Testing Gravity with Atom Interferometry

Peter Graham

with

Savas Dimopoulos

Jason Hogan

Mark Kasevich

Stanford University

Atom Interferometry

Atomic physics has made tremendous progress recently

unprecedented precision: 16 digit clock synchronization

many possibilities for improvement

can test e.g. time variation of fundamental constants

There must be more fundamental physics to be done with it

We will consider using atom interferometry to test gravity at many length scales

Outline

1. Atom Interferometry

2. Gravity waves

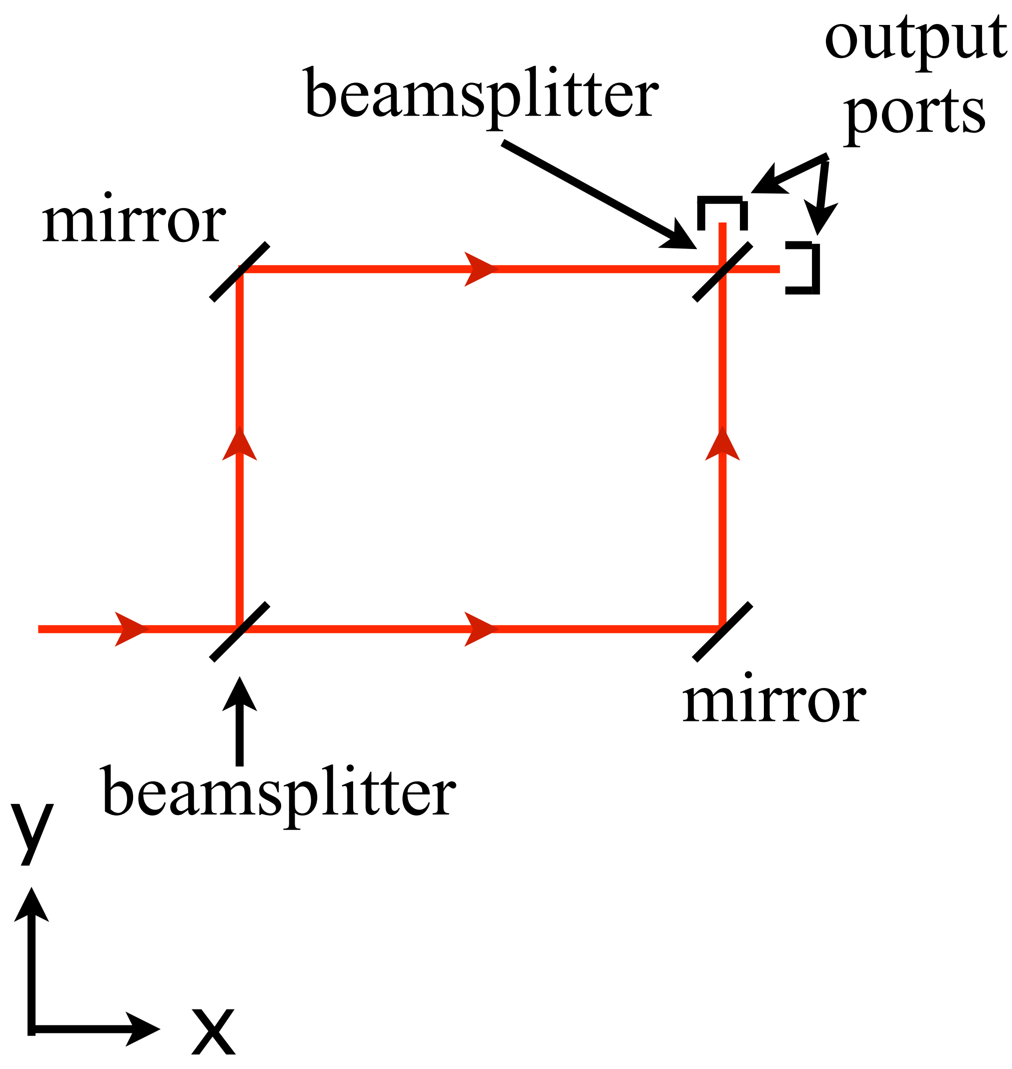
3. Testing (long-distance) General Relativity

4. Testing short-distance gravity?

Atom Interferometry

Light Interferometry

Space-space Interferometry

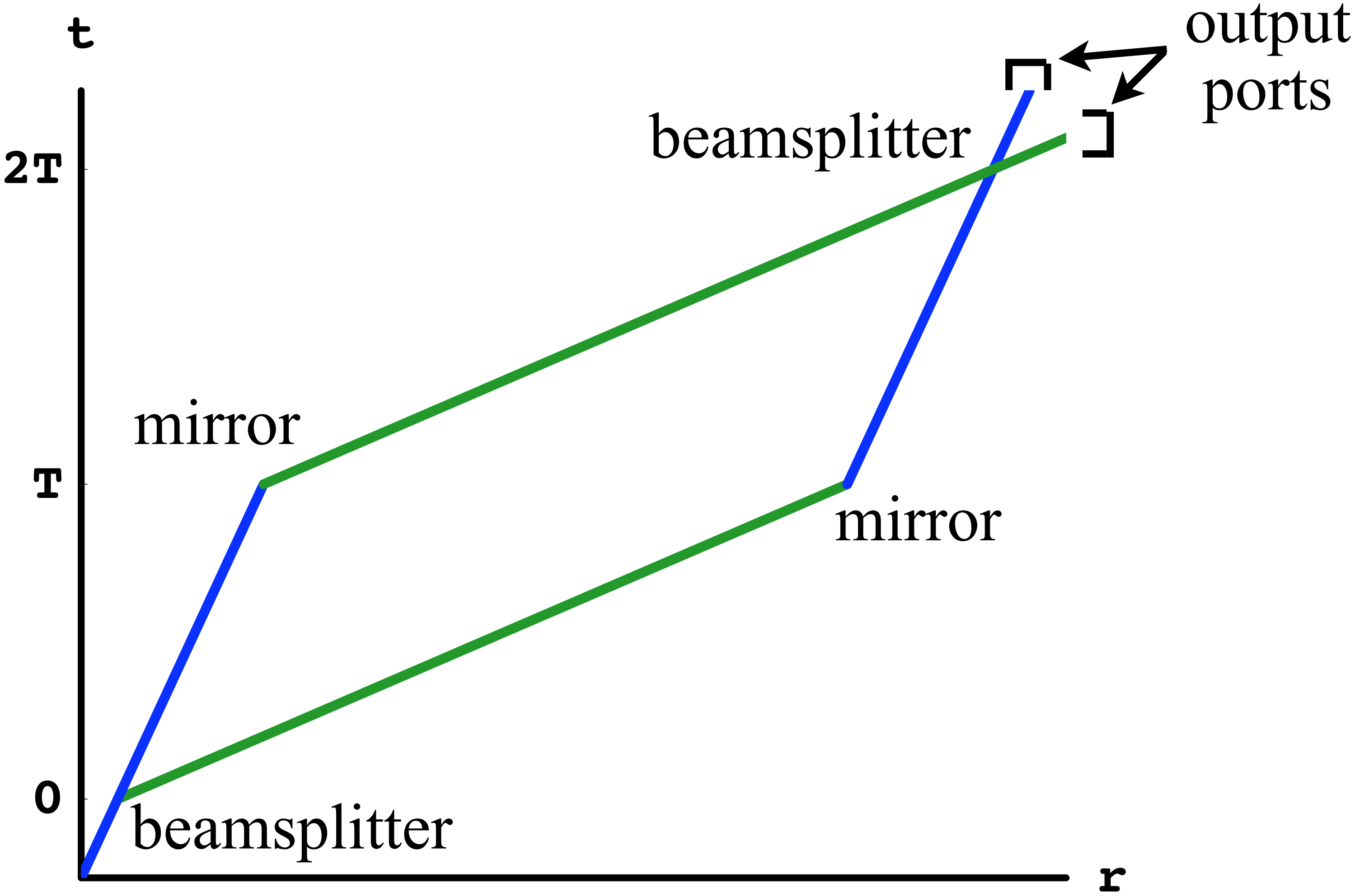


accurate measurement of

$$\frac{\Delta L}{L} \sim \frac{\lambda}{L} \times \text{(phase resolution)}$$

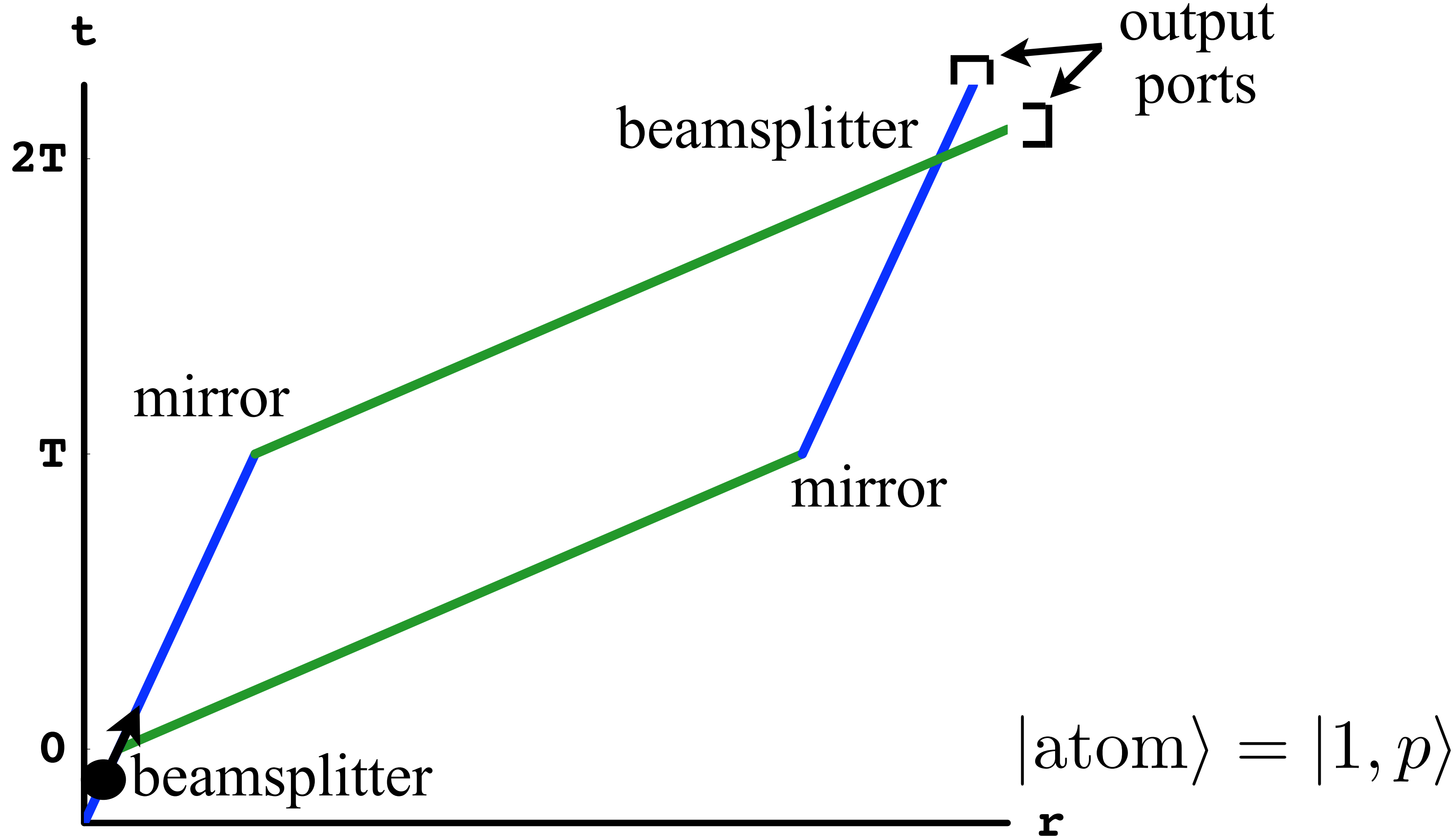
Atom Interferometry

Space-time Interferometry



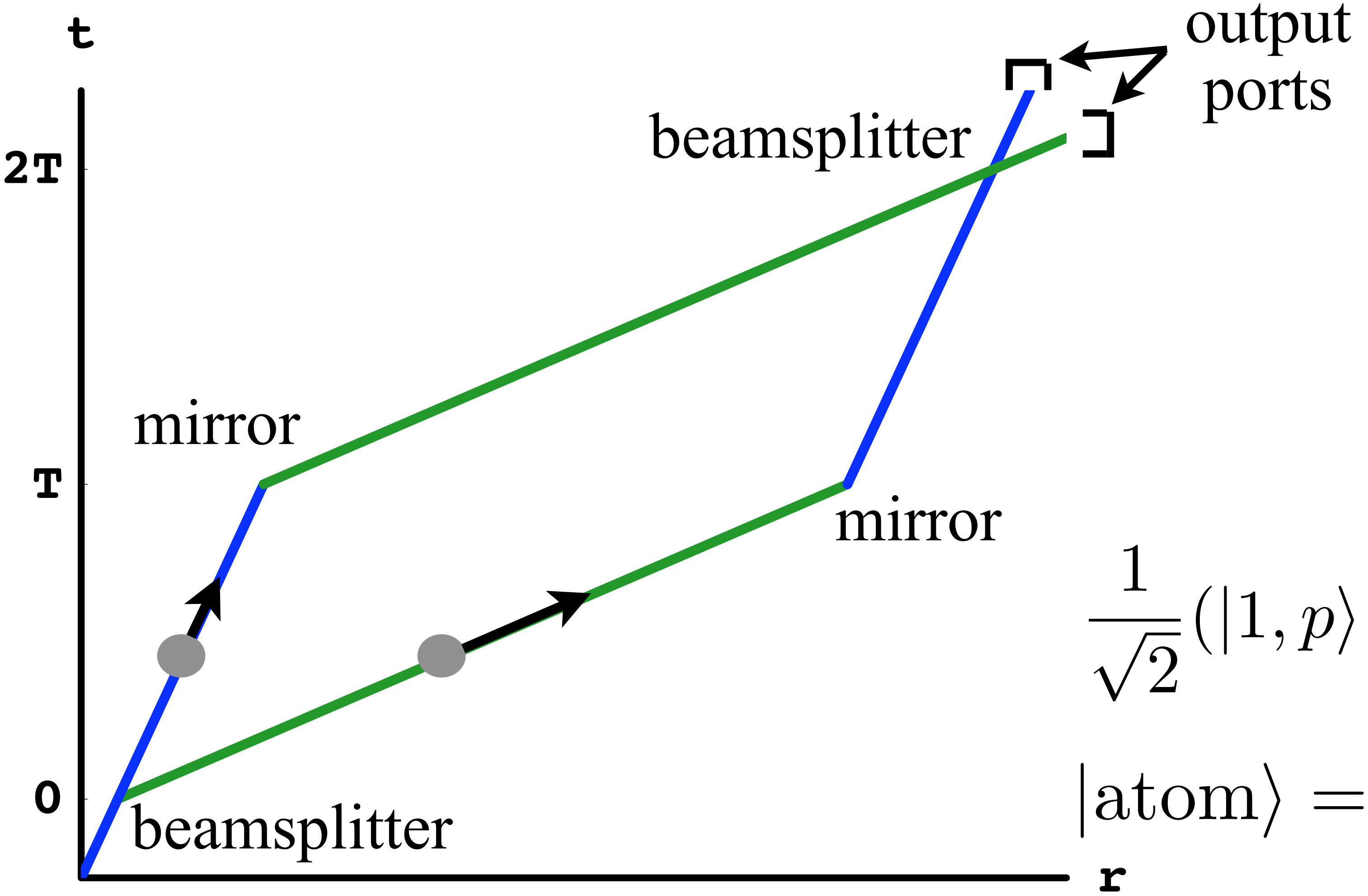
Atom Interferometry

Space-time Interferometry



Atom Interferometry

Space-time Interferometry

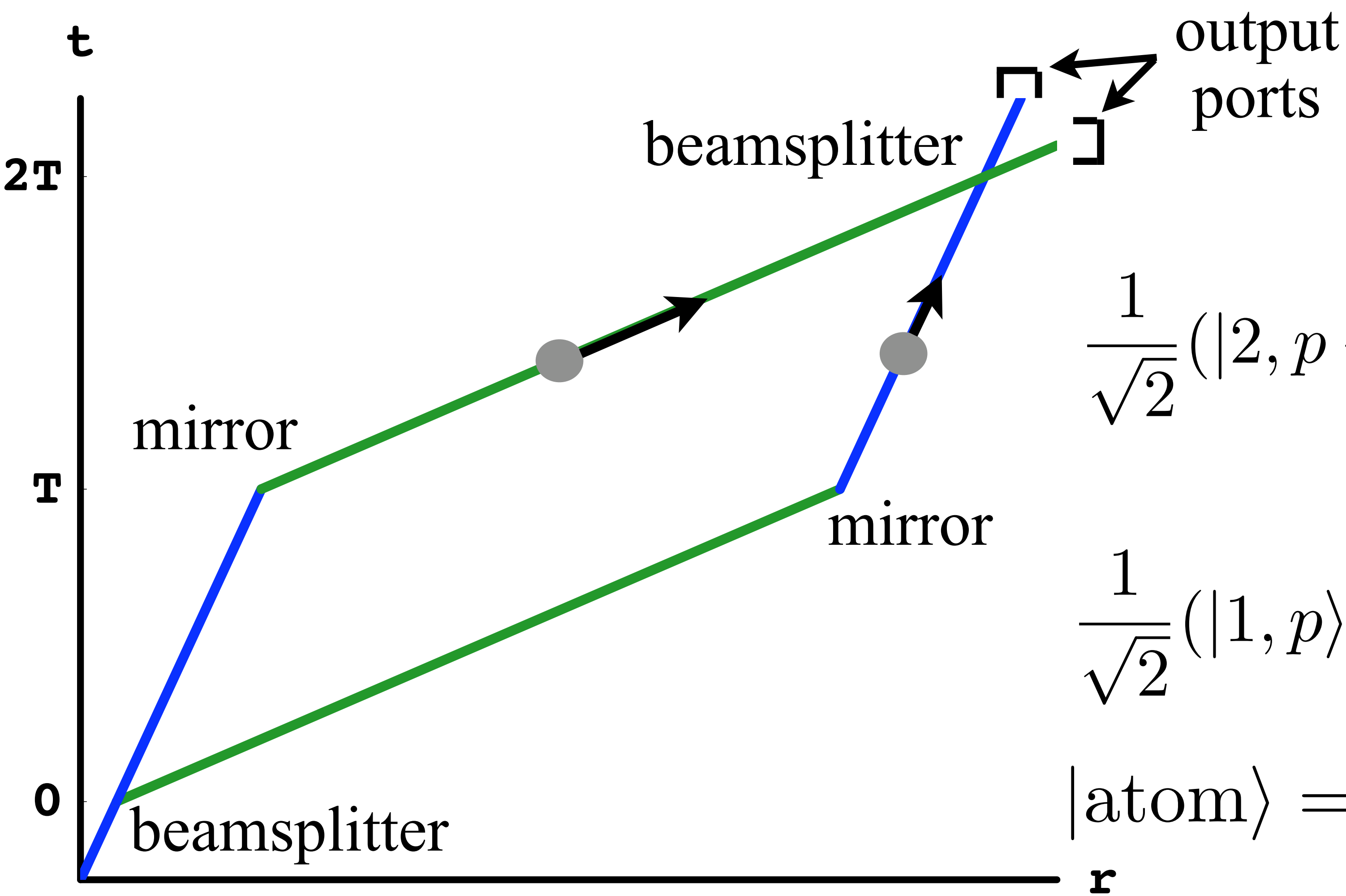


$$\frac{1}{\sqrt{2}}(|1,p\rangle + e^{i\Delta\phi}|2,p+k\rangle)$$

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

Atom Interferometry

Space-time Interferometry



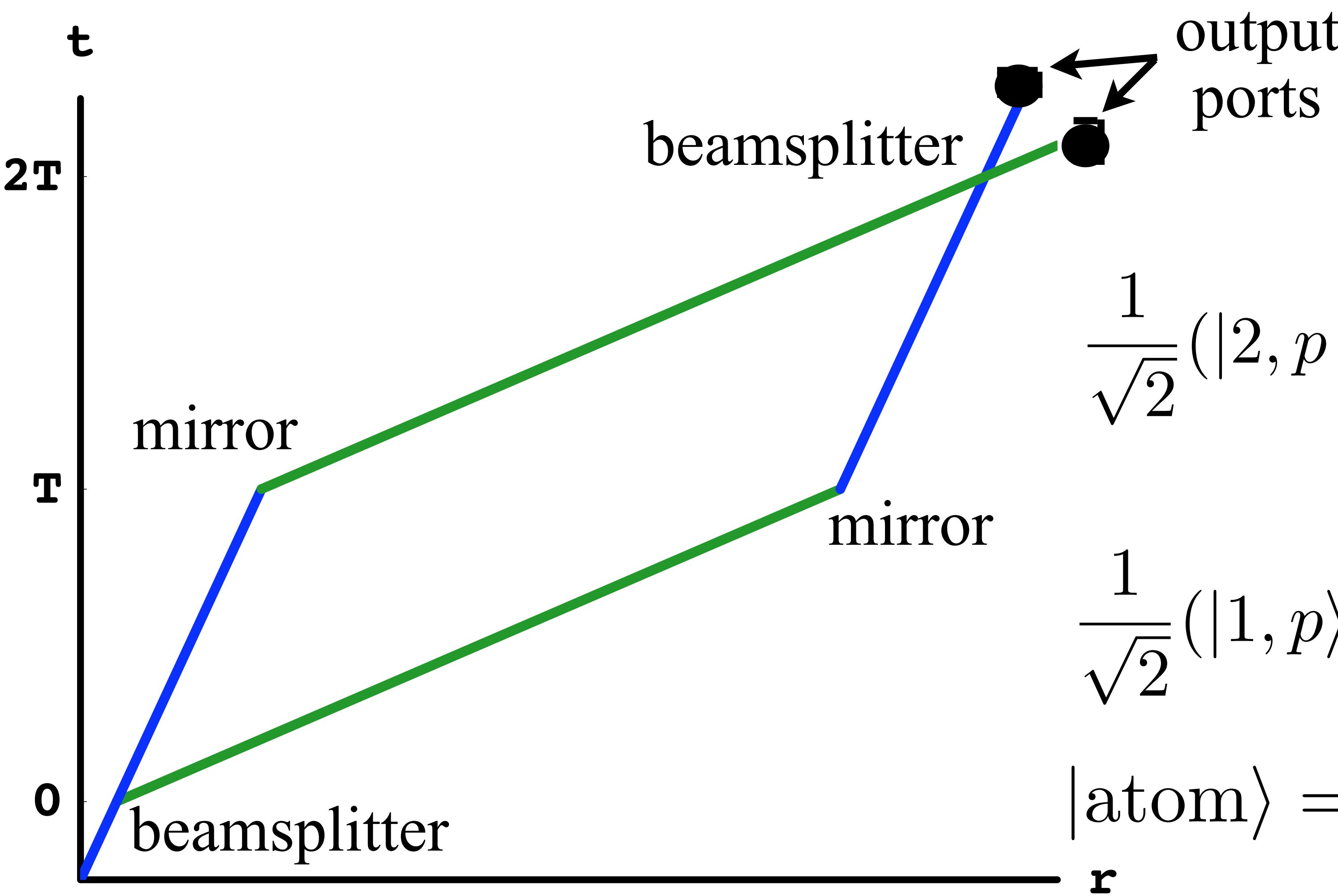
$$\frac{1}{\sqrt{2}}(|2, p+k\rangle + e^{i\Delta\phi}|1, p\rangle)$$

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

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

Atom Interferometry

Space-time Interferometry



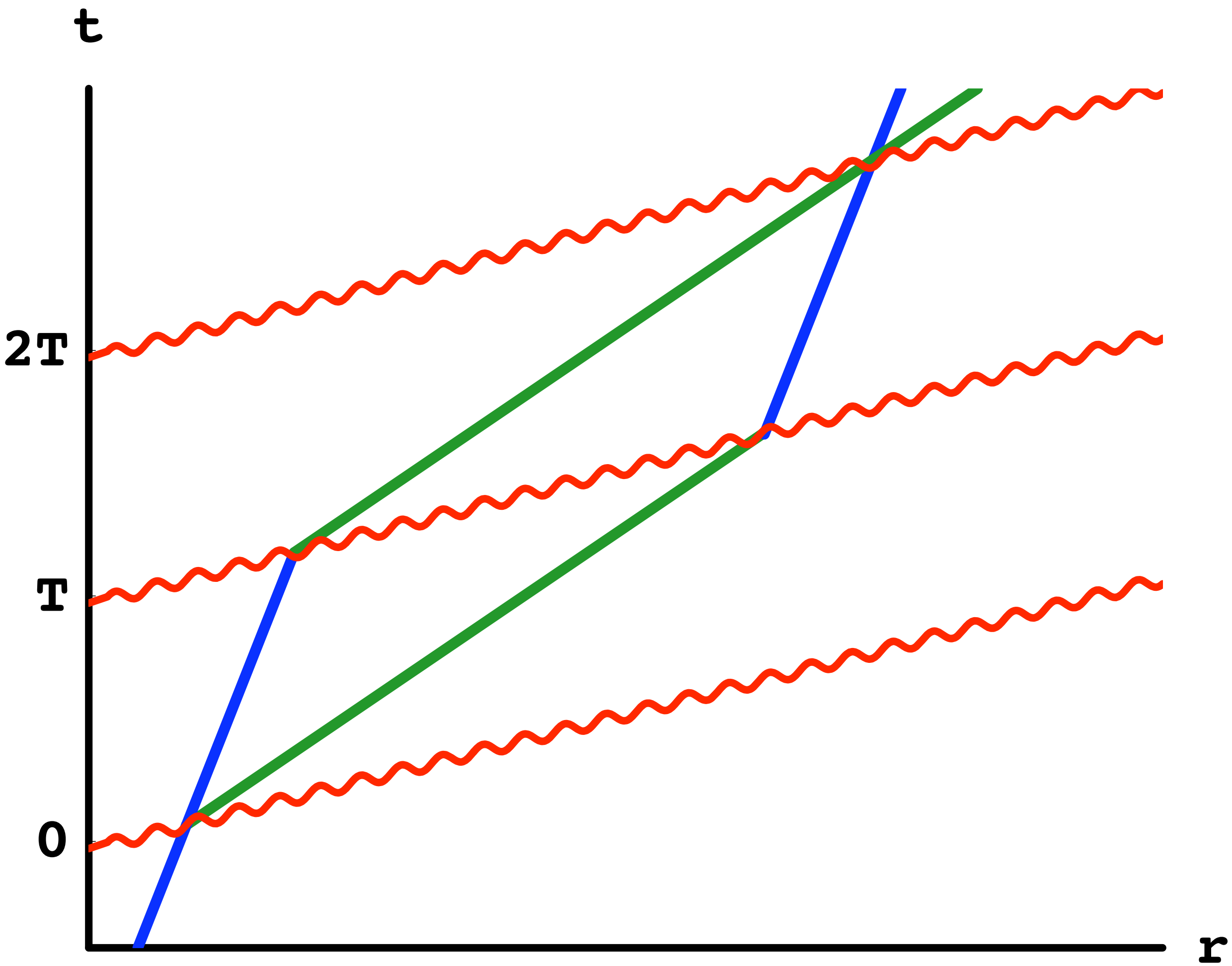
$$\frac{1}{\sqrt{2}}(|2, p+k\rangle + e^{i\Delta\phi}|1, p\rangle)$$

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

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

Atom Interferometry

Space-time Interferometry



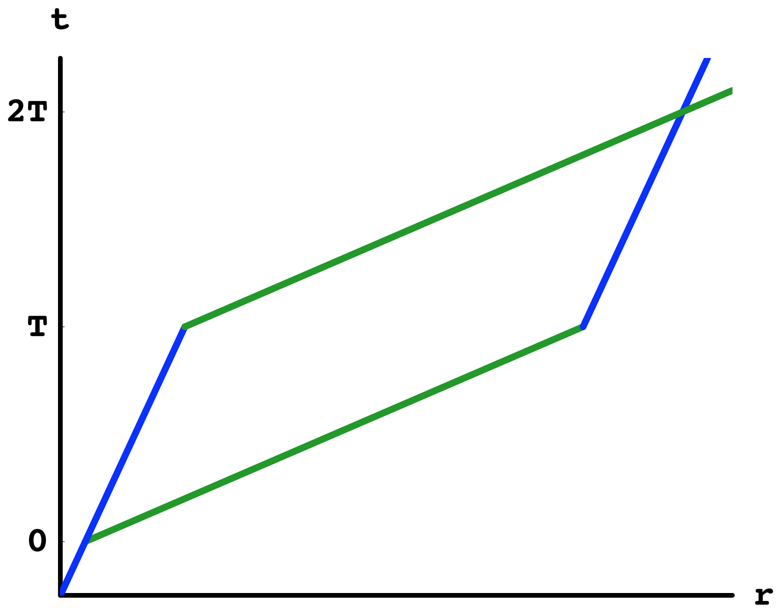
controllable parameters

- v_L initial velocity
- R initial height
- k momentum splitting
- T interrogation time
- θ angle

Measuring Gravity

$$\phi_{\text{propagation}} = \int m d\tau = \int L dt = \int p_\mu dx^\mu$$

a constant gravitational field produces a phase shift:



$$\phi_{\text{propagation}} = \int \left(\frac{1}{2} m v^2 - m g h \right) dt$$

$$\Delta\phi_{\text{propagation}} \sim mg(\Delta h)T \sim$$

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

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

Gravity Waves

Savas Dimopoulos
PWG
Jason Hogan
Mark Kasevich
Surjeet Rajendran

Gravity Wave Signal

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

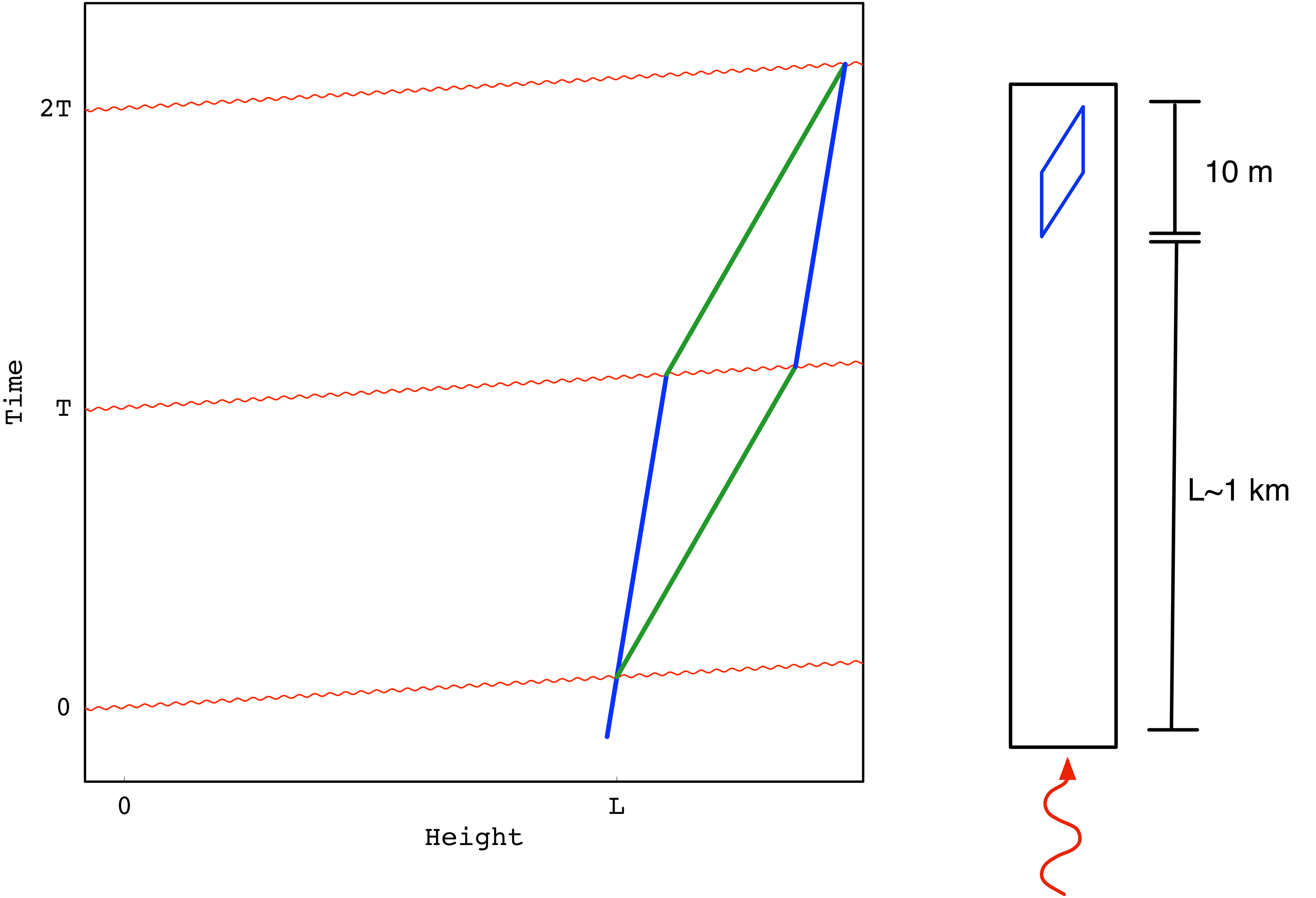
laser ranging an atom (or mirror) from a starting distance L sees a position:

$$x \sim L(1 + hcos(\omega t))$$

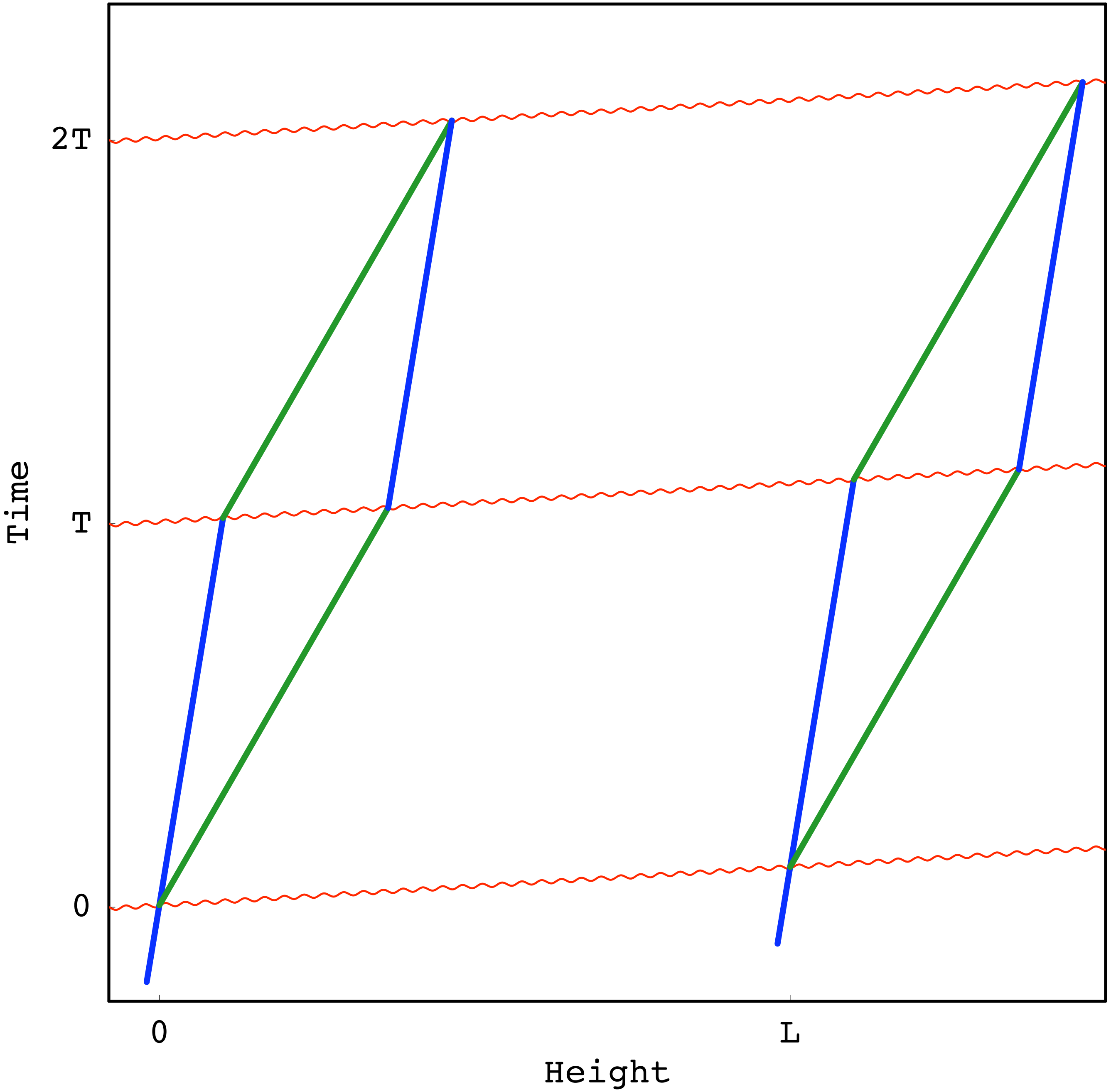
and an acceleration $a \sim hL\omega^2 cos(\omega t)$

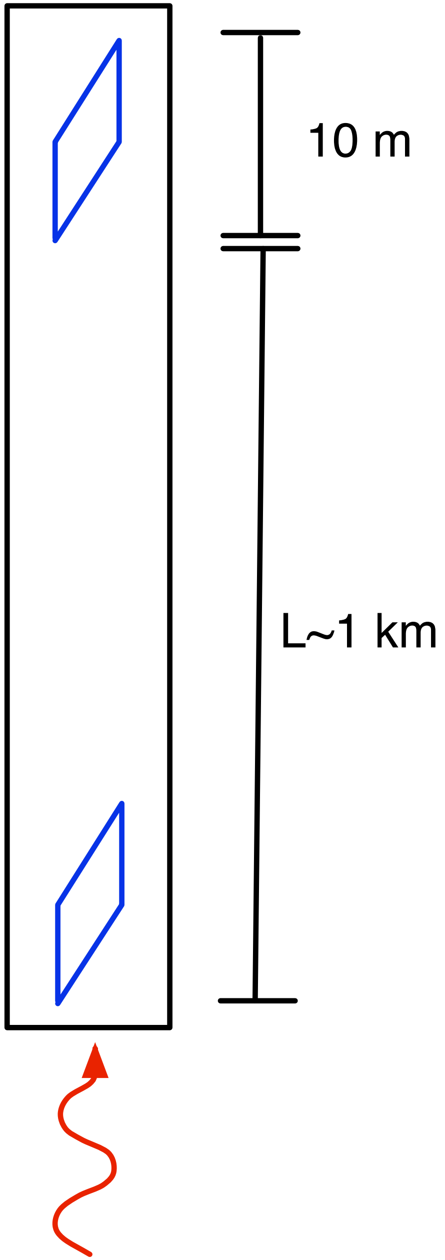
gives a phase shift $\Delta\phi = kaT^2 \sim khL\omega^2 cos(\omega t)T^2$

Gravity Wave Signal ~ 1 Hz



Differential Measurement





sensitivity increases with L and T up to T,L ~ $1/\omega = \lambda$

Earth Backgrounds

vibrations	requires damping to ~ pm at 10^5 Hz
laser phase noise	control to μrad at 10^5 Hz
timing errors	control common launch velocity to ~ 1 cm/s
time-varying gravity gradient	earth vibrations naturally < 10^{-15} m^2/Hz at 1 Hz (Fix '72) leads to GW detection down to h ~ 10^{-22} (Hughes and Thorne '98)
launch position uncertainty coupled to gravity gradient	cancels common mode between two interferometers, lock initial launch positions with optical lattice
variable earth rotation rate	at 1 Hz well below required nrad/s uncertainty

all backgrounds seem controllable down to shot noise level

Space Backgrounds

vacuum quality	space vacuum equivalent better than 10^{-10} torr satellite debris?
earth + moon gravity gradient	either earth orbit at moon distance or solar orbit
satellite gravity gradient	either do experiment ~10m away or control satellite position to 10^{-6} m $s^{-2}/Hz^{1/2}$ (far below LPF)
ambient magnetic field	~ 1 nT, easily overcome by applied bias field

all backgrounds seem controllable down to shot noise level

Sensitivity

experimental sensitivity
for continuous sources

L~10 m and LMT $\qquad h \sim 10^{-17}$

L~10 km $\qquad h \sim 10^{-20}$

Heisenberg statistics $\qquad h \sim 10^{-22}$

on earth $\omega \sim 1$ Hz

in space $\omega \sim 10^{-3}$ to 1 Hz

waves from solar mass binaries:

$$h \sim \frac{(GM)^2}{rR}$$

galaxy $\qquad h \sim 10^{-18}$

cluster $\qquad h \sim 10^{-21}$

universe $\qquad h \sim 10^{-23}$

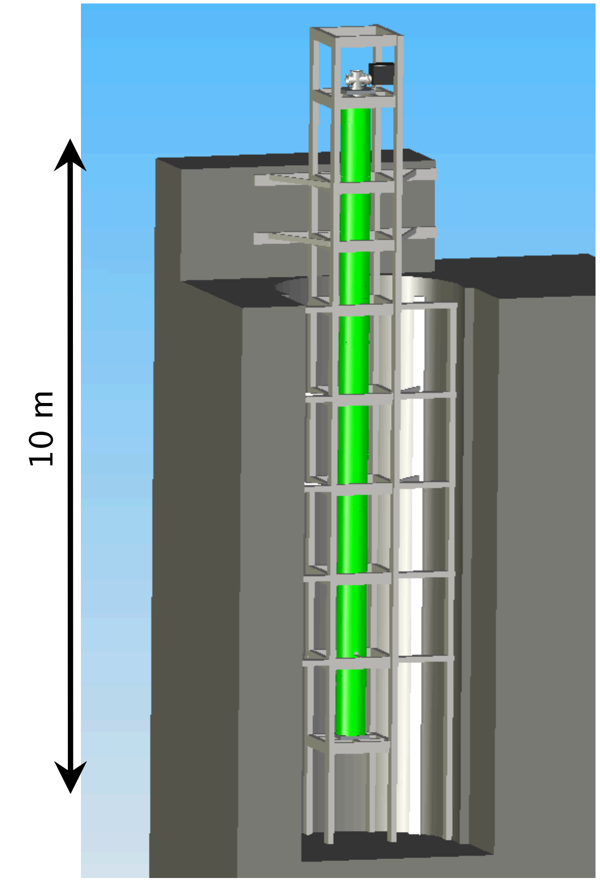
maybe IMBH $\longrightarrow$ h up to 10^5 larger

opens a new window for stochastic gravity wave searches
from phase transitions, inflation, cosmic strings...

Testing (long-distance) General Relativity with Atom Interferometry

PRL 98(2007)
gr-qc/0610047

Stanford 10m Interferometer



10 m atom drop tower.

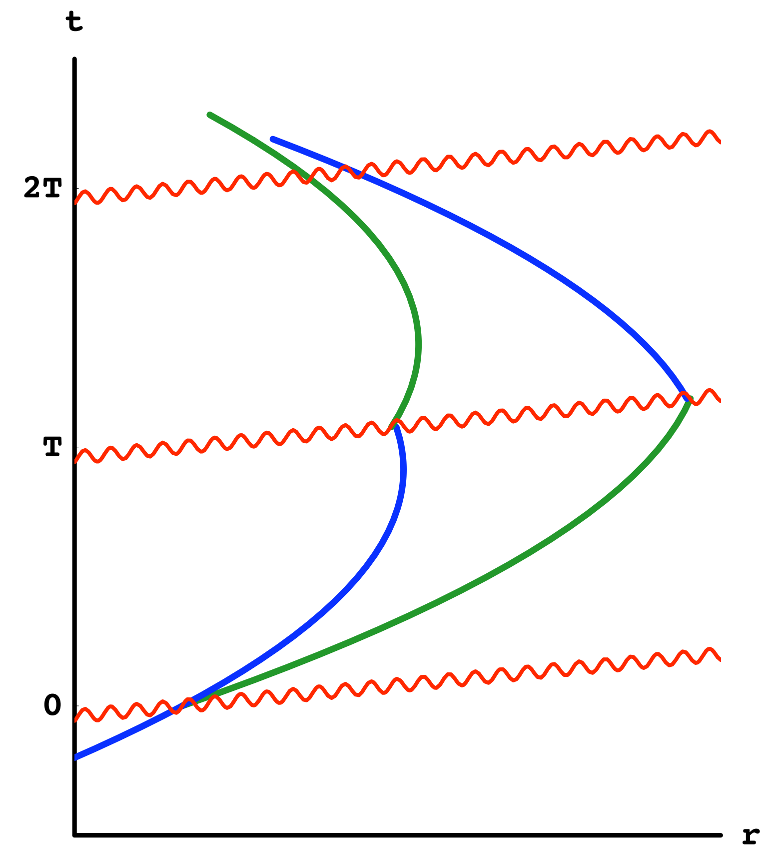
colocated ^{85}Rb and ^{87}Rb clouds test Principle of Equivalence initially to 10^{-15} in controlled (lab) conditions

GR Calculation

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

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

paths are (approximate) geodesics



GR Calculation

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

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

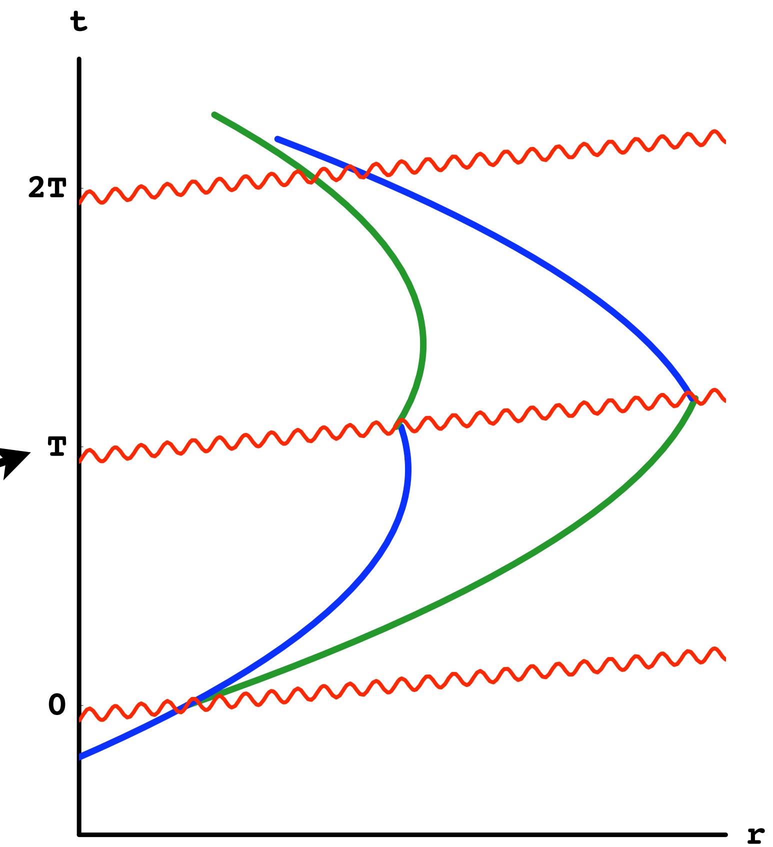
paths are (approximate) geodesics

must use physical variables:

e.g. time $\frac{T}{\sqrt{g_{00}}}$

laser frequency $p_{\text{light}} \cdot v_{\text{laser}} \equiv k$

launch velocity...



General Relativity

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

acceleration of a massive particle

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

General Relativity

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

acceleration of a massive particle

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

in the lab g $10^{-9} g$

General Relativity

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

acceleration of a massive particle

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

in the lab g $10^{-9}g$

$$10^{-9}g \times \frac{10\text{m}}{R_{\text{earth}}} \approx 10^{-15}g$$

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 $\nabla \cdot \vec{a} = 0$

General Relativity

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

acceleration of a massive particle

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}(\phi + (\beta + \gamma)\phi^2) + \gamma\underbrace{(3(\vec{v}\cdot\hat{r})^2 - 2\vec{v}^2)\vec{\nabla}\phi + 2\vec{v}(\vec{v}\cdot\vec{\nabla}\phi)}_{10^{-15}g}$$

in the lab g $10^{-9}g$ $10^{-15}g$ $v \approx 10\frac{\mathrm{m}}{\mathrm{s}}$

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

General Relativity

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

acceleration of a massive particle

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

in the lab g $10^{-9}g$ $10^{-15}g$

$$10^{-9}g \times \frac{10\text{m}}{R_{\text{earth}}} \approx 10^{-15}g$$

← measurable size of GR effects

General Relativity

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

acceleration of a massive particle

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}(\phi + (\beta + \gamma)\phi^2) + \underbrace{\gamma(3(\vec{v}\cdot\hat{r})^2 - 2\vec{v}^2)\vec{\nabla}\phi + 2\vec{v}(\vec{v}\cdot\vec{\nabla}\phi)}_{10^{-15} g}$$

in the lab $\quad g \quad 10^{-9} g$

$$10^{-9} g \times \frac{10\text{m}}{R_{\text{earth}}} \approx 10^{-15} g$$

← measurable size of GR effects

falling of light also observable at same level

Future Prospects

Experimental Precision for:	Principle of Equivalence	GR effects	
current limits	10^{-13}	10^{-4}-10^{-5}	
AI initial	10^{-15}	10^{-1}	10 m experiment
upgrade	10^{-16}	10^{-2}	$200\hbar k$ beamsplitters
future	10^{-17}	10^{-4}	100 m experiment
far future	10^{-19}	10^{-6}	Heisenberg statistics

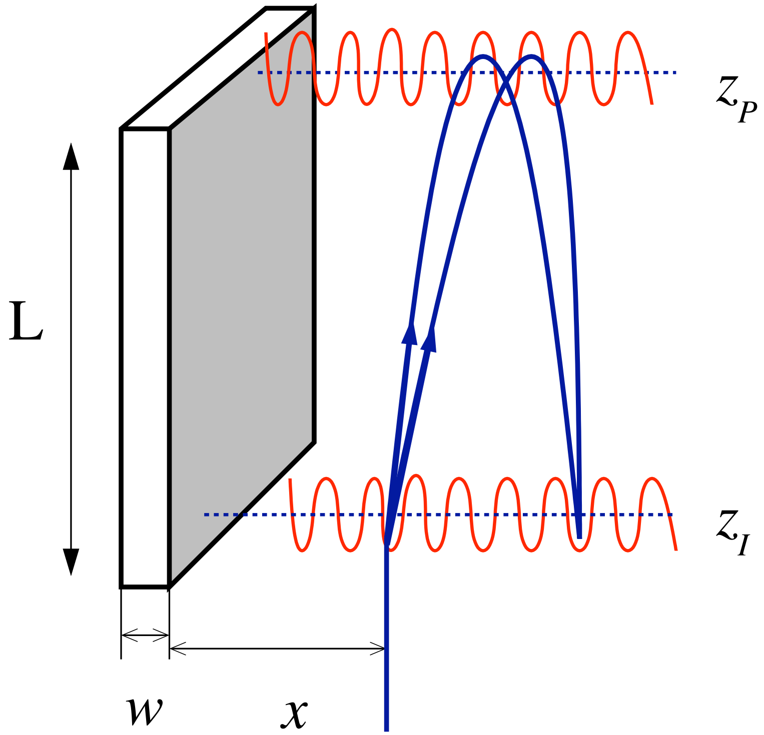
Testing Short Distance Gravity

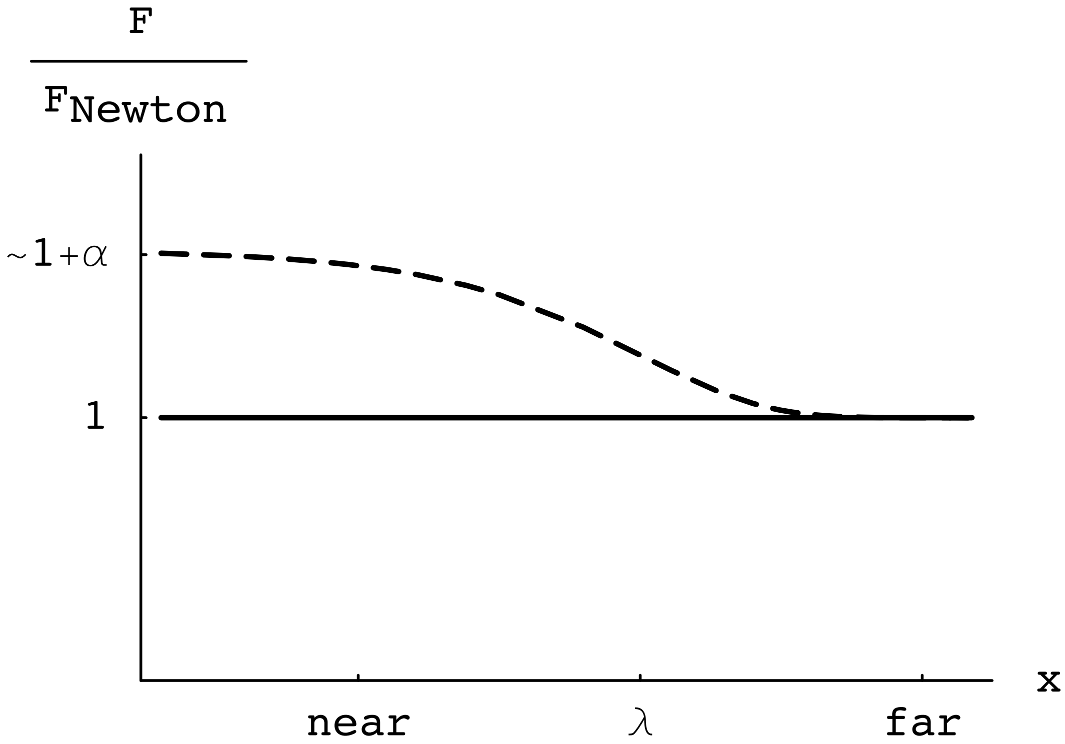
(in progress)

Savas Dimopoulos
PWG
Mark Kasevich
Jay Wacker

Searching for a Yukawa Force

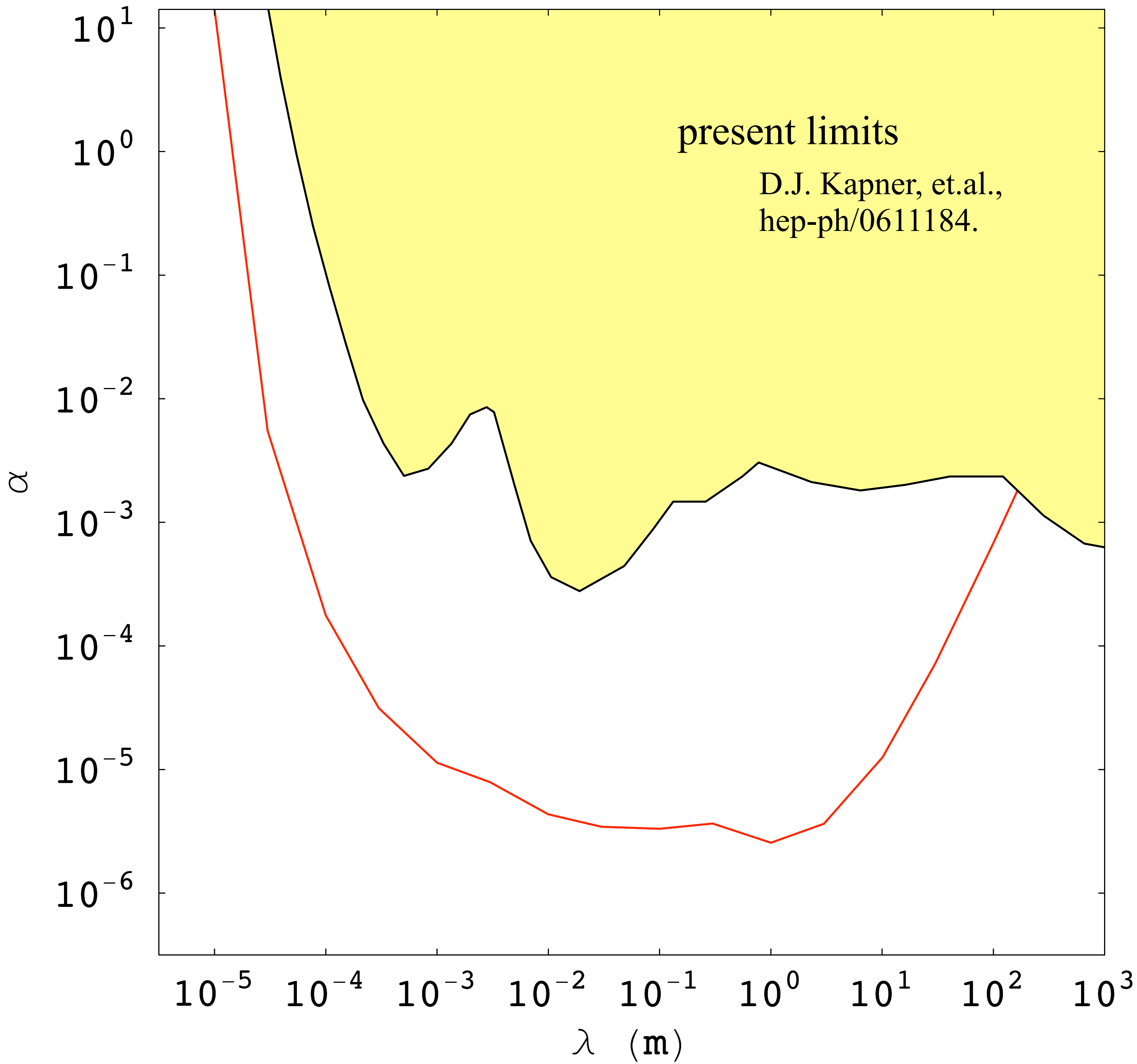
$$V = -\alpha \frac{G m e^{-\frac{r}{\lambda}}}{r}$$



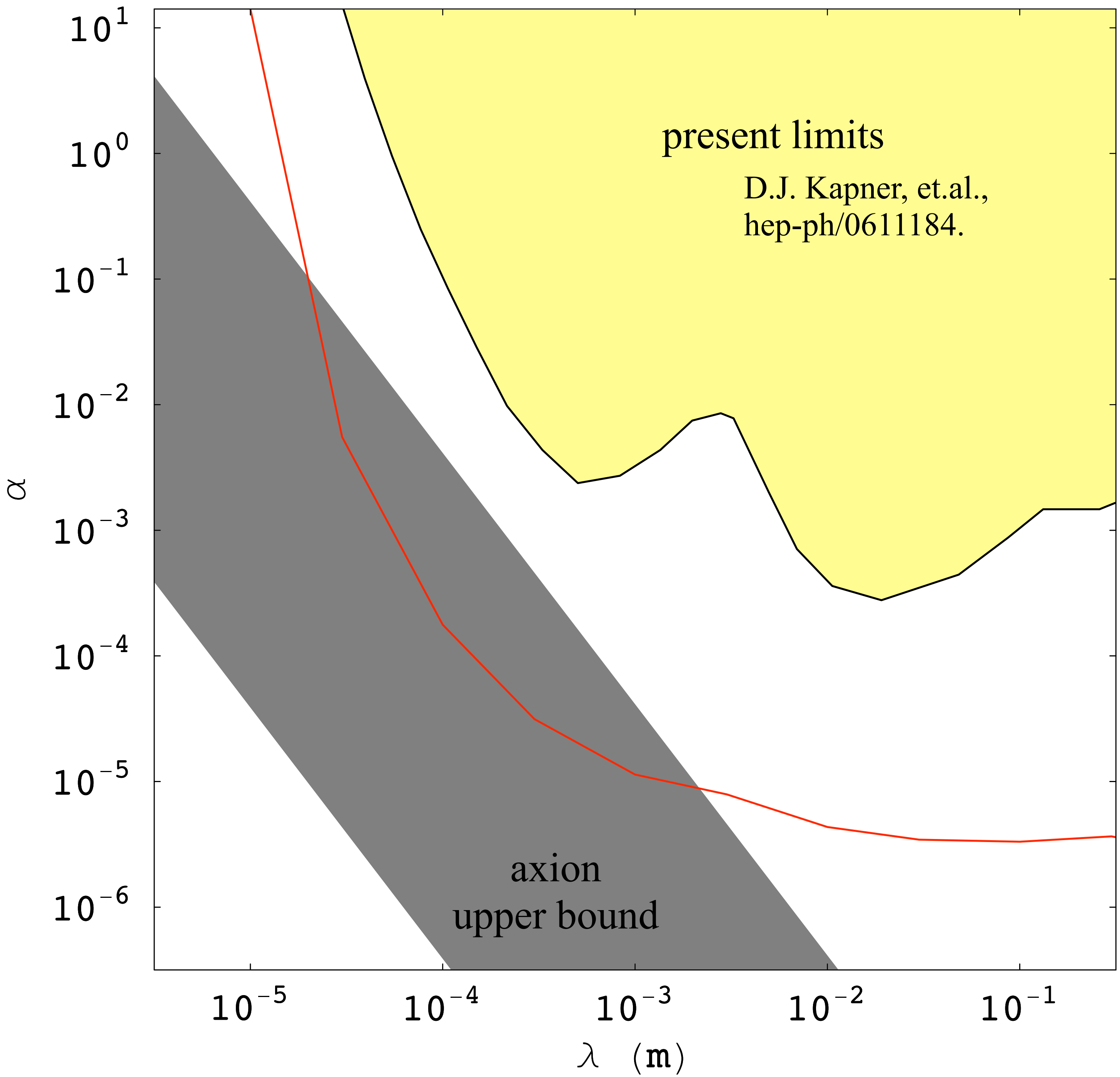


$$\text{for } L = 1\text{m and } \Delta x = 1\mu\text{m} \Rightarrow \alpha \sim 10^{-5}$$

Sensitivity



Sensitivity



Hubble Expansion

Atomic physics is close to 18 digit precision in experiments lasting 1 sec.

$$H \times (1\mathrm{sec}) = 10^{-18}$$

laser ranging an atom similar to radio ranging Pioneer

Principle of Equivalence $\Longrightarrow$ only tidal effects measurable

any local experiment sees Riemann $\propto H^2$

Prospects

We are about to enter a new era for atom interferometry where the rapid advance of these techniques will (hopefully) allow many new tests of fundamental physics

Gravity waves

General relativity and the equivalence principle

Short distance gravity

Quantum mechanics (e.g. Weinberg ’89)?

New ideas?