External Constraints on Dark Energy Theories

Clare Burrage

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Outline:

Dark energy and dynamical scalar fields

Precision measurements and screening of interactions

Novel behaviour in the laboratory

Novel behaviour on galactic scales

University of Nottingham
UK | CHINA | MALAYSIA

Local Searches for Dynamical Dark Energy Scalars

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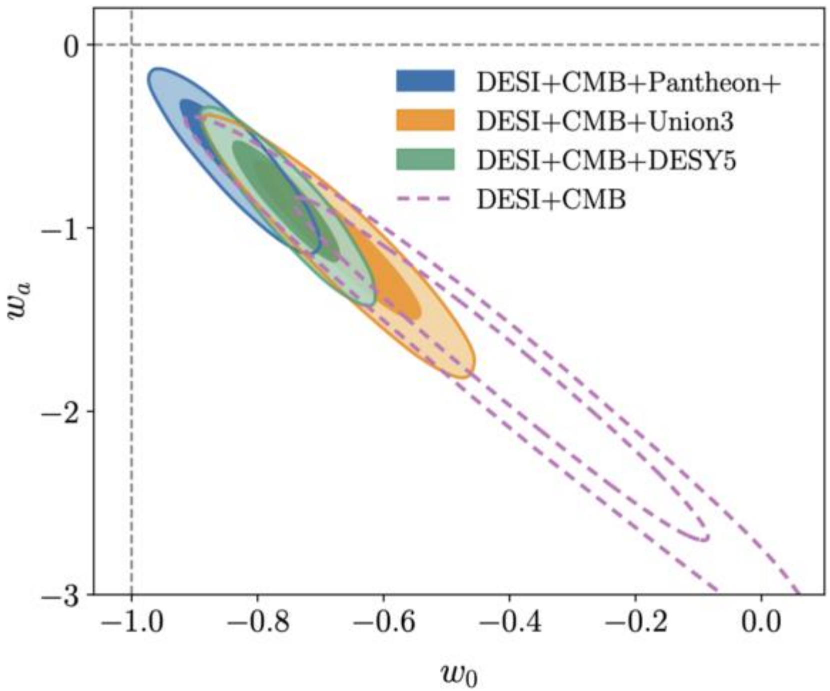
The Cosmological Constant?

Accelerated expansion can be driven by a cosmological constant

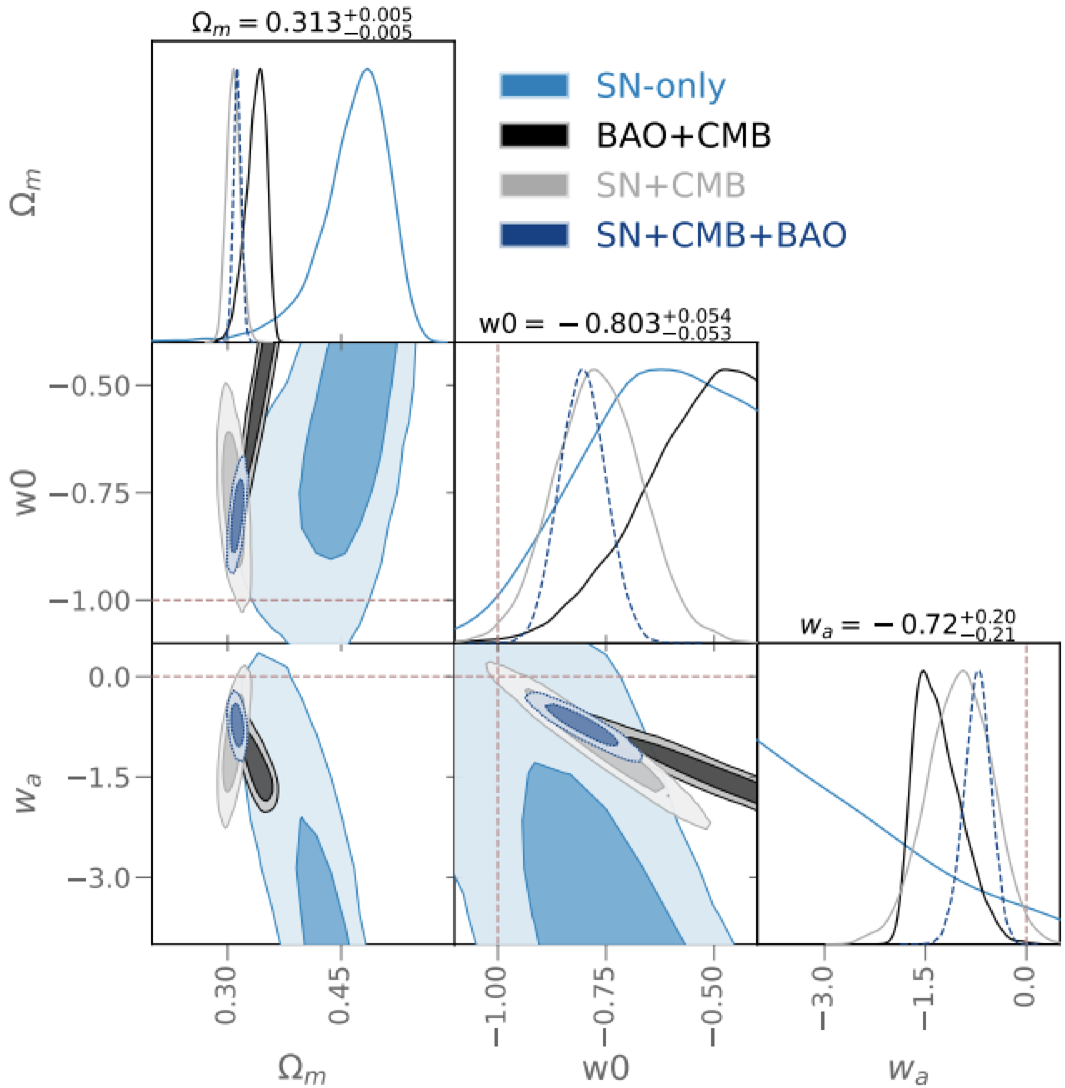
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda_{\rm B} g_{\mu\nu} = \kappa T_{\mu\nu} \, ,$$

Possible time varying equation of state (at 2.8-4.2σ)



DESI collaboration. Phys. Rev. D 112, 083515, 2025

The Cosmological Constant?



DES collaboration. arXiv:2511.07517

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

A modification of gravity

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

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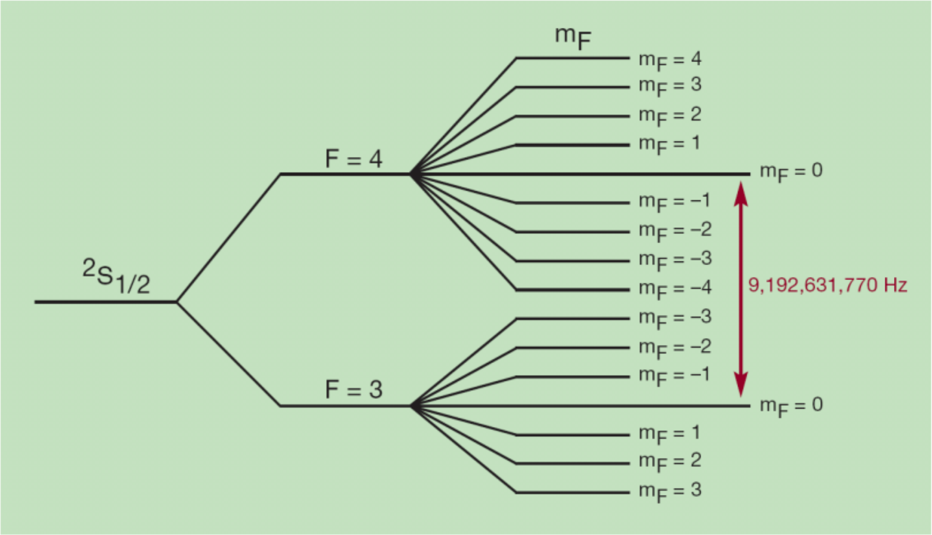
Can we sense the time evolution of the background field?

Can we see scalar mediated forces?

Atomic Clocks

Driven oscillations in a ‘two state’ system



1 sec = 9,192,631,770 transitions between hyperfine levels of ground state of caesium 133 (at 0K)

Typical accuracy $\Delta f / f \sim 10^{-18}$

Atomic Clocks

Interactions with matter

$$\mathcal{L} = (\kappa\phi)^n \left(d_\gamma^{(n)} \tfrac{1}{4} F_{\mu\nu}F^{\mu\nu} - d_{m_e}^{(n)} m_e \bar{\psi}_e \psi_e \right)$$

Lead to variations in fundamental constants

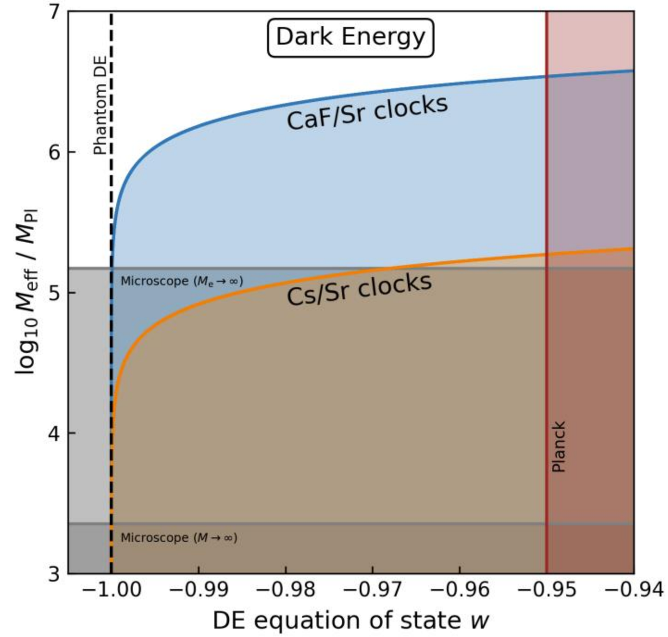
$$\frac{\delta\alpha}{\alpha} \equiv d_\gamma^{(n)} (\kappa\phi)^n \qquad \frac{\delta m_f}{m_f} \equiv d_{m_f}^{(n)} (\kappa\phi)^n \qquad \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} \equiv d_g^{(n)} (\kappa\phi)^n$$

Sherrill et al, New J. Phys. 25 093012 (2023)

Quintessence

Atomic clocks can constrain the dark energy equation of state

$$M_{\mathrm{eff}} \equiv \left(M^{-1} - M_e^{-1}\right)^{-1}$$



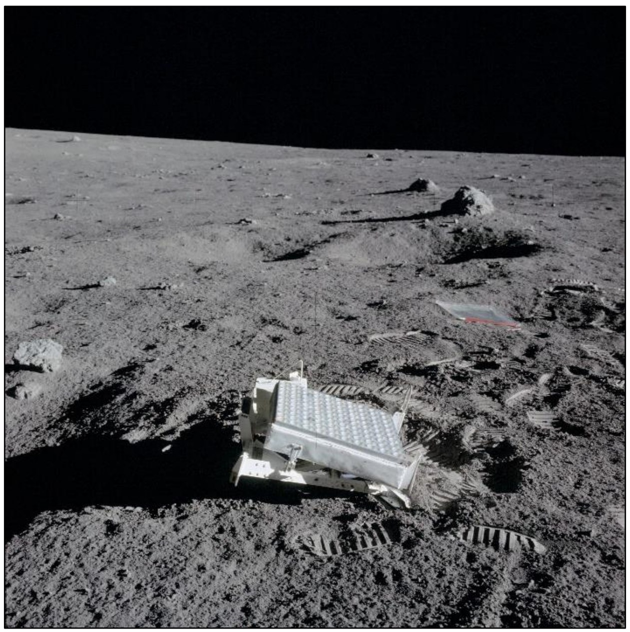
Requires dark energy to couple differently to electrons and nucleons

Elder, Mentasti, Pasatembou, Baynham, Buchmueller, Contaldi, de Rham, Hobson, Tolley
arXiv:2504.07179

Lunar Laser Ranging

Lunar Laser ranging requires

$$\left|\frac{\dot{G}}{G}\right| \lesssim 0.002 H_0$$



Linearised parameterisation of Horndeski dark energy

$$\alpha_M := -H^{-1}\dot{G}/G$$

Can local constraints be translated to cosmological scales?

Hofmann, Müller. Class. Quantum Grav. 35 035015 (2018)
Bellini, Sawicki. JCAP 1407 (2014) 050
See also Babichev, Deffayet, Esposito-Farèse. Phys.Rev.Lett. 107 (2011) 251102
See also talk by Tessa Baker

Local time evolution of constants

Cosmological time evolution of fundamental constants implies equivalent local time evolution if:

- local fifth forces are weak
- the weak equivalence principle holds
- fifth forces are parallel to gravitational forces

CB, Dombrowski. JCAP 07 (2020) 060

Local time evolution of constants

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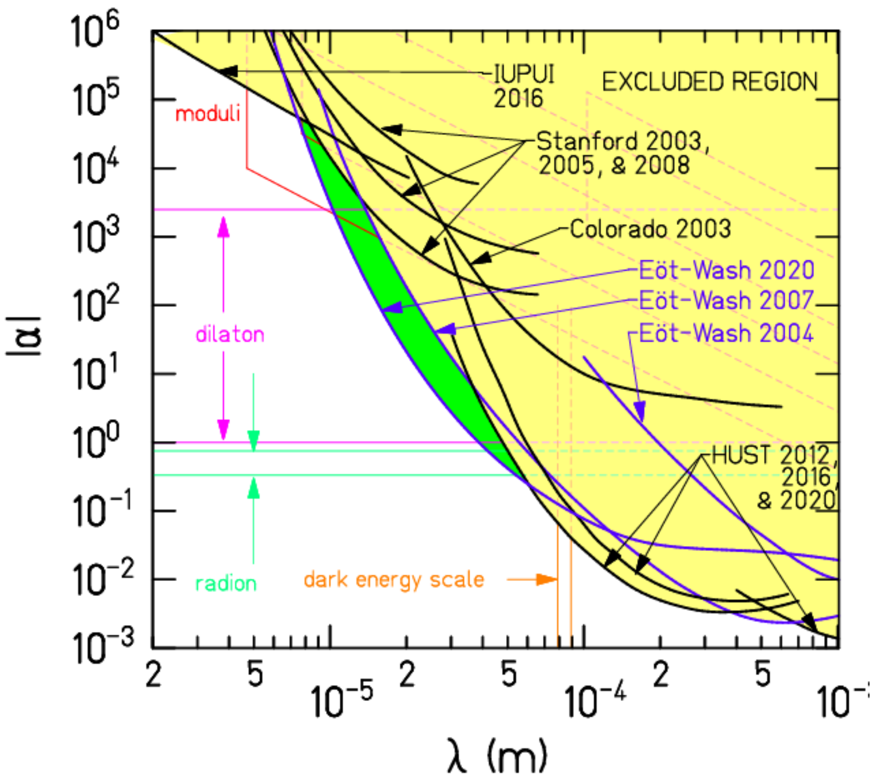
Conditions will hold for Vainshtein screening
Equivalence principle violation possible for thin-shell screening

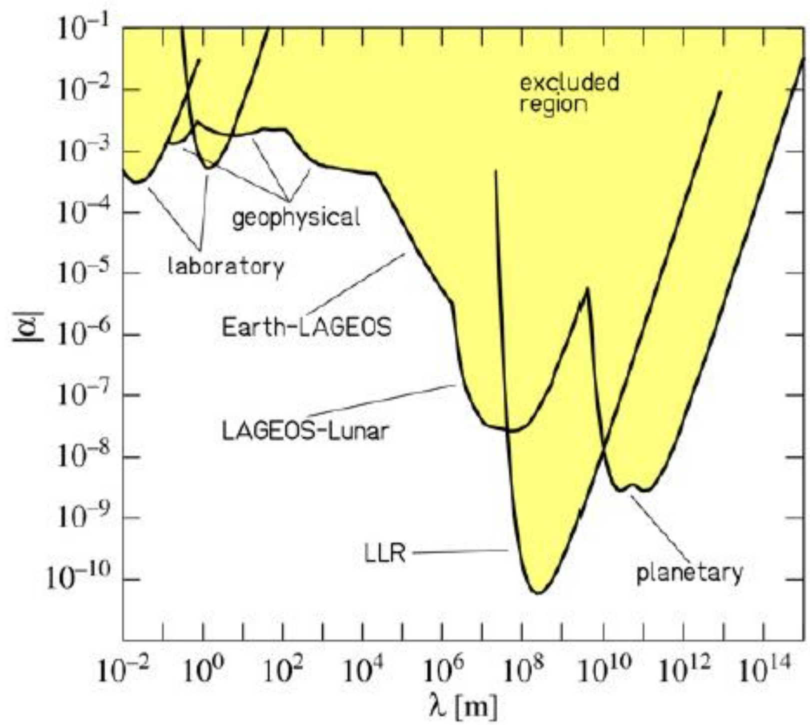
CB, Dombrowski. JCAP 07 (2020) 060

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. Prog. Part. Nucl. Phys. 62 (2009) 102. Lee et al. PRL 124 (2020) 10, 101101.

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 Phys.Rev.D 72 (2005) 043535. Olive, Pospelov Phys.Rev.D 77 (2008) 043524. Hinterbichler, Khoury Phys.Rev.Lett. 104 (2010) 231301.

- **Locally large mass**

Chameleon models, quadratically coupled ULDM

Khoury, Weltman Phys.Rev.Lett. 93 (2004) 171104.
Hees et al. Phys.Rev. D 98, 064051 (2018)

- **Locally large kinetic coefficient**

Vainshtein mechanism, Galileon and k-mouflage models

Vainshtein Phys.Lett.B 39 (1972) 393-394. Nicolis, Rattazzi, Trincherini Phys.Rev.D 79 (2009) 064036. Babichev, Deffayet, Ziour JHEP 05 (2009) 098.

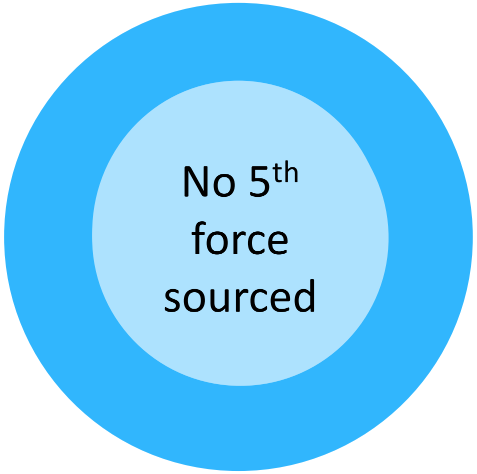
Screening Phenomenology

Compare to Yukawa fifth force

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

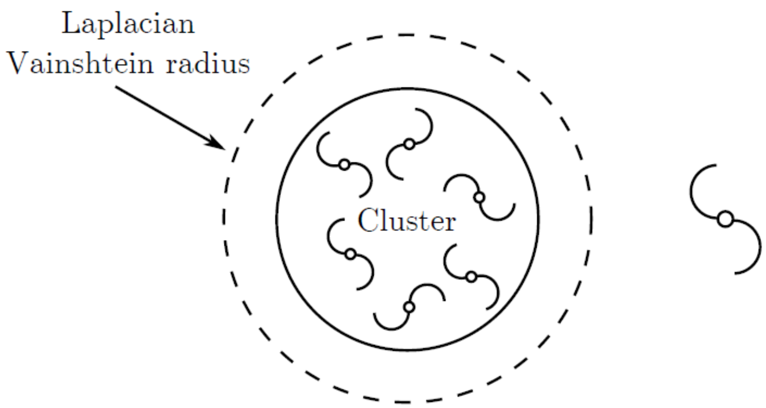
Change the way in which matter sources the scalar field

- thin-shell effect



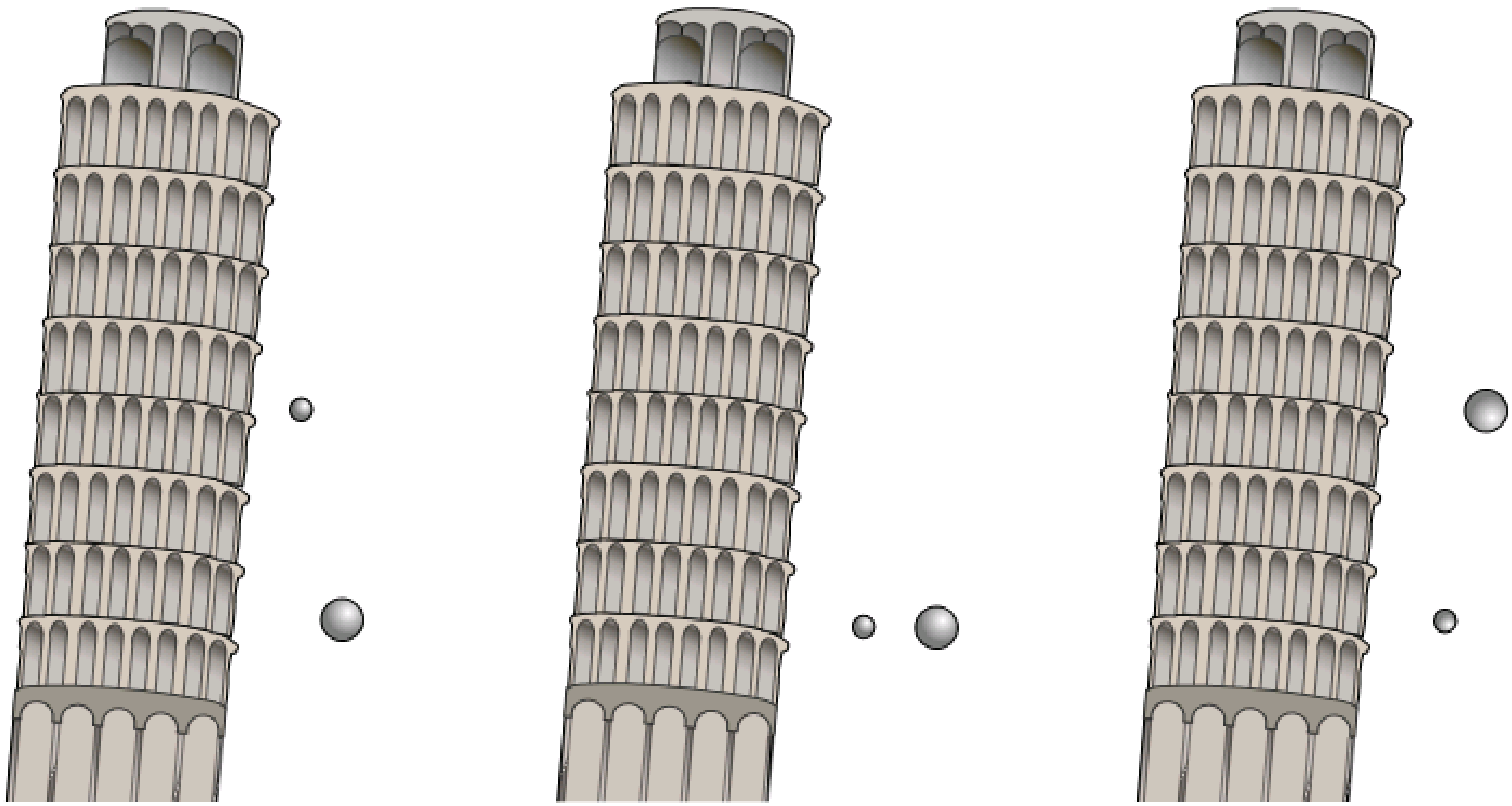
Change the dependence on distance

- Vainshtein screening



Tests of the equivalence principle

Do objects with different composition fall at the same rate?



Old idea | Galileo | Dark Energy?

Image credit: Theresa Knott

The Chameleon

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

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

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

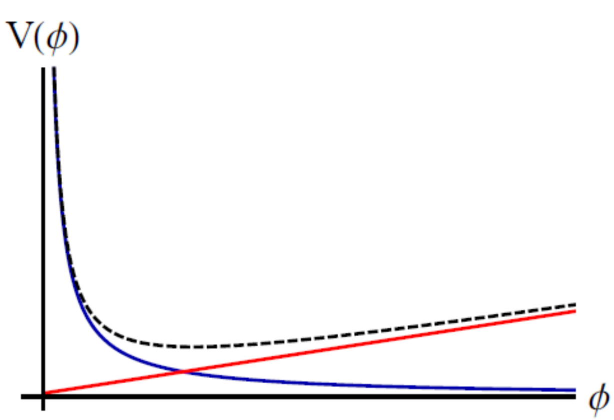
Khoury, Weltman. Phys.Rev.Lett. 93 (2004) 171104. Image credit: Nanosanchez

Varying Mass

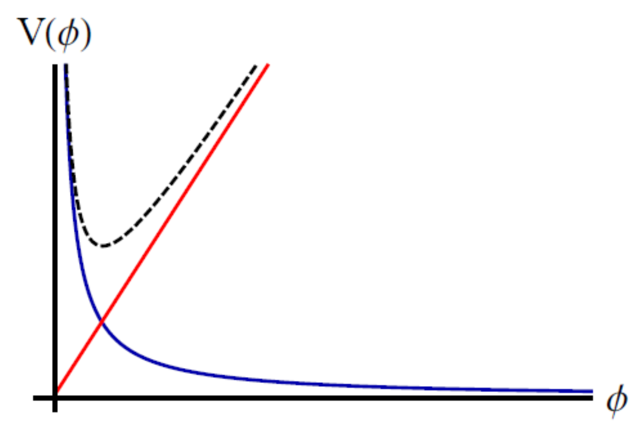
Dynamics governed by an effective potential

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

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



Low density



High density

Field is suppressed inside compact objects

The Scalar Potential

Around a static, spherically symmetric source of constant density

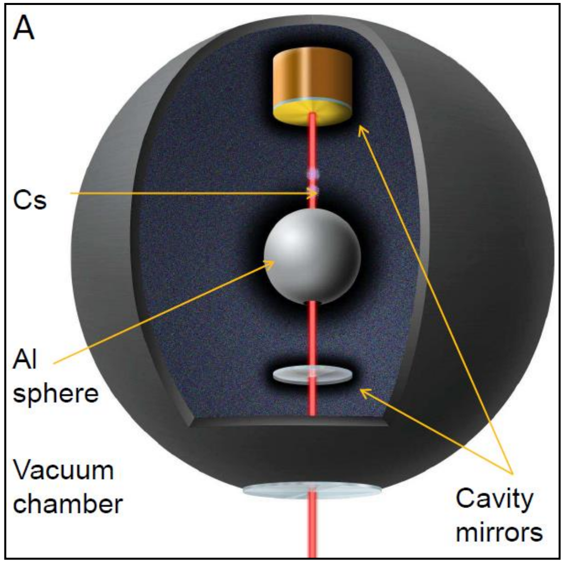
$$\phi = \phi_{\rm bg} - \lambda_A \frac{1}{4\pi R_A} \frac{M_A}{M} \frac{R_A}{r} e^{-m_{\rm bg} r}$$

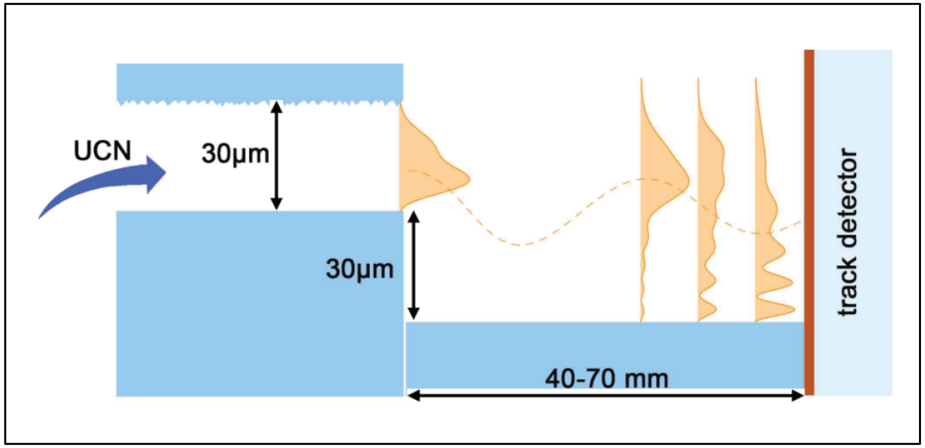
$$\lambda_A = \begin{cases} 1\,, & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg}\,, & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

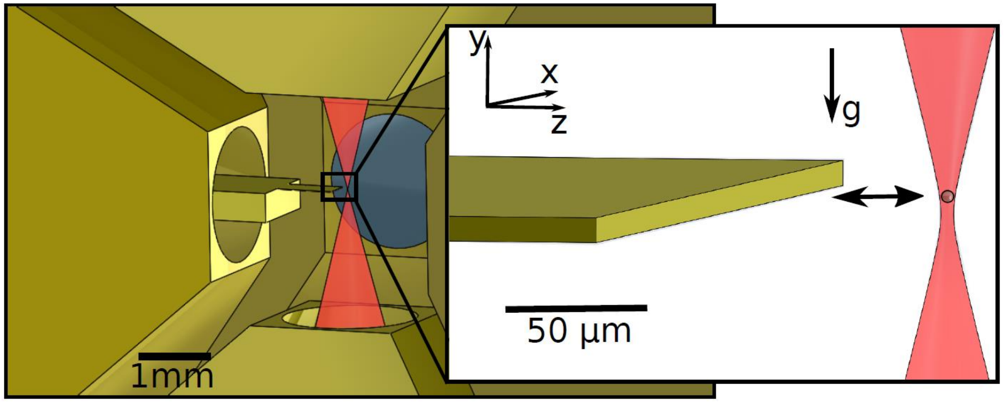
Compactness determines how ‘screened’ an object is from the chameleon field

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

Laboratory Searches – EP violation



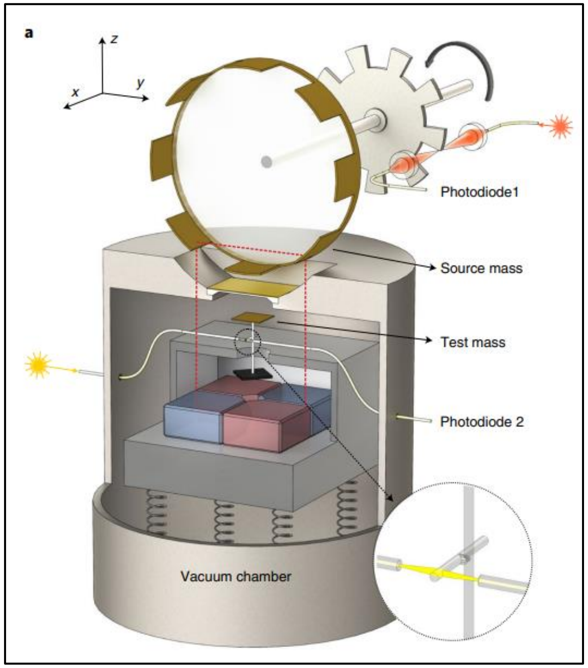


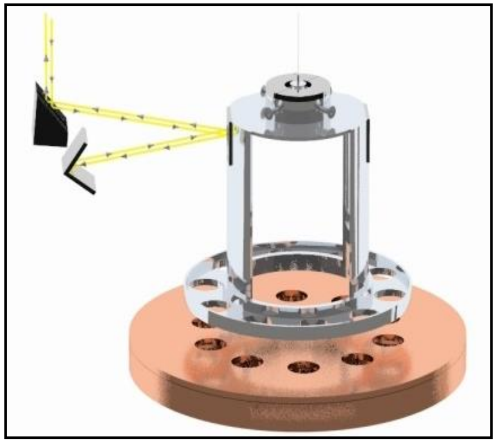


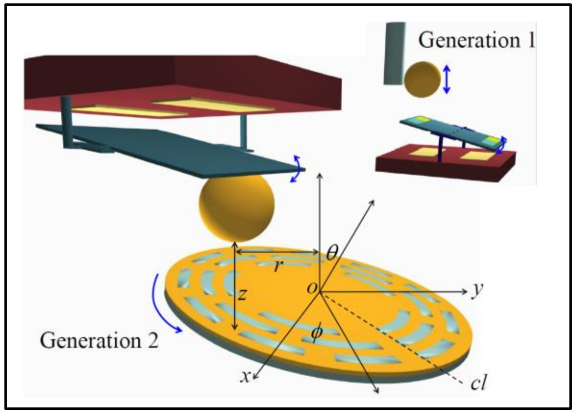
Jaffe et al. Nature Phys. 13 (2017) 938. Rider et al. Phys.Rev.Lett. 117 (2016) 10, 101101. Ivanov et al. Phys.Rev.D 87 (2013) 10, 105013.

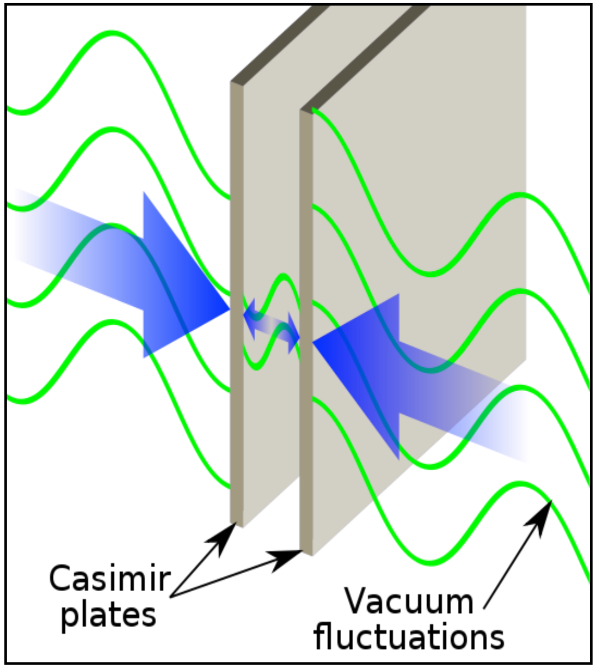
For a review see CB, Sakstein Living Rev.Rel. 21 (2018) 1, 1. Brax, Casas, Desmond, Elder. Universe 8 (2021) 1, 11

Laboratory Searches – Short Range Forces







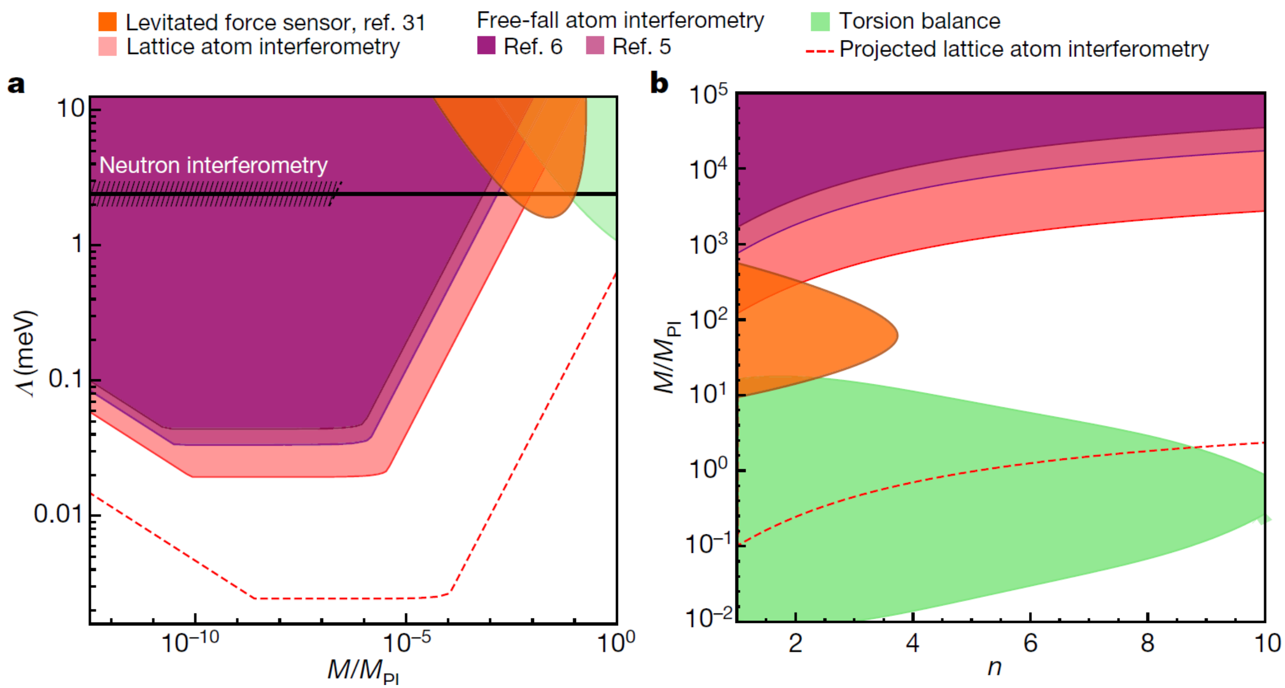


Upadhye Phys.Rev.D 86 (2012) 102003. Kapner et al. Phys.Rev.Lett. 98 (2007) 021101. Brax et al. Phys.Rev.D 76 (2007) 124034 . Brax et al. Phys.Rev.D 107 (2023) 8, 084025. Yin et al. Nature Phys. 18 (2022) 10, 1181. **For a review** see CB, Sakstein Living Rev.Rel. 21 (2018) 1, 1. Brax, Casas, Desmond, Elder. Universe 8 (2021) 1, 11

Chameleon: Combined Constraints

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

Bare matter coupling: M

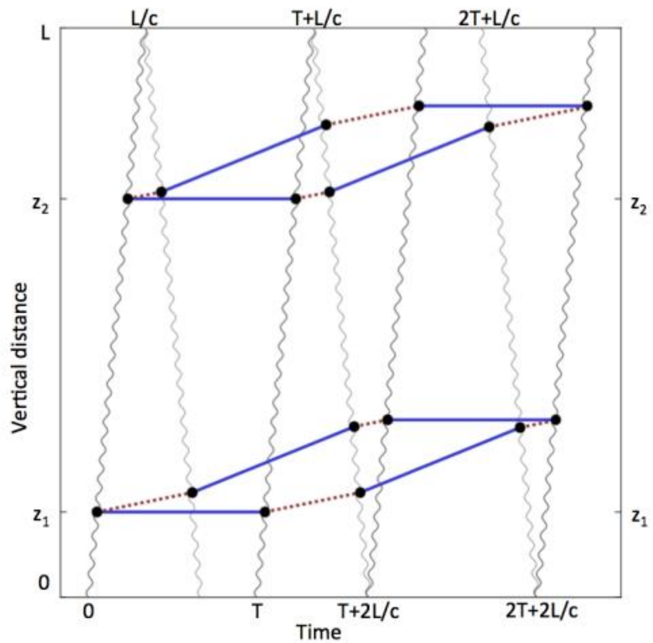


AI bounds anomalous acceleration < 6.2 nm s^{-2}

Panda, Tao, Ceja, Khoury, Tino, Muller. Nature 631, 515–520 (2024)
See also: Sabulsky, Dutta, Hinds, Elder, CB, Copeland. Phys.Rev.Lett. 123 (2019) 6, 061102
Brax, Davis, Elder. Phys. Rev. D 107 (2023) 084025

Long-baseline atom interferometry

Differential interferometer, one laser interacts with (at least) two spatially separated clouds of atoms



TVLBAI, e.g. AION, Magis, 100m and 1km baseline
Space based AEDGE,~ 10^5 km baseline

Arvanitaki et al. Phys. Rev. D 97, 075020 (2018). Badurina et al. JCAP 05 (2020) 011
Abdalla et al. EPJ Quant. Technol. 12 (2025) 1 42. Abou El-Neaj et al. EPJ Quant. Technol. 7 (2020) 6

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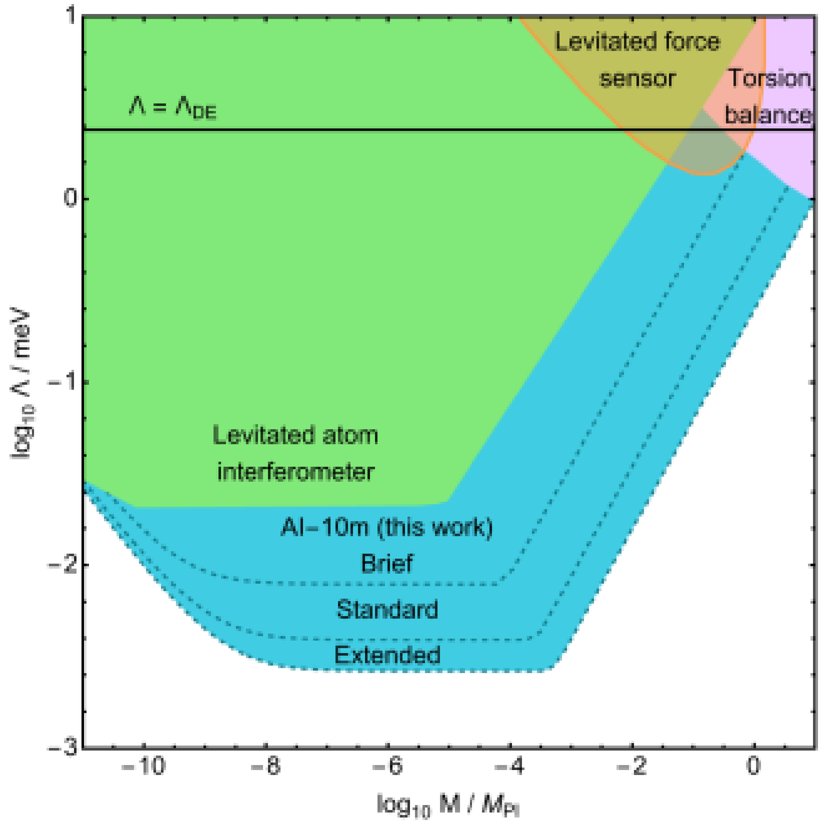
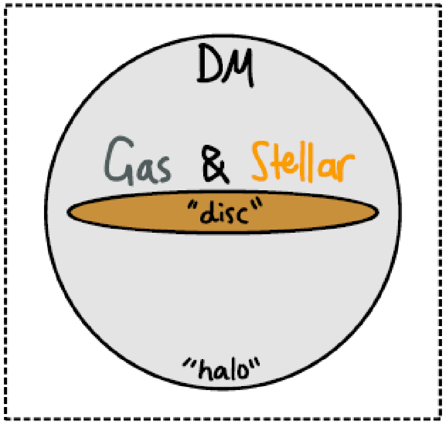


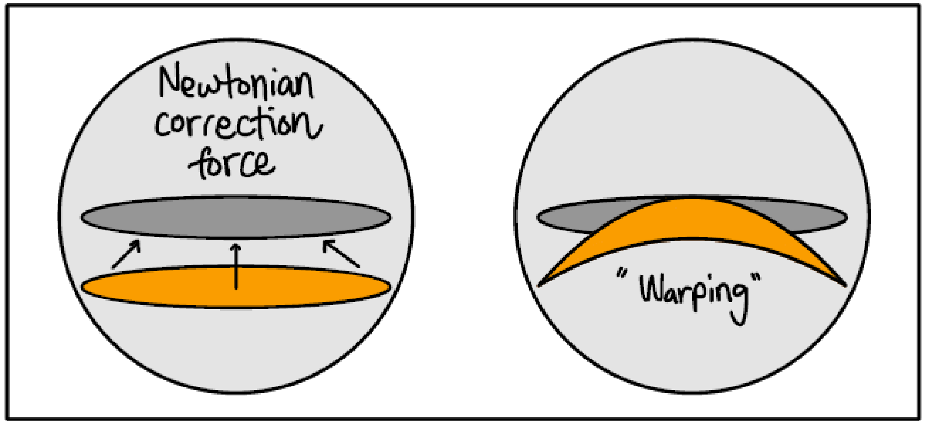
Banks, Carlton, Elder, Hird, McCabe. arXiv:2511.09750

Tests on Galactic Scales

Different components of a dwarf galaxy may fall in a gravitational field at different rates

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





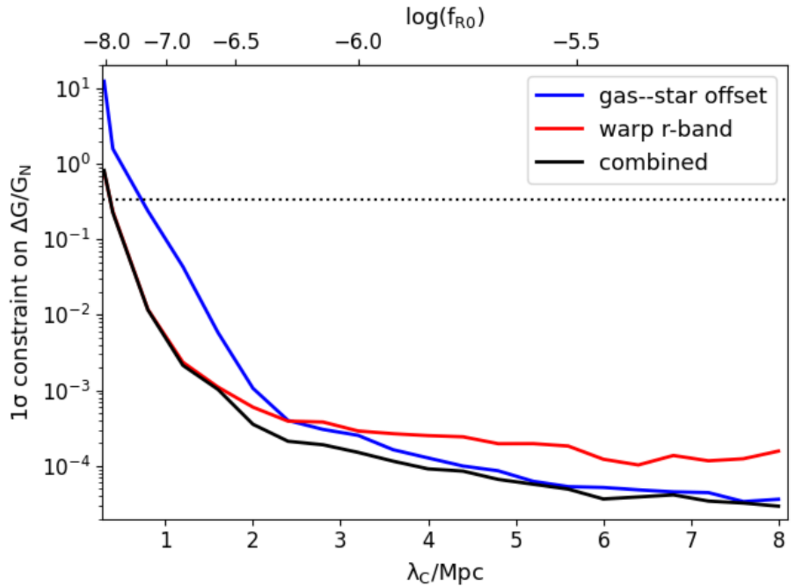
Hui, Nicolis, Stubbs. Phys.Rev.D 80 (2009) 104002. Jain, VanderPlas. JCAP 10 (2011) 032 Desmond, Ferreira, Lavaux, Jasche. Phys.Rev.D 98 (2018) 6, 064015. Phys.Rev.D 98 (2018) 8, 083010. Desmond, Ferreira. Phys.Rev.D 102 (2020) 10, 104060

Image credit: Bradley March

Tests on Galactic Scales

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

Force screened if Newtonian potential (inferred from virial velocity) too deep



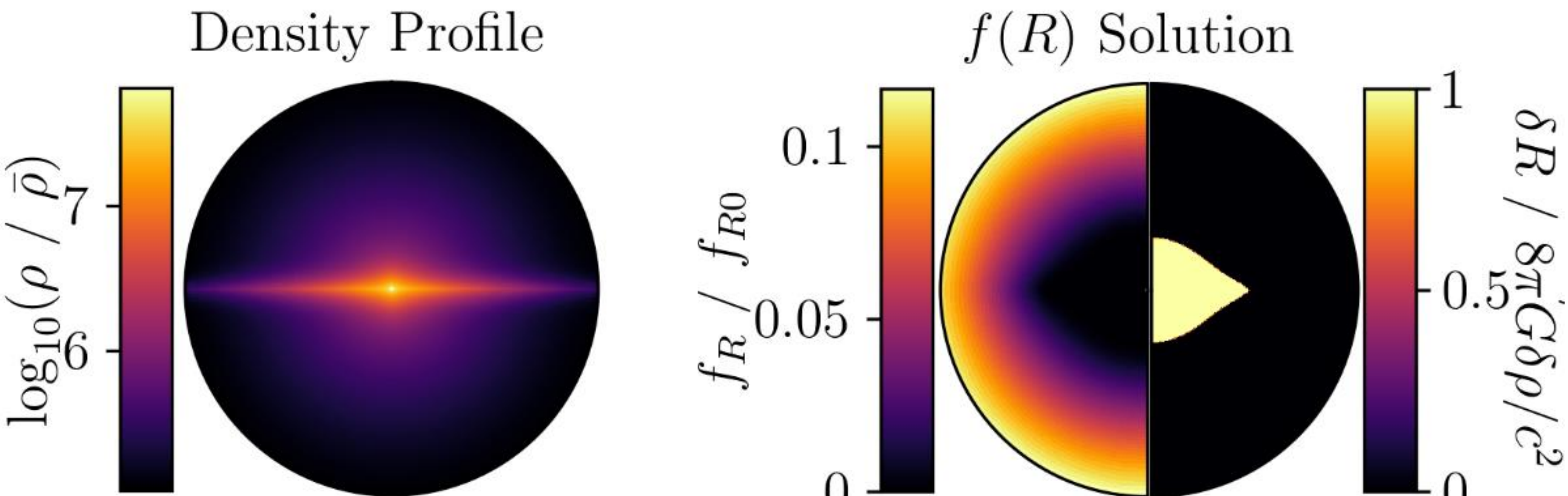
Desmond, Ferreira. Phys.Rev.D 102 (2020) 10, 104060

Scalar Field Inside a Galaxy

Hu- Sawicki f(R)

NFW dark matter halo, plus double exponential disc

'Maximally typical' galaxy



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

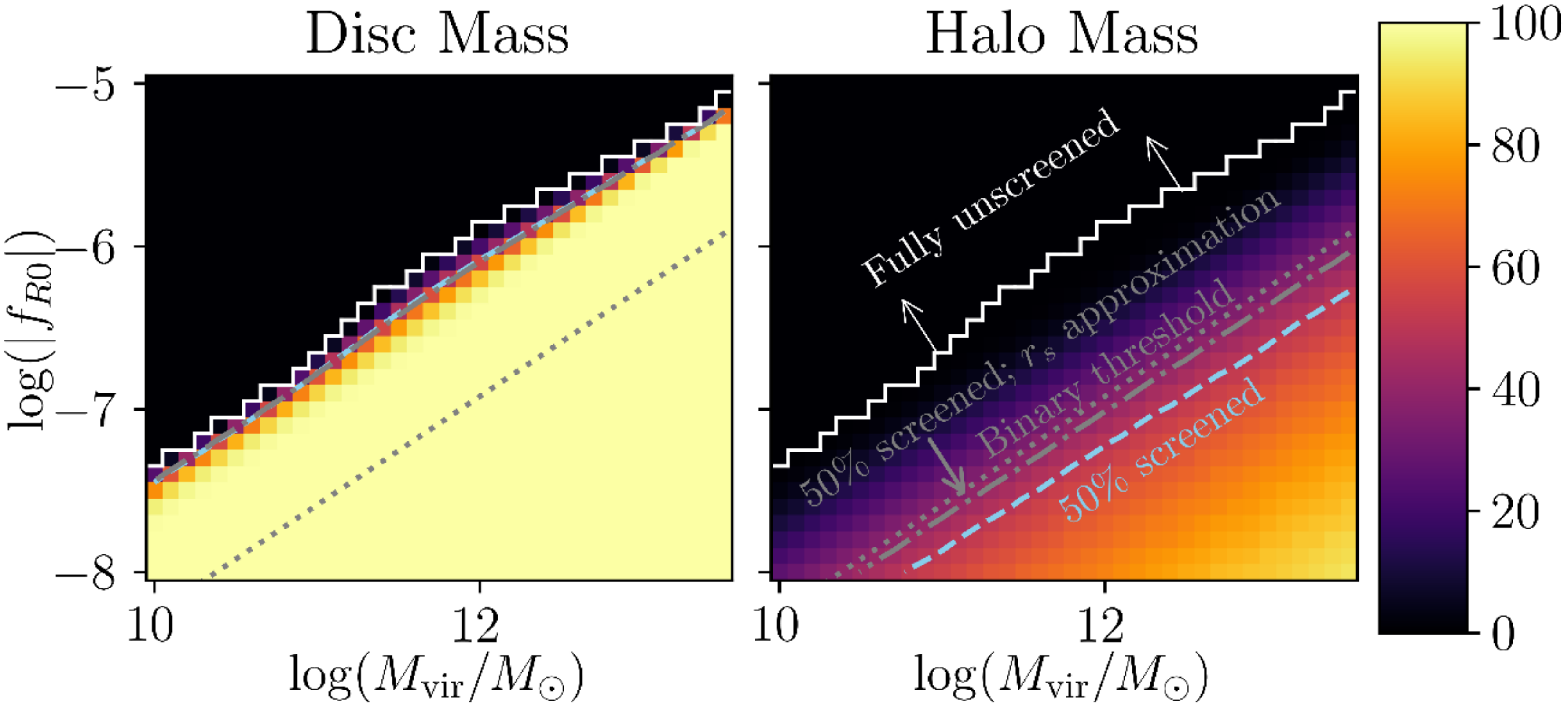
$\rho_{\rm NFW} = 5.2 \times 10^6\, M_\odot\,{\rm kpc}^{-3}$, $r_{\rm NFW} = 15\,{\rm kpc}$, $\Sigma_{\rm disc} = 6.4 \times 10^8\, M_\odot\,{\rm kpc}^{-2}$, $R_{\rm disc} = 1.6\,{\rm kpc}$

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

Hu, Sawicki. Phys. Rev. D 76 (2007) 064004. CB, March, Naik. JCAP 04 (2024) 004

Fifth Force Screening on Galactic Scales

Estimate of galactic screening based on Newtonian potential can be wrong by ~ an order of magnitude



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

Summary

We don’t understand why the expansion of the universe is accelerating

Explanations often introduce light scalar fields

Screening explains why we don’t see corresponding fifth forces

But we may still see time variation of constants

Screening also provides new opportunities for detection

Care needed to ensure accuracy of theoretical predictions