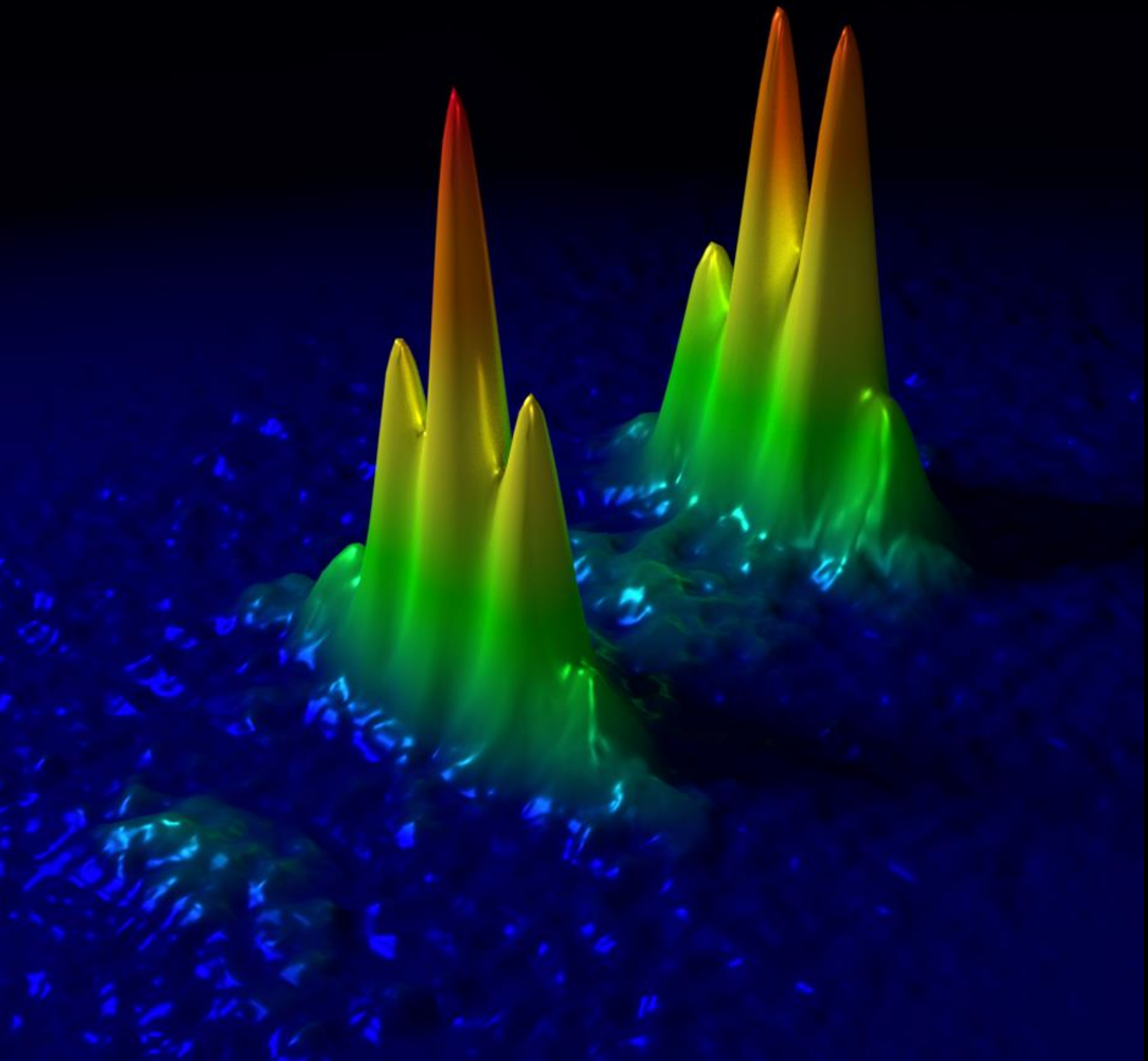
Atom interferometry for fundamental physics and gravitational wave detection



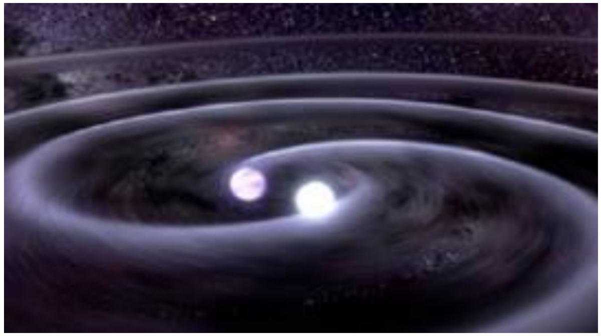
CERN

Jason Hogan
Stanford University

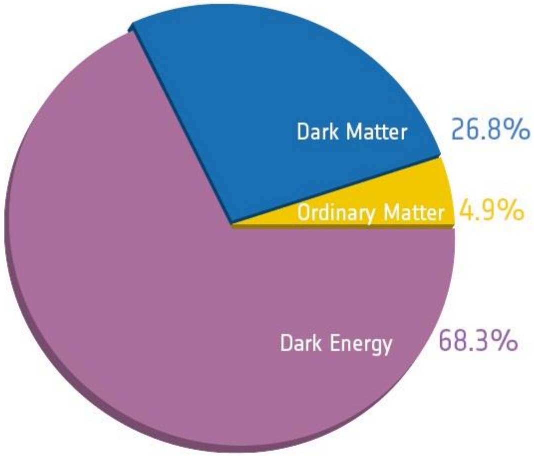
September 12, 2019

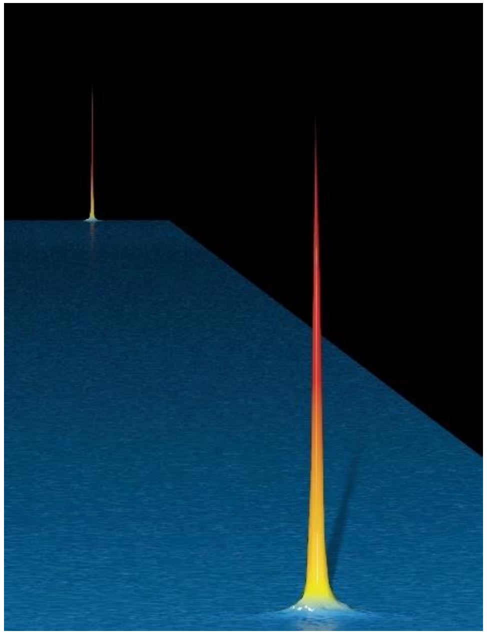
Science applications

- Gravitational wave detection
- Quantum mechanics at macroscopic scales
- QED tests (alpha measurements)
- Quantum entanglement for enhanced readout
- Equivalence principle tests, tests of GR
- Short distance gravity
- Search for dark matter
- Atom charge neutrality



Compact binary inspiral



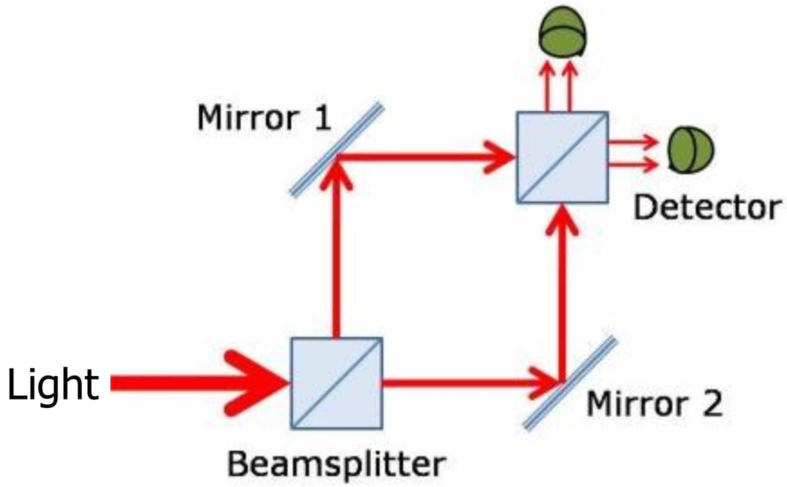


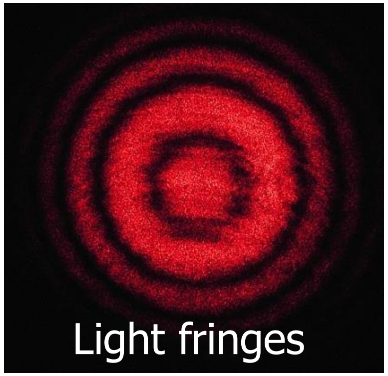
Rb wavepackets separated by 54 cm

Image: https://www2.physics.ox.ac.uk/research/dark-matter-dark-energy

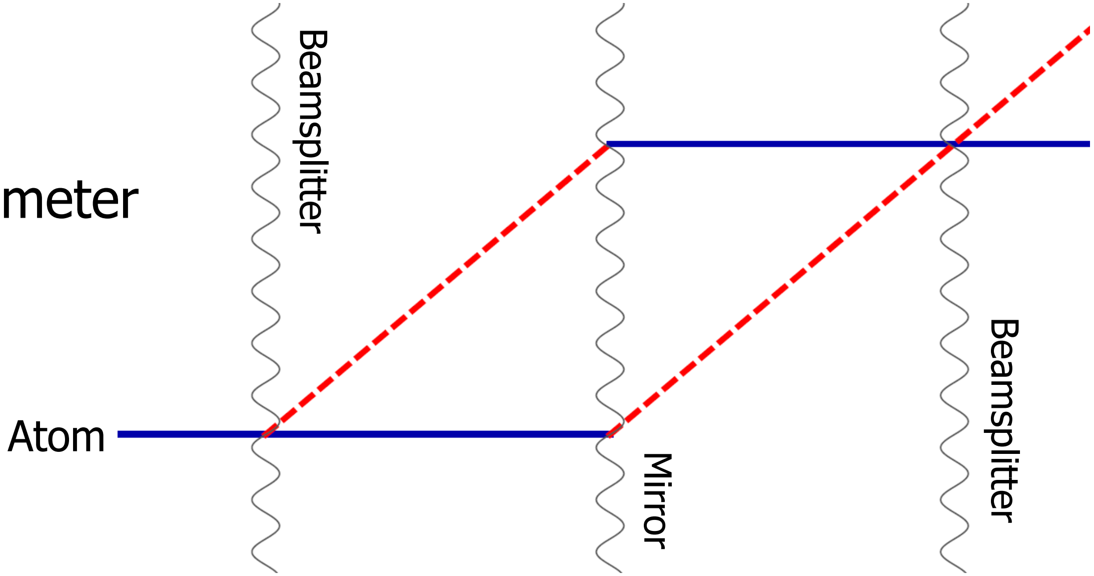
Atom interference

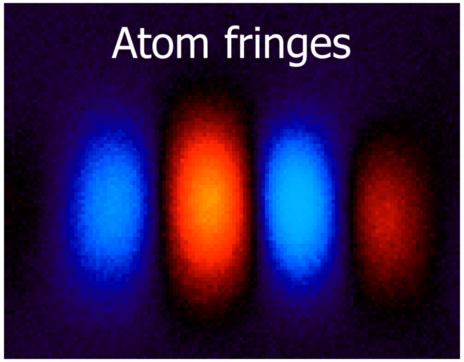
Light interferometer





Atom interferometer

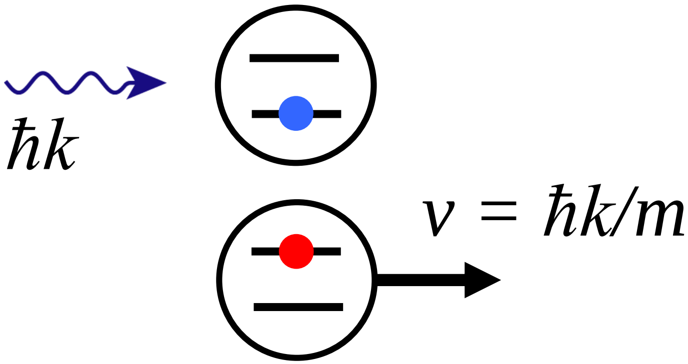




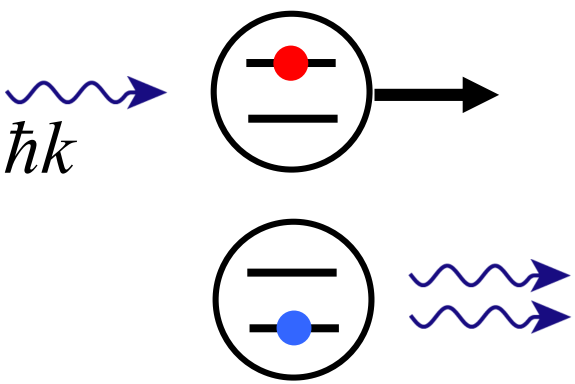
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Atom optics using light

(1) Light absorption:

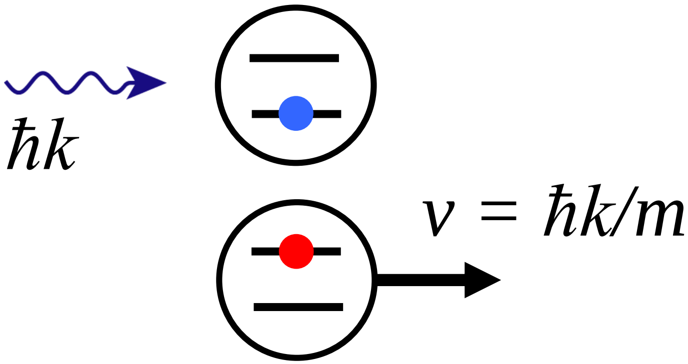


(2) Stimulated emission:

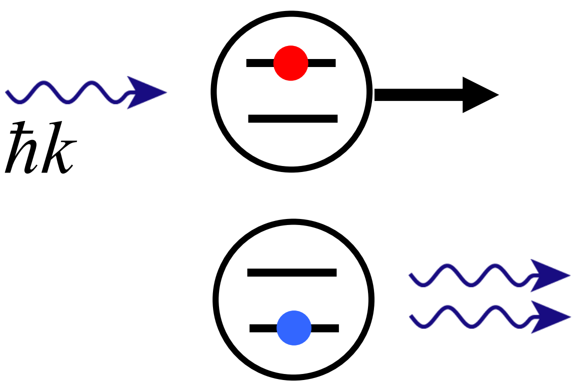


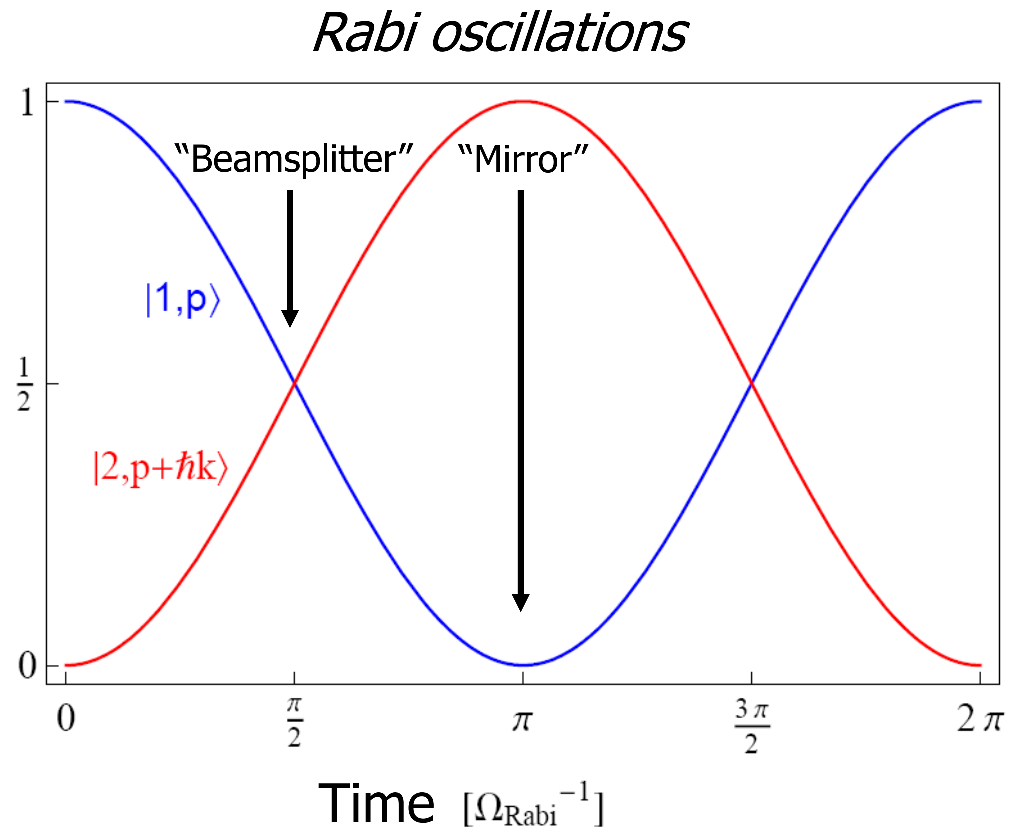
Atom optics using light

(1) Light absorption:



(2) Stimulated emission:





Light Pulse Atom Interferometry

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

π/2 pulse "beamsplitter"

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

π pulse "mirror"

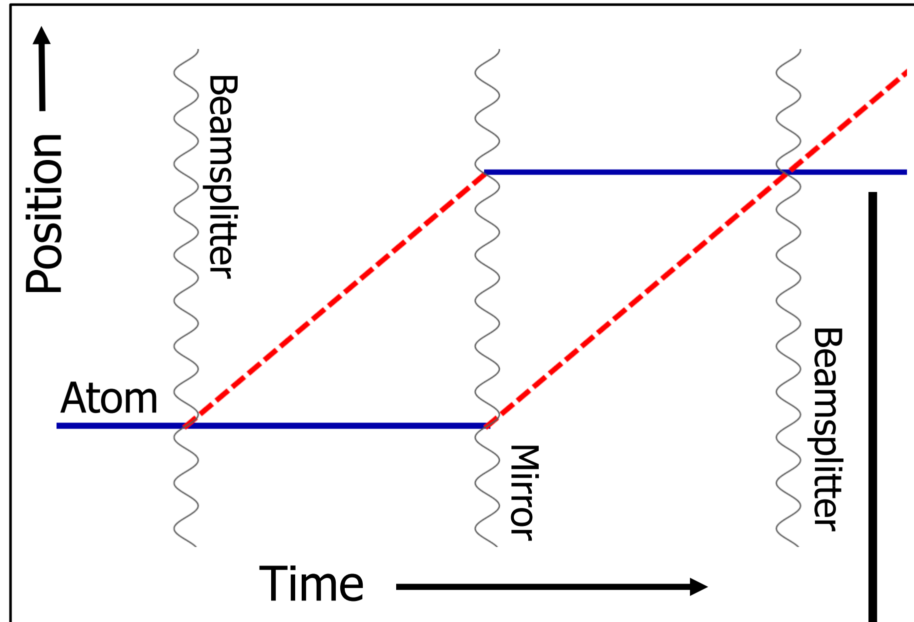
$$\frac{1}{\sqrt{2}}\left(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle\right)$$

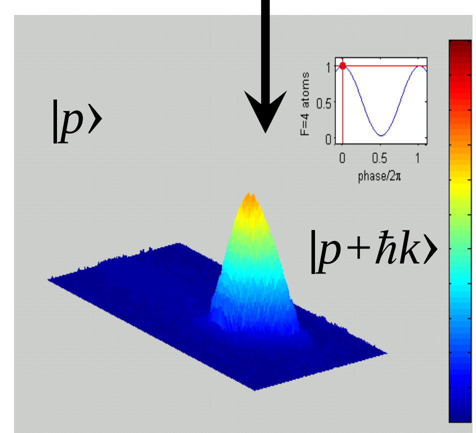
π/2 pulse "beamsplitter"

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

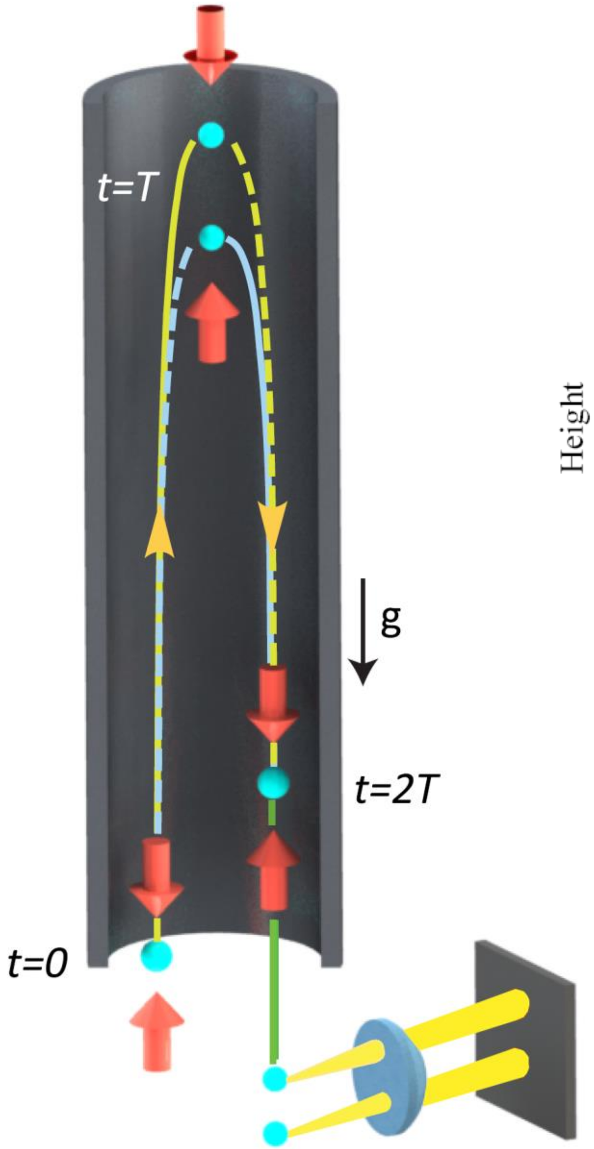
$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

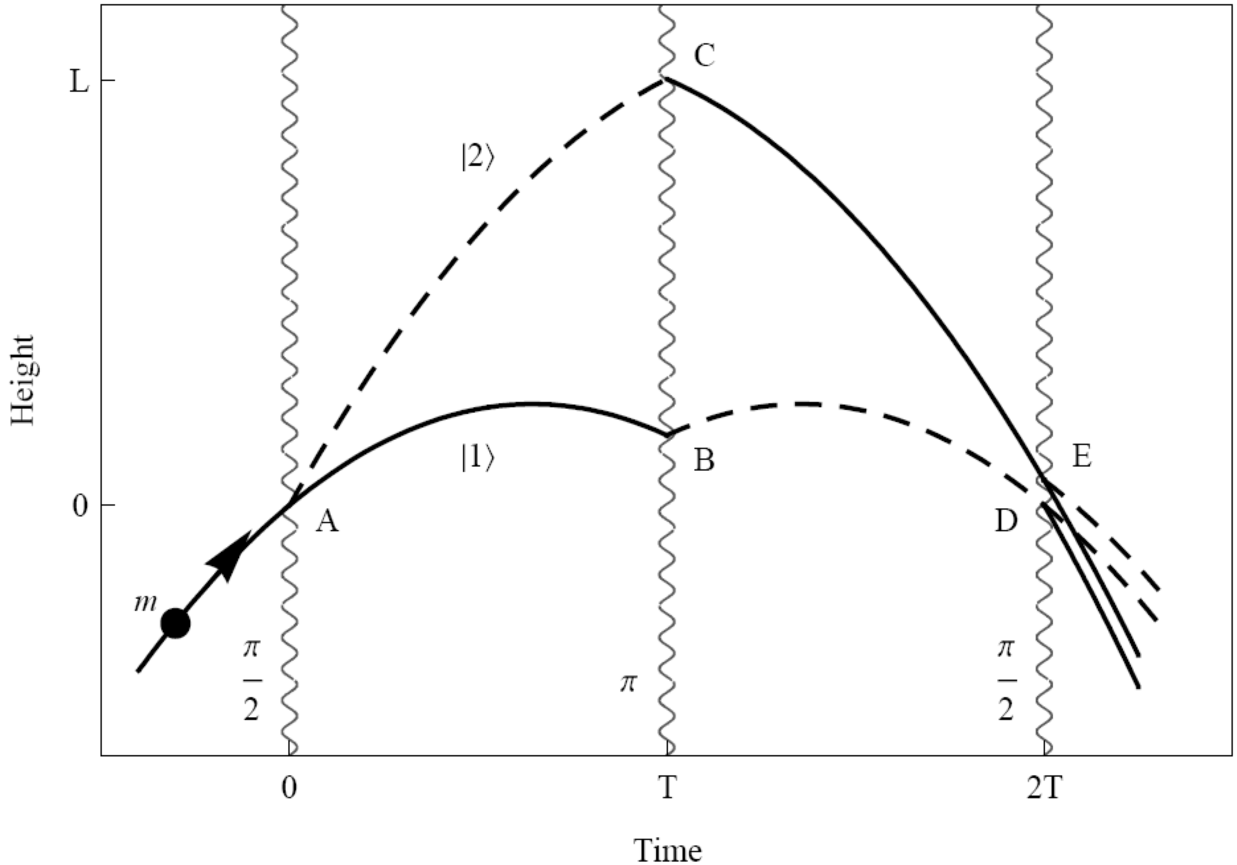
$$\text{Probability in State } |p + \hbar k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$





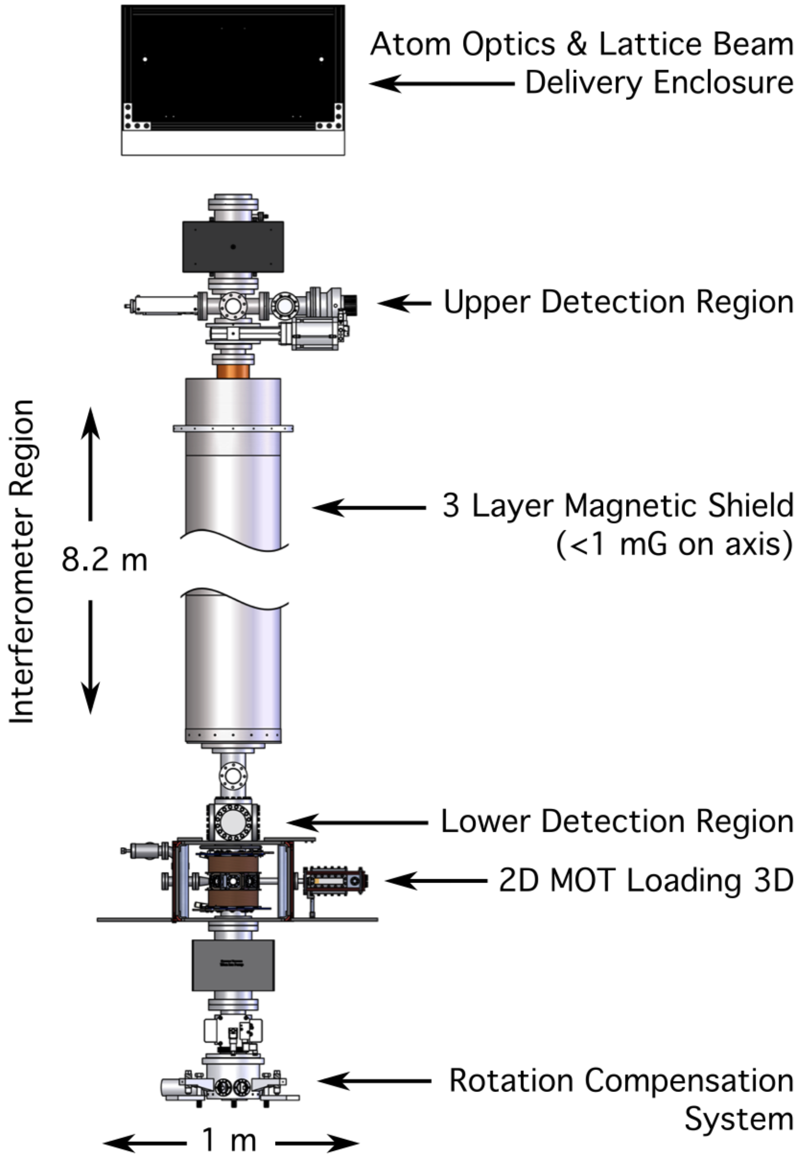
Light Pulse Atom Interferometry



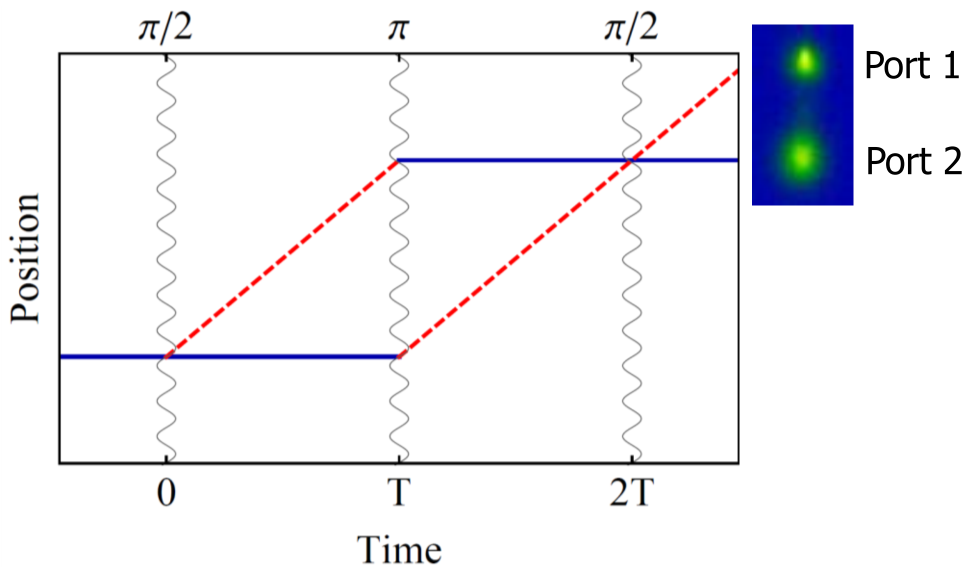


- Long duration
- Large wavepacket separation

10 meter scale atomic fountain

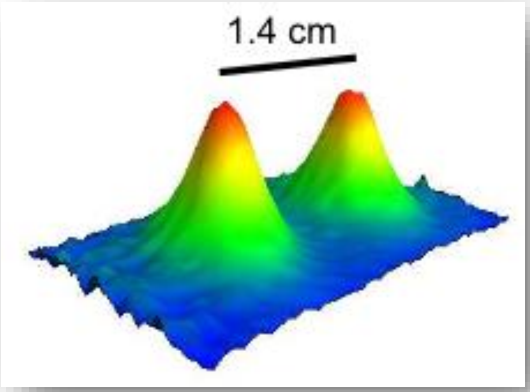


Interference at long interrogation time



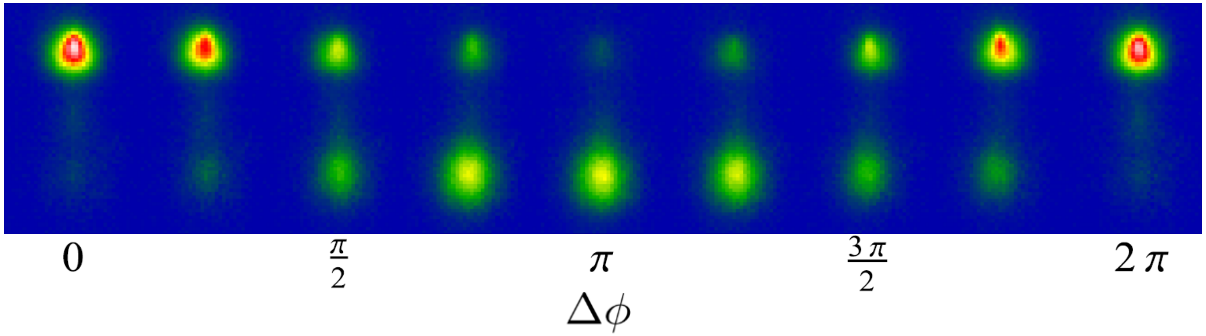
2T = 2.3 seconds

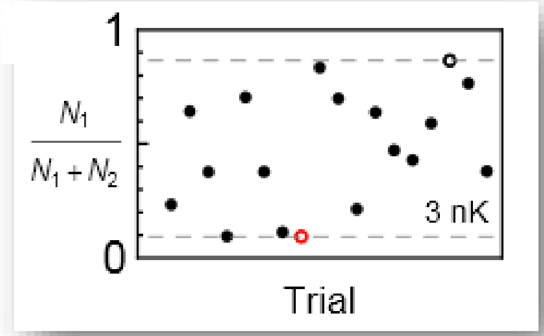
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

Interference (3 nK cloud)



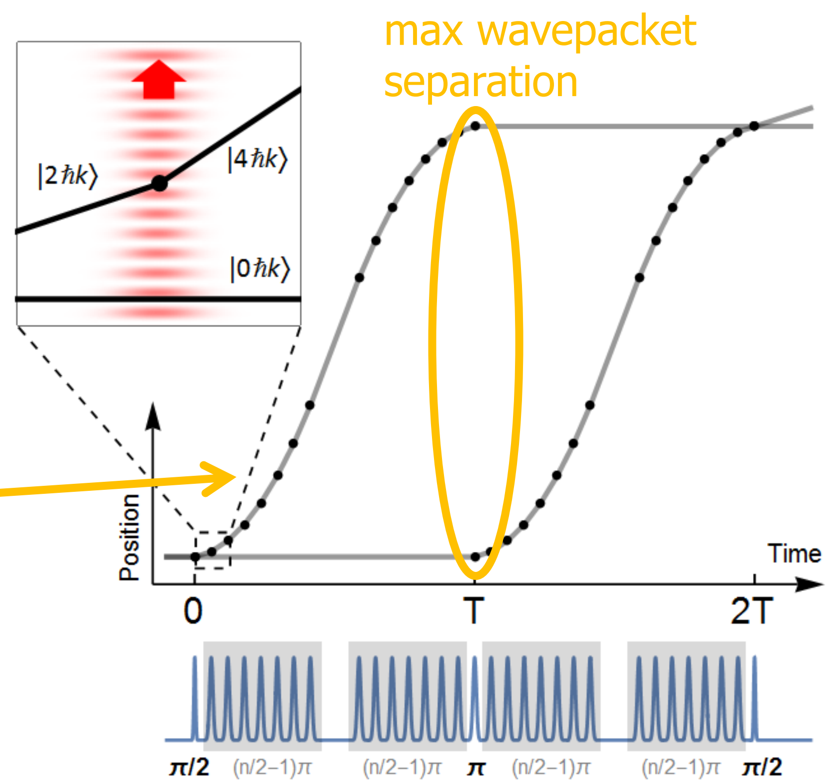


Dickerson, et al., PRL **111**, 083001 (2013).

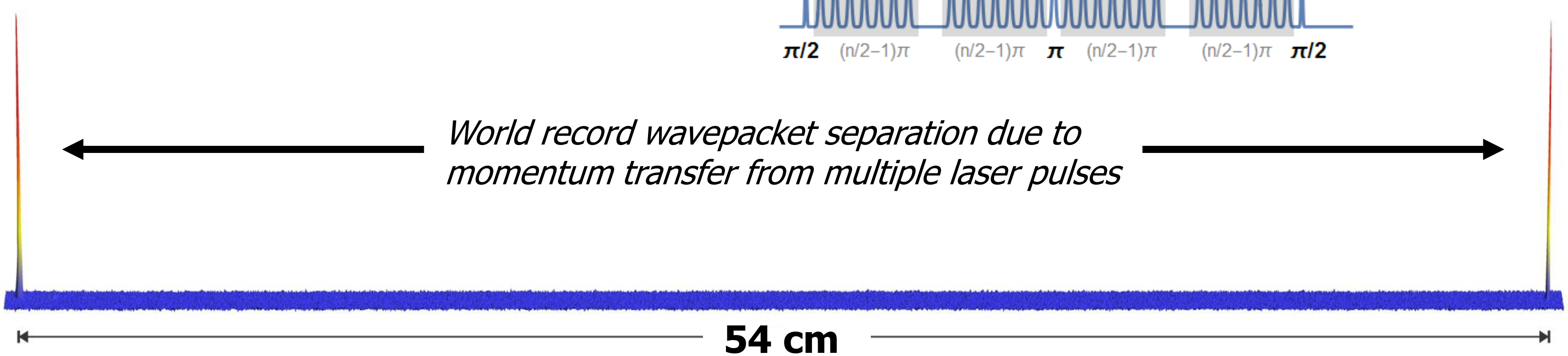
Large space-time area atom interferometry

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

90 photons worth of momentum



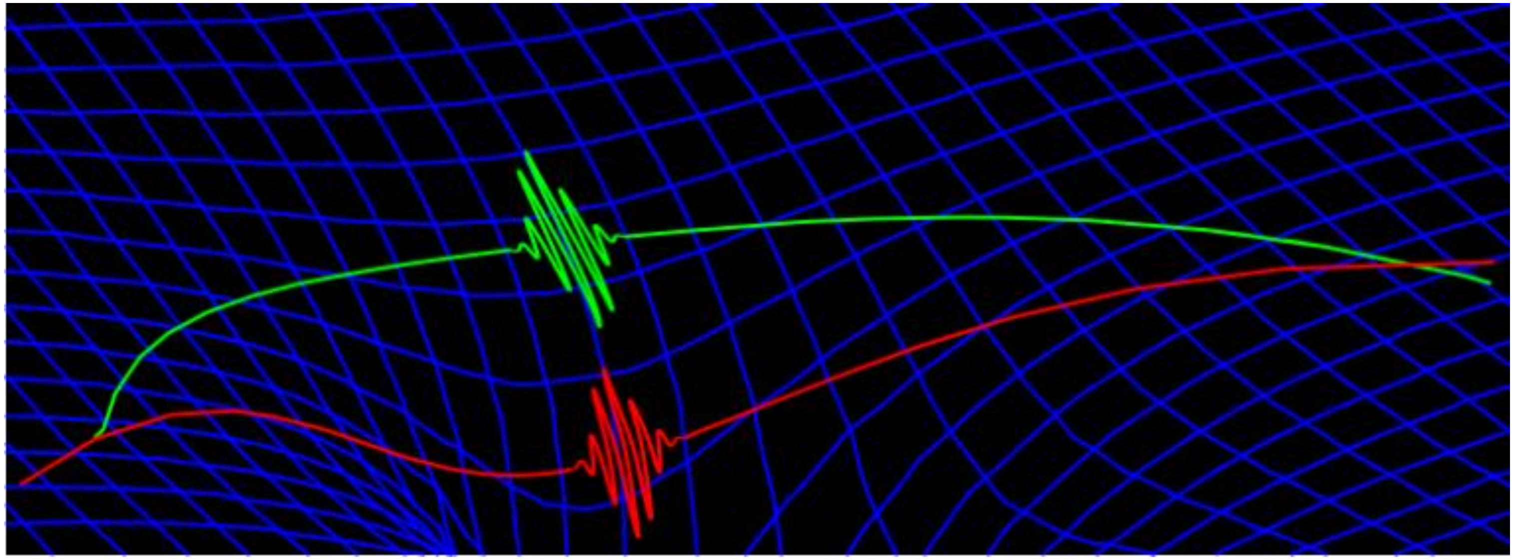
World record wavepacket separation due to momentum transfer from multiple laser pulses



Kovachy et al., *Nature* 2015

Phase shift from spacetime curvature

Spacetime curvature across a single particle's wavefunction

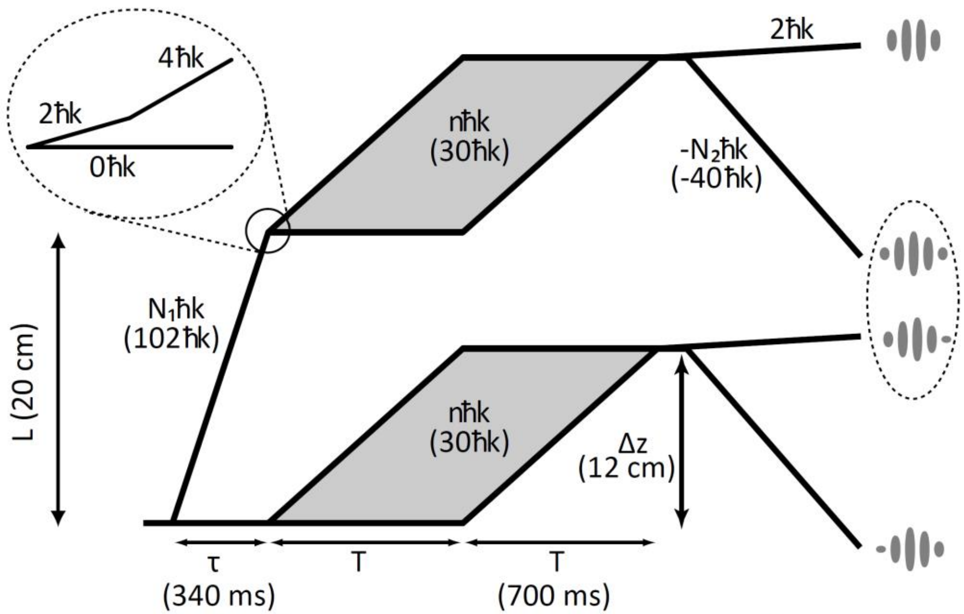


<u>General relativity:</u> gravity = curvature (tidal forces)

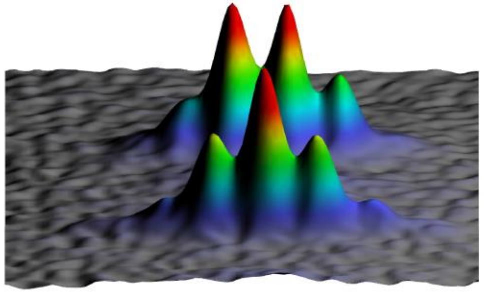
Uniform acceleration is an artifact of your choice of reference and can be transformed away (Einstein elevator).

Gravity Gradiometer

Need a "reference" atom interferometer to suppress technical noise.

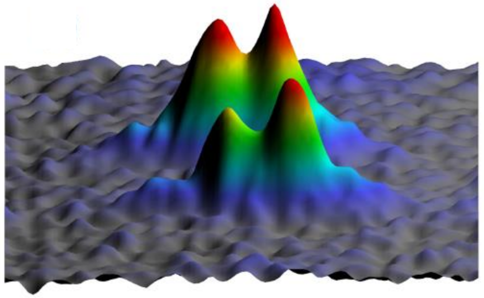


Measure *phase difference*



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

10 ħk



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

30 ħk

Gradiometer interference fringes

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

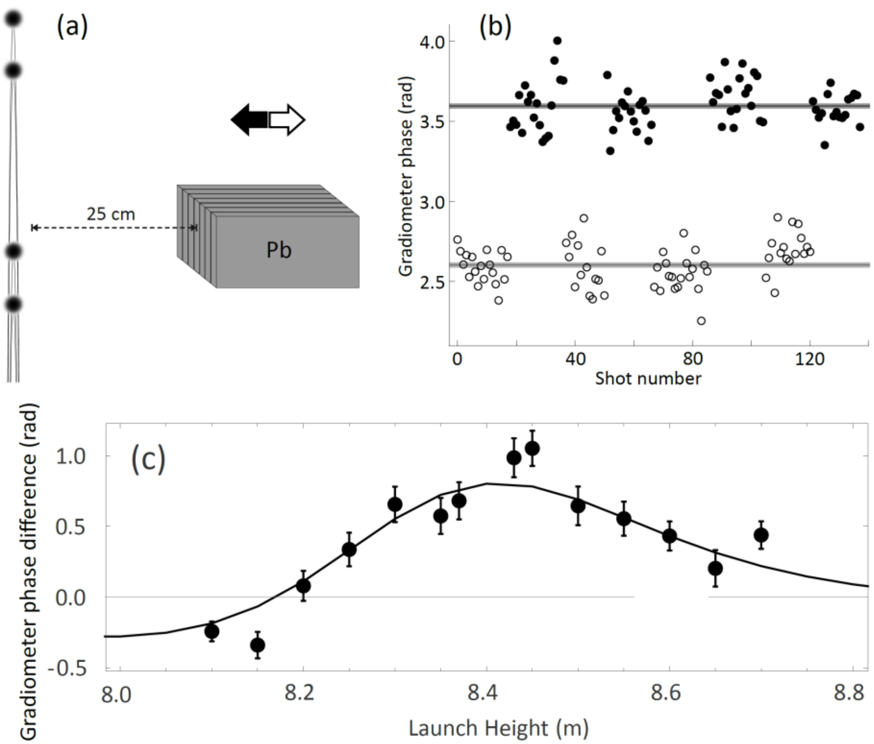
Phase shift from tidal force

Gradiometer response to 84 kg lead test mass

Upper interferometer

Lower interferometer

(experiences tidal force from Pb)



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

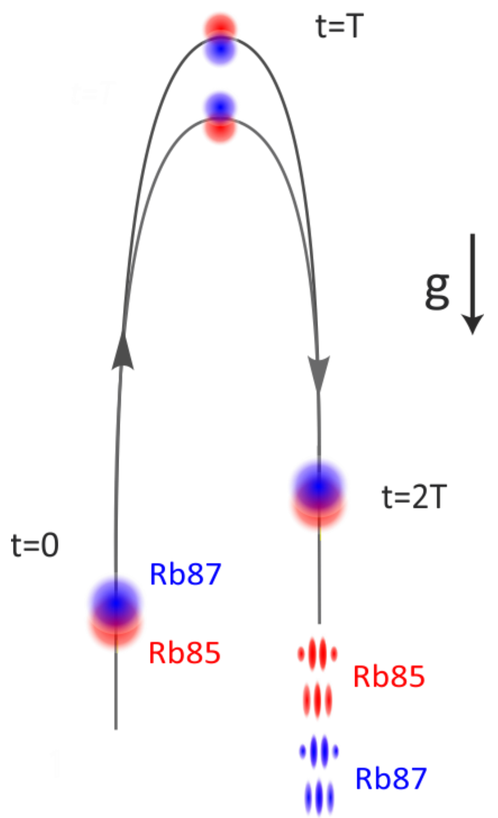
Results can *only* be described by accounting for tidal force across the interferometer arms.

Curvature-induced phase shifts have been described as first *true manifestation* of gravitation in a quantum system

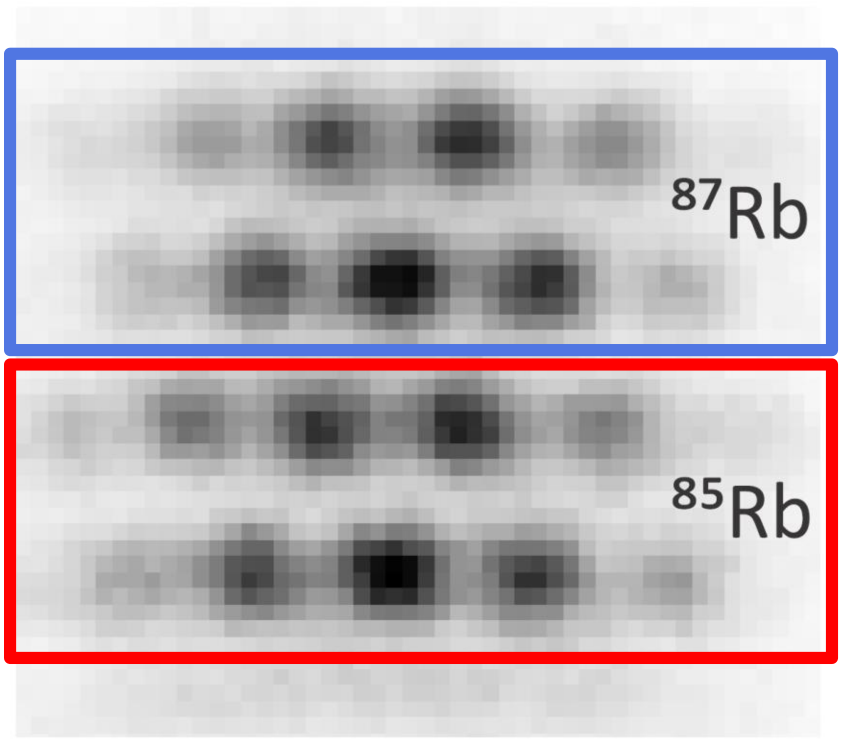
Asenbaum et al., PRL **118**, 183602 (2017)

Stanford 10-meter equivalence principle test

Simultaneous Dual Interferometer



Dual interferometer fringes



Sensitivity target for static EP: $< 10^{-14}$

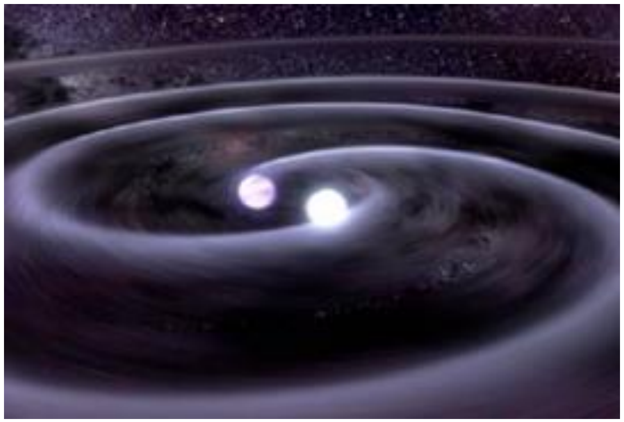
Can also look for time-varying forces (MAGIS)

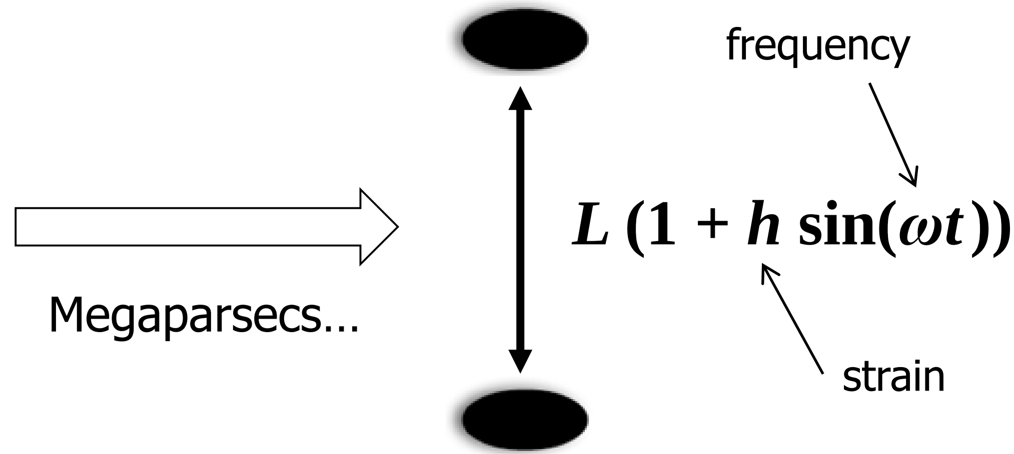
Recent results: Suppressed gravity gradient sensitivity by x100

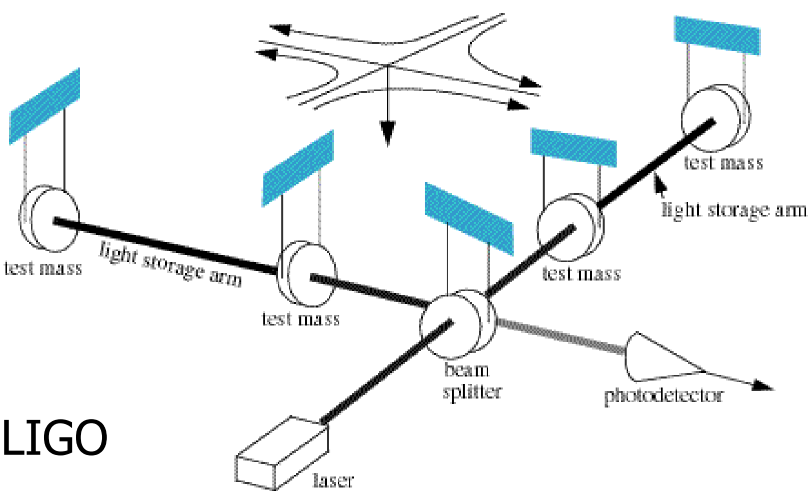
Overstreet et al., PRL **120**, 183604 (2018)

Gravitational Wave Detection

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







LIGO

- LIGO and other optical interferometers **use two baselines**
- In principle, **only one is required**
- Second baseline needed to reject laser technical noise

MAGIS concept

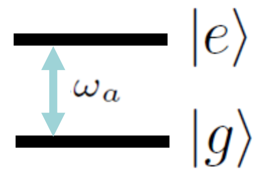
Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

Passing gravitational waves cause a small modulation in the distance between objects. Detecting this modulation requires two ingredients:

1. **Inertial references**
   - Freely-falling objects, separated by some baseline
   - Must be insensitive to perturbations from non-gravitational forces
2. **Clock**
   - Used to monitor the separation between the inertial references
   - Typically measures the time for light to cross the baseline

In MAGIS, atoms play both roles.

Simple Example: Two Atomic Clocks



Time

Phase evolved by atom after time T

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

Simple Example: Two Atomic Clocks

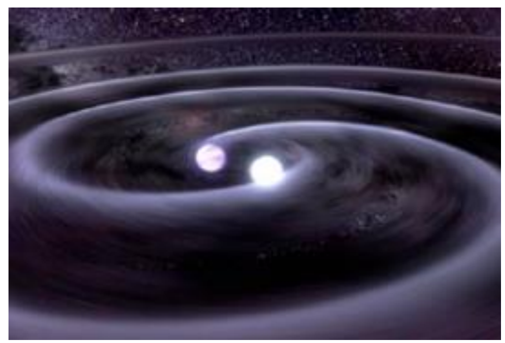
$|e\rangle$

ω_a

$|g\rangle$

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

Time

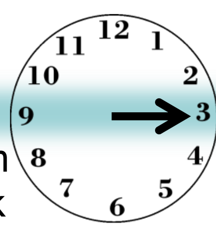


GW changes light travel time

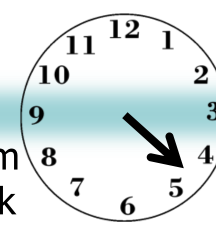
$$\Delta T \sim hL/c$$

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

Atom clock



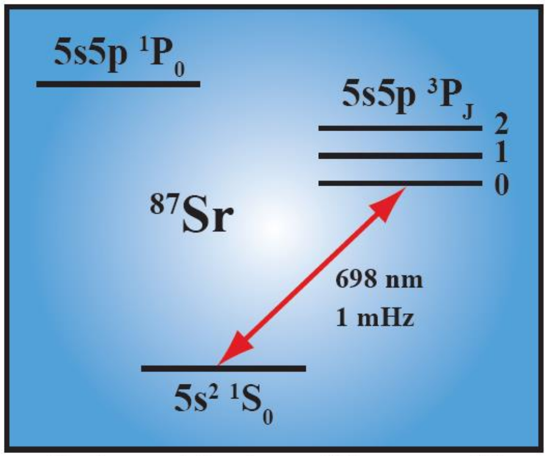
Atom clock



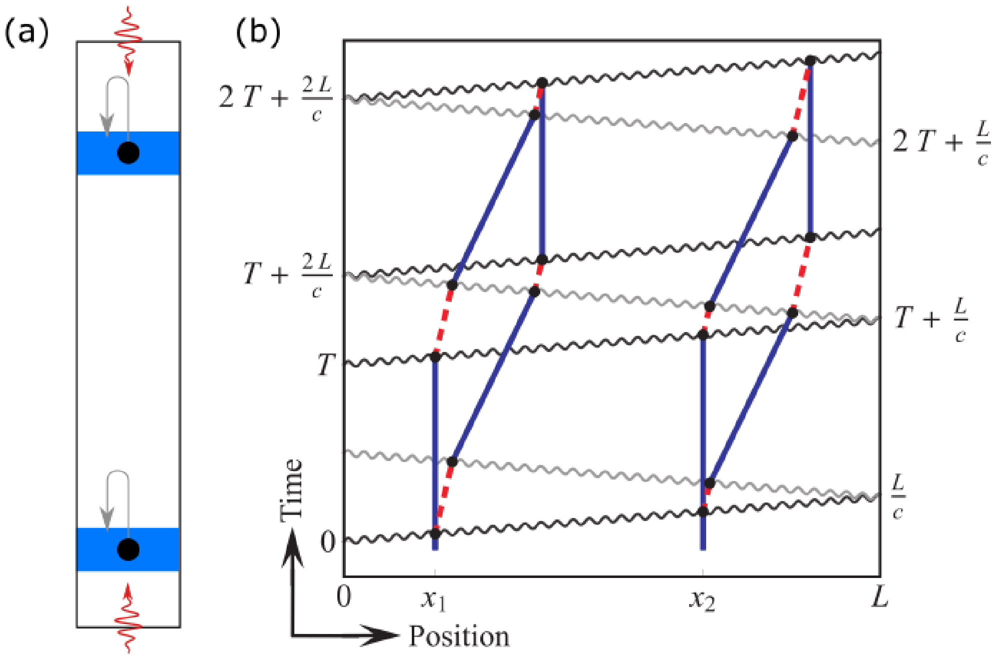
A different kind of atom interferometer

Hybrid “clock accelerometer”

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



Clock transition in candidate atom ⁸⁷Sr

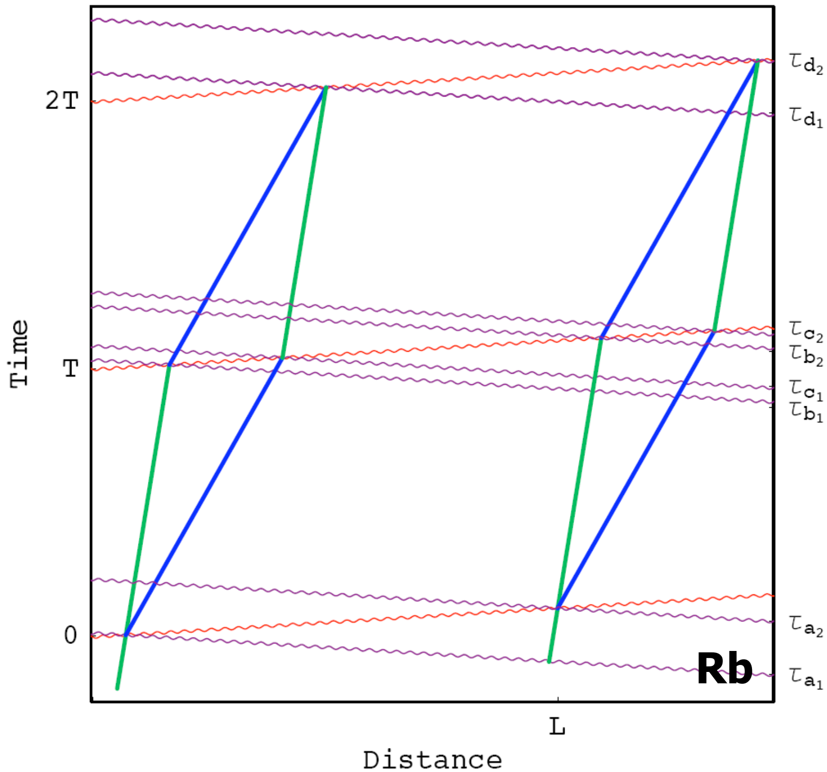


Clock: measure light travel time ➜ remove laser noise with *single baseline*

Accelerometer: atoms excellent inertial test masses

Two-photon vs. single photon transitions

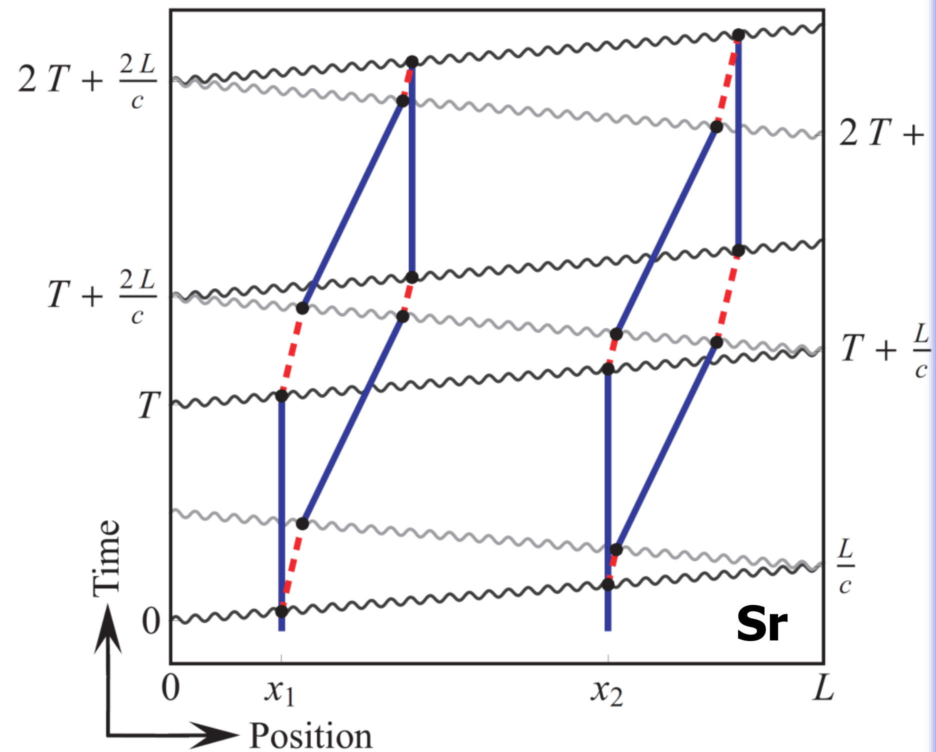
2-photon transitions



GW signal from relative positions of atoms w.r.t. optical phase fronts.

$$\Delta\Phi = k_{\text{eff}} a T^2$$

1-photon transitions



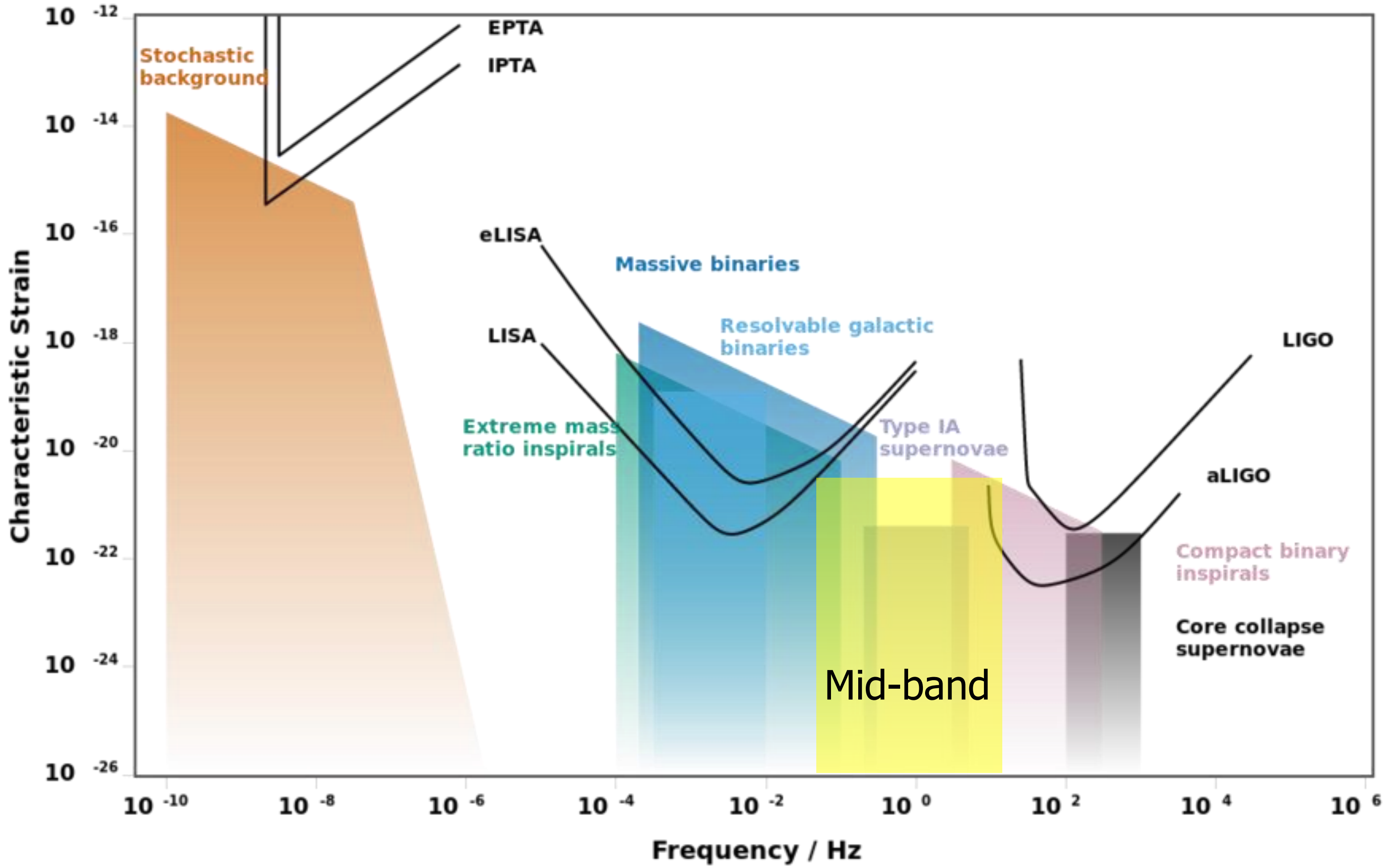
GW signal from light propagation time between atom ensembles.

MAGIS $$\Delta\Phi = (\omega_A/c) a T^2$$

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

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

Gravitational wave frequency bands



There is a gap between the LIGO and LISA detectors (0.1 Hz – 10 Hz).

Moore et al., CQG **32**, 015014 (2014)

Mid-band Gravitational Wave Science

Mid-band discovery potential

Historically every new band/modality has led to discovery

Observe LIGO sources when they are younger

Excellent sky localization

Predict *when* and *where* events will occur (before they reach LIGO)

Observe run-up using electromagnetic telescopes

Cosmology and Astrophysics

Black hole, neutron star, and white dwarf binaries

Parameter estimation (e.g., BH spin)

Ultralight scalar dark matter discovery potential

Early Universe stochastic sources (cosmic GW background)

Sky position determination

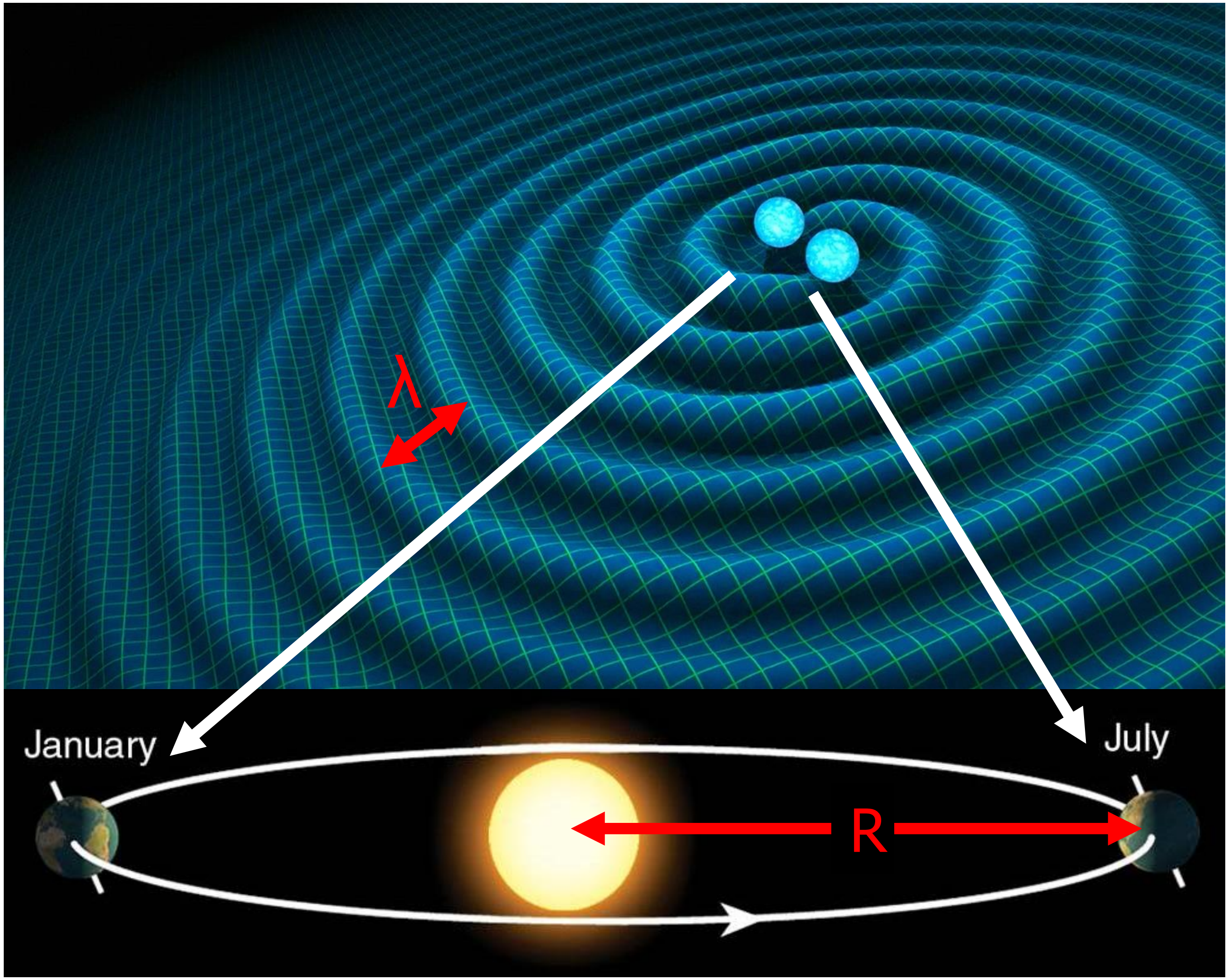
Sky localization precision:

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

Mid-band advantages

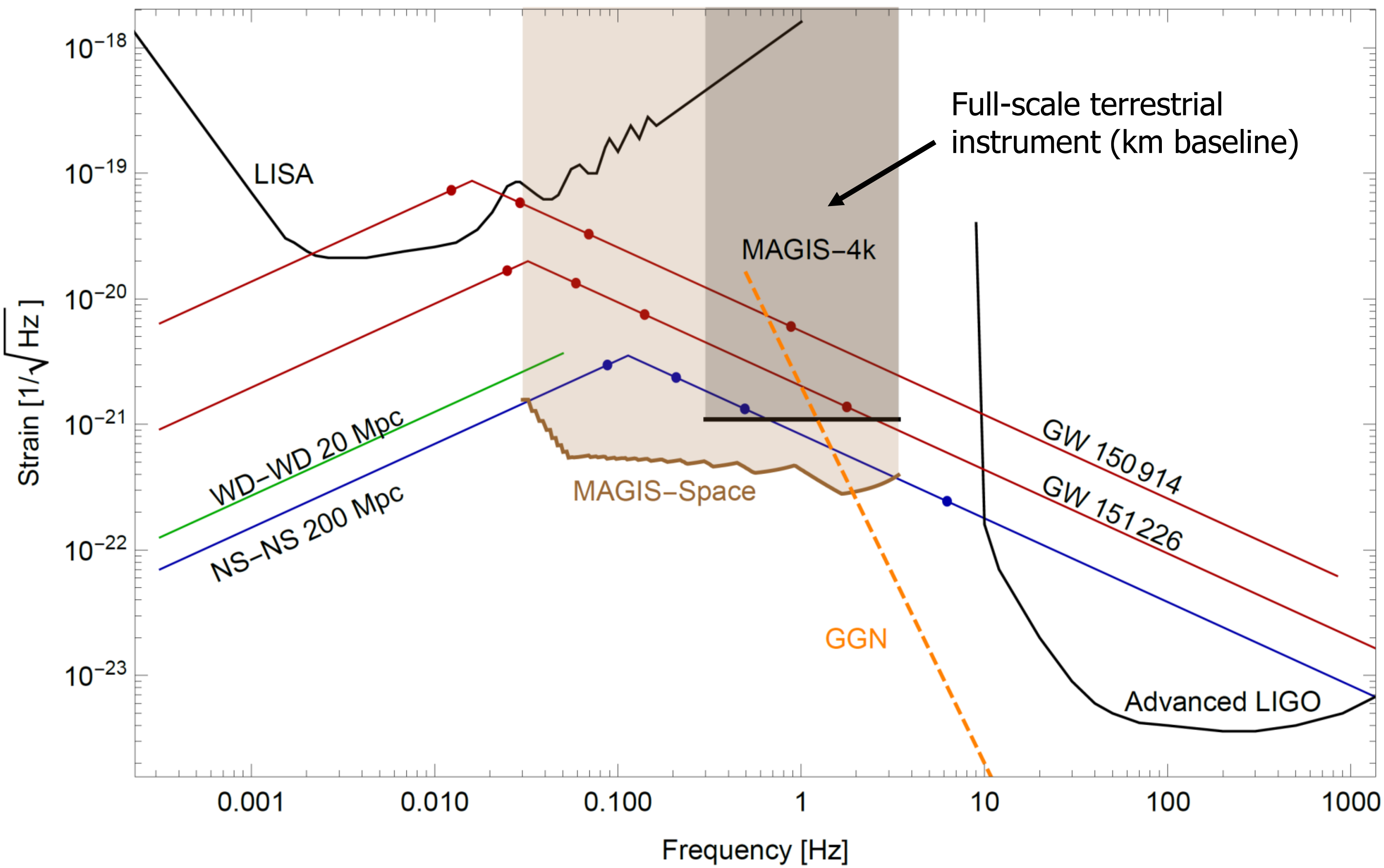
- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

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

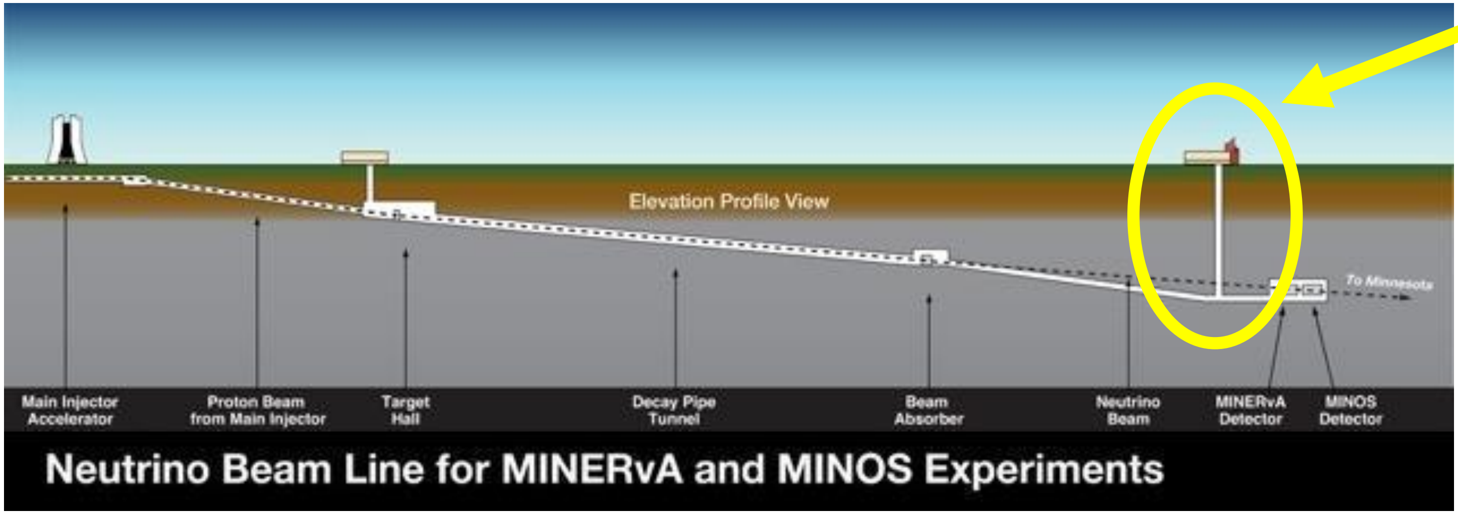
Projected gravitational wave sensitivity

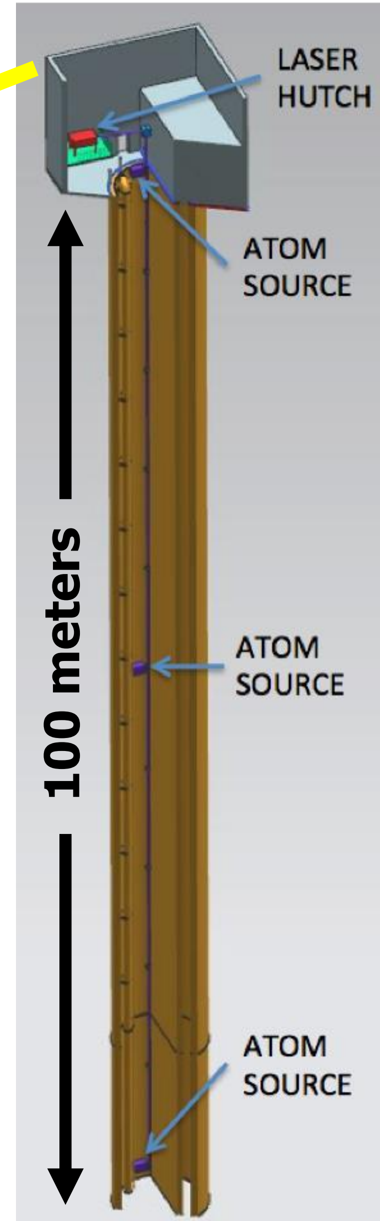


Dots indicate remaining lifetimes of 10 years, 1 year, 0.1 years, and 0.01 years

MAGIS-100: Detector prototype at Fermilab

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

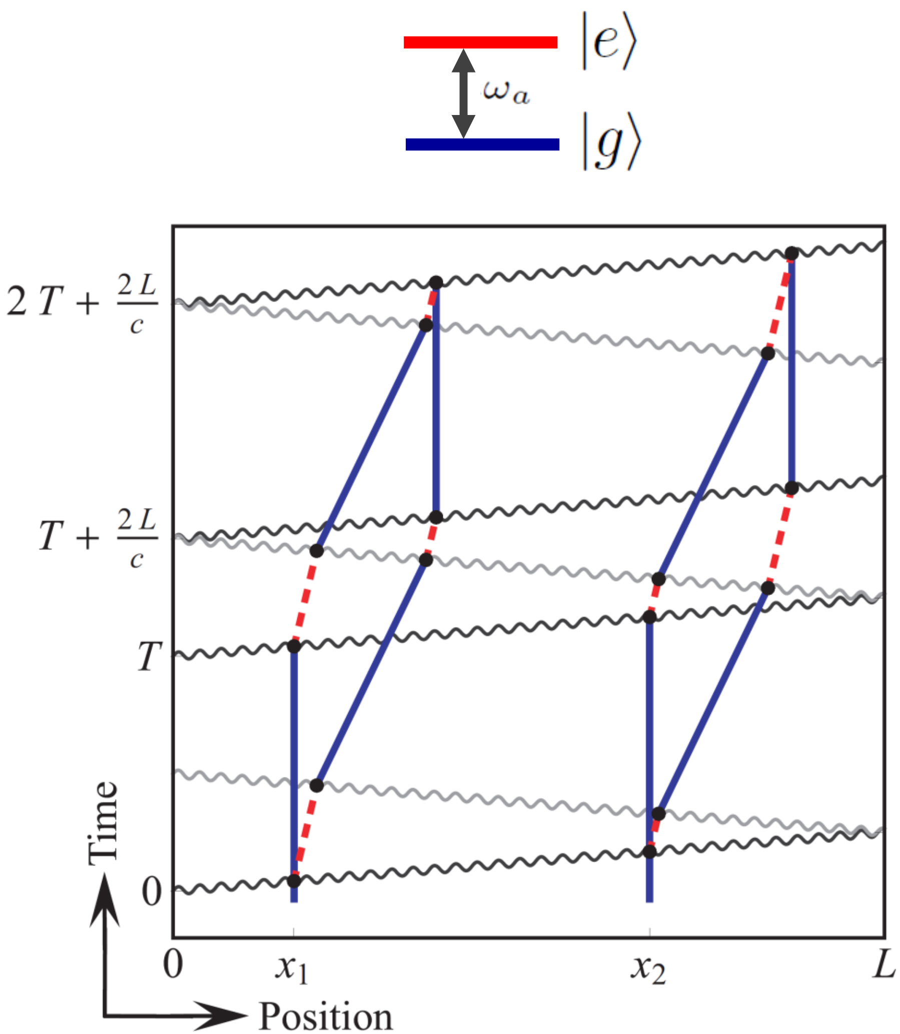




- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

STANFORD · Fermilab · Johns Hopkins University · University of Liverpool · Northwestern University · Northern Illinois University

Clock gradiometer



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

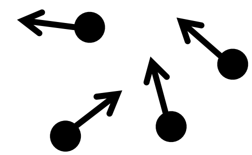
Laser noise is common-mode suppressed in the gradiometer

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

Ultralight dark matter

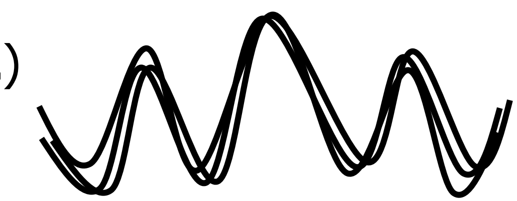
WIMPS

- Mass ~10 GeV (10x proton)
- Particle-like (deposit energy in detector)

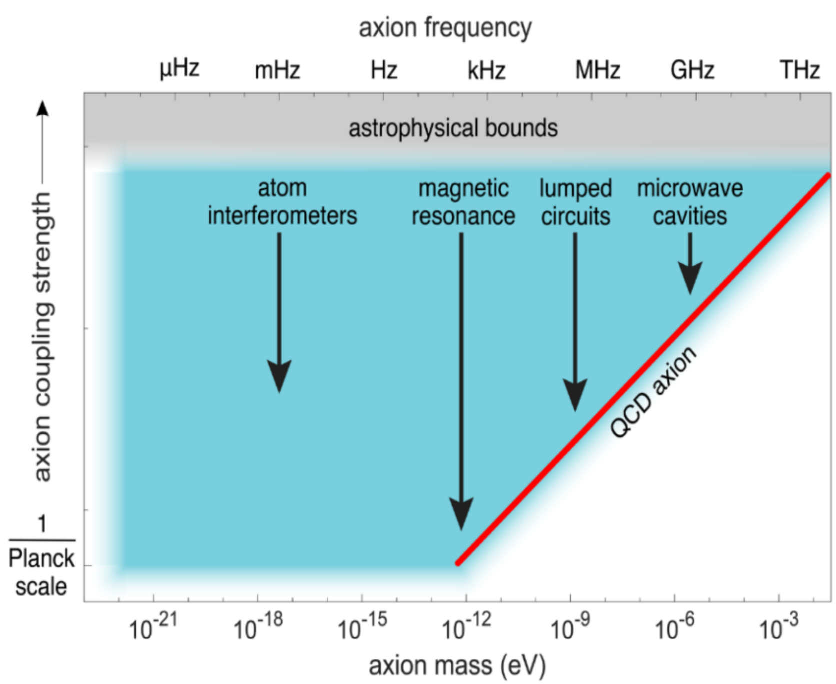


"Ultralight" dark matter (e.g., axions, dilatons, etc.)

- Low mass, high number density
- Would act like a **classical field**



One example is the axion, and axion-like particles



Dark matter BRN report

Ultralight scalar dark matter

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

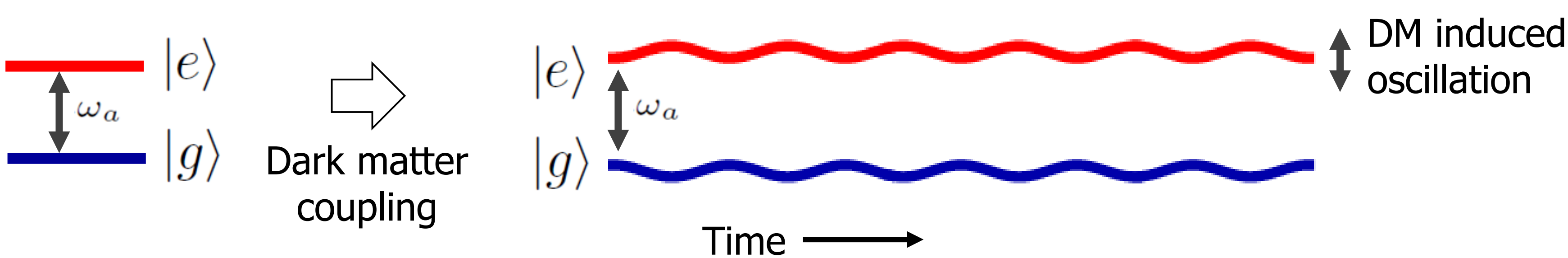
$$\mathcal{L} = +\underbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g.,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

DM scalar field

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

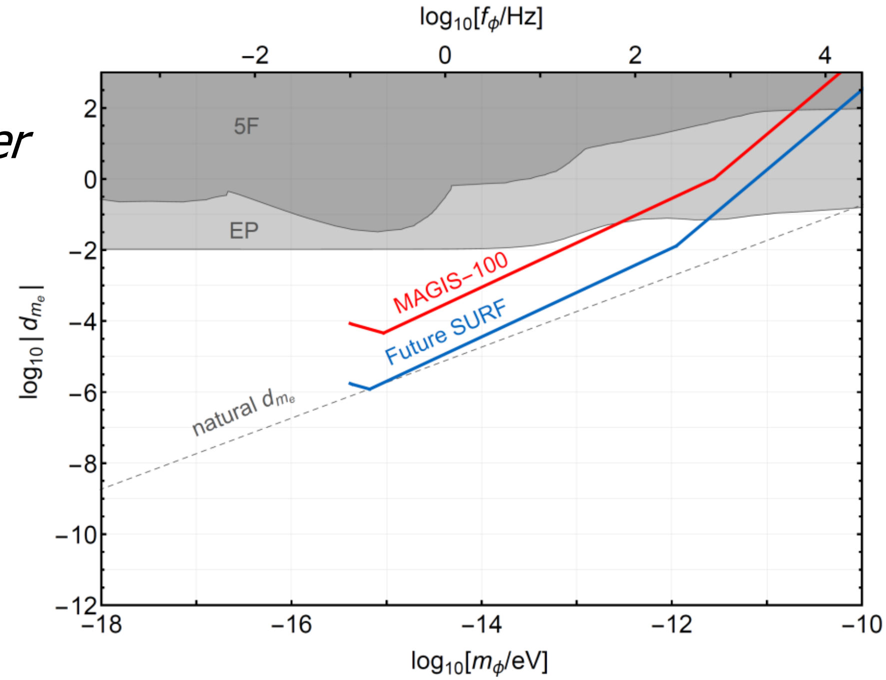
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

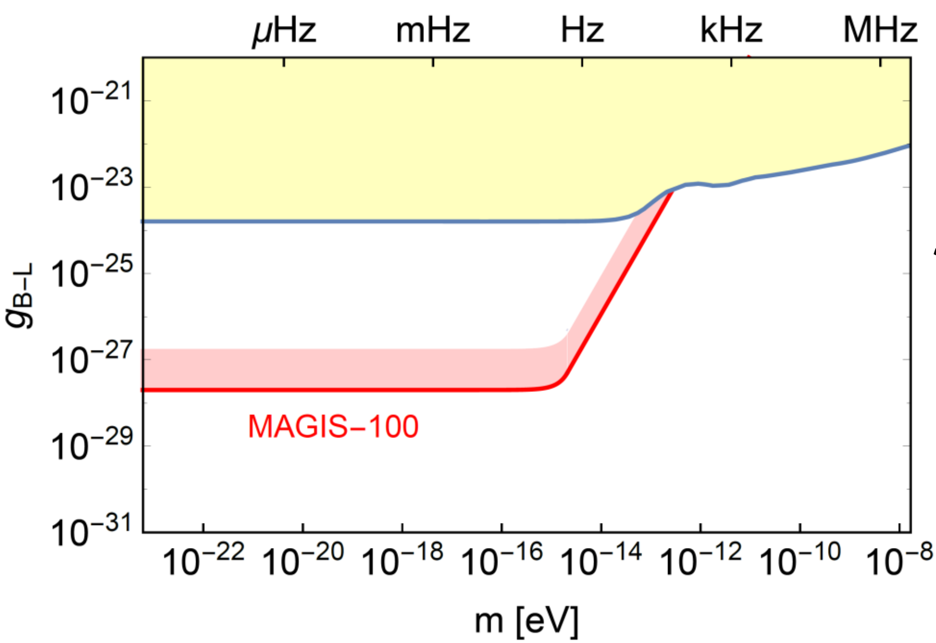
DM coupling causes time-varying atomic energy levels:



Projected sensitivity to dark matter for MAGIS-100

Sensitivity to ultralight scalar dark matter





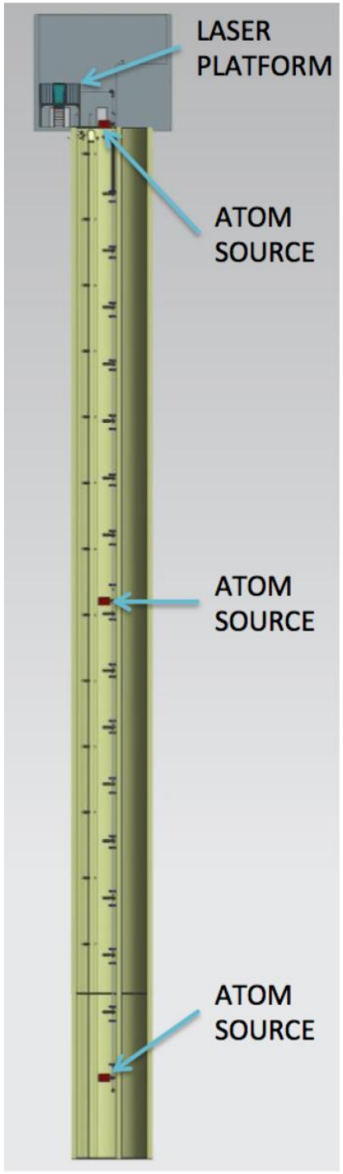
Sensitivity to B-L coupled new force

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

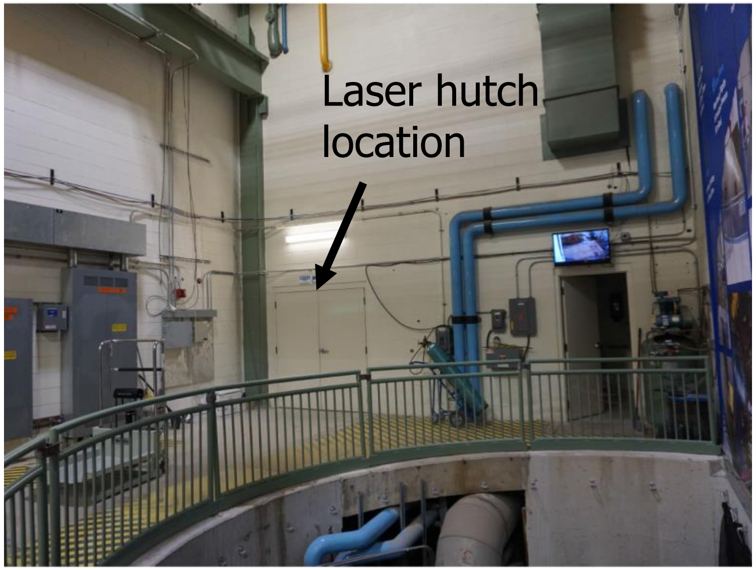
Graham et al. PRD **93**, 075029 (2016).

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

MAGIS-100 at Fermilab

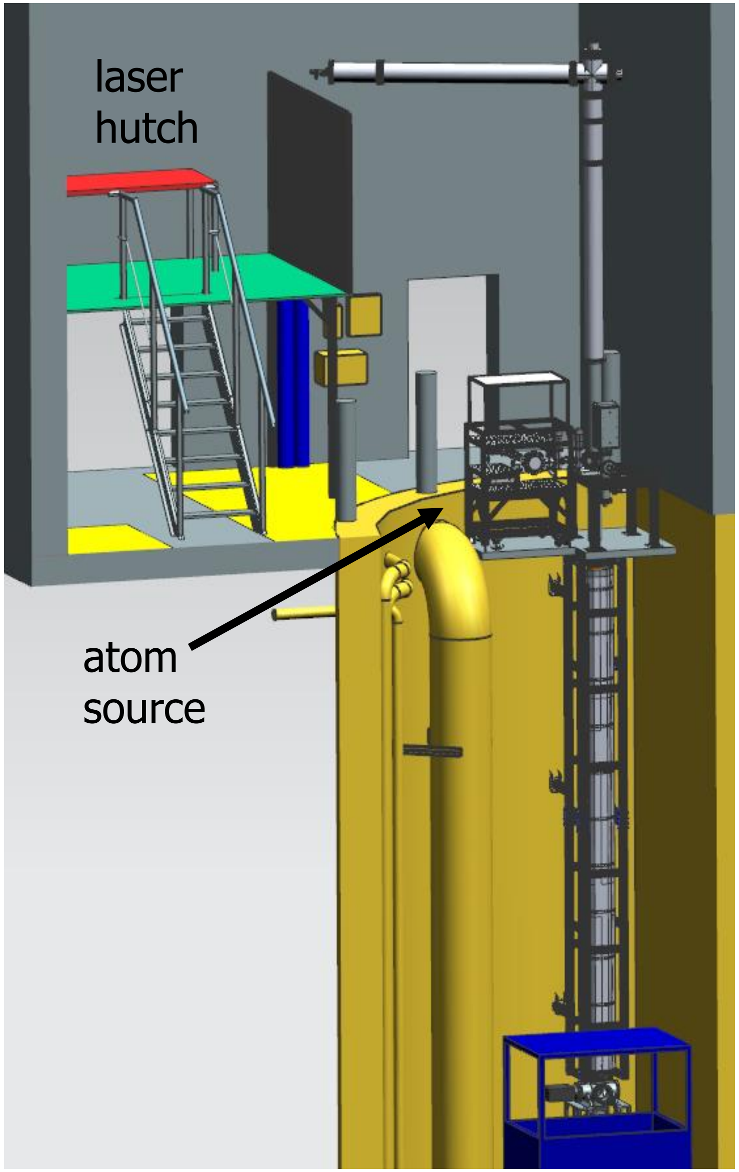


Cross section full detector



System Components:

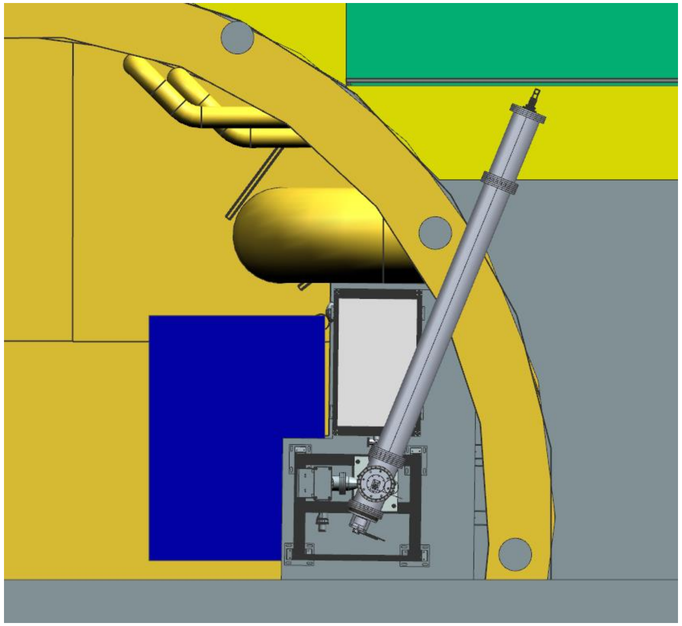
- 10 times larger than Stanford setup
- Located in MINOS shaft
- 90 meter vacuum tube (vertical)
- Three atoms sources
- Laser system for implementing atom interferometry (hutch at top)



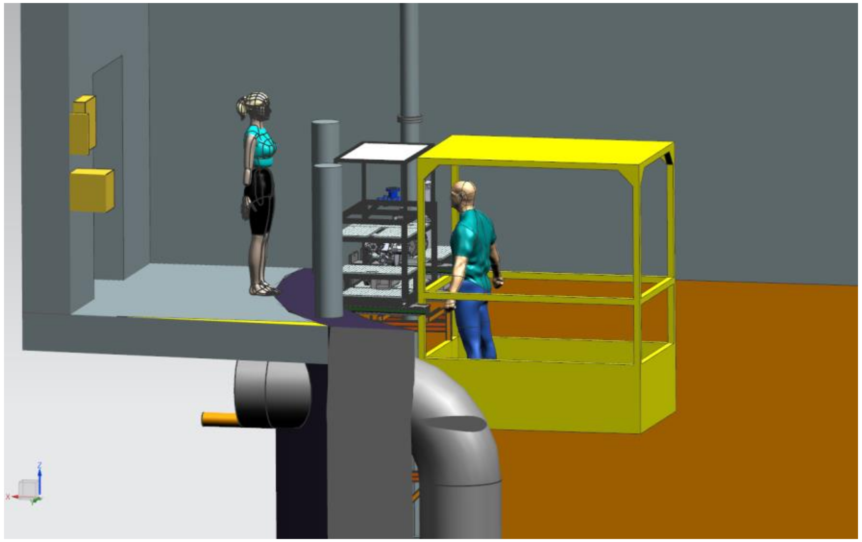
Top of detector

MAGIS-100 at Fermilab

Minos access shaft

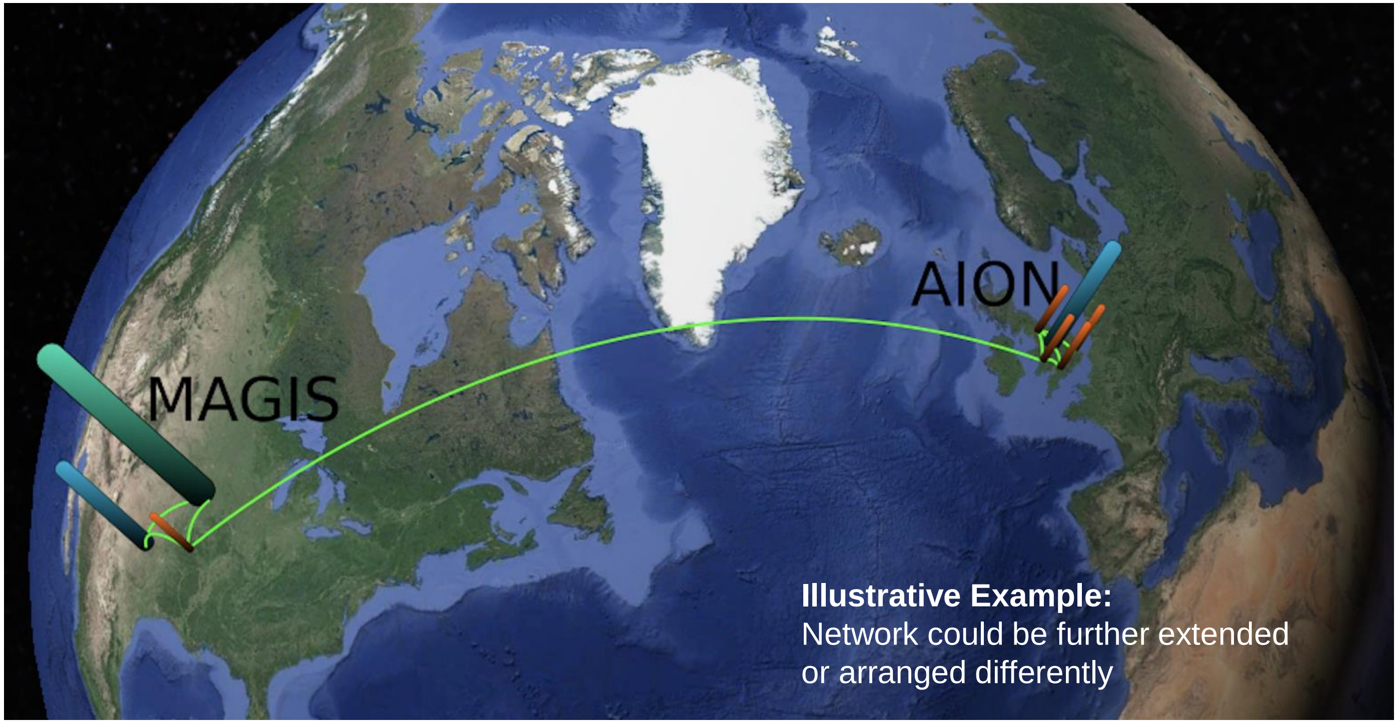


Top view of MAGIS installation

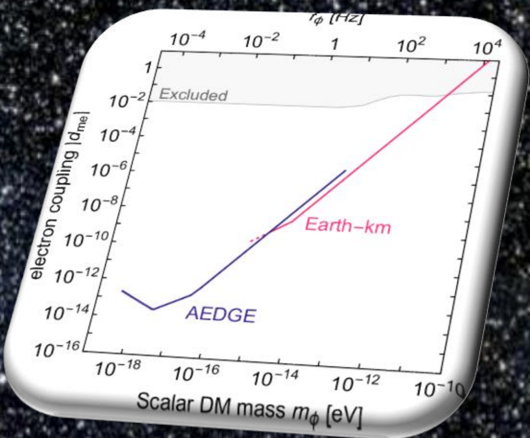


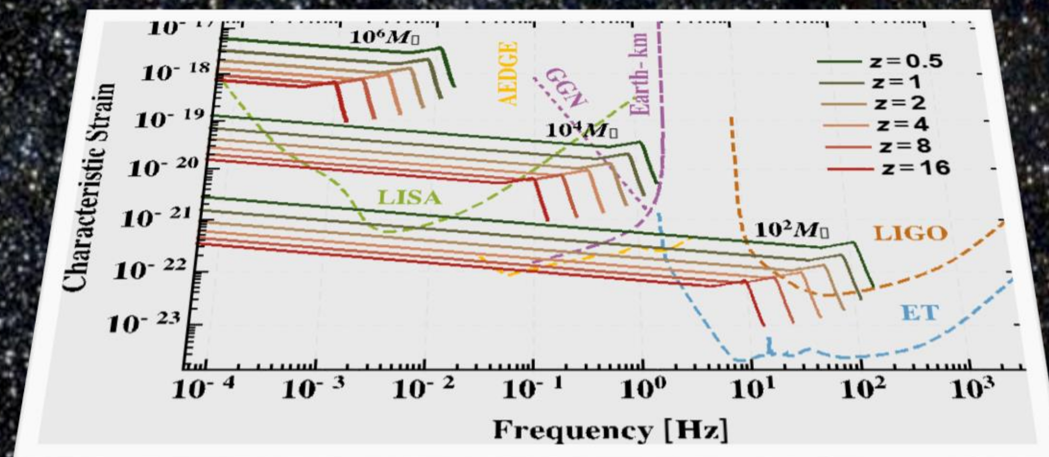
AION: Atom Interferometer Observatory and Network

- Proposed UK effort to network with MAGIS
- Develop a LIGO/VIRGO style collaboration
- Rejection of non-common mode backgrounds
  - Unequivocal proof of any observation



AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration





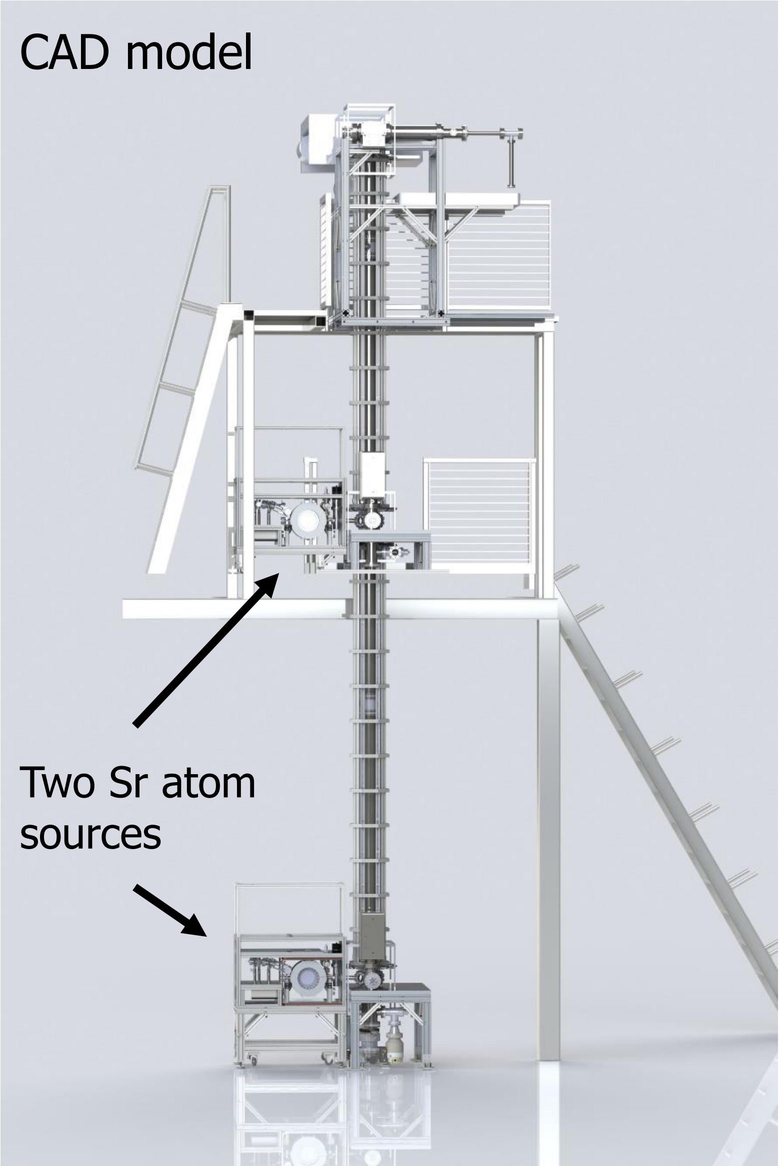
Informal Workshop
CERN, July 22/23 2019

Organizers:
Kai Bongs(CA), Philippe Bouyer(CA), Oliver Buchmueller(PP),
Albert De Roeck(PP), John Ellis(PP, Theory), Peter Graham (CA, Theory),
Jason Hogan (CA), Wolf von Klitzing(CA), Guglielmo Tino(CA), and AtomQT
PP=Particle Physics
CA=Cold Atoms

Stanford 10-meter Sr prototype

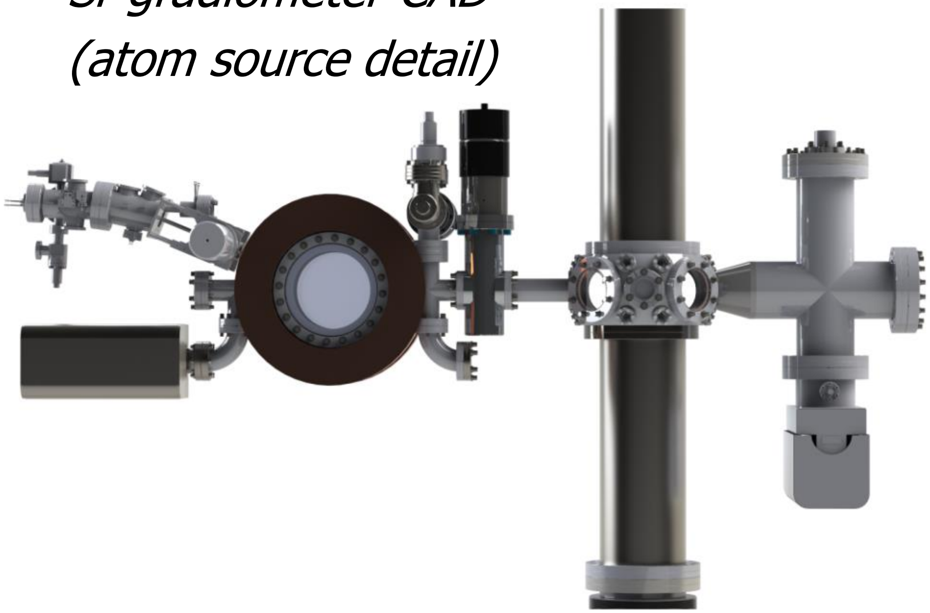
Hardware testing
- Vacuum system performance
- Magnetic shield performance
- Bias field generation
- Atom source connection nodes
- Atom interferometer laser delivery optics

Atomic physics testing
- Clock interferometry sequences
- LMT sequences
- Atom shuttle and launch systems
- Matter wave lensing
- Mixed isotope ensemble preparation

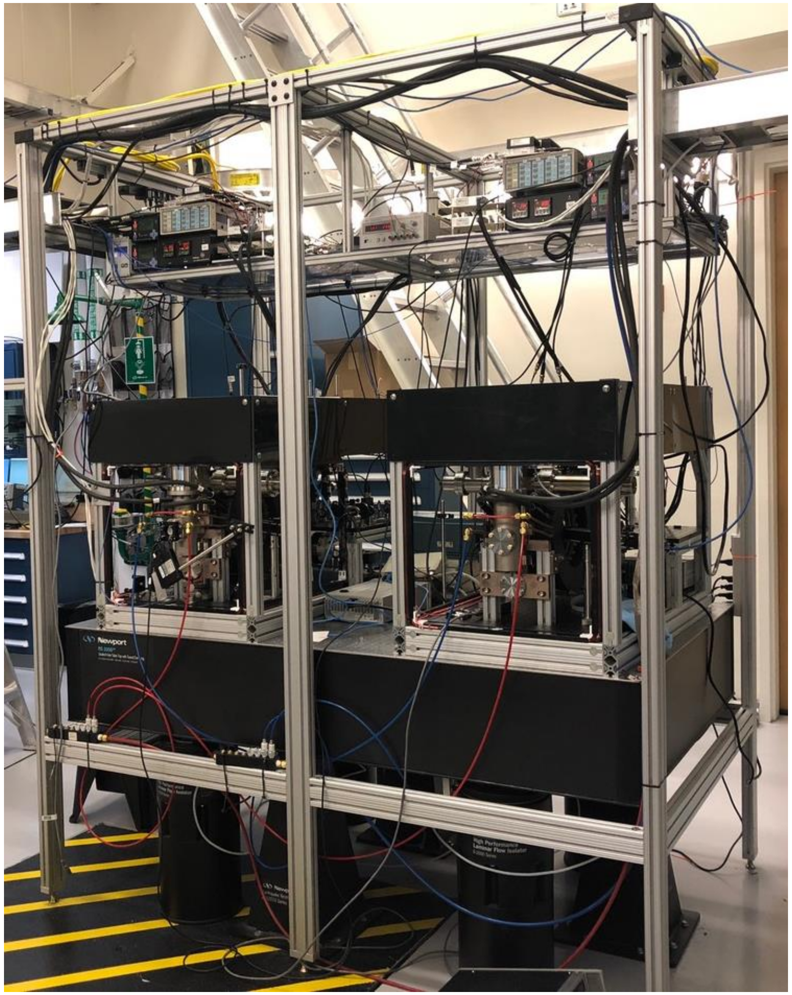


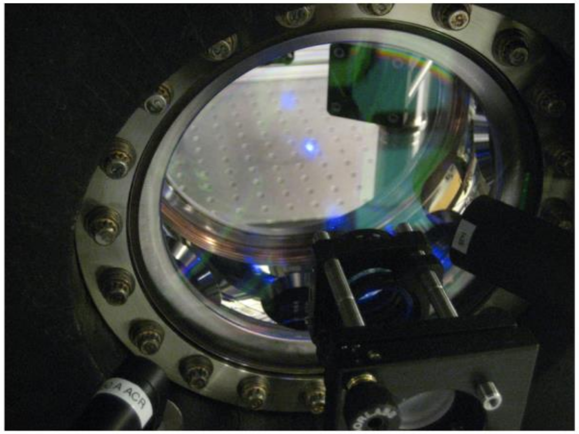
Stanford 10-meter Sr prototype

Sr gradiometer CAD (atom source detail)



Two assembled Sr atom sources

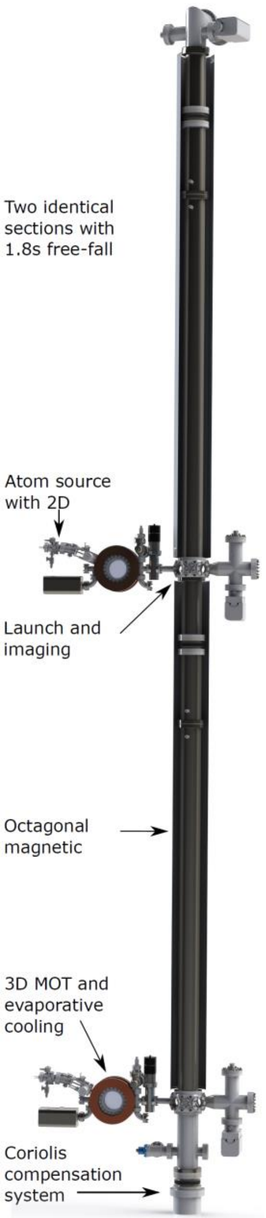




Trapped Sr atom cloud (Blue MOT)

10-meter Sr prototype design at Stanford

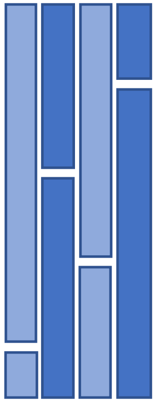
Vacuum system CAD



Magnetic shield design and simulations

Example multi-layer design

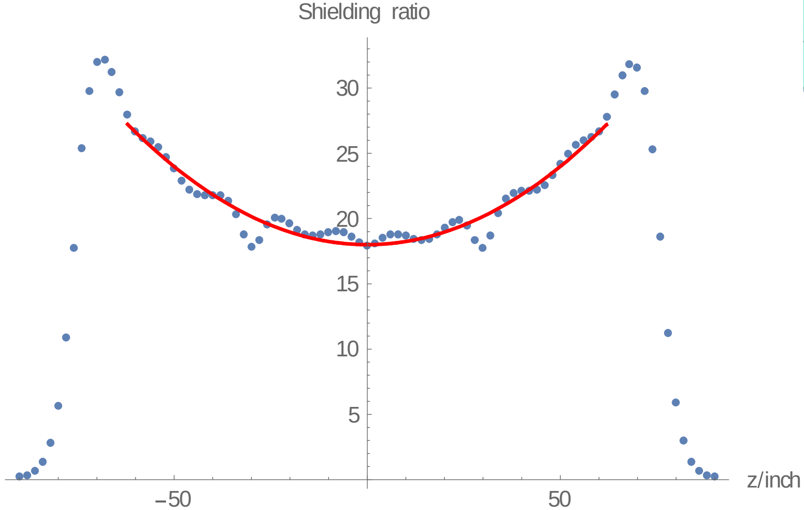
staggered layer design



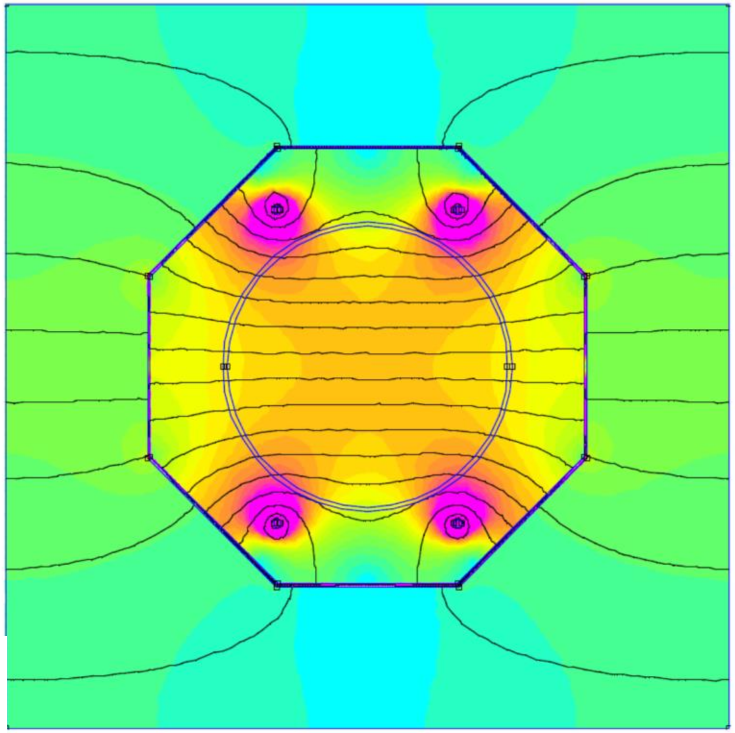
Layer thickness 0.02 inch

Conservative 100 μm gaps

2D FEM shielding results



Bias magnetic field simulation

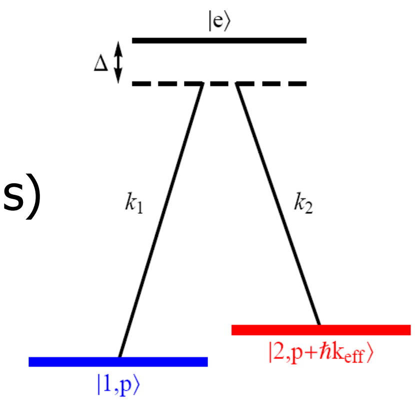


2D transverse octagonal shield simulation, with coils for transverse bias field

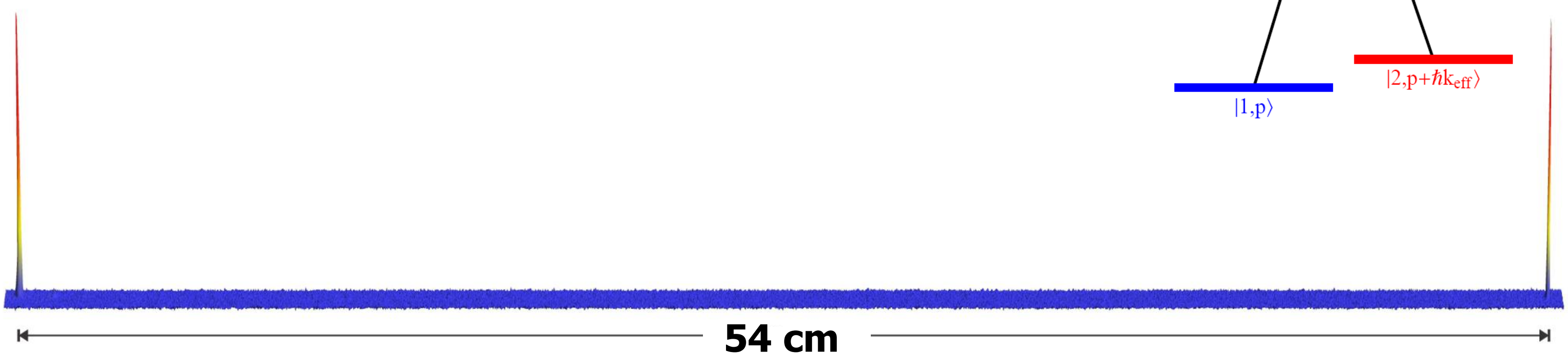
Prototype assembly begins late 2019

Large Momentum Transfer (LMT) techniques

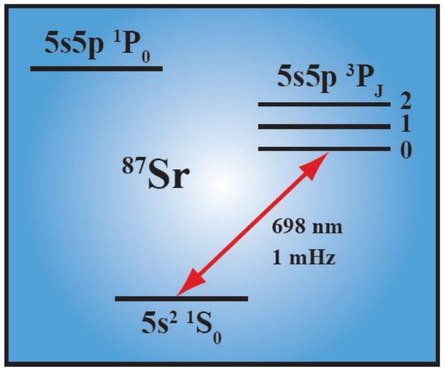
- Increase space-time area of interferometer
- Increase sensitivity



Previous work: Rb atoms (sequential two-photon transitions)



For GW detection, need to switch to **single-photon transitions** in Sr

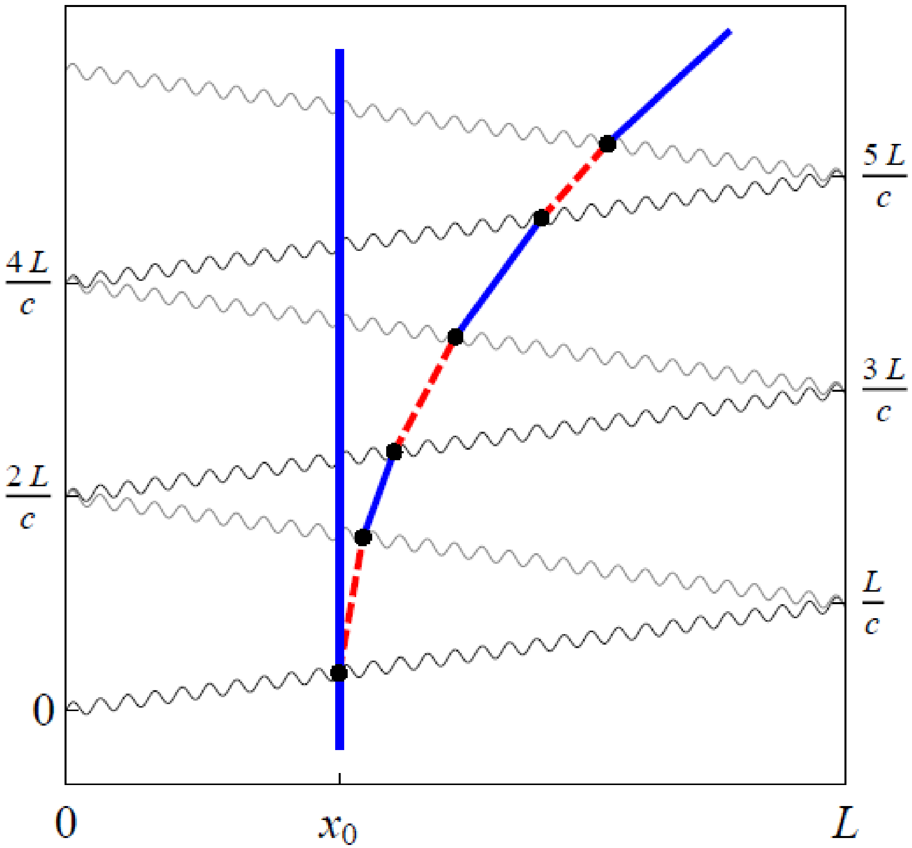


"Clock atom interferometry"

LMT and Resonant Pulse Sequences

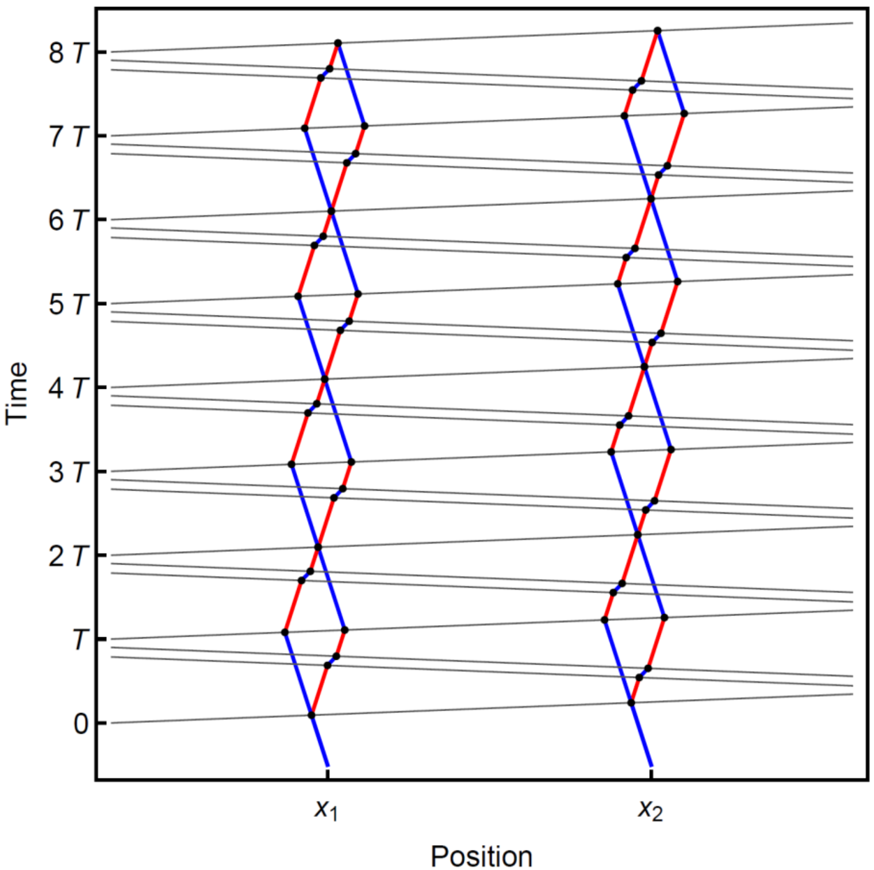
Sequential single-photon transitions are still laser noise immune

LMT beamsplitter (N = 3)



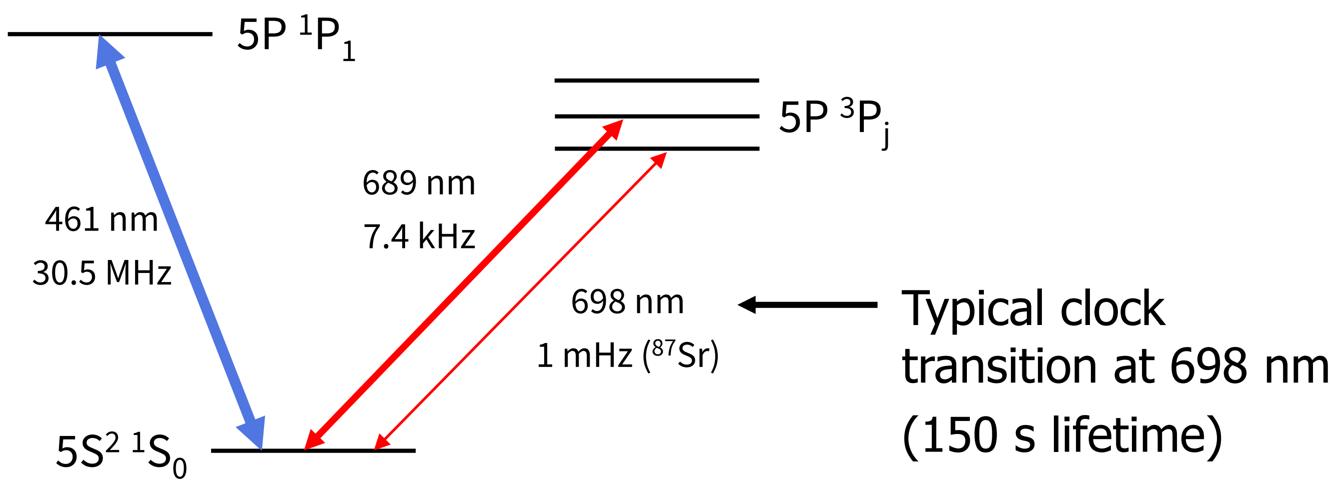
Graham, *et al.*, PRL (2013)

Resonant sequence (Q = 4)



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

Clock atom interferometry demonstration

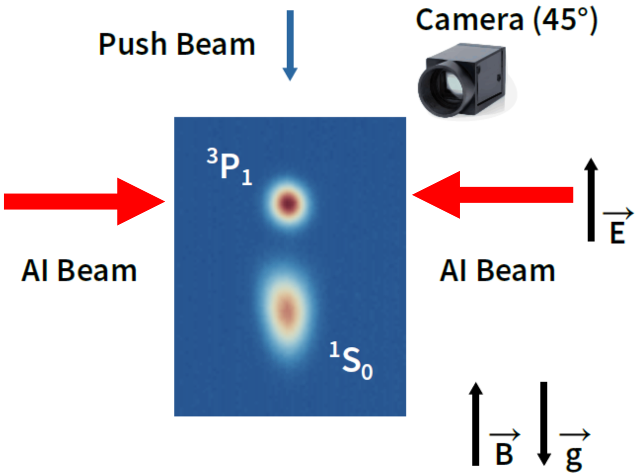


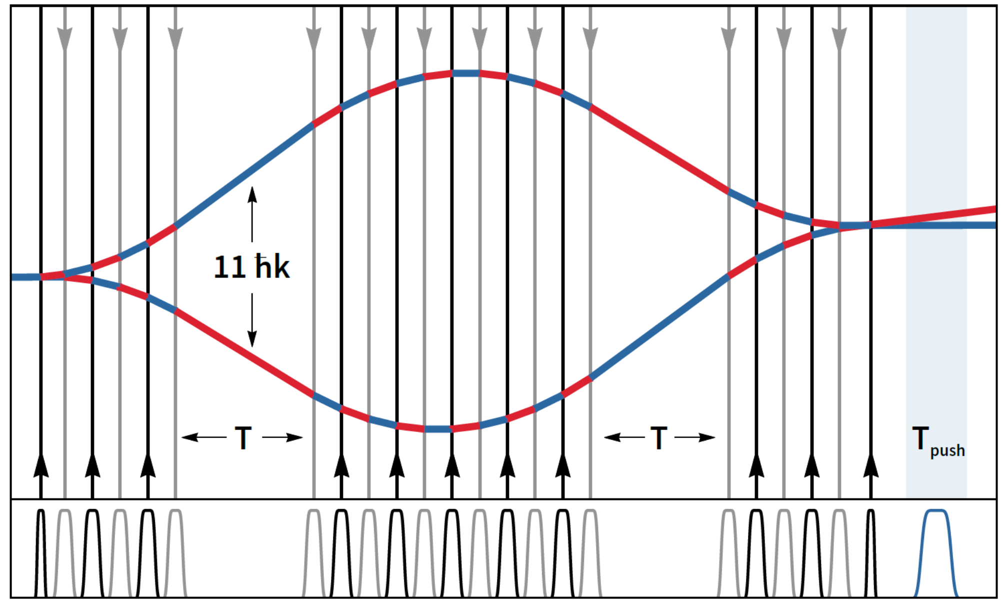
Instead, use **689 nm transition** for initial demonstration of LMT clock atom interferometry

<u>689 transition features:</u>

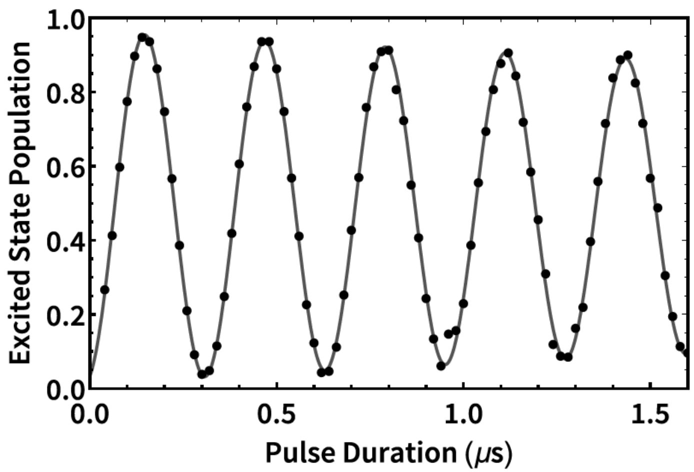
- 1-photon atom interferometry possible
- 22 μs lifetime (limits coherence time?)
- Supports high Rabi frequency (fast pulses)
- Easier technical requirements (laser stability, isotope)

Clock atom interferometry demonstration





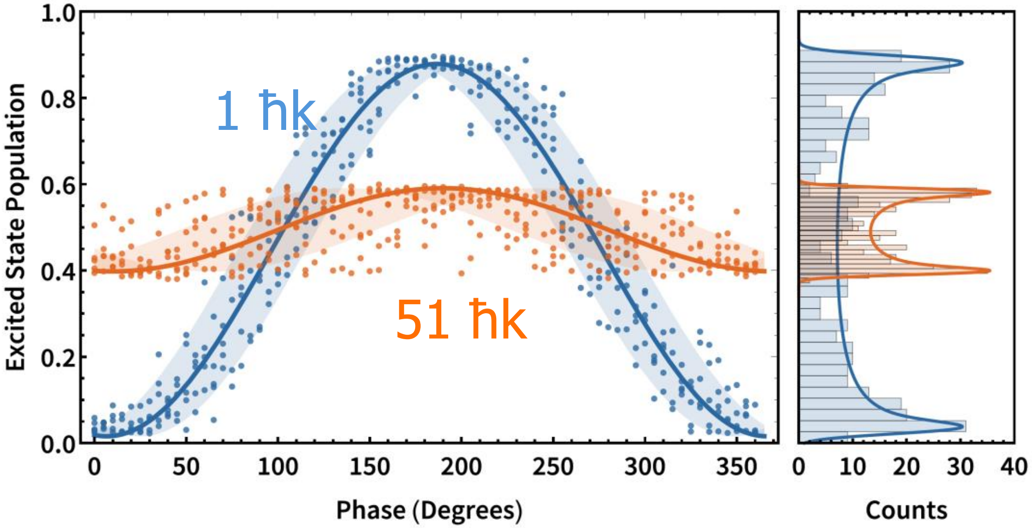
~99% π-pulse efficiency



- Perform LMT atom optics using π pulses from alternating directions
- Each π pulse interacts with both arms due to high Rabi Frequency (+2 ħk)

LMT clock interferometer

Example: 51 ħk interferometer (100 total π pulses)



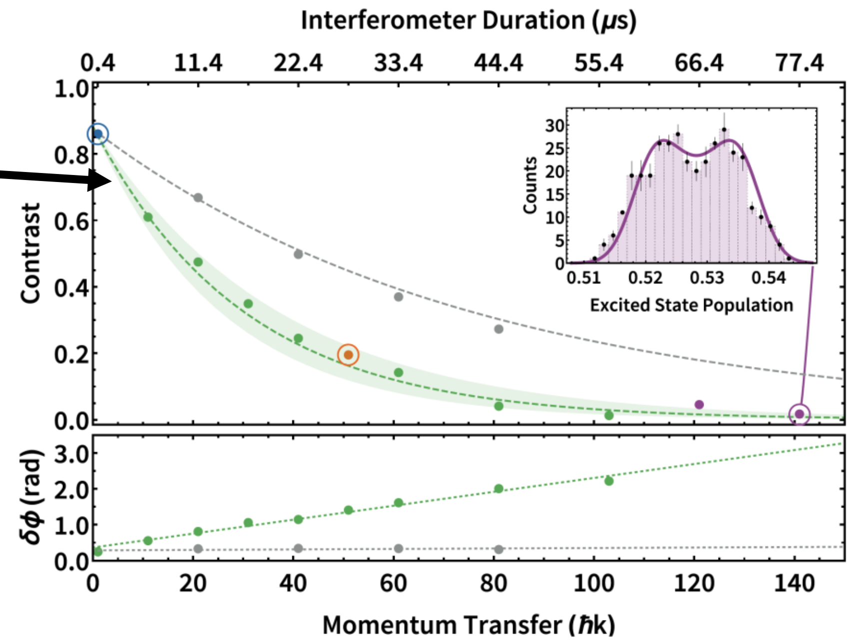
$$C_{51} = 22\%$$
$$\delta\phi_{51} = 1.4 \text{ rad}$$

(per shot)

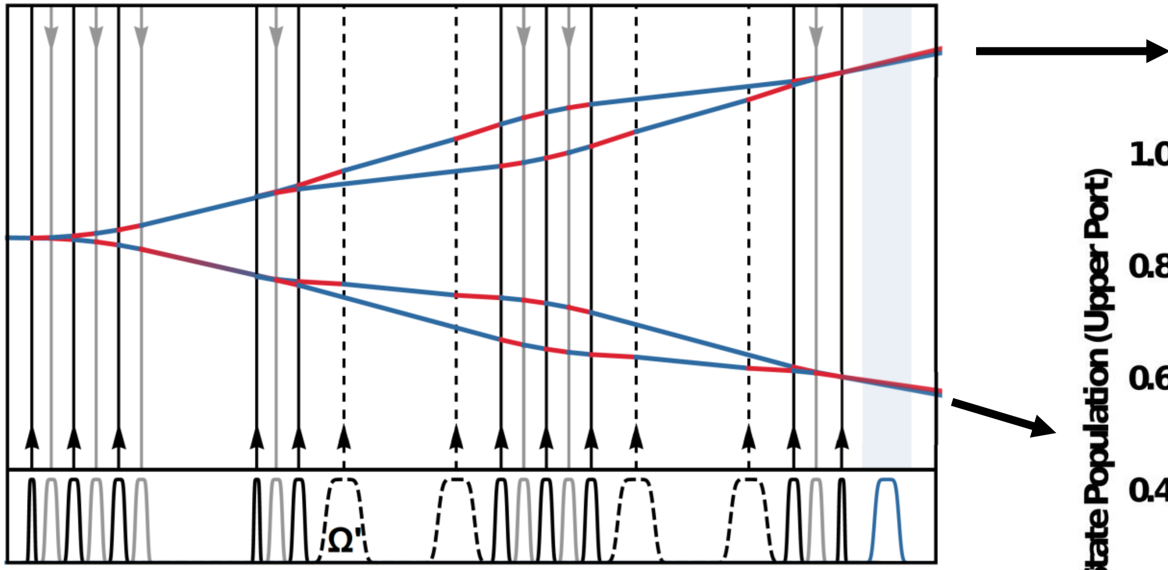
First LMT clock interferometers using sequential single-photon transitions (to our knowledge)

Contrast loss prediction (not a fit) includes excited state decay (22 μs lifetime) + measured π-pulse efficiency

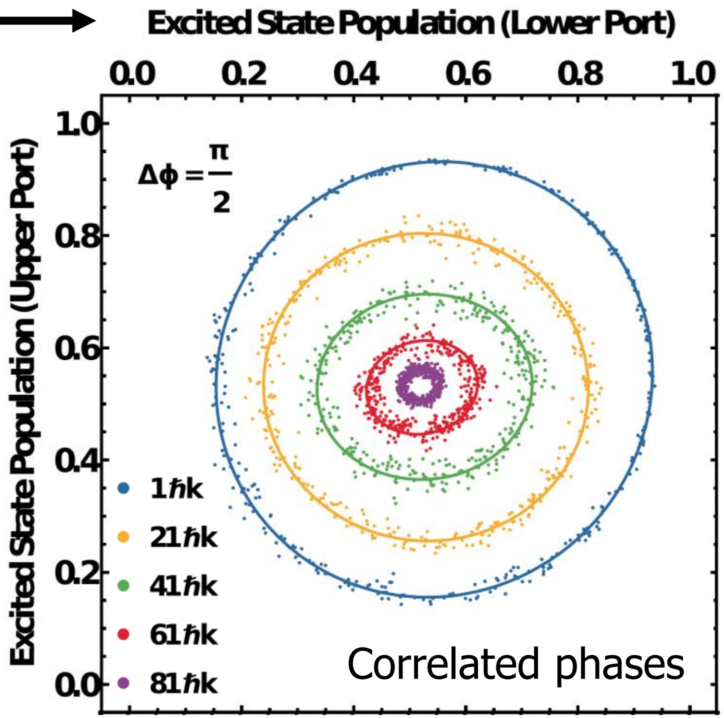
LMT in demo limited by available 689 nm power (~100 mW)



Clock Atom Gradiometer demonstration



Run two interferometers simultaneously



- Laser phase noise is common to the interferometers
- Demonstrated 81 ħk (power limited)
- Demonstrated T > 1 ms (>> lifetime)

Summary

MAGIS-100

- 100-m atom gradiometer at Fermilab
- **Mid-band gravitational wave** detector prototype
- **Dark matter** detection: scalar and vector couplings, ultralight mass range
- Macroscopic quantum mechanics: **seconds, meters**
- **Next steps:** Design and construction; targeting commissioning in **2021**

Clock atom interferometry on 689 nm in Sr

- Demonstrated LMT clock atom interferometry on 689 nm transition
- Proof of concept for 698 nm transition, **required for MAGIS**
- Sensing applications: High Rabi frequency allows for hot atoms, broad laser, high repetition rate, etc.
- **Next steps:** Aim for 1000 $\hbar k$; use 698 nm clock transition

Collaborators

Sr Atom Interferometry

Jan Rudolph
TJ Wilkason
Hunter Swan
Yijun Jiang
Ben Garber
Connor Holland
Megan Nantel
Sam Carman

Theory

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

Rb Atom Interferometry

Mark Kasevich
Tim Kovachy
Chris Overstreet
Peter Asenbaum
Remy Notermans

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)
Mark Kasevich (Stanford)
Peter Graham (Stanford)
Surjeet Rajendran (John Hopkins)

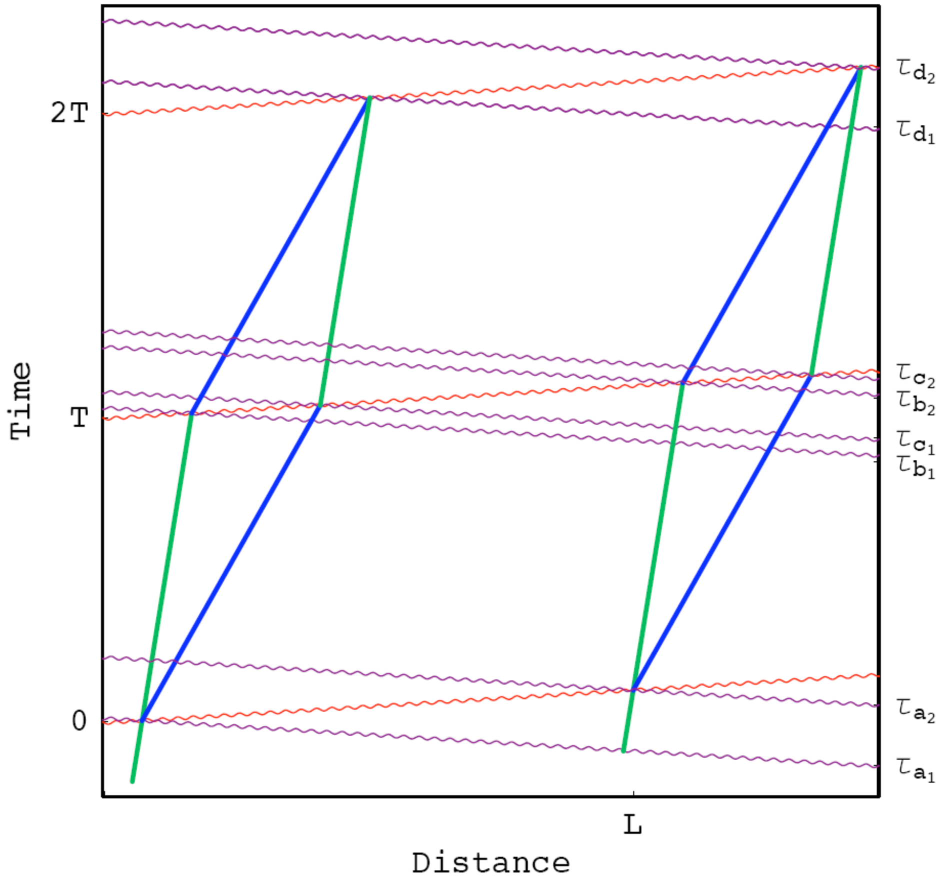
GBMF7945

DE-SC0019174

N00014-17-1-2247

Backup

Two photon laser frequency noise



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

Phase error:

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

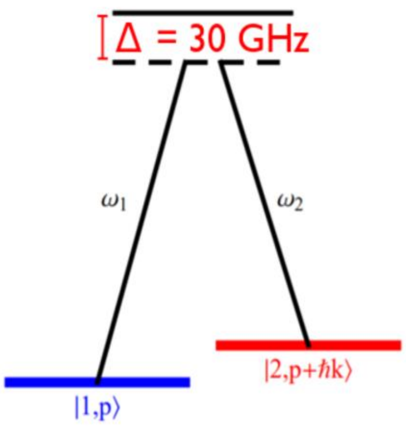
GW Signal:

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

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

Extreme LMT with clock atoms

Alkali atoms (e.g. rubidium)

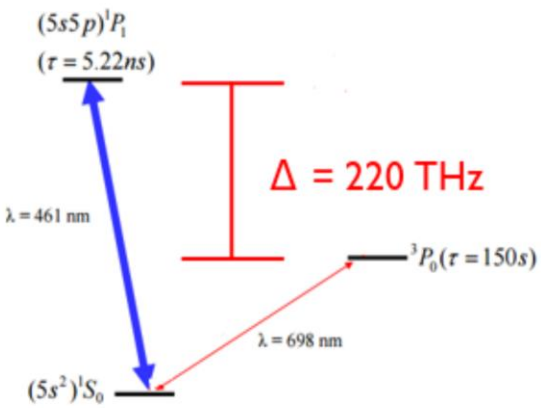


- Two photon Raman/Bragg transitions for atom optics

- 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

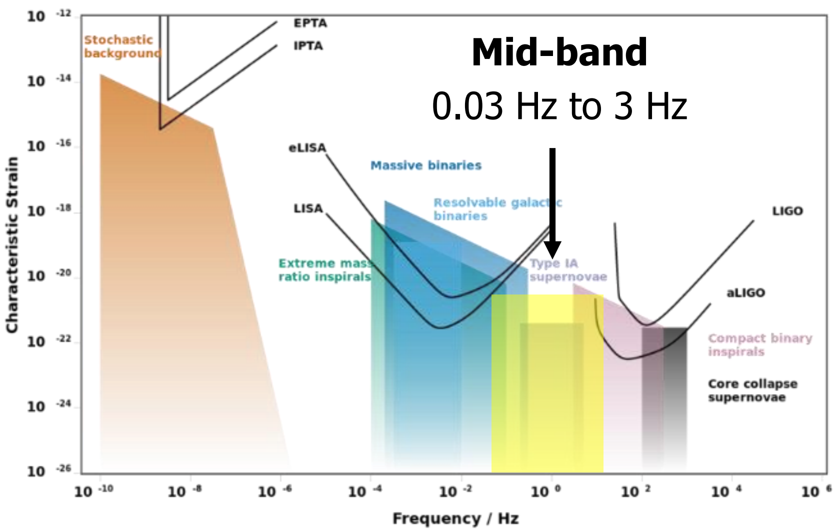
- Spontaneous emission naturally highly suppressed (150 s lifetime clock state, other levels far detuned)

- Possibility to support > 10^6 pulses

Atomic sensors for gravitational wave detection

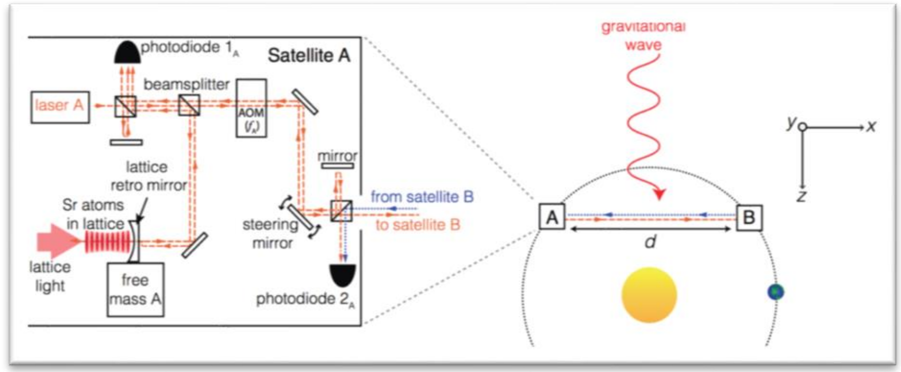
Atomic clocks and atom interferometry offer the potential for gravitational wave detection in an unexplored frequency range ("mid-band")

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

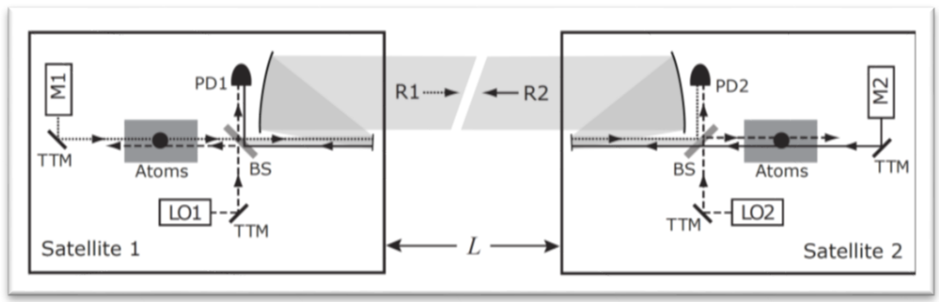


Mid-band science

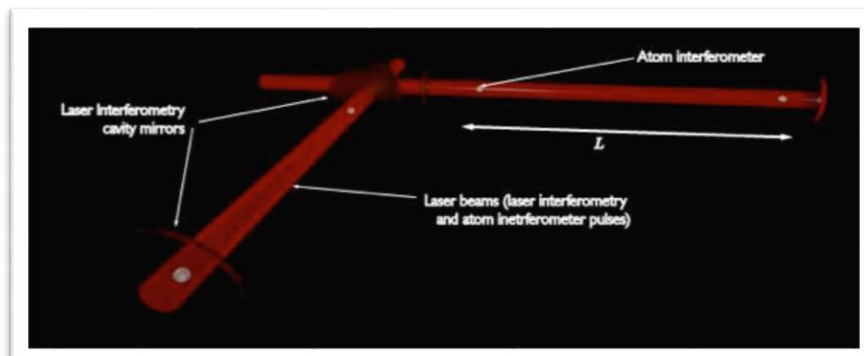
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)



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

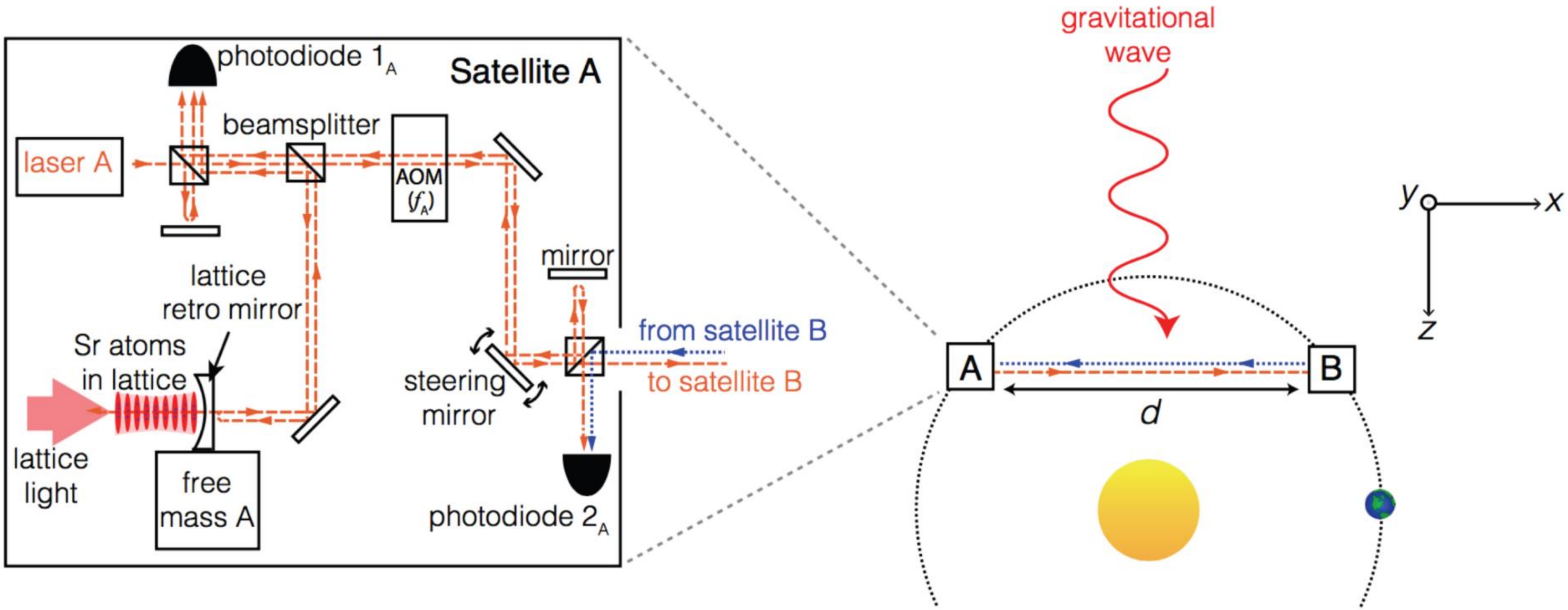


MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich)



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

Lattice Clocks



- Optical lattice atomic clocks
- Resonant (dynamical decoupling)
- Drag-free satellites

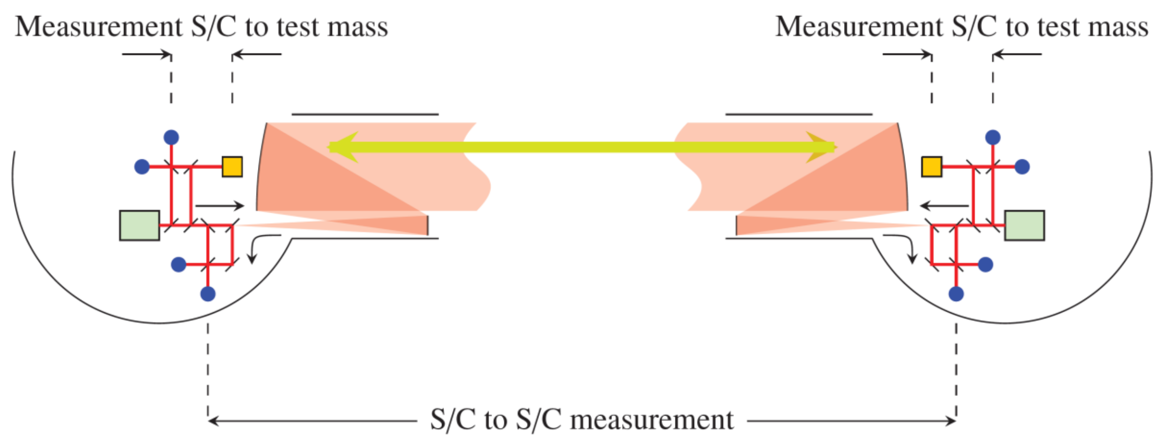
S. Kolkowitz, I. Pikovski, N. Langellier, M. D. Lukin, R. L. Walsworth, and J. Ye, Phys. Rev. D **94**, 124043 (2016)

GW Detector Comparison

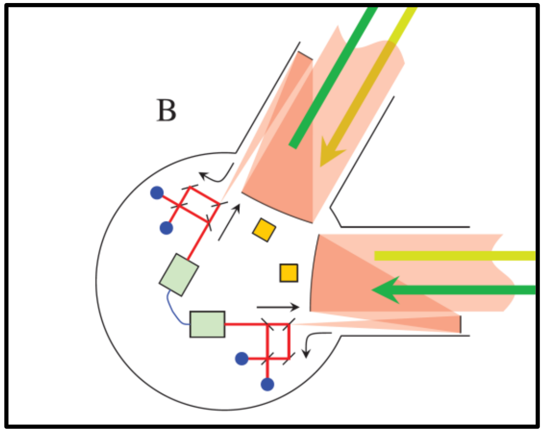
	Inertial reference	Laser phase reference
LIGO	Suspended end mirrors	Second arm
LISA	Drag-free proof masses	Second baseline
MAGIS	Atom	Atom
Atomic clock	Drag-free proof mass	Atom

Compare to LISA

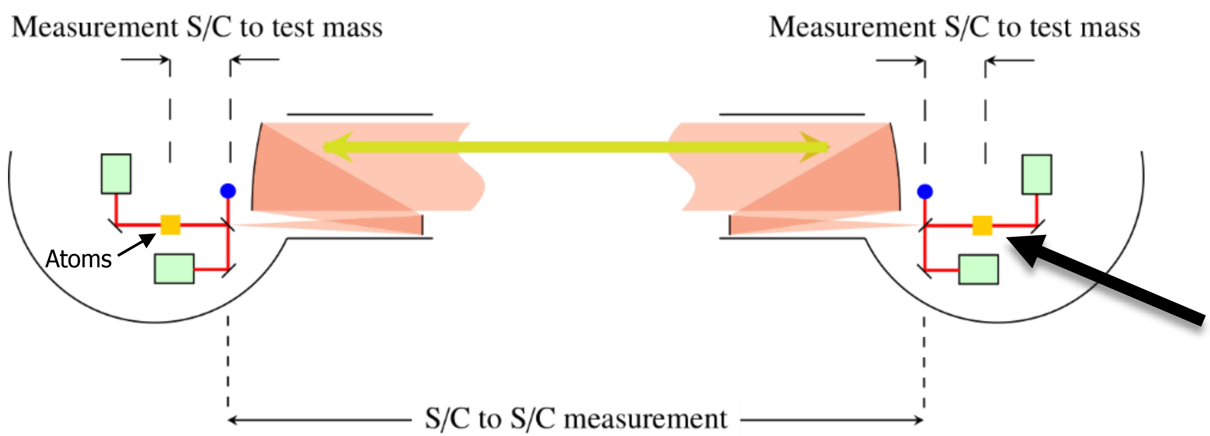
LISA:



Second baseline needed for phase reference:



Atom interferometer:

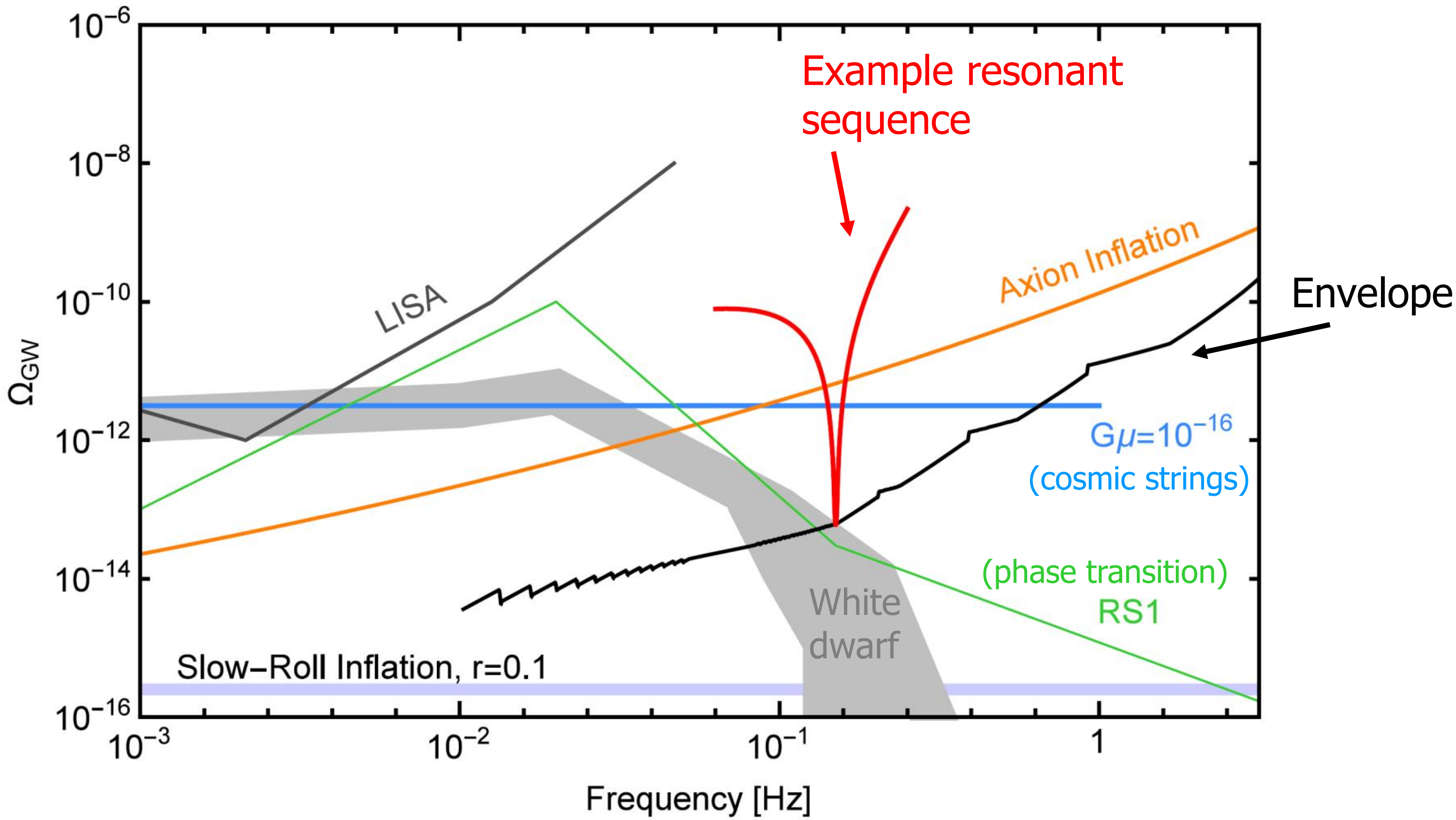


Atom test mass

- Records laser noise
- Acts as phase reference

(Figures adapted from LISA yellow book.)

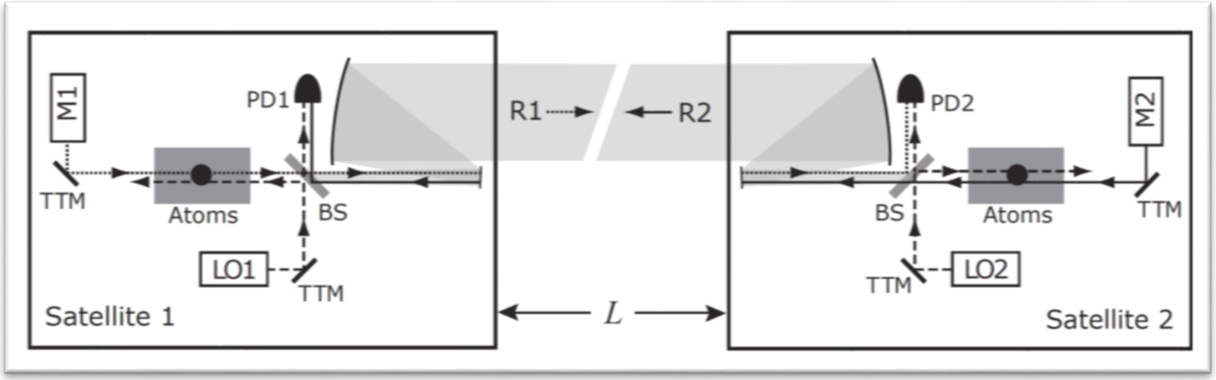
Bounds on stochastic GW sources



Narrow band sensitivity possible in 1 year

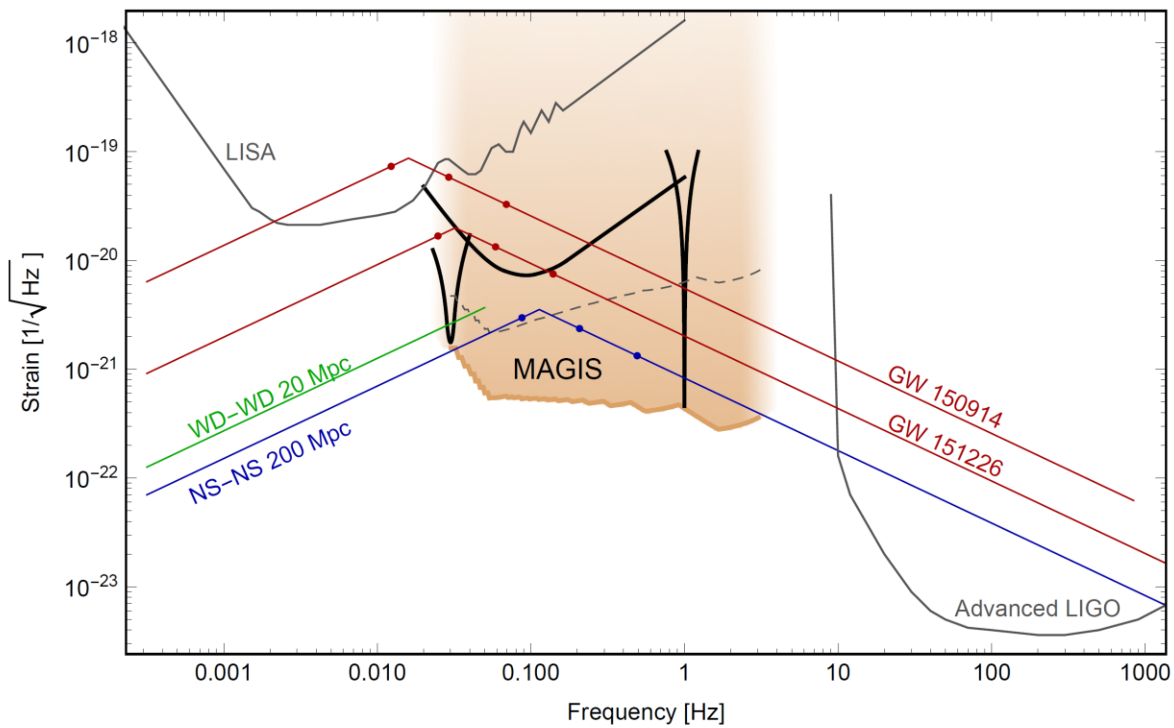
Graham, *et al.*, arXiv:1606.01860 (2016)

GW Sensitivity for a Satellite Detector



Satellite detector concept

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



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

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

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

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

$$n_p < 10^3$$

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