New Searches for Subgravitational Forces

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with

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New Era in Fundamental Physics

Energy Frontier

LHC

Nature of Electroweak Symmetry Breaking

(Higgs, Naturalness, New Symmetries/Dimensions)

New Era in Fundamental Physics

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Nature of Electroweak Symmetry Breaking

(Higgs, Naturalness, New Symmetries/Dimensions)

Precision Frontier

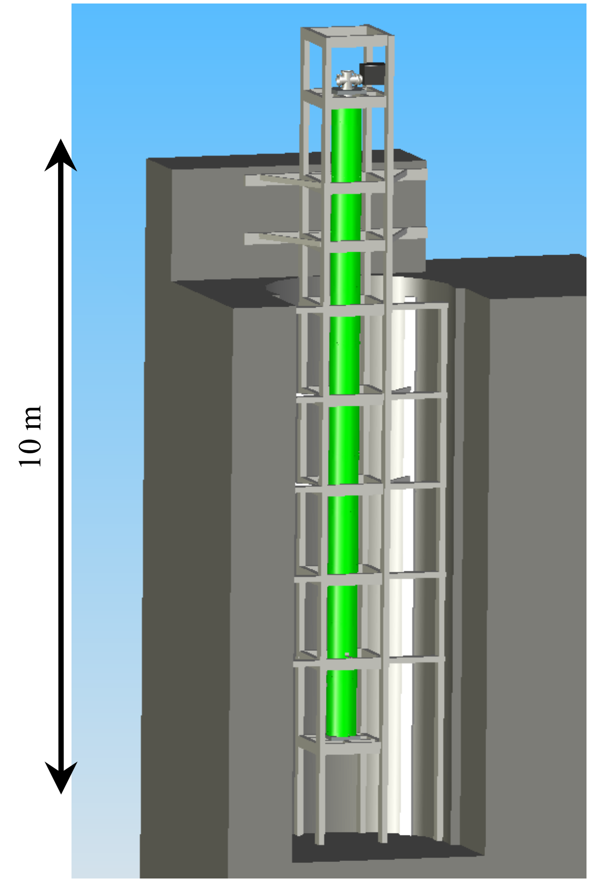
Atom Interferometry

Strong CP Solution, Nature of CC/DM

(Axions, Naturalness, New Forces, Violations of GR)

Rapidly advancing - Gaining 10 in sensitivity per year

Atomic Interferometer



10 m atom drop tower.

currently under construction at Stanford

Outline

Motivation for New Forces

Atom Interferometry

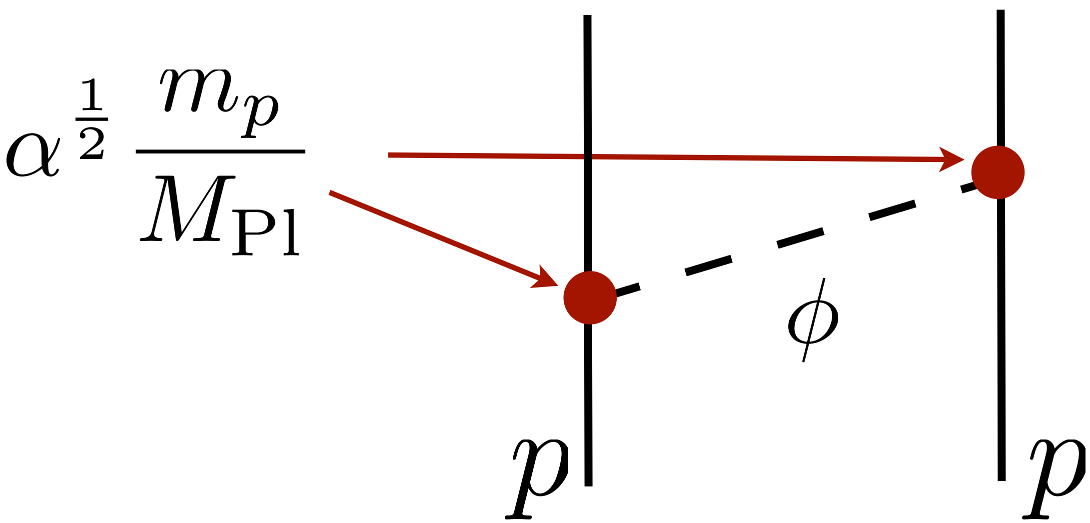
Fifth Force Experiments

- Deviations in Newtonian Gravity
- Equivalence Principle Violating Forces

Outlook

One Precision Frontier:
Short Distance Gravity

Many suggestions for fifth forces



$$\lambda = \frac{\hbar}{m_\phi c}$$

Parameterization of new force

$$\delta V(r) = \alpha \frac{G_N M m}{r} \exp(-r/\lambda) \qquad G_N \simeq \frac{1}{M_{\rm Pl}^2}$$

α Strength relative to gravity

λ Range (i.e. Compton wavelength)

Moduli Mediated Forces

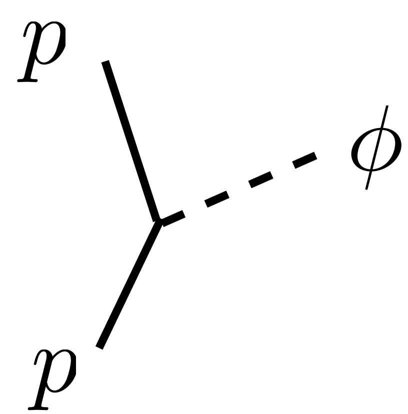
In Supersymmetry some particles only get mass from supersymmetry breaking

$$m_\phi \sim \frac{m_{\rm susy}^2}{M_{\rm Pl}}$$

If $\quad m_{\rm susy} \sim 1\ {\rm TeV} \Longrightarrow \lambda = \frac{\hbar}{m_\phi c} \sim 1\ {\rm mm}$

Generically have gravitational size couplings to matter

$$\mathcal{L}_{\rm int} = \alpha^{\frac{1}{2}} \frac{m_p}{M_{\rm Pl}}\ \phi \bar{p} p$$



Large Extra Dimensions

$$V(r) \sim \frac{1}{r} \longrightarrow \frac{L^n}{r^{n+1}}$$

M_{Planck}

EM+ QCD

Strength

Gravity

$$E \sim \frac{1}{r}$$

M_{Weak}

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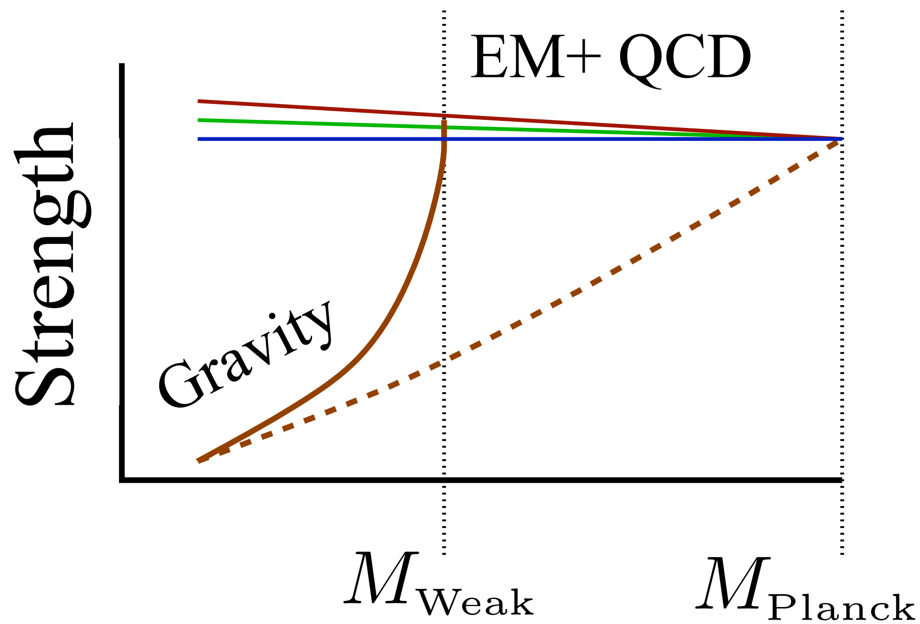


$$E \sim \frac{1}{r}$$

M_{Planck}

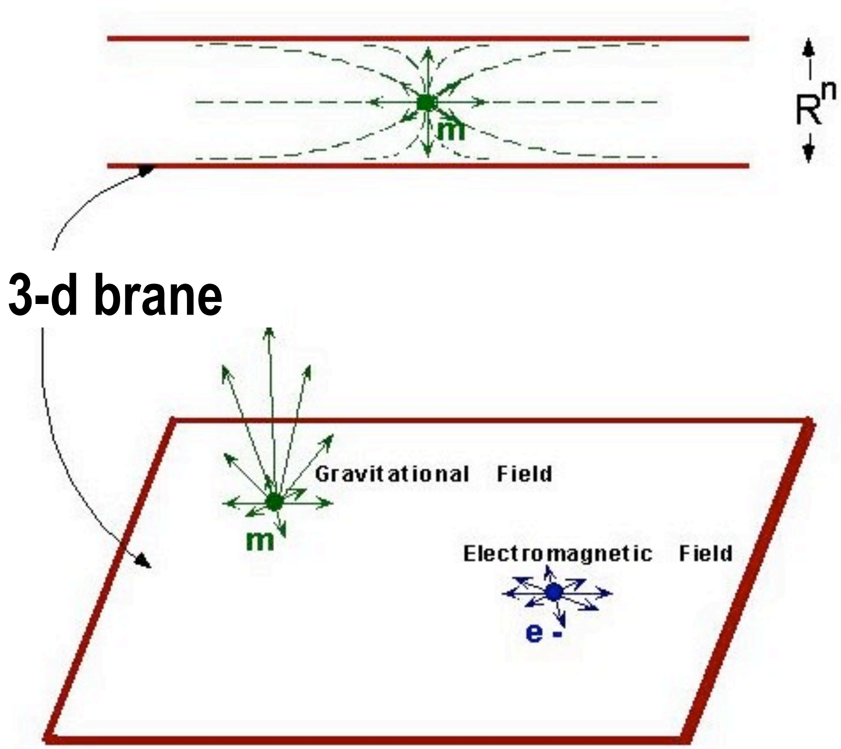
M_{Weak}

Basic Idea

All forces start out equal at weak scale

EM & QCD live in 4 dimensions,
gravity lives in more and dilutes

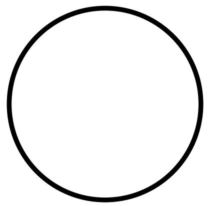
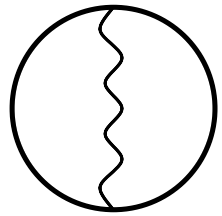
High scale physics is just a mirage



Gravity is different at
a new scale: mm to fm

Composite Gravity

The Cosmological Constant $\Lambda_{\mathrm{CC}} \simeq \dfrac{\hbar c}{(50\,\mu\mathrm{m})^4}$

$\Lambda_{\mathrm{CC}} =$  $+$  $+ \quad ... \quad \sim \dfrac{\hbar c}{\epsilon^4}$

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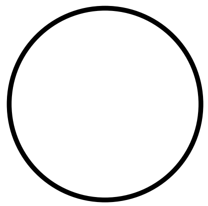
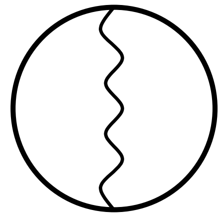
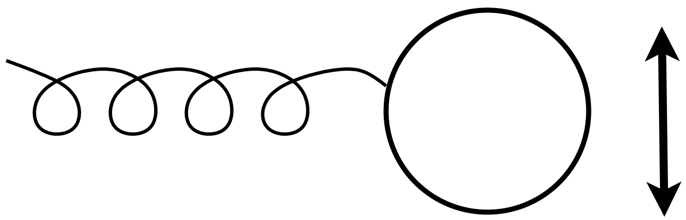
$\Lambda_{\mathrm{CC}} =$  $+$  $+ \; ... \sim \dfrac{\hbar c}{\epsilon^4}$

Cosmological expansion driven by coupling to gravity

$h_{\mu\nu}$  L $\quad \Lambda_{\mathrm{CC}} \sim \dfrac{\hbar c}{L^4}$

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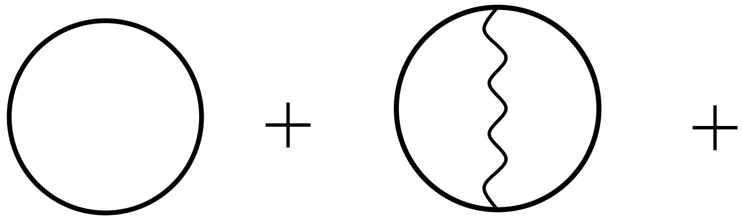
$\Lambda_{\rm CC} =$  $+ \;\ldots\; \sim \dfrac{\hbar c}{\epsilon^4}$

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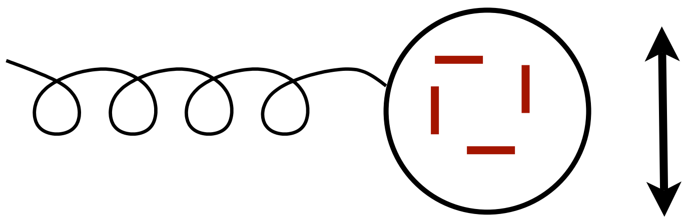
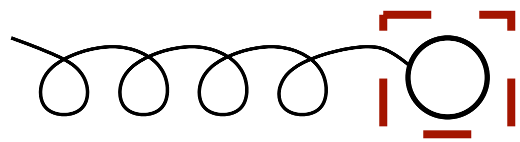
$h_{\mu\nu}$  L $\quad \Lambda_{\rm CC} \sim \dfrac{\hbar c}{L^4}$

If the graviton is composite with a size $50\mu{\rm m}$

no coupling to small loops  $L < \epsilon$

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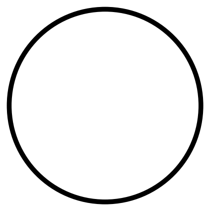
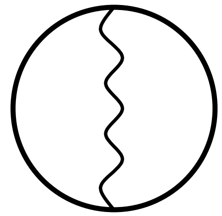
$\Lambda_{\rm CC} =$  $+$  $+ \quad \ldots \quad \sim \dfrac{\hbar c}{\epsilon^4}$

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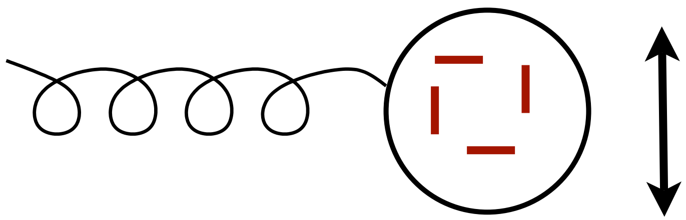
$h_{\mu\nu}$  L $\quad \Lambda_{\rm CC} \sim \dfrac{\hbar c}{L^4}$

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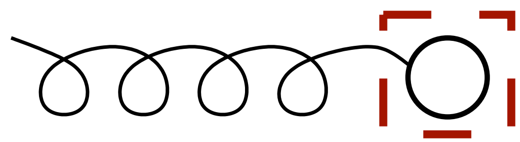
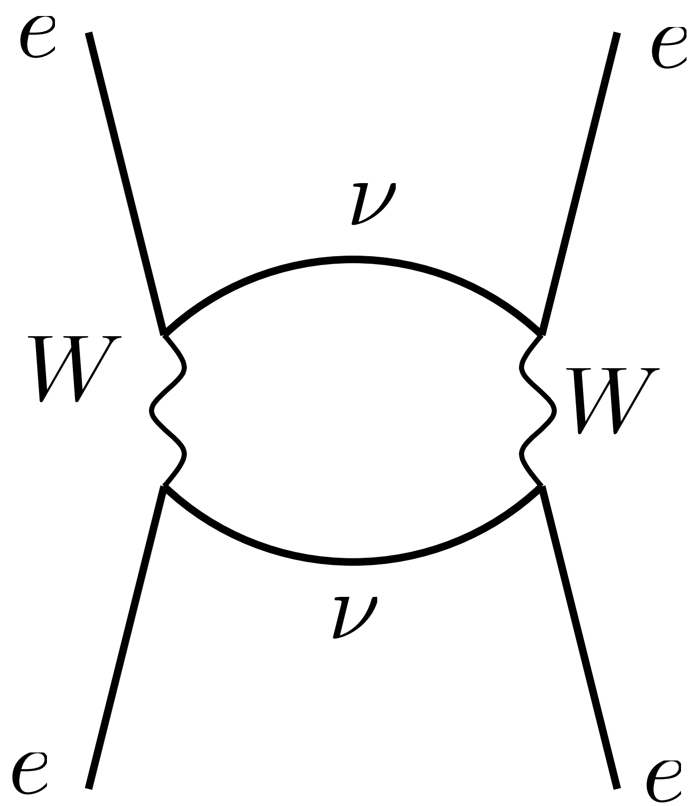
no coupling to small loops  $L < \epsilon$

No known theory does this

Motivates looking at short distance gravity

Neutrinos in the Standard Model

mediate a very tiny, unscreenable force



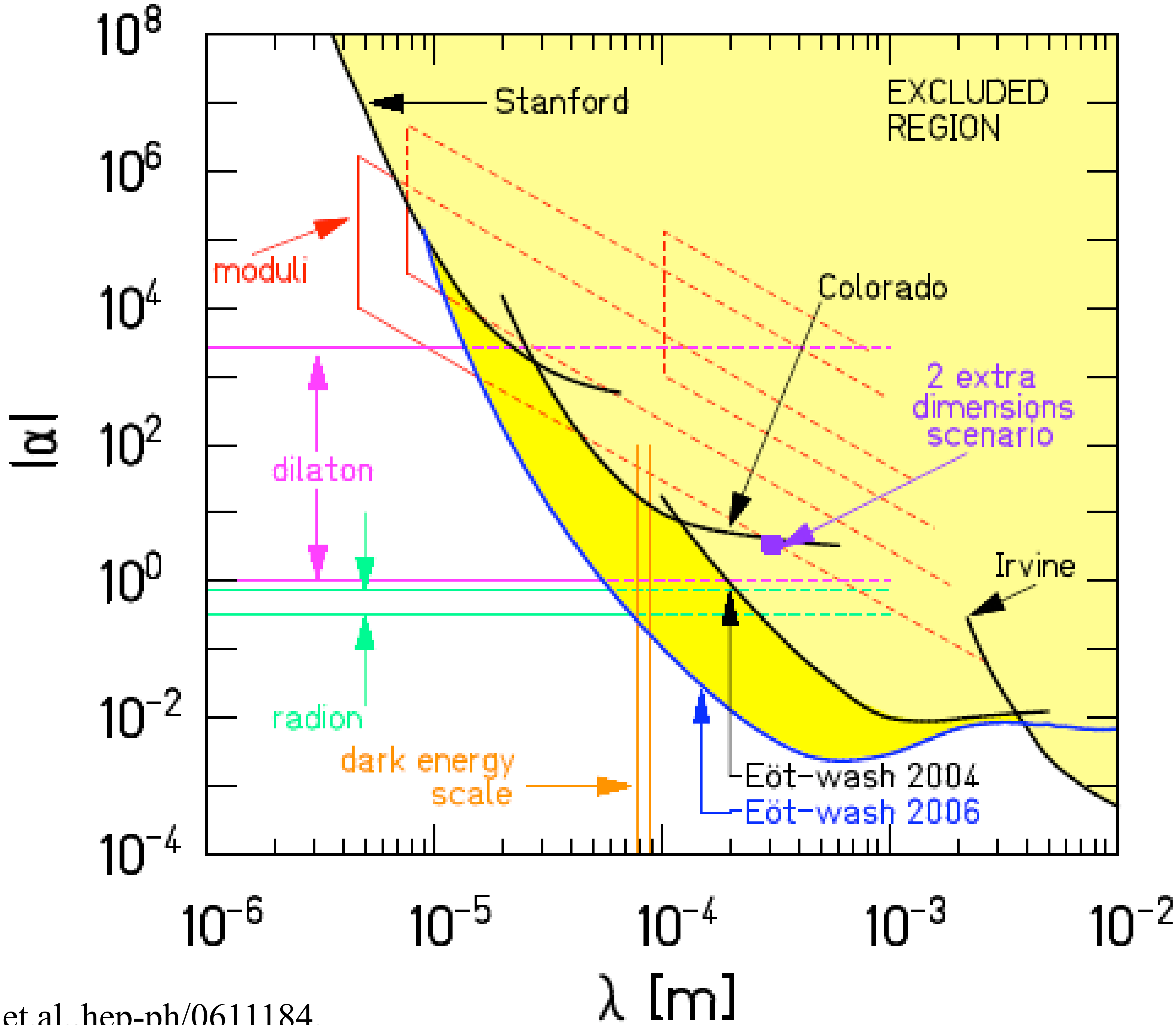
$$V_\nu \simeq \frac{G_F^2}{16\pi^2}\frac{e^{-m_\nu c\, r/\hbar}}{r^5}$$

$$\frac{\hbar}{m_\nu c} \sim 1 \text{ mm}$$

$$\sim 10^{-15}\ V_N(r \sim 100\mu\text{m})$$

Still futuristic, but something to aim for!

Short Distance Gravity Experiments



D.J. Kapner, et.al.,hep-ph/0611184.

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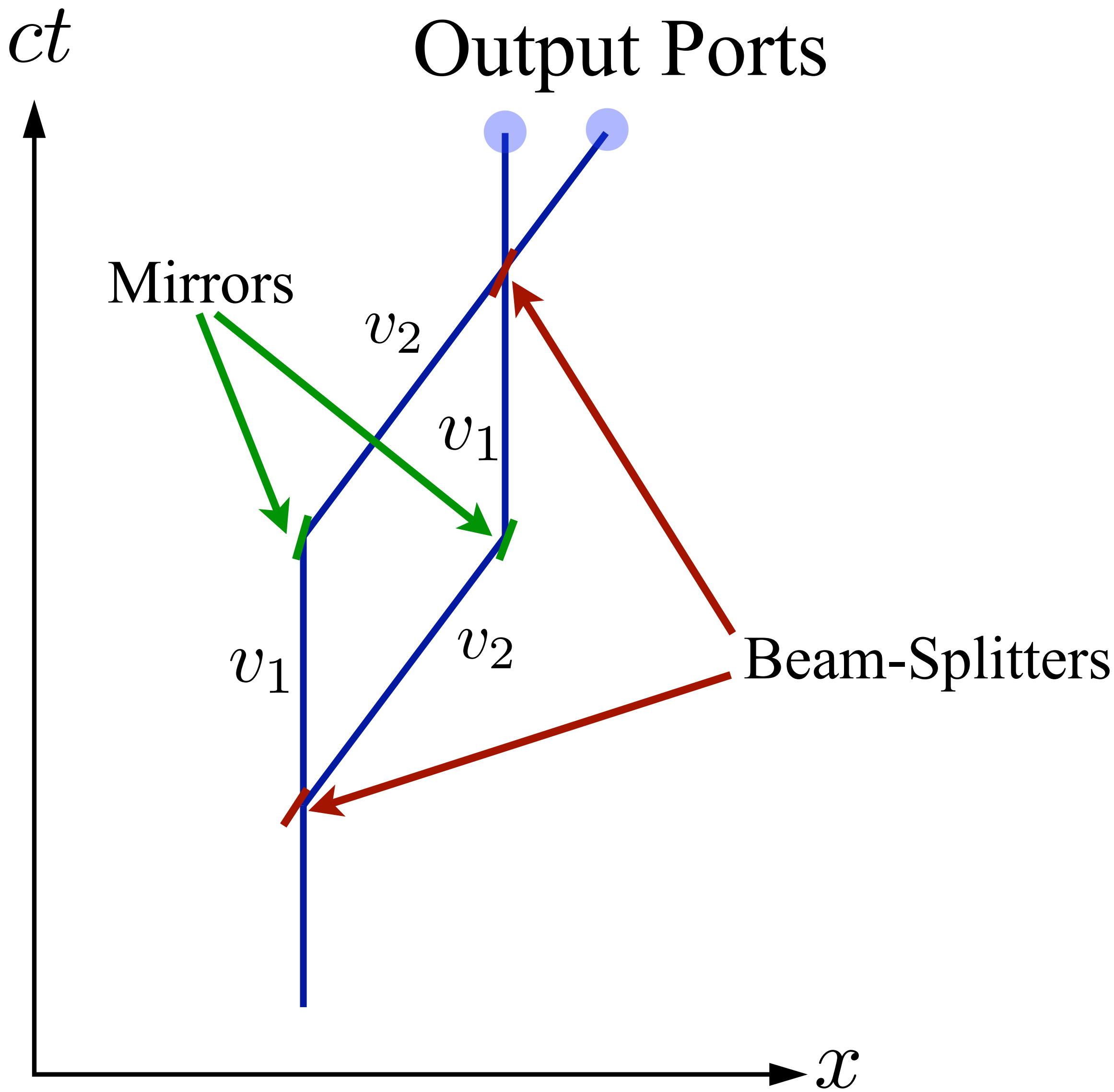
Space-time Interferometry

Mach-Zehnder Inteferometer



10m Stanford Inteferometer

Kasevich & Hogan

$$\Delta x \sim 1 \text{ m}$$

$$c\tau = 10^8 \text{ m}$$

$$A_{\text{AI}} \sim 10^8 \text{ m}^2$$

$$A_{\text{Ligo}} \sim 10^7 \text{ m}^2$$

Time is a big lever-arm in area

Raman Transitions

Two photon transition

Fine Split

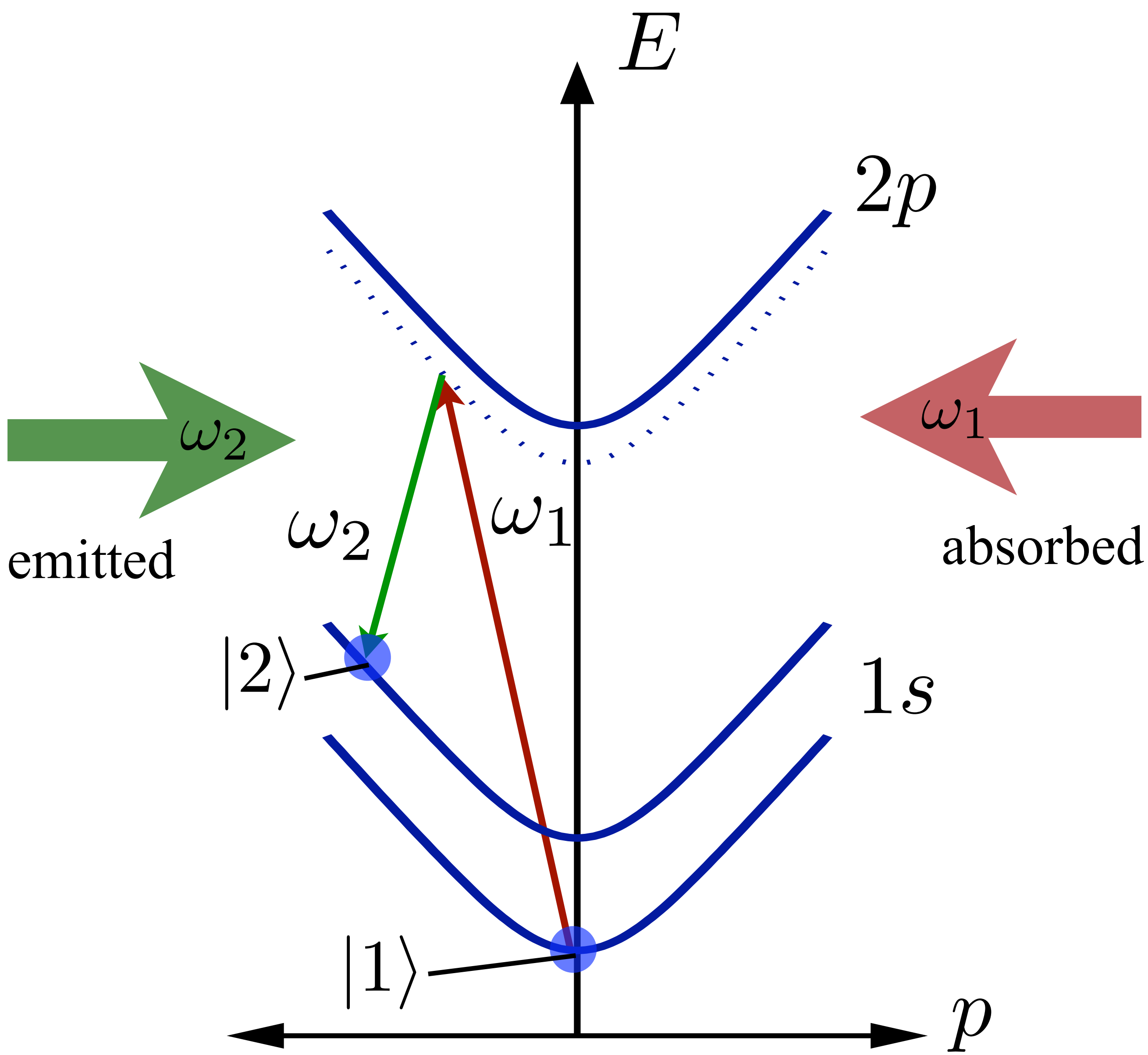
1 eV

Hyperfine Split

10^{-5} eV

$\Delta p \sim 1$ eV

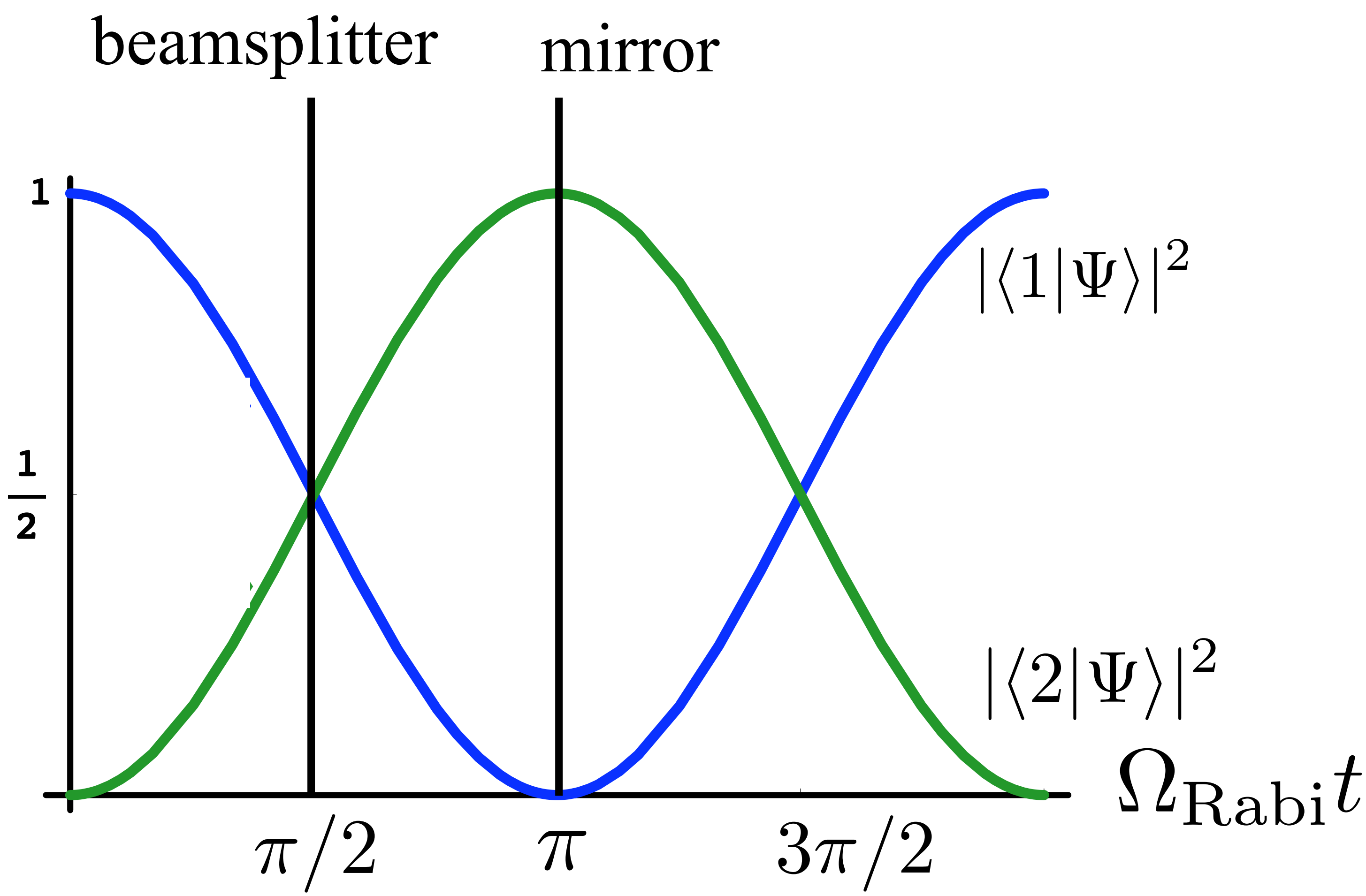
$\Delta E \sim 0$



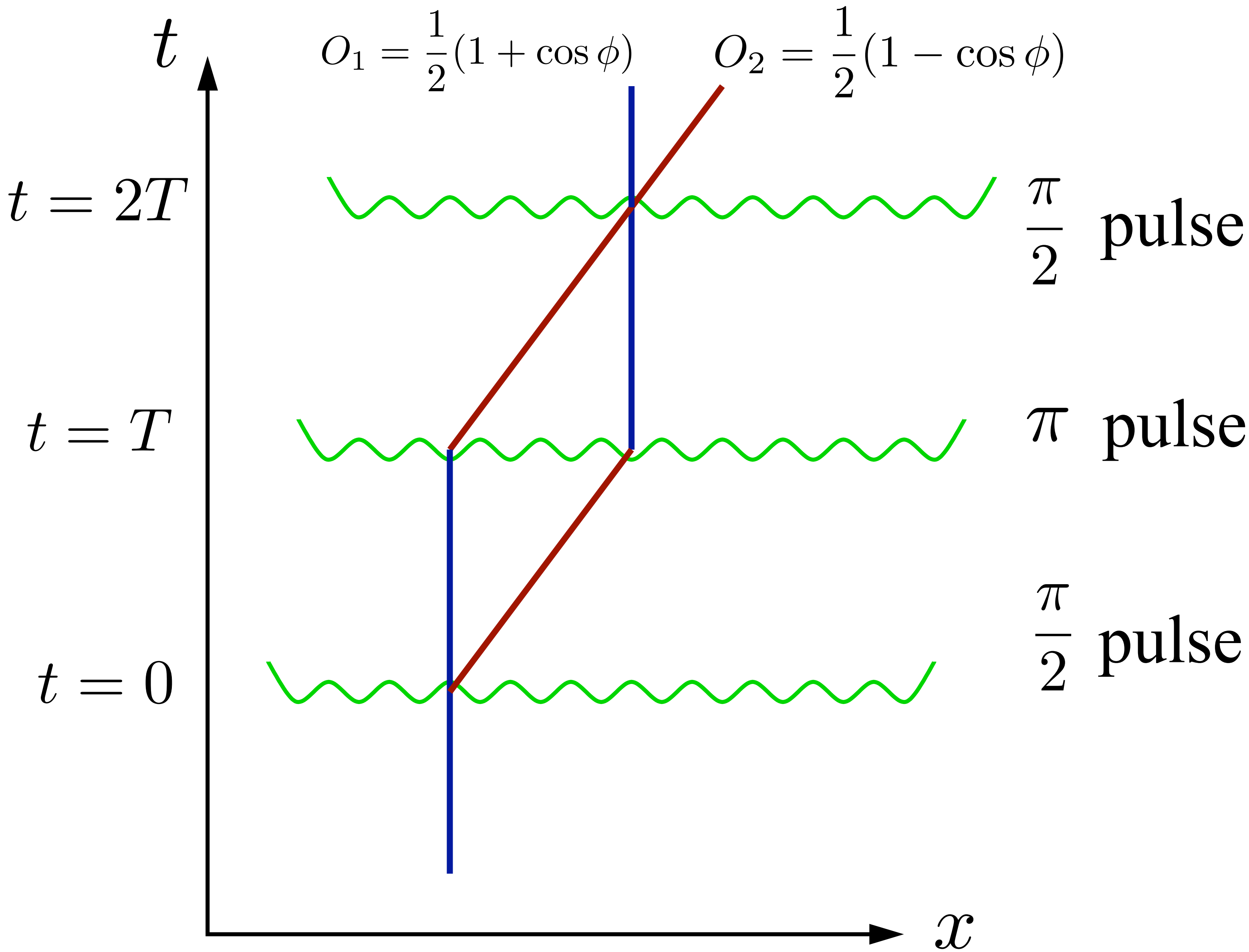
Rabi Oscillations

Effectively 2 state oscillations

$$i\frac{d}{dt}\begin{pmatrix}|1\rangle\\|2\rangle\end{pmatrix}=\begin{pmatrix}0 & \Omega_{\mathrm{Rabi}}/2\\ \Omega_{\mathrm{Rabi}}/2 & 0\end{pmatrix}\begin{pmatrix}|1\rangle\\|2\rangle\end{pmatrix}$$



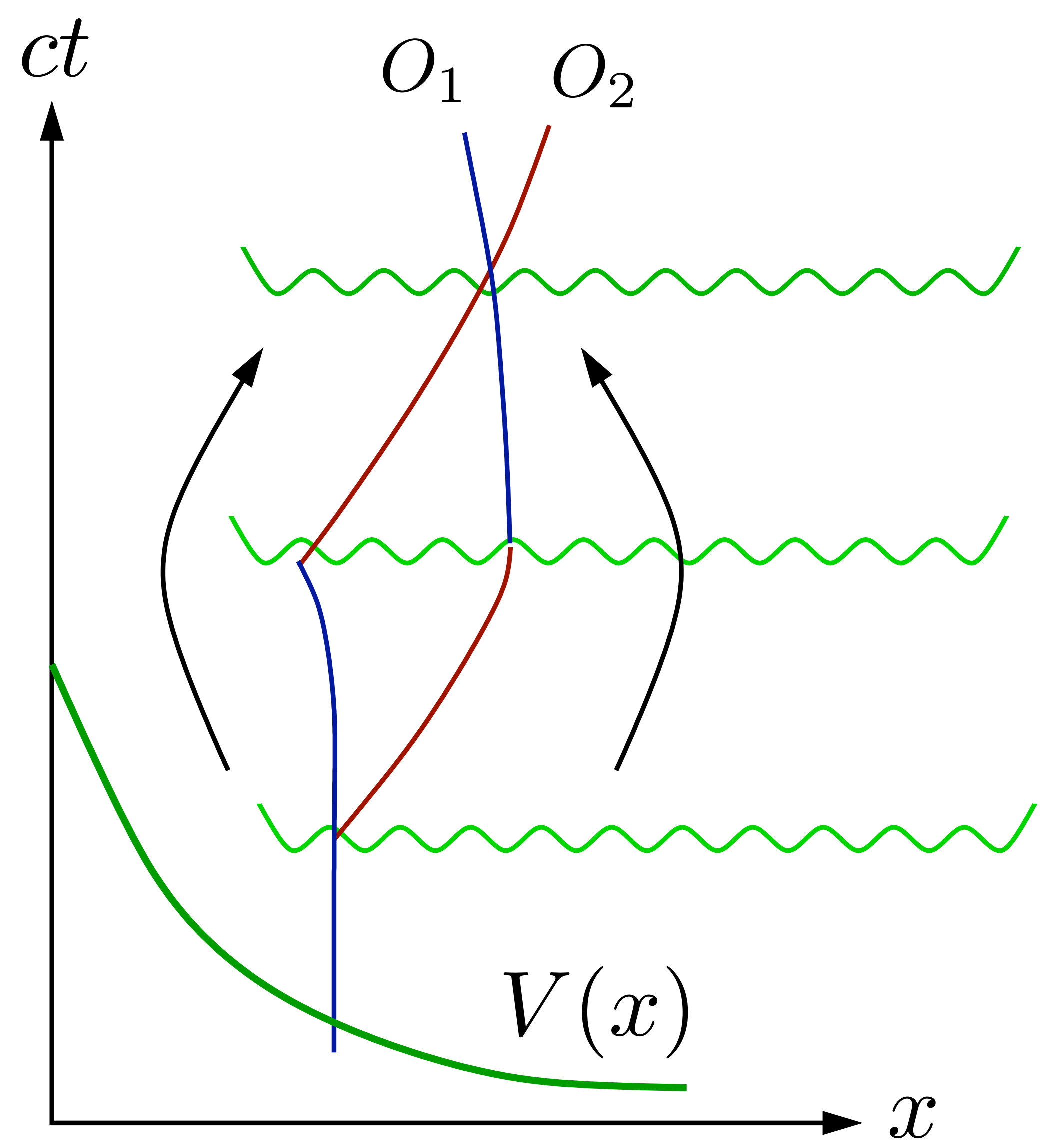
Atom Interferometry



mirrors and beamsplitters are lasers

Difference of Phases

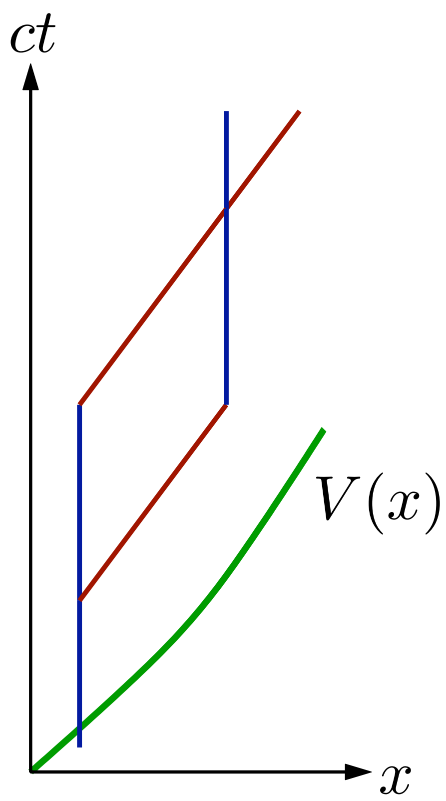
$$\hbar\Phi = [V(0) - V(v_r T)]\,\Delta T$$



Slowly changing potentials

For optical transitions and Rb

$$\Delta x = v_r\, T \sim 1 \text{ mm}$$



$$V(x) = V_0 + V'\, x(t) + V''\, x^2(t)$$

$$\phi = \Delta V\ T \qquad \Delta V \sim V' \Delta x$$

$$\phi \sim F\, v_r T\, T$$

$$\sim \text{Force} \cdot \text{Area}$$

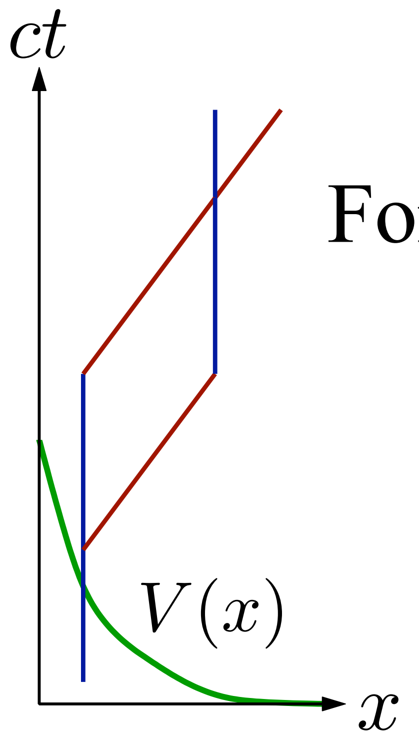
Interferometers are accelerometers

for $V'' \Delta x \,/\, V' \ll 1$

Quickly changing potentials

Consider Yukawa potential

$$V(x) = V_0 \ \exp(-x/\lambda)$$



For $\Delta x \gg \lambda$ measures potential differences

$$\Delta\Phi \sim V_0 \, T \qquad\qquad V_0 \sim m \, a \, \lambda$$

Insensitive to momentum imparted

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Outlook

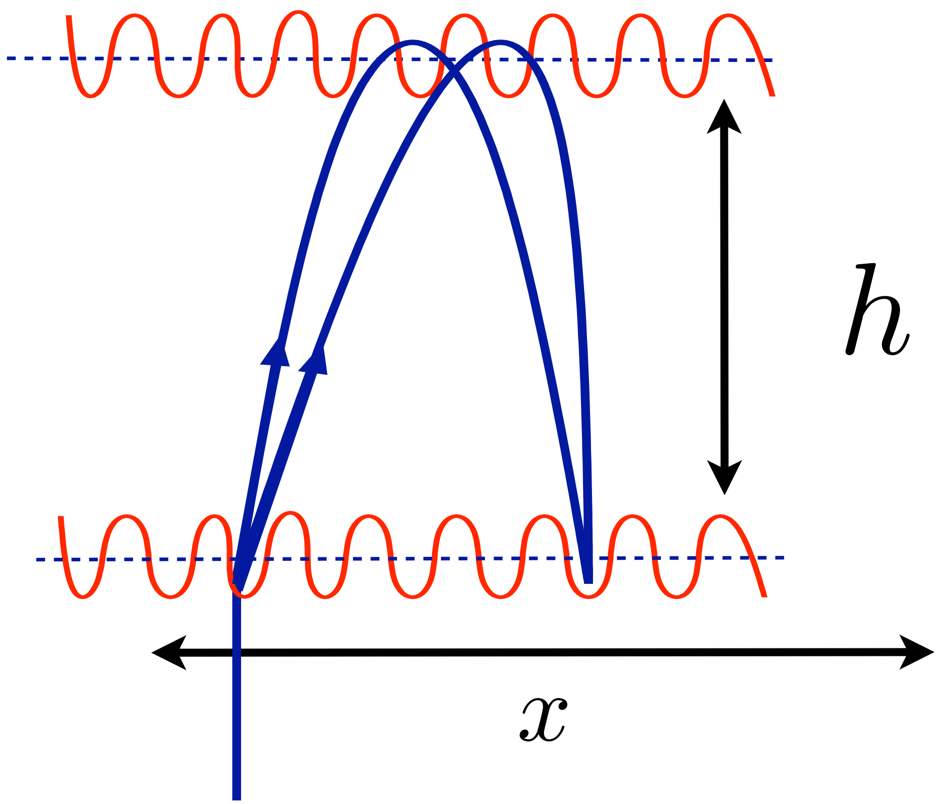
The “Gyroscope” Configuration

Launch vertically but shine lasers horizontally

Measures the force in laser’s direction

Free motion in horizontal direction

Ballistic motion - time and height the same

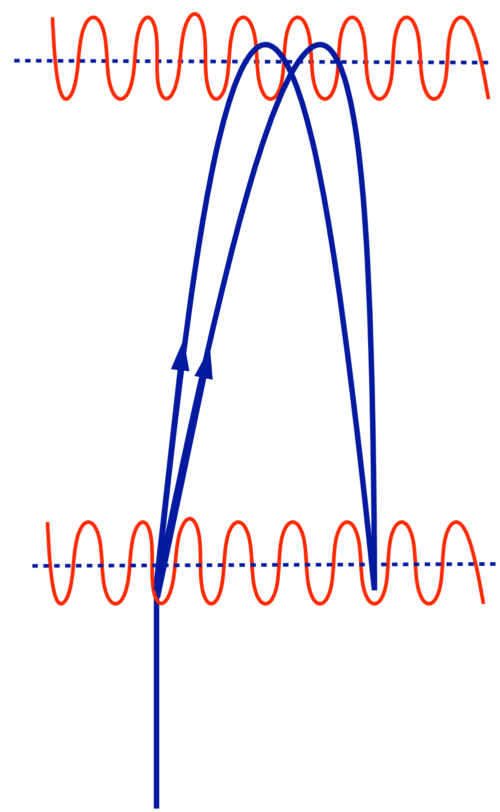


$$h = gT^2$$

x

Experimental Set-up

First measure "null"

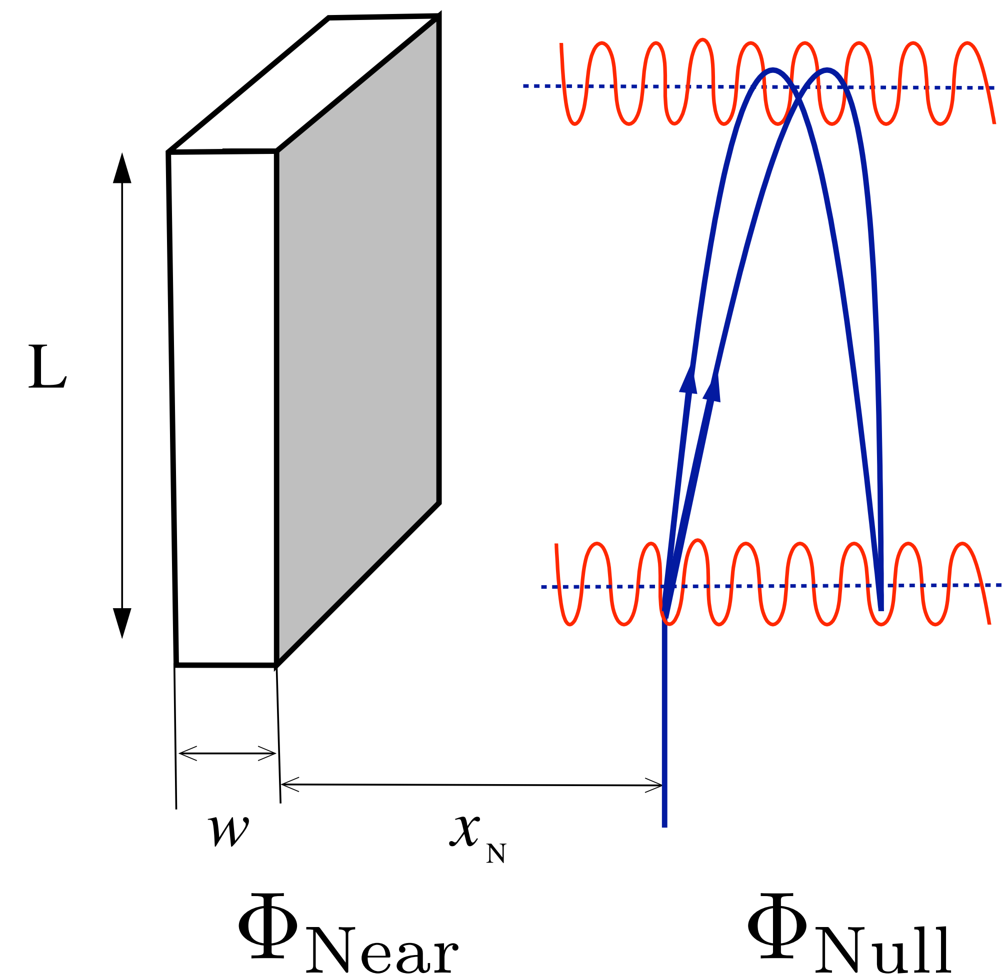


Φ_{Null}

Experimental Set-up

Lasers shine horizontally towards test mass

Move test mass in and out and measure its gravity



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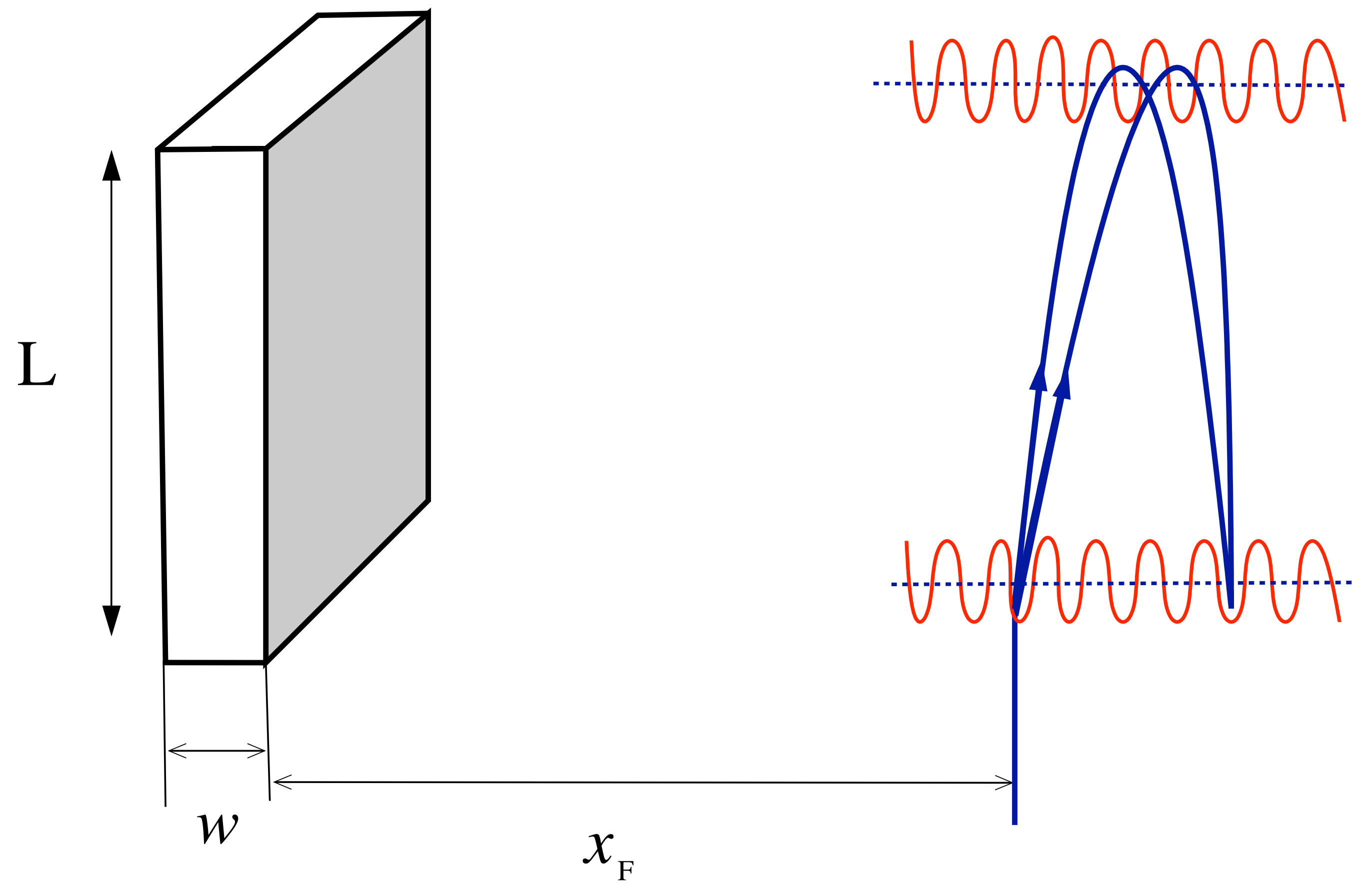

Φ_{Far} Φ_{Near} Φ_{Null}

Precision

$$\Phi = kaT^2 = \frac{h}{\lambda}\frac{a}{g}$$

Dimensions of experiment

$\lambda \sim 500 \text{ nm}$ $\quad a \sim G_N \rho w \sim 10^{-8} g$ $\quad h \sim 10 \text{ cm}$

Signal Size

$$\Phi \sim 10^{-2}$$

Resolution

$$\delta\Phi \sim 10^{-1}$$

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Signal Size

$$\Phi \sim 10^{-2}$$

$$N_{\mathrm{atoms}} \sim 10^6$$

Resolution

$$\delta\Phi \sim 10^{-1}$$

$$N_{\mathrm{bunches}} \sim 10^6$$

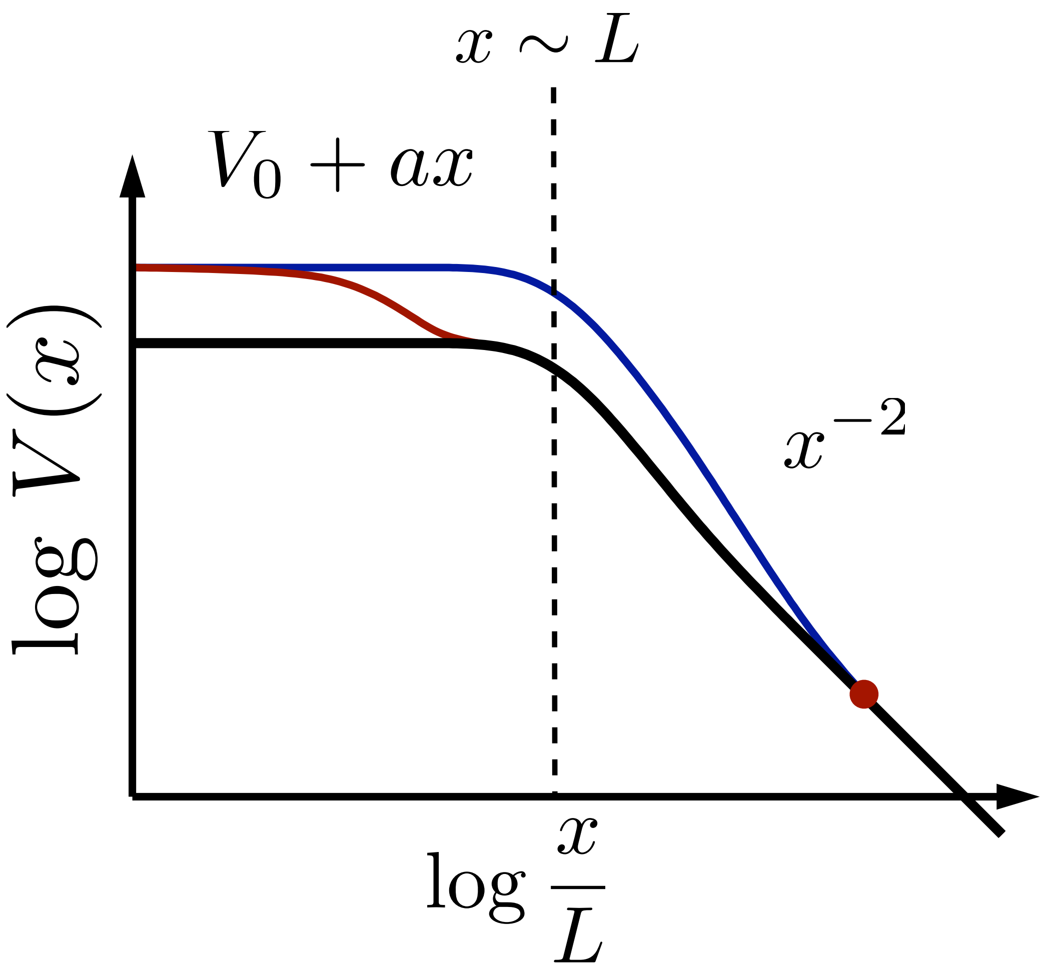
Ultimate Resolution

$$\frac{1}{\sqrt{N_{\mathrm{b}} N_{\mathrm{a}}}} \frac{\delta\Phi}{\Phi} \sim 10^{-5}$$

Measurement Strategy

G_N unknown $\implies$ Normalization of $V(x)$ unknown

Must measure at two distances



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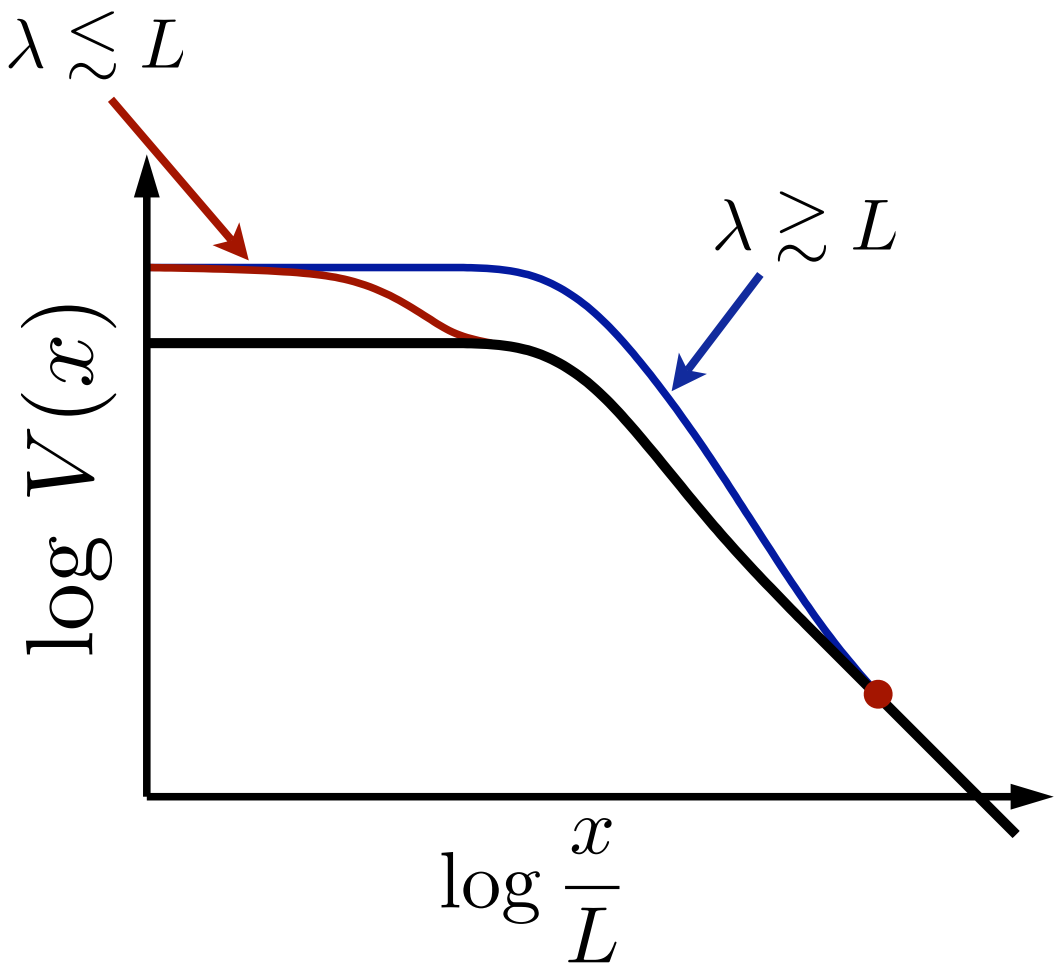

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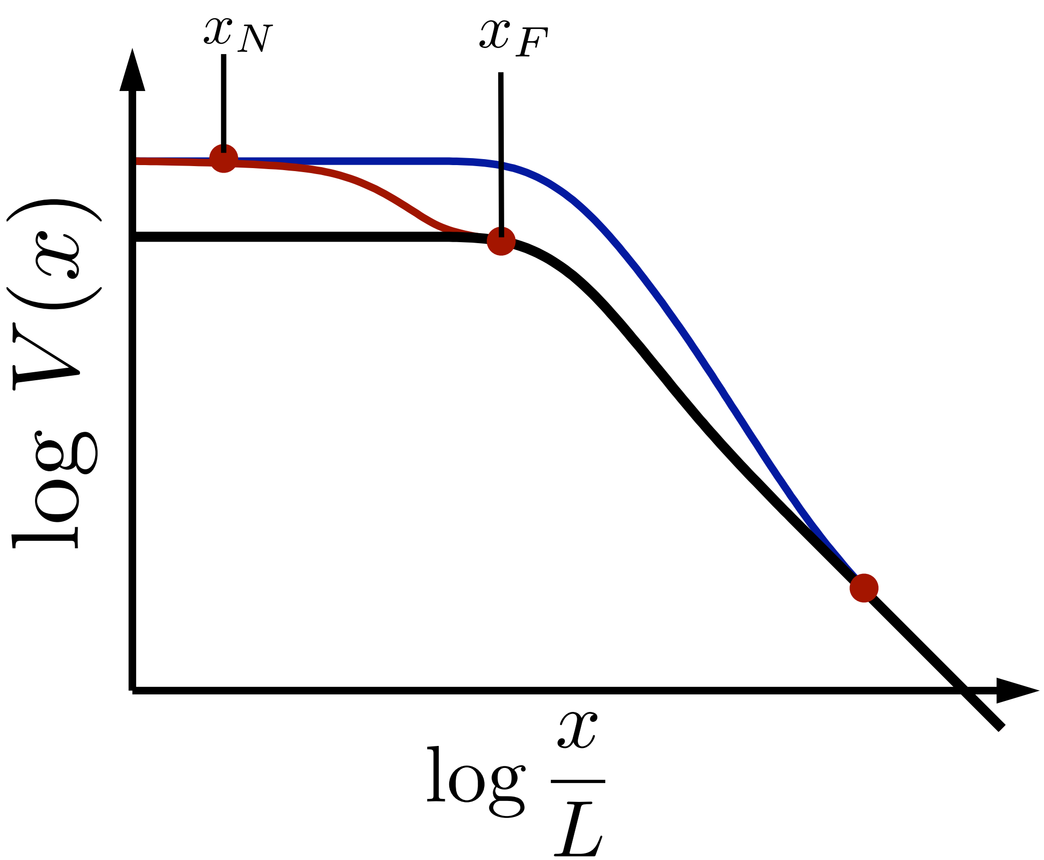

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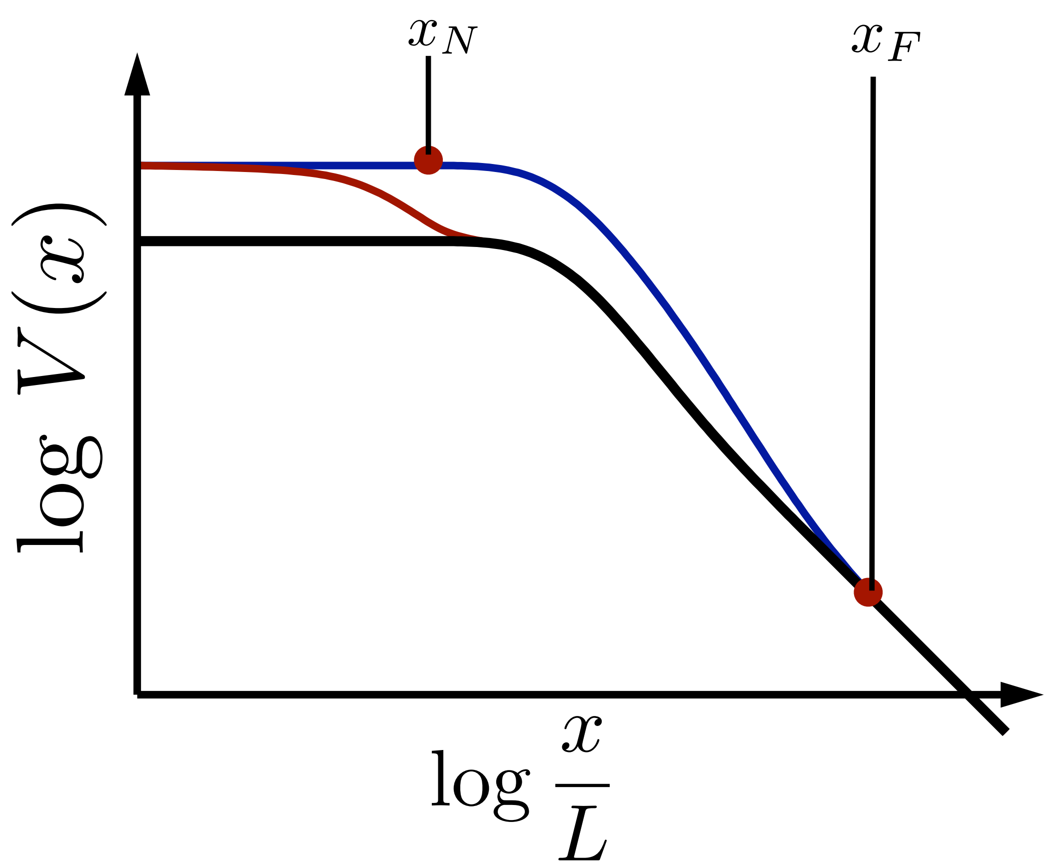
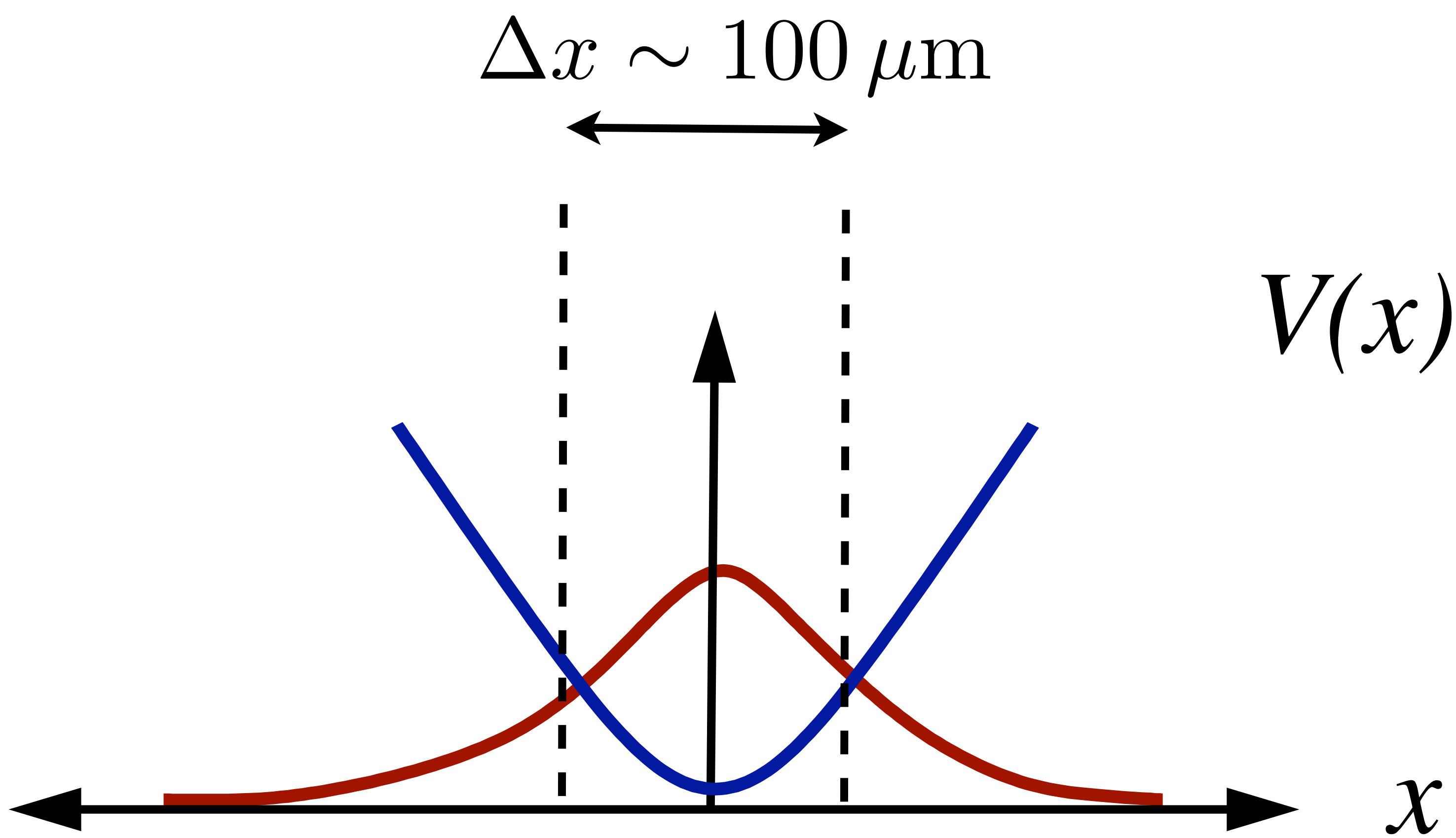


Limits on Resolution

Newtonian Prediction

Atoms initially held in laser trap

Wide wave packet



Limits on Resolution

Newtonian Prediction

Limits on source mass geometry

$$V \sim m\,a\,x\,(1 + \mathcal{O}(x/L))$$ Planar Geometry

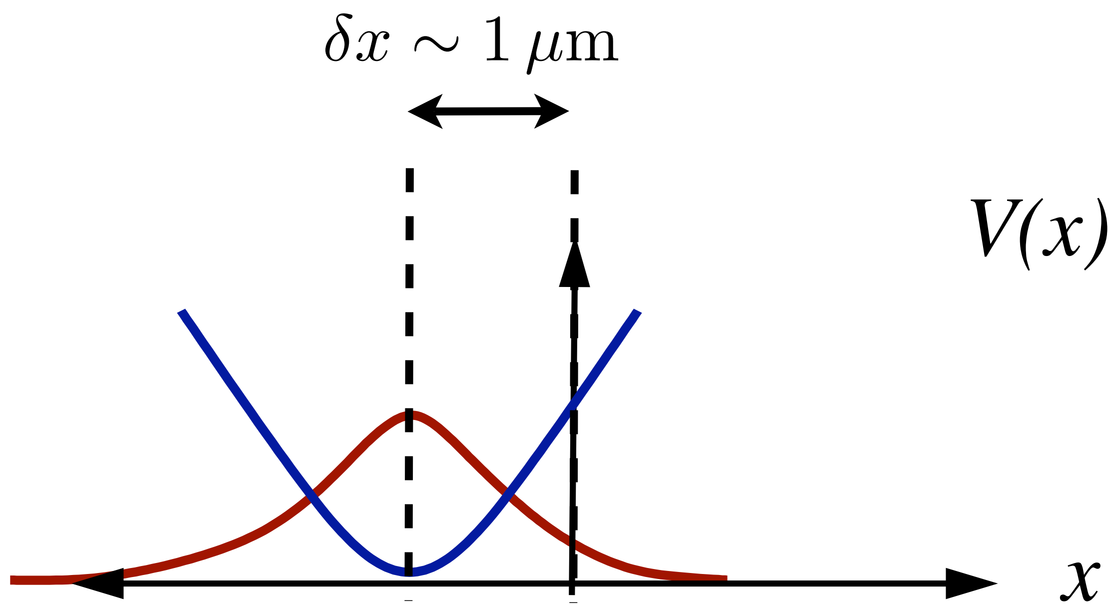
Uncertainty in the position looks like new force

Systematic

$$\delta V/V \sim 10^{-6}$$

Stochastic

$$\frac{\delta V}{\sqrt{N_b}\,V} \sim 10^{-9}$$



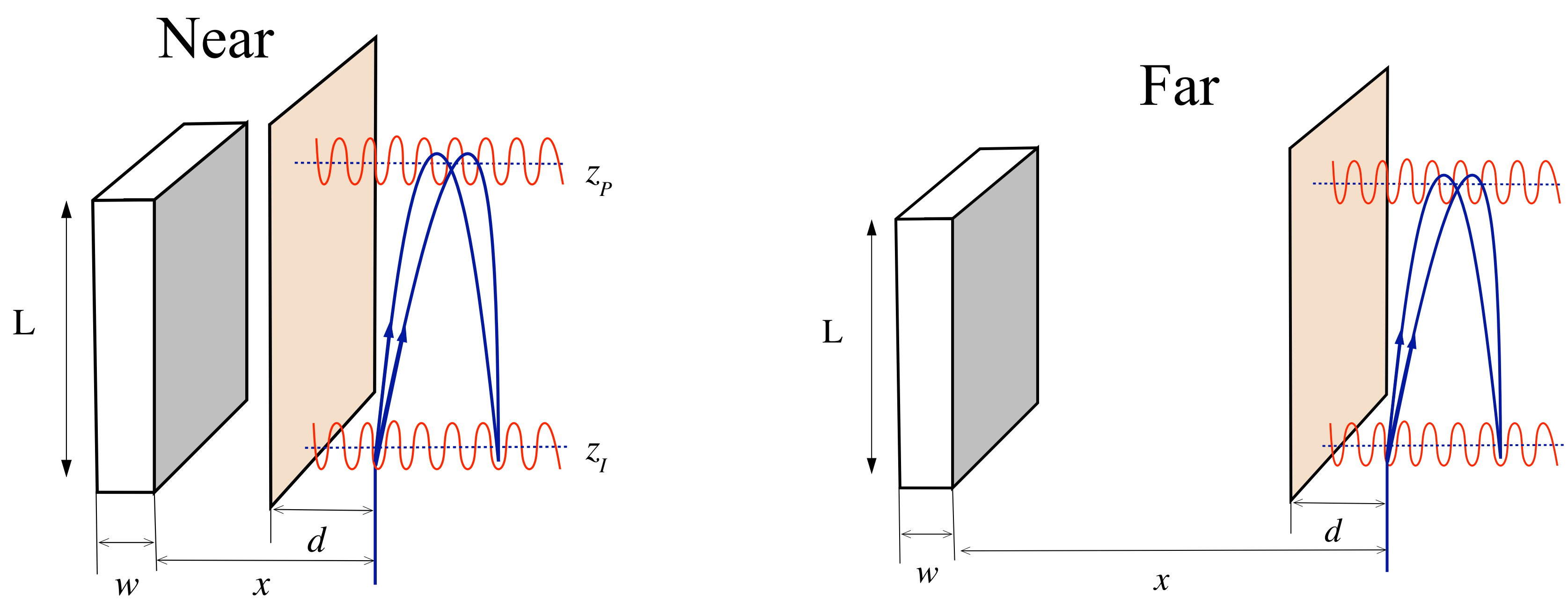
Casimir / van der Waal's Force

$$V(r) = \frac{\alpha_0}{r^4}$$

α_0 polarizability $\sim 20\ \text{Å}^3$

Put in shield to keep environment constant

$30\,\mu\text{m}$ shield bends by $1\ \text{nm}$



Coriolis Force

$$\phi_{\mathrm{Cor}} = m\,\omega\,v_l\,v_r\,T^2 \sim 10^3$$

Methods of actively reducing it by 10^{-5}

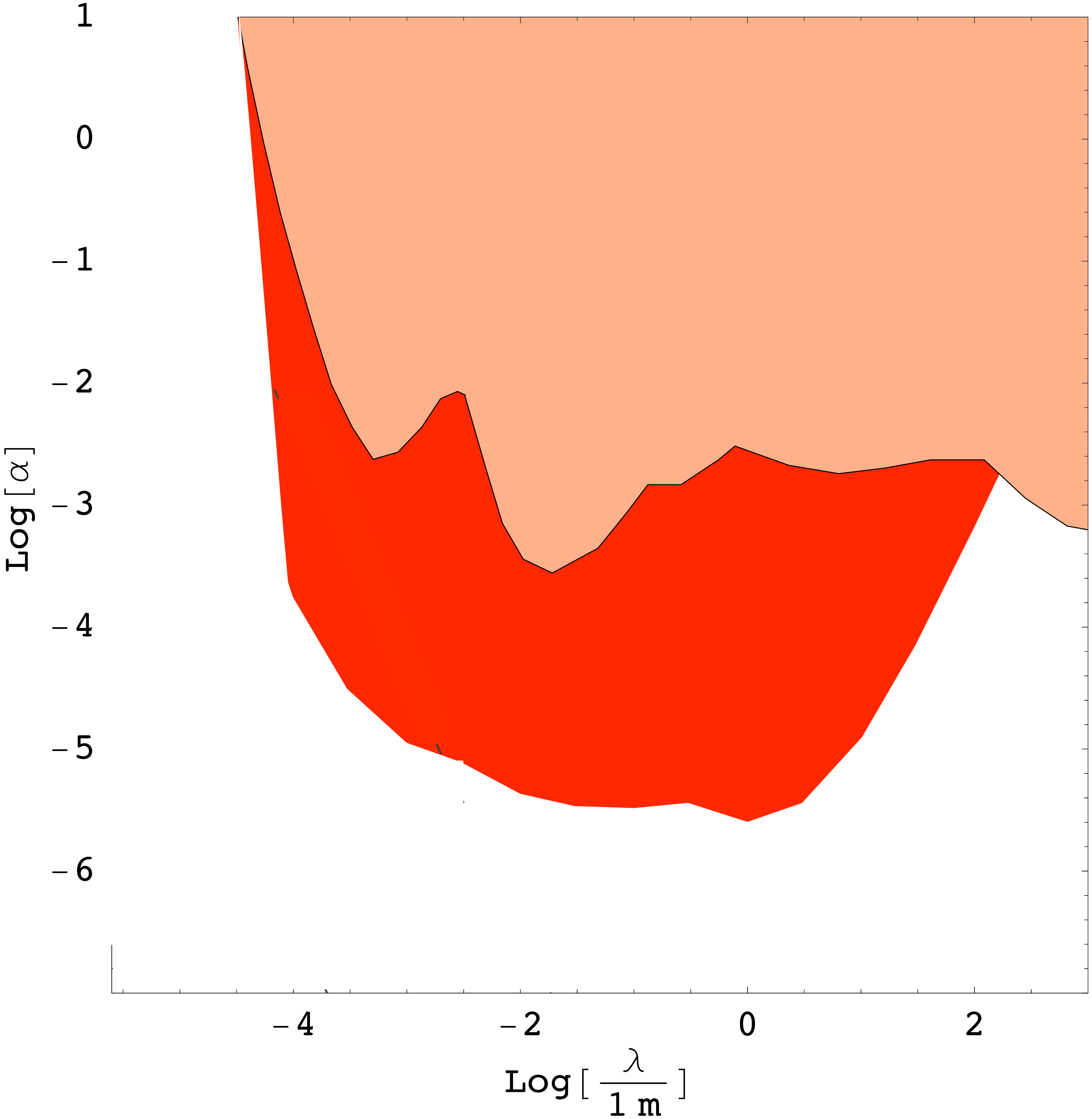
Is common mode noise - up to jitter and vibrations

Stochastic with bunches 10^{-3}

still need $\delta v_{\mathrm{vib}} \lesssim 10^{-4}\ \mathrm{m/s}$

good vibration isolation

Preliminary Reach



Equivalence Principle

New forces often violate EP

Way of distinguishing from Gravity

Useful for long distances

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New force couples to Z & $(A-Z)$ as

$$F \sim (1+c)Z + (1-c)(A-Z)$$

Equivalence Principle

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New force couples to Z & $(A-Z)$ as

$$F \sim (1+c)Z + (1-c)(A-Z)$$

Introduce $\zeta \equiv Z/A$ Proton fraction of nucleus

$$a = \frac{F}{m} \sim a_0(1 + c\,\zeta)$$

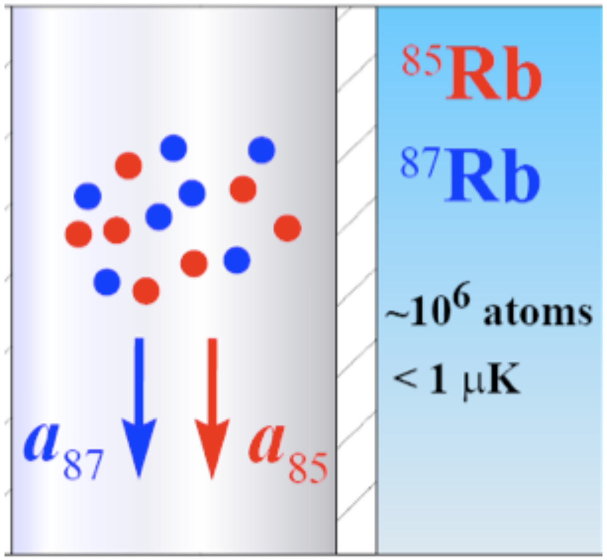
Composition dependent force

Multiple Isotopic Species

Use composition dependent force

Perform differential measurements

$$\Delta\Phi = \Phi_1 - \Phi_2$$



Different isotopes at *same* time

$$\Delta\Phi \propto a_1 - a_2 \sim a_0\, c(\zeta_1 - \zeta_2)$$

Want to maximize isotopic differences

$$\delta\zeta_{\mathrm{Rb}} \sim 1\% \qquad \delta\zeta_{\mathrm{Li}} \sim 7\%$$

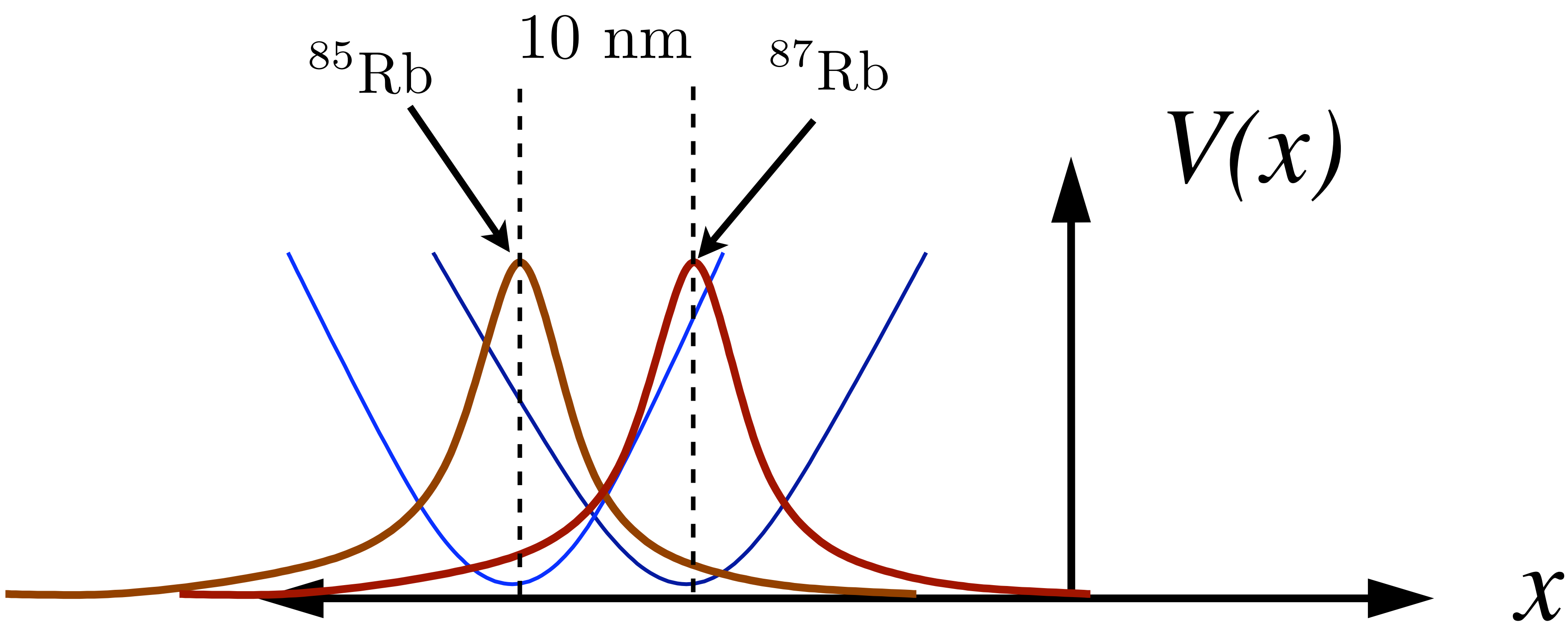
$$\delta\zeta_{\mathrm{He}} \sim 25\% \qquad \delta\zeta_{\mathrm{H}} \sim 50\%$$

Co-Location

Electronically identical

Nuclear moments differ, atoms see slightly different potential

Changes to a null experiment



Backgrounds

Coriolis is greatly reduced

Uncontrolled gravitational sources
are not a problem

easier environment to find

Casimir is important at 0.1 mm

Double differential measurement as before

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Improvements

Consider the phase

$$\frac{\Phi}{\Delta\Phi_{\mathrm{res}}} \sim p\, a\, T^2\, N_{\mathrm{atom}}^{\frac{1}{2}}\, N_{\mathrm{bunch}}^{\frac{1}{2}}$$

Can't make signal bigger

Big cost to make taller drop towers

Number of bunches
sets length of experiment

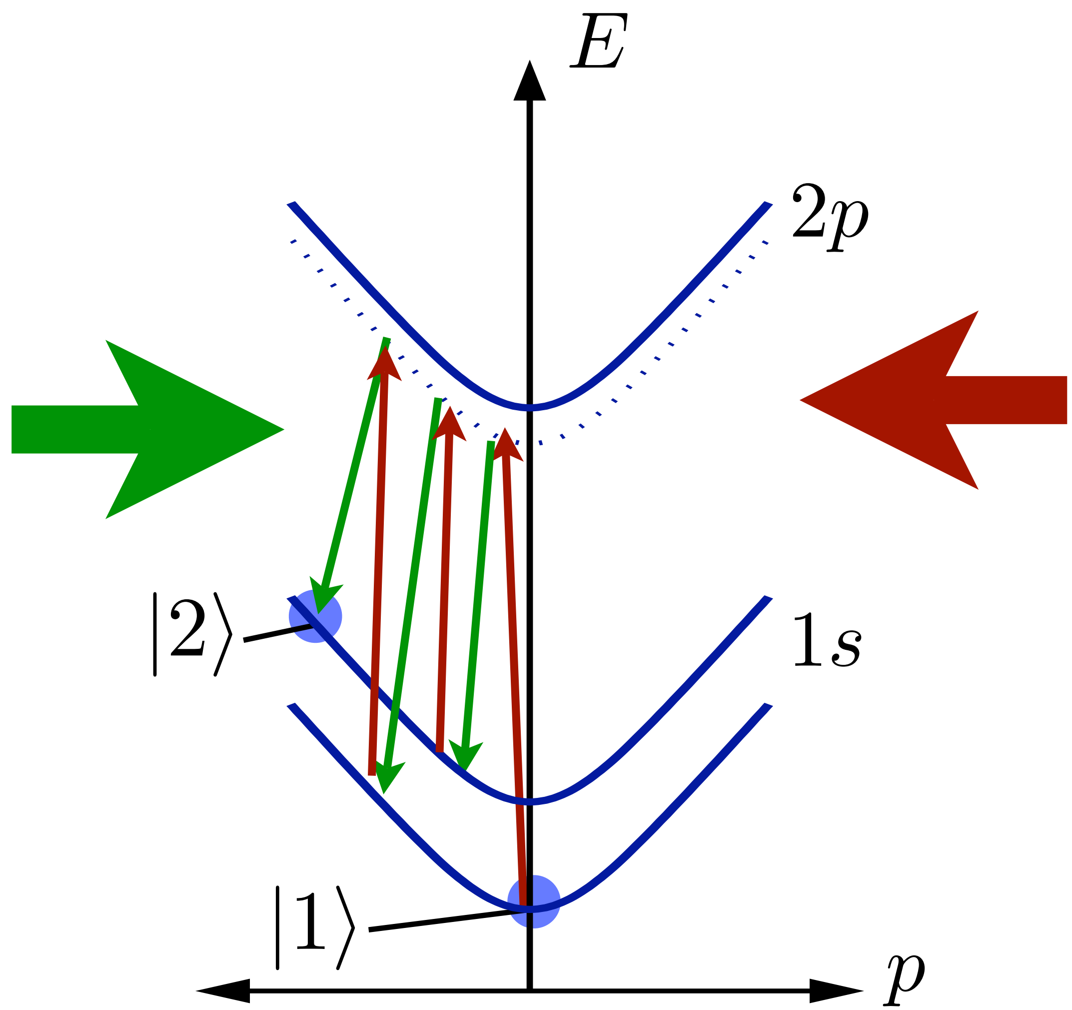
Large Momentum Transfer

$$\Phi \sim p\, a\, T^2\, N_{\text{atom}}^{\frac{1}{2}}\, N_{\text{bunch}}^{\frac{1}{2}}$$

changing the frequency to walk up momentum

$\Delta p \sim 10^2$ eV

2 orders of magnitude
improvement
on long ranged forces



no gain on
short ranged forces

$\Delta x \sim 10$ cm

Improvements

$$\Phi \sim p\,a\,T^2\,N_{\mathrm{atom}}^{\frac{1}{2}}\,N_{\mathrm{bunch}}^{\frac{1}{2}}$$

Could do more atoms...

$$|\psi\rangle \sim \left(|1\rangle + |2\rangle\right)^{N_{\mathrm{Atom}}}$$

Resolution goes as $N_{\mathrm{Atom}}^{-\frac{1}{2}}$

Improvements

$$\Phi \sim p\,a\,T^2\, N_{\mathrm{atom}}^{\frac{1}{2}}\, N_{\mathrm{bunch}}^{\frac{1}{2}}$$

Could do more atoms...

$$|\psi\rangle \sim (|1\rangle + |2\rangle)^{N_{\mathrm{Atom}}}$$

Resolution goes as $N_{\mathrm{Atom}}^{-\frac{1}{2}}$

$$|\psi\rangle \sim (|1\rangle)^{N_{\mathrm{Atom}}} + (|2\rangle)^{N_{\mathrm{Atom}}}$$

Resolution goes as N_{Atom}^{-1}

known as Heisenberg Statistics

10^3 Gain!

Other experiments

Equivalence Principle

Hogan, Kasevich

Precision GR

Dimopoulos, Graham, Hogan, Kasevich
gr-qc/0610047

Gravity Waves

Dimopoulos, Graham, Hogan, Kasevich, Rajendran

Electric Neutrality of Atoms

Arvanitaki, Dimopoulos, Geraci, Hogan, Kasevich

Atom Interferometry

New method for searching for
beyond the SM physics

Many possibilities for
future improvements

Need creativity for new
methods of searching