitation of extreme LMT is fidelity of the atomic transitions
- Technical noise (e.g., laser intensity, frequency) reduces transfer efficiency
- Well-known techniques can be used to avoid this, at the cost of pulse area

Composite pulse sequences



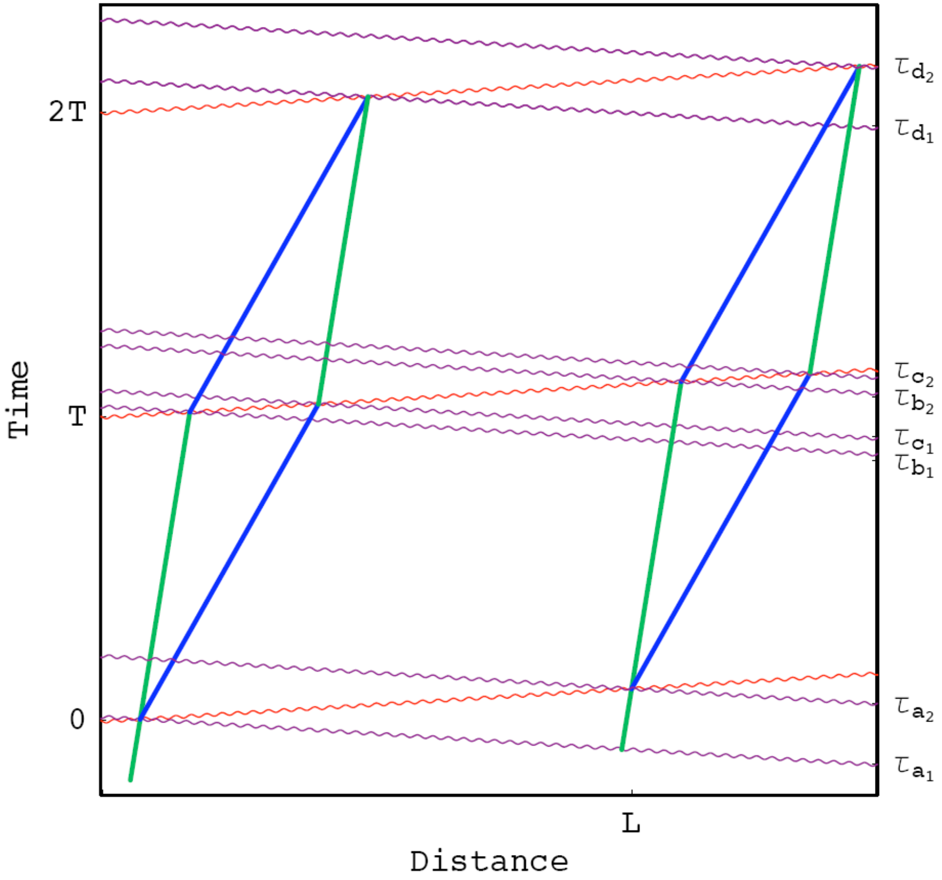
Initial State $\pi/2$ $\pi/2$ π_{90} $\pi/2$ π_{90} $\pi/2$

Adiabatic rapid passage (ARP)



ARP figures from: Kovachy et al., PRA 86, 011606 (2012).

Two-photon laser frequency noise in a gradiometer



Consider a laser frequency error $\delta\omega$ that varies at the GW frequency

Phase error:

$$\updownarrow \quad \delta\phi_L = \delta\omega\,\Delta t \sim \delta\omega\,L/c$$

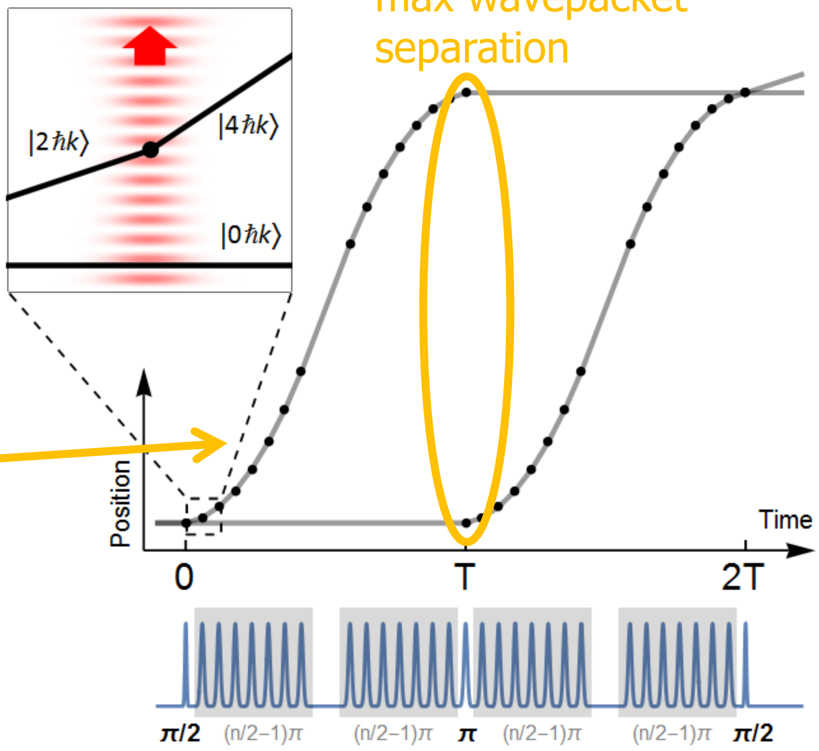
GW Signal:

$$\Delta\Phi_{GW} \sim k\,\delta L \sim khL$$

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

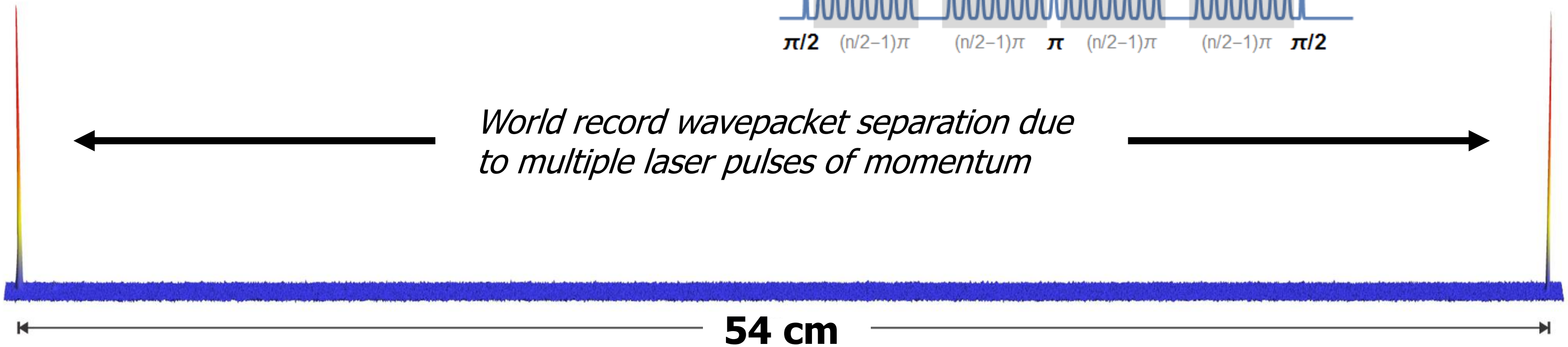
Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer



max wavepacket separation

90 photons worth of momentum



World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., *Nature* 2015

Ultralight scalar dark matter

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

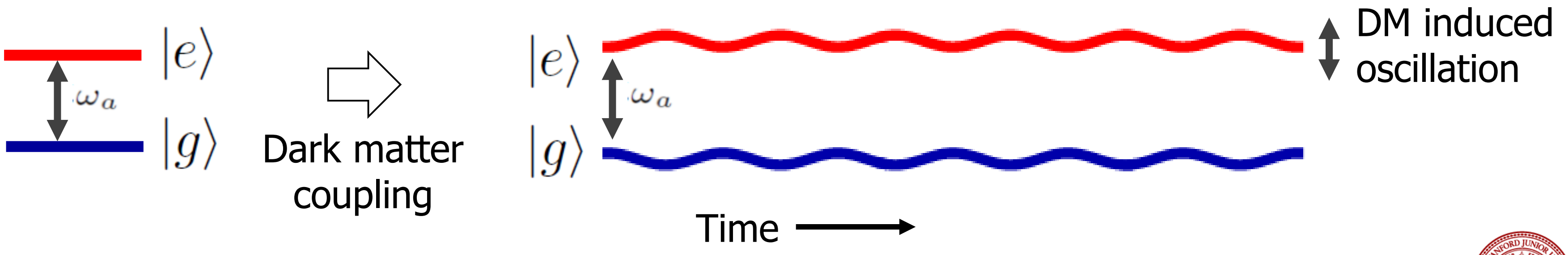
$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\,\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g.,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

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

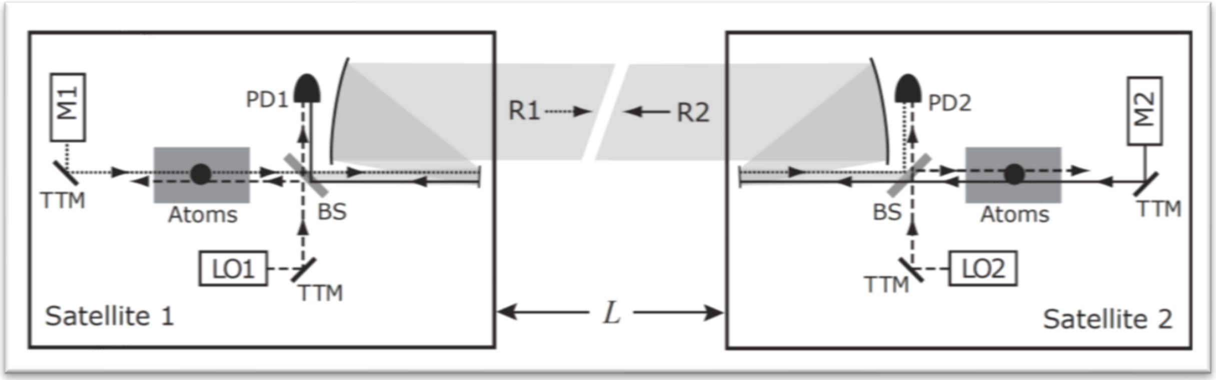
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$

DM mass density

DM coupling causes time-varying atomic energy levels:

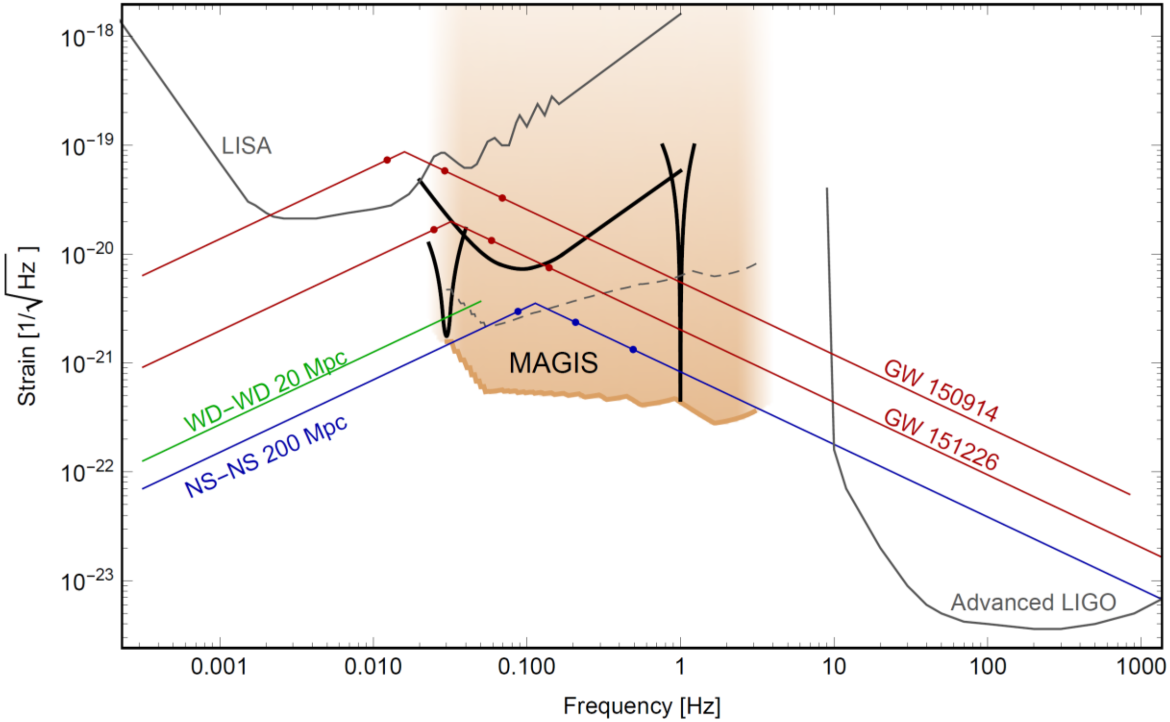


GW Sensitivity for a Satellite Detector



Satellite detector concept

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



Dots indicate remaining lifetimes of 10 years, 1 year and 0.1 years

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

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

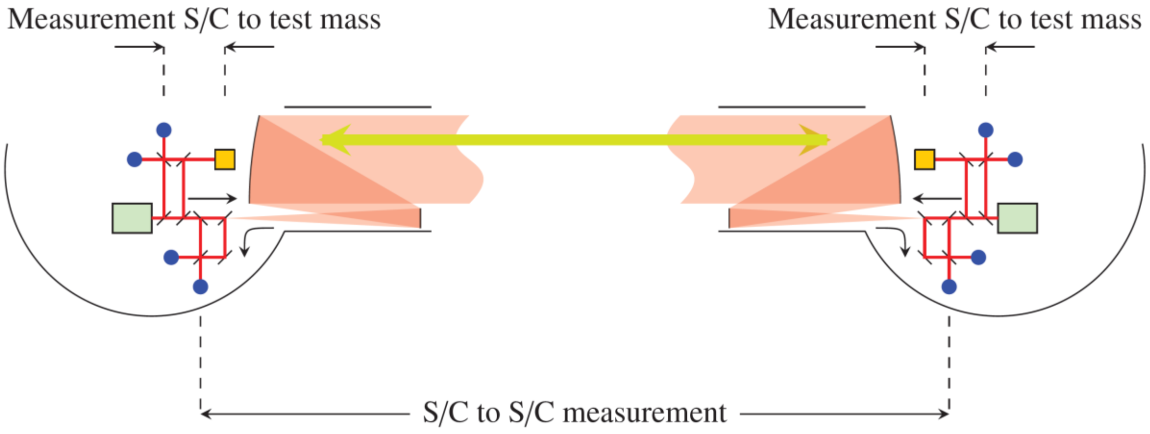
$$\frac{n\hbar k}{m}T < 1\ \mathrm{m}$$

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

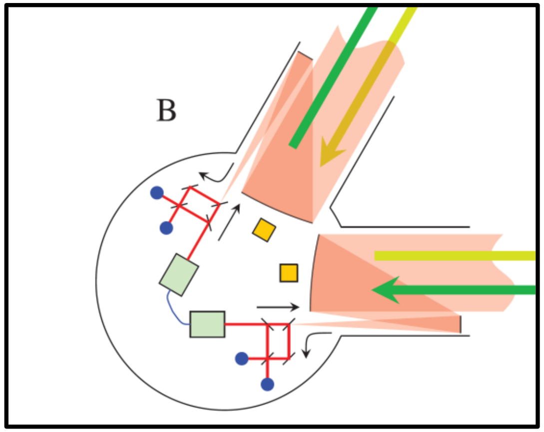
$$n_p < 10^3$$

Compare to LISA

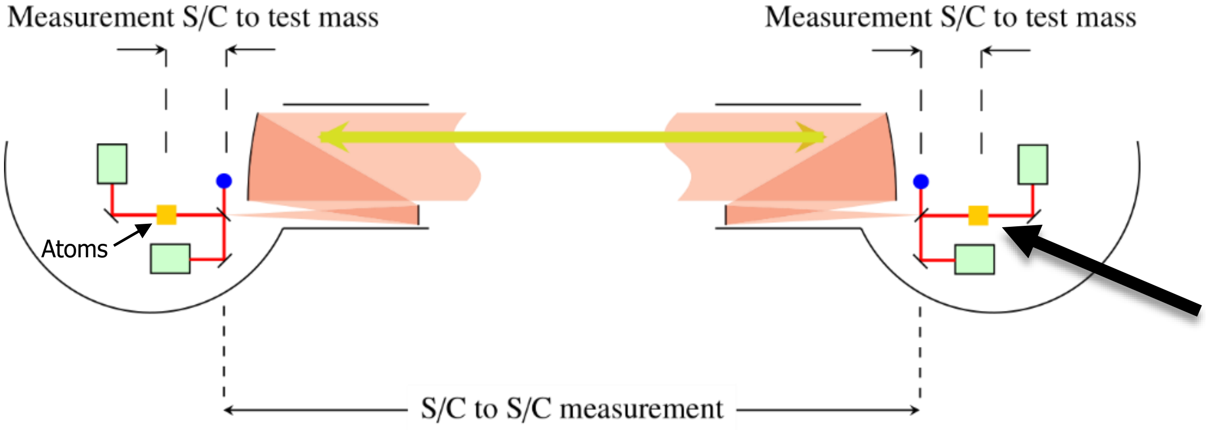
LISA:



Second baseline needed for phase reference:



Atom interferometer:



Atom test mass

- Records laser noise
- Acts as phase reference

STANFORD UNIVERSITY

(Figures adapted from LISA yellow book.)