Cosmological Scalars : theory and tests

Cosmic Wispers — 2nd General Meeting Istanbul

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Outline

- Introduction to scalar-tensor theories
- Chameleon theories
- Symmetrons and Dilatons
- Laboratory Tests of Modified Gravity models
- Constraints
- Including the photon coupling and constraints
- Discussion

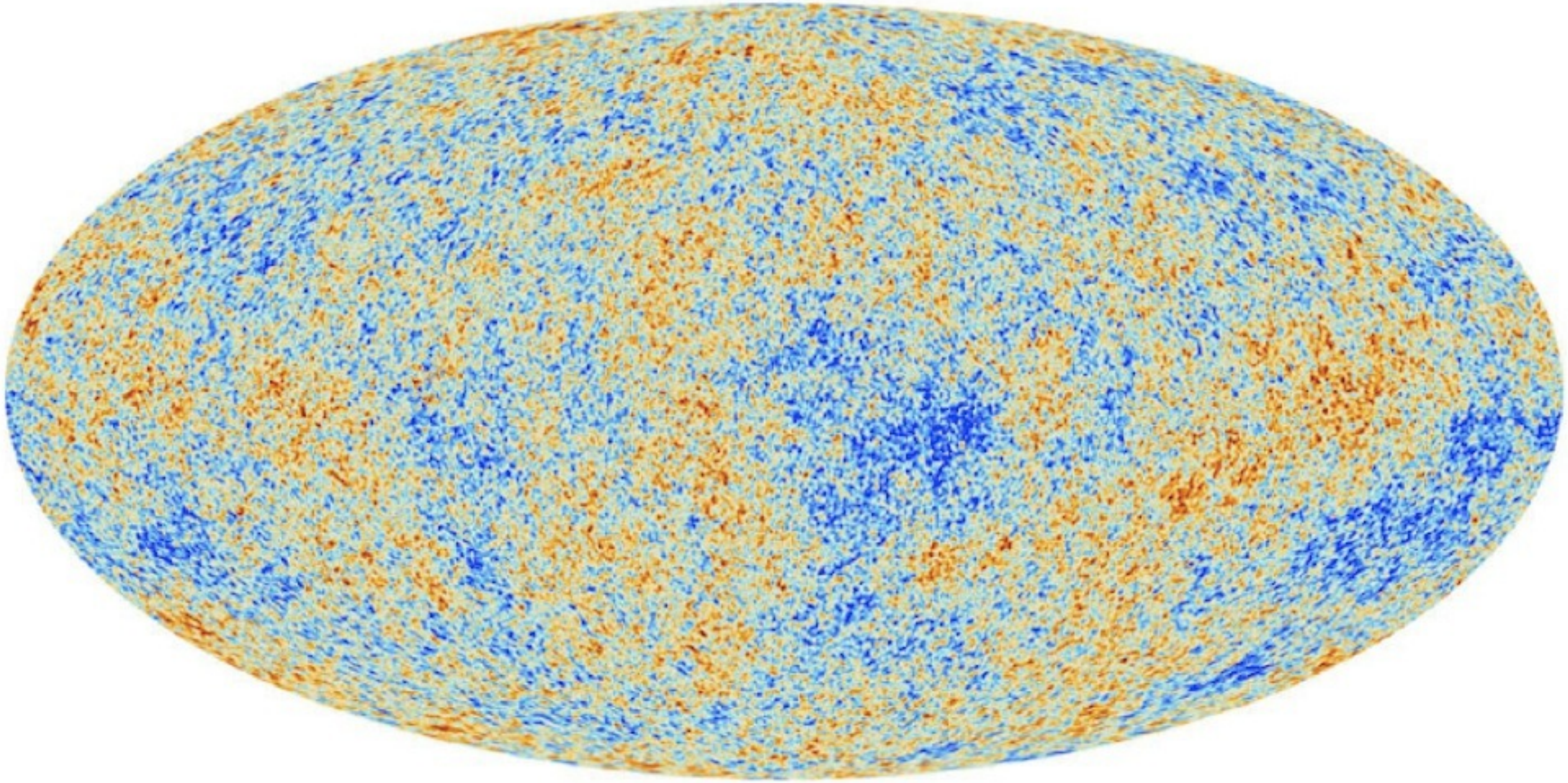
- Why Modified Gravity?

There are several reasons to investigate modified gravity theories. These are theories which modify Einstein theory, but reduce to Einstein relativity in certain limits

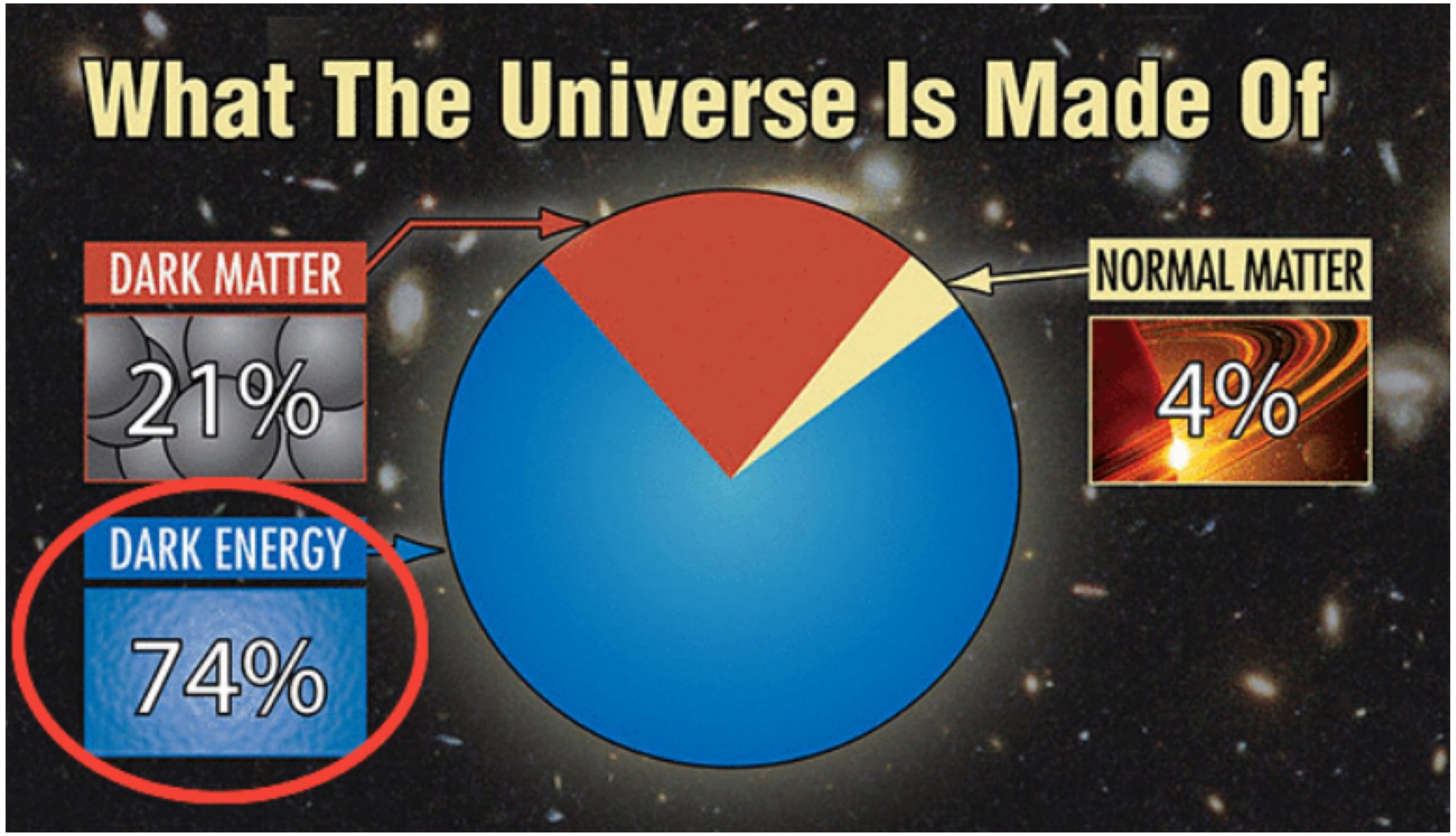
Modified Gravity could account for the observed accelerated expansion of the Universe today.

Modified Gravity allows one to test General Relativity in new regimes one hadn't originally thought of.

Cosmic Microwave Background



Dark Energy



The Universe is undergoing accelerated expansion today.

It could be a cosmological constant

$$\Lambda \approx (H_0 M_{pl})^2 \approx (meV)^4$$

or the dynamics of a light scalar field

$$m_\phi < H_0 \approx 10^{-33} eV$$

If coupled to gravity this will give rise to a fifth force, unless screened

For a scalar field

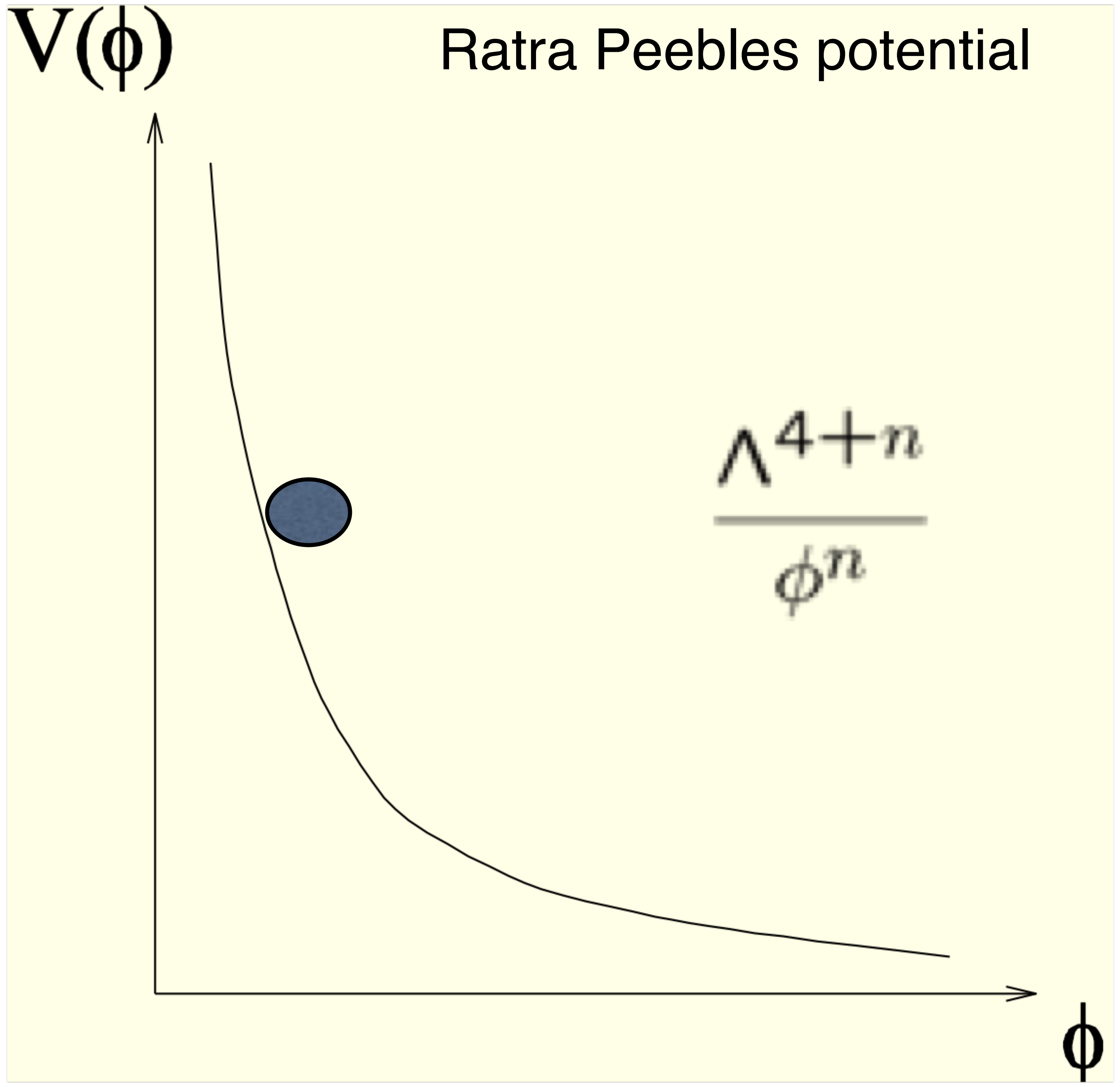
$$\rho_\phi = 1/2\dot{\phi}^2 + V(\phi)$$ kinetic energy + potential energy

$$p_\phi = 1/2\dot{\phi}^2 - V(\phi)$$ kinetic energy - potential energy

If the potential dominates then

$$p_\phi \approx -\rho_\phi$$

so the scalar field plays the role of an effective cosmological constant. Since it's dynamical, this wouldn't have been the case for all times in the universe. We only need the scalar field to dominate the energy density of the universe today



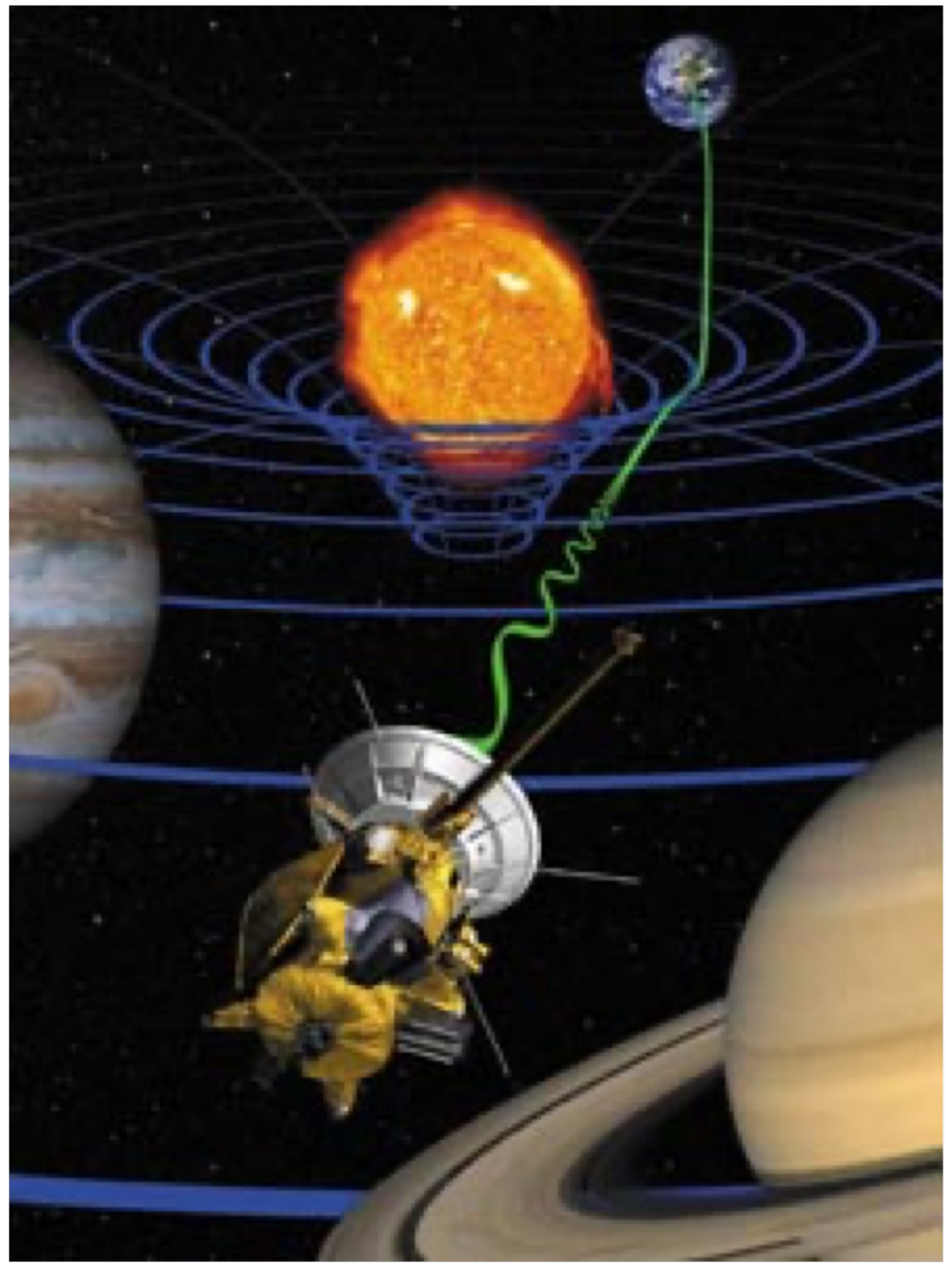
Deviations from Newton's Laws parametrised by

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

tightest constraint from Cassini

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

Fifth Force must be screened



Two general classes of theories

1) Chameleon type screening. Can be tested in the lab, in the solar system, astrophysics and cosmology. Does not affect speed of gravitational waves, so no test from LIGO/VIRGO or eLISA

2) Vainshtein screening. For example Galileons, Horndeski, massive gravity, k-mouflage. Vainshtein radius is very large, so no laboratory tests, but astrophysical and cosmological tests. Some models give speed of gravitational waves to be different from that of photons, so severely constrained by pulsar constraints and by LIGO/VIRGO and will be even more constrained by eLISA

The Chameleon Mechanism

Khoury&Weltman astro-ph/0309411; Brax et al astro-ph/0408415

consider the action

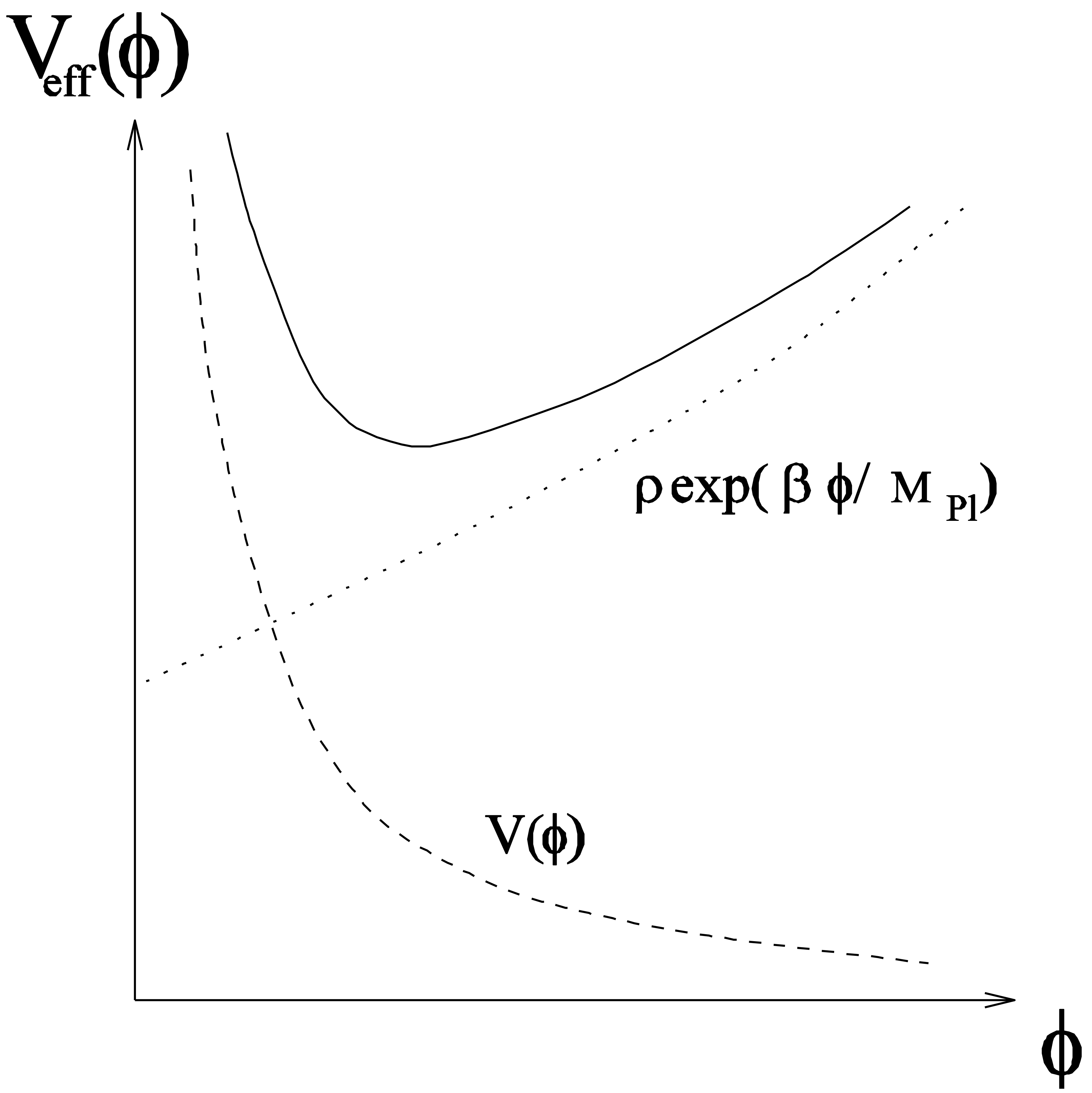
$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi) \right) + S_m(\psi_i, A^2(\phi) g_{\mu\nu})$$

gives the effective potential

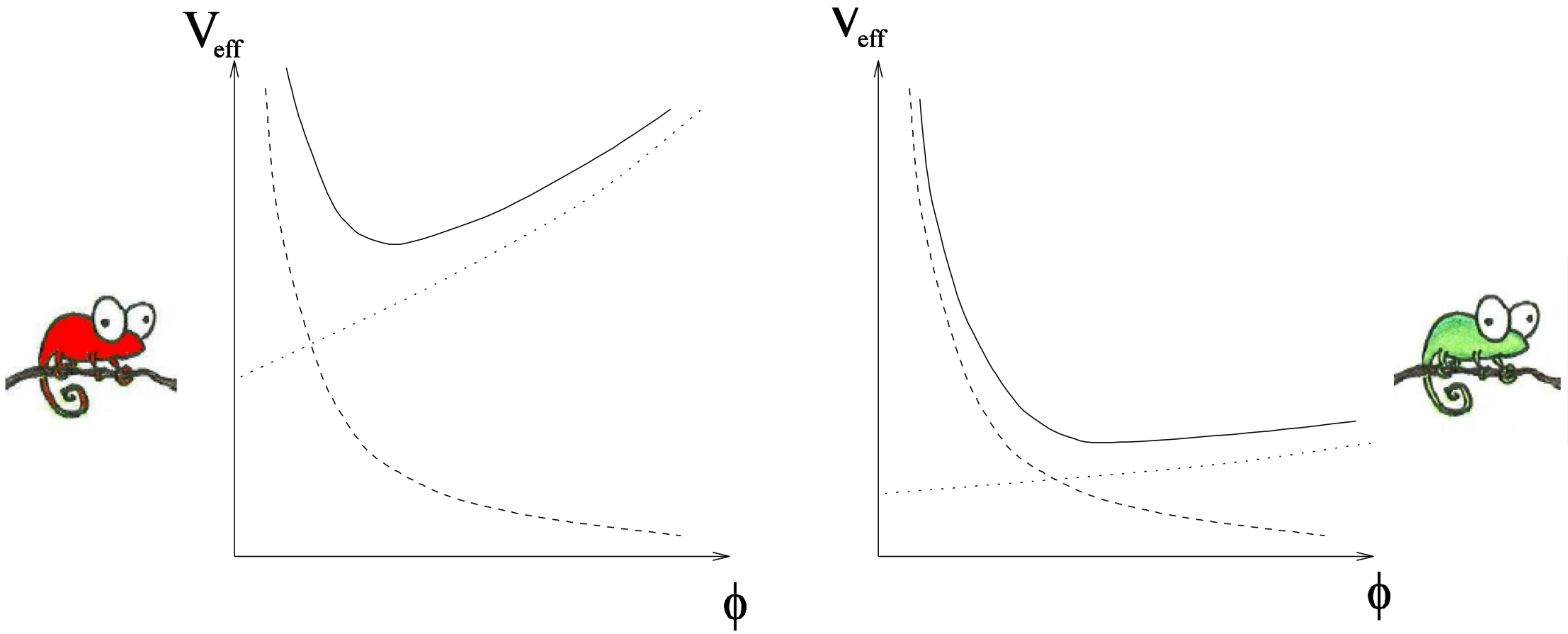
$$V_{\text{eff}}(\phi) = V(\phi) - (A(\phi) - 1)T$$

$$V(\phi) = \frac{\Lambda^{4+n}}{\phi^n}$$

There is an environmental effect: when coupled to matter the potential depends on the ambient matter density as well



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

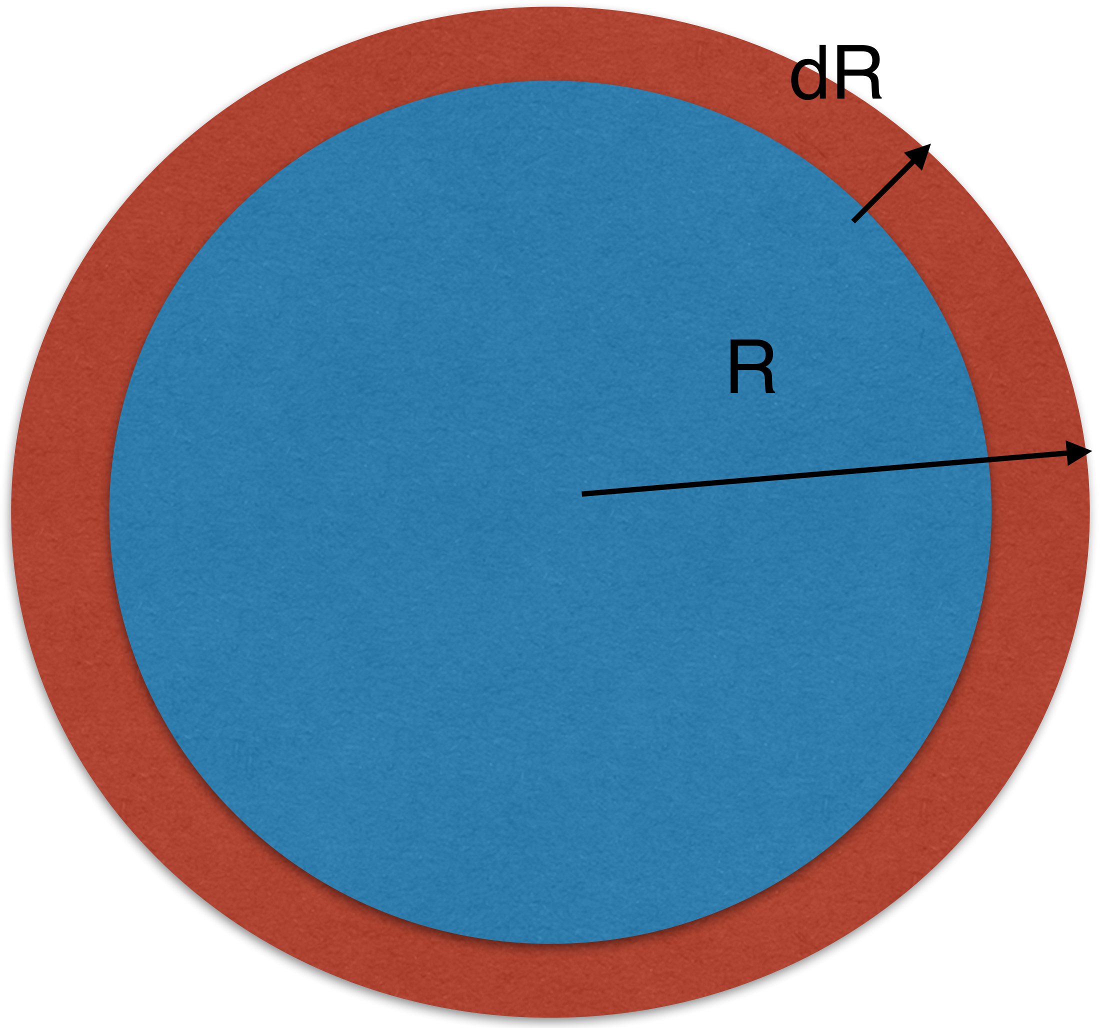


Large ρ Small ρ

mass is proportional to the second derivative of minimum of the potential
Hence it can be heavy when ρ is large and light when ρ is small

$$m_\phi^2(\rho) = \partial^2 V(\rho)/\partial\phi^2$$

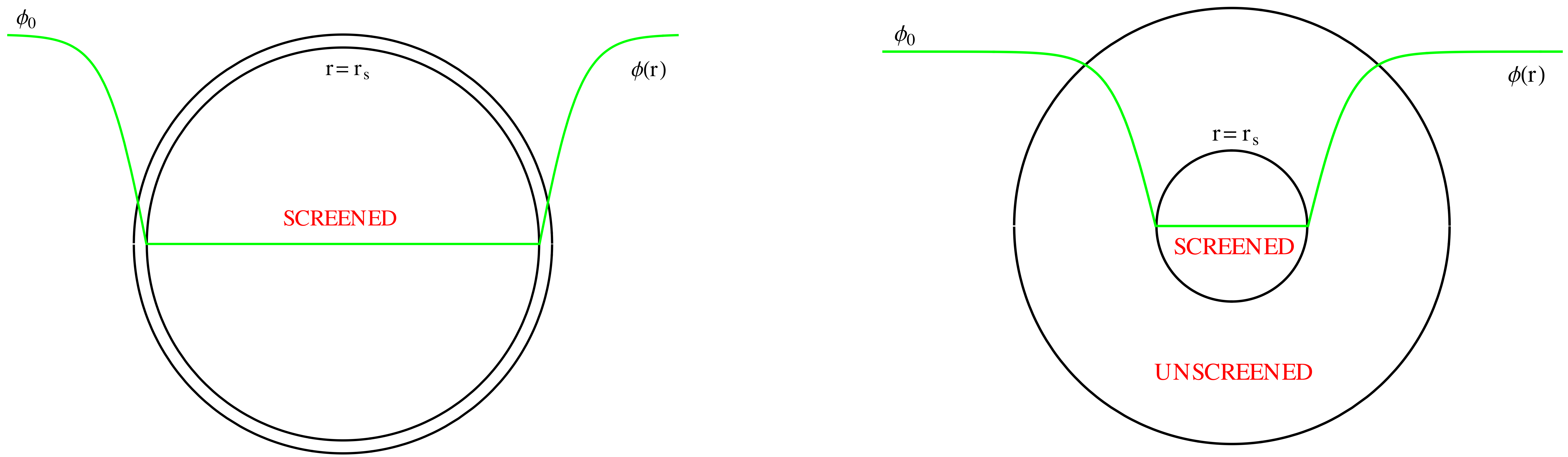
To screen fifth forces in the solar system one needs the thin shell effect.



$$F_\phi \approx \frac{\Delta R}{R\Phi_N}$$

The fifth force is proportional to the size of the thin shell where the field varies

Object	Φ_{N}
Main-sequence star	10^{-6}
Post-main-sequence star (1–$10M_\odot$)	10^{-7}–10^{-8}
Spiral Galaxy	10^{-6}
Dwarf Galaxy	10^{-8}



ϕ_0
$r = r_s$
$\phi(r)$
SCREENED
ϕ_0
$\phi(r)$
$r = r_s$
SCREENED
UNSCREENED

Symmetrons

Khoury&Hinterbichler, 1001.4525

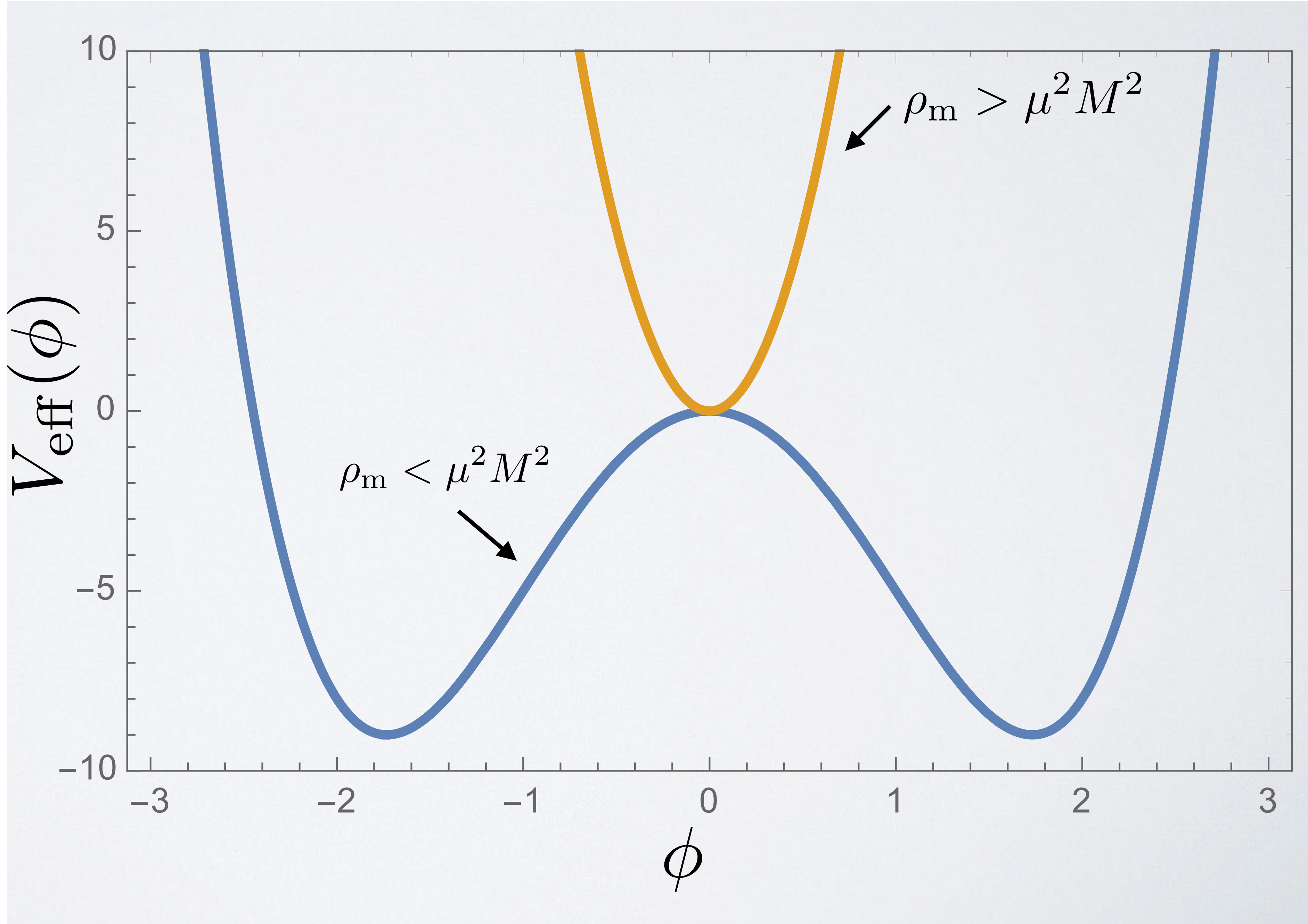
This has potential

$$V(\phi) = V_0 + \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

and coupling function

$$A(\phi) = 1 + \frac{\beta_\star}{2\phi_\star m_{\rm Pl}}\phi^2$$

In a dense environment the field is at the origin whilst in a sparser one the field is at the minimum of the potential with the transition happening at density ρ_*



The Runaway DIlaton

In the strong coupling limit of string theory the dilaton has a runaway potential

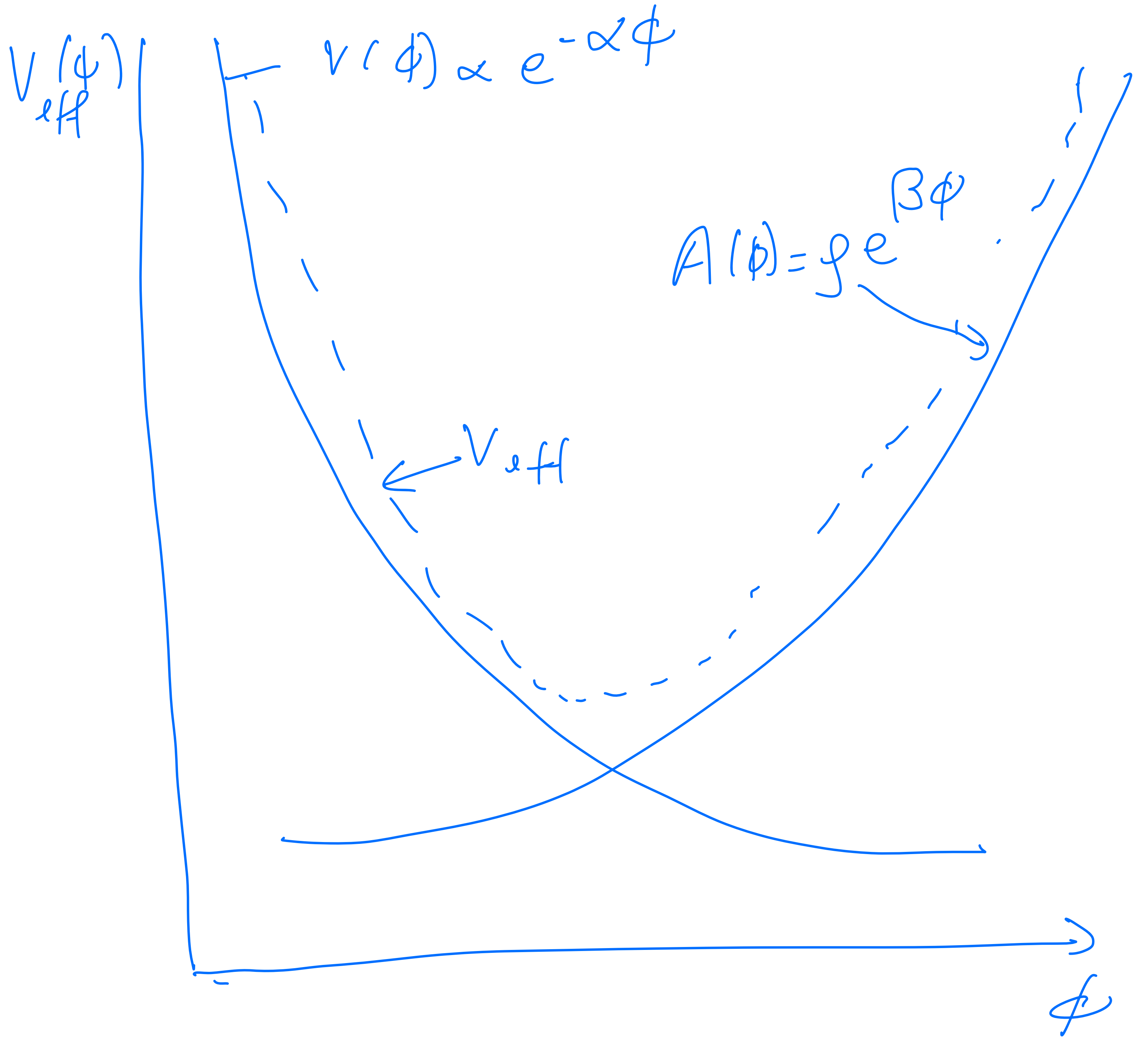
$$V(\phi) = V_0 e^{-\alpha\phi}$$

Gasperini et al, gr-qc/0108016, investigated the runaway dilaton as a quintessence field. With Damour, gr-qc/0204094, they realised there were equivalence violations when the dilaton coupled to matter

In the weak coupling limit the dilaton coupling to matter is

$$A(\phi) = e^{\beta\phi}$$

Does this have a screening mechanism? Actually NO. You might think it is viable until computing the thin shell condition — such a model doesn't have a thin shell so will not pass all solar system tests



Environmentally Dependent Dilaton

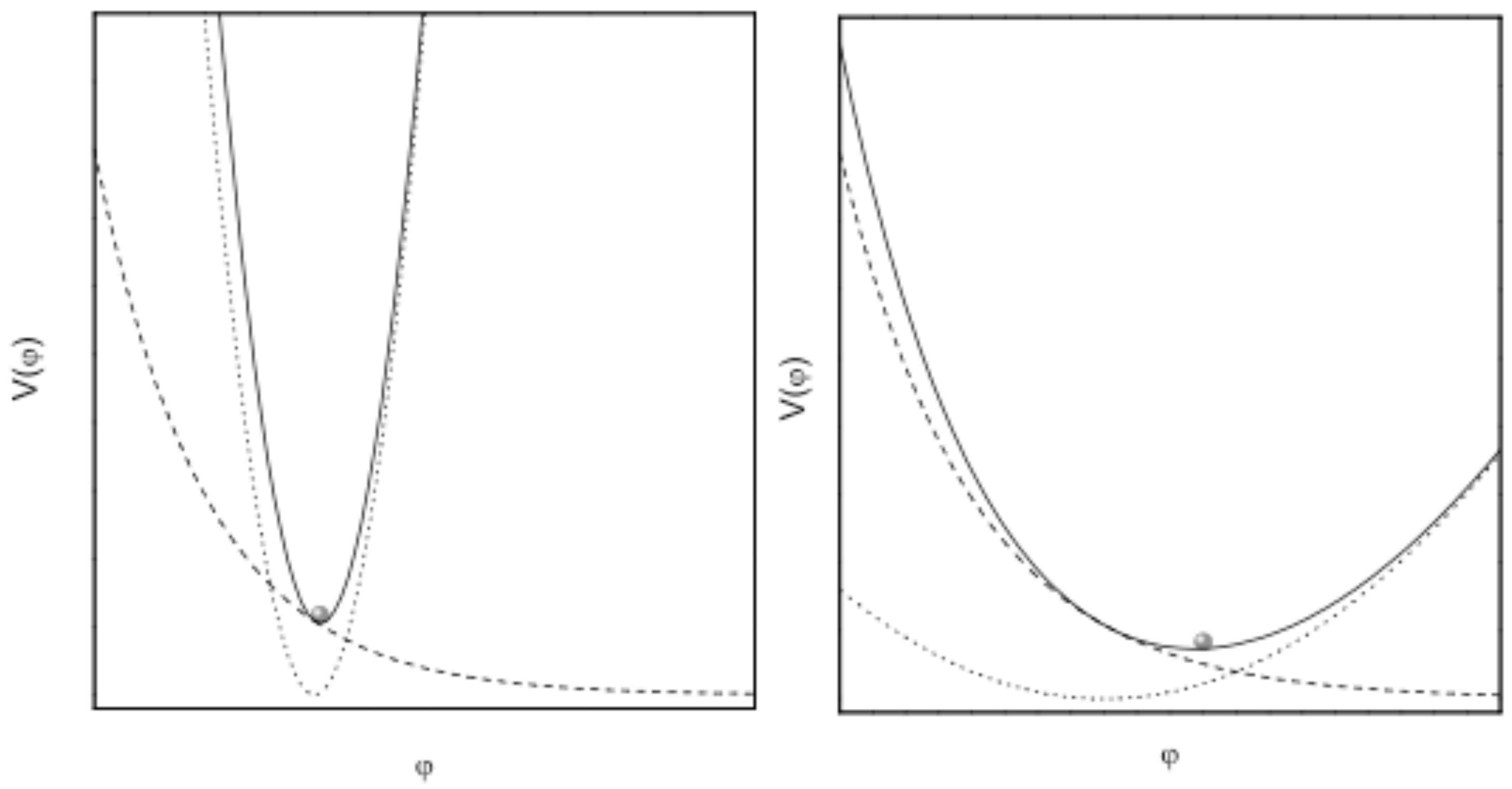
Brax, van de Bruck, ACD& Shaw 1005.3735

$$V(\phi) = V_0 e^{-\alpha\phi}$$

Where the potential is derived from string theory in the strong coupling limit. We chose the coupling to matter to be

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_\star)^2$$

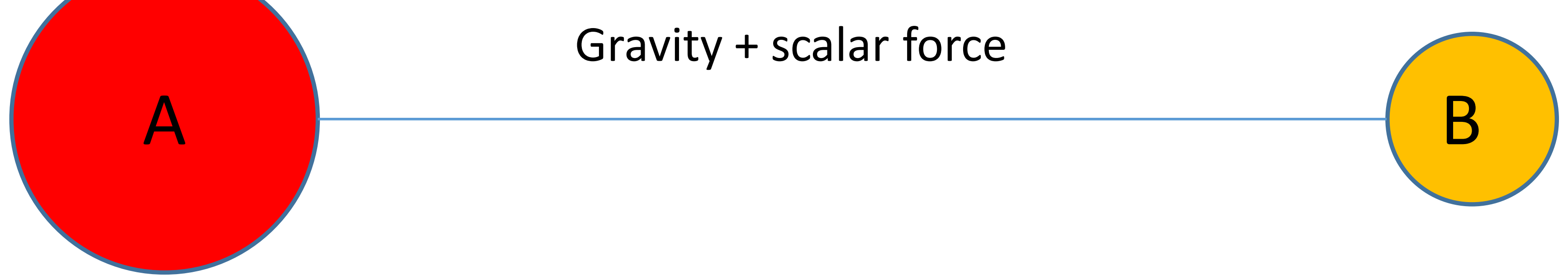
This keeps the scalar in the strong coupling regime as the Universe evolves. See Brax et al 1005.3735 for full details of the cosmological behaviour, local constraints and linear perturbation theory



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

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

Newtonian potential at the surface of the body.

$$Q_A \leq \beta_\infty$$

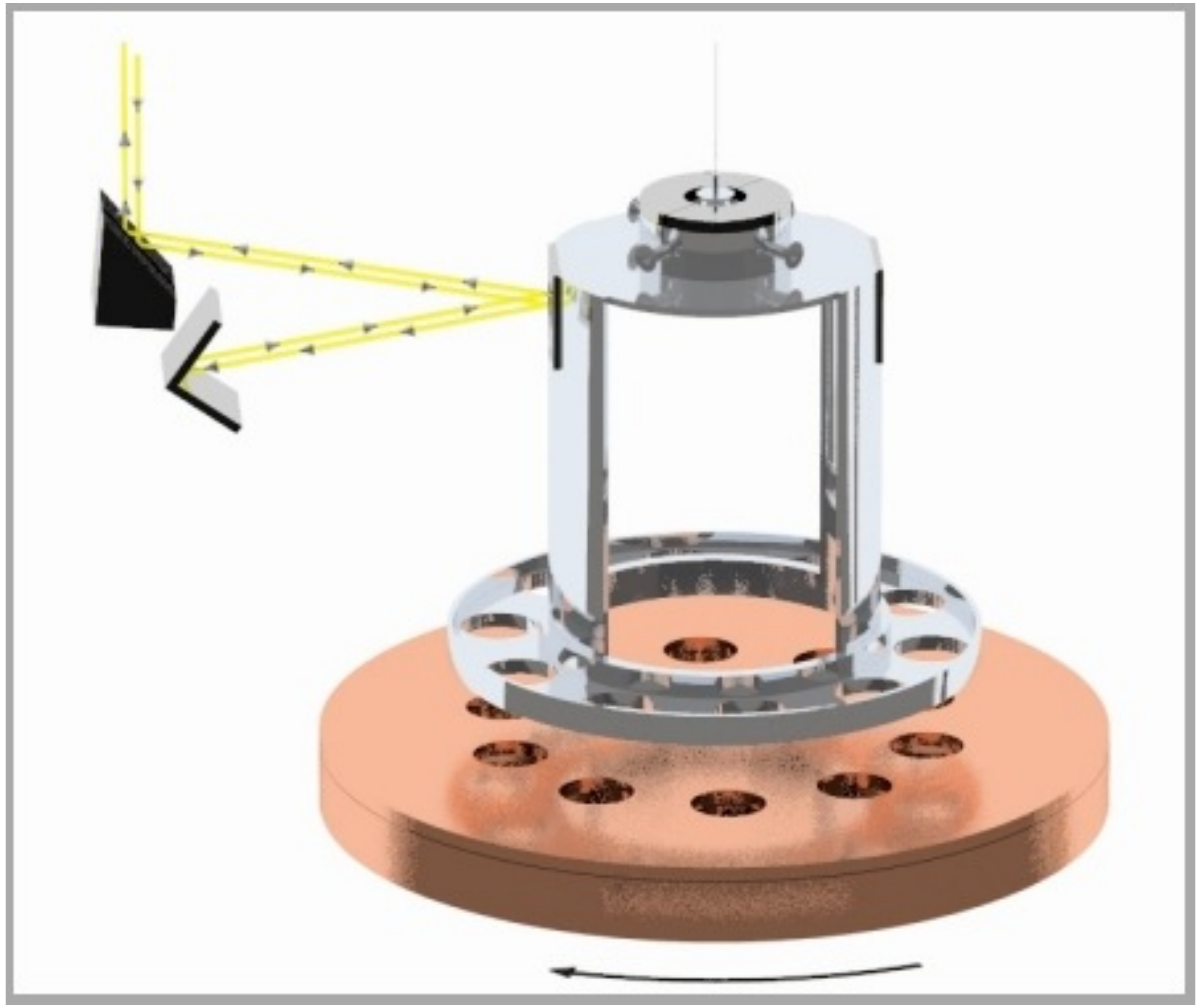
Screening criterion for compact objects

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

Eot-Wash Experiment

For a review see Wagner et al 1207.2442

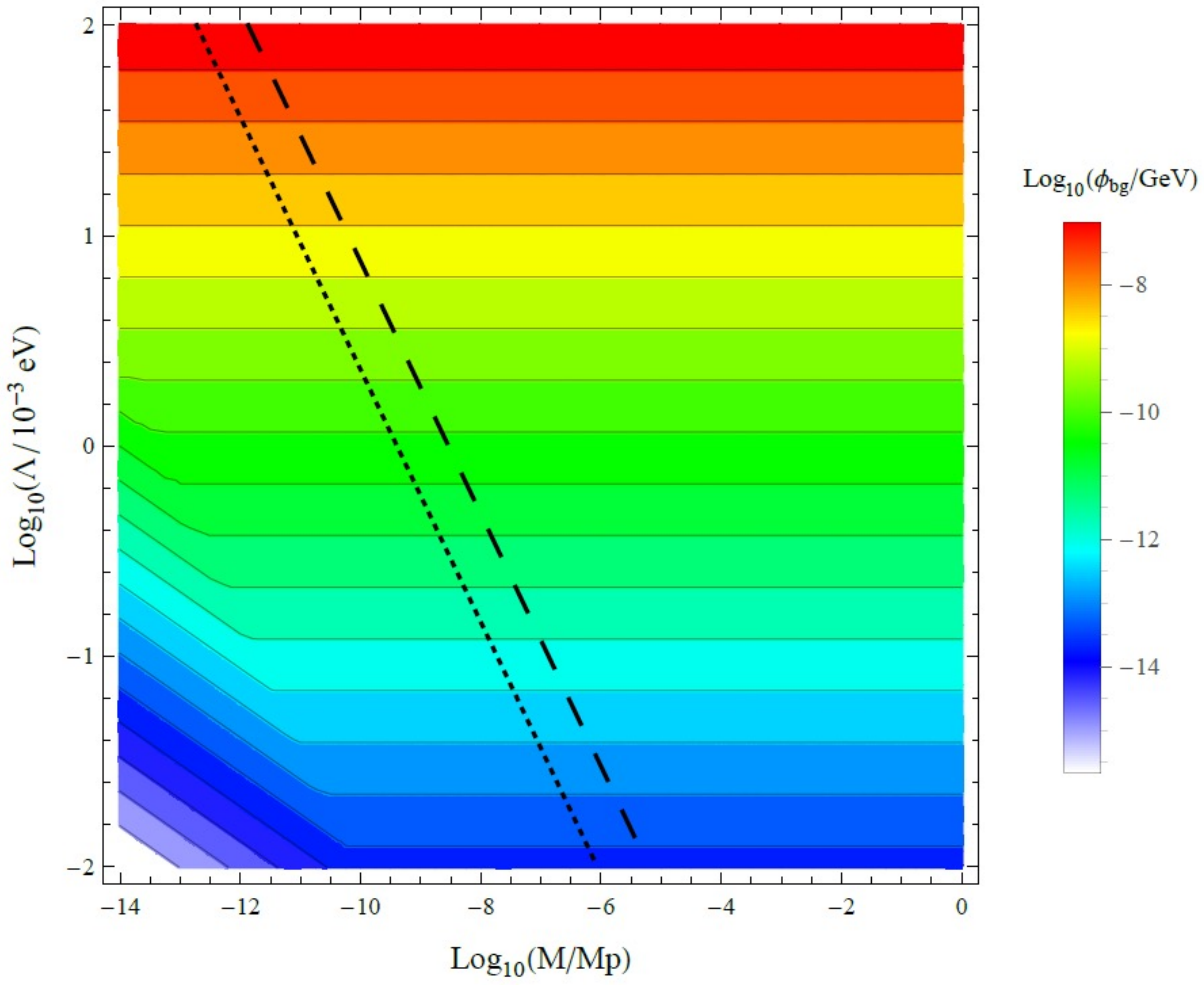
Be-Ti and
Be-Al test
masses



Why Atom Interferometry?

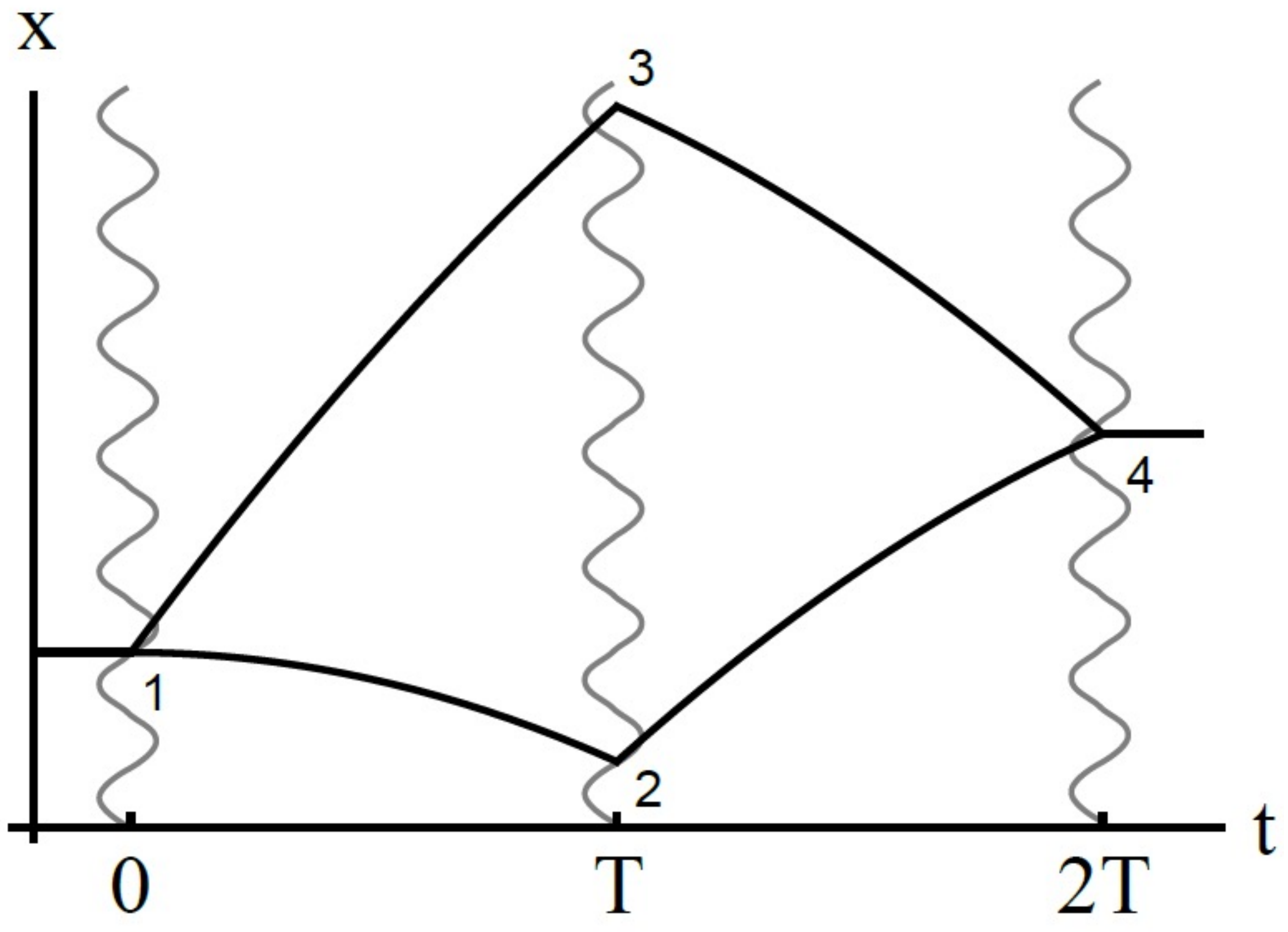
In a spherical vacuum chamber, radius 10 cm, pressure 10^{-10} Torr

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



Burrage CB, Copeland, Hinds. (2015) 1408.1409, JCAP 03 (15) 042

Atom Interferometry



Probability measured in excited state at output

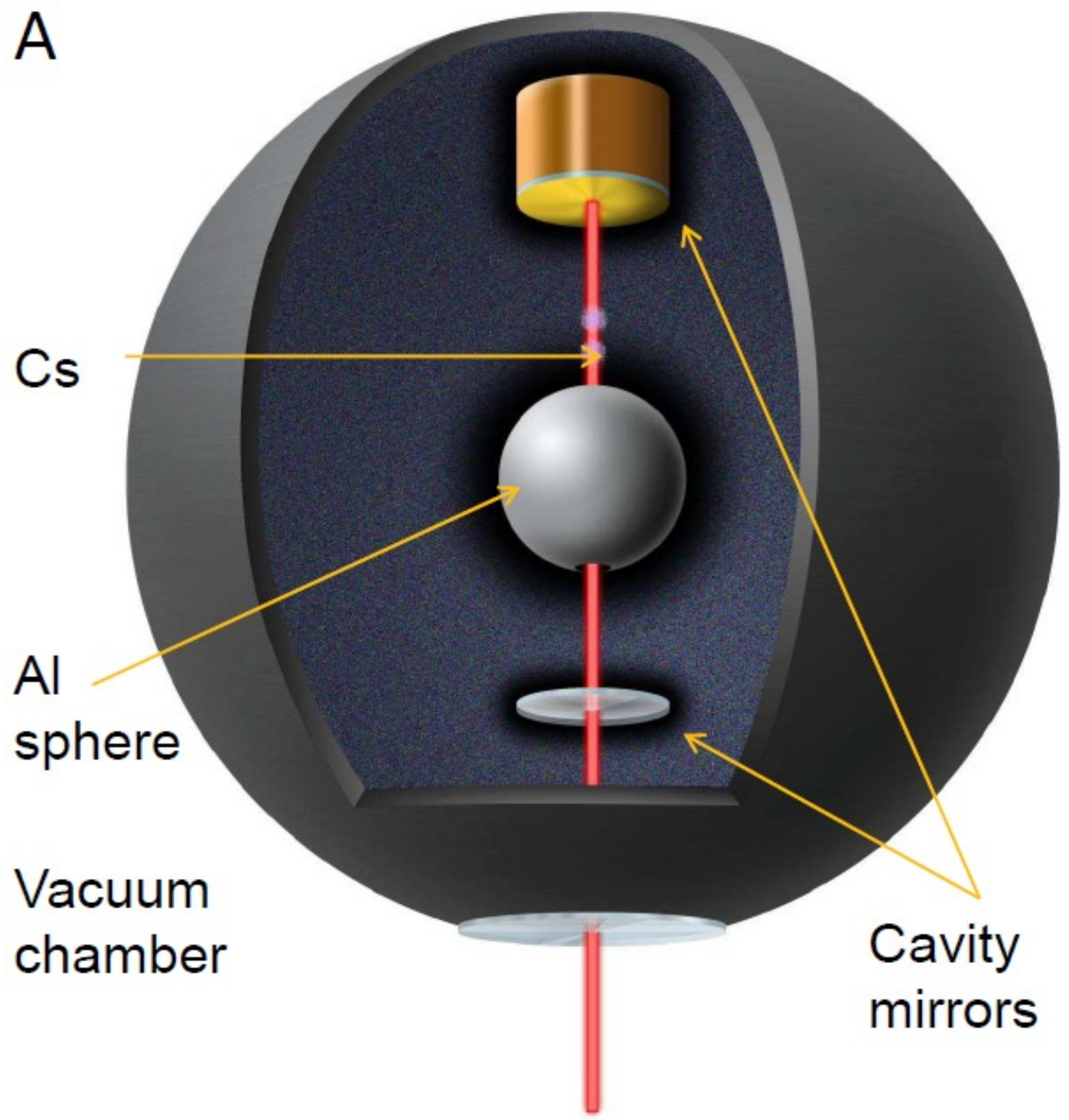
$$P = \cos^2\left(\frac{kaT^2}{2}\right)$$

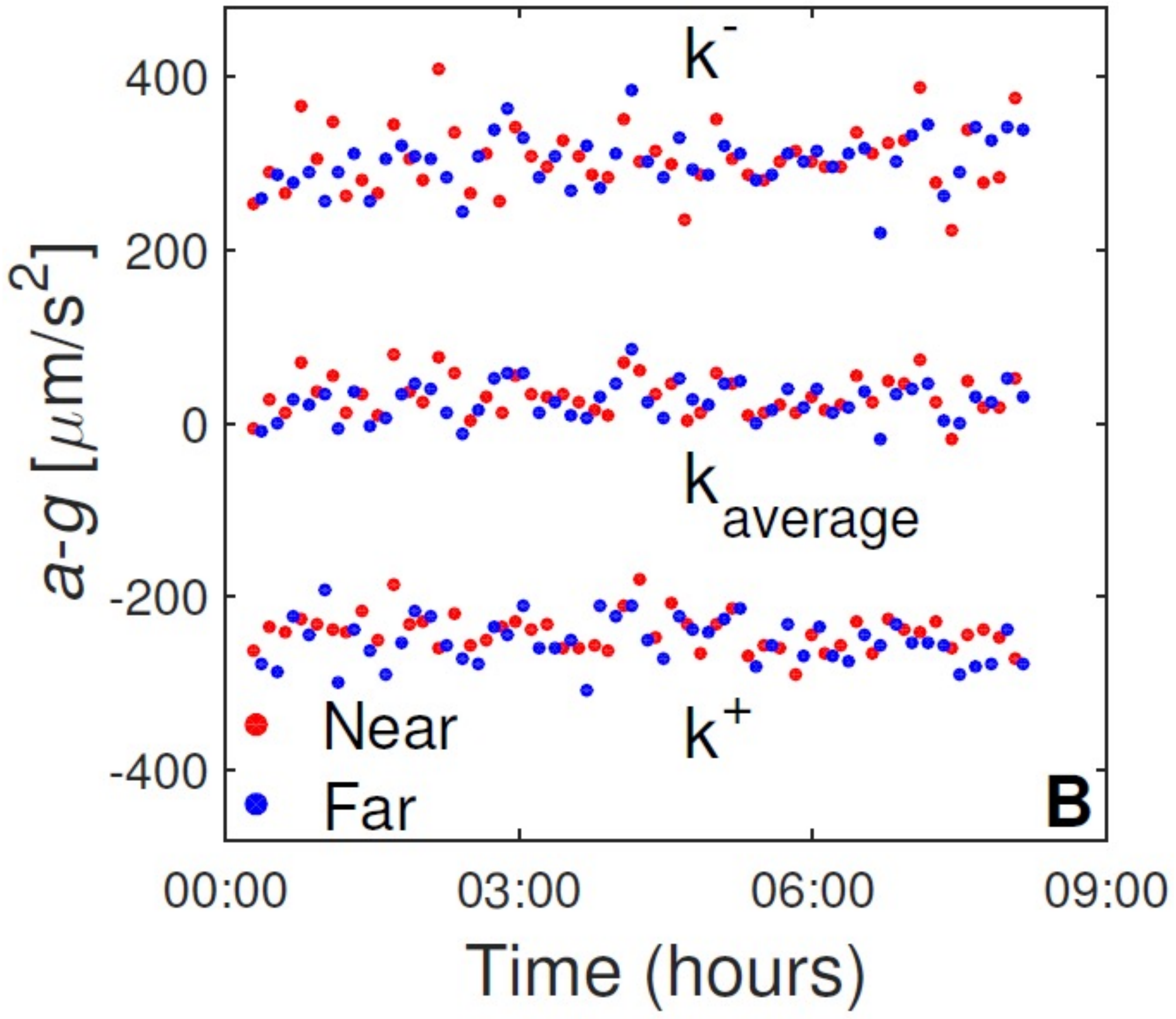
Berkley Experiment

Using an existing set up with an optical cavity, looking for a signal on top of the Earth's magnetic field

Anomalous acceleration = 11 ± 24 nm s^{-2}

Sphere radius = .95cm
distance to interferometer = .88cm
apparatus embedded in cylinder of R=6.1cm





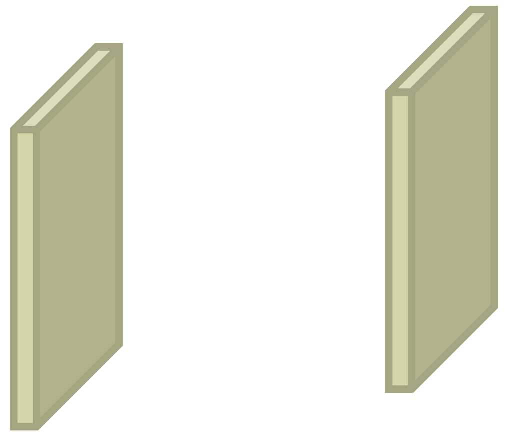
Jaffe, Haslinger, Xu, Hamilton, Upadhye, Elder, Khoury, Müller. (2017)
Elder, Khoury, Haslinger, Jaffe, Müller, Hamilton. (2016)

Casimir Force Experiments

Brax et al PRD76(07)124034

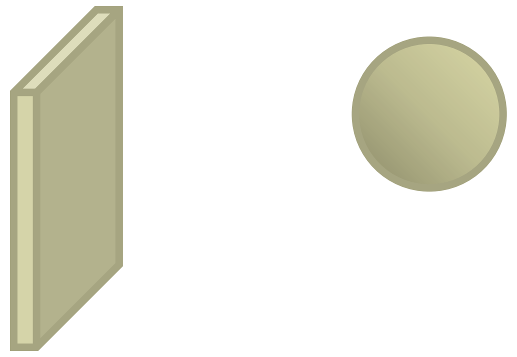
The scalar force could be detected in Casimir type experiments

force between parallel plates



$$F_{cas} \approx d^{-4}$$

force between a plate and a sphere



chameleonic force

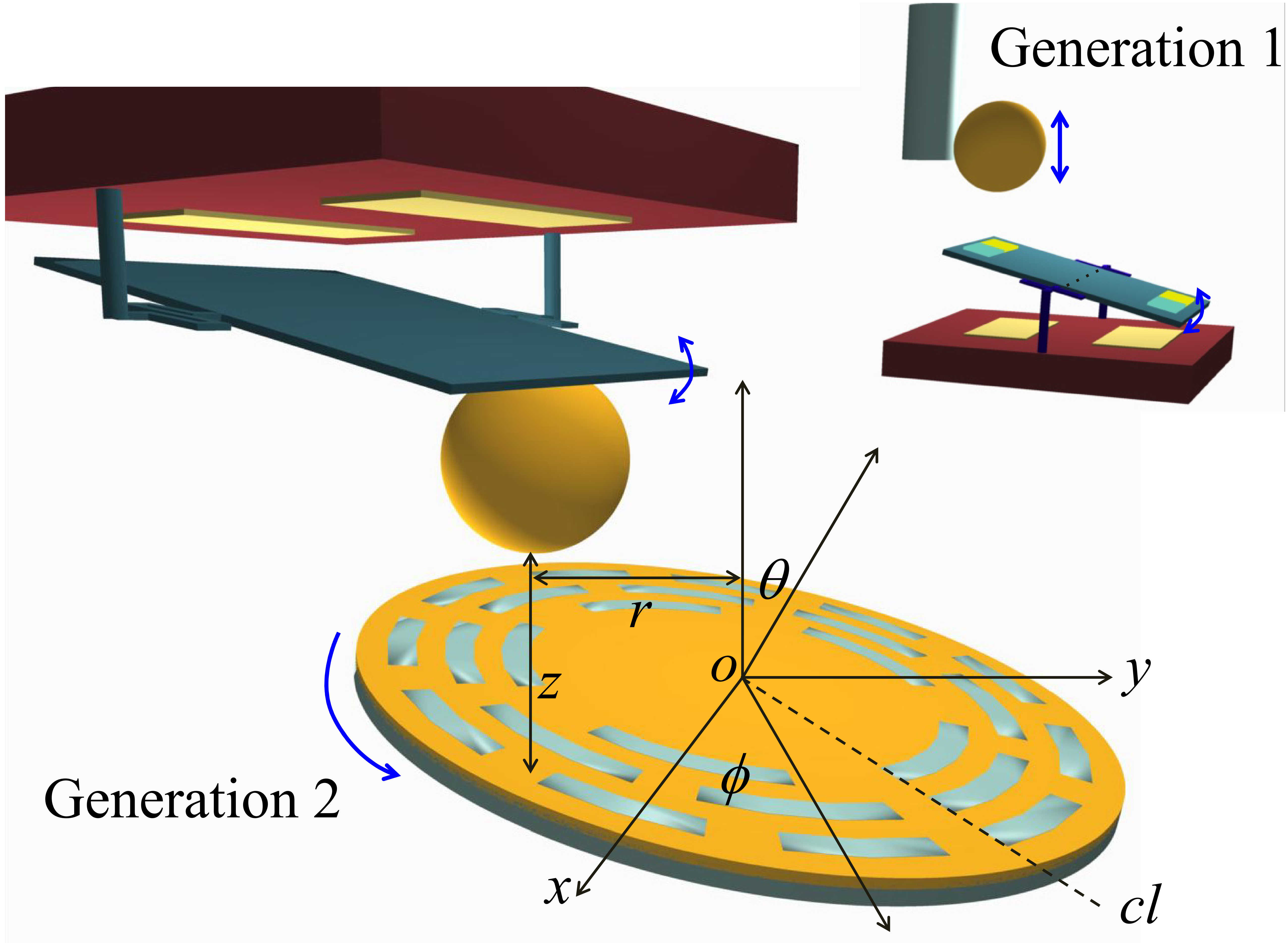
$$\frac{F_\phi}{A} \sim \Lambda^4 (\Lambda d)^{-\frac{2n}{n+2}}$$

$$\frac{F_\phi}{F_{\rm cas}} \sim \frac{240}{\pi^2} (\Lambda d)^{\frac{2(n+4)}{n+2}}$$

dark energy scale is

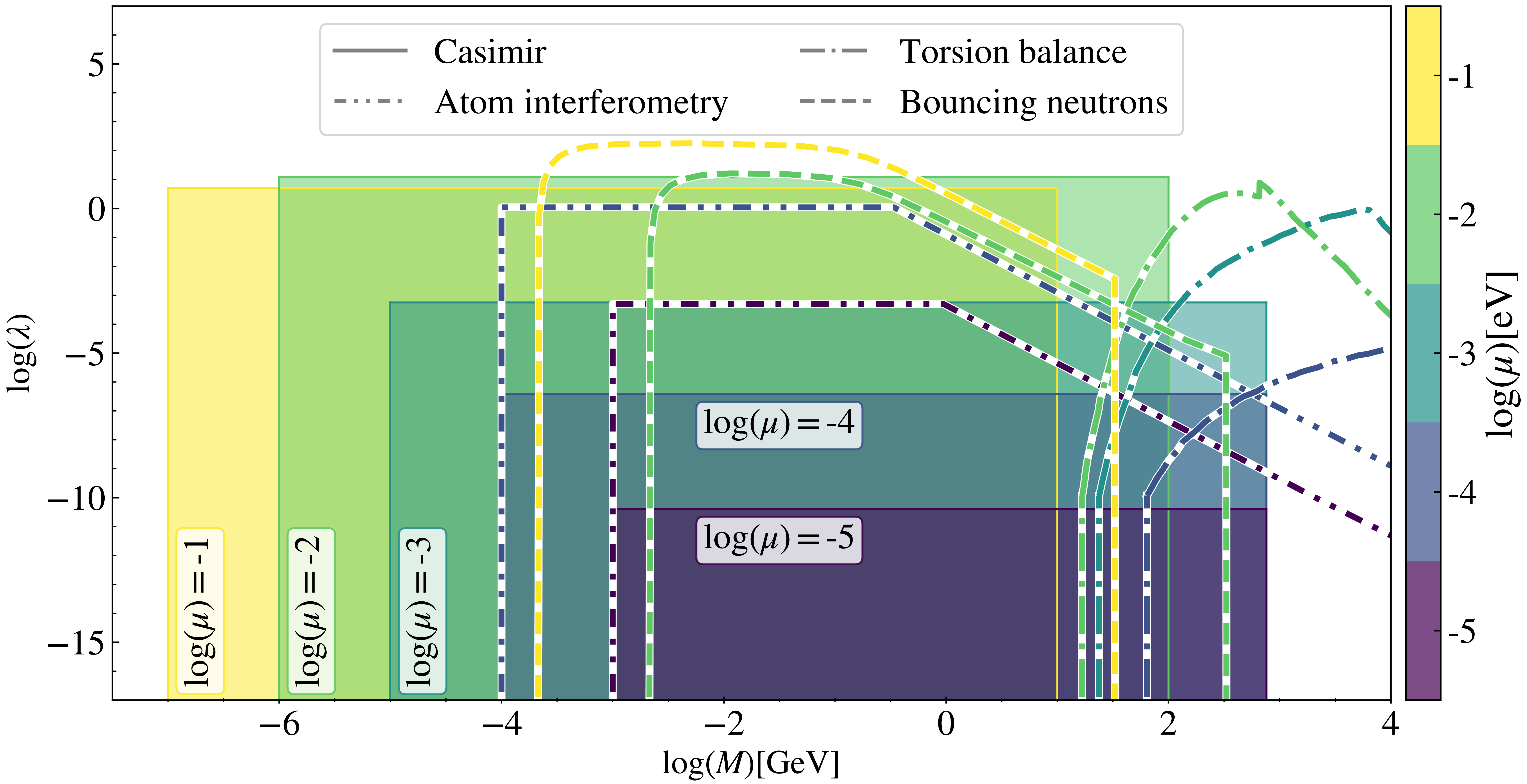
$$\Lambda^{-1} \sim 82 \mu m$$

Decca Experiment —
1410.7267; 1509.05349

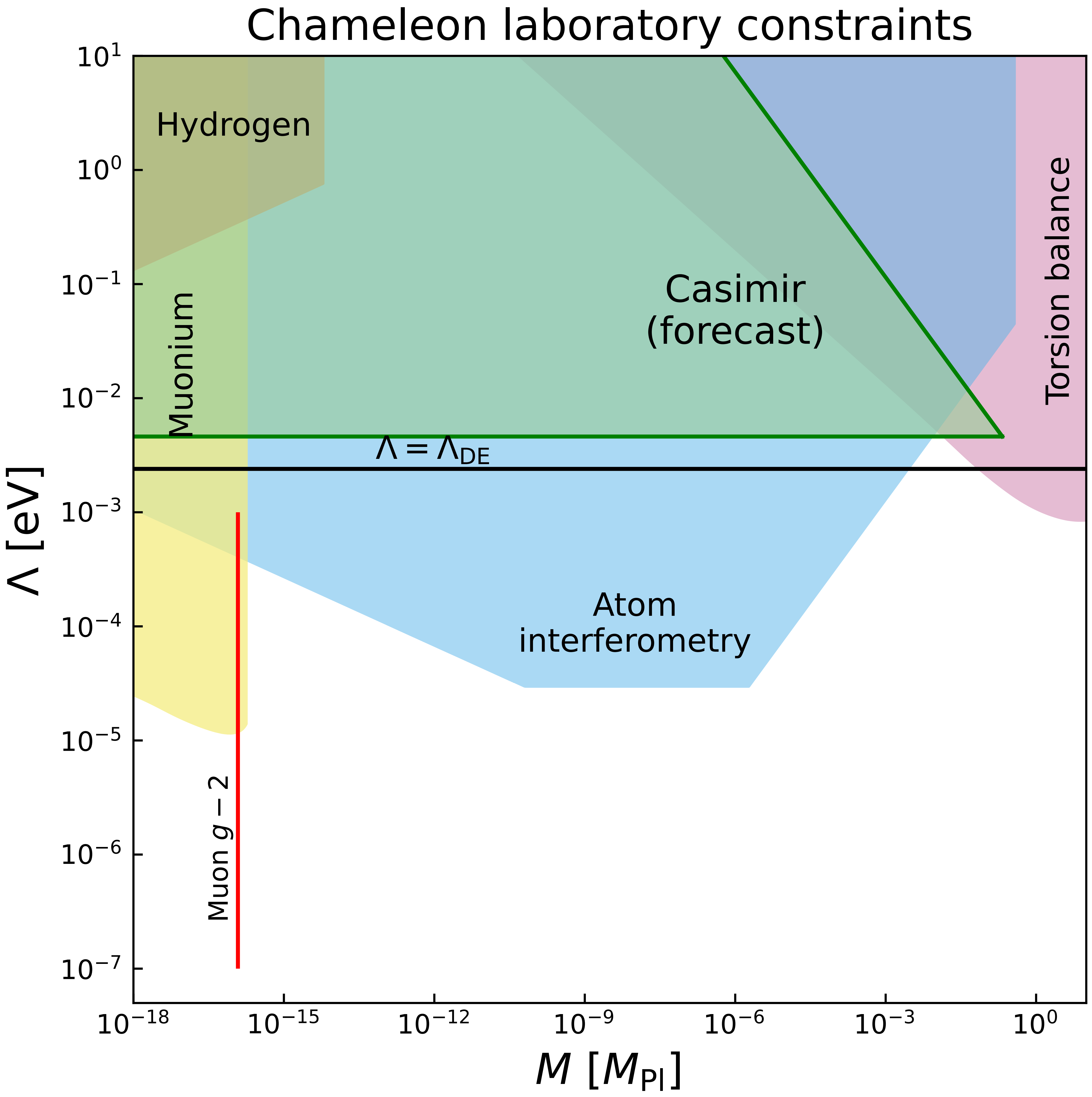


Casimir Symmetron Forecasts, Elder, Vardanyan, Akrami, Brax, ACD, Decca; 1912.10015

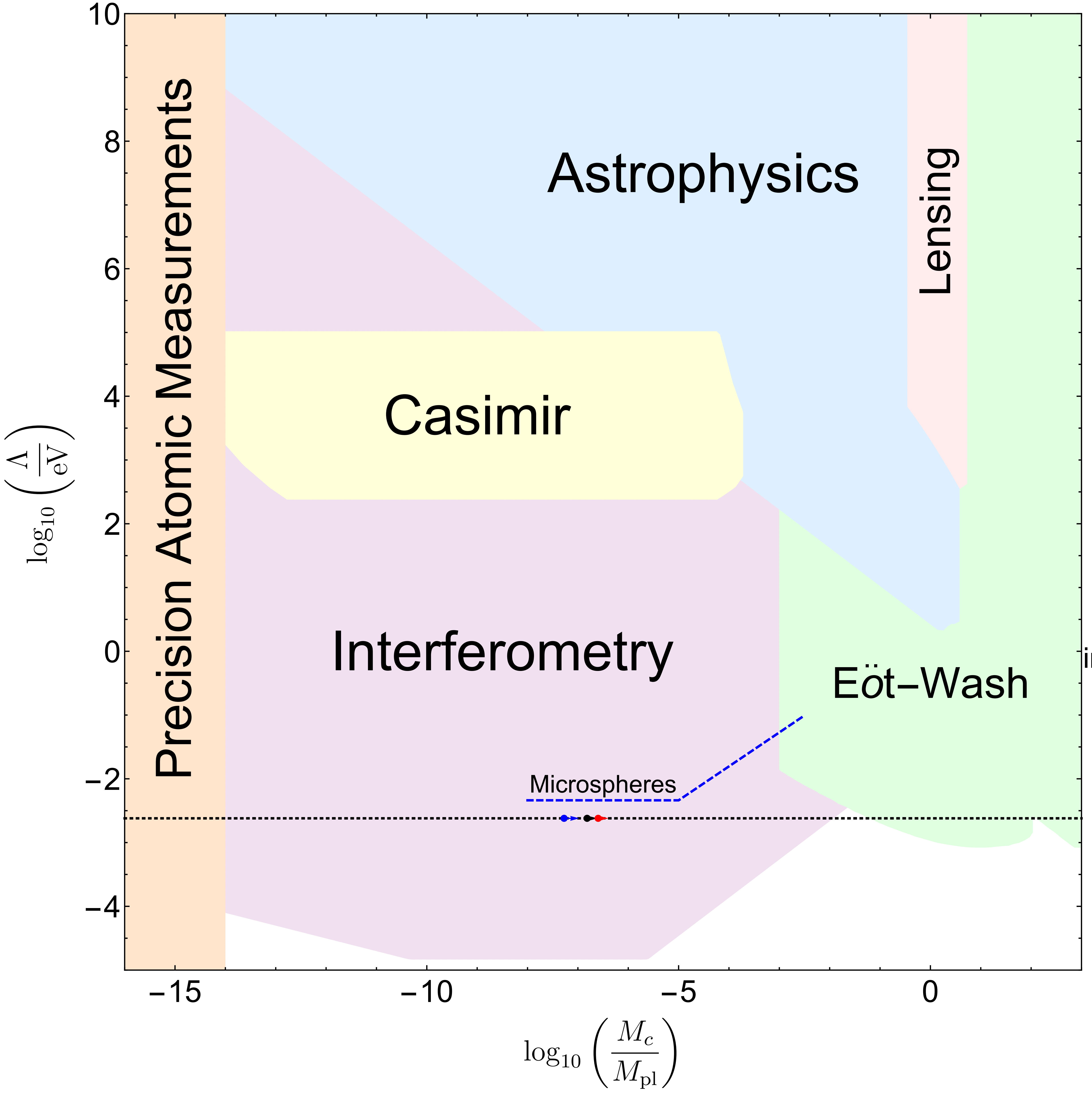
$R = 150\ \mu m$ $D_{near} = 15\ \mu m$ $D_{far} = 65\ \mu m$ $\delta Force \lesssim 0.1\ fN$



Brax, ACD and Elder, 2211.07840, 2207.11633, 2111.01188

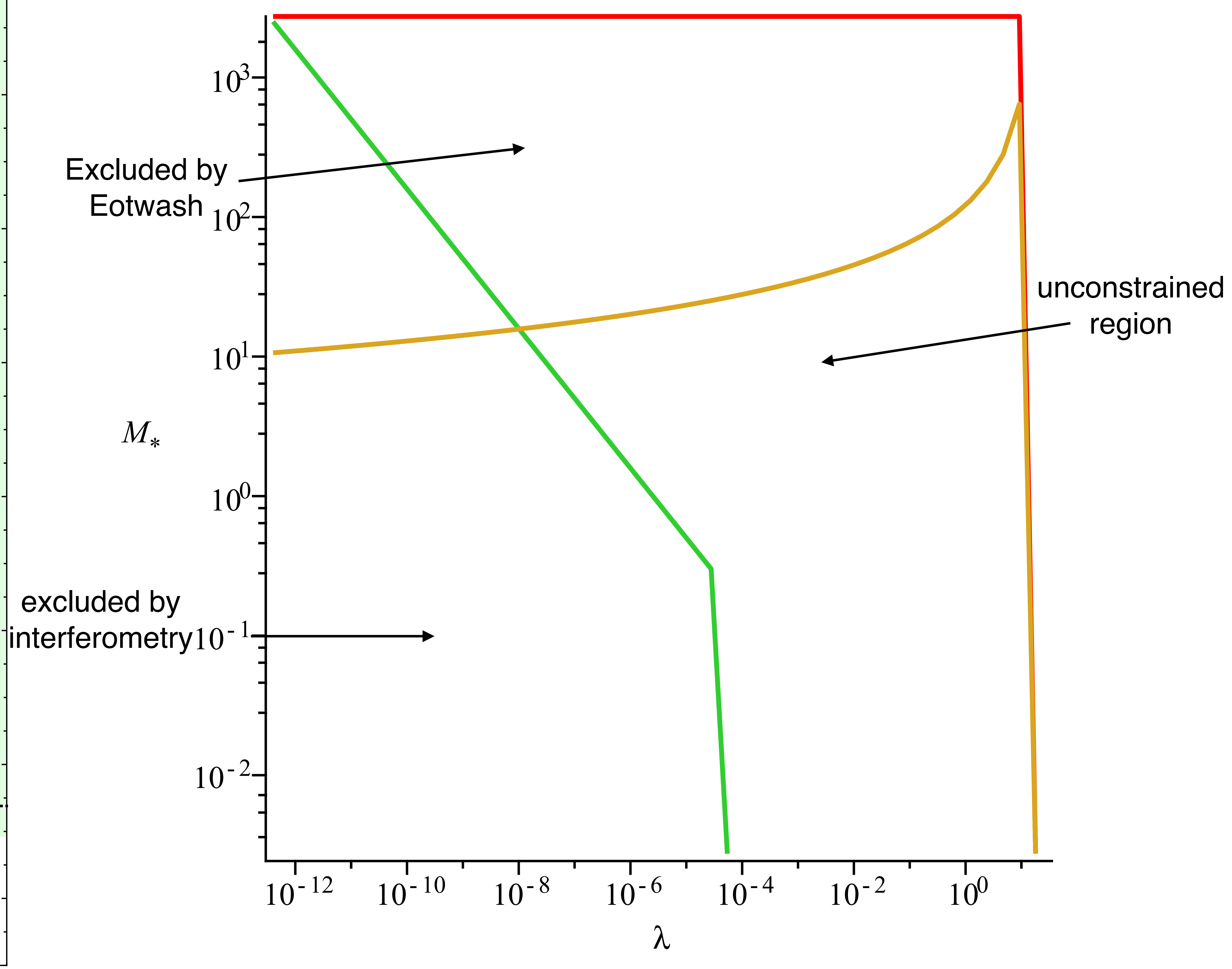


Chameleon Constraints — Burrage and Sakstein 1709.09071

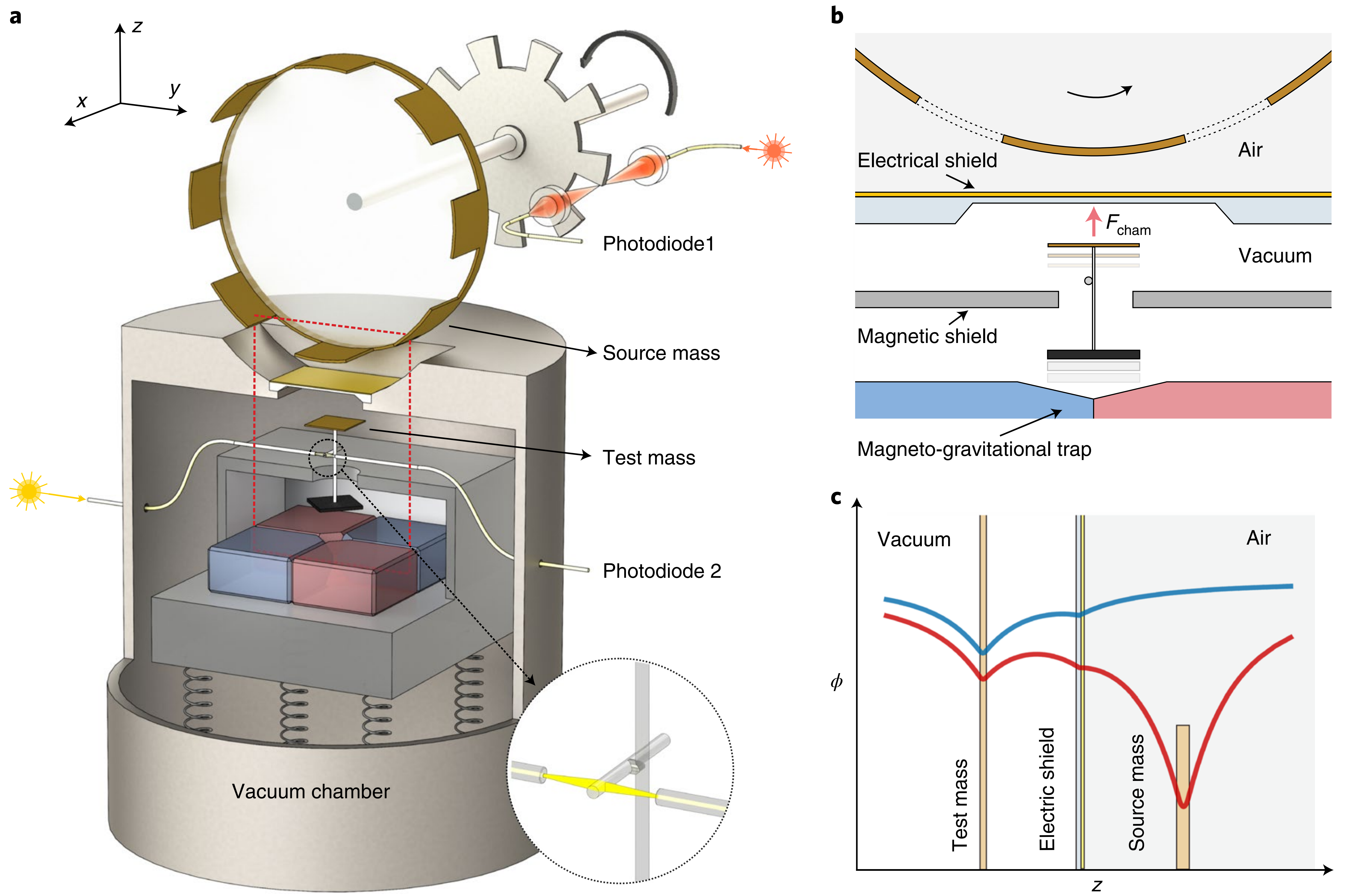


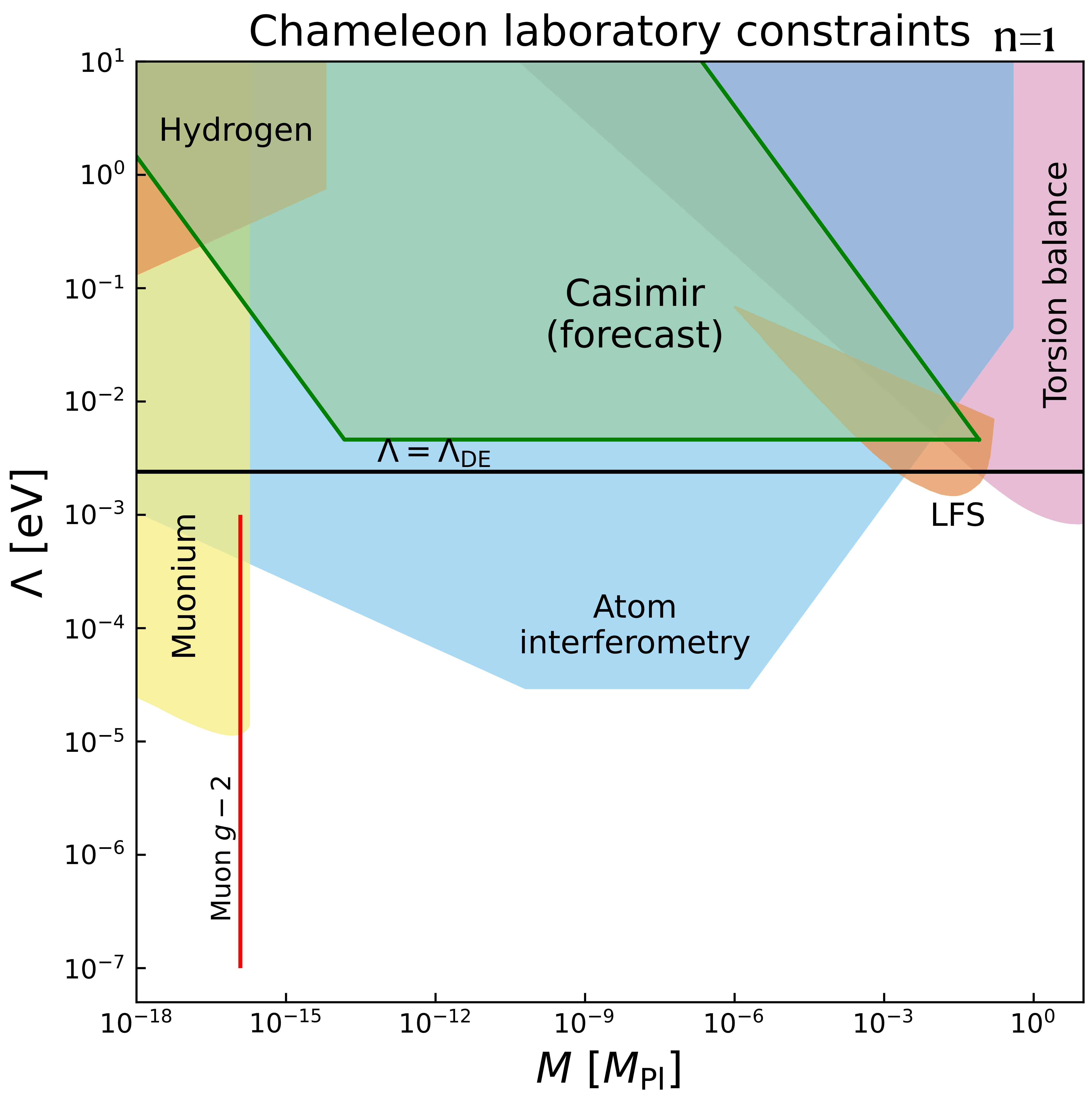
Symmetron Constraints

Brax and ACD 1609.09242



Levitating spheres Yin et al Nature Physics Vol 18 (2022) 1181




Chameleon laboratory constraints n=1
Hydrogen
Casimir
(forecast)
Torsion balance
$\Lambda = \Lambda_{DE}$
LFS
Muonium
Atom
interferometry
Muon $g-2$
Λ [eV]
M [M_{Pl}]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}

The scalar can couple to photons via

$$\frac{\beta_\gamma \phi F^2}{M_{Pl}}$$ for chameleons

$$\frac{\beta_\gamma \phi^2 F^2}{M_{Pl}^2}$$ for symmetrons

note the scalar coupling to photons; different from the axion coupling

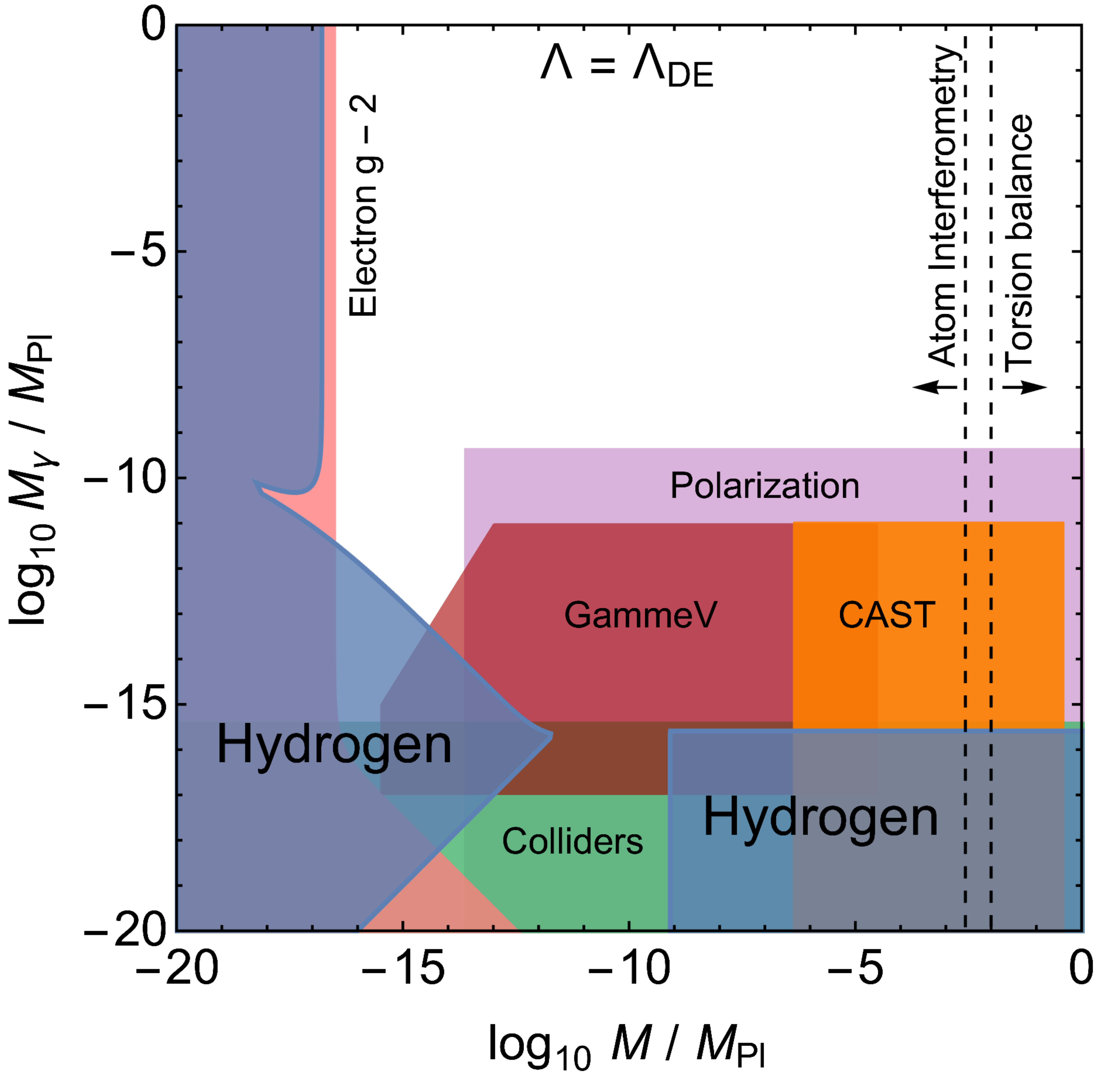
Bekenstein showed the most general coupling to matter contained a conformal and disformal term

$$g_{\mu\nu} = A^2(\phi) g^E_{\mu\nu} + B^2(\phi, X)\partial_\mu \phi \partial_\nu \phi$$

we usually take $B(\phi, X) = \frac{1}{M^4}$

the disformal term gives a natural coupling to photons chameleon photon coupling

from Elder &Sakstein 2305.15638



Discussion

- We presented scalar-tensor models with screening, in particular the chameleon model
- Discussed laboratory tests
- Constraints on the matter coupling
- Introduced the coupling to photons
- Constraints on the photon coupling
- What about production from the Sun — see Tom O'Shea (2406.01691) ; Luca Visinelli 2103.15834