Search for Dark Energy — beyond ΛCDM

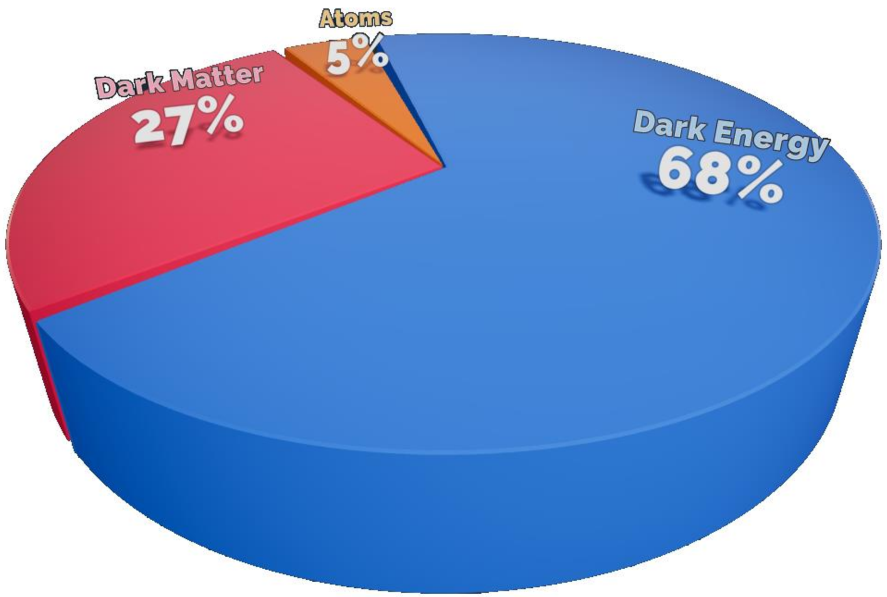
Hauke Fischer

Parallel talk at the TAUP conference, Vienna 29 / 09 / 23

Background

- Dark energy comprises the largest portion of energy in the universe[1]
- Its simplest description is given by a cosmological constant

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu}$$



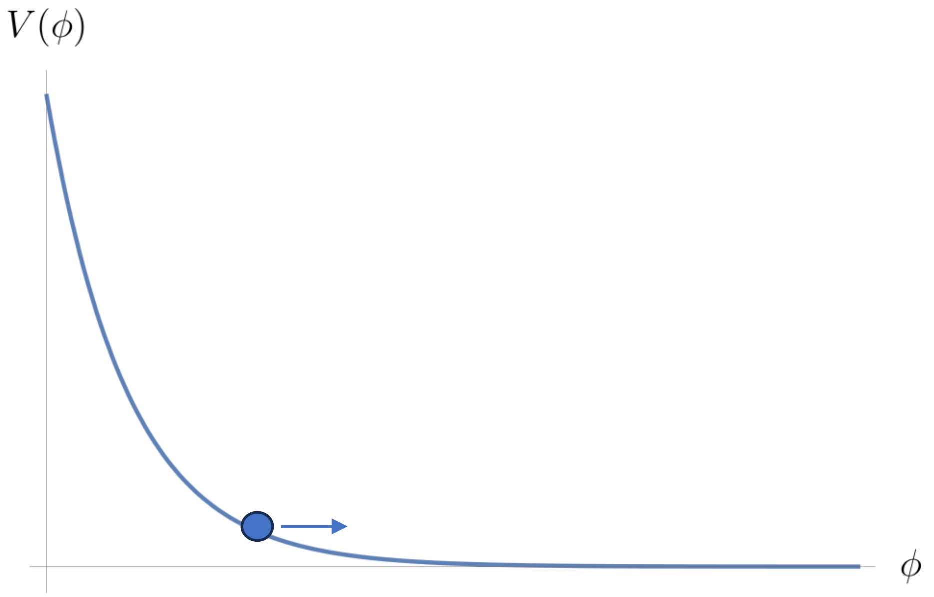
1. Planck Collab. 2018 Results VI, Astron. Astrophys.641, A6 (2020),[arXiv:1807.06209].

Background

- Λ might be assosciated with the zero point energy of quantum fields, but there is a discrepancy of ~ 55-60 orders of magnitude[2,3]
- Alternatively, dark energy could be due to a slowly rolling scalar field

$$T^{\phi}_{\mu\nu} = \partial_\mu \phi \partial_\mu \phi - g_{\mu\nu}(\frac{1}{2}(\partial\phi)^2 - V[\phi]) \approx g_{\mu\nu} V[\phi]$$

$$\rightarrow \Lambda_\phi = \frac{8\pi G}{c^4} V(\phi).$$



2. JOYCE, Austin, et al. Beyond the cosmological standard model. Physics Reports, 2015, 568. Jg., S. 1-98.

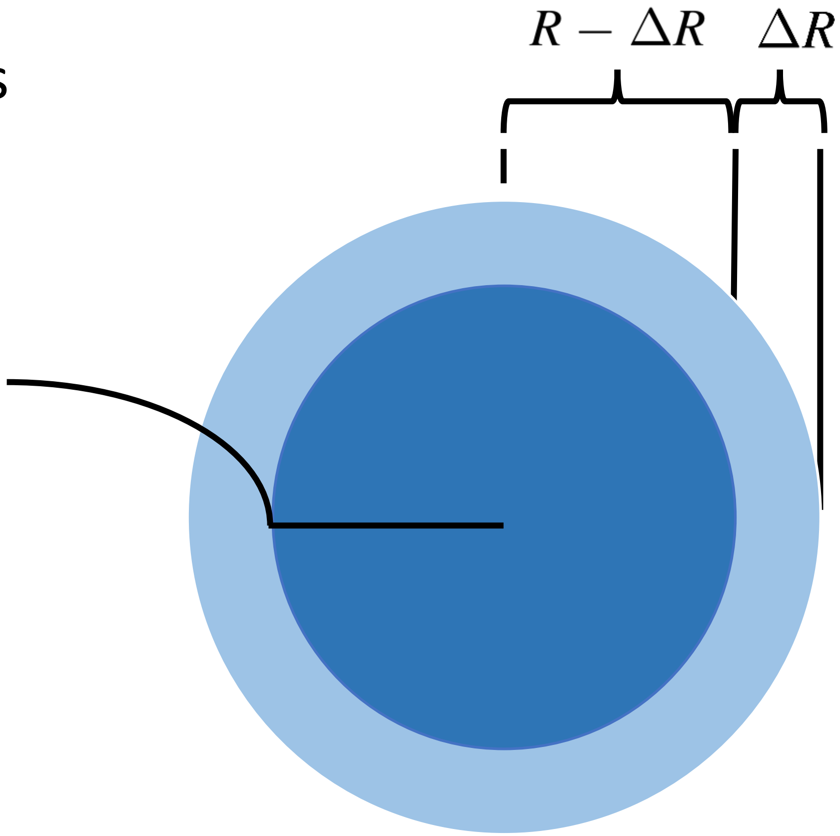
3. Sola, Joan. "Cosmological constant and vacuum energy: old and new ideas." Journal of Physics: Conference Series. Vol. 453. No. 1. IOP Publishing, 2013

Background

- These scalar fields generically lead to fifth forces in the solar system
- Some *screening mechanism*[4] should be present, in order to explain the null results from solar system tests

$$S = \int d^4x\sqrt{-g}\left(-\frac{m_{\rm pl}}{2}R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right) + \int d^4x\sqrt{-\tilde{g}}L_m[\tilde{g}_{\mu\nu},\Psi_i],$$

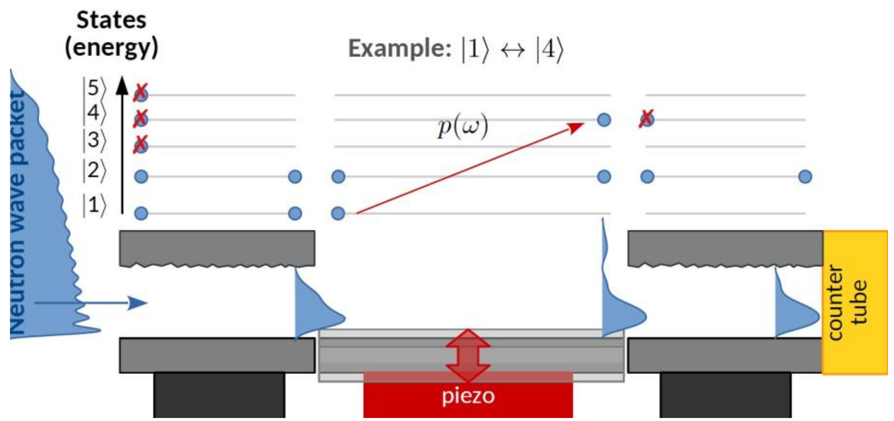
$$\tilde{g}_{\mu\nu} = A(\phi)g_{\mu\nu}$$



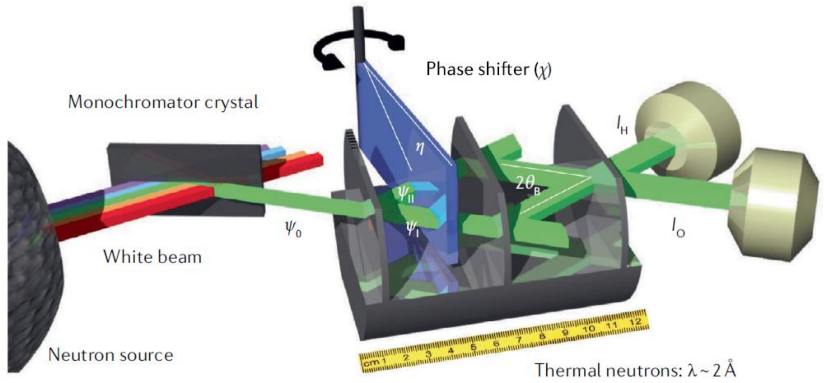
4. Burrage, Clare, and Jeremy Sakstein. "Tests of chameleon gravity." Living reviews in relativity 21 (2018): 1-58.

Methods: Analysis of experiments

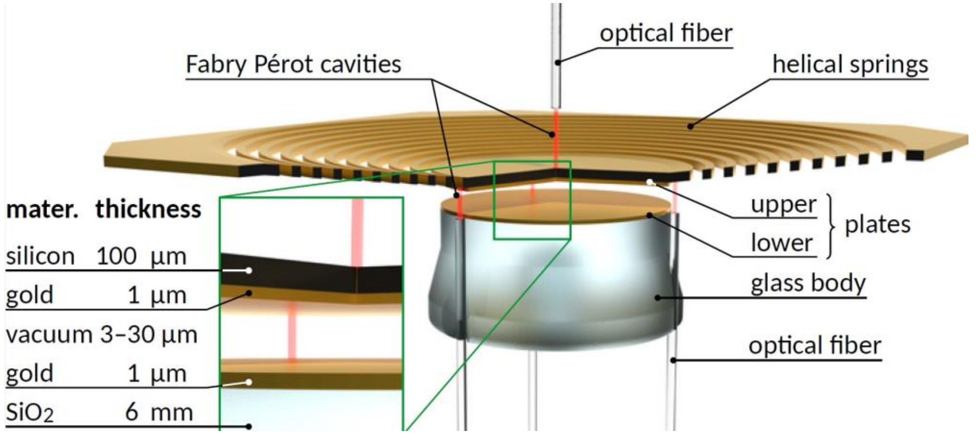
qBounce



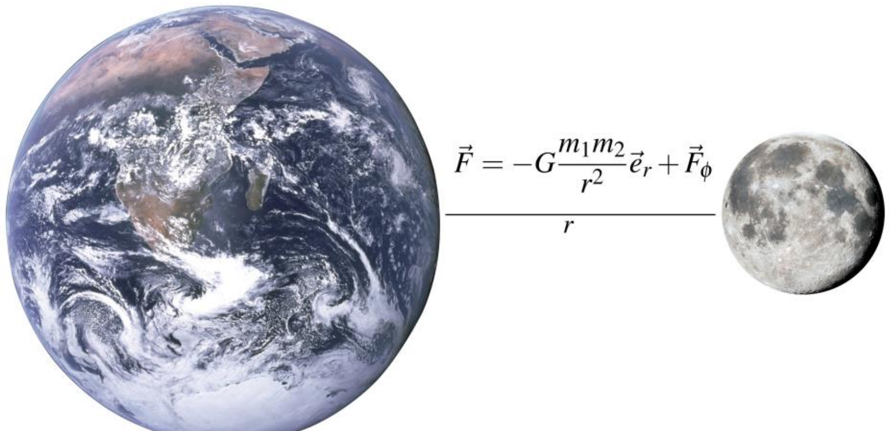
Neutron interferometry[5]



CANNEX



Lunar Laser Ranging



5. Sponar, Stephan, et al. "Tests of fundamental quantum mechanics and dark interactions with low-energy neutrons." Nature Reviews Physics 3.5 (2021): 309-327.

Research goals

- Constrain the parameter space with table top experiments at the ATI
  - Dilaton[6]: $V_D(\phi) = V_0 e^{-\lambda\phi/m_{pl}}$, $A_D(\phi) = 1 + \frac{A_2}{2m_{pl}^2}\phi^2$,
  - Symmetron[6]: $V_S(\phi) = -\frac{\mu}{2}\phi^2 + \frac{\lambda}{4}\phi^4$, $A_S(\phi) = 1 + \frac{\phi^2}{2M^2}$,
  - Chameleon[6]: $V_C(\phi) = -\frac{\Lambda^n}{\phi^n}$, $A_C(\phi) = e^{\phi/M_c}$.
- Consult experimentalists
- Gain physical insight into these models

6. Brax, Philippe, Clare Burrage, and Anne-Christine Davis. "Laboratory constraints." International Journal of Modern Physics D 27.15 (2018): 1848009.

Analytical results

- Derivation of scalar field dependent physical effects

  - Pressure between plates (CANNEX)
  - Relative phase shift (Interferometry)
  - …

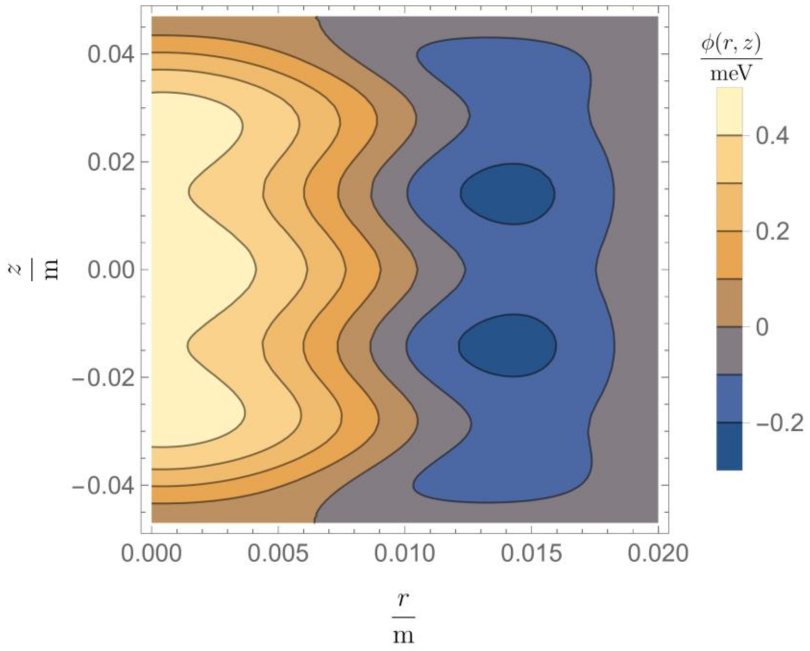
$$P_z = \frac{\rho_M}{\rho_M - \rho_V}\left(V_{\text{eff}}(\phi_V, \rho_V) - V_{\text{eff}}(\phi_0, \rho_V)\right)$$

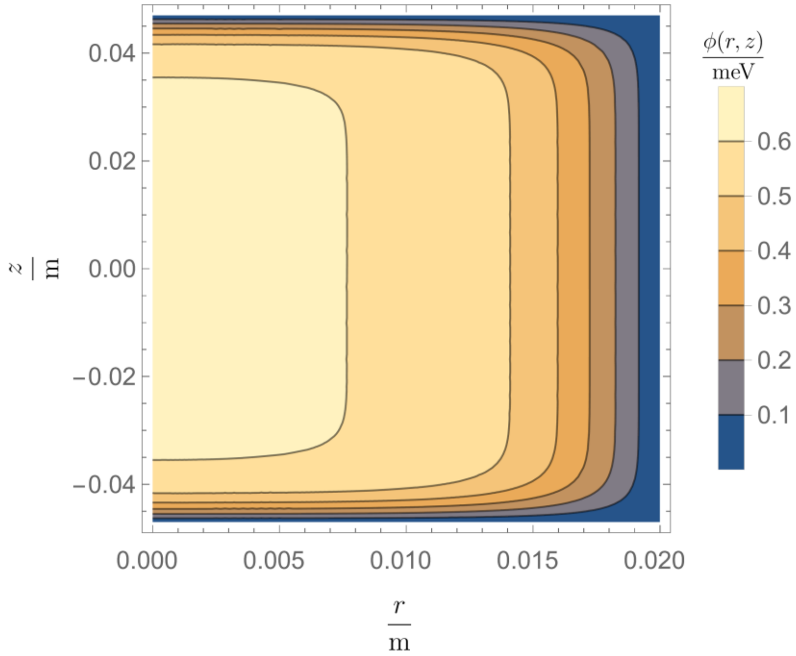
$$\Delta\varphi = -\mho\frac{m_N^2}{k_0}\int_0^L dz \frac{A_2}{2m_{pl}^2}\left(\phi^2(\vec{x}) - \phi_{\text{Air}}^2\right)$$

- Derivation of precise screening mechanisms of the Dilaton field

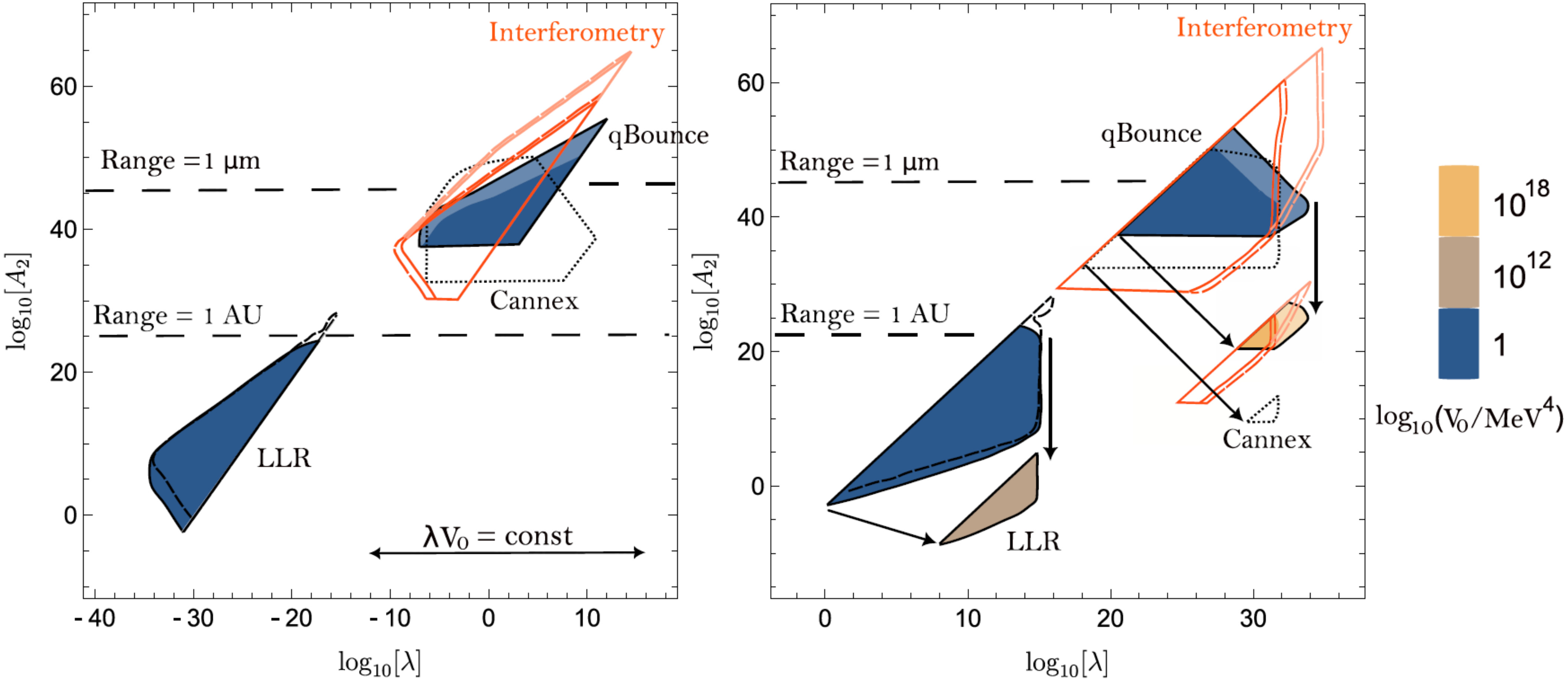
Numerical results

- Solve non-linear field equations numerically



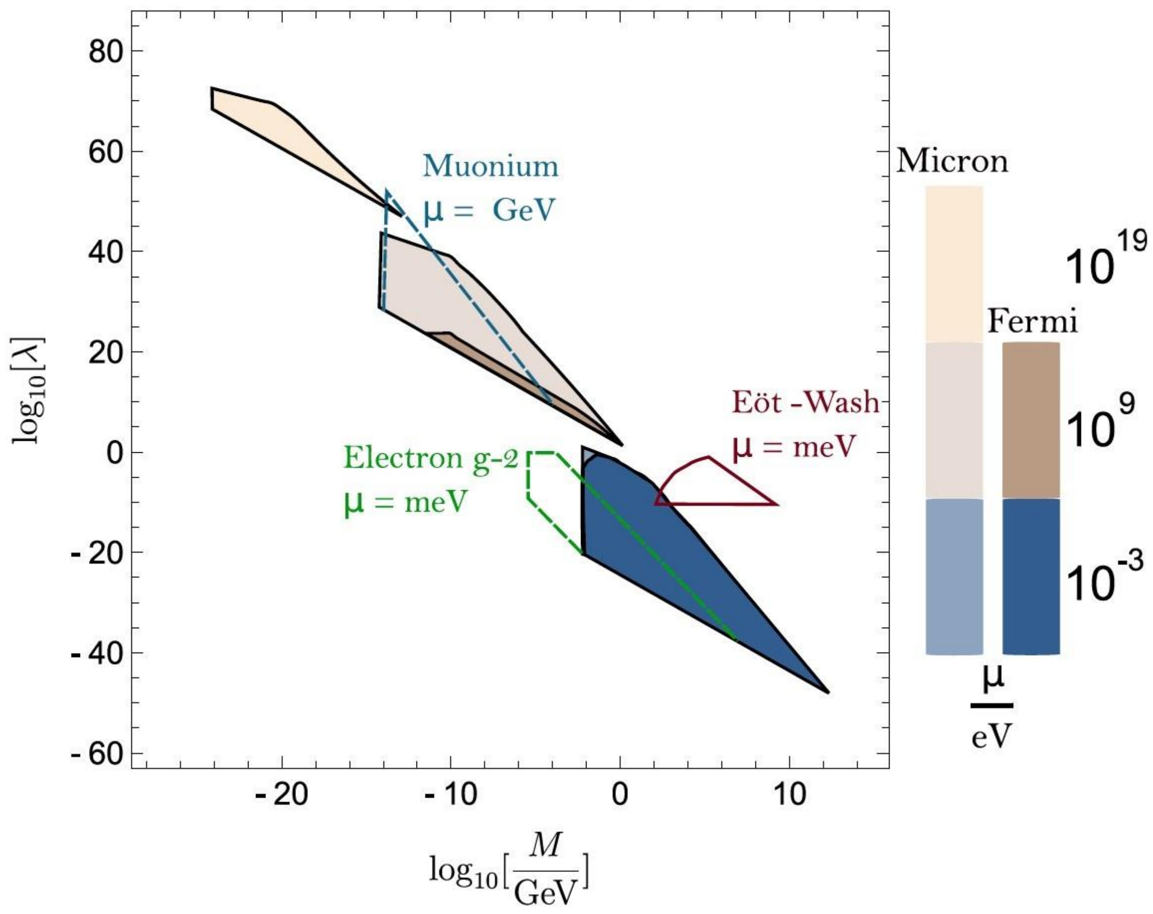


Resulting constraints on the dilaton model



7. H.F, et al. "Search for environment-dependent dilatons." arXiv preprint arXiv:2307.00243 (2023).

Resulting constraints on the symmetron model

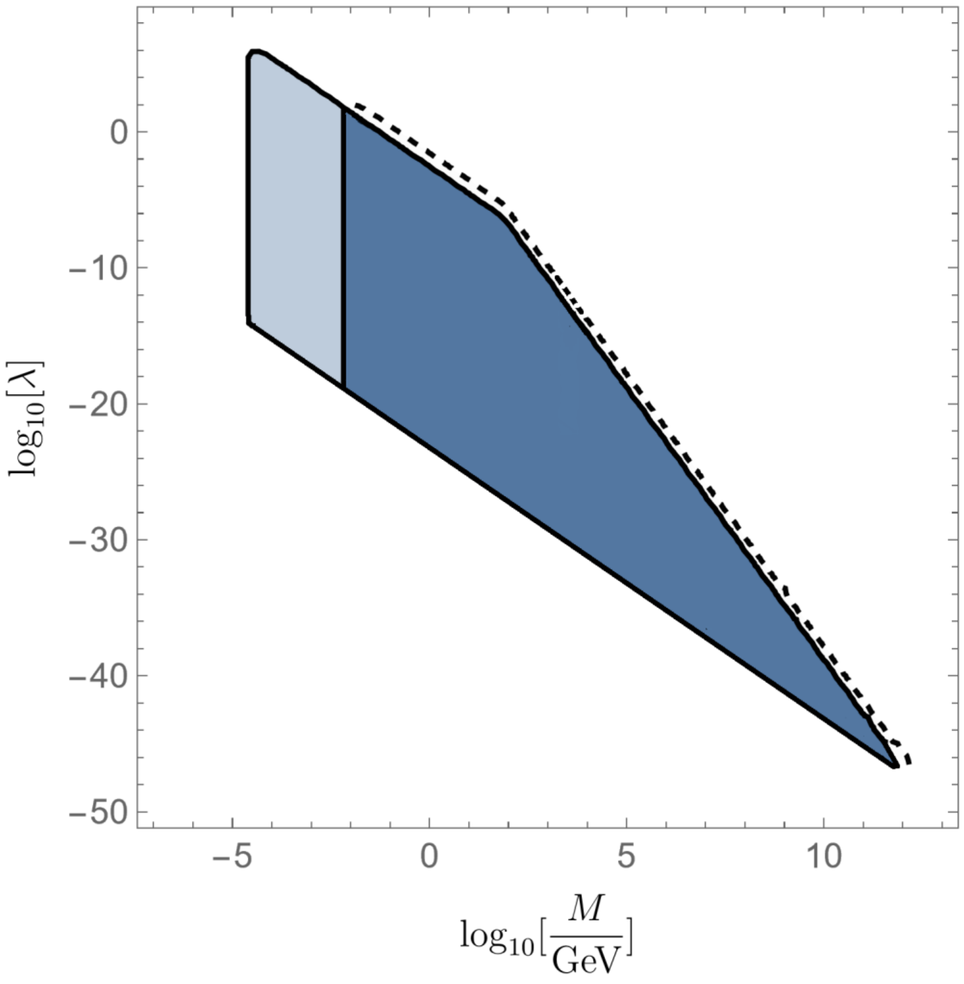


8. Burrage, Clare, and Jeremy Sakstein. "Tests of chameleon gravity." Living reviews in relativity 21 (2018): 1-58.

9. Brax, Philippe, Anne-Christine Davis, and Benjamin Elder. "Screened scalar fields in hydrogen and muonium." Physical Review D 107.4 (2023): 044008.

Future improvements

- Dashed Line: Chamber length X 10
- Light area: Better vacuum pressure
- Ideal: Tunable vacuum pressure



Further material

[I] Philippe Brax, H.F., Christian Käding, Mario Pitschmann. The environment dependent dilaton in the laboratory and the solar system. *The European Physical Journal C 82.10 (2022): 934*

[II] H.F., Christian Käding, Réne Sedmik, Harmut Abele, Philippe Brax, Mario Pitschmann. Search for environment-dependent dilatons. arXiv preprint arXiv: 2307.00243 (2023) (submitted)

[III] H.F., Christian Käding, Stephan Sponar, Hartmut Lemmel and Mario Pischmann. Search for dark energy with neutron interferometry. (to be submitted soon)

Contributiors

Theorists @ ATI:
M. Pitschmann
H. Fischer
C. Käding



Experimentalists @ ATI:
H. Abele
R. Sedmik
H. Lemmel
S. Sponar




Theorist @ Université Paris-Saclay:
P. Brax

Thank you for your attention!

Backup-slides

Recap Scalar Tensor theory

Scalar Tensor theory

The Dilaton ϕ is motivated by string theory and is defined by a Scalar Tensor theory

$$S = \int d^4x\sqrt{-g}\left(\frac{m_{pl}^2}{2}R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right) + \int d^4x\sqrt{-\tilde{g}}L_m[\tilde{g}_{\mu\nu}, \psi_i], \tag{6}$$

$$\tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}. \tag{7}$$

This generalizes the Einstein Hilbert action in two ways:

- Adding an additional degree of freedom ϕ.
- Non-minimal coupling of ϕ to the metric, by a Weyl-rescaling factor $A(\phi)$.

Physical effects in NR limit

ϕ has an effective potential ($\Box\phi = V_{\text{eff},\phi}(\phi)$)

$$V_{\text{eff}}(\phi) = V(\phi) + \rho A(\phi) \tag{8}$$

The Dilaton field causes a fifth force on point particles

$$\vec{f} = -m\vec{\nabla}\ln A(\phi) \tag{9}$$

Possible screening mechanism

In a general scalar tensor theory (with canonical kinetic term) there are two possible screening mechanisms.

Screening mechanisms

- The *Chameleon mechanism*

$$\mu_\rho = \sqrt{V_{\text{eff},\phi\phi}(\phi_\rho)}, \tag{10}$$

  large mass / short range of the Dilaton force in dense environments, where ϕ_ρ minimizes the effective potential.

- The coupling β to matter is weakened in dense environments (e.g. Symmetron field).

$$\vec{f} = -m\vec{\nabla}\ln A(\phi) = -\beta(\phi)\frac{m}{m_{pl}}\vec{\nabla}\phi \tag{11}$$

$$\beta(\phi) = \beta(\rho) = m_{pl}\frac{d\ln A}{d\phi} \tag{12}$$

Energy shifts in qBounce

The first order perturbative *energy correction* of state n

$$E_n^{(1)} = \int d^3x\, \Psi_n^{(0)*}(\vec{x},t)\, V\, \Psi_n^{(0)}(\vec{x},t)$$

After Separation into free transversal and bound vertical states this leads to a *resonance frequency shift*

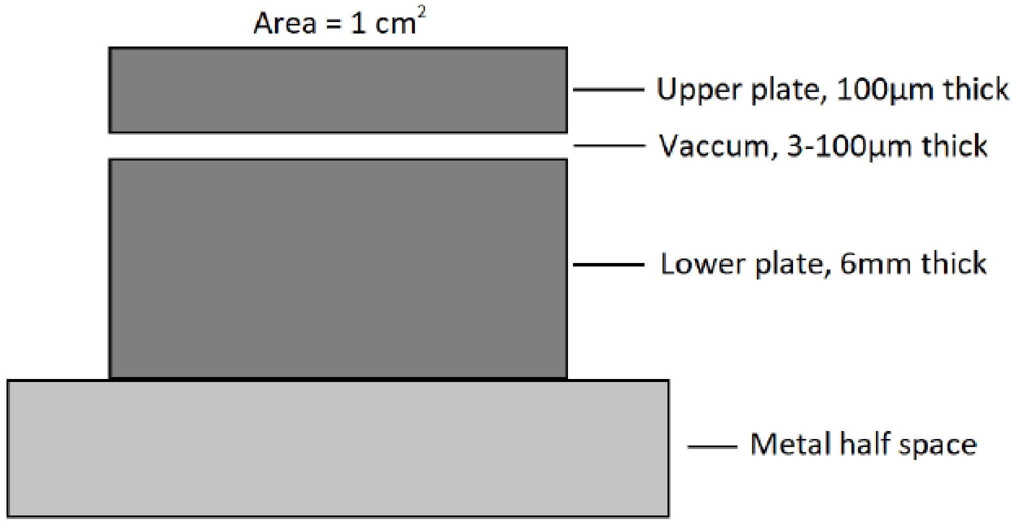
$$\begin{aligned} \delta E_{mn}^{(1)} &\equiv E_m^{(1)} - E_n^{(1)} \\ &= \frac{A_2}{2}\frac{m_N}{m_{pl}^2}\int_{-\infty}^{\infty} dz\, \left(|\psi_m^{(0)}|^2 - |\psi_n^{(0)}|^2\right)\phi(z)^2 \end{aligned}$$

and for 1-Mirror

$$\delta E_{mn}^{(1)} =$$

$$\mathfrak{Q}\frac{A_2}{2}\frac{m_N}{m_{\text{Pl}}^2}\frac{1}{z_0}\int_0^{\infty} dz\, \left(\phi_V + (\phi_0 - \phi_V)\, e^{-\mu_V z}\right)^2 \left\{\frac{\text{Ai}\left(\frac{z-z_m}{z_0}\right)^2}{\text{Ai}'\left(-\frac{z_m}{z_0}\right)^2} - \frac{\text{Ai}\left(\frac{z-z_n}{z_0}\right)^2}{\text{Ai}'\left(-\frac{z_n}{z_0}\right)^2}\right\}$$

CANNEX



CANNEX *Pressure on Slab*

$$p_z = -\rho_M \int_0^D dz\, \partial_z \ln A(\phi)$$
$$= \frac{\rho_M}{\rho_M - \rho_V}\left(V_{eff}(\phi_V, \rho_V) - (V_{eff}(\phi_0, \rho_V)\right)$$

LLR: Equivalence principle violations sun-earth-moon system

$$\delta_{\mathrm{em}} = 2\frac{|\vec{a}_{\oplus} - \vec{a}_{\leftmoon}|}{|\vec{a}_{\oplus} + \vec{a}_{\leftmoon}|} \simeq \frac{|\vec{a}_{\phi\oplus} - \vec{a}_{\phi\leftmoon}|}{|\vec{a}_G|}$$

$$\simeq \frac{\mathfrak{Q}_{\odot}|\mathfrak{Q}_{\oplus} - \mathfrak{Q}_{\leftmoon}|}{|\vec{a}_G|} \frac{A_2}{m_{\mathrm{Pl}}^2} \frac{\mu_V \mu_{\odot}^2 R_{\odot}^3}{3} \phi_V \left(\phi_V - \phi_{\odot}\right) \frac{e^{-\mu_V (r_{AU} - R_{\odot})}}{r_{AU}}$$

LLR:Precession of Lunar Perigee caused by Fifth Forces

$$\frac{\delta\Omega}{\Omega} \simeq -\frac{R^2}{GM_{\oplus}}\left(\delta f(R) + \frac{R}{2}\delta f'(R)\right)$$

$$\simeq -\mathfrak{Q}_{\oplus}\mathfrak{Q}_{\leftmoon} \frac{A_2}{m_{\mathrm{Pl}}^2} \frac{\mu_V \mu_{\oplus}^2 R_{\oplus}^3}{3} \frac{R}{GM_{\oplus}} \phi_V \left(\phi_V - \phi_{\oplus}\right) \left(1 - \frac{\mu_V R}{2}\right) e^{-\mu_V (R - R_{\oplus})}$$

Derivation of the three parameter regions, the screening mechanisms and the parameter symmetry

In this section, we describe the three regions of the parameter space obtained by varying the magnitude of λ. Increasing λ while keeping the other parameters fixed eventually leads to

$$\frac{\lambda^2 V_0}{\Lambda_2 \rho} \gg 1 \,. \tag{1}$$

Using $W(x) \simeq \ln(x) - \ln(\ln(x))$ for large x we can approximate

$$\phi_\rho \simeq \frac{m_{\rm pl}}{\lambda} \left\{ \ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right) - \ln\left[\ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right)\right] \right\}, \tag{2}$$

which shows that

$$e^{-\lambda\phi_\rho/m_{\rm pl}} \simeq \ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right) \Big/ \left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right) \ll 1 \,. \tag{3}$$

The mass μ_ρ of the dilaton is given by [1]

$$\mu_\rho = \frac{1}{m_{\rm pl}} \sqrt{\lambda^2 V_0 \, e^{-\lambda\phi_\rho/m_{\rm pl}} + \Lambda_2 \rho} \simeq \frac{\sqrt{\Lambda_2 \rho}}{m_{\rm pl}} \sqrt{1 + \ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right)} \simeq \frac{1}{m_{\rm pl}} \sqrt{\Lambda_2 \rho \, \ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right)} \,. \tag{4}$$

Then, the full coupling to matter is approximately

$$\beta(\phi_\rho) = \frac{\Lambda_2 \phi_\rho}{m_{\rm pl}} \simeq \frac{\Lambda_2}{\lambda} \left\{ \ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right) - \ln\left[\ln\left(\frac{\lambda^2 V_0}{\Lambda_2 \rho}\right)\right] \right\}. \tag{5}$$

Since ρ effects $\beta(\phi_\rho)$ only logarithmically (as long as Eq. (1) holds), while the mass has a square root dependence, increasing the density primarily leads to an increase in the mass of the field but only a negligible decrease of $\beta(\phi_\rho)$.

Decreasing λ inside this region increases ϕ_ρ according to Eq. (2), which eventually leads to a violation of the condition $\Lambda_2\phi^2/(2m_{\rm pl}^2) \ll 1$. Eventually, however, λ gets small enough such that $\lambda^2 V_0/(\Lambda_2\rho) \ll 1$ holds. Hence, using $W(x) \simeq x$ for small x, we obtain in this second region

$$\phi_\rho \simeq m_{\rm pl}\,\frac{\lambda V_0}{\Lambda_2\rho}\,, \tag{6}$$

$$e^{-\lambda\phi_\rho/m_{\rm pl}} \simeq e^{-\frac{\lambda^2 V_0}{\Lambda_2\rho}} \simeq 1\,, \tag{7}$$

$$\mu_\rho \simeq \frac{\sqrt{\Lambda_2\rho}}{m_{\rm pl}}\,, \tag{8}$$

$$\beta(\phi_\rho) \simeq \frac{\lambda V_0}{\rho}\,. \tag{9}$$

Decreasing λ inside this second region decreases ϕ_ρ (in contrast to the behaviour in the first region) and hence the condition $\Lambda_2\phi^2/(2m_{\rm pl}^2) \ll 1$ is eventually fulfilled again. Inside this parameter region, $\beta(\phi_\rho)$ decreases considerably by increasing ρ. Finally, since

$$V_{\rm eff}(\phi) = V_0\,e^{-\lambda\phi/m_{\rm pl}} + \frac{\Lambda_2\rho}{2m_{\rm pl}^2}\,\phi^2 \simeq V_0 - \lambda V_0\,\frac{\phi}{m_{\rm pl}} + \frac{\Lambda_2\rho}{2m_{\rm pl}^2}\,\phi^2\,, \tag{10}$$

only the product of λV_0 enters the equations of motion, which explains the parameter symmetry that was observed also numerically, i.e. changing the parameters λ and V_0 whilst keeping their product λV_0 fixed preserves the constraints on the parameter space for small enough λ.

$$\Delta\varphi = -\frac{1}{2\pi} m_N \lambda \int U(x)dx = -\frac{m_N}{k_0} \int U(x)dx, \quad \text{(B8)}$$

$$k_0 = \frac{2\pi}{\lambda}. \quad \text{(B9)}$$