A Search for Direct Detection of Dark Contents of the Vacuum and Dark Energy

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On Behalf of the Collaboration

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Martin Perl et al.
http://arxiv.org/abs/1101.5626

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Introduction

- Motivate the search to detect dark energy terrestrially.
- What is the technology and how does it work?

Dark Energy

Nobelprize.org

The Official Web Site of the Nobel Prize

The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

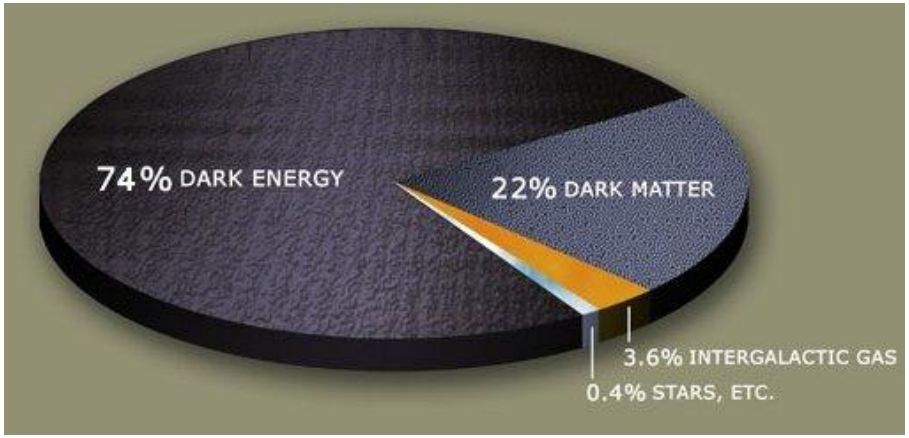
Photo: U. Montan

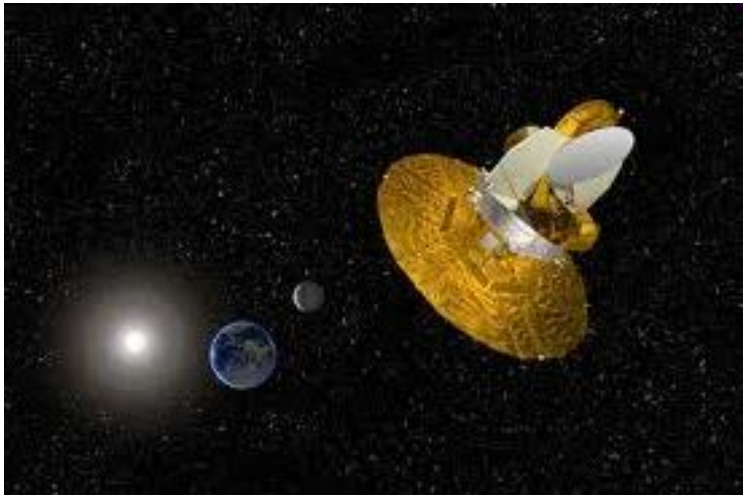
Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Dark Energy

- 74% of the universe is dark energy.
- Causes the expansion of the universe to accelerate.





- Observations from Super Novae, CMB and large scale structures all agree with the Λ -CDM cosmological model of the universe.
- Can dark energy be explored terrestrially?

Terrestrial search

- Average energy density of dark energy is $\rho_{DE} = 6.3 \times 10^{-10}$ J m^{-3}.
- Same energy density as a 12Vm^{-1} electric field!

- 12 Vm^{-1} electric field easily detectable in lab.
- Dark energy is small but non zero, may be detectable.

a SQUID in a Undergrad Lab…

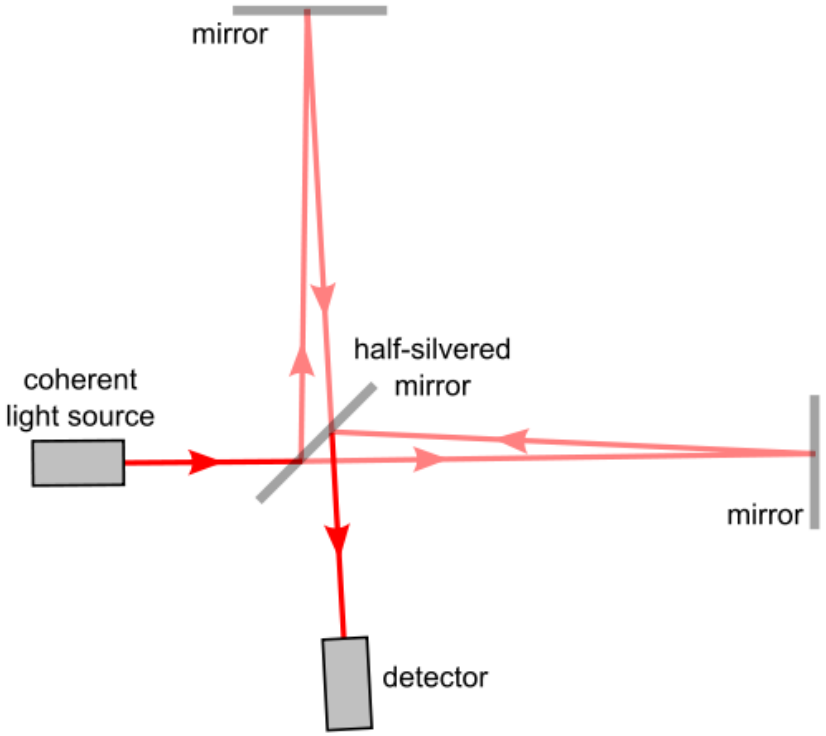
Conditions on detection

Dark energy can be detected **if**;

1. Dark energy is spatially inhomogeneous on the lab scale.
2. Dark energy interacts with atoms in a non gravitational way.

How does interferometry work?

- Split light into two beams.
- Beams travels two different paths.
- Recombine the beams into one.
- Measure the phase difference between the two paths.
- Phase difference related to difference in paths.



Why Atoms?

- Smaller wavelengths lead to a higher accuracy.
- Atoms have a wavelength $\lambda = h/p$

Laser Cooling

Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

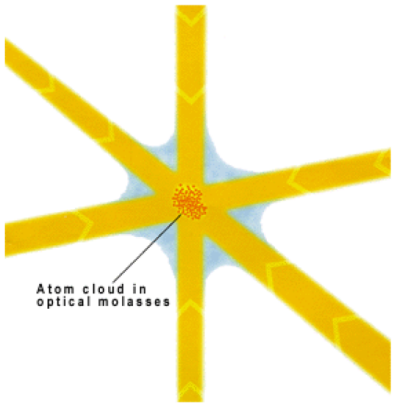
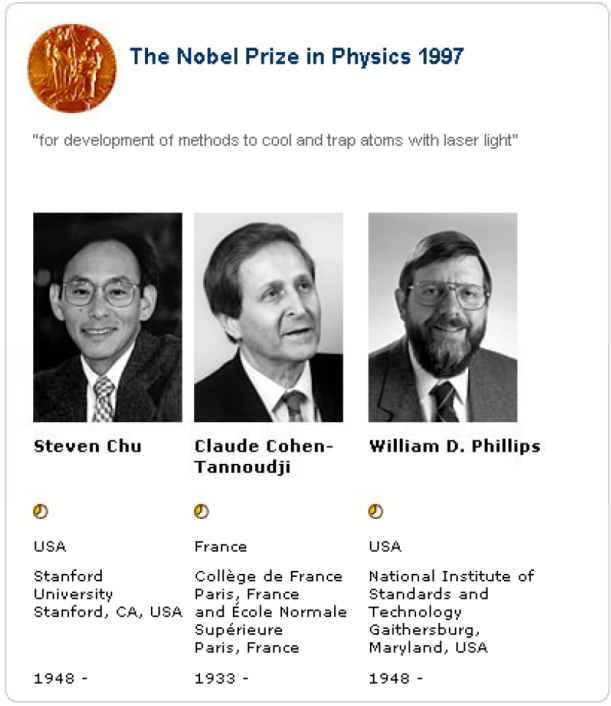


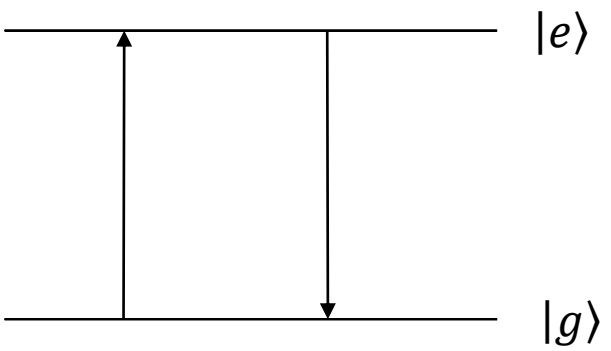
Image source:www.nobel.se/physics

Laser cooling: Laser light is used to cool atomic vapors to temperatures of $\sim 10^{-6}$ deg K.



Atomic mirrors and beam splitters

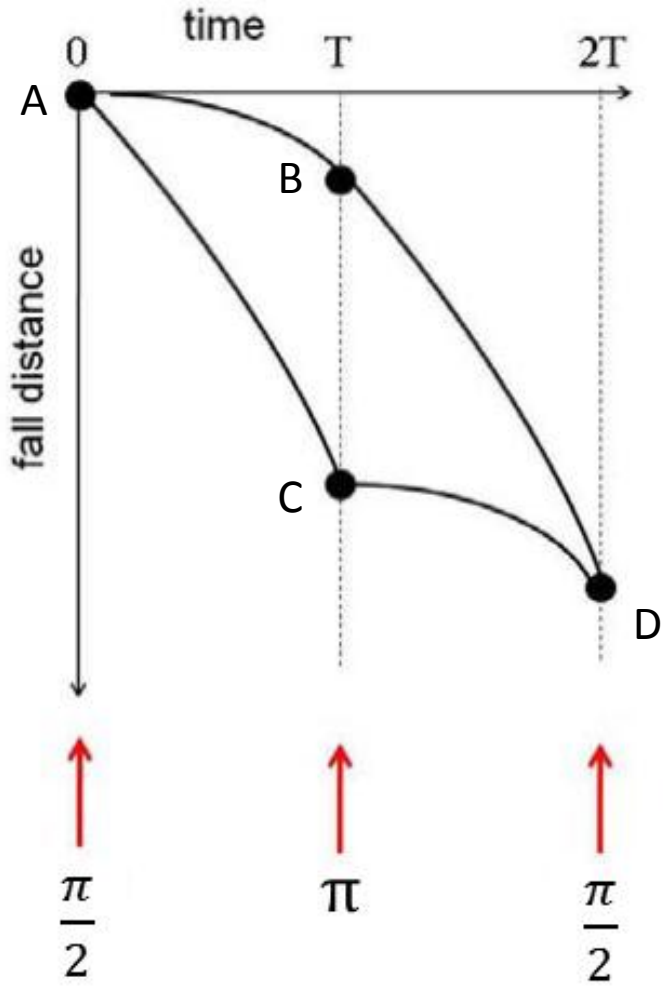
- A Rabi cycle $|g\rangle \rightarrow |e\rangle \rightarrow |g\rangle$ under stimulated emission/absorption.
- Half an cycle is a π pulse.
- π pulses switches $|g\rangle$ for $|e\rangle$ and visa verse.
- Quarter of a cycle is a $\frac{\pi}{2}$ pulse.



- A $\frac{\pi}{2}$ pulse can put the atom into a superposition of two states

$$\text{i.e. } |g\rangle \rightarrow \frac{1}{\sqrt{2}} \left(|g\rangle + e^{-i\omega t} |e\rangle\right)$$

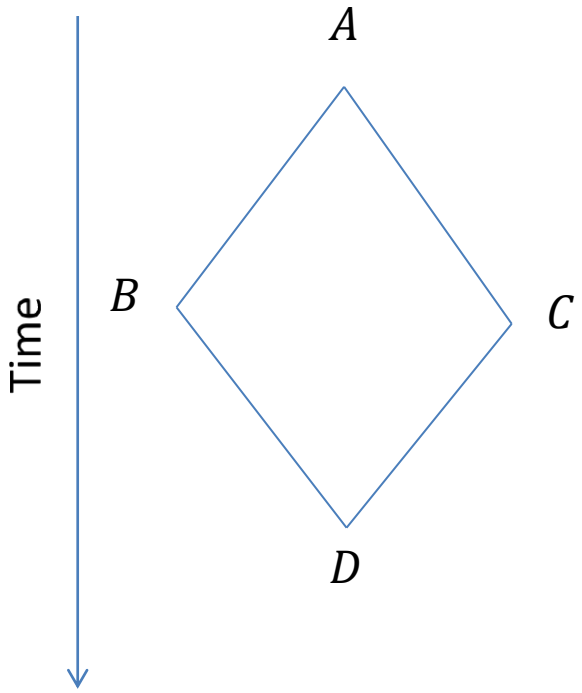
Interferometry Sequence



Time	0	T	2T
Pulse type	$\frac{\pi}{2}$	π	$\frac{\pi}{2}$
Analogy	Beam-splitter	Mirror	Beam-splitter

- Figure shows different paths in the atom interferometer.

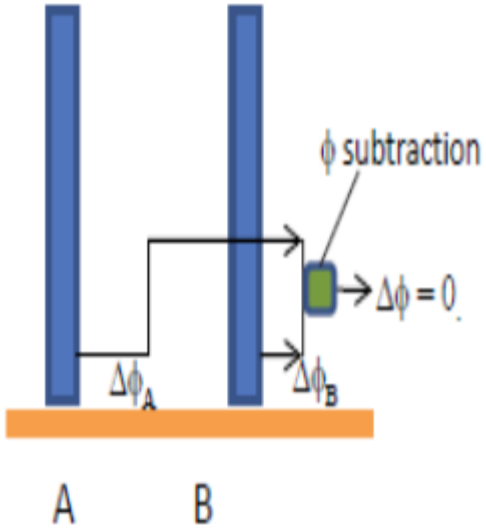
Measurement



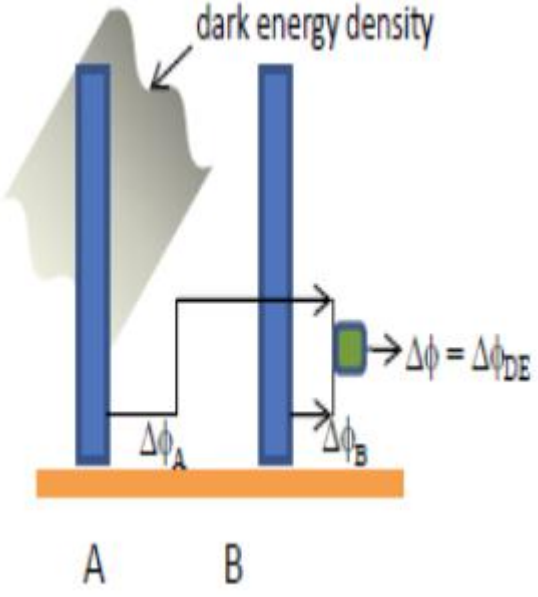
- ϕ_{ABD} is the phase from the path integral for an atom that has travelled the path ABD.
- ϕ_{ACD} is the phase from from the path integral for an atom that has travelled the path ACD.
- $\Delta\phi = \phi_{ABD} - \phi_{ACD}$ is the phase difference for the interferometry measurement.

Atom Interferometry

- An atom interferometer measures phase difference $\Delta\phi$ of the atoms.
- Two interferometers should measure the same $\Delta\phi$



- But if there is a greater dark energy density in one interferometer, it could affect the $\Delta\phi$ in one interferometer.
- This appears as a noise like signal.



Progress

- Designing and constructing our first interferometer prototype now.
- Vacuum system operating at > 10^{-10}mbar.
- Waiting on last pieces of equipment to trap the atoms, should be trapping in the next few weeks.
- Expect to have a working interferometer within the next 12 months.

Summary

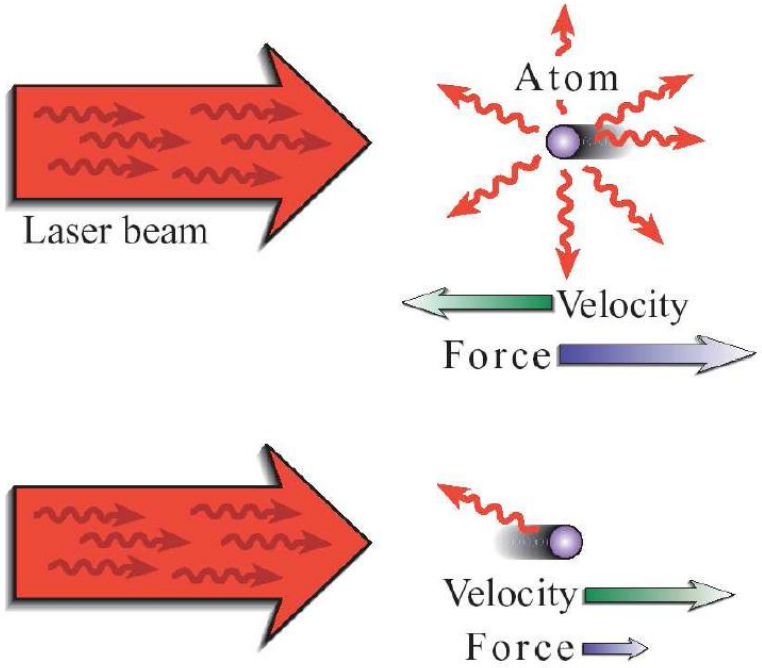
- Dark energy could be detected using atom interferometry if it is;
  - Spatially inhomogeneous on lab scale.
  - Interacts in a non gravitational way with matter.
- Explained how atom interferometry works.
- How a dark energy can produce a noise like signal between two atom interferometers.

Thanks for listening!

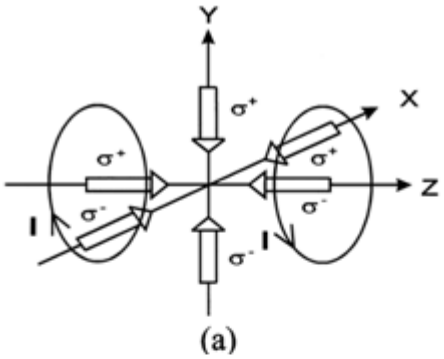
Any questions?

Atom Trapping

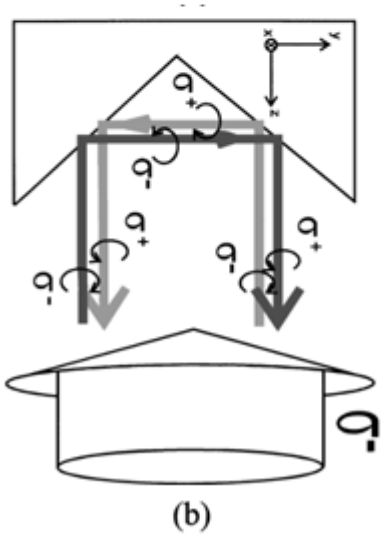
- Cooling laser frequency is just less than a transition.
- Atoms moving towards laser beam interact and slow down.
- Atoms emits photon in random direction.
- Overall beam slows down atoms.



Beam of atoms



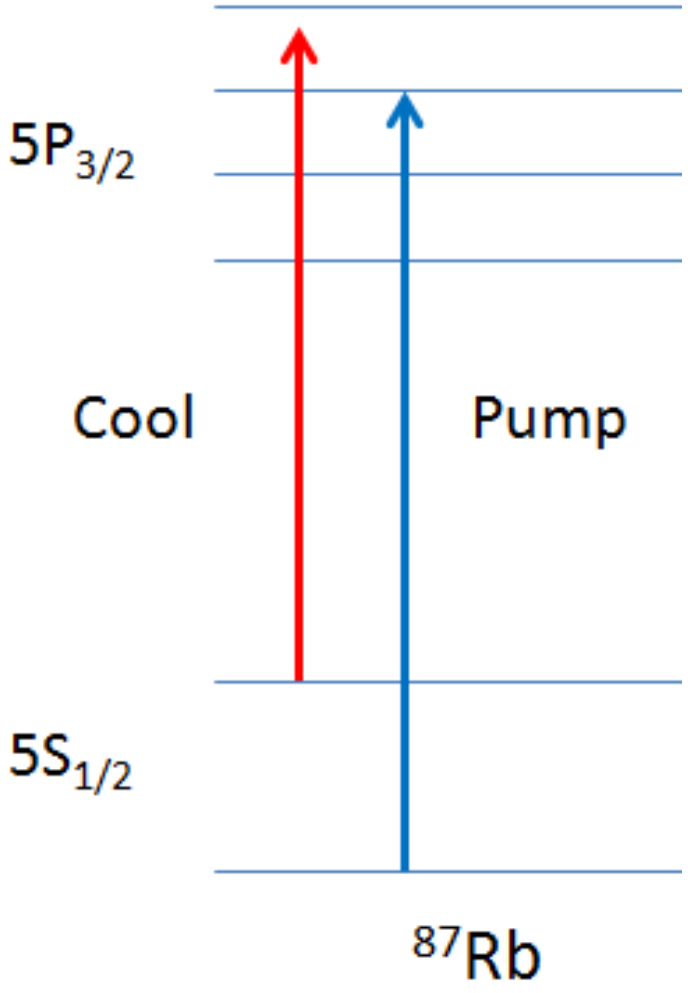
•Beam of atoms dropped from an optical trap.



•Calibrating 6 independent beams – difficult!

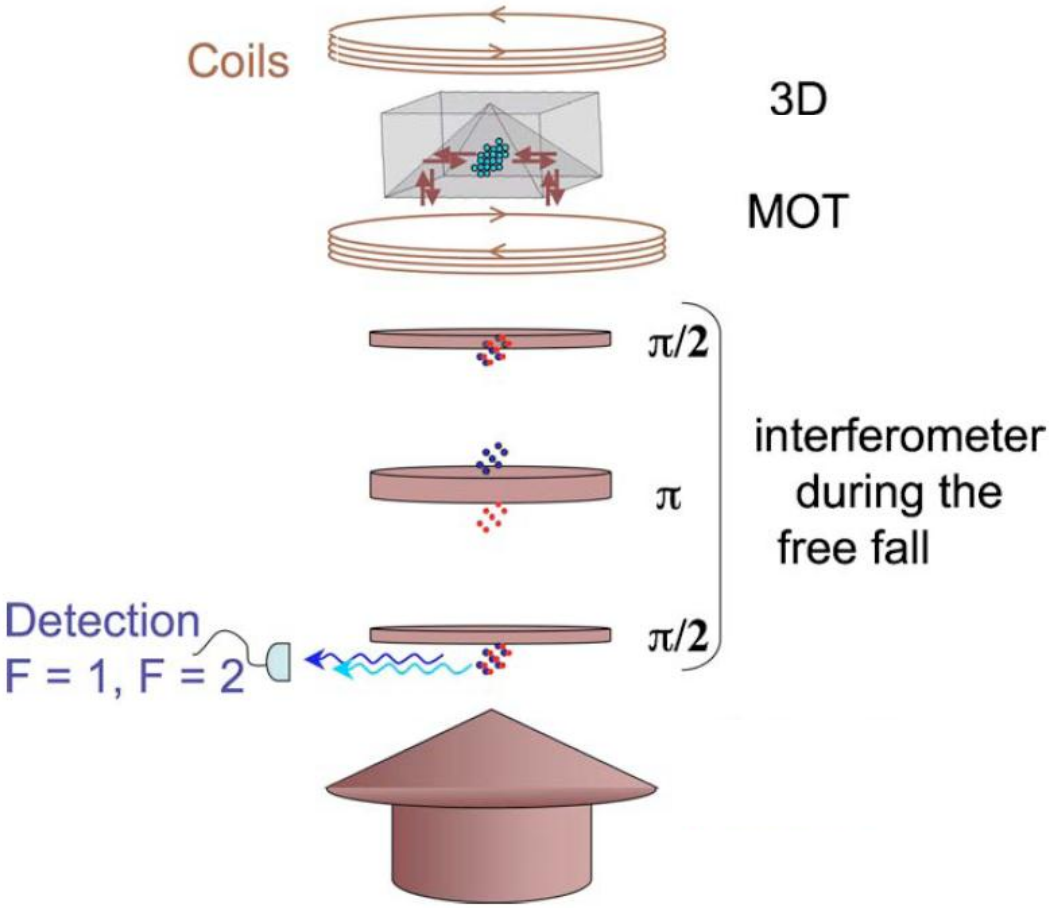
•Hollow pyramidal mirror creates 6 beams when illuminated with the laser light.

Rubidium

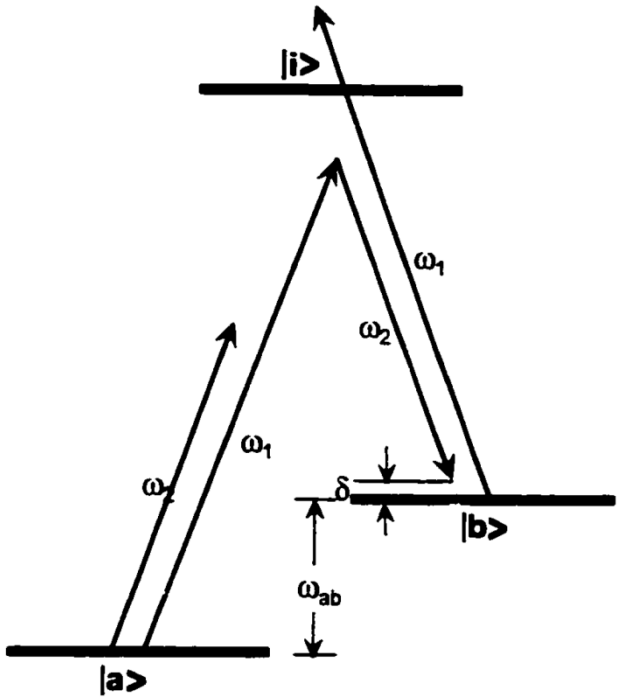


- Having just 1 electron in the outer shell makes alkali metals good for atomic cooling experiments.
- Easy to manipulate the one electron.

Interferometry Sequence

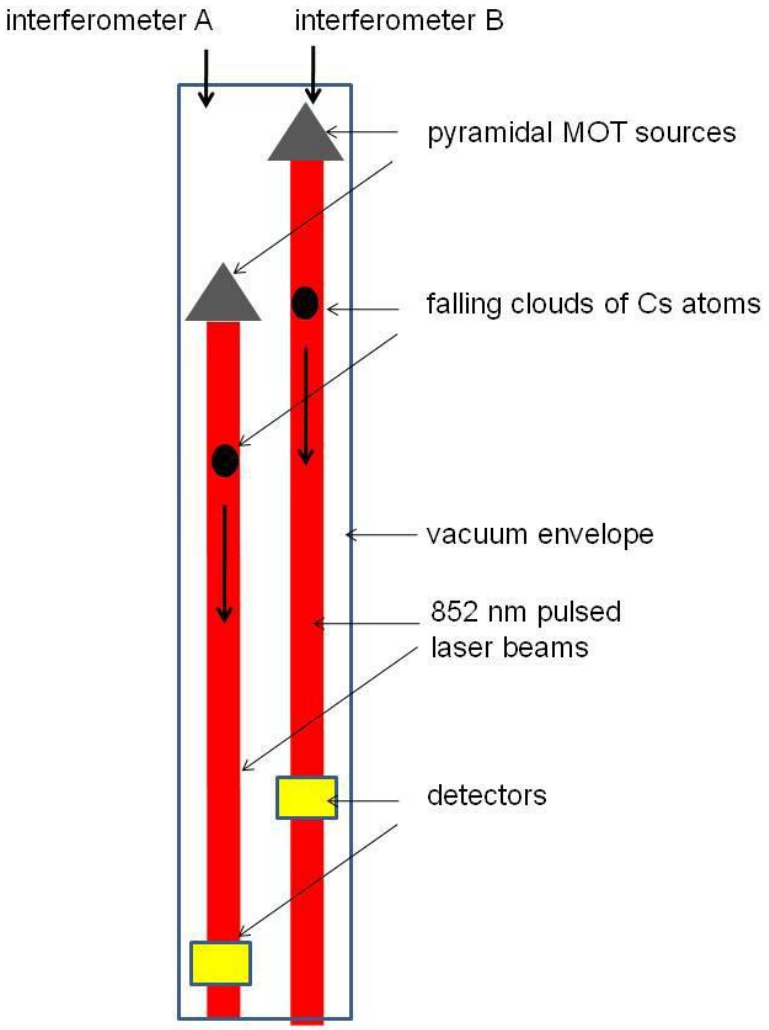


Raman Pulses



- Want the atoms in stable states – oscillate between the two spin states of ground state.
- Need laser light of two frequencies, with frequency difference equal to required transition.
- Think of 2 photon transition via virtual state.

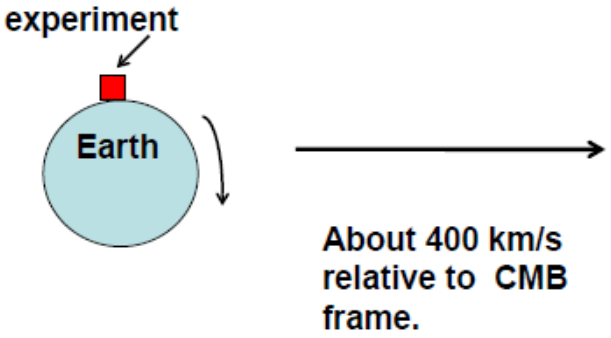
Experimental Configuration



- To cancel systematic effects:
- Incorporate two interferometers in one vacuum envelope,
  - reduce problems from common mode noises such as vibrations.
  - drop sources for simplicity.
- Sources are staggered vertically,
  - total phase change for each atom is measured during the same velocity period.

NATURE OF THE SOUGHT SIGNAL

- We do not record $\Delta\phi$ which will average to zero, we record the root mean square $\Delta\phi$ rms. We can then determine the dark energy equivalent acceleration, g_{DE}.
- We expect to be able to detect the dark energy equivalent acceleration, g_{DE} with a precision of $\rightarrow 10^{-15}$ m/s^2.



Apparatus sampling rate is of the order of Hertz.

Hence the dark energy signal is a noise signal.

Improving Sensitivity

- A crucial factor in the sensitivity of the experiment depends upon having a large phase shift ϕ where

$$\phi = \text{constant } (gT^2)$$

- Here g is the acceleration of gravity and T is the time it takes for the atom cloud to fall from the source at the top to the detector at the bottom of the interferometer.
- In the apparatus under construction the fall height, h, is 1 m and f is about 107 radians.
- Since T^2 is proportional to h, f is proportional to h. if h = 10 m would give 10 times the present f, in principle the higher the better.
- Daresbury tower, is ~100 m high, benefits of exploiting this structure are obvious.

Progress

- The construction of two symbiotic experiments, began about one year ago using:
  - start-up funds from the President's Office of Stanford University.
  - Seed-corn funding and technical support from particle physics group @ U. of Liverpool, and the Cockcroft Institute, UK.