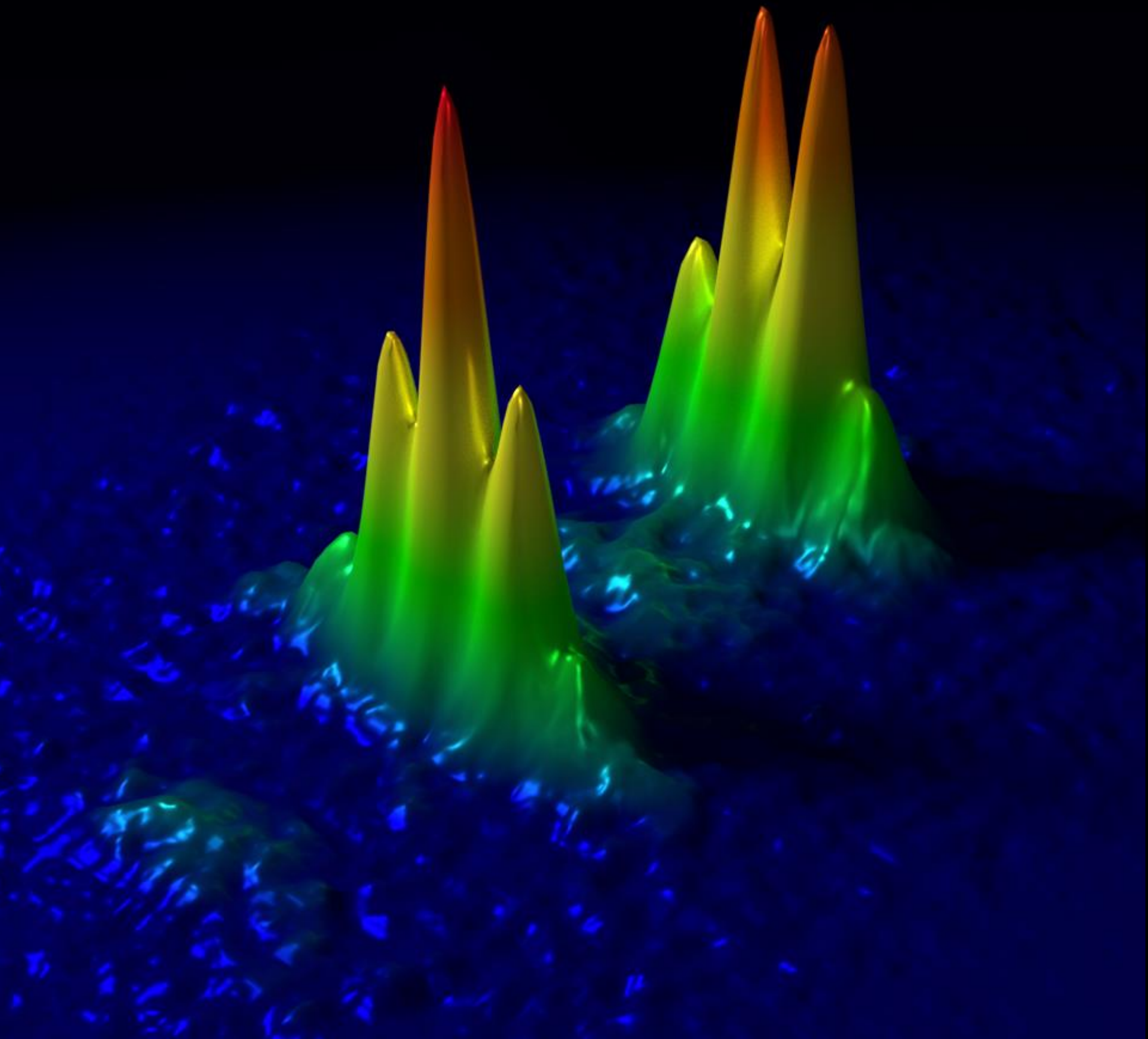
Matter wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)



PAC Meeting

Jason Hogan

on behalf of the MAGIS collaboration

January 16, 2019

July 2018 PAC Report

From the July 2018 PAC Report:

The PAC heard a detailed report covering the MAGIS-100 Letter of Intent for the next-generation MAGIS experiment. The hundred-meter MAGIS-100 experiment is an atom interferometric gradiometer that would be housed in the NuMI shaft, containing three atom sources (top, middle, bottom), associated lasers, and a high-vacuum ~100m pipe. The experiment would function as a pathfinder for a km-scale instrument (which could potentially be hosted at SURF in South Dakota) **to measure low-frequency gravitational waves**, an exciting and unique opportunity made possible by this technology. Additionally, MAGIS-100 will **set limits on low-mass dark matter candidates** in a class of scenarios predicting oscillations in a background classical field, exotic new forces, and time-dependence of fundamental constants. It will also function as a **demonstrator for long-range quantum superpositions** setting strict limits on certain models of intrinsic quantum decoherence.

Given the work already carried out at Stanford (MAGIS-10) and the relative maturity of the proposed strontium-based technology which will be fully tested at Stanford before bringing the experiment to Fermilab, MAGIS-100 **represents both an exciting science opportunity** that leverages quantum science and technology as well as one that poses a low risk for the Laboratory. The PAC finds that the request by MAGIS-100 for engineering and drafting resources to develop **a full proposal appears reasonable and strongly supports it. The PAC looks forward to receiving a MAGIS-100 proposal in the near future.**

Updates:
- Proposal submitted to the PAC in December 2018
- Grant received from the Gordon and Betty Moore Foundation for MAGIS-100

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]

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[6] *Northwestern University; Evanston, Illinois, USA*

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

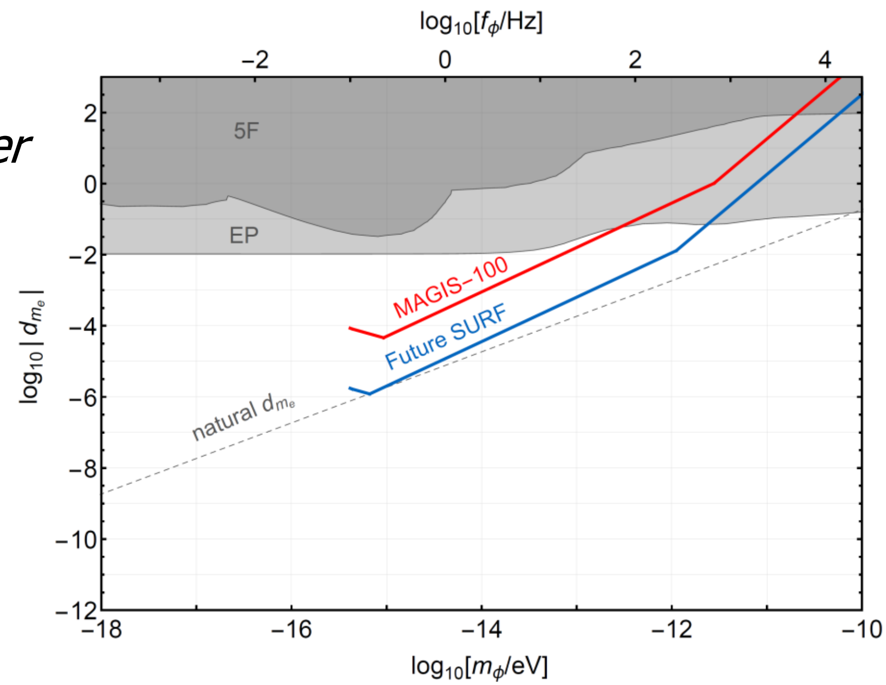
- Atom de Broglie wavepackets in superposition separated by up to 10 meters
- Durations of many seconds, up to 9 seconds (full height launch)
- Quantum entanglement to reduce sensor noise below the standard quantum limit

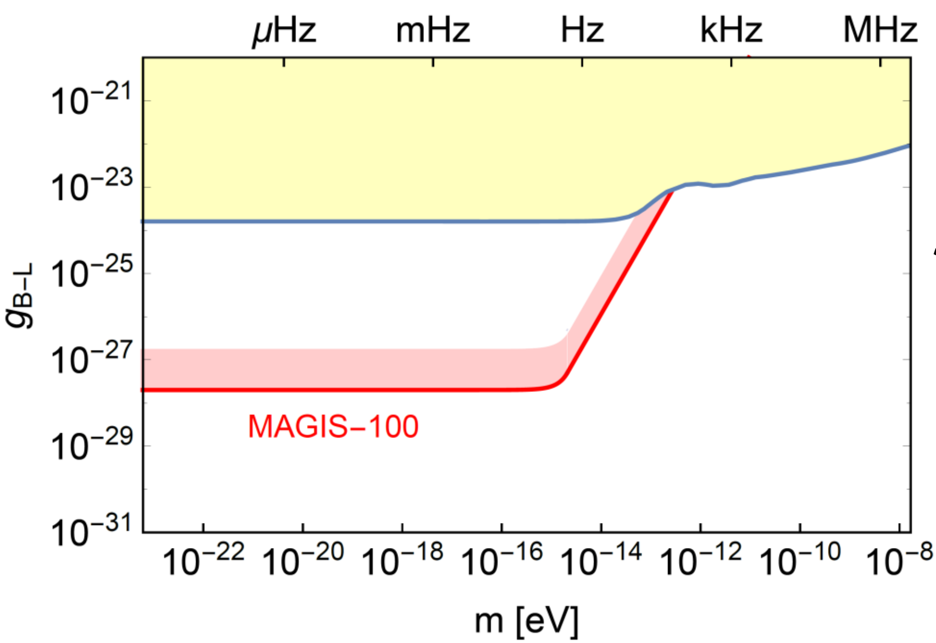
Gravitational wave detector development

- 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)

Projected sensitivity to dark matter

Sensitivity to ultralight scalar dark matter





Sensitivity to B-L coupled new force

~ 1 year data taking
10^{15} dropped atoms, assuming shot-noise limited phase resolution

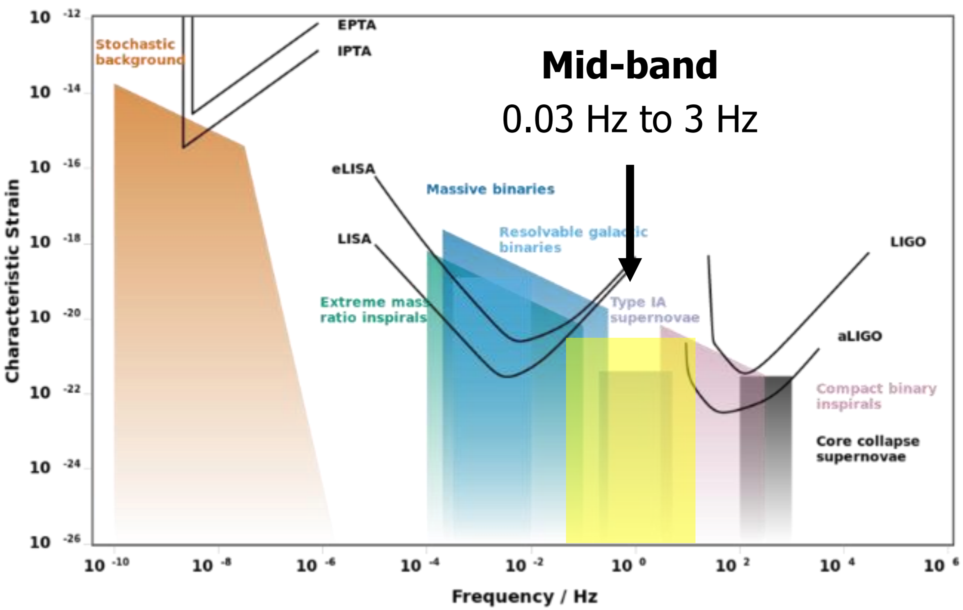
Graham et al. PRD **93**, 075029 (2016).

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

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 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, …)

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)

Detector technology: Atom interferometry and clocks

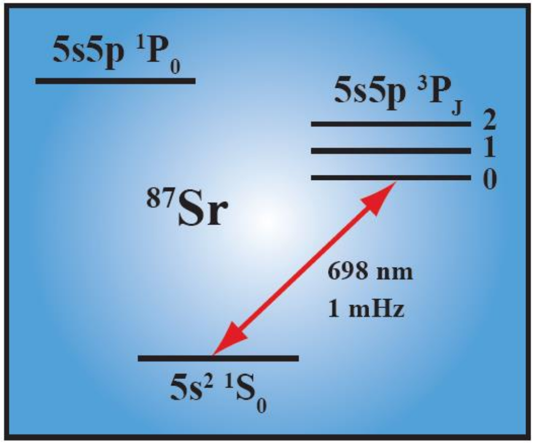
- Best clocks in the world now lose <1 second in 10^{18} seconds

- MAGIS-100 is based on same physics as Sr optical lattice clock

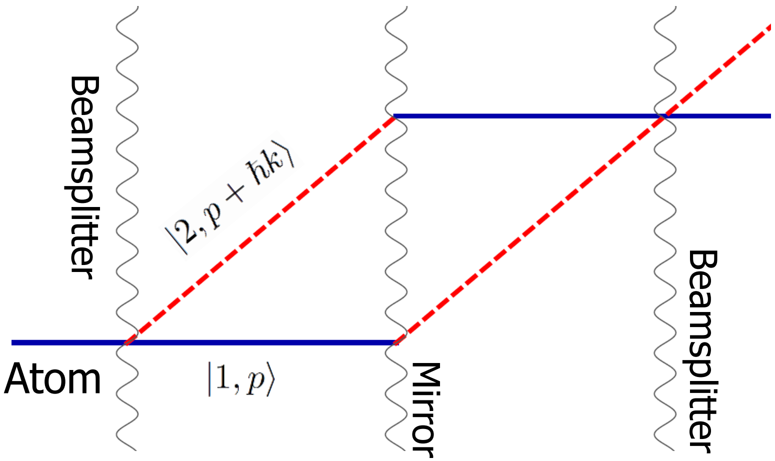
- Atom interferometry provides a pristine inertial reference

- Compare two (or more) atom ensembles separated by a large baseline

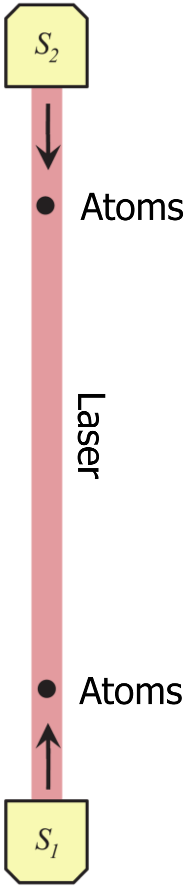
- Differential measurement suppresses many sources of common noise and systematic errors



Atomic clock transition



Atom interferometer



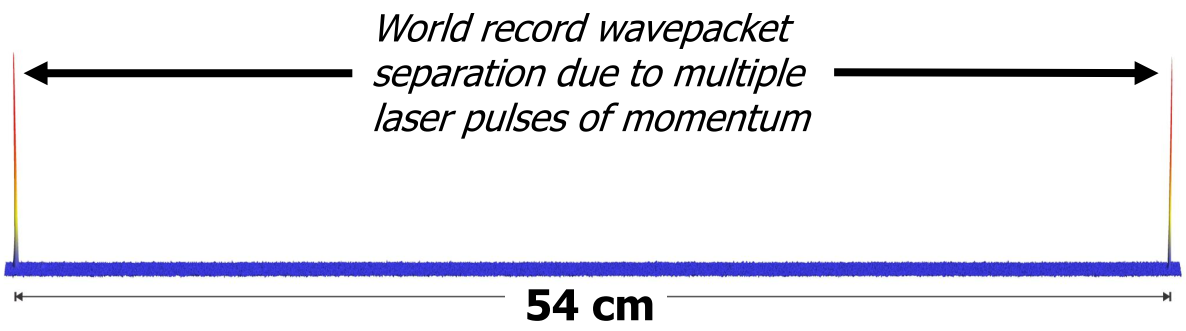
Gradiometer

Current generation: Stanford 10-meter scale

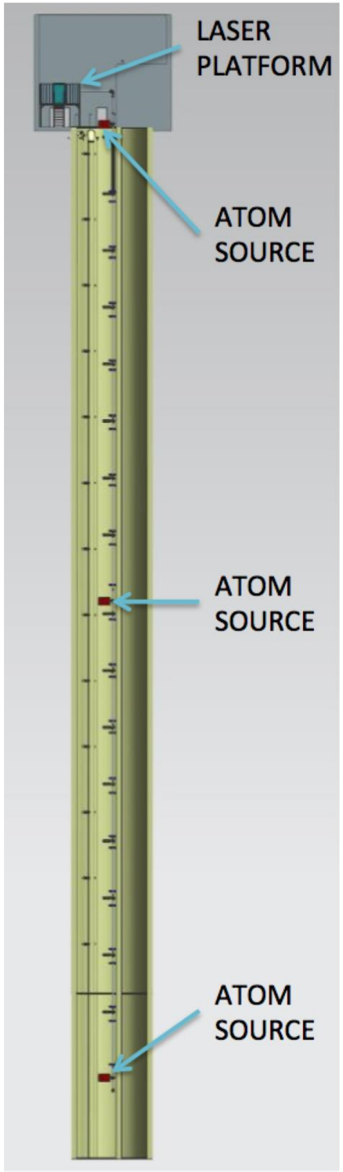
10-meter tall Rb atomic fountain

Milestones

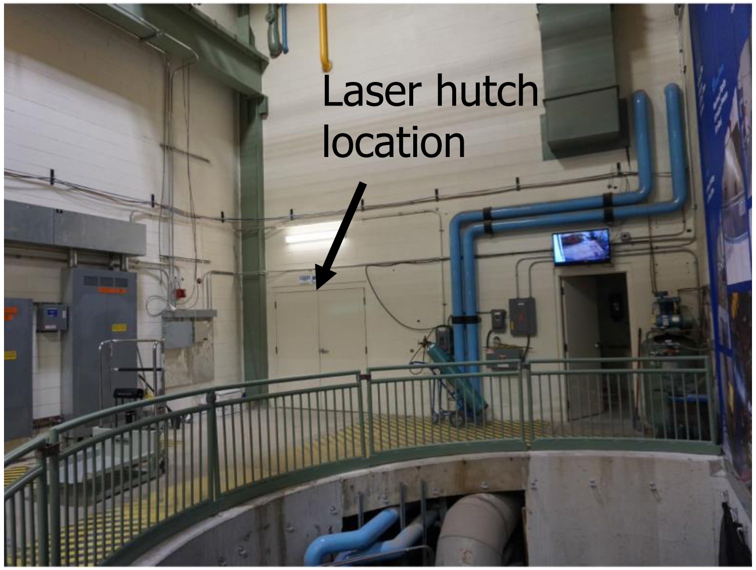
- Record matter wave interferometer duration (>2 s)
- Record wavepacket separation (>0.5 meter)
- Record effective temperature (< 50 pK)
- First observation of phase shift due to space-time curvature across a single particle's wavefunction
- Large momentum transfer 90 ħk
- Record accelerometer scale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

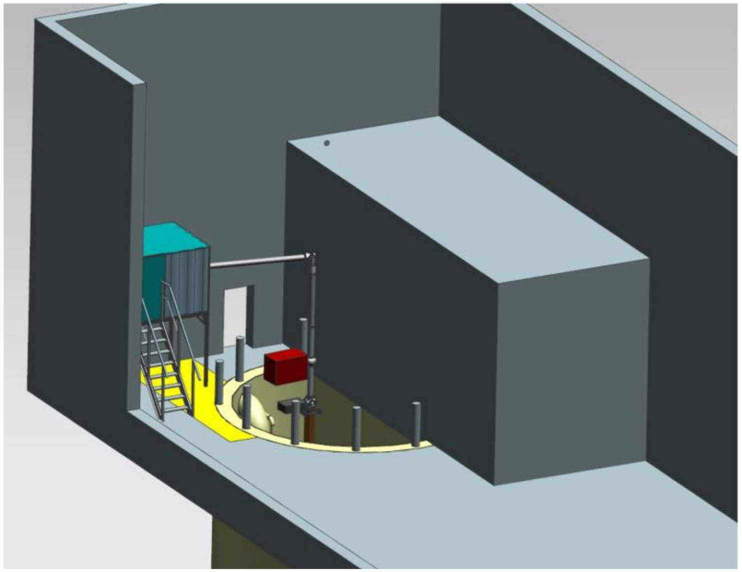


Proposed MAGIS-100 at Fermilab



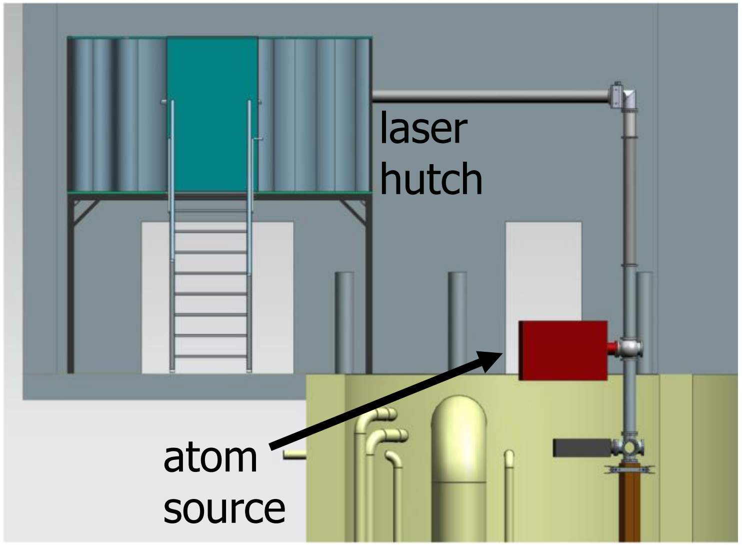
Cross section full detector





System Components:

- 10 times larger than Stanford setup
- Located in MINOS shaft
- 90 meter vacuum tube (vertical)
- Three atoms sources
- Laser system for implementing atom interferometry (hutch at top)



Side view of top of detector

Components and Requirements

6.1 Site

- ✓ 100 meter shaft of sufficient diameter to install hardware

6.2 Vacuum and Vacuum pipe

- ✓ 20 cm vertical pipe at 10^{-11} Torr pressure

6.3 Magnetic shielding and magnetic field control

- ✓ Shield Earth magnetic field to 10 mG (benefits from low susceptibility of Sr)
- ✓ Uniform horizontal bias field of 1 G

6.4 Atom source

- ✓ Three cold atom sources
- ✓ $>10^6$ atoms/s cooled to 10 nK

6.5 Transfer and Launch

- ✓ Optical dipole trap and optical lattice acceleration

6.6 Atom optics laser system

- ✓ >4 W at 698 nm stabilized to <10 Hz linewidth

6.7 Laser wavefront aberrations

- ✓ milliradian aberrations, with free-propagation spatial filtering, characterization, and feedback

6.8 Tip-tilt mirrors and rotation compensation

- ✓ Imprint spatial phase on cloud, suppress Coriolis phase shifts and other systematics

6.9 Controls and monitoring

- ✓ FPGA timing control

6.10 Cameras and Data Acquisition

- ✓ Low read noise CCDs (3e rms) with < 10 Hz sample rate

6.11 Computing

- ✓ 1-2 TB data/day before compression

The proposed experiment meets each of these requirements

Estimated scientific effort

- Steady operations the 10m baseline experiment at Stanford has a scientific staff (students/postdocs/scientists) of **3.3 FTEs**

- The effort in this table is sufficient for operating and analyzing MAGIS-100 24/7 during data runs

- Stanford effort covered by GBMF grant

- Will be requesting support from DOE for Fermilab effort

	Institution	Scientists	Postdocs	Students	TOTAL FTEs
Year 1	Berkeley	0.2	0	0.5	0.7
	Fermilab	1.7	0	0	1.7
	Liverpool	0.5	0	0	0.5
	NIU	0.5	0	1	1.5
	Northwestern	0.3	1	1	2.3
	Stanford	0.5	2	4	6.5
	Total	**3.7**	**3.0**	**6.5**	13.2
Year 2	Berkeley	0.2	0	0.5	0.7
	Fermilab	1.7	1	0	2.7
	Liverpool	0.5	1	1	2.5
	NIU	0.5	0	2	2.5
	Northwestern	0.3	1	1	2.3
	Stanford	0.5	2	4	6.5
	Total	**3.7**	**5.0**	**8.5**	17.2
Year 3	Berkeley	0.2	0	0.5	0.7
	Fermilab	1.7	1	0	2.7
	Liverpool	0.5	1	2	3.5
	NIU	0.7	1	2	3.7
	Northwestern	0.3	1	1	2.3
	Stanford	0.5	1	4	5.5
	Total	**3.9**	**5.0**	**9.5**	18.4

MAGIS-100 is a 5 year project; above shows FTEs for 3 year construction phase

Gordon and Betty Moore Foundation grant

GORDON AND BETTY MOORE FOUNDATION

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

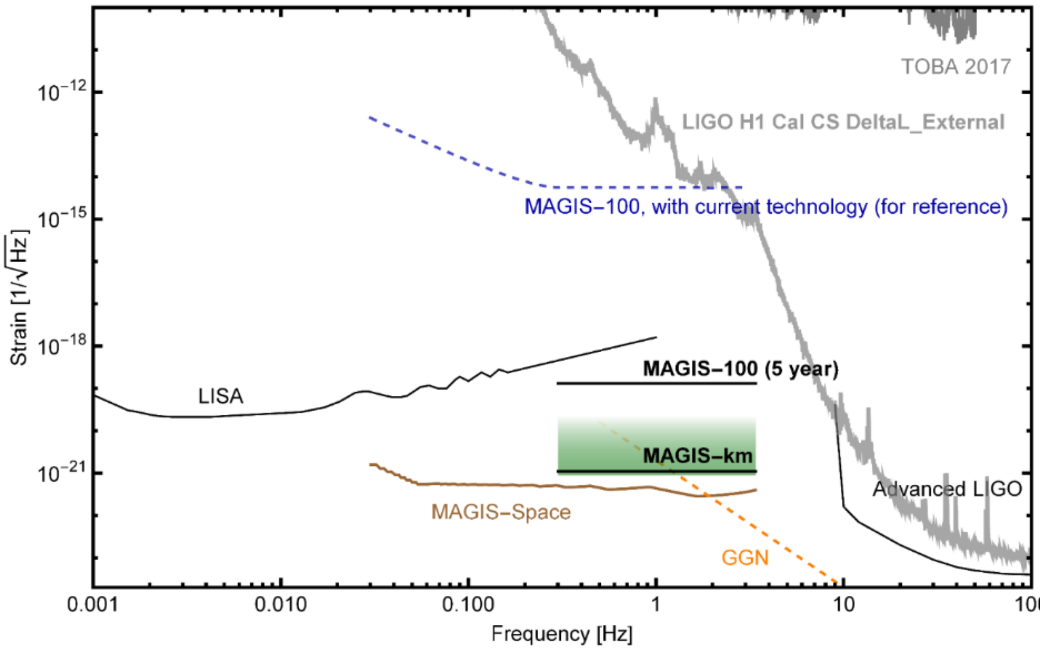
MAGIS-100 at Fermilab ($3.39M)

- 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 ($6.41M)

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

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)

Preliminary Project Milestones and Budget

	Task	Description	Location
Year 1	Atom source design and procurement	Adapt existing designs and add environmental protection and other hardware needed to integrate into MAGIS-100.	Stanford
	Laser system design and procurement	Design high-power atom optics laser system based on coherently combined Ti:sapphire lasers. Procure necessary equipment.	Stanford
	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
	100 m vacuum vessel design and procurement	Design system of vacuum pumps, viewports, and atom source connection nodes. Procure necessary equipment.	Stanford/ FNAL
Year 2	Build 100 m vacuum segments	Install viewports and connection nodes.	Stanford
	Complete site design	Finalize vibration, magnetic, and temperature engineering.	Fermilab
	Atom source qualification	Build atom sources. Verify that necessary atom flux is delivered.	Stanford
	Laser system qualification	Build laser system. Verify that power delivered, frequency and amplitude agility, and phase noise meet specifications.	Stanford
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
	Atom interferometry in 100 meter vacuum	Run atom interferometers using each of the three atom sources. Implement LMT atom optics in interferometers.	Fermilab
Year 4	Gradiometer with two sources	Long baseline gradiometer. Study noise sources.	Fermilab
	Science data runs	Long science data runs with two-source gradiometer (gravitational wave detector prototype).	Fermilab
Year 5	Gradiometer with three sources	Incorporate third source into long baseline gradiometer.	Fermilab
	Study GGN suppression	Use three-source gradiometer to study gravity gradient noise (GGN) impact and mitigation strategies. Additional long science data runs.	Fermilab

Proposal Table 4 (page 41)

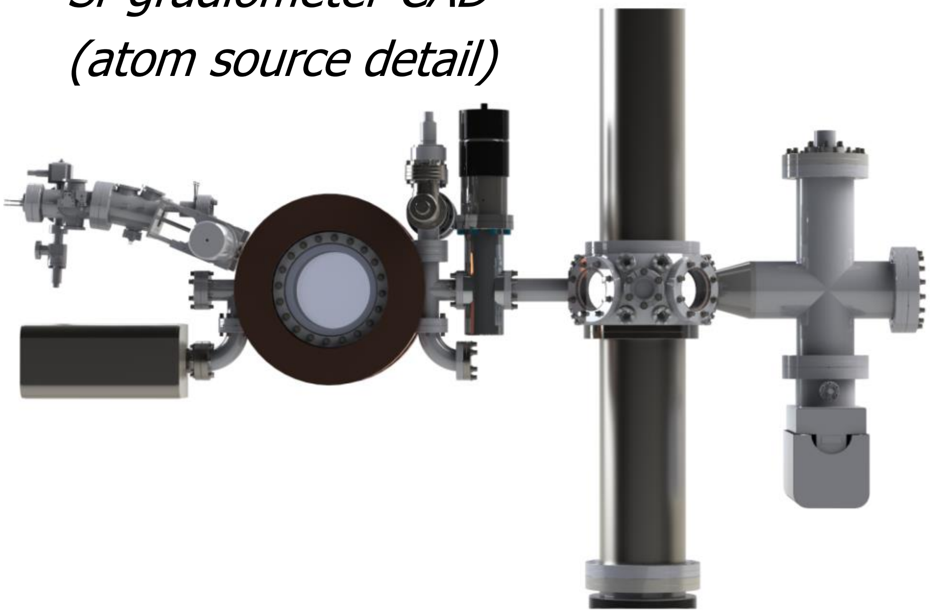
		Direct Cost ($)
Moore Funding	Fabricate Atom Sources (Stanford)	1,869,000
	Vacuum Tube Procurement (Stanford)	931,060
	Interferometer Laser (Stanford)	593,200
	Sub-Total	**3,393,260**
Estimated DOE Request	Interferometer Shaft Support Structure	99,000
	Laser hutch and support platform	21,000
	Engineering (FNAL)	367,000
	Drafting and Technical	304,000
	Installation Equipment	28,000
	Installation	51,000
	Operation and Materials	49,000
	Sub-Total	**919,000**
TOTALS	**DIRECT**	**4,312,260**
	INDIRECT	**691,000**
	FULLY BURDENED	**5,003,260**

M&S + technical effort

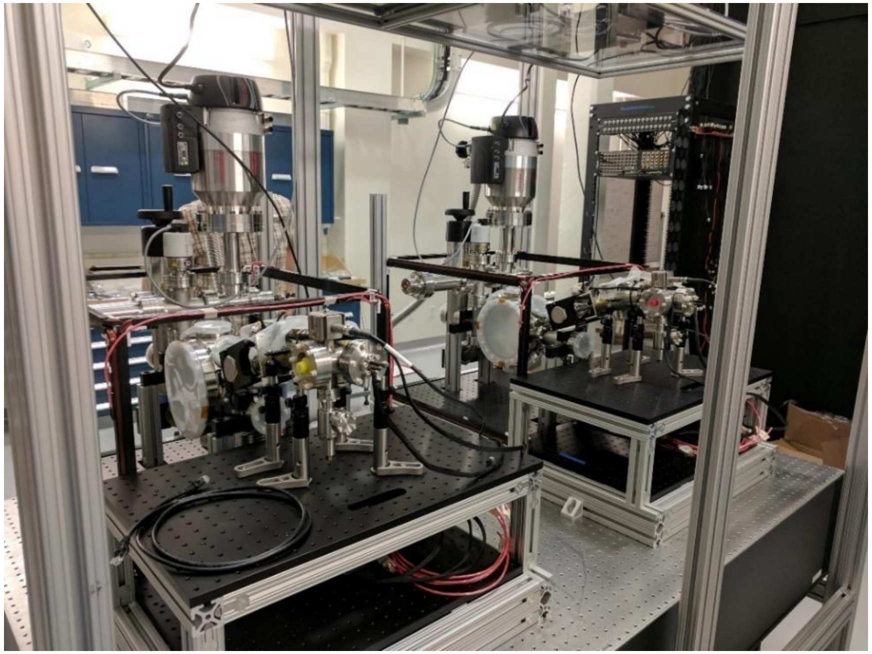
Proposal Table 5 (page 43)

Stanford MAGIS prototype

Sr gradiometer CAD
(atom source detail)

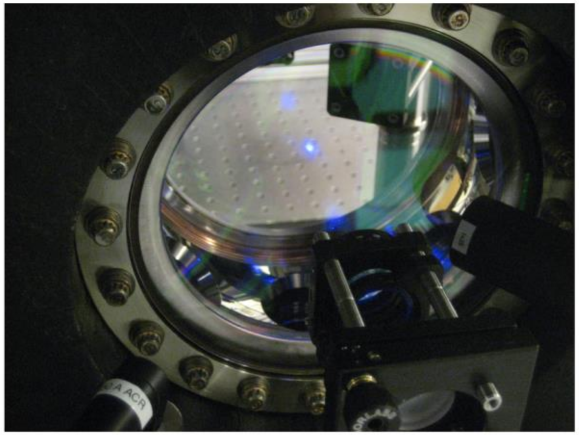


Two assembled Sr atom sources



Atom optics laser
(M Squared SolsTiS)

Trapped Sr atom cloud
(Blue MOT)



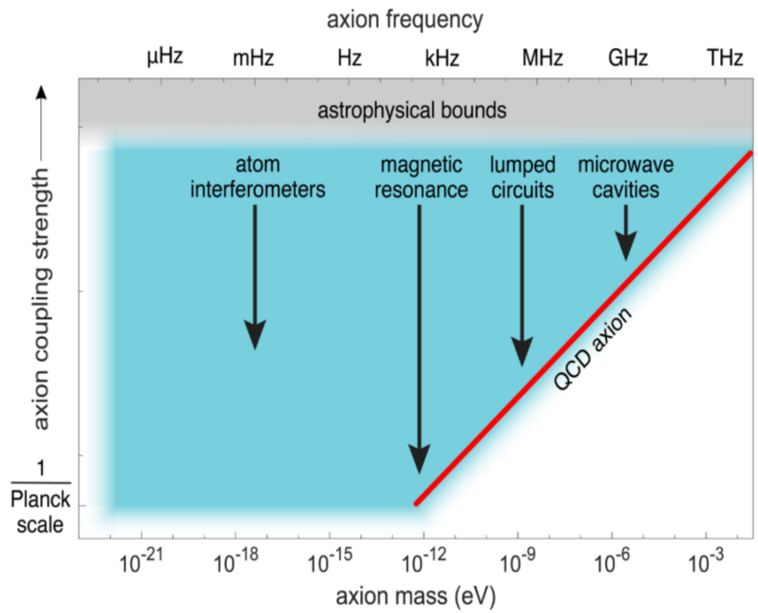
PAC charge questions

a) Is the science in the proposal interesting and/or compelling?

"…MAGIS-100 represents both an exciting science opportunity that leverages quantum science and technology as well as one that poses a low risk for the Laboratory" – PAC Report, July 2018

b) Is the technique proposed appropriate for, and likely to be capable of, reaching the physics goals of the experiment?

Yes, the community has endorsed this approach (e.g., BRN process). The first set of science goals (DM, quantum) use proven technology. Additional science (GW, DM) will depend on the outcome of parallel R&D program (already funded by GBMF).



Dark matter BRN report (Kolb) presented to HEPAP

PAC charge questions

c) What is the competition for reaching the physics goals of the proposed experiment? Does the proposed experiment have particular advantages or disadvantages relative to the competition?

See next

d) What is needed to make such an experiment successful?

DOE support for Fermilab components of program (Effort + M&S)

- Will submit to next quantum science call (expected shortly)

Aggressive hiring (postdocs, students) to maintain GBMF grant schedule.

Other efforts

In our frequency range, in our time frame

- Clocks: Compare two species (some overlap at lowest frequencies, less sensitive to d_{me})
- Eöt-Wash: Torsion pendulum experiments (overlap at low frequency, less sensitivity in our time frame)
- MIGA: Terrestrial atom interferometer detector in France (complementary technique with different systematics; e.g., susceptible to laser noise, needs two baselines)
- AION: MAGIS-like proposal based in the UK (needs 10 m prototype first)

Not in our frequency range, not in our time frame

- LIGO/LISA/ET (complementary; targeting different frequencies ranges)
- DECIGO, LISA variants in mid-band (space-based, 2030s)
- Axion searches with NMR/lumped circuit/microwave cavities (complementary, higher frequencies)

Request to the PAC

We request the PAC to recommend Stage 1 approval for MAGIS-100, so that the collaboration can make the best case possible to the DOE for funding in the upcoming quantum science funding opportunity.

Backup

GBMF Grant Budget Summary

Direct Costs	
Personnel	4,503,459
Travel	23,905
M&S for R&D	374,000
M&S for MAGIS-100	682,200
Equipment for R&D	1,124,000
Equipment for MAGIS-100	2,711,060
Total Direct	**9, 418, 624**
Indirect	398,608
TOTAL ($)	**9,817,232**

Table 6: Summary of Funding from the Moore Foundation.

M&S for MAGIS-100	682,200
Equipment for MAGIS-100	2,711,060
Total ($)	**3,393,260**

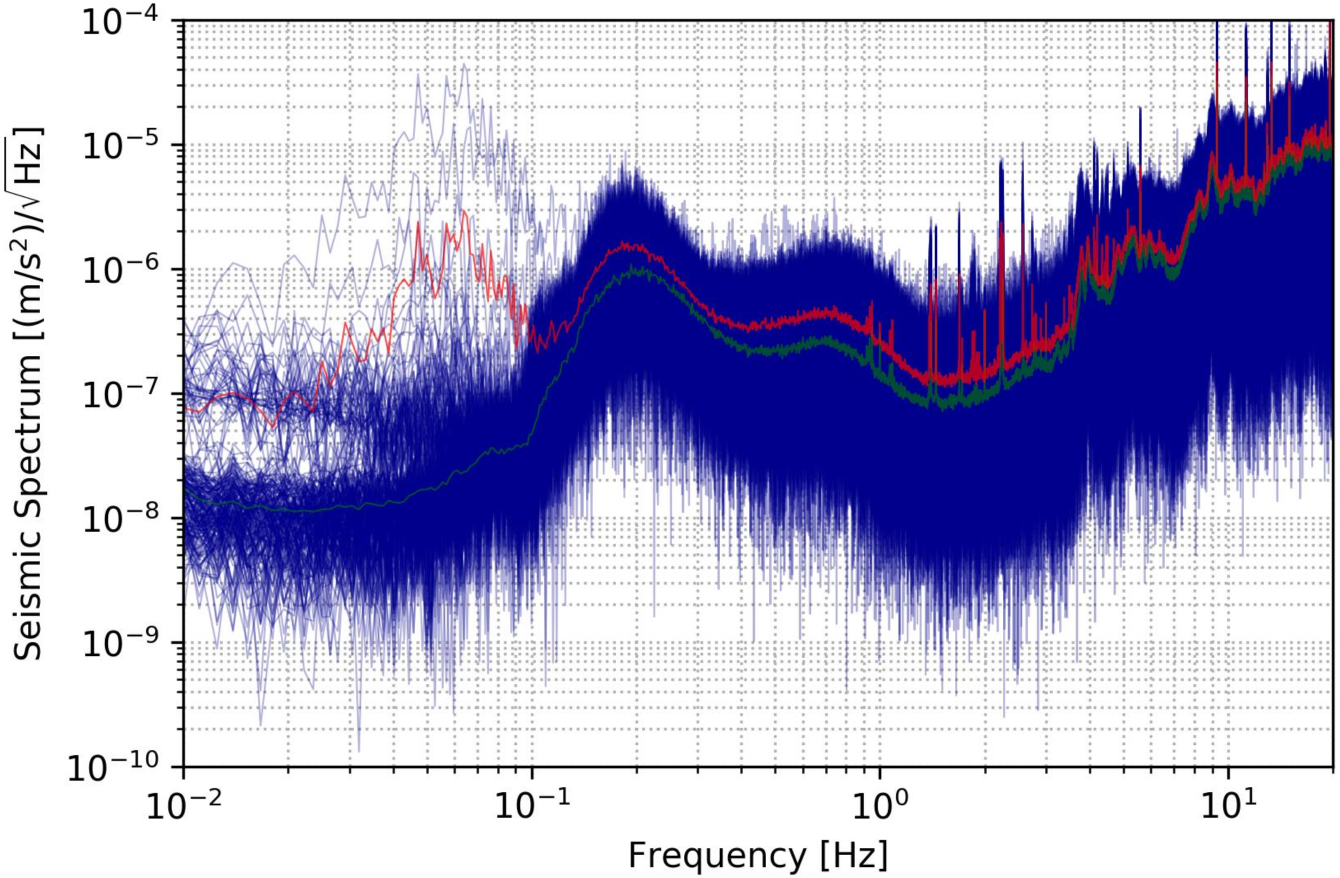
MAGIS-100 assembly milestones

Year		Stanford	Fermilab
1	Q1		
	Q2	Complete prelim. engineering	Complete prelim. engineering
	Q3	Atom sources & lasers procured	
	Q4	Vac. vessel & shielding procured	Complete vac. vessel design
2	Q1		Complete site design
	Q2	Delivery of interferometer vac. vessel	
	Q3		
	Q4	Atom sources & lasers delivered	Vac. system pre-assembly complete
3	Q1		
	Q2		Site outfitting complete.
	Q3		Begin commissioning. First quantum physics results
	Q4		First Dark Matter results

MAGIS-100 run time

Science Topic	Required number of atoms	Atoms/sec when taking science data	Fraction of calendar taking science data	Estimated run time (years)
Commissioning	N/A	N/A	N/A	1
Phase 1: Quantum Science	3×10^{12}	10^{6}	0.1	0.5
Phase 2: Dark Sector Campaign	10^{15}	10^{8}	0.3	1
Phase 3: Mid-band development	10^{15}	10^{8}	0.3	1

Preliminary seismic data at MINOS shaft



- REF TEK 151B-120 Observer
- 20 samples/s
- 10 days sample period
- Mean (red), median (green)

Systematic Errors

- Leading systematic errors and associated initial requirements for MAGIS-100
  - Wavefront aberrations: $\lambda/100$ optics
  - Pointing jitter: control or monitoring at the level of 1 nrad/Hz$^{(1/2)}$ in relevant frequency band (can use split photodetectors to measure)
  - AC Stark shifts: 0.1% /Hz$^{(1/2)}$ laser intensity stabilization
  - Initial kinematic jitter: measure atom kinematics on each shot at the level of 1 micron (achievable with CCD cameras for spatial resolution)

Ultralight scalar dark matter

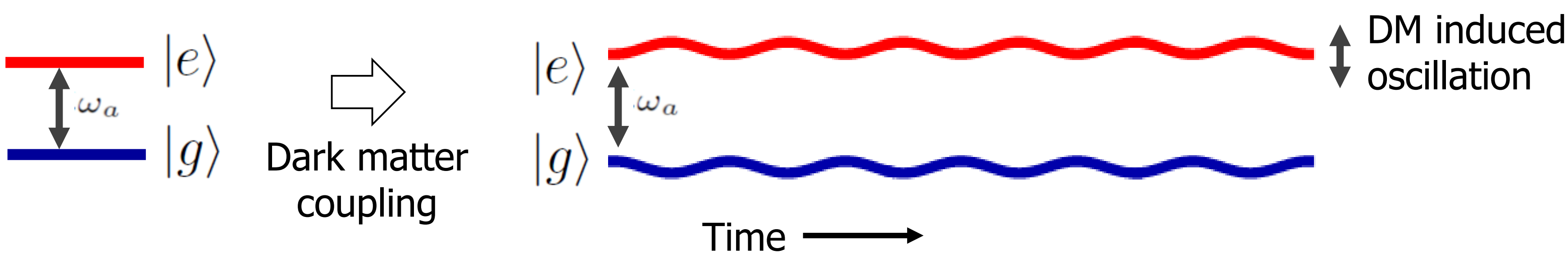
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

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

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

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

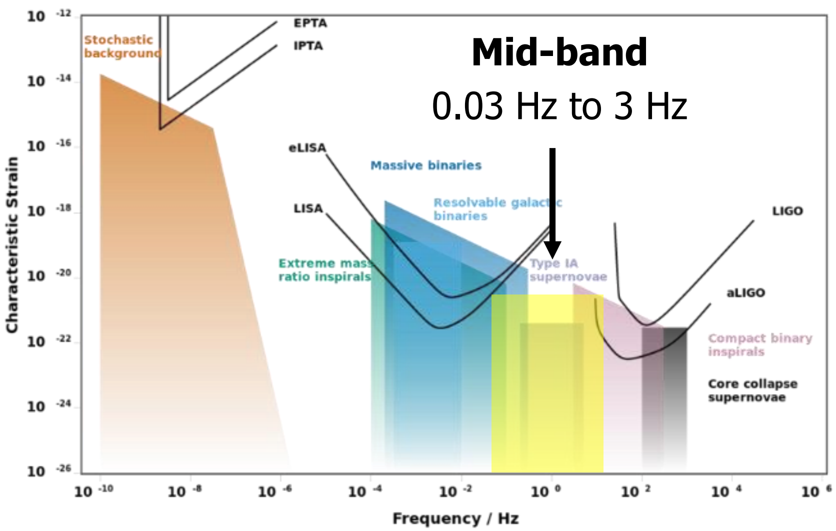
DM coupling causes time-varying atomic energy levels:

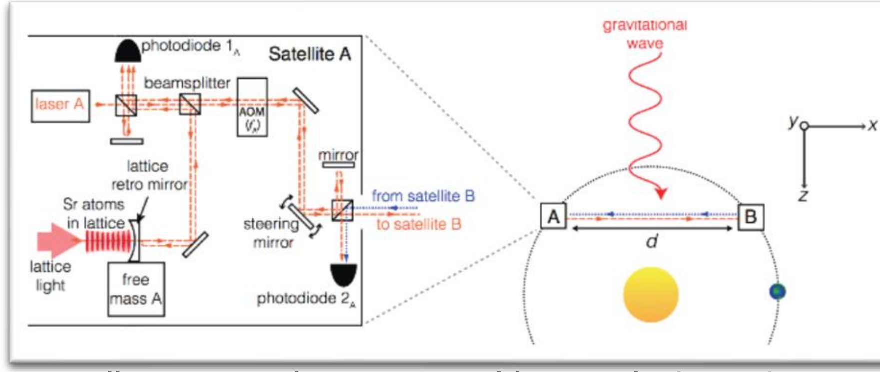


Atomic sensors for gravitational wave detection

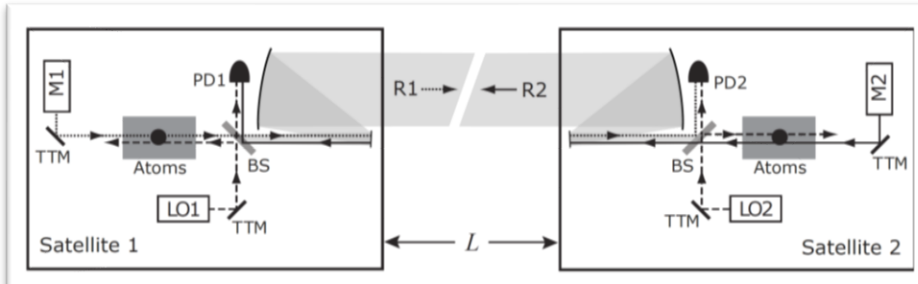
Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range ("mid-band")

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

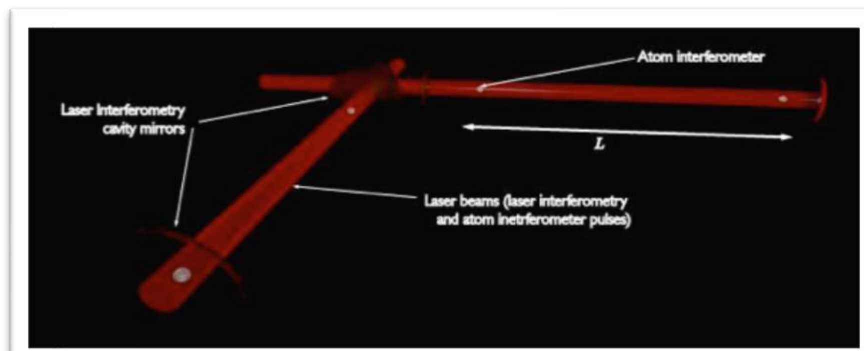




Satellite proposal using optical lattice clocks + drag free inertial reference (Kolkowitz et al., **PRD** 2016)



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)

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, …)

Sky position determination

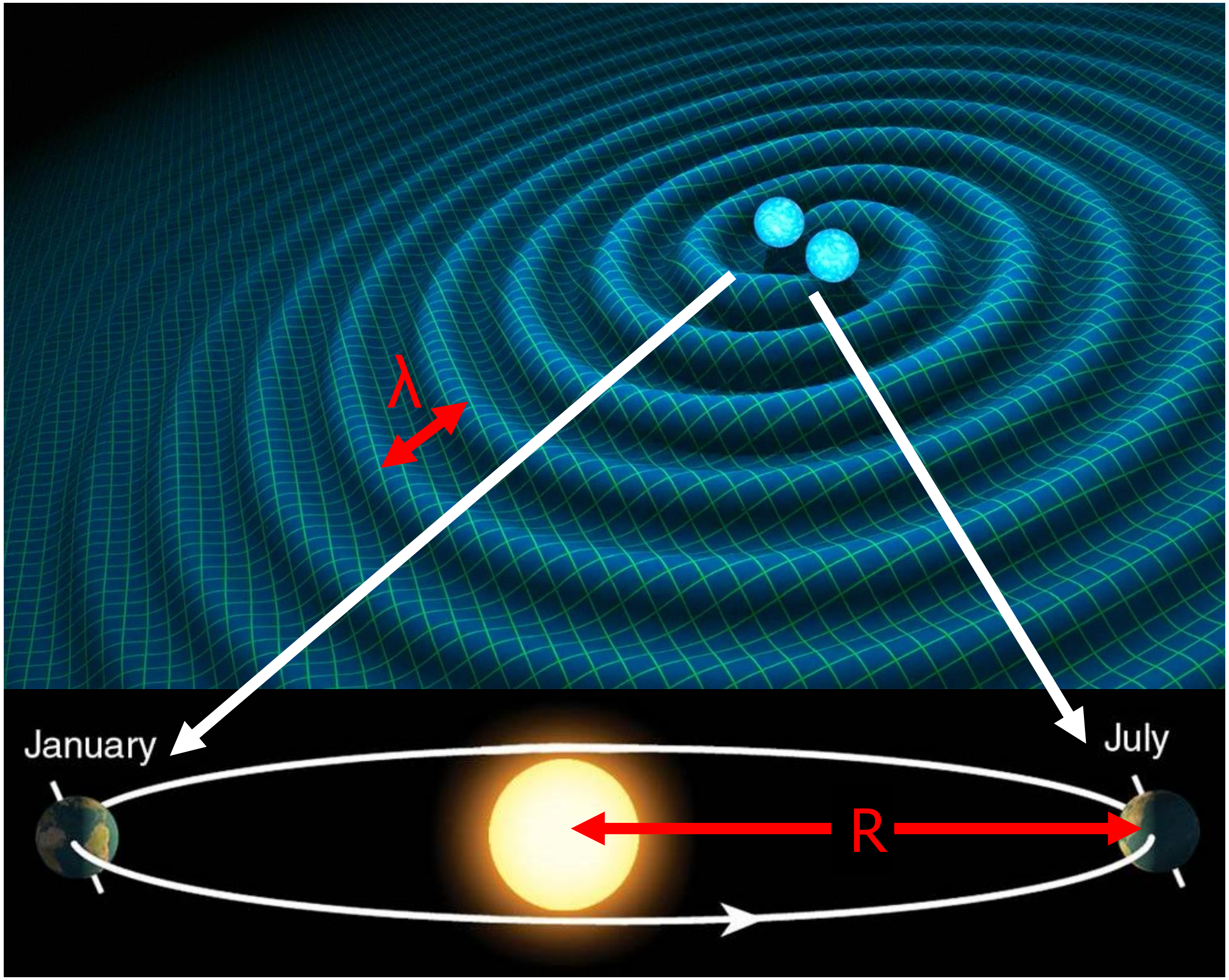
Sky localization precision:

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

Mid-band advantages

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

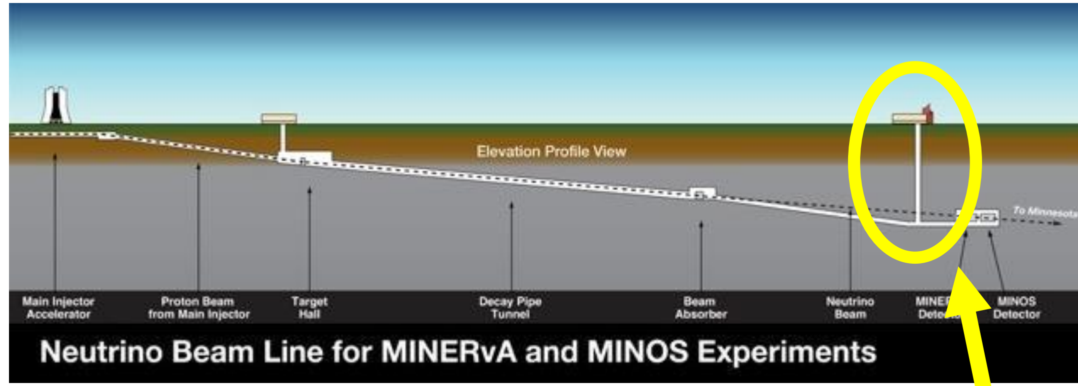
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19



MAGIS-100: GW detector prototype at Fermilab

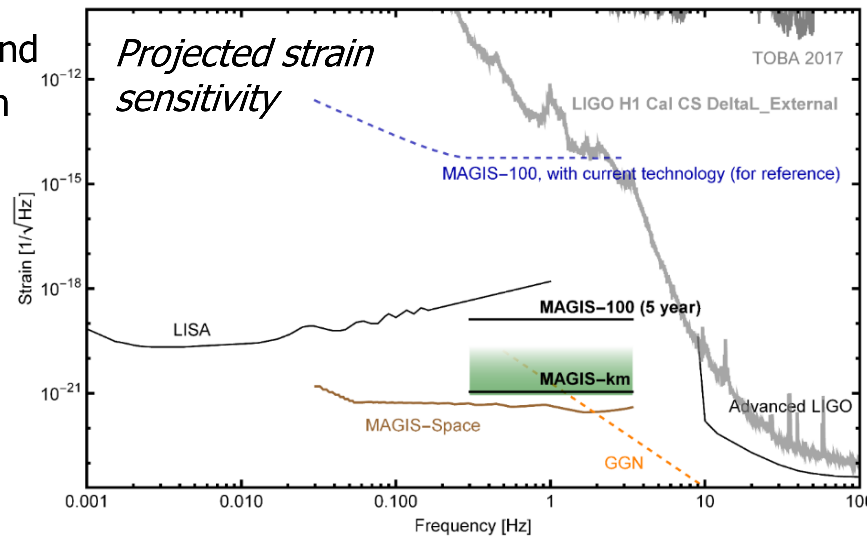
Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

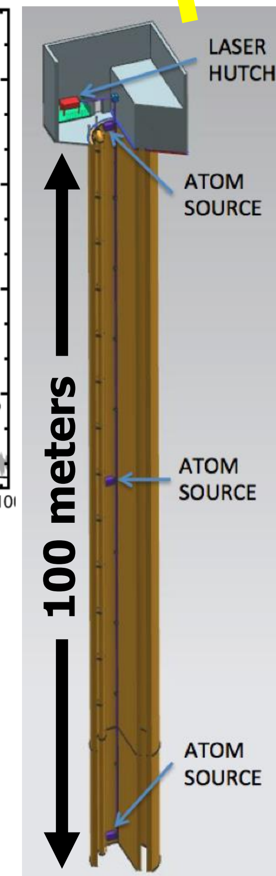
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves



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)
- BH, NS, WD binaries
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration





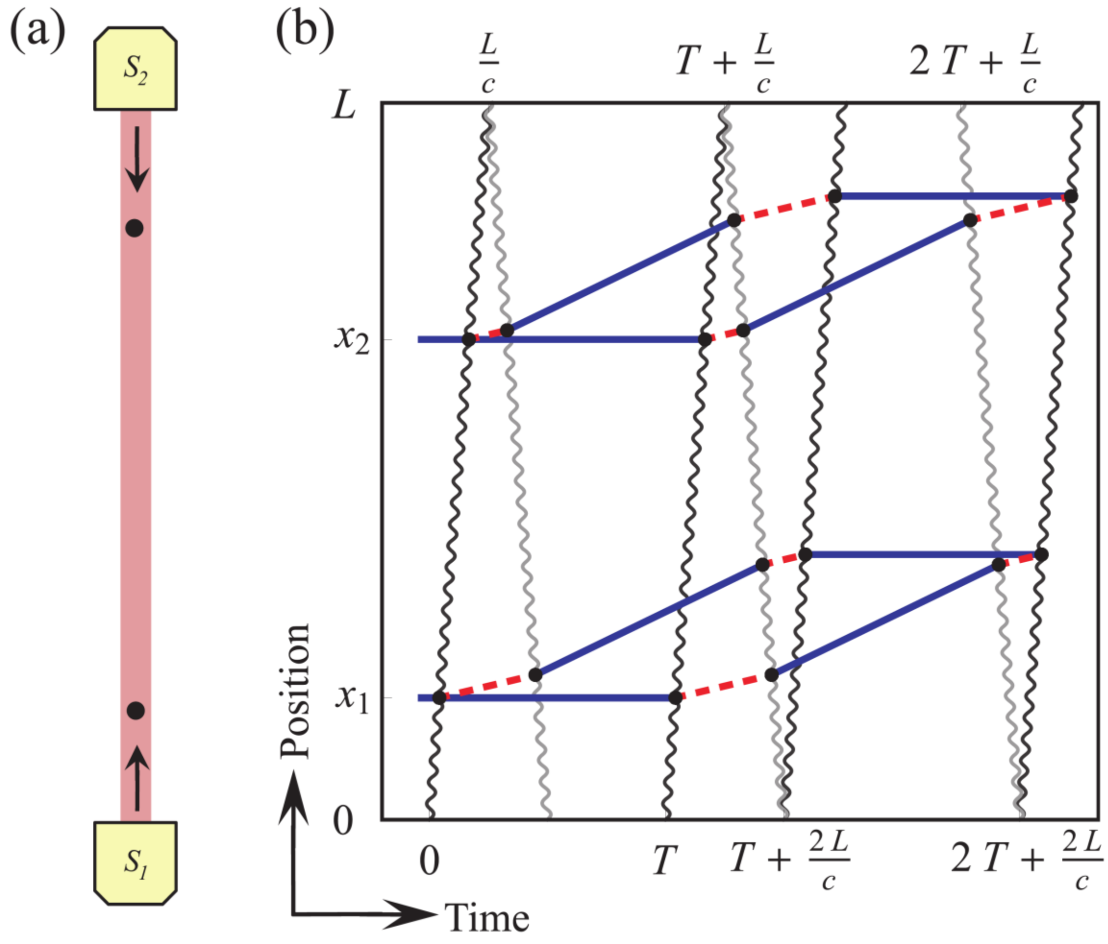
Timeline

- 2019 – 2023: MAGIS-100 at Fermilab (100-meter prototype detector)
- *2023 – 2028: Kilometer-scale GW detector (e.g., SURF Homestake site)* **[Proposed]**

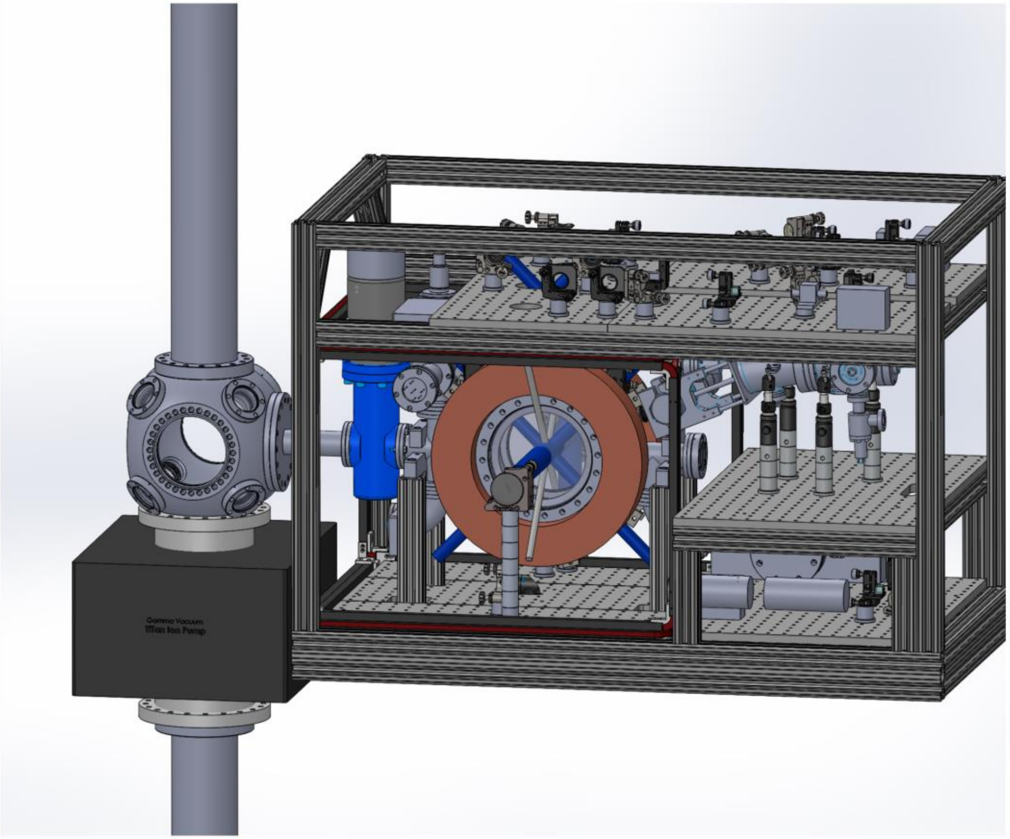
GORDON AND BETTY MOORE FOUNDATION

STANFORD · Fermilab · UNIVERSITY OF CALIFORNIA BERKELEY · UNIVERSITY OF LIVERPOOL · Northwestern University · NIU Northern Illinois University

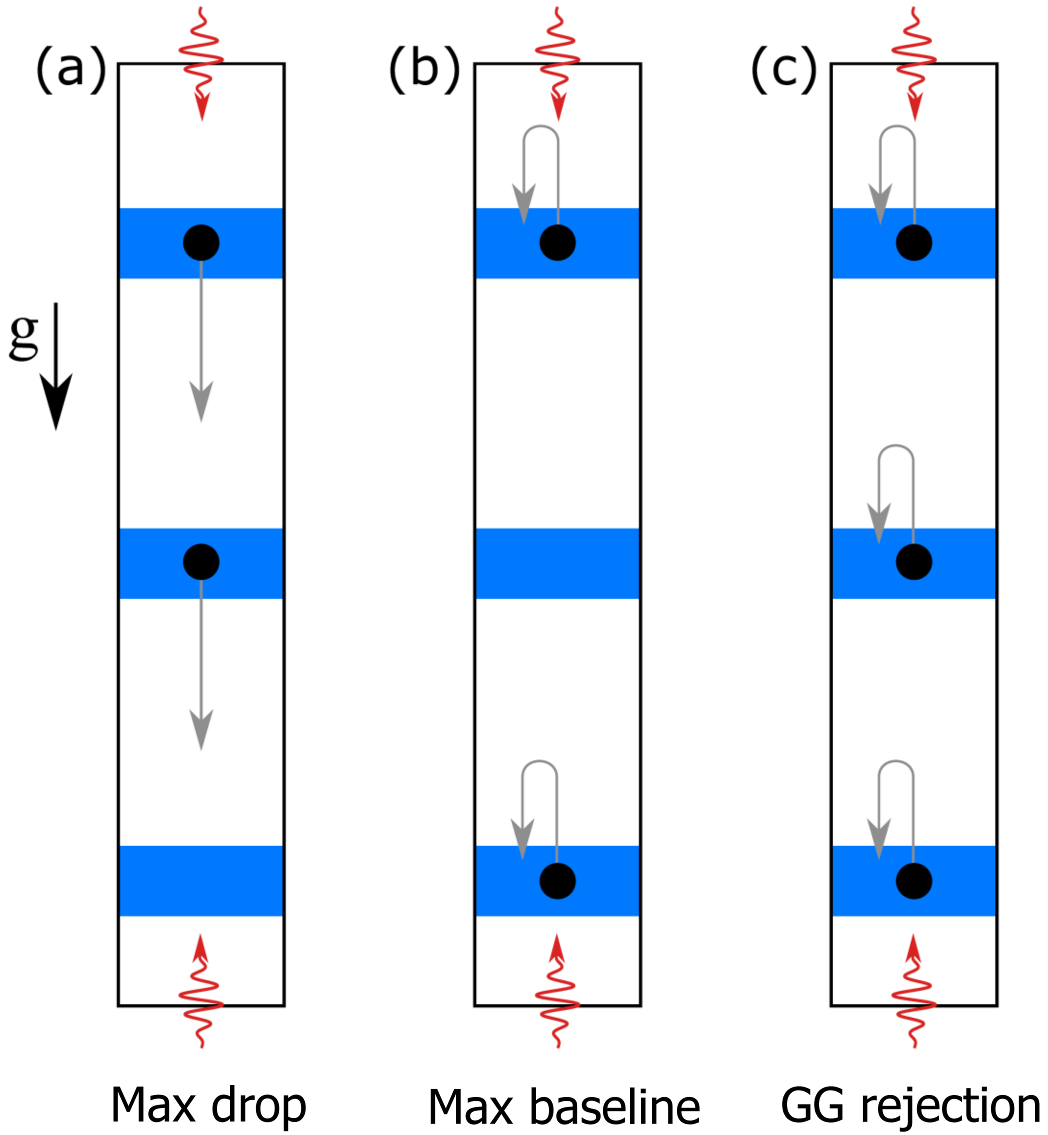
Gradiometer



Atom Source



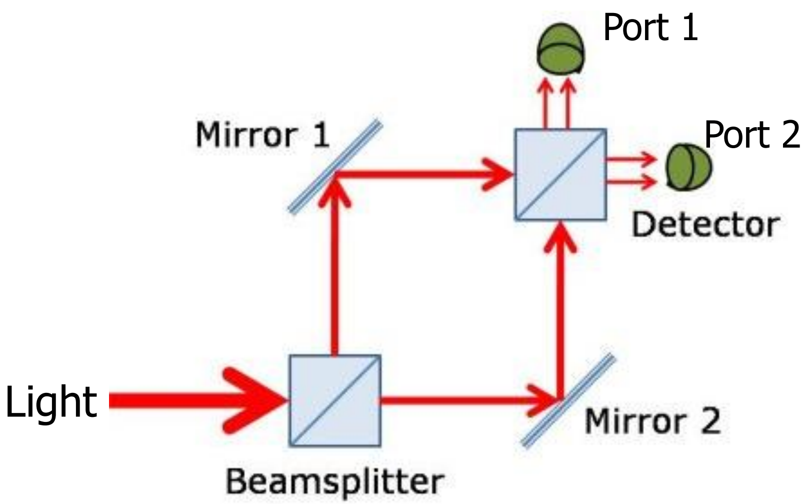
Detector operation modes

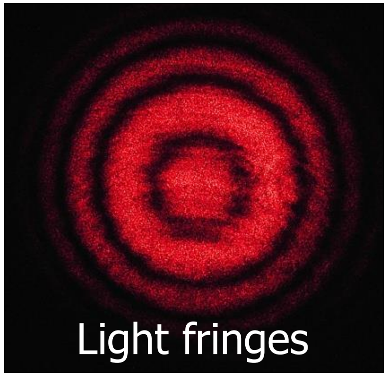


Atom Interferometry

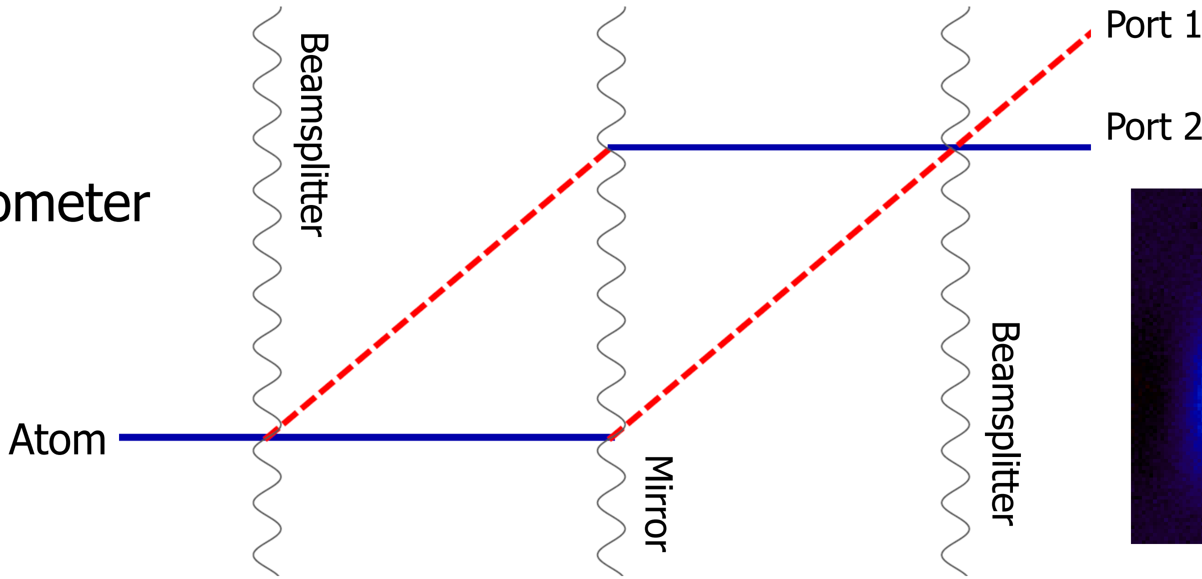
Atom interference

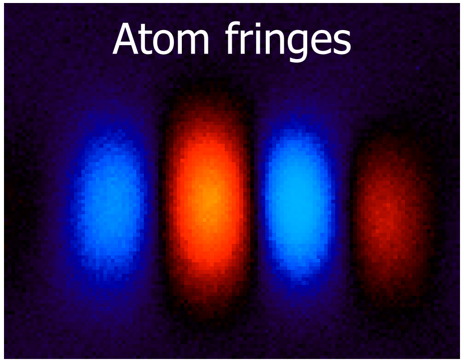
Light interferometer





Atom interferometer

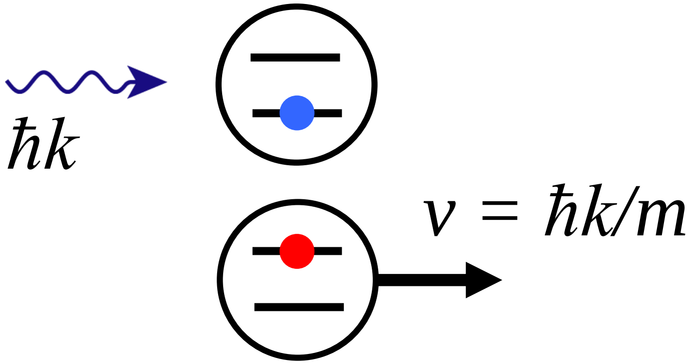




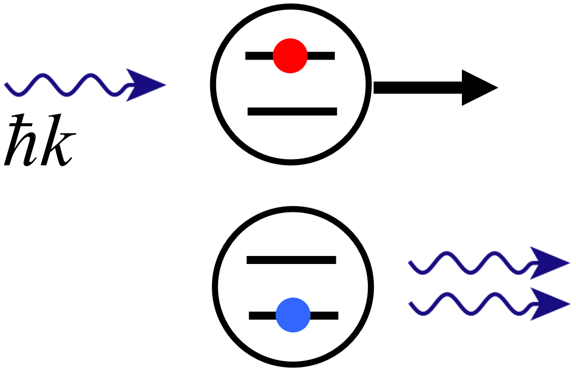
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Atom optics using light

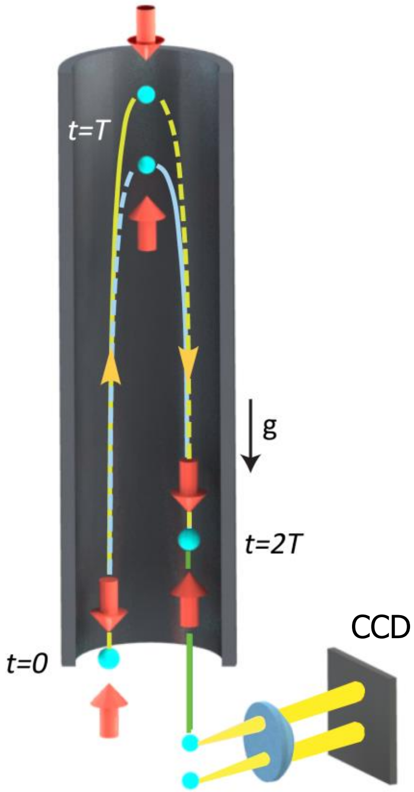
Light absorption:

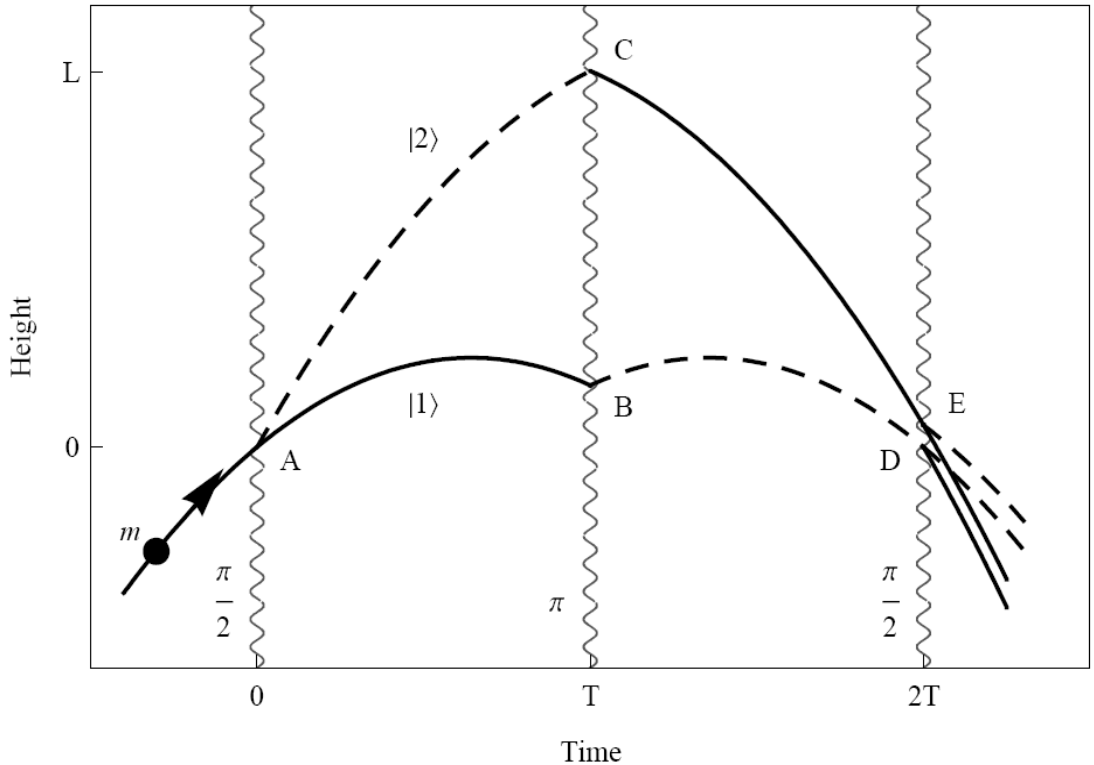


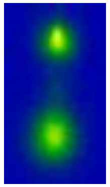
Stimulated emission:



Light Pulse Atom Interferometry





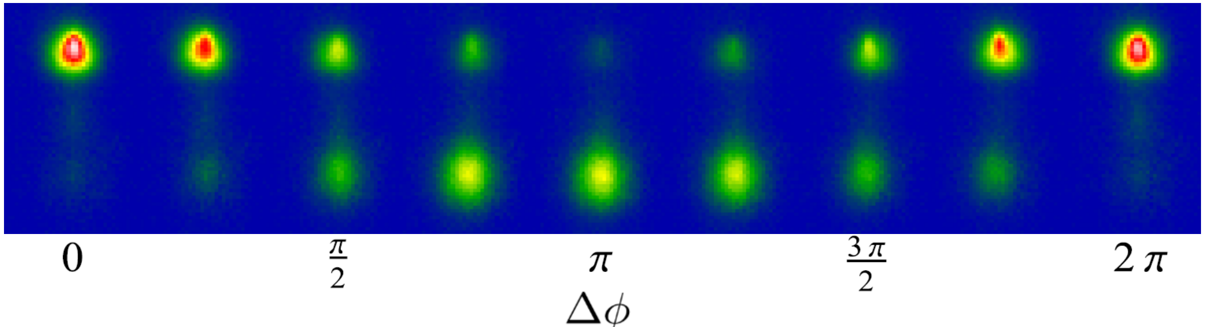


Port 1

Port 2

Images of atom port populations vs phase

Science signal (CCD images):



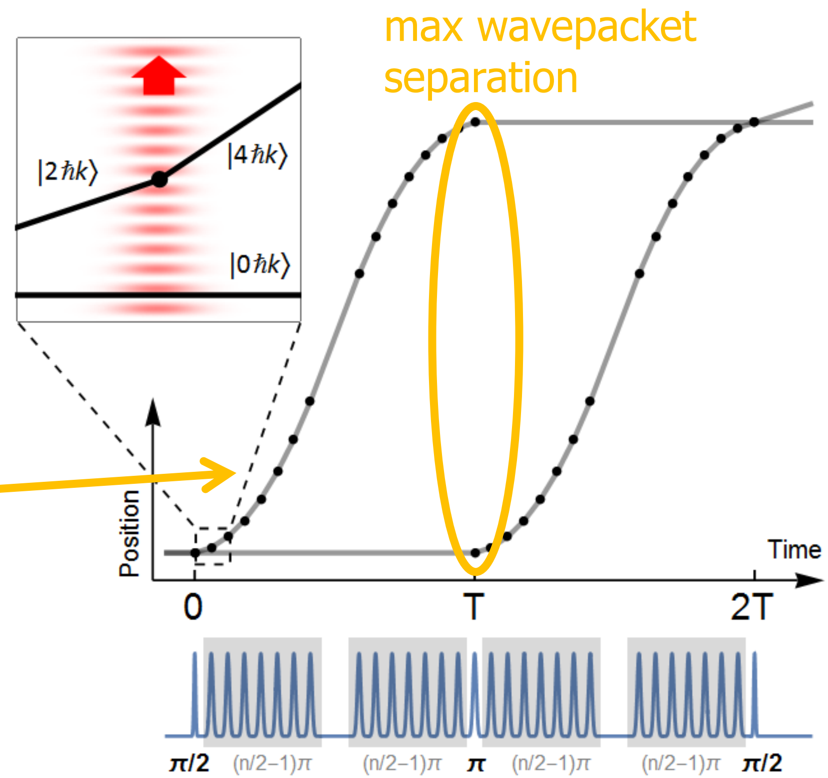
Data from world record atom interferometer duration (>2 seconds) at Stanford

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

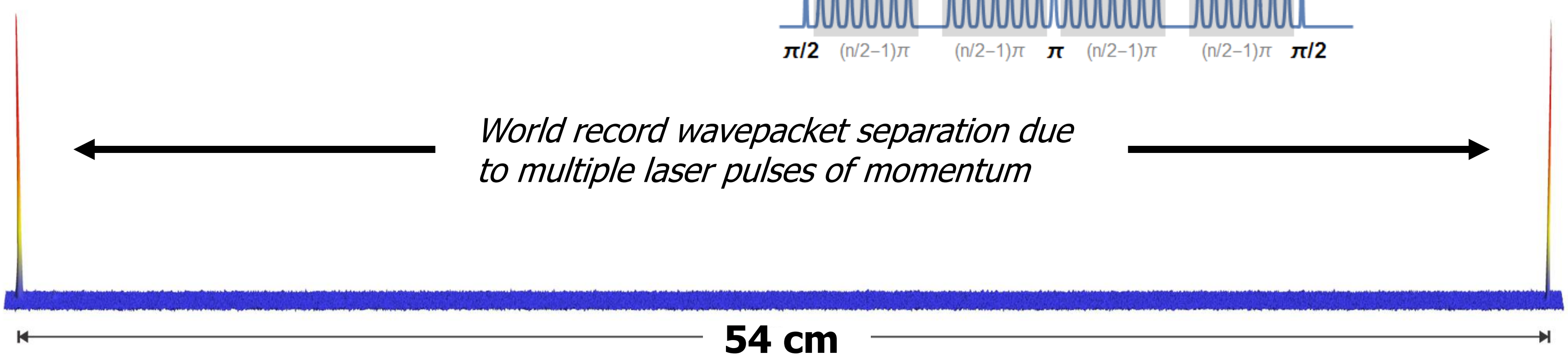
Large space-time area atom interferometry

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

90 photons worth of momentum

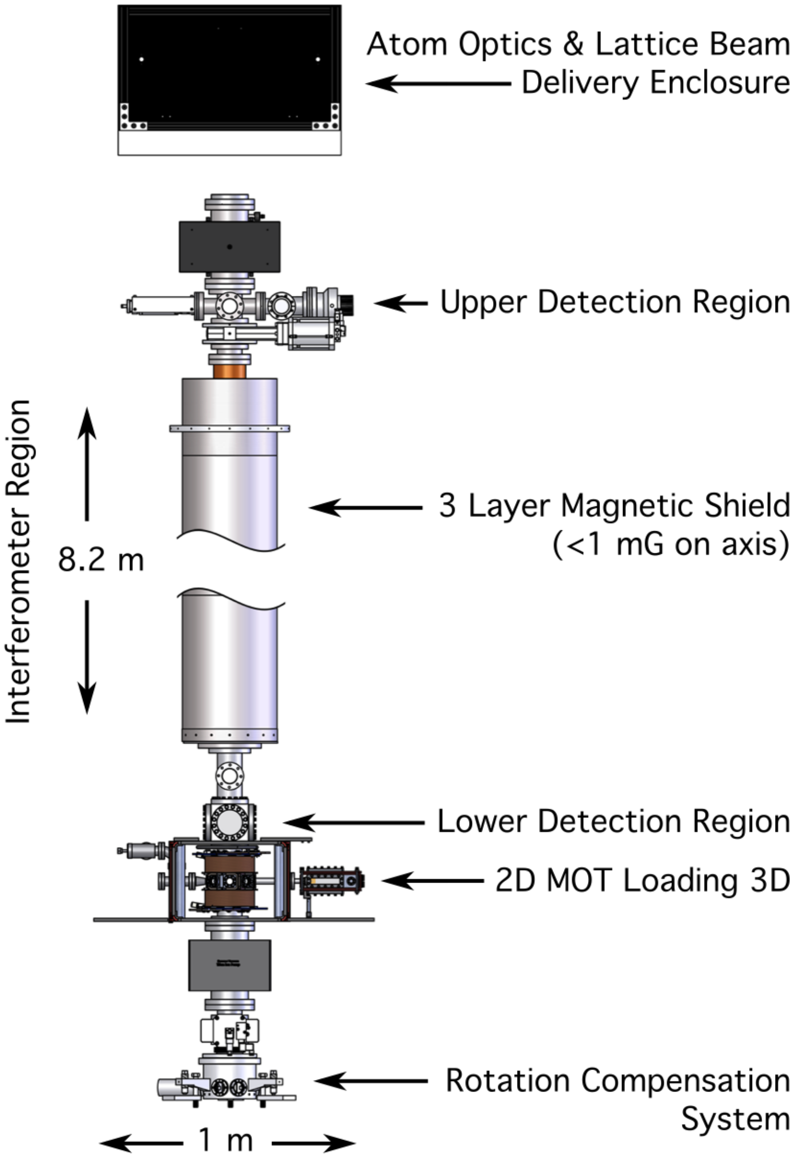


World record wavepacket separation due to multiple laser pulses of momentum

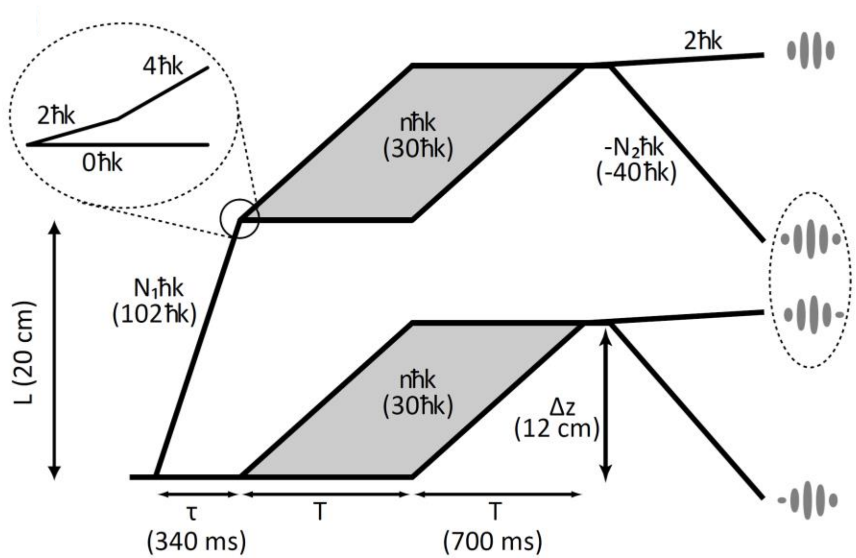


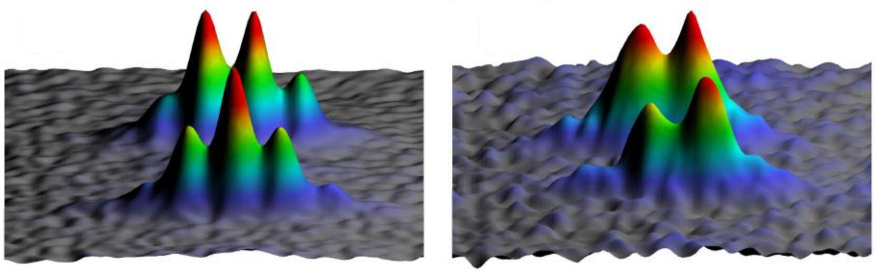
Kovachy et al., *Nature* 2015

Current generation: Stanford 10-meter scale



Gradiometer Demonstration (Rb)





$\Delta z = 4\,\mathrm{cm}$

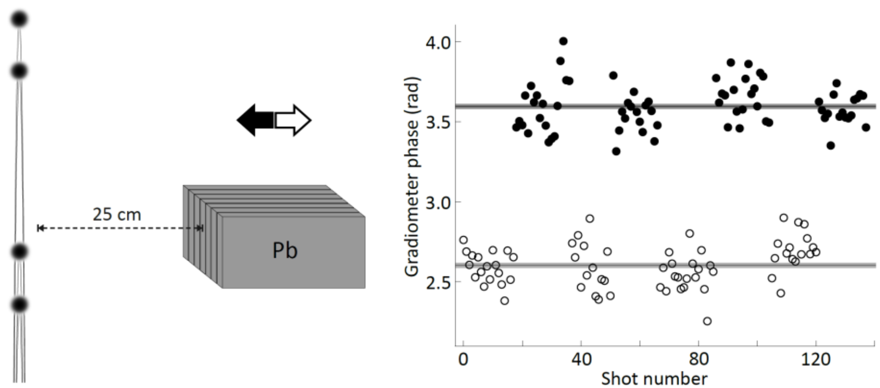
10 ħk

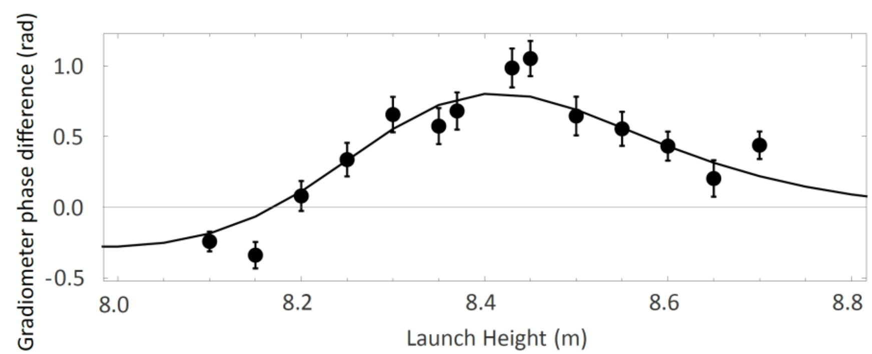
$\Delta z = 12\,\mathrm{cm}$

30 ħk

Gradiometer interference fringes

Gradiometer response to 84 kg lead test mass



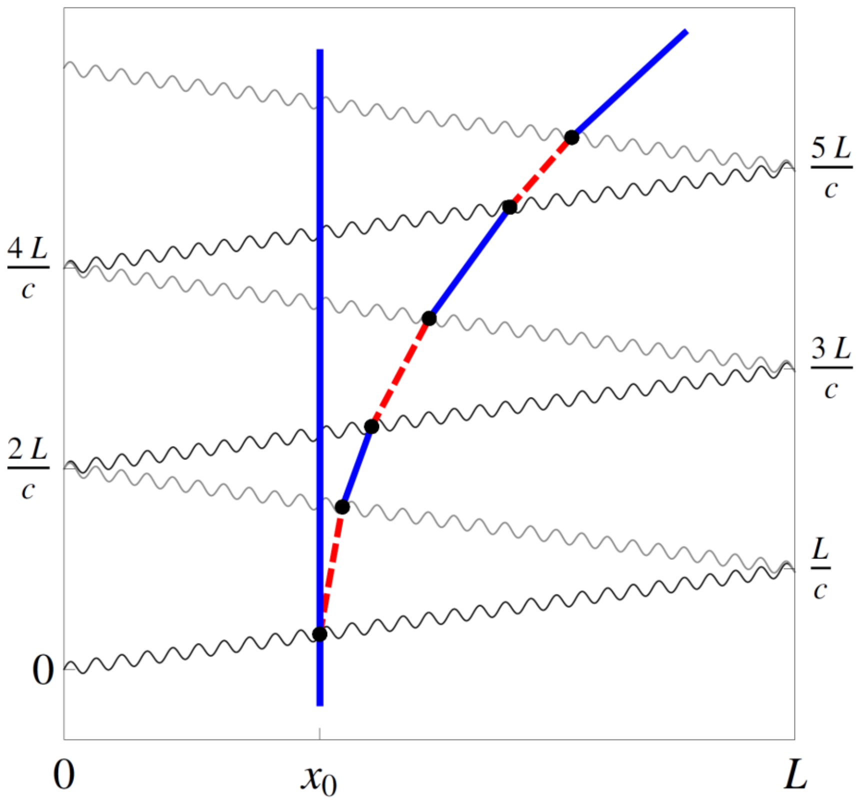


$L = 10\,\mathrm{cm}$, $n = 30$, and $T = 900\,\mathrm{ms}$ $(\Delta z = 16\,\mathrm{cm})$

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

Advanced atom optics

Large momentum transfer atom optics



Resonant interferometer sequence