

Chameleon theory

Dark energy:

- Makes up over two-thirds of our universe,
- Seems to be driving the expansion of the universe on large scales,
- Doesn't seem to have any effect near the Earth.

One solution for this is a so-called 'chameleon' field:

- A dynamic scalar field which is suppressed in regions of high matter density.
 - * So we cannot detect it on or near the Earth.
 - * However, can take a much higher value in the vacuum of space.

We can describe the non-relativistic steady-state of such a field by¹

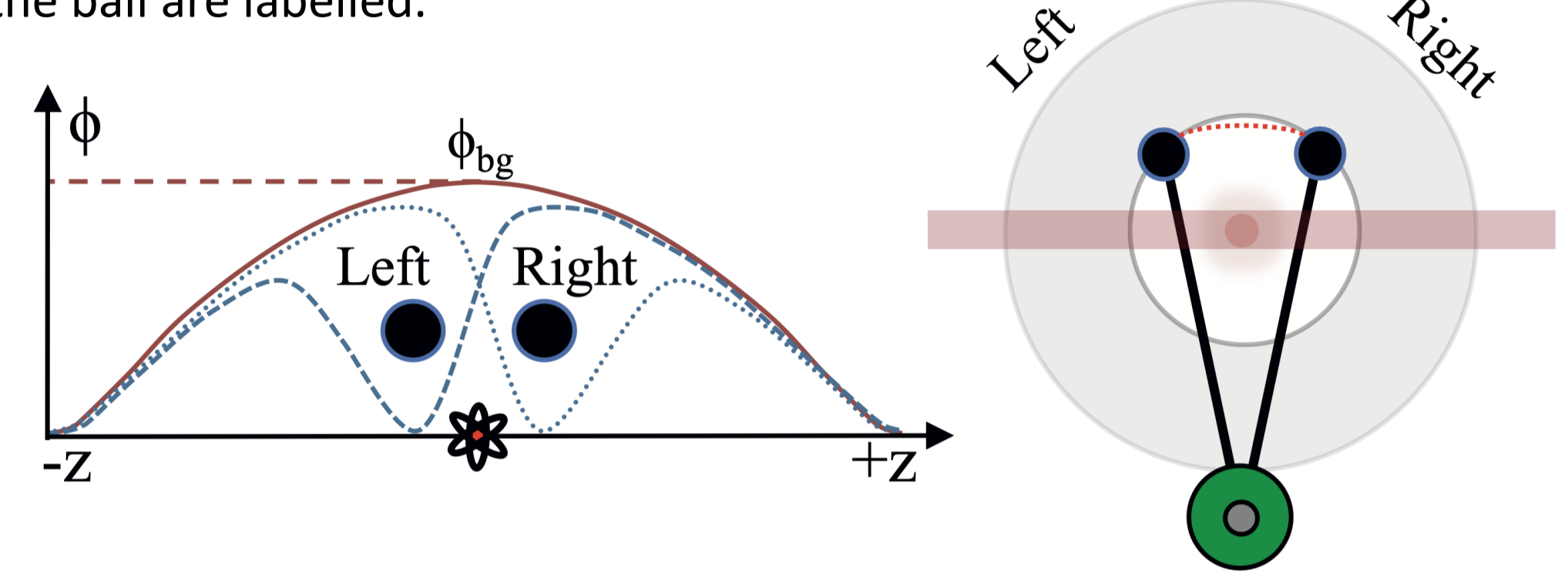
$$\nabla^2 \phi = -\frac{\Lambda^5}{\phi^2} + \frac{\rho}{M}$$

- * Λ is the strength of the self-interaction
- * ρ is the local matter density
- * M is the coupling between chameleons and 'normal' matter.

- The chameleon field ϕ is large in a vacuum, however very small near mass.
- This means that, in a vacuum chamber, the chameleon field ϕ will be:
 - * At its maximum ϕ_{bg} in the centre of the vacuum chamber,
 - * Near zero at the walls of the chamber
- If we place an aluminium ball *inside* the vacuum chamber, then it will perturb ϕ , reducing it to near zero on the surface of the ball.

Experimental concept

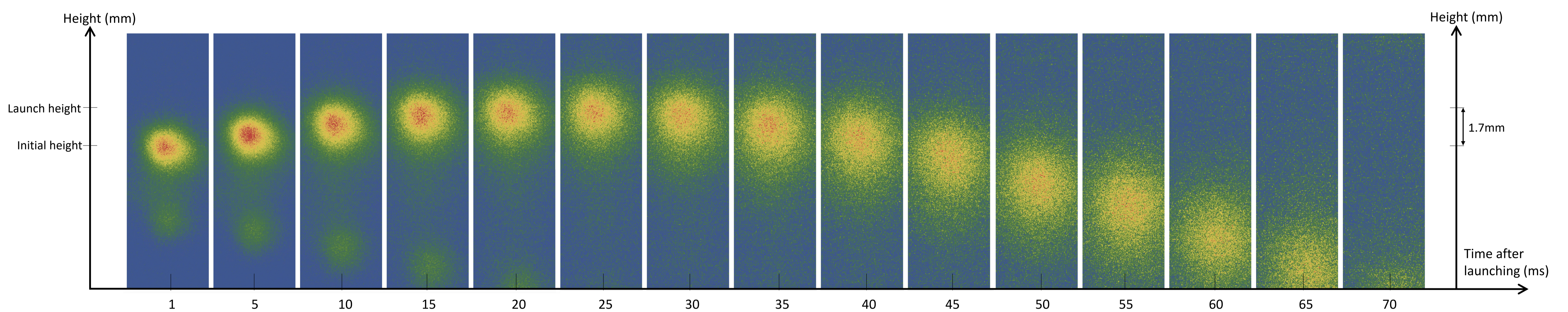
- By shifting where in the vacuum chamber the ball is located, we can shift the perturbation in ϕ from the ball, as is illustrated below.
 - * 'Left' and 'Right' refer to the two potential positions for the ball.
 - * The left image shows the chameleon field inside the vacuum chamber; at zero at the walls of the chamber ($\pm z$), at a maximum where the atoms are positioned in the centre.
 - * The right image is a depiction of the set up as seen from above – the grey disc shows the walls of the vacuum chamber with a hazy atom cloud in the centre, and the two positions of the ball are labelled.



- The gradient of ϕ induced by the ball results in a small acceleration towards the ball, a_ϕ .
- What we actually measure is the phase φ , which is related to the acceleration of the atoms by

$$\varphi = 2 \mathbf{k} \cdot \mathbf{a} T^2$$
- By measuring φ for different positions of the ball we can see if this acceleration a changes, thus whether there is any sign of a changing gradient of ϕ .

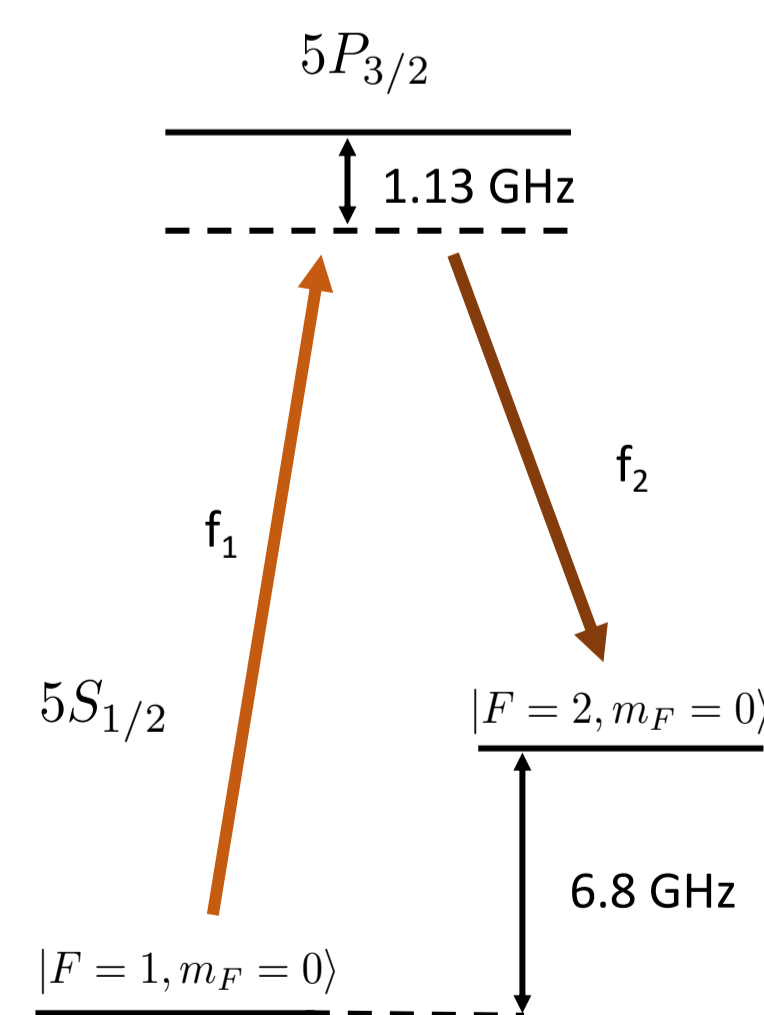
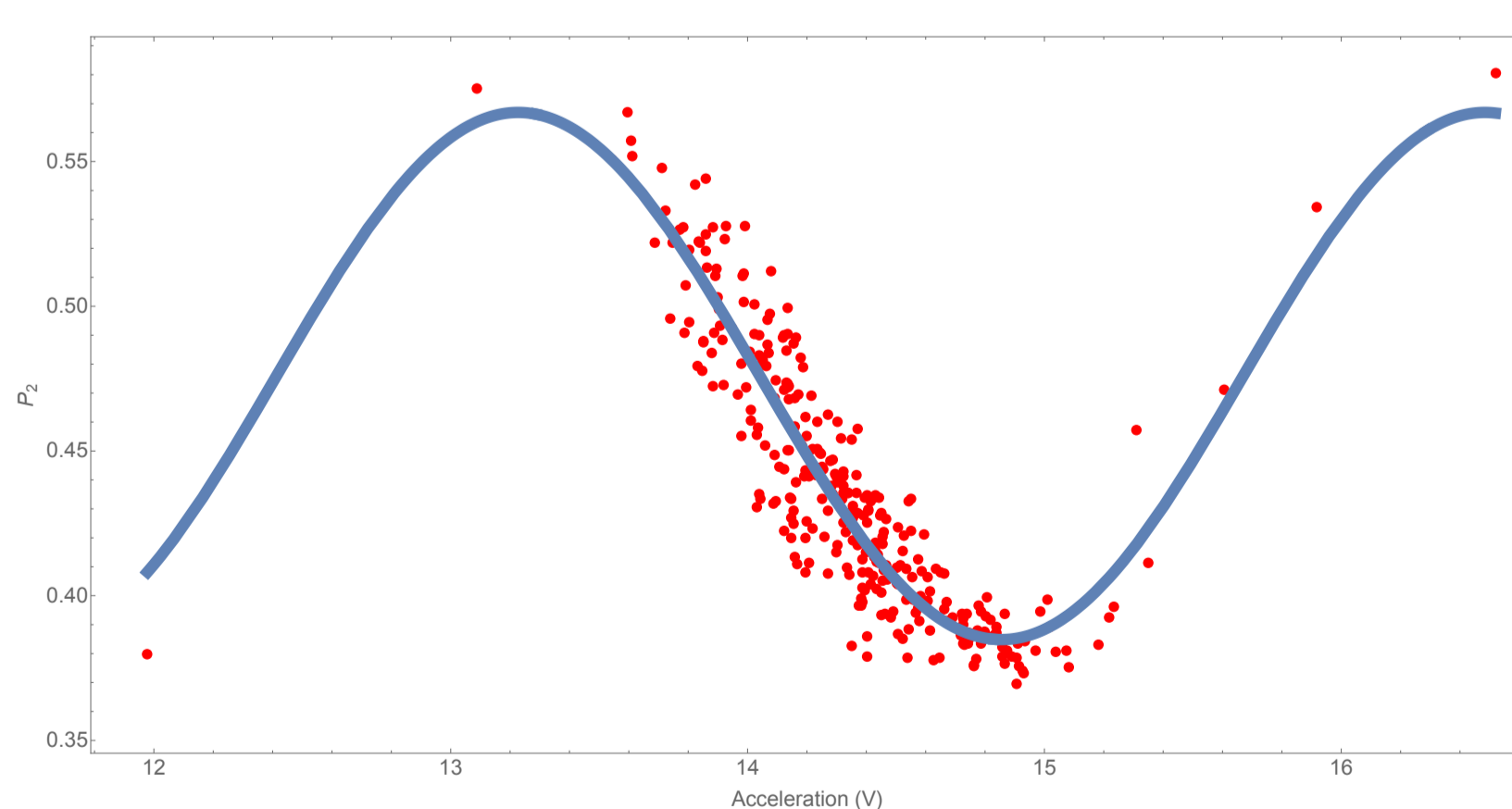
Launching atoms



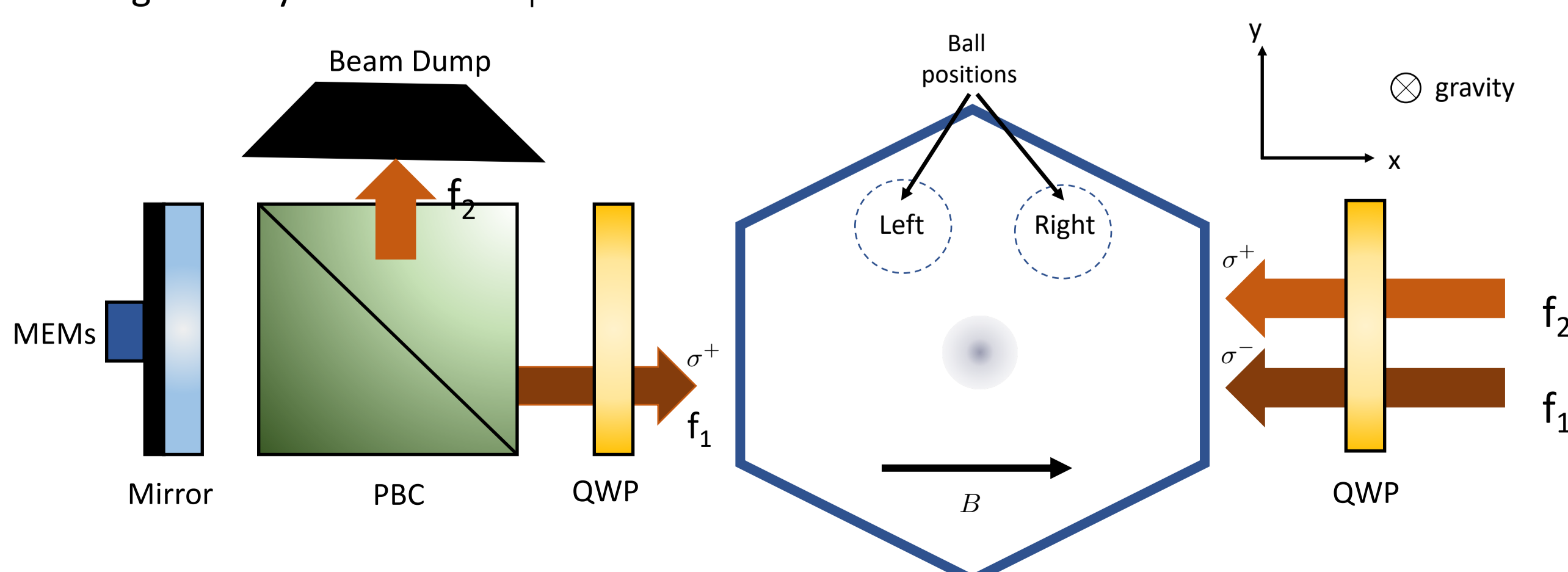
- Our interferometer scheme is a three-pulse Mach-Zehnder interferometer
 - * The first pulse that puts the atoms into a superposition of two states, the second pulse that swaps their states, and the final pulse recombines the wavepackets.
 - * We measure the relative number of atoms in the upper state vs the lower state after the interferometer, and use this to find the phase.
- The atoms are in free-fall between the first/second, and then second/third pulses. This is the T in the equation above.
 - * The phase depends on the square of this free-fall time, and so increasing it is an obvious way of increasing your sensitivity.
- In order to measure the state of the atoms at the end, the atoms must be visible to our photodiode. In a free-fall configuration, our atoms fall outside the detection region after 32ms.
- However, by launching the atoms, we can effectively double the distance available for the atoms to travel, doubling the free-fall time, quadrupling the potential sensitivity.

Experimental setup

- We use Rubidium-87 atoms, specifically measuring the difference in populations between the $5S_{1/2}$ F=1 and F=2 hyperfine states.
- To move between the two levels we use Raman light, with the $5P_{3/2}$ as our intermediate state, as shown in the graphic to the right.
- We measure the population of the F=2 state (P_2), and plot it against the acceleration (as a voltage) measured by a classical accelerometer (MEMs) stuck on the back of the Raman mirror and build up a fringe. (example shown underneath.)



- At the bottom is a schematic³ showing our Raman optics system, showing the polarisation of the two Raman beams. We are assuming that all our atoms start in F=1 in the magnetically insensitive $m_F=0$ state.



Improvements

- There have been a number of improvements made to the experiment since the 2019 acceleration measurement of $a_\phi = -77 \pm 201 \text{ nm/s}^2$.
- Here are some major ones, with their values and estimated impact recorded in the table.
 - * Number of atoms loaded per second
 - * Interferometer contrast, calculated by

$$\frac{\mathcal{P}^{\max} - \mathcal{P}^{\min}}{\mathcal{P}^{\max} + \mathcal{P}^{\min}}$$
 - ▷ Where \mathcal{P} is the maximum/minimum population in the F=2 state, related to the phase difference φ by

$$\mathcal{P} = \frac{1}{2}(1 - \eta \cos(\varphi + \varphi_0))$$
 - * Phase (φ) uncertainty

	2019	2023	Est. improvement
Number of atoms per second	$\sim 10^6$	$\sim 10^8$	100 x
Interferometer contrast	21%	61%	3 x
Phase uncertainty	$\sim 220 \text{ mrad/shot}$	$\sim 50 \text{ mrad/shot}$	4 x
Overall measurement sensitivity	$\sim 60 \mu\text{m/s}^2/\sqrt{\text{Hz}}$	$\sim 4 \mu\text{m/s}^2/\sqrt{\text{Hz}}$ * projected	> 10 x

- With the projected measurement sensitivity, we would be able to reproduce the result from 2019 in **4 hours**, rather than the **49 hours** that was required then.

References

1. Burrage, C., Copeland, E. J., & Hinds, E. A. (2015). Probing dark energy with atom interferometry. *Journal of Cosmology and Astroparticle Physics*, 2015(03), 042.
2. Sabulsky, D.O., Ph.D. thesis, Imperial College, London, 2018.
3. Adapted from Peng, G., Ph.D. thesis, Imperial College, London, *in progress*.