Connections between Modified Gravity and Particle Physics

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Outline:

Fifth forces and scale invariance

Screening fifth forces

Screened forces on galactic scales

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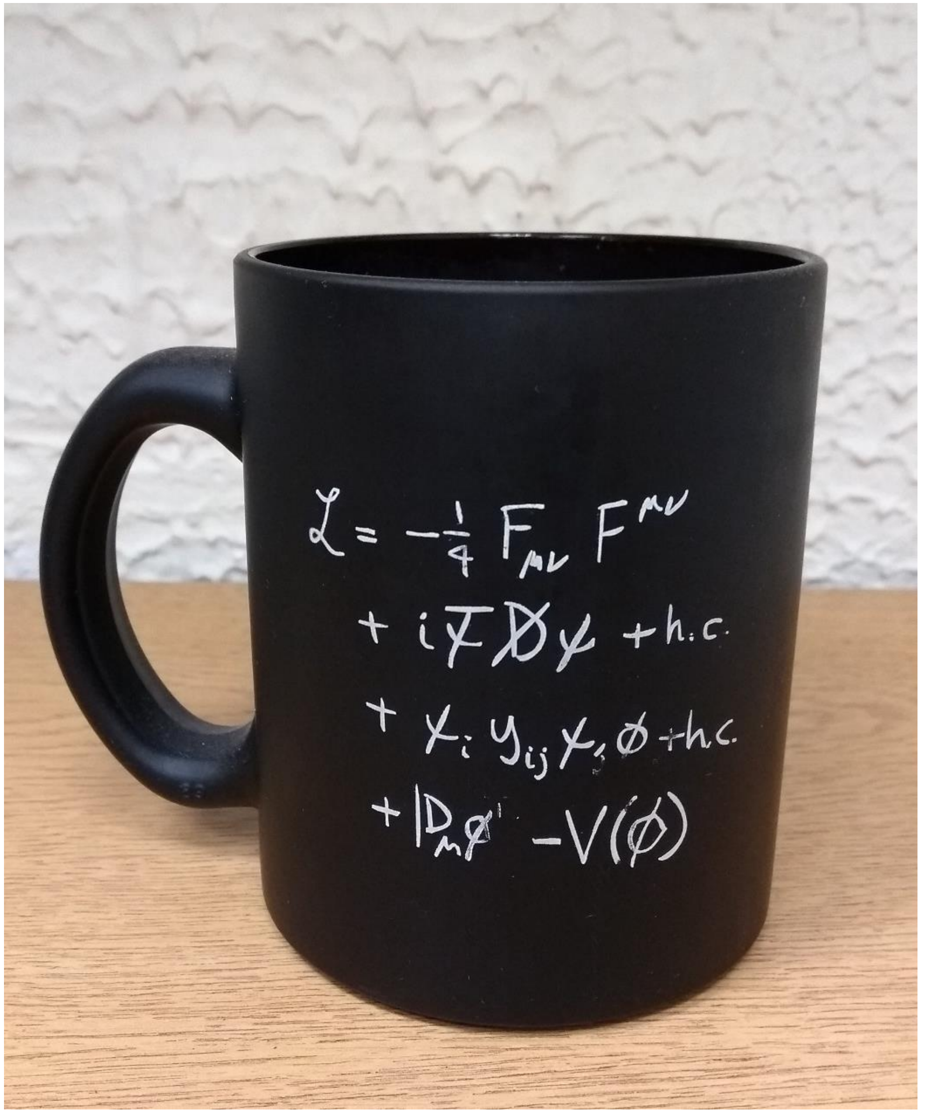
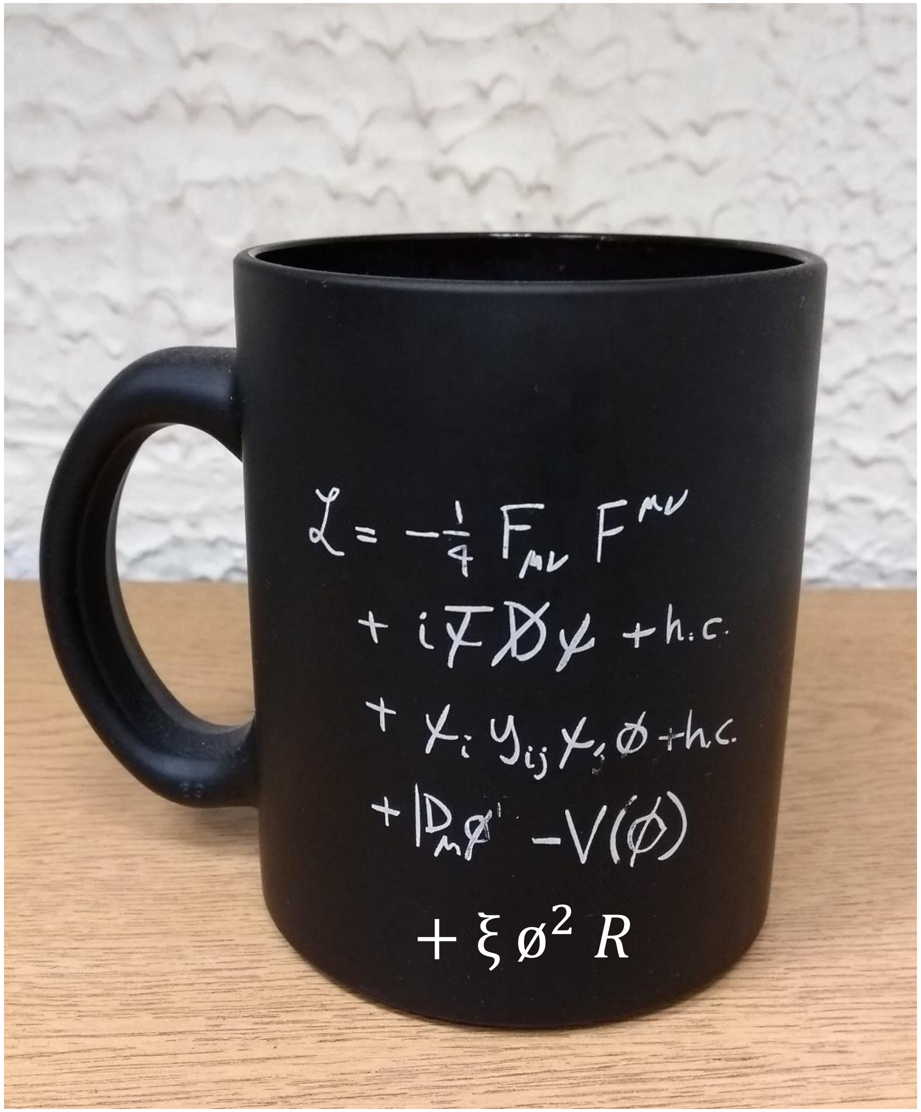
Modified
Gravity
Physics Beyond
Standard Model

The Standard Model



The Standard Model



Chernikov, Tagirov (1968). Callan, Coleman, Jackiw (1970). Tagirov (1973)

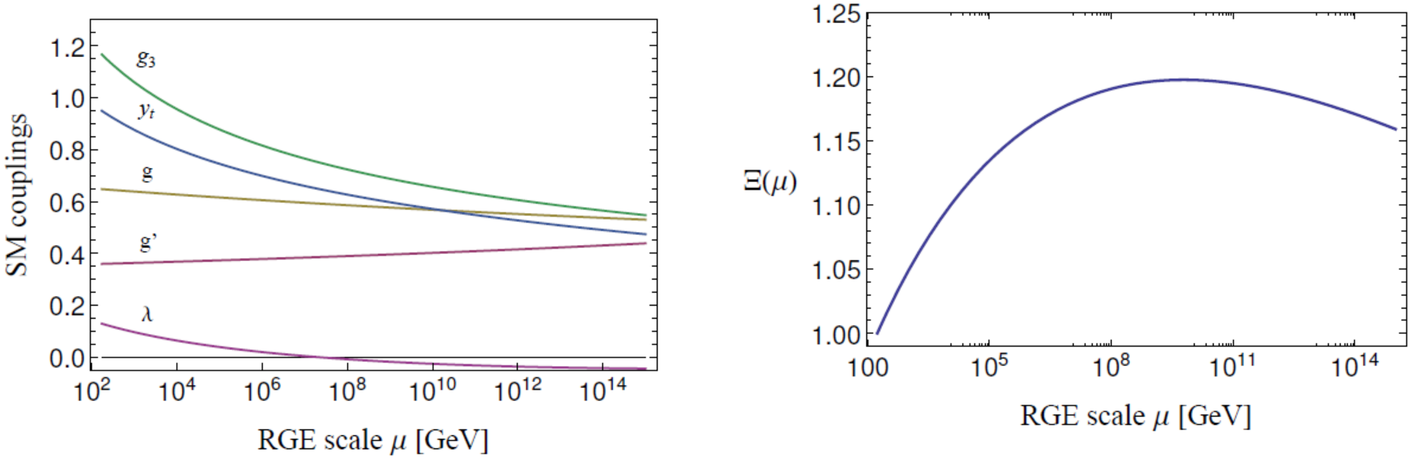
Conformally Coupled Scalar Fields

Non-minimal couplings to gravity are generated radiatively for scalar fields with interactions

If the Lagrangian contains

$$\xi(\mu) R \Phi^\dagger \Phi$$

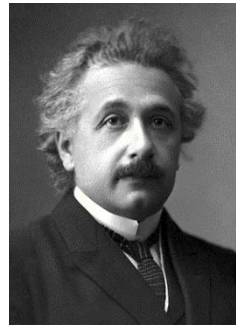
Cannot set this to zero at all scales



$$\Xi \equiv (\xi - 1/6)/(\xi_{\rm EW} - 1/6)$$

Herranen, Markkanen, Nurmi, Rajantie. (2015)

Jordan vs Einstein Frame



Jordan Frame

- Scalar field coupled directly to gravity
- No direct coupling to matter
- Matter fields move on geodesics of a metric which depends on spin 0 and spin 2 fields

Einstein Frame

- Scalar field coupled directly to matter
- No non-minimal couplings to gravity
- Matter fields don't move on geodesics of the metric, as they also experience a fifth force

Scalar Tensor Theories

Jordan and Einstein frame for a Brans-Dicke theory

$$S = \int d^4x\sqrt{-\tilde{g}}\phi\tilde{R} + S_m[\tilde{g}_{\mu\nu},\psi_m]$$
$$= \int d^4x\sqrt{-g}\left[R + \frac{3\Box\phi}{\phi} - \frac{9}{2}(\nabla \ln \phi)^2\right] + S_m[\phi^{-1}g_{\mu\nu},\psi_m]$$

More generally

$$S = \int d^4x\sqrt{-g}F(\phi)R = \int d^4x\sqrt{-\tilde{g}}\tilde{R}$$

$$\tilde{g}_{\mu\nu} = F(\phi)g_{\mu\nu}$$

Fifth Forces

Coupling to matter can be expanded as

$$S_{\rm SM}[A^2(\chi)\tilde{g}_{\mu\nu},\{\psi\}] \;=\; S_{\rm SM}[\tilde{g}_{\mu\nu},\{\psi\}] \;+\; \frac{\chi^n}{nM^n}\,\tilde{g}_{\mu\nu}\tilde{T}^{\mu\nu} \;+\; \ldots$$

The scalar field is sourced by matter – through the trace of the energy momentum tensor

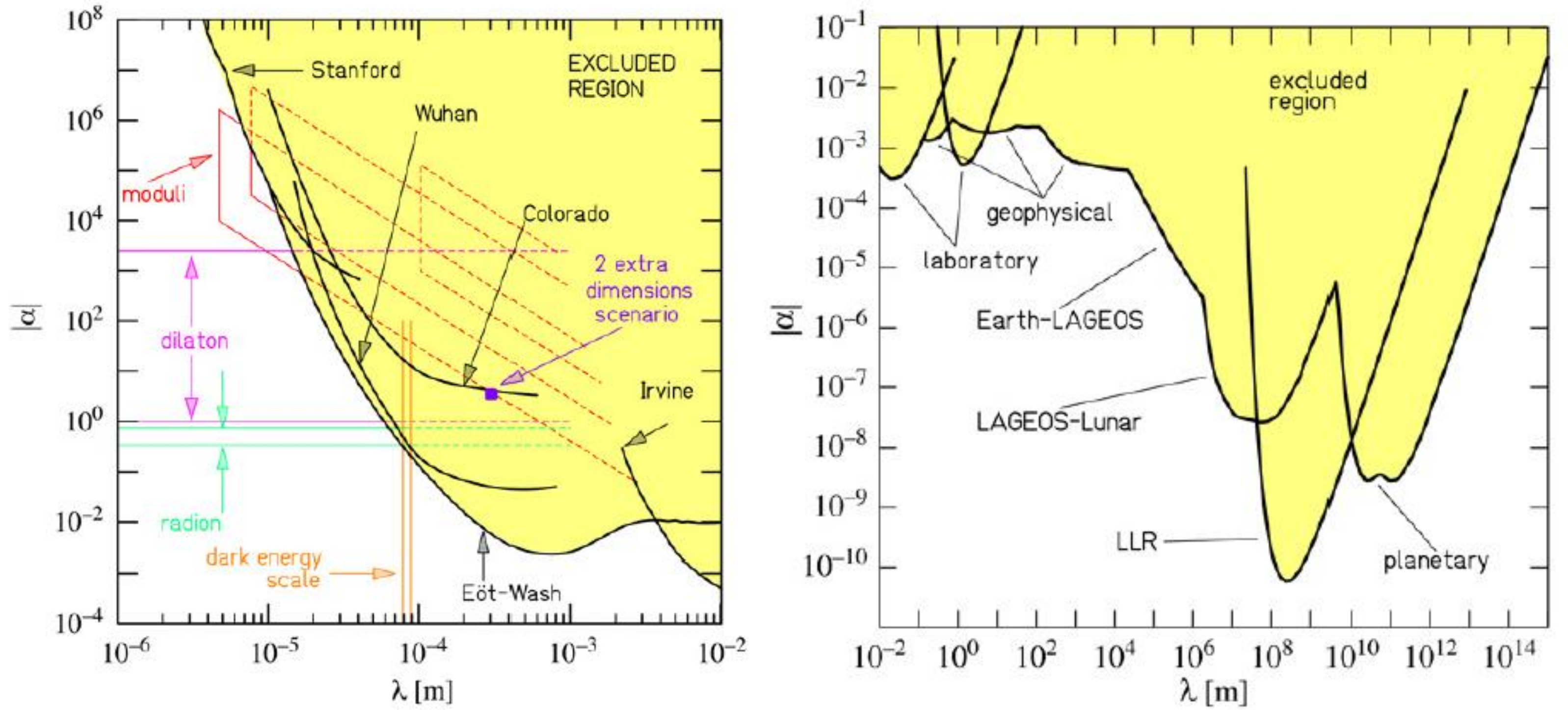
Test particles feel a fifth force

$$\vec{F} \;=\; -\,\frac{\chi^{n-1}}{M^{n-1}}\,\vec{\nabla}\,\frac{\chi}{M}$$

Yukawa Fifth Forces

The existence of a Yukawa 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)

FIFTH FORCES AND SCALE INVARIANCE

With Ed Copeland and Pete Millington,
arXiv: 1804.07180

Related work:

Wetterich, 1988. Buchmüller, Dragon, 1989. Shaposhnikov, Zenhausern, 2009. Blas, Shaposhnikov, Zenhausern, 2011. Brax, Davis, 2014. Ferreira, Hill, Ross, 2017.

Toy Standard Model

$$S_{\rm SM}[g_{\mu\nu},\{\psi\}] \;=\; \int {\rm d}^4x\,\sqrt{-g}\bigg[-\,\frac{1}{2}\,g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi\;+\;\frac{1}{2}\,\mu^2\,\phi^2\;-\;\frac{\lambda}{4!}\,\phi^4$$
$$-\;\bar{\psi}ie^{\mu}_{a}\gamma^a\overset{\leftrightarrow}{\partial}_\mu\psi\;-\;y\,\bar{\psi}\phi\psi\bigg]\,,$$

Transform to the Einstein frame and rescale SM fields

$$\tilde{\mathcal{L}}\;=\;-\,\frac{1}{2}\,\tilde{g}^{\mu\nu}\,\partial_\mu\tilde{\phi}\,\partial_\nu\tilde{\phi}\;+\;\tilde{g}^{\mu\nu}\,\tilde{\phi}\,\partial_\mu\tilde{\phi}\,\partial_\nu\ln A(\chi)\;-\;\frac{1}{2}\,\tilde{g}^{\mu\nu}\,\tilde{\phi}^2\,\partial_\mu\ln A(\chi)\,\partial_\nu\ln A(\chi)$$
$$+\;\frac{1}{2}\,\mu^2\,A^2(\chi)\,\tilde{\phi}^2\;-\;\frac{\lambda}{4!}\,\tilde{\phi}^4\;-\;\bar{\tilde{\psi}}i\overset{\leftrightarrow}{\tilde{\not{\partial}}}\tilde{\psi}\;-\;y\,\bar{\tilde{\psi}}\tilde{\phi}\tilde{\psi}\,,$$

No explicit coupling to fermions – only Higgs portal interactions

Higgs Portals and Fifth Forces

Expanding

$$A^2(\chi) \;=\; a \,+\, b\,\frac{\chi}{M} \,+\, c\,\frac{\chi^2}{M^2} \,+\, \mathcal{O}\left(\frac{\chi^3}{M^3}\right)$$

Find three types of interaction with the Higgs

- Mass mixing

$$\tilde{\mathcal{L}}_M \;=\; \alpha_M\,\tilde{\phi}\,\tilde{\chi}$$

- Higgs portal

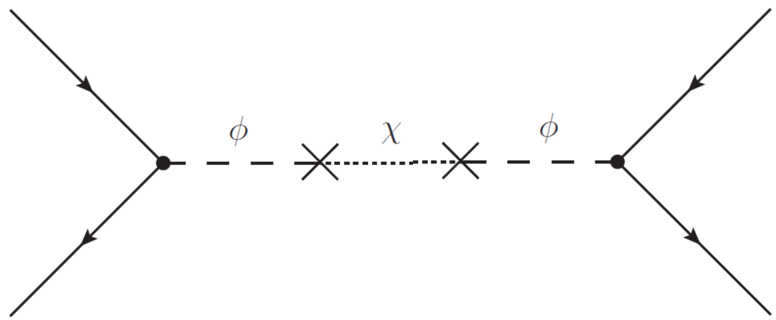
$$\tilde{\mathcal{L}}_P \;=\; \frac{1}{2}\alpha_{P12}\,\tilde{\phi}\,\tilde{\chi}^2 \,+\, \frac{1}{4}\alpha_{P22}\,\tilde{\phi}^2\,\tilde{\chi}^2 \,+\, \frac{1}{2}\alpha_{P21}\,\tilde{\phi}^2\,\tilde{\chi}$$

- Kinetic mixing/braiding

$$\tilde{\mathcal{L}}_B \;=\; \alpha_B\,\tilde{g}^{\mu\nu}\,\partial_\mu\tilde{\phi}\,\partial_\nu\tilde{\chi}$$

Fifth Forces

Consider Higgs mediated scattering of electrons (Møller scattering)



Mass mixing of Higgs with conformally coupled scalar

$$\tilde{\mathcal{L}}_M = \alpha_M \tilde{\phi} \tilde{\chi}$$

Leads to long range fifth force potential

$$V(r) = -y^2 \int \frac{\mathrm{d}^3\mathbf{Q}}{(2\pi)^3} e^{i\mathbf{Q}\cdot\mathbf{x}} \frac{\mathbf{Q}^2 + m_\chi^2}{(\mathbf{Q}^2 + m_\chi^2)(\mathbf{Q}^2 + m_\phi^2) - \alpha_M^2}$$

$$\approx -\frac{y^2}{4\pi}\left(1 - \frac{\alpha_M^2}{m_\phi^4}\right)\frac{e^{-m_h r}}{r} - \frac{y^2}{4\pi}\frac{\alpha_M^2}{m_\phi^4}\frac{e^{-m_\zeta r}}{r},$$

Fifth Forces

On distances shorter than the Compton wavelength of the light scalar

$$V(r) \supset -\frac{y^2}{4\pi}\frac{\alpha_M^2}{m_\phi^4}\frac{1}{r}$$

$$y^2\frac{\alpha_M^2}{m_\phi^4} = \frac{m_e^2}{M^2}\frac{4\mu^4}{m_\phi^4}$$

Fifth force suppressed if (part of) the mass of the Higgs comes from spontaneous symmetry breaking, eg

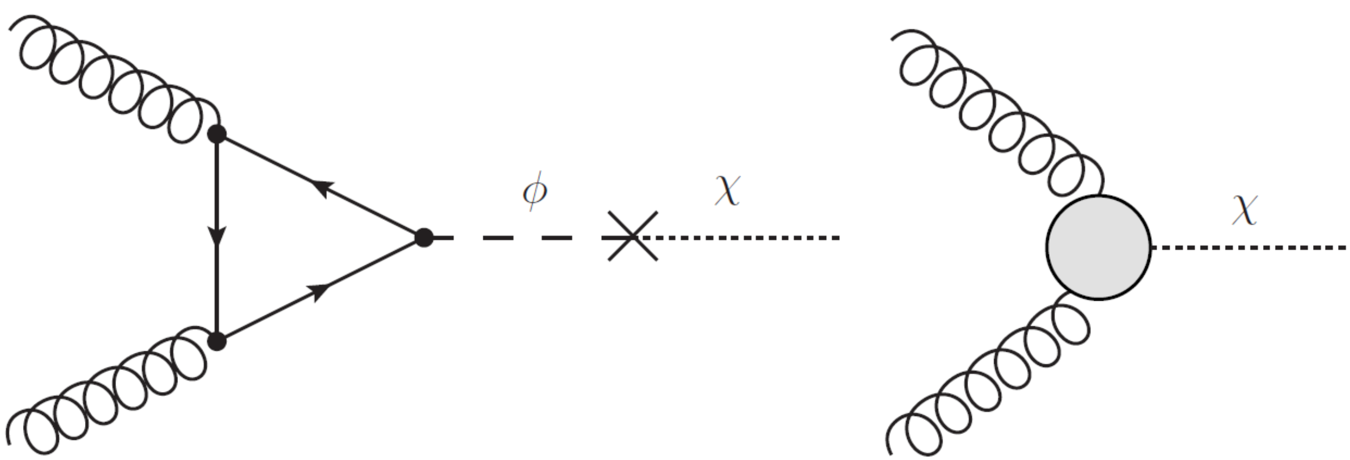
$$U(\phi,\theta,\chi) \supset \frac{\lambda}{4!}\left(\phi^2 - \frac{\beta}{\lambda}\theta^2\right)^2 - \frac{1}{2}\mu^2\left(\phi^2 - \frac{\beta}{\lambda}\theta^2\right) + \frac{3}{2}\frac{\mu^4}{\lambda}$$

What About Hadrons?

No direct coupling to fermions & classically conformally coupled field does not interact with gauge fields

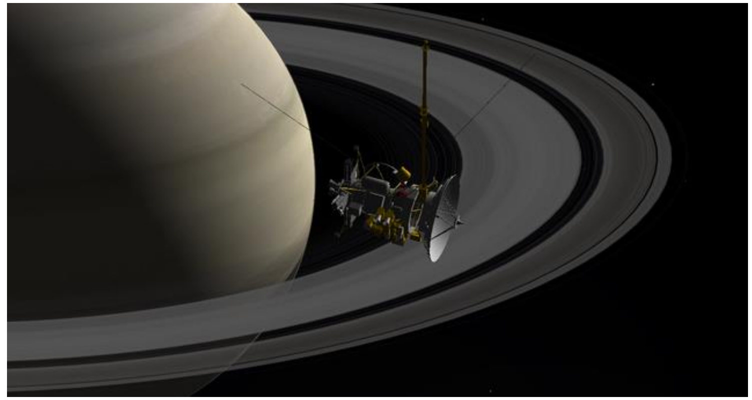
Gauge coupling can be generated by quantum corrections

$$\mathcal{L}_{\rm eff} \supset -\frac{C}{4M}\tilde{\chi}G^a_{\mu\nu}G^{\mu\nu,a}$$



Coupling still mediated by mass mixing with the Higgs

PPN Constraints



The effective Brans Dicke parameter is

$$3 + 2\omega_{\text{eff}} \;\equiv\; \frac{m_h^4}{4\mu^4}(3+2\omega) \;=\; \frac{m_h^4}{4\mu^4}\,\frac{M^2}{2M_{\text{Pl}}^2}$$

Tracking of the Cassini satellite constrains

$$|\gamma - 1| < 2.3\times 10^{-5} \qquad\qquad |\gamma - 1| \;=\; \left|\frac{1}{2+\omega_{\text{eff}}}\right|$$

$$\frac{\mu}{m_h} \;\lesssim\; 0.03\left(\frac{M}{M_{\text{Pl}}}\right)^{1/2}$$

Screening Fifth Forces

Scalar Screening Mechanisms

- **Locally large mass**

Chameleon models

Khoury, Weltman (2004).

- **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).

Symmetron Screening

Canonical scalar with potential and coupling to matter

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

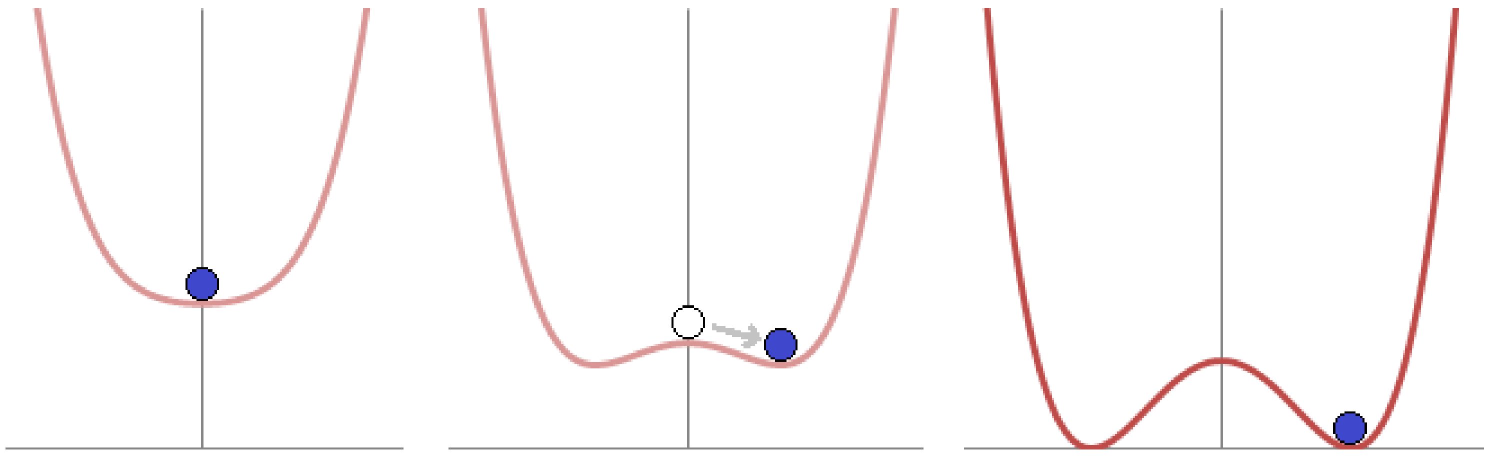
Effective potential

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

Symmetry breaking transition occurs as the density is lowered

Hinterbichler, Khoury. (2010).

Symmetron Screening



Force on test particle vanishes when symmetry is restored

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

Hinterbichler, Khoury. (2010).

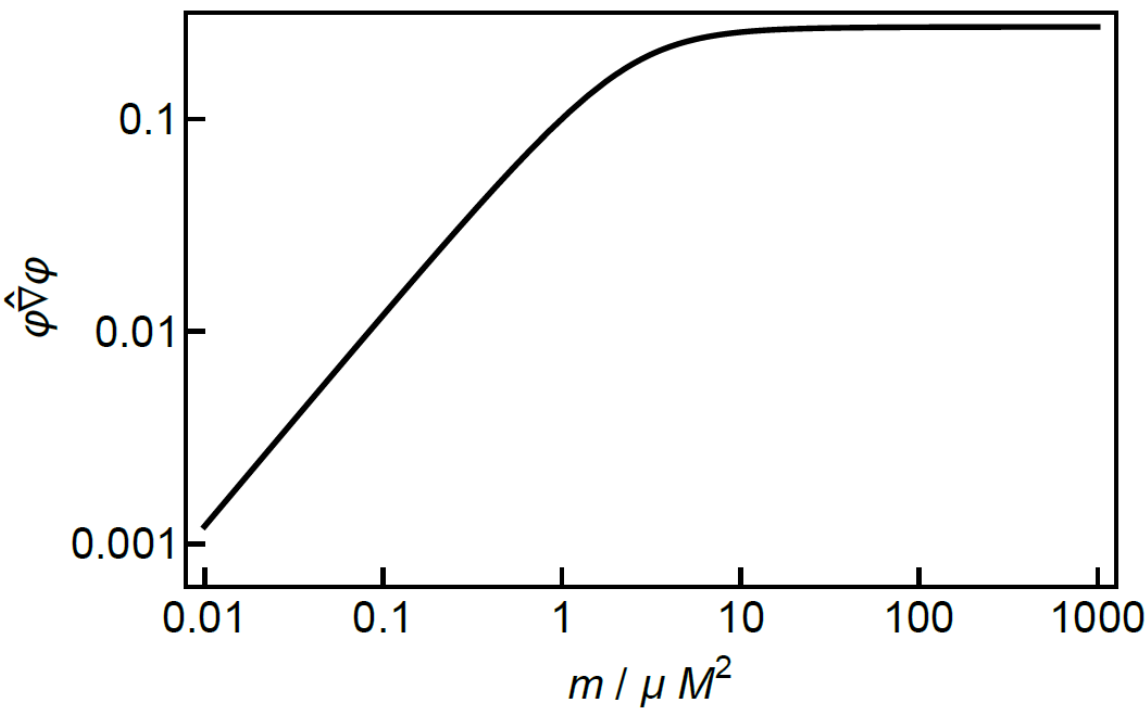
POINT PARTICLE SCREENING

With Ben Elder and Pete Millington,
arXiv: 1810.01890

Point Particle Screening

In one spatial dimension

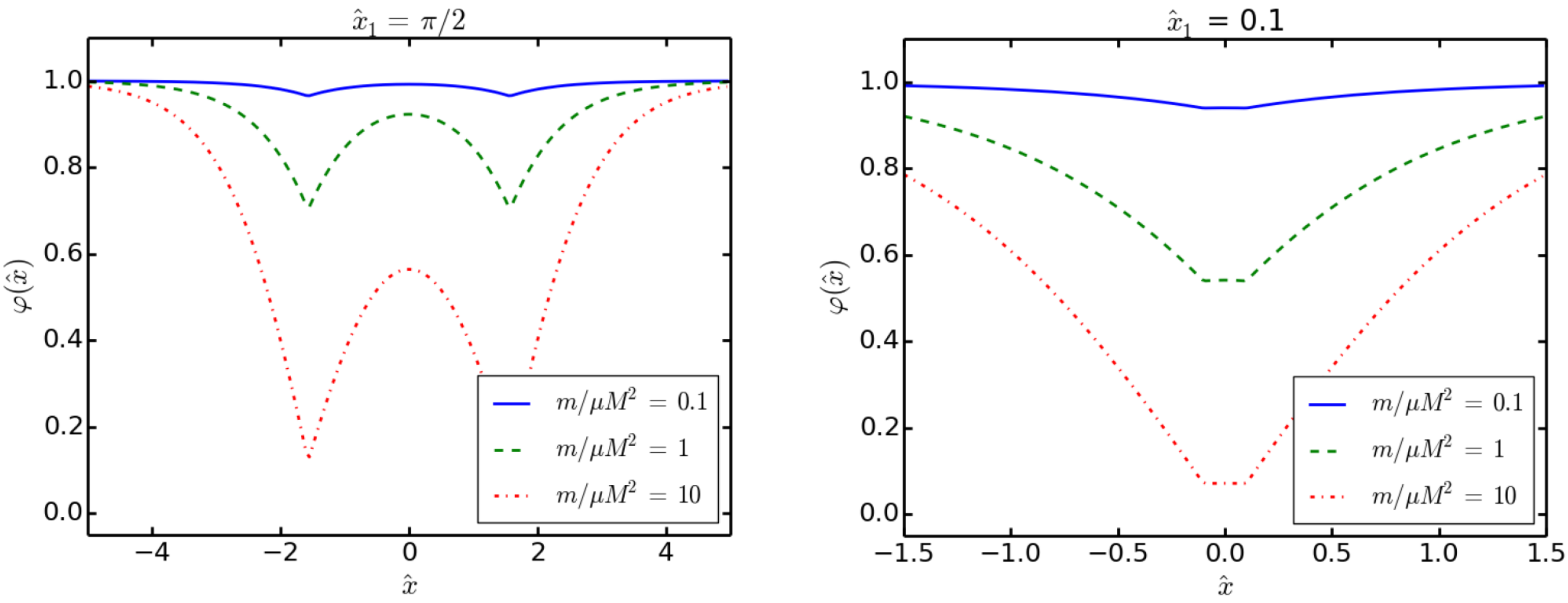
$$\phi_{\text{point}}(x) = \phi_\infty \tanh\left(\frac{\mu}{\sqrt{2}}|x - x_1| + \operatorname{arctanh}\varphi_1\right)$$



Point Particle Screening

In one spatial dimension

$$\varphi = \begin{cases} \varphi_0 \,\mathrm{cd}\left(\frac{1}{\sqrt{2}}|\hat{x}|\sqrt{2-\varphi_0^2}, \frac{\varphi_0^2}{2-\varphi_0^2}\right) & |\hat{x}| < \hat{x}_1 \\ \tanh\left(\frac{1}{\sqrt{2}}(|\hat{x}| - \hat{x}_1) + \mathrm{arctanh}\,\varphi_1\right) & |\hat{x}| > \hat{x}_1 \end{cases}$$



Toy Higgs model in 1+1 D

$$\mathcal{L} \supset -\bar{\psi} i \partial\!\!\!/ \psi - y \bar{\psi} \phi \psi$$

Rescaled Higgs equation with a point-like Fermion source

$$\varphi'' = -\varphi(1-\varphi^2) + \frac{yv}{\mu}\delta(\hat{x})$$

Which has vev

$$\varphi_1 = \pm\sqrt{1 - \frac{yv}{\sqrt{2}\mu}}$$

Fermion mass arising from this Yukawa coupling

$$m_f = yv\varphi_1 = yv\sqrt{1 - yv/(\sqrt{2}\mu)} \leq \sqrt{8/27}\, m_\varphi$$

$$H = \frac{1}{3} m_\varphi (2+\varphi_1)(1-\varphi_1)^2 + yv\varphi_1 \leq \frac{2}{3} m_\varphi$$

Scalar Fields and Galactic Dynamics

Missing Mass or Modified Gravity?

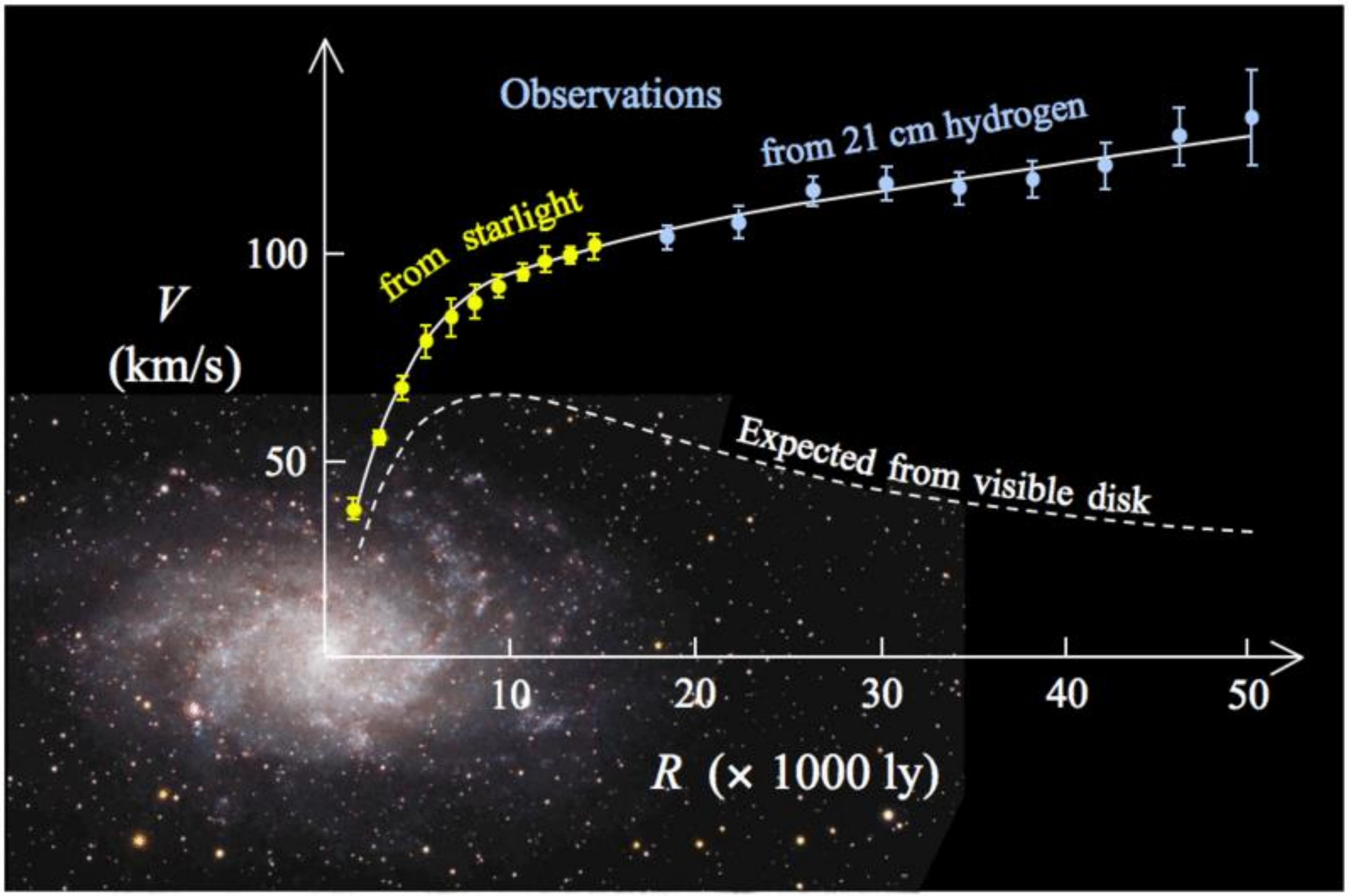
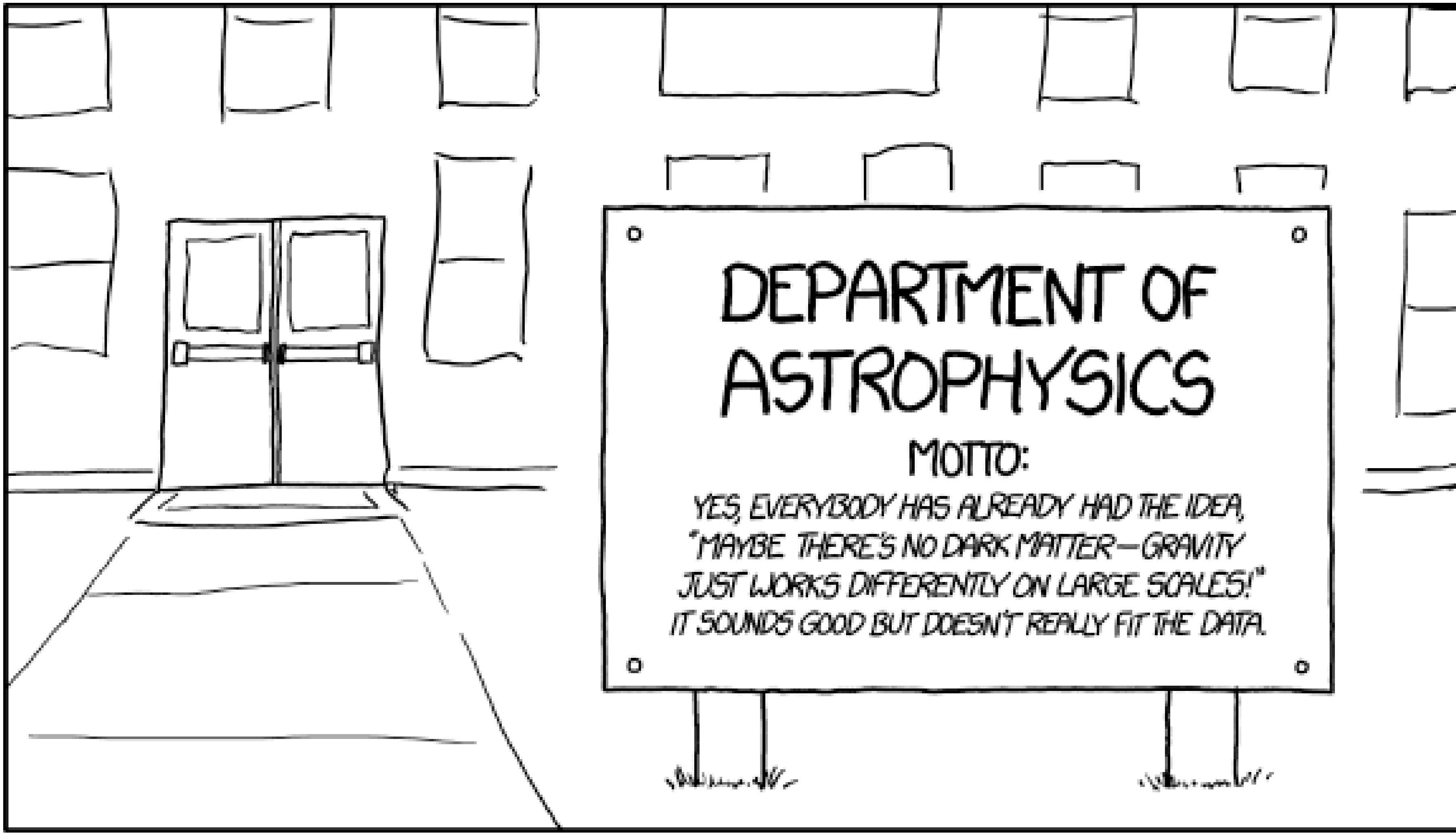


Image Credit: Stefania.deluca



https://www.xkcd.com/1758/

Gravitational Dark Matter Production

A non-minimal coupling to gravity means that light scalar dark matter can be produced non-thermally

- Through quantum fluctuations during inflation

Alonso-Alvarez and Jaeckel. 2018.

- During reheating

Markkanen, Nurmi. 2017. Fairbairn, Kainulainen, Markkanen, Nurmi. 2018. Ema, Nakayama, Tang. 2018.

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{1}{2} \left(M^2 - \xi \phi^2 \right) R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 + \mathcal{L}_{\mathrm{back}} \left(\sigma_i \right) \right)$$

Alternative production of light scalars by 'misalignment mechanism' requires fine tuning

FIFTH FORCES ON GALACTIC SCALES

With Ed Copeland and Pete Millington,
(arXiv: 1610.07529) Phys Rev. D95 064050

With Ciaran O'Hare,
(arXiv:1805.05226) Phys. Rev. D98 064019

Light Scalar Fields for Dark Matter

Possible modifications of gravity on galactic scales

Milgrom 1983 (MOND). Moffat 2006 (MOG). Bekenstein 2004 (TeVeS).

Khoury 2014.

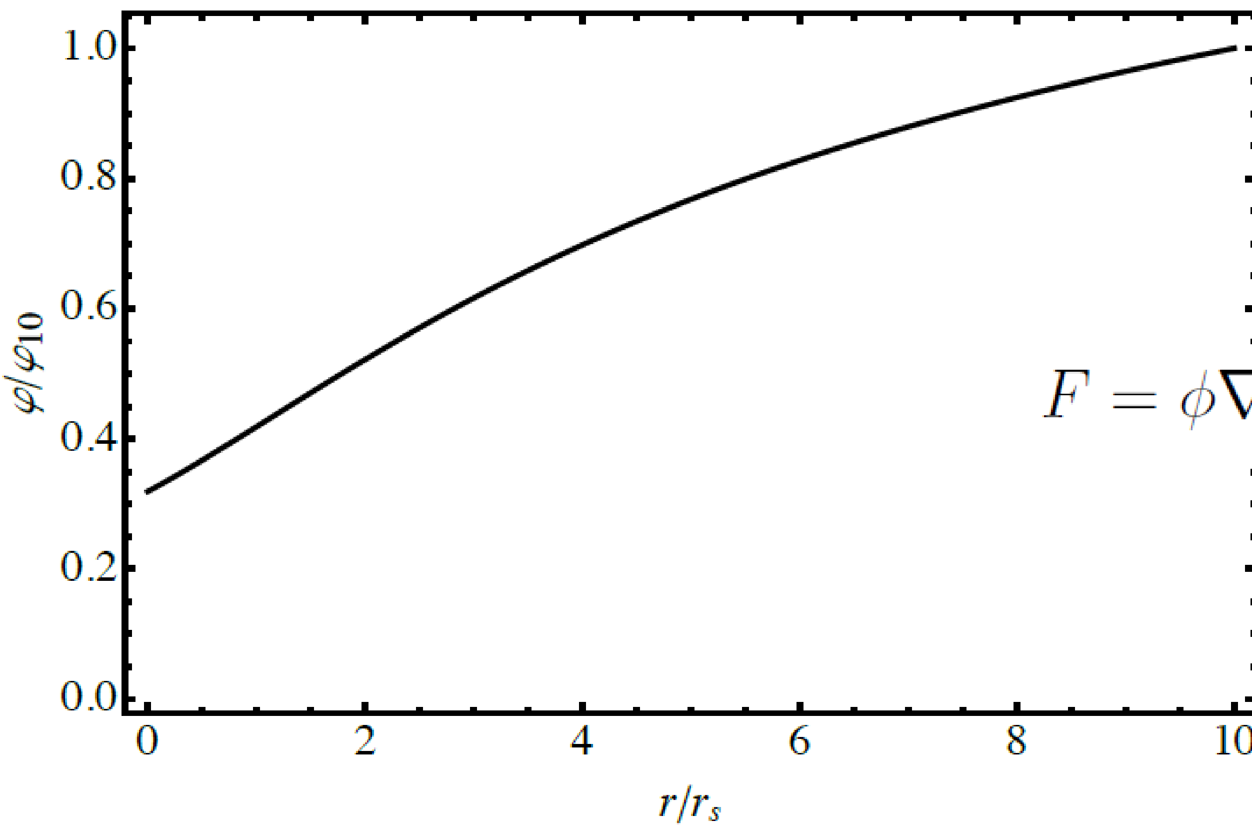
Light Scalars as dark matter

BEC dark matter, Scalar Field dark matter, Fuzzy dark matter, Ultra-Light Axion dark matter, Wave dark matter…

For a review see: Lee 1704.05057

Symmetron Field Profile for a Galaxy

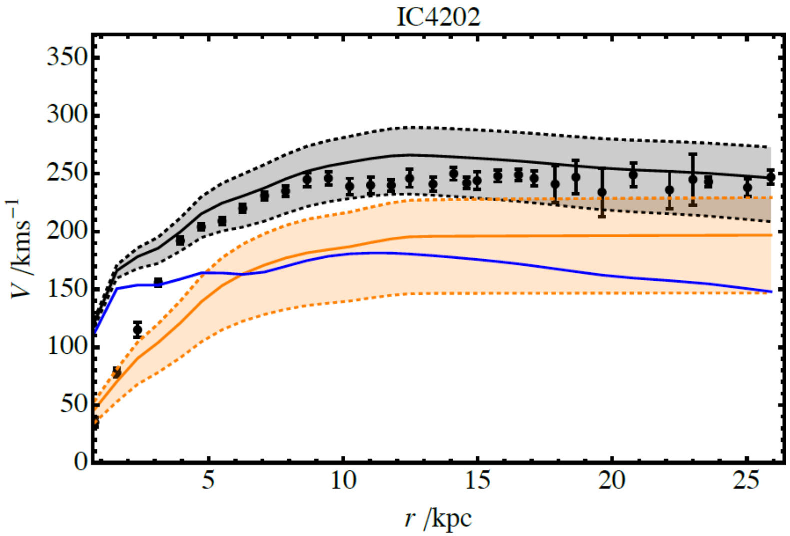
To explain rotation curve of a ‘typical’ galaxy with only a symmetron force and no particle dark matter

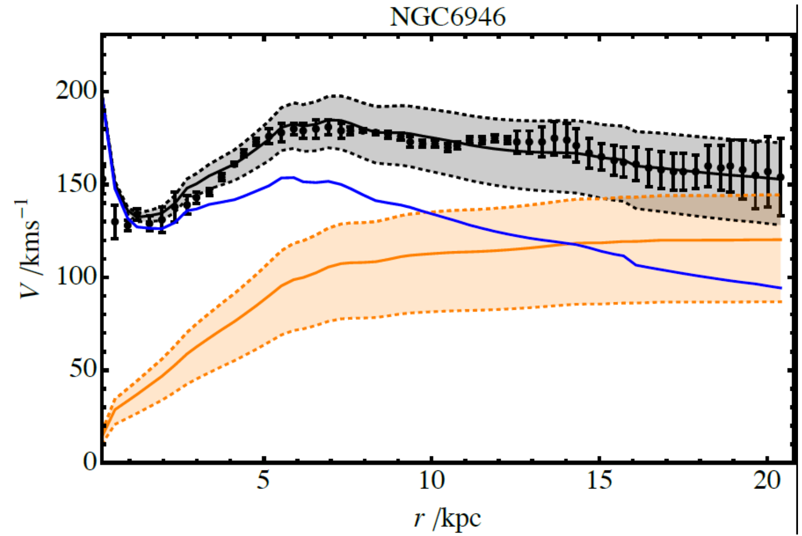


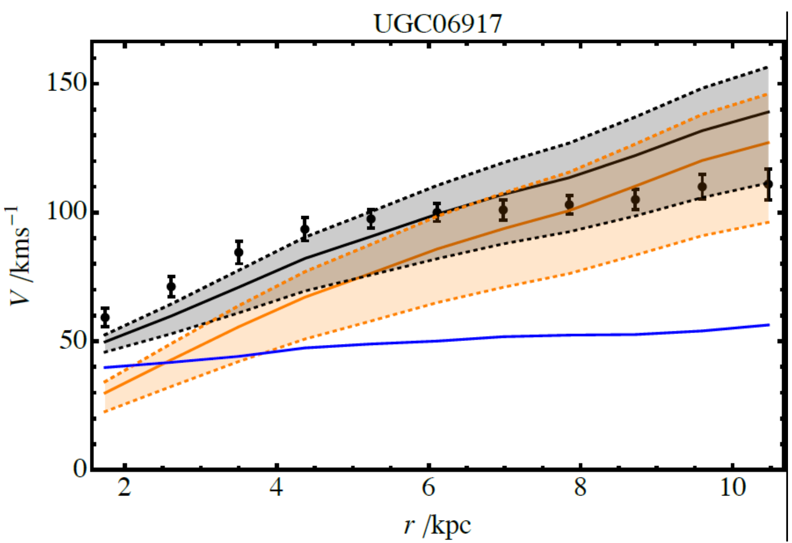
$$F = \phi \nabla \phi / M^2$$

CB, Copeland, Millington (2016)

Galaxy Rotation Curves







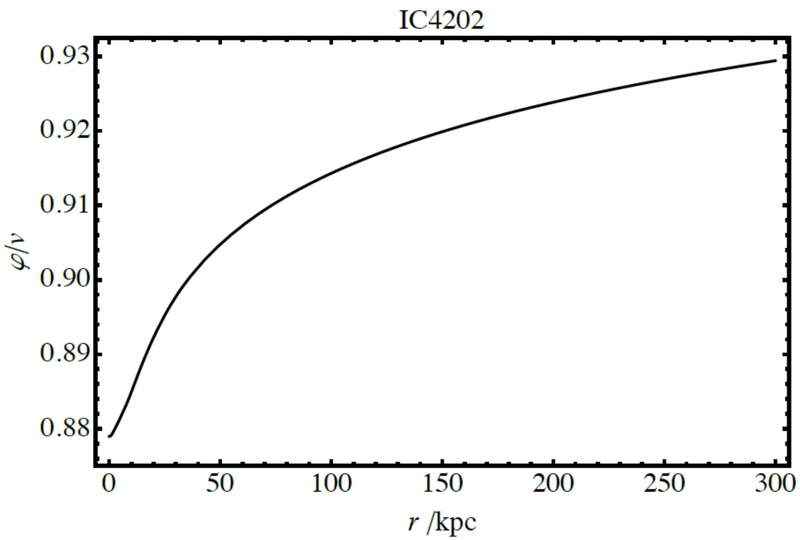
$$\mu = 10^{-40}\ \mathrm{GeV}$$

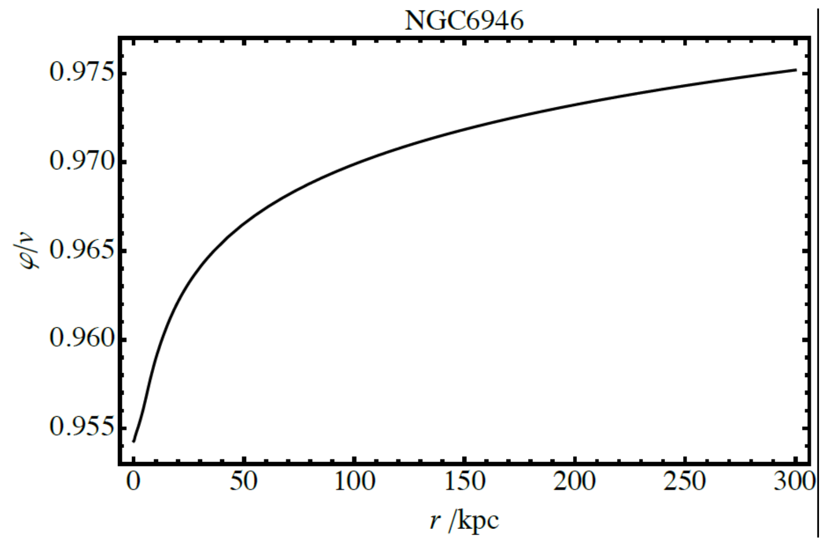
$$M = M_{\mathrm{Pl}}/10$$

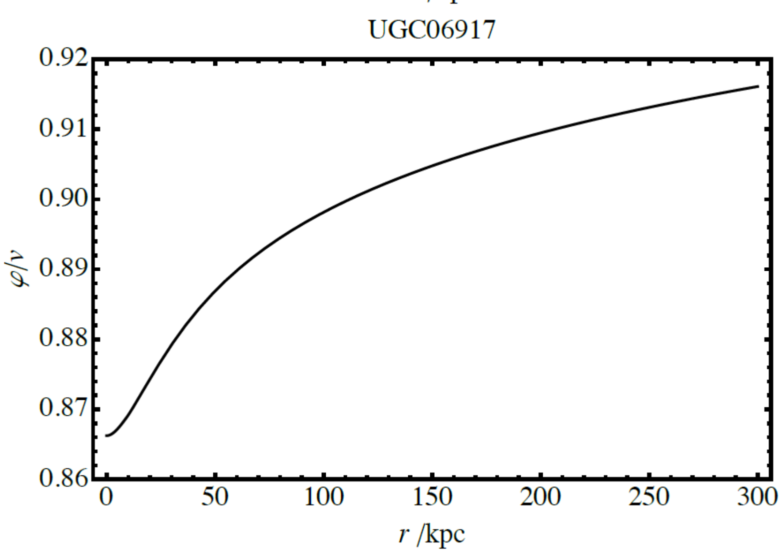
$$v = M/170$$

CB, Copeland, Millington (2016). SPARC data: McGaugh, Lelli, Schombert (2016)

Symmetron Field Profiles







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

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

$$v = M/170$$

See also: Gessner (1992).

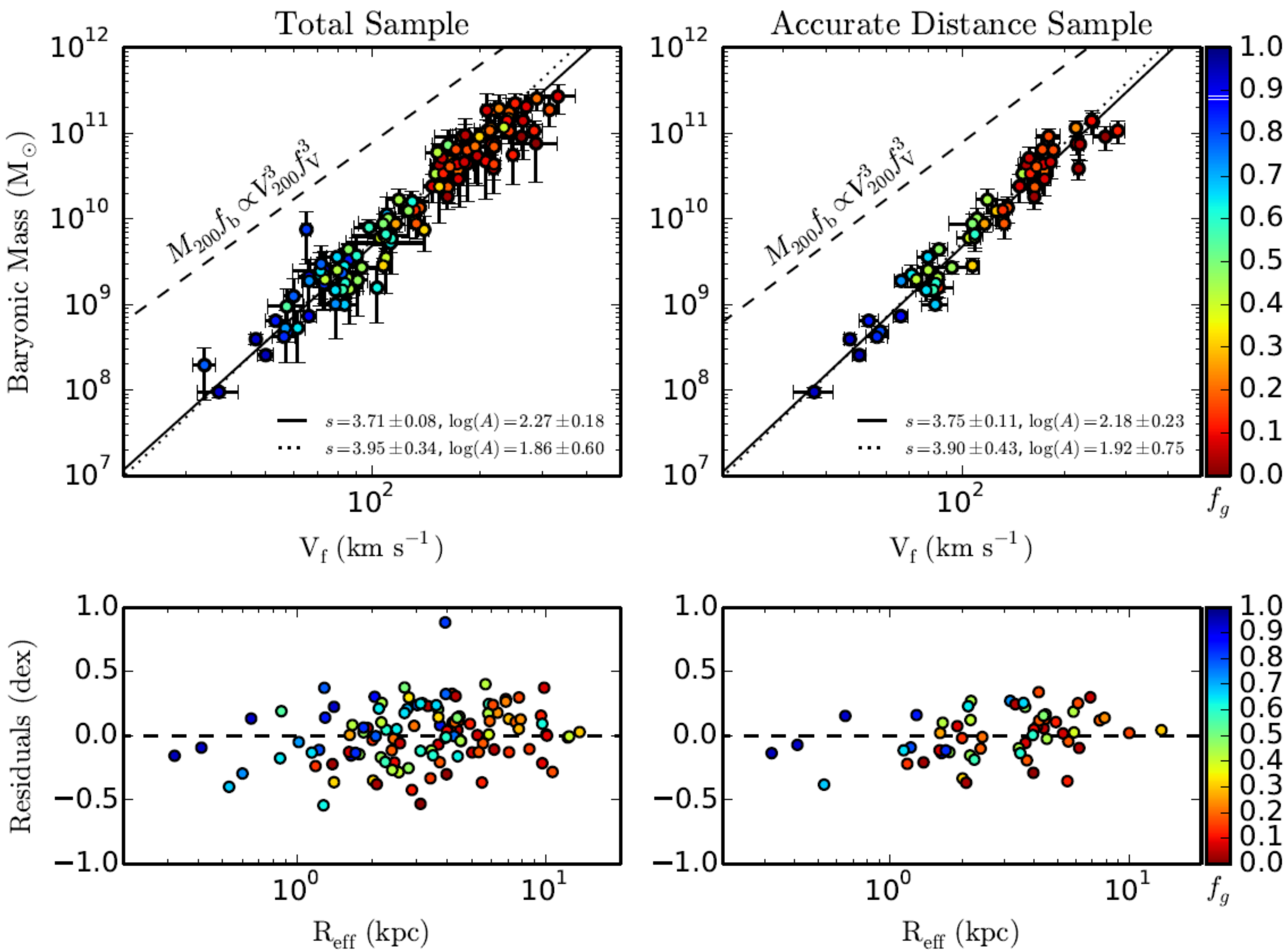
What can we conclude from this?

The fifth forces from a canonical scalar can *in principle* explain galactic rotation curves and stability

This is a long way from being an alternative to dark matter, many other observational tests to pass

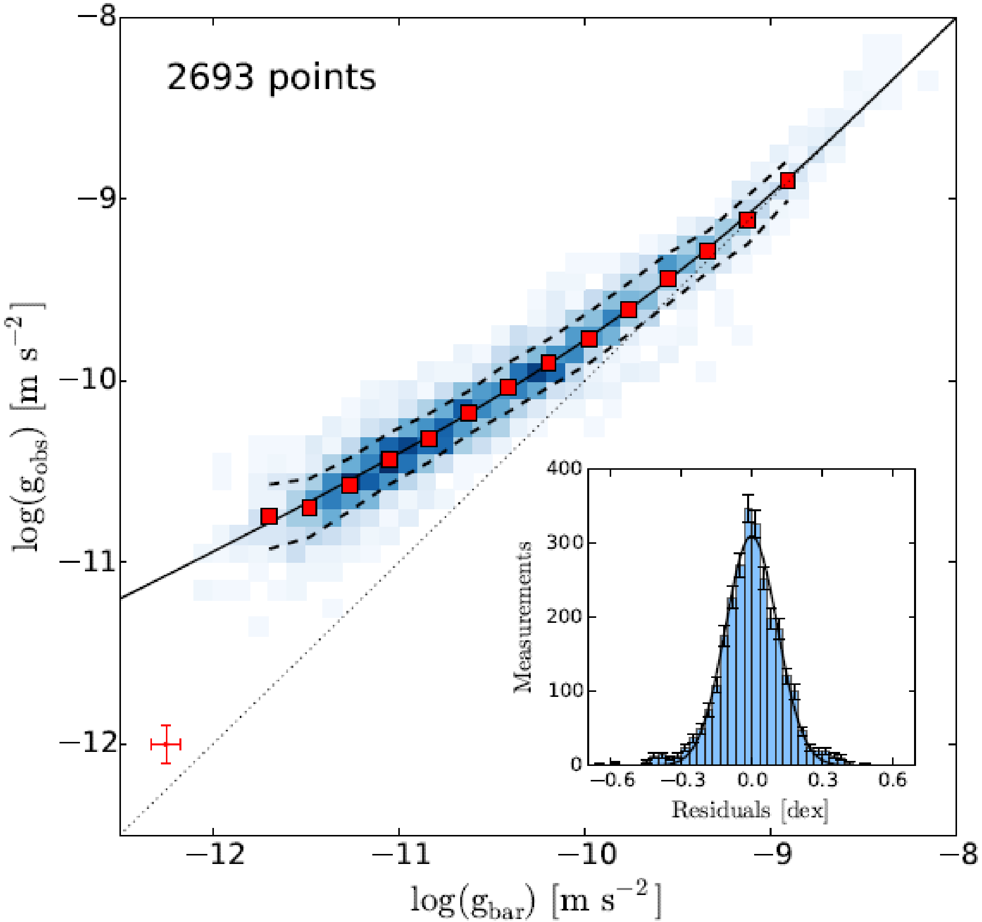
Additional component needed to explain galaxy lensing (work in progress)

Baryonic Tully-Fisher Relation



Lelli, McGaugh, Schombert. 2015

Radial Acceleration Relation



153 galaxies,

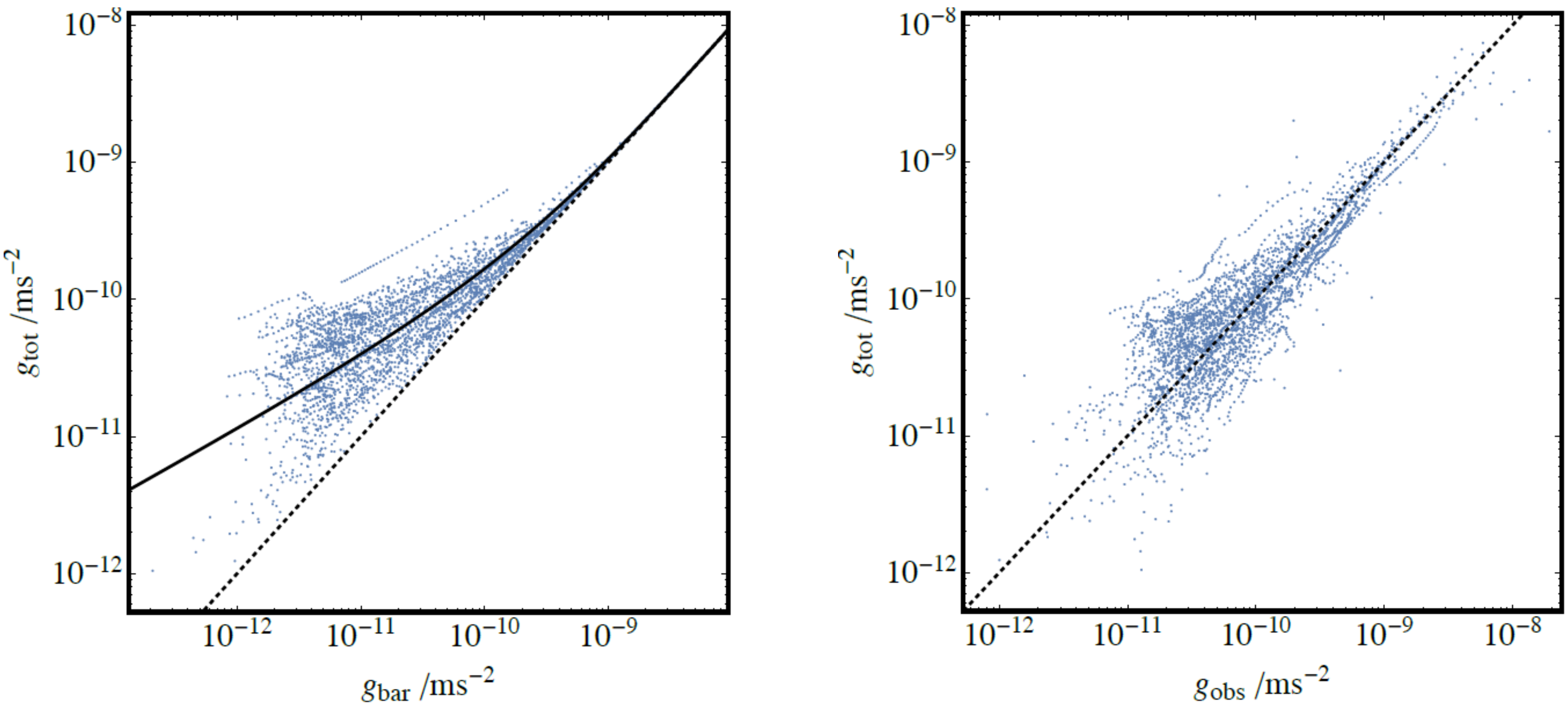
~ 2700 data points

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

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

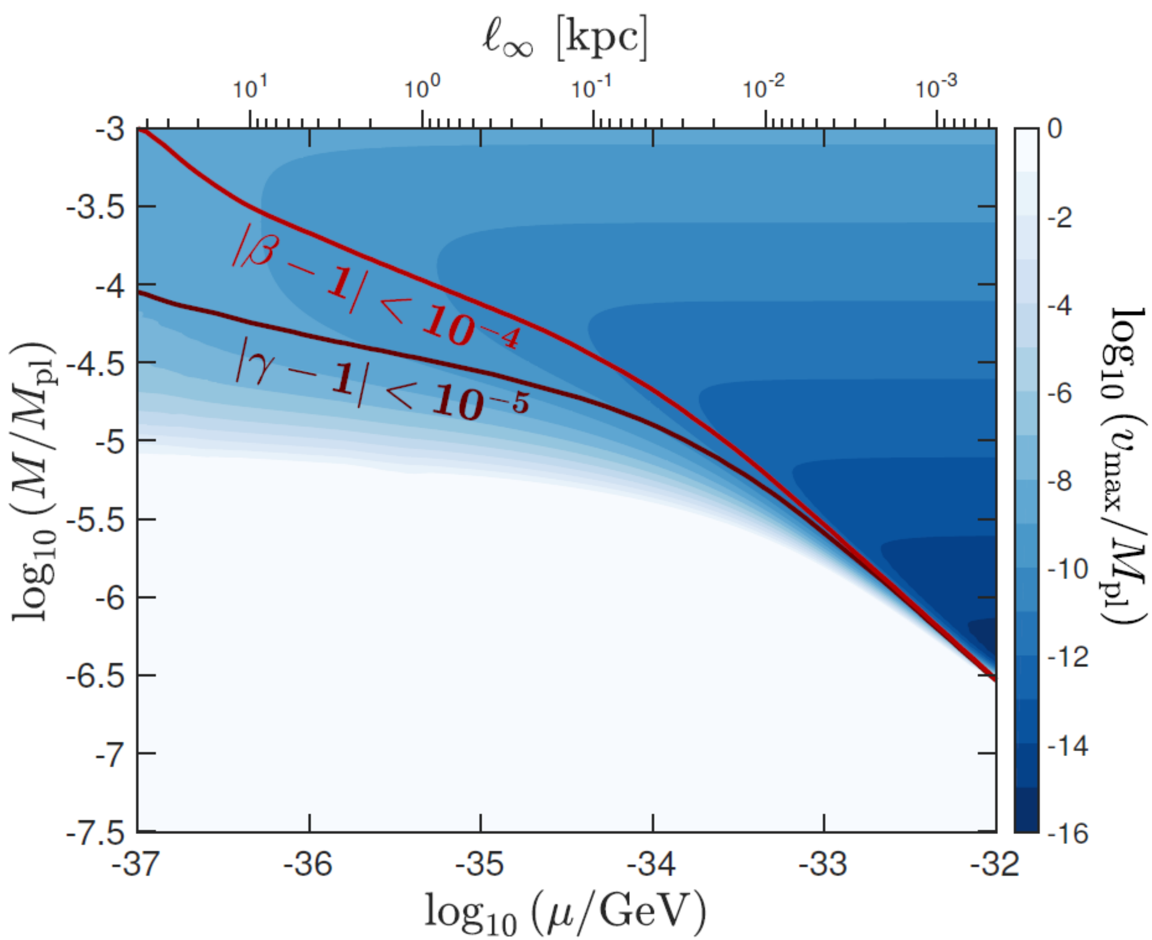
McGaugh, Lelli, Schombert (2016). See also: Keller and Wadsley (2016).

Symmetron Acceleration Relation



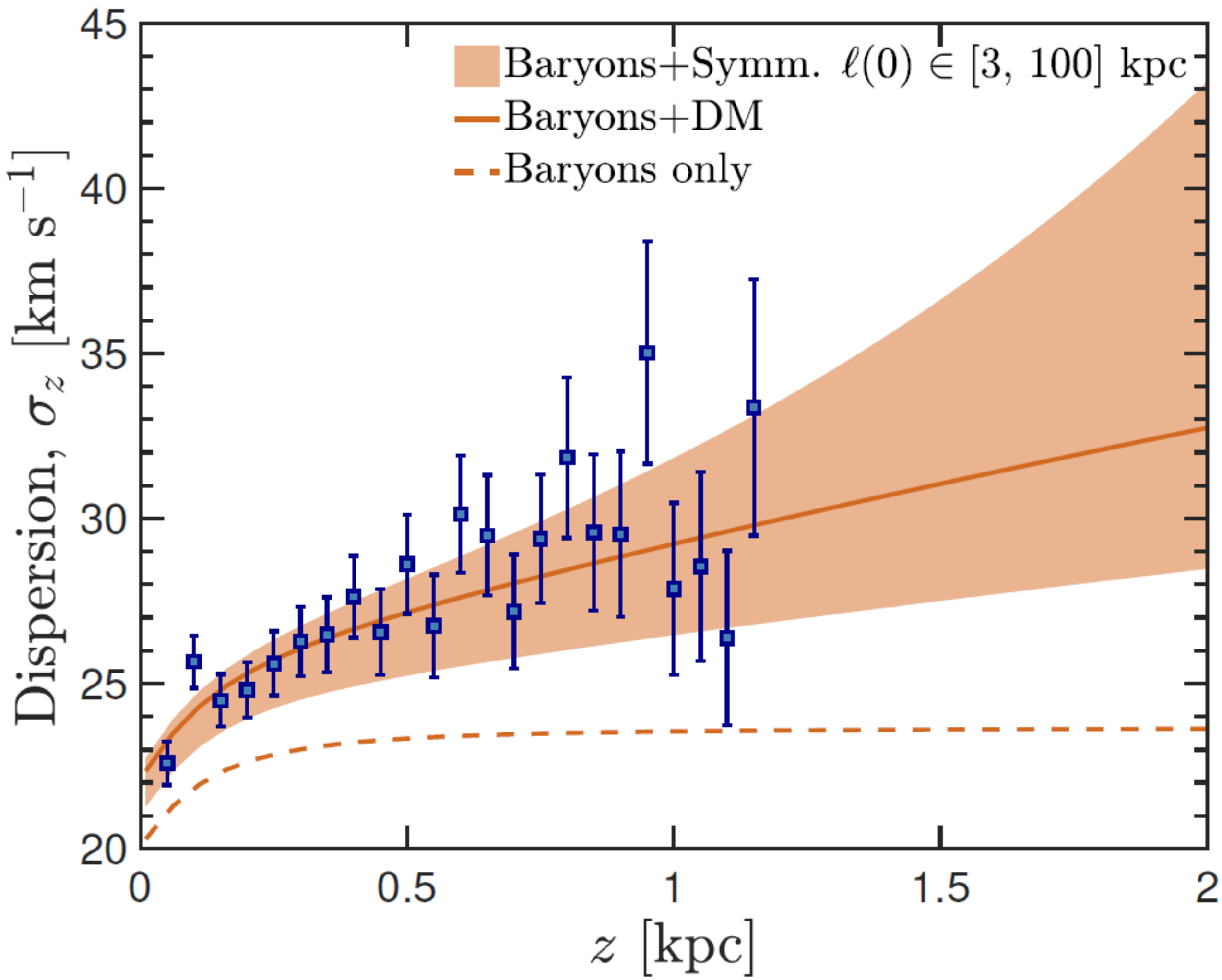
CB, Copeland, Millington (2016)

PPN Bounds



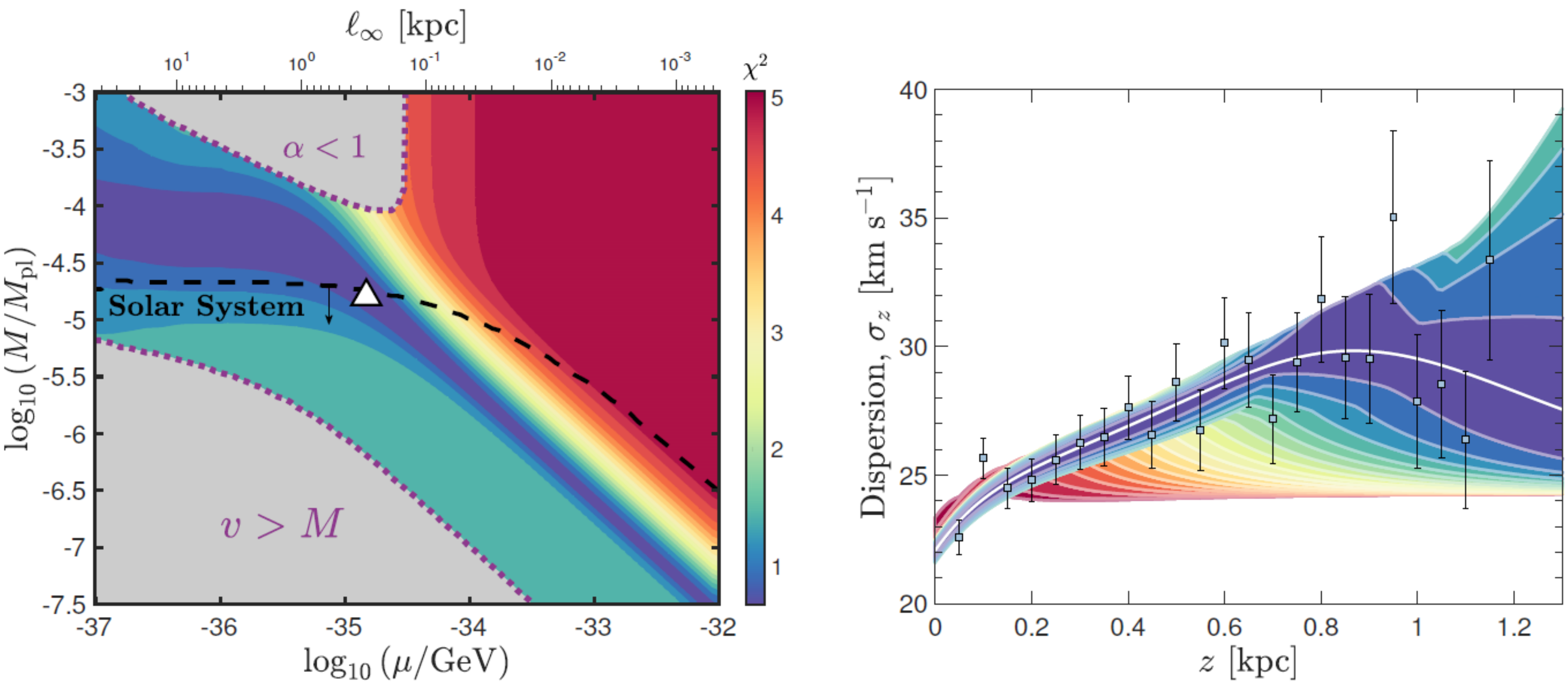
CB, C. A. J. O'Hare. 2018

Vertical Motion of Stars



CB, C. A. J. O'Hare. 2018

Vertical Motion of Stars



CB, C. A. J. O'Hare. 2018

Implications

If fifth forces are present on galactic scales we may be over estimating dark matter abundances

If dark matter is a light scalar we should consider non-minimal couplings and the resulting fifth forces.

Summary

We expect scalar fields to couple to the Ricci scalar

If scalar fields are light this gives rise to long range fifth forces

These can be suppressed by approximate scale invariance of the Standard Model

Or by screening mechanisms

Scalar fifth forces can be relevant on galactic scales and can have implications for our understanding of dark matter