New Tests of Sub-gravitational Forces

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SLAC

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with
Savas Dimopoulos
Peter Graham
Mark Kasevich

New Era in Fundamental Physics

LHC

Energy Frontier

Nature of EWSB

(Higgs, Naturalness, New Symmetries/Dimensions)

Atom Interferometry

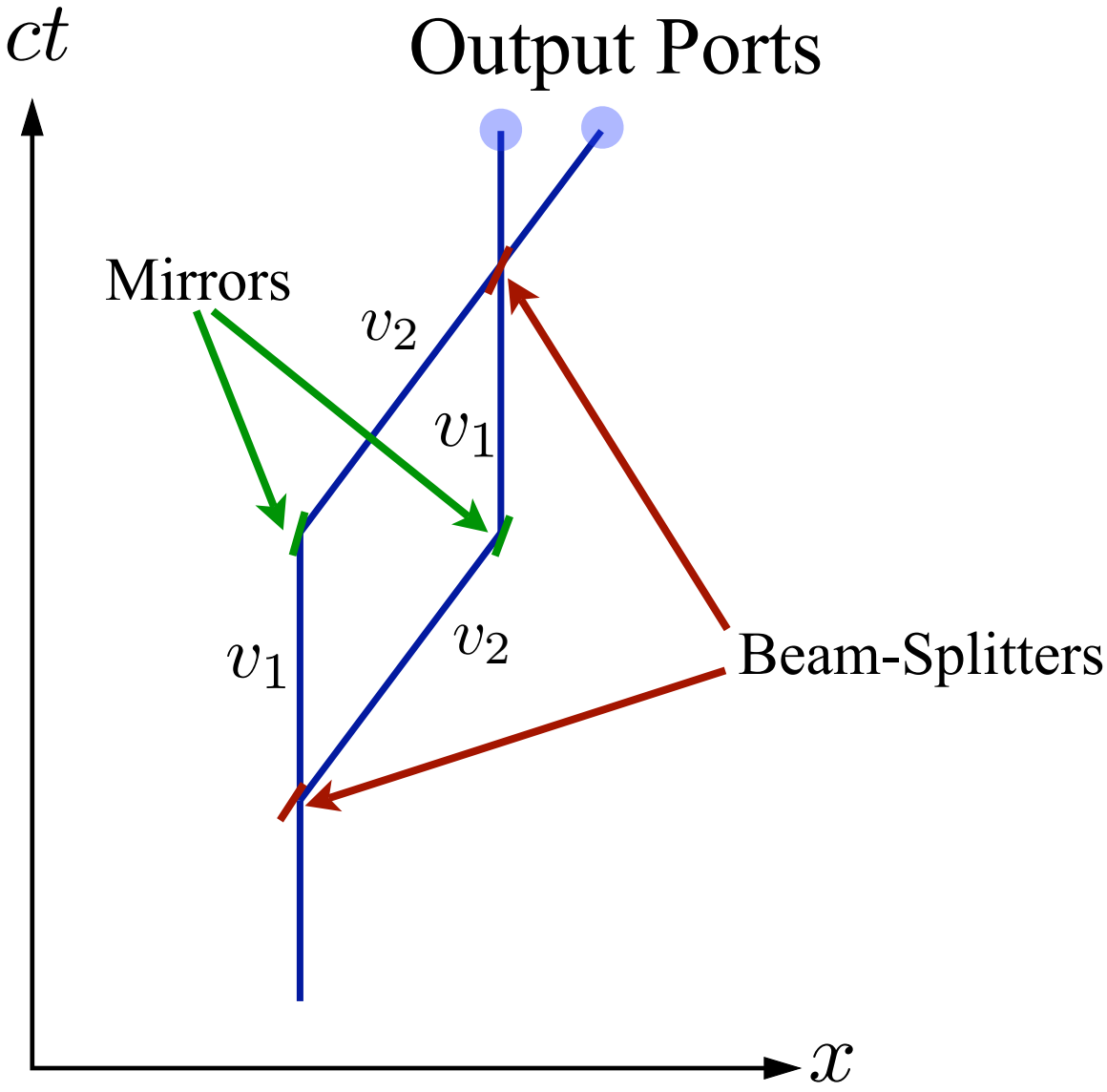
Precision Frontier

Strong CP Solution, Nature of CC/DM

(PQ Axion, Naturalness, New Forces, Violations of GR)

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

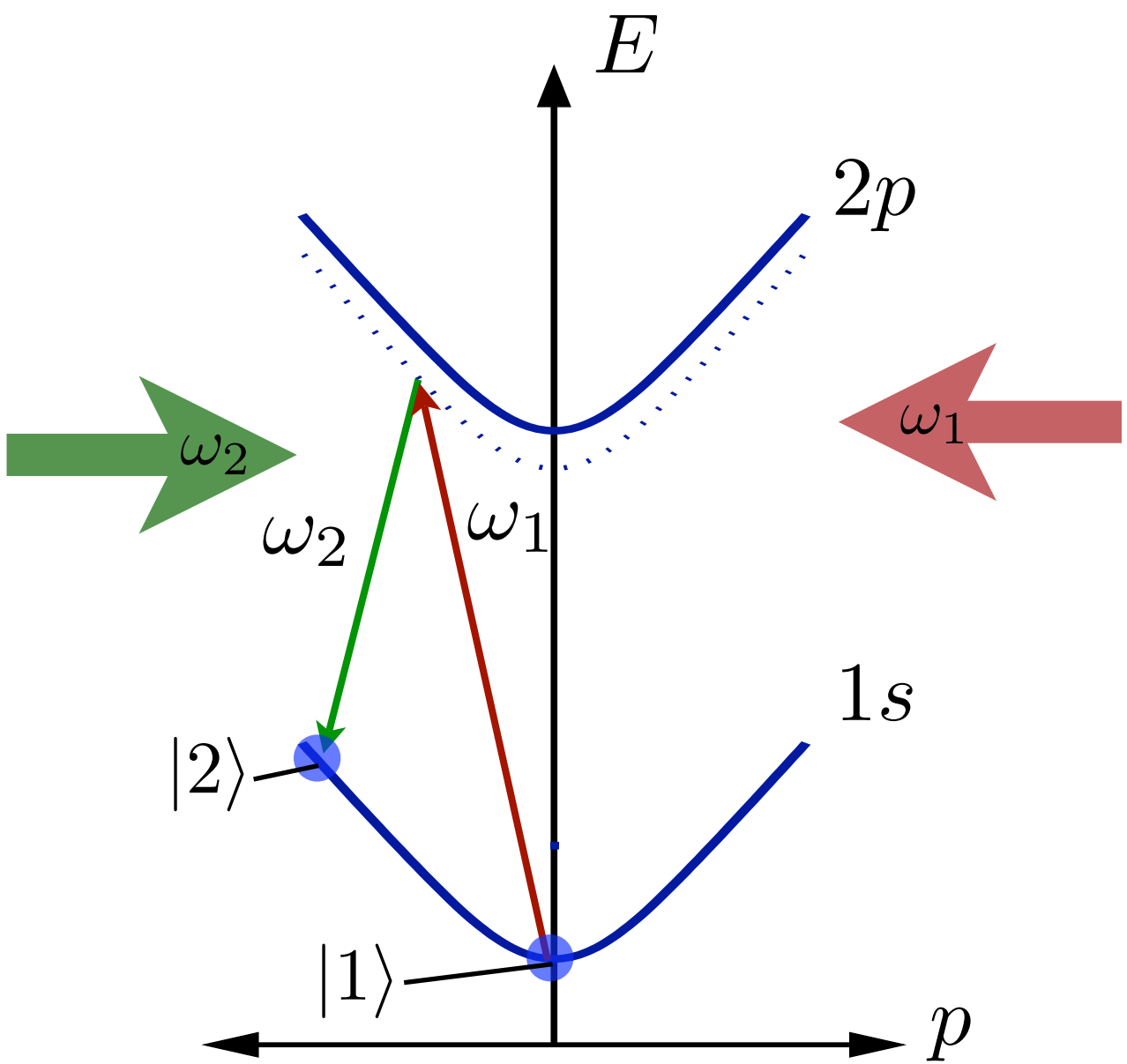
Principle Split

$\omega \sim \alpha^2 m_e$

1 eV

$\Delta p \sim 1$ eV

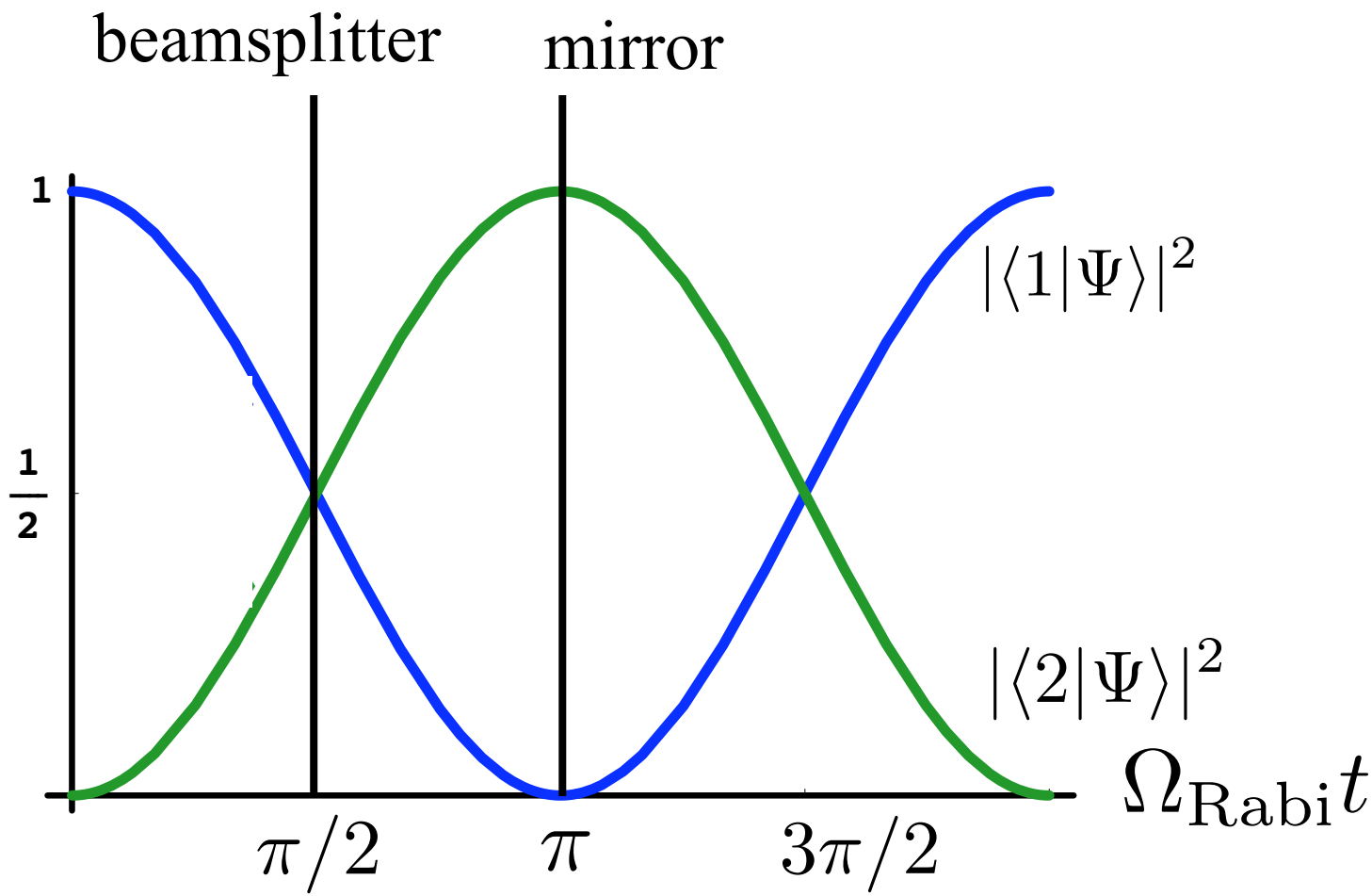
$\Delta E \sim 0$



Rabi Oscillations

Effectively 2 state oscillations

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



Sources of Relative Phase

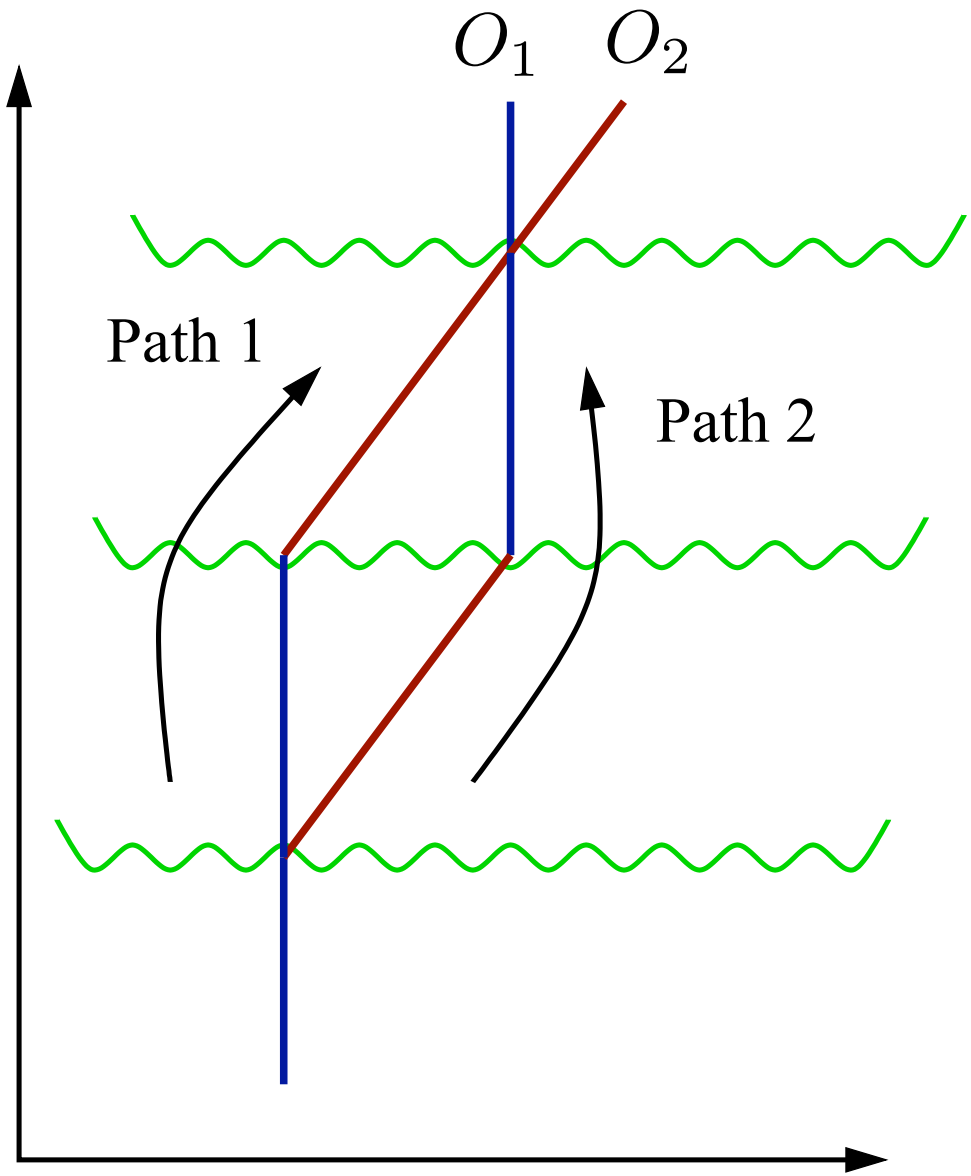
$$\Delta\Phi = \Phi_{\text{Path 1}} - \Phi_{\text{Path 2}}$$

3 Sources

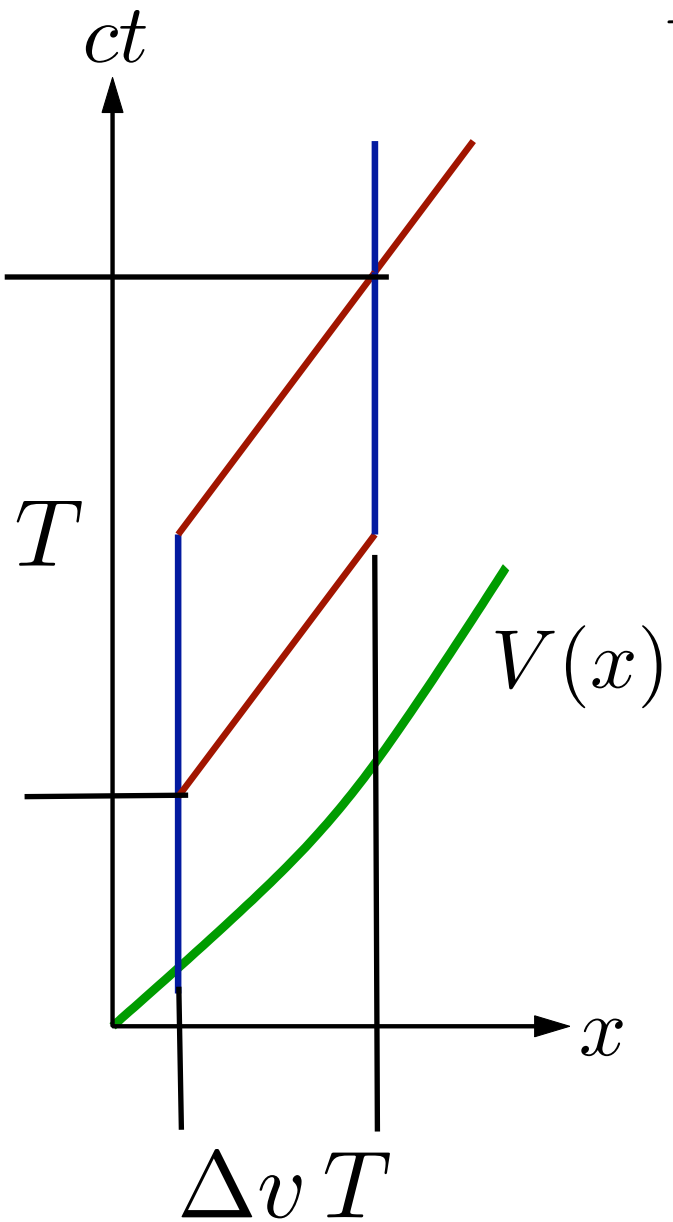
Propagation Phase

Separation Phase

Laser Phase



Interferometers are accelerometers



$$F = V' = m\,a$$

$$\Delta v = \Delta p / m$$

$$\Delta\Phi \sim \Delta p\, a\, T^2$$

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

Sub-gravitational Forces

Many suggestions for fifth forces

Moduli

Extra Dimensions

The Cosmological Constant

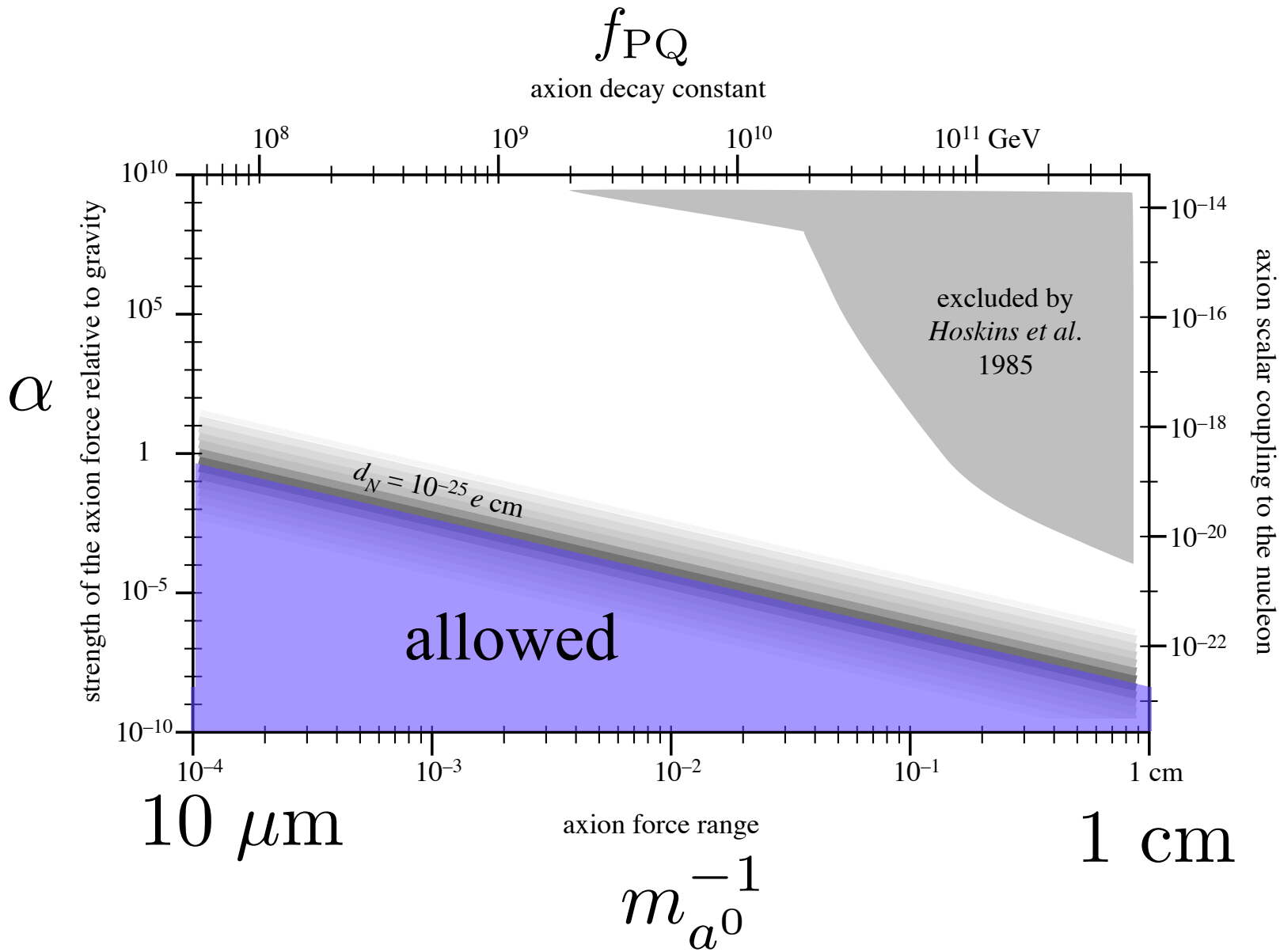
Parameterization of new force

$$\delta V(r) = \alpha \frac{G_N M m}{r} \exp(-r/\lambda)$$

α Strength relative to gravity

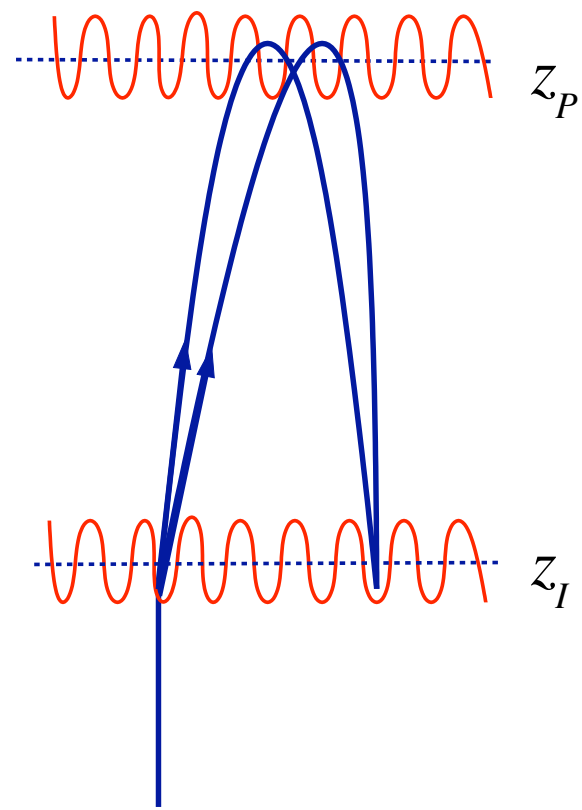
λ Range (i.e. Compton wavelength)

Axion mediated Scalar Forces



Experimental Set-up

First measure “null”

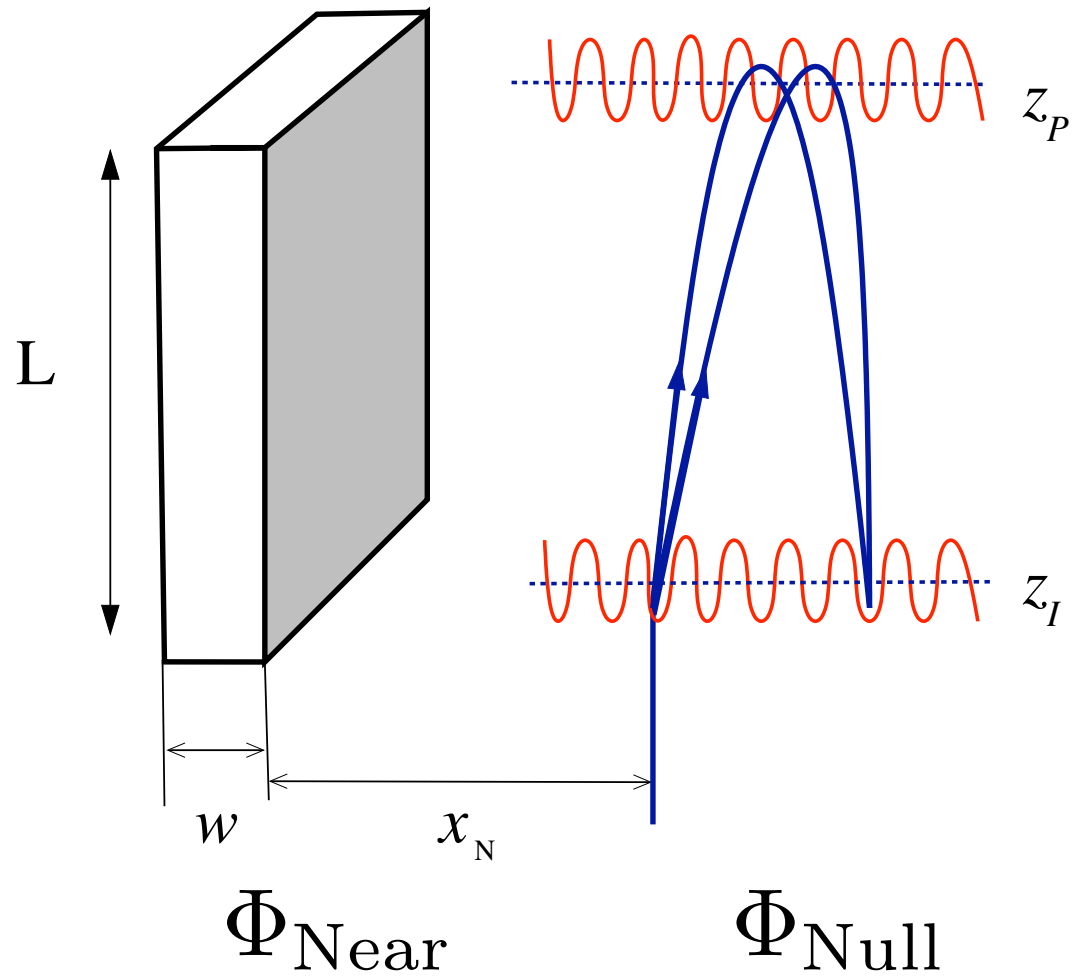


Φ_{Null}

Experimental Set-up

Interferometer set horizontally displaced test mass

Move test mass in and out and measure gravity



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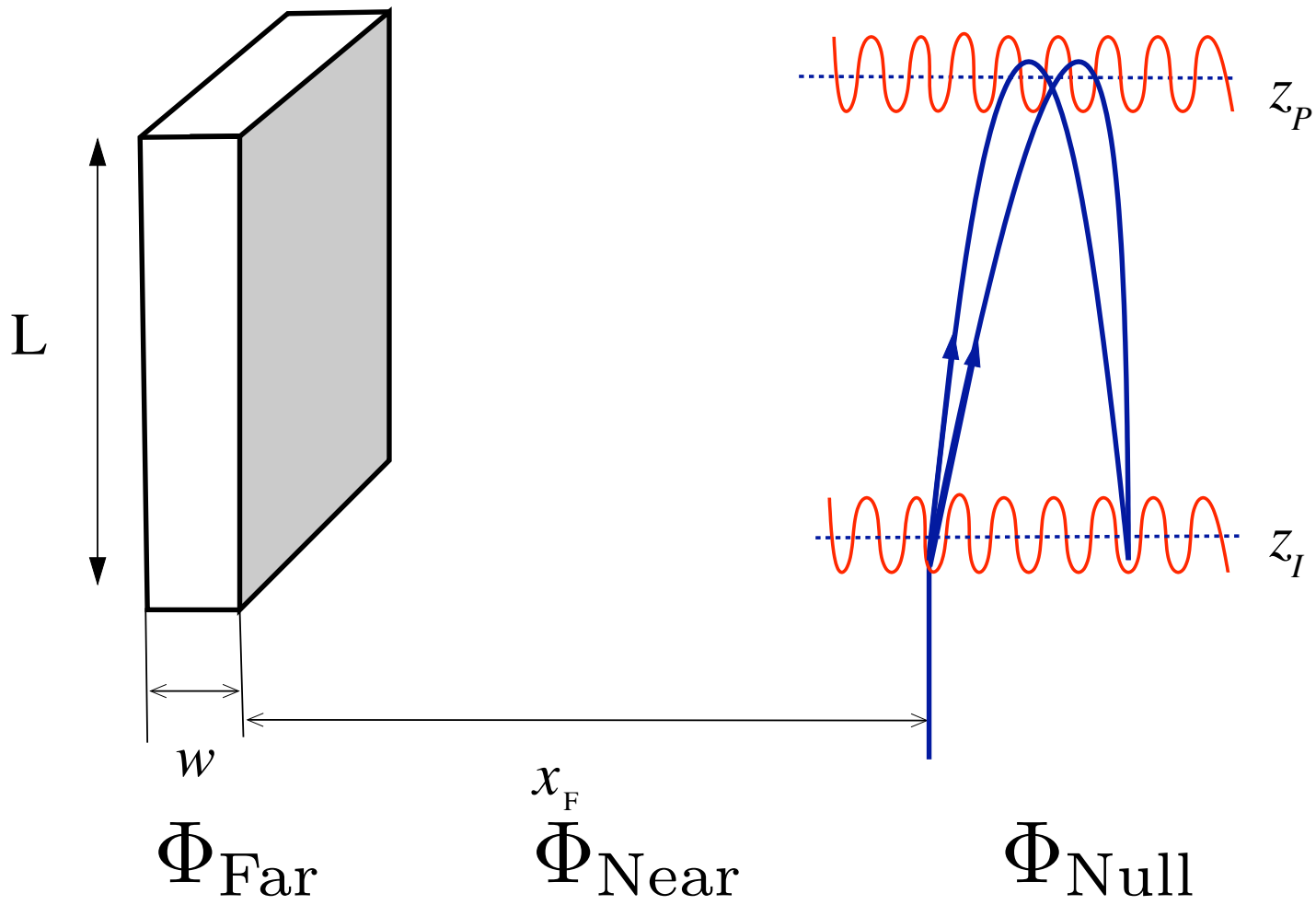

Precision

$$\Phi = kaT^2$$

Dimensions of experiment

$k \sim 10\ \mathrm{nm}$ $\quad a \sim G_N \rho w \sim 10^{-6} \mathrm{m/s}^2$ $\quad T \sim 0.1\ \mathrm{s}$

Signal Size

$\Phi \sim 1$

Resolution

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

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

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

Ultimate Resolution

$$\delta\Phi/\Phi \sim 10^{-7}$$

Backgrounds

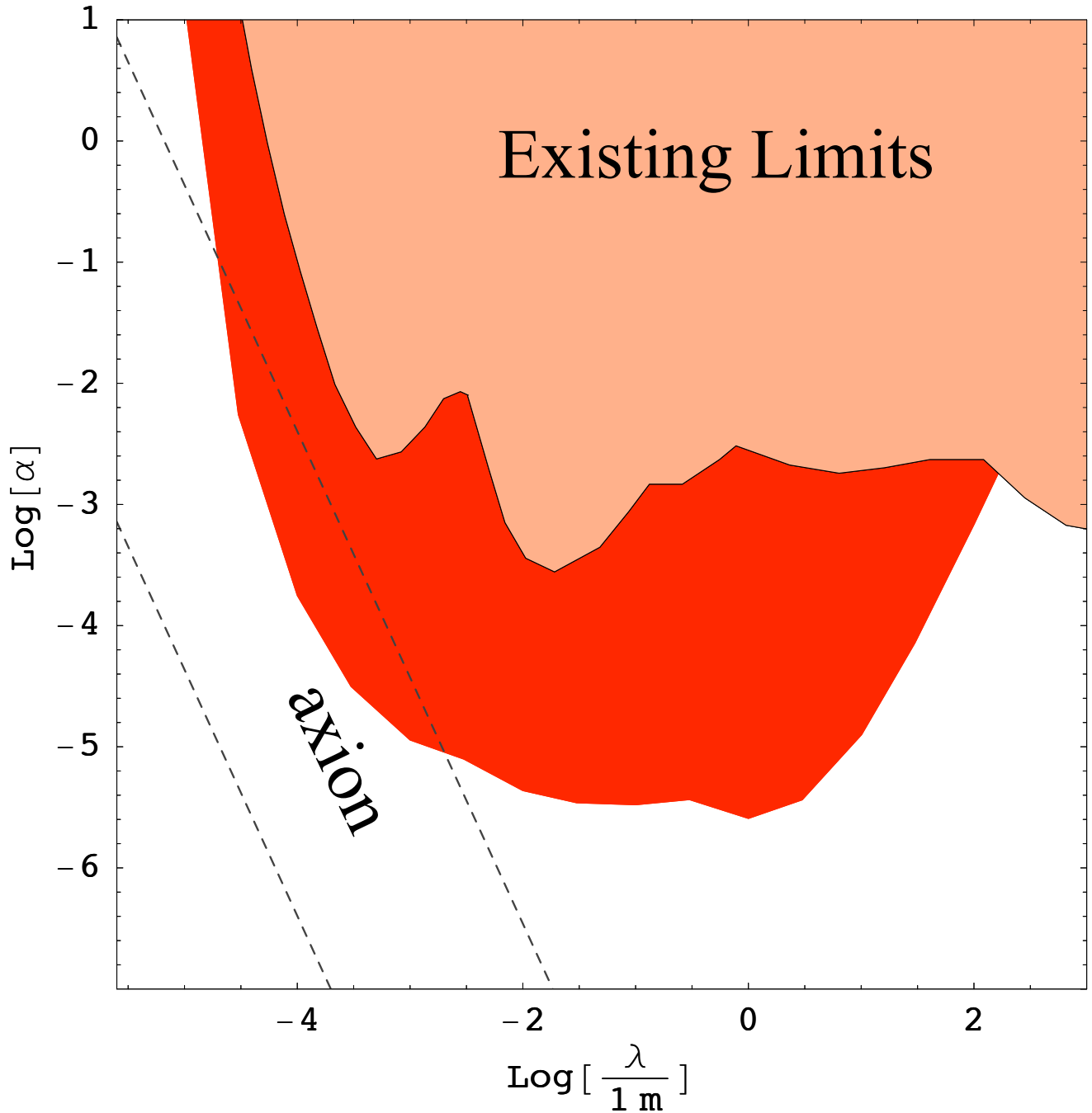
Main background is the source's Newtonian gravity!

Coriolis is not a problem

Uncontrolled gravitational sources
are not a problem

Casimir is important at 0.1 mm

Probable Limits



Improvements

Consider the phase

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

Can't make signal bigger

Big cost to make taller drop towers

Number of bunches
sets length of experiment

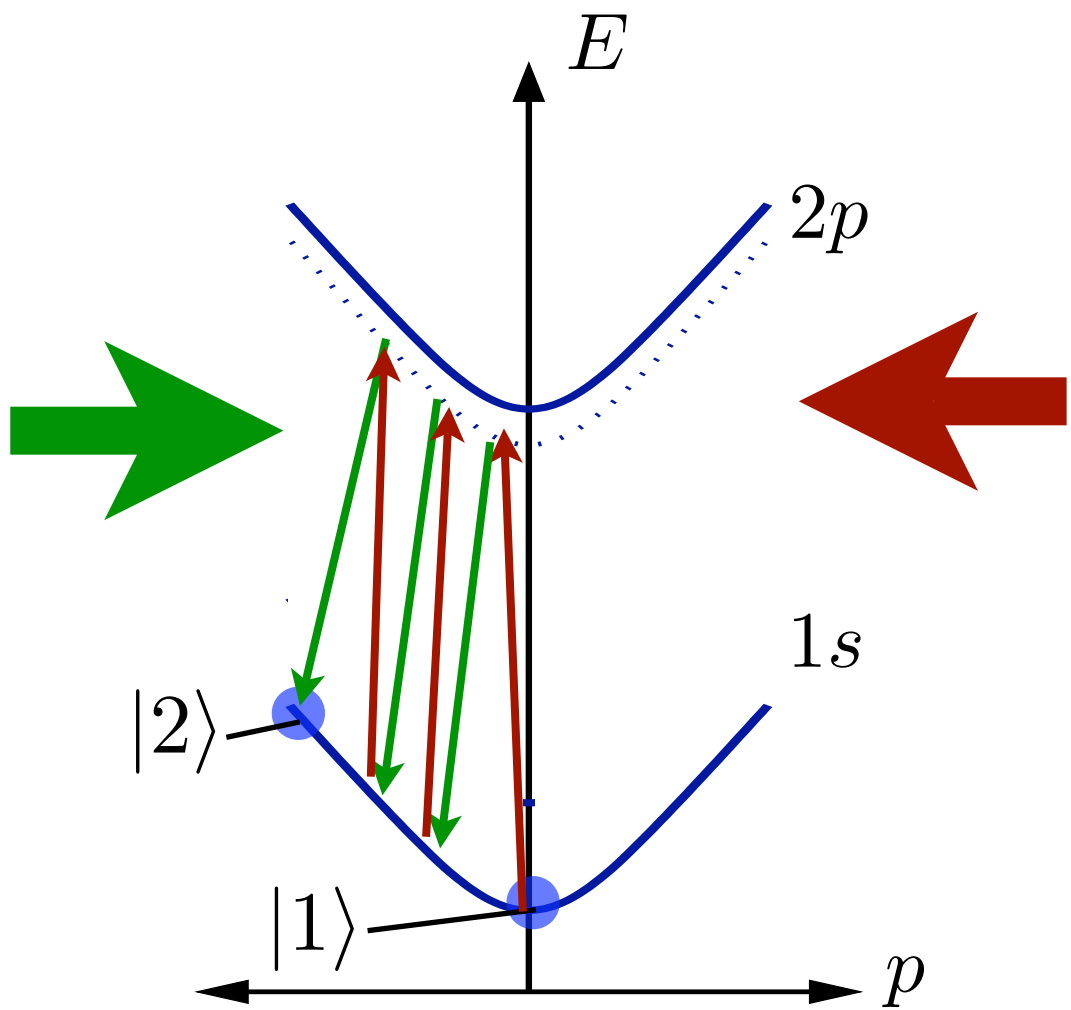
Large Momentum Transfer

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

changing the frequency to walk up momentum

$$\Delta p \sim 10^2 \text{ eV}$$

2 orders of magnitude improvement



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

GHZ state

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

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

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