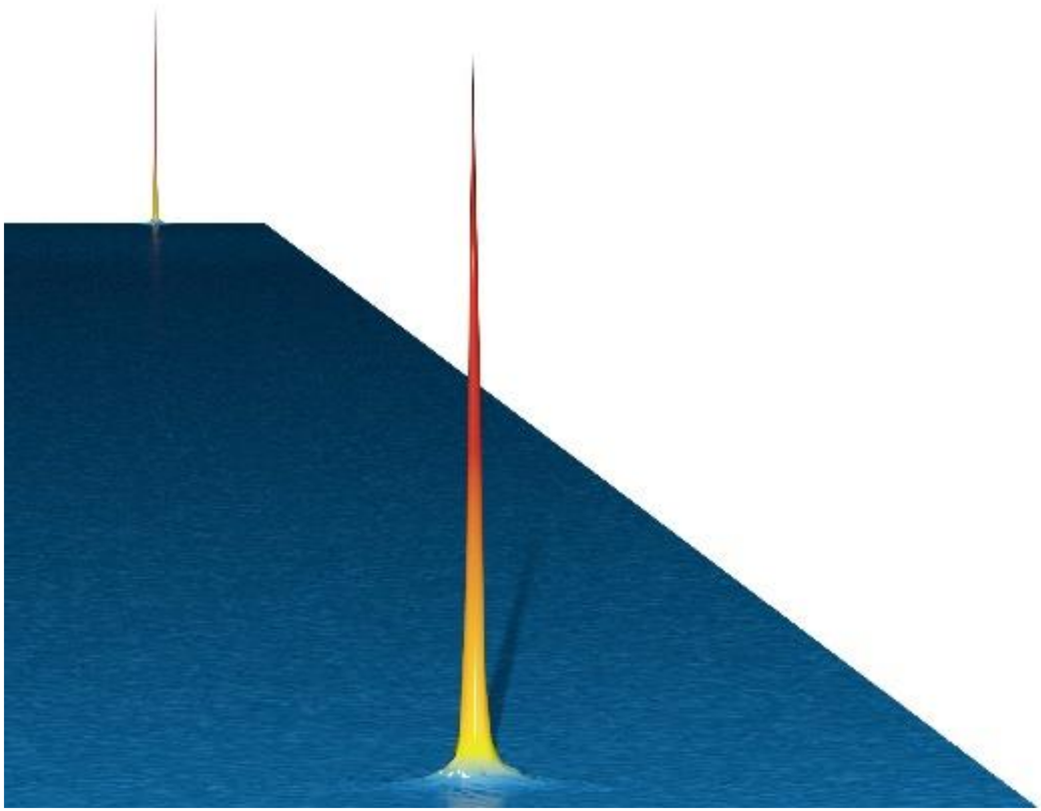
Foundational Quantum Science

Can quantum superposition extend to distance and time scales of everyday life, many meters and tens of seconds?

Various models that limit the size/duration/mass of superposition have been proposed

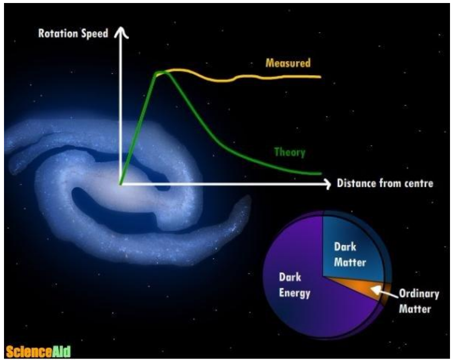
Can test by implementing such superpositions in an atom interferometer



Arndt and Hornberger, Nature Physics 2014
Bassi et al., RMP 2013
Nimmrichter and Hornberger, PRL 2013
Altimirano et al., Classical and Quantum Gravity, 2018
Bassi et al., Classical and Quantum Gravity, 2017

Dark Matter

We know it's there, but what is it?



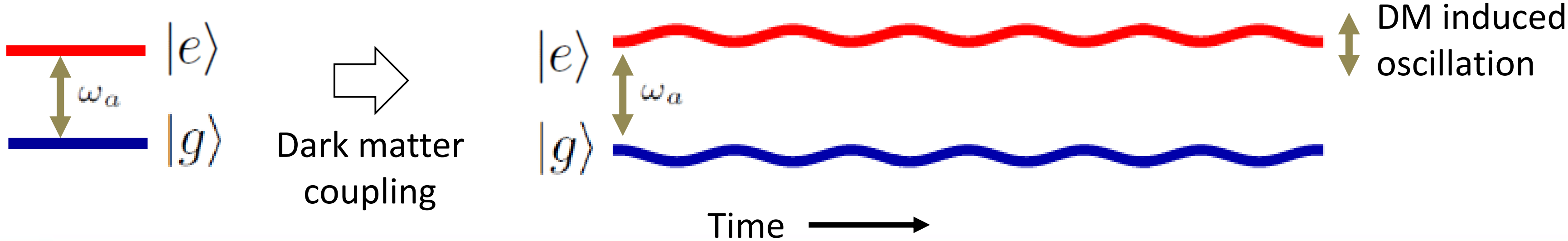
Galactic rotation curves not consistent with luminous matter only

Gravitational lensing that is not explained by luminous matter

Other evidence includes dynamics of galaxy interactions, structure of cosmic microwave background, etc…

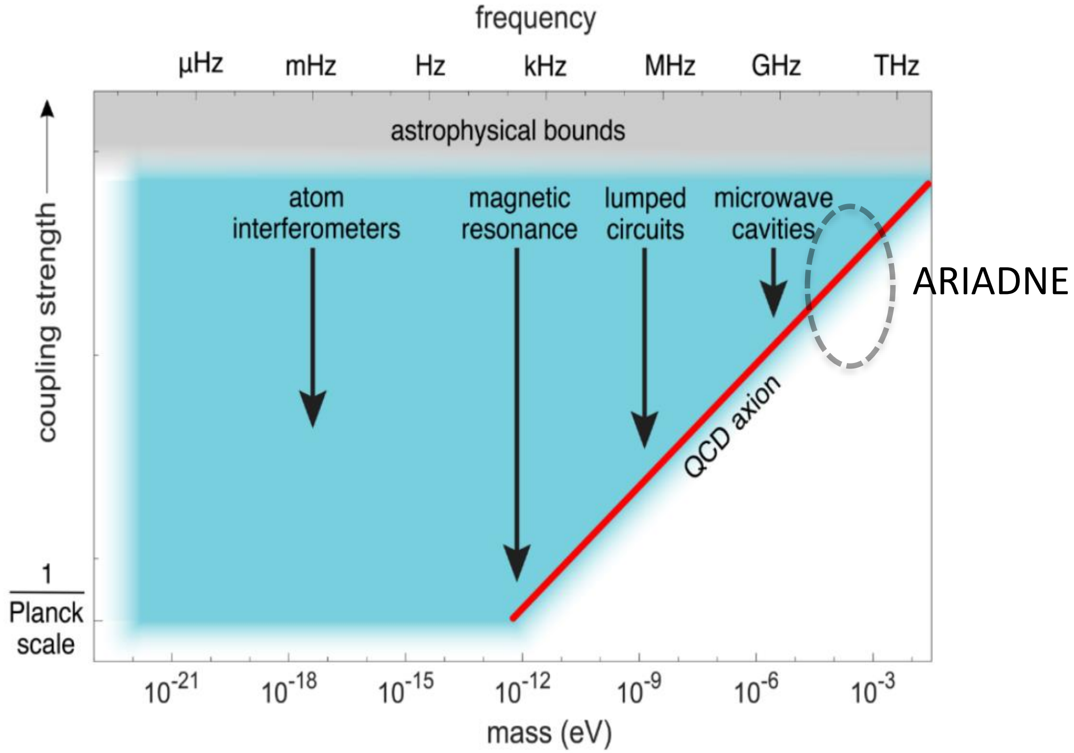
One well-motivated candidate: wavelike dark matter, coherently oscillating field

Can lead to small oscillations in atomic energy levels



Technologies to Cover Range of Wave DM Masses

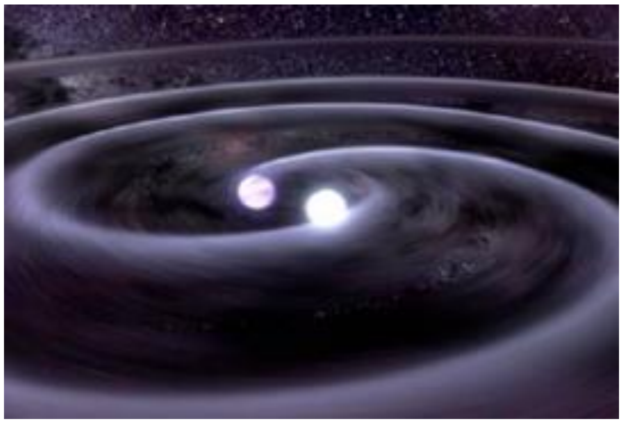
- Atom interferometry well-suited to the lightest part of this mass range
- DM signatures include time-dependent atomic energy levels and time-dependent, differential accelerations between different atomic species (use dual isotope interferometer for latter case)

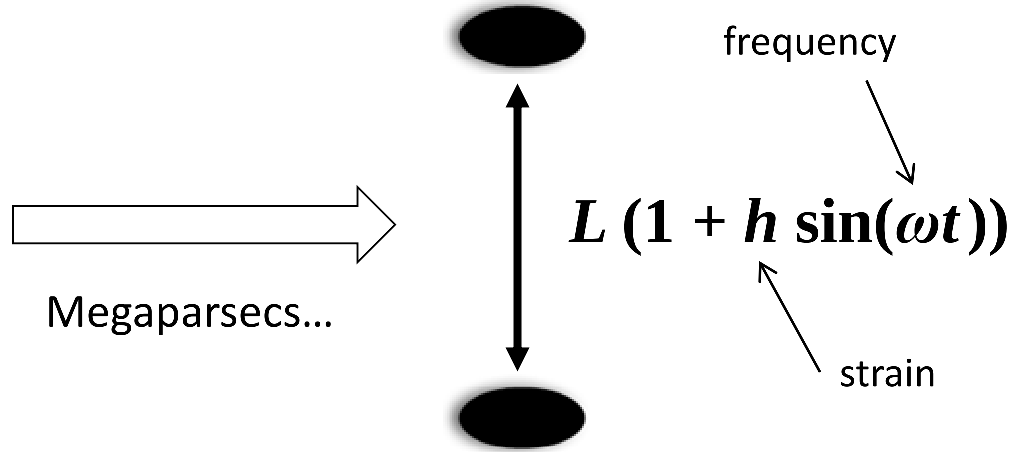


From Rocky Kolb presentation at HEPAP.

Gravitational Wave Detection

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





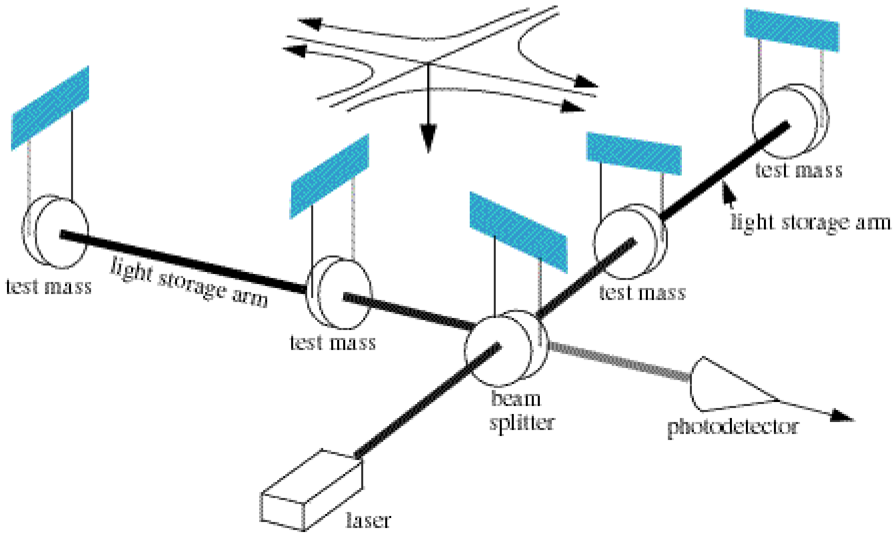
Gravitational waves science:

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

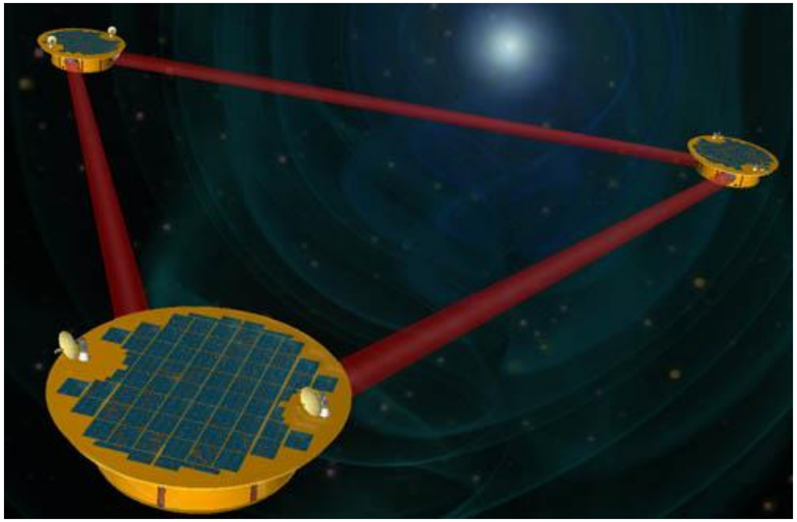
Probing the early universe: Can see to the earliest times in the universe, study corresponding high energy scales

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

Laser Interferometer Detectors

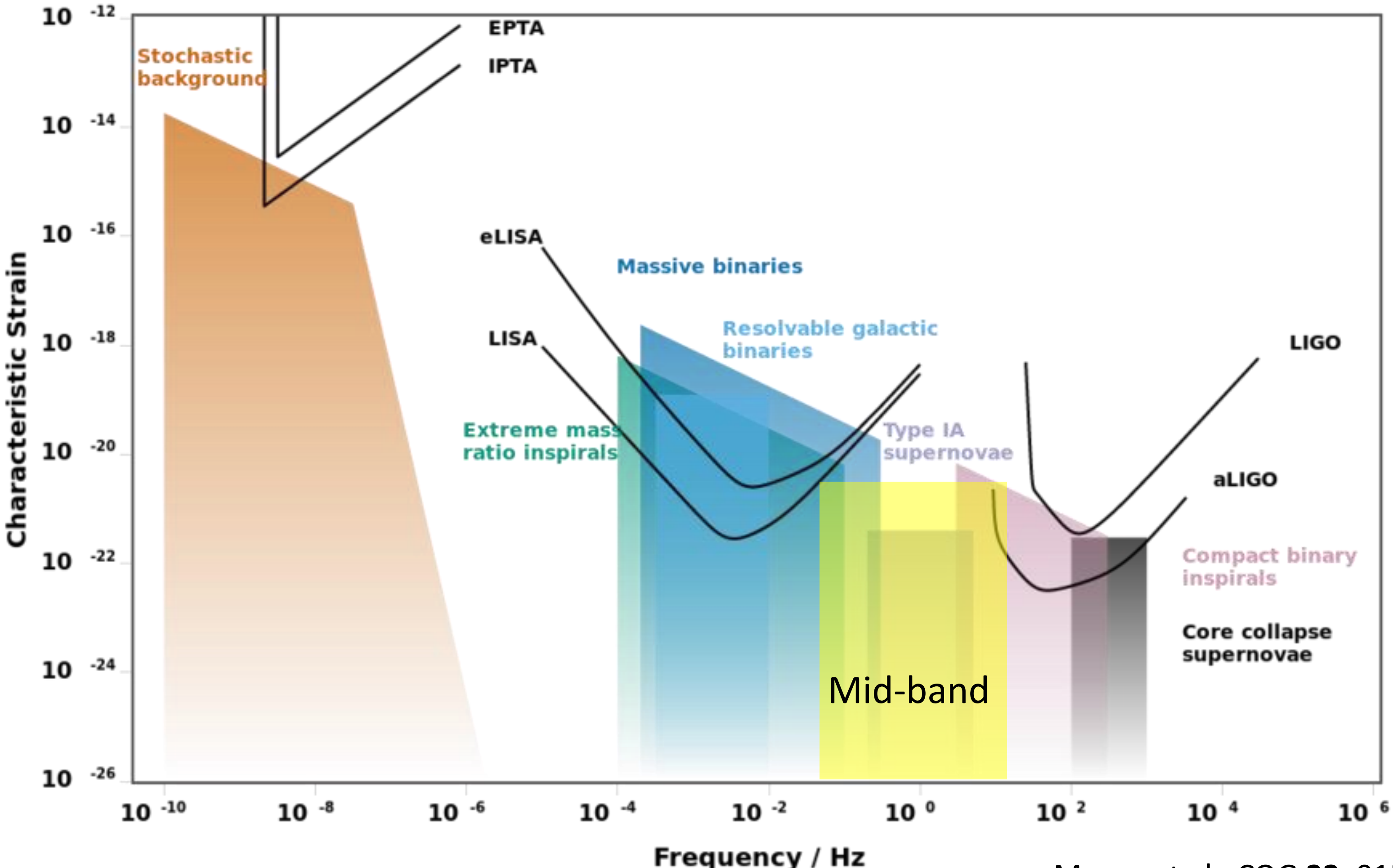


Gound-based detectors: e.g.: LIGO, VIRGO, GEO, proposed ET (> ~3 Hz)



Space-based detector: planned LISA mission (1 mHz – 100 mHz), also proposals to extend LISA concept to higher frequencies (e.g., DECIGO)

Gravitational wave frequency bands



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

There is a gap between the LIGO and LISA detectors (~ 0.3 Hz – 3 Hz).

Mid-band Science

Mid-band discovery potential
-Potential to discovery something unexpected
-Observe LIGO sources when they are younger, provide advance notice for electromagnetic telescopes to observe run-up to coalescence

Cosmological signals that give insight into high energy physics
-operating in mid-band instead of lower frequencies advantageous for avoiding background signals from white dwarfs

Astrophysical Sources
White dwarf binaries (Type IA supernovae), black hole binaries, intermediate mass black holes, and neutron star binaries

Measurement Concept

Essential Features

1. Light propagates across the baseline at a constant speed
2. Atoms are good clocks and good inertial proof masses (freely falling in vacuum, not mechanically connected to Earth).
3. Clocks read transit time signal over baseline
4. GW changes number of clock ticks associated with transit by modifying light travel time across baseline, DM changes number of clock ticks by modulating clock frequency (i.e., atomic transition frequency)
5. Many pulses sent across baseline (large momentum transfer) to coherently enhance signal

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

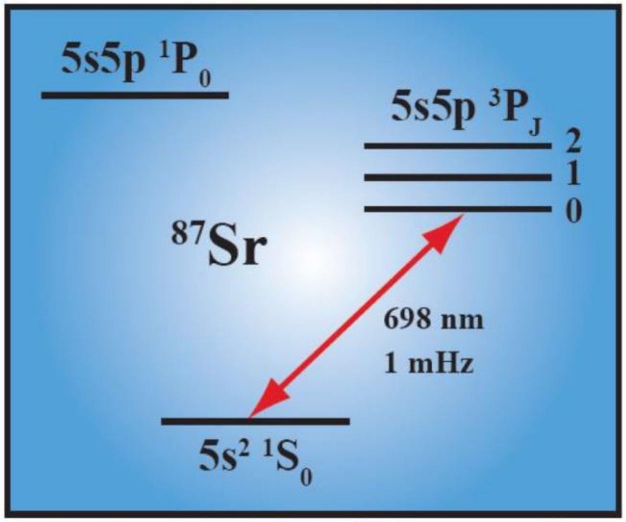
Yu and Tinto, GRG 2011; Graham et al., PRL 2013; Arvanitaki et al., PRD 2018

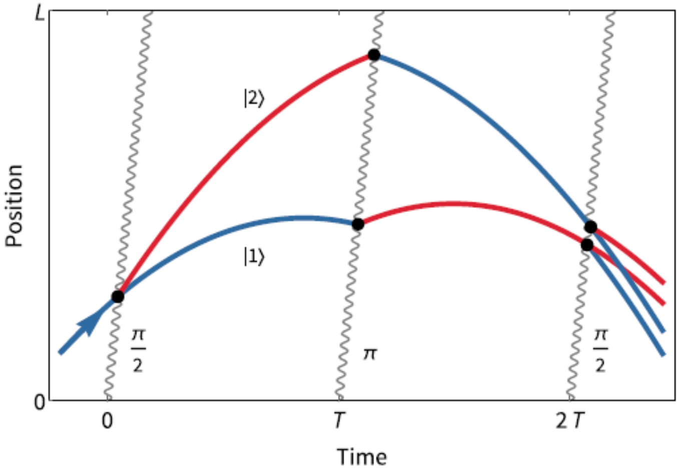
Clock Atom Interferometry

Perform atom interferometry using narrow optical clock transition of Sr with a long-lived excited state (natural lifetime >100 s)

Can have long lived superpositions of ground + excited state with a large energy difference, useful for very precise timing measurements

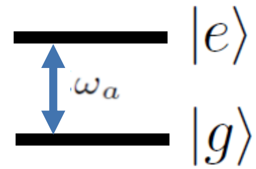
In combination with high laser power, potentially enables many thousands of pulses for delocalizing atoms by macroscopic distances and levitating them against gravity, overcoming previous limitations

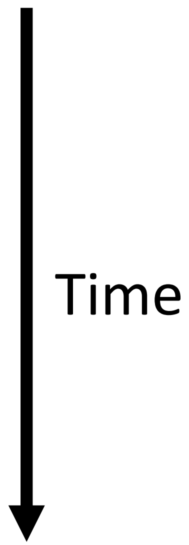




Hu et al., PRL 2017; Rudolph et al., PRL 2020

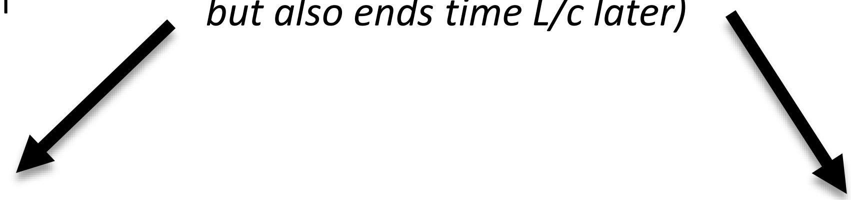
Concept: Two Atomic Clocks





1. Laser pulses creates superposition of clock states, "starts clock ticking"
2. Second pulse represents end of measurement, phase reflects amount clock ticked during measurement time

Phase evolved by atom after time T (second clock starts slightly later, by amount L/c for baseline length L, than first because of light travel time, but also ends time L/c later)

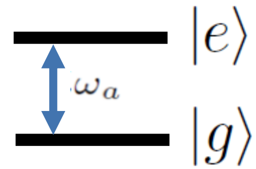


$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

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

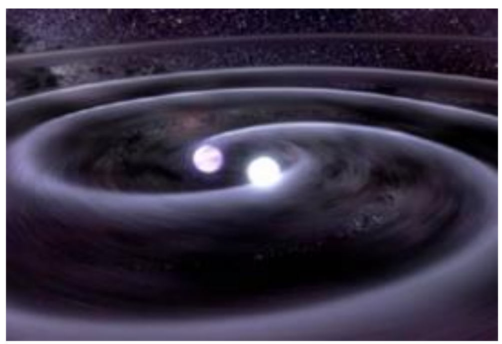
Note: in actual measurement, there are more pulses in between first and final pulse

Concept: Two Atomic Clocks



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

Time

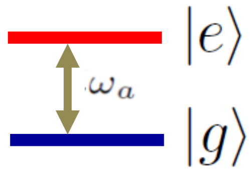


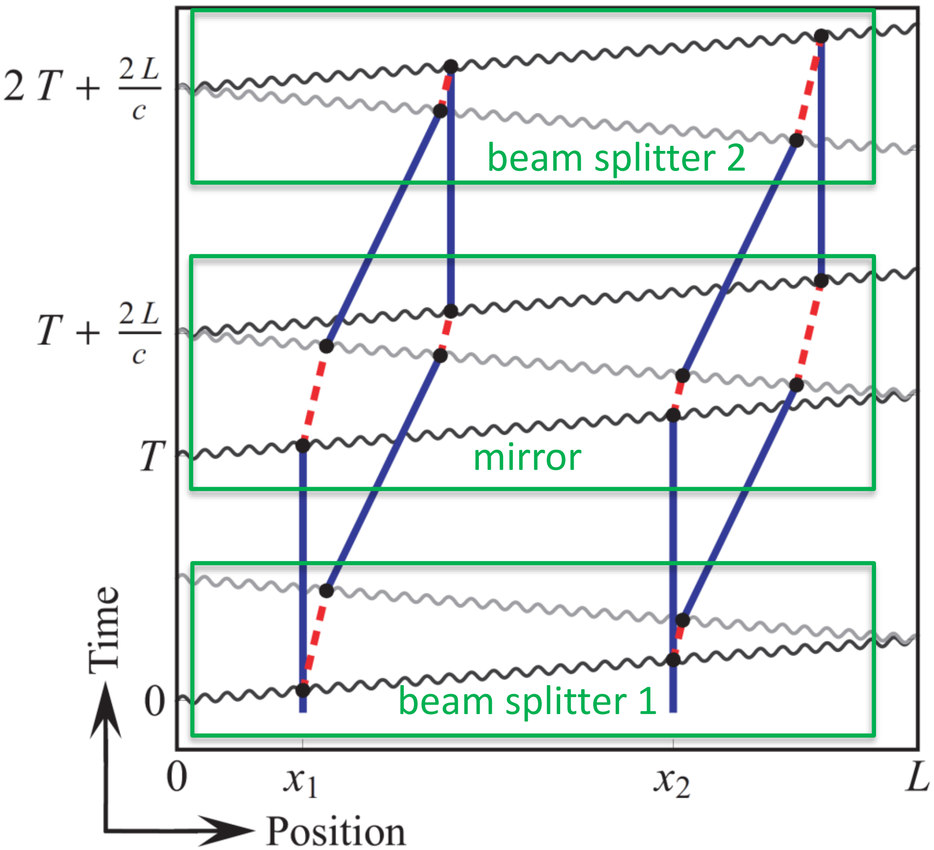
GW changes baseline, and therefore light travel time, between pulses (signal maximized when GW period on scale of time between pulses)

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

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

Gradiometer Signal





Phase shift of an interferometer determined by difference in times spent in excited clock state for arm 1 vs arm 2

Look at difference in phase shifts for two interferometers separated by baseline ~L (gradiometer phase shift)

Magnitude of contribution to gradiometer phase shift from each interferometer zone: $\Delta\phi \sim \omega_A \left(2L/c\right)$

For constant (or linearly drifting) L and transition frequency, gradiometer phase shift cancels between all three zones

To have a nonzero gradiometer phase shift, need transition frequency or L to vary on the time scale of time T between each zone

Two ways to get a signal:

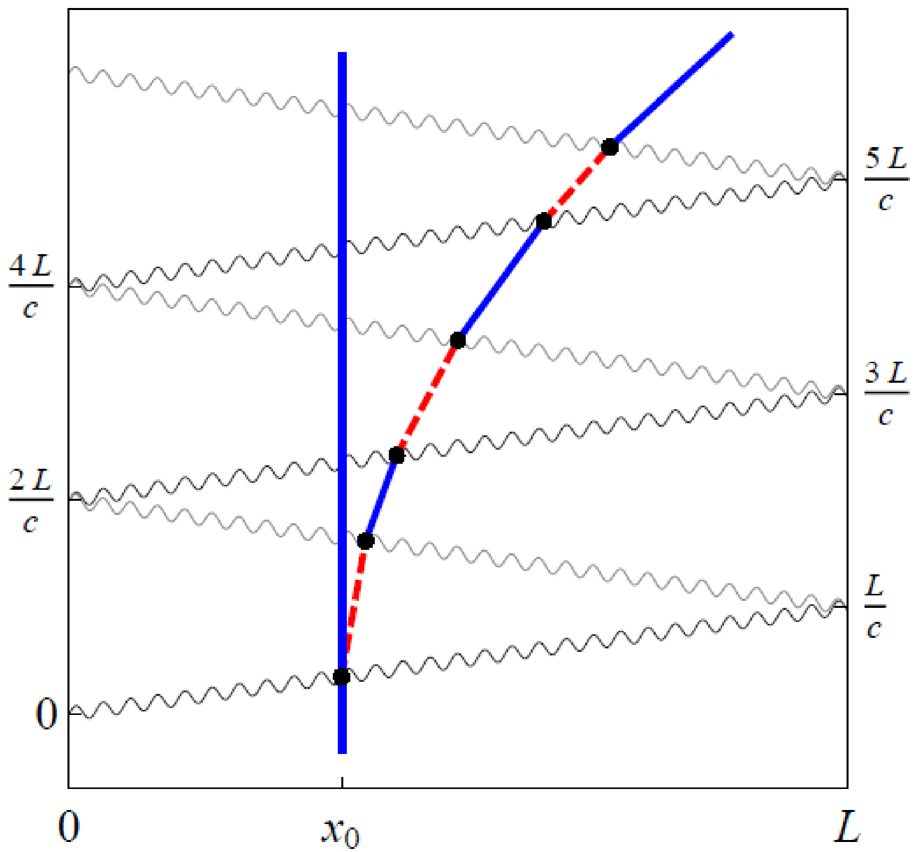
$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

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

Large Momentum Transfer (LMT) Pulse Sequences

Sequential single-photon transitions remain laser noise immune

LMT beamsplitter



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

- Additional laser pulses exchanged across baseline, further accelerate one of the interferometer arms (detuned from second arm due to Doppler shift)

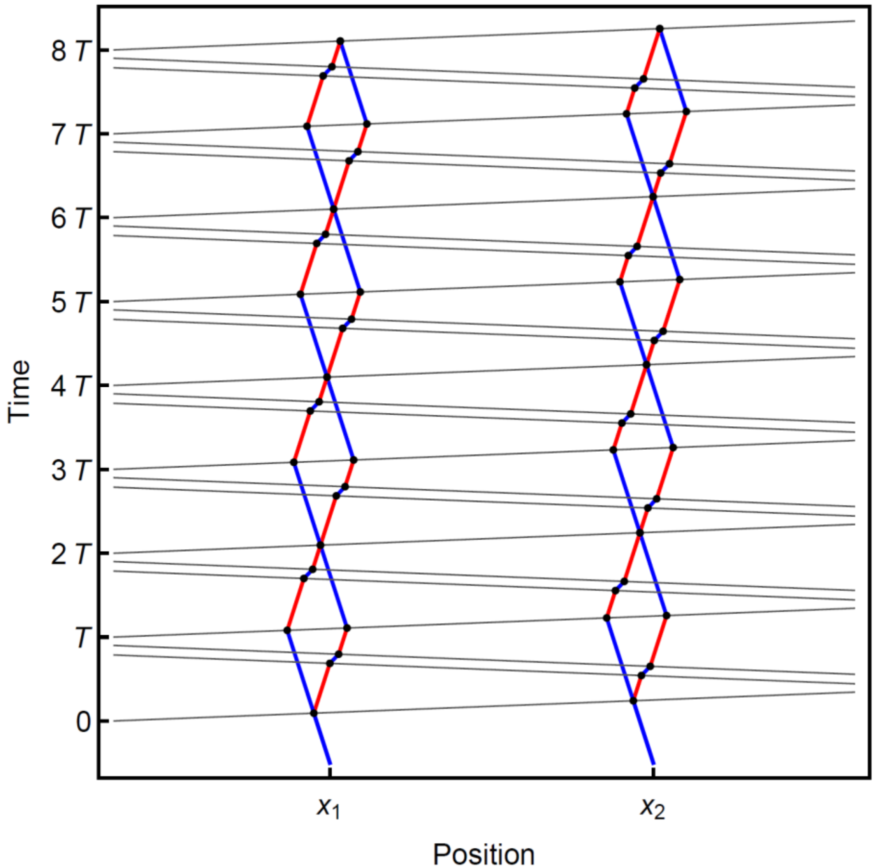
- Additional pulses coherently enhance differential clock signal: total amount of time spent in excited state during beam splitter decreases as x increases from 0 to L (giving differential signal) **and is proportional to number of pulses**

- Magnitude of contribution to differential phase shift from each interferometer zone for beam splitters with 2n pulses:

$$\Delta\phi \sim 2n\omega_A \left(L/c\right)$$

Resonant Detection

Resonant sequence (Q = 4)



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

- Multiple interferometer loops (Q loops) can enhance sensitivity by a factor of Q at the resonance frequency
- Analogy to lock-in detection
- Comes at the cost of decreased bandwidth
- With same hardware, can rapidly tune resonance frequency and switch between resonant and non-resonant modes

The Standard Quantum Limit

- For an interferometer, we would like to estimate the phase evolved between the two branches of the wave function based on the probability of detecting a particle in one state vs. the other after the final beam splitter
- Say that we perform this measurement for N uncorrelated particles, each with the same evolved phase ϕ
- Probability of finding a given particle in output state 1

$$p_1 = \frac{1}{2} - \frac{1}{2}\cos(\phi)$$

- Mean number of particles found in state 1

$$\bar{N}_1 = N p_1$$

- *Which statistical distribution should we use to describe the probabilities of finding a given number of particles in state 1?*
- *How would we expect the uncertainty in the evolved phase to scale with N?*

The Standard Quantum Limit

- The *binomial distribution* is appropriate here
- Based on the properties of this distribution, the standard deviation in the number of particles found in state 1 is

$$\delta N_1 = \sqrt{N p_1 (1 - p_1)} = \frac{\sqrt{N}}{2} \left|\sin(\phi)\right|$$

- Applying uncertainty propagation to the equation $\bar{N}_1 = N p_1$, we obtain the additional relation

$$\delta N_1 = \frac{N}{2} \left|\sin(\phi)\right| \delta\phi$$

- The uncertainty in the estimated phase is thus

$$\delta\phi = 1/\sqrt{N}$$

Number-Phase Uncertainty Relation

- It turns out that there is a general relationship between the uncertainty in the number of excitations of a quantum system and the uncertainty in the phase of the quantum state

- Consider that each excitation corresponds to energy $\hbar\omega$
  - Could corresponds to photons each of energy $\hbar\omega$
  - Could correspond to how many atoms in a two-level system are in the excited state, with transition energy $\hbar\omega$

- Back-of-the-envelope derivation from energy-time uncertainty principle

$$\delta E \delta t \gtrsim \hbar \qquad \delta E = \delta N \hbar\omega \qquad \delta t = \delta\phi/\omega$$

$$\delta N \delta\phi \gtrsim 1$$

- Can also be derived more formally

Number-Phase Uncertainty Relation

- For typical uncorrelated systems, such as nominally classical light sources or collections of uncorrelated two-level systems, the state of the system is well described as a *coherent state*

- Coherent states reach the lower bound of the number-phase uncertainty relation, with the following balance between the uncertainty in the number of excitations and the uncertainty in the phase

$$\delta N \sim \sqrt{N} \qquad \delta\phi \sim 1/\sqrt{N}$$

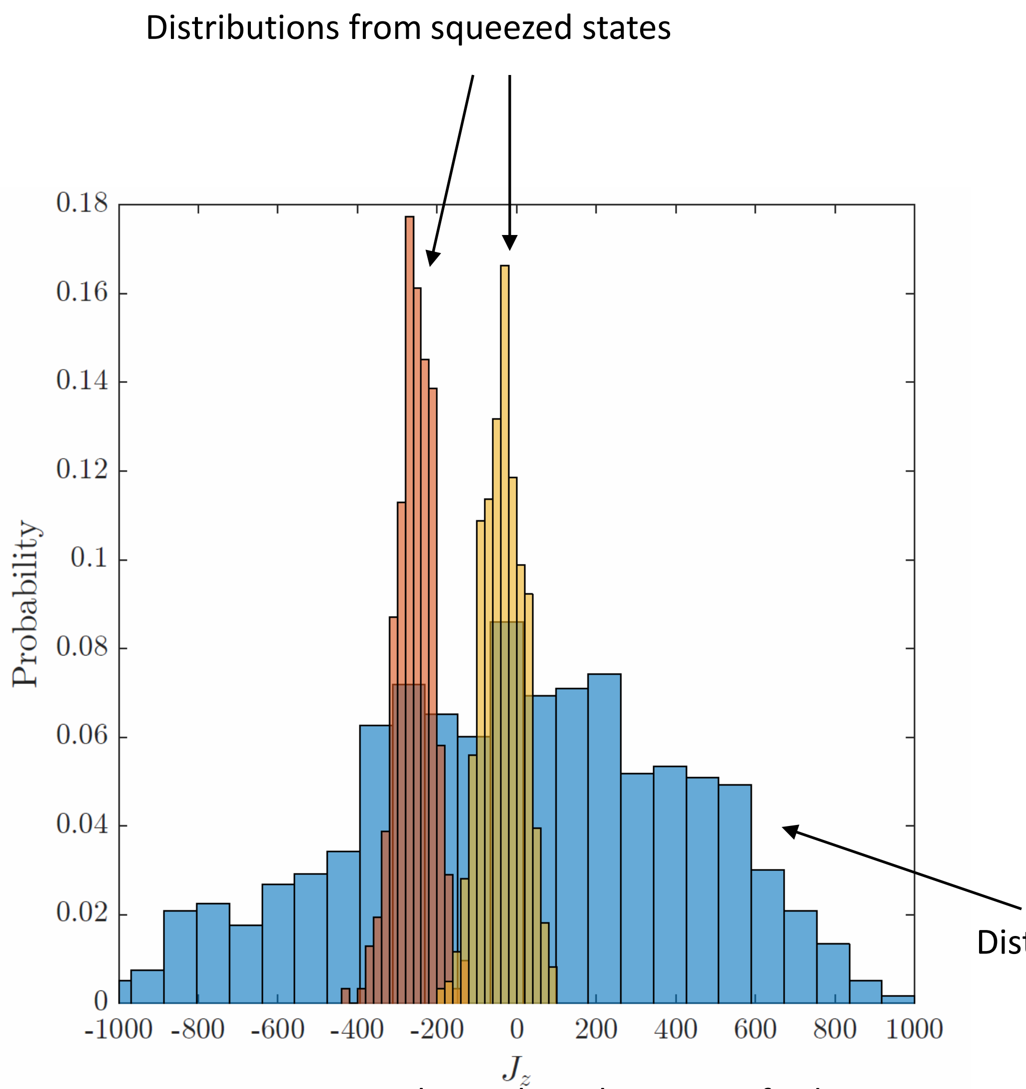
- Can trade off greater uncertainty in number for reduced uncertainty in phase by employing entanglement, often referred to as *squeezed states*

- For N particles, maximum possible uncertainty in number of excitations is N

- Implies the *Heisenberg limit* for phase resolution:

$$\delta\phi \sim 1/N$$

Squeezing Example



N. Engelson, Ph.D. thesis, Stanford University

- Entanglement between atoms used for a Ramsey sequence generated by using the interaction between atoms and light in an optical cavity
- Phase uncertainty, and resulting population uncertainty in interferometer output ports, reduced by a factor of ~10 beyond standard quantum limit
- Another example: squeezing used to improved sensitivity of LIGO (Aasi et al., Nature Photonics 7, 613 (2013))

Atom Interferometric Equivalence Principle Tests

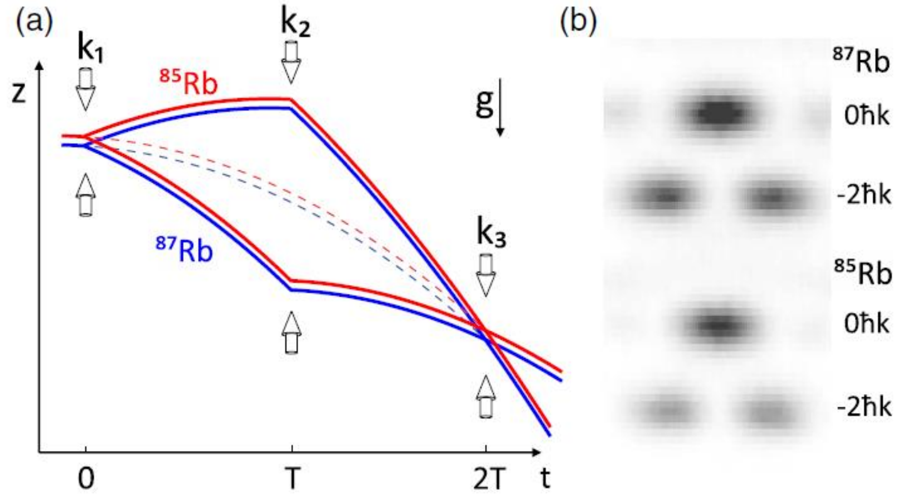
Macroscopic scale atom interferometers simultaneously comparing accelerations of two different isotopes of Rb tested weak equivalence principle (WEP) to ~1 part in 10^{12}

Rapid progress: 4 order of magnitude improvement over previous dual-species atom interferometry WEP measurements

Further improvements could lead to sensitivity competitive with best classical tests

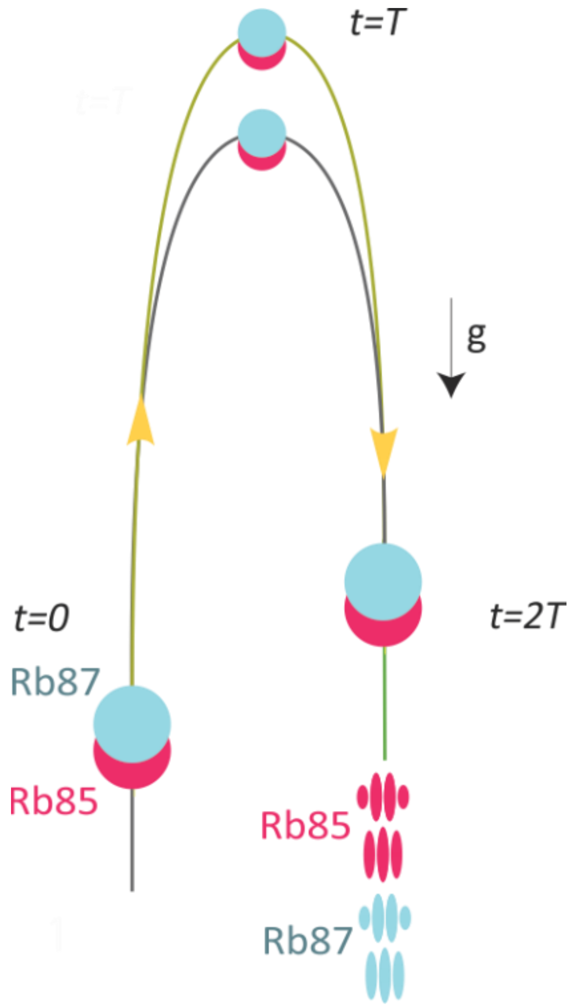
- -torsion balances: ~1 part in 10^{13} (Schlamminger et al. PRL 100, 041101 (2008))
- -MICROSCOPE space mission: ~1 part in 10^{14} (Touboul et al., PRL 119, 231101 (2017))

WEP tests probe fundamental aspects of gravity, also powerful tool to search for new interactions beyond the standard model



P. Asenbaum et al., PRL 125, 191101 (2020)

Simultaneous dual species interferometers



Suppresses time varying effects

Mirror motion

…

Bragg Interferometer

Common Bragg laser beams

Common velocity selection

AC stark shift compensation

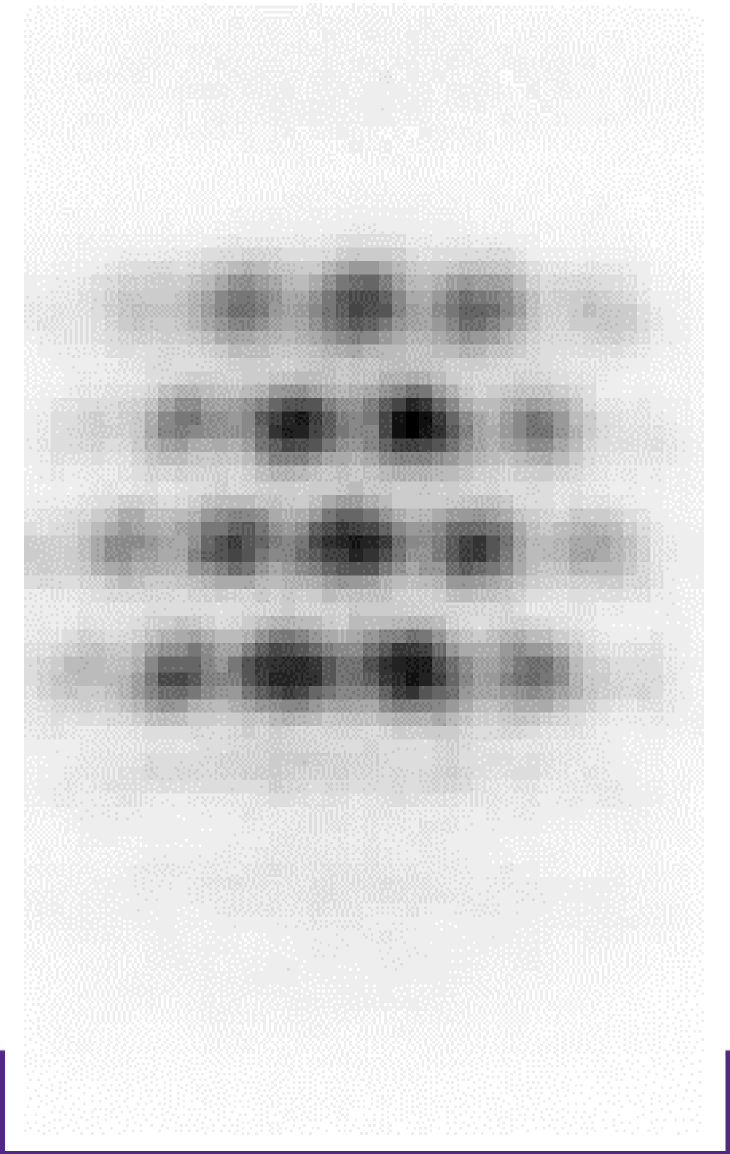
Phase shear readout

Contrast & amplitude noise

Sugarbaker et al, PRL 2013

$10\hbar k$ Dual Species Run

Rb-85



Rb-87

Rb-85 and Rb-87 are in phase

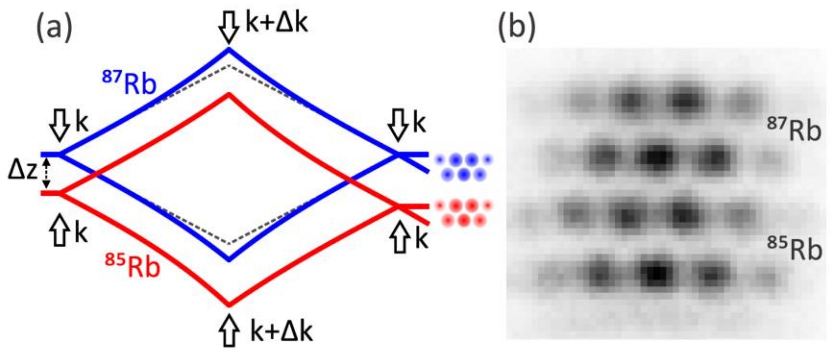
$2T = 1.8$ s

Gravity Gradient Compensation for WEP Test

Leading systematic for WEP test: initial kinematic offsets between the two species couple to gravity gradient, causes local *g* experienced by two species to differ

$$g_{\mathrm{A}} - g_{\mathrm{B}} = T_{zz}[\Delta z + \Delta v\, T] \equiv T_{zz}\Delta\bar{z}$$

Roura PRL 2017: proposes jumping frequency for middle interferometer pulses



$$-\left(nkT_{zz}T^2 + 2n\Delta k\right)(\Delta z + \Delta v_z T)$$

$$\Delta k/k = -T_{zz}T^2/2$$

Appropriate choice of frequency jump compensates gravity gradient phase shift

C. Overstreet, P. Asenbaum, T. Kovachy, R. Notermans, J. Hogan, and M. Kasevich, PRL (2018)

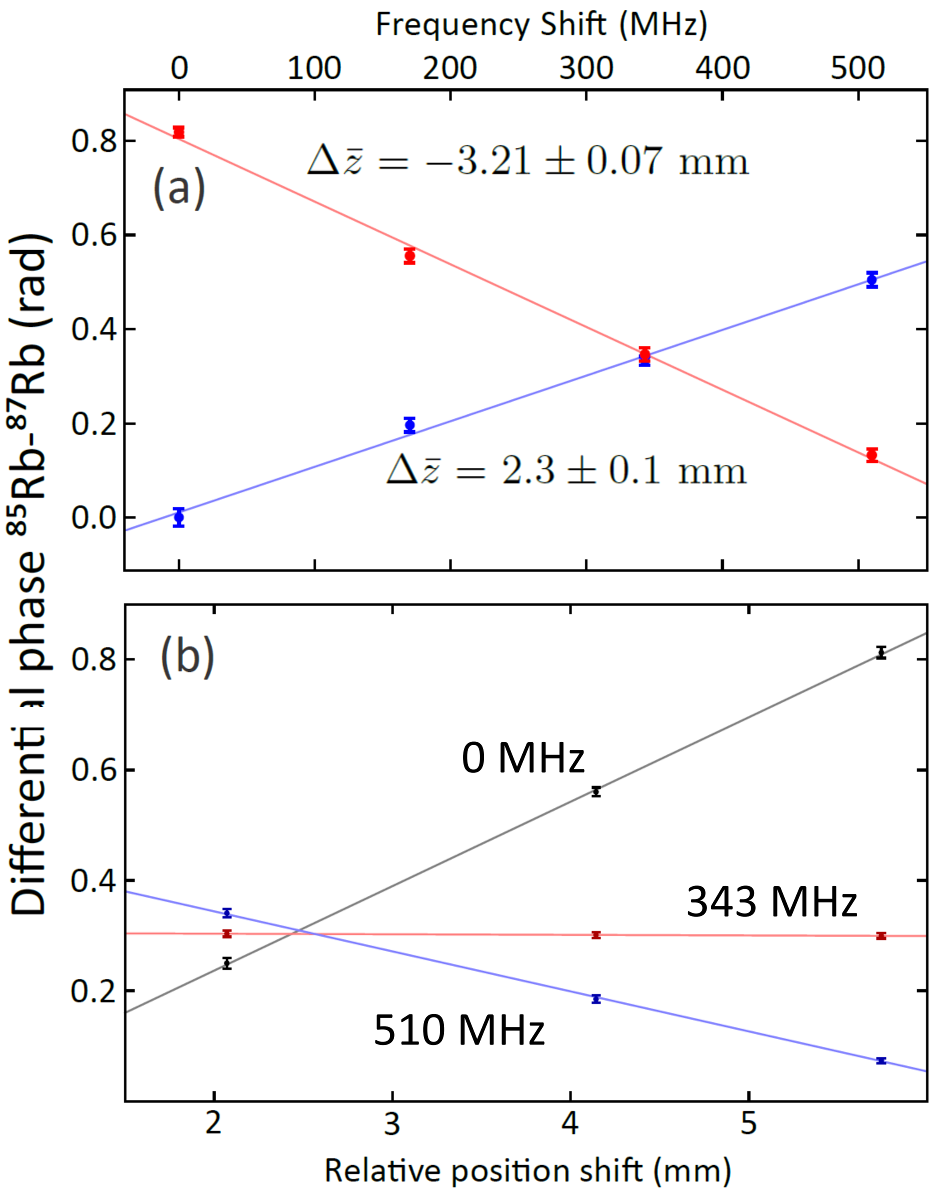
Gravity Gradient Compensation Results

- Apply relative position shift between Rb-85 and Rb-87 before interferometer using a combination of Raman and Bragg pulses

- Factor of 100 reduction in phase shift from coupling of gravity gradient to initial kinematic offsets

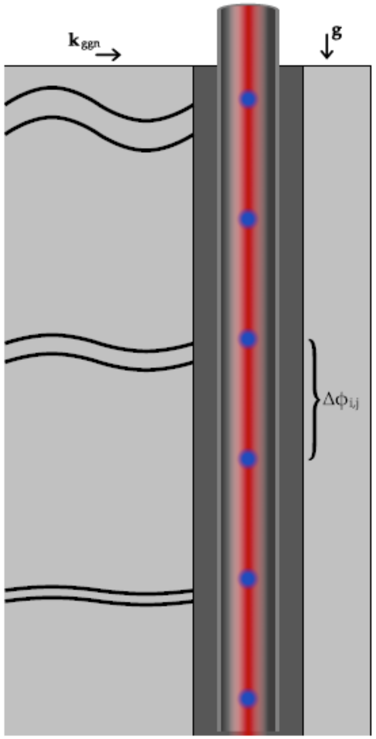
- By finding relative position shift for which phase shift is insensitive to the value of the frequency jump, can overlap initial kinematics to 40 microns

- Taken together, reduces gravity gradient systematics to below 1 part in 10^{13}



Extra Slides

Gravity Gradient Noise Suppression



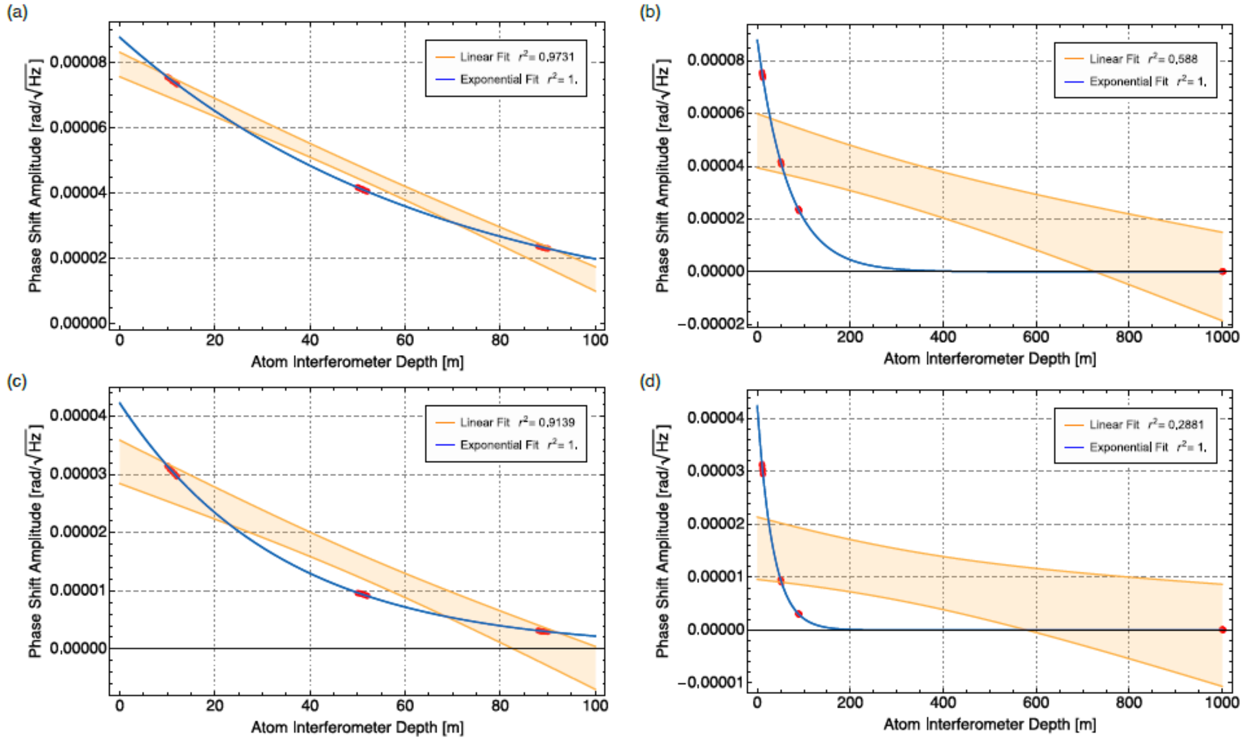


Figure 13. Fits of GGN phase shift Fourier amplitude at various depths along the atom interferometer baseline with phase noise of 1% of the maximum GGN signal added. (a, b) are fits of 0.5 Hz peak at 100 m and 1 km baselines respectively. (c, d) are fits of 1 Hz peak.

Measurements at multiple heights can strongly distinguish between exponential dependence of GGN signal on depth and a linear dependence

Gravity Gradient Noise Suppression

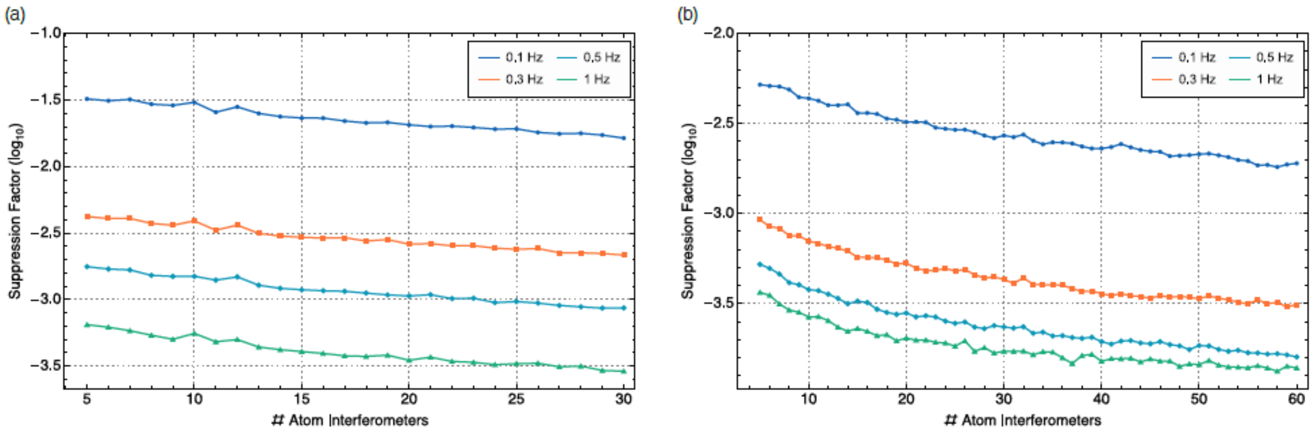


Figure 14. Suppression factor of GGN noise versus number of atom interferometers down the baseline for (a) 100 m and (b) 250 m. Plots show the effect for a Rayleigh wave with a frequency: 0.1 Hz, 0.3 Hz, 0.5 Hz, and 1 Hz. A sample period of 60 s and sample rate of 10 Hz is used for the signal. Suppression factor amplitudes are RMS values calculated after 1000 sets of fits each with randomized Gaussian phase noise of 1% of the maximum GGN signal amplitude at the surface.

-Preliminary studies suggest potential to suppress GGN noise by multiple orders of magnitude

-More detailed analysis needed, e.g., taking into account effects such as variation of soil/rock density with depth and body wave terms