Probing dark energy with atom interferometry

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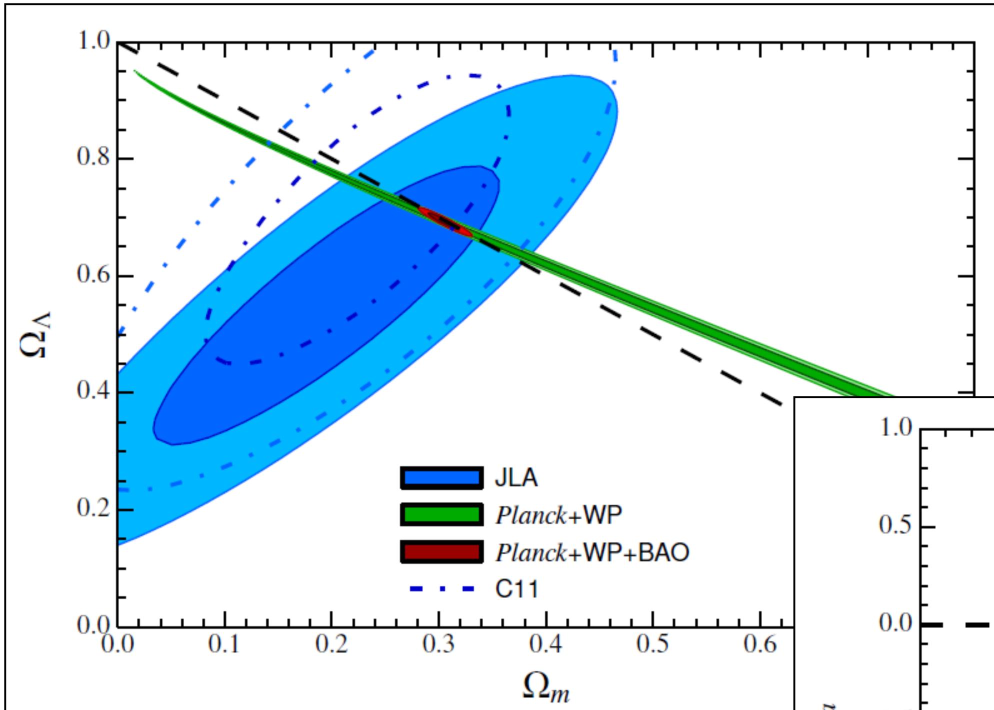
Outline:

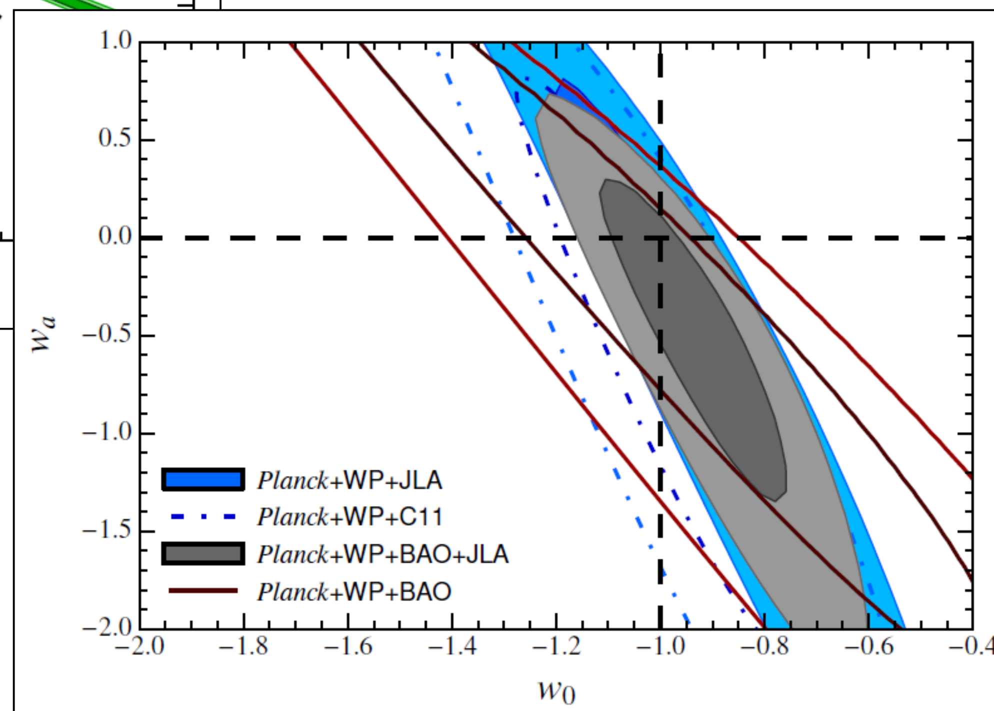
Dark energy and screened fifth forces

How to search for screening

Atom interferometry constraints

Dark Energy Today





Equation of state:

$$w = w_0 + (1 - a)w_a$$

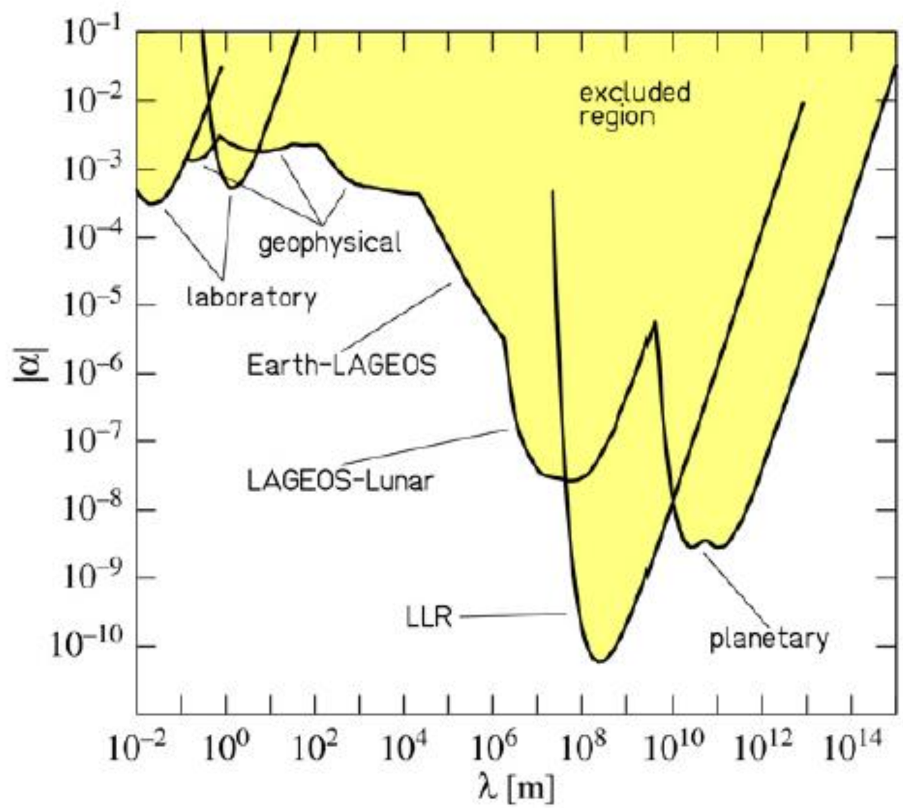
Betoule et al. (2014)

New fields and New Forces

Explanations for dark energy typically introduce new, light scalar fields

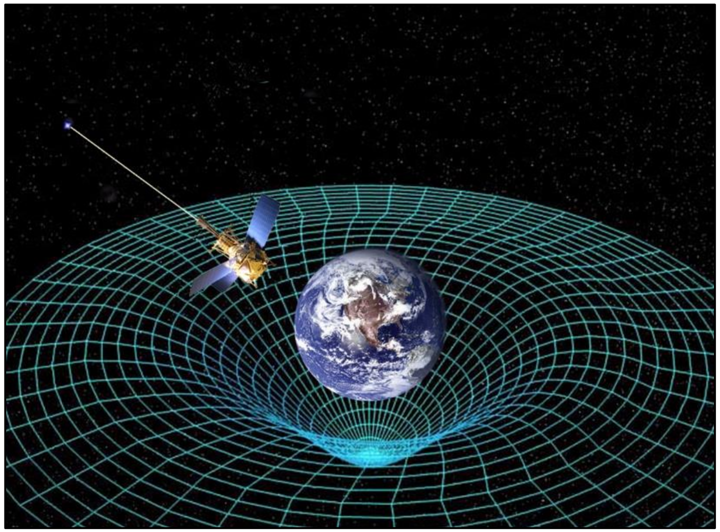
But Yukawa fifth forces are excluded to a high degree of precision

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



Adelberger et al. (2009)

Is the New Physics Linear?



General relativity is a non-linear theory

Higgs scalar has a non-linear potential

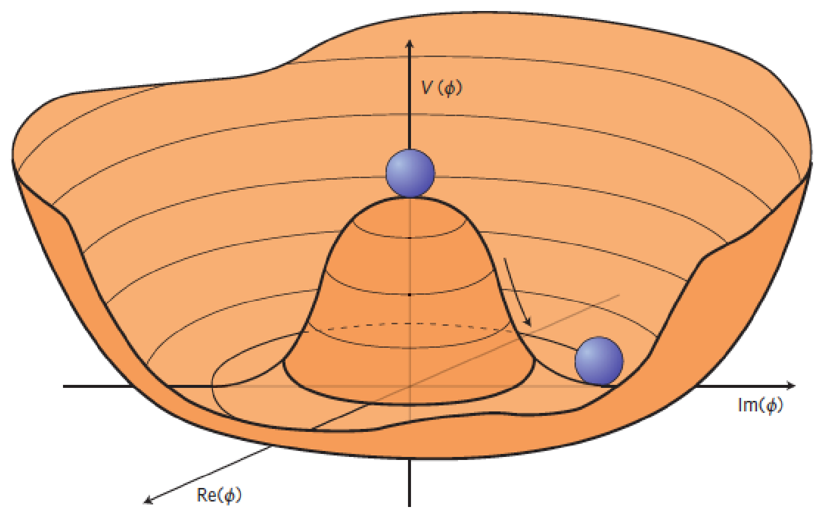


Image credits: NASA, John Ellis (1312.5672)

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

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

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

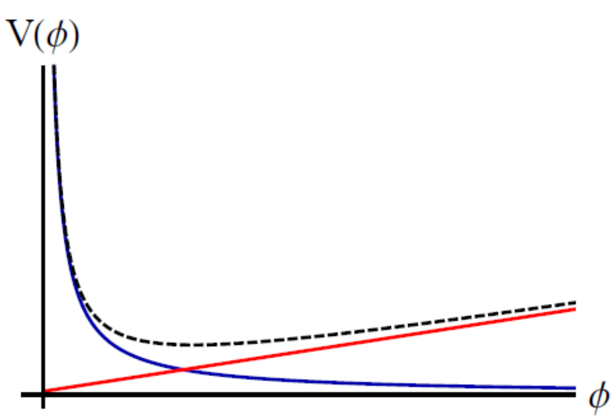
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

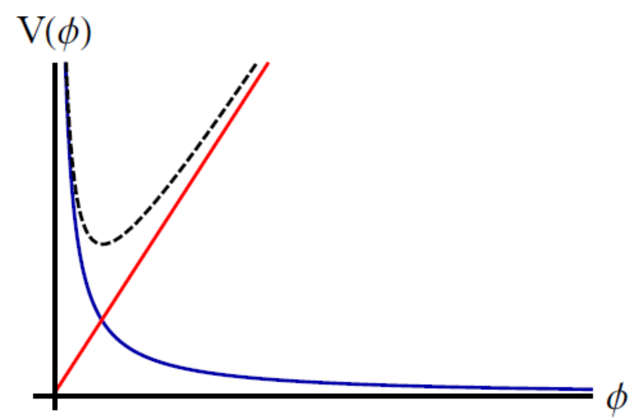
Dynamics governed by an effective potential

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

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



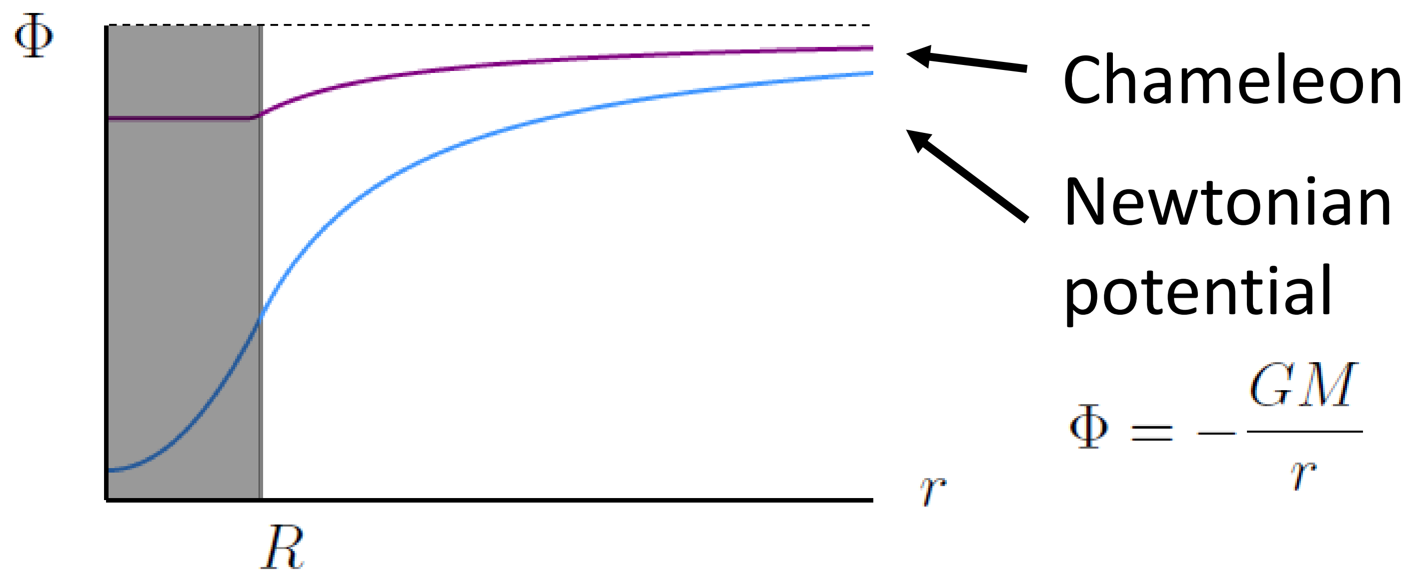
Low density



High density

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

The Scalar Potential

Around a static, spherically symmetric source of constant density

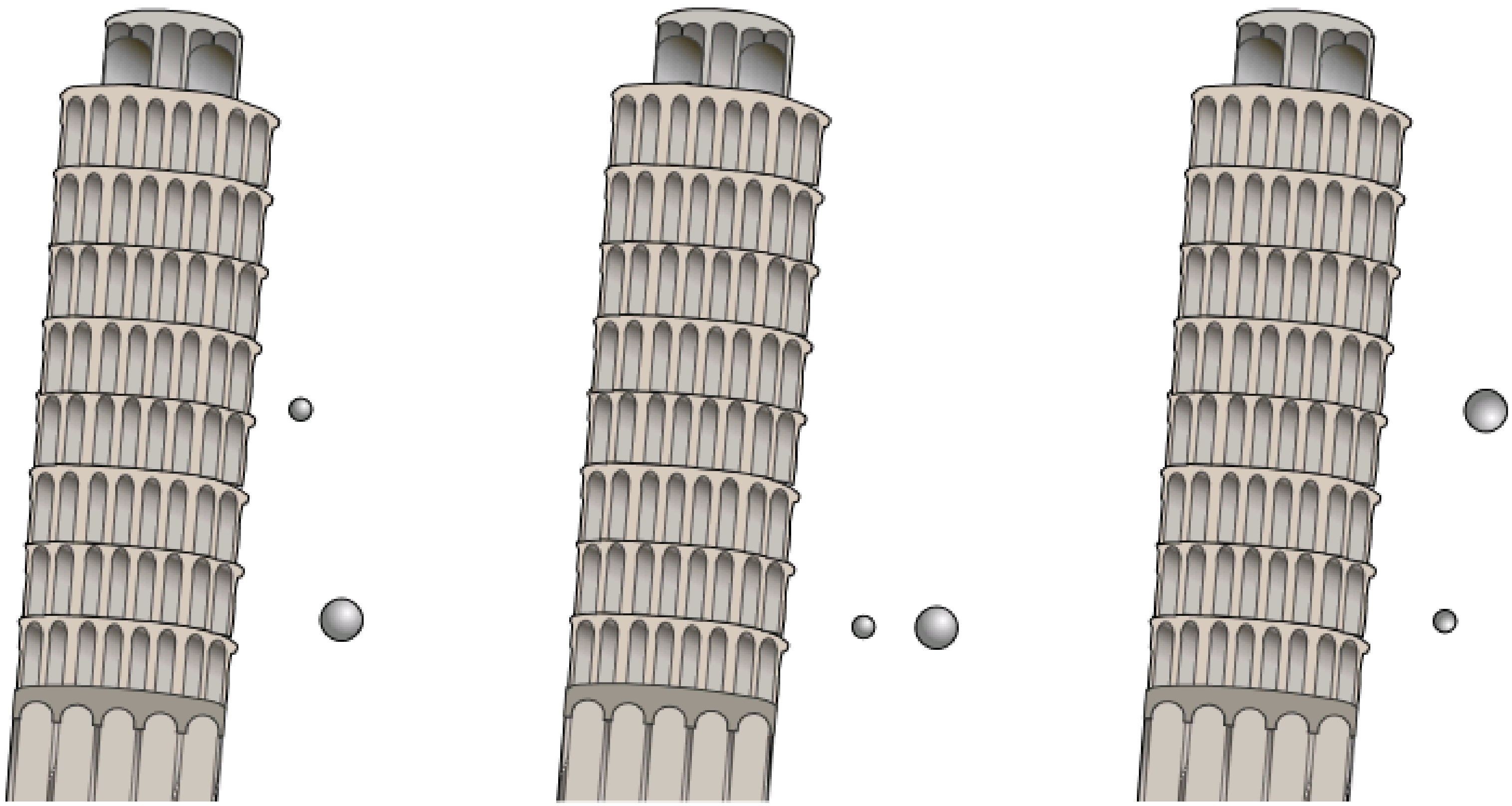
$$\phi = \phi_{\rm bg} - \lambda_A \frac{1}{4\pi R_A} \frac{M_A}{M} \frac{R_A}{r} e^{-m_{\rm bg} r}$$

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

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

A Very Old Idea

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



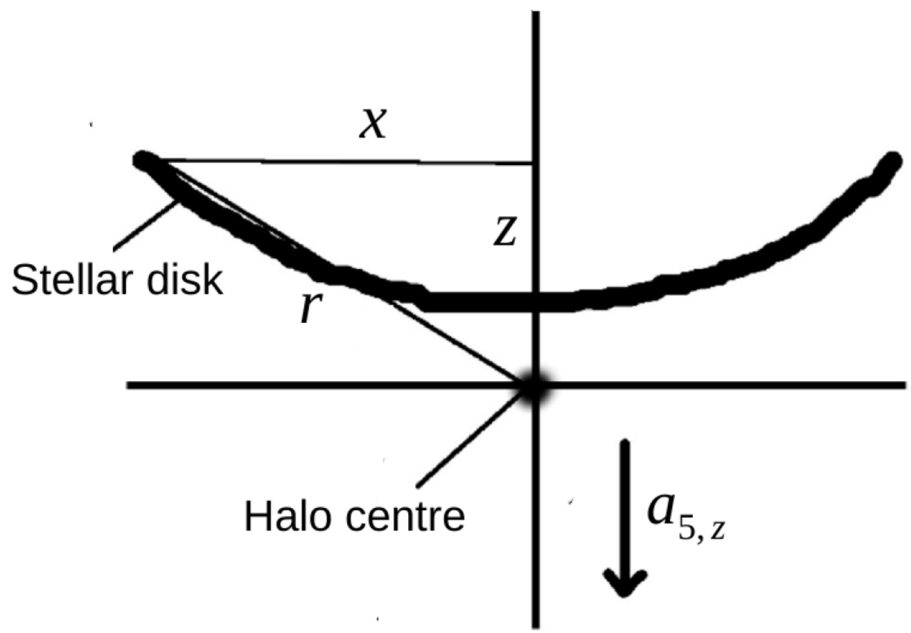
Old idea | Galileo | Chameleon?

Image credit: Theresa Knott

Astrophysical Hints?

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

- Stars are screened, gas and dark matter are not
- Look for gas-star offsets & warping of galactic discs



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

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, $M \sim 10\, M_{Pl}$, and vacuum Compton wavelength ~1.8 Mpc

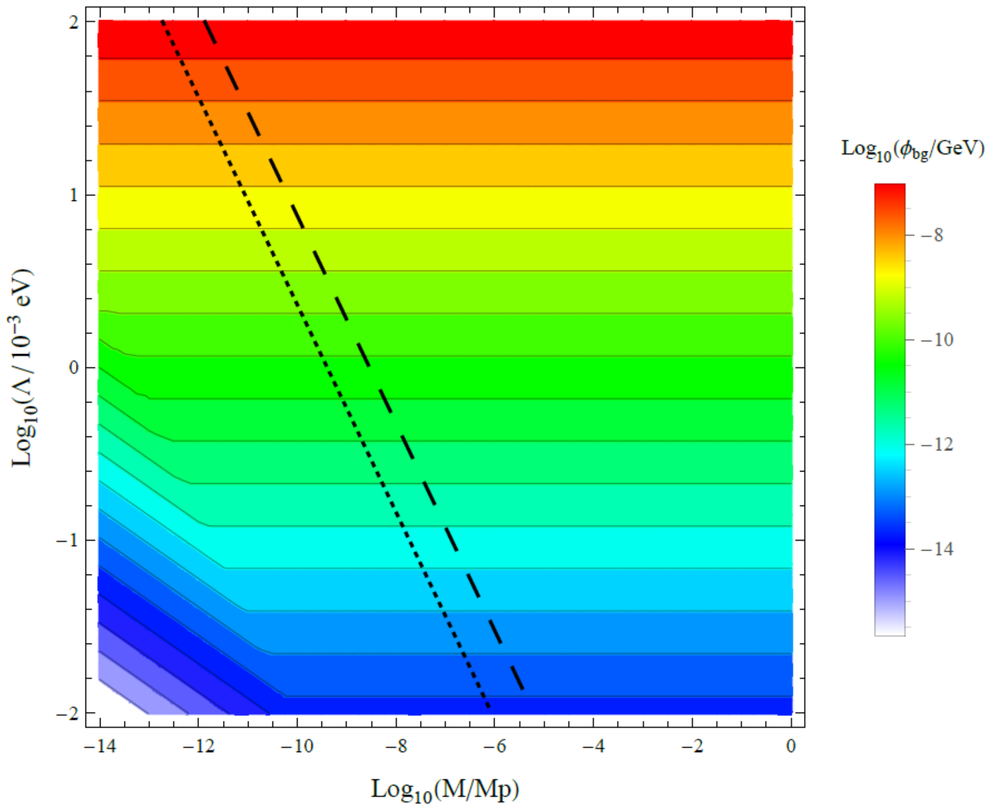
Claimed ~7σ significance, but challenging systematics

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

Why Atom Interferometry?

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

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

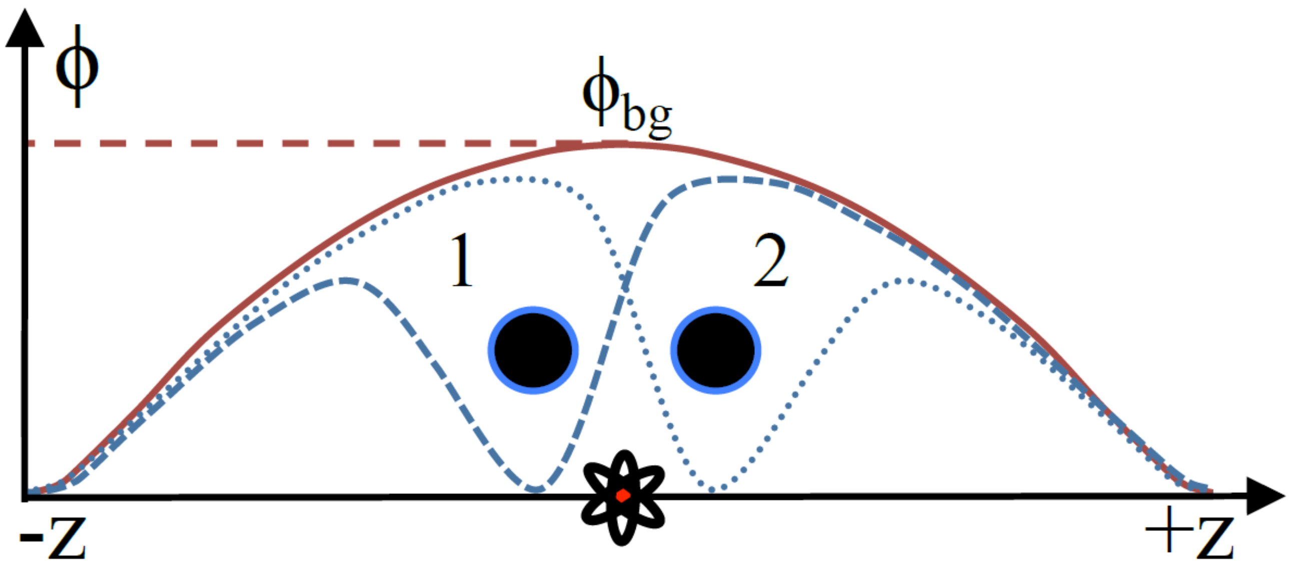


CB, Copeland, Hinds. (2015)

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

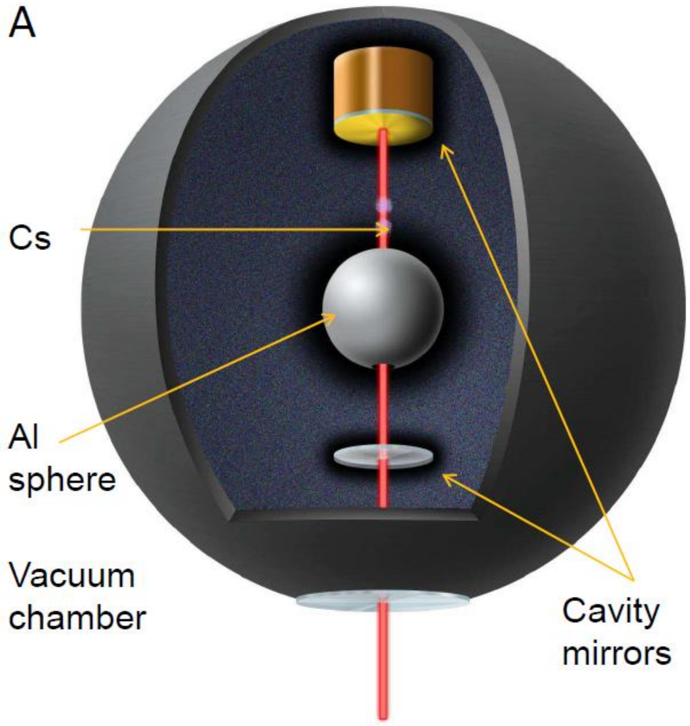


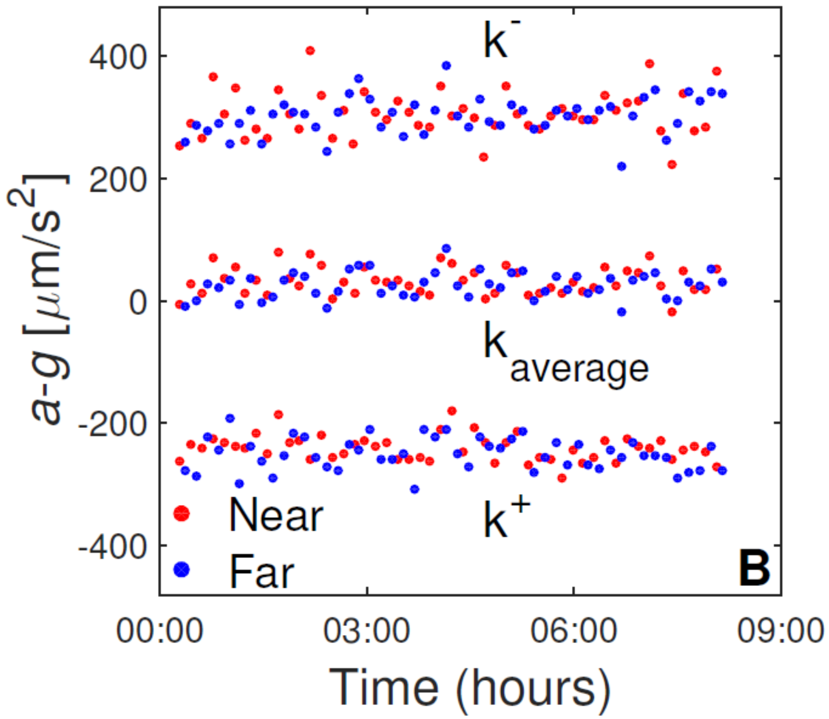
Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Berkley Experiment

Using an existing set up with an optical cavity, looking for a signal on top of the Earth's magnetic field

Anomalous acceleration $= 11 \pm 24 \text{ nm s}^{-2}$



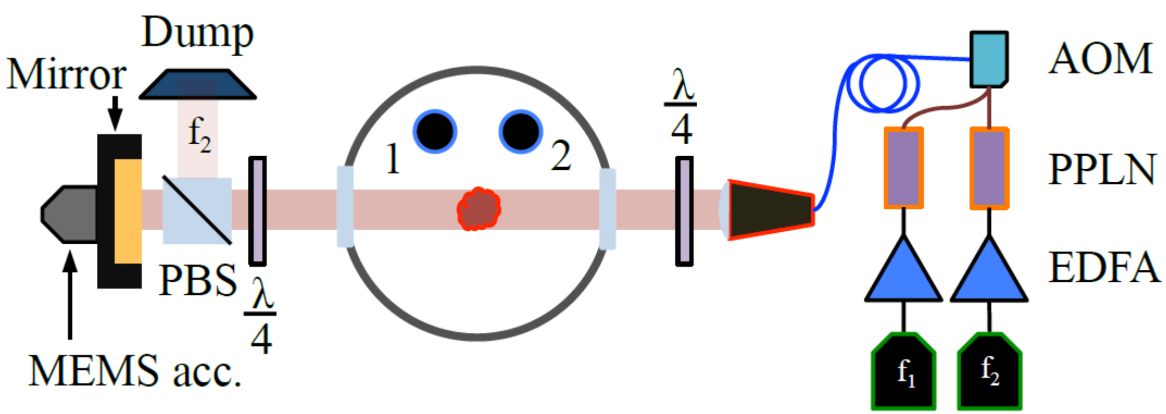


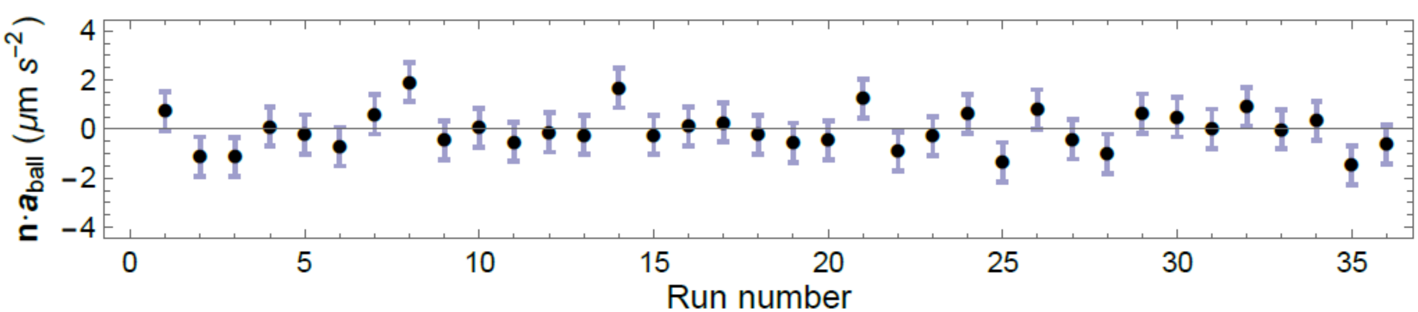
Jaffe, Haslinger, Xu, Hamilton, Upadhye, Elder, Khoury, Müller. (2017)
Elder, Khoury, Haslinger, Jaffe, Müller, Hamilton. (2016)

Imperial Experiment

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

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





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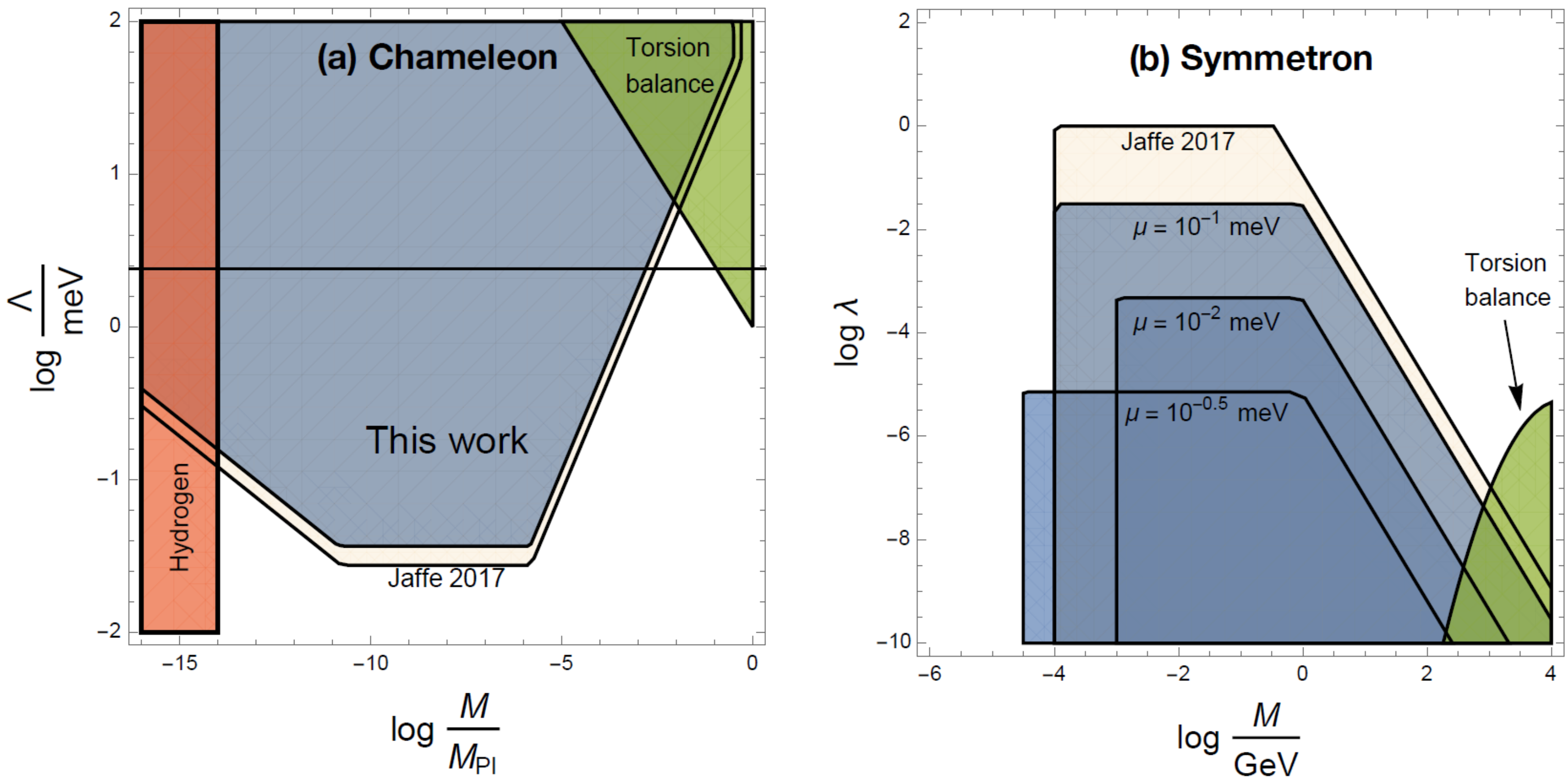
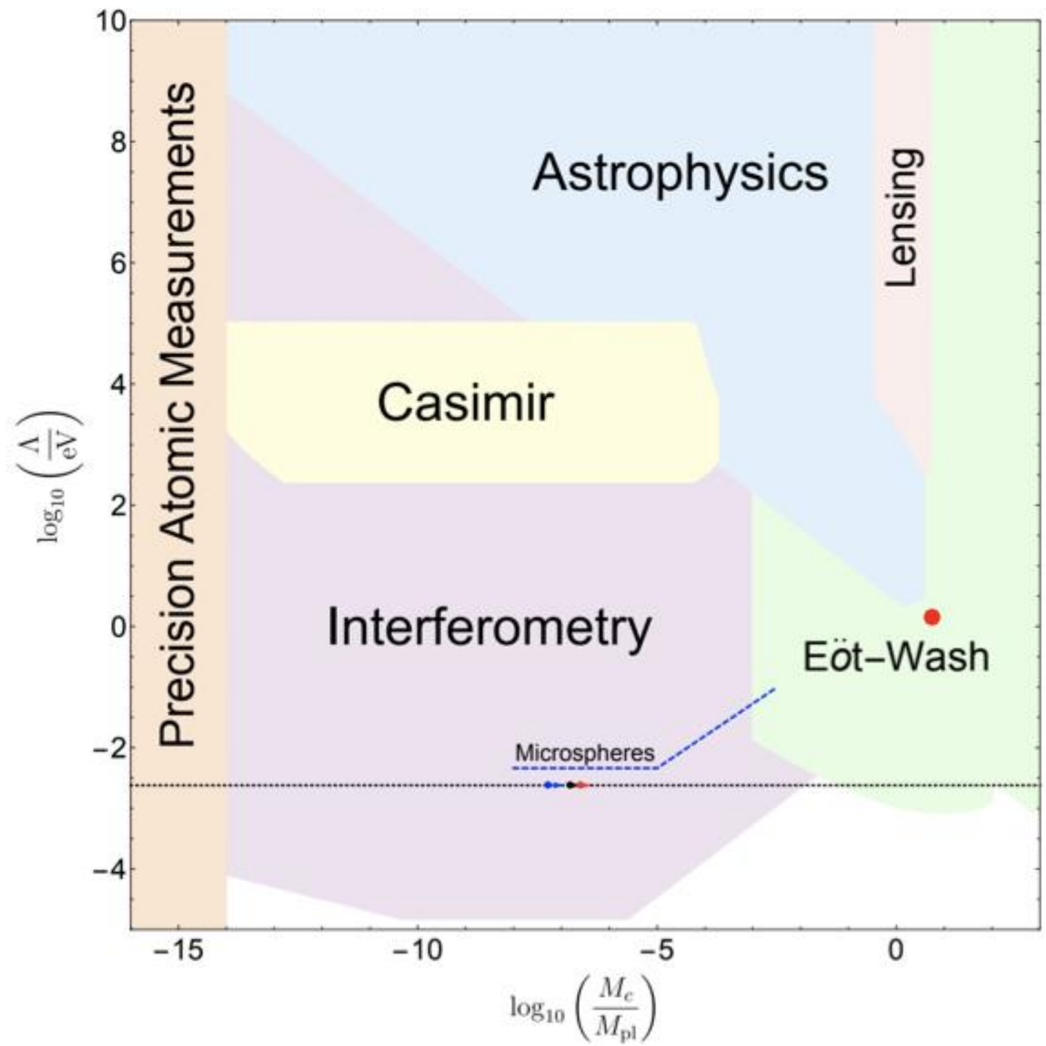
Imperial Experiment



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

Astrophysical Hints?

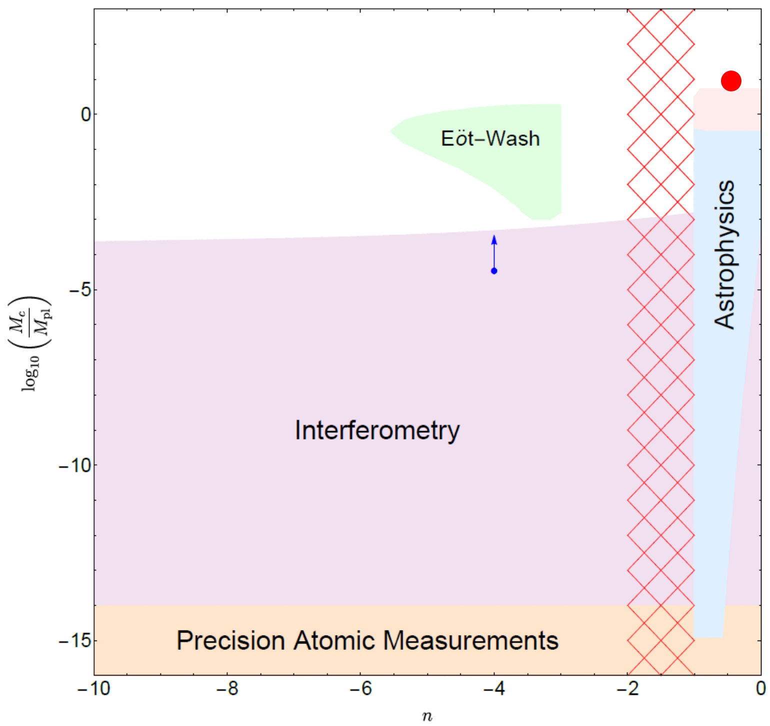


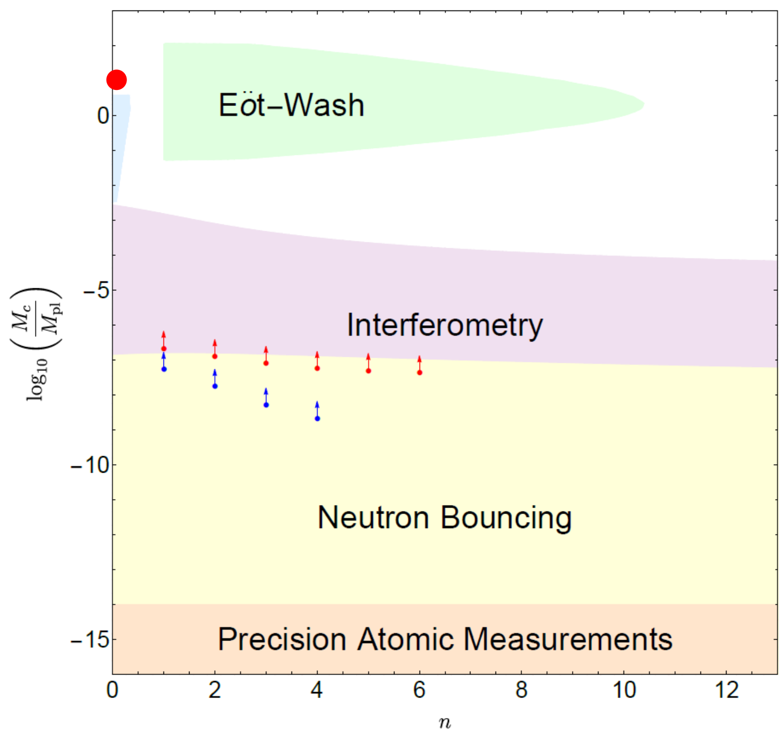
CB, Sakstein. (2017). With thanks to Ben Elder

Combined Chameleon Constraints

$$V(\phi) = \frac{\Lambda^{n+4}}{\phi^n}$$

$$\Lambda = \Lambda_{\mathrm{DE}} = 2.4 \text{ meV}$$





CB, Sakstein. (2017). With thanks to Ben Elder

Summary

Explanations for dark energy typically introduce new scalar fields but the corresponding 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

Possible astrophysical hints for screened forces could be within reach of future experiments

Symmetron Screening

Canonical scalar with potential and coupling to matter

$$V(\phi) = \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2 \qquad \mathcal{L} \supset \frac{\phi^2}{2M^2}T^\mu_\mu$$

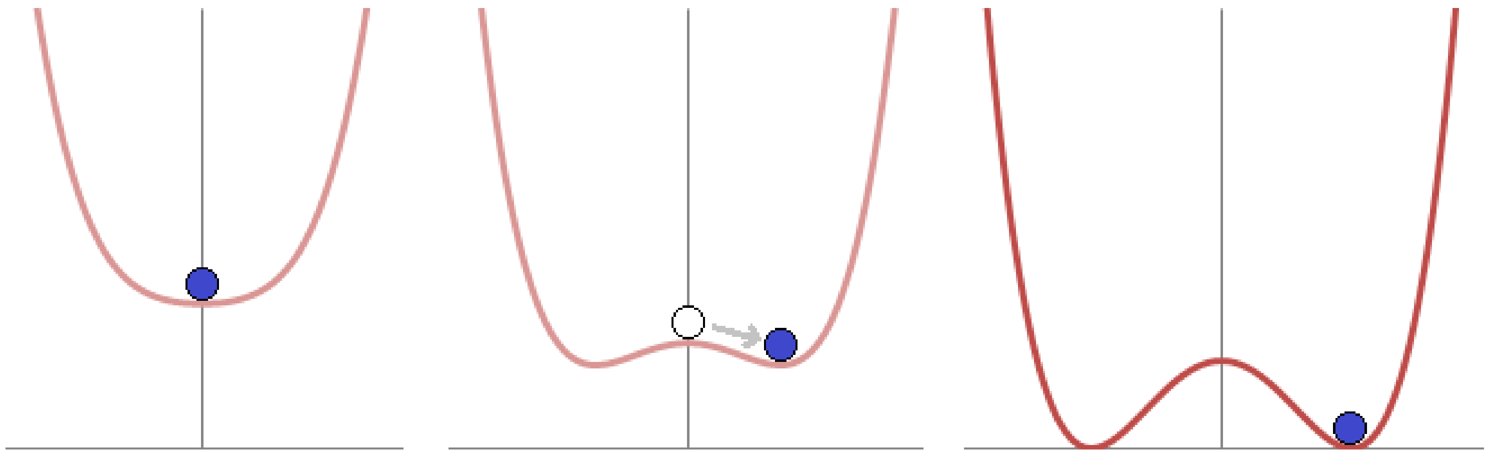
Effective potential

$$V_{\text{eff}}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$

Symmetry breaking transition occurs as the density is lowered

Hinterbichler, Khoury. (2010).

Symmetron Screening



Force on test particle vanishes when symmetry is restored

$$F = \phi \nabla \phi / M^2$$

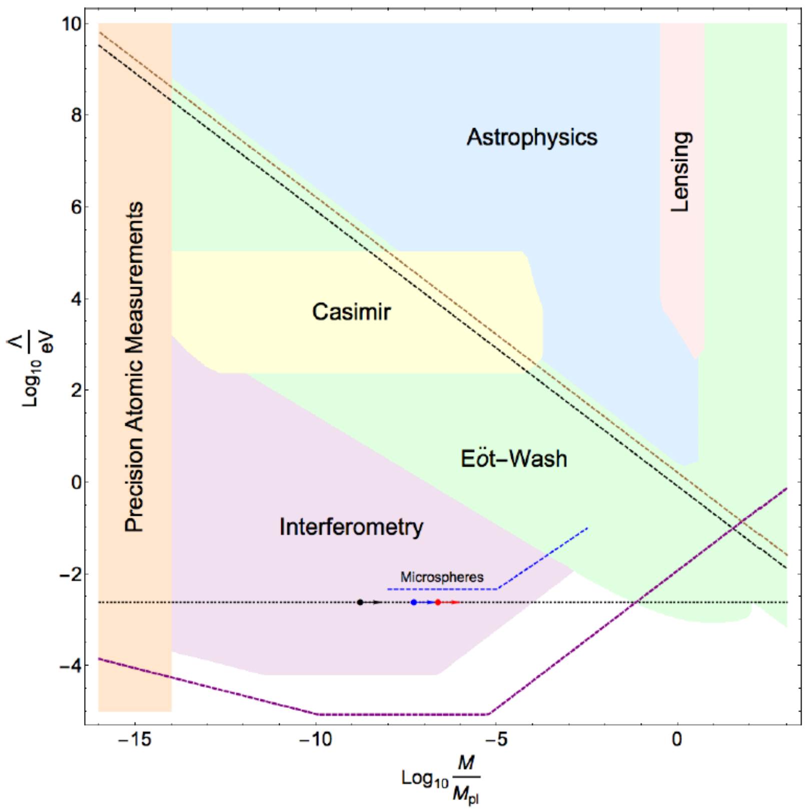
Radiatively stable model has been constructed

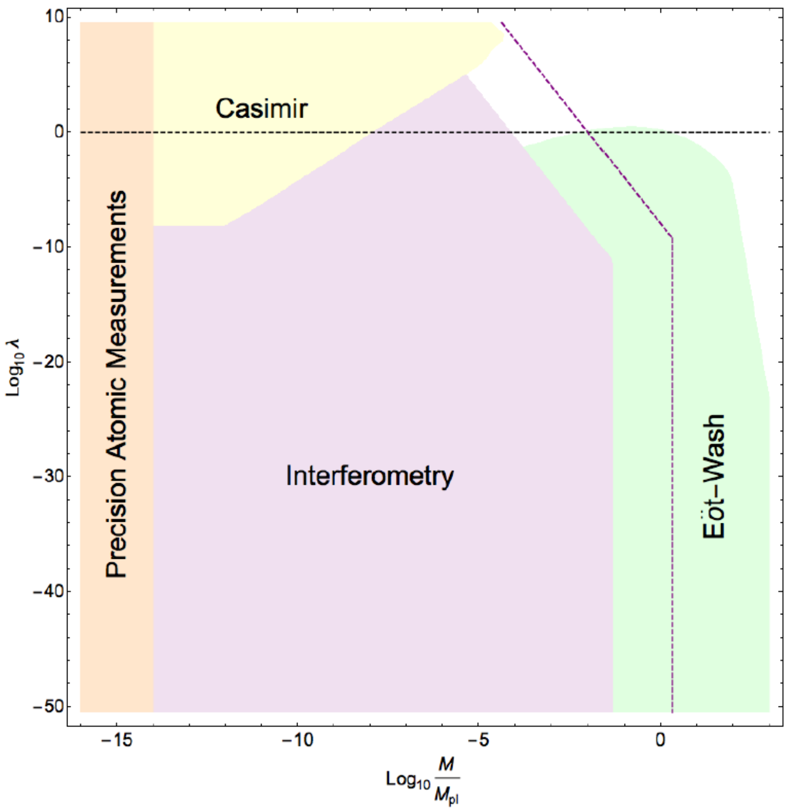
CB, Copeland, Millington. (2016).

Combined Chameleon Constraints

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

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





CB, Sakstein. (2016)

New Results

Aluminium sphere replaced by cylindrical tungsten source, mass 0.19 kg, height = diameter = 2.54 cm

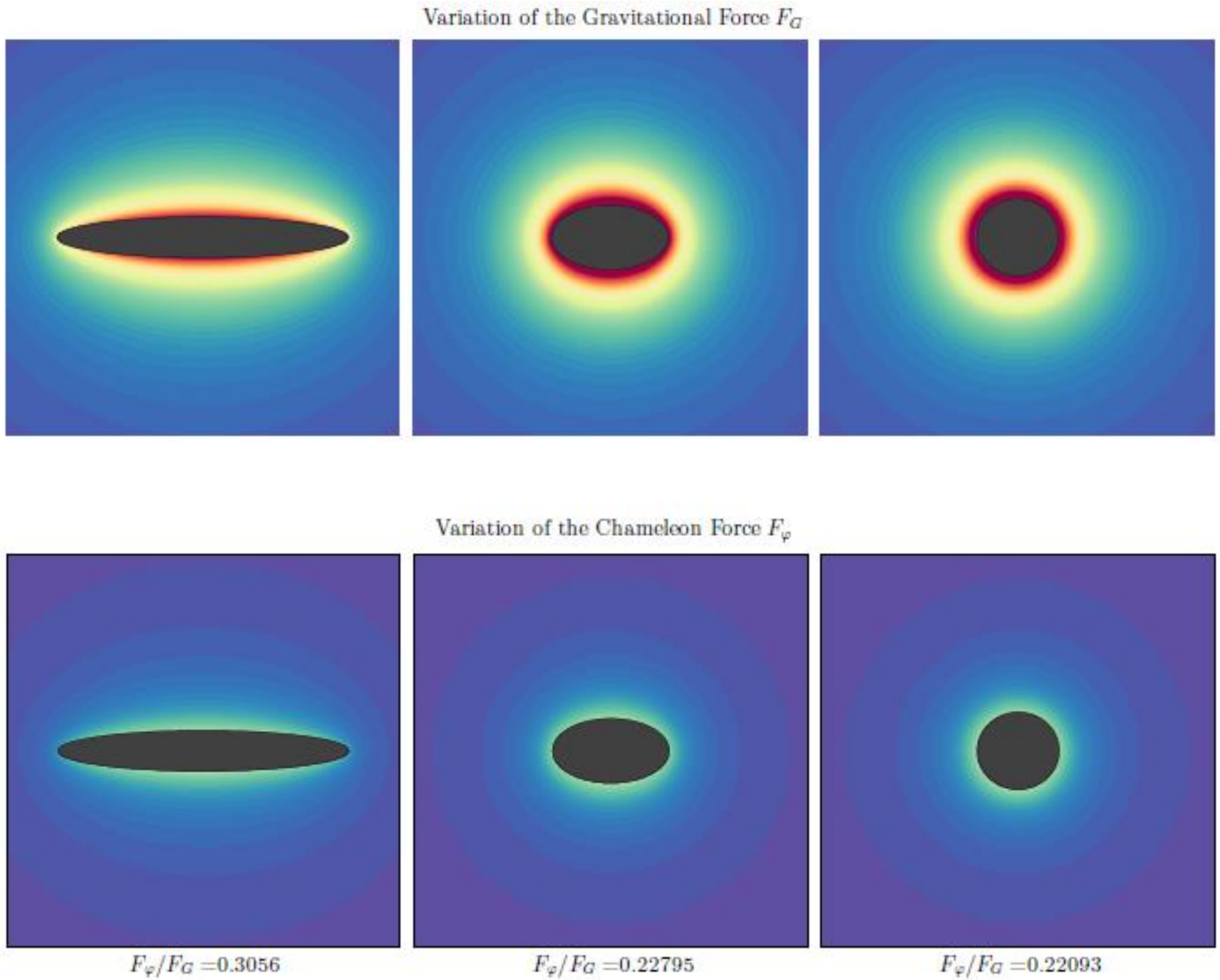
Additional vibration isolation and control of systematics

Detection of the gravitational force between the cylinder and caesium atoms at 2σ

$$F \sim 10^{-32}\ \mathrm{N}$$

Jaffe et al. (2016)

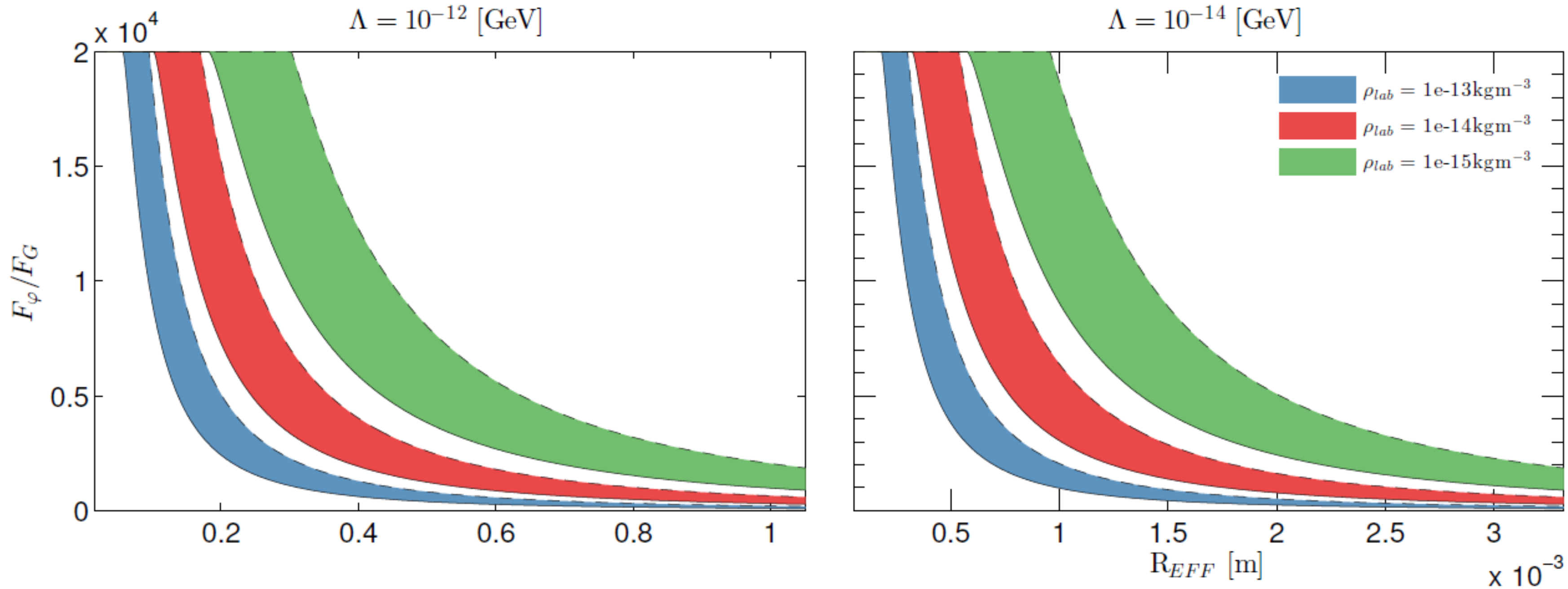
Future Prospects: Source Shape



CB, Copeland, Stevenson (2015)

Shape Dependence of Chameleon Force

Deviations from spherical symmetry impede the formation of a thin shell



CB, Copeland, Stevenson (2015)

ars TECHNICA

BIZ & IT TECH SCIENCE POLICY CARS GAMIN

EINSTEIN IS STILL RIGHT —

Colliding neutron stars apply kiss of death to theories of gravity

ASTROPHYSICS

Troubled Times for Alternatives to Einstein's Theory of Gravity

22

New observations of extreme astrophysical systems have "brutally and pitilessly murdered" attempts to replace Einstein's general theory of relativity.

NEWS COSMOLOGY, GRAVITATIONAL WAVES

What detecting gravitational waves means for the expansion of the universe

Speed of spacetime ripples rules out some alternatives to dark energy

BY LISA GROSSMAN 5:34PM, OCTOBER 24, 2017

Galileon Theories

$$\mathcal{L} = \left(1 + 2\frac{c_0\phi}{m_{\rm Pl}}\right)\frac{R}{16\pi G_N} - \frac{c_2}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{c_4}{\Lambda^6}\mathcal{L}_4 - \frac{c_5}{\Lambda^9}\mathcal{L}_5$$

$$\begin{aligned}\mathcal{L}_4 =& (\partial\phi)^2\left[2(\Box\phi)^2 - 2D_\mu D_\nu\phi D^\nu D^\mu\phi - R\frac{(\partial\phi)^2}{2}\right]\\ \mathcal{L}_5 =& (\partial\phi)^2\left[(\Box\phi)^3 - 3(\Box\phi)D_\mu D_\nu\phi D^\nu D^\mu\phi + 2D_\mu D^\nu\phi D_\nu D^\rho\phi D_\rho D^\mu\phi\right.\\ &\left.-6D_\mu\phi D^\mu D^\nu\phi D^\rho\phi G_{\nu\rho}\right].\end{aligned}$$

Has ‘self accelerating’ solutions, with late time accelerated expansion due to dynamics of the scalar and zero cosmological constant

Nicolis, Ratazzi, Trincherini. (2008)

Speed of Gravitational Waves

$$c_T^2 = \frac{\frac{A^2(\phi)}{16\pi G_N} + 2\frac{c_4}{\Lambda^6}X^2}{\frac{A^2(\phi)}{16\pi G_N} - 6\frac{c_4}{\Lambda^6}X^2}$$

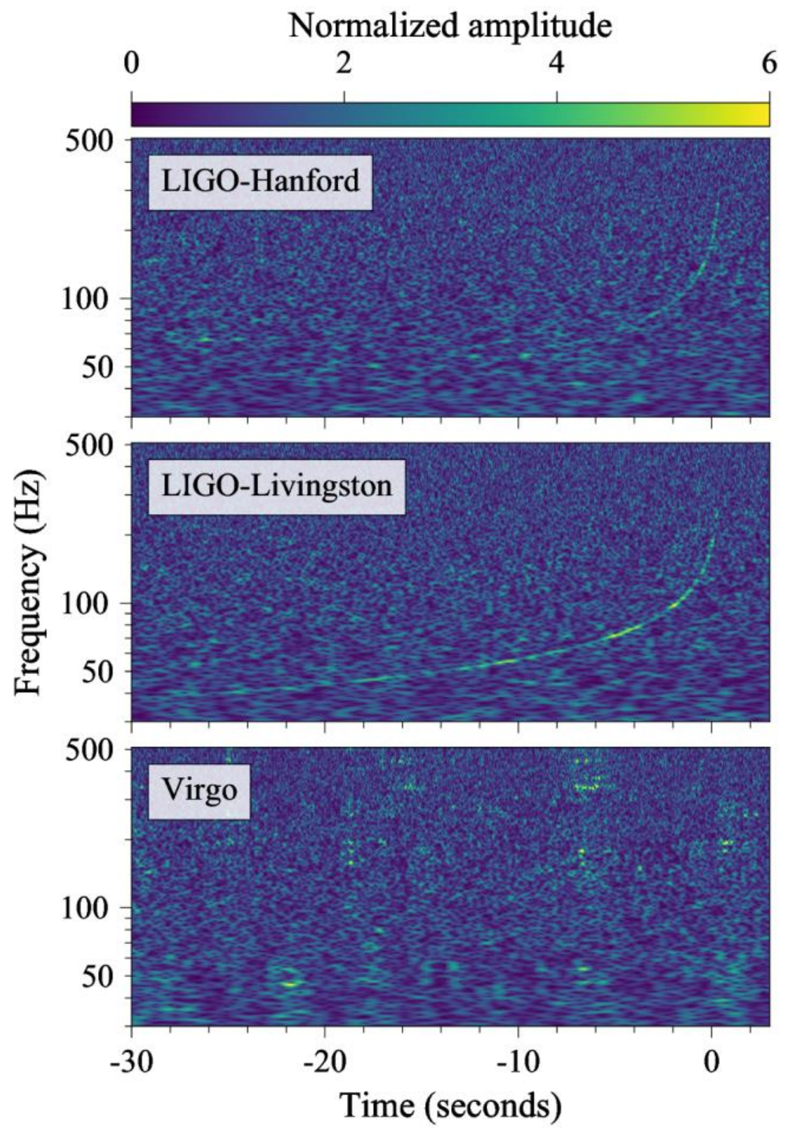
where

$$A(\phi) = 1 + \frac{c_0\phi}{m_{\rm Pl}} \qquad X = -\frac{(\partial\phi)^2}{2}$$

Mixing between the scalar and gravitational fields changes the speed of gravitational waves

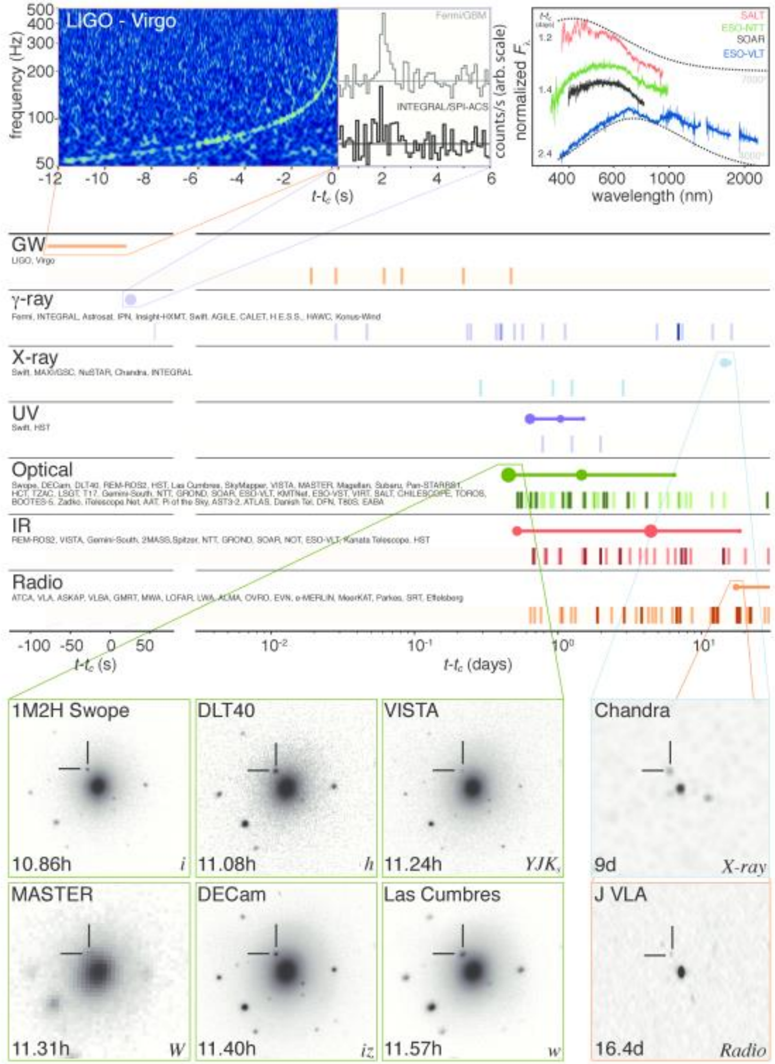
CB, Brax, Davis. (2016)

GW170817



Abbott et al. (2017)

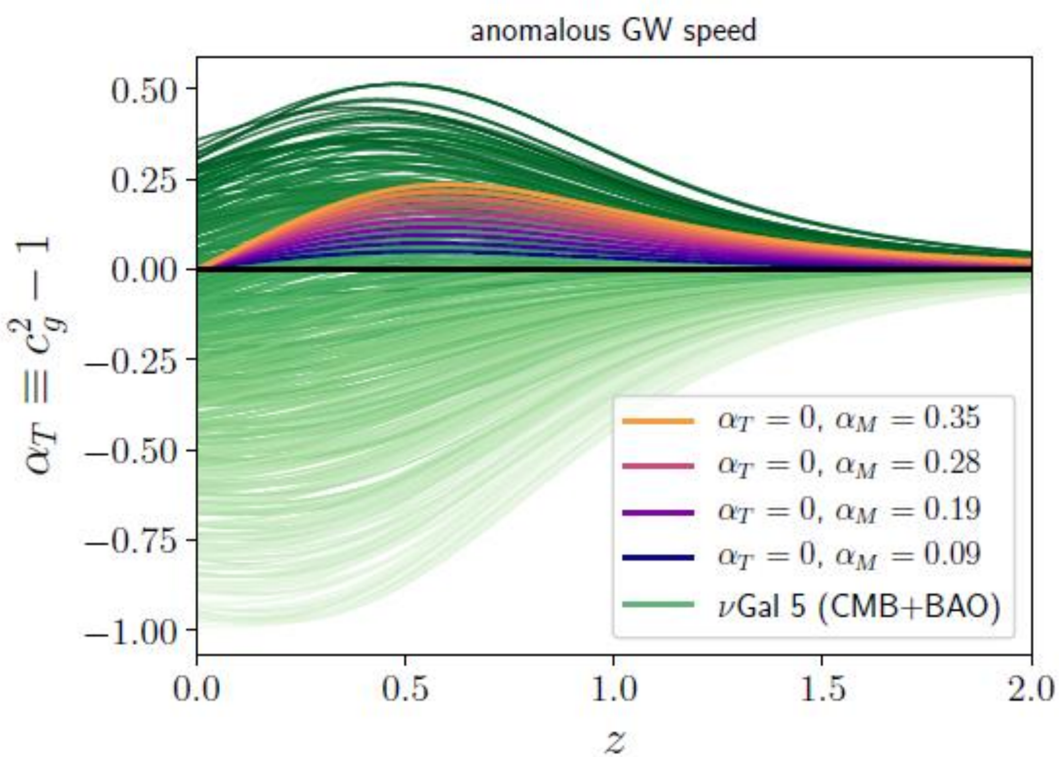
Optical Counterparts



Abbott et al. (2017)

GW170817 & GRB170817a

Self-accelerating cosmologies (zero cosmological constant) typically predict modifications of the speed of gravitational waves today



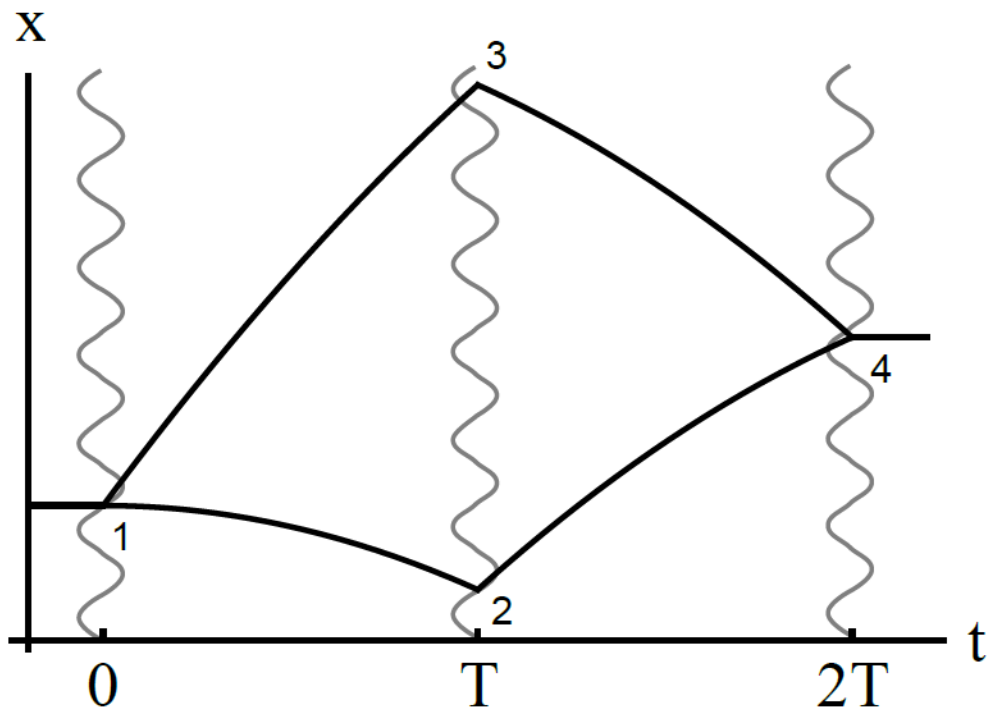
Ezquiaga, Zumalacárregui arXiv:1710.05901

What is Atom Interferometry?

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons

An Atom Interferometer



Probability measured in excited state at output

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

The Atomic Wavefunction

The probability of measuring atoms in the unexcited state at the output of the interferometer is a function of the wave function phase difference along the two paths

$$P \propto \cos^2\left(\frac{\varphi_1 - \varphi_2}{2}\right)$$

For freely falling atoms the contribution of each path has a phase proportional to the classical action

$$\theta[x(t)] = Ce^{(i/\hbar)S[x(t)]}$$

Additional contributions from interactions with photons, proportional to

$$(i/\hbar)(\omega t - \vec{k} \cdot \vec{x})$$

The Cosmological Constant Problem

Vacuum fluctuations of standard model fields generate a large cosmological constant-like term

Expected:

$$\rho^{vac} \sim M^4$$

Observed:

$$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$$

Phase transitions in the early universe also induce large changes in the vacuum energy

Such a large hierarchy is not protected in a quantum theory

Solutions to the Cosmological Constant Problem

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

There are new types of matter in the universe

- Quintessence directly introduces new fields
- New, light (fundamental or emergent) scalars

The theory of gravity is wrong

- General Relativity is the unique interacting theory of a Lorentz invariant, massless, helicity-2 particle

  Papapetrou (1948). Weinberg (1965).

- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

Screening Mechanisms

Start with a non-linear scalar field theory

$$\mathcal{L} = -\frac{1}{2}Z^{\mu\nu}(\phi, \partial\phi, ...)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Split the field into background and perturbation

$$\phi = \bar{\phi} + \varphi$$

Where the perturbation is sourced by a static, non-relativistic point mass

$$\rho = \mathcal{M}\delta^3(\vec{x})$$

Screening Mechanisms

Euler-Lagrange equation

$$Z(\bar{\phi})\left(\ddot{\varphi}-c_s^2(\bar{\phi})\nabla^2\varphi\right)+m^2(\bar{\phi})\varphi=g(\bar{\phi})\mathcal{M}\delta^3(\vec{x})$$

where

$$Z(\bar{\phi})=Z^{\mu}_{\mu}(\bar{\phi}) \quad c_s^2(\bar{\phi})=Z_{ii}(\bar{\phi})/Z(\bar{\phi}) \quad m^2(\bar{\phi})\equiv\frac{d^2V}{d\phi^2}|_{\bar{\phi}}$$

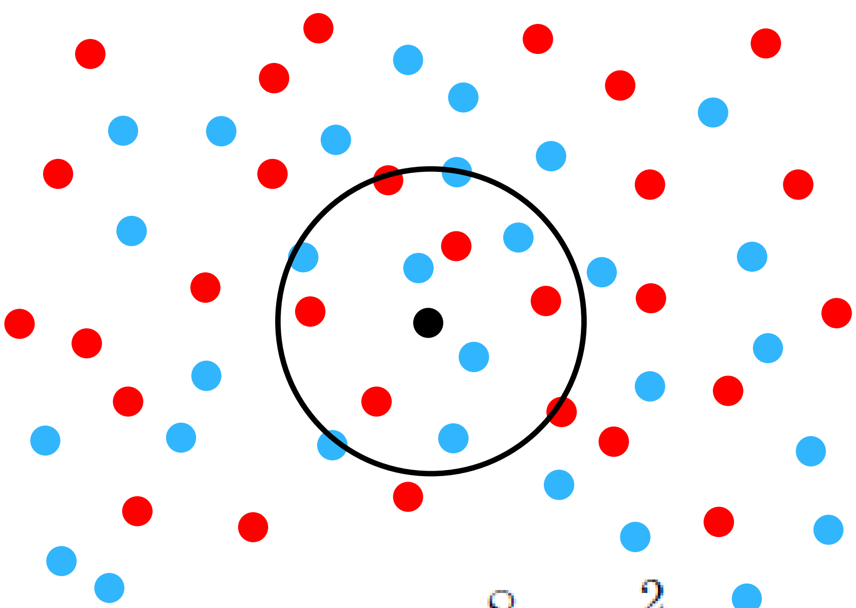
Resulting in a scalar potential for a test mass

$$V(r)=-\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})}\frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}c_s(\bar{\phi})}r}}{4\pi r}\mathcal{M}$$

Debye Screening of Electromagnetism

The influence of a charged particle in a plasma is only felt up to the Debye length

~ $1/m_{Debye}$



$$m^2_{\text{Debye}} = \frac{8\pi n e^2}{k_B T}$$