Physics with Cold Atoms

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Outline

1. Atom Interferometry

2. Testing (long-distance) General Relativity

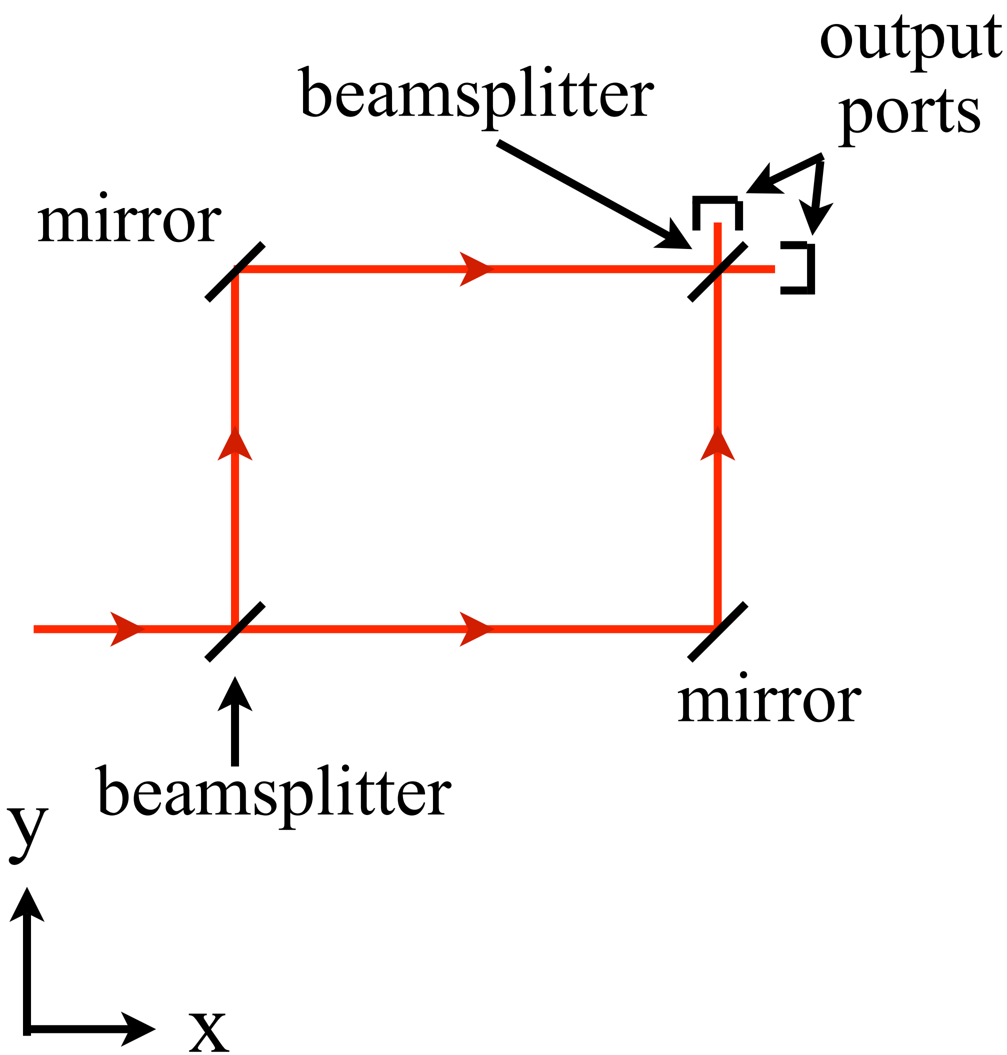
3. Gravity waves

4. Testing short-distance gravity

5. Testing Atom Neutrality

Light Interferometry

Space-space Interferometry

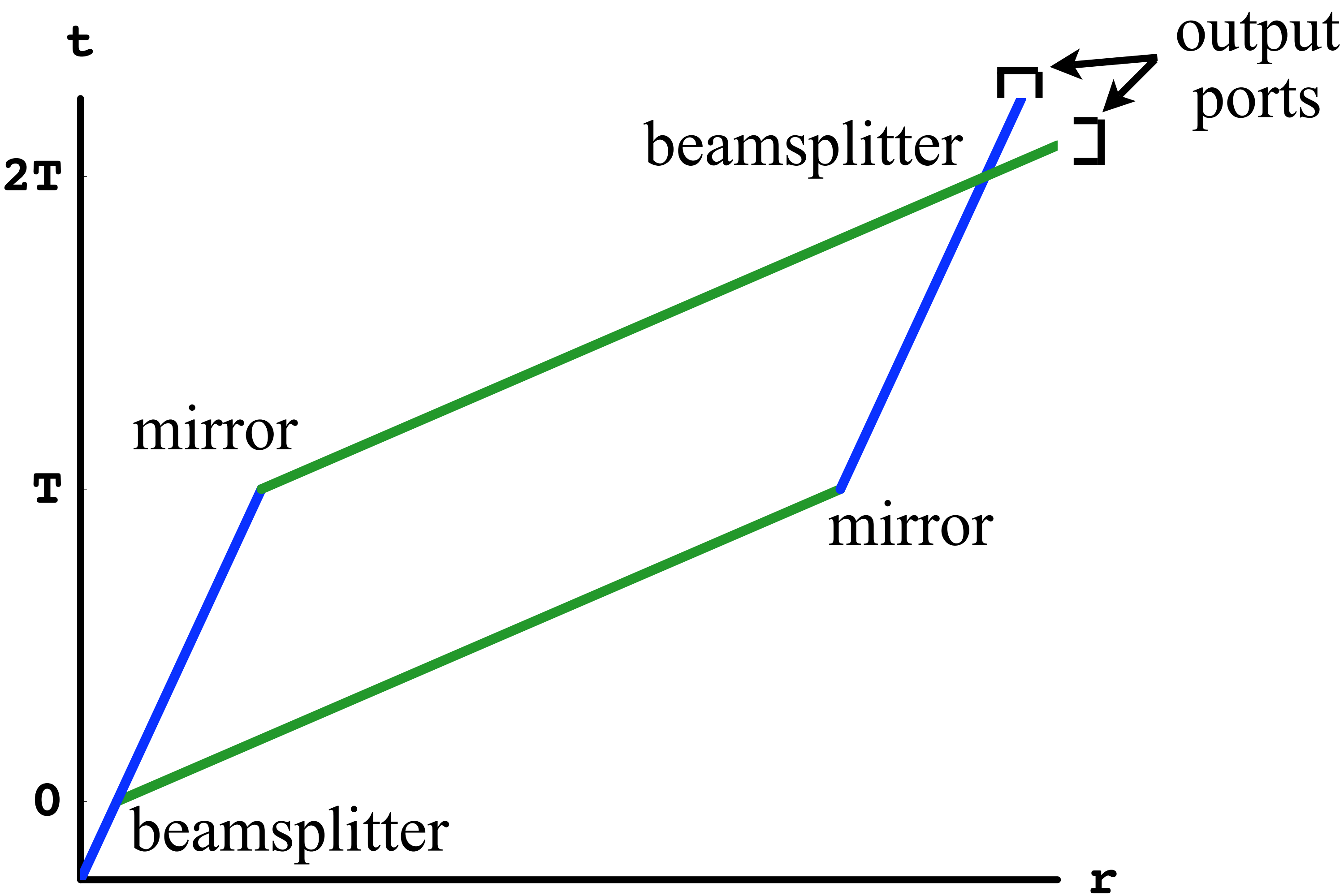


accuracy of measurement

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

Atom Interferometry

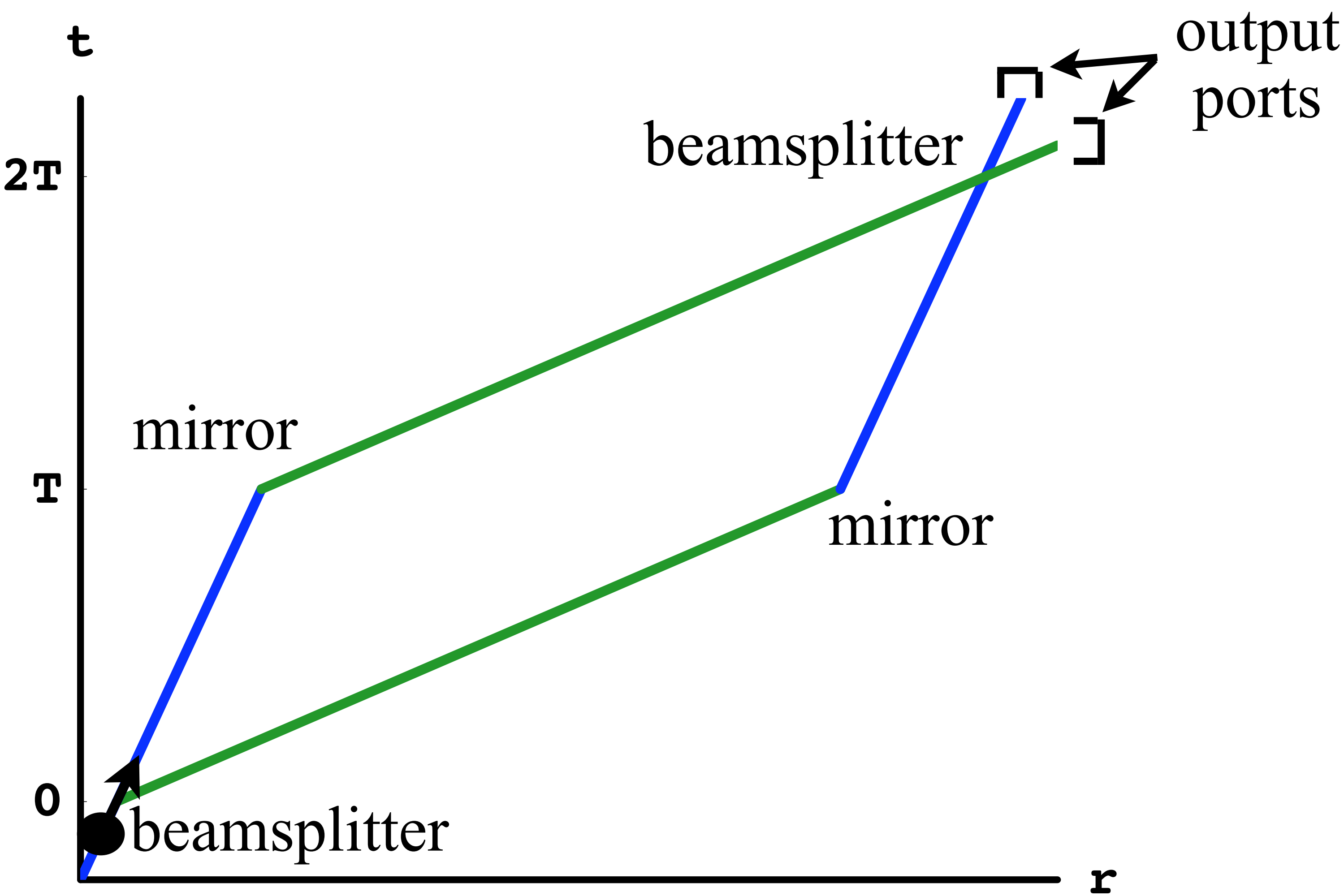
Space-time Interferometry



mirrors and beamsplitters are lasers

Atom Interferometry

Space-time Interferometry



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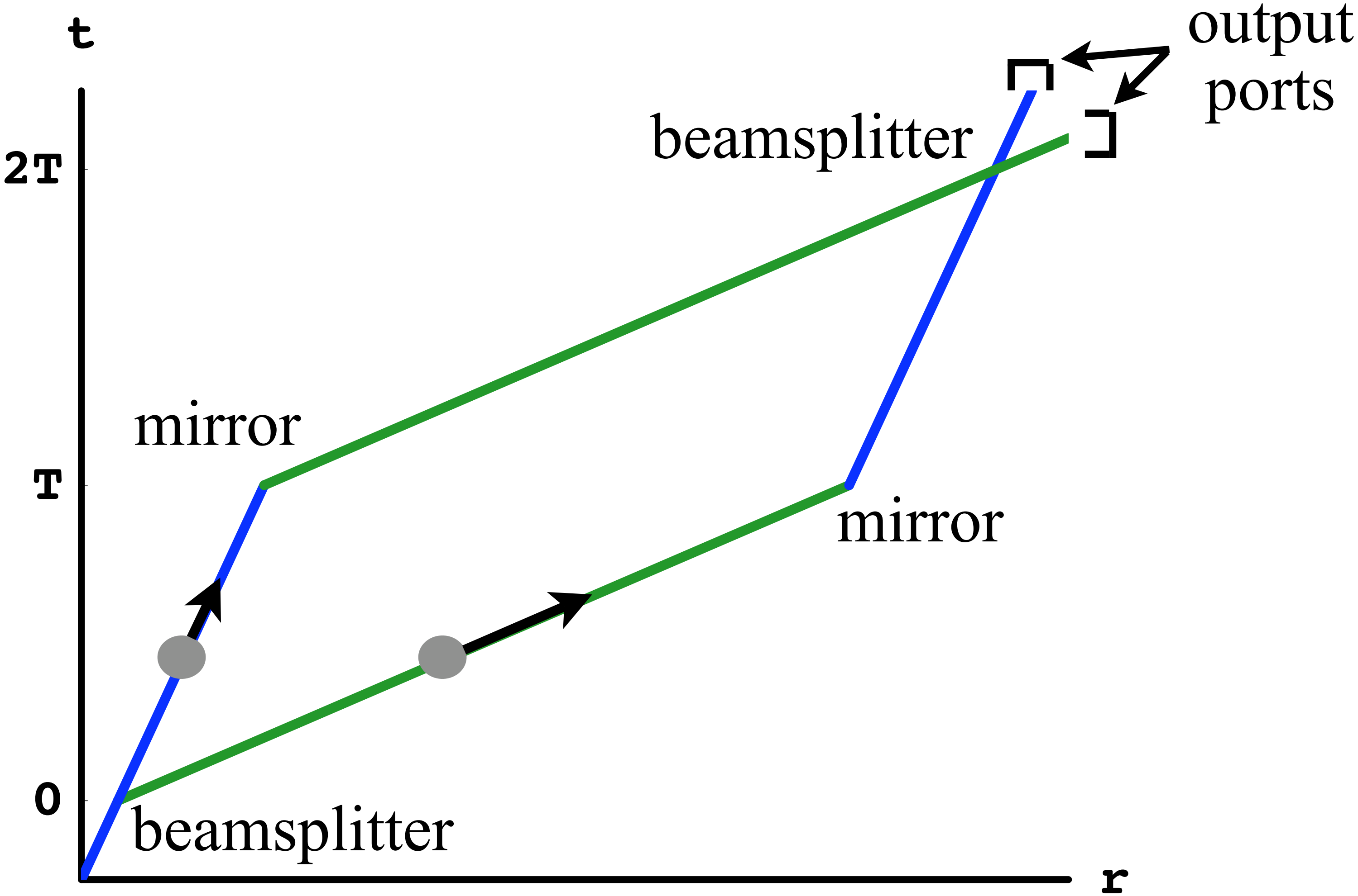

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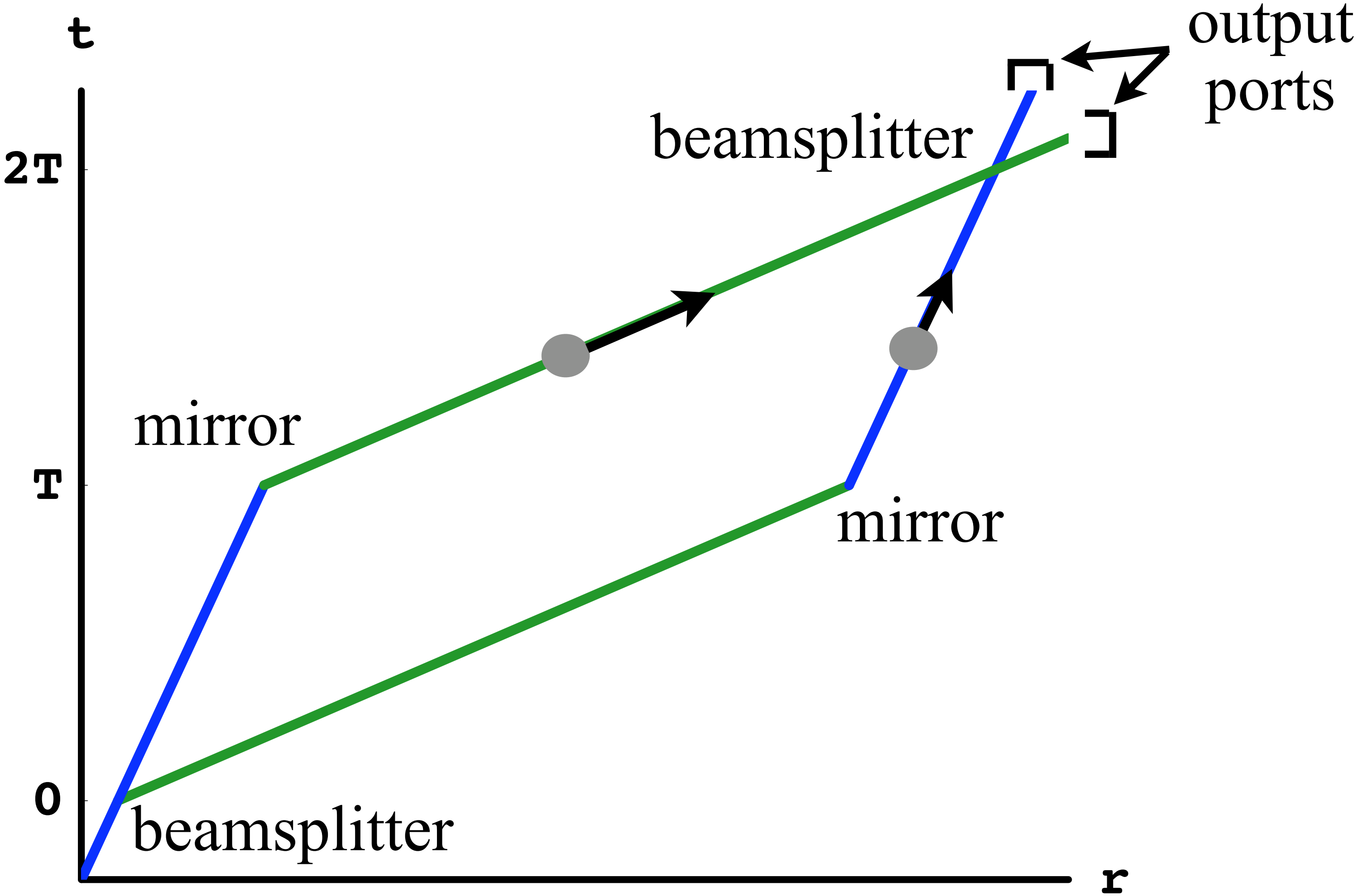

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Atom Interferometry

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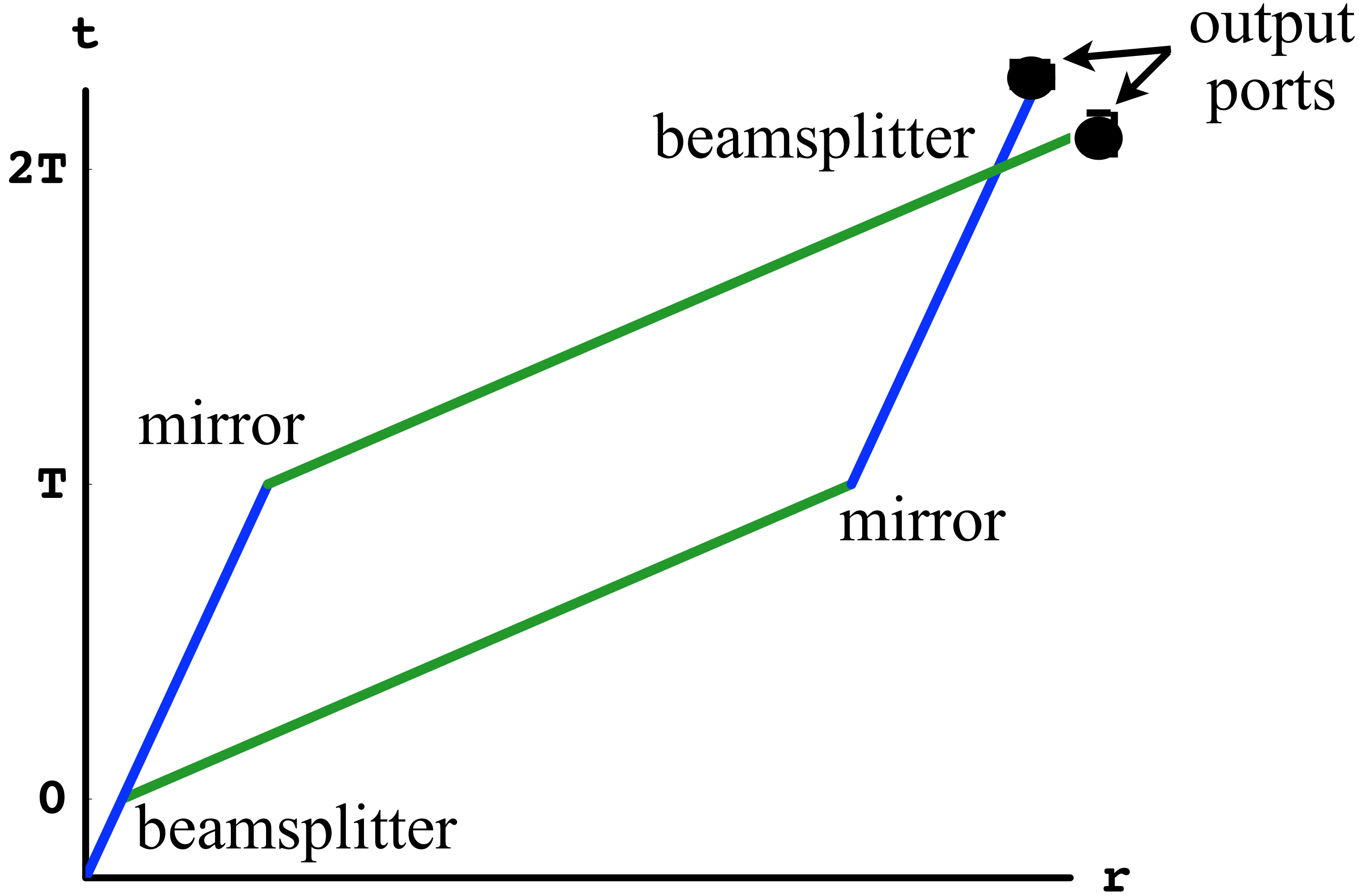

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Atom Interferometry

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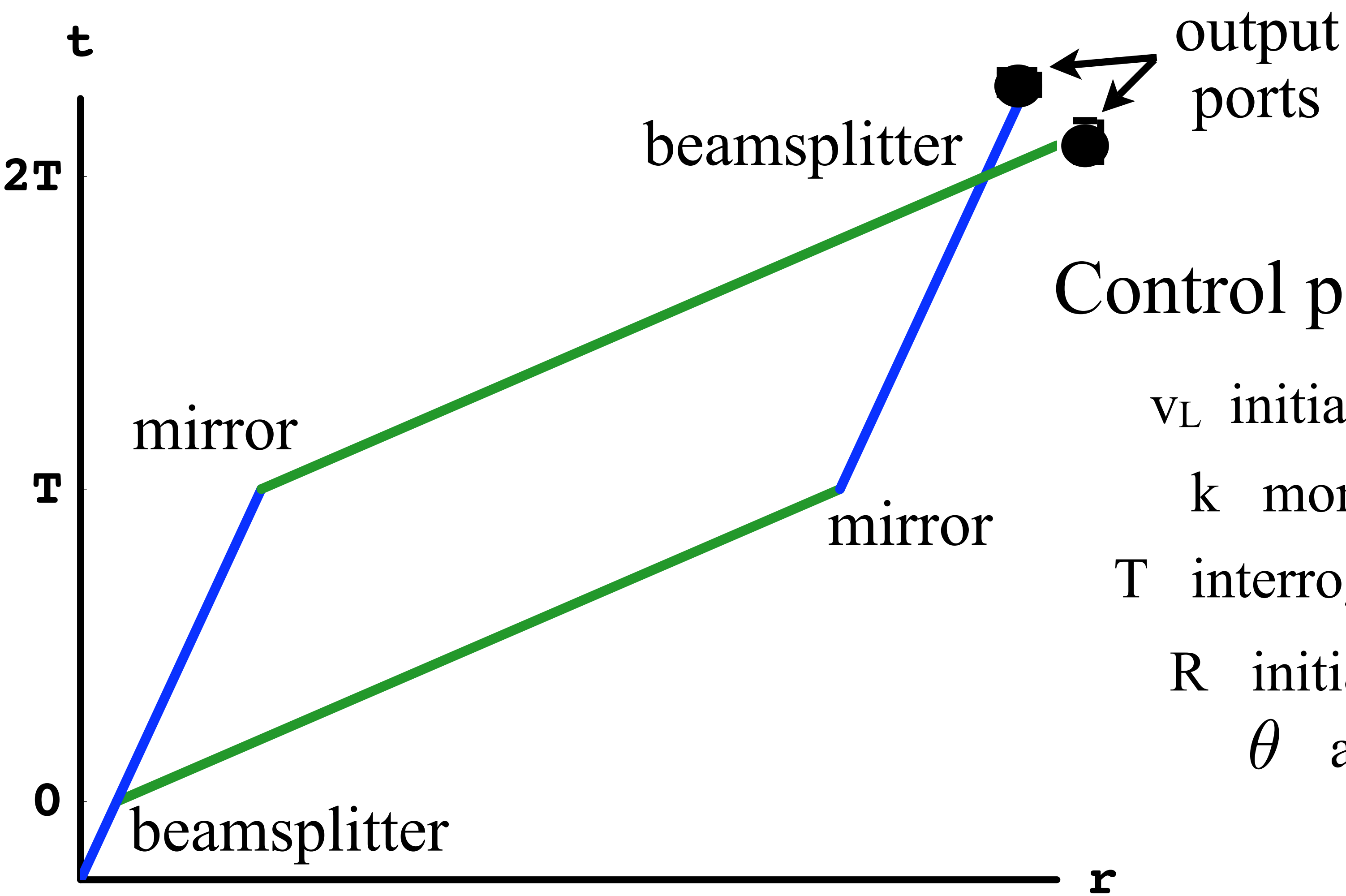


Control parameters:

v_L initial velocity

k momentum

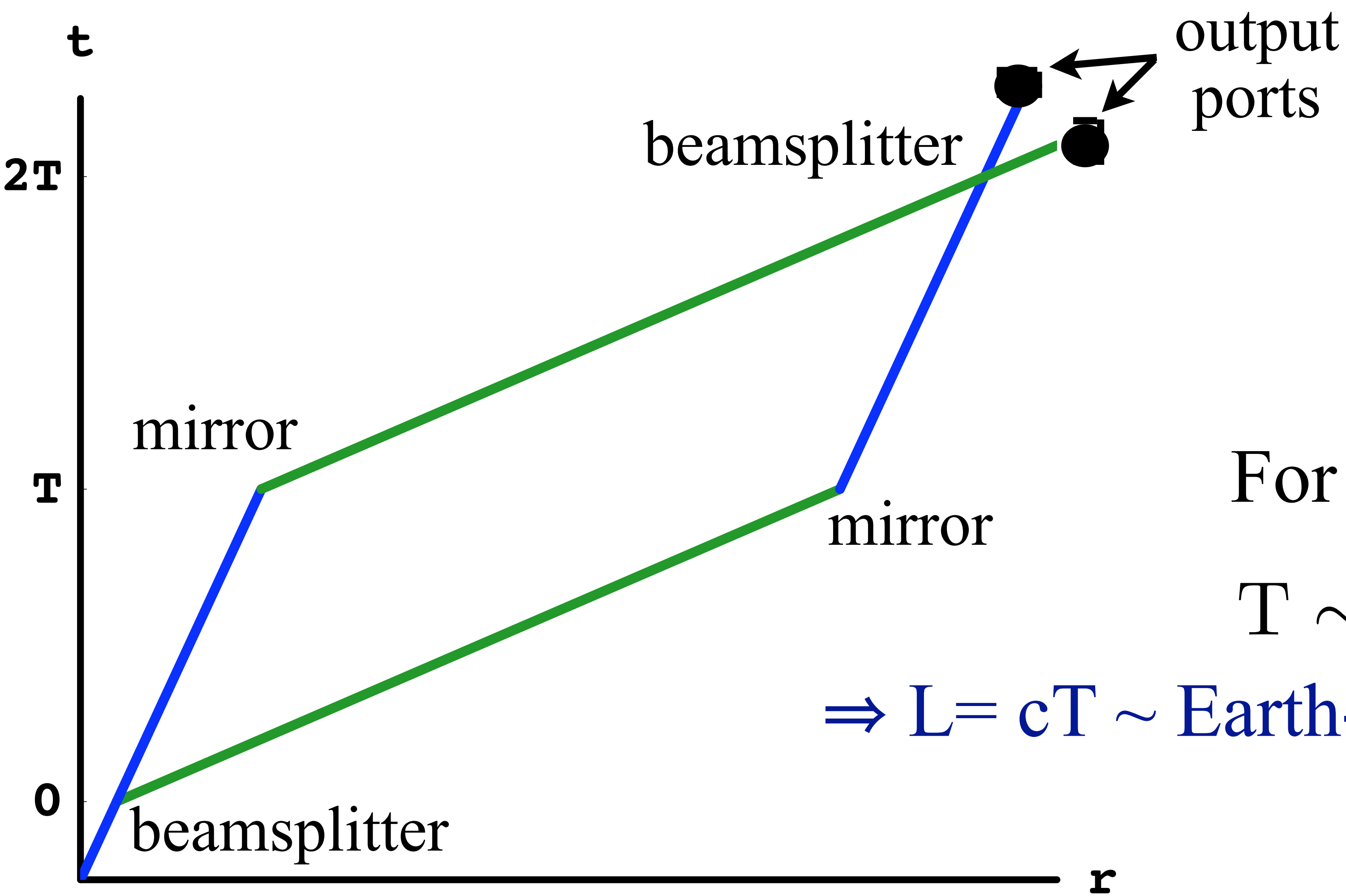
T interrogation time

R initial height

θ angle

Atom Interferometry

Space-time Interferometry



For atoms:

$T \sim 1$ sec

$\Rightarrow$ L= cT ~ Earth-Moon distance!

A new tool for testing fundamental physics

- Earth - Moon distance “arm length”
- Unprecedented precision: 10^{-17}
  (Nobel lectures: 1997, 2001, 2005)
- Atoms’ deBroglie wavelength is a smaller yardstick than optical light wavelength

$$\frac{1}{10\ \mathrm{keV}} \ \mathrm{vs}\ \frac{1}{10\ \mathrm{eV}}$$

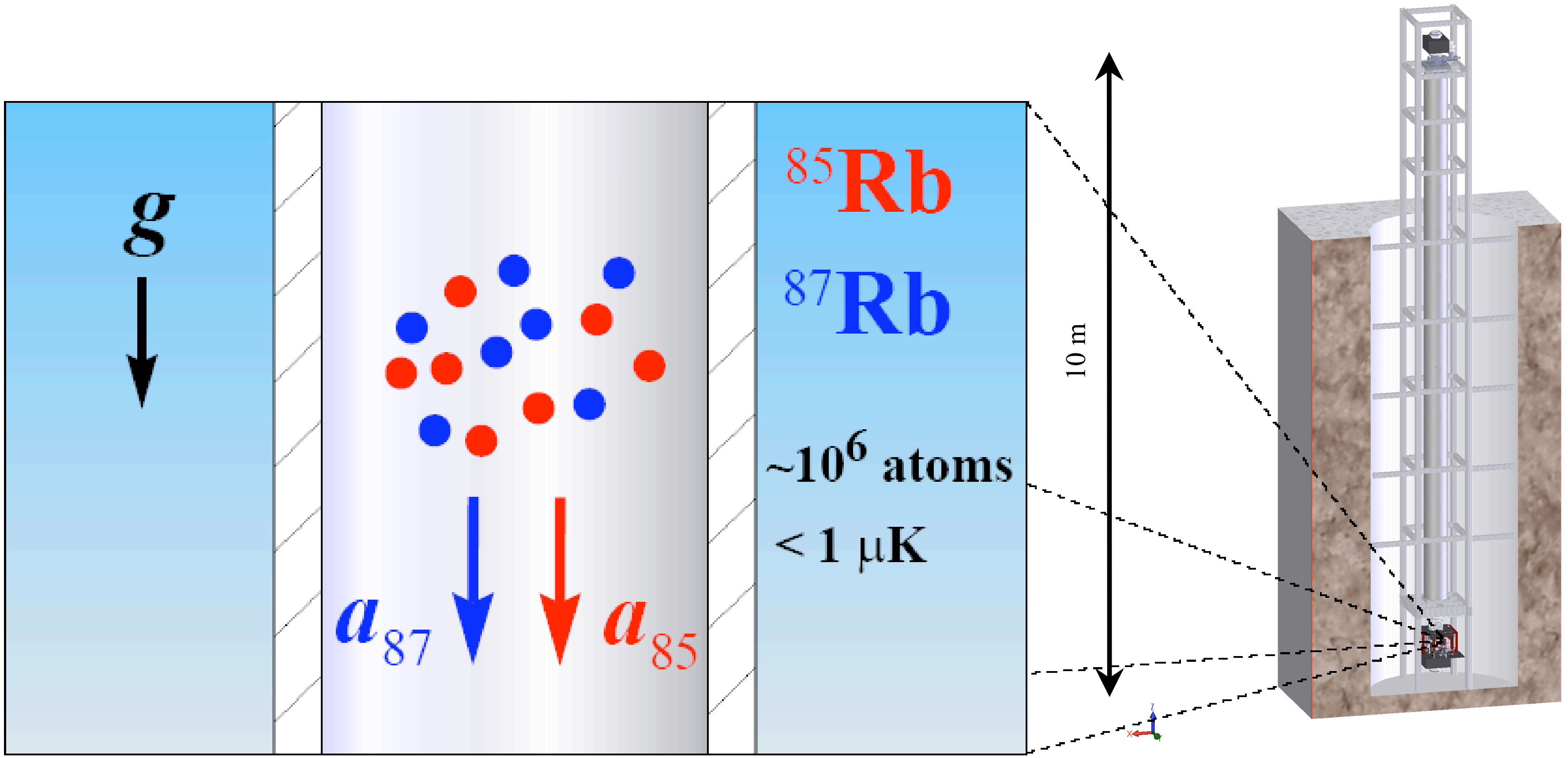
- Atoms have many “handles” (atoms vs neutrons)
- Table-top experiment ⇒ controlled conditions

  (atoms vs astrophysics)

Testing the Equivalence Principle and General Relativity

Savas Dimopoulos
Peter Graham
Jason Hogan
Mark Kasevich

Atomic Equivalence Principle Test



Co-falling ^{85}Rb and ^{87}Rb ensembles

10 m atom drop tower.

Initial accuracy $\sim 10^{-15}$

Compared to Lunar Laser Ranging $\sim 3 \times 10^{-13}$

Testing Gravity at Large Distances

Atom interferometry measures minute accelerations

$$\text{signal} \sim \int L_{\text{fast}} dt - \int L_{\text{slow}} dt \qquad \left(L = \frac{mv^2}{2} - mgh \right)$$

$$\sim mg\Delta hT \sim mg(v_{\text{fast}} - v_{\text{slow}})T^2$$

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$$\frac{dv}{dt} = -\nabla\phi + \boxed{\text{GR}}$$

$$\phi = G_N \frac{M_e}{R_e}$$

Post-Newtonian Approximation

Particle equation of motion:

$$\frac{d\vec{v}}{dt} = -\nabla\phi \qquad -\nabla\phi^2 \qquad -\vec{v}^2\nabla\phi$$

Newton's Gravity

Gravity Gravitates

Kinetic Energy Gravitates

Future Prospects

Experimental Precision for:	Principle of Equivalence	GR effects	
current limits	3×10^{-13}	10^{-4}-10^{-5}	
AI initial	10^{-15}	10^{-1}	10 m experiment
upgrade	10^{-16}	10^{-2}	$200\,\hbar k$ (LMT) beamsplitters
future	10^{-17}	10^{-4}	100 m experiment
far future	10^{-19}	10^{-6}	Heisenberg statistics

Gravity Waves

Savas Dimopoulos
Peter Graham
Jason Hogan
Mark Kasevich
Surjeet Rajendran

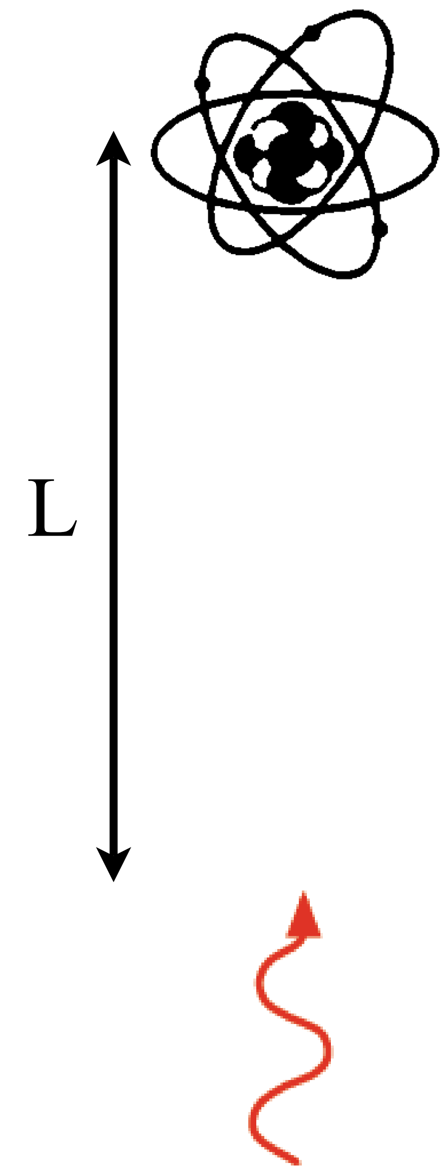
Gravity Wave Signal

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

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

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

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



Gravity Wave Signal

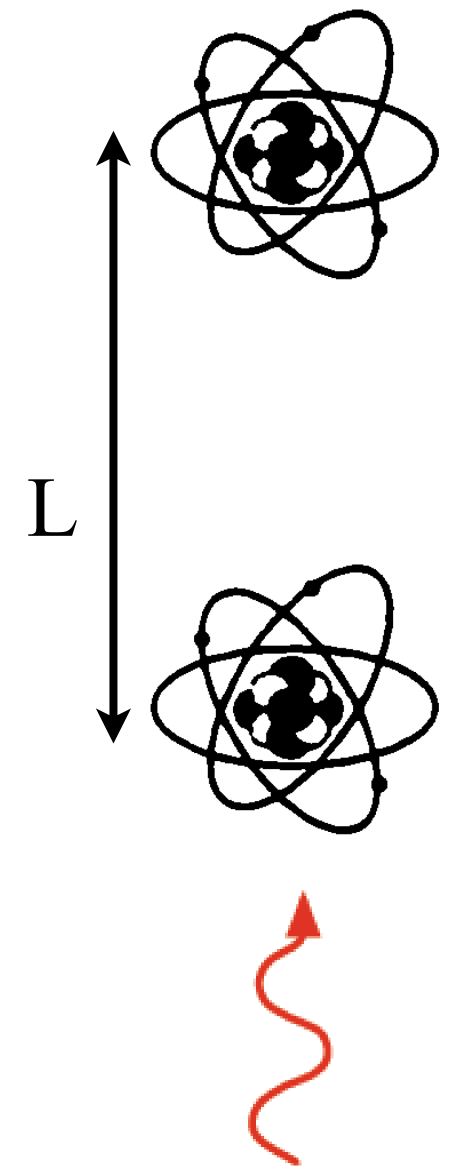
$$ds^2 = dt^2 - (1 + h\cos(\omega(t-y)))dx^2 - dy^2 - (1 - h\cos(\omega(t-y)))dz^2$$

differential measurement with two atoms
to cancel systematics

sensitivity increases with L and T
up to T,L ~ 1/ω = λ

GW phase

$$\sim kaT^2 \sim khL\omega^2\cos(\omega t)T^2$$



Sensitivity

on earth $\omega \sim 1$ Hz

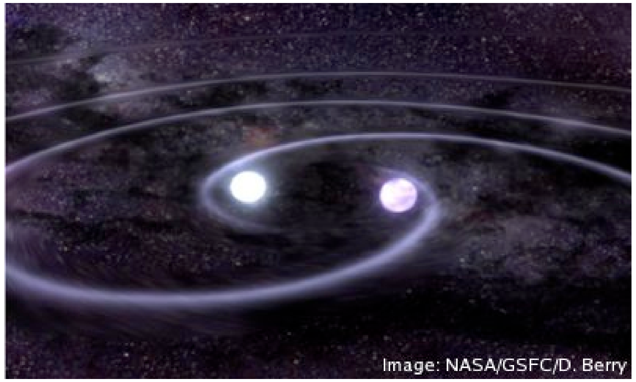
experimental sensitivity
for continuous sources

L~10 m and LMT	$h \sim 10^{-17}$
L~10 km	$h \sim 10^{-20}$
Heisenberg statistics	$h \sim 10^{-22}$

in space $\omega \sim 10^{-2}$ to 1 Hz

waves from solar mass binaries:

galaxy	$h \sim 10^{-19}$
cluster	$h \sim 10^{-22}$

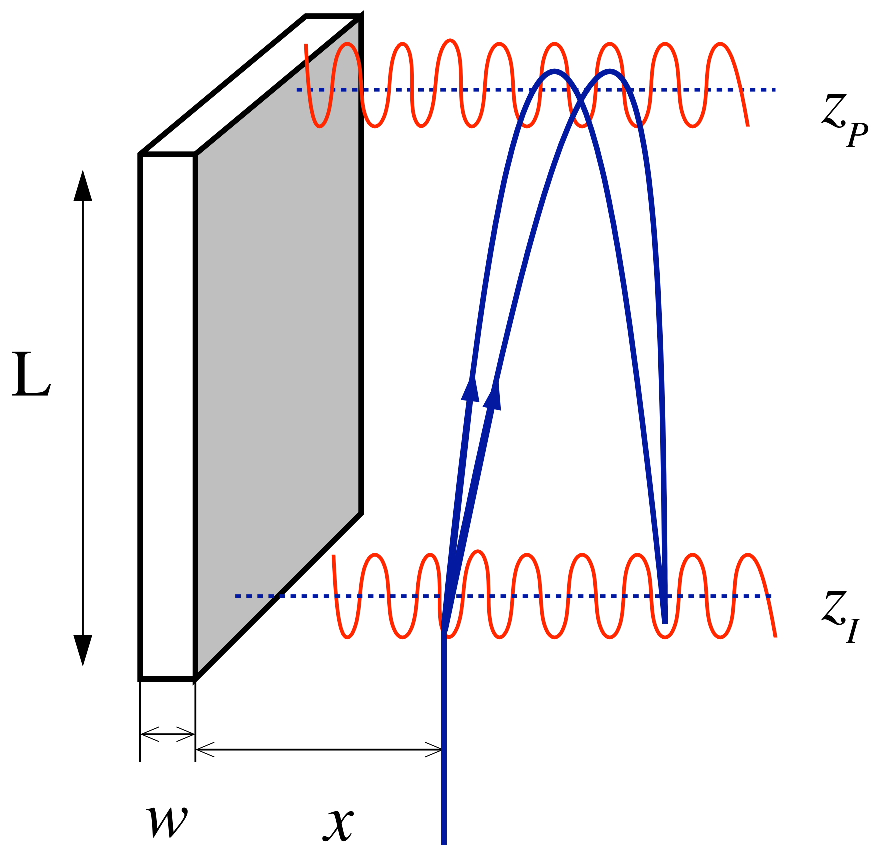


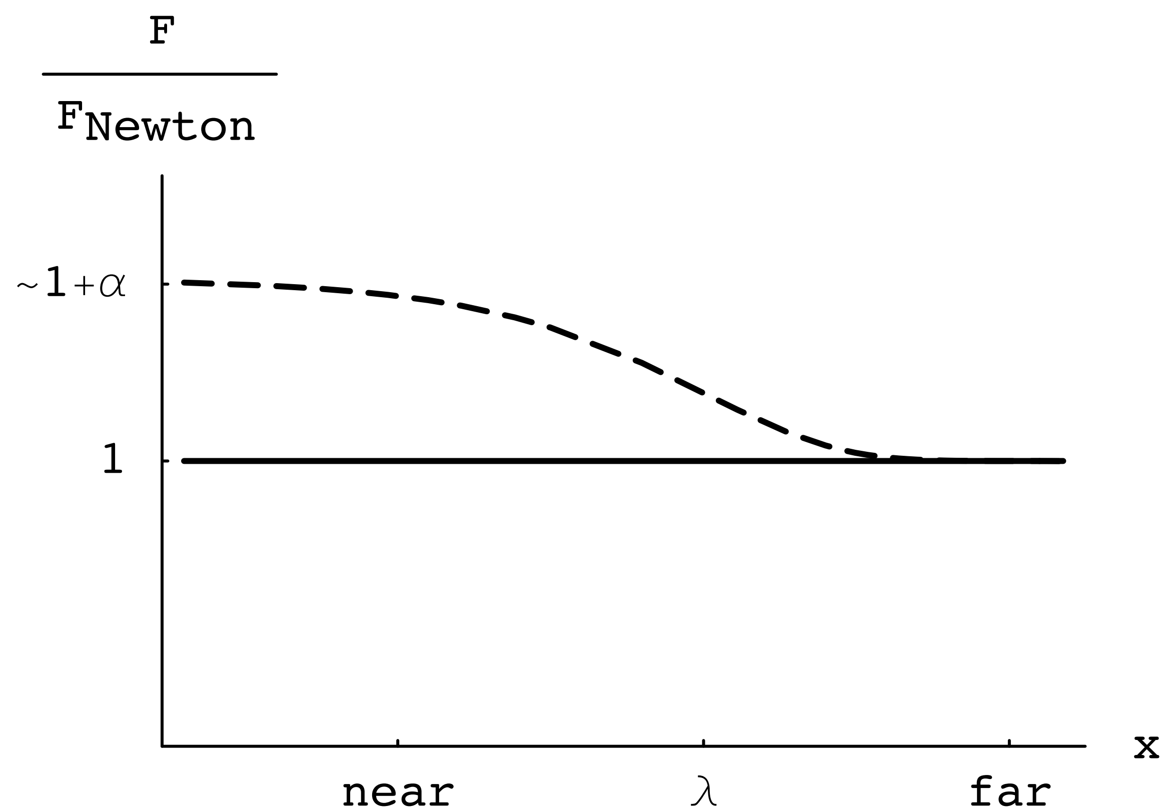
opens a new window for stochastic gravity wave searches
from phase transitions, inflation, cosmic strings...

Testing Short-Distance Gravity

Savas Dimopoulos
Peter Graham
Jason Hogan
Mark Kasevich
Jay Wacker

Searching for a Yukawa Force





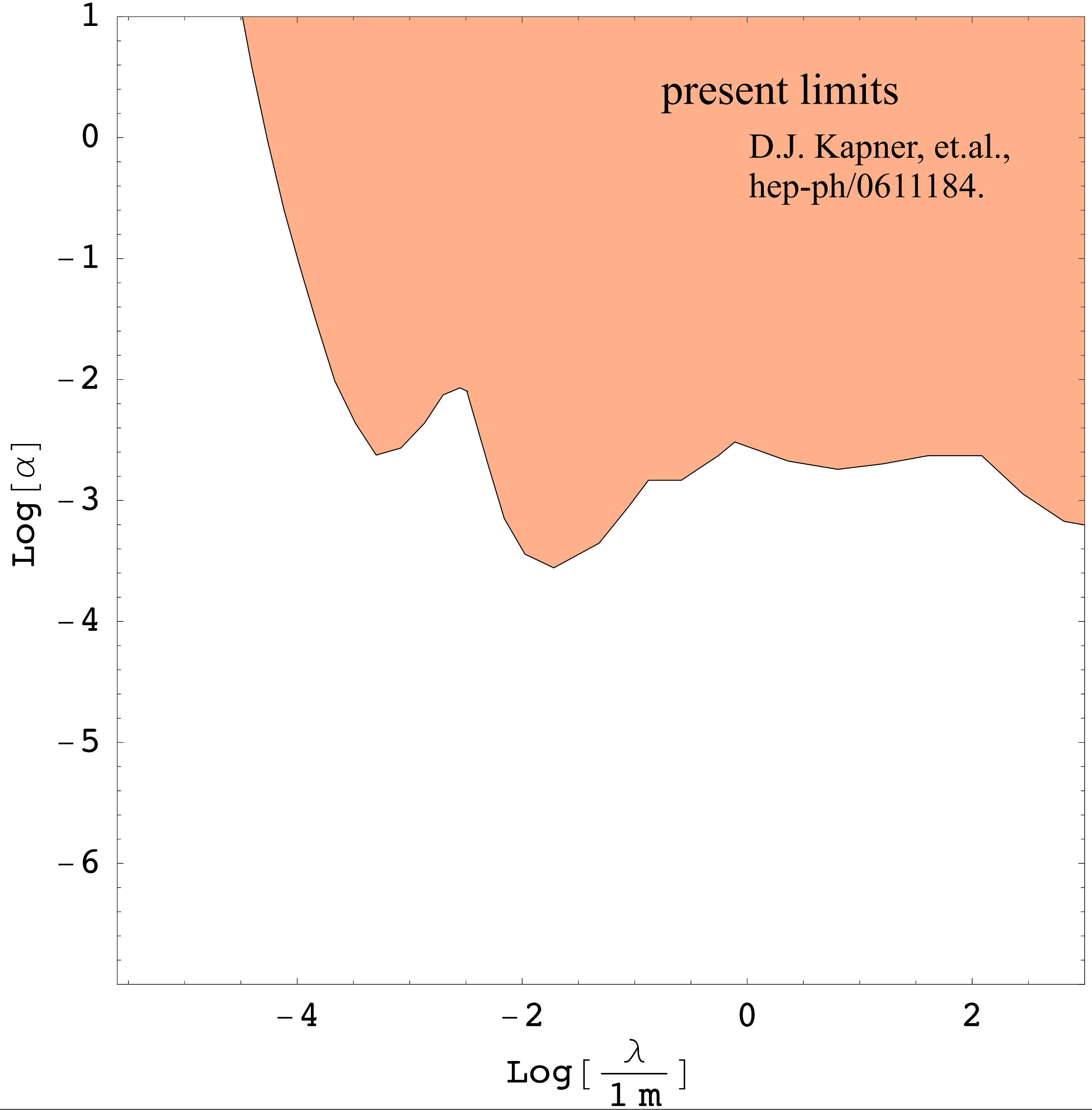
$$V = -\alpha \frac{G_N m e^{-\frac{r}{\lambda}}}{r}$$

Reach: $\alpha \sim 10^{-5}$

for 100 μm < λ < 1 m

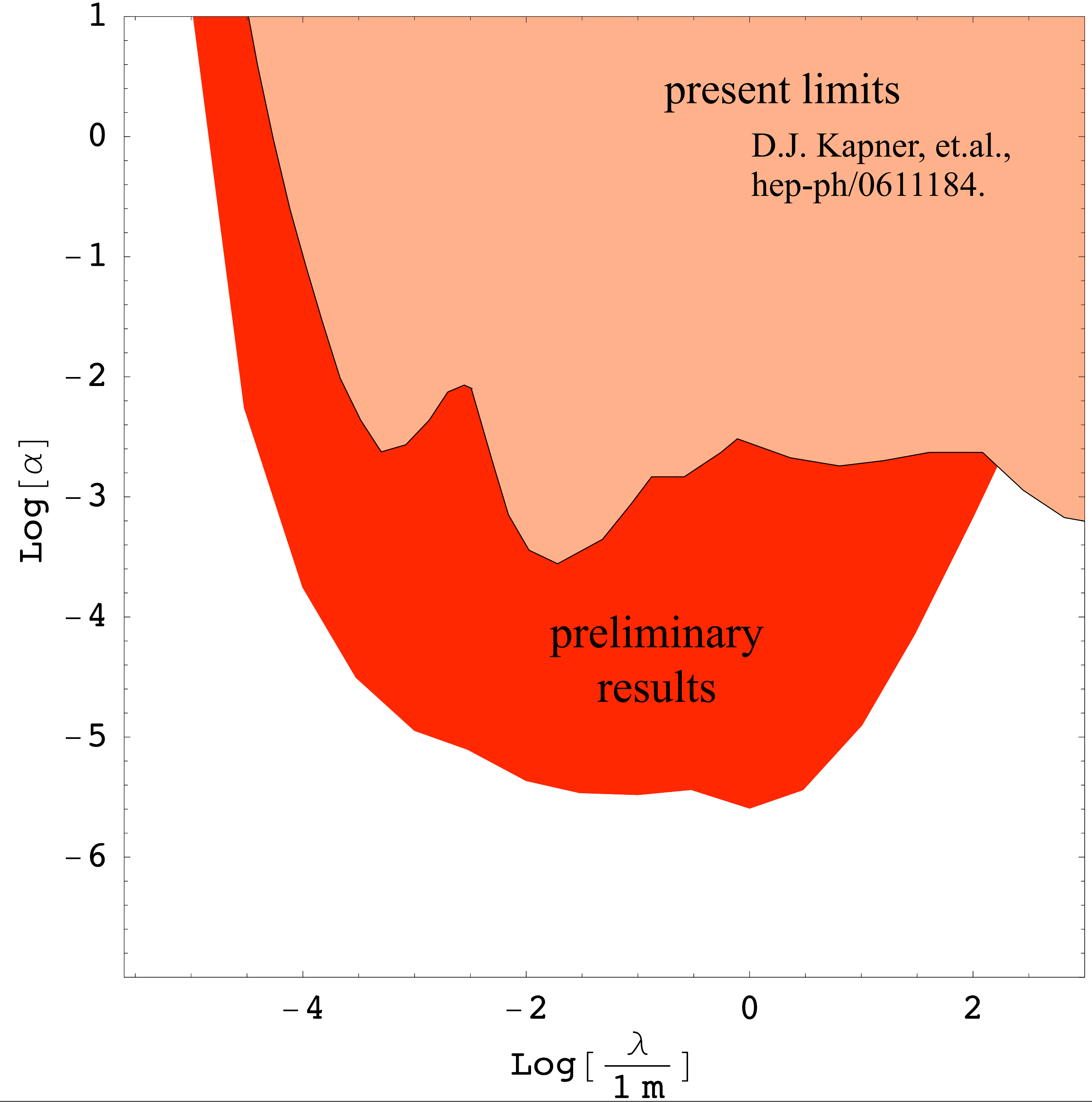
$$V = -\alpha \frac{G_N m e^{-\frac{r}{\lambda}}}{r}$$

Sensitivity



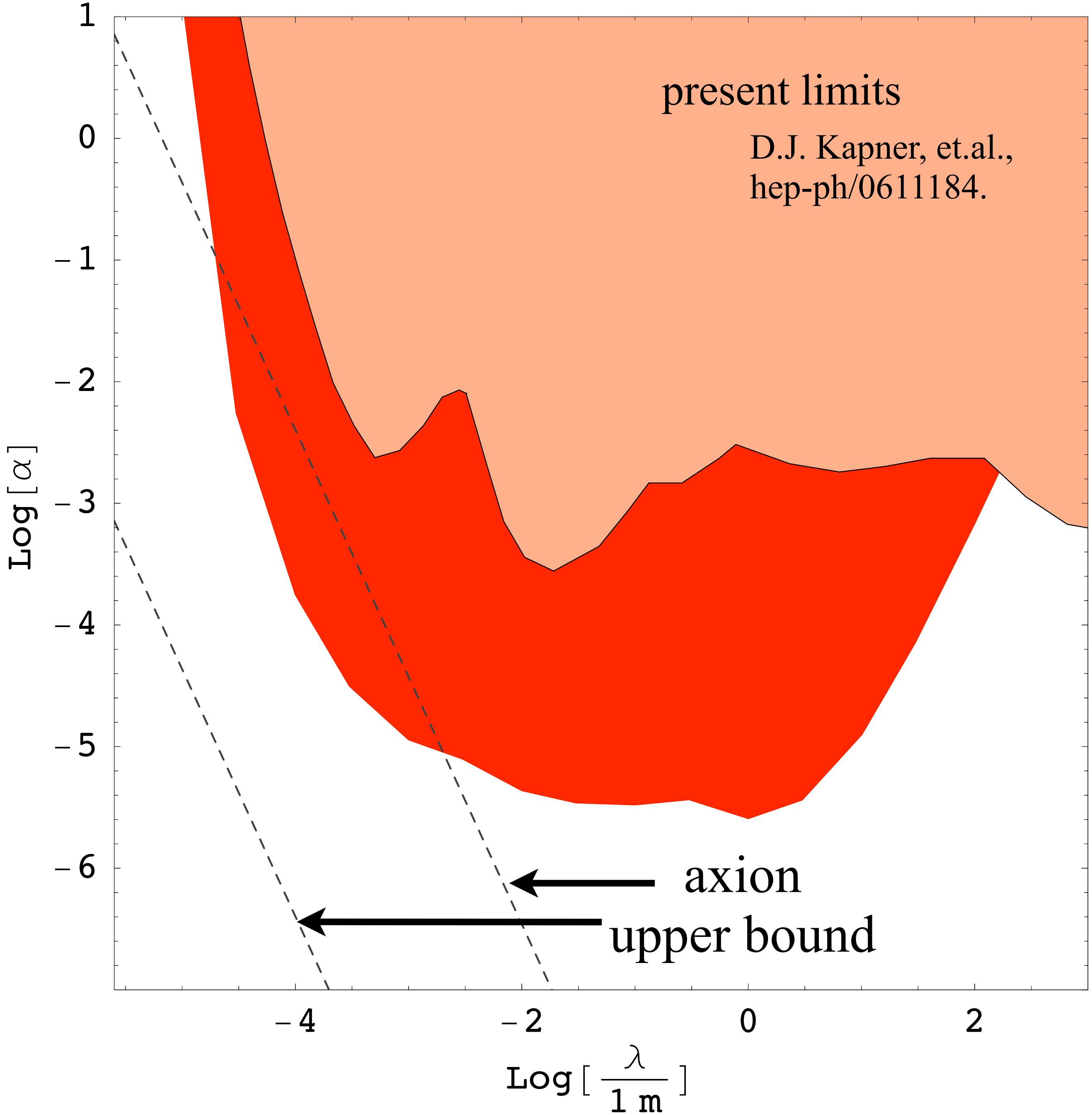
$$V = -\alpha \frac{G_N m e^{-\frac{r}{\lambda}}}{r}$$

AI Sensitivity



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

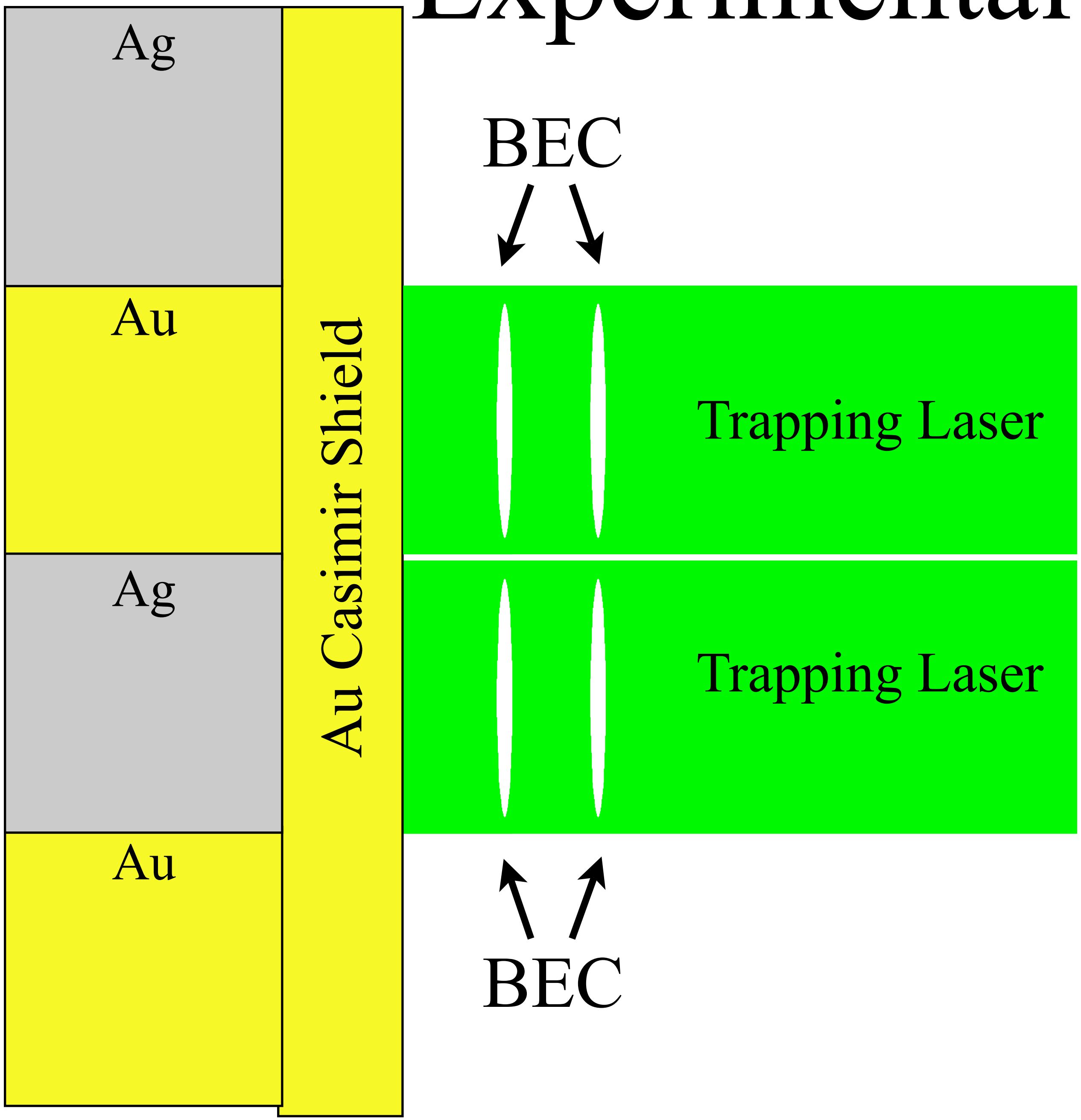
Axion reach



Testing Short-Distance Gravity with BEC's

Savas Dimopoulos
Andy Geraci
(2003)

Experimental Concept



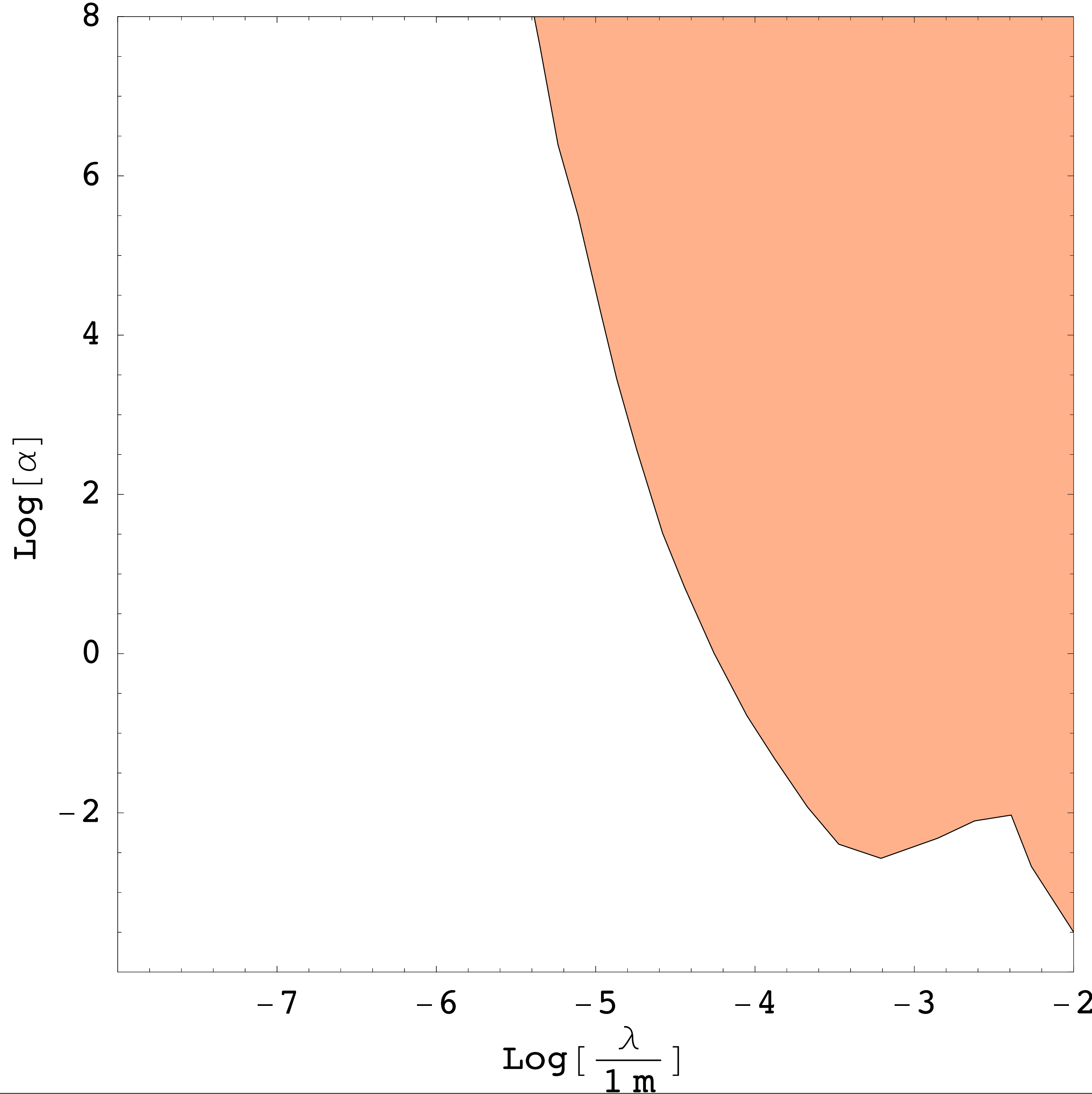
1)Trap BEC near surface by laser

2) accumulate differential phase shift due to interaction with Au vs. Ag

3) Turn off laser, allow BECs to interfere

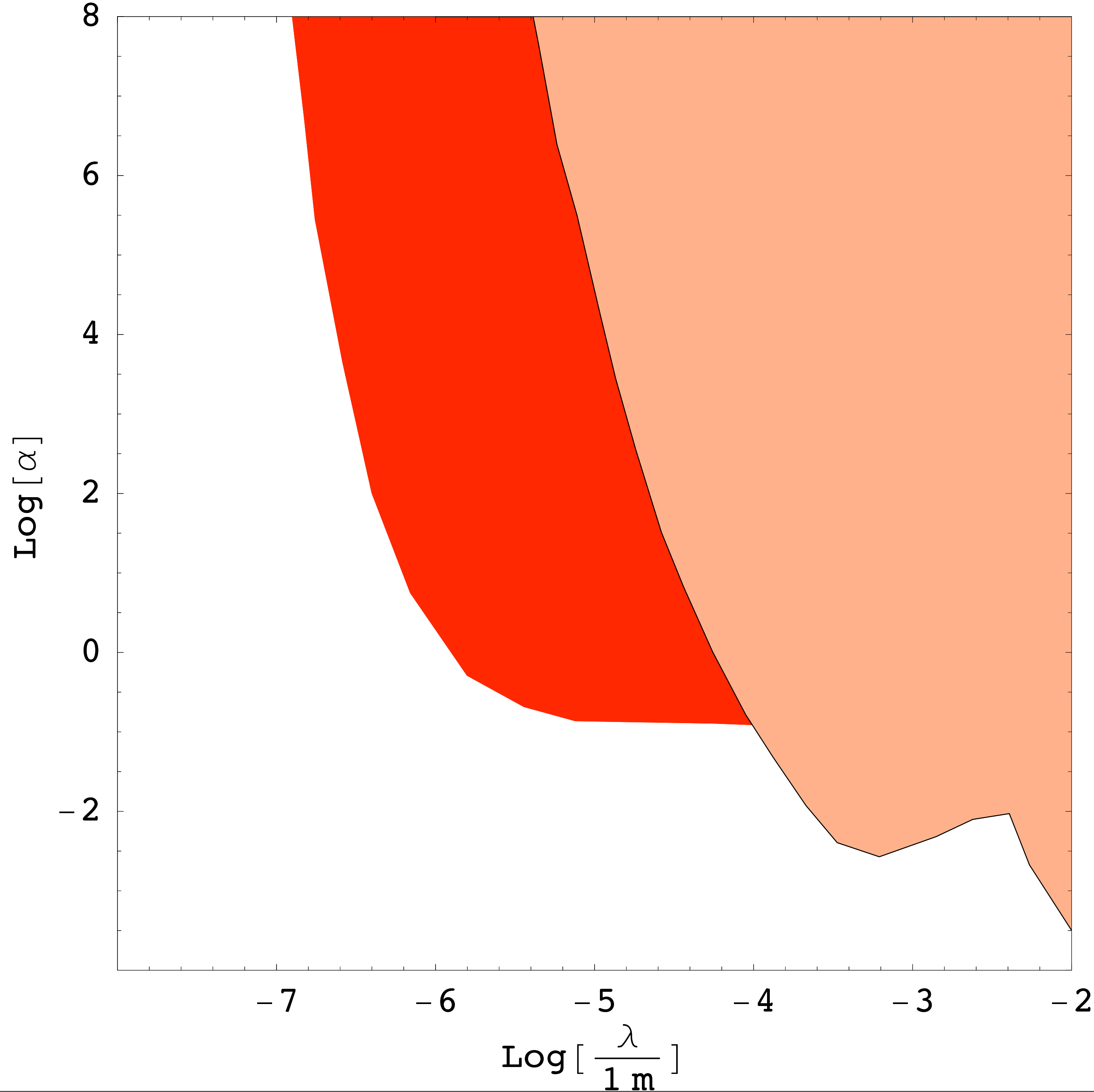
$$V = -\alpha \frac{G_N m e^{-\frac{r}{\lambda}}}{r}$$

Current bounds



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

BEC sensitivity



Testing Atom Neutrality

AA
Savas Dimopoulos
Andrew Geraci
Jason Hogan
Mark Kasevich

The mystery of charge quantization

proton charge = - electron charge

2 u+ d = - e with u= - d/2 = 2e/3

Coincidence?

Not in a GUT theory

The mystery of charge quantization

proton charge = - electron charge

2 u+ d = - e with u= - d/2 = 2e/3

Coincidence?

Not in a GUT theory

But GUT symmetry must be broken

Maybe charge quantization violated

θ-terms and violation of charge quantization

In a theory of a gauge U(1) with electric *and* magnetic charges

$$\nabla \cdot \vec{B} = \rho_m \neq 0$$

$$\vec{E} = -\nabla \phi$$

magnetic charges source electric fields in the presence of a θ-term

$$\theta F \wedge F = \theta \vec{E} \cdot \vec{B} = \theta \phi \nabla \cdot \vec{B}$$

$$= \theta \phi \rho_m$$

θ-terms and violation of charge quantization

If ordinary particles carry magnetic charge under $U(1)_1$ and electric charge under $U(1)_2$

$$\nabla \cdot \vec{B}_1 = \rho_{m_1} \neq 0$$

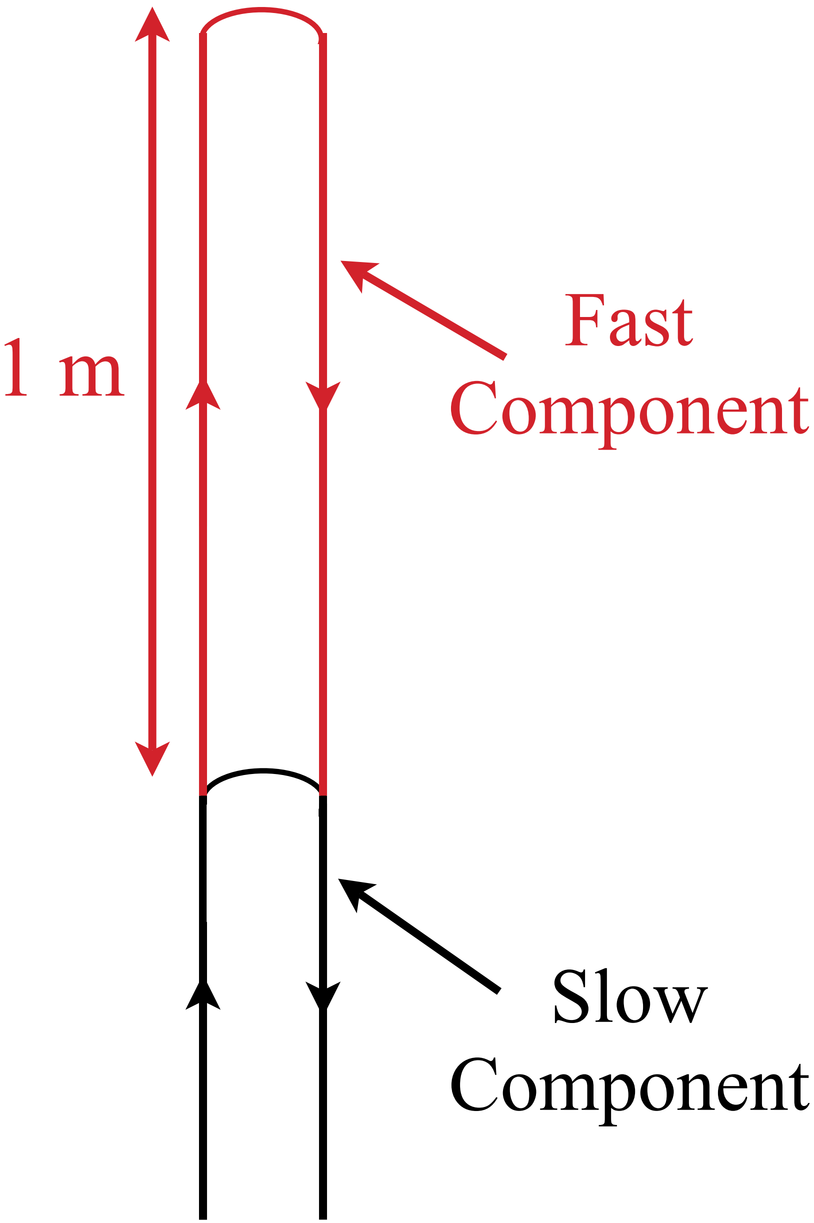
$$\vec{E}_2 = -\nabla \phi_2$$

electric charges shift in the presence of a θ-term coupling

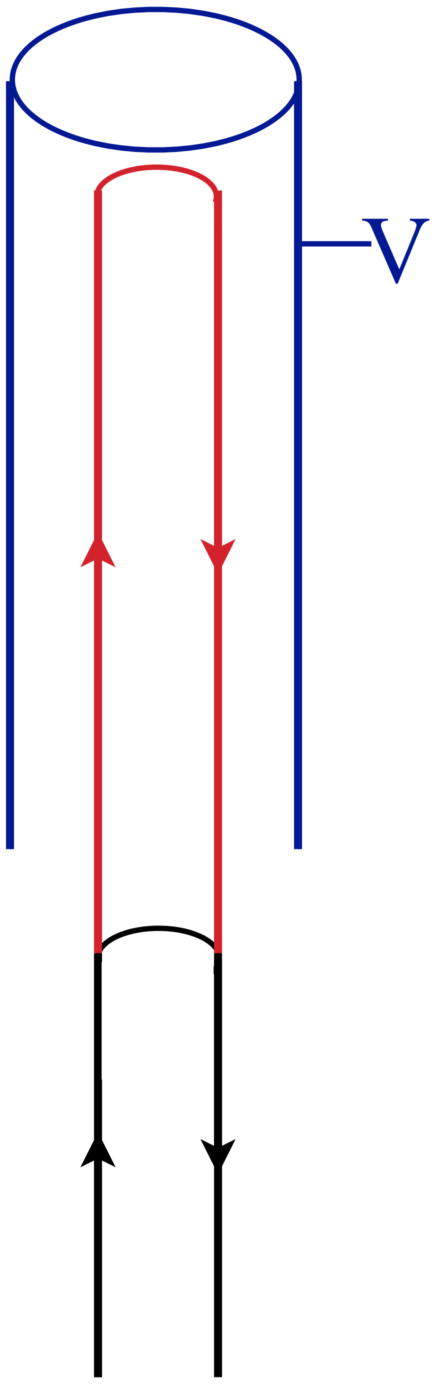
$$\theta F_2 \wedge F_1 = \theta \vec{E}_2 \cdot \vec{B}_1 = \theta \phi_2 \nabla \cdot \vec{B}_1$$

$$= \theta \phi_2 \rho_{m_1}$$

Testing Atom Neutrality



Testing Atom Neutrality



Electric Aharonov-Bohm Effect

$$\Delta\phi \sim \epsilon e V t$$

Atom interferometry bounds on charge per nucleon:

$\epsilon \sim 10^{-30}$

Current bounds: $\epsilon \sim 10^{-22}$

Physics Prospects for Cold Atoms

- Equivalence principle
- General Relativity tests
- Gravity wave detection
- Short-distance gravity
- Tests of atom neutrality

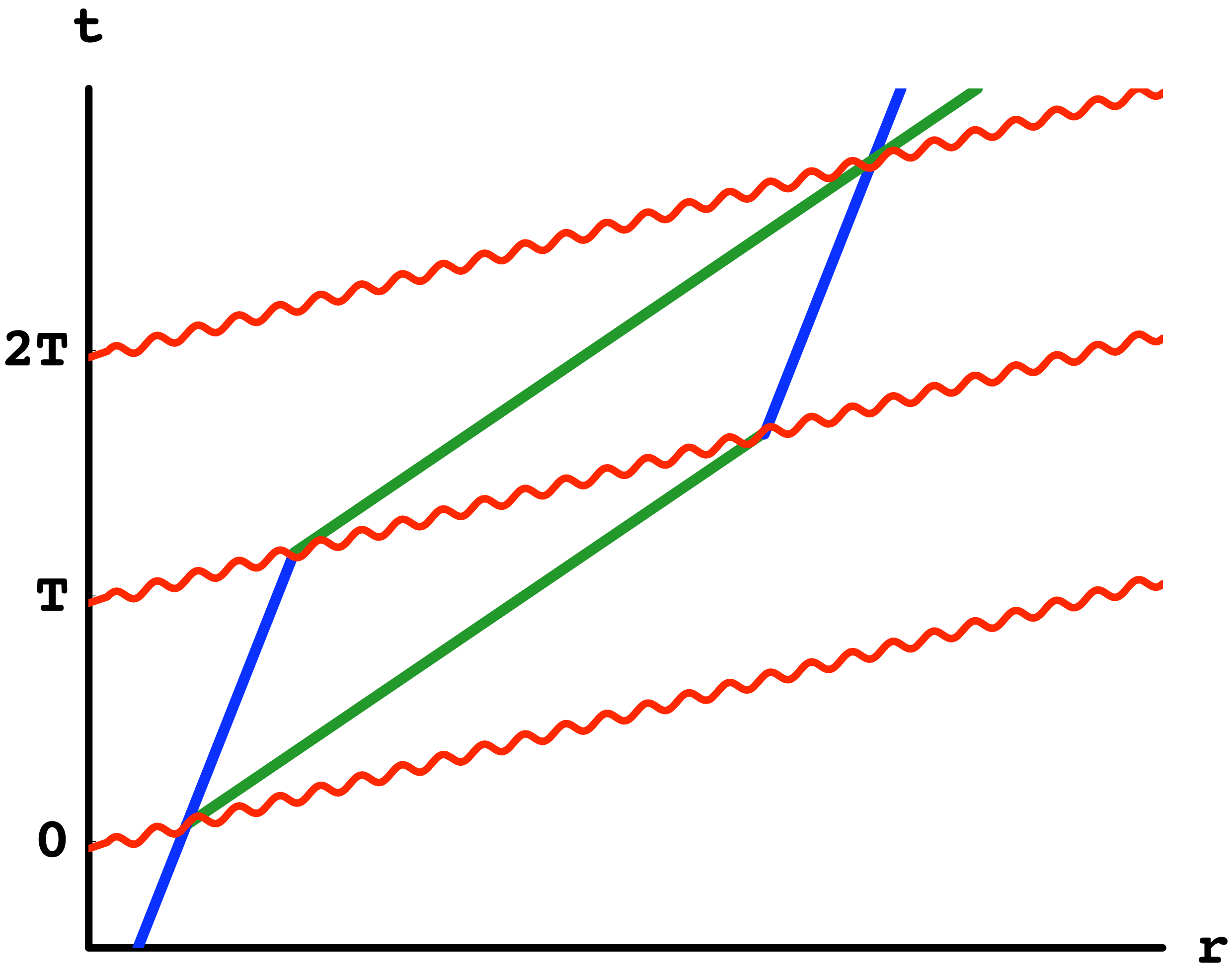
Physics Prospects for Cold Atoms

- Equivalence principle
- General Relativity tests
- Gravity wave detection
- Short-distance gravity
- Tests of atom neutrality
- Measurement of G_N
- Electric Dipole Moment searches
- Time variation of fundamental constants
- Tests of Quantum Mechanics (linearity, decoherence)...
- Cave detection, ship container characterization...

We are about to enter a golden era for atom interferometry, where technological and scientific applications will mature to (hopefully) have impact beyond the narrow confines of atomic physics

Atom Interferometry

Space-time Interferometry



controllable parameters

v_L initial velocity

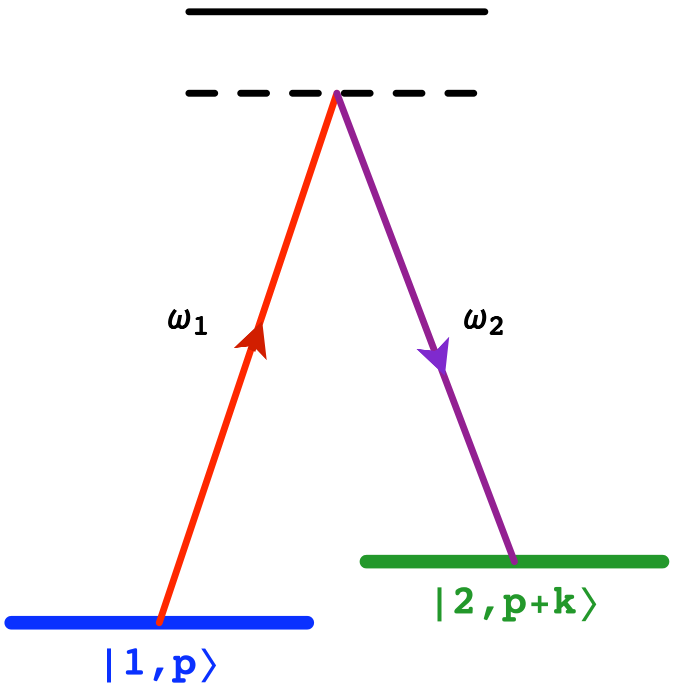
R initial height

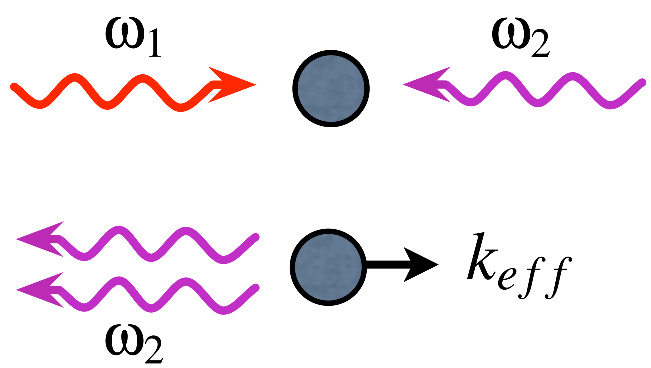
k momentum splitting

T interrogation time

θ angle

Raman Transition



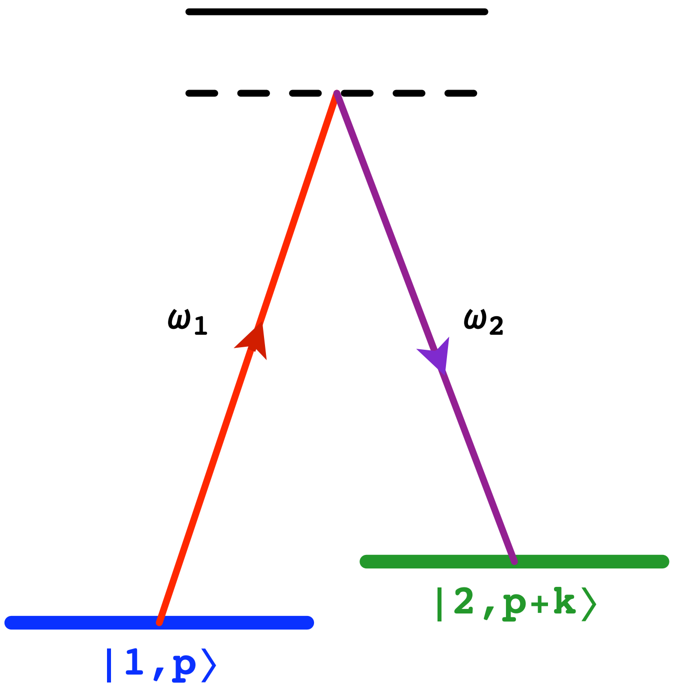


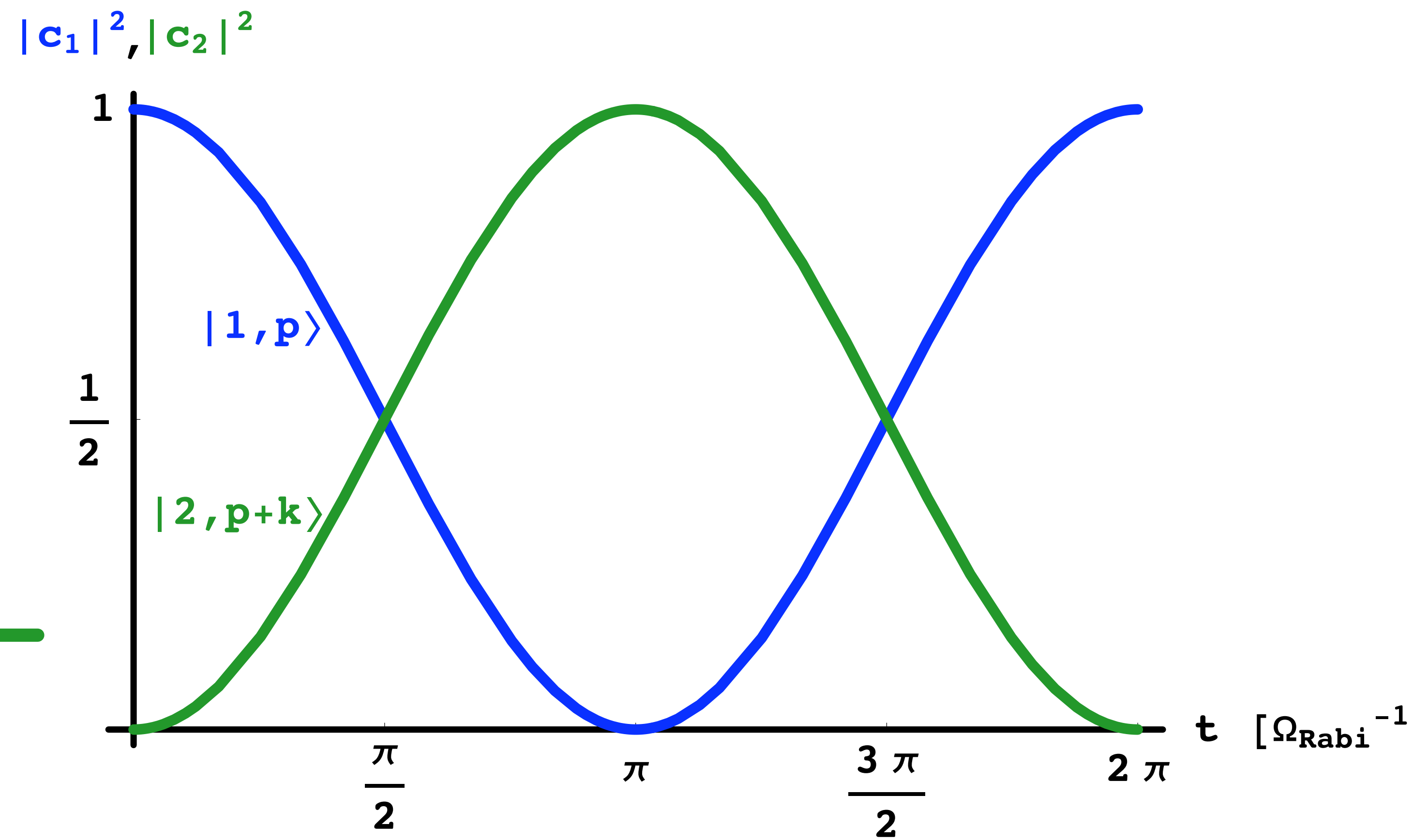
$$k_{eff} = \omega_1 + \omega_2 \sim 1 \text{ eV}$$

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

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

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

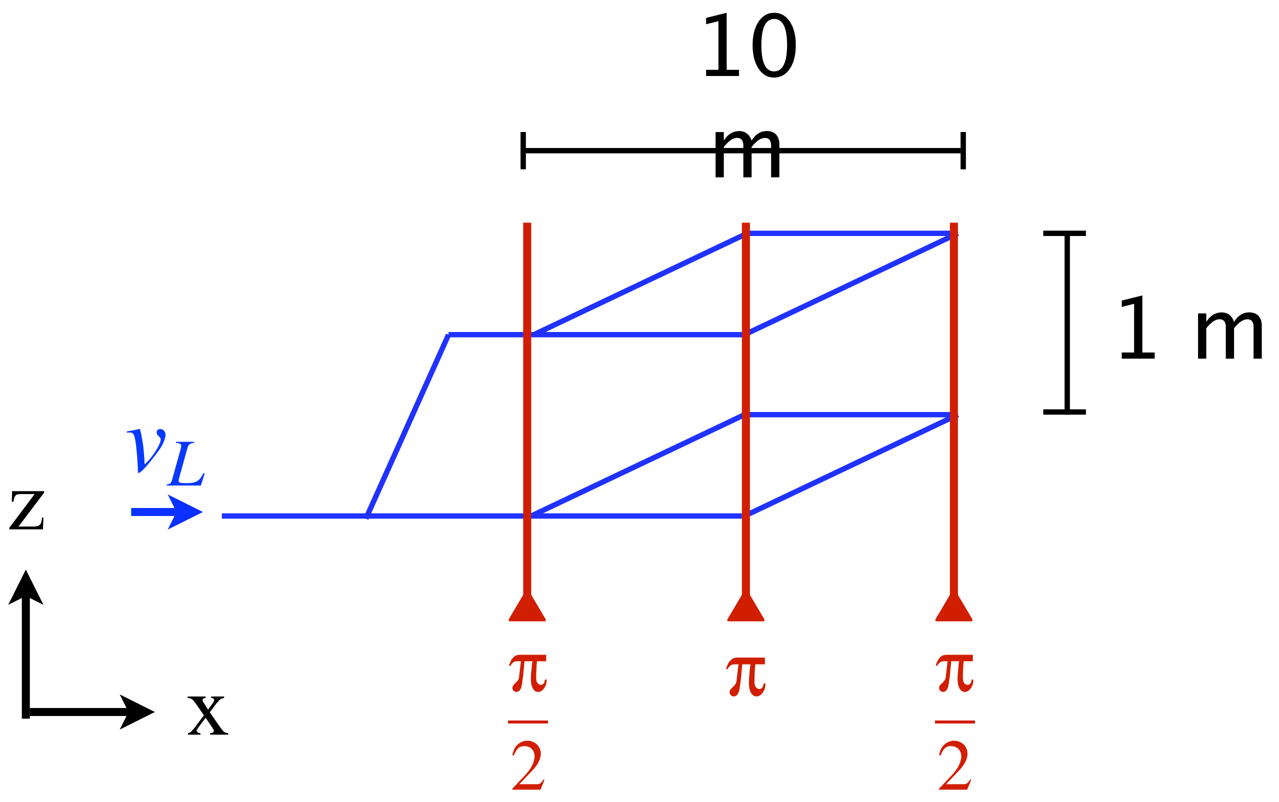
all backgrounds seem controllable down to shot noise level


UNITED STATES OF AMERICA
LIBE
IN
MARK WE
TRUST
S
QUARTER DOLLAR

Gravitomagnetism

Coriolis $\vec{a}_{cor} = 2\vec{v} \times \vec{\omega}$

Lense-Thirring $a = \vec{v} \times (\nabla \times \vec{\zeta}) \sim a_{\rm cor}\phi$



Simultaneous vertically displaced atom gyroscopes

Gravitomagnetism

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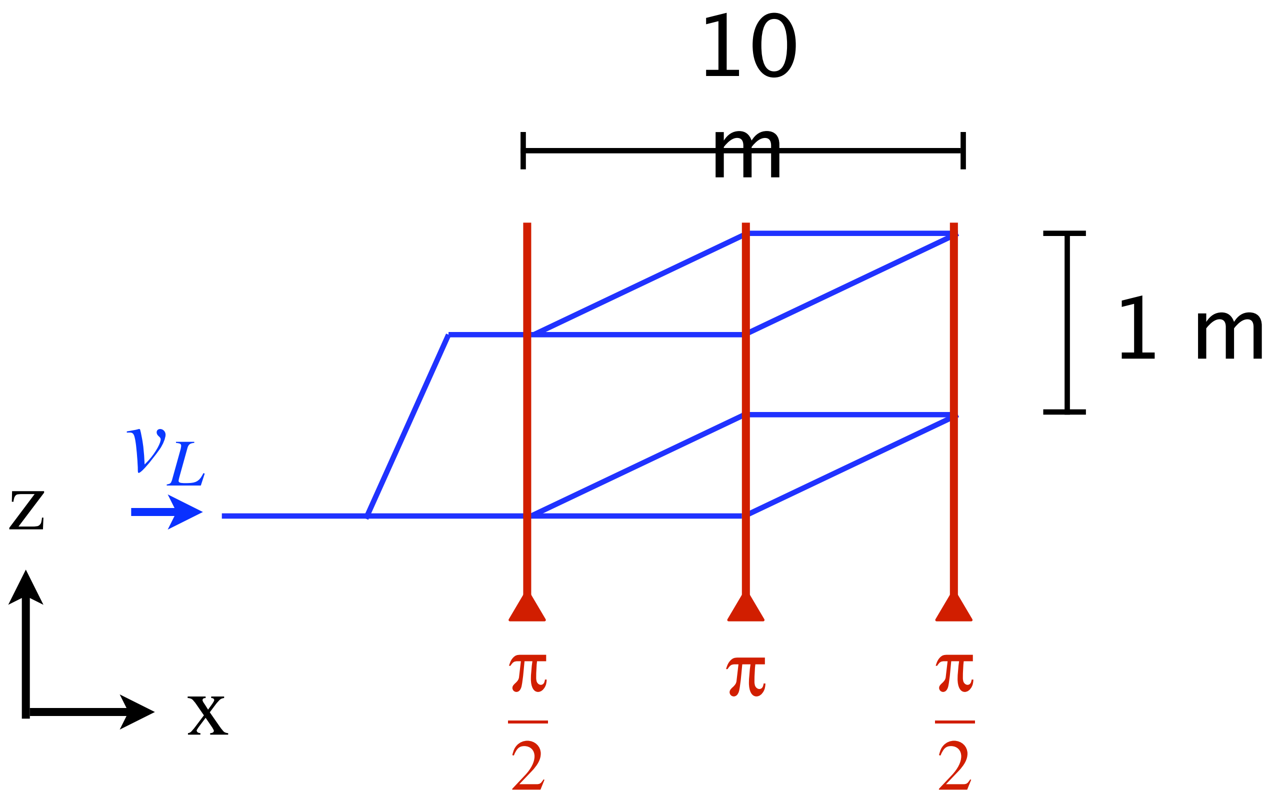

Simultaneous vertically displaced atom gyroscopes

with initial dimensions, this is a factor ~ 10^4 below precision