Hide and Seek: Screening Mechanisms Present and Future

Jeremy Sakstein
DAMTP, Cambridge & Perimeter Institute, Canada

Non-Linear Structure in the Modified Universe

Lorentz Center
Leiden
16^{th} July 2014

Outline

Why astrophysics

- Can probe parameters inaccessible on other scales.
- $\mathcal{O}(1)$ signals — can account for systematics.
- Low sample sizes — no need for dedicated surveys.
- Mildly non-linear $\Rightarrow$ smoking guns.

The art of messing around with the Poisson equation

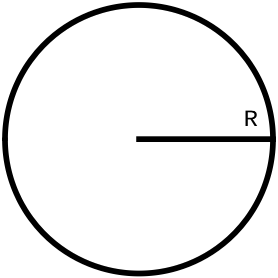
Newtonian limit of GR:

$$\nabla^2 \Phi_{\mathrm{N}} = 4\pi G \rho(r) \quad F_{\mathrm{N}} = \frac{\mathrm{d}\Phi_{\mathrm{N}}}{\mathrm{d}r}$$

Solution:

$$r^2 \frac{\mathrm{d}\Phi_{\mathrm{N}}}{\mathrm{d}r} = G \int_0^R 4\pi r^2 \rho \Rightarrow F_{\mathrm{N}} = \frac{GM}{r^2}$$

Field profile sourced by entire mass of object:



Scalar-Tensor theories

Additional scalar field coupled to matter:

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset -\frac{1}{2} M_{\mathrm{pl}}^2 \nabla_\mu \phi \nabla^\mu \phi + \beta \phi T \quad F_5 = \beta \frac{\mathrm{d}\phi}{\mathrm{d}r}$$

(NB ϕ is dimensionless)

Gives Poisson equation in the non-relativistic limit:

$$\nabla^2 \phi = 8\pi \beta G \rho(r) \Rightarrow F_5 = 2\beta^2 F_{\mathrm{N}}$$

Need for screening

Tune $\beta \ll 1$ to match local tests $\Rightarrow$ MG turned off on all scales $\Rightarrow$ DE not driven by MG.

Screening mechanisms decouple scales:

- Solar system — $F_5 \ll F_\mathrm{N}$.
- Cosmological scales — F_5 important.

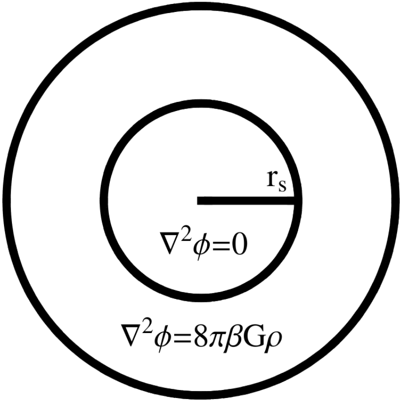
Possibility for MG to drive acceleration.

Chameleons et al.

Screen by killing off the source:

$$\nabla^2 \phi = 8\pi\beta G\rho + V(\phi)_{,\phi}$$

Inside the screening radius $r_{\rm s}$: $V(\phi)_\phi = -8\pi\beta G\rho$.
Outside: $V(\phi)_\phi$ negligible.



Chameleons et al.

Screen by killing off the source:

$$\nabla^2\phi = 8\pi\beta G + V(\phi)_{,\phi}$$

RHS is unsourced when $r \leq r_{\mathrm{s}}$

$$r^2\frac{\mathrm{d}\phi}{\mathrm{d}r} = \beta G\int_{r_{\mathrm{s}}}^{R} 4\pi r^2\rho \Rightarrow F_5 = 2\beta^2\frac{G\left(M(R) - M(r_{\mathrm{s}})\right)}{r^2}$$

$r_{\mathrm{s}} \approx R \Rightarrow$ screened.

Vainshtein mechanism

Screen by introducing new non-linear kinetic terms e.g. cubic galileon:

$$\nabla^2\phi + \frac{1}{\Lambda_3^3 r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\phi'^2\right) = 8\pi\beta G\rho$$

When non-linear term dominates:

$$r\phi'^2 = \Lambda_3^{3/2}\left[\beta G\int_0^R 4\pi r^2\rho\right]^{1/2} \Rightarrow \beta\frac{\mathrm{d}\phi}{\mathrm{d}r} = \frac{\sqrt{2\Lambda_3^3\beta GM}}{r^{1/2}}$$

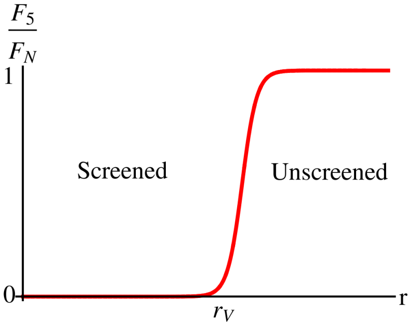
Vainshtein mechanism

$$\frac{F_5}{F_{\rm N}} = 2\beta^2 \left(\frac{r}{r_{\rm V}}\right)^{\frac{3}{2}} \qquad r_{\rm V} = \left(\frac{\beta M}{4\pi M_{\rm pl}}\right)^{\frac{1}{3}}$$

$r_{\rm V}$ is the Vainshtein radius

$$r \ll r_{\rm V} \Rightarrow \text{ non-linear term dominates } \Rightarrow \text{ screened}$$

$$r \gg r_{\rm V} \Rightarrow \text{ linear term dominates } \Rightarrow \text{ unscreened}$$



Equivalence principle violations

GR:

$$M\ddot{\vec{x}} = -M\nabla{\Phi_{\mathrm{N}}}^{\mathrm{ext}}$$

Scalar-Tensor theories:

$$M\ddot{\vec{x}} = -M\nabla{\Phi_{\mathrm{N}}}^{\mathrm{ext}} - Q\nabla\phi^{\mathrm{ext}}$$

Chameleons: $Q = M(r) - M(r_{\mathrm{s}}) \Rightarrow$ EP violated

Vainshtein: $Q = M \Rightarrow$ EP preserved*

*With one or two exceptions (see later).

Common myths

1) "Screening mechanisms screen the force in high density environments"

What is high?

$$\frac{\rho_{\text{Dark Matter Halo}}}{\rho_{\text{Cosmological}}} \sim 10^6 \quad \frac{\rho_{\text{Earth}}}{\rho_{\text{Cosmological}}} \sim 10^{29}$$

$\rho \to 0$ at the surface of most objects.

- Chameleons screen according the the Newtonian potential.
- Vainshtein radius is a weak function of mass only (c.f. cubic galileon $r_{\mathrm{V}} \propto M^{1/3}$).

Correct statement: *Screening utilises the environment-dependence of the field equations.*

Common myths

2) "Taking the $\rho \to \infty$ limit..."

Not self-consistent and $\rho \to 0$ at the surface of the source.

$$\text{E.g. } \nabla^2\phi + \frac{\rho}{\mu^2}\phi^2 = 8\pi\beta G\rho$$

$$\rho \to \infty : \phi = \text{const} \Rightarrow \phi' = 0 \Rightarrow \text{screened}$$

This is tautological (have implicitly assumed $\rho\phi^2 \gg \mu^2\nabla^2\phi$).

Gradients are small because I say they are

Need to be self-consistent!

Common myths

3) "The non-relativistic limit is $g_{\mu\nu} = \eta_{\mu\nu}$, $\dot{\phi} = 0$"

NR limit is a controlled expansion in metric perturbations Ψ, Φ_{N}. E.g

$$(1 + \frac{\phi'^2}{\Lambda^2})\nabla^2\phi = 8\pi\beta G\rho \quad \phi'^2 \gg \Lambda^2$$

Screens using Vainshtein but 0-0 Einstein equation is

$$\nabla^2\Phi_{\mathrm{N}} = 4\pi G\rho \left(1 + \frac{\phi'^2}{\Lambda^2}\nabla^2\phi\right) + \cdots$$

NR limit of GR destroyed in the process — not self-consistent!

Where to look?

Model parameters:

1. Self-screening parameter χ_0: $\chi_0 < \Phi_{\mathrm{N}} \Rightarrow$ screening.
2. Fifth-force strength $\alpha \equiv 2\beta^2$: $G \to G(1+\alpha)$ when fully unscreened. $\alpha = 1/3$ for $f(R)$.

This tells us where to look:

Chameleons best probed in non-relativistic environments.

Where to look?

$$\chi_0 > \Phi_\mathrm{N} \Rightarrow \text{ unscreened}$$

Astrophysics probes the smallest values:

- Main-sequence stars, spiral galaxies, MW $\Phi_\mathrm{N} \sim 10^{-6}$
- Post-main-sequence stars $\Phi_\mathrm{N} \sim 10^{-7}$
- Dwarf galaxies $\Phi_\mathrm{N} \sim 10^{-8}$

Use unscreened dwarf galaxies as laboratories.

Cabre et al '12 have produced a screening map of the nearby universe.

Nothing unscreened when $\chi_0 < 10^{-8}$.

Main idea

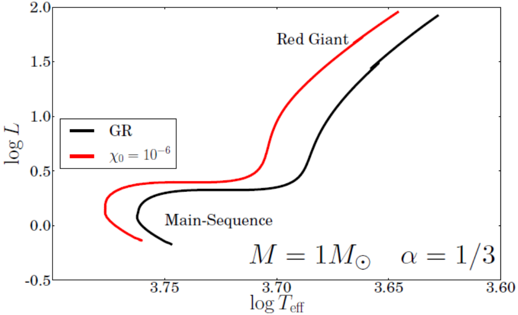
Exploit equivalence principle violations in unscreened galaxies:

1. Look for unscreened objects — stellar tests
2. Dynamics and kinematics of dwarf galaxies

Stars

Unscreened stars: hotter, brighter, more ephemeral.

MESA has been updated to include chameleons:



Davis, Lim, JS & Shaw '11

Powerful tool — can make quantitative MG predictions.

Cepheid stars

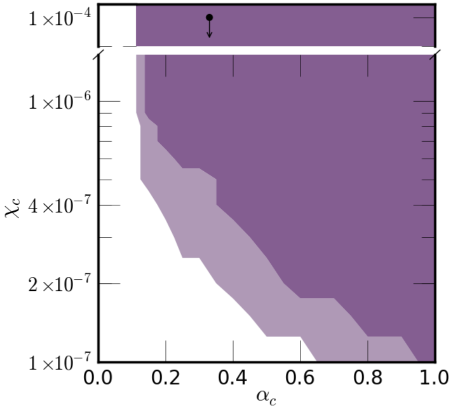
Period of pulsation of Cepheid stars $\tau \propto G^{-1/2} \Rightarrow$ under-estimate the distance to unscreened galaxies:

$$\frac{\Delta d}{d} \approx -0.3 \frac{\Delta G}{G}$$

Compare with a measurement insensitive to the theory of gravity.

Cepheid stars

We compared Cepheid and TRGB distances to unscreened galaxies:



Jain, Vikram & JS '12

The are currently the strongest constraints in the literature.

Cepheid stars

A full hydrodynamic calculation shows that these constraints are conservative.

$\Delta d/d$ three times larger than predicted:

χ_0	α
$1/3$	9×10^{-8}
0.5	7×10^{-8}
1	3×10^{-8}

JS '13

Could improve constraints — need enough unscreened galaxies.

Rotation curves

Can measure the rotation curves for two galactic components:

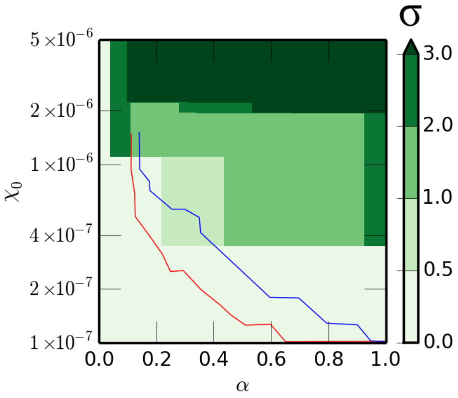
1. Main-sequence stars — screened when $\chi_0 \lesssim\ 5 \times 10^{-6}$
2. Gas — unscreened

Orbits are Keplarian ($v \propto \sqrt{G}$):

$$\frac{v_{\mathrm{gas}}}{v_\star} = \sqrt{1+\alpha}$$

Rotation curves

Have measured these for six unscreened galaxies:



Vikram, JS & Jain et al. in preparation

Similar to Cepheids but not as strong. Can rule out small α.

Where to look?

No simple classification scheme.

- Fewer tests than chameleons.
- Lack of calculational control.
- No EP violation (but see next slide).

$$r_{\rm V} = \left(\beta r_{\rm Schw} L^2\right)^{1/3}$$

Strongest constraint comes from lunar ranging: $L \geq 150$ Mpc ($\beta \sim 1$) Afshordi et al. '09.

Black hole tests

Black hole has no scalar hair ⇒ no scalar charge:

$$\begin{aligned} \text{Stars:} \quad \ddot{\vec{x}} &= -M\nabla\Phi_{\rm N} - M\nabla\phi_{\rm ext} \\ \text{BH:} \quad \ddot{\vec{x}} &= -M\nabla\Phi_{\rm N} \end{aligned}$$

Black hole falls slower than rest of galaxy ⇒ visible offset Hui & Nicolis '12.

Black hole tests

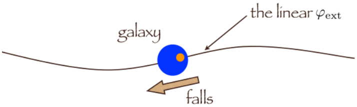


Figure: Lam Hui

BH drags a disc of stars $\Rightarrow$ offset between optical and dark matter centroids.

Can probe this by comparing visible and lensing observations (work in progress w/ Jain, VanderPlas & Vikram).

Only probes matter coupling!

Other tests

None!

Problem: Can't calculate anything except for isolated objects!
Field equations are non-linear!

Screened $\Rightarrow$ non-linearities are important $\Rightarrow$ can't use perturbation theory.

Some attempts by Andrews, Chu & Trodden '13 using EFT. Approach breaks down in any useful system.

E.g. Can't calculate LLR once we include the Sun — does LLR get stronger or weaker?

Future directions

- Chameleons — well constrained but what is left?
- Vainshtein — lack of novel probes!

“Chameleons can’t be dark energy”

Wang, Hui & Khoury ’12

Precise statement: *Nothing more to say about DE than quintessence*.

$$w_\phi = \underbrace{w_{\text{Quintessence}}}_{\approx -1} + \underbrace{w_{\text{MG}}}_{\approx 0}$$

Should we abandon them?

Multi-field chameleons don’t help Kunesch, Davis & JS in preparation.

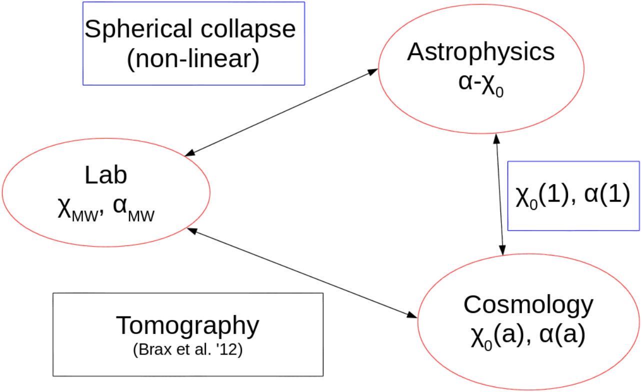
Are chameleons extinct?

$\chi_0 \lesssim 4 \times 10^{-7} \Rightarrow$ only unscreened objects are massive giant stars and dwarf galaxies.

Are chameleons extinct?

χ_0–α no good in screened objects or early times.

- Lab: $\chi_{\rm MW}$–$\alpha_{\rm MW}$ (in a model-by-model way)
- Cosmology: $\chi_0(a)$–$\alpha(a)$ (in a model-by-model way)



Are chameleons extinct?

- Which models are more viable than others?
- Where are some models best probed?

Requires non-linear collapse models to relate parametrisations.

Future prospects

Better data could improve constraints:

- More variable stars — LSST
- Radio & Optical surveys of galaxies — VLA, ALFALFA
- Need more unscreened galaxies!

Prospects for testing Vainshtein

Biggest problem: Can't calculate anything!

- No superposition: what is the field sourced by many bodies? Some numerical progress by Hiramatsu et al. '12.
- Departures from spherical symmetry? Difficult problem!
- Hints that time dependence weakens screening — any viable systems? Likely to be relativistic.
- Violation of the no-hair theorem?
- No classification scheme for screening.

Not sure where to look!

Prospects for testing Vainshtein

Interesting observation: objects where the density increases outwards are unscreened $F_5/F_N \sim (r_{\rm V}/r)^n$:

- Accretion discs? — In progress.
- Voids?

Does the best-fit cosmology screen all objects?

What do local tests say about cosmology?

Are all local tests compatible?

Can we even answer these questions?

Summary

	Chameleons	Vainshtein
Status	Well-constrained	Unconstrained
Self-acceleration	✗	✓
Open issues	Combined constraints	Real systems?
Future prospects	Need more data	Lack of novel probes

- A mess of iguanas
- A lounge of lizards
- No collective noun for chameleons