An Experiment to Explore the Detection of Dark Energy on Earth Using Atom Interferometry

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Yet all experience is an arch wherethro'

Gleams that untravell'd world, whose margin fades

For ever and for ever when I move

From Tennyson's' poem Ulysses

The majority of astronomers and physicists accept the reality of dark energy but also believe it can only be studied indirectly through observation of the structure and motions of galaxies

This talk describes an *experimental* investigation of whether it is possible to directly detect dark energy on earth using atom interferometry and assuming (a) that the dark energy density distribution is Inhomogeneous and (b) that dark energy exerts a direct force on atoms.

Outline of Presentation

1. Introduction to Atom Interferometry

2. Conventional *beliefs* about the nature of dark energy.

3. Comparison of dark energy density with energy density of a weak electric field.

4. The terrestrial gravitational force field and a possible dark energy force.

5.Preliminary considerations on how well we can null out *g.*

6. Our assumptions about the properties of dark energy that make the experiment feasible.

7. General description of experimental method.

8. Nature of sought signal

1. Atom Interferometry

The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences awarded the 1997 Nobel Prize in Physics jointly to

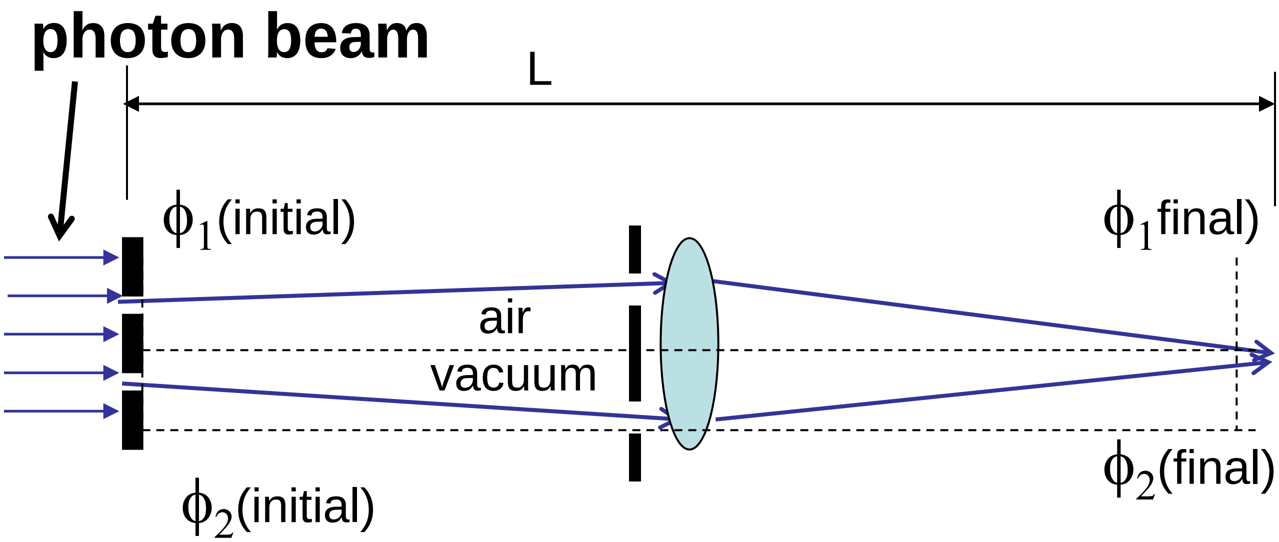
Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

for their developments of methods to cool and trap atoms with laser light.

Optical Interferometer Analogy

λ=wavelength of light = 500 nm

n_{air} =air index =1.0003



$\Delta\phi_1 = \phi_1(\text{final}) - \phi_1(\text{inital}) = 2\pi L n_{air} / \lambda$

$\Delta\phi_2 = \phi_2(\text{final}) - \phi_2(\text{inital}) = 2\pi L / \lambda$

$\Delta\phi = \Delta\phi_1 - \Delta\phi_2 = 2\pi L(n_{air}-1) / \lambda$

For L=0.1 m

$\Delta\phi$ = 377 rad

Basic Equation 1 for Atom interferometry

$$\Psi_{atom} = e^{i(2\pi x/\lambda - \omega t + \phi)}$$

λ = wavelength = h/momentum = h/mv

ϕ = phase

Cesium mass $m = 2.21 \times 10^{-25}$ kg
Use Cesium velocity = v =1 m/s

$\lambda = 3.0\ 10^{-9}$ m = 3.0 nm

Compare to visible light wavelength of 400 to 700 nm

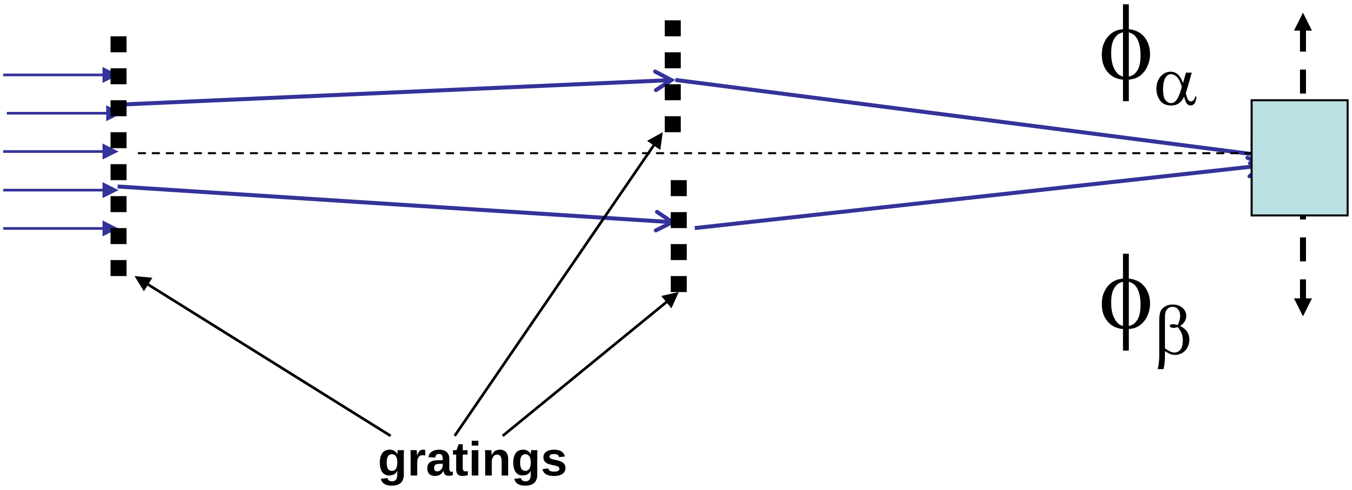
Basic Equation 2 for Atom interferometry

Change of phase of atomic wave function called $\Delta\phi$

$$\Delta\phi = (2\pi/hv)\int_{x_1}^{x_2} U(x)\, dx$$

When atom moves from x_1 to x_2 through potential $U(x)$

Atom Interferometer



$$\Psi_{\alpha\,\text{atom}} = e^{i(2\pi L_\alpha/\lambda - \omega t + \phi_\alpha)}$$

$$\Psi_{\beta\,\text{atom}} = e^{i(2\pi L_\beta/\lambda - \omega t + \phi_\beta)}$$

Basic Equation 3 for Atom interferometry

$$\Psi_{\alpha\,\mathrm{atom}} = e^{i(2\pi L_\alpha/\lambda - \omega t + \phi_\alpha)}$$

$$\Psi_{\beta\,\mathrm{atom}} = e^{i(2\pi L_\beta/\lambda - \omega t + \phi_\beta)}$$

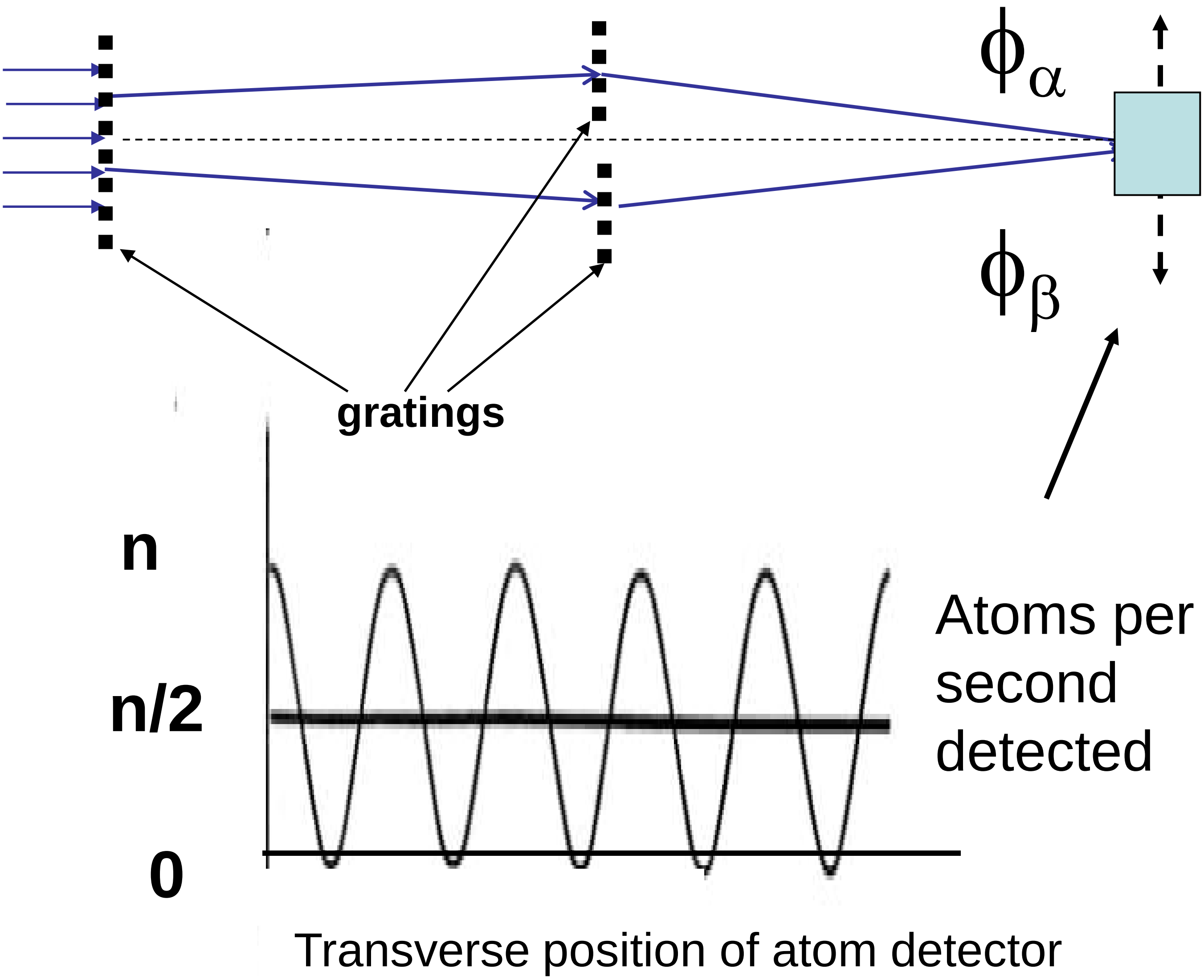
When $L_\alpha = L_\beta$

$$|\psi_1 + \psi_2|^2 = 2(1+\cos(\phi_1 - \phi_2))$$

Then for $L_\alpha \neq L_\beta$ one obtains

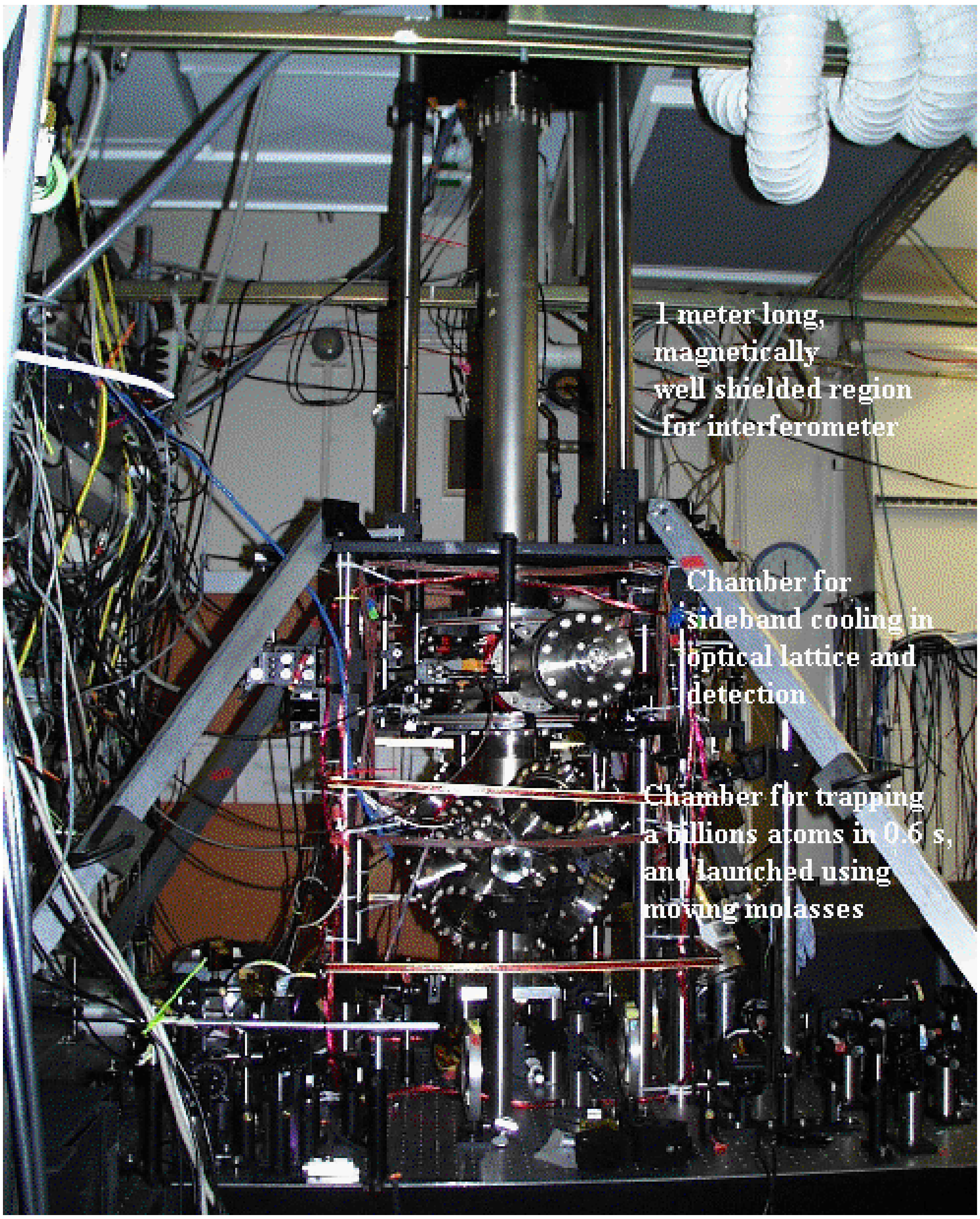
a 1+cos interference pattern

Atom Interferometer



A

Atom Interferometer of vertical, atomic fountain, type



2. Present *beliefs* about the nature of dark energy

Magnitude of dark energy density:

Counting mass as energy via $E=Mc^2$,the average density of all energy is the critical energy

$\rho_{crit} = 9 \times 10^{-10}\ J/m^3$

$\rho_{mass} \approx 0.3 \times \rho_{crit} = 2.7 \times 10^{-10}\ J/m^3$

$\rho_{dark\ energy} \approx 0.7 \times \rho_{crit} = 6.3 \times 10^{-10}\ J/m^3$

Use ρ_{DE} to denote $\rho_{dark\ energy}$

$\rho_{DE} \approx 6.3 \times 10^{-10}$ J/m^3 is a very small energy density but as shown in the next section we work with smaller electric field densities in the laboratory

ρ_{DE} is taken to be at least approximately uniformly distributed in space

3. Comparison of dark energy density with energy density of a weak electric field.

$\rho_{DE} \approx 6.3 \times 10^{-10}$ **Joules/m^3**

Compare to electric field of *E*=1 volt/m

using ρ_E = electric field energy density. Then

$$\rho_E = \varepsilon_0 E^2/2 = 4.4 \times 10^{-12}\ \mathrm{J/m^3}$$

This is easily detected and measured. Thus we work with fields whose energy densities are much less than ρ_{DE}

Of course, it is easy to sense tiny electromagnetic fields using electronic devices such as field effect transistors or superconducting quantum interference devices (SQUIDs).

Obvious reasons for difficulty or perhaps impossibility of working with dark energy fields:

- **Cannot turn dark energy on and off.**
- **Cannot find a zero dark energy field for reference.**
- **In some hypothesis about dark energy, it may not exert a force on any material object beyond the gravitational force of its mass equivalent.**

4. The terrestrial gravitational force field and a possible dark energy force.

Recall phase change of atoms depends upon the force on the atom.

If dark energy exerts such a force, use g_{DE} to describe in analogy to g

Atom interferometry studies have reached a sensitivity of better than 10^{-9} g in measurements of g and found no anomaly.

There is no evidence for a g_{DE} larger than 10^{-9} g.

Therefore $g_{DE} \leq 10^{-8}$ m/s^2

5. Preliminary considerations on how well we can null out *g*.

Based on preliminary considerations we believe we can null out *g* to a precision perhaps as small as 10^{-17}. This sets the smallest g_{DE} that we can investigate at 10^{-16} m/s^2.

6. Our 3 assumptions about the properties of dark energy that make the experiment interesting.

1. **A dark energy force, F_{DE} exists, other than the gravitational force equivalent of ρ_{DE},**

2. **F_{DE} is sufficiently local and ρ_{DE} is sufficiently non-uniform so that F_{DE} varies over a length of the order of a meter.**

3. **F_{DE} acts on atoms leading to a potential energy U_{DE} The ratio g_{DE}/g is large enough for g_{DE} to be detected in this experiment by nulling signals from *g*.**

4. **Note: if dark energy density is inhomogeneous, *w* is not exactly -1 in**

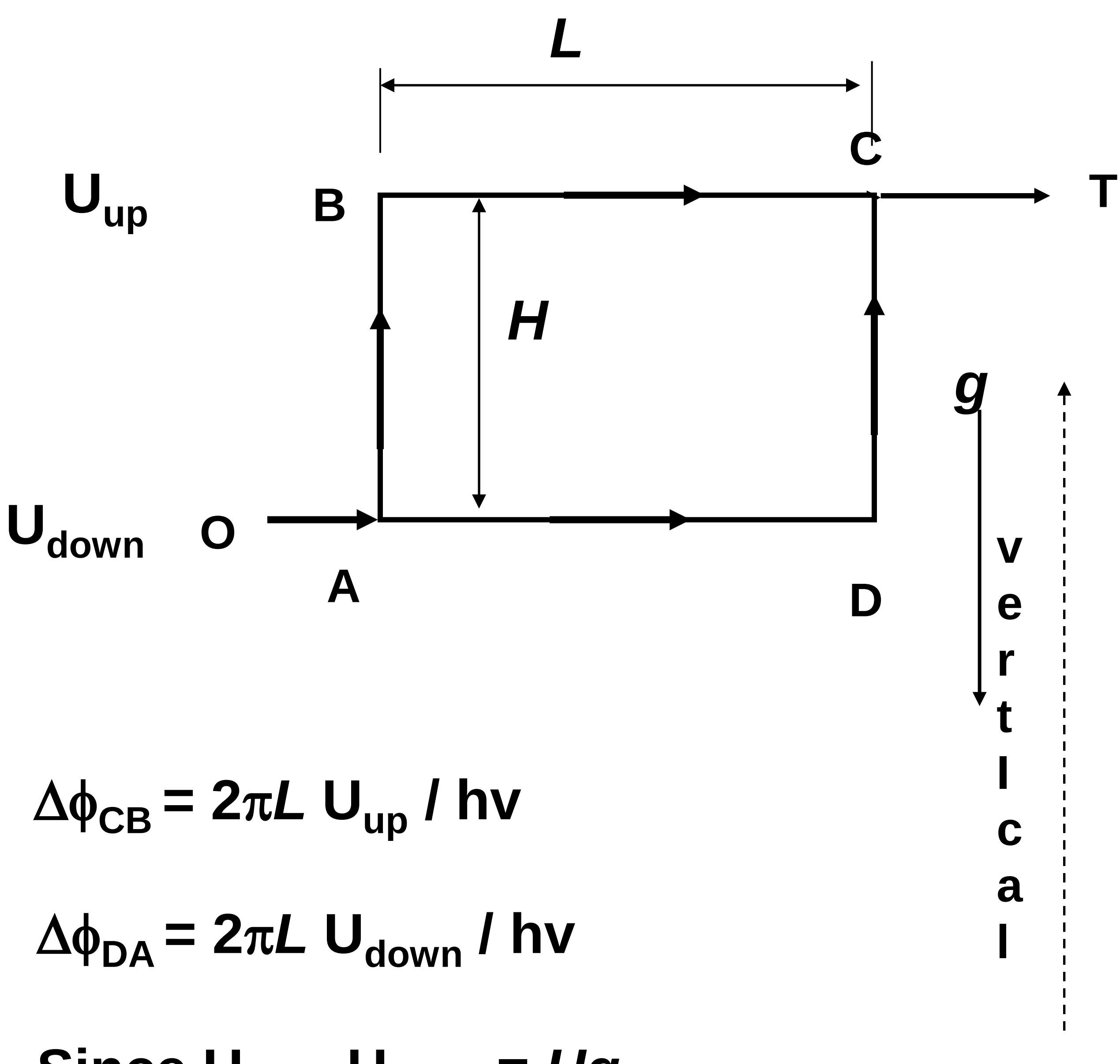
   $Pressure_{DE} = w\,\rho_{DE}$

7. General description of experimental method.

- **Effects of electric and magnetic forces are nulled by shielding and by using atoms (Cs for example) in quantum states which are not sensitive to the linear Zeeman and Stark effects.**

- **The gravitational force is nulled by using two identical atom interferometers.**

Interferometer in vertical plane



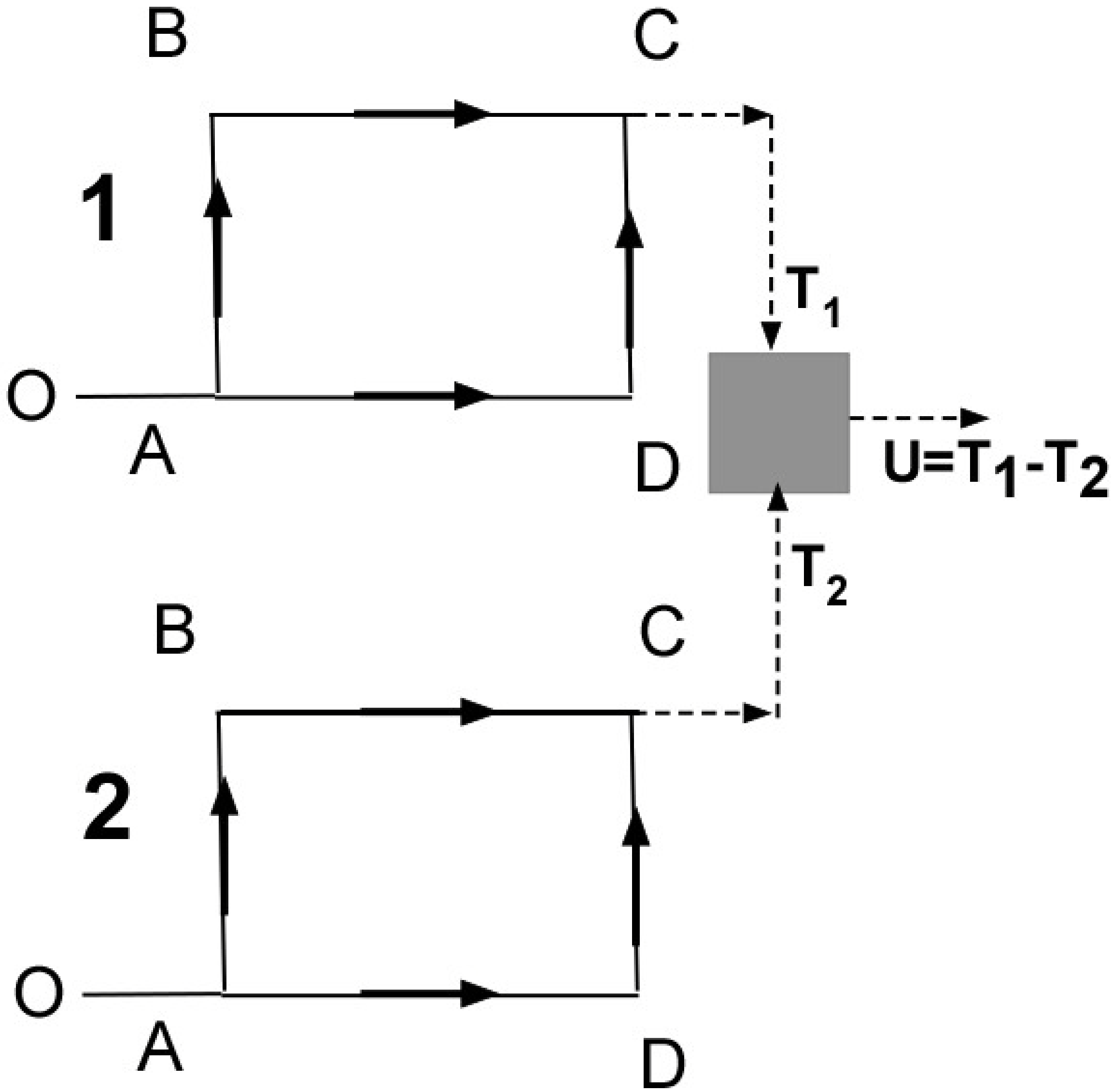
$\Delta\phi_{CB} = 2\pi L\ U_{up}\ /\ hv$

$\Delta\phi_{DA} = 2\pi L\ U_{down}\ /\ hv$

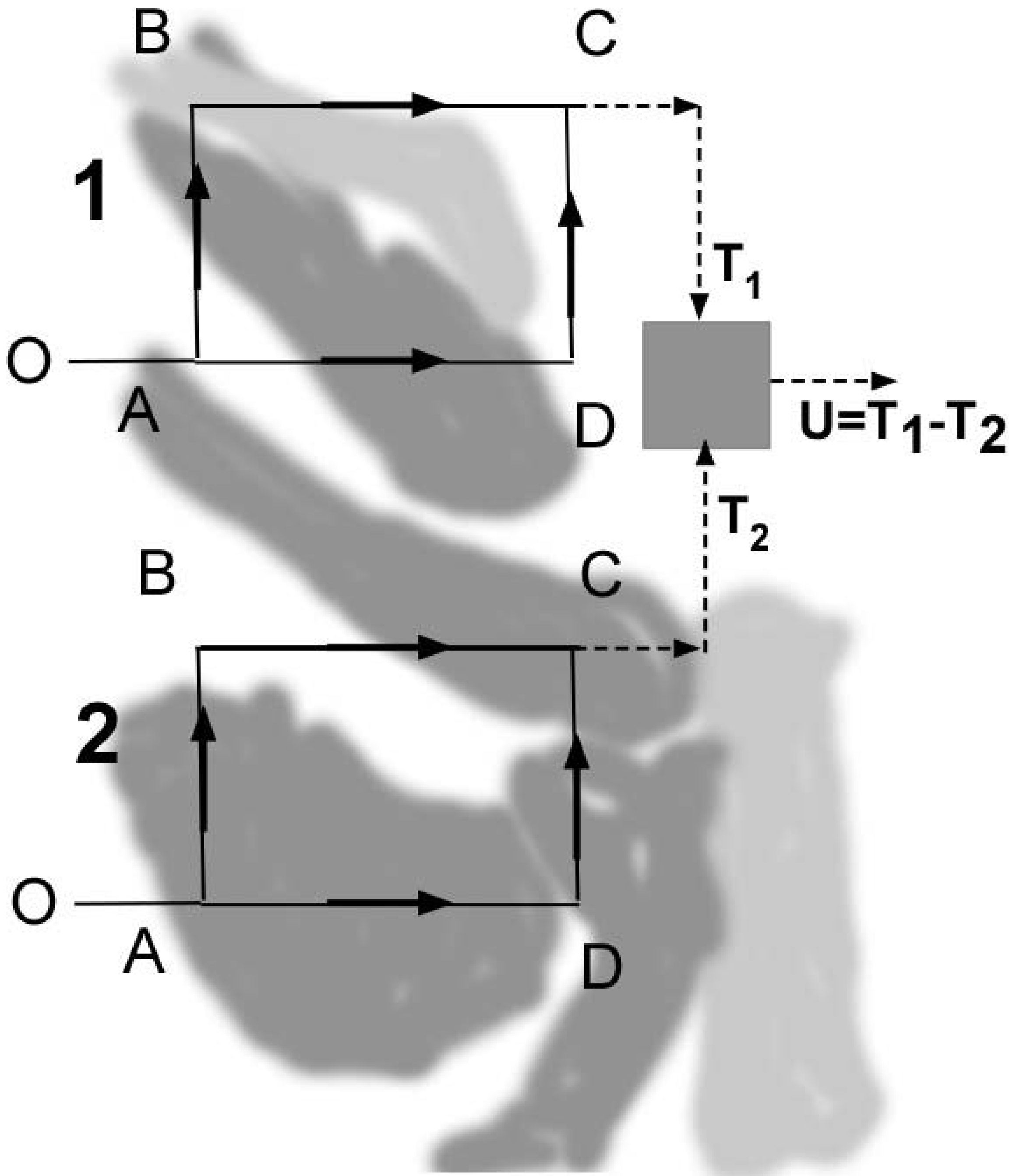
Since $U_{up} - U_{down} = Hg$

$\Delta\phi_T = \Delta\phi_{CB} - \Delta\phi_{DA} = 2\pi LH\ g/\ hv$

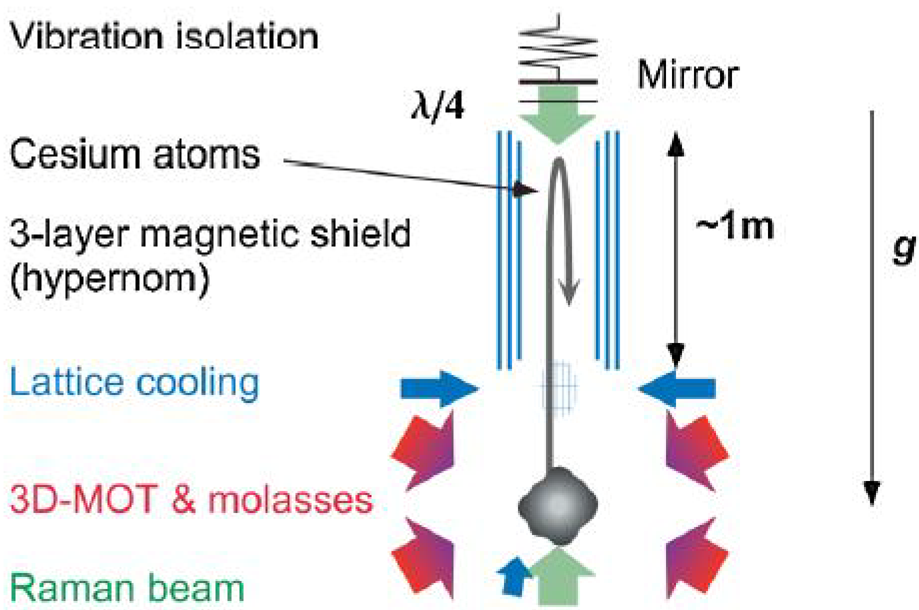
Double interferometer to be used



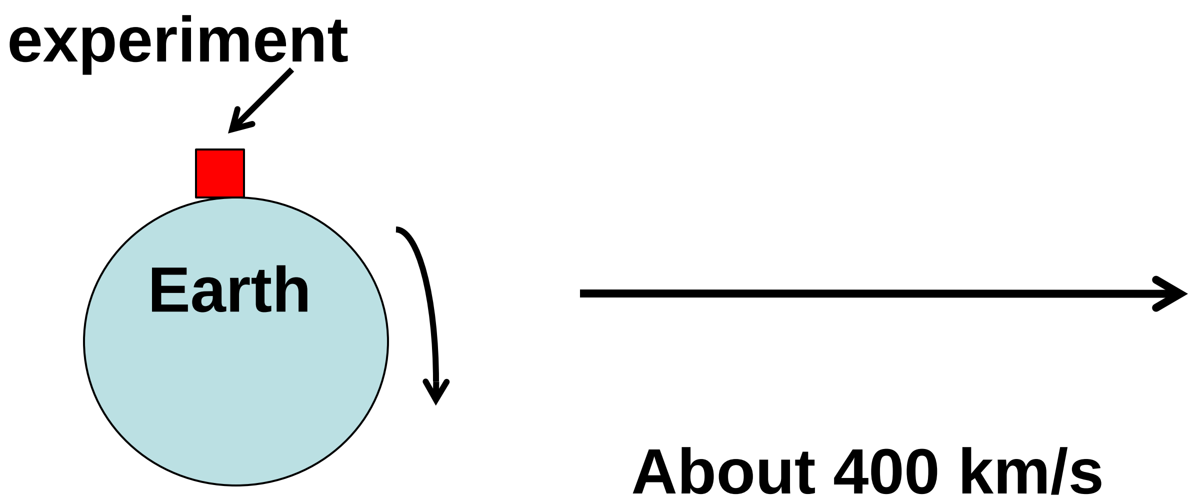
Detecting dark energy density



The construction of an atomic Fountain, atom interferometer at UC-Berkeley will be completed in about six months. We will use it for this dark energy search



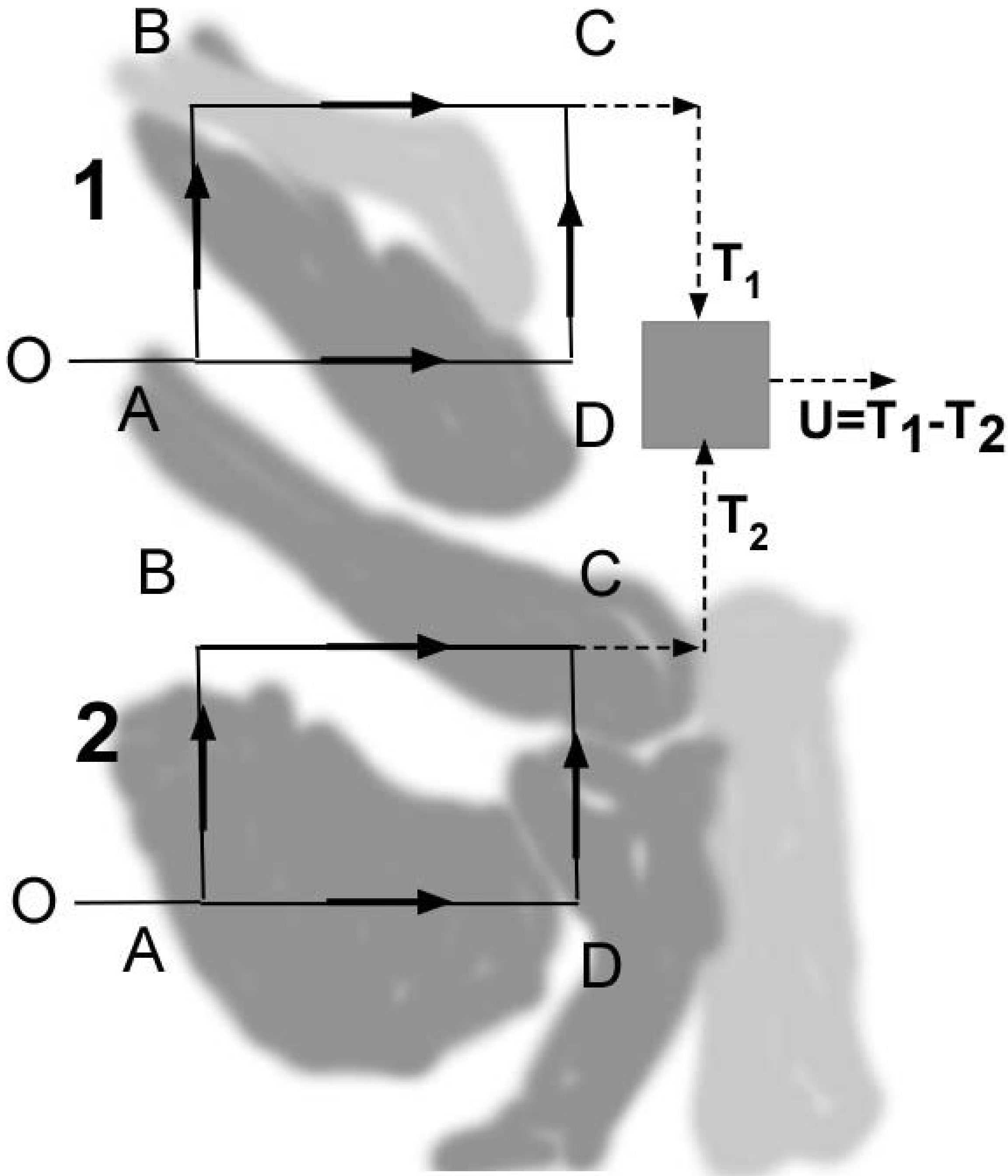
8. Nature of sought signal.

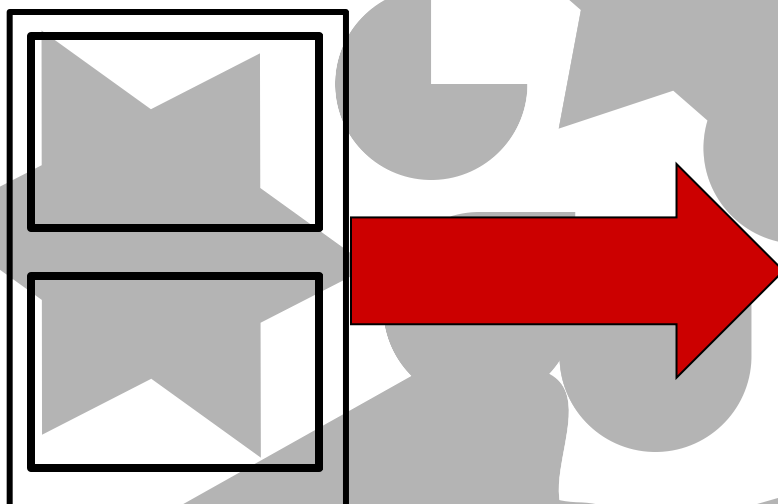


About 400 km/s relative to CMB frame.

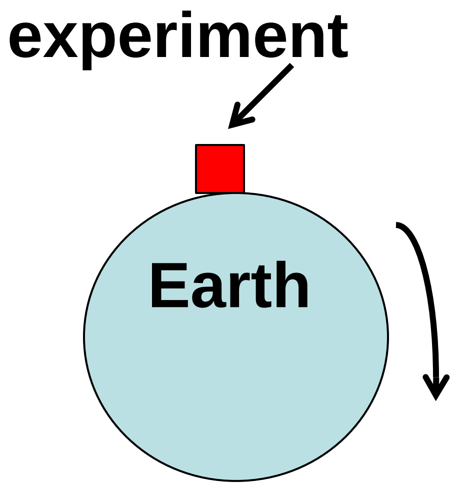
If dark energy is inhomogeneous, we assume the dark energy Clumps are at rest or move Relative to the CMB frame.

Detecting dark energy density





Double spectrometer moving 400 km/s through dark matter clumps



About 400 km/s relative to CMB frame.

Apparatus sampling rate is of the order of Hertz.

Hence the dark energy signal is a noise signal.

1. If we find such a noise signal, we can and must show it is not Instrumental noise.

2. But at present we do not know how to prove such a signal comes from dark energy.

3. In general we are searching for signals not caused by electric, magnetic, or gravitational fields.

Thank you