Probing the Dark Sector with Ultracold Neutrons/*qBounce*

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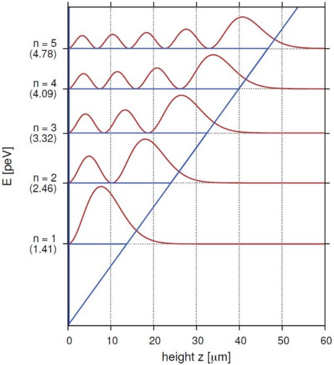


Ultracold Neutrons/*qBounce*

Ultracold Neutrons [1]

Neutron

- no *electric charge*: $q = (-0.2 \pm 0.8) \times 10^{-21} e$
- small *polarizability*: $\alpha = (11.8 \pm 1.1) \times 10^{-4}$ fm^3 ($\propto 10^{-19} \alpha_{\text{atom}}$)
- small *EDM*: $d_n < 0.29 \times 10^{-25} e$ cm
- "ultralong" *mean life*: $\tau = 880.3 \pm 1.1$ s

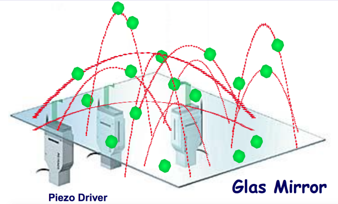
Ultracold Neutrons (UCNs)

- are "slow enough" to be reflected from surfaces at all angles of incident

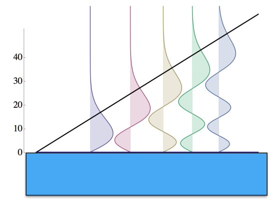
	Fission neutrons	Thermal neutrons	Cold neutrons	Ultracold neutrons	Gravity experiment
Energy	2 MeV	25 meV	3 meV	<100 neV	1.4 peV ($E_\perp$)
Temperature	10^{10} K	300 K	40 K	~1 mK	–
Velocity	10^7 m/s	2200 m/s	800 m/s	~5 m/s	$v_\perp \sim 2$ cm/s
Wavelength		0.18 nm	0.5 nm	~80 nm	

[1] H. Abele, Progress in Particle and Nuclear Physics 60 (2008) 1.

- *Classical limit*



- *Quantum regime*



- Low-energy neutron-nucleon scattering

Fermi pseudo-potential

$$V(\vec{r}) = \sum_i \frac{2\pi\hbar^2}{m} a\,\delta^{(3)}(\vec{r} - \vec{r}_i)$$

- Since $\lambda_n \gg d_A$

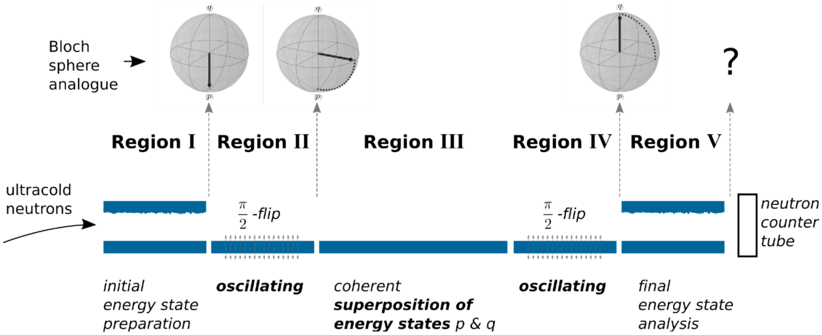
$$V \simeq \frac{1}{L^3} \int d^3x\, V(\vec{r}) = \frac{2\pi\hbar^2}{m} Na$$

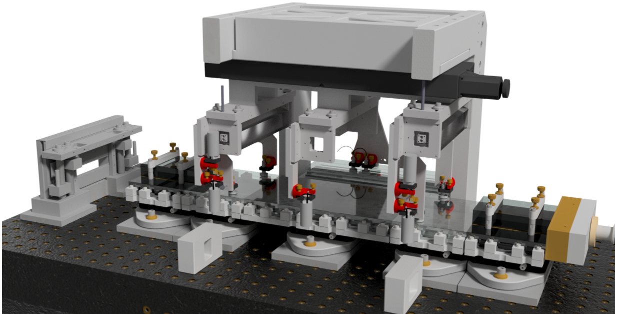
- Total reflection for neutron energy

$E_n < V$

Material	V $[neV]$	v_c $[m/s]$
Diamond	304	7.65
BeO	261	6.99
Beryllium	252	6.89
Nickel	252	6.84
Sitall glass	125	~ 5

[2] V.I. Luschikov and A.I. Frank, JETP Lett. 28 (1978) 559.; V. Nesvizhevsky *et al.*, Nature, 415 (2002) 297.; Ignatovich V. K., Ultracold Neutrons, Clarendon Press, Oxford, 1990.; Duesing C., Diploma Thesis, Uni Mainz 2010.


Bloch
sphere
analogue
?
Region I
Region II
Region III
Region IV
Region V
ultracold
neutrons
$\frac{\pi}{2}$ -flip
$\frac{\pi}{2}$ -flip
neutron
counter
tube
initial
energy state
preparation
oscillating
coherent
superposition of
energy states p & q
oscillating
final
energy state
analysis



Axions in a Nutshell...

Axions [3]

$$\mathcal{L} = \theta \, \frac{g_s^2}{32\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$$

- Only CP violating *dim 4 operator* in SM: $CP(\vec{E}_G \cdot \vec{B}_G) = -\vec{E}_G \cdot \vec{B}_G$
- *No suppression* by heavy scale $\Lambda \;\Rightarrow$ Large neutron EDM (*strong CP problem*)
- *Total derivative term* ($\Rightarrow$ no Feynman diagrams)

$$Z[J] = \int \mathcal{D}\psi \mathcal{D}\bar{\psi} \, e^{i \int d^4x \, \theta \, \frac{g_s^2}{32\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}} \ldots$$

Physics must be invariant under transformation of *dummy integration variables* ψ, $\bar{\psi}$

$$\psi \to e^{-i\alpha\gamma^5} \psi \quad , \quad \bar{\psi} \to \bar{\psi} \, e^{-i\alpha\gamma^5}$$

$$\mathcal{D}\psi \mathcal{D}\bar{\psi} \to \mathcal{D}\psi \mathcal{D}\bar{\psi} \, e^{i \int d^4x \, \frac{g_s^2 \alpha}{16\pi^2} \, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}}$$

$$\theta \to \theta + 2\alpha$$

[3] S. Mantry, M. P., M. J. Ramsey-Musolf, Phys. Rev. D90 (2014), 054016.

Axions

$U(1)_A$ Transformation of Lagrangian ($N_f = 1$)

$$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi$$

$$\downarrow \quad U(1)_A$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \cos\theta \, \bar{\psi}\psi + m \sin\theta \, \bar{\psi} i\gamma^5 \psi$$

$$\downarrow \quad \mathcal{O}(\theta)$$

$$\mathcal{L} = \bar{\psi} i \not{D} \psi - m \bar{\psi}\psi + m \theta \, \bar{\psi} i\gamma^5 \psi$$

Physical Consequences

- For *vanishing quark mass* θ-term can be rotated away and becomes *unphysical*
- *Physical (invariant) quantity* : $\bar{\theta} = \theta + \arg\det m$
- *Strong CP problem* : Why is $\bar{\theta}$ so small?

Axions

Consider adding to the SM a *complex scalar field* Φ and *massless quark* Ψ with *Yukawa coupling* y

$$\mathcal{L}_{PQ} = \partial_\mu \Phi^\dagger \partial^\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 + \bar{\Psi} i \not{D} \Psi + y \, \Phi \, \bar{\Psi}_R \Psi_L + h.c.$$

$\mathcal{L}_{SM} + \mathcal{L}_{PQ}$ *invariant* under *global chiral* $U(1)_{PQ}$ *Peccei-Quinn transformation*

$$\Psi \rightarrow e^{-i\alpha\gamma^5} \Psi, \quad \bar{\Psi} \rightarrow \bar{\Psi} \, e^{-i\alpha\gamma^5}, \quad \Phi \rightarrow e^{-2i\alpha} \, \Phi$$

Spontaneous breaking of $U(1)_{PQ}$ leads to *massless pseudo-scalar goldstone boson* – the *axion* $\mathrm{a}(x)$

$$\Phi(x) = \frac{f_a + \rho(x)}{\sqrt{2}} \, e^{i\mathrm{a}(x)/f_a}$$

Peccei-Quinn Transformation leads to

$$\bar{\theta} \rightarrow \bar{\theta} + 2\alpha \quad \& \quad \frac{\mathrm{a}(x)}{f_a} \rightarrow \frac{\mathrm{a}(x)}{f_a} - 2\alpha$$

Axions

At low energies $\rho(x)$ and Ψ are integrated out

– only the *Standard Model* & *axion* $\mathrm{a}(x)$ are the remaining d.o.f.

The *physical (invariant) quantity* becomes: $\bar{\theta} + \frac{\mathrm{a}(x)}{f_a}$

$U(1)_A$ *Transformation of Lagrangian* $(N_f = 1)$

$$\mathcal{L} = \left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right)\frac{g_s^2}{32\pi^2}\tilde{G}^a_{\mu\nu}G^{a\mu\nu} + \bar{\psi}i\not{D}\psi - m\,\bar{\psi}\psi$$

$$\downarrow \quad {\scriptstyle U(1)_A}$$

$$\mathcal{L} = \bar{\psi}i\not{D}\psi - m\cos\left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right)\bar{\psi}\psi + m\sin\left(\bar{\theta}_{ind} + \frac{a(x)}{f_a}\right)\bar{\psi}\,i\gamma^5\psi$$

$$\downarrow$$

$$\mathcal{L} = \bar{\psi}i\not{D}\psi - m\,\bar{\psi}\psi + \frac{m\,\bar{\theta}^2_{ind}}{2}\bar{\psi}\psi + \frac{m}{2f_a^2}a^2\bar{\psi}\psi + m\,\bar{\theta}_{ind}\,\bar{\psi}\,i\gamma^5\psi$$

$$+\underbrace{\frac{m\,\bar{\theta}_{ind}}{f_a}}_{g_s^q}a\bar{\psi}\psi + \underbrace{\frac{m}{f_a}}_{g_p^q}a\bar{\psi}\,i\gamma^5\psi + \dots$$

Axions

Leading source of EDM

$$\mathcal{L} = m\,\bar{\theta}_{ind}\,\bar{\psi}\,i\gamma^5\psi$$

induces *CP violating propagator correction*

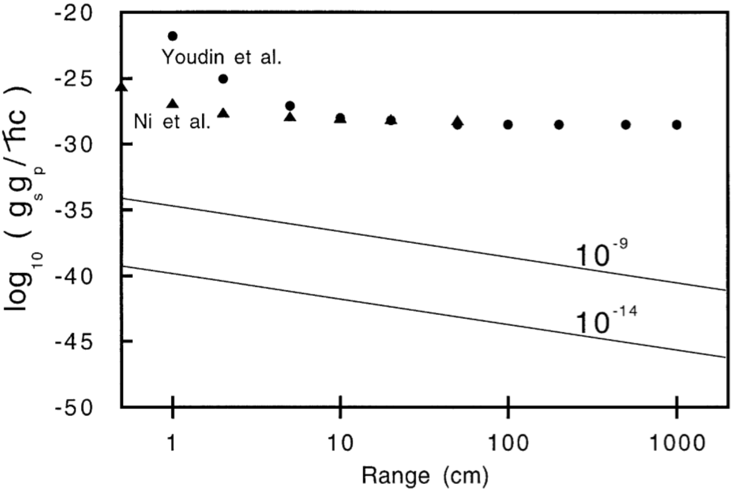
$$\frac{i}{\not{k} - m} \rightarrow \frac{i}{\not{k} - m} + \frac{im}{k^2 + m^2}\,\bar{\theta}_{ind}\,i\gamma^5$$

Sub-leading source of EDM by "one axion-exchange"

$$g_s^q = \frac{m\,\bar{\theta}_{ind}}{f_a} \qquad \& \qquad g_p^q = \frac{m}{f_a}$$

induces $axion\ mediated\ "fifth - force"$

This implies that *EDM measurements* put bounds on $\bar{\theta}_{ind}$ and thus on g_s^q



$$g_s^q g_p^q = \frac{m^2\, \bar{\theta}_{ind}}{f_a^2} \propto \frac{\bar{\theta}_{ind}}{\lambda^2}$$

Axion-like Particles (ALPs)

ALPs

If we do not consider only *Peccei-Quinn* then g_s, g_s and m_φ are a priori *free parameters* without a relation to the QCD θ-term

(Pseudo-)scalar Vertices

$$\mathcal{L} = g_s\,\varphi\,\bar{\psi}\psi$$
$$\mathcal{L} = g_p\,\varphi\,\bar{\psi}\,i\gamma^5\,\psi$$

The *scattering amplitudes*

$$\mathcal{M} = -g_s g_p\,\bar{u}_m(k')u_m(k)\,\frac{1}{q^2 - m_\varphi^2}\,\bar{u}_n(p')\,i\gamma^5 u_n(p)$$
$$\downarrow \quad \textit{non-relativistic limit}$$
$$-g_s g_p\,2m_n\,\frac{1}{\vec{q}^{\,2} + m_\varphi^2}\,i\,\vec{\sigma}_n\cdot\vec{q}$$

lead to the *potential* via a *Fourier transformation*

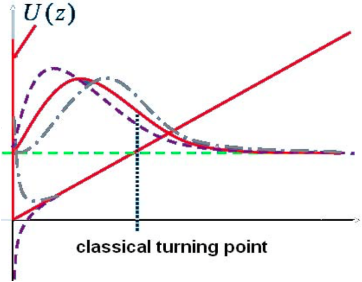
$$\delta V(r) = g_s g_p\,\frac{\vec{\sigma}_n\cdot\vec{e}_r}{8\pi m_n}\left(\frac{m_\varphi}{r} + \frac{1}{r^2}\right)e^{-m_\varphi r}$$

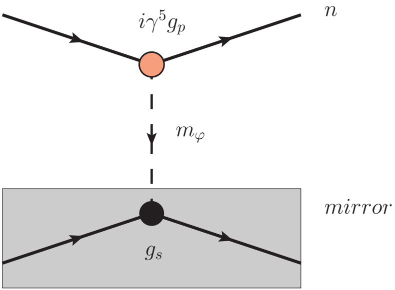
ALPs

ALP Potential

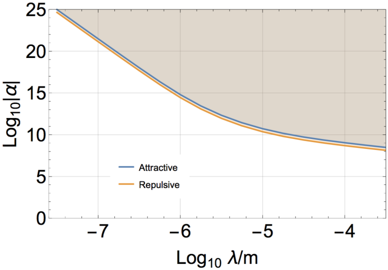
$$\delta V(r) = g_s g_p \frac{\vec{\sigma}_n \cdot \vec{e}_r}{8\pi m_n} \left(\frac{m_\varphi}{r} + \frac{1}{r^2} \right) e^{-m_\varphi r}$$

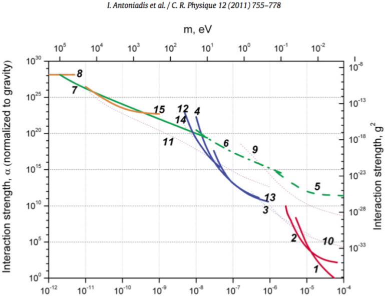
- (*Yukawa*) *force* deforms *wavefunction*: $\psi(z) \rightarrow \psi(z) + \delta\psi(z; \sigma_n)$
- Changes the *energy*
- from the *3 possible exchanges* $g_s g_s$, $g_s g_p$ & $g_p g_p$ only $g_s g_p$ violates P and T (and hence CP if CPT holds)

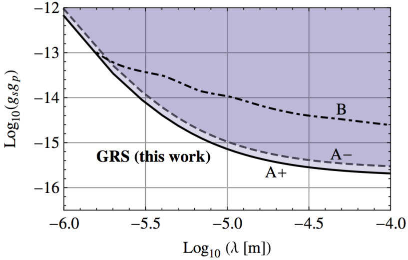


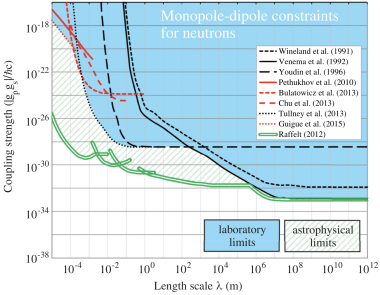


ALPs [4]









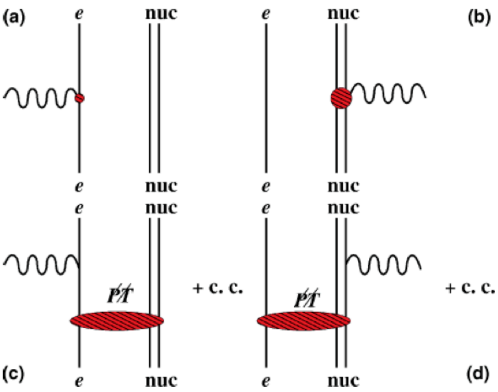
[4] G. Cronenberg *et al.*, PoS, EPS-HEP2015 (2015) 408.; T. Jenke *et al.*, Phys. Rev. Lett., 112 (2014) 151105.; M. S. Safronova *et al.*, Rev. Mod. Phys., 90 (2018) 025008.

^{199}Hg – Electric Dipole Moment

In following analysis we assume the ALP to couple to *quarks* (and hence π and N)

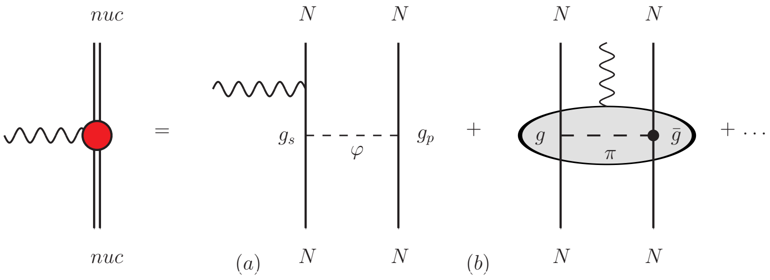
Coupling to *lepton* and *photons* is neglected ($\sim$ *axion*)

Non-vanishing contribution only from (b)



^{199}Hg – Electric Dipole Moment

Nucleus–EDM Contributions



(a) *Leading Contribution*

Direct scalar exchange – no nuclear calculation available

(b) *Sub-leading Contribution*

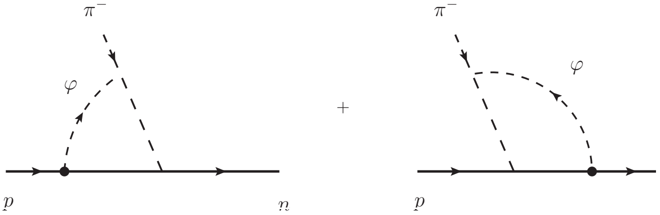
CPV π-exchange – "loop-suppressed" ($\sim$ 2 orders of magnitude)

– nuclear calculation available

$CPV\ \bar{N}N\pi$ – Vertex

Two contributions to a $CPV\ \bar{N}N\pi$ – vertex are *leading and not suppressed*

ALP coupling g_s^π at π, g_p at N

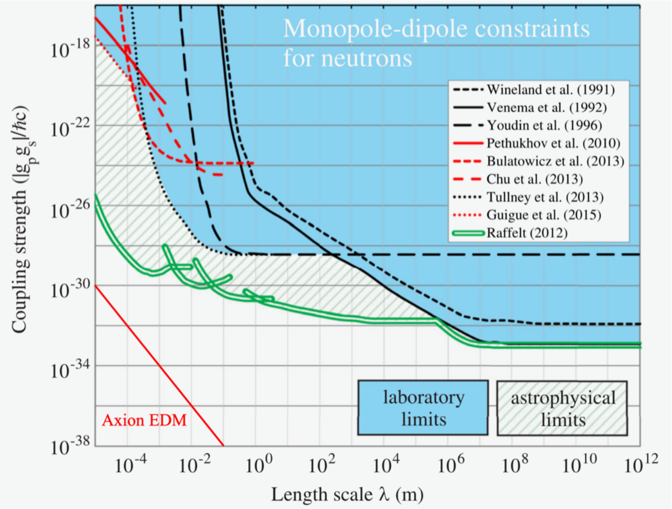


Diagrams evaluated with *Heavy Baryon* χ*PT* in the limit $q^2 \to 0$

$$\mathcal{L}_{\pi\bar{N}N}^{CPV} = \frac{1}{16\pi} \frac{m_\pi^2 + m_\pi m_\varphi + m_\varphi^2}{m_\pi + m_\varphi} \frac{g_s^\pi g_p g_A}{m_N f_\pi} \pi^a \bar{N} \sigma^a N$$

$$\simeq \frac{g_s^\pi g_p}{16\pi} \frac{m_\pi g_A}{m_N f_\pi} \pi^a \bar{N} \sigma^a N \quad \text{for} \quad m_\varphi \ll m_\pi$$

EDM



[5] M. S. Safronova *et al.*, Rev. Mod. Phys., 90 (2018) 025008.

Symmetrons

Symmetron

- "Invented" by *K. Hinterbichler & J. Khoury* in 2010[a]
- based on *Spontanous Symmetry Breaking* similar to the *Higgs mechanism* but with a real scalar field ϕ

[a] PRL **104**, 231301 (2010)

Definition

$$\mathcal{V}_{\text{eff}}[\phi] = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4}\phi^4$$

1. "mass parameter" $\mu > 0$ with dimension energy
2. $\lambda > 0$ dimensionless
3. coupling to matter $M > 0$ with dimension energy

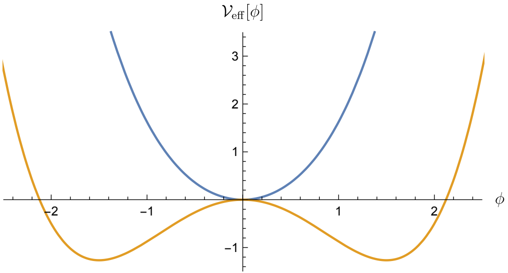
Equations of Motion

$$\Box\phi + \left(\frac{\rho}{M^2} - \mu^2\right)\phi + \lambda\,\phi^3 = 0$$

Symmetron

Effective Potential

$$\mathcal{V}_{\text{eff}}[\phi] = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4}\phi^4$$



2 Phases

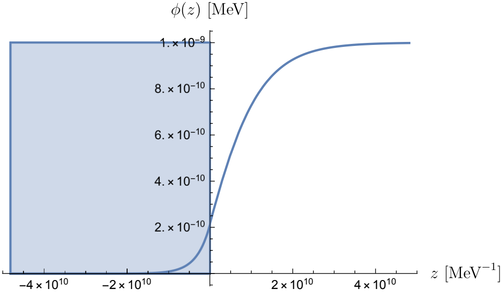
1. *Spontanous Symmetry Breaking*: $\frac{\rho}{M^2} < \mu^2$ (*"vacuum value"* $\phi_V = \pm\frac{\mu_{\text{eff}}}{\sqrt{\lambda}}$)
2. *Symmetric Phase*: $\frac{\rho}{M^2} \geq \mu^2$ *"dense matter"*

Symmetron

1-Mirror at $z \leq 0$

$$\frac{\rho_{\text{eff}}}{M^2} = \frac{\rho_M}{M^2} - \mu^2 \qquad \text{inside the } \textit{mirror}$$

$$\mu_{\text{eff}}^2 = \mu^2 - \frac{\rho_V}{M^2} \qquad \text{in } \textit{vacuum}$$



$$\lambda = 10^{-2}$$

$$\mu_{\text{eff}} = 10^{-10}\ \text{MeV}$$

$$M = 10^{7}\ \text{MeV}$$

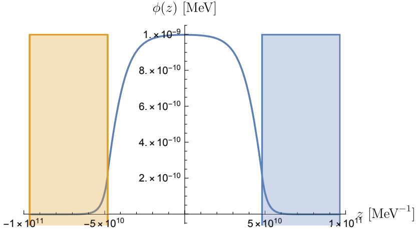
$$k = 0.215$$

$$\rho_M = 1.082 \times 10^{-5}\ \text{MeV}^4$$

$$\rho_{\text{eff}} = 9.820 \times 10^{-6}\ \text{MeV}^4$$

Symmetron

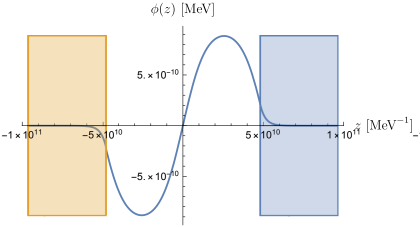
2-Mirrors at $|z| \geq d$: "*Ground State*"

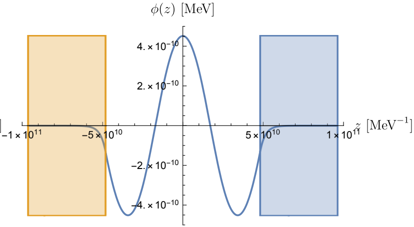


$$\frac{\rho_{\text{eff}}}{M^2} = \frac{\rho_M}{M^2} - \mu^2 \qquad \textit{mirror}$$

$$\mu_{\text{eff}}^2 = \mu^2 - \frac{\rho_V}{M^2} \qquad \textit{vacuum}$$

2-Mirrors at $|z| \geq d$: "*Excited Modes*"





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Symmetron

Effective Potential

$$\mathcal{V}_{\text{eff}}[\phi] = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{\lambda}{4}\phi^4$$

allows to read off the coupling to neutrons, *viz*. the

Schroedinger Potential

$$\mathrm{V} = \frac{m_N}{2M^2}\phi^2$$

This assumes the neutron with mass m_N as a source of the symmetron field is distributed *semi-classically*

$$\rho = m_N\,\psi^*\psi$$

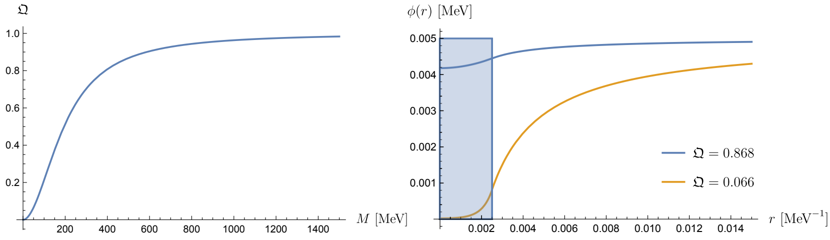
and leads to a *resonance frequency shift*

$$\Delta E_{mn}^{(1)} \equiv \delta E_m^{(1)} - \delta E_n^{(1)} = \frac{1}{2}\frac{m_N}{M^2}\int_{-\infty}^{\infty} dz\left(\left|\psi_m^{(0)}(z)\right|^2 - \left|\psi_n^{(0)}(z)\right|^2\right)\phi(z)^2$$

Symmetron

"Screening Charge"

$$\mathfrak{Q}(\mu, M) \to \begin{cases} 0 & \text{for } \textit{screened} \text{ bodies} \\ 1 & \text{for } \textit{unscreened} \text{ bodies} \end{cases} \implies \delta E_{mn}^{(1)} \to \mathfrak{Q}(\mu, M)\, \delta E_{mn}^{(1)}$$

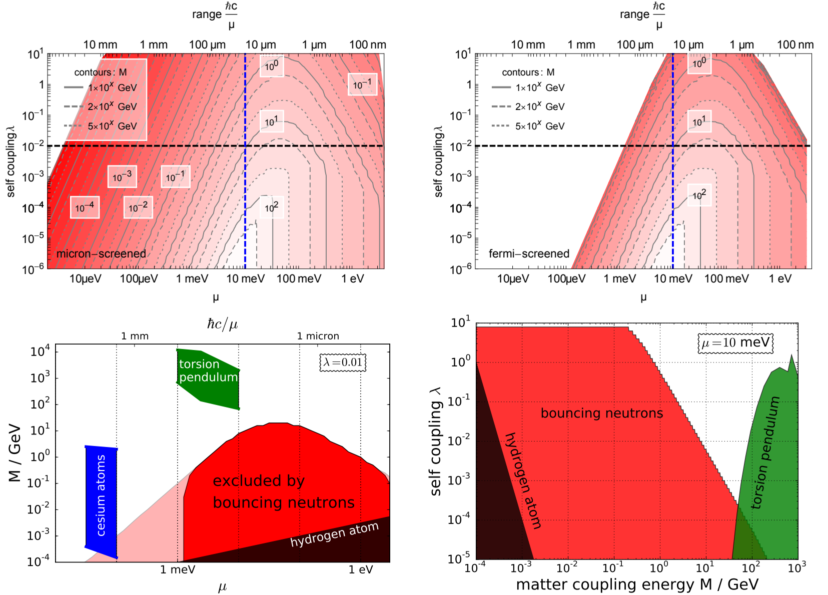


Induced Acceleration on Small Test Body

$$\vec{a} = -\frac{\phi}{M^2}\,\vec{\nabla}\phi$$

$$\underbrace{\to}_{r\to\infty} -\mathfrak{Q}(\mu, M)\,\phi_V^2\,\frac{\rho R^3}{3M^4}\,\frac{\sqrt{2}\mu}{1+\sqrt{2}\mu R}\,\frac{e^{-\sqrt{2}\mu r}}{r}\,\frac{\vec{r}}{r}$$

Symmetron [6]

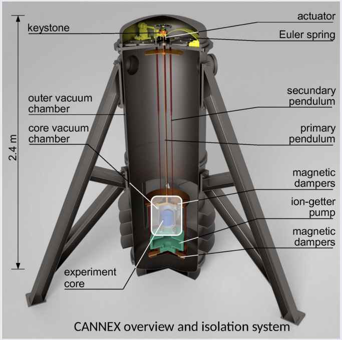


[6] P. Brax, M.P., Phys. Rev. D 97 (2018) 064015.; G. Cronenberg, P. Brax, H. Filter, P. Geltenbort, T. Jenke, G. Pignol, M. P., M. Thalhammer & H. Abele, Nature Physics 14 (2018) 1022.

Collaboration

Outlook

- *Refined Analysis* of *Dark Energy Models*
- René Sedmik: *CANNEX* & *Lunar Laser Ranging*



CANNEX overview and isolation system

- *Equivalence Principle Tests*
- *Torsion*
- . . .

Collaboration

The results, expounded in this talk, were obtained in Collaboration with

- *Hartmut Abele* – TU Wien
- *Michael J. Ramsey-Musolf* – SJTU & Caltech
- *Craig D. Roberts* – ANL
- *Philippe Brax* – CNRS
- *Sonny Mantry* – University of North Georgia
- *Tobias Jenke* – ILL
- *Gunther Cronenberg* – TU Wien
- *Guillaume Pignol* – LPSC
- *Hanno Filter* – TU München
- *Martin Thalhammer* – TU Wien

Thank You For Your Attention!