Direct detection of dark energy?

Based on 2103.15834, 2102.00023, 200408403

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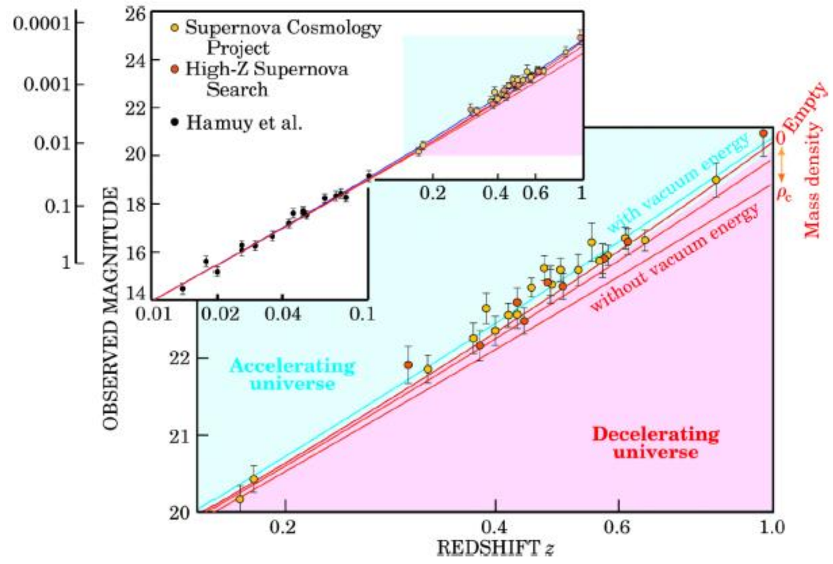
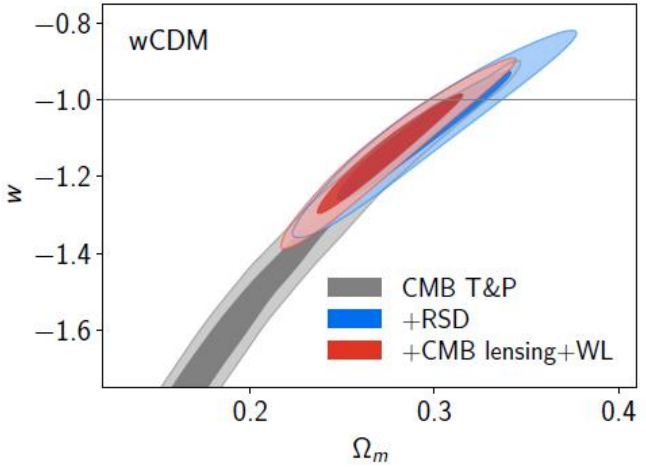
Relatively strong evidence in favour of **acceleration of expansion**:

Phenomenologically described by a fluid of pressure:

$$p = \omega\rho, \quad \omega \sim -1$$



Credits: Perlmutter, Physics Today 56 (2003) 53



eBOSS collaboration, PRD 103 (2021) 083533

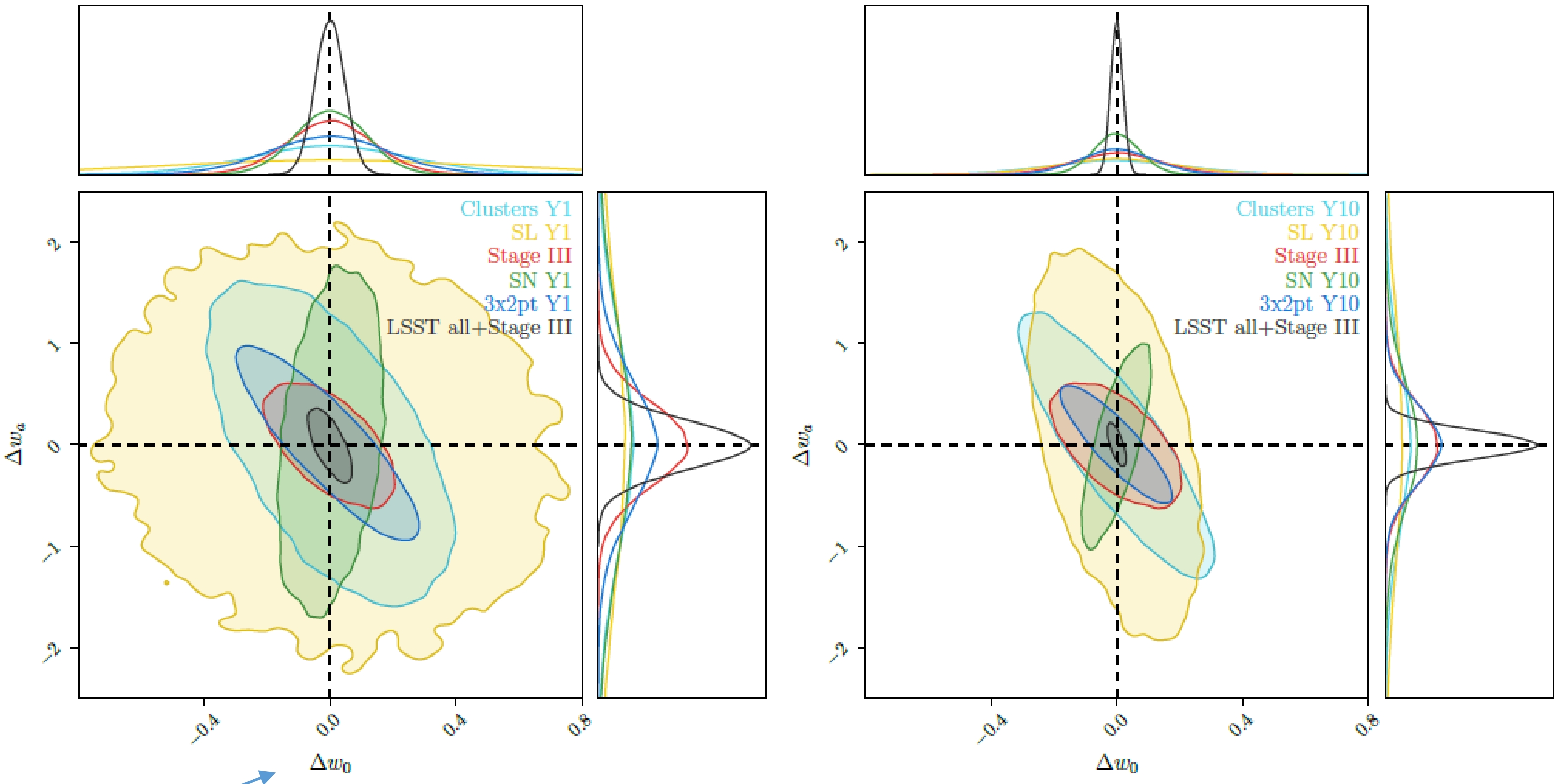
Hubble diagram

Equation of state vs matter fraction

Future large scale galaxy surveys will test the evolution of the ***background cosmology***.

$w = -1$ cosmological constant

$w \neq -1$ *dynamical dark energy*



2% level

$$w = w_0 + w_a(1-a)$$

LSST collaboration

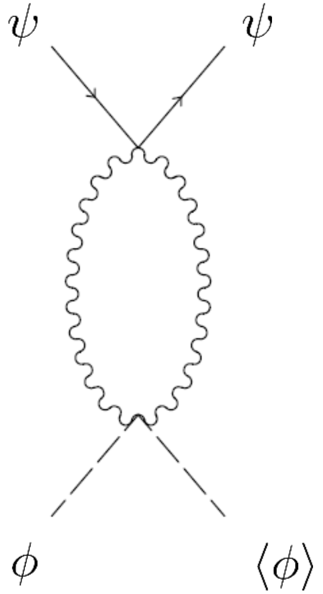
The dark energy recipe book:

Long range field

$$m_\phi = \mathcal{O}(H_0) = \mathcal{O}(10^{-33})\ \text{eV}$$

Coupled to matter

Coupling strength β



$$\equiv \frac{\beta}{m_{\text{Pl}}}\phi\bar{\psi}\psi$$

Solar system tests of gravity:

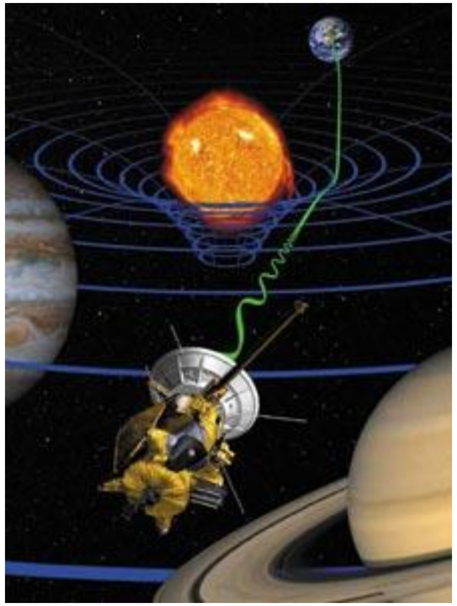
Deviations from Newton's law are parametrised by:

$$\Phi = -\frac{G_N M}{r}(1 + 2\beta^2 e^{-r/\lambda})$$

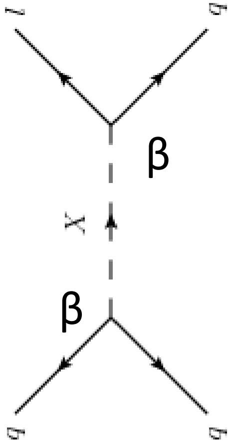
For long range forces with large λ, the tightest constraint on the coupling β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta^2 \leq 4 \cdot 10^{-5}$$

Fine tuning issue?



Bertotti et al. (2004)



The archetypical example: f(R) gravity

Models with the action

$$S = \frac{1}{16\pi G_N}\int d^4x f(R)$$

modify gravity when $f(R) \neq R$

Metric in the Einstein frame

$$g_{\mu\nu} = e^{2\beta\phi/m_{\rm Pl}} g^E_{\mu\nu}$$

Jordan metric coupled to matter

These models are equivalent to scalar-tensor models using the mapping

$$\frac{df}{dR} = e^{-2\beta\phi/m_{\rm Pl}}$$

Links the curvature to the scalar

The scalar tensor model is determined by the coupling function:

$$A^2(\phi) = e^{2\beta\phi/m_{\rm Pl}}$$

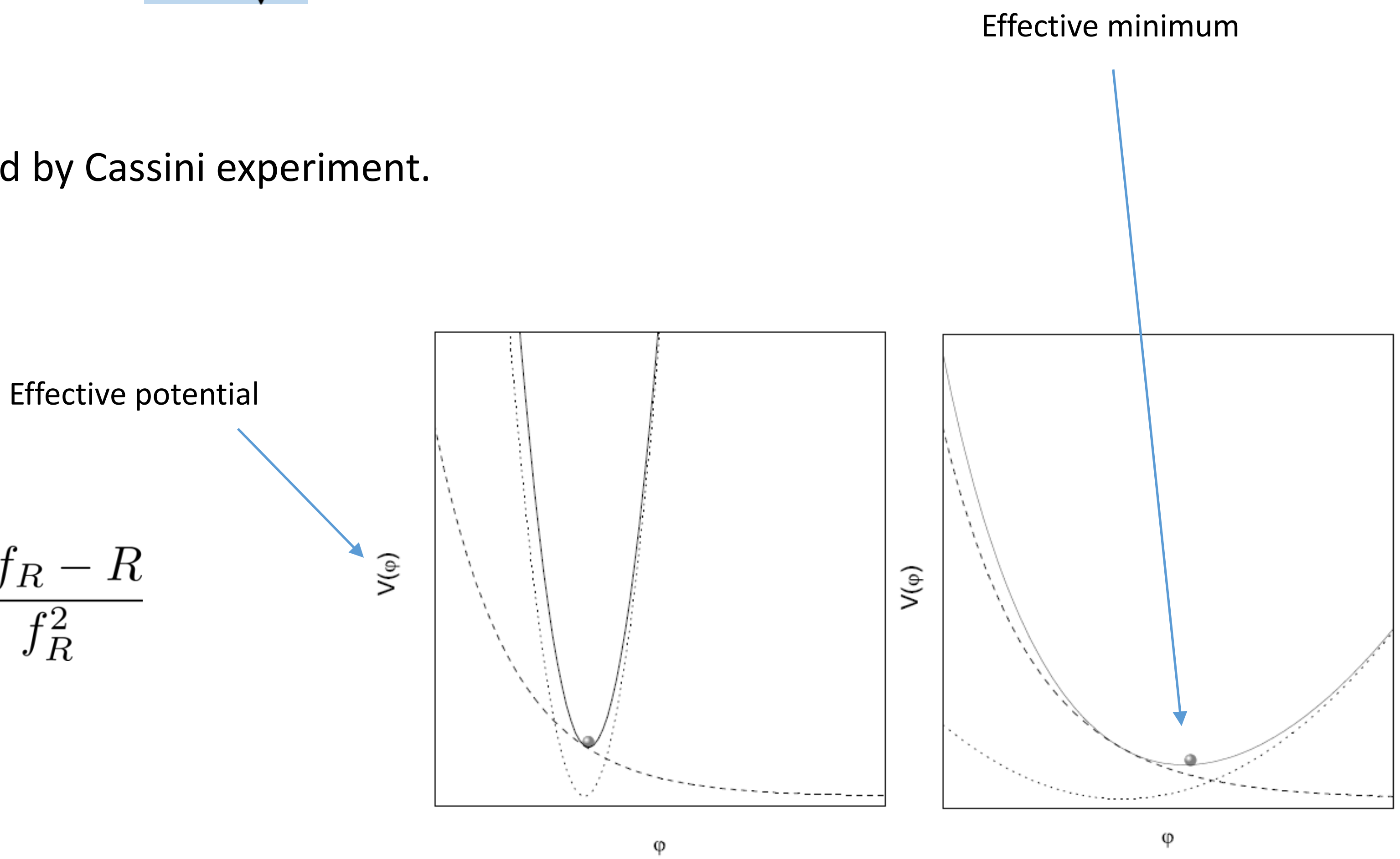
The coupling between the scalar and matter is fixed and equal to:

$$\beta = \frac{1}{\sqrt{6}}$$

PROBLEM: too big!! Would be excluded by Cassini experiment.

Solution: Chameleon screening

$$V(\phi) = \frac{m_{\rm Pl}^2}{2} \frac{R f_R - R}{f_R^2}$$



SCREENING:

Crucial coupling between scalar and matter.

For a recent review: 2201.10817

$$\mathcal{L} \supset -\frac{Z(\phi_0)}{2}(\partial\varphi)^2 - \frac{m^2(\phi_0)}{2}\varphi^2 + \delta g_{\mu\nu}\delta T^{\mu\nu} \,,$$

$$\delta g_{\mu\nu} = \frac{\beta}{m_{\rm Pl}}\varphi\eta_{\mu\nu} + d(\phi_0)\frac{(\partial\varphi)^2}{\Lambda^4}\eta_{\mu\nu} - \gamma(\phi_0)\partial_\mu\partial_\nu\varphi + \delta(\phi_0)\partial_\mu\varphi\partial_\nu\varphi + \dots$$

conformal

disformal

$$Z(\phi_0) = 1 + a(\phi_0)r_c^2\frac{\Box\varphi}{m_{\rm Pl}} + b(\phi_0)\frac{(\partial\varphi)^2}{\Lambda^4} + c(\phi_0)\frac{\Box^2\varphi}{\Lambda^5} + \dots$$

Vainshtein for Galileons

K-mouflage

Vainshtein for massive gravity

Chameleon Screening:

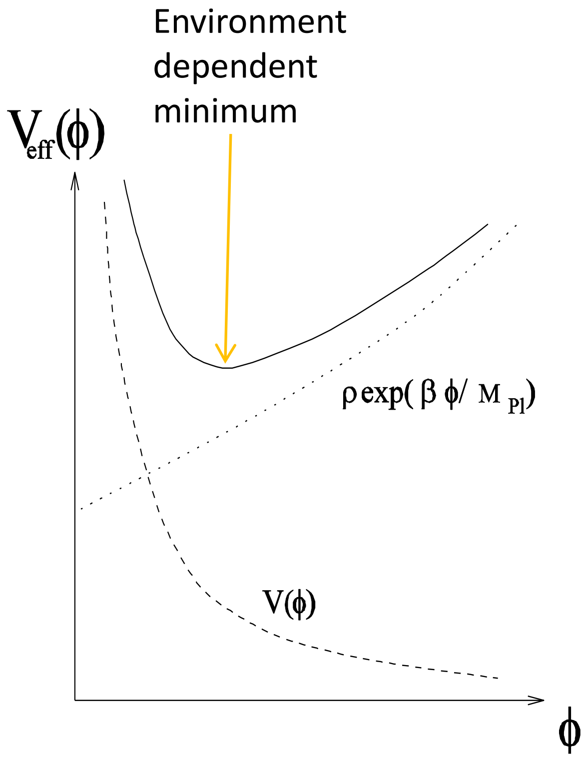
$$\mathcal{L} \supset -\frac{1}{2}(\partial\delta\phi)^2 - \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T \ ,$$

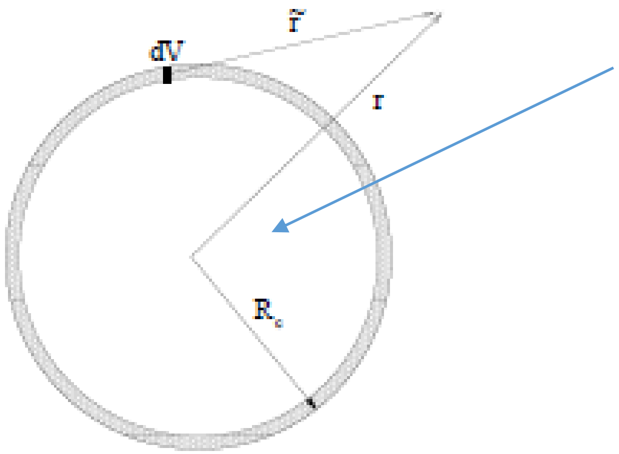
The *chameleon mechanism* increases the scalar mass in dense environments.

Chameleon Screening

When coupled to matter, scalar fields have a ***matter dependent effective potential***

$$V_{eff}(\phi) = V(\phi) + \rho_m(A(\phi) - 1)$$





Large mass inside object

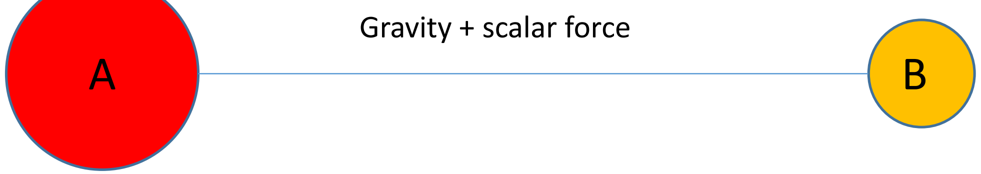
$$m_{\rm in} R \gg 1$$

The field generated from deep inside is Yukawa suppressed. Only a *thin shell* radiates outside the body. Hence suppressed scalar contribution to the fifth force.

Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for screened objects:

$$G_{A,B} = G_N(1 + 2Q_A Q_B)$$

Interaction rate depending on the objects



Value of the field far away

$$Q_A = \frac{\phi_\infty}{2 m_{\mathrm{Pl}} \Phi_A}$$

Newtonian potential at the surface of the body.

$$Q_A \leq \beta_\infty$$

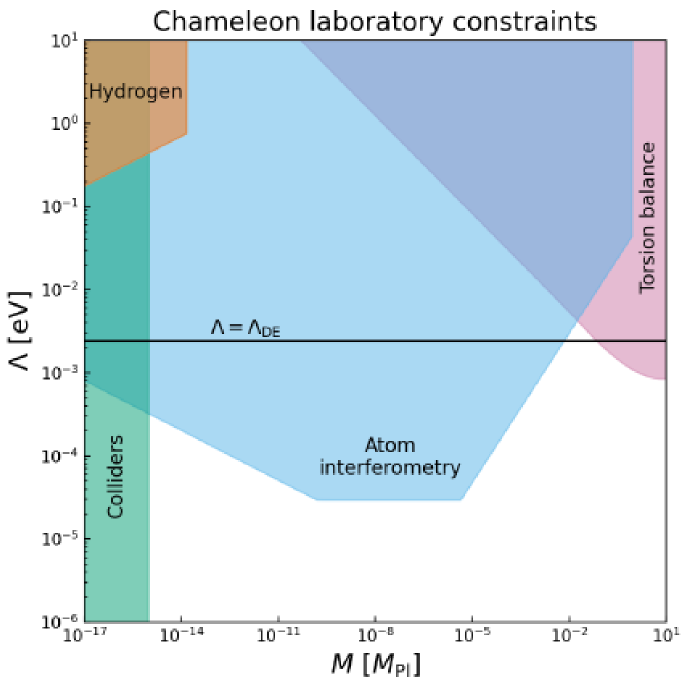
Screening criterion for compact objects

Massive bodies with differ scalar charges fall differently. Hence a violation of the strong equivalence principle.

A typical example: ***the Ratra Peebles chameleon***

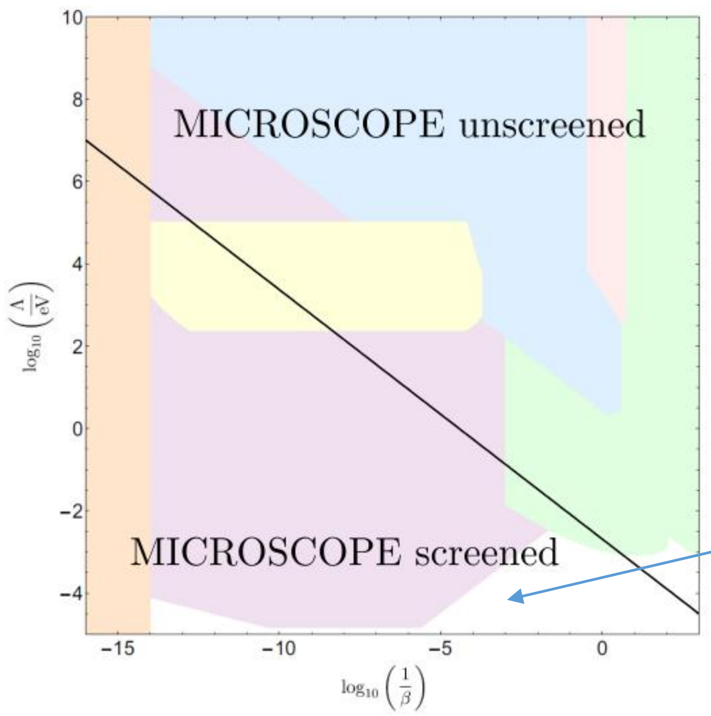
$$A(\phi) = e^{\beta\phi/m_{\rm Pl}} \qquad V(\phi) = \Lambda_0^4 + \frac{\Lambda^{n+4}}{\phi^n} + \dots$$

$$M = \frac{m_{\rm Pl}}{\beta}$$

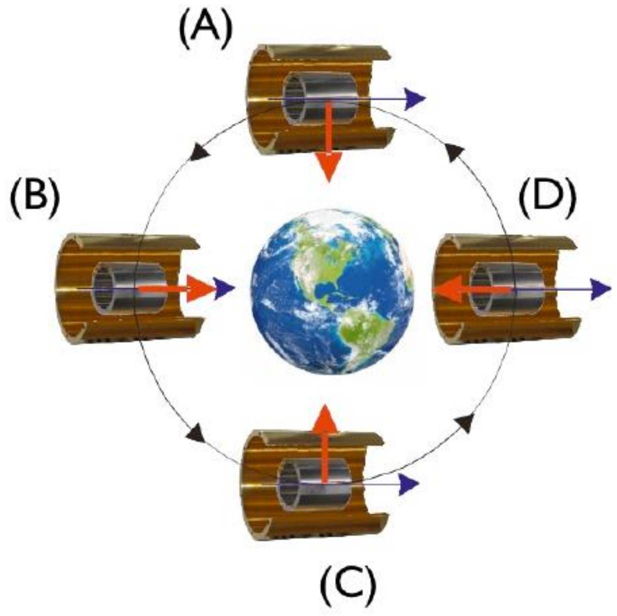


In these models the cosmic acceleration is mostly due to the constant term in the potential and the environmental dependence is via the inverse power law.

Back in 2004, there was hope that satellite experiments would be unscreened and show a full deviation from GR (Khoury-Weltman)



Mostly screened!

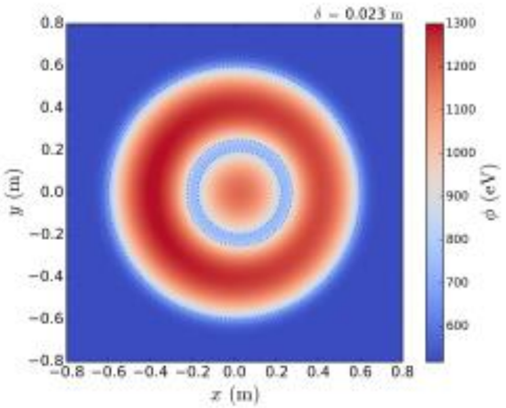


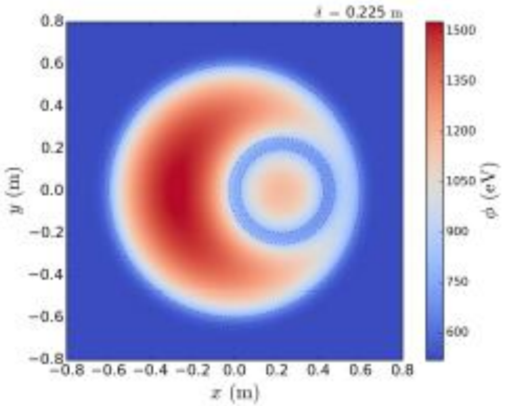
The MICROSCOPE experiment has tested the equivalence principle.

$$\eta_{\mathrm{Pt-Ti}} \leq 1.3\ 10^{-14}$$

What has been measured is the stiffness of the experiment in the radial direction:

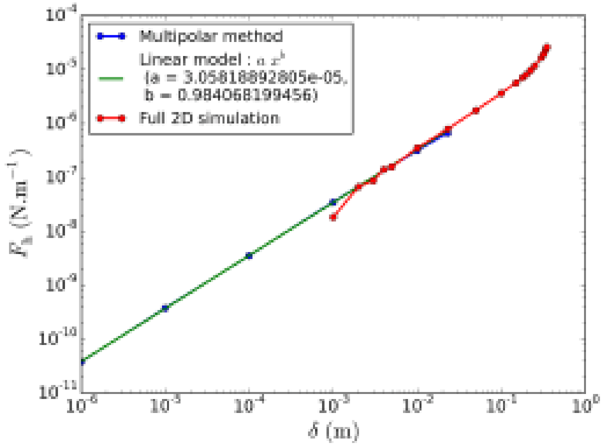
$$F_r = k\delta,\ \ \delta = \text{displacement}$$



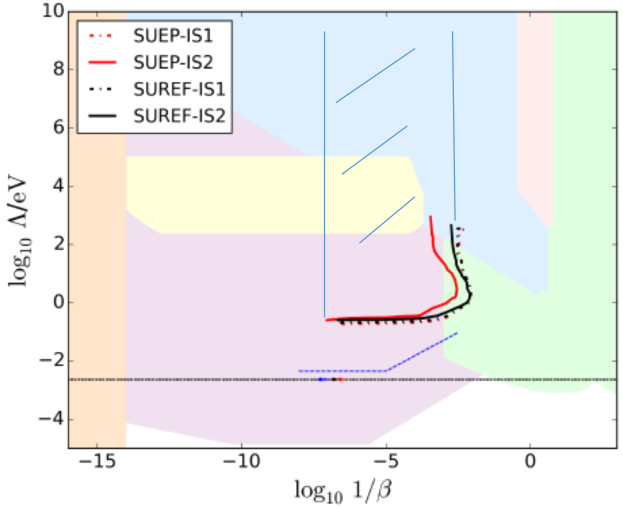


See: 2102.00023, 200408403

Stiffness due to the screened scalar



Not competitive but Microscope was not a dedicated experiment. Hopefully next experiment could test more models.



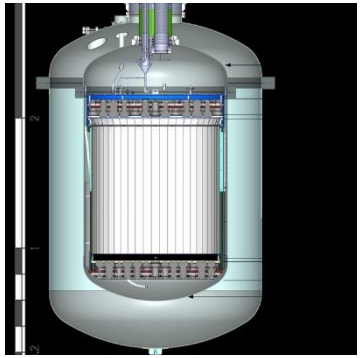
The chameleon field is associated to a particle:

Could we detect the effects of a chameleon particle?

Questions:

Where could it be produced and how?

How could it be detected?

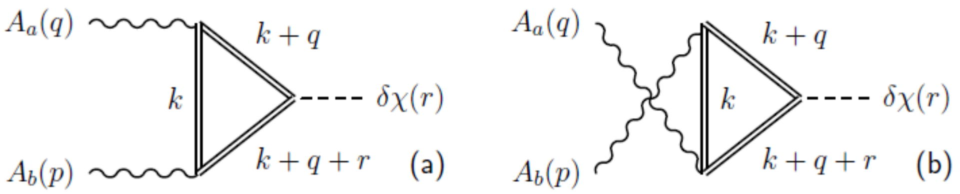


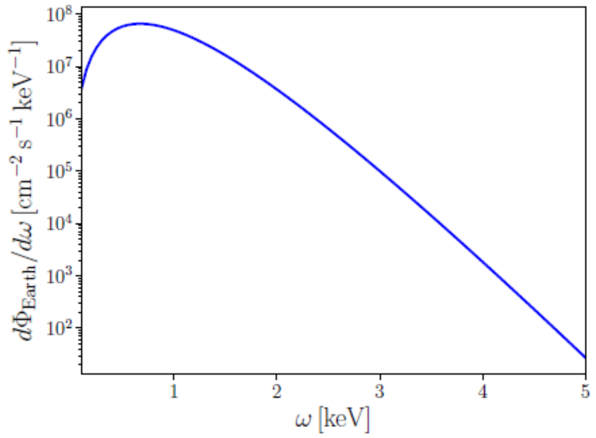
Dark matter detector

Sun

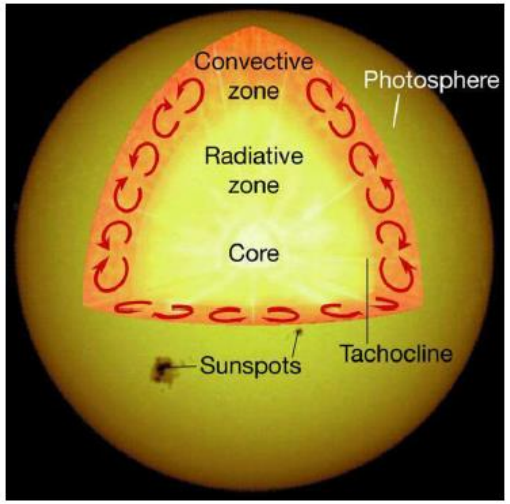
Chameleon production:

Quantum processes induce a coupling to photons





$$\mathcal{L}_{\gamma\phi} = -\frac{\beta_\gamma \phi}{m_{\rm Pl}} F_{\mu\nu}F^{\mu\nu} + \frac{\partial_\mu\phi\partial_\nu\phi}{M_\gamma^4} T_\gamma^{\mu\nu}$$



Flux of chameleons received on Earth from Sun

Chameleons are produced in the strong magnetic field of the tachocline B=30T.

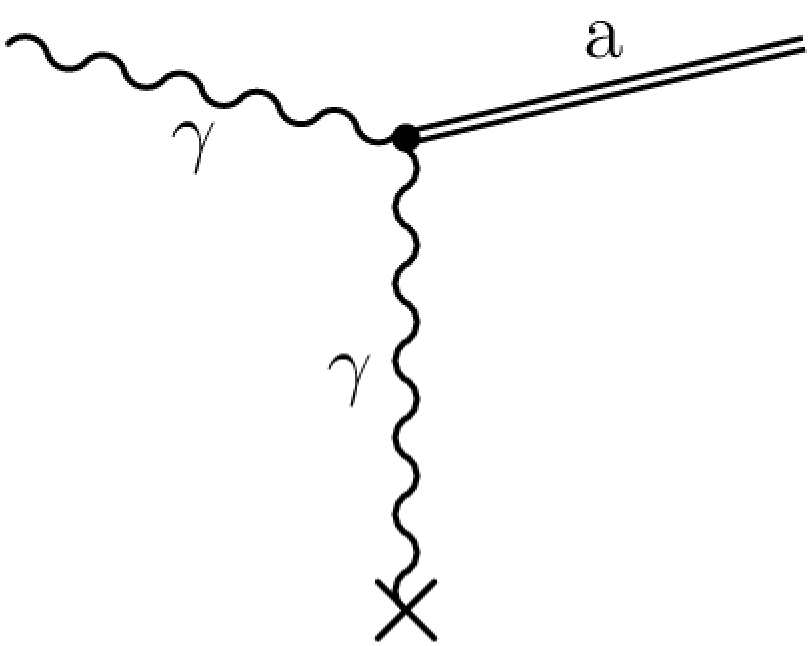
$$R_{\rm tacho} = 0.7 R_\odot$$

Screened production:

In dense regions, contrary to axions, chameleon production is kinematically forbidden:

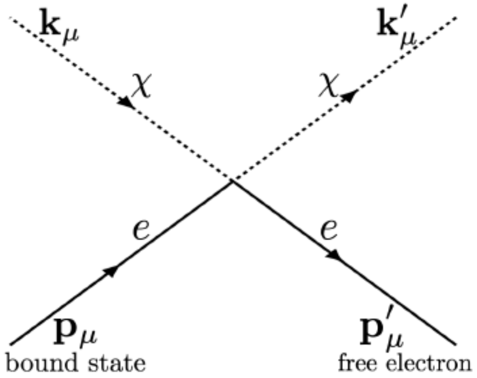
$$m_\phi \geq T$$

Stellar object	ρ_{core} (typical) [g/cm^3]	T_{core} (typical) [keV]	m_{core} [keV]
Sun	150	1.3	6
White dwarfs	10^6	$\mathcal{O}(1)$	~ 6000
Red giants	5×10^5	$\mathcal{O}(10)$	~ 4000
Horizontal branch stars	5×10^4	$\mathcal{O}(10)$	~ 100



Chameleon are coupled to photons in a way similar to axions

Chameleon detection:



Chameleon interaction with bound electrons.

Chameleons interact with matter as:

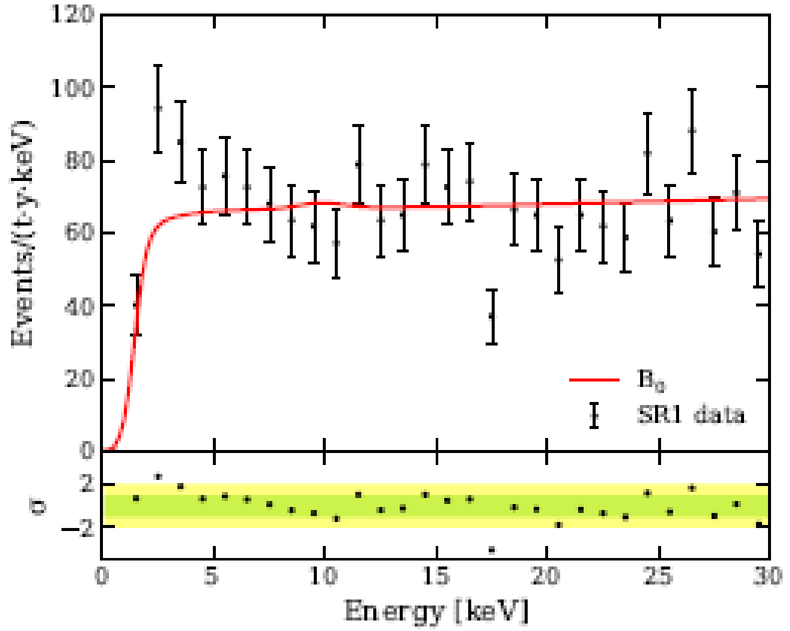
$$\mathcal{L}_m = \frac{\beta}{m_{\rm Pl}} T_i - c_i \frac{(\partial\phi)^2}{M^4} T_i + \frac{\partial_\mu\phi\partial_\nu\phi}{M_i^4} T_i^{\mu\nu}$$

$$\sigma \propto \frac{m_{\rm SM}^2 p_\phi^4}{M_i^8}$$

$$\sigma \propto \frac{p_{\rm SM}^2 p_\phi^4}{M_i^8}$$

Dominated by disformal interaction

An example: excess of e- recoil in Xenon1T



See: 2103.15834

The event rate in the detector is given by:

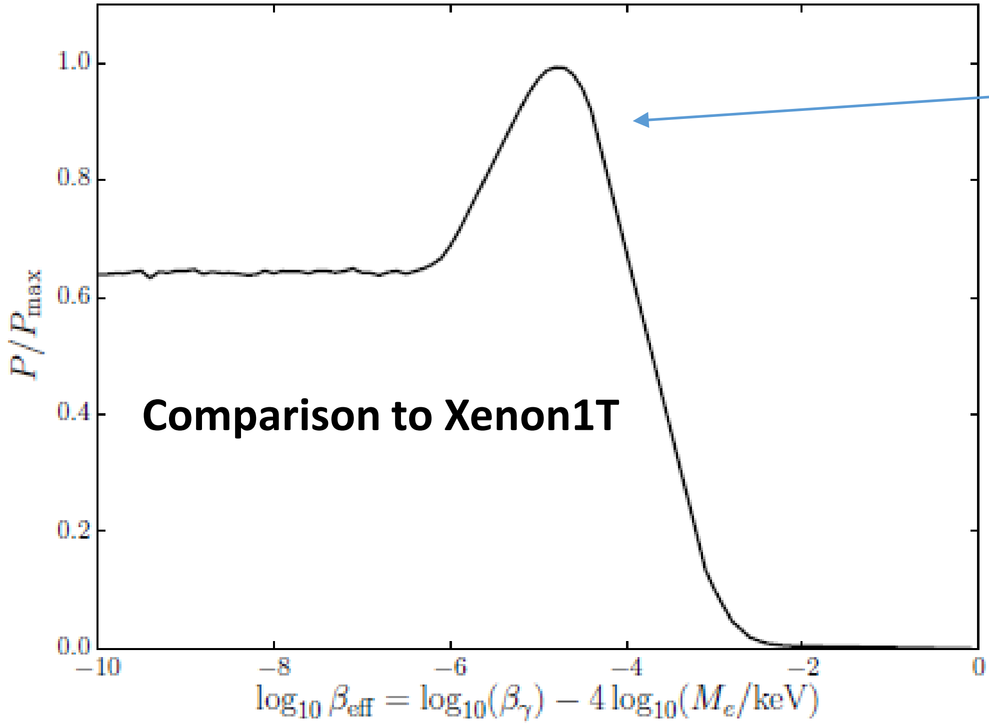
Number of electrons

Chameleon flux

$$\frac{dR}{d\omega} = N_e \sigma \frac{d\Phi}{d\omega}$$

The effective parameter:

$$\beta_{\rm eff} = \beta_\gamma \left(\frac{\rm keV}{M_e}\right)^4$$



Peaked around -4.5

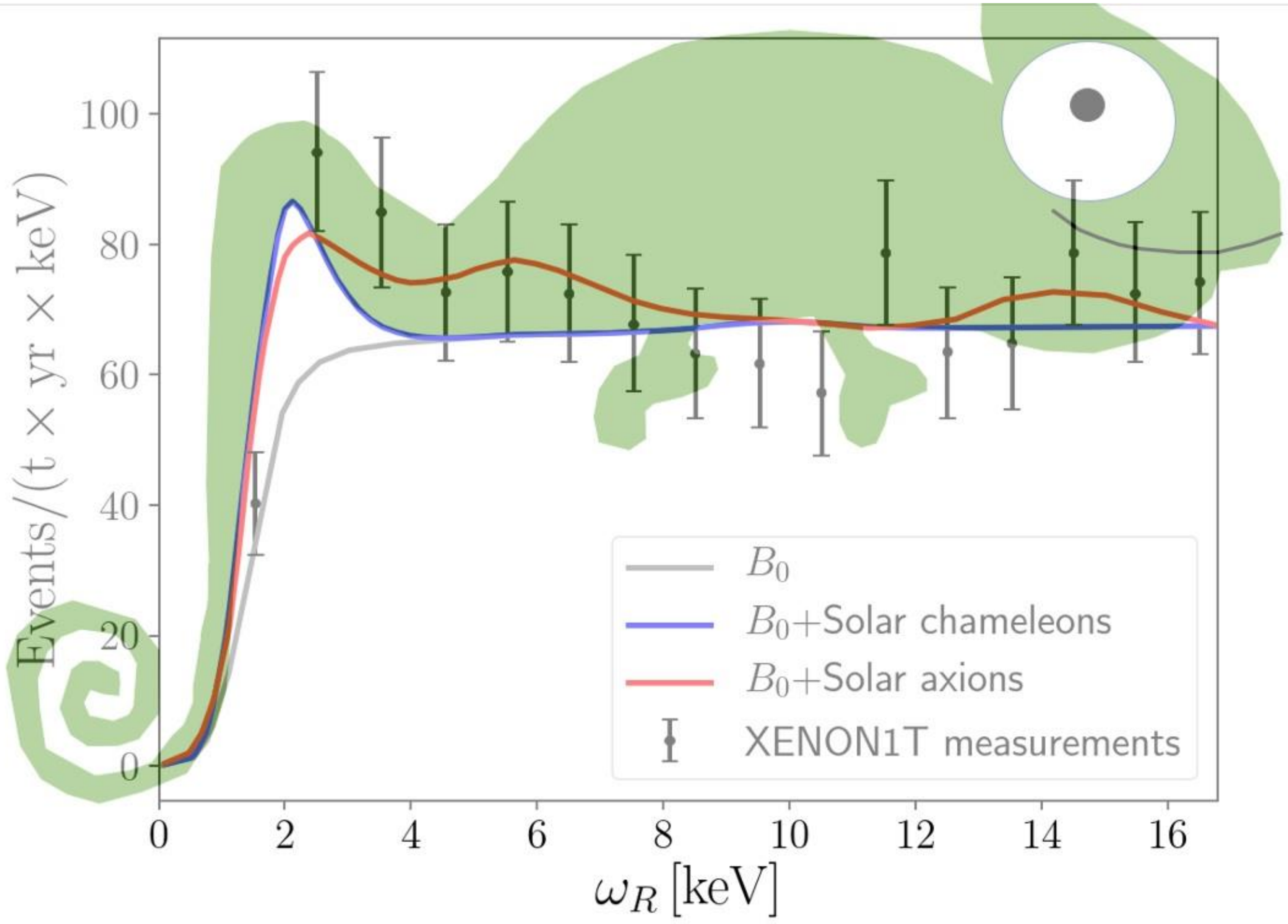
Template:

$$\beta_\gamma = 10^{10}, \quad M_e = 10^{3.6}\ {\rm keV}$$

$$\Lambda = 1\mu{\rm eV} \quad \beta_e = 10^2$$

Posterior distribution $P = {\rm Prob}(\beta_{\rm eff}|{\rm data})$

Preferred at 2σ over background.



Events/(t × yr × keV)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
ω_R [keV]
B_0
B_0+Solar chameleons
B_0+Solar axions
XENON1T measurements

Forecast for future experiments:

Experiment	Exposure (ton × yr)	Electron recoil background (ton × yr × keV)$^{-1}$	Events / yr (expected)
XENON1T [80]	0.65	76.0	20
XENONnT [146]	20.0	12.3	180
PandaX-4T [145]	5.6	18.0	130
LUX-ZEPLIN [141]	15.0	14.0	250

Conclusion:

Screened dark energy has many features:

- Acts on cosmic scales but hardly locally
- Tiny effects can be tested in the laboratory
- Can be produced in the Sun and detected on Earth
- Testable by future direct detection experiments