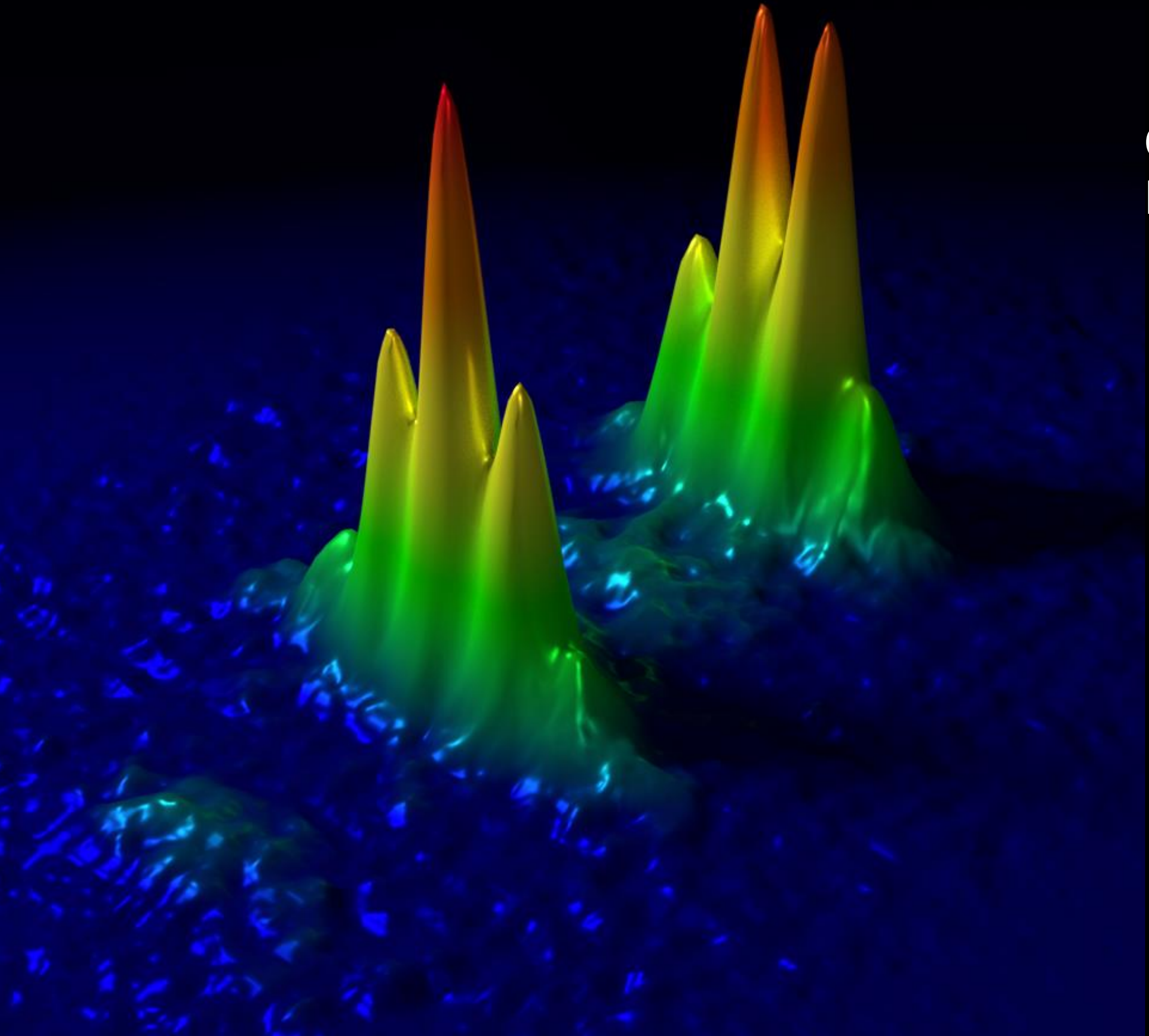
Atom interferometry and application to fundamental physics



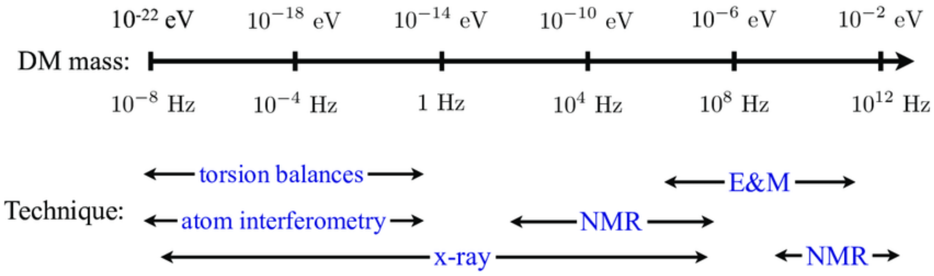
Quantum Sensors for Fundamental Physics

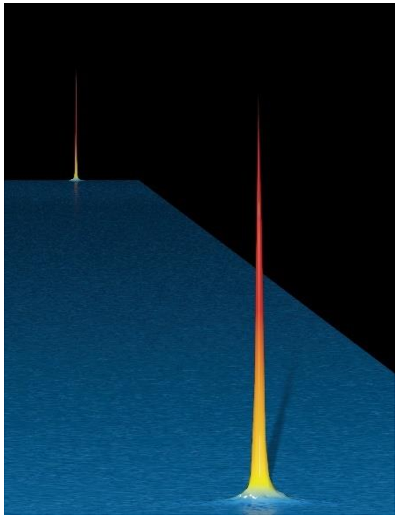
Oxford, UK

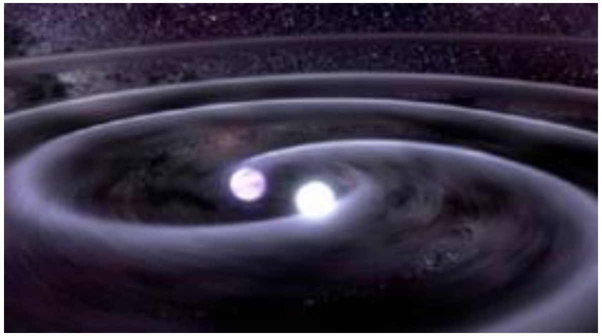
Jason Hogan
Stanford University
October 16, 2018

Science applications

- Equivalence principle tests
- Short distance gravity
- Dark sector physics
- QED tests (alpha measurements)
- Quantum mechanics at macroscopic scales
- Quantum entanglement for enhanced readout
- Gravitational wave detection, sky localization

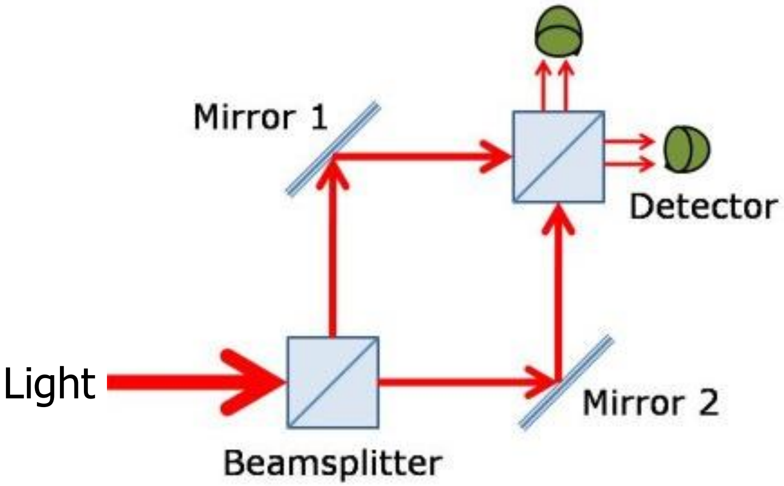


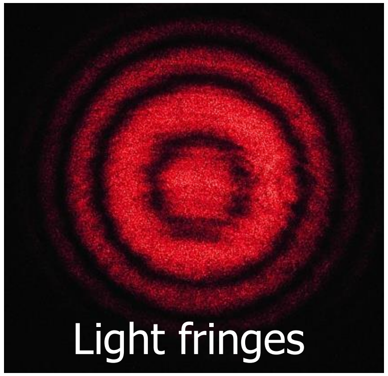




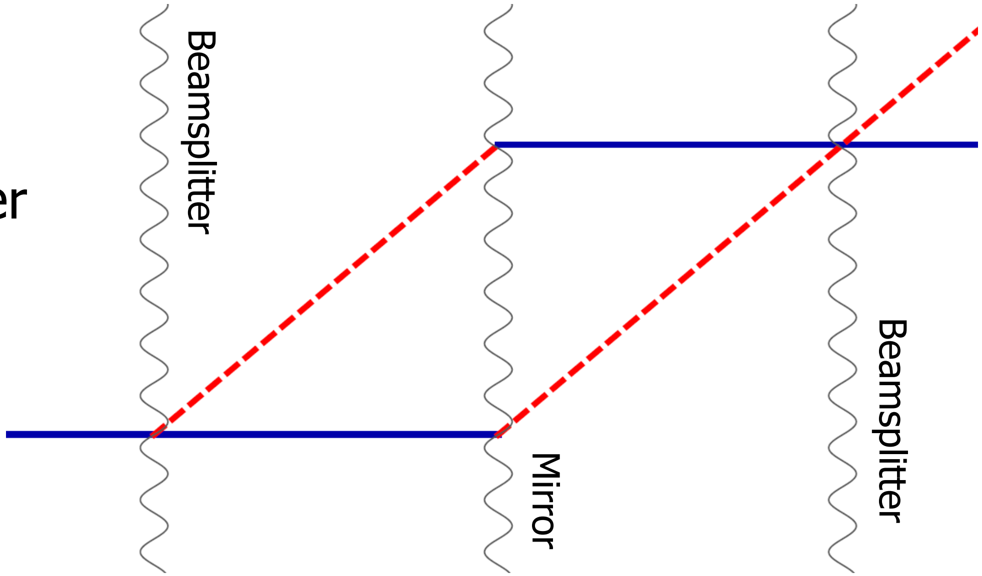
Atom interference

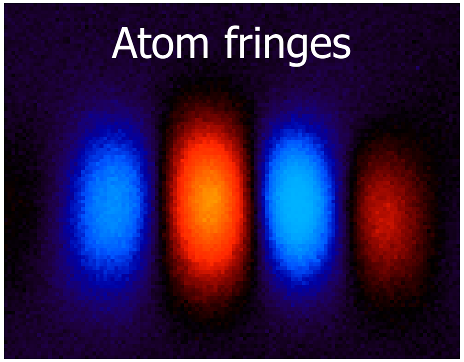
Light interferometer




Light fringes

Atom interferometer

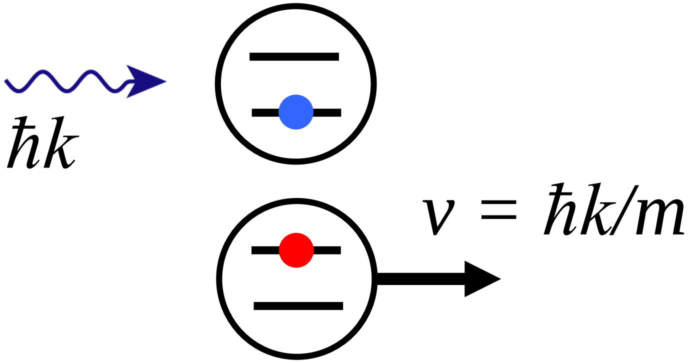



Atom fringes

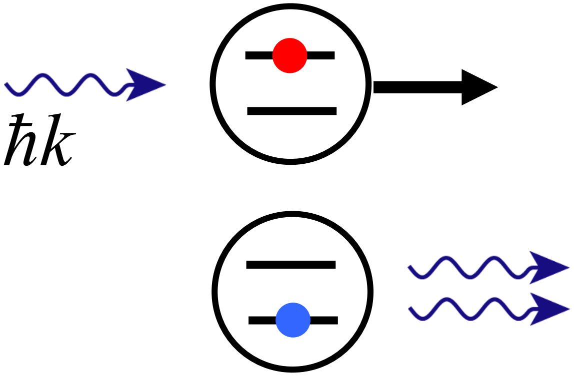
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

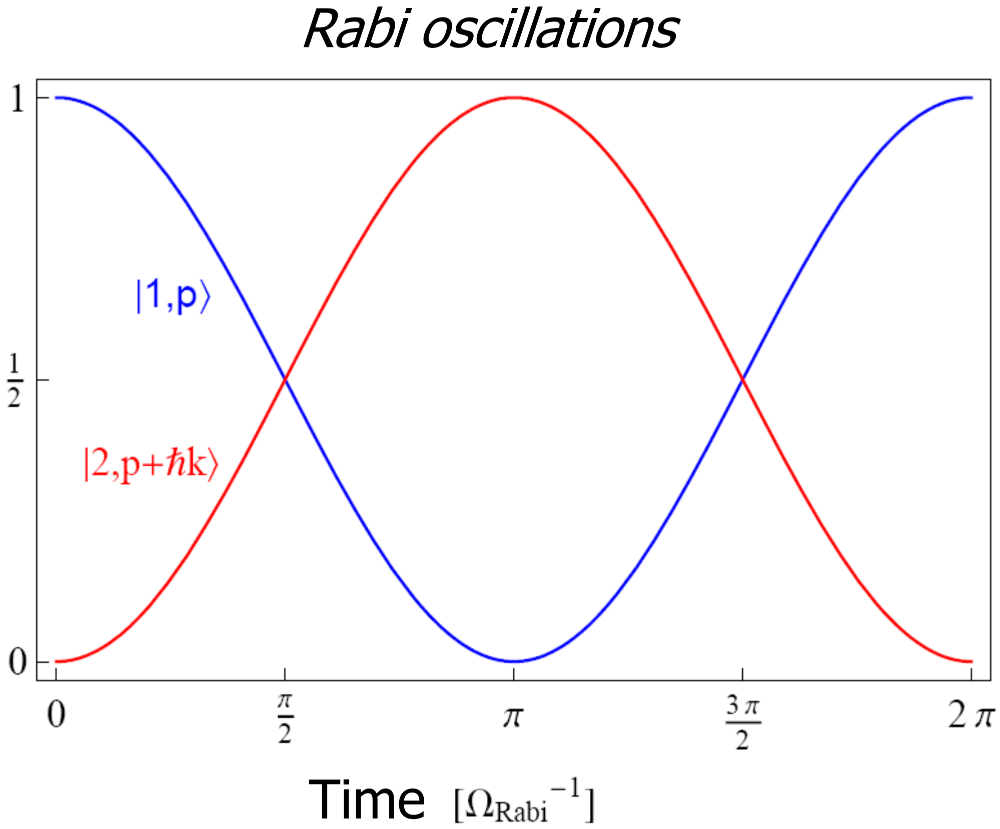
Atom optics using light

(1) Light absorption:

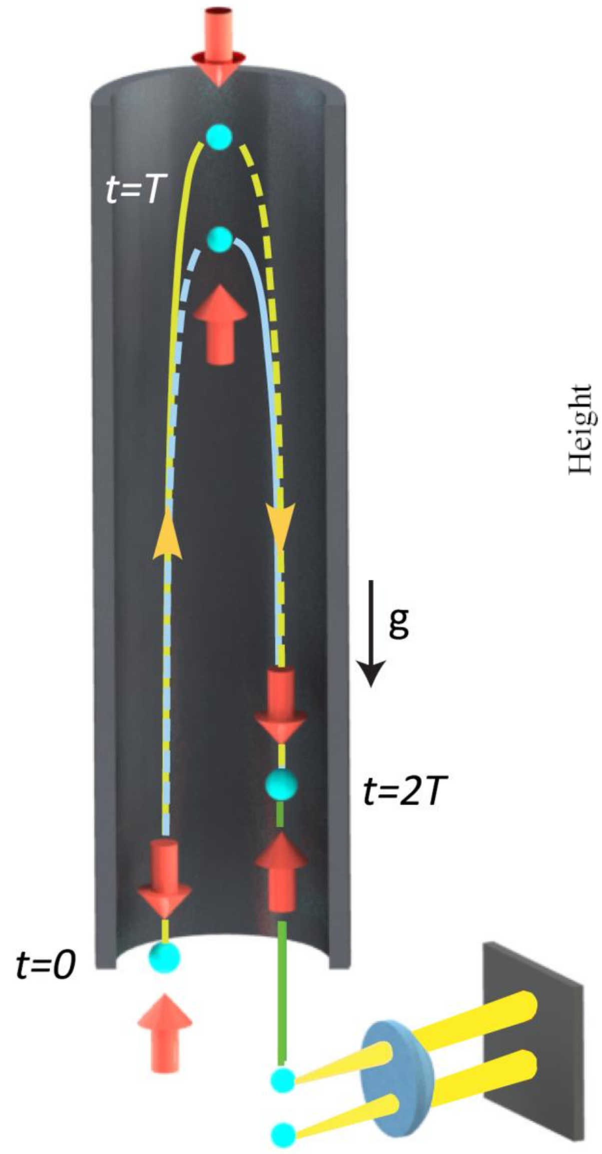


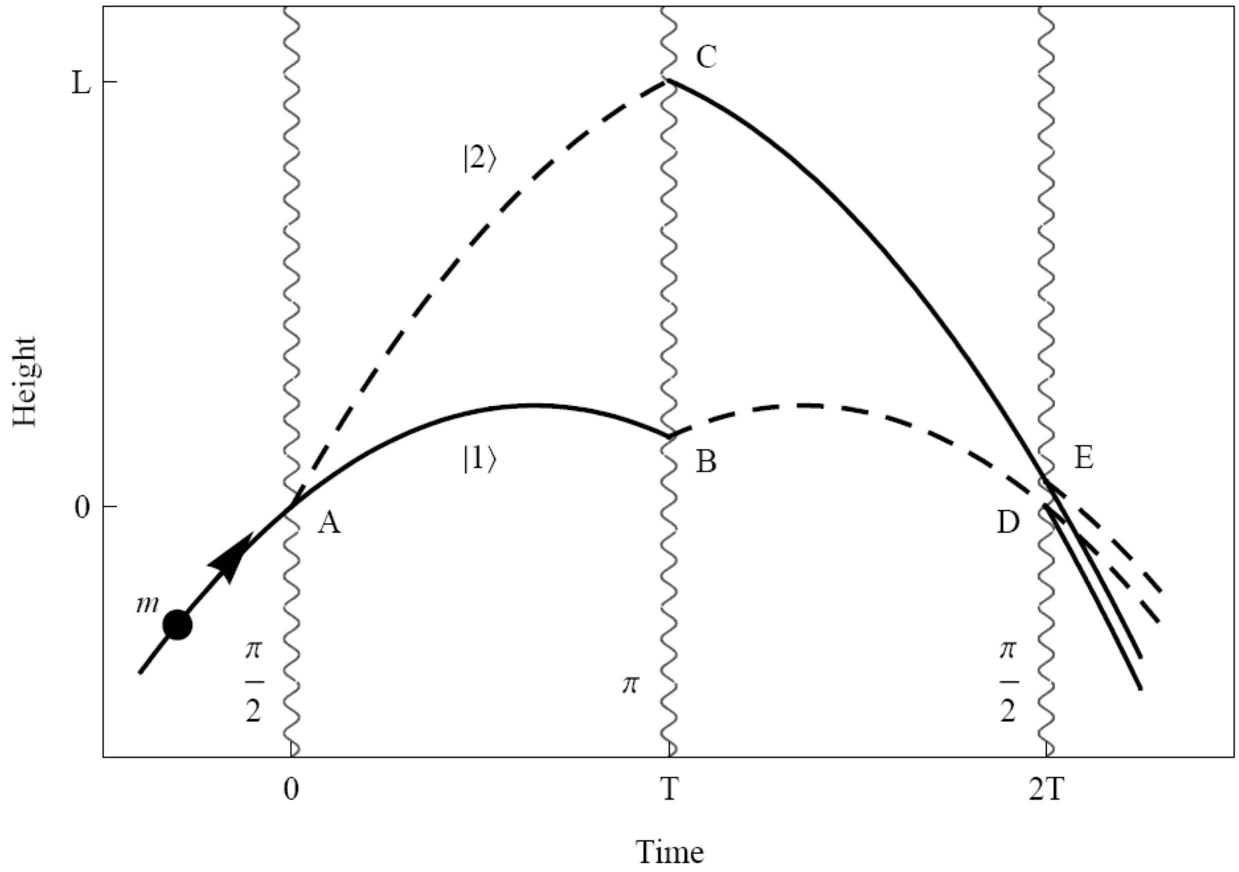
(2) Stimulated emission:





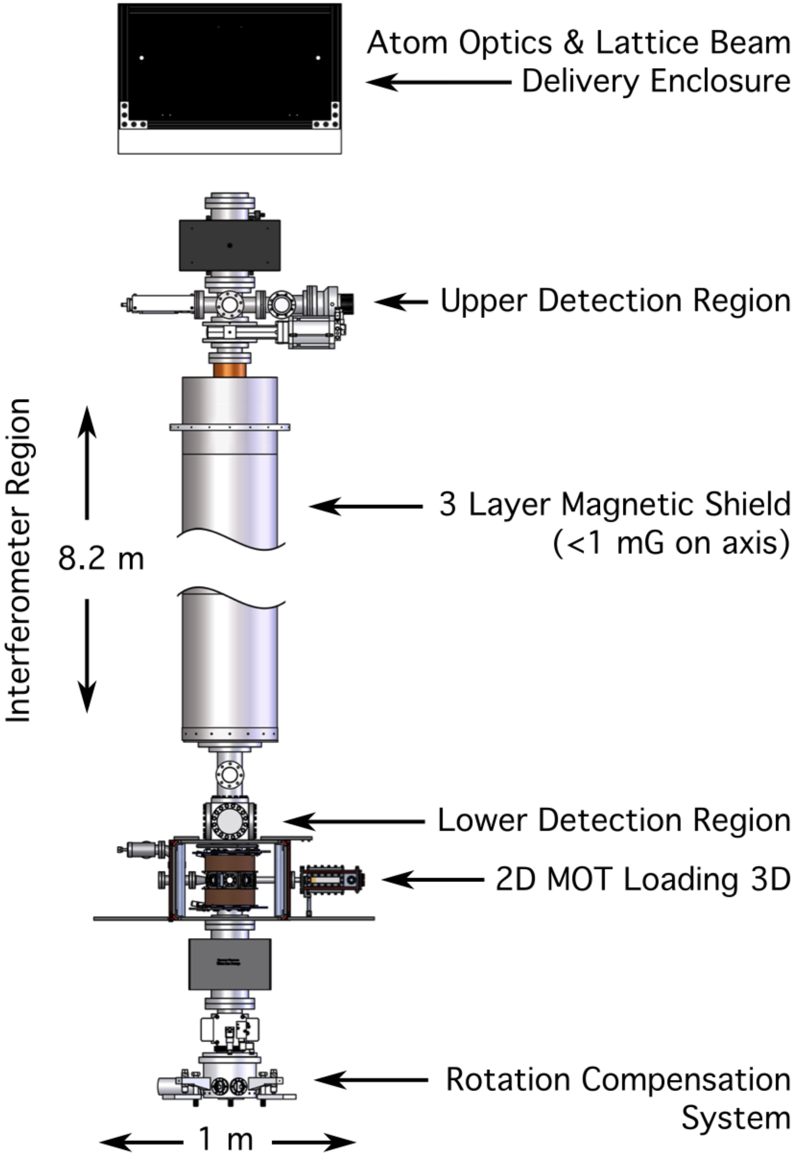
Light Pulse Atom Interferometry





- Long duration
- Large wavepacket separation

10 meter scale atomic fountain



Atom Optics & Lattice Beam Delivery Enclosure

Upper Detection Region

Interferometer Region

8.2 m

3 Layer Magnetic Shield (<1 mG on axis)

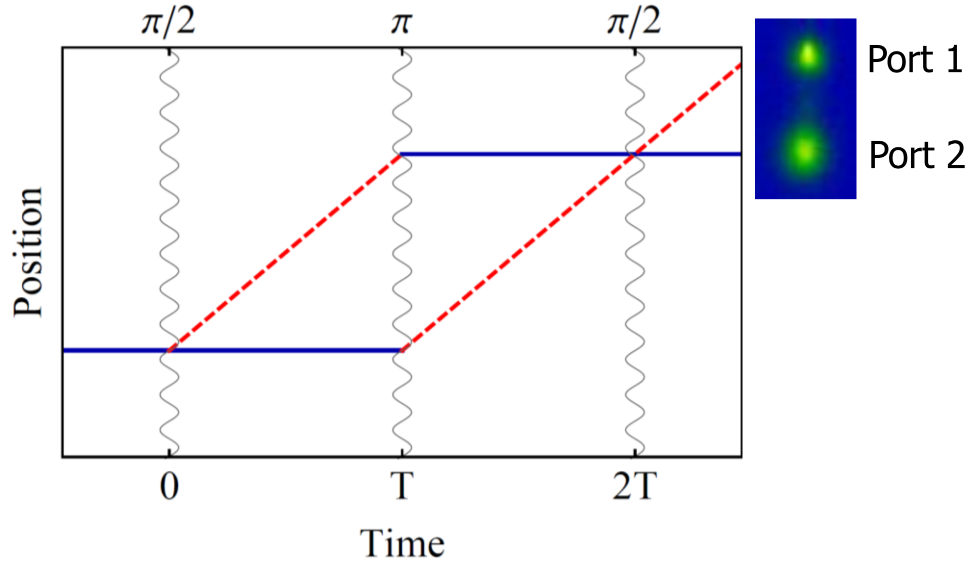
Lower Detection Region

2D MOT Loading 3D

Rotation Compensation System

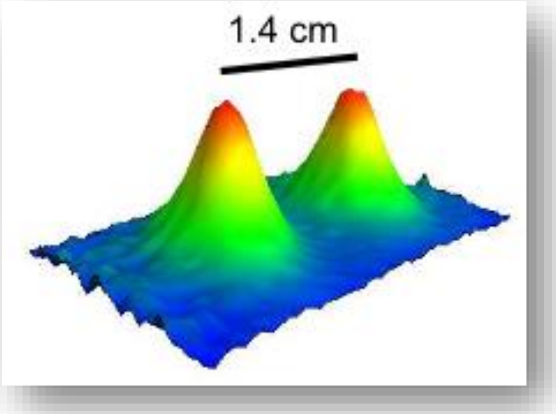
1 m

Interference at long interrogation time



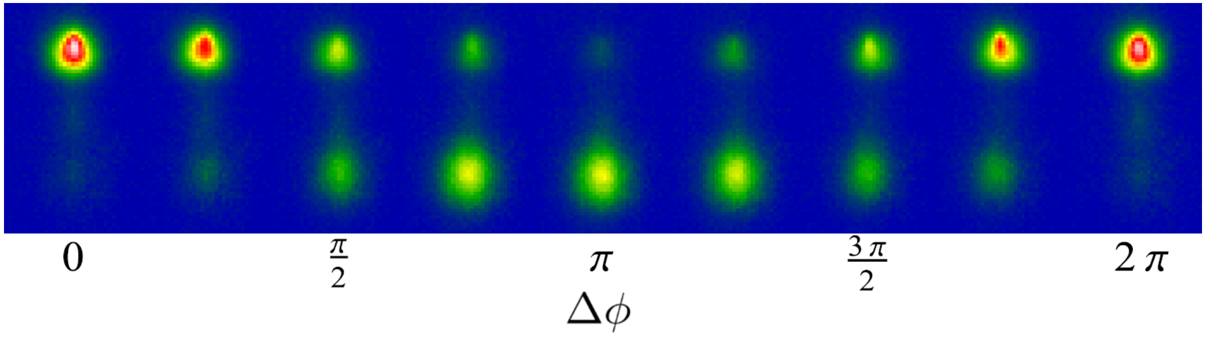
2T = 2.3 seconds

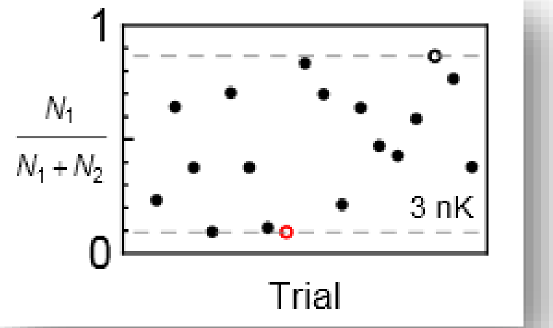
1.4 cm wavepacket separation



Wavepacket separation at apex (this data 50 nK)

Interference (3 nK cloud)

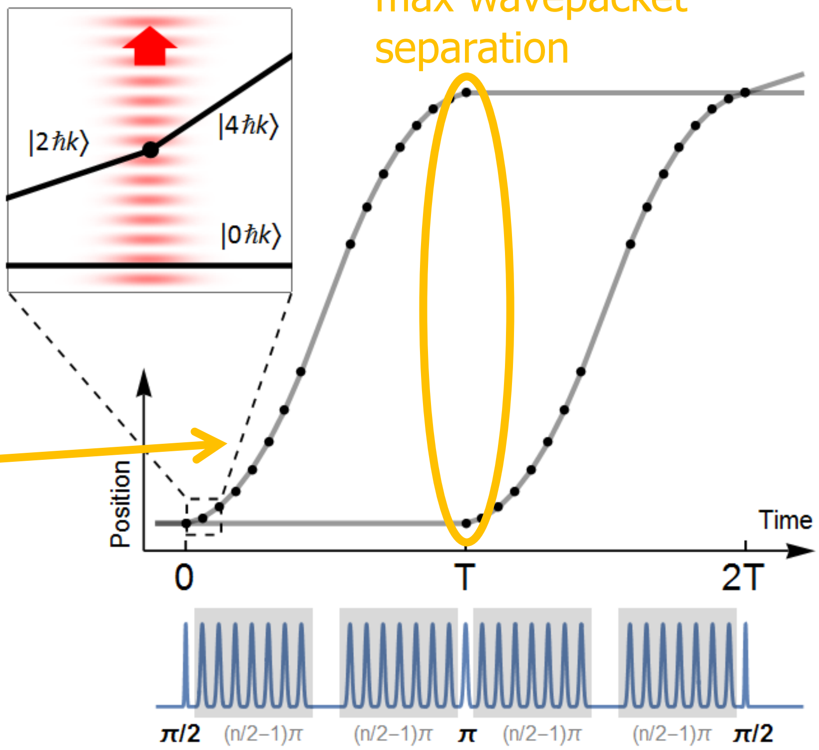




Dickerson, et al., PRL **111**, 083001 (2013).

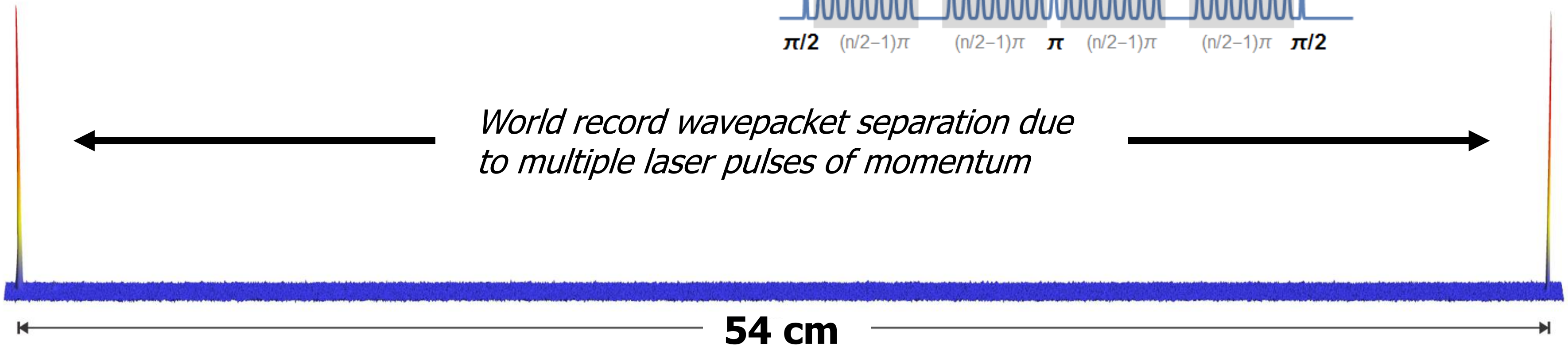
Large space-time area atom interferometry

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



max wavepacket separation

90 photons worth of momentum

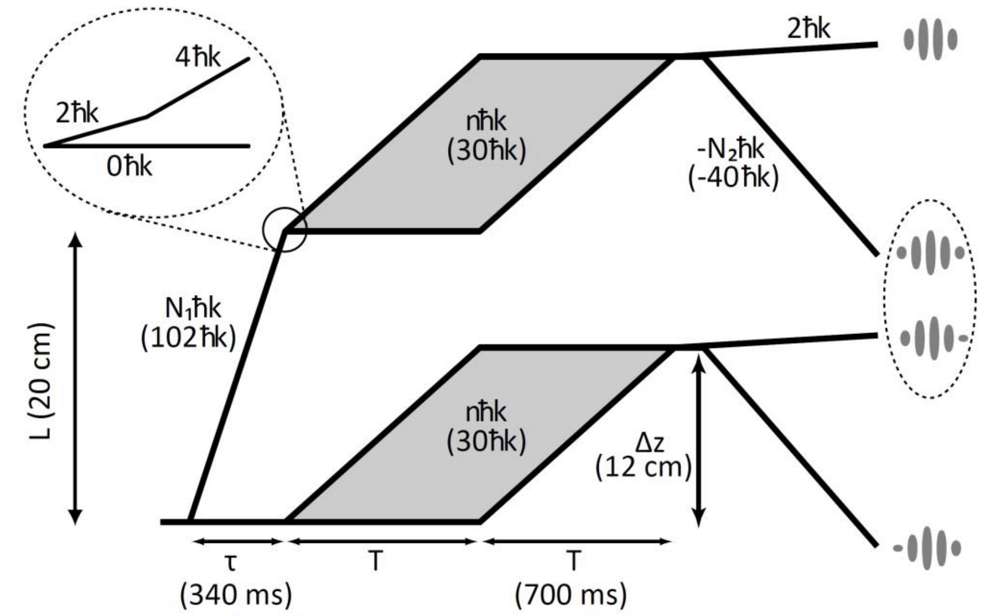


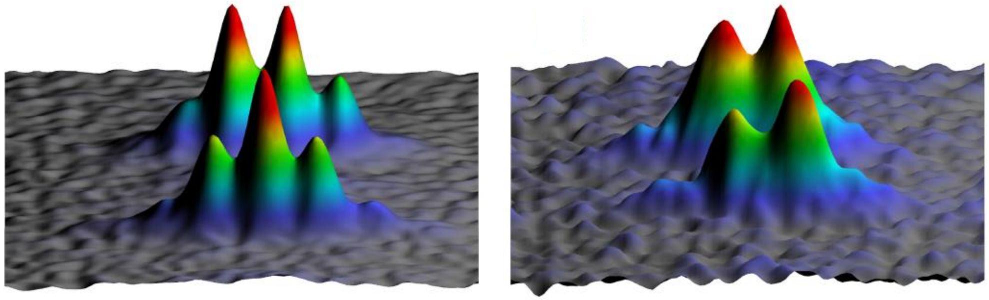
World record wavepacket separation due to multiple laser pulses of momentum

54 cm

Kovachy et al., *Nature* 2015

Gravity Gradiometer





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

10 ħk

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

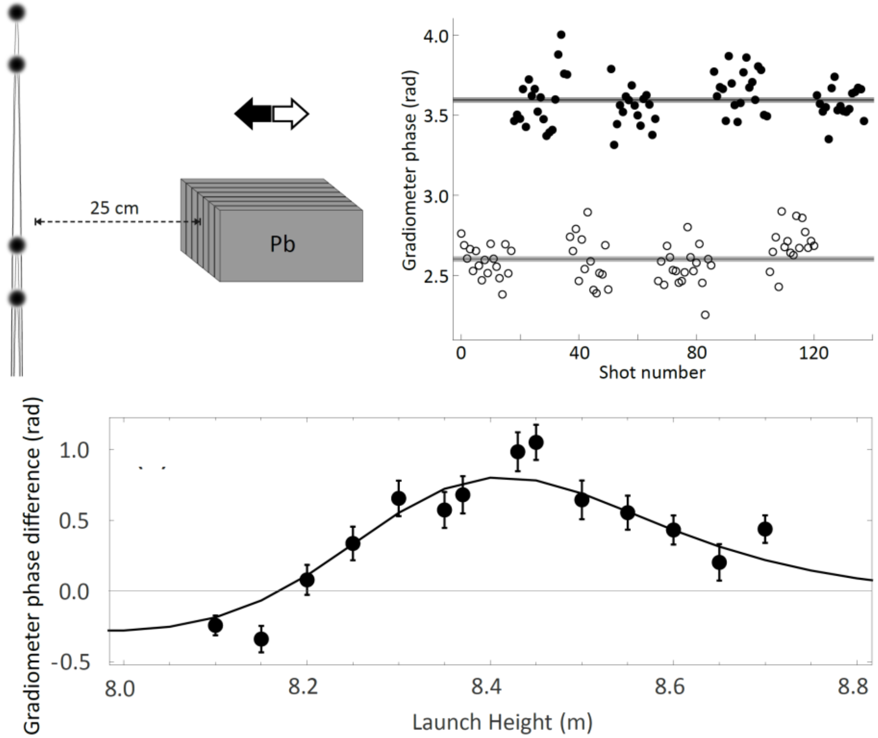
30 ħk

Gradiometer interference fringes

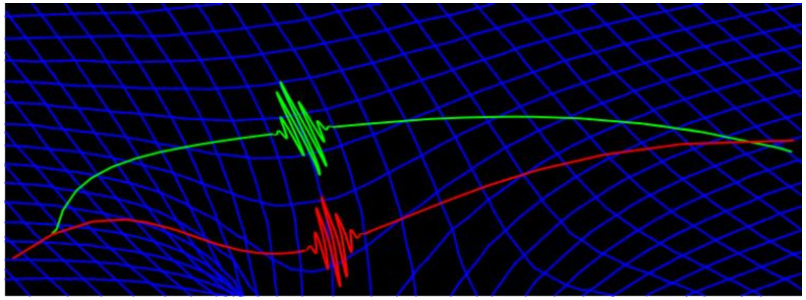
Asenbaum et al., PRL **118**, 183602 (2017)

Gradiometer Demonstration

Gradiometer response to 84 kg lead test mass



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



Detected the gravitational tidal force (spacetime curvature) across a *single particle's* wavefunction

GR: gravity = curvature

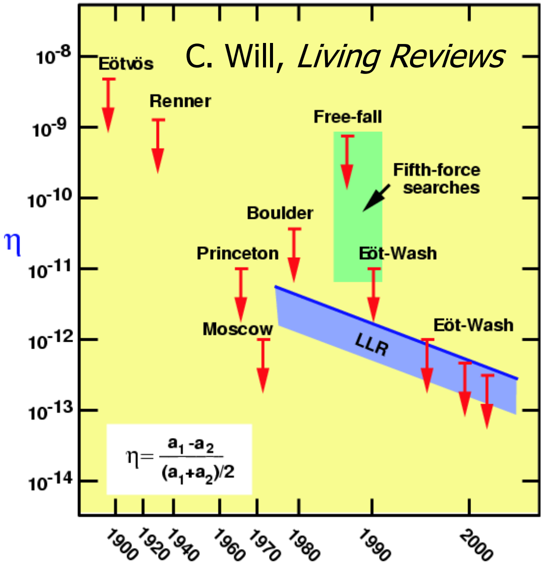
→ First *true manifestation* of gravitation in a quantum system

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

Equivalence Principle

Static EP tests

- Free-fall tests, torsion balance, Lunar Ranging
- Test foundation of General Relativity
- Search for new forces (e.g, Yukawa potential)



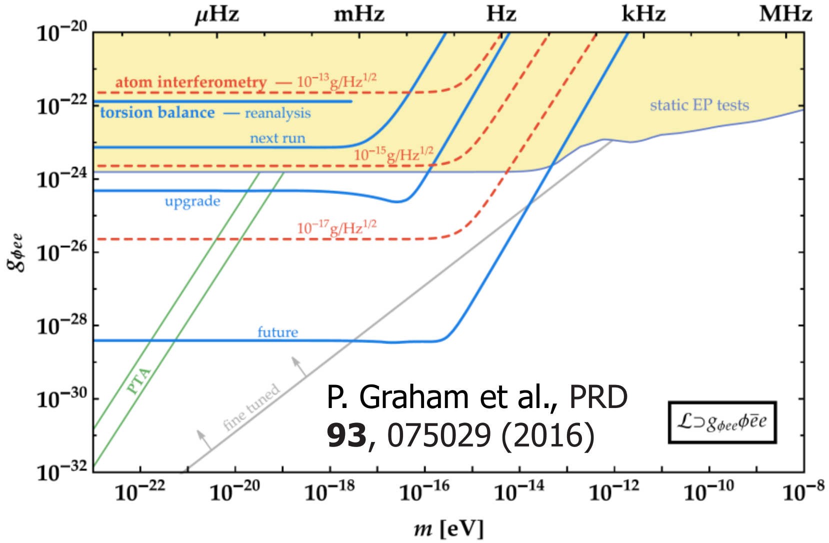
C. Will, *Living Reviews*

Time-varying EP tests

- New scalar (or vector) field that varies in space
- The field could be dark matter
- Force is oscillatory and EP violating:

$$F \propto g \sqrt{\rho_{\rm DM}} \cos(m_{\rm DM} t)$$

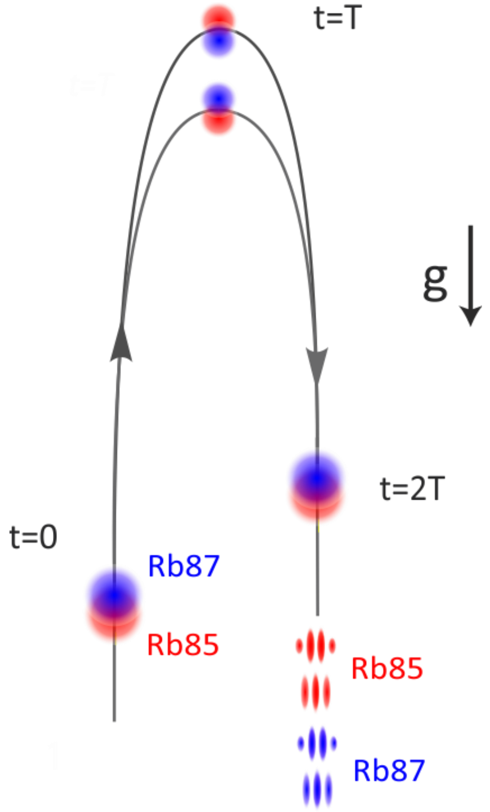
Example: Coupling to electron mass



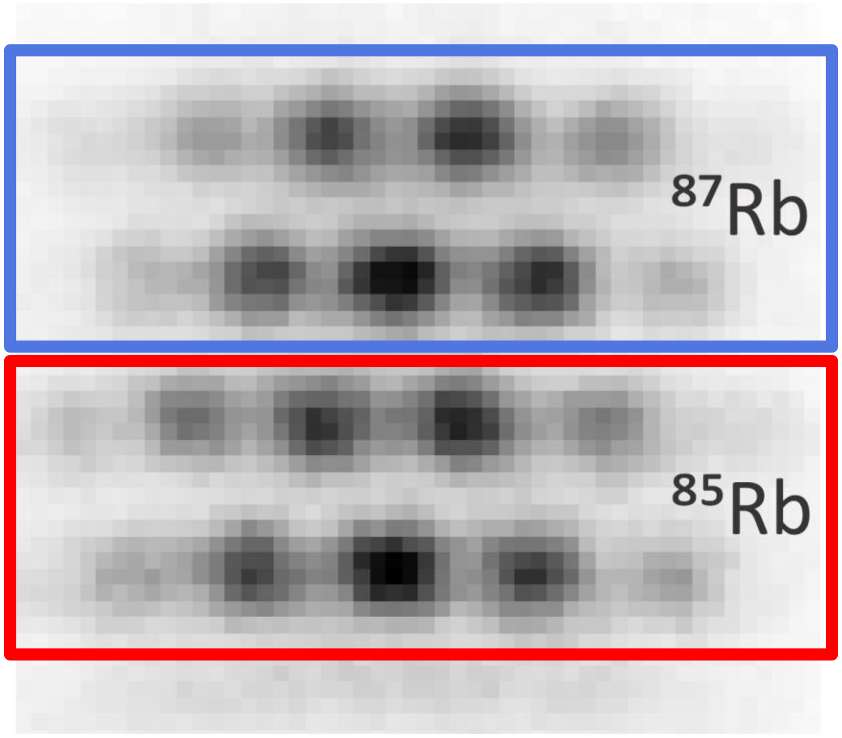
P. Graham et al., PRD **93**, 075029 (2016)

Stanford 10-meter EP test

Simultaneous Dual Interferometer



Dual interferometer fringes



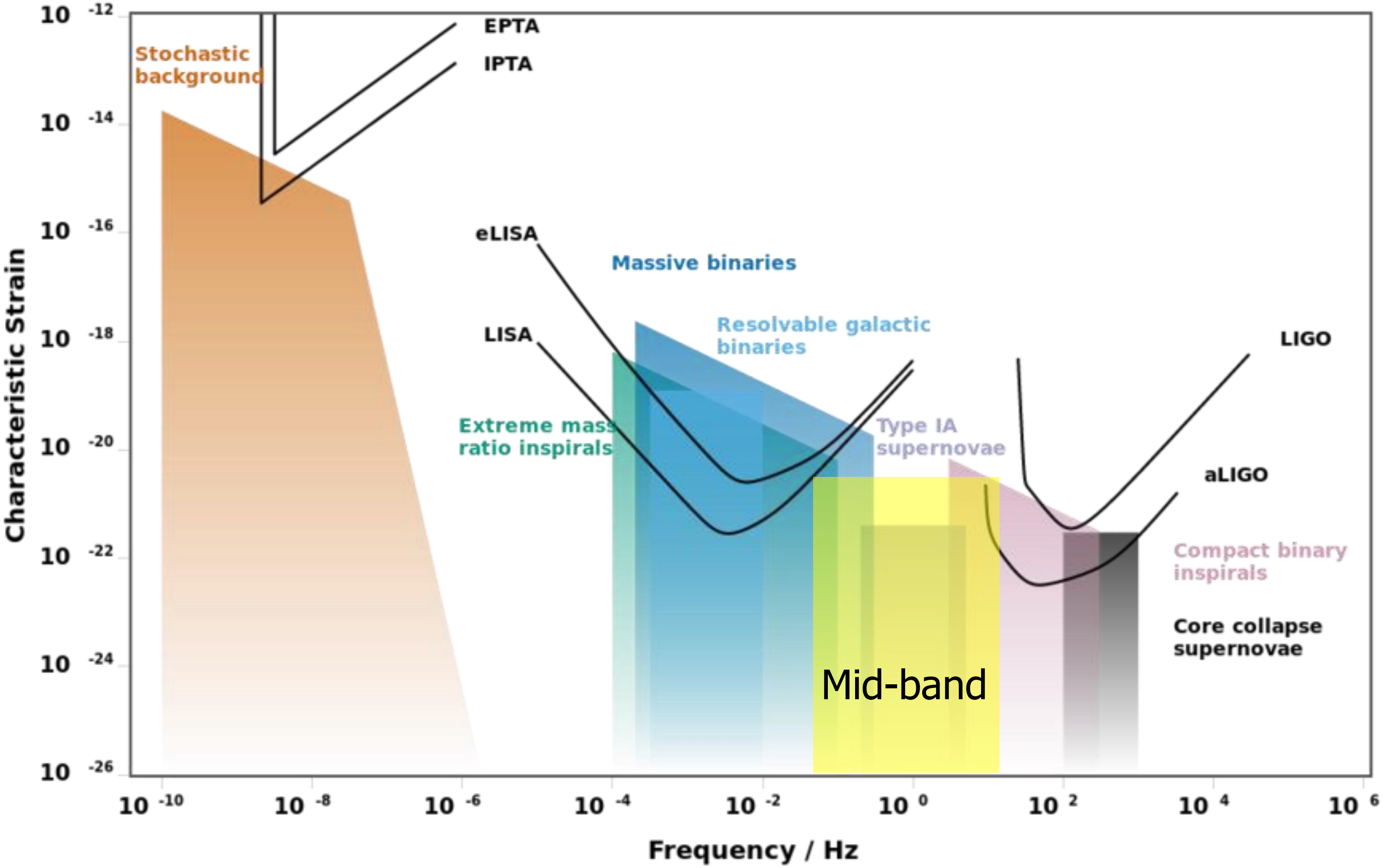
Sensitivity target for static EP: $< 10^{-14}$

Can also look for time-varying forces

Recent results: Suppressed GG sensitivity by x100

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

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 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

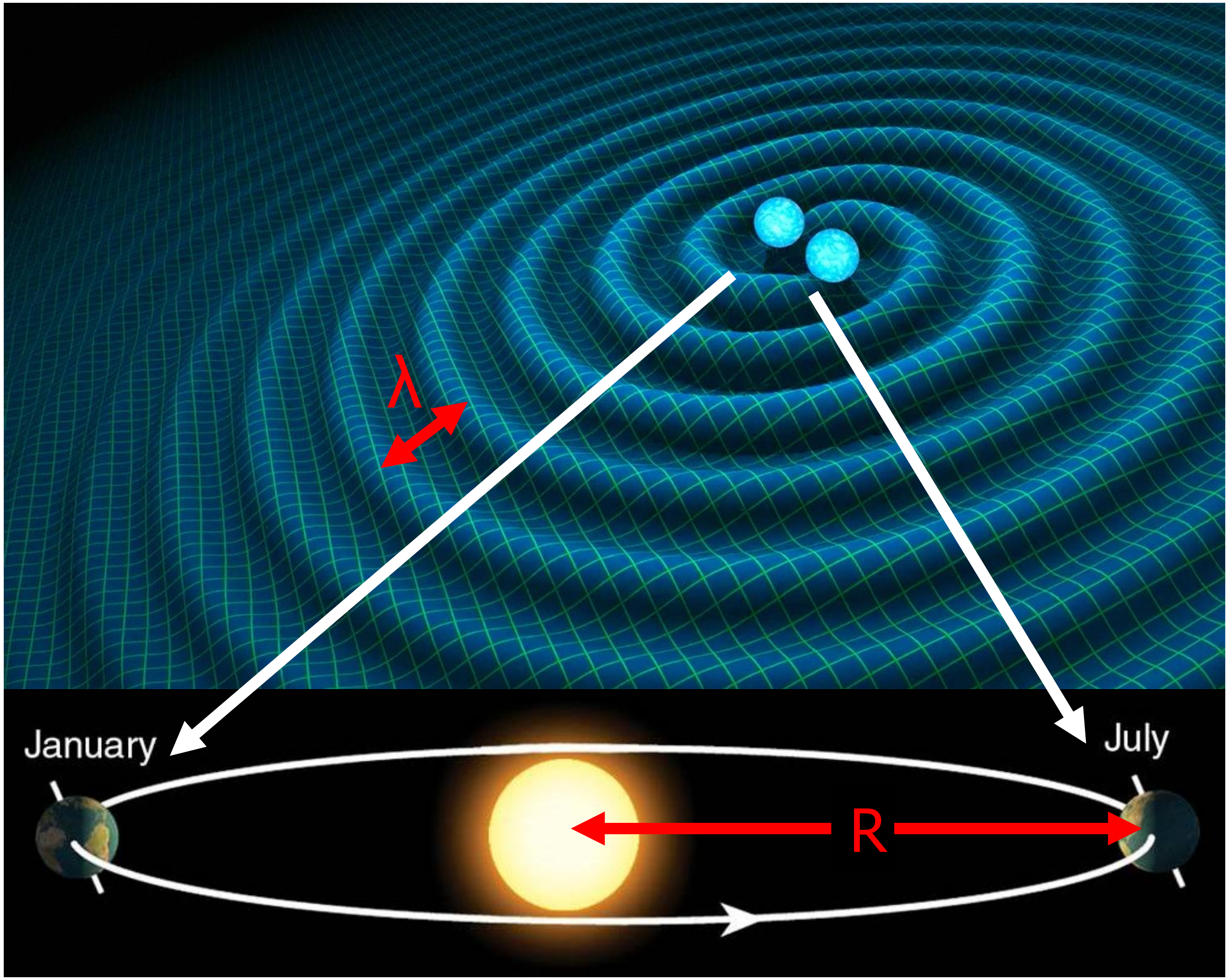
Sky localization precision:

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

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

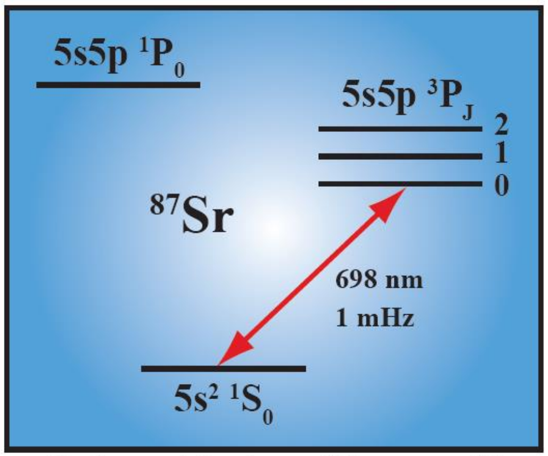


Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

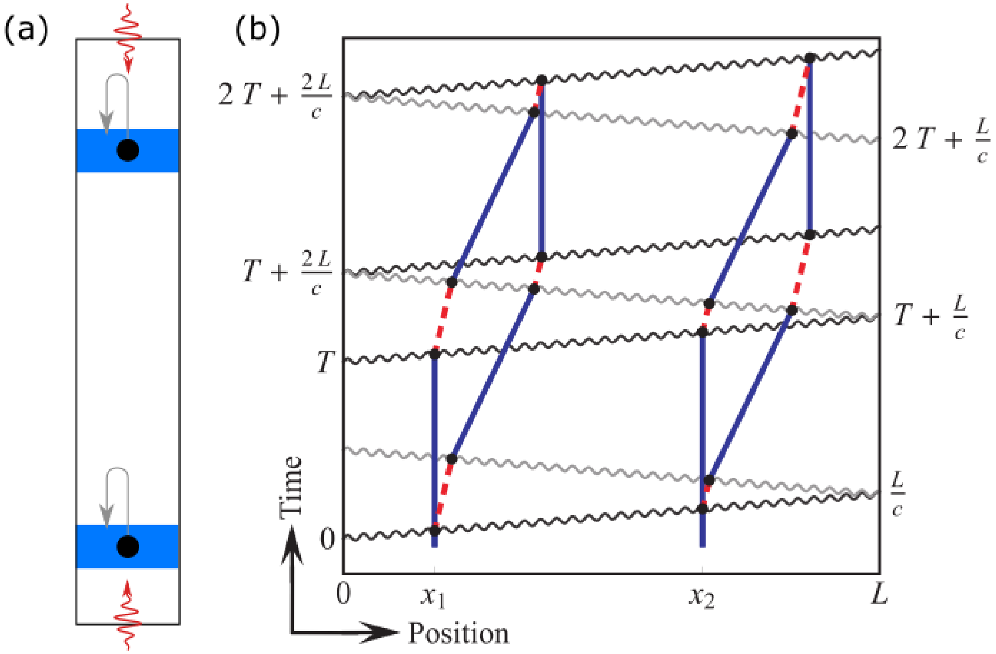
A different kind of atom interferometer

Hybrid “clock accelerometer”

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



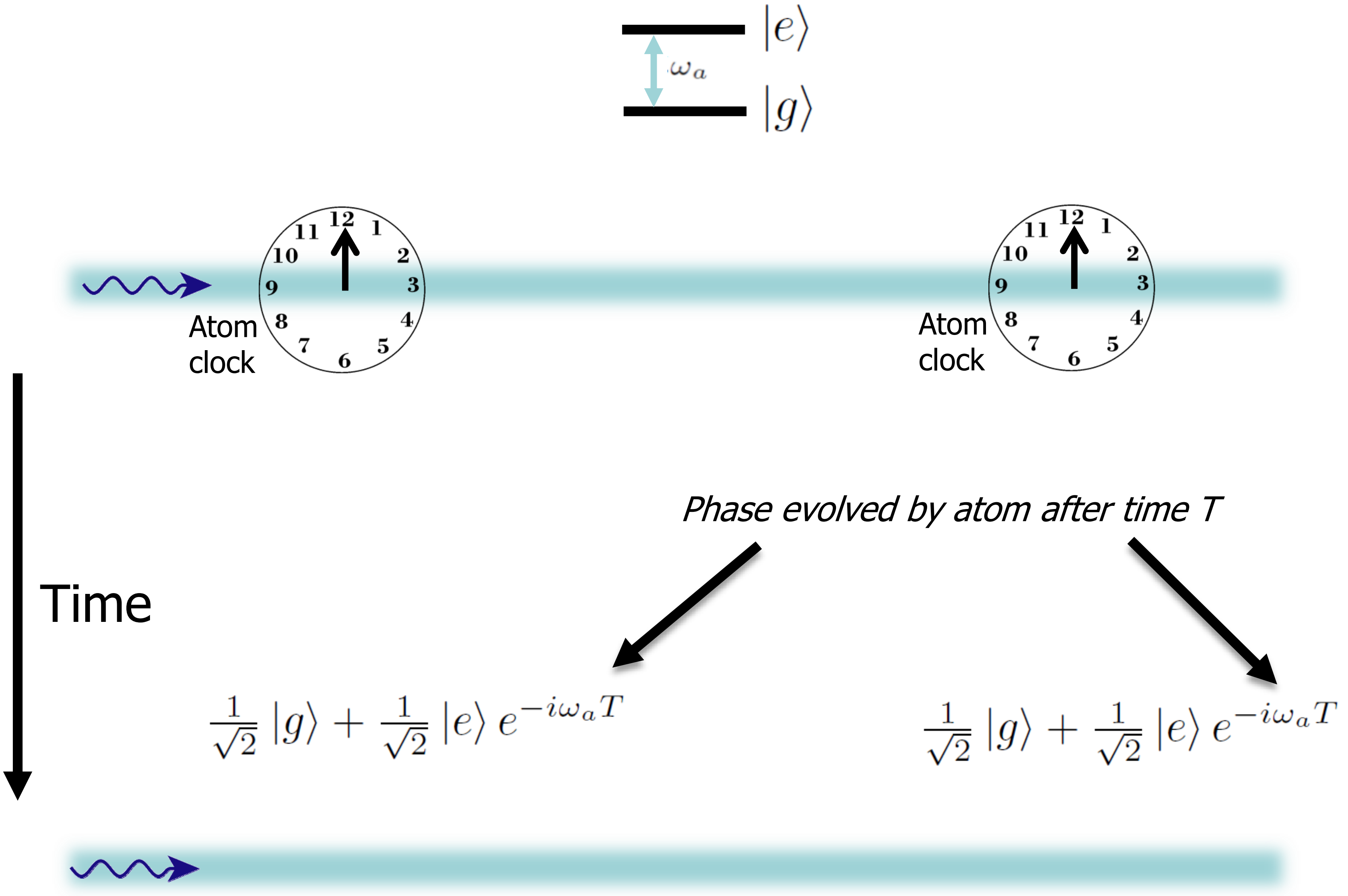
Clock transition in candidate atom ^{87}Sr



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

Accelerometer: atoms excellent inertial test masses

Simple Example: Two Atomic Clocks



Atom clock

Atom clock

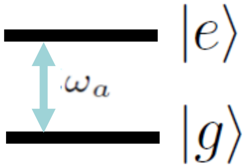
Time

Phase evolved by atom after time T

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

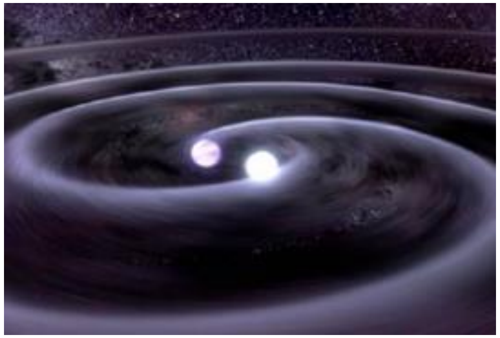
$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

Simple Example: Two Atomic Clocks



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

Time



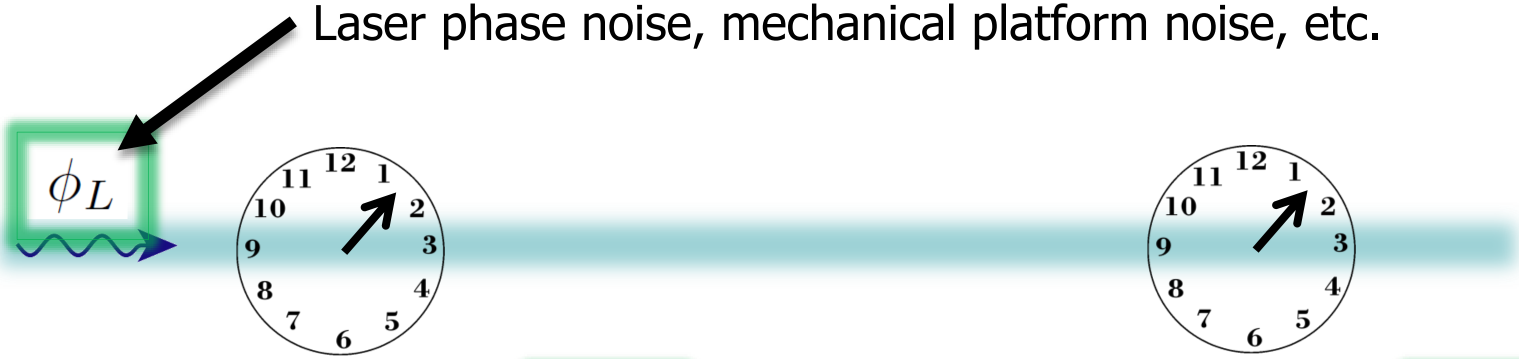
GW changes light travel time

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

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

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.

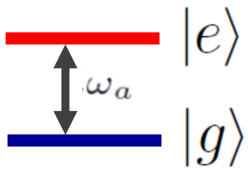


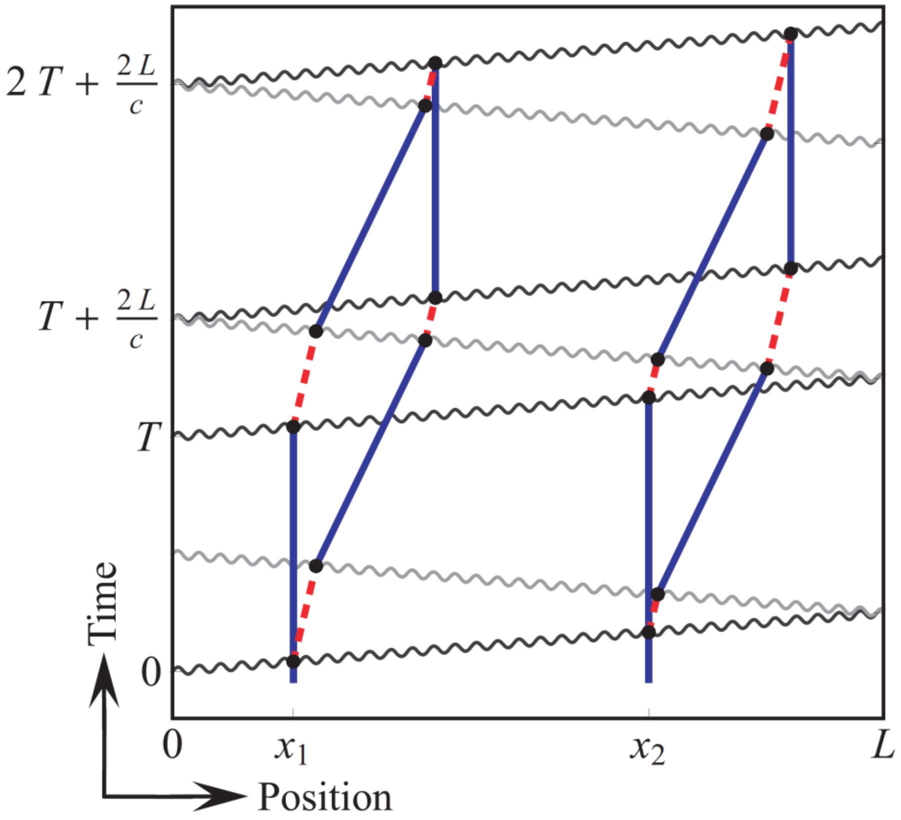
Laser phase noise, mechanical platform noise, etc.

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

*Laser phase is **common** to both atoms – rejected in a differential measurement.*

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 scalar dark matter

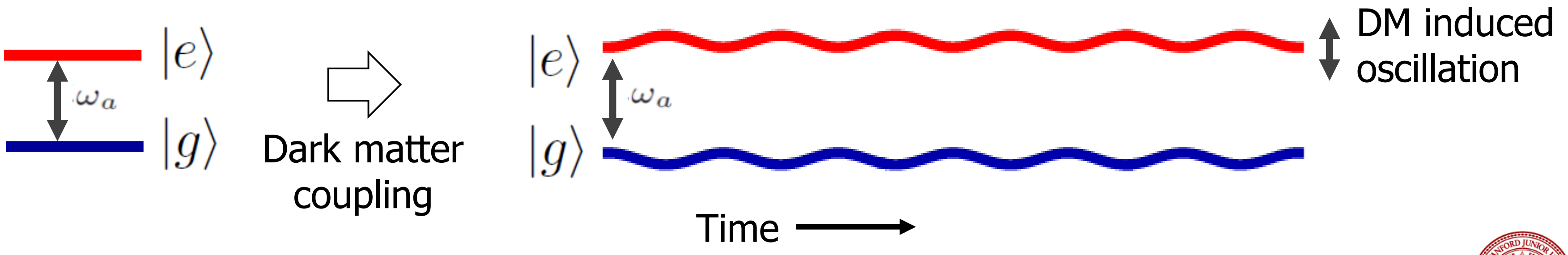
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

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

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

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

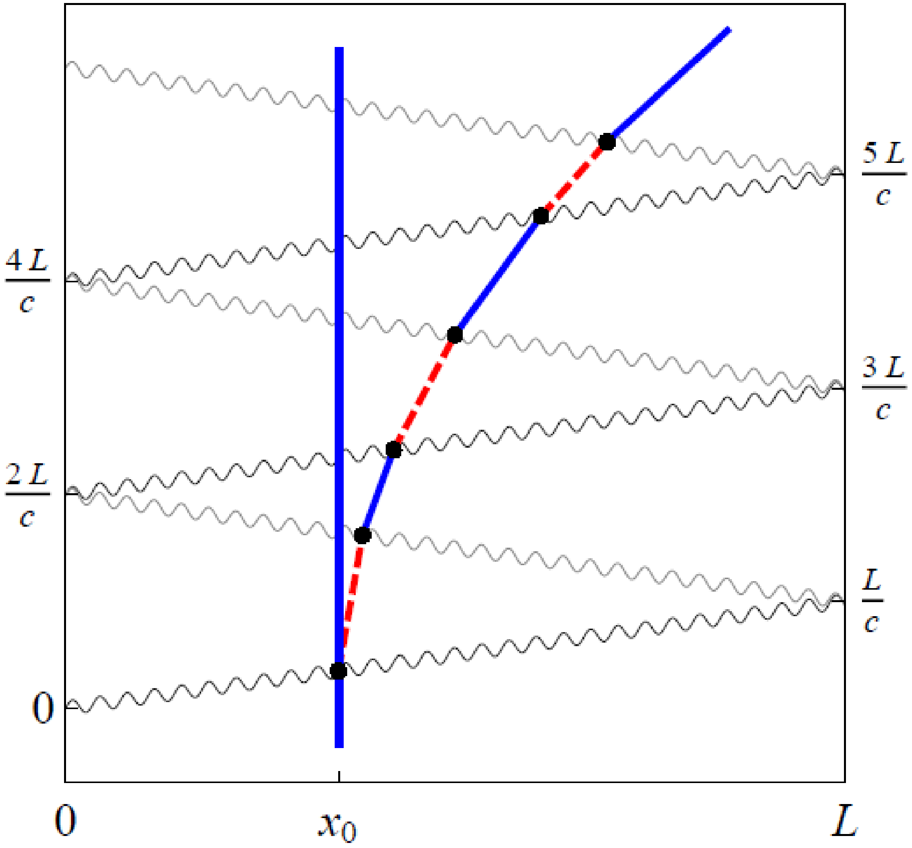
DM coupling causes time-varying atomic energy levels:



LMT and Resonant Pulse Sequences

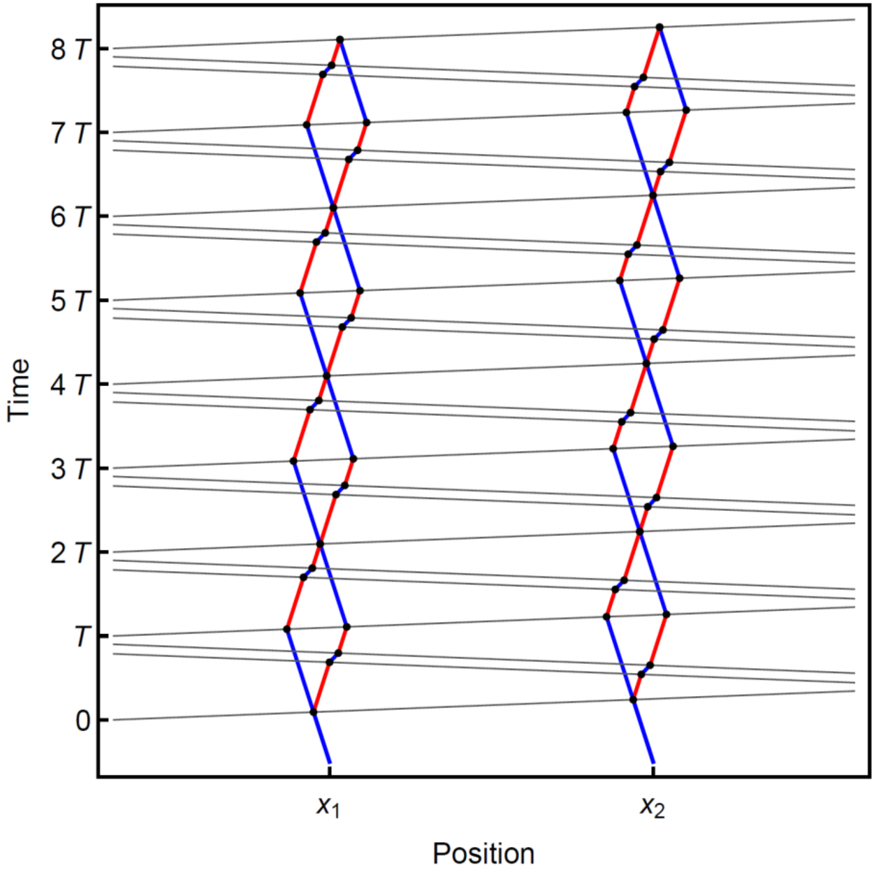
Sequential single-photon transitions remain laser noise immune

LMT beamsplitter (N = 3)



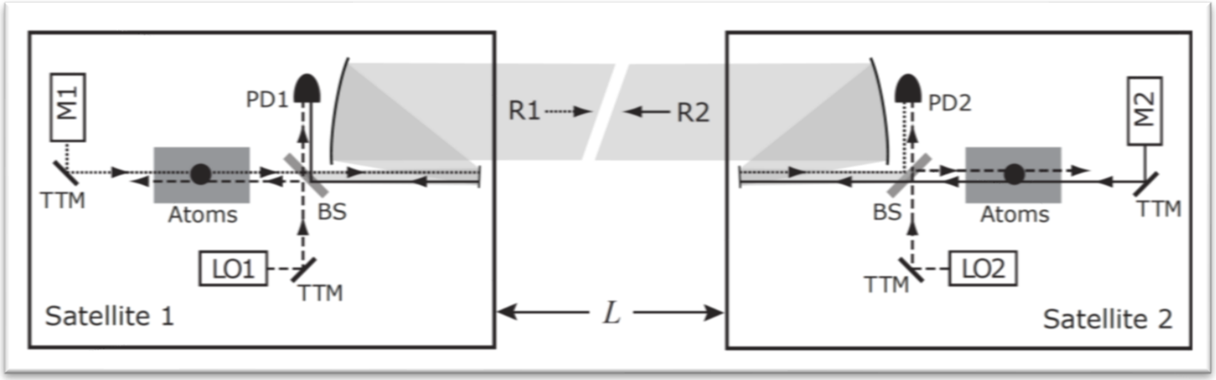
Graham, *et al.*, PRL (2013)

Resonant sequence (Q = 4)



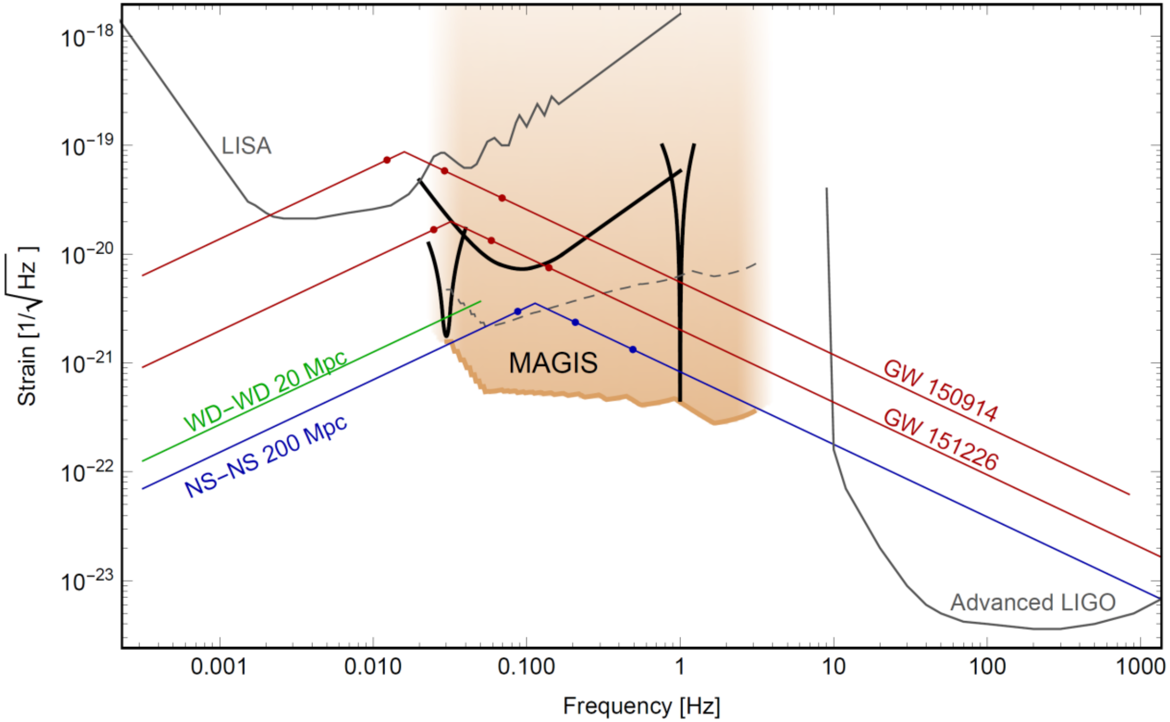
Graham, *et al.*, PRD (2016)

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

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

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

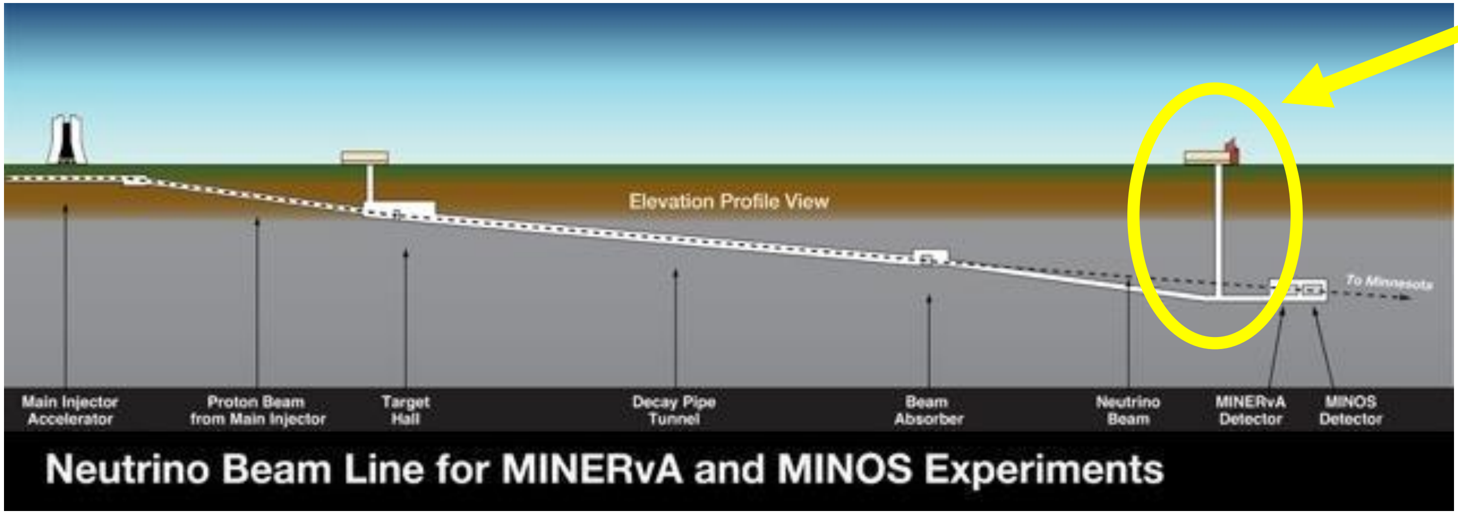
$$\frac{n\hbar k}{m} T < 1\ \mathrm{m}$$

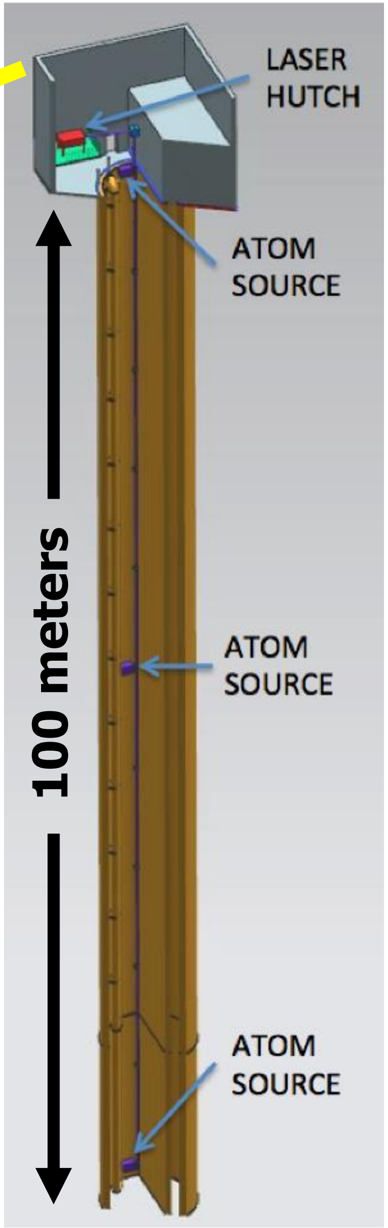
$$2TQ < 300\ \mathrm{s}$$

$$n_p < 10^3$$

MAGIS-100: Proposed GW detector prototype at Fermilab

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

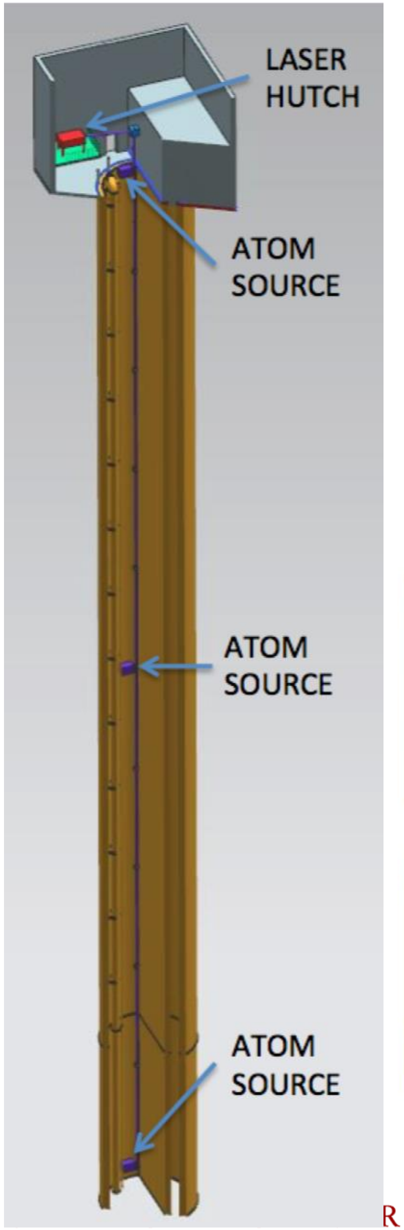




- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

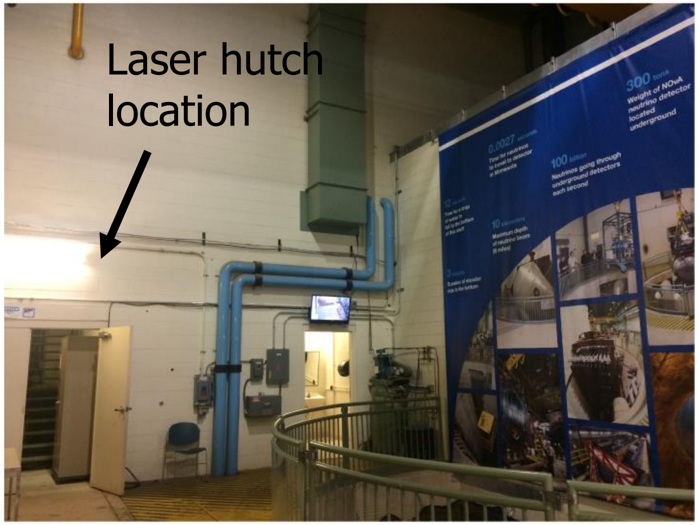
STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

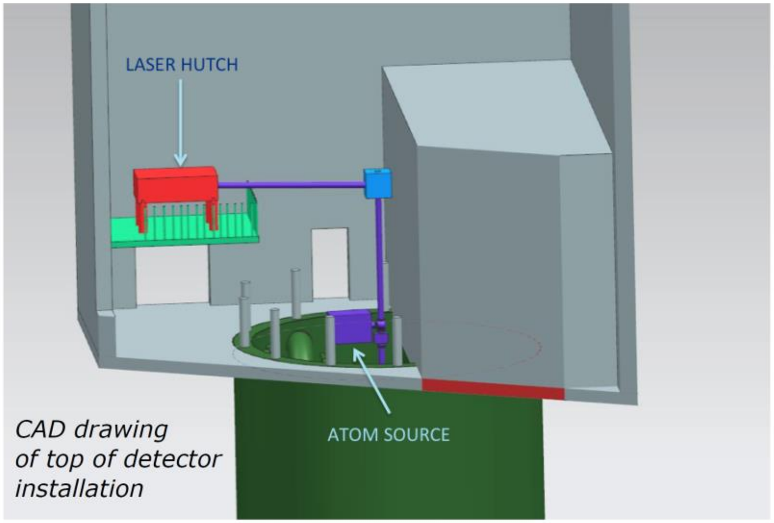
MAGIS-100 Design



System Components:

- ~90 meter vacuum tube (vertical)
- Atoms sources (three, attached to tube)
- Laser system for implementing atom interferometry (hutch at top)

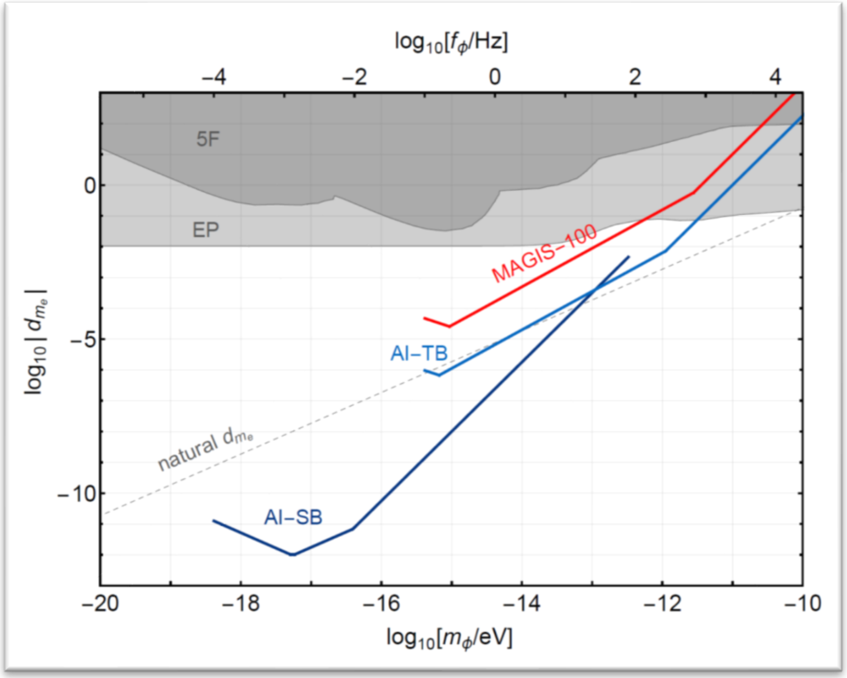




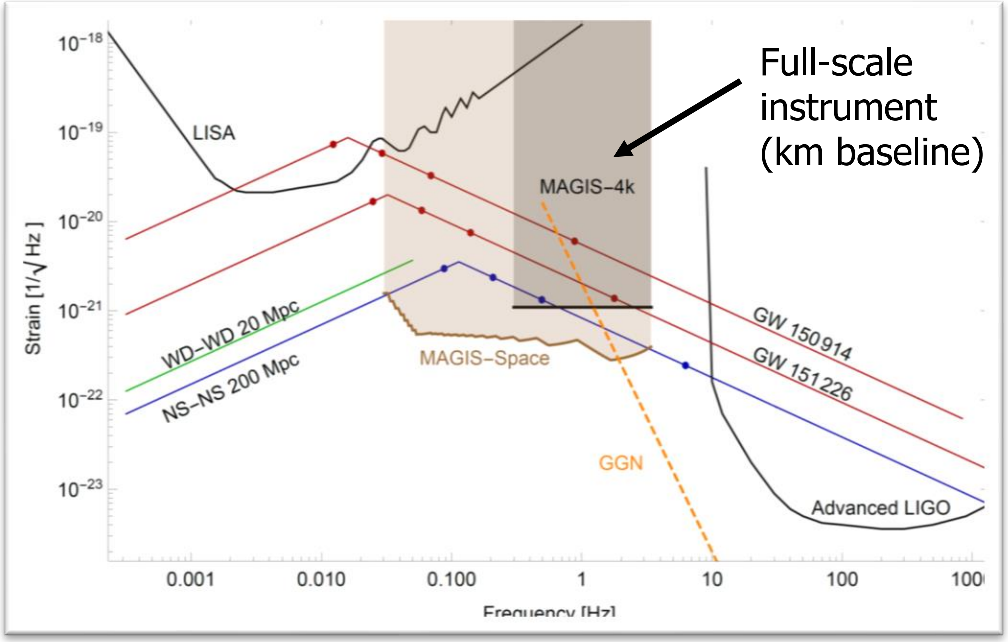
CAD drawing of top of detector installation

MAGIS Estimated Sensitivity

DM sensitivity
(coupling to electron mass)



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

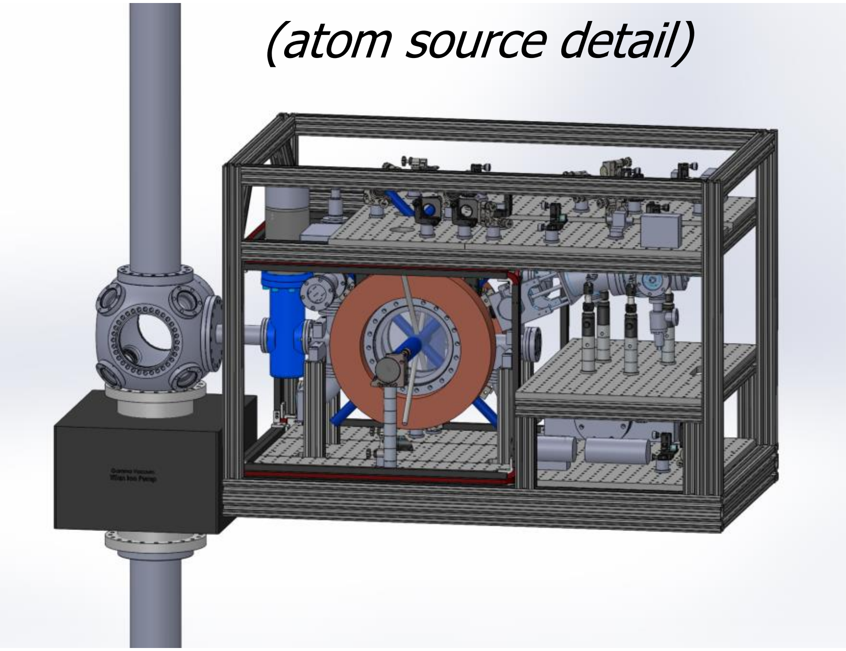


Full-scale
instrument
(km baseline)

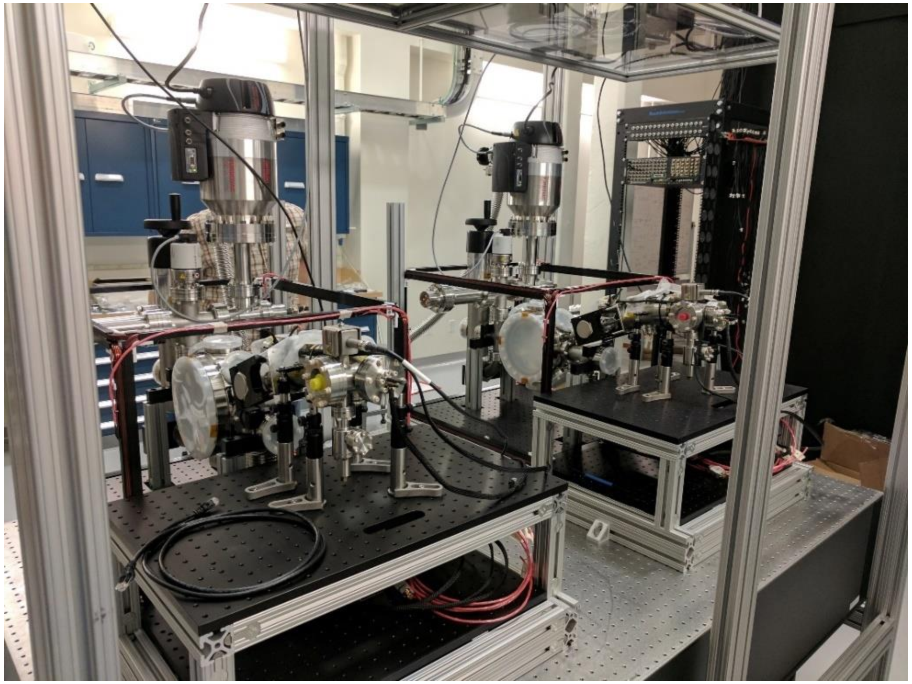
GW strain sensitivity

Stanford MAGIS prototype

Sr gradiometer CAD
(atom source detail)

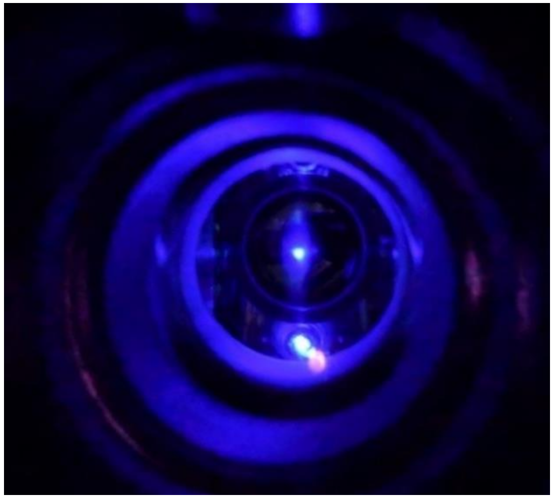


Two assembled Sr atom sources



Atom optics laser
(M Squared SolsTiS)

Trapped Sr atom cloud
(Blue MOT)



Collaborators

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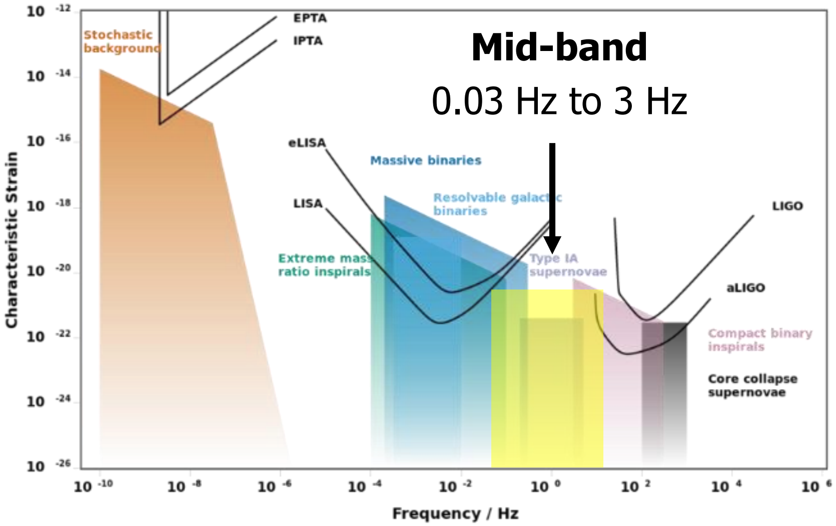
Atomic sensors for gravitational wave detection

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)

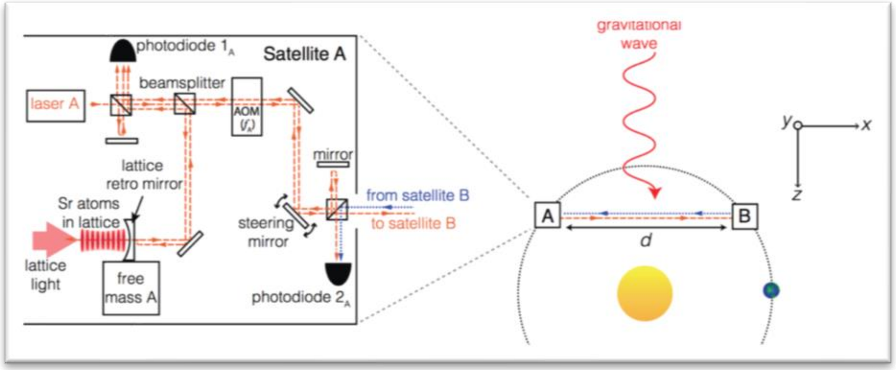


Mid-band

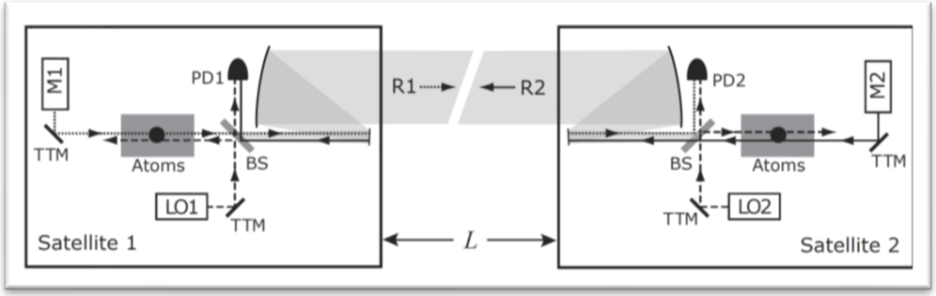
0.03 Hz to 3 Hz

Mid-band science

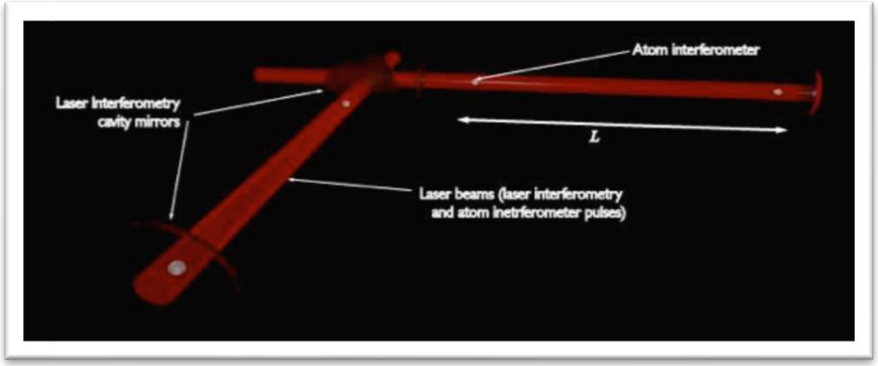
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)



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

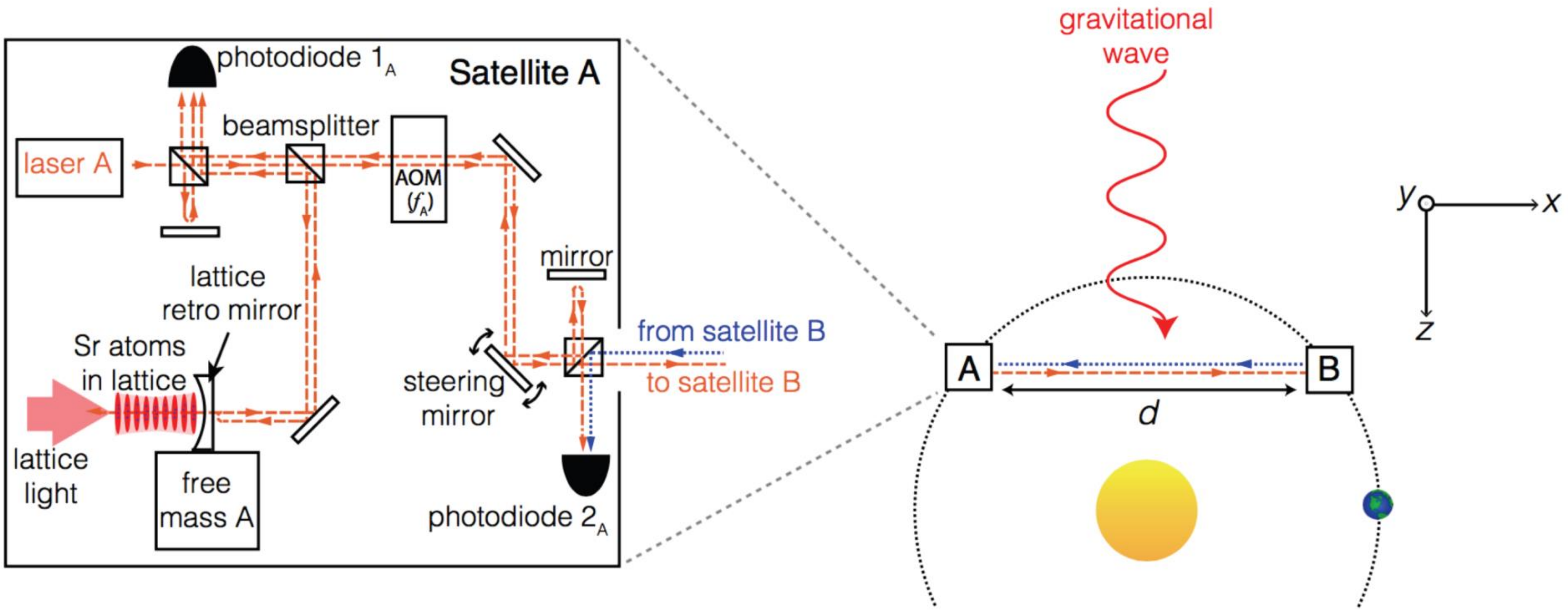


MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich)



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

Lattice Clocks



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

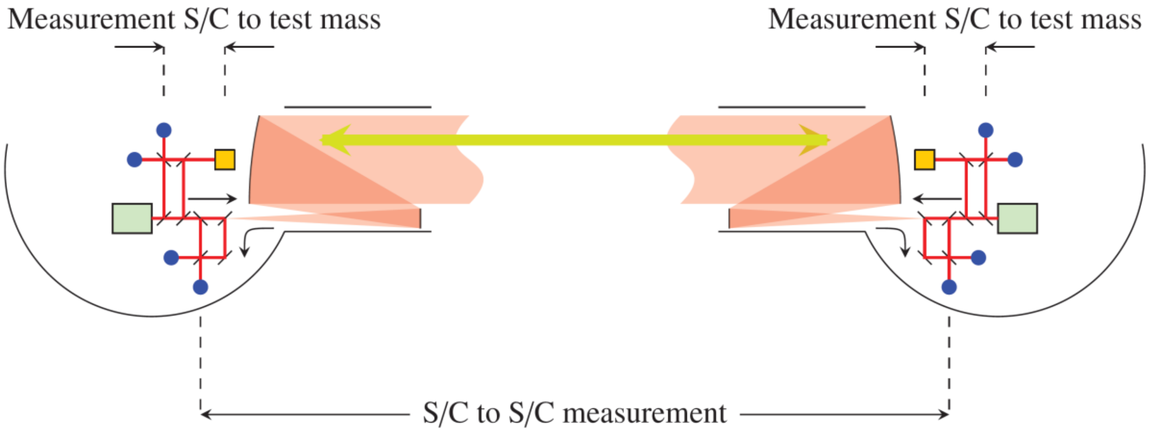
S. Kolkowitz, I. Pikovski, N. Langellier, M. D. Lukin, R. L. Walsworth, and J. Ye, Phys. Rev. D **94**, 124043 (2016)

GW Detector Comparison

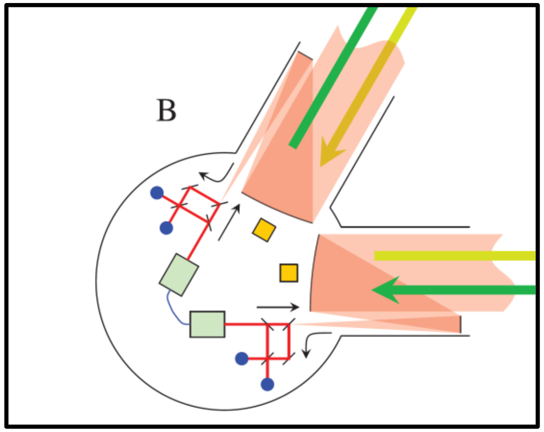
	Inertial reference	**Laser phase reference**
LIGO	Suspended end mirrors	Second arm
LISA	Drag-free proof masses	Second baseline
MAGIS	Atom	Atom
Atomic clock	Drag-free proof mass	Atom

Compare to LISA

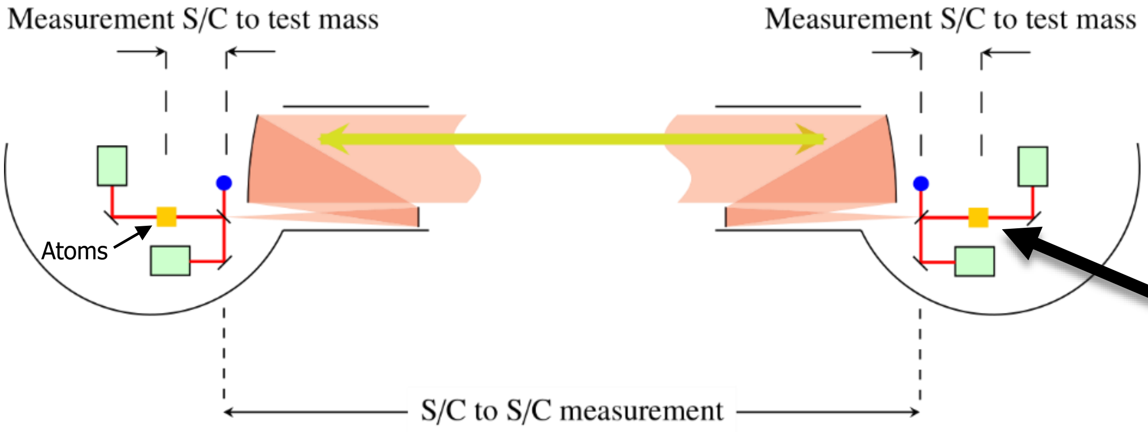
LISA:



Second baseline needed for phase reference:



Atom interferometer:

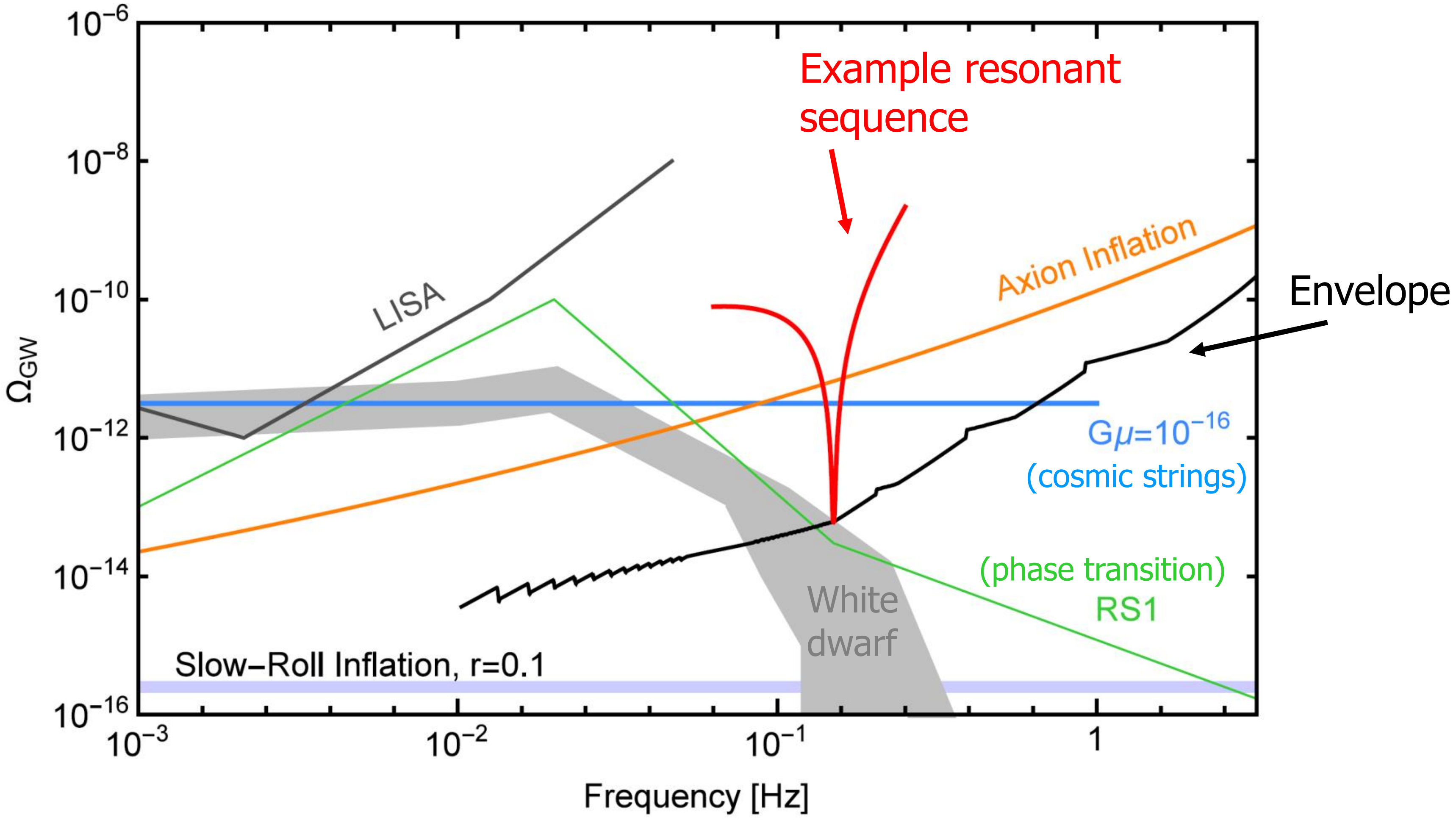


Atom test mass

- 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)