Searching for Fifth Forces and Modifications of Gravity

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University of Nottingham

Outline:

Light scalar fields and fifth forces

Non-linearities and screening

F(R) screening in galaxies

Chameleon screening in the lab

University of Nottingham
UK | CHINA | MALAYSIA

Why Introduce Light Scalar Fields?

New matter: dark energy

- Light scalars can drive accelerated expansion
- Can be a consequence of mechanisms that solve the cosmological constant problem

New matter: dark matter

- Light scalars, produced non-thermally, can provide a non-relativistic matter component

A modification of gravity

- New physics in the gravitational sector can introduce new degrees of freedom, often Lorentz scalars

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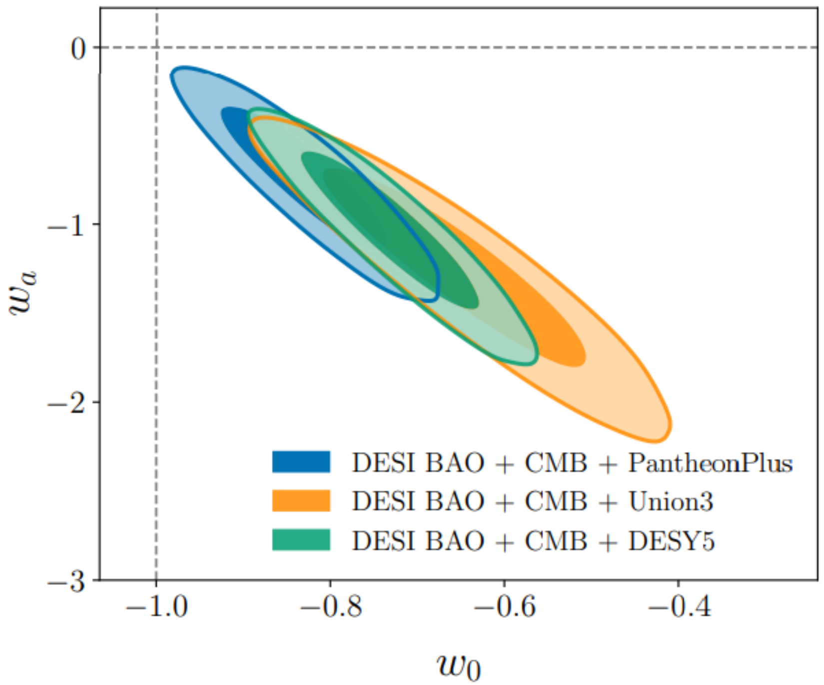

DESI collaboration. arXiv:2404.03002

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An Example: Conformally Coupled Scalars

Can start from an f(R) modification of gravity, which has an extra (hidden) scalar degree of freedom

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\,[R + f(R)] + S_m[g]\,,$$

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$$\phi = -\sqrt{\frac{3}{2}}M_{\rm pl}\ln(1+f_R)\,, \qquad V(\phi) = \frac{M_{\rm pl}^2}{2}\frac{\phi f_R - f(R)}{(1+f_R)^2}$$

$$\tilde{g}_{\mu\nu} = e^{2\phi/\sqrt{6}}g_{\mu\nu}$$

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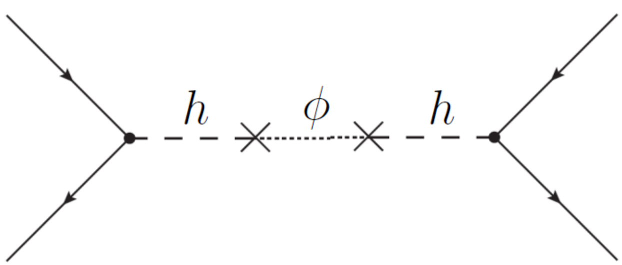
$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi)\right] + S_m\left[\tilde{g}_{\mu\nu}, \psi_i^{SM}\right]\,,$$

An Example: Conformally Coupled Scalars

At leading order this is a Higgs portal model

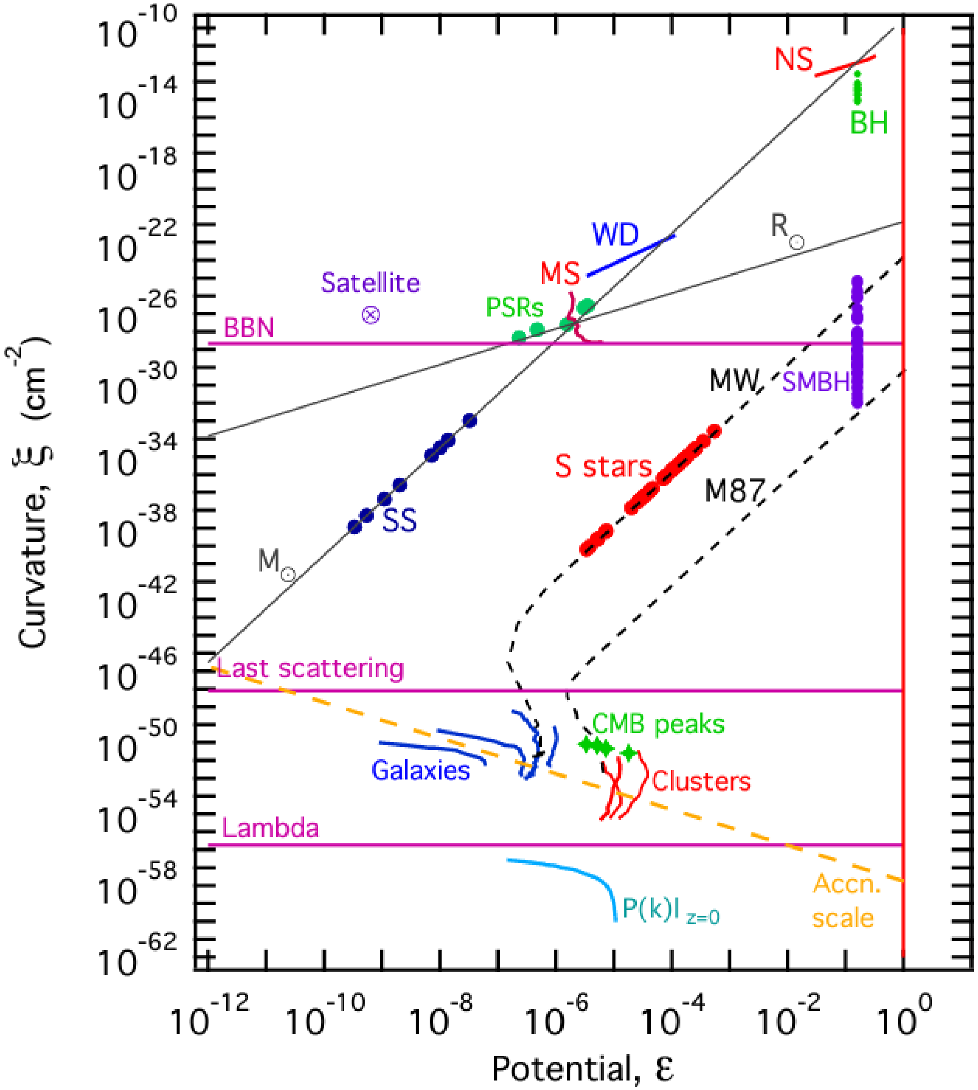
$$\begin{aligned}\tilde{\mathcal{L}} \;=\; & -\frac{1}{2}\,\tilde{g}^{\mu\nu}\,\partial_\mu\tilde{H}\,\partial_\nu\tilde{H} \;+\; \tilde{g}^{\mu\nu}\,\tilde{H}\,\partial_\mu\tilde{H}\,\partial_\nu\ln A(\phi) \\ & -\;\frac{1}{2}\,\tilde{g}^{\mu\nu}\,\tilde{H}^2\,\partial_\mu\ln A(\phi)\,\partial_\nu\ln A(\phi) \\ & +\;\frac{1}{2}\,\mu_H^2\,A^2(\phi)\,\tilde{H}^2 \;-\; \frac{\lambda_H}{4!}\,\tilde{H}^4 \;-\; \frac{3}{2}\,A^4(\phi)\,\frac{\mu_H^4}{\lambda_H} \\ & -\;\bar{\tilde{\psi}}\,i\overset{\leftrightarrow}{\tilde{\not{\partial}}}\,\tilde{\psi} \;-\; y\,\bar{\tilde{\psi}}\tilde{H}\tilde{\psi}\,,\end{aligned}$$



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

CB, Copeland, Millington, Spannowsky. JCAP 11 (2018) 036.

Testing Gravity



Baker, Psaltis, Skordis. ApJ 802 63, 2015

Non-linearities and Screening

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

- **Locally weak coupling**

Symmetron and varying dilaton models

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

- **Locally large mass**

Chameleon models

Khoury, Weltman (2004).

- **Locally large kinetic coefficient**

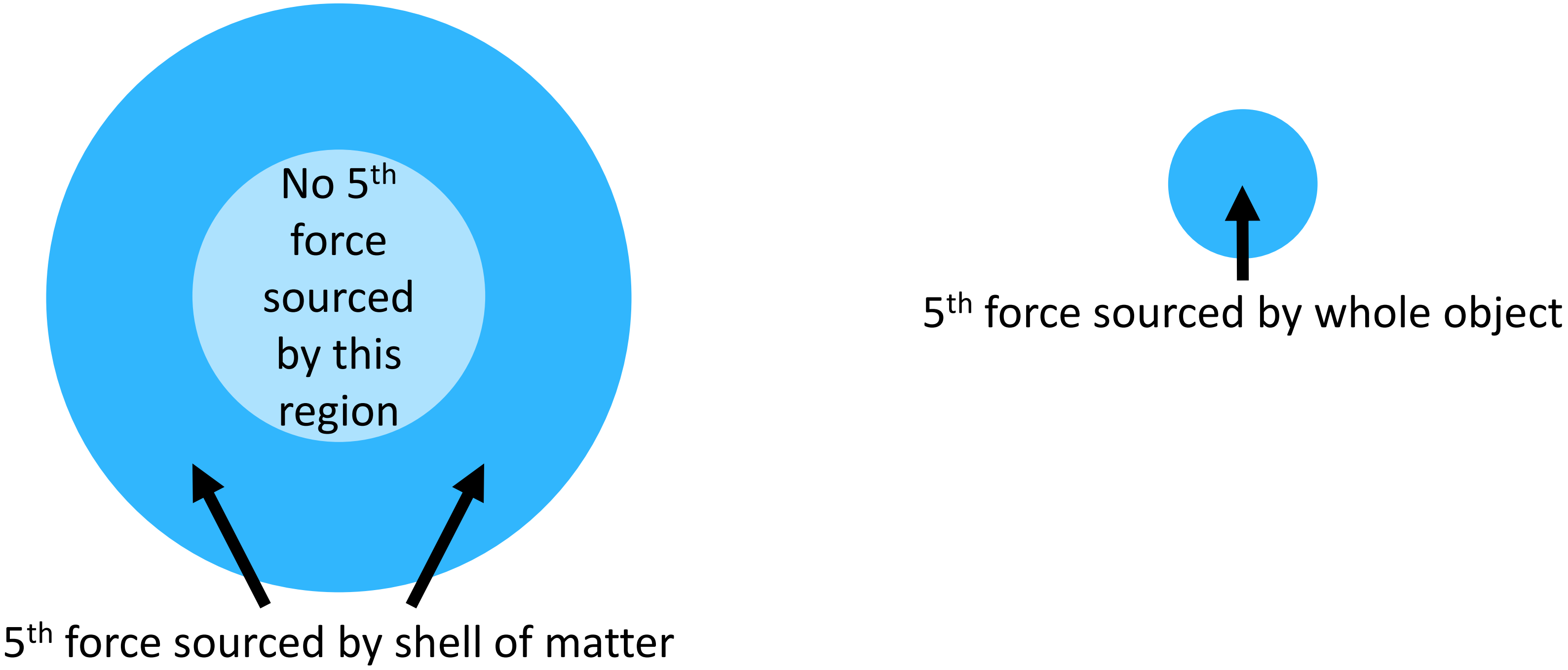
Vainshtein mechanism, Galileon and k-mouflage models

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

Thin Shell Effect

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

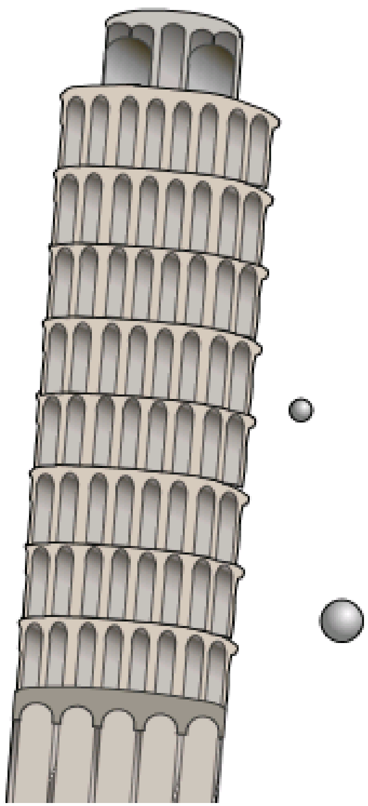
Change the way in which matter sources the scalar field



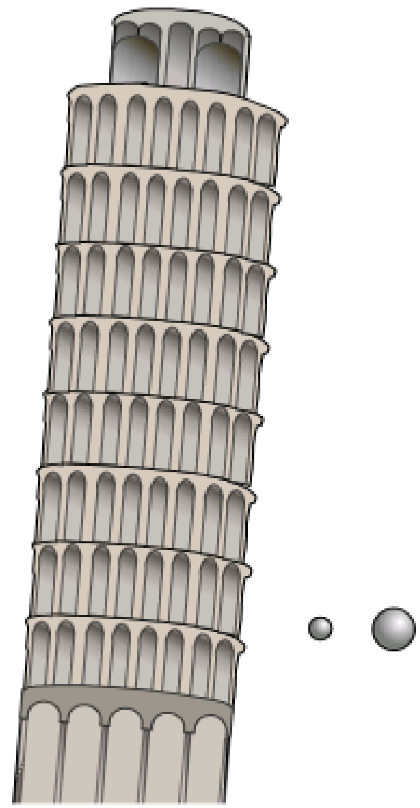
Large objects are 'screened' from the 5th force

Testing the Equivalence Principle

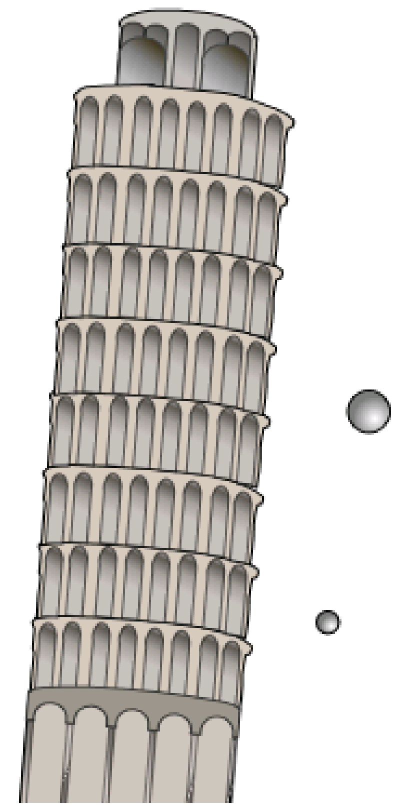
Do large objects and small objects fall at the same rate?



Old idea



Galileo



Fifth force with thin shell?

Image credit: Theresa Knott

f(R) SCREENING IN GALAXIES

f(R) with Screening

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,[R + f(R)] + S_m[\tilde{g}]\,,$$

Use Hu-Sawicki model that recovers ΛCDM above a curvature threshold

$$f(R) = -\frac{am^2}{1+(R/m^2)^{-b}}$$

$$a = -\frac{4\Omega_\Lambda^2}{(\Omega_m + 4\Omega_\Lambda)^2}\frac{1}{f_{R0}} \qquad m^2 = -\frac{3H_0^2(\Omega_m + 4\Omega_\Lambda)^2}{2\Omega_\Lambda c^2} f_{R0}$$

Static equation of motion for scalar mode is

$$\nabla^2 f_R = \frac{1}{3}\left(\delta R - \frac{8\pi G}{c^2}\delta\rho\right) \qquad \delta R = R_0\left[\sqrt{\frac{f_{R0}}{f_R}} - 1\right]$$

Hu & Sawicki. Phys. Rev. D 76 (2007) 064004

Understanding Screening

Integrate equation of motion

$$\nabla^2 f_R = \frac{1}{3}\left(\delta R - \frac{8\pi G}{c^2}\delta\rho\right)$$

from infinity to the 'screening radius' where field and its derivatives vanish

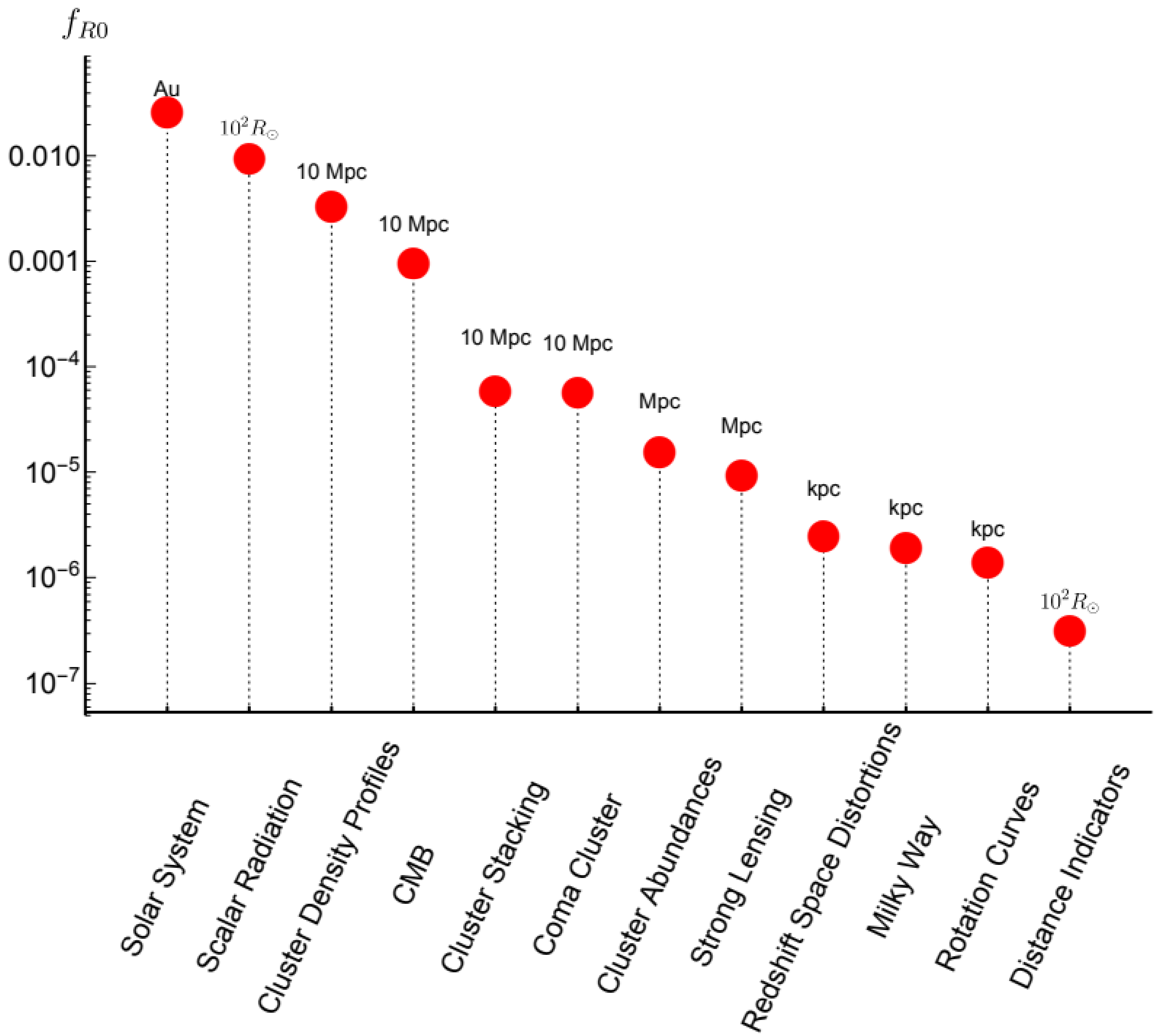
$$\chi = -\frac{3}{2} f_{R0} = -\frac{1}{c^2}\left(\Phi_N(r_s) + r_s \Phi_N'(r_s)\right)$$

Object is screened if:

$$\chi < |\Phi_N|/c^2$$

Derivation makes a number of assumptions including: negligible scalar mass, constant coupling function, spherical NFW halo …

Constraints on f(R)

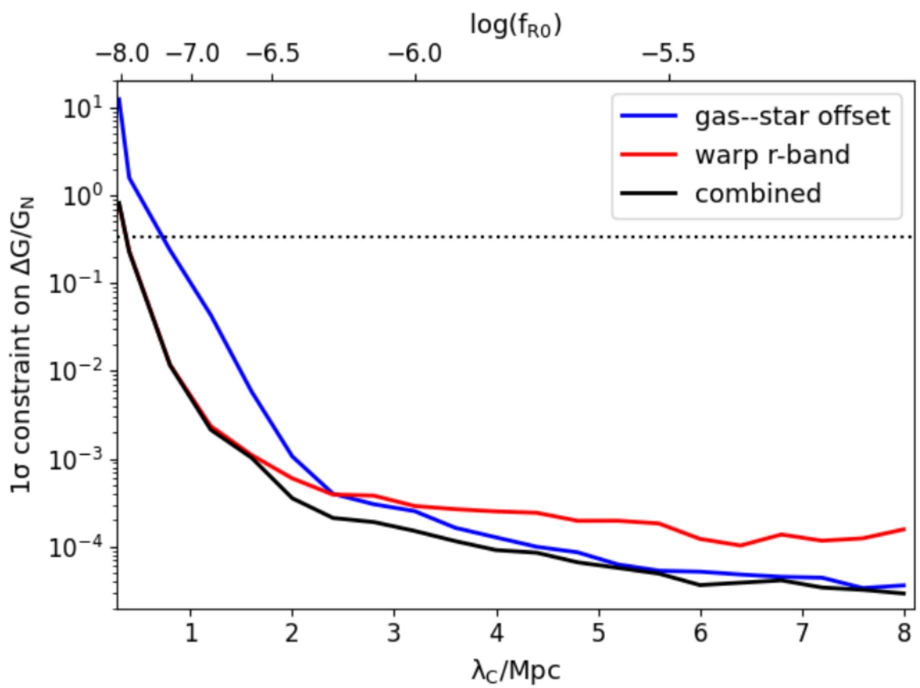


CB & Sakstein. Living Rev.Rel. 21 (2018) 1, 1

Tests on Galactic Scales

Equivalence principle violating gas-star offsets [ALFALFA & NASA Sloan Atlas (NSA)], and resulting warps of galactic disc [NSA]

Newtonian potential from the virial velocity



Desmond, Ferreira. Phys.Rev.D 102 (2020) 10, 104060.
See also: Landim, Desmond, Koyama, Penny arXiv:2407.08825

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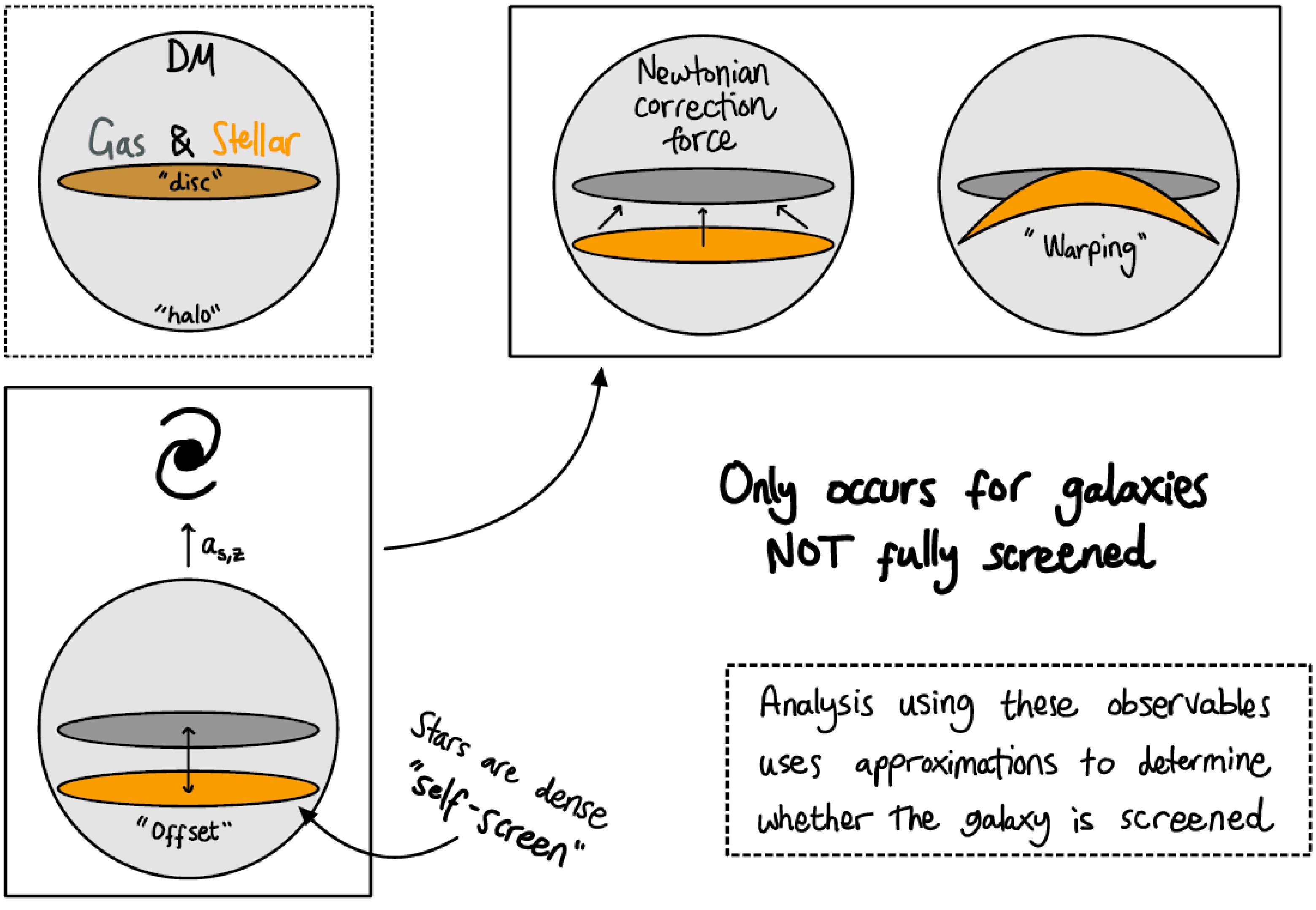

Image credit: Bradley March

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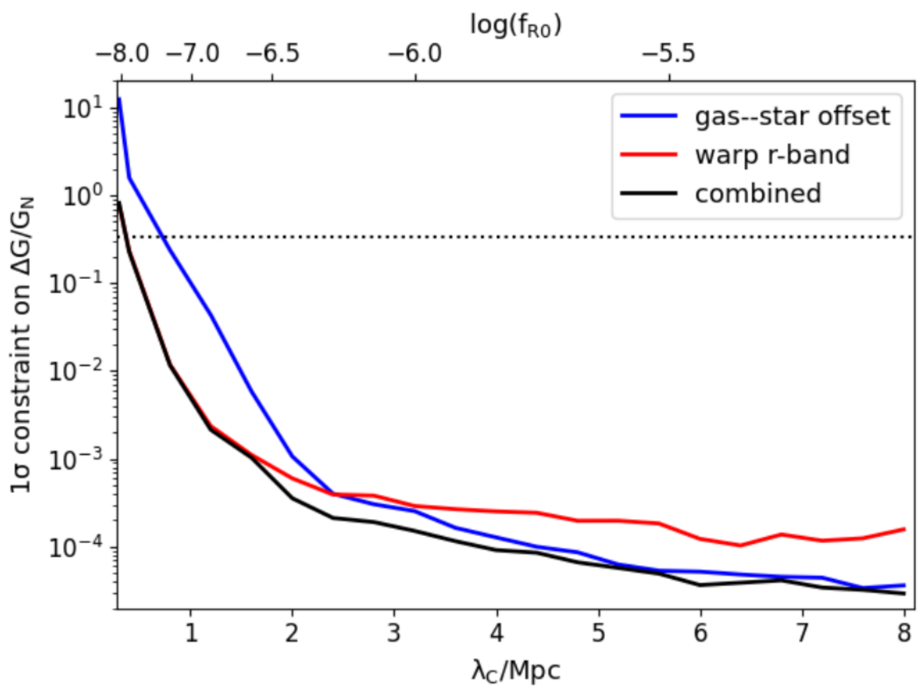

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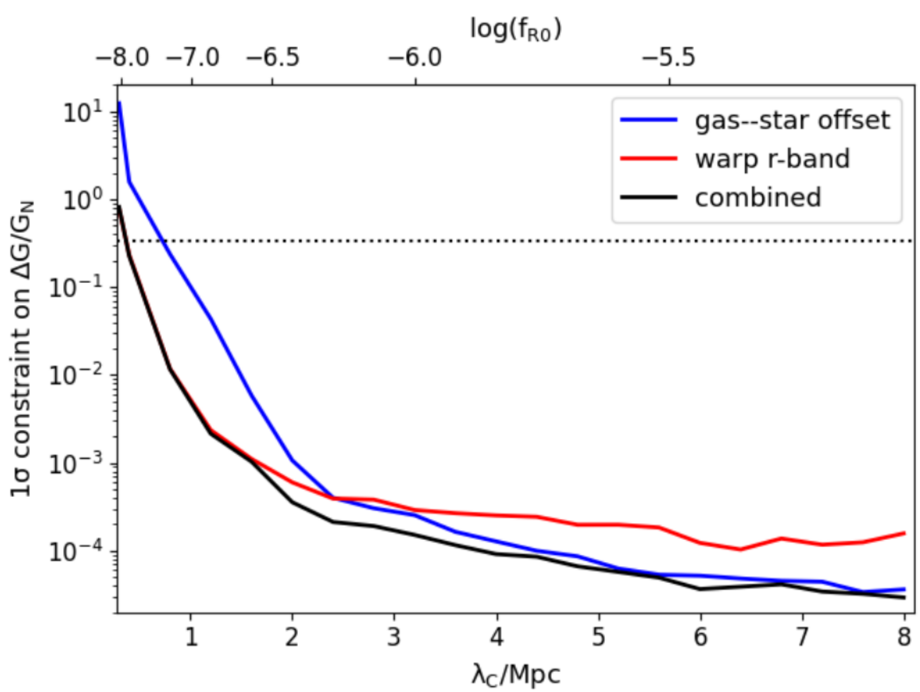
Tests on Galactic Scales

"We conclude that this model can have no relevance to astrophysics or cosmology."



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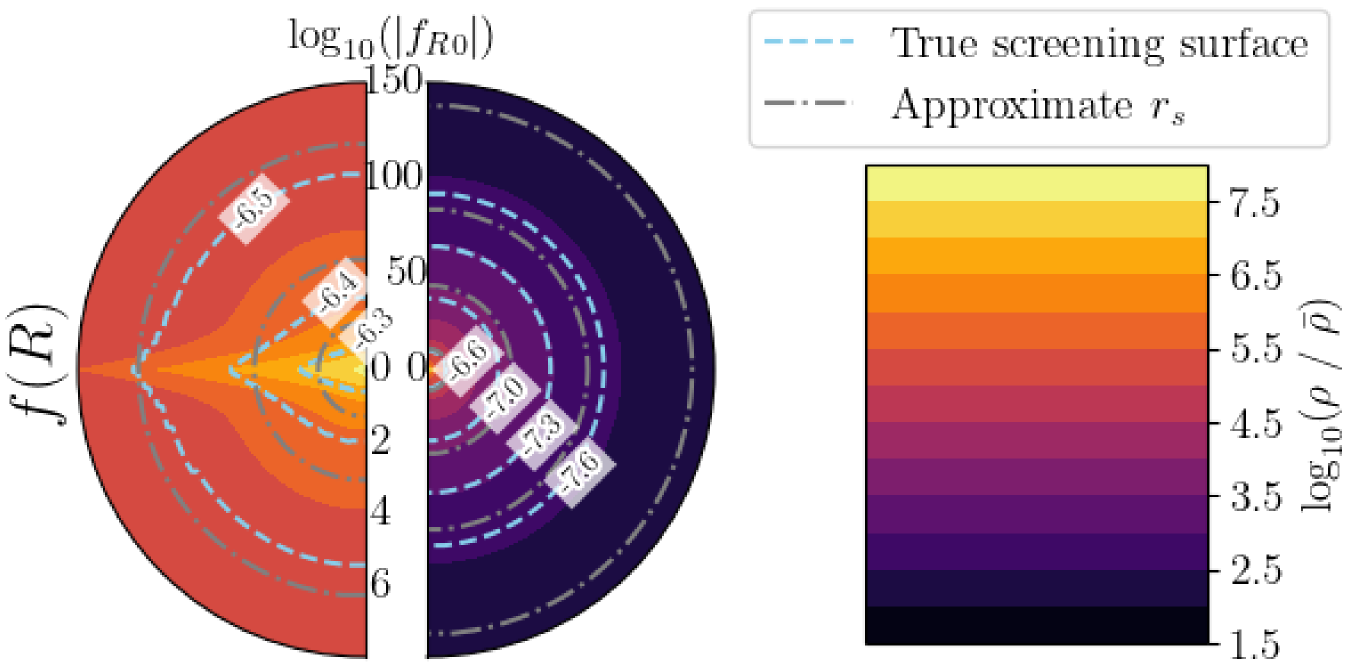
Screening Surfaces

Define our threshold for screening

$$\left.\frac{c^2\delta R(r,\theta)}{8\pi G\delta\rho(r,\theta)}\right|_{r=r_s(\theta)} = 0.9$$



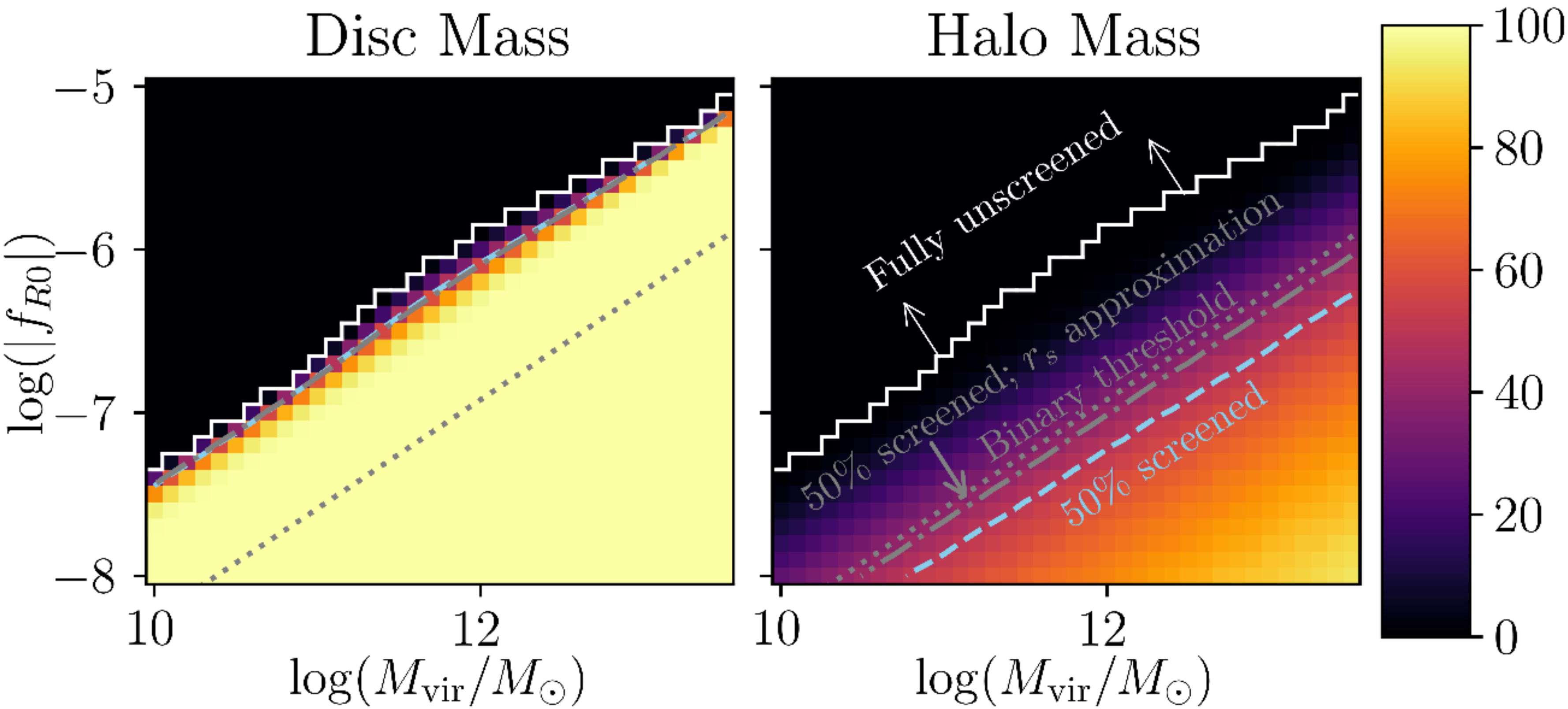
$M_{\rm vir} = 10^{11.5}\, M_\odot$

$\rho_{\rm NFW} = 5.2\times 10^6\, M_\odot\,{\rm kpc}^{-3},\ r_{\rm NFW} = 15\,{\rm kpc},\ \Sigma_{\rm disc} = 6.4\times 10^8\, M_\odot\,{\rm kpc}^{-2},\ R_{\rm disc} = 1.6\,{\rm kpc}$

$z_{\rm disc} = 0.26\,{\rm kpc}$

CB, March, Naik. JCAP 04 (2024) 004

Fifth Force Screening on Galactic Scales



CB, March, Naik. JCAP 04 (2024) 004

CHAMELEON SCREENING IN THE LABORATORY

The Chameleon

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

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

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

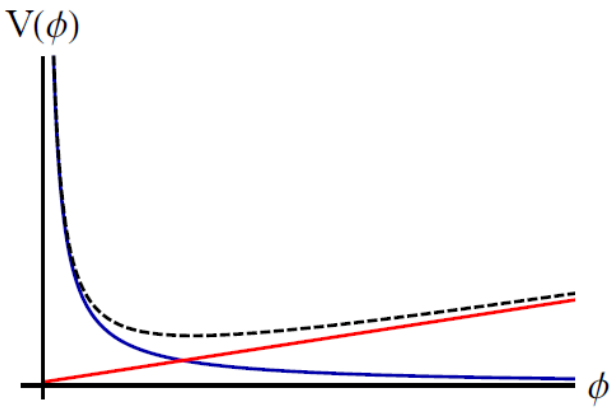
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

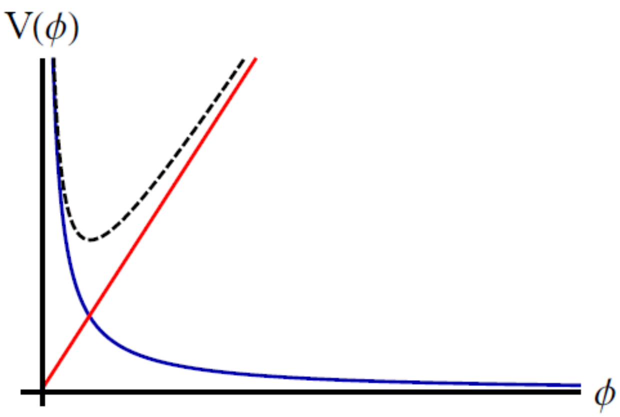
Dynamics governed by an effective potential

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

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



Low density



High density

The Scalar Potential

Around a static, spherically symmetric source of constant density

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

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

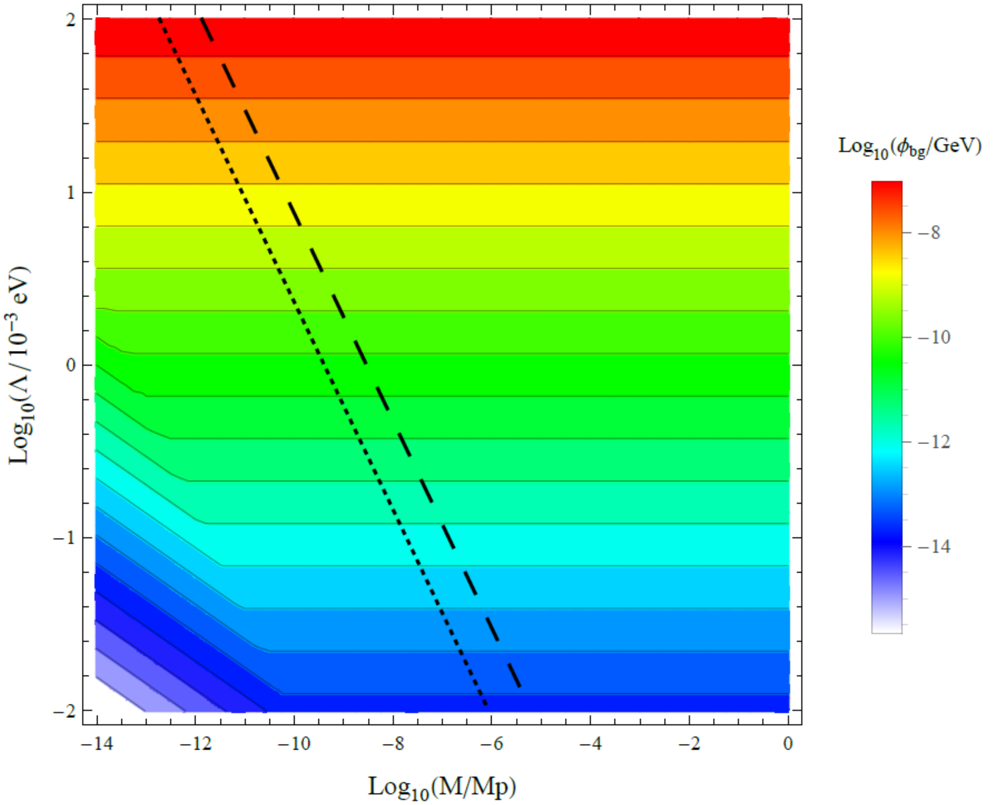
This determines how 'screened' an object is from the chameleon field

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

Why Atom Interferometry?

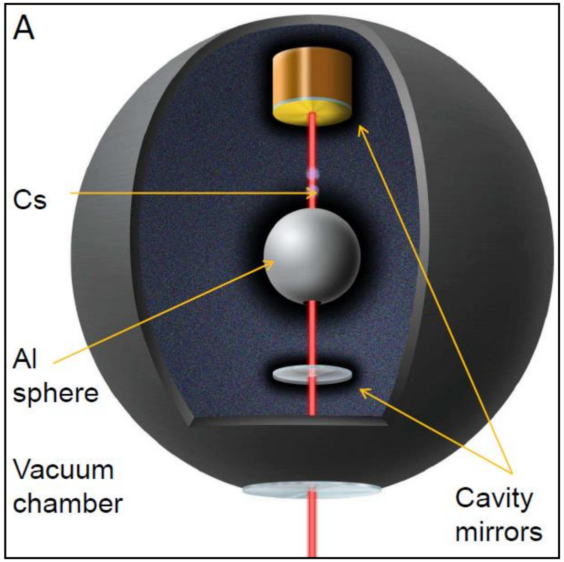
In a spherical vacuum chamber, radius 10 cm, pressure 10^{-10} Torr

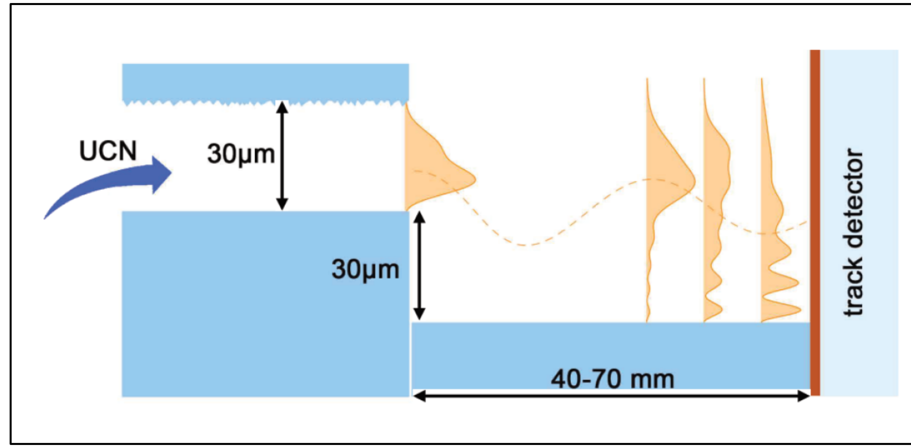
Atoms are unscreened above black lines
(dashed = caesium, dotted = lithium)

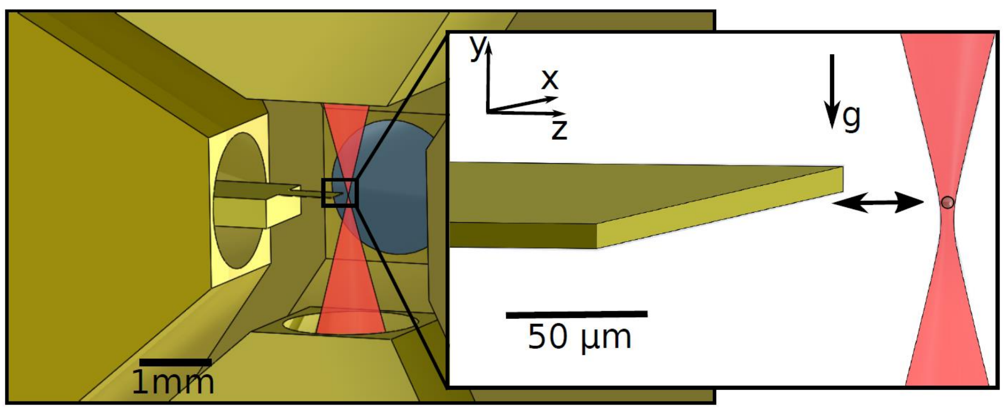


CB, Copeland, Hinds. JCAP 03 042 (2015)

Laboratory Searches – EP violation

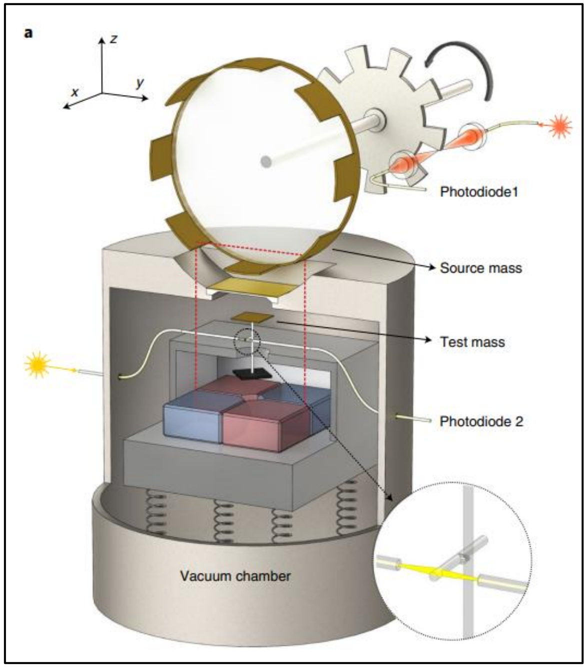


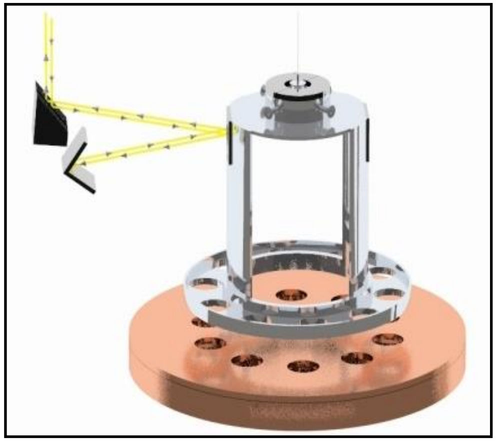


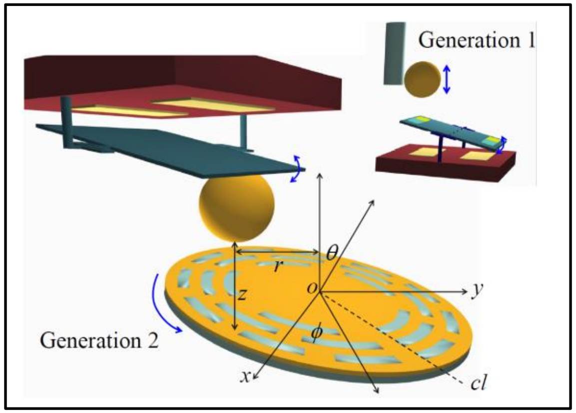


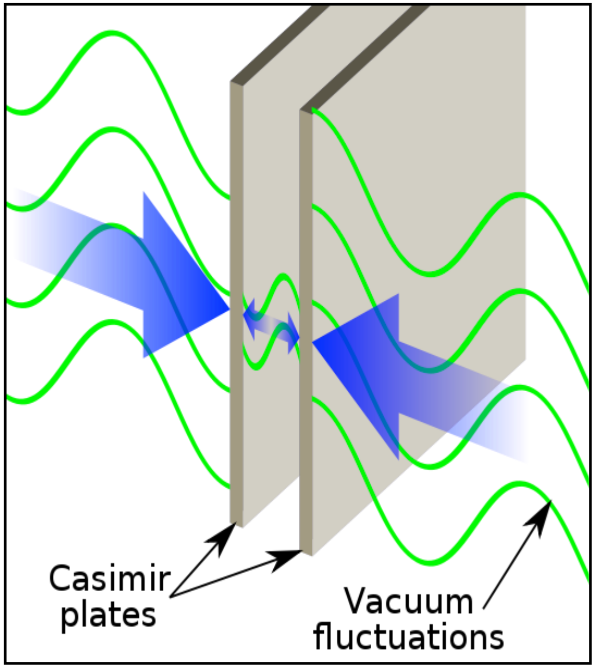
Jaffe, Haslinger, Xu, Hamilton, Upadhye, Elder, Khoury, Müller. (2017)
Rider, Moore, Blakemore, Louis, Lu, Gratta. (2016)
Ivanov, Hollwieser, Jenke, Wellenzohen, Abele (2013)
For a review see CB & Sakstein (2017). Brax, Casas, Desmond, Elder. (2022)

Laboratory Searches – Short Range Forces







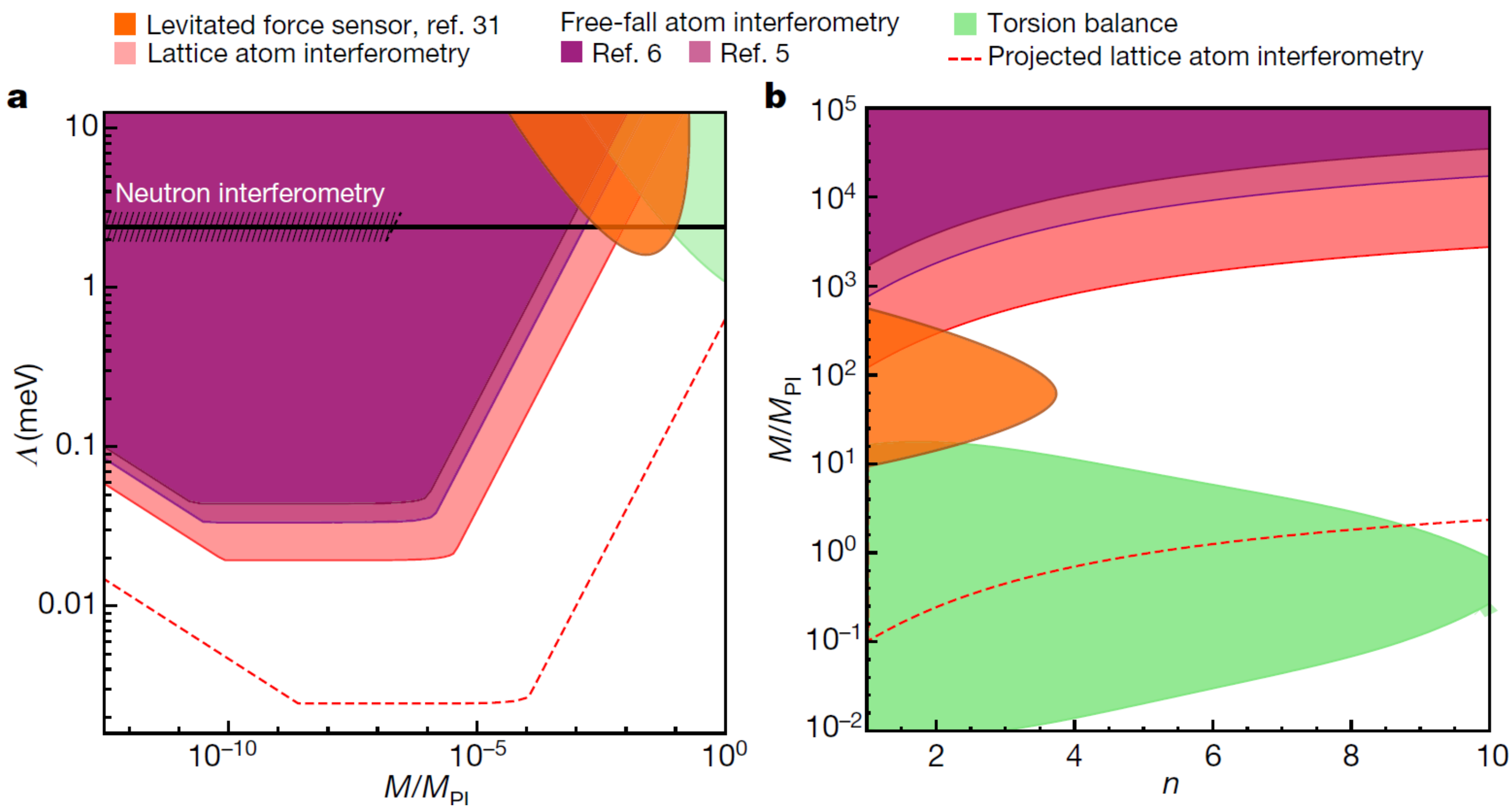


Upadhye (2012). Kapner et al. (2006).Brax et al. (2007). Elder et al. (2019). Yin et al. (2022)
For a review see CB & Sakstein (2017). Brax, Casas, Desmond, Elder. (2022)

Chameleon: Combined Constraints

Bare potential: $V(\phi) = \Lambda^{n+4}/\phi^n$

Bare matter coupling: M



Panda, Tao, Ceja, Khoury, Tino, Muller. Nature 631, 515–520 (2024)

For a review of constraints see: Brax, Davis, Elder. Phys. Rev. D 107 (2023) 084025

Summary

Explanations for dark energy, dark matter and other modifications of gravity often introduce new scalar fields

Corresponding long range forces are not seen

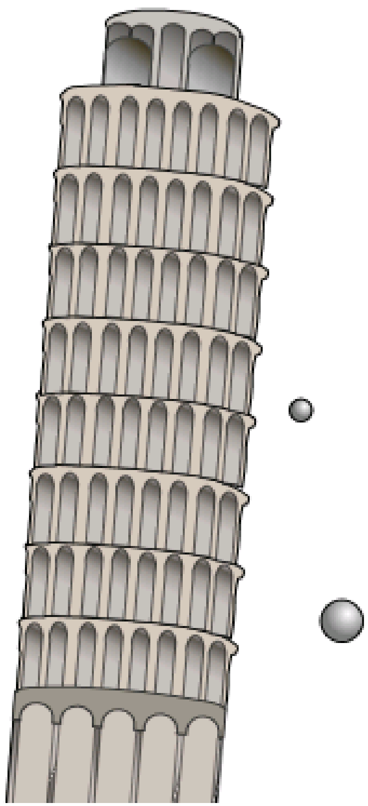
Screening mechanisms (non-linearities) hide these forces from fifth force searches

Can still be detected in suitably designed experiments and observations

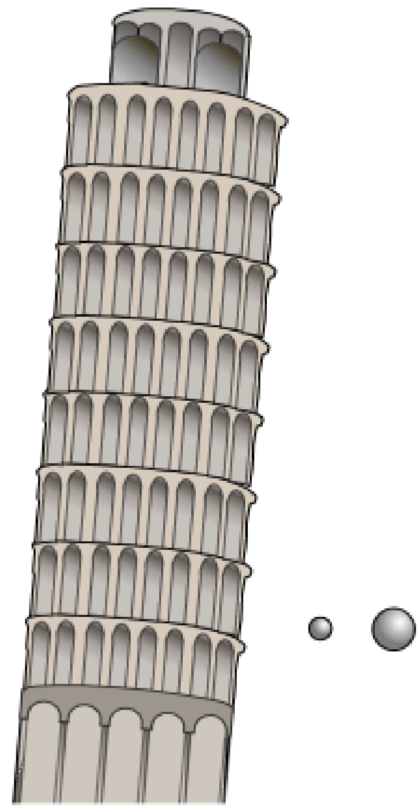
But care needed to make sure theoretical accuracy matches observational precision

Testing the Equivalence Principle

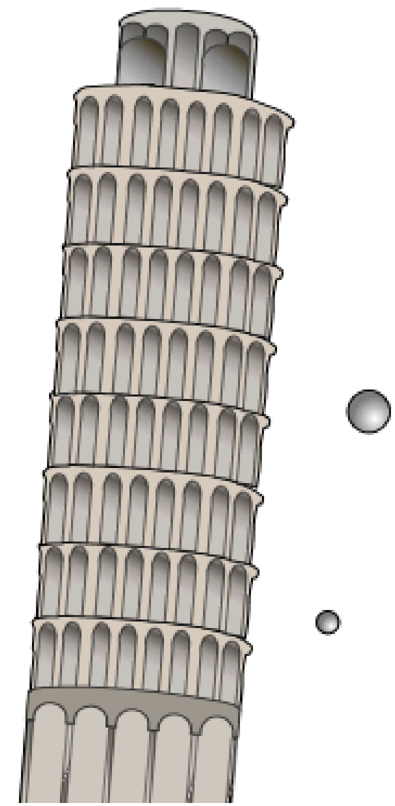
Do large objects and small objects fall at the same rate?



Old idea



Galileo



Fifth force with thin shell?

Image credit: Theresa Knott

Can we forbid a coupling to matter?

Yes, through scale invariance! But then all mass scales must arise spontaneously

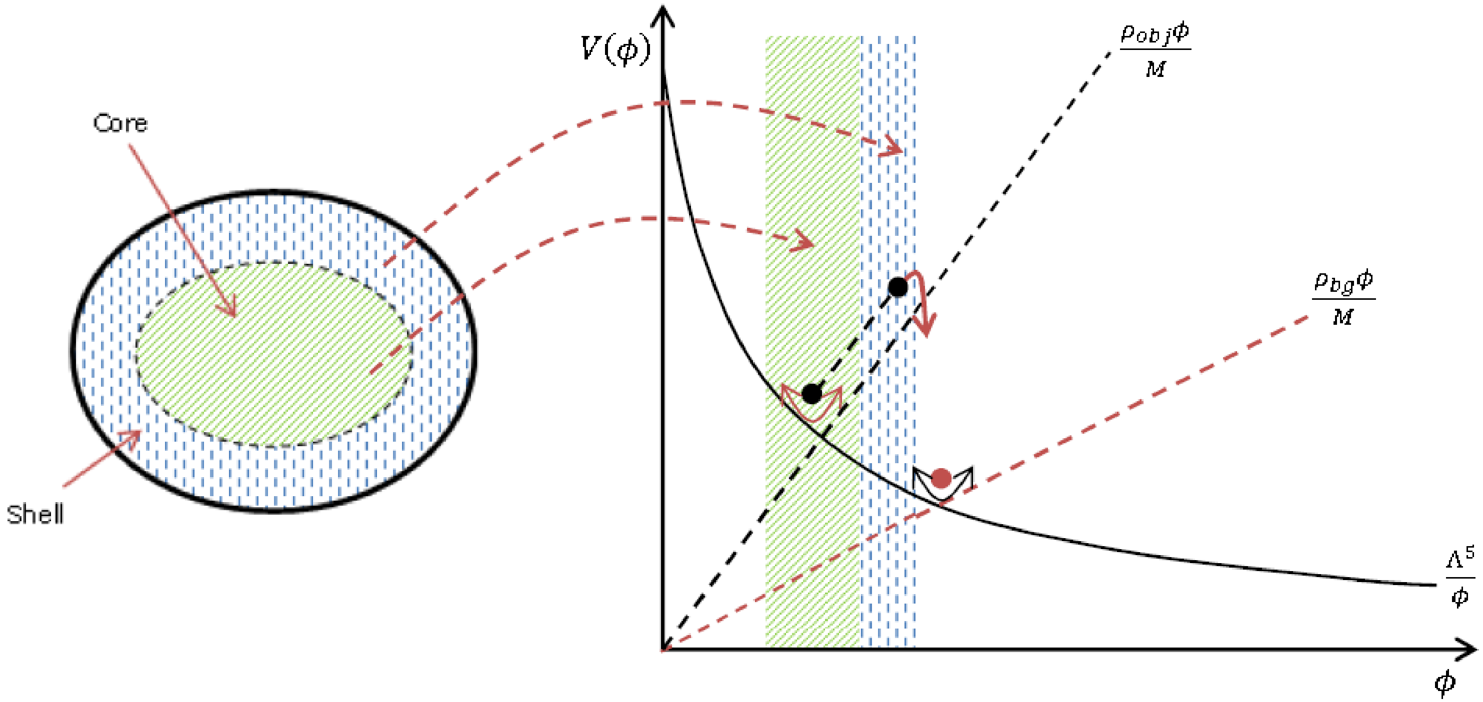
Soft breaking allowed, but constrained by observations

Suggestions for how to preserve this invariance at the loop level – but renormalisation then becomes challenging

Shaposhnikov, Zenhausern, 2009. Ghilencea, 2016. Ghilenceas, Lalak, Olszewski, 2016. Ferreira, Hill, Ross, 2017.

Chameleon Screening

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

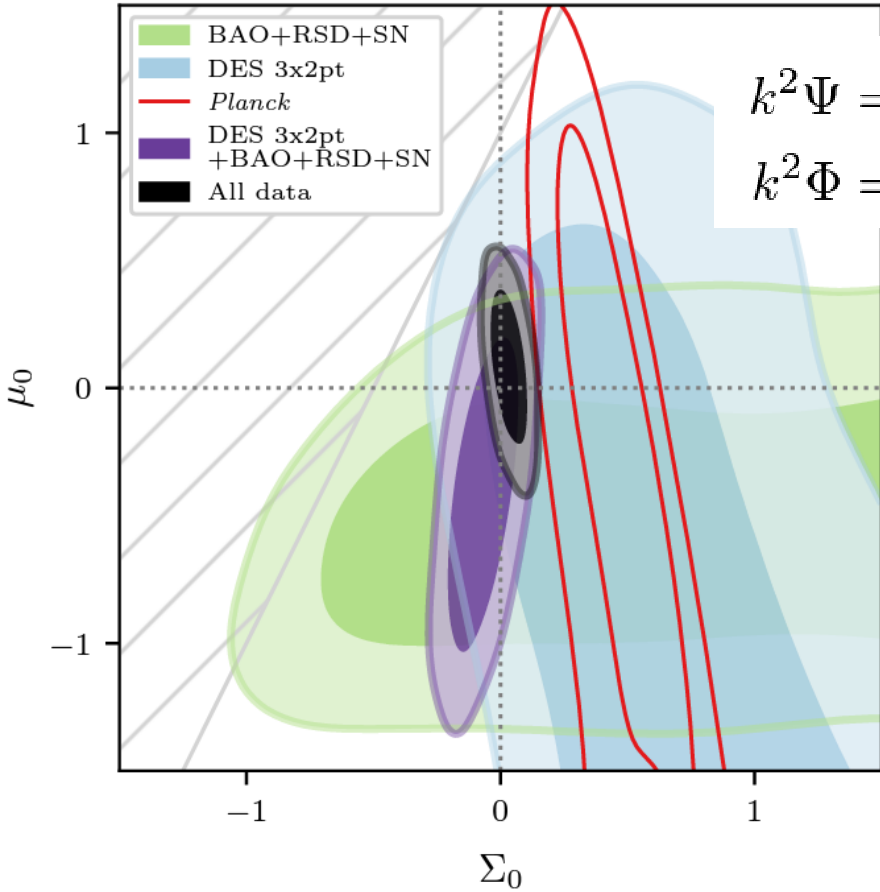


The chameleon potential well around 'large' objects is shallower than for canonical light scalar fields

CB, Copeland, Stevenson. (2015)

Testing Gravity on Cosmological Scales

For example: Parameterise modifications to the Poisson and lensing equations



$$k^2\Psi = -4\pi G a^2 \left[1+\mu(a,k)\right]\left(\rho\delta + 3(\rho+P)\sigma\right),$$

$$k^2\Phi = -4\pi G a^2 \left[1+\Sigma(a,k)\right]\left(2\rho\delta + 3(\rho+P)\sigma\right).$$

$$\Sigma(a,k) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}$$

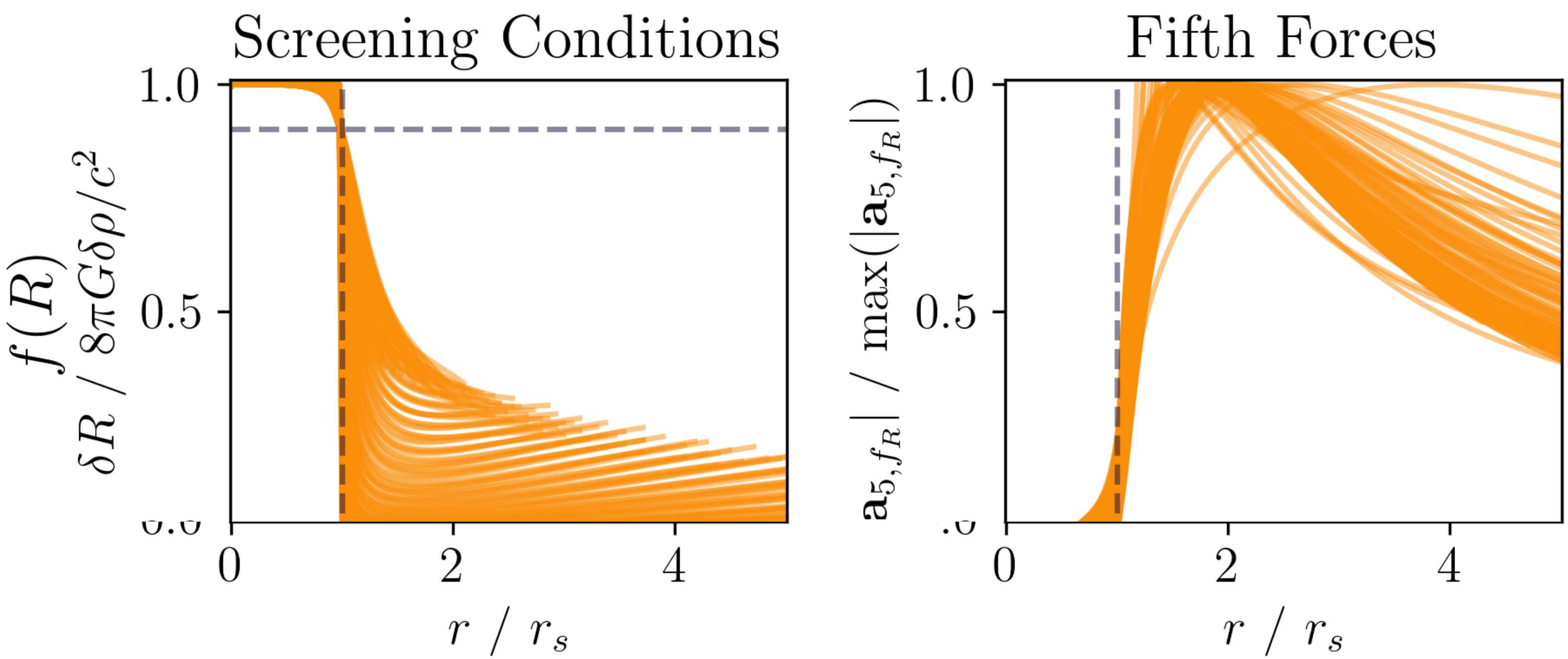
$$\mu(a,k) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}.$$

Dark Energy Survey Year 3 Results, Phys. Rev. D 107 (2022) 083504

Defining Screening

Define our threshold for screening

$$\left.\frac{c^2 \delta R(r,\theta)}{8\pi G \delta\rho(r,\theta)}\right|_{r=r_s(\theta)} = 0.9$$



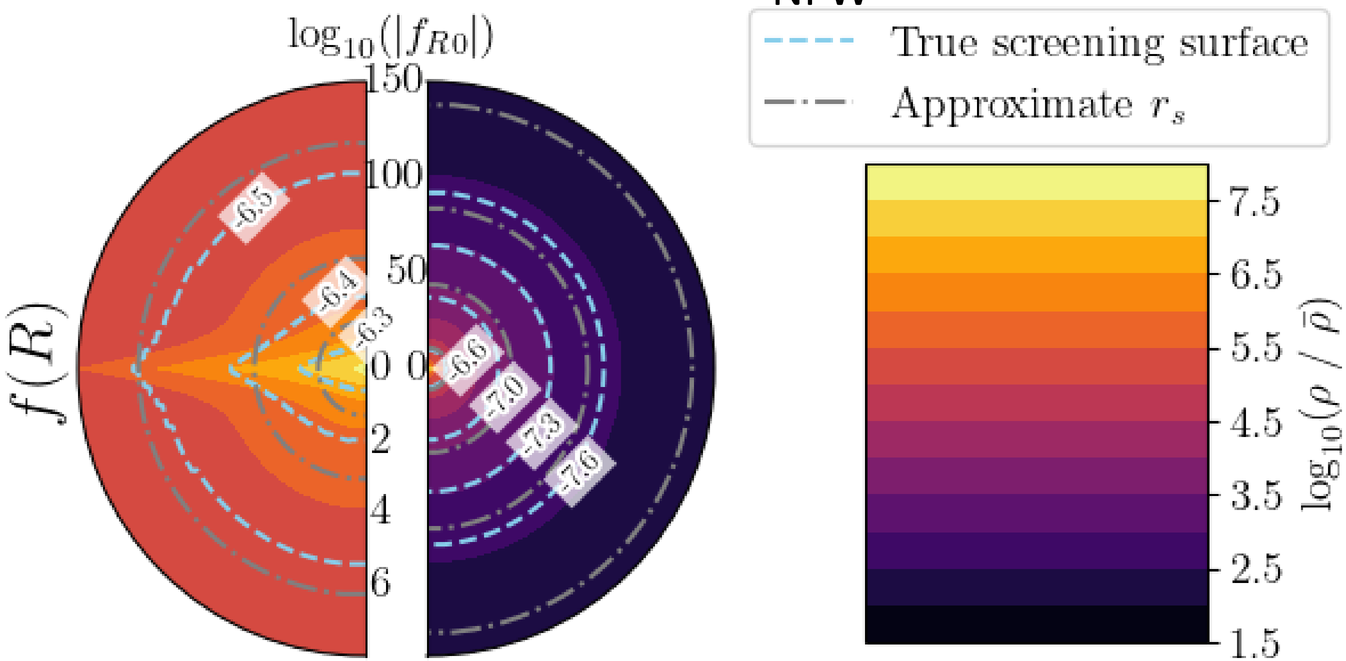
CB, March, Naik. arXiv:2310.19955

Screening Surfaces

For a range of f_{R0}

Left panel to 5 R_{disc} (~8 kpc)

Right panel to 10 R_{NFW} (~ 150 kpc)



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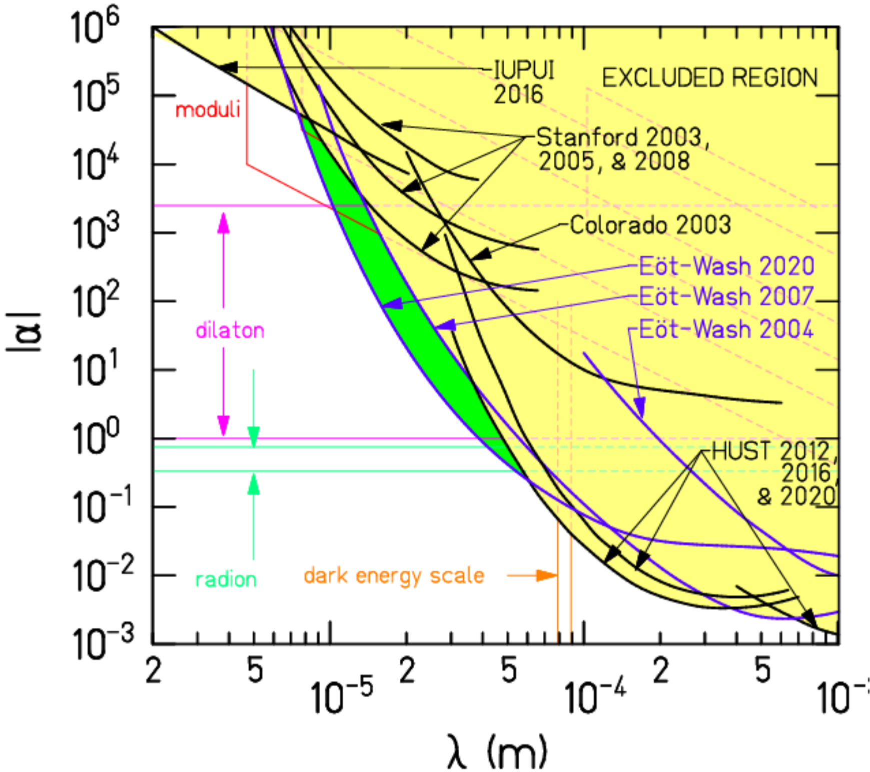
$z_{\rm disc} = 0.26\,{\rm kpc}$

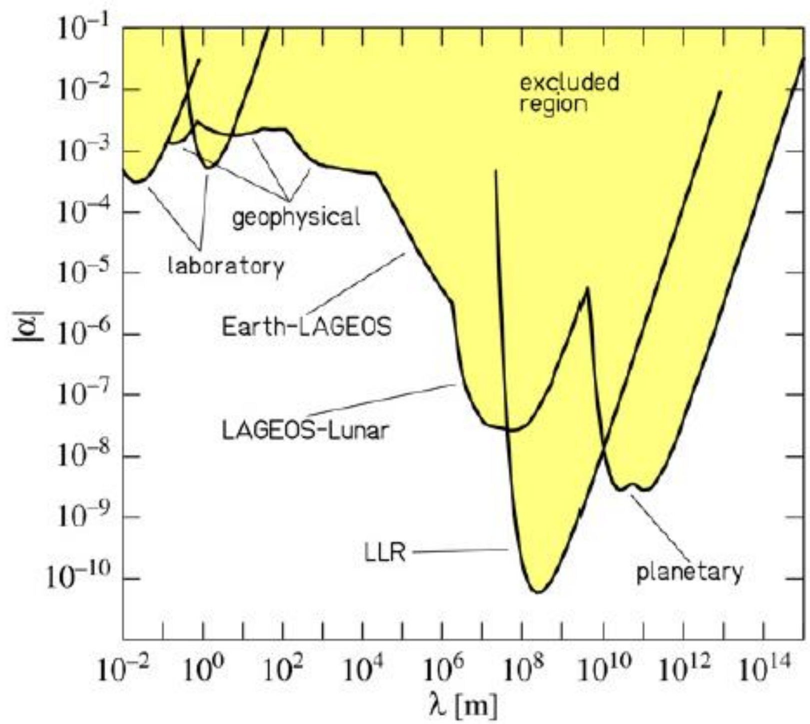
CB, March, Naik. arXiv:2310.19955

Yukawa Fifth Forces

A long-range Yukawa fifth force is excluded to a high degree of precision in the solar system

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



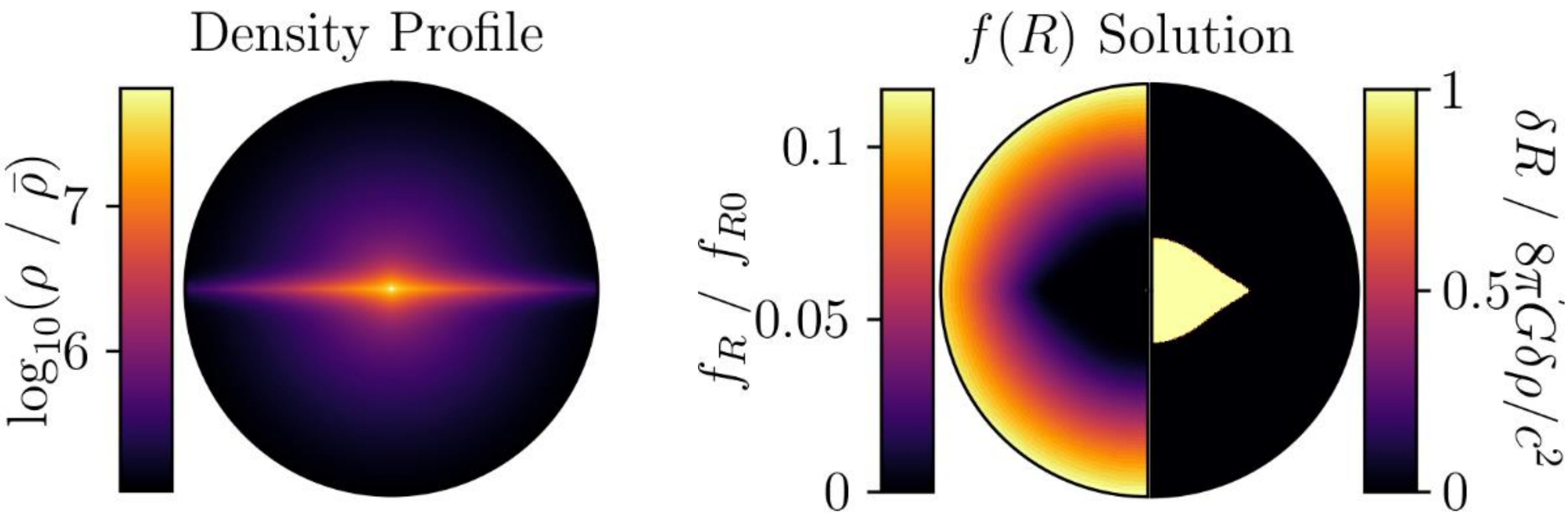


Adelberger et al. 2009. Lee et al. 2020.

Scalar Field Inside a Galaxy

NFW dark matter halo, plus double exponential disc

Define a galaxy in terms of its virial mass, use known empirical relations to derive other properties



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CB, March, Naik. JCAP 04 (2024) 004