Scalar-Tensor Screening Mechanisms

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Screening Fifth-Forces

Scalar Field ϕ coupled to matter.

Expand fluctuations about the background $\phi = \phi_0 + \delta\phi$ to second order:

$$\begin{aligned}\frac{\mathcal{L}}{\sqrt{-g}} \supset & - Z^2_{\mu\nu}(\phi_0, \partial_\alpha \phi_0, \Box\phi_0, \cdots)\partial^\mu \delta\phi \partial^\nu \delta\phi \\ & - m^2_{\rm eff}(\phi_0)\delta\phi^2 - \beta(\phi_0)\frac{\delta\phi}{M_{\rm pl}}T + \cdots\end{aligned}$$

The coupling to matter gives rise to new or "fifth" forces.

Screening Fifth-Forces

The fifth-force is screened if:

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset -\underbrace{Z^2_{\mu\nu}}_{\text{Large}}\partial^\mu\delta\phi\partial^\nu\delta\phi - \underbrace{m^2_{\text{eff}}}_{\text{large}}\delta\phi^2 - \underbrace{\beta(\phi_0)}_{\text{small}}\frac{\delta\phi}{M_{\text{pl}}}T + \cdots$$

Screening Fifth-Forces

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset - \underbrace{Z^2_{\mu\nu}}_{\text{Vainsthein}} \partial^\mu\delta\phi\partial^\nu\delta\phi - \overbrace{\underbrace{m^2_{\text{eff}}}_{\text{Chameleon}} \delta\phi - \underbrace{\beta(\phi_0)}_{\substack{\text{Symmetron}\\ \text{Dilaton}}} \frac{\delta\phi}{M_{\text{pl}}}}^{\text{Scalar-Tensor Theories}} T + \cdots$$

Scalar-Tensor Screening

Most studied theories are conformally coupled theories.

Scalar field is conformally coupled to matter via the "coupling function" $A(\phi)$ in the Einstein Frame:

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{pl}}^2R}{2}-\nabla_\mu\phi\nabla^\mu\phi-V(\phi)\right]+S_{\mathrm{m}}\left[\psi_{\mathrm{i}};A^2(\phi)g_{\mu\nu}\right]$$

Matter moves on geodesics of the Jordan Frame metric $\tilde{g}_{\mu\nu}=A^2(\phi)g_{\mu\nu}\Rightarrow$ observers in the Einstein frame infer a fifth-force

$$\vec{F}_\phi=\frac{\beta(\phi)}{M_{\mathrm{pl}}}\vec{\nabla}\phi \quad \beta(\phi)=M_{\mathrm{pl}}\frac{\mathrm{d}\ln(A)}{\mathrm{d}\phi}$$

Scalar-Tensor Screening

The equations of motion imply an effective potential for ϕ:

$$V_{\mathrm{eff}}(\phi) = V(\phi) - TA(\phi) = V(\phi) + \rho A(\phi).$$

If this has a minimum then we can move the field value around as a function of the local density and can screen the fifth-force in dense environments if either:

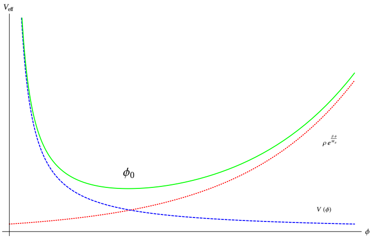
- $m_{\mathrm{eff}}(\phi_{\mathrm{min}})R \gg 1$ - the force is sub-mm (Chameleon).
- $\beta(\phi) \ll 1$ - the coupling to matter is negligible (Symmetron, Dilaton).

$$m_{\mathrm{eff}} = V_{\mathrm{eff}}(\phi)_{\mathrm{min}\,,\phi\phi} \quad \vec{F}_\phi = \frac{\beta(\phi)}{M_{\mathrm{pl}}}\vec{\nabla}\phi$$

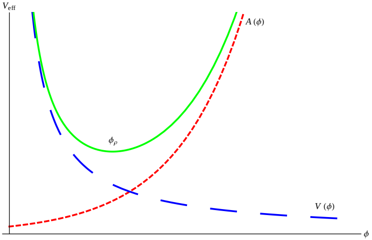
Chameleon Screening

Khoury & Weltman 03

$$V(\phi) = \frac{M^{4+n}}{\phi^n} \quad A(\phi) = e^{\beta \frac{\phi}{M_{\rm pl}}}$$



Low ρ



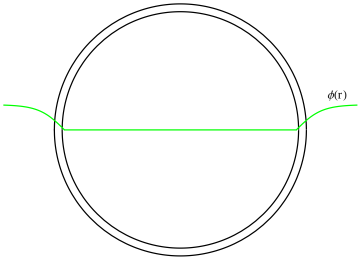
High ρ

$$m_{\rm eff}(\phi_\rho) \gg m_{\rm eff}(\phi_0)$$

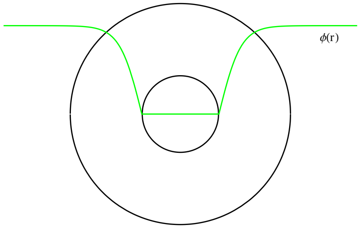
$F(R)$ gravity is a chameleon.

Spherical Screening

An object will be screened if the field can reach its minimum over most of the objects radius.



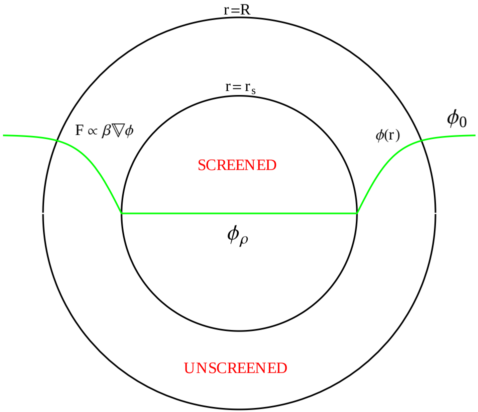
screened



unscreened

Whether or not an object is screened depends on its Newtonian potential (see later).

Spherical Screening



Laboratory Constraints

Several lab tests have been considered as probes of these theories:

- Eöt-Wash (see talk by Upadhye).
- Casimir Force (Not powerful enough yet Brax et al. 07 but see talk by Davis).
- WEP tests (not yet optimised Mota & Shaw 08).
- etc.

Most searches focus on Eöt-Wash.

Laboratory tests constrain β and $m_{\text{eff}}(\rho_{\oplus})$: These are highly model dependent.

Screening Parameterisation

There is a model-independent parameterisation perfect for small-scale tests:

$\alpha \equiv 2\beta(\phi_0)^2 \quad G \to G(1+\alpha)$ when the object is fully unscreened.

$$\alpha = 1/3 \text{ in } f(R)$$

$$\chi_0(f_{R0}) \equiv \frac{\phi_0}{2M_{\rm pl}\beta(\phi_0)} \text{ - the self-screening parameter.}$$

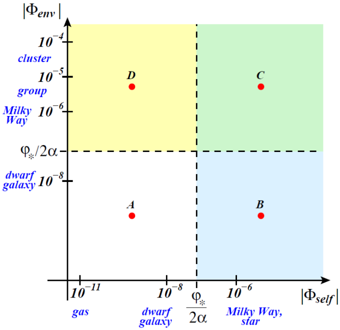
Rule of thumb: and object is partially unscreened if

$$\chi_0 > \Phi_{\rm N}.$$

$\Phi_{\rm N}$ is the Newtonian Potential.

Environmental Effects

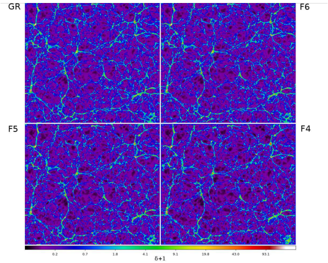
An object can be self-screened or screened by the potential of its environment.



Hui, Nicolis & Stubbs 09

Cosmological Tests

$$\chi_0 \sim 10^{-4} - 10^{-5}$$



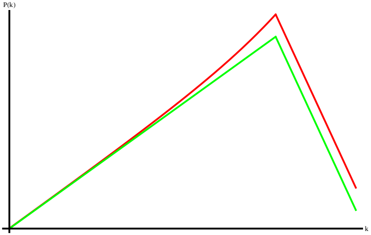
Brax et al. 13

At large screening parameters, cosmological scales become unscreened.

This can effect both linear and non-linear scales.

Linear Perturbations

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}\Omega_c(a)H^2 \underbrace{\left(1 + \frac{2\beta^2}{1 + \frac{m_{\mathrm{eff}}^2 a^2}{k^2}}\right)}_{G_{\mathrm{eff}}(k)} \delta = 0$$

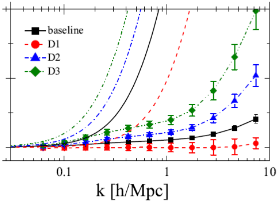


Gives more power on small scales but there is evidence that the force only acts on non-linear scales Brax, Davis, Li & Winther 12, Wang, Hui & Khoury 12.

Non-Linear Perturbations

N-Body codes have been used to predict the non-linear statistics such as halo power spectra, velocity power spectra and mass functions.

$$m = m_0 a^{-3} \quad \beta = 0.5$$



Brax et al. 13

Current Constraints

Current constraints come from cluster statistics:

$$\chi_0 \lesssim 10^{-5}$$ (Schmidt, Lima, Oyaizu& Hu 09)

(see talk by Lombriser, Schmidt).

Cosmological Tests

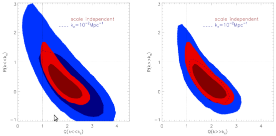
Advantages:

- Clean Signal.
- Can combine many different cosmological probes.

Disadvantages:

- Small signal.
- Doesn't probe small χ_0.
- Can be degenerate with other MG models.

Cosmological Tests



Bean & Tangmatitham 10

$$ds^2 = a^2 \left[- (1 + 2\psi)\, d\tau^2 + (1 - 2\phi)\right]$$

$$k^2\phi \sim -4\pi Q G \rho a^2 \delta \quad \text{Modified Poission}$$

$$\psi - R\phi \sim -12\pi G Q \frac{a^2 \rho\sigma}{k^2} \quad \text{Modified Slip}$$

Astrophysical Probes

Astrophysical Probes:

- Stars in unscreened galaxies.
- Dwarf galaxies in voids.

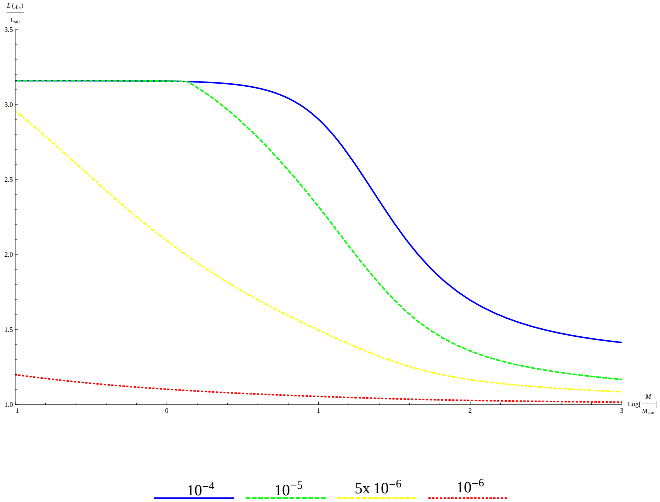
Stars in Modified Gravity

Chang & Hui 11, Davis, Lim, JS & Shaw 12, Jain, Vikram & JS 12 Stars are balls of gas that support themselves against gravitational collapse by burning fuel to provide outward pressure.

The gravitational force is stronger in the outer layers of an unscreened star:

- Star burns more fuel per unit time to create more pressure.
- This releases energy at a faster rate.
- The star is hotter and more luminous.
- The star evolves faster and dies faster.

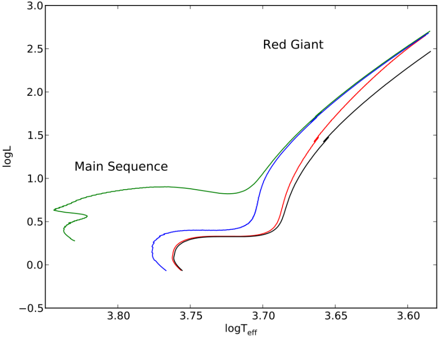
Main Sequence Stars



Davis, Lim, JS, Shaw 12

Implementation into MESA

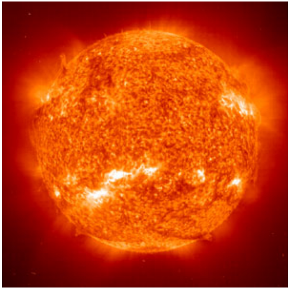
We have modified the publicly available code MESA to include MG effects. We can simulate a star in 1.5 minutes using COSMOS

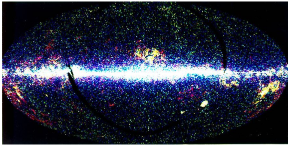


Davis, Lim, JS, Shaw 12

Main Sequence Stars

$$\chi_0 \sim 10^{-6}$$



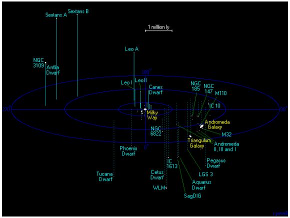


The Sun and Milky Way have Newtonian potential $\Phi_N \sim 10^{-6}$
(Chang & Hui 11, Davis, Lim, JS & Shaw 11)

Does this give a Constraint?

Does this then constrain $\chi_0 \lesssim 10^{-6}$?

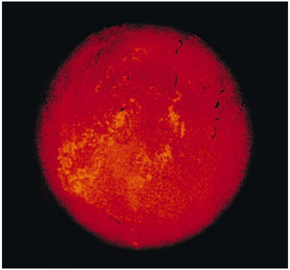
Not necessarily: the milky way could be screened by the local group.



An independent constraint from comparing water maser and TRGB distances rules this possibility out Jain, Vikram JS 2012 (see talk by Jain, Vikram).

Post-Main Sequence Stars

$$\chi_0 \sim 10^{-7}$$

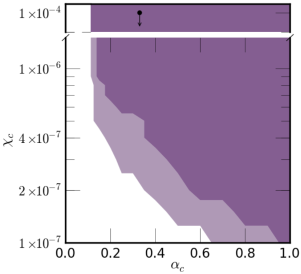


Red giant stars have $\Phi_N \sim 10^{-7}$ (Jain, Vikram & JS 12) (see talk by Vikram)

Current Constraints

$$\chi_0 \lesssim 4 \times 10^{-7}$$

Current constraints come from comparing Cepheid and TRGB distances to the same unscreened galaxies (see talk by Vikram).

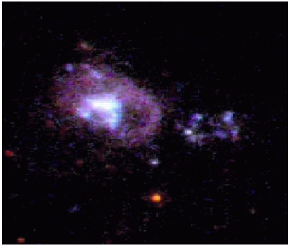


Jain, Vikram & JS 12

These are currently the strongest constraints in the literature.

Dwarf Galaxies

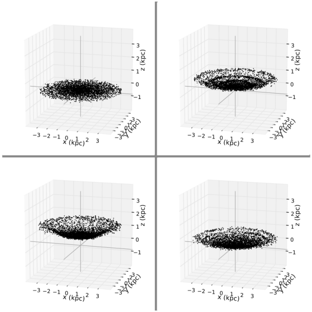
$$\chi_0 \sim 10^{-8}$$



Dwarf galaxies in cosmic voids have $\Phi_{\rm N} \sim 10^{-8}$ (Jain & Vanderplas 11, Vikram, Cabre, Jain & Jake VanderPlas 13) (see talk by VanderPlas)

Current Constraints

The HI and dark matter disc feels a fifth-force, which the stars do not. This warps their morphology (see talk by VanderPlas).



Jain & VanderPlas 11

Current tests are not competitive with Red Giant tests (Vikram, Cabre, Jain & VanderPlas 13).

Astrophysical Tests

Advantages:

- Large Signal (effects are $\mathcal{O}(1)$).
- Unique probe of scalar-tensor gravity.
- Can probe down to screening parameters that lab and cosmological tests cannot.

Disadvantages:

- Messy signal - highly degenerate with other astrophysical phenomena.
- Not a lot of data and need a good handle on the systematics.

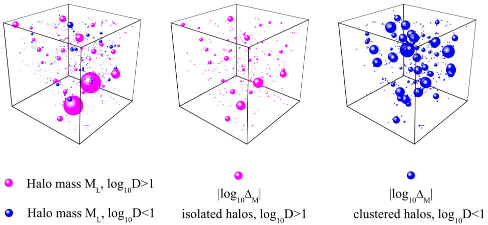
Dwarf Galaxies as Laboratories

Dwarf galaxies in voids have $\Phi_{\rm N} \sim 10^{-8}$, they are the perfect testing ground for scalar-tensor theories. Lots of work has been done to identify voids using N-body codes:

$$\Delta_{\rm m} = \frac{M_{\rm dynamical}}{M_{\rm lensing}} - 1 \, (= 0 \text{ in GR})$$

$$D = \frac{\text{distance to nearest neighbour of same mass}}{\text{virial radius}}$$

Dwarf Galaxies as Laboratories



Zhao, Li & Koyama 11

(See talk by Clampitt.)

A Screening Map

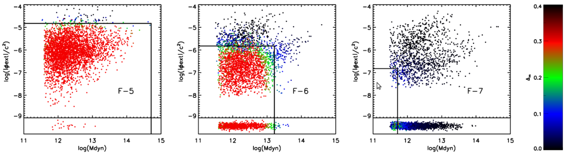
Screening maps for $f_{R0} = 10^{-5}$, 10^{-6} and 10^{-7} have been made using SDSS data and are publicly available:

$$\Phi_{\mathrm{N}}^{\mathrm{self}} < \frac{3}{2} f_{R0} \Rightarrow \text{ self-screened}$$

$$\Phi_{\mathrm{N}}^{\mathrm{ext}} < \frac{3}{2} f_{R0} \Rightarrow \text{ enviornmentally-screened}$$

$$\Phi_{\mathrm{N}}^{\mathrm{ext}} \equiv \sum_{d_i < r_c + r_i} \frac{GM_i}{d_i}$$

A Screening Map



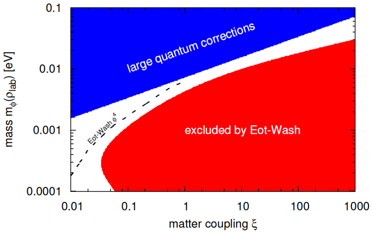
Cabre et al. 12

Theoretical Issues

(See talk by Upadhye)

$$\Delta V_{\text{1-loop}} = m_{\text{eff}}^4 \ln\left(\frac{m_{\text{eff}}^2}{\mu^2}\right)$$

Screening mechanism also destroys quantum stability.



Upahdye, Hu & Khoury 12

There are also issues in the radiation era (see talk by Erikeck): chameleons may not be a good effective field theory.

Summary

- Scalar-Tensor theories have a rich phenomenology and may have interesting features on small scales.
- A lot of work has gone into ruling them out but we are not there yet.
- Lots of novel probes used do far but there are probably more to be found!