Experimental Searches for Screened Dark Energy

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Outline:

Screening scalar fields

Radiatively Stable Screening

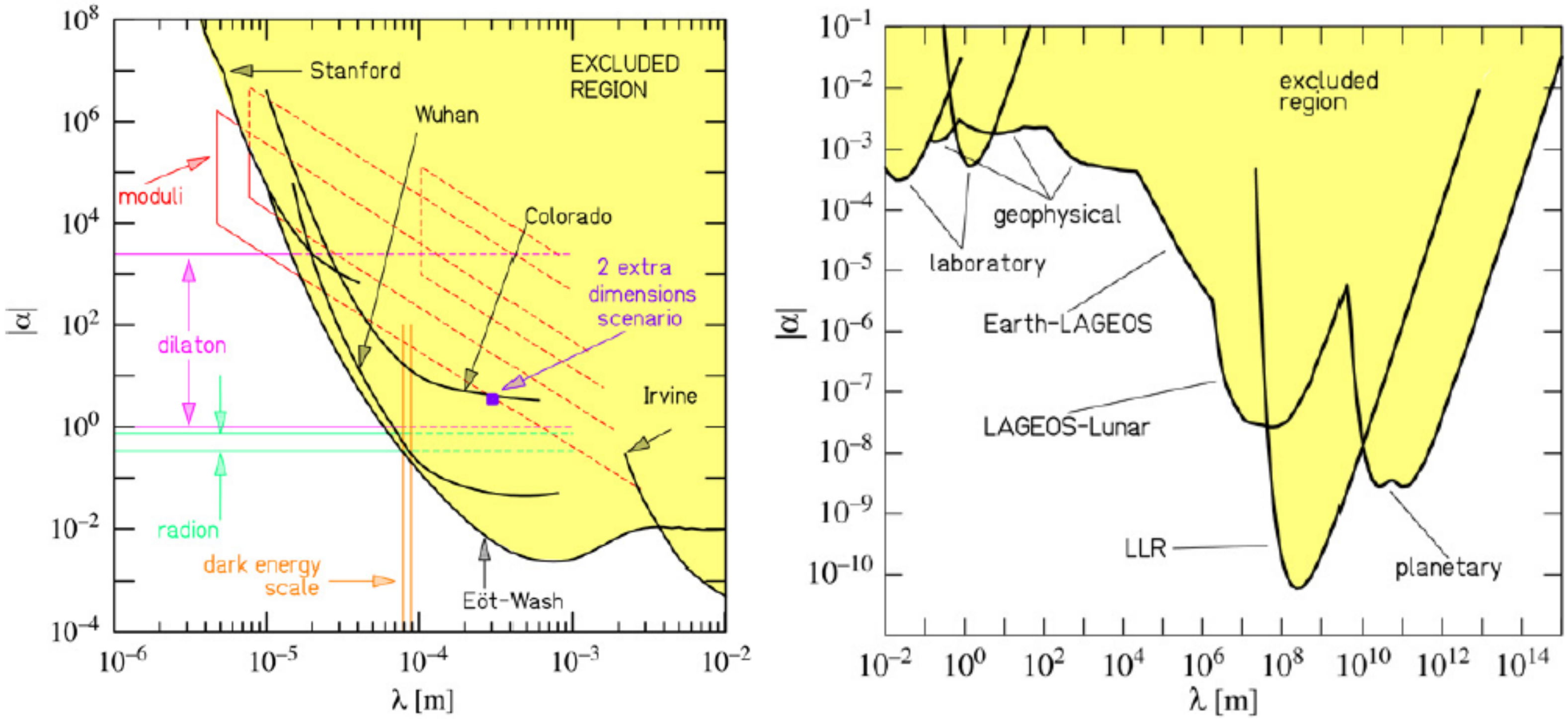
Atom Interferometry

Collider Constraints

Problem: New Fields and New Forces

The existence of a fifth force is 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)

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

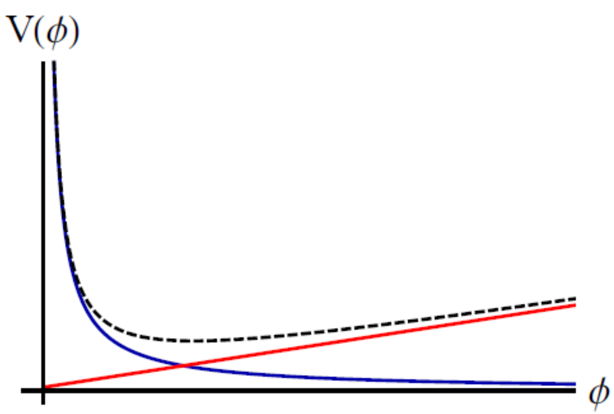
Khoury, Weltman (2004).

Chameleon Screening

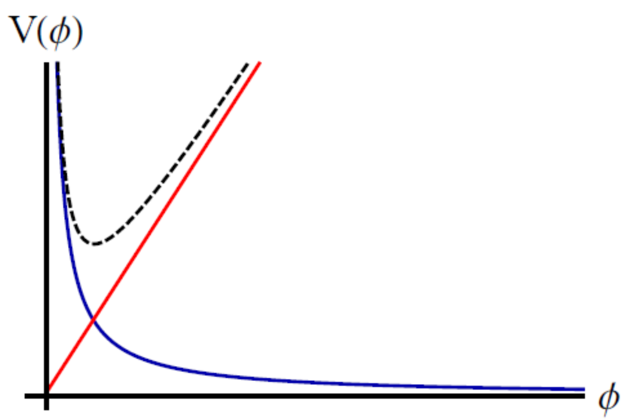
The mass of the chameleon changes with the environment

Field is governed by an effective potential

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



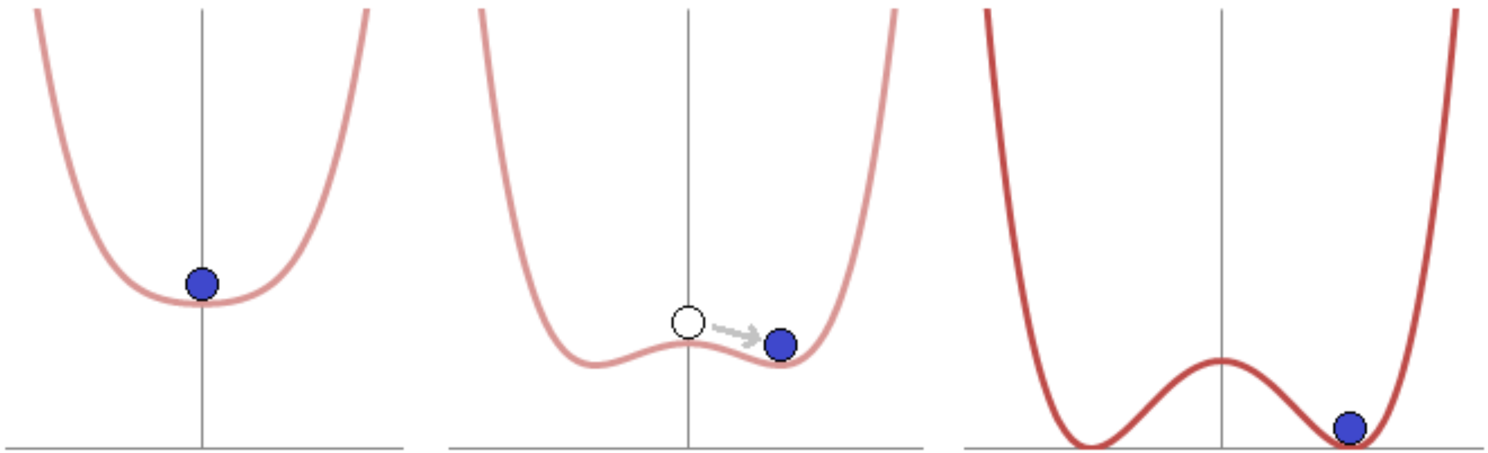
Low density



High density

Symmetron Screening

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



Force on test particle vanishes when symmetry is restored

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

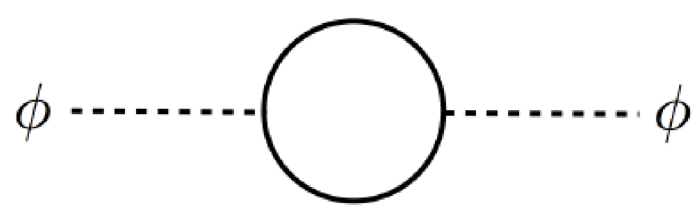
Hinterbichler, Khoury (2010).

Radiative Stability

Screening mechanisms rely on non-linearities

- Requires the introduction of non-renormalisible operators
- In the absence of a symmetry (e.g. Galileon, DBI), relevance of these terms would indicate break down of EFT

Coupling to matter can also generate large corrections. E.g. standard model loops generate a large scalar mass



Radiatively Stable Symmetron

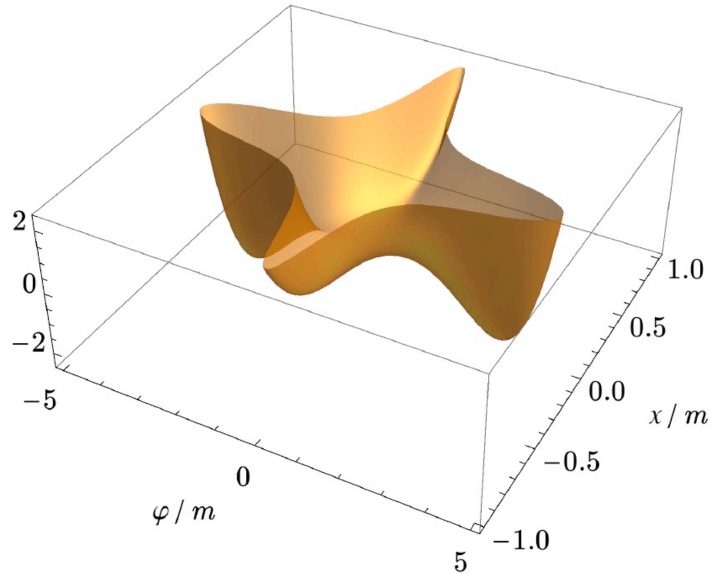
Start with a scale invariant model

$$-\mathcal{L} = \frac{1}{2}\phi_{,\mu}\phi^{,\mu} + \frac{1}{2}X_{,\mu}X^{,\mu} + \frac{\lambda}{4}\phi^2 X^2 + \frac{\kappa}{4!}X^4$$

Minimally couple to gravity in the Jordan frame

$$F(\phi) = 1 + \frac{\phi^2}{M^2}$$

One loop potential



Garbrecht, Millington. (2015). CB, Copeland, Millington. (2016).

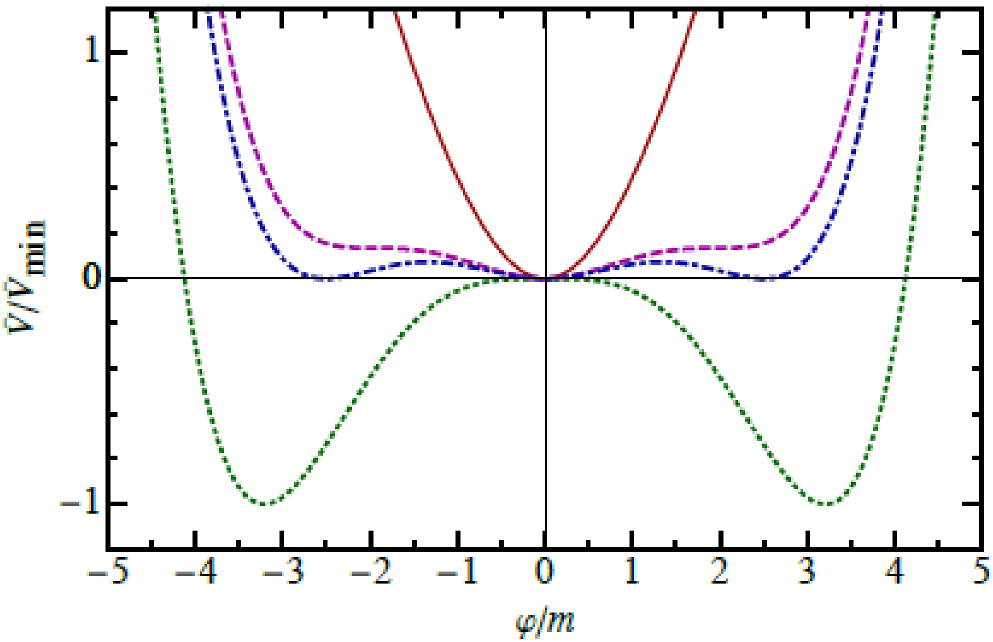
Radiatively Stable Symmetron

One loop bare potential for ‘symmetron’ field, if λ=κ,

$$V^{(1)}(\varphi) = \left(\frac{\lambda}{16\pi}\right)^2 \varphi^4 \left(\ln \frac{\varphi^2}{m^2} - Y\right)$$

Global minima at

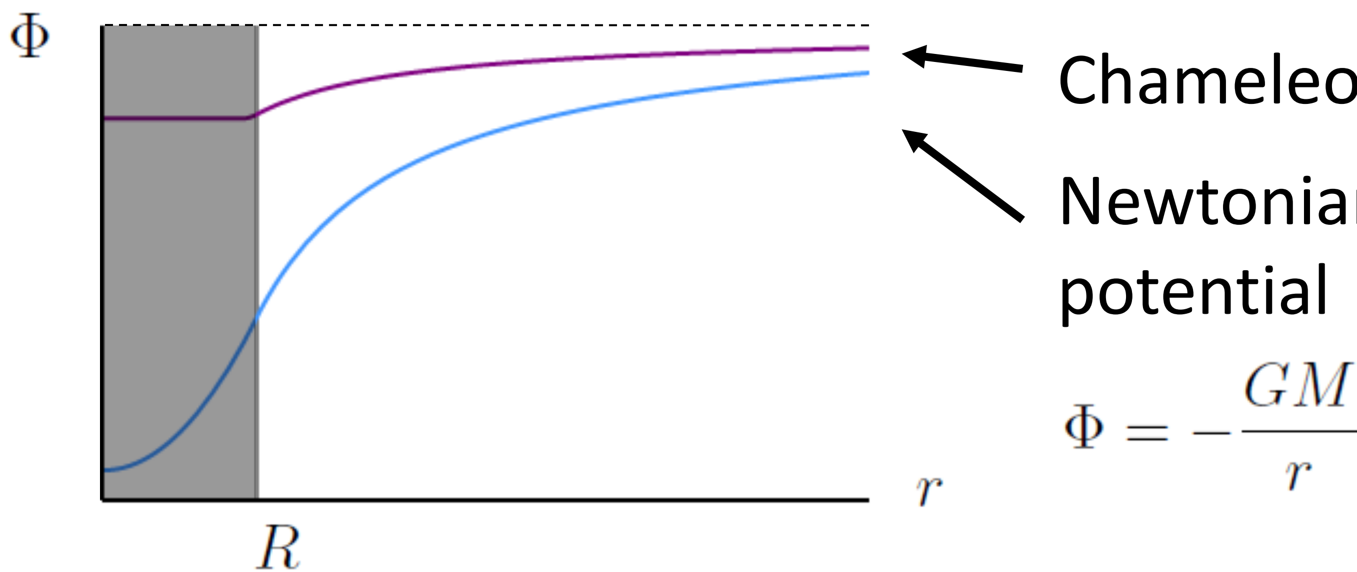
$$\chi = 0$$



CB, Copeland, Millington. (2016).

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 standard light scalar fields

The Chameleon Potential

Around a static, spherically symmetric source of constant density

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

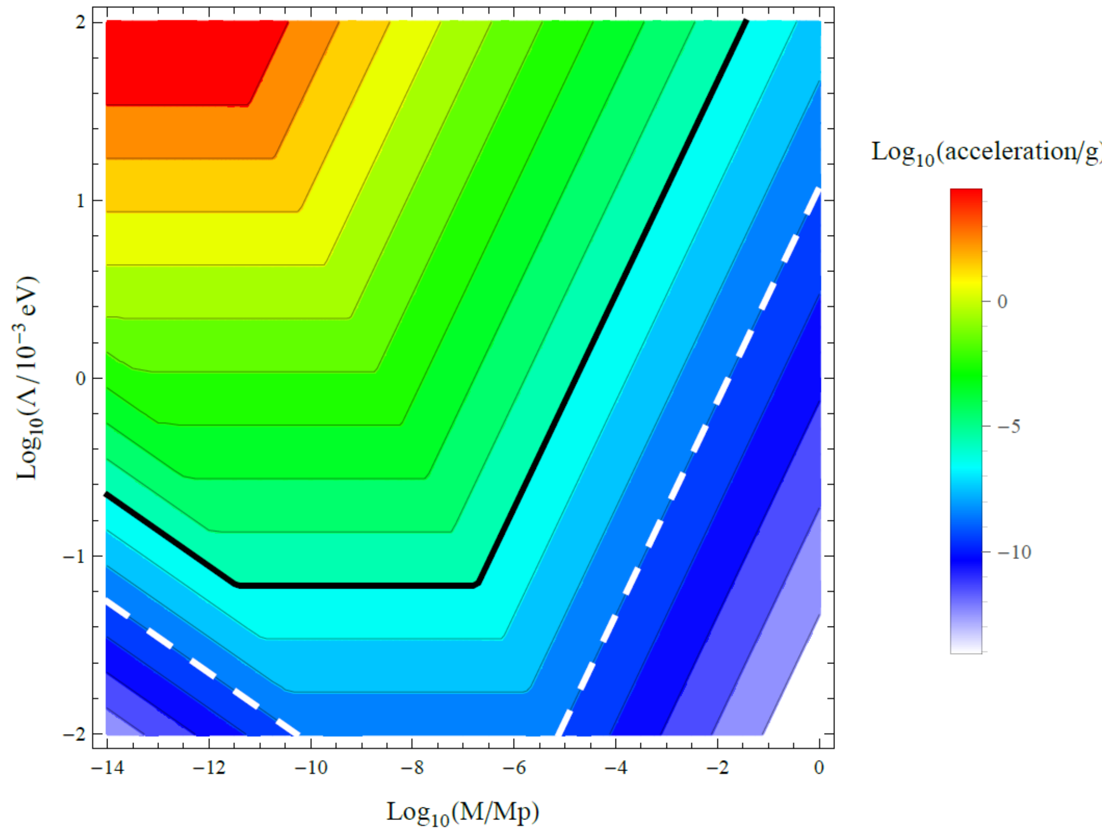
$$\lambda_A = \begin{cases} 1\,, & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg}\,, & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

'Small' objects feel an unscreened fifth force

E.g. Over a large part of the chameleon parameter space atoms are unscreened in a laboratory vacuum

Proposed Sensitivity of Atom Interferometry

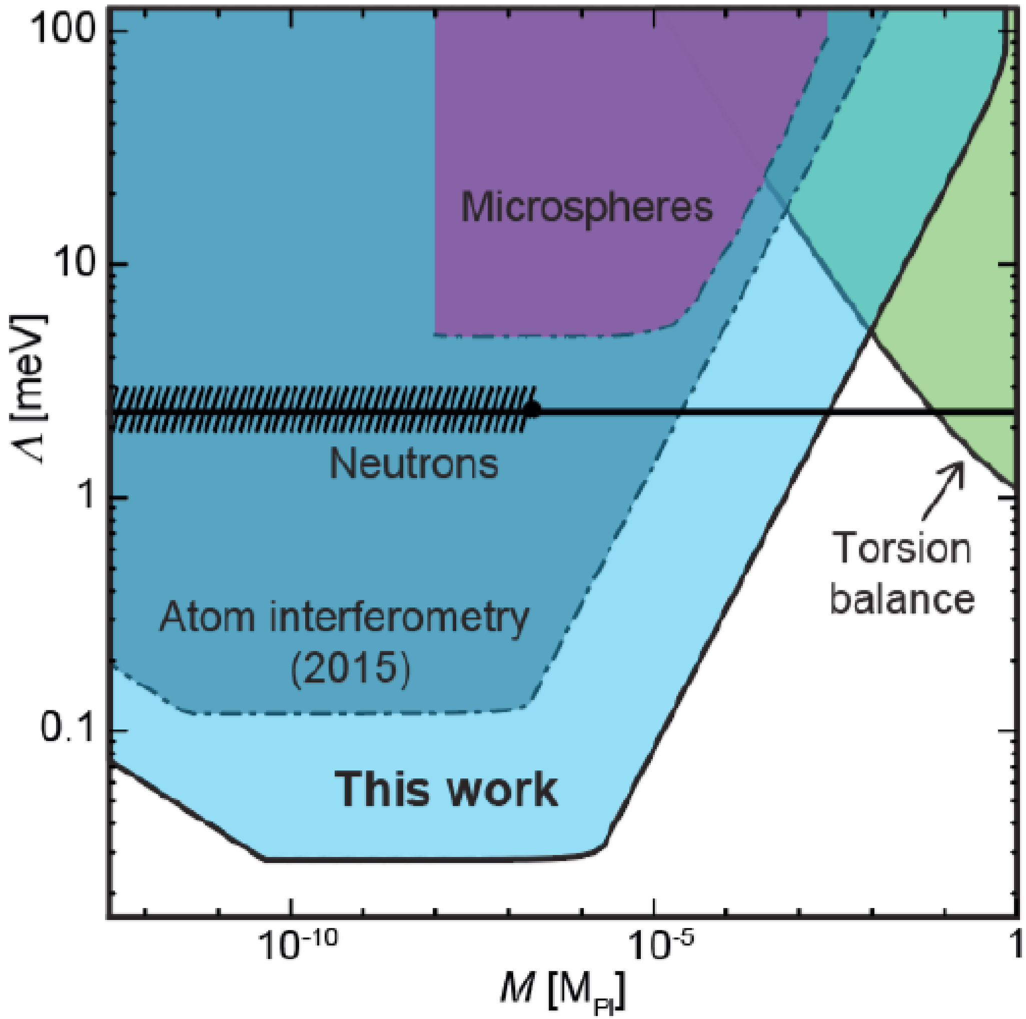
- Systematics: Stark effect, Zeeman effect, phase shifts due to scattered light, movement of beams
- All negligible at 10^{-6} g sensitivity (solid black line)
- Controllable down to 10^{-9} g (dashed white line)



CB, Copeland, Hinds. (2015)

For numerical estimates see: Schlögel, Clesse, Füzfa (2015). Elder et al. (2016).

Berkley Experiment

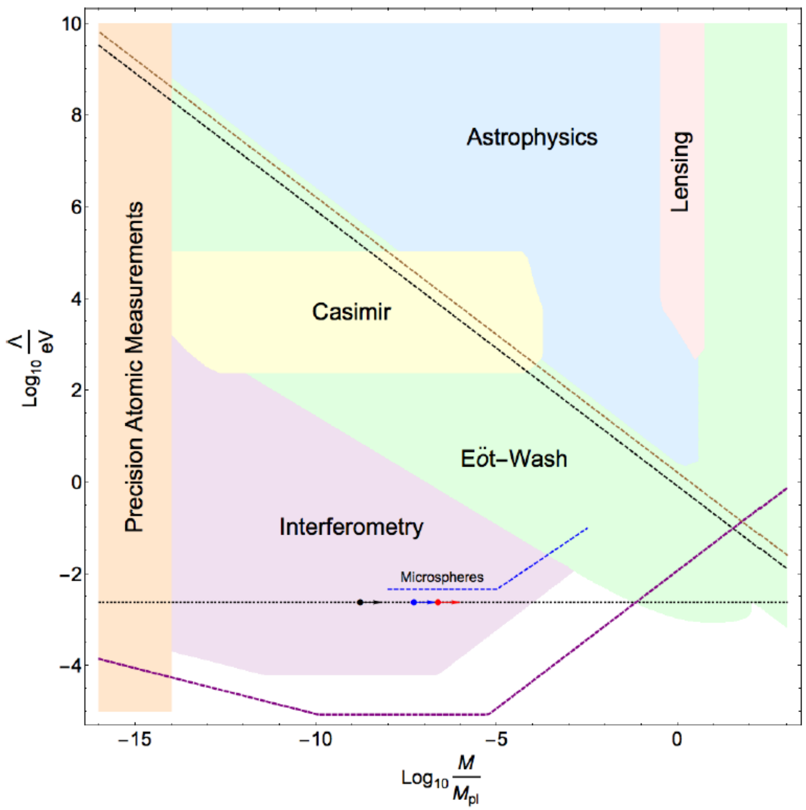


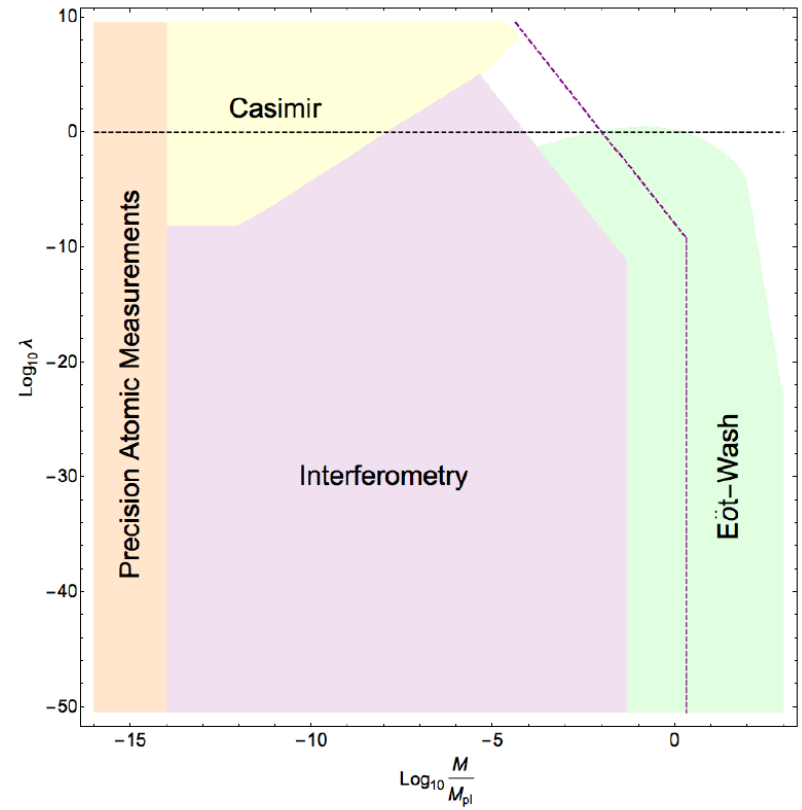
Hamilton et al. (2015) Jaffe et al. (2016)
See also: Neutron interferometry experiments: Lemmel et al. (2015)
Optically levitated microspheres: Rider et al. (2016)

Combined Chameleon Constraints

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

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

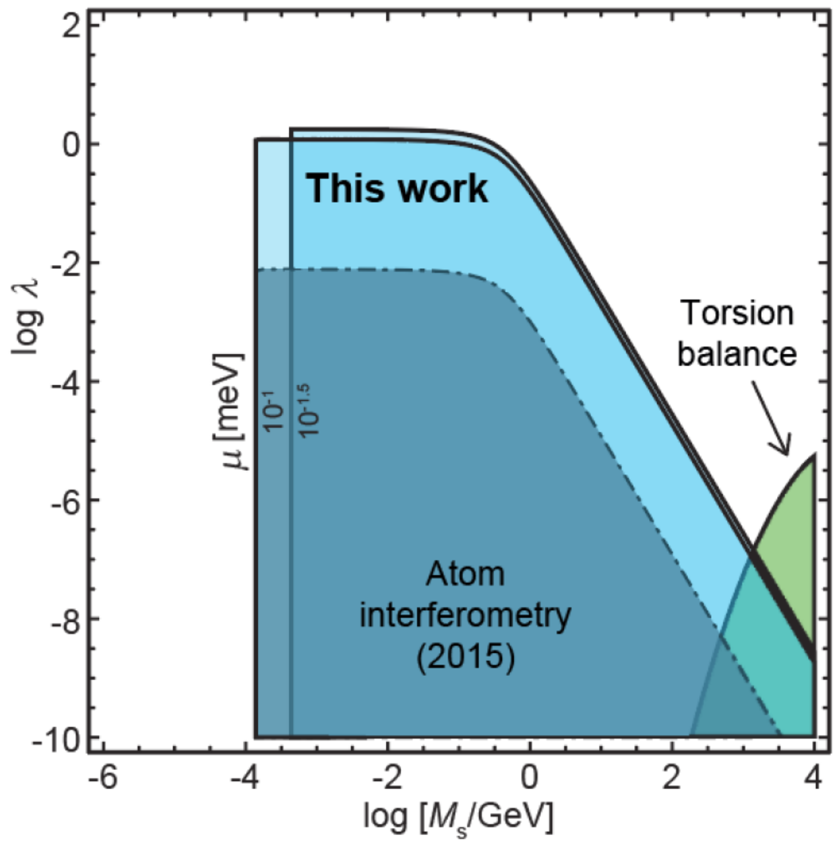




CB, Sakstein. (2016)

Symmetron Constraints

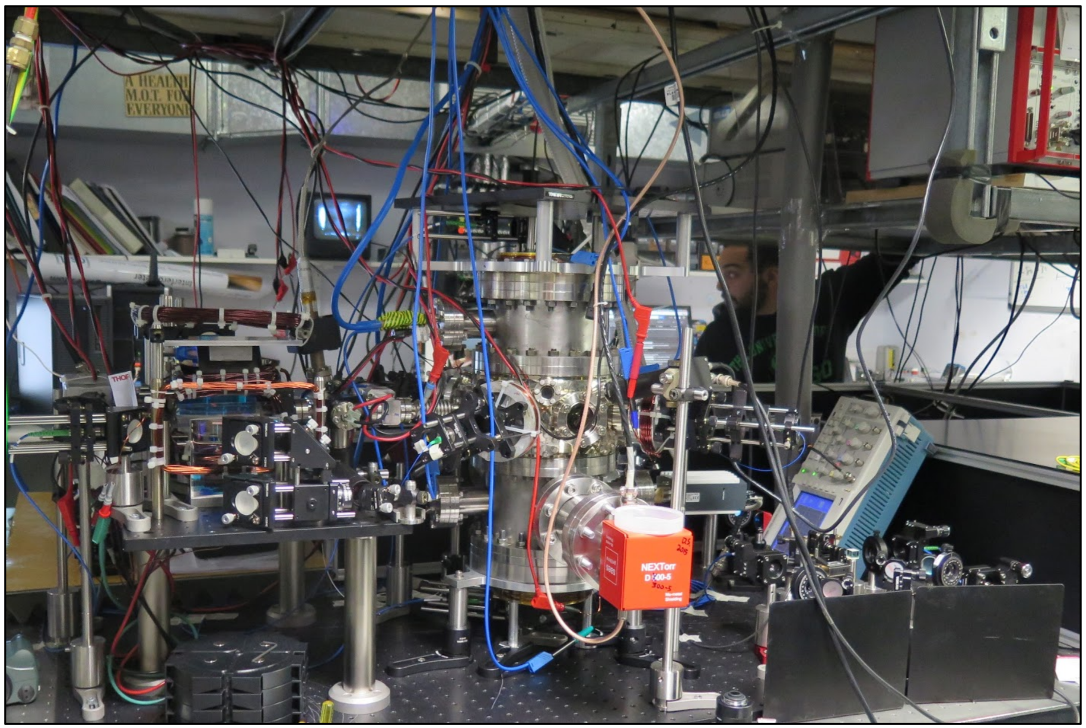
$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$



Jaffe et al. (2016). CB, Kuribayashi-Coleman, Stevenson, Thrussell. (2016). Brax, Davis 2016

Imperial Experiment

Development underway at the Centre for Cold Matter, Imperial College (Group of Ed Hinds)



Experiment rotated by 90 degrees from the Berkeley experiment, so that no sensitivity to Earth’s gravity

Missing Energy at the LHC

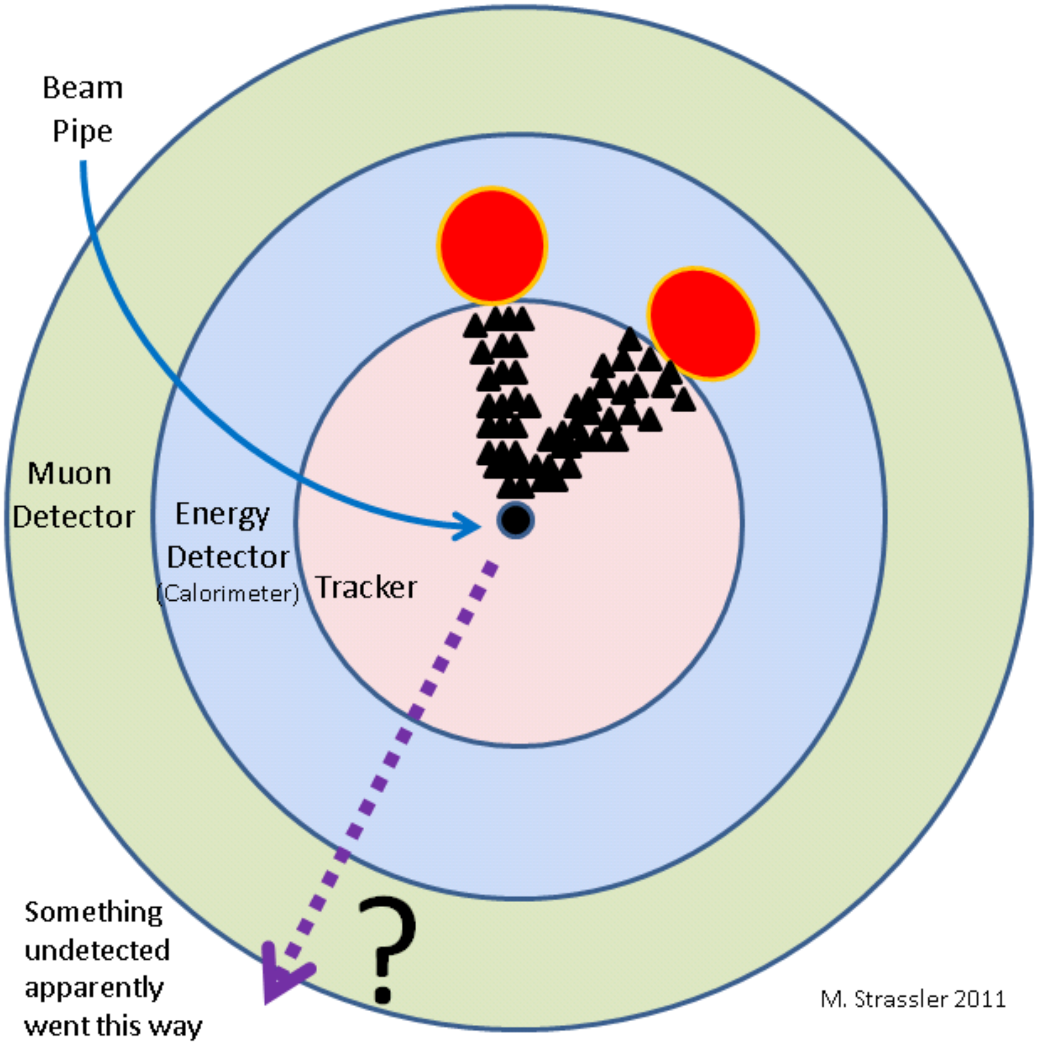
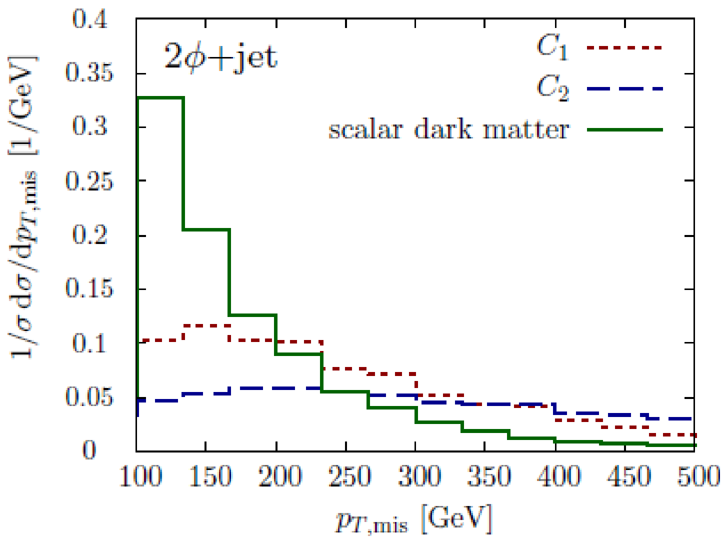


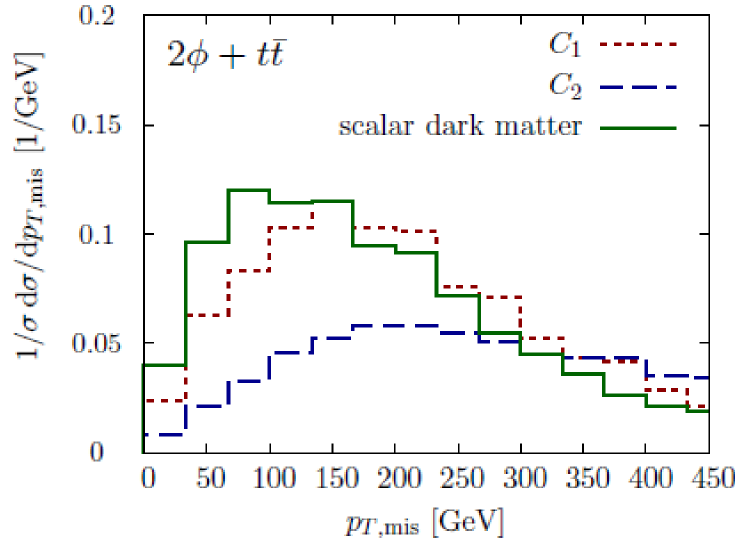
Image credit: Matt Strassler. https://profmattstrassler.com/

Missing Energy at the LHC

Lowest order couplings to matter in a shift symmetric theory

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu \qquad \mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$





CB, Brax, Englert, Spannowsky (2016)

For Comparison

Source of bound	Lower bound on M in GeV	Environment
Unitarity at the LHC	30	Lab. vac.
CMS mono-lepton	120	Lab. vac.
CMS mono-photon	490	Lab. vac.
Torsion Balance	7×10^{-5}	Lab. vac.
Casimir effect	0.1	Lab. vac.
Hydrogen spectroscopy	0.2	Lab. vac.
Neutron scattering	0.03	Lab. vac.
Bremsstrahlung	4×10^{-2}	Sun
	0.18	Horizontal Branch
Compton Scattering	0.24	Sun
	0.81	Horizontal Branch
Primakov	4×10^{-2}	Sun
	0.35	Horizontal Branch
Pion exchange	~ 92	SN1987a

PPN constraints from solar system measurement

$$\mathcal{M} \gtrsim \mathcal{O}(\mathrm{eV})$$

Brax, CB (2014). Sakstein (2014).

Collider Constraints

Recasting existing dark matter missing energy searches

$$\mathcal{L}_1 \qquad M \gtrsim 237.4 \text{ GeV} \qquad \text{(ATLAS)}$$
$$2\phi + t\bar{t} \qquad M \gtrsim 192.8 \text{ GeV} \qquad \text{(CMS)}$$

$$\mathcal{L}_2 \qquad M \gtrsim 693.9 \text{ GeV} \qquad \text{(ATLAS)}$$
$$2\phi + \text{jet} \qquad M \gtrsim 822.8 \text{ GeV} \qquad \text{(CMS)}$$

Excludes e.g. disformal cosmological models.

Brax, CB, Englert (2015). Brax, CB, Englert, Spannowsky (2016).

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Summary

Light scalar fields can exist in our universe if they possess a screening mechanism

It is possible to build radiatively stable models that are not shift-symetric

Screening does not mean these fields are impossible to detect

Atom interferometry is a particularly powerful technique

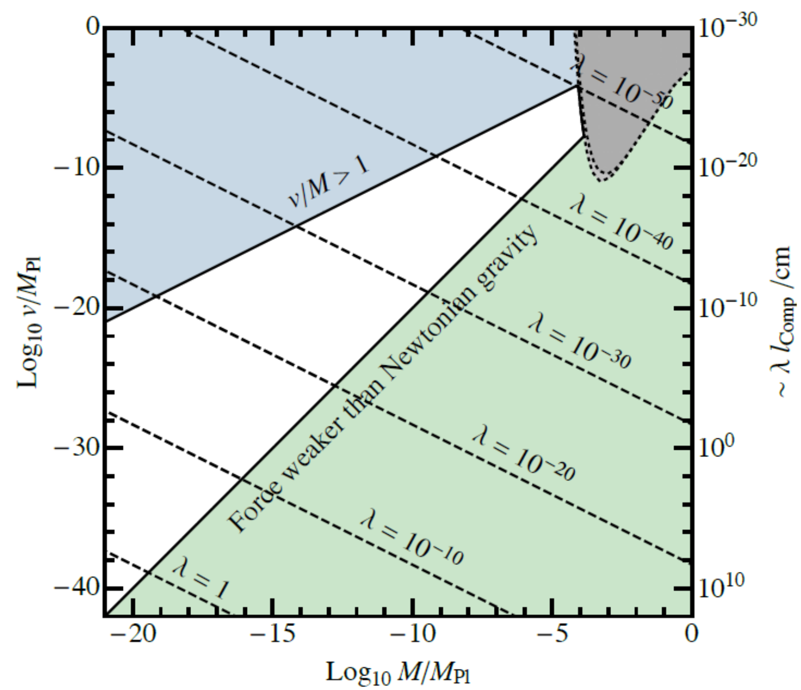
The most strongly coupled models could be detected at the LHC

Available Parameter Space

Radiatively stable if

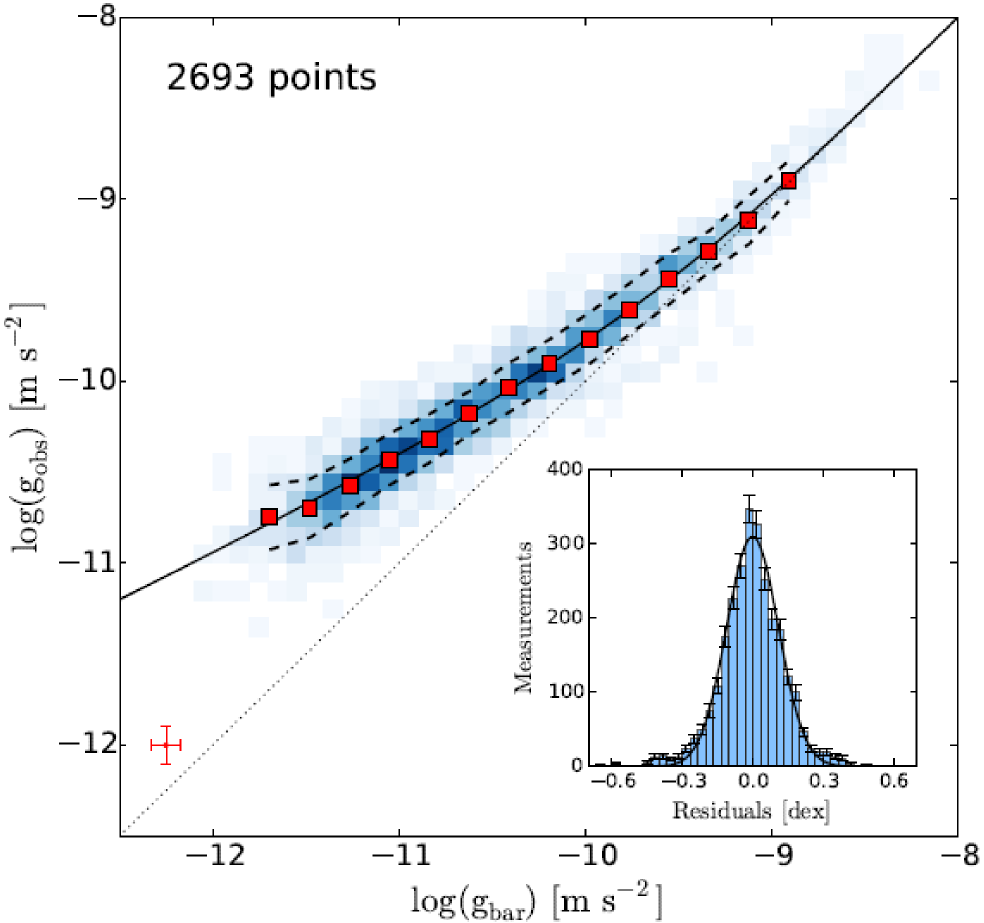
$$\frac{\phi_{\rm min}}{M} < 1 \qquad\qquad \lambda > \left(\frac{v_H}{M_P}\right)^2$$

Also need to satisfy Eöt-Wash, and be in symmetry broken phase in current cosmological vacuum



Screened Forces in Galaxies

Radial Acceleration Relation



153 galaxies,

~ 2700 data points

$$g_{\rm obs} = \frac{V^2(R)}{R}$$

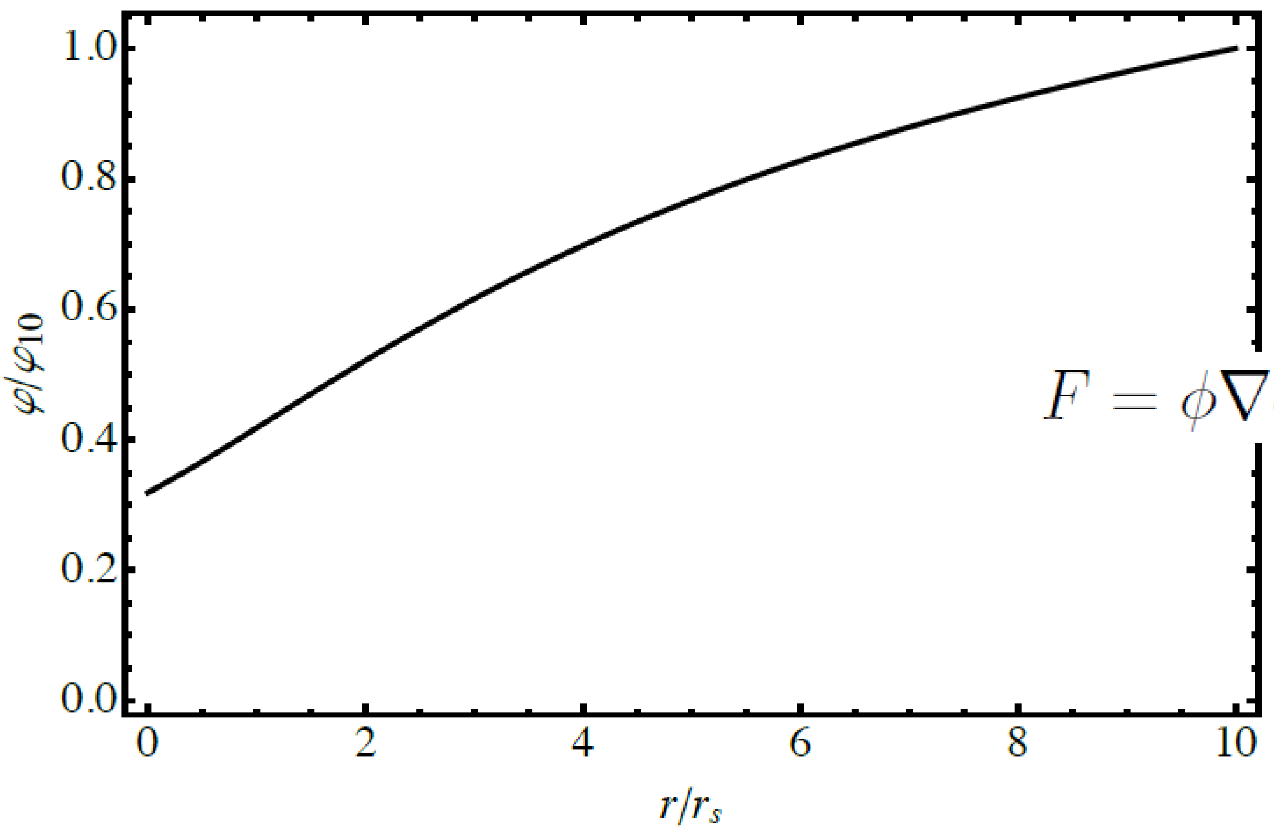
Extension of the baryonic Tully-Fisher relation

$$g_{\rm obs} = \mathcal{F}(g_{\rm bar}) = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_{\dagger}}}}$$

McGaugh, Lelli, Schombert. 2016. See also Keller and Wadsley 2016.

Symmetron Field Profile for a Galaxy

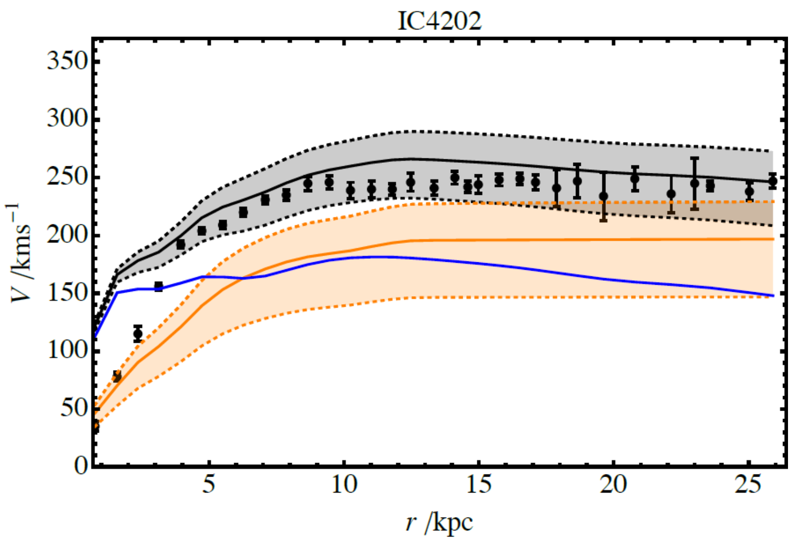
To explain rotation curves and the acceleration relation with only a symmetron force and no dark matter

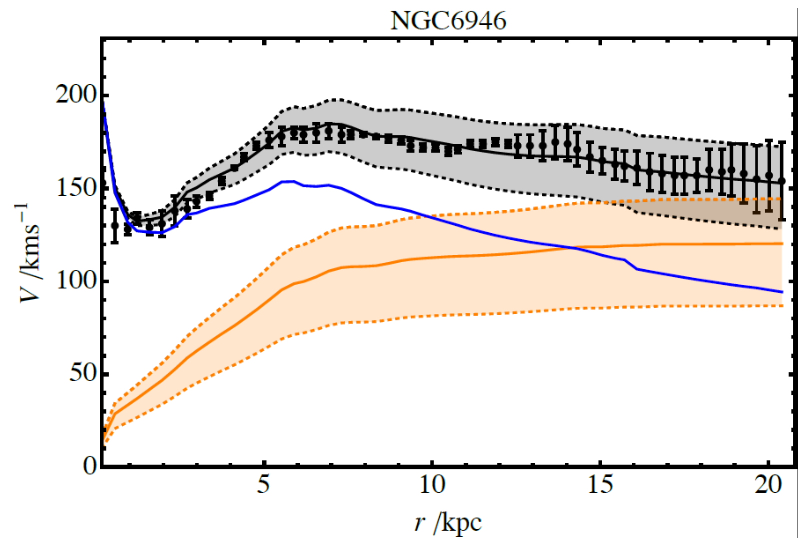


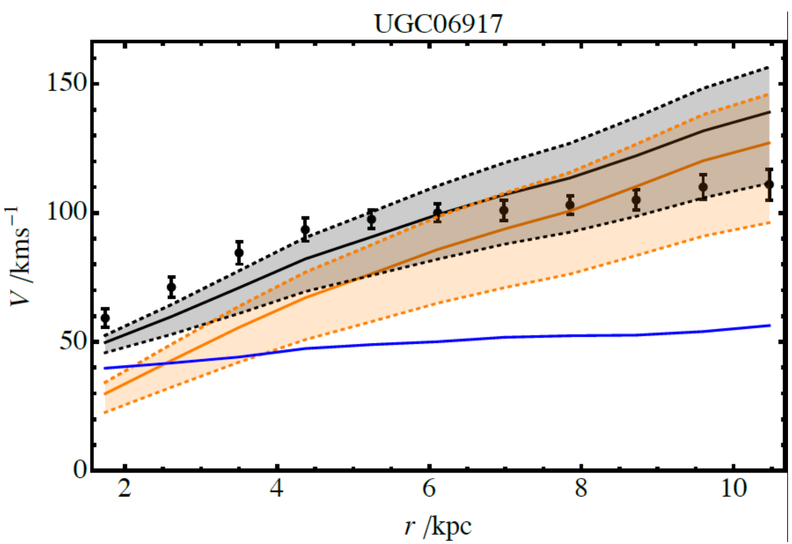
$$F = \phi \nabla \phi / M^2$$

CB, Copeland, Millington. (2016)

Galaxy Rotation Curves







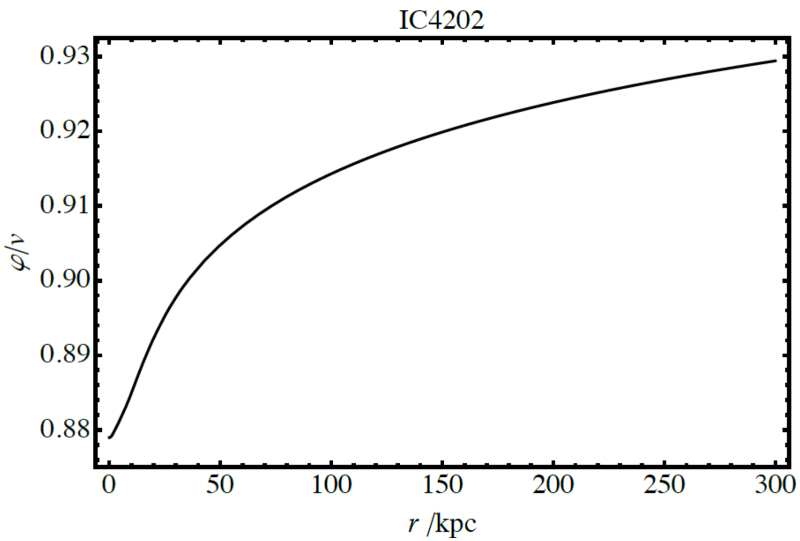
$$\mu = 10^{-40}\ \mathrm{GeV}$$

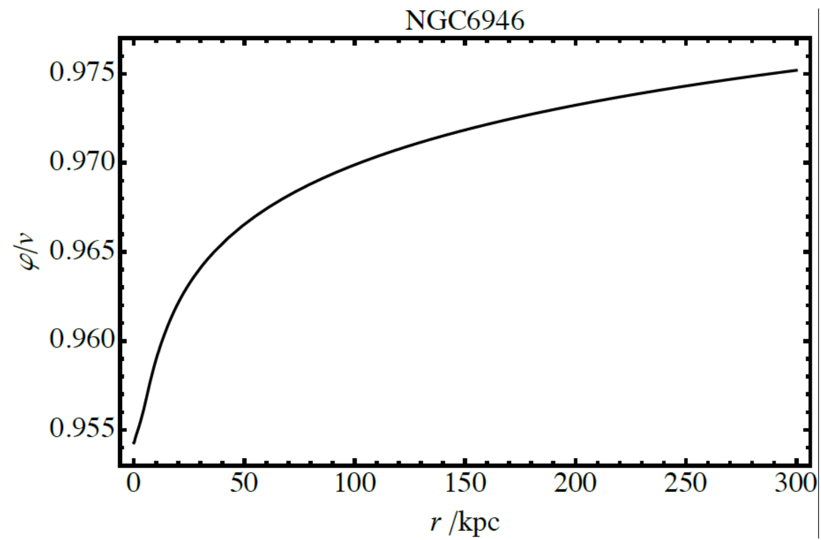
$$M = M_{\mathrm{Pl}}/10$$

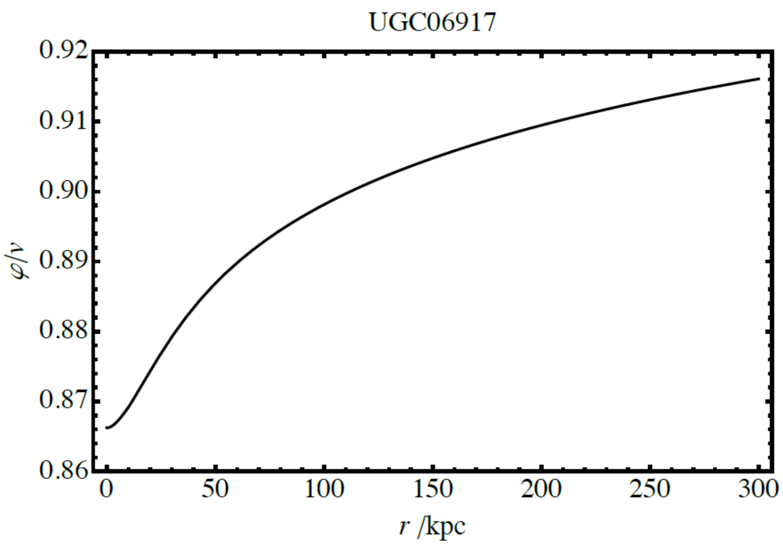
$$v = M/170$$

CB, Copeland, Millington. (2016)

Symmetron Field Profiles







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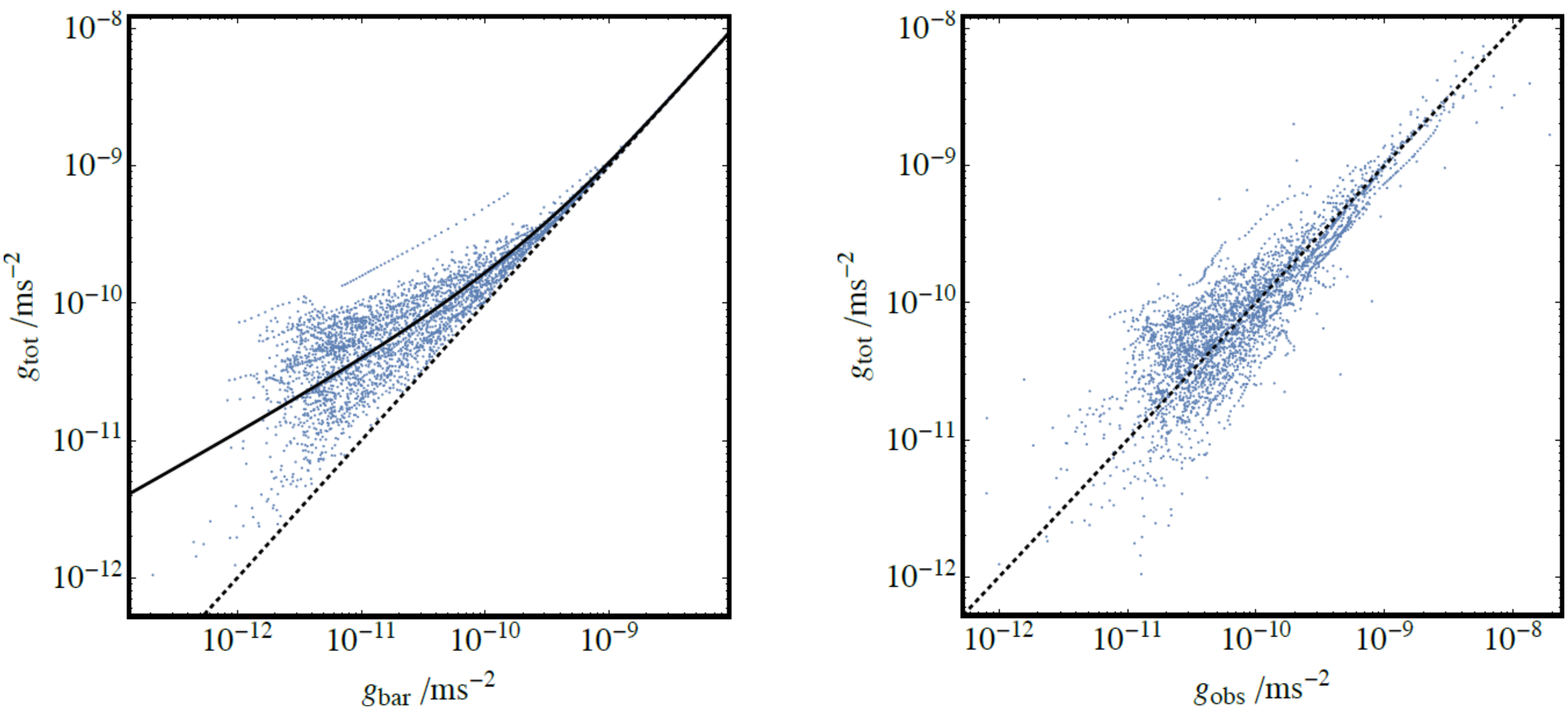
CB, Copeland, Millington. (2016)

Symmetron Acceleration Relation



CB, Copeland, Millington. (2016)