Gravitational Wave Detection with Atom Interferometry

Peter Graham
Stanford

PRL **110** (2013) arXiv: 1206.0818
PLB **678** (2009) arXiv: 0712.1250
PRD **78** (2008) arXiv: 0806.2125
PRD **78** (2008) arXiv: 0802.4098
PRL **98** (2007) gr-qc/0610046
GRG **43** (2011) arXiv:1009.2702

Outline

1. Motivation

2. Atom Interferometry

3. Gravitational Wave Detection

   - Atomic Gravitational Wave Interferometric Sensor (AGIS)
   - Laser Noise Insensitive Detection (“Bing-Bang”)

4. Testing General Relativity in the Lab

Gravitational Wave Motivation

Gravitational waves open a new window to the universe:

sourced by mass, not charge

universe is transparent to gravity waves

- provide unique astrophysical information

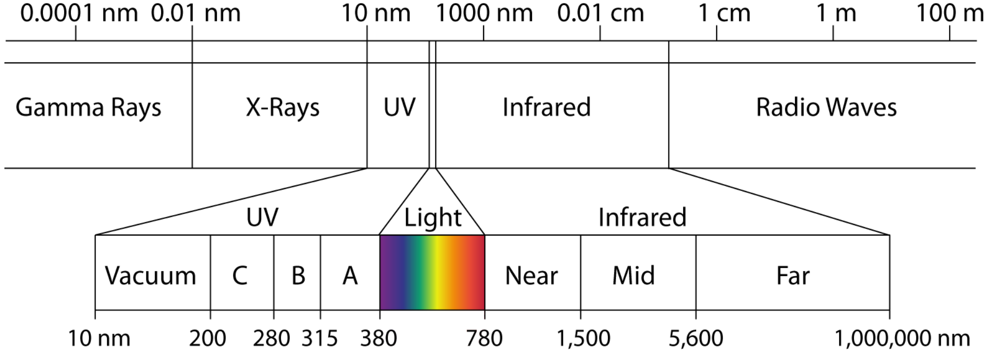
  compact object binaries

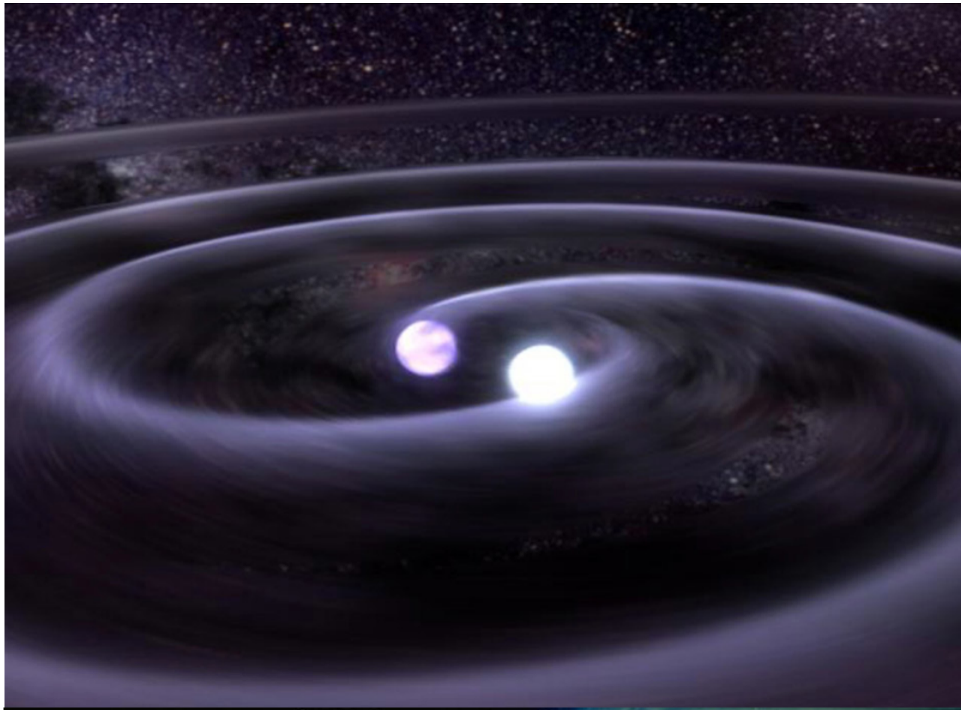
  black holes, white dwarfs, neutron stars

  near horizon geometry of black hole

  test strong field gravity

- Every new band opened has revealed unexpected discoveries





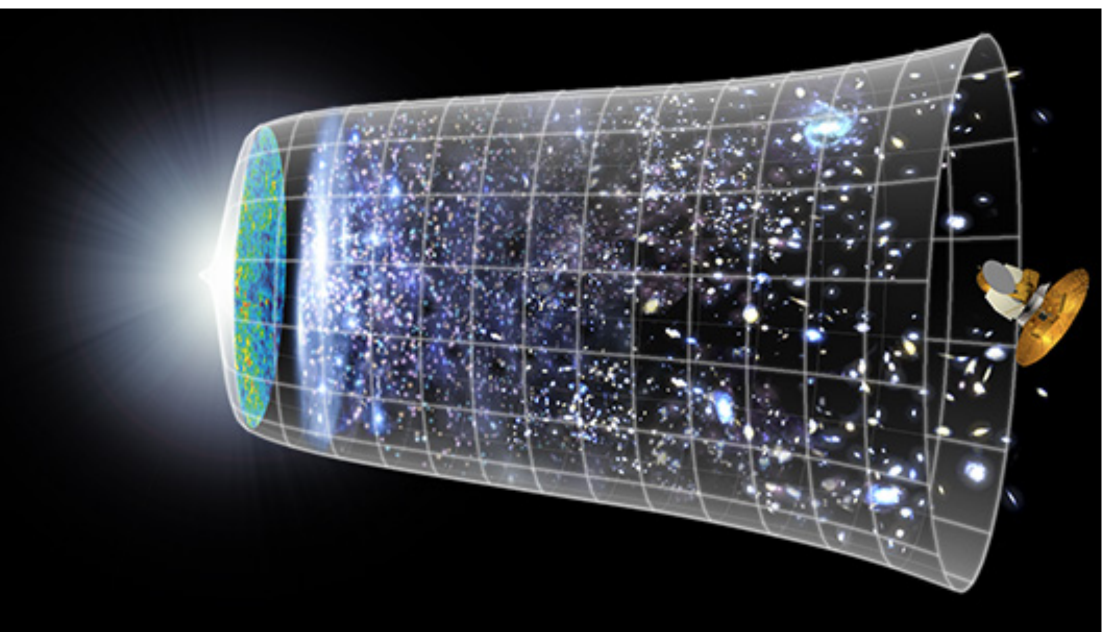
Cosmology

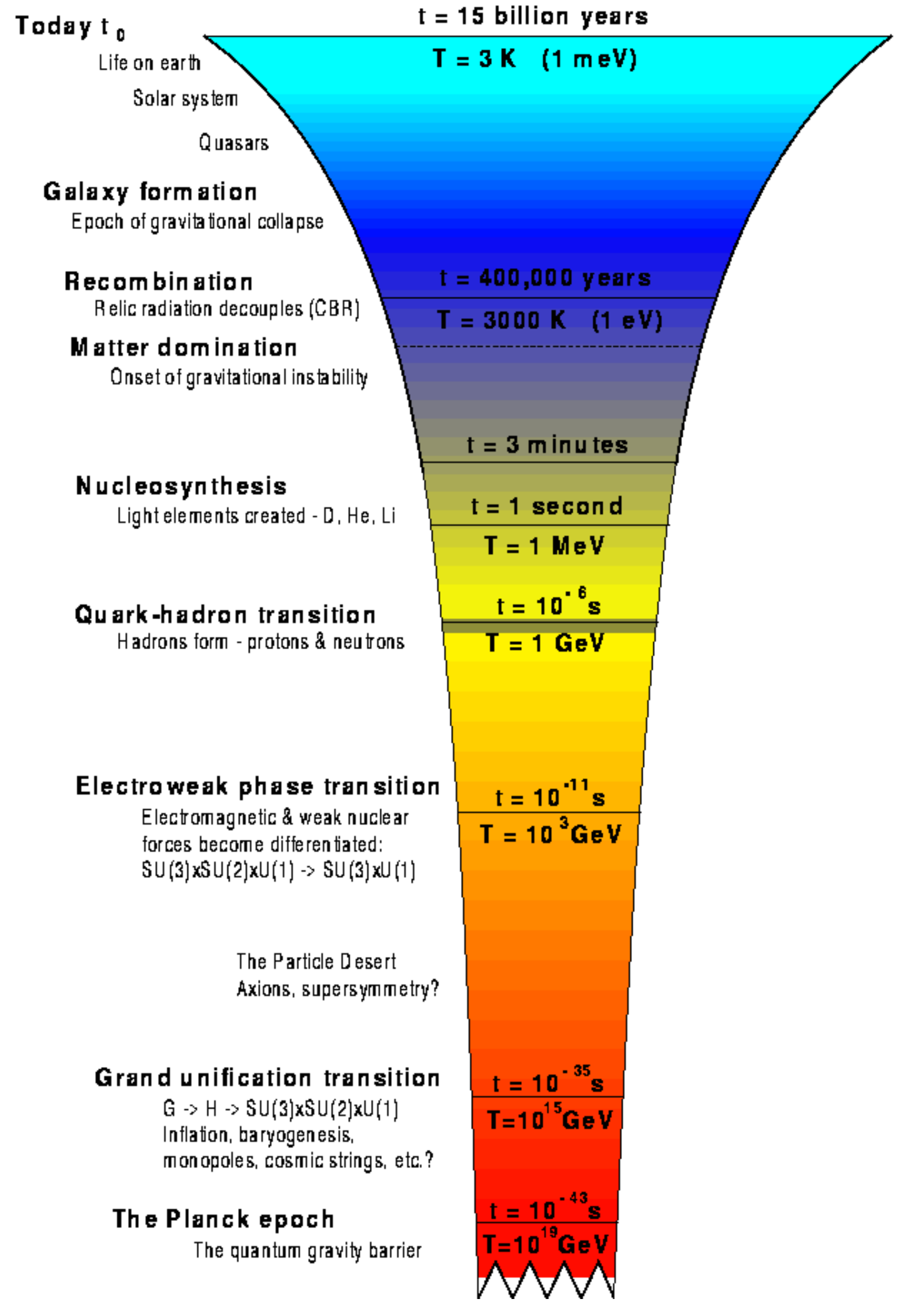
Gravitational waves open a new window to the universe:

sourced by mass, not charge

universe is transparent to gravity waves

- rare opportunity to study cosmology before last scattering
  - inflation and reheating
  - early universe phase transitions
  - cosmic strings ...

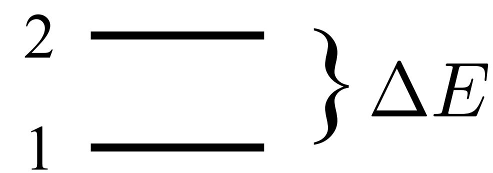




Atomic Interferometry

Atomic Clock

$$|\mathrm{atom}\rangle = |1\rangle$$

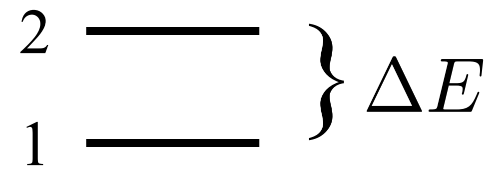


Atomic Clock

$$|\mathrm{atom}\rangle = |1\rangle$$

beamsplitter

$$\frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$



Atomic Clock

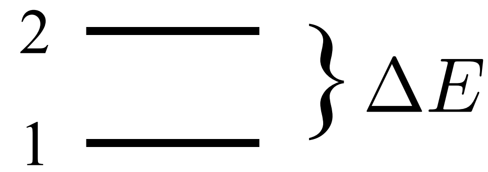
$$|\text{atom}\rangle = |1\rangle$$

beamsplitter

$$\frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$

wait time t

$$\frac{1}{\sqrt{2}}\left(|1\rangle + e^{i(\Delta E)t}|2\rangle\right)$$



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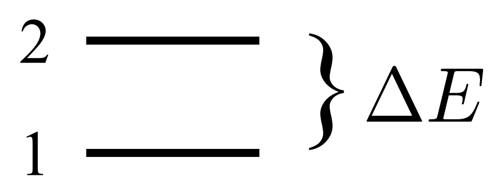


wait time t

$$\frac{1}{\sqrt{2}}\left(|1\rangle + e^{i(\Delta E)t}|2\rangle\right)$$

beamsplitter

$$\frac{1}{2}\left[\left(1 - e^{i(\Delta E)t}\right)|1\rangle + \left(1 + e^{i(\Delta E)t}\right)|2\rangle\right]$$

Atomic Clock

$$|\text{atom}\rangle = |1\rangle$$

beamsplitter

$$\frac{1}{\sqrt{2}}\left(|1\rangle + |2\rangle\right)$$

wait time t

$$\frac{1}{\sqrt{2}}\left(|1\rangle + e^{i(\Delta E)t}|2\rangle\right)$$

beamsplitter

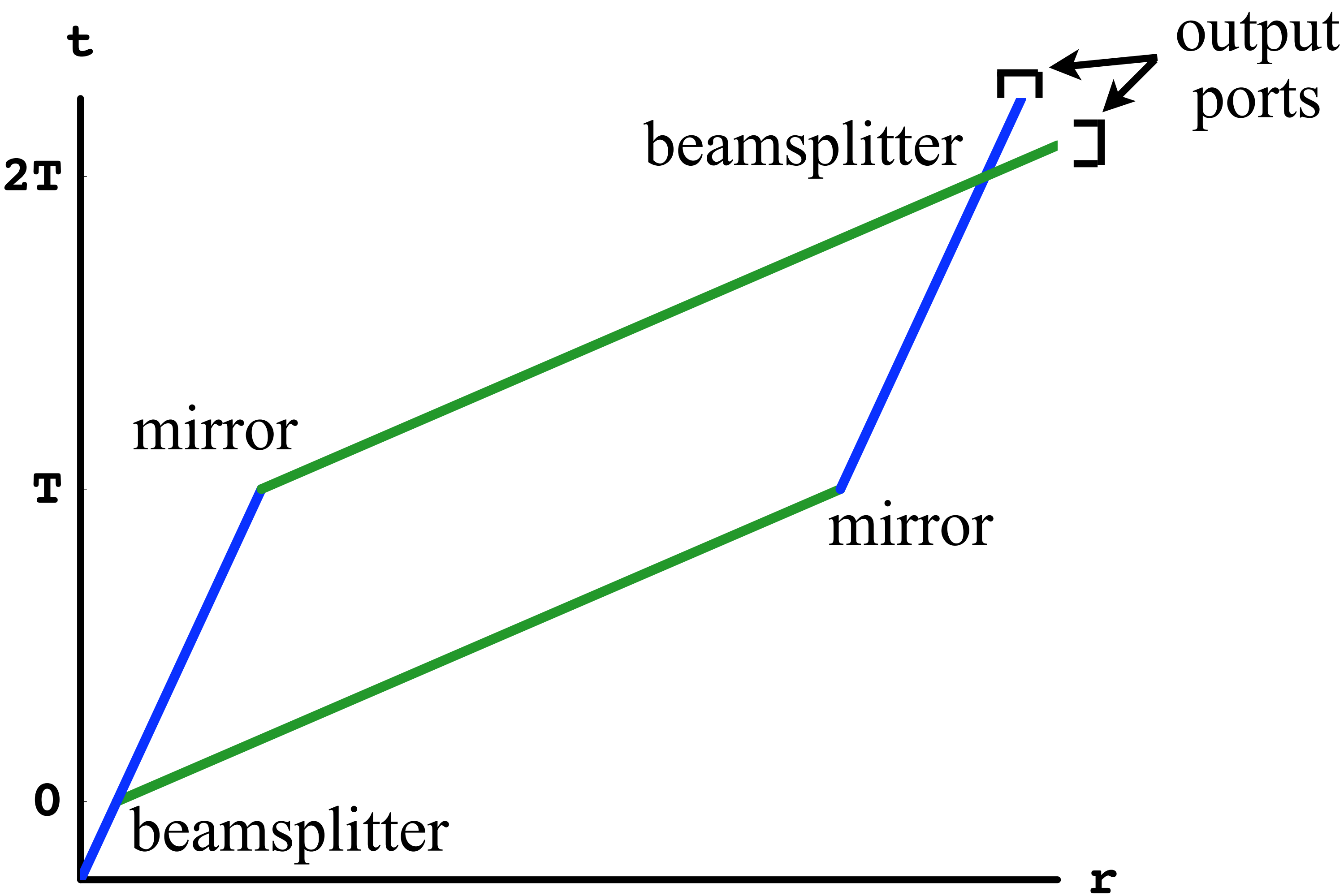
$$\frac{1}{2}\left[\left(\underbrace{1 - e^{i(\Delta E)t}}_{N_1}\right)|1\rangle + \left(\underbrace{1 + e^{i(\Delta E)t}}_{N_2}\right)|2\rangle\right]$$

output ports

can measure times $t \sim \frac{1}{\Delta E} \sim 10^{-10}\,\text{s}$

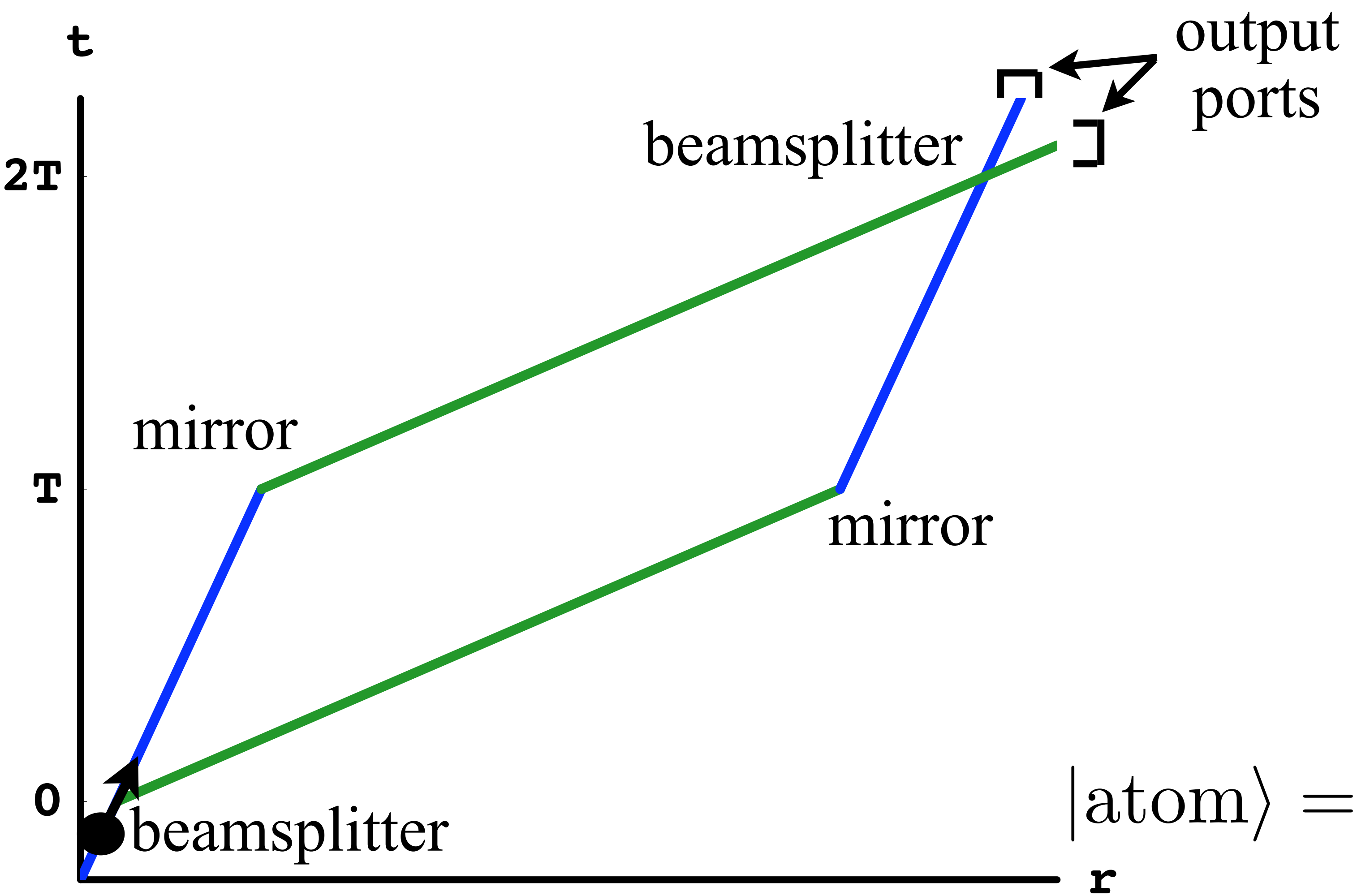
Atom Interferometry

Space-time Interferometry



Atom Interferometry

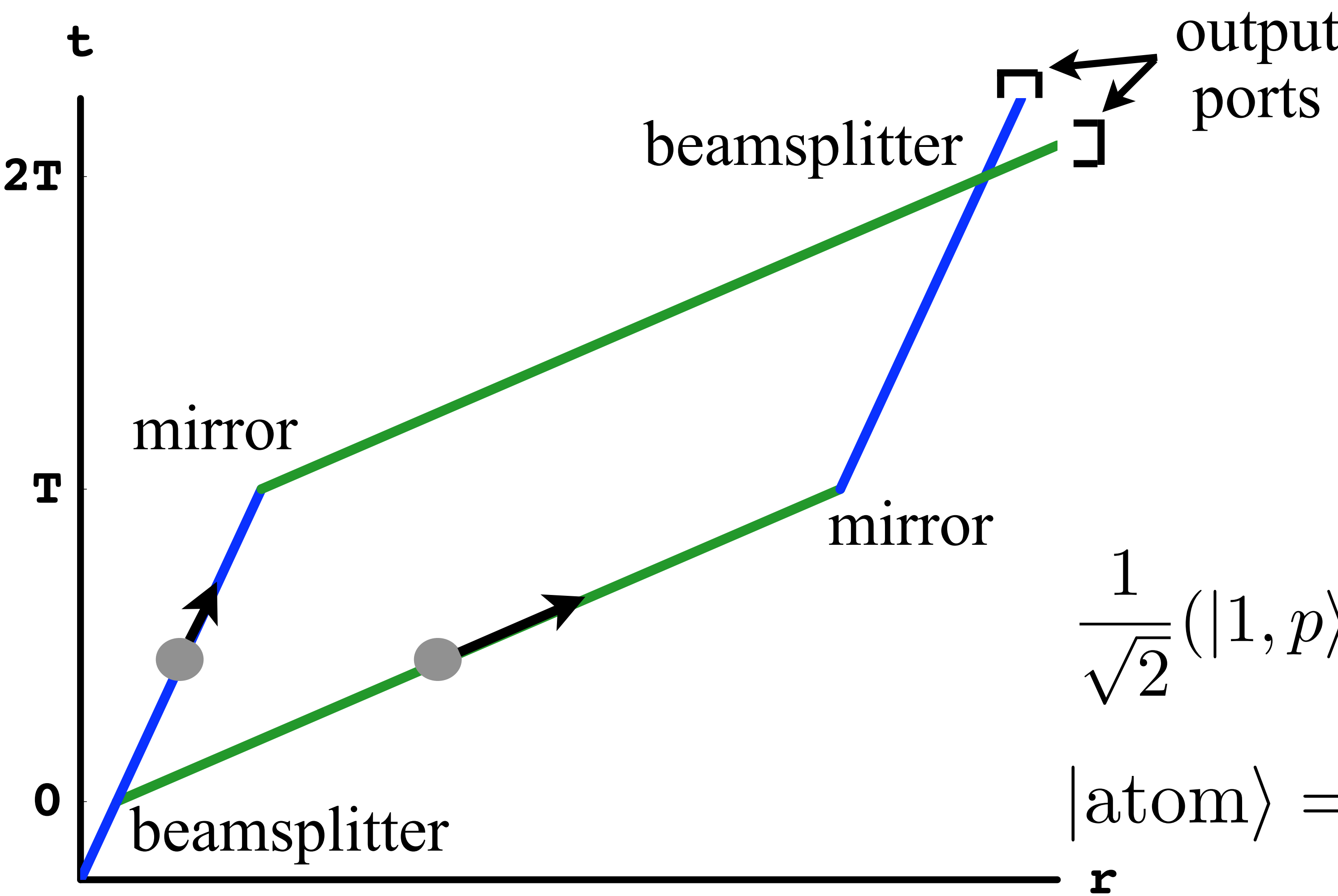
Space-time Interferometry



$$|\text{atom}\rangle = |1, p\rangle$$

Atom Interferometry

Space-time Interferometry

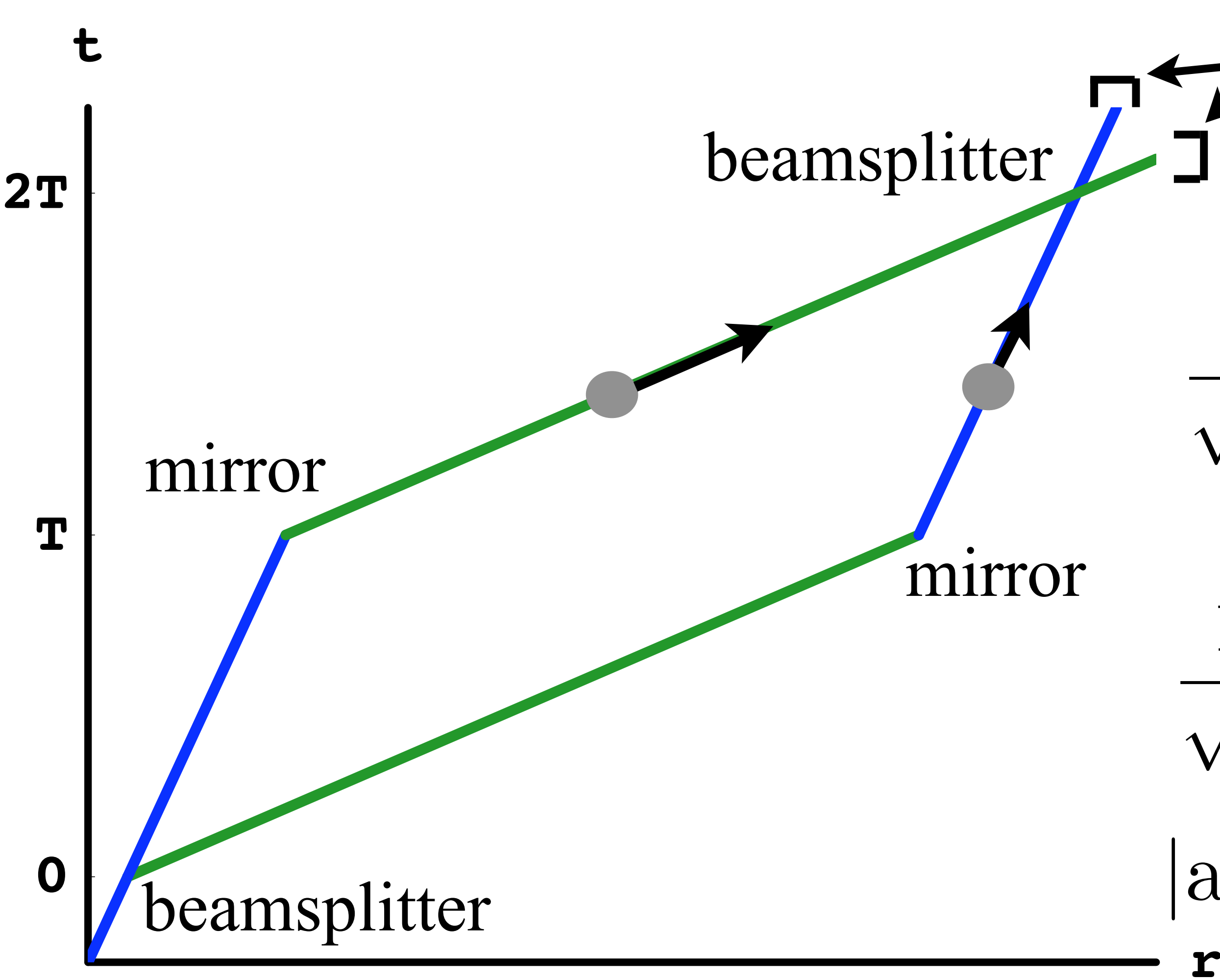


$$\frac{1}{\sqrt{2}}(|1,p\rangle + e^{i\Delta\phi}|2,p+k\rangle)$$

$$|\text{atom}\rangle = |1,p\rangle$$

Atom Interferometry

Space-time Interferometry



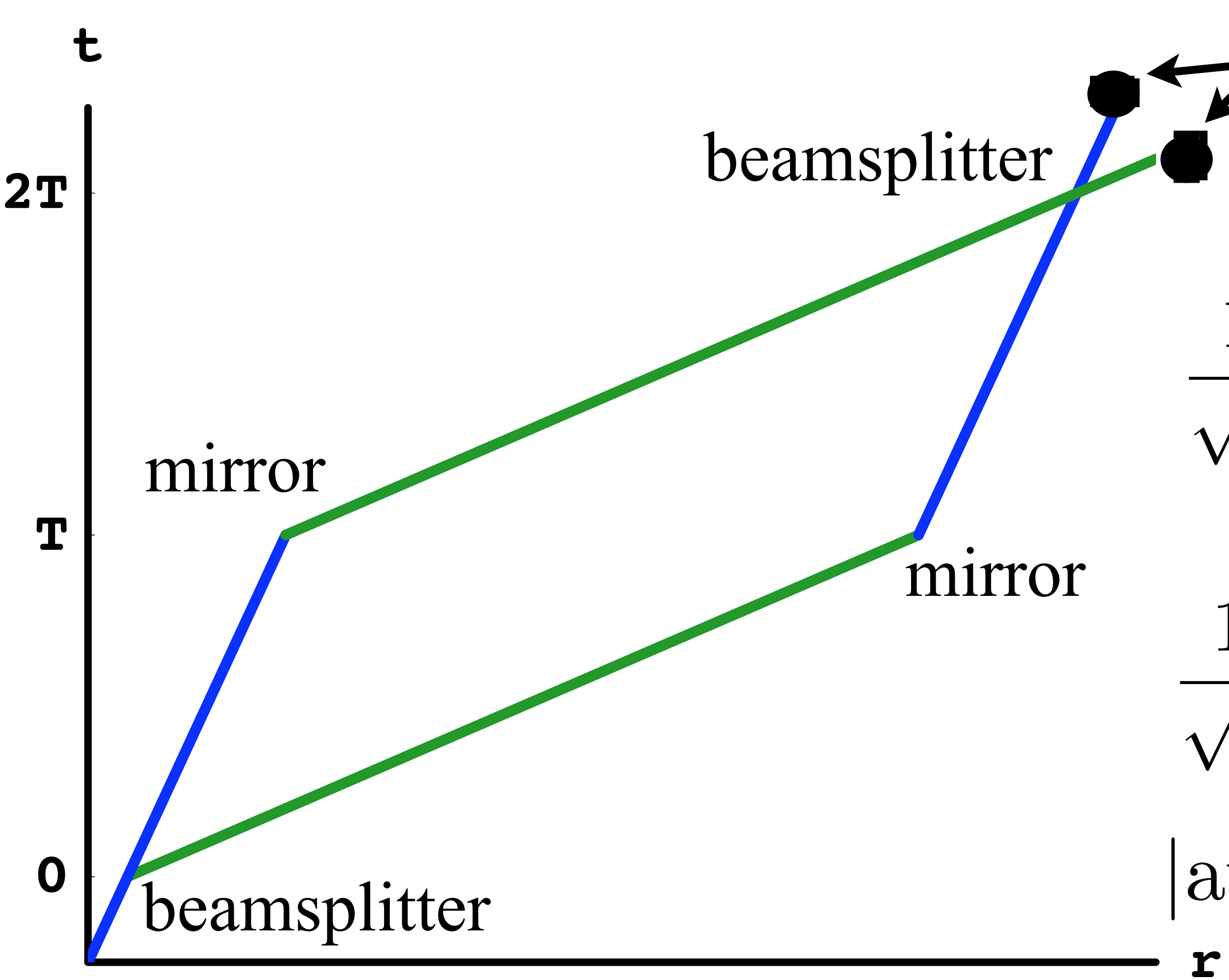
$$\frac{1}{\sqrt{2}}(|2, p+k\rangle + e^{i\Delta\phi}|1, p\rangle)$$

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

$$|\mathrm{atom}\rangle = |1, p\rangle$$

Atom Interferometry

Space-time Interferometry



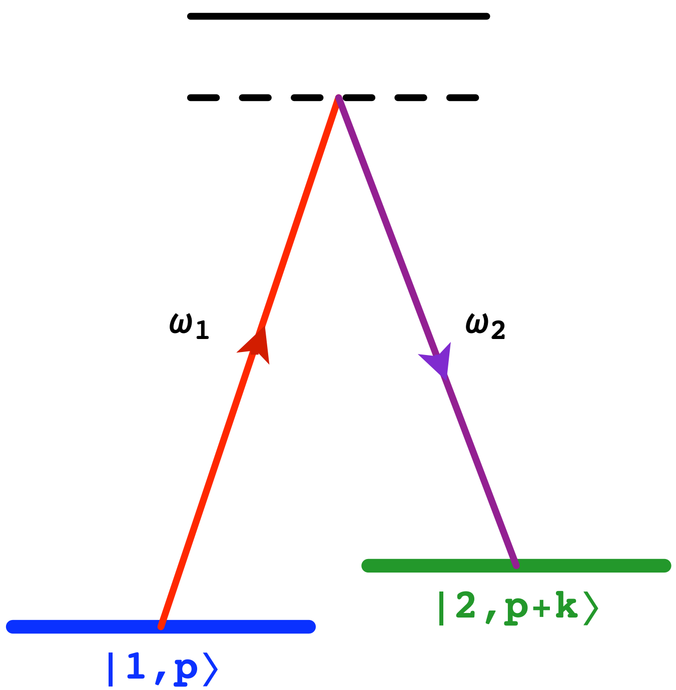
$$\frac{1}{\sqrt{2}}(|2, p+k\rangle + e^{i\Delta\phi}|1, p\rangle)$$

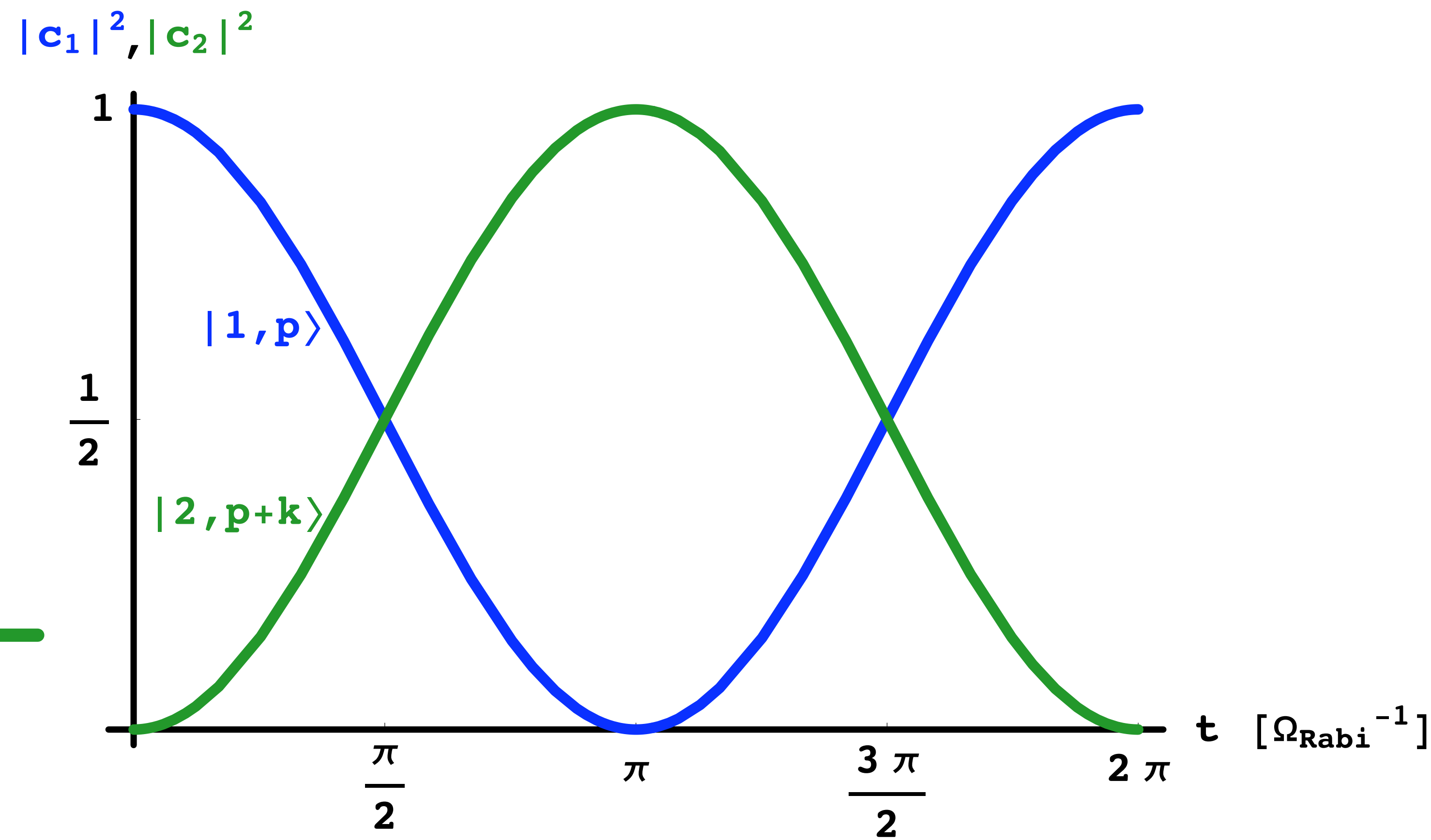
$$\frac{1}{\sqrt{2}}(|1, p\rangle + e^{i\Delta\phi}|2, p+k\rangle)$$

$$|\mathrm{atom}\rangle = |1, p\rangle$$

Raman Transition

$$\psi = c_1|1,p\rangle + c_2|2,p+k\rangle$$

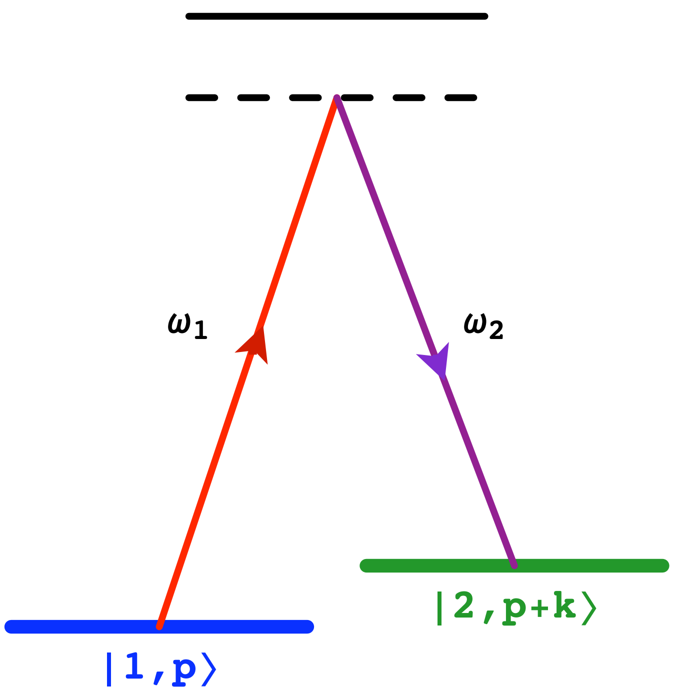


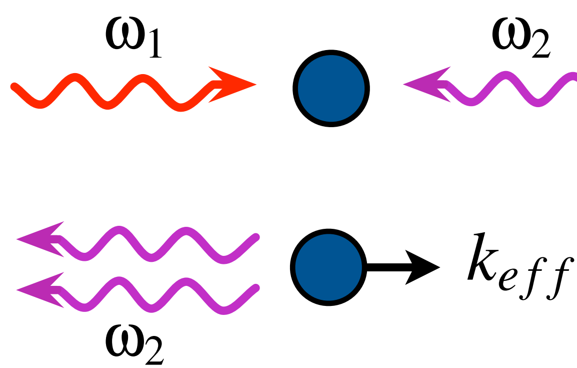


$\pi/2$ pulse is a beamsplitter

π pulse is a mirror

Raman Transition



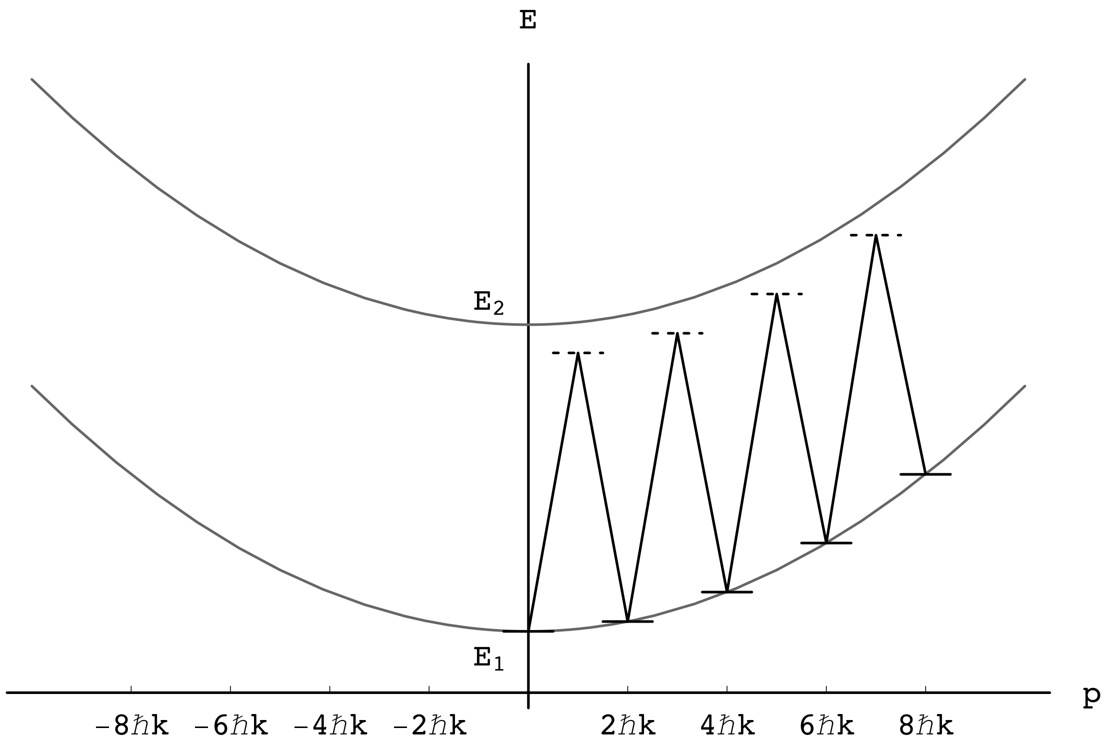


$$k_{eff} = \omega_1 + \omega_2 \sim 1 \text{ eV}$$

$$\omega_{eff} = \omega_1 - \omega_2 \sim 10^{-5} \text{ eV}$$

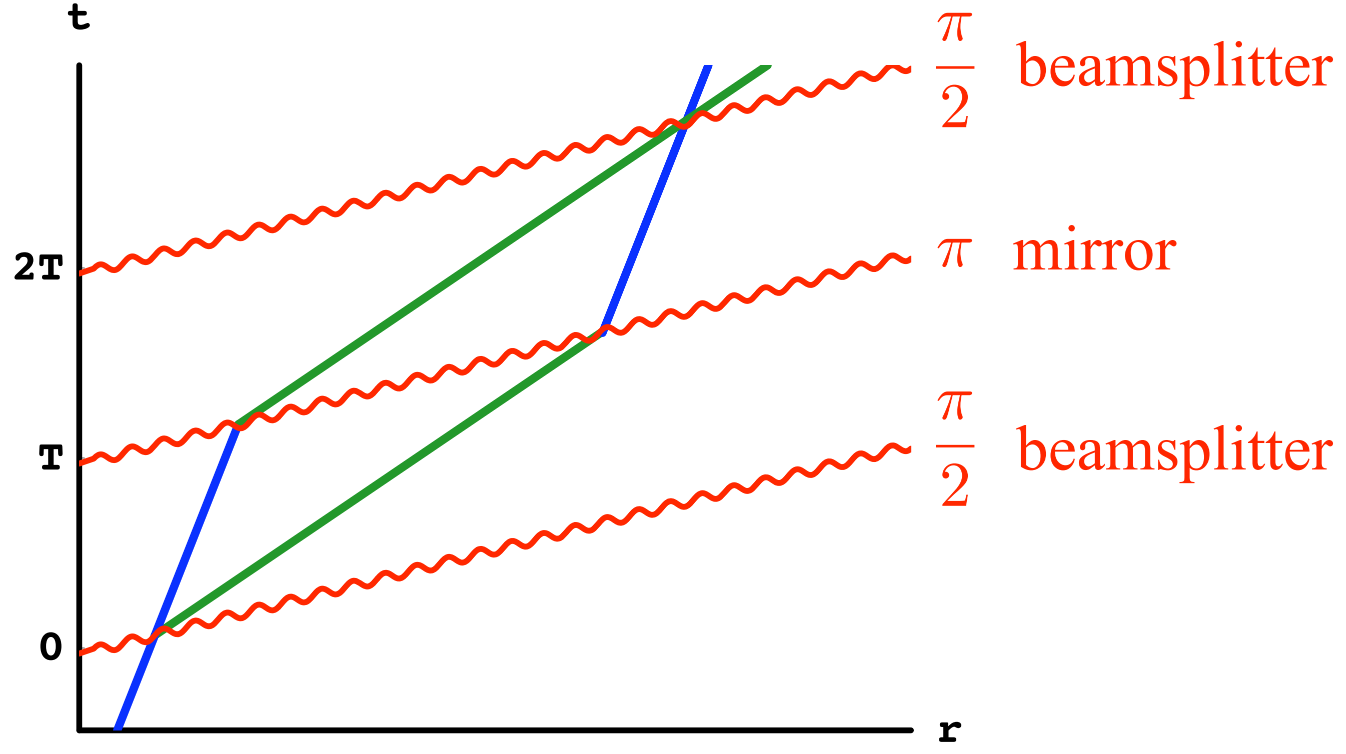
Large Momentum Transfer (LMT)

better beamsplitters:

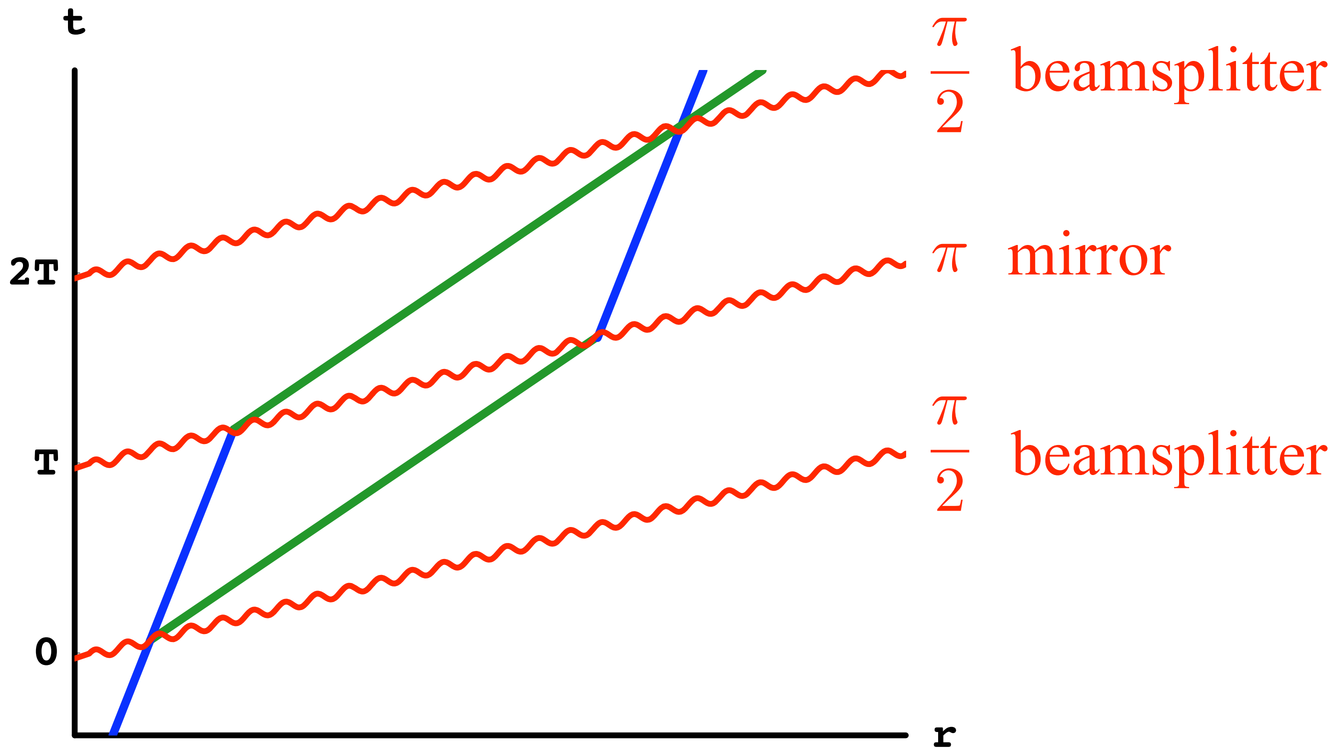


Improves signal by factor of N (could be ~100)

Light Pulse Atom Interferometry



Light Pulse Atom Interferometry



GR calculation PRD **78** (2008) $\Delta\phi = \int L dt = \int m d\tau = \int p_\mu dx^\mu$

a constant gravitational field produces a phase shift:

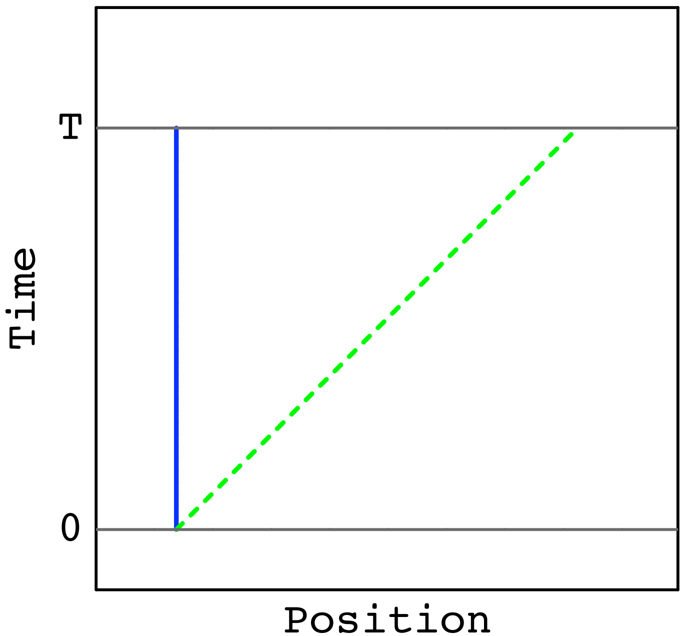
$$\Delta\phi \sim mg(\Delta h)T \sim mg\left(\frac{k}{m}T\right)T = kgT^2 \sim 10^8 \text{ rad}$$

sensitivity ~ 10^{-7} rad

the interferometer can be as long as T ~ 1 sec ~ earth-moon distance!

The Tools

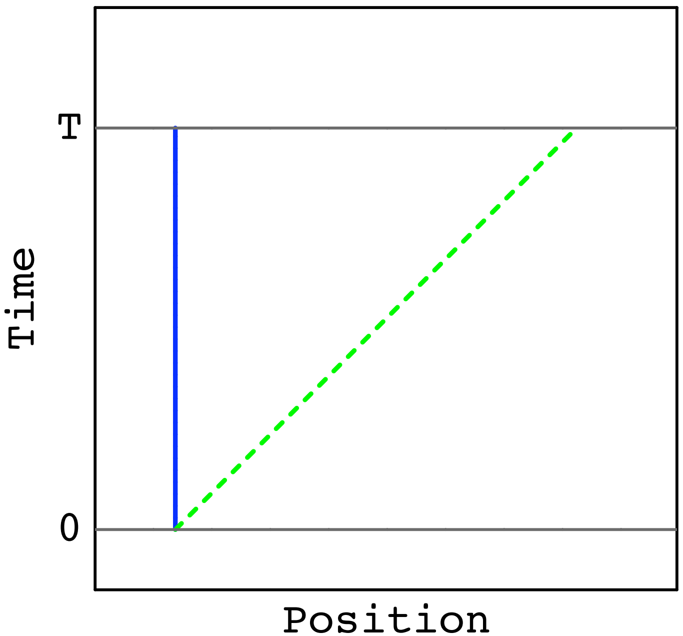
clock



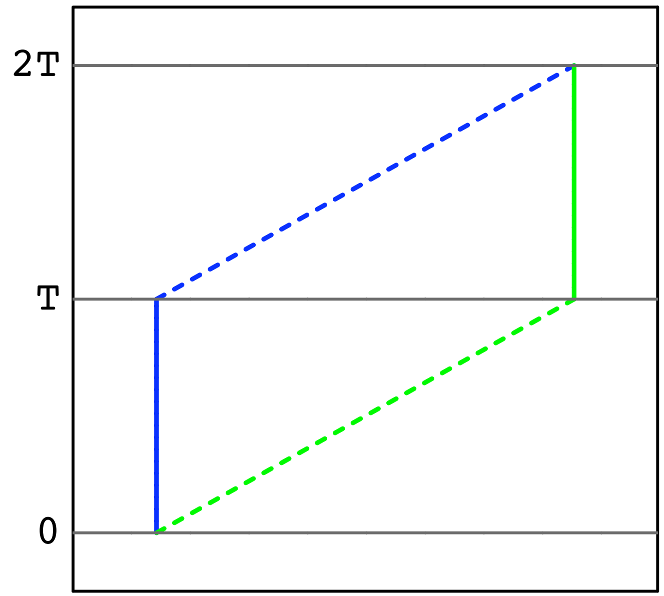
measures: v

The Tools

clock



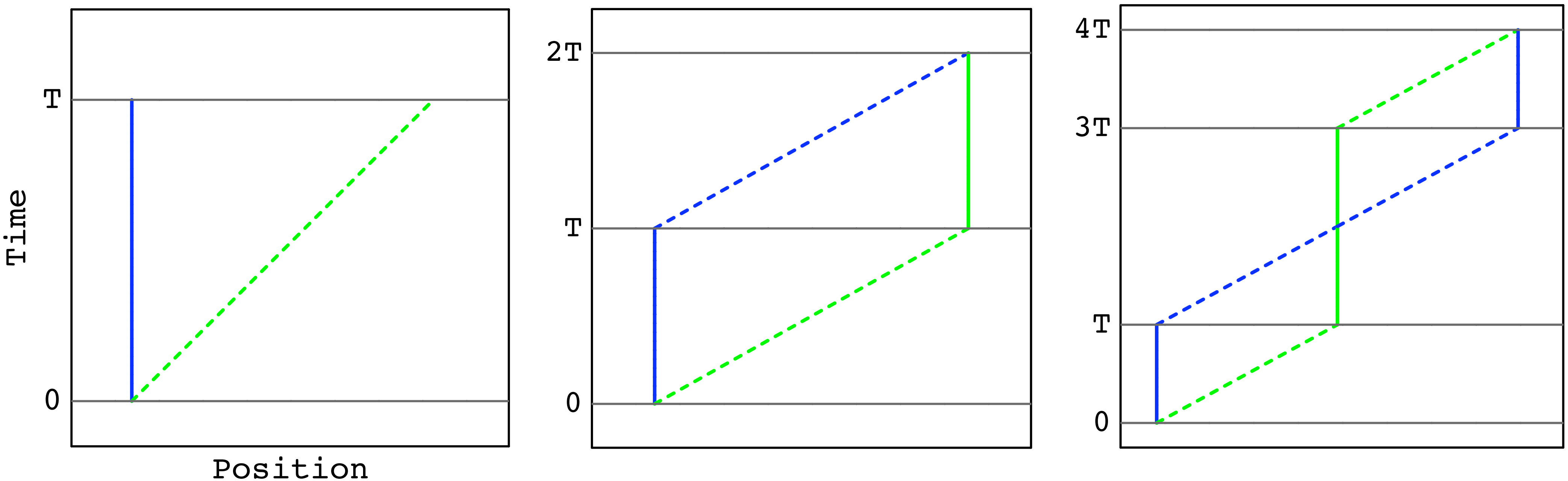
accelerometer



measures: v a

The Tools

clock accelerometer



measures: v a $\dot{a}$

Gravitational Wave Detection

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

Gravity Wave Signal

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

laser ranging an atom (or mirror) from a starting distance L sees a position:

$$x \sim L(1 + h\sin(\omega t))$$

Gravity Wave Signal

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

laser ranging an atom (or mirror) from a starting distance L sees a position:

$$x \sim L(1 + h\sin(\omega t))$$

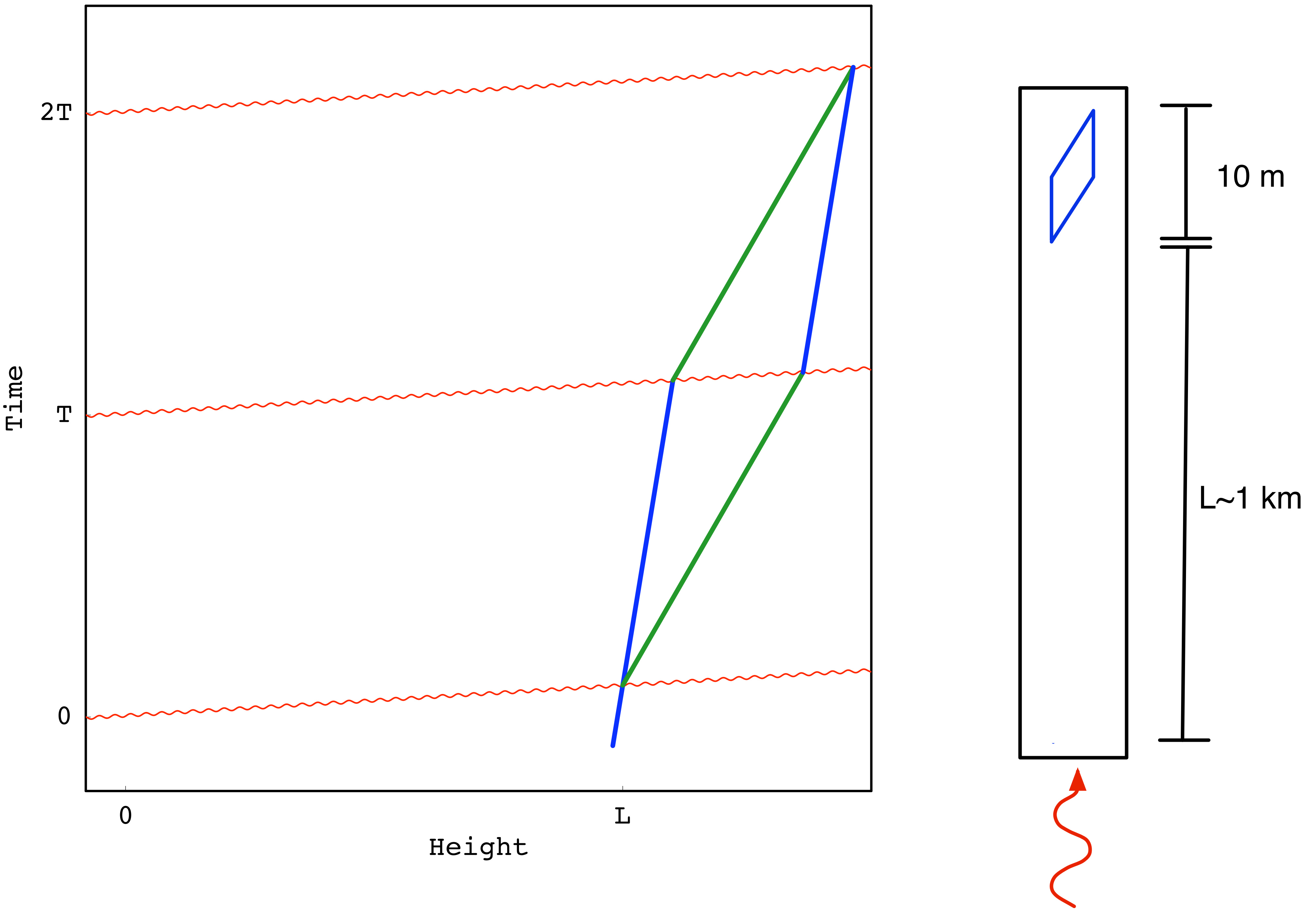
and an acceleration $a \sim hL\omega^2 \sin(\omega t)$

gives a phase shift $\Delta\phi = kaT^2 \sim khL\omega^2 \sin(\omega t)T^2$

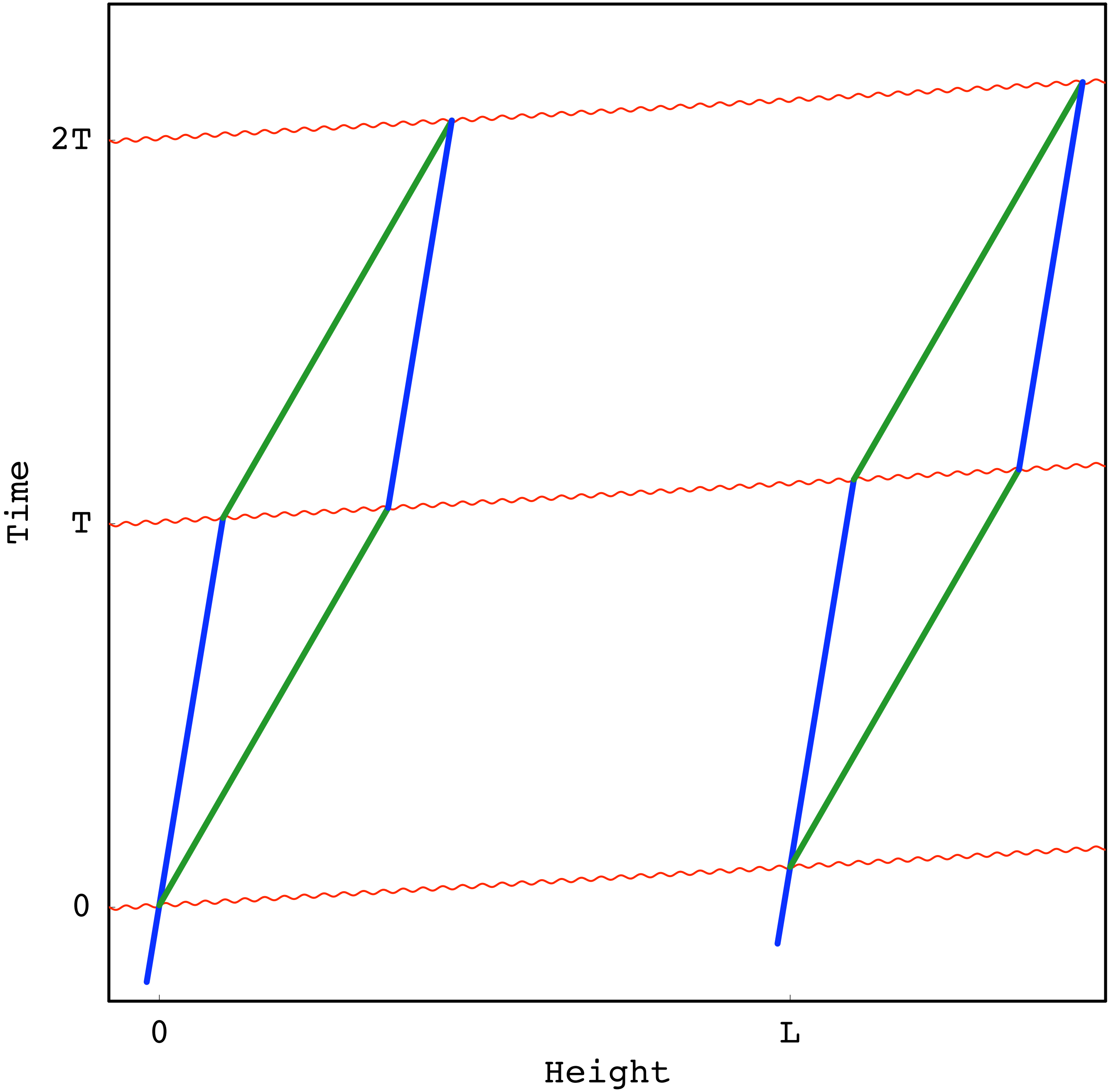
actual answer: $\Delta\phi_{\mathrm{tot}} = 4\frac{hk}{\omega}\sin^2\left(\frac{\omega T}{2}\right)\sin\left(\omega L\right)\sin\left(\omega t\right)$

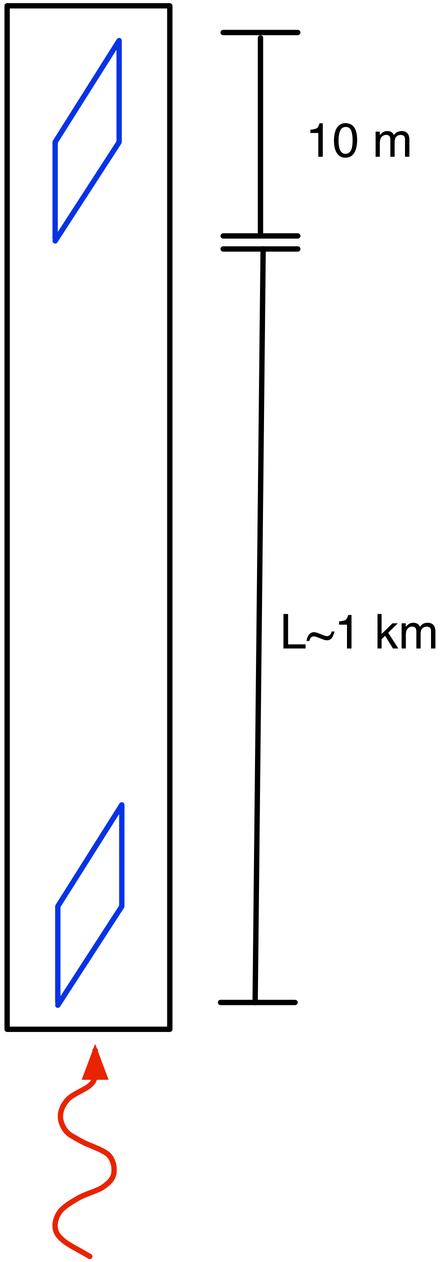
PRD **78** (2008)

Gravity Wave Signal



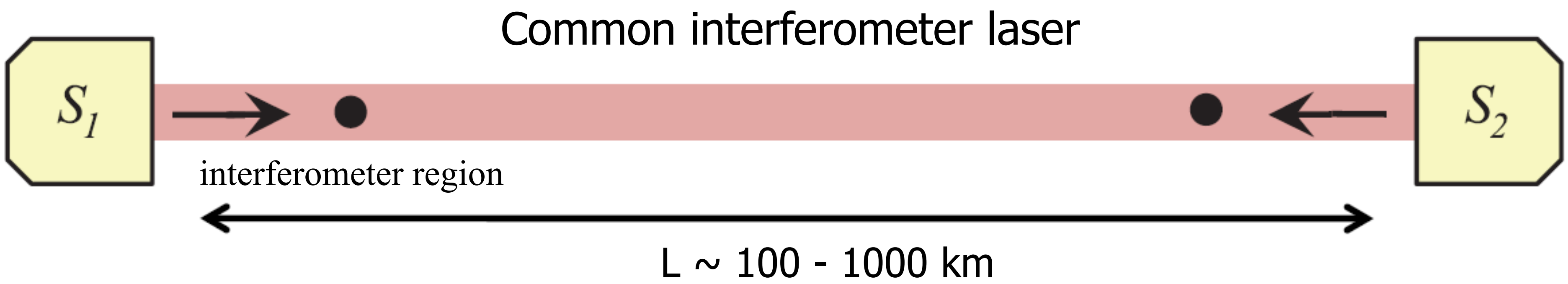
Differential Measurement





measures differential acceleration between two atoms

Atomic Gravitational Wave Interferometric Sensor (AGIS)



Atom Interferometry (AGIS)

baseline L ~ 10^3 km

requires satellite control (at 10^{-2} Hz) to $10 \frac{\mu\mathrm{m}}{\sqrt{\mathrm{Hz}}}$

atoms provide inertial proof mass, neutral

gas collisions remove atoms, not a noise source

LISA

baseline L = 5×10^6 km

satellite control to $1 \frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}}$

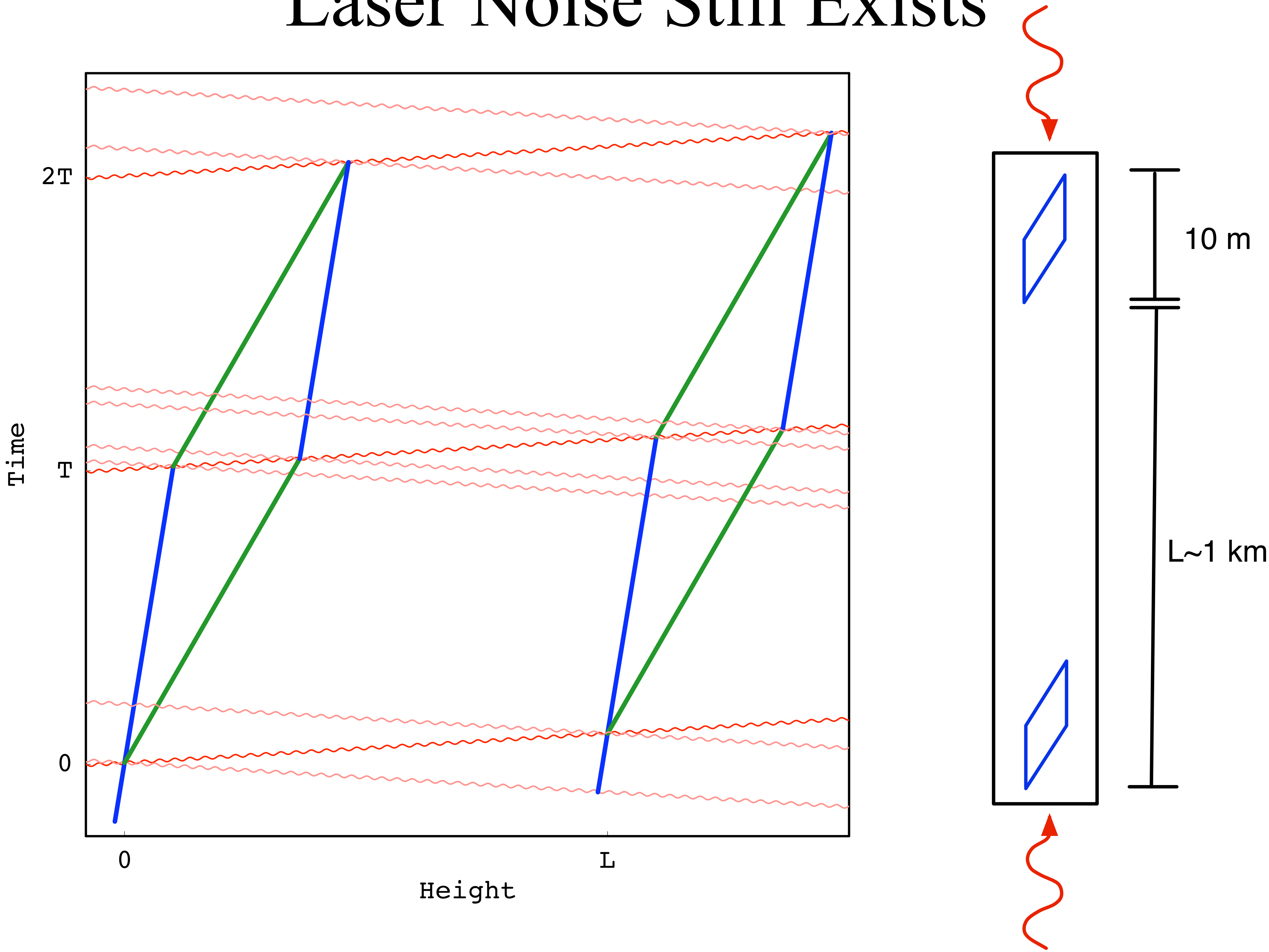
large EM force on charged proof mass

collisions with background gas are noise

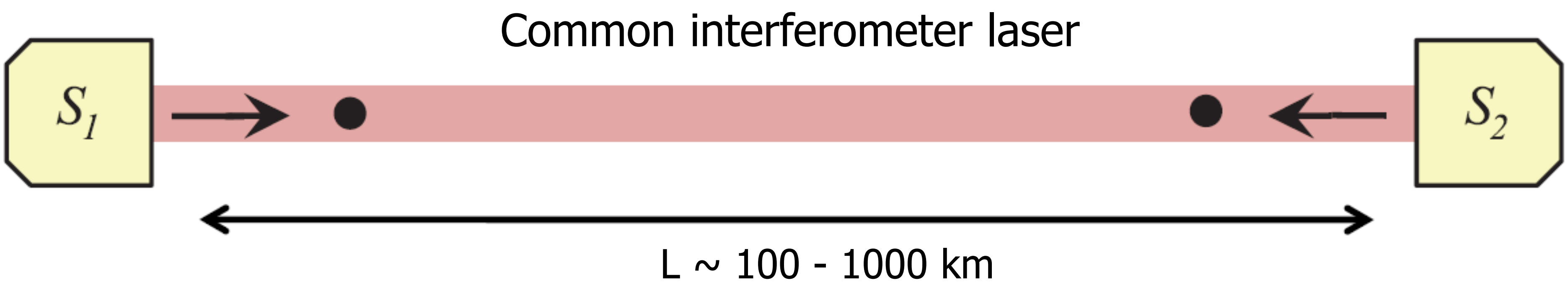
several backgrounds and technical requirements may be easier with AI

motivates more careful consideration of engineering details

Laser Noise Still Exists

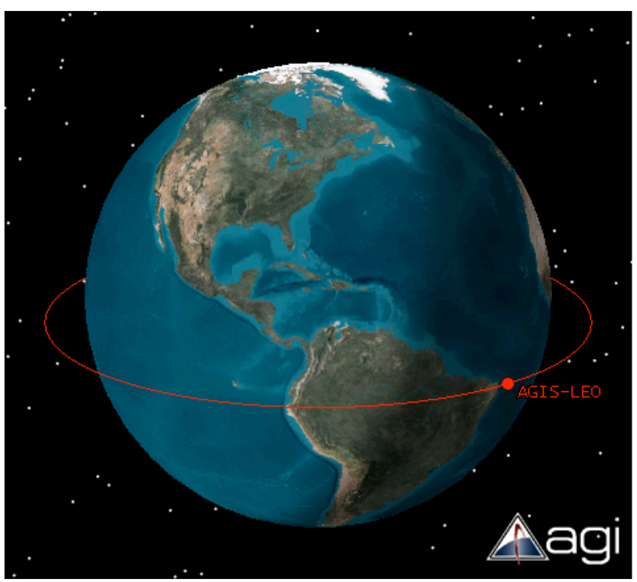


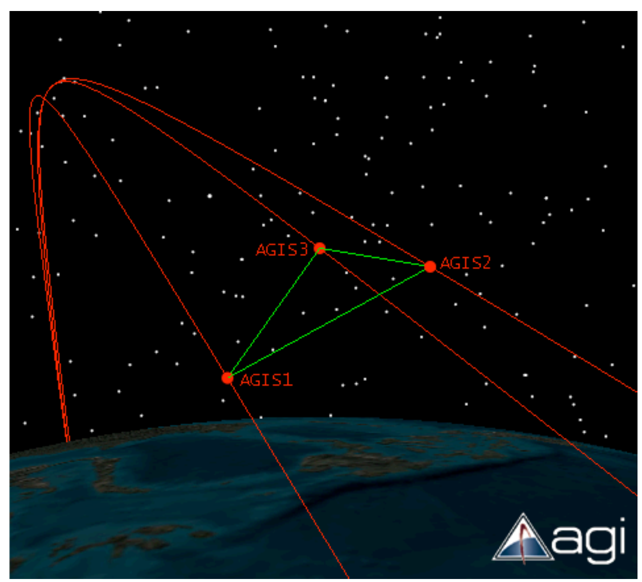
Atomic Gravitational Wave Interferometric Sensor (AGIS)



Several techniques to remove laser noise: e.g. triangle configuration

small baseline may allow earth orbit (AGIS-LEO):

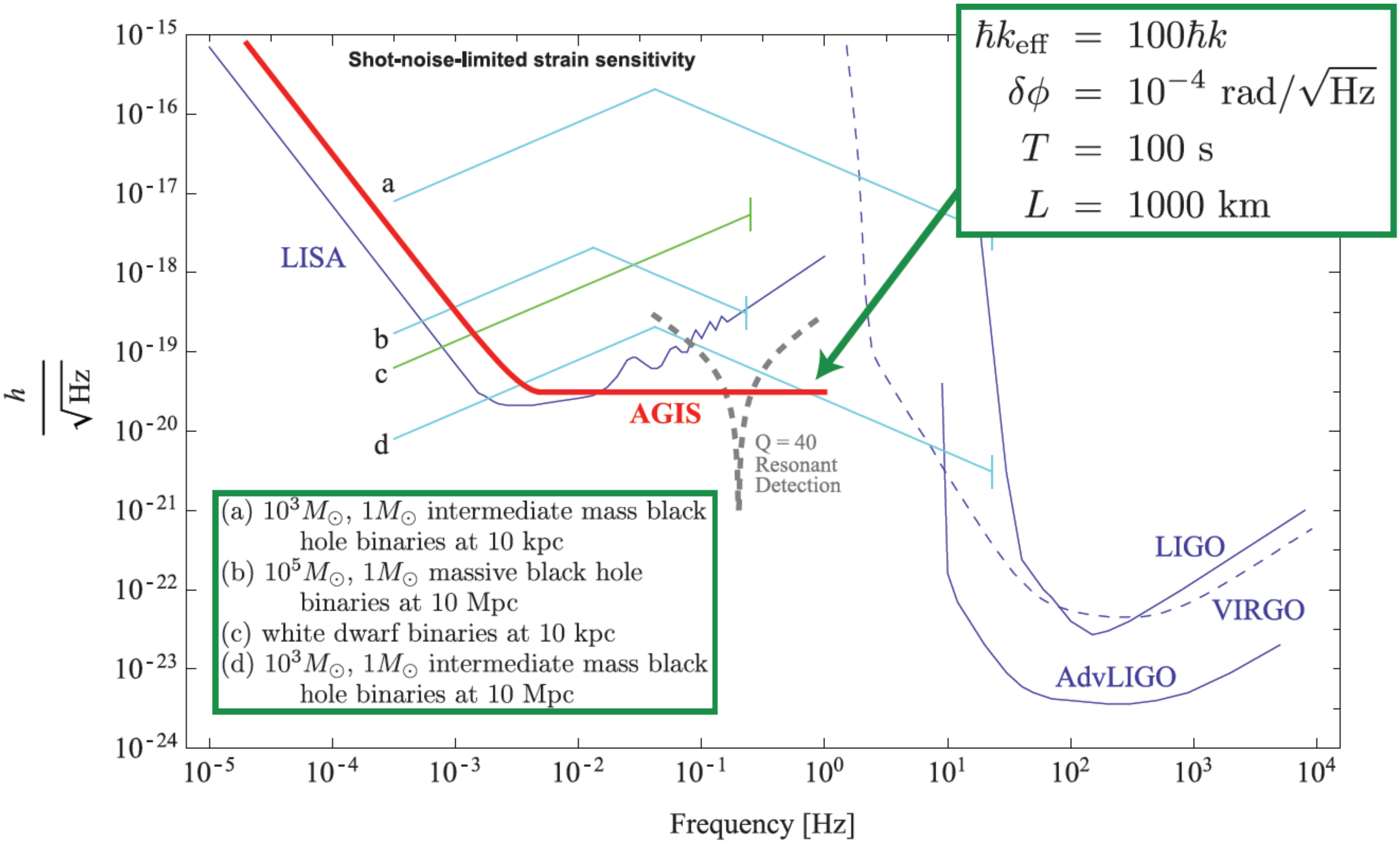




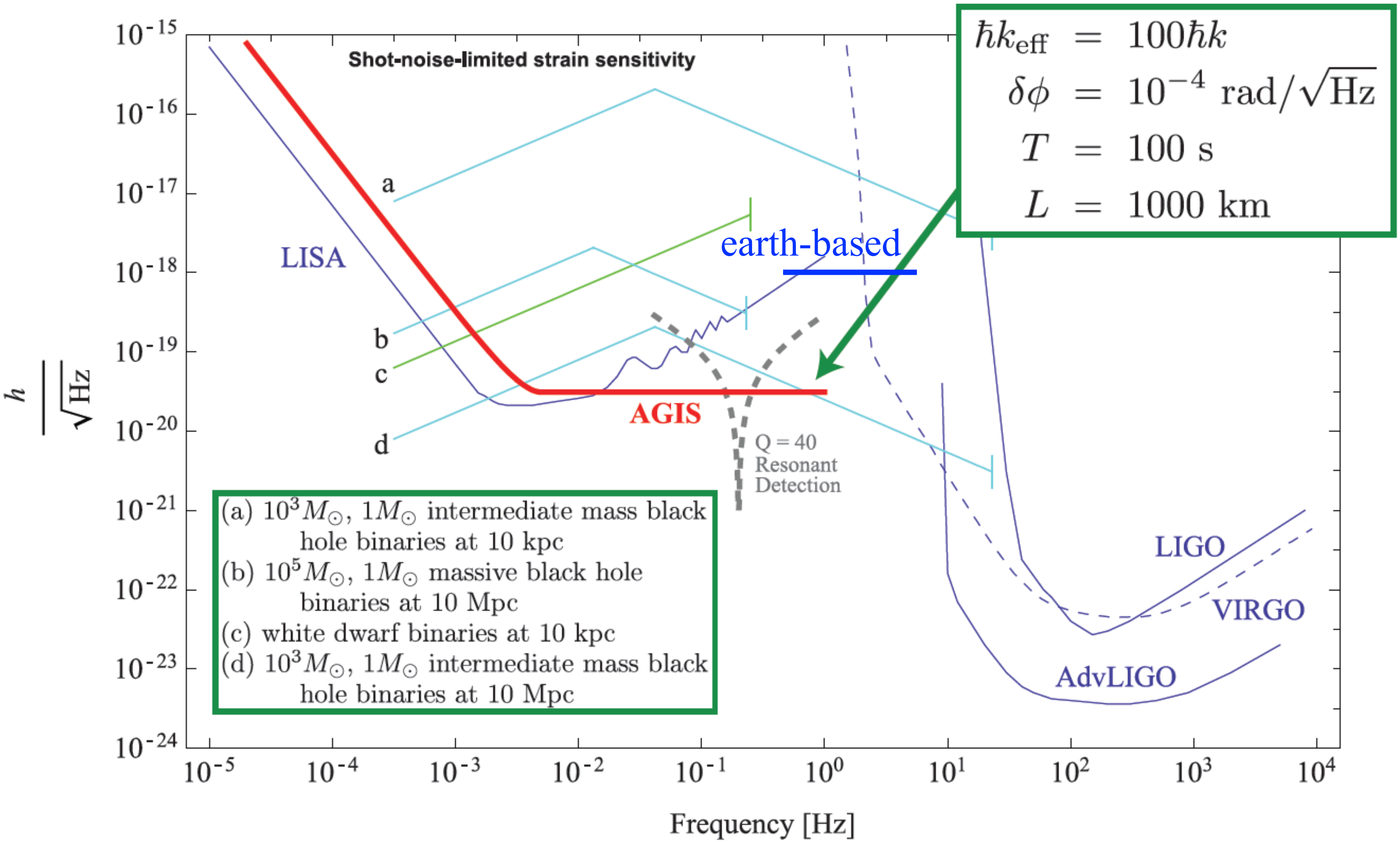
NIAC
NASA Innovative Advanced Concepts

NASA

Atomic Gravitational Wave Interferometric Sensor (AGIS)

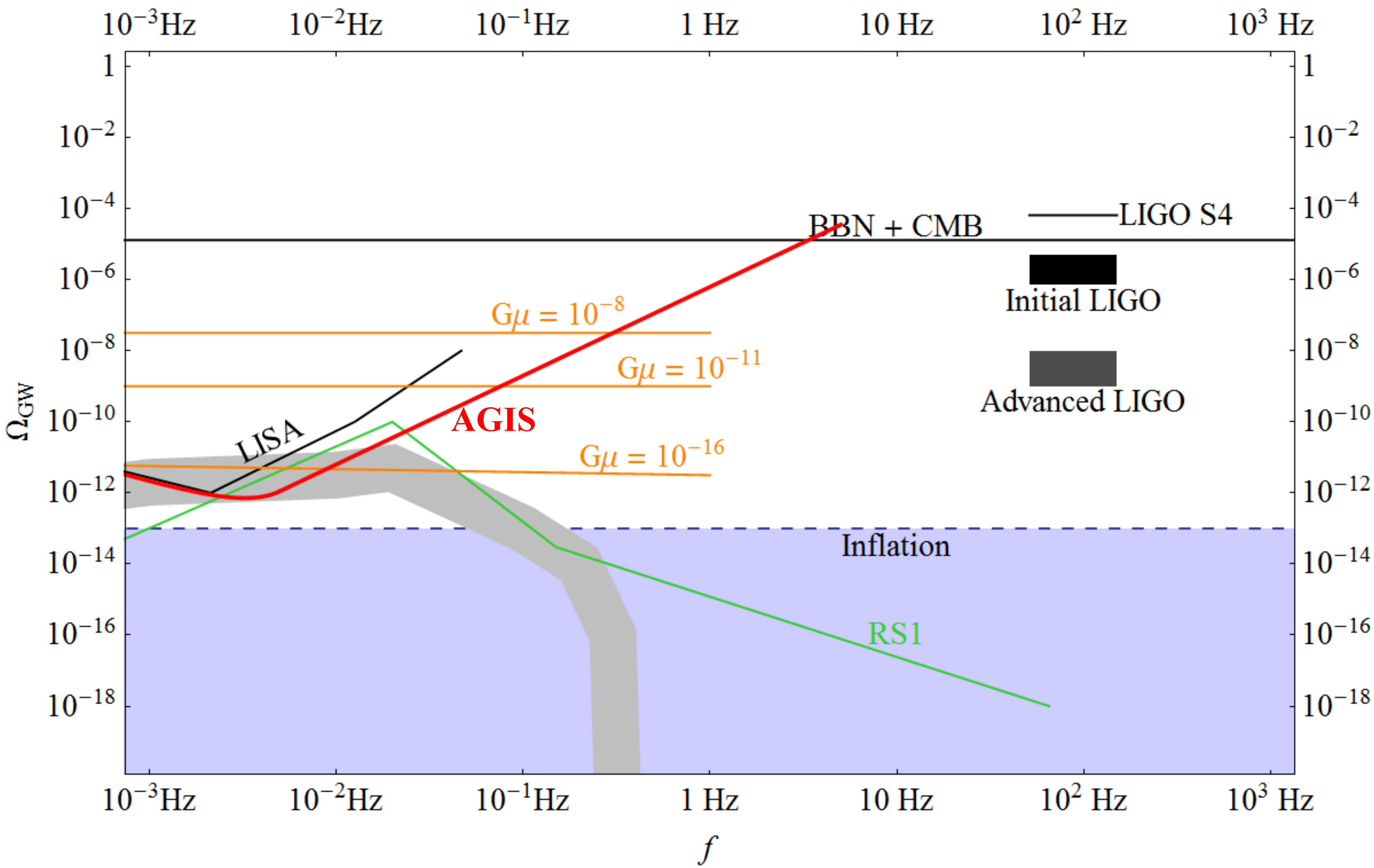


Atomic Gravitational Wave Interferometric Sensor (AGIS)



Stochastic Gravitational Wave Sensitivity

Directly observe early universe cosmology



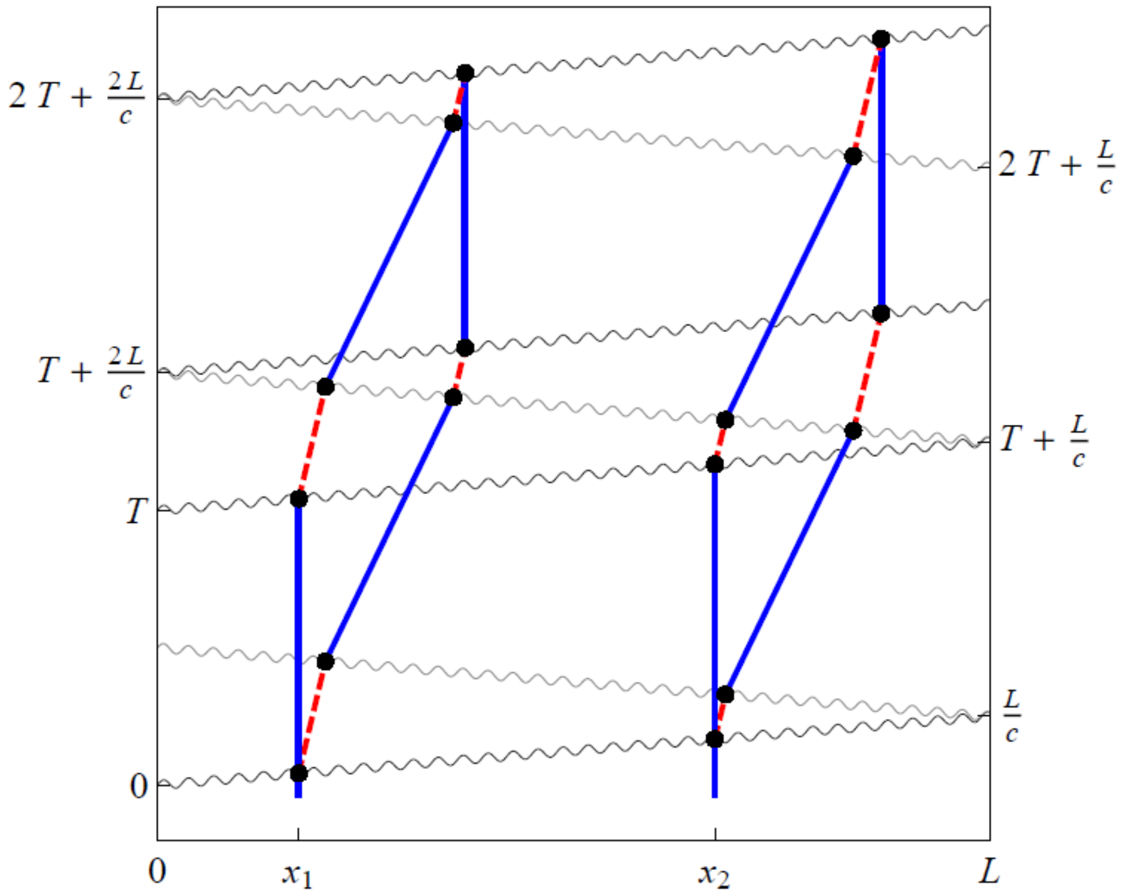
requires correlating two independent baselines

Laser Phase Noise

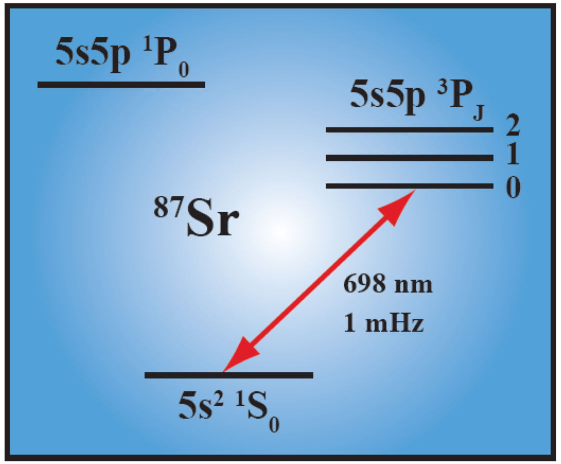
remove laser noise using multiple baselines

Laser Phase Noise Insensitive Detector

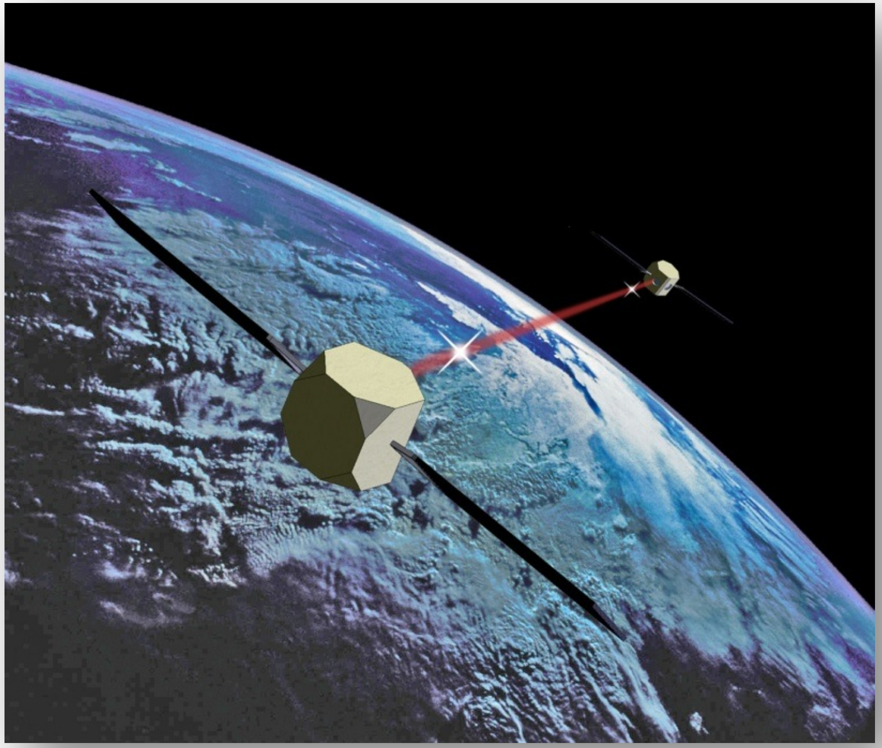
atoms act as clocks, measure light travel time



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



Clock transition in candidate atom ^{87}Sr

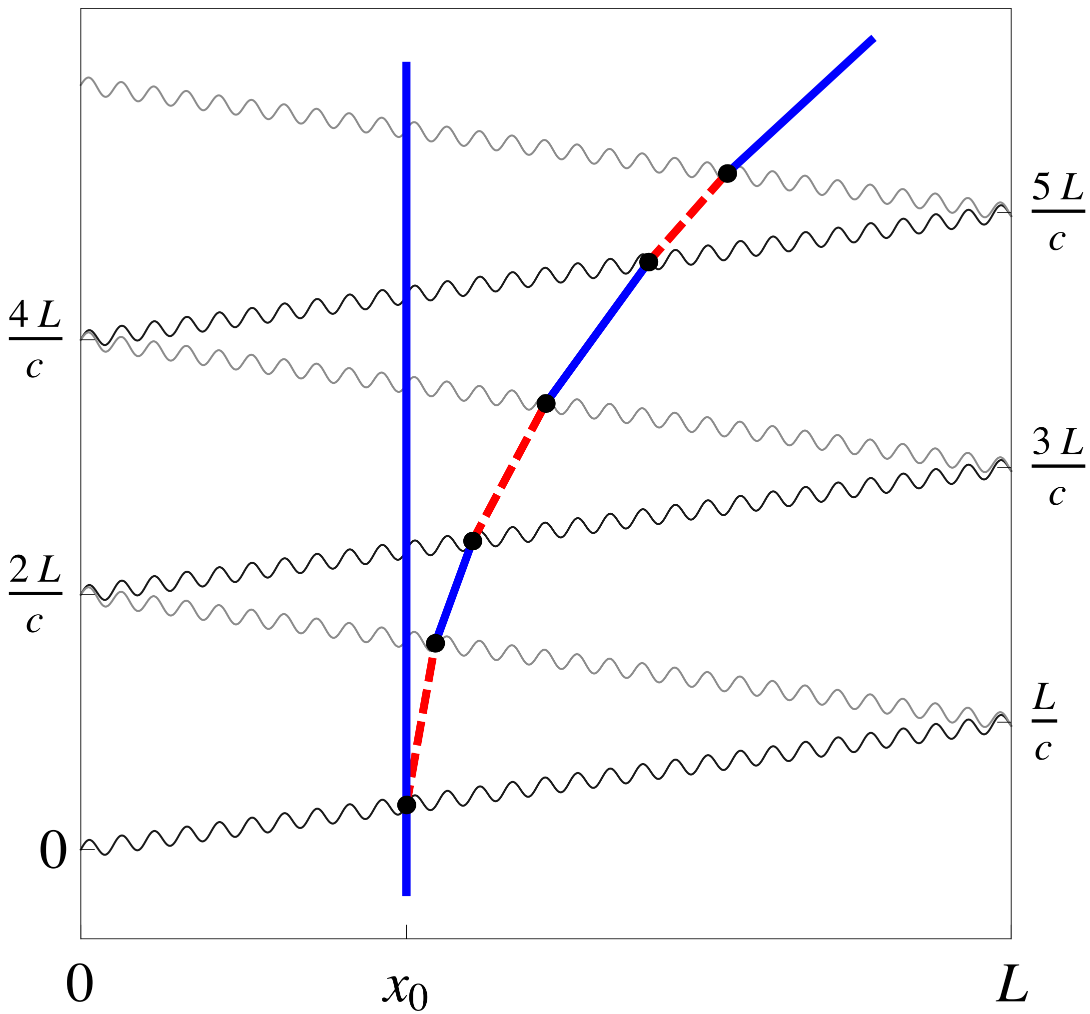


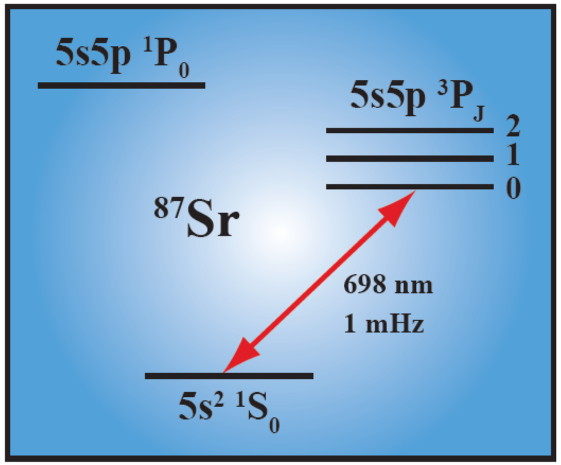
Removes laser noise, allows single baseline detection

A New Type of LMT Beamsplitter

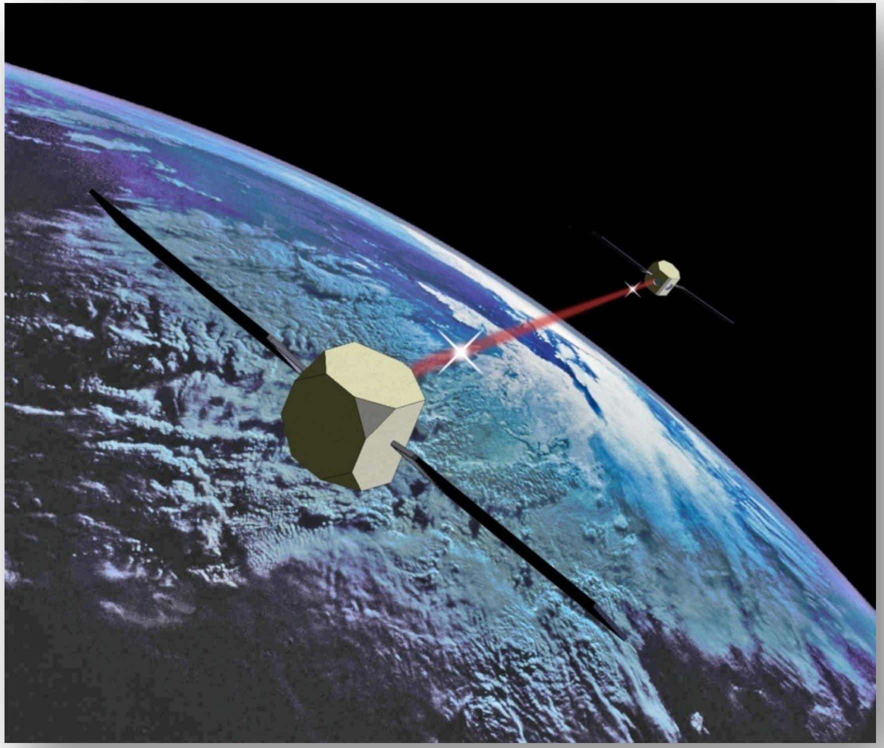
Graham, Hogan, Kasevich, Rajendran, PRL **110** (2013)

"bing-bang"





Clock transition in candidate atom ^{87}Sr



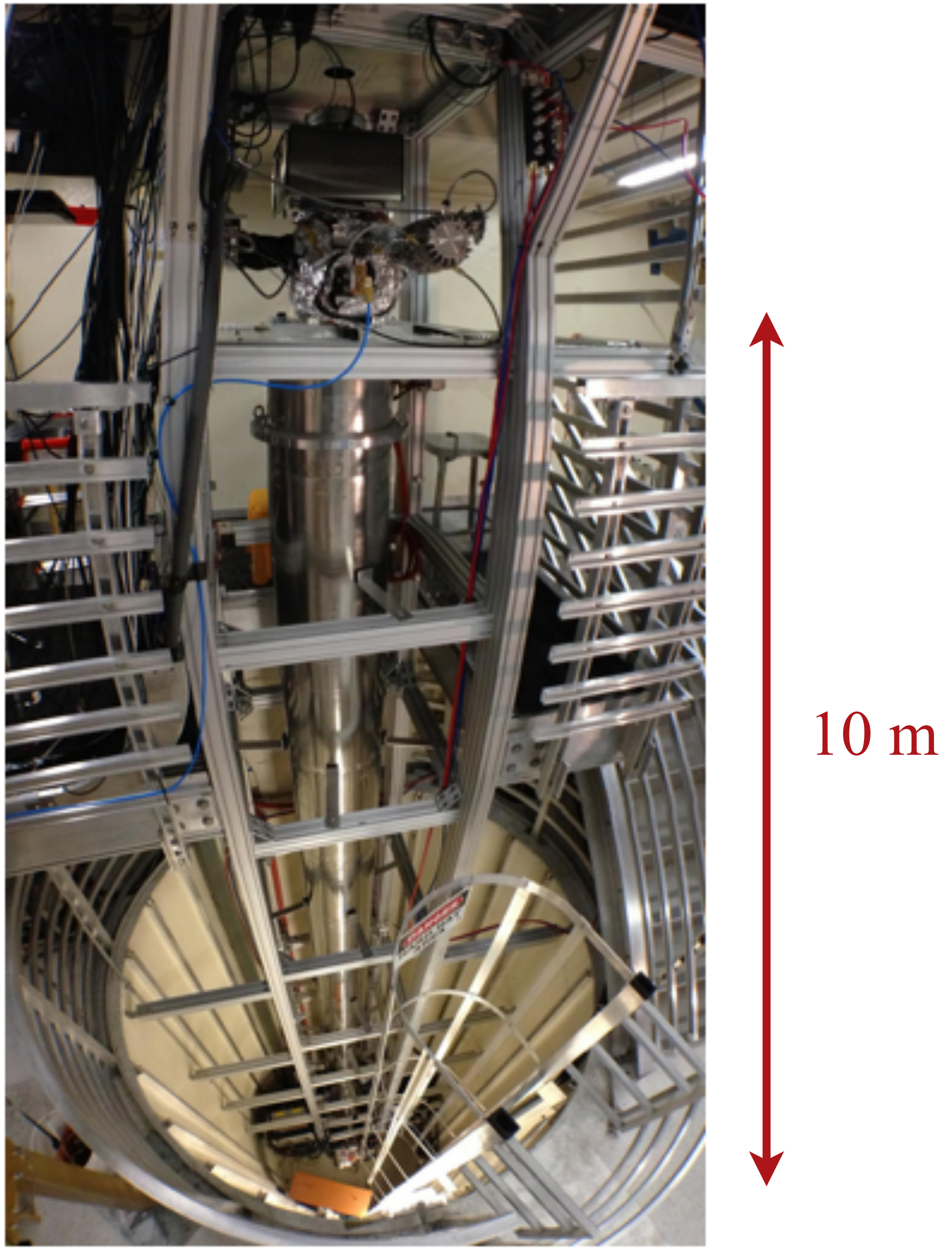
Allows same sensitivity as AGIS (and LISA) in a single baseline

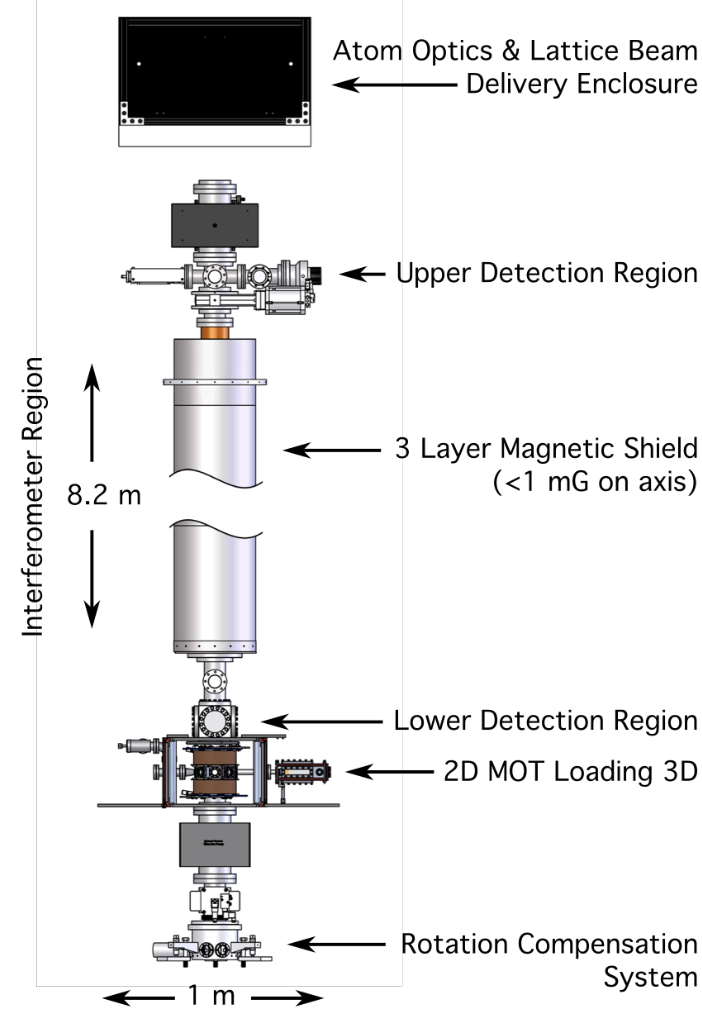
Demonstrated Results

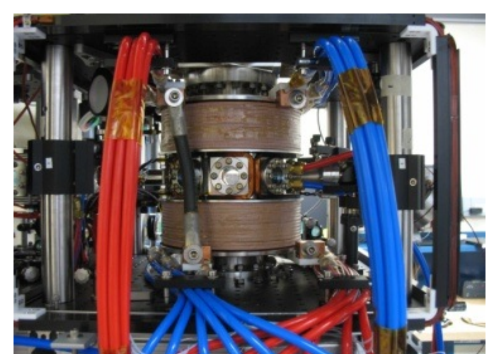
Kasevich and Hogan groups

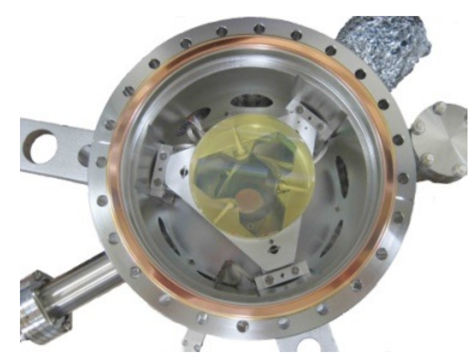
AGIS Test Facility at Stanford

Stanford Test Facility









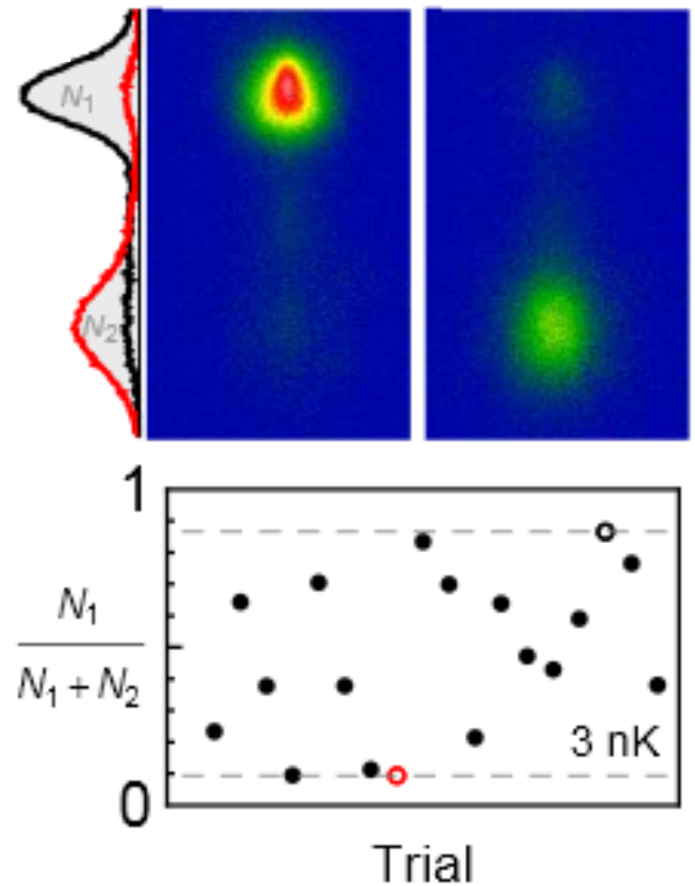
AGIS Test Facility at Stanford

Stanford Test Facility

10 m

demonstrated interference at 2T = 2.3 s

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



Atom Lens Cooling

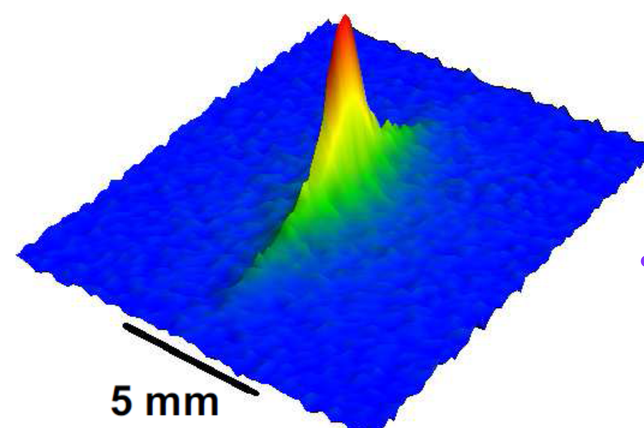
Stanford Test Facility

Standard techniques (laser and evaporative cooling) reach ~ few nK

GW detection needs ~ 10 pK

New atom-lens cooling technique (Kasevich group):

Kovachy et. al., arXiv: 1407.6995



➜ 50 pK

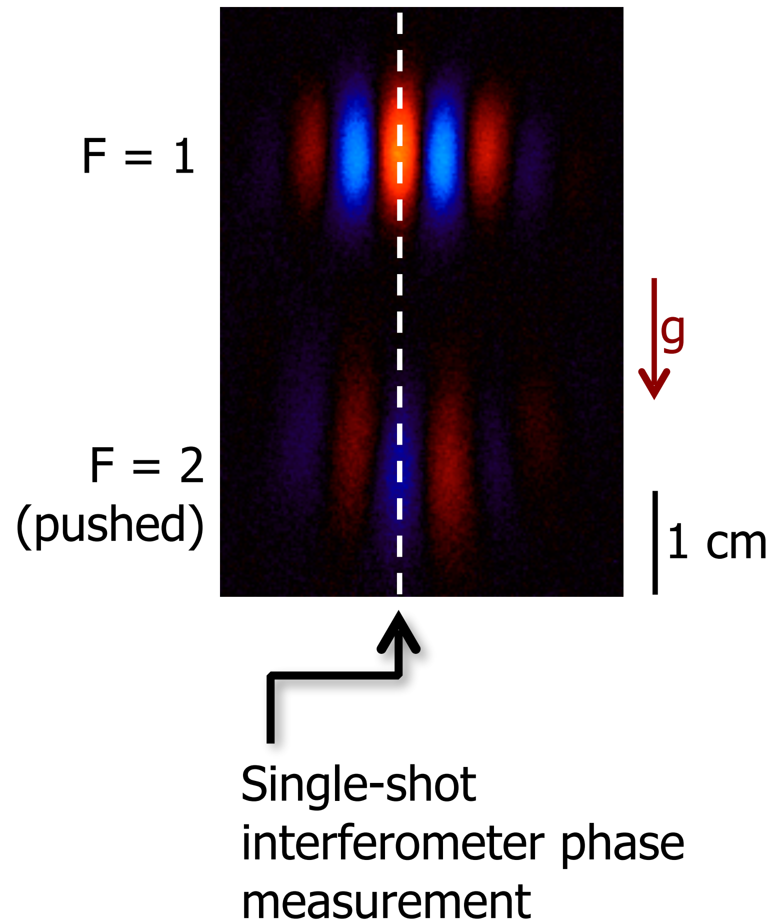
Rotation Noise Reduction

Stanford Test Facility

Rotation of laser can give noise for GW detection

Sugarbaker et. al., PRL **111** (2013)

Phase Shear Readout (PSR)



Mitigates noise sources:

✓ Pointing jitter and residual rotation readout

✓ Laser wavefront aberration in situ characterization

Large Momentum Transfer (LMT) Beamsplitters

Stanford Test Facility

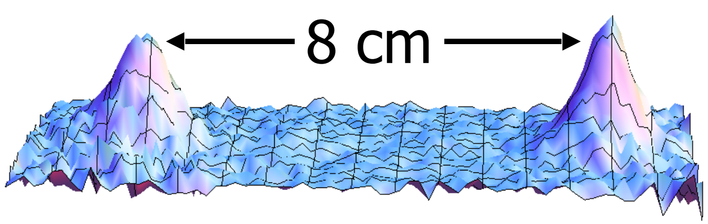
need N = 100 for AGIS

current results (unpublished):

demonstrated LMT at 2T = 2.3 s

demonstrated enhancement factor N ~ 20

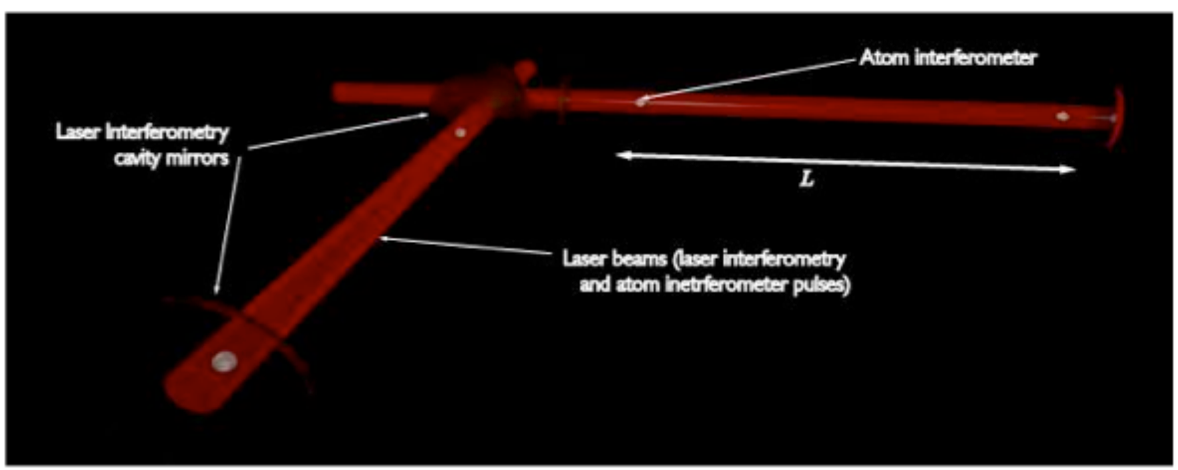
Macroscopic splitting of atomic wavefunction:



Future Work

Hogan group setting up 2nd Stanford Test Facility,
test laser noise insensitive technique

MIGA; ~1 km baseline (P. Bouyer, France)

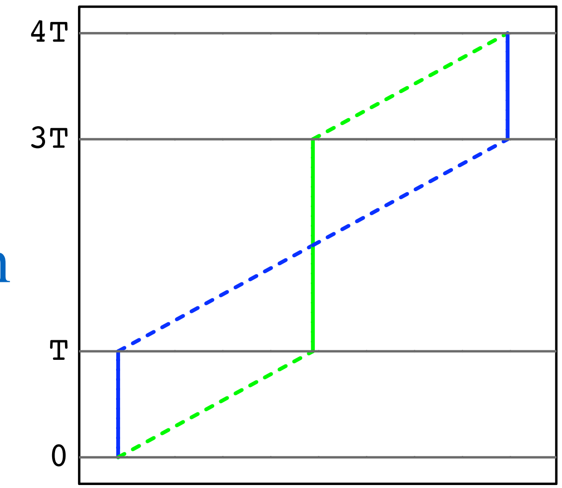


Resonant Detection and Inflation

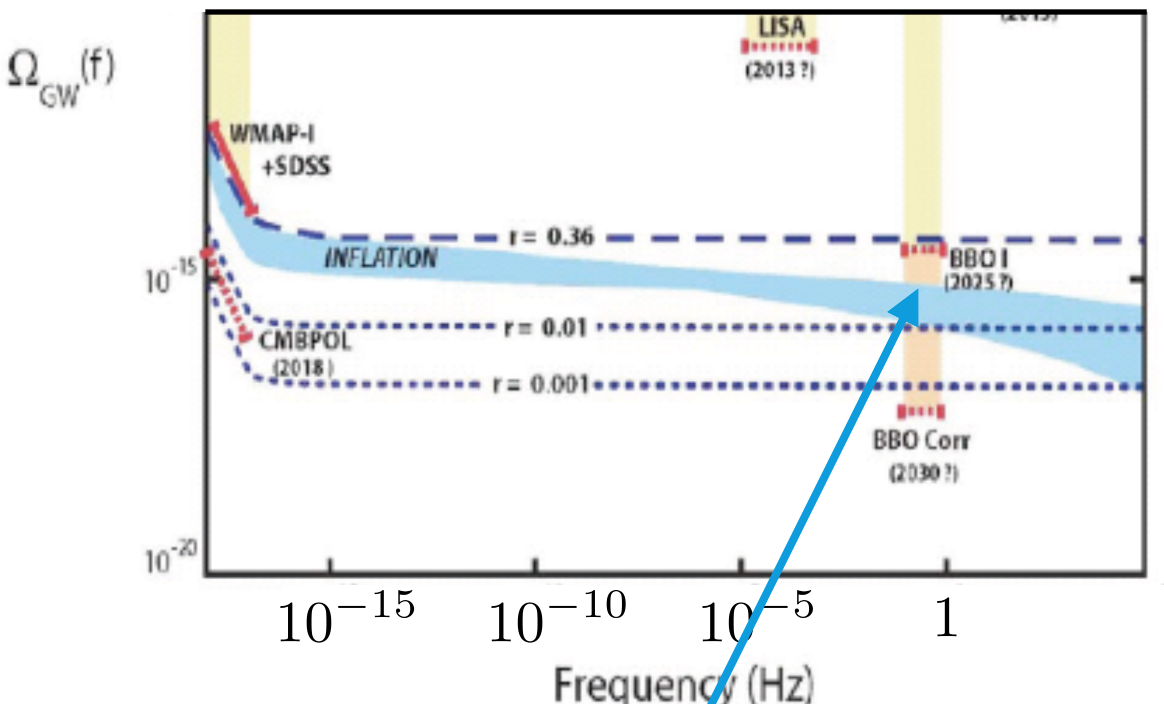
(Preliminary!)

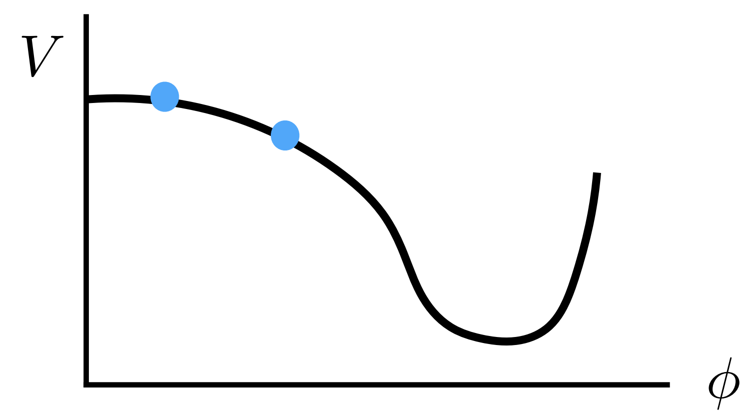
Resonant Detection and Inflation

(Preliminary!)



Atomic detector can run in resonant mode,
may be able to reach highest level of GW's from inflation





observe many e-folds in to inflation

probe inflation potential

detect at ~1 Hz

Testing General Relativity in the Lab

PRL **98** (2007)
PRD **78** (2008)

General Relativity

$$ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2 d\Omega^2$$

where $\phi = -\frac{GM}{r} \sim 10^{-9}$ and in GR $\beta = \gamma = 1$

acceleration of a massive particle

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}(\phi + (\beta + \gamma)\phi^2) + \gamma(3(\vec{v} \cdot \hat{r})^2 - 2\vec{v}^2)\vec{\nabla}\phi + 2\vec{v}(\vec{v} \cdot \vec{\nabla}\phi)$$

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in the lab: g

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in the lab: g $10^{-15}g$ $v \approx 10\frac{\mathrm{m}}{\mathrm{s}}$

a velocity-dependent force is distinguishable from backgrounds

arises from “gravitation of kinetic energy”

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in GR gravitational field energy $\rho \sim g^2 = (\nabla\phi)^2 \sim \nabla^2\phi^2$

that energy must gravitate $\nabla \cdot \vec{a} \propto \rho \sim \nabla^2\phi^2$

discriminate from Newtonian gravity in vacuum $\nabla \cdot \vec{a} = 0$

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$$10^{-9} g \times \frac{10\mathrm{m}}{R_{\mathrm{earth}}} \approx 10^{-15} g$$ ← observable in 10 m interferometer

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General Relativity

Schwarzschild metric, PPN expansion:

$$ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2 d\Omega^2$$

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}[\phi + (\beta+\gamma)\phi^2] + \gamma[3(\vec{v}\cdot\hat{r})^2 - 2\vec{v}^2]\vec{\nabla}\phi + 2\vec{v}(\vec{v}\cdot\vec{\nabla}\phi).$$

Newtonian Gravity

Gravity Gravitates

Kinetic Energy Gravitates

Corresponding AI phase shifts:

	Phase Shift	Size (rad)	Interpretation
1.	$-k_{\text{eff}} g T^2$	3×10^8	gravity
2.	$-k_{\text{eff}} (\partial_r g) T^3 v_L$	-2×10^3	1st gradient
3.	$-3 k_{\text{eff}} g T^2 v_L$	4×10^1	Doppler shift
4.	$(2-2\beta-\gamma) k_{\text{eff}} g \phi T^2$	2×10^{-1}	GR
5.	$-\frac{7}{12} k_{\text{eff}} (\partial_r^2 g) T^4 v_L^2$	8×10^{-3}	2nd gradient
6.	$-5 k_{\text{eff}} g T^2 v_L^2$	3×10^{-6}	GR
7.	$(2-2\beta-\gamma) k_{\text{eff}} \partial_r (g\phi) T^3 v_L$	2×10^{-6}	GR 1st grad
8.	$-12 k_{\text{eff}} g^2 T^3 v_L$	-6×10^{-7}	GR

Projected experimental limits:

Tested Effect	current limit	AI initial	AI upgrade	AI future	AI far future
PoE	3×10^{-13}	10^{-15}	10^{-16}	10^{-17}	10^{-19}
PPN (β, γ)	10^{-4}-10^{-5}	10^{-1}	10^{-2}	10^{-4}	10^{-6}

(Dimopoulos, *et al.*, PRL 2007; PRD 2008)

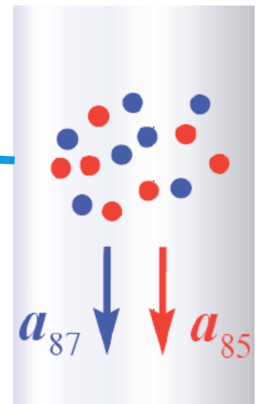
Equivalence Principle Test

Stanford Test Facility

Shot noise limited detection @ 10^7 atoms per shot:

$$\delta\phi \sim \frac{1}{\sqrt{N}} \sim 3 \times 10^{-7}\mathrm{rad} \qquad (\sim 1 \text{ month})$$

$$\Delta\phi = k_{\mathrm{eff}}\, g T^2 \approx 3\times 10^8 \ \mathrm{rad} \ \rightarrow \ \boxed{\delta g < 10^{-15} g}$$



colocated ^{85}Rb and ^{87}Rb clouds test Principle of Equivalence initially to 10^{-15} in controlled (lab) conditions

Summary

1. Atom Interferometry is a promising tool for detection of GW's

2. Most of the major technology is testable on ground
   - Cooling, LMT beamsplitters, long interrogation times already demonstrated
   - Test facility for new single-baseline technique now under construction @ Stanford

3. Laboratory tests of General Relativity
   - including test of Equivalence Principle to 10^{-15} under construction

Gravitational waves will be major part of future of astronomy, astrophysics and cosmology