UNIVERSITY OF LIVERPOOL

Interplay between Particle & Astroparticle physics 2014

An Experiment for Direct Detection of Dark Energy

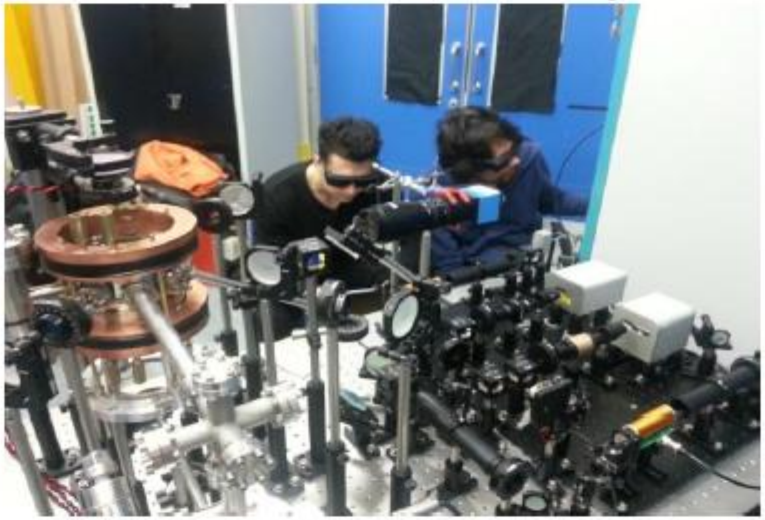
Jonathon Coleman

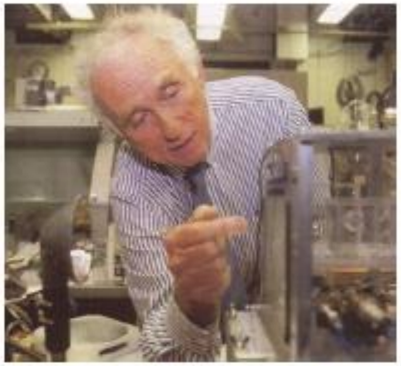
Royal Society Research Fellow

THE ROYAL SOCIETY

Ultra Cold Atom Interferometry

Developing Next Generation Gravity Sensors & Gyroscopes for Direct Dark Energy Detection and Fundamental Physics





Work in Collaboration with Martin Perl (Nobel Laureate, visiting professor @ U. Of Liverpool)

Particle Physics Proto-Collaboration:

UNIVERSITY OF LIVERPOOL

UNM

TRINITY UNIVERSITY

The Cockcroft Institute of Accelerator Science and Technology

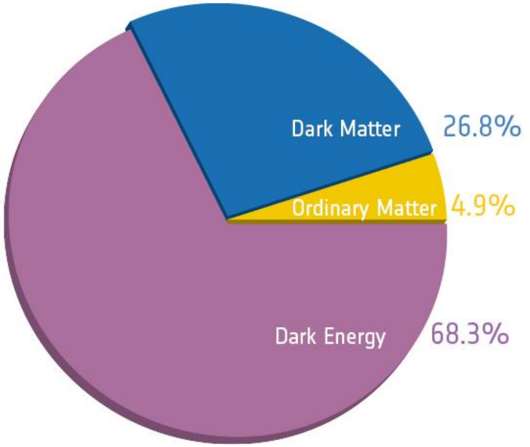
Introduction

- Motivate a parameter space search for direct detection of the dark contents of the vacuum
- Introduce the concept of atom interferometry
- Construction of the prototype at Liverpool
- Future Upgrade Scenarios

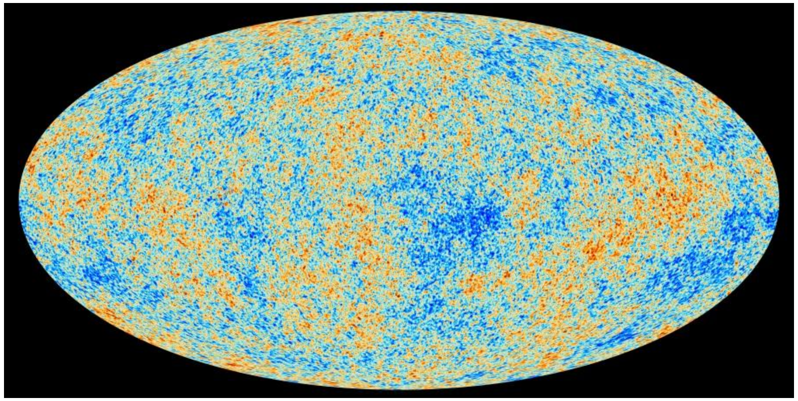
M. Perl et al, A terrestrial search for dark contents of the vacuum, such as dark energy, using atom interferometry
arXiv:1101.5626

Nature of Dark Energy

- Cosmological observations indicate 68% of the universe is dark energy.
- Present theory offers no fundamental understanding of the nature of dark energy
- Dark energy has a small but non-zero density $1.67\text{x}10^{-27}$ kg m^{-3}. Is this measureable on a terrestrial scale?



Planck Results
arXiv:1303.5062



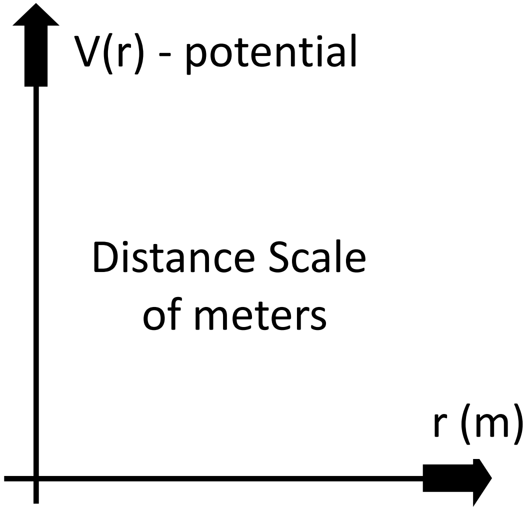
Conditions of Detection

An experiment to investigate the effect of Gravity on quantum systems.

Allows for the **Direct Detection** of Dark Energy **if**:

- Vacuum fluctuations are spatially inhomogeneous on the lab scale.
- The vacuum interacts with atoms in a non gravitational way.

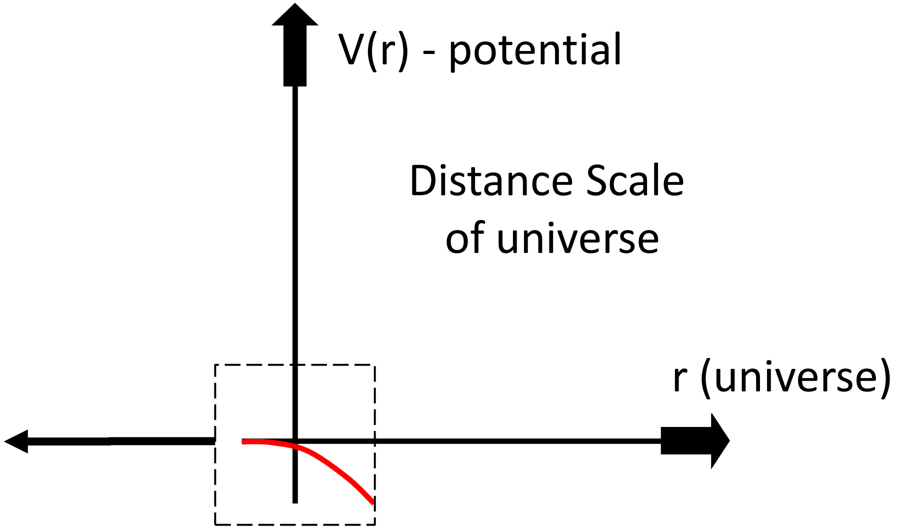
Theory with Caveats:



V(r) - potential

Distance Scale of meters

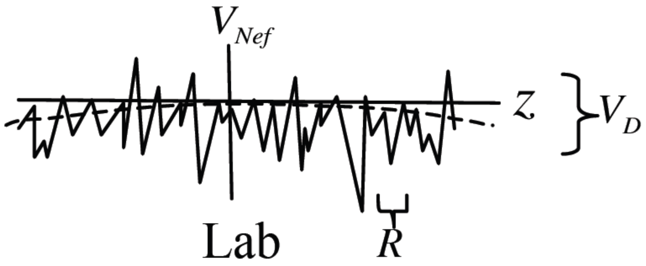
r (m)

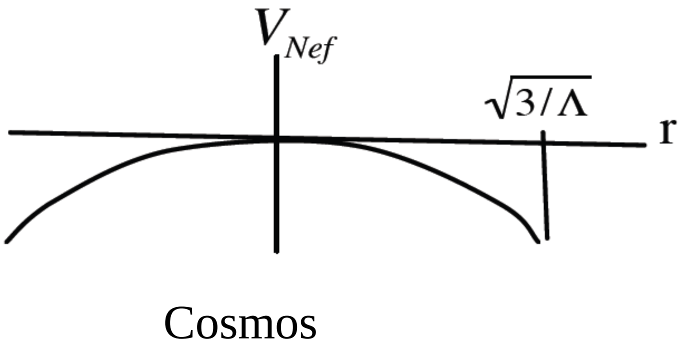


V(r) - potential

Distance Scale of universe

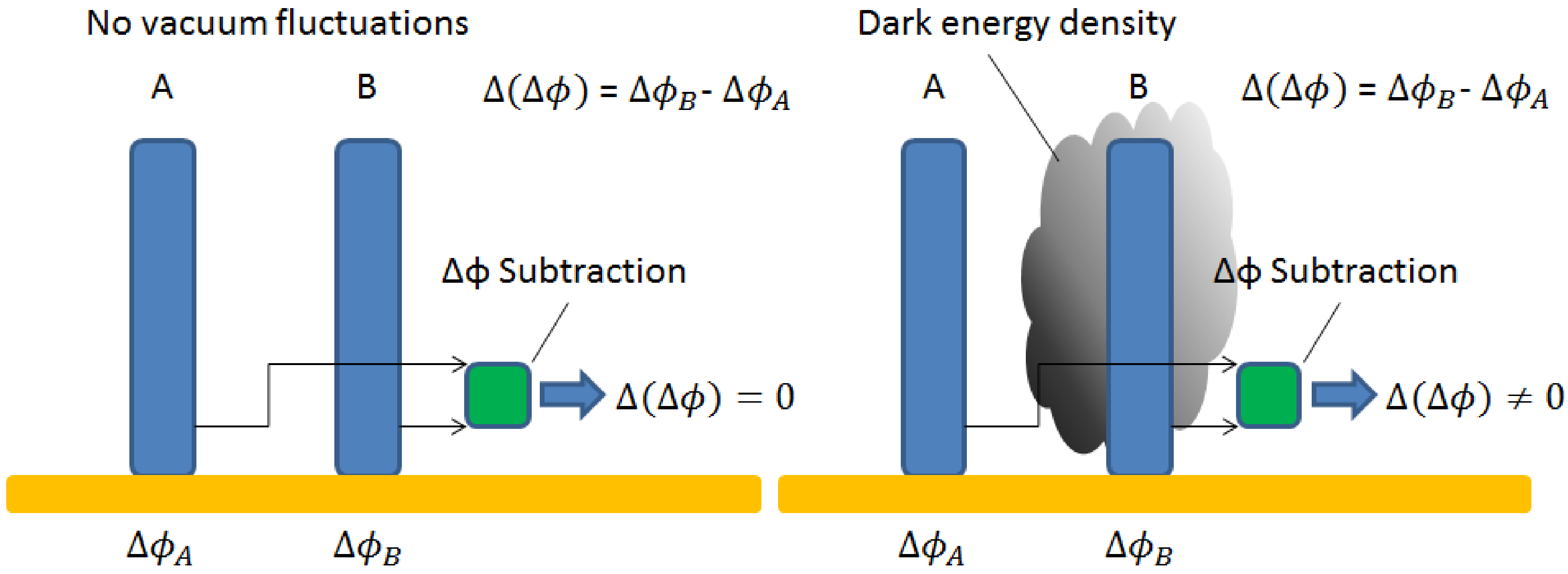
r (universe)





Dark Energy Potential

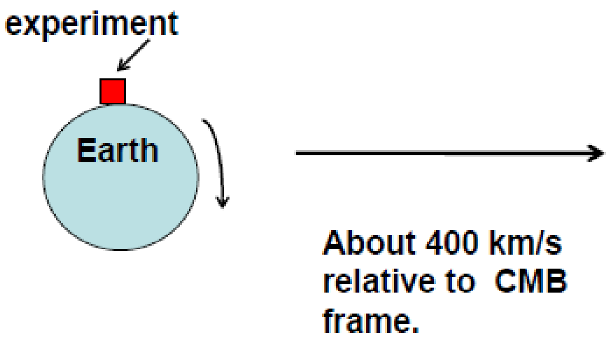
Experimental Concept



- Two spatially separated interferometers in the same noise conditions.
- System is designed to minimize/ eliminate the effects of gravity and many other sources of noise

Nature of Measurement

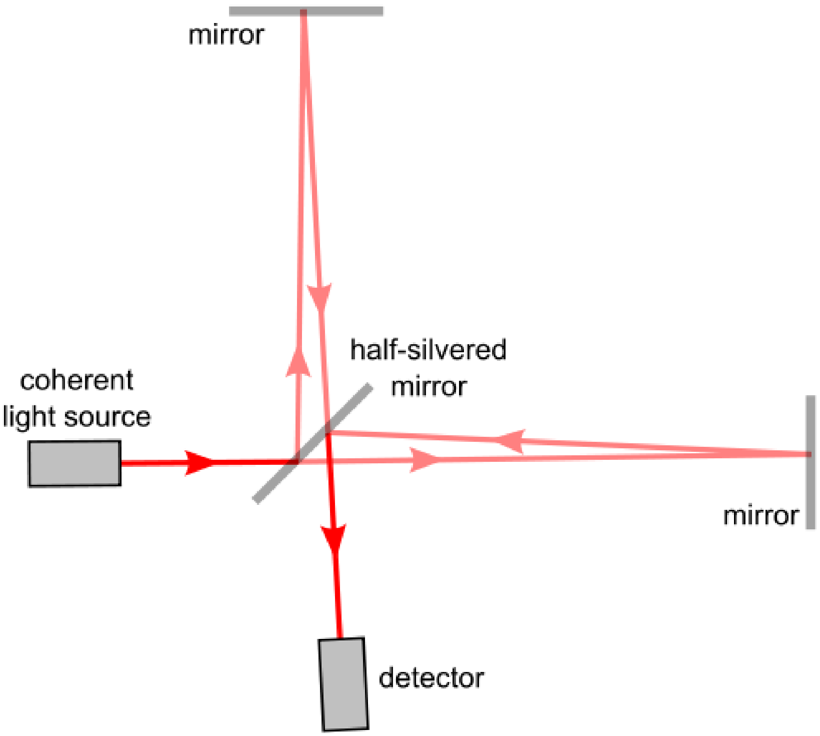
- not recording $\Delta\phi$ which will average to zero,
- measure instead the root mean square $\Delta\phi$ rms.
- can then determine the dark energy equivalent acceleration, g_{DE}.
- We expect to be able to detect the dark energy equivalent acceleration, g_{DE} with a precision of →10^{-15} m/s^2.



- sampling rate - order of Hertz.
- Hence signal is a noise like.

Analogy with Light Interferometer

- 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 change in path.

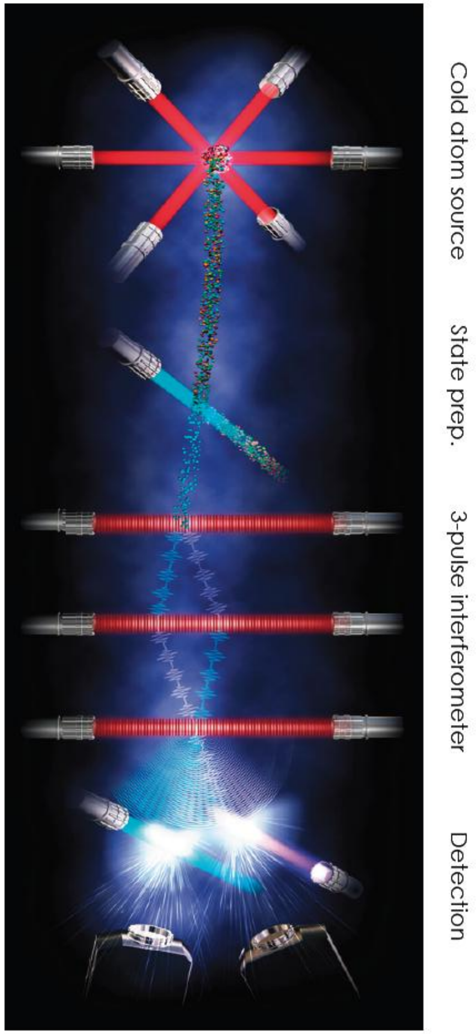


Why Atoms?

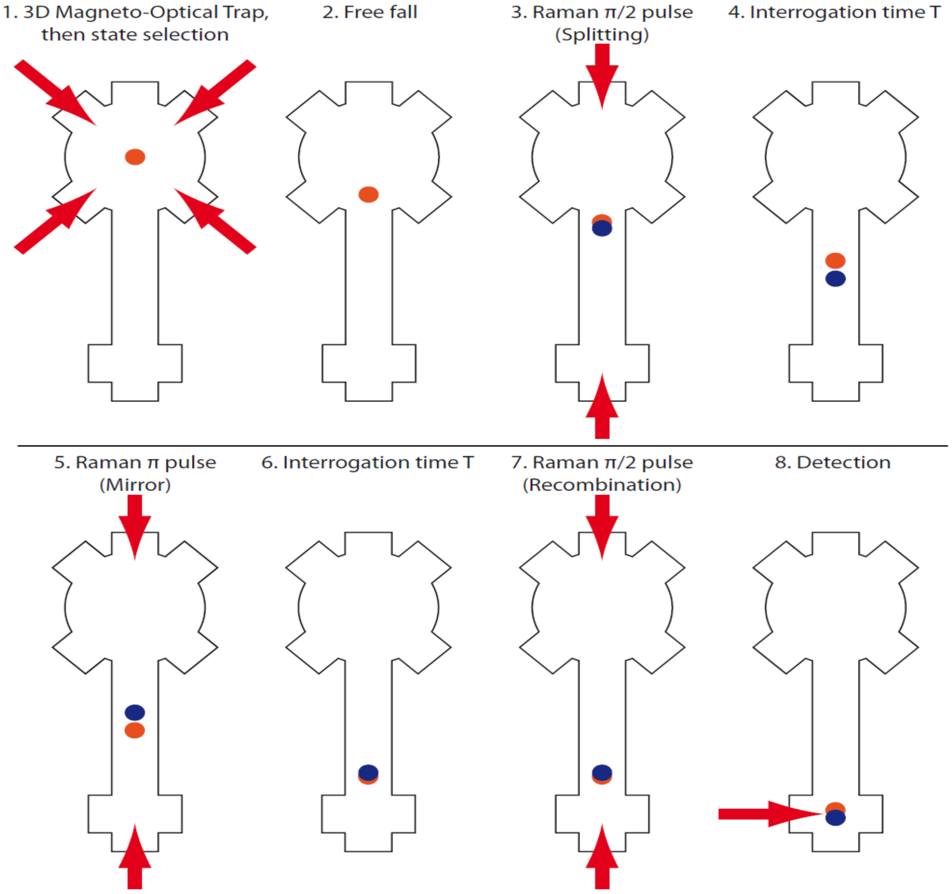
- Smaller wavelengths lead to a higher accuracy.
- Atoms have a wavelength $\lambda = h/p$

Atom Interferometer Overview

- Magneto optical trap (MOT) sources cold atom cloud.
- Atoms form optical molasses and dropped.
- Selects atoms in magnetically insensitive state and a narrower range of velocities.
- Interferometry splits the atom cloud, allow phase to accumulate and recombine cloud.
- Detect ratio of atoms in different states at bottom – related to phase difference.



Interferometry sequence



Phase Accumulation

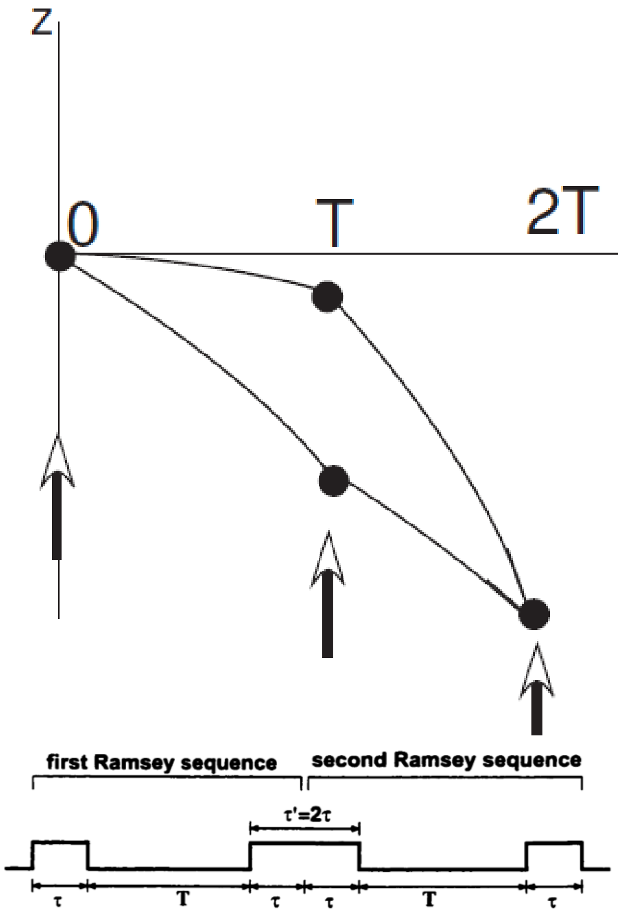
- Three components contribute to atoms phase.
- Phase is accumulated in free fall.

Systematics

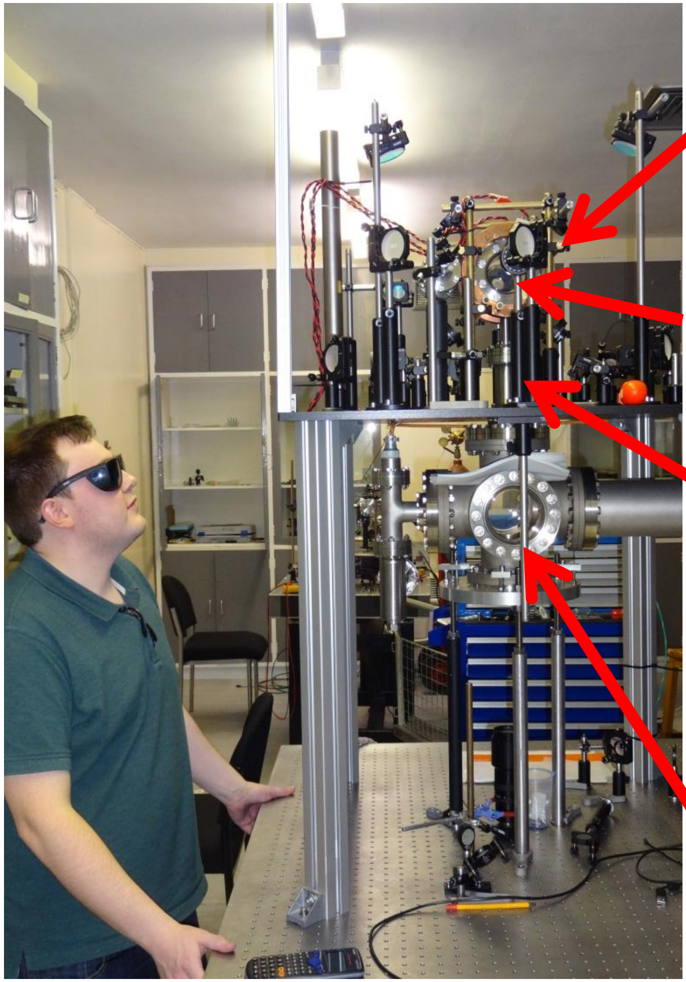
- Laser phase is printed on the atoms with ‘beamsplitters’ or ‘mirrors’
- A phase is associated with the atoms not quite recombining for detection.

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$

Classical trajectories of atoms in the drop experiment.



Atom Interferometer at Liverpool

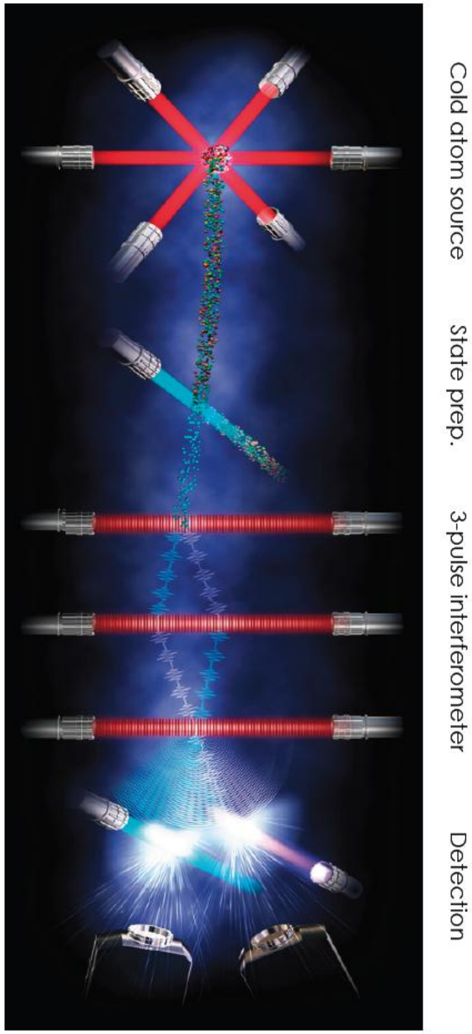


Ultra-cold atom source.

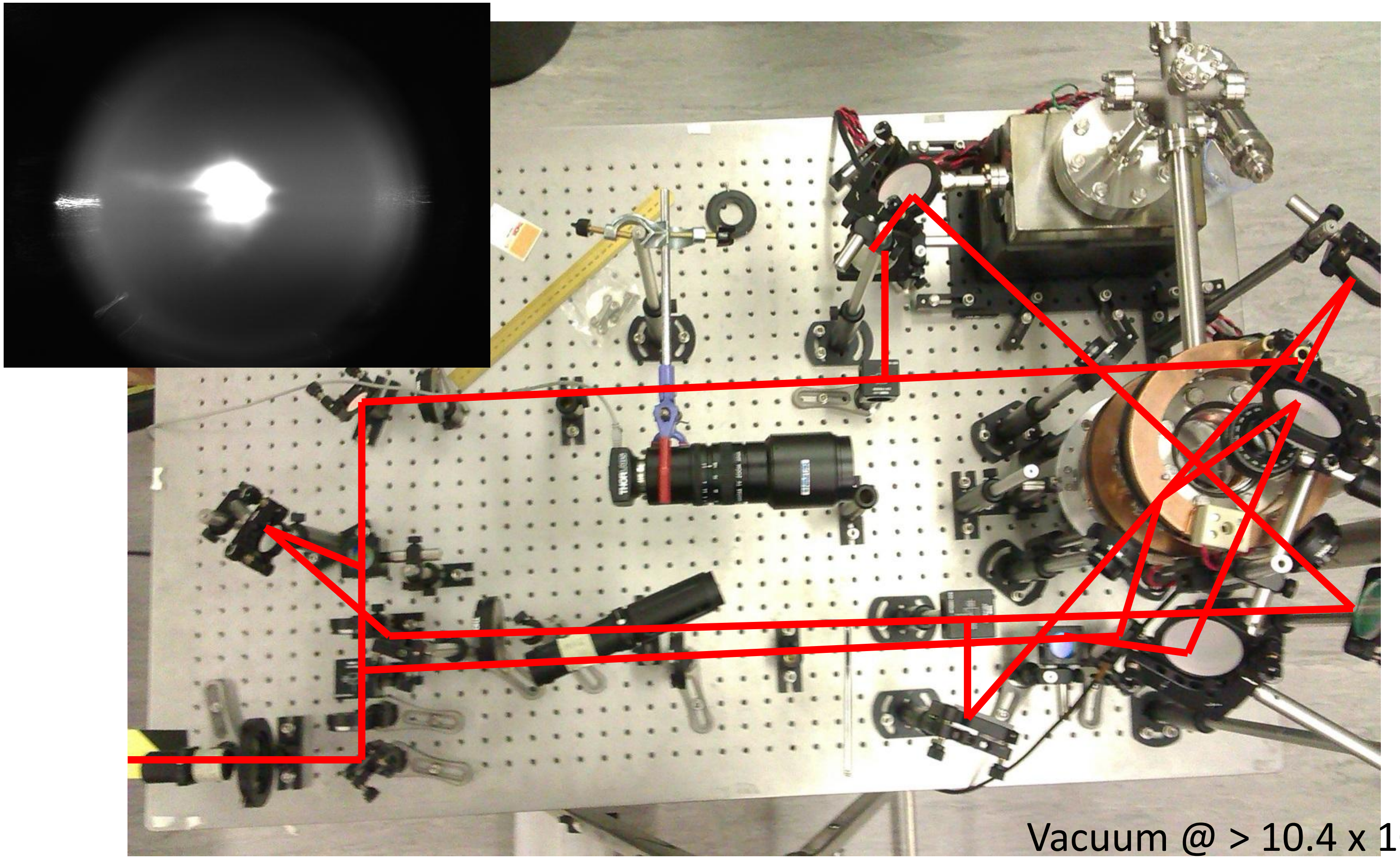
State selection

Light pulse interferometry region

Detection.



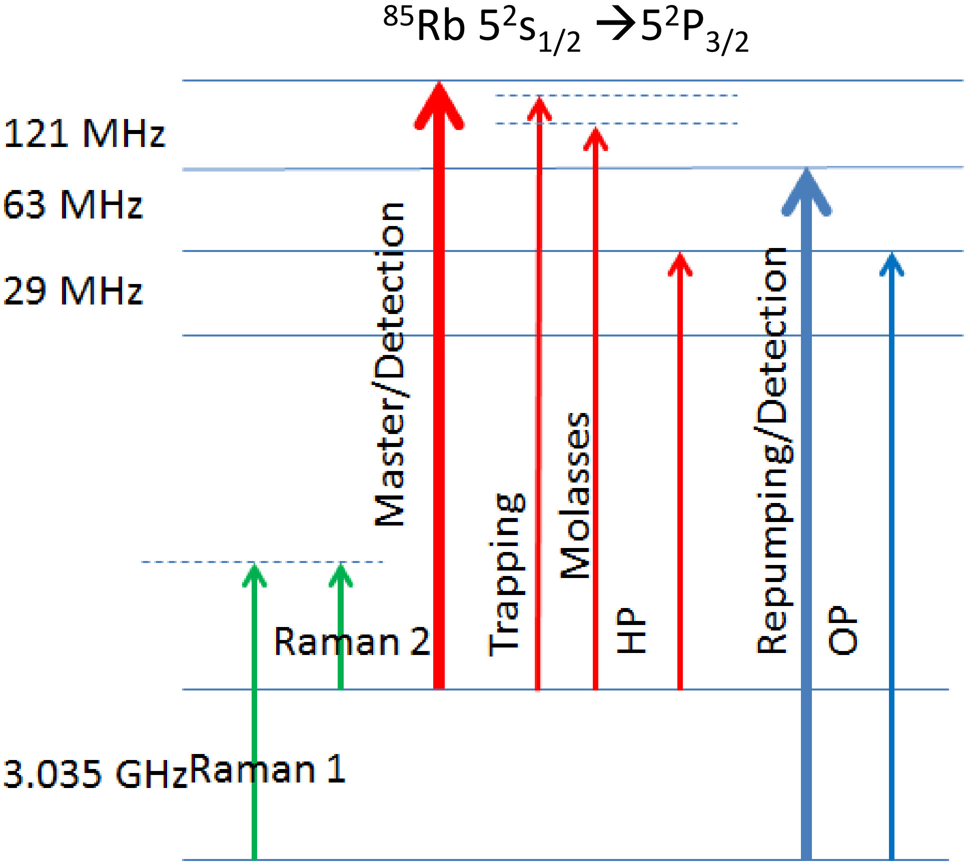
3D Atom Trap - Interferometer Source



Vacuum @ > 10.4 x 10^{-10} mbar

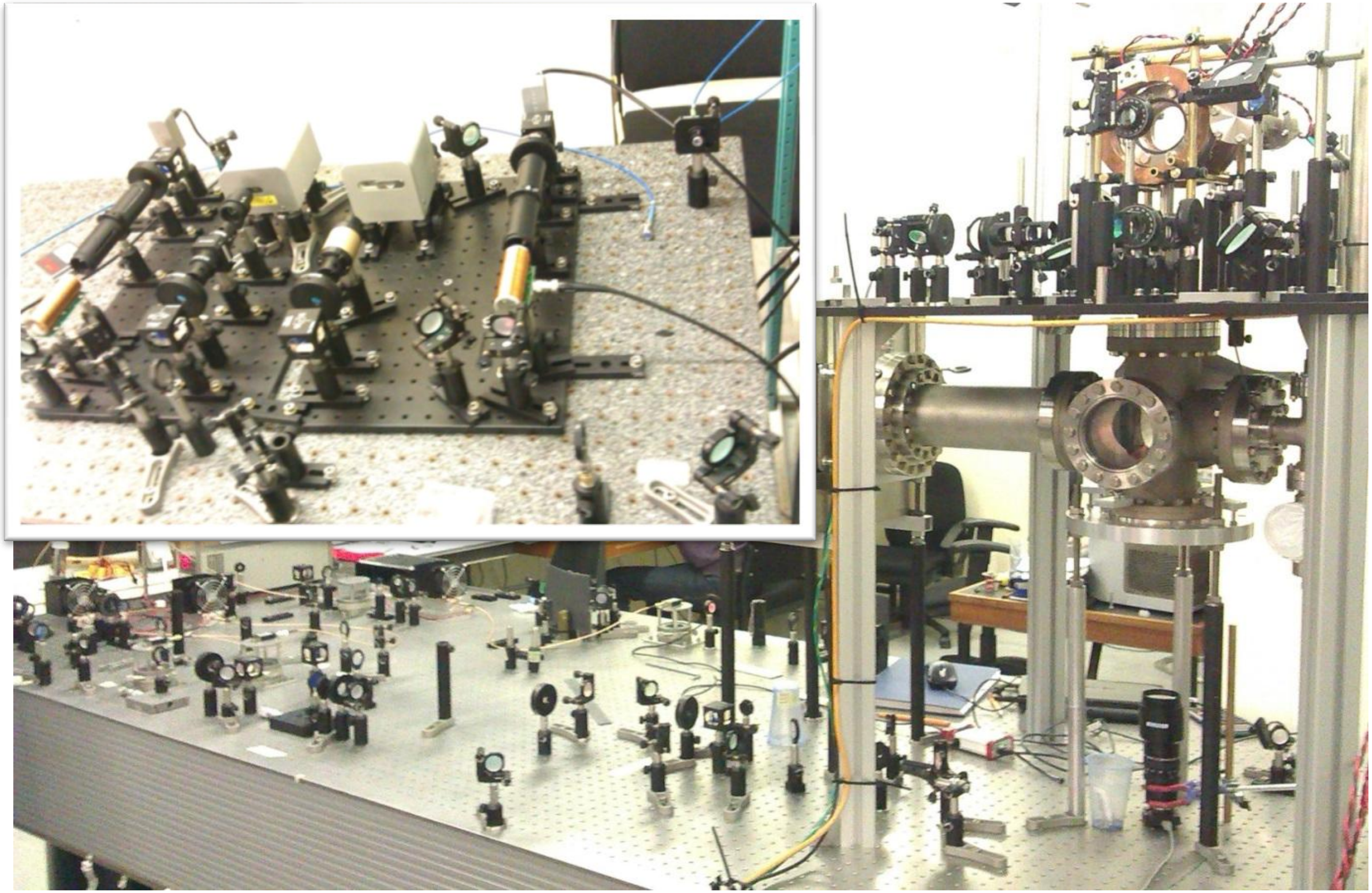
Frequency Control System

- Many different frequencies required for the atom interferometer.
- Optical circuit generates all required frequencies from extended cavity diode lasers (ECDL) and acousto-optical modulators (AOM).



Required transitions for atom interferometer transitions

Frequency generation and detection sequence components currently being commissioned and optimised



Improving Sensitivity

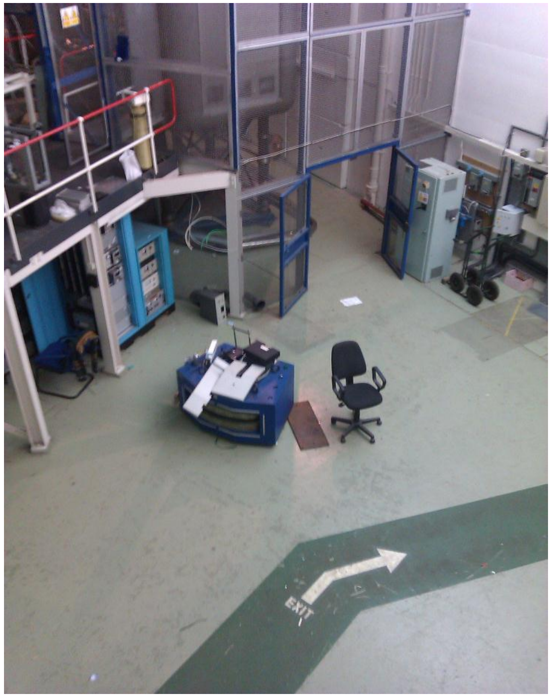
- depends upon having large phase shift ϕ:

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

- T is time of flight for the atom cloud
- Prototype under construction height ~ 1 m and ϕ ~107 radians
- T^2 is proportional to h,
- h = 10 m, approx 10 x improvement in ϕ,
- Daresbury tower ~ 100 m
- benefits of exploiting this structure are obvious.

Possible Site Location

- Highly stable bedrock as foundations of Tower structure
- 8 m high previous Medium Energy Ion Source (MEIS) room ?



The Future?

- 10 m Atom Interferometers are being developed worldwide
- Daresbury Tower is ideal for this

Center for Cold *Atom* Physics,
Chinese Academy of Sciences, Wuhan

Stanford, USA

Roadmap

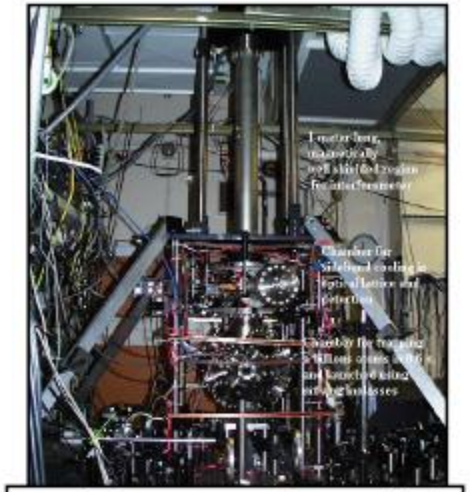
- Key Milestones Identified
- Manufacture & Cost Identified for Core Components
- Collaboration gaining critical Mass

Summary

- An Experiment to Investigate the Dark Content of the Vacuum
- Possible signature for Direct Detection of Dark Energy
- Investigating a new area of experiment
    - Unexplored phase space
- Rich area of Physics Measurements
- A possible future use of the tower
- **New Collaborators are Welcome**

Backup slides

State of Art: AI Gravimeters + Gradiometers

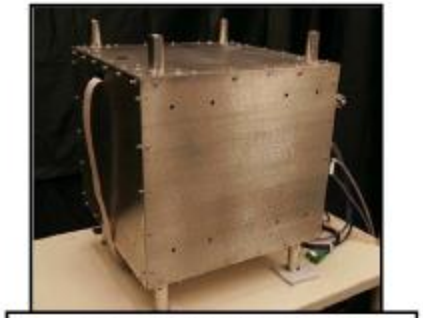


Stanford Gravimeter (non-mobile)

Achieved Accuracy: $4 \cdot 10^{-9}$ g (?)

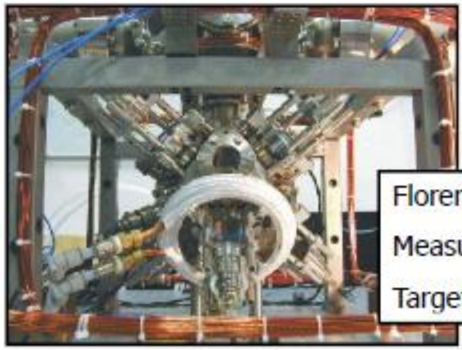
Paris Gravimeter („mobile")

Achieved Accuracy: $4 \cdot 10^{-9}$ g



Kasevich Gravimeter (mobile)

Bias Stability: $< 10^{-10}$ g



Florenz INFN Gravity Gradiometer MAGIA

Measurement of the gravitational constant G

Targeted Accuracy: $\Delta G/G \; 1 \cdot 10^{-4}$

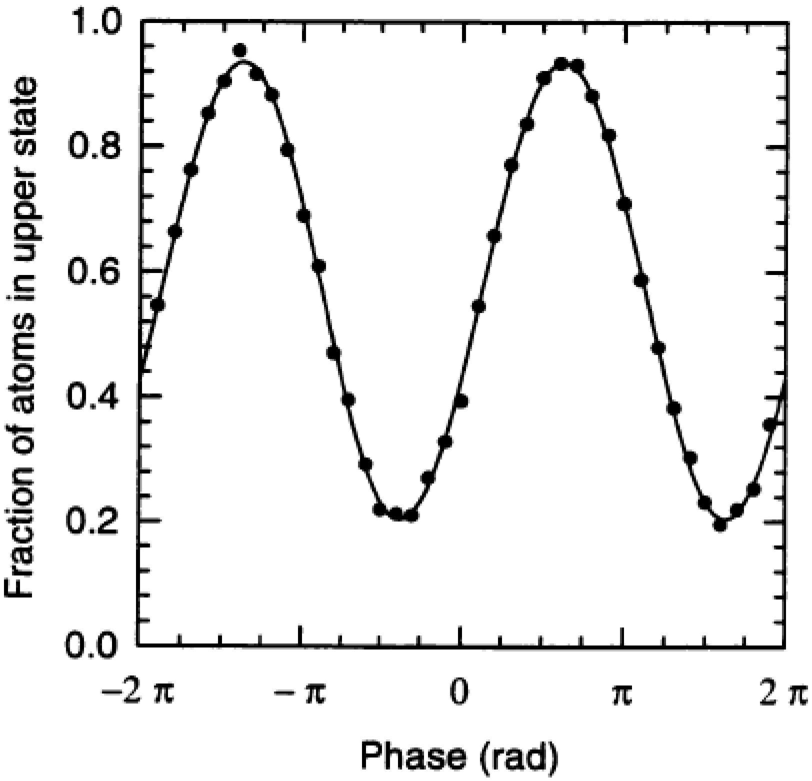
Berlin Gravimeter GAIN

(mobile, under construction)

Targeted Accuracy: $5 \cdot 10^{-10}$ g

Measuring gravity as a Benchmark

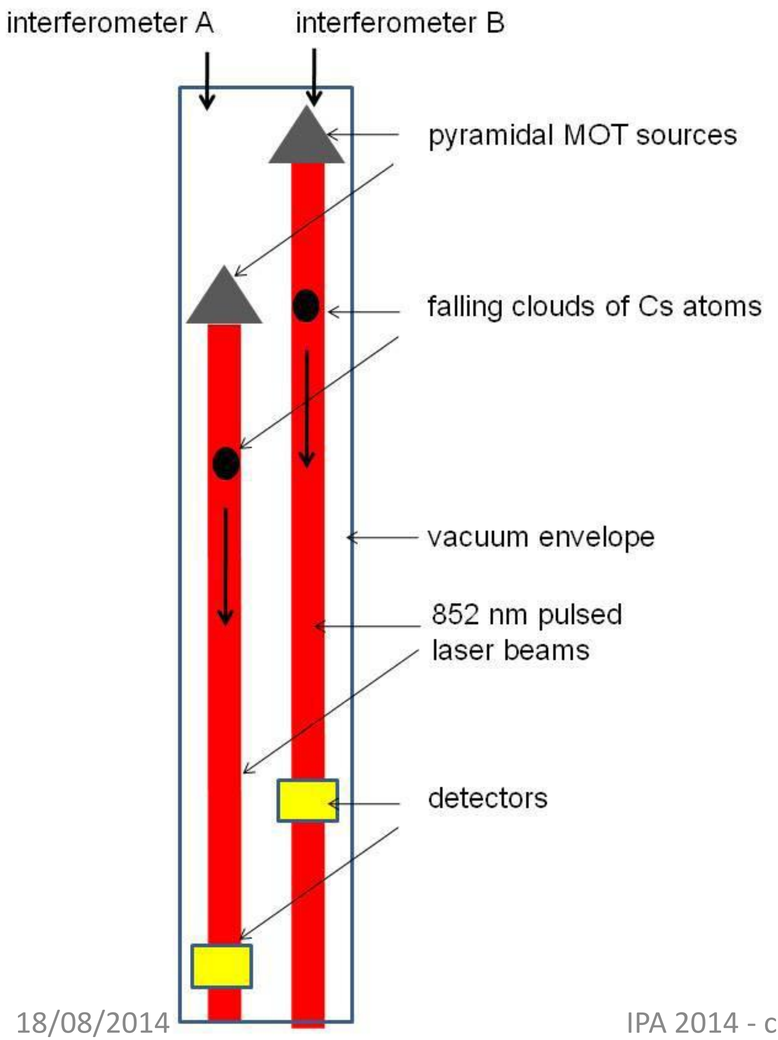
- Laser frequencies need chirping to account for the Doppler shift of atoms.
- Varying chirping scans the interferometer fringes, which can be fit to obtain value of g.



A. Peters et al

doi:10.1088/0026-1394/38/1/4

Experimental Configuration



To cancel systematic effects:

- Incorporate the 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.