Testing dark energy models with atom interferometry

Clare Burrage

University of Nottingham

Outline:

Dark energy and screened fifth forces

How to search for screening

Atom interferometry constraints

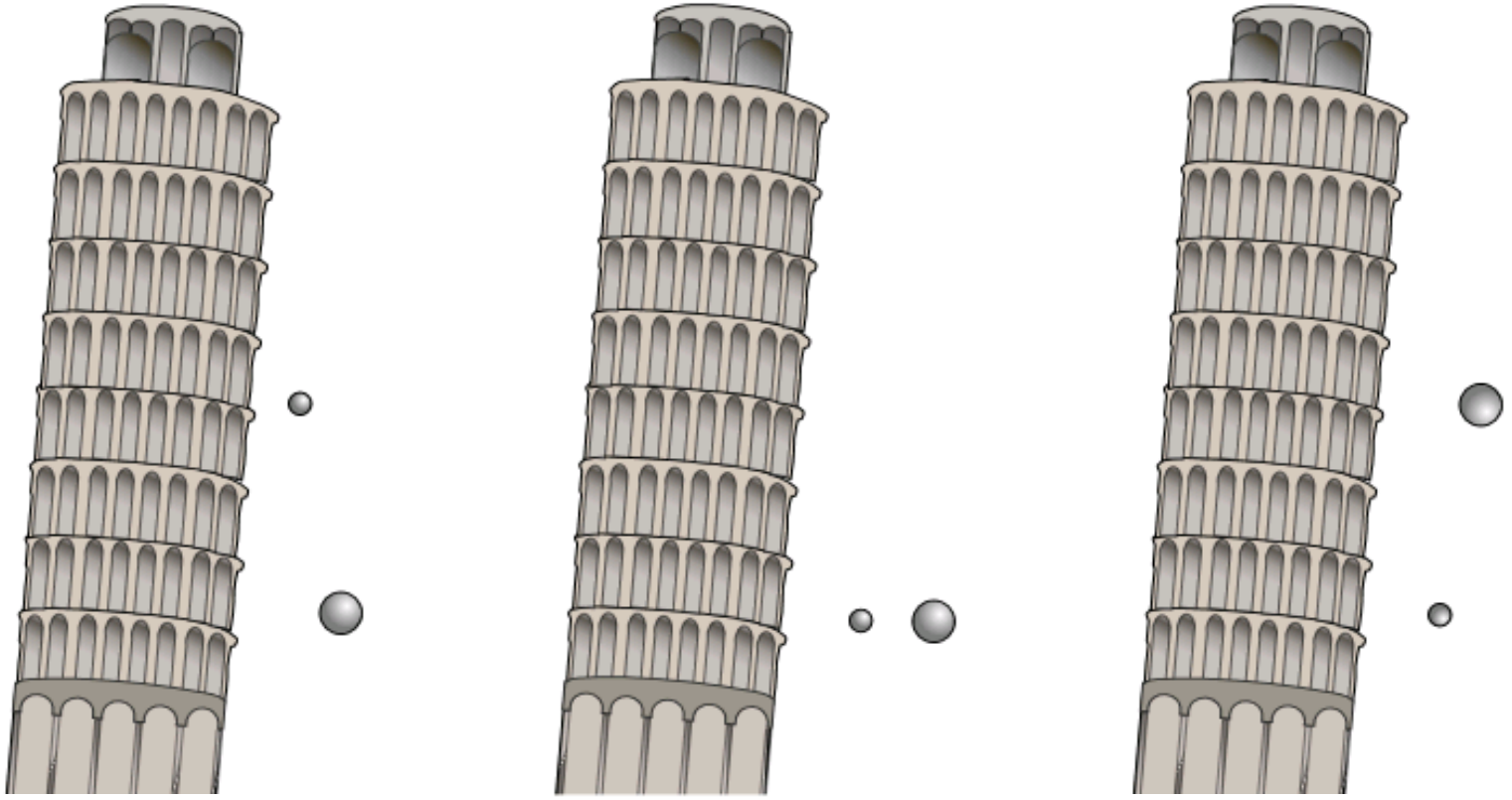
THE ROYAL SOCIETY

University of Nottingham
UK | CHINA | MALAYSIA

LEVERHULME TRUST

A Very Old Idea

Do large objects and small objects fall at the same rate?



Old idea

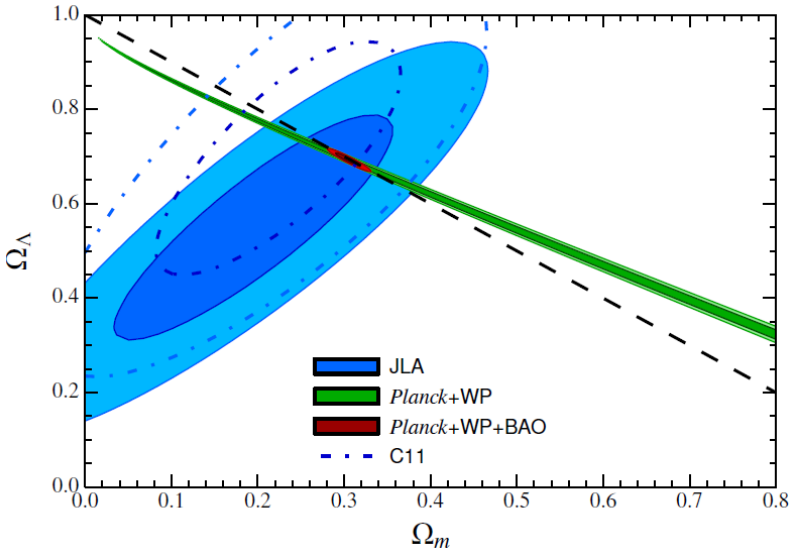
Galileo

Dark Energy?

Image credit: Theresa Knott

Dark Energy

Challenging to explain current accelerated expansion without extreme fine tuning



Possible approaches: New types of matter or new theory of gravity

New light scalars a common consequence

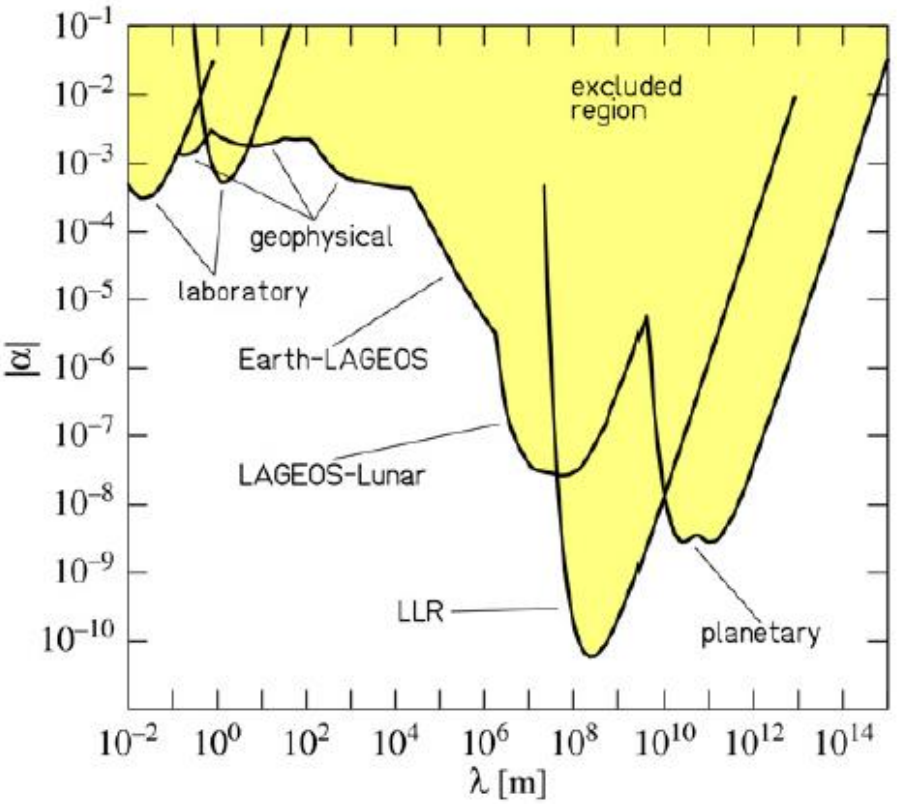
Betoule et al. 2014

New Fields and New Forces

Explanations for dark energy typically introduce new, light scalar fields conformally coupled to matter

Assuming the new physics is linear:

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$



Adelberger et al. (2009)

New Physics is Non-linear: Screening Mechanisms

- **Locally weak coupling**

Symmetron and varying dilaton models

Pietroni (2005). Olive, Pospelov (2008). Hinterbichler, Khoury (2010). Brax et al. (2011).

- **Locally large kinetic coefficient**

Vainshtein mechanism, Galileon and k-mouflage models

Vainshtein (1972). Nicolis, Rattazzi, Trincherini (2008). Babichev, Deffayet, Ziour (2009).

- **Locally large mass**

Chameleon models

Khoury, Weltman (2004).

The Chameleon

A scalar field with canonical kinetic terms, non-linear potential, and direct coupling to matter

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)\rho_\mathrm{m}\right)$$

$$V(\phi) = \frac{\Lambda^5}{\phi}, \quad A(\phi) = \frac{\phi}{M} \ ,$$

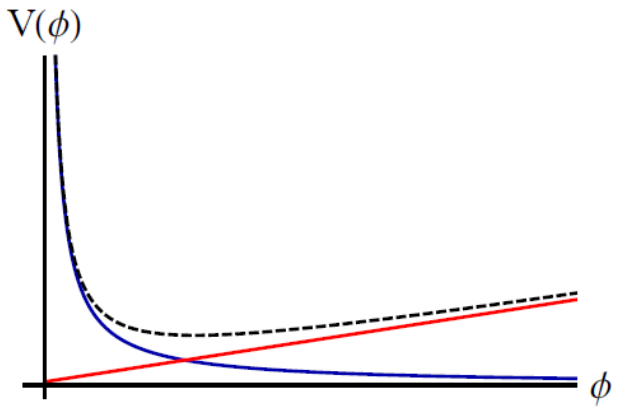
Khoury, Weltman. (2004). Image credit: Nanosanchez
Equivalent description as Higgs portal model:
CB, Copeland, Millington, Spannowsky. (2018)

Varying Mass

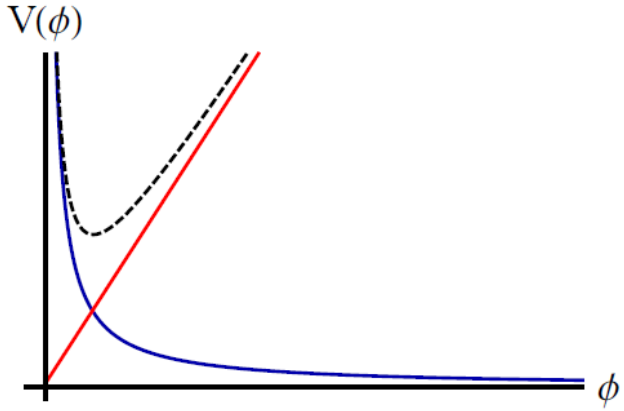
Dynamics governed by an effective potential

$$V_{\rm eff} = \frac{\Lambda^5}{\phi} + \frac{\phi}{M}\rho$$

Non-linearities in the potential mean that the mass of the field depends on the local energy density



Low density

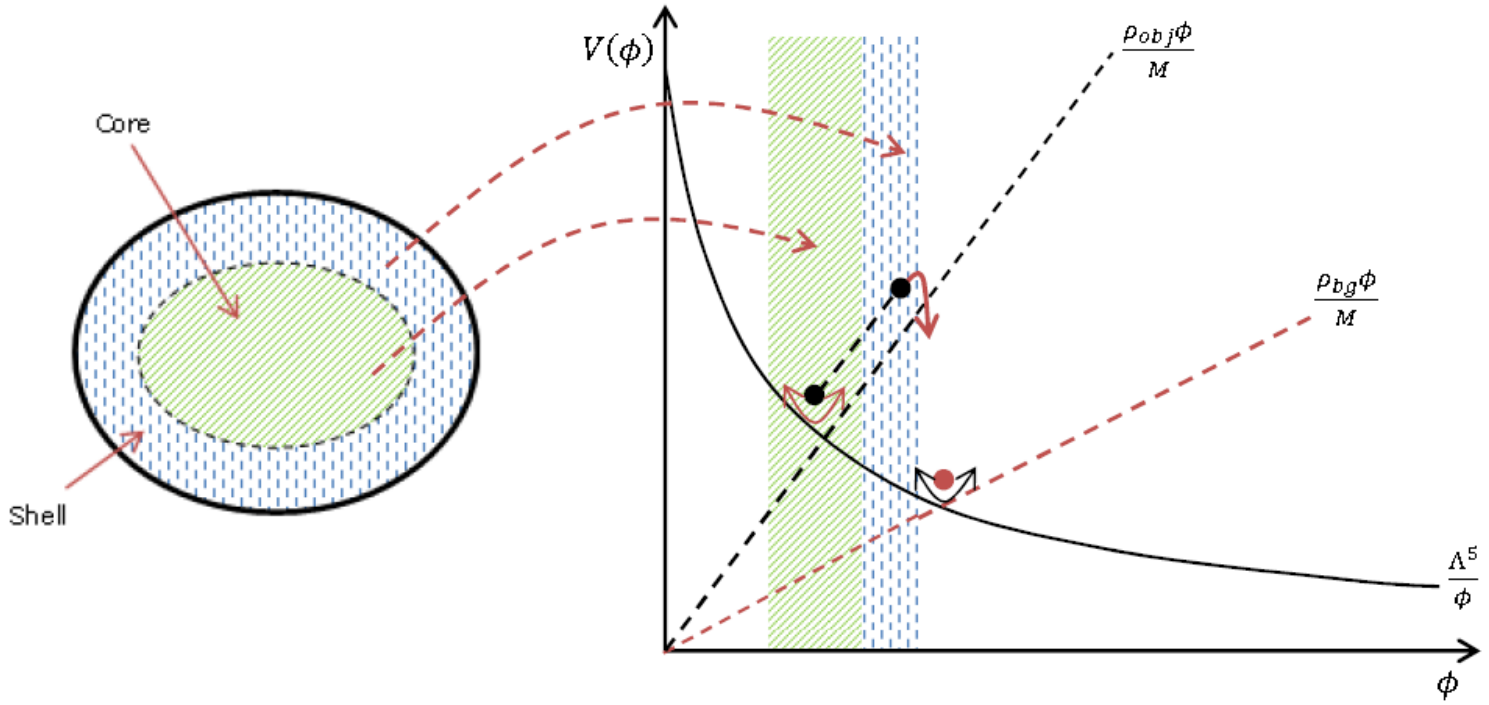


High density

Equivalent description as Higgs portal model:
CB, Copeland, Millington, Spannowsky. (2018)

Chameleon Screening

The increased mass makes it hard for the chameleon field to adjust its value



The chameleon potential well around ‘large’ objects is shallower than for canonical light scalar fields

CB, Copeland, Stevenson. (2015)

The Scalar Potential

Around a static, spherically symmetric source of constant density

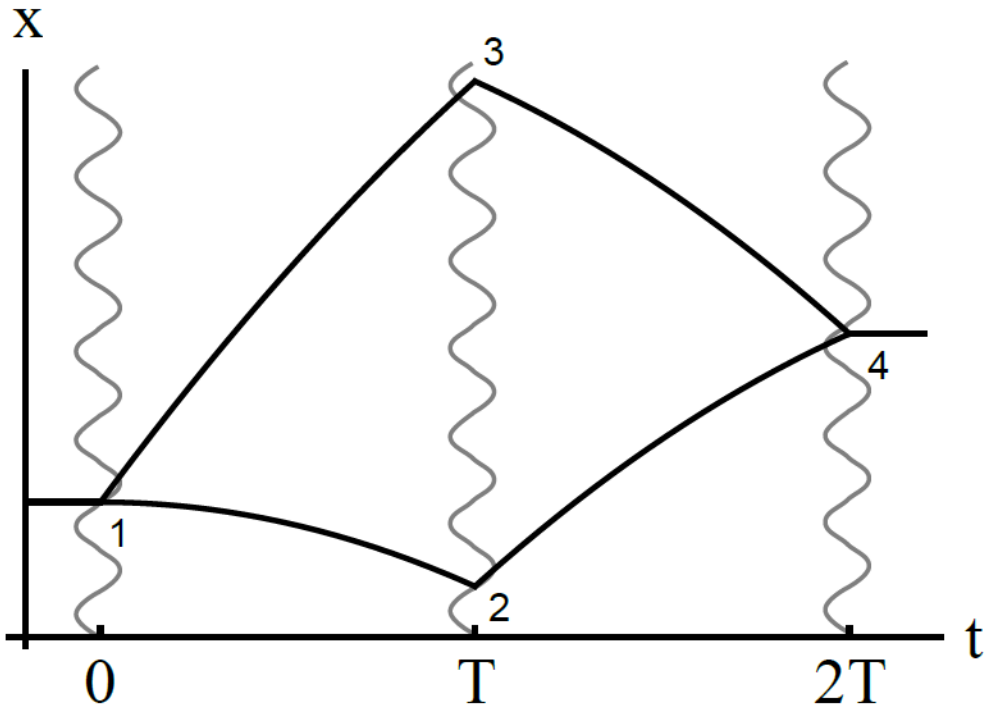
$$\phi = \phi_{\rm bg} - \lambda_A \frac{1}{4\pi R_A} \frac{M_A}{M} \frac{R_A}{r} e^{-m_{\rm bg} r}$$

$$\lambda_A = \begin{cases} 1\,, & \rho_A R_A^2 < 3 M \phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A} \phi_{\rm bg}\,, & \rho_A R_A^2 > 3 M \phi_{\rm bg} \end{cases}$$

This determines how ‘screened’ an object is from the chameleon field

Ideal experiments use unscreened test masses e.g. atomic nuclei, neutrons, microspheres

An Atom Interferometer



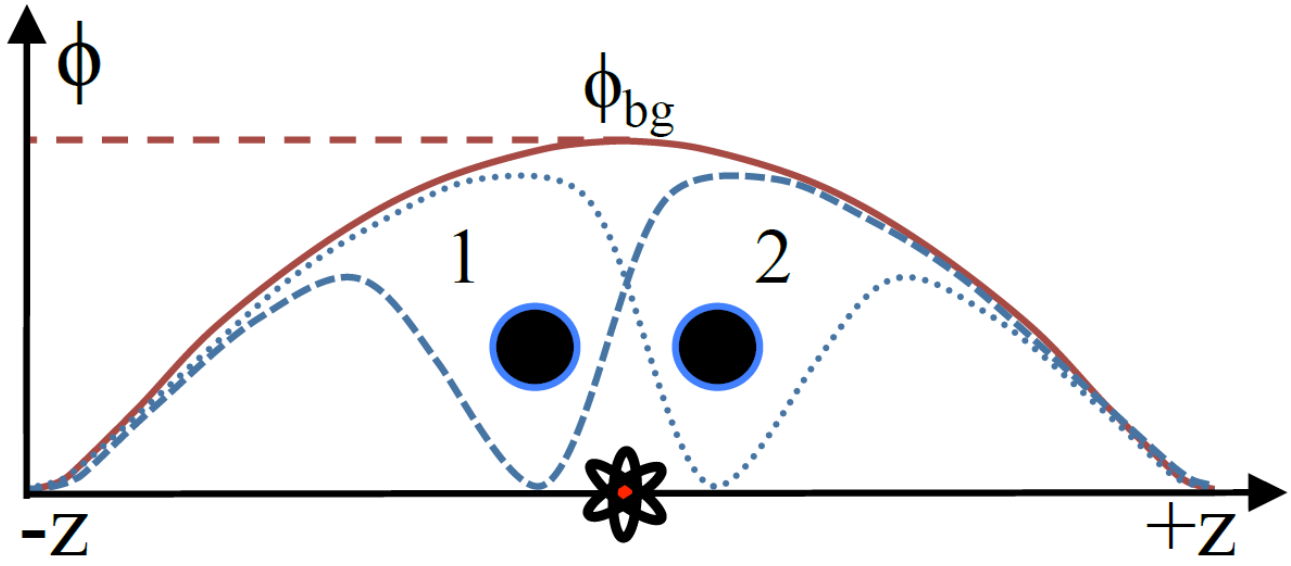
Probability measured in excited state at output

$$P = \cos^2\left(\frac{kaT^2}{2}\right)$$

Atom Interferometry for Chameleons

The walls of the vacuum chamber screen out any external chameleon forces

Macroscopic spherical mass, produces chameleon potential felt by cloud of atoms



Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Imperial Experiment

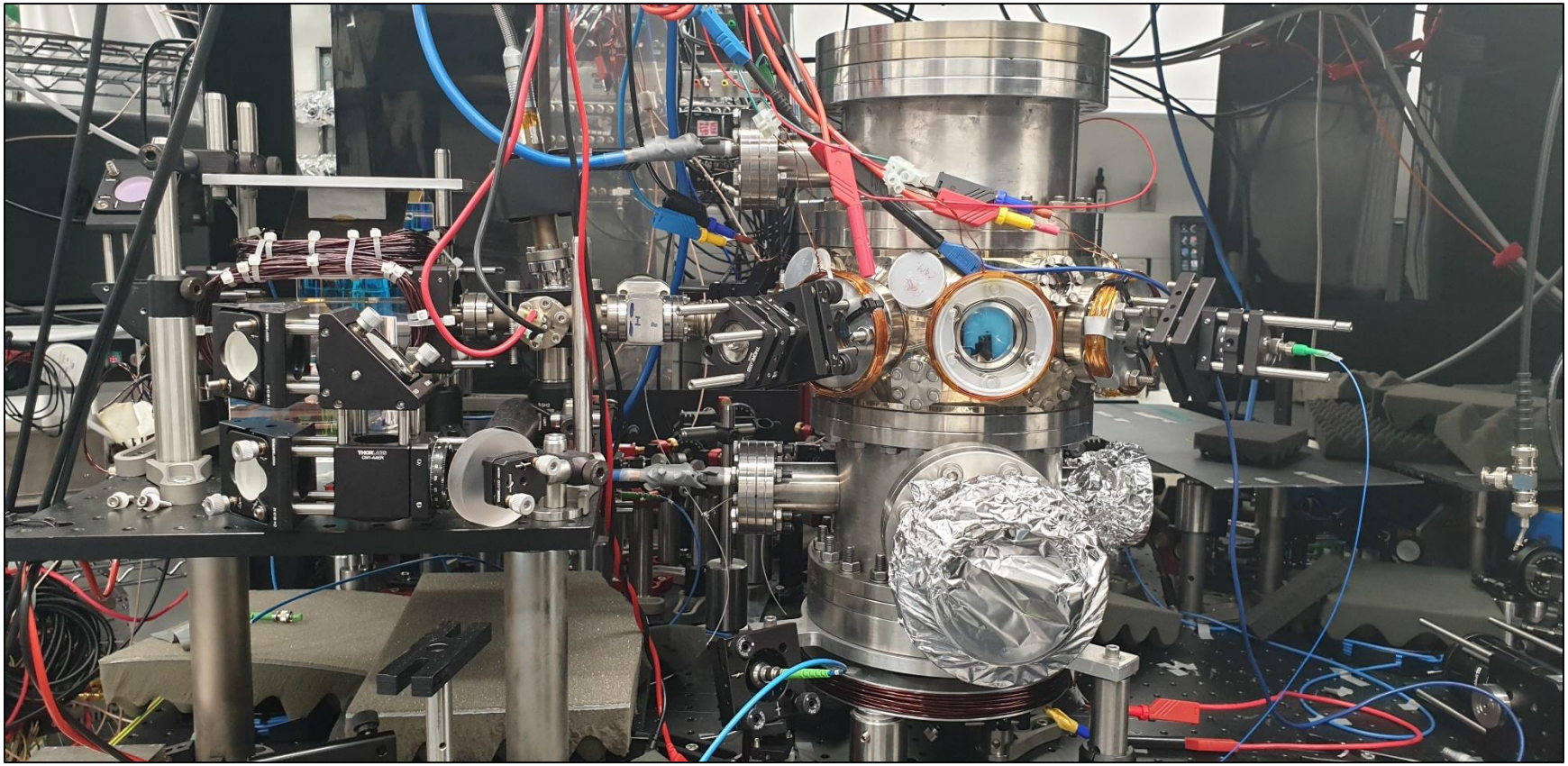
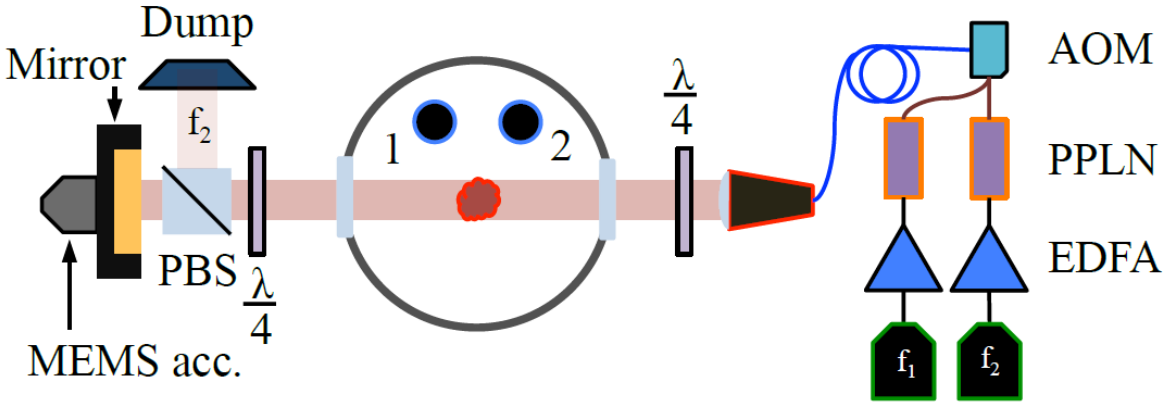


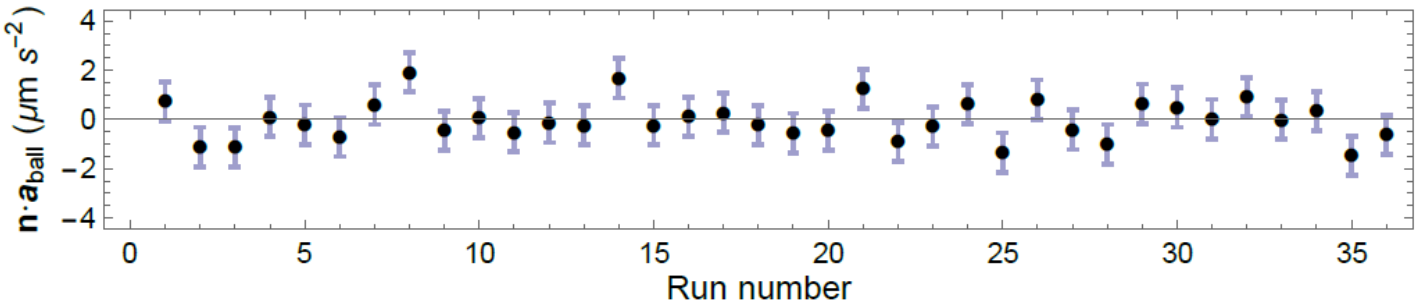
Image credit: E. Hinds

Imperial Experiment

Dedicated chameleon experiment, insensitive to the Earth's gravitational field

Anomalous acceleration = -77 ± 201 nm s^{-2}

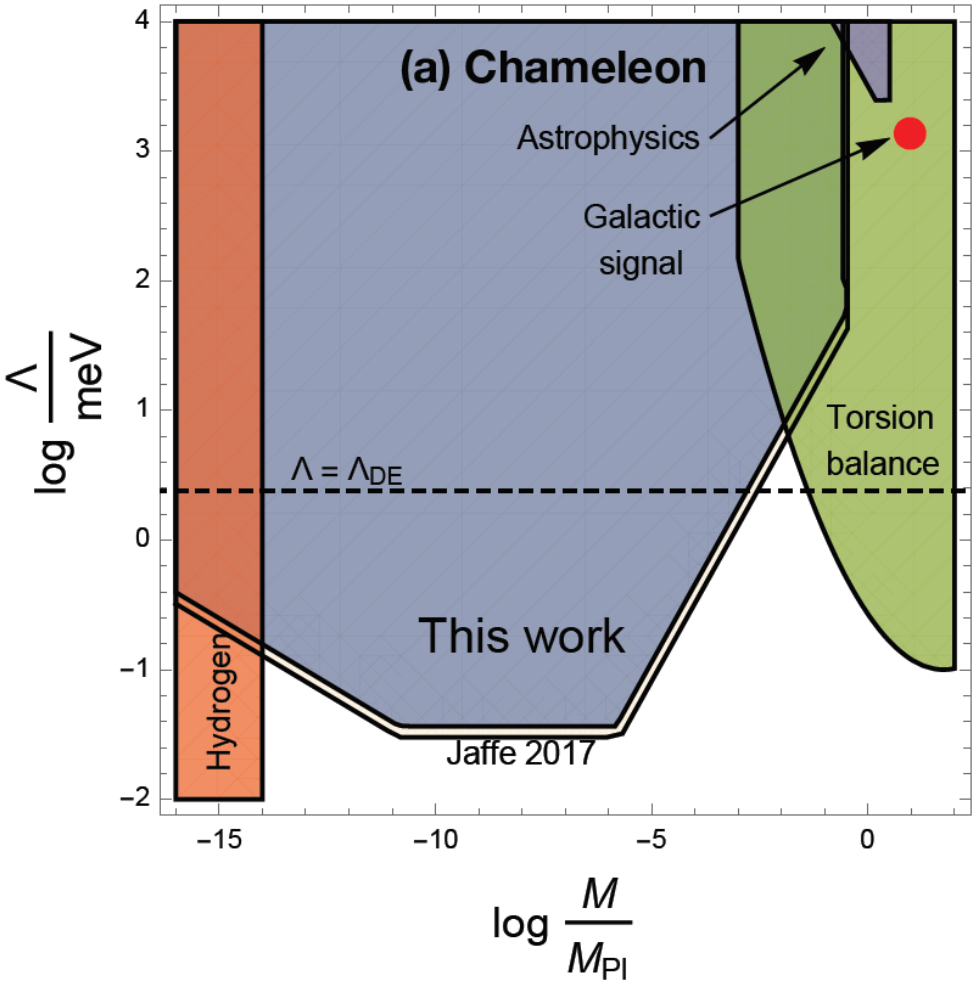




Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

See also: Jaffe et al. (2017)

Imperial Experiment

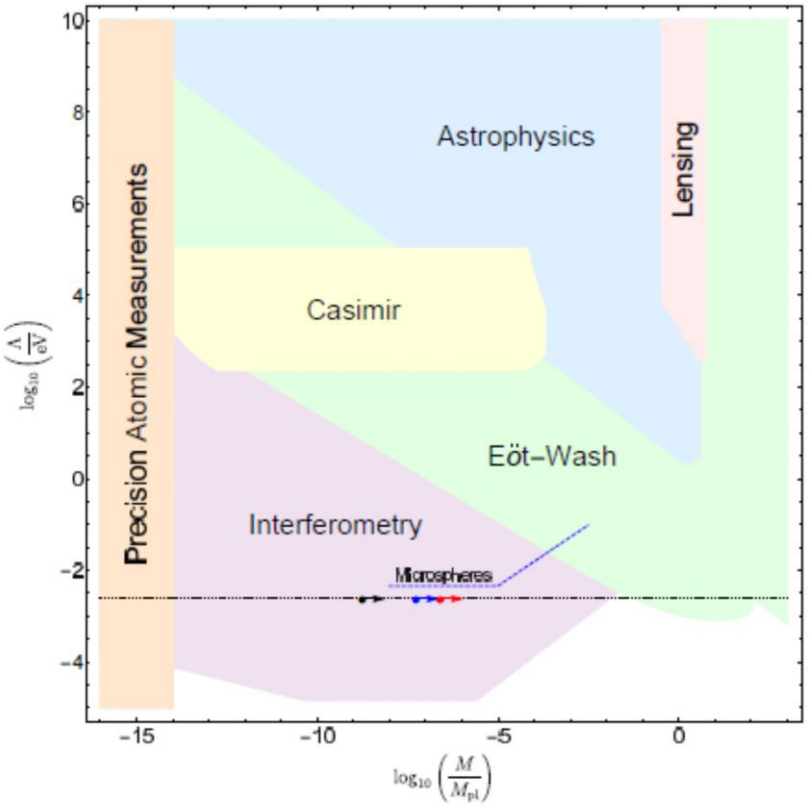


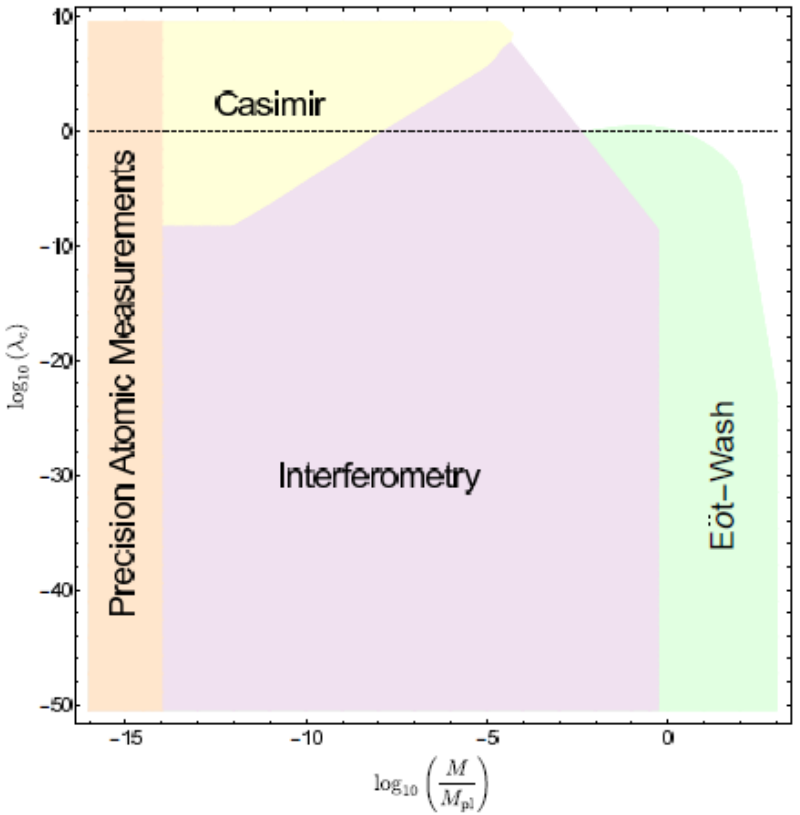
Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Combined Chameleon Constraints

$$V(\phi) = \frac{\Lambda^5}{\phi}$$

$$V(\phi) = \frac{\lambda}{4}\phi^4$$





CB, Sakstein. (2016, 2017)

See also talks by: Spyridon Argyropoulos, Justin Baier, Hartmut Abele,

Summary

Explanations for dark energy typically introduce new scalar fields but the corresponding long range forces are not seen

Screening mechanisms (non-linearities) hide these forces from fifth force searches

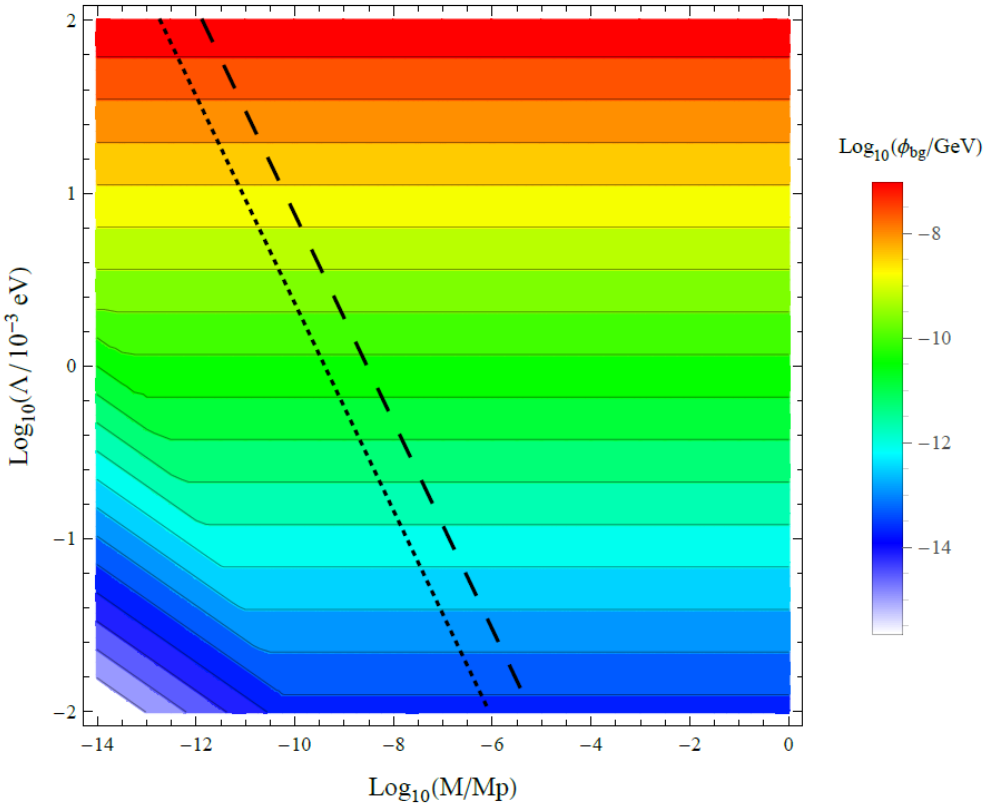
- Can still be detected in suitably designed experiments
- Atom interferometry a particularly powerful technique

Complementary to large scale cosmological surveys e.g. Euclid, LSST

Atoms can be Unscreened

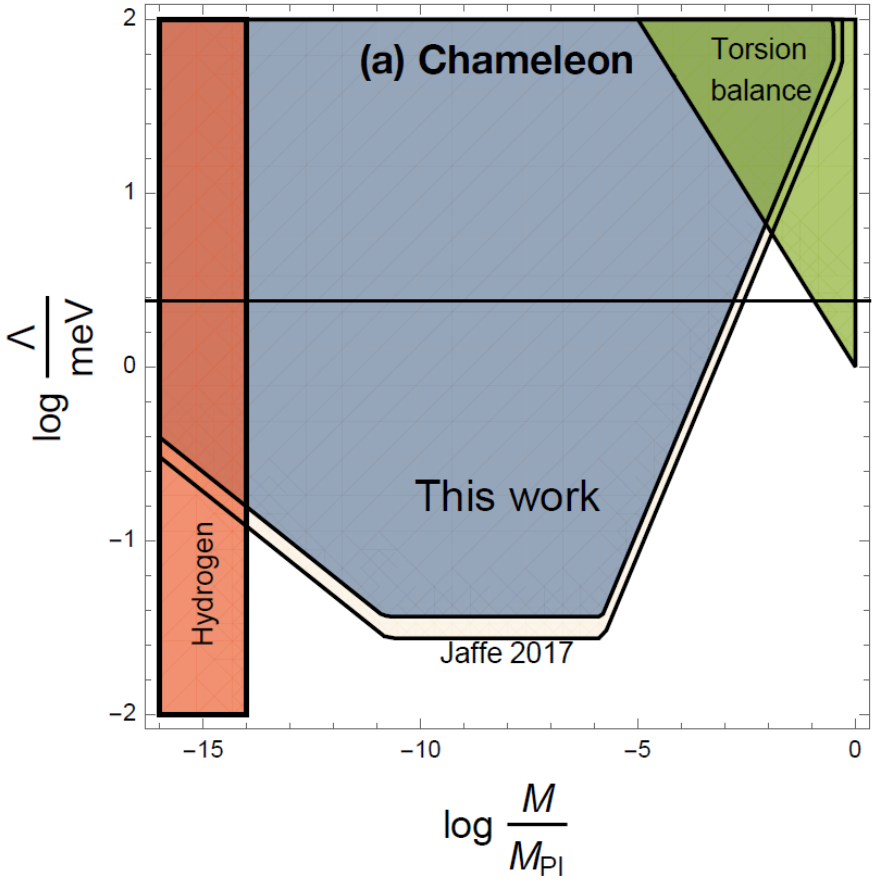
In a spherical vacuum chamber, radius 10 cm, pressure 10^{-10} Torr

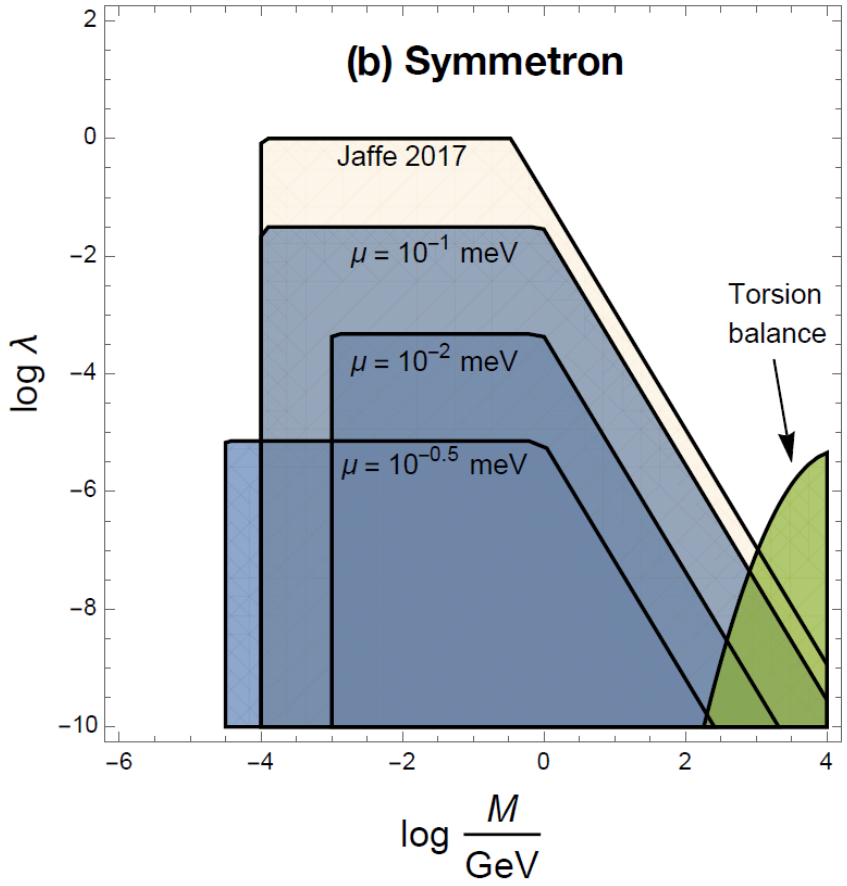
Atoms are unscreened above black lines
(dashed = caesium, dotted = lithium)



CB, Copeland, Hinds. (2015)

Imperial Experiment





Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Astrophysical Hints

Different components of a dwarf galaxy may fall towards a cluster at different rates

Evidence for offsets using ~10,000 HI detections from the ALFALFA survey

Evidence for galaxy warps using ~4,000 images from the Nasa Sloan Atlas

Both consistent with screened force, M~10 M_{Pl}, and vacuum Compton wavelength ~1.8 Mpc

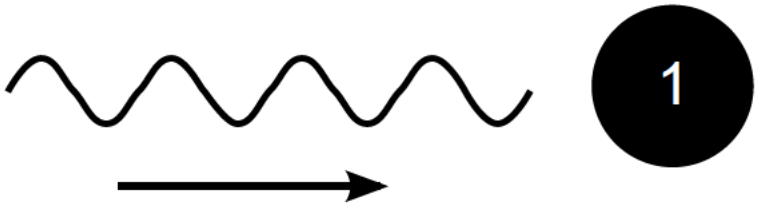
~7σ significance, but challenging systematics

Desmond, Ferreira, Lavaux, Jasche. (2018)
Tests proposed by Hui, Nicolis, Stubbs. (2009). Jain, VanderPlas. (2011)

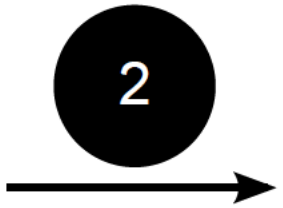
What is Atom Interferometry?

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons



Photon Momentum = k
Atom in ground state



Atom in excited state
with velocity = V