Potential of the neutron Lloyd's mirror interferometer to search for new fundamental interactions

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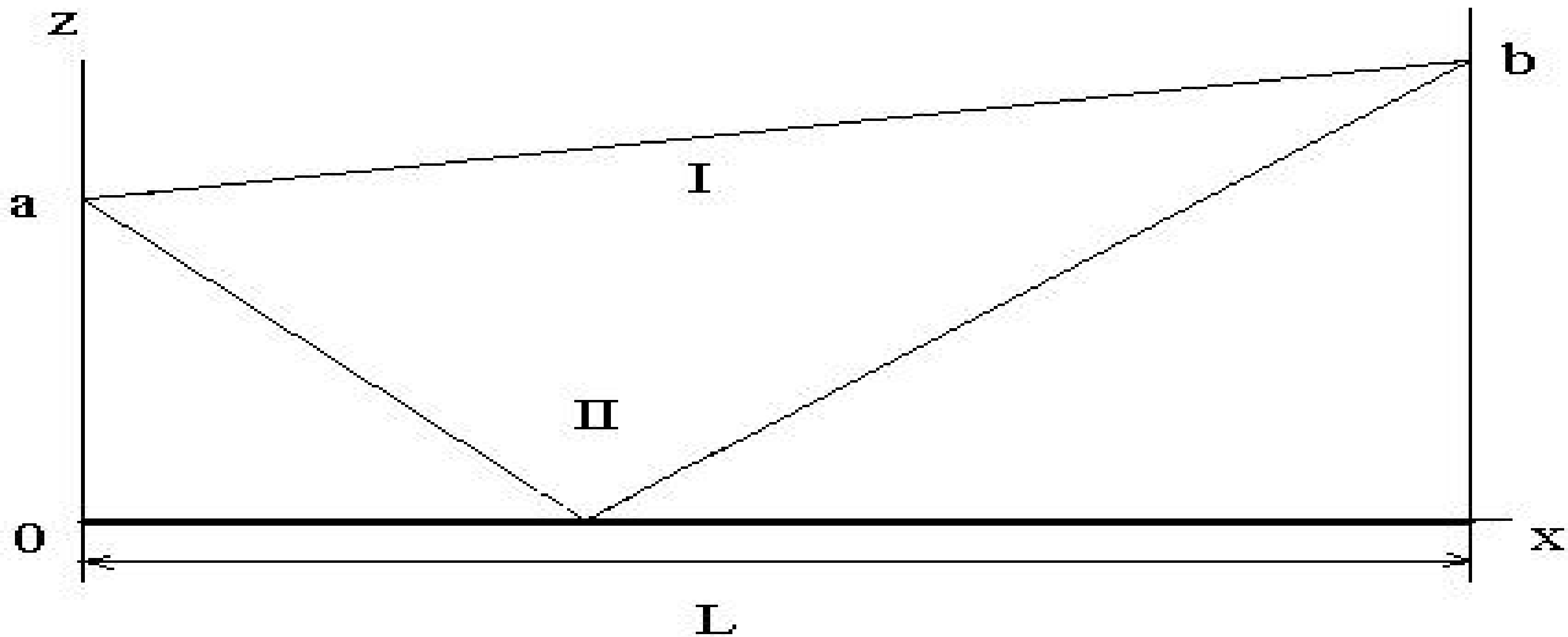
Lloyd’s mirror interferometer



period of oscillations $d = \lambda_n L/(2a)$

Possible applications:

Chameleon scalar fields

Axion-like short-range interactions

Non-Newtonian gravity

New scalar field is the cause of the accelerated expansion:
B. Ratra and P.J.E. Peebles, Phys. Rev. D37 (1988) 3406
Idea of the chameleon fields in cosmology:
J. Khoury and A . Weltman,
Phys. Rev. Lett. 93 (2004) 171104;
Phys. Rev. D69 (2004) 044026

$$\hbar H_0/c^2 = 10^{-33}\, eV/c^2$$

$$V_{eff}(\phi) = V(\phi) + e^{\beta\phi/M_{Pl}}\rho,$$

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

P. Brax, P. Pignol, Phys. Rev. Lett. 107 (2011) 111301
Chameleon induced potential of a neutron
in vicinity of bulk matter

$$V(z) = \beta \frac{m}{M_{Pl}\lambda}\left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)}\left(\frac{z}{\lambda}\right)^{2/(2+n)} =$$

$$\beta \cdot 0.9 \cdot 10^{-21}\, eV\left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)}\left(\frac{z}{\lambda}\right)^{2/(2+n)} = V_0\left(\frac{z}{\lambda}\right)^{2/(2+n)};$$

$$V_0 = \beta \cdot 0.9 \cdot 10^{-9}\, peV\left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)}$$

$$k'^2 = k^2 - \frac{2mV}{\hbar^2}; \qquad k' = k - \frac{mV}{k\hbar^2}$$

$$\varphi = \oint k' ds = \varphi_{II} - \varphi_I$$

- Chameleon induced phase shift

$$\varphi_{cham} = \varphi_{II,cham} - \varphi_{I,cham} = \frac{\gamma}{\lambda^{\alpha_n - 1}\alpha_n} 2ab \frac{b^{\alpha_n - 1} - a^{\alpha_n - 1}}{b^2 - a^2}$$

$$\gamma = (mV_0 L)/(k\hbar^2)$$

The Earth gravitation phase shift

$$\varphi_{gr} = \varphi_{II,gr} - \varphi_{I,gr} \approx \frac{cgm^2}{k\hbar^2}\frac{abL}{a+b}$$

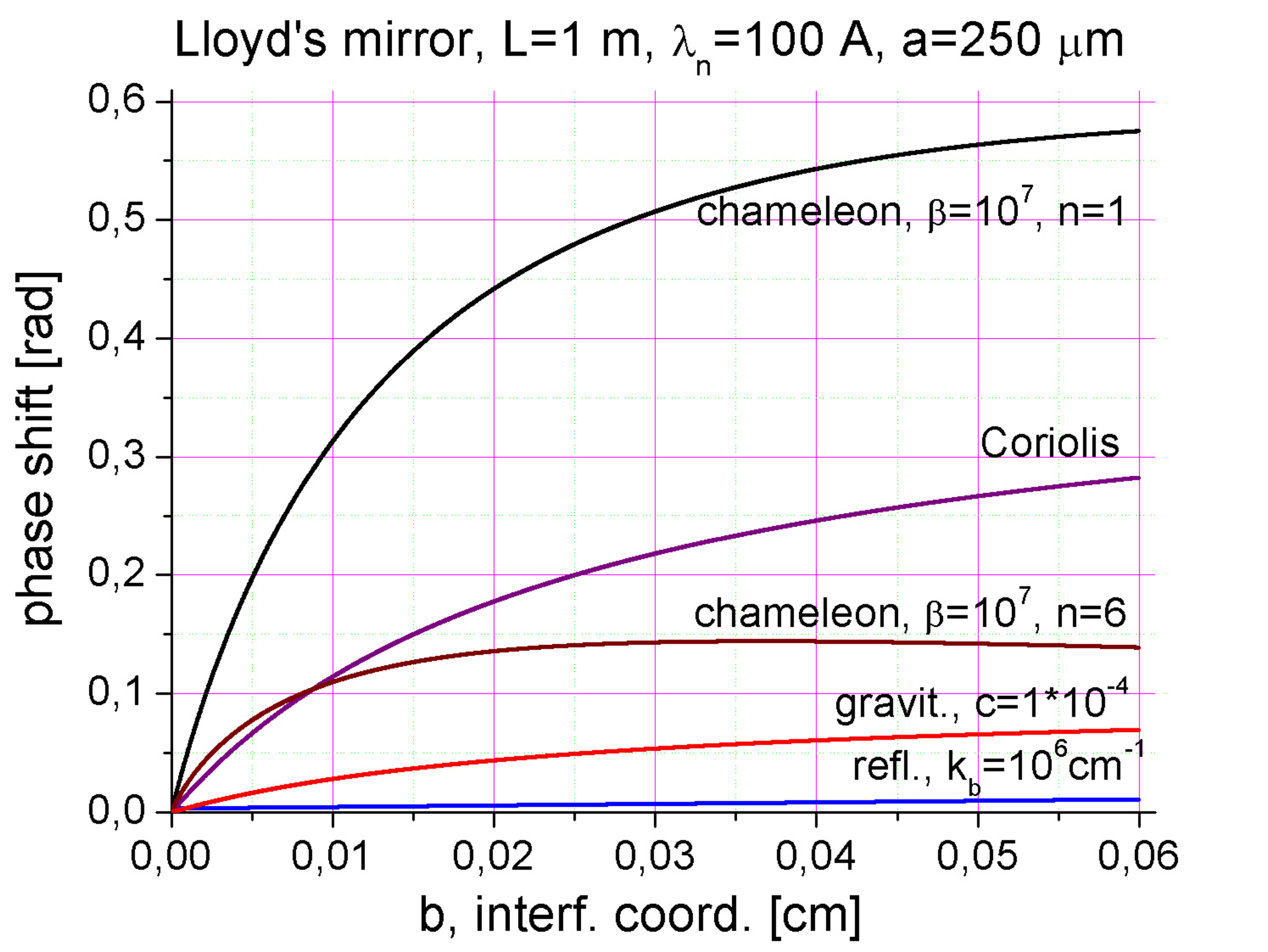
- The Coriolis phase shift

$$\varphi_{Cor} = \frac{2m}{\hbar}(\Omega A) = 0.16(abL)/(2(a+b))\,\mathrm{rad}$$

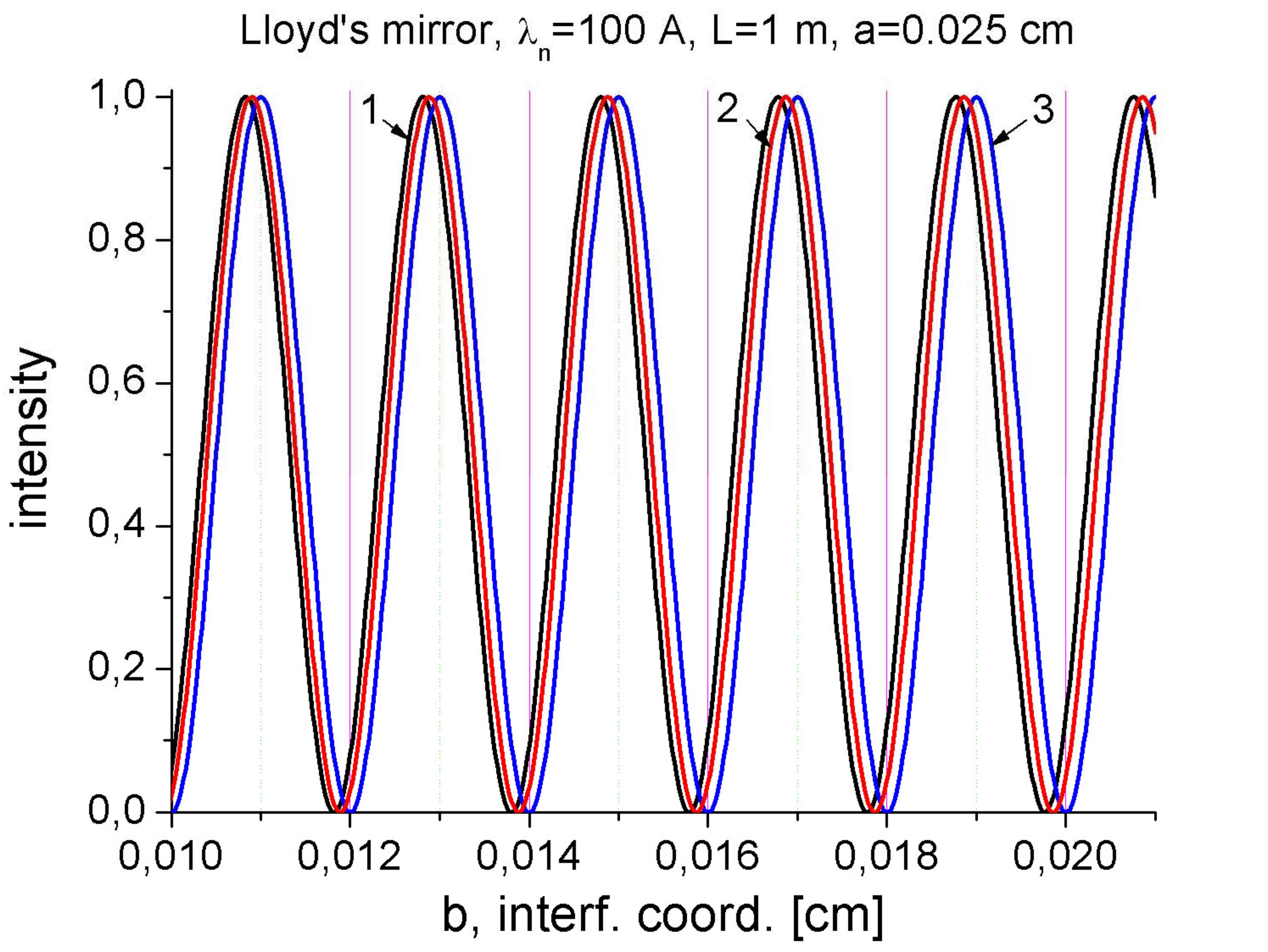
reflection phase shift

$$r = e^{-i\varphi_{refl}}$$

$$\varphi_{refl} = 2\arccos(k_{norm}/k_b) \approx \pi - 2\frac{k}{k_b}\frac{a+b}{L}$$

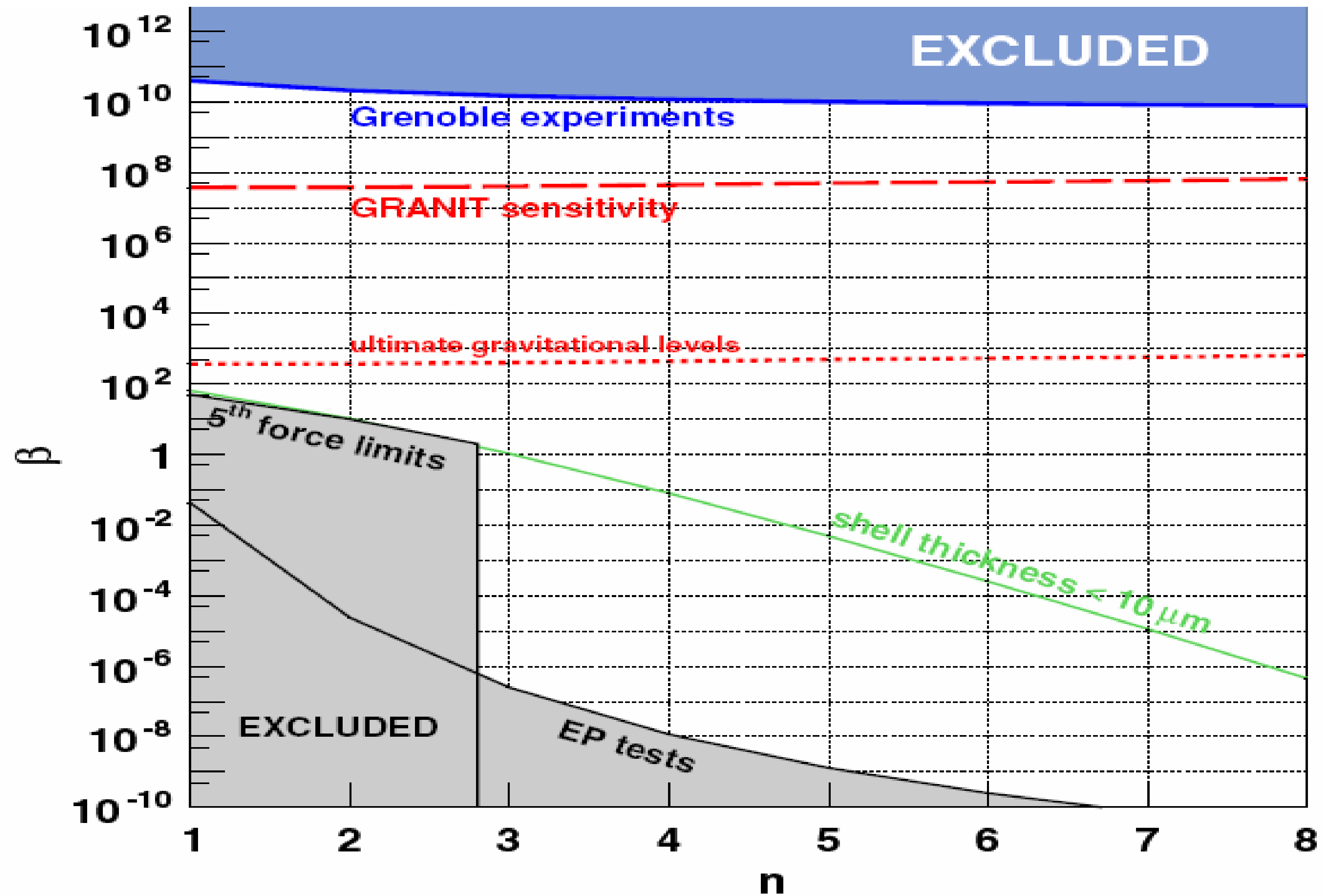


Lloyd's mirror, L=1 m, λn=100 A, a=250 μm
phase shift [rad]
0,0
0,1
0,2
0,3
0,4
0,5
0,6
chameleon, β=10^7, n=1
Coriolis
chameleon, β=10^7, n=6
gravit., c=1*10^-4
refl., kb=10^6cm^-1
0,00
0,01
0,02
0,03
0,04
0,05
0,06
b, interf. coord. [cm]



Lloyd's mirror, λ_n=100 A, L=1 m, a=0.025 cm
intensity
1,0
0,8
0,6
0,4
0,2
0,0
1
2
3
0,010
0,012
0,014
0,016
0,018
0,020
b, interf. coord. [cm]

Constraints on the chameleon-matter interaction strength from P. Brax, G. Pignol, Phys. Rev. Lett. 107 (2011)111301

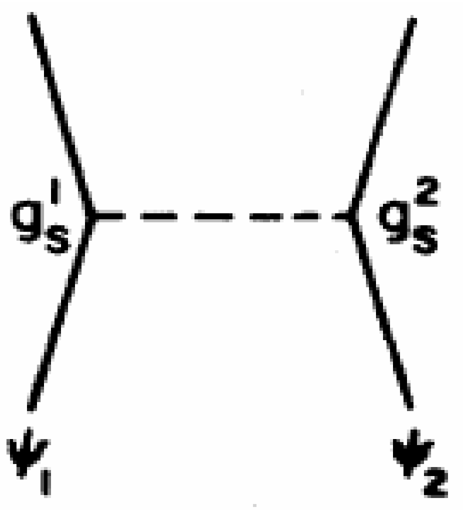


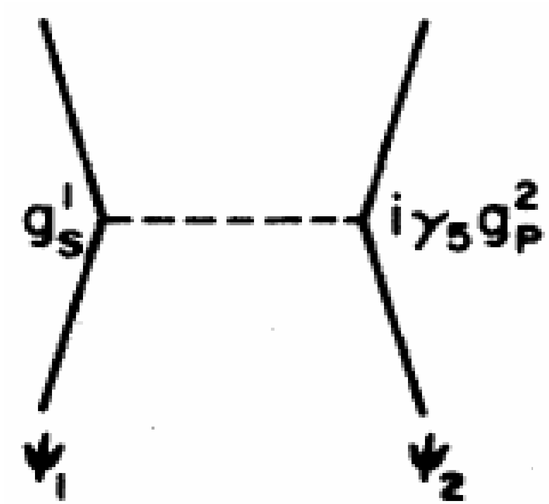
Axion and axion-like interactions:

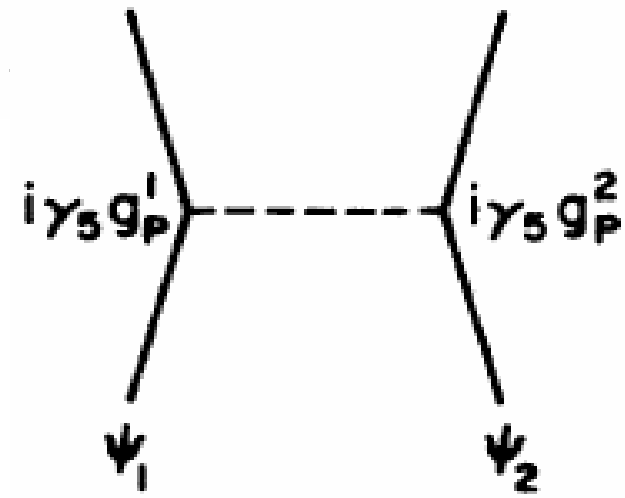
S. Weinberg, Phys. Rev. Lett. 40 (1978) 223

F. Wilczek, Phys. Rev. Lett. 40 (1978) 279

J.E. Moody, F. Wilczek
Phys. Rev. D30 (1984) 130

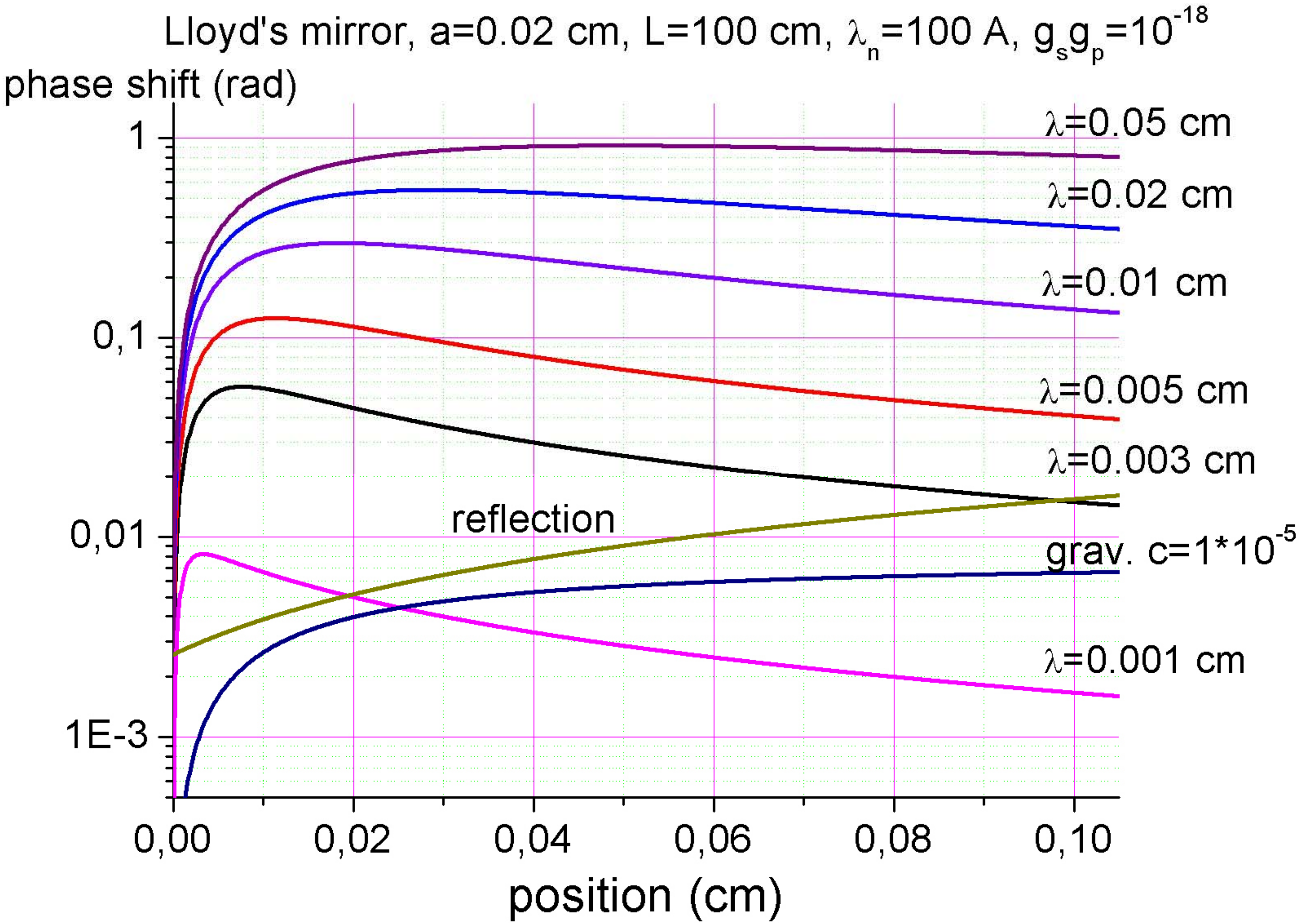

g_S^1
g_S^2
ψ_1
ψ_2


g_S^1
iγ_5 g_P^2
ψ_1
ψ_2


iγ_5 g_P^1
iγ_5 g_P^2
ψ_1
ψ_2

$$V_{mon-dip}(\mathbf{r}) = g_s g_p \frac{\hbar^2 \boldsymbol{\sigma} \cdot \mathbf{n}}{8\pi m_n}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda},$$

$$V_{mon-dip}(x) = \pm g_s g_p \frac{\hbar^2 N \lambda}{4 m_n}(e^{-|x|/\lambda} - e^{-|x+d|/\lambda})$$

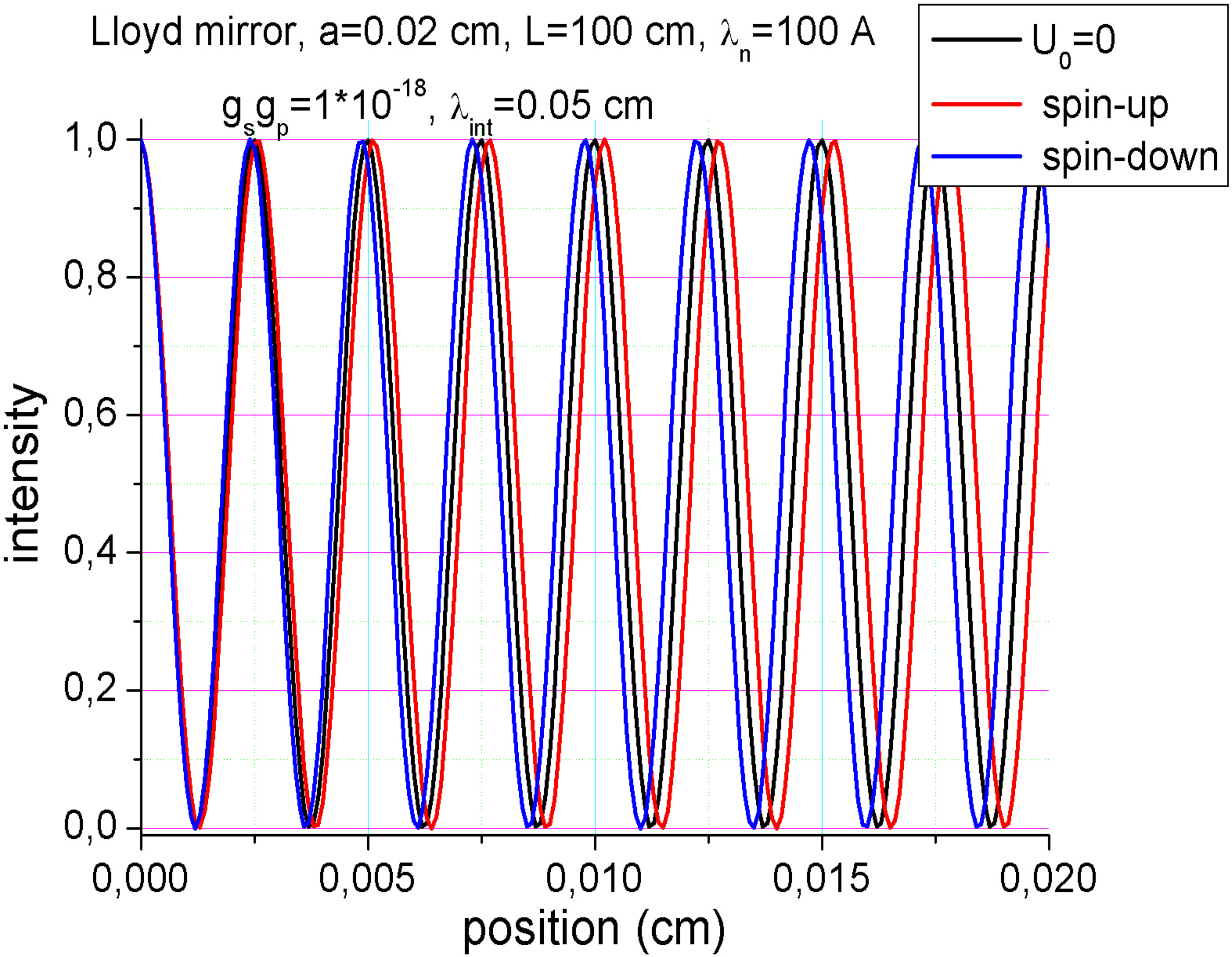


Lloyd's mirror, a=0.02 cm, L=100 cm, λ_n=100 A, $g_s g_p=10^{-18}$
phase shift (rad)
1
0,1
0,01
1E-3
λ=0.05 cm
λ=0.02 cm
λ=0.01 cm
λ=0.005 cm
λ=0.003 cm
reflection
grav. c=1*10^{-5}
λ=0.001 cm
0,00
0,02
0,04
0,06
0,08
0,10
position (cm)

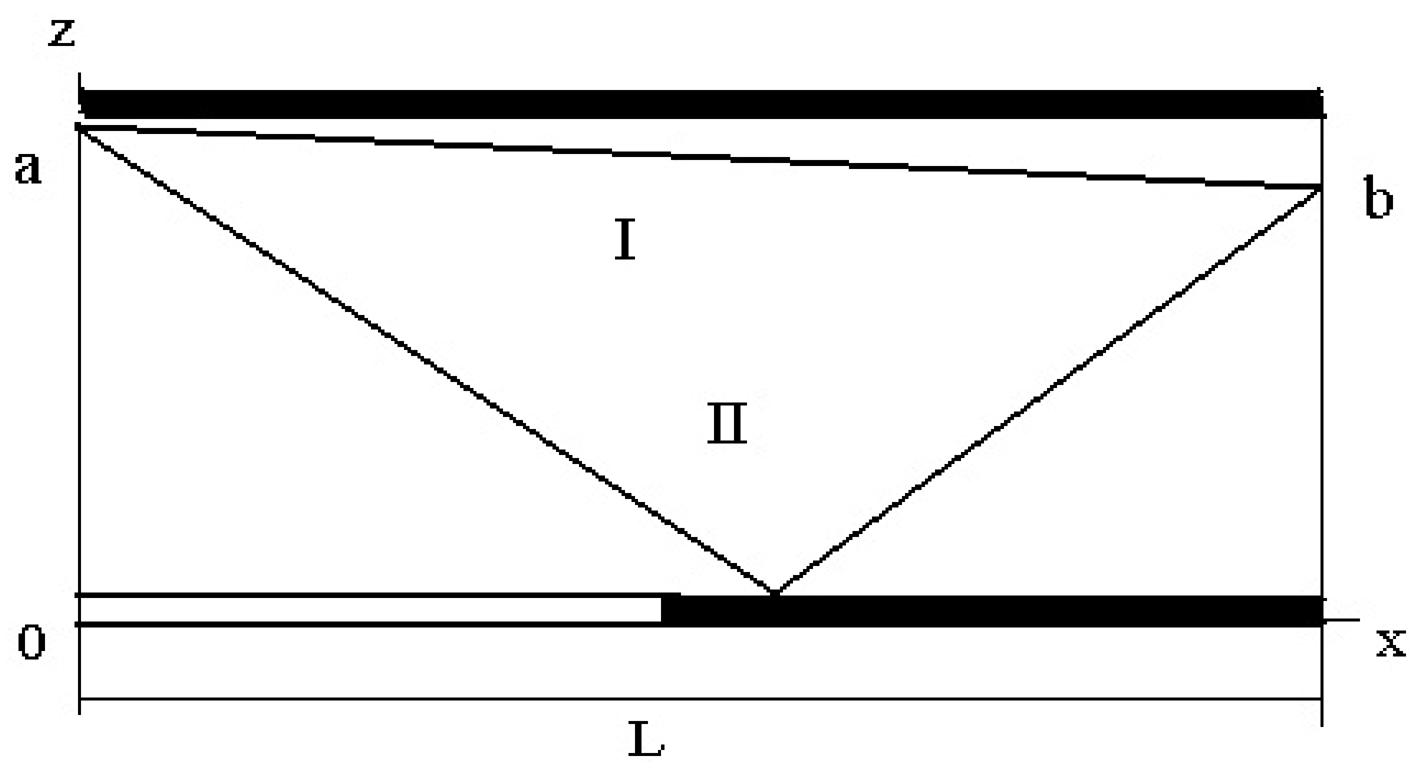
$$\varphi_I = \varphi_{geom.I} + \frac{mV_0}{k\hbar^2}\sqrt{L^2+(b-a)^2}\frac{\lambda}{b-a}\left(e^{-a/\lambda}-e^{-b/\lambda}\right)$$

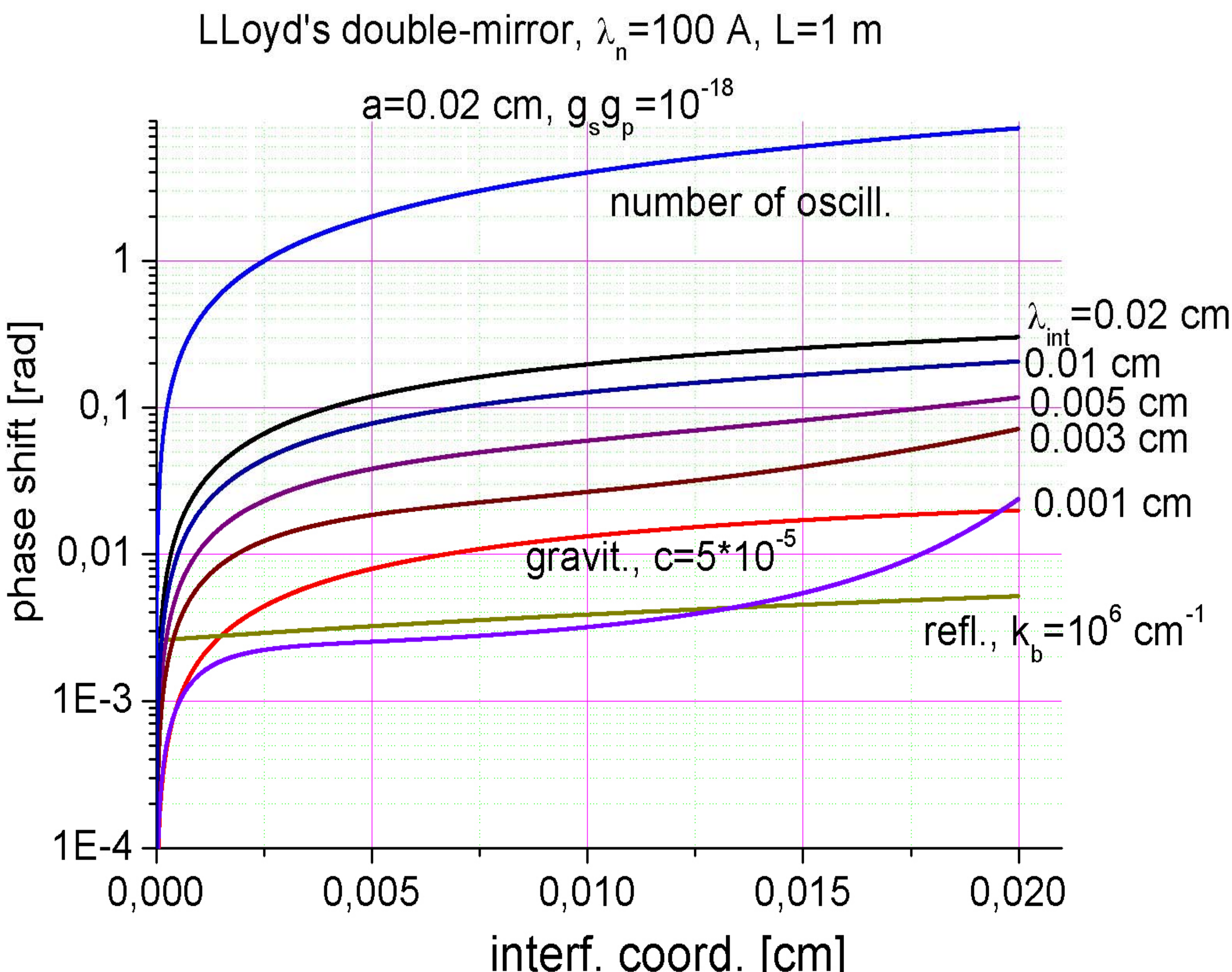
$$\varphi_{II} = \varphi_{geom.II} + \frac{mV_0}{k\hbar^2}\sqrt{L^2+(b+a)^2}\frac{\lambda}{b+a}\left(2-e^{-a/\lambda}-e^{-b/\lambda}\right)$$

$$\left(\varphi_I^+ - \varphi_{II}^+\right) - \left(\varphi_I^- - \varphi_{II}^-\right) = 2\left(\varphi_I - \varphi_{II}\right) = \delta\varphi$$



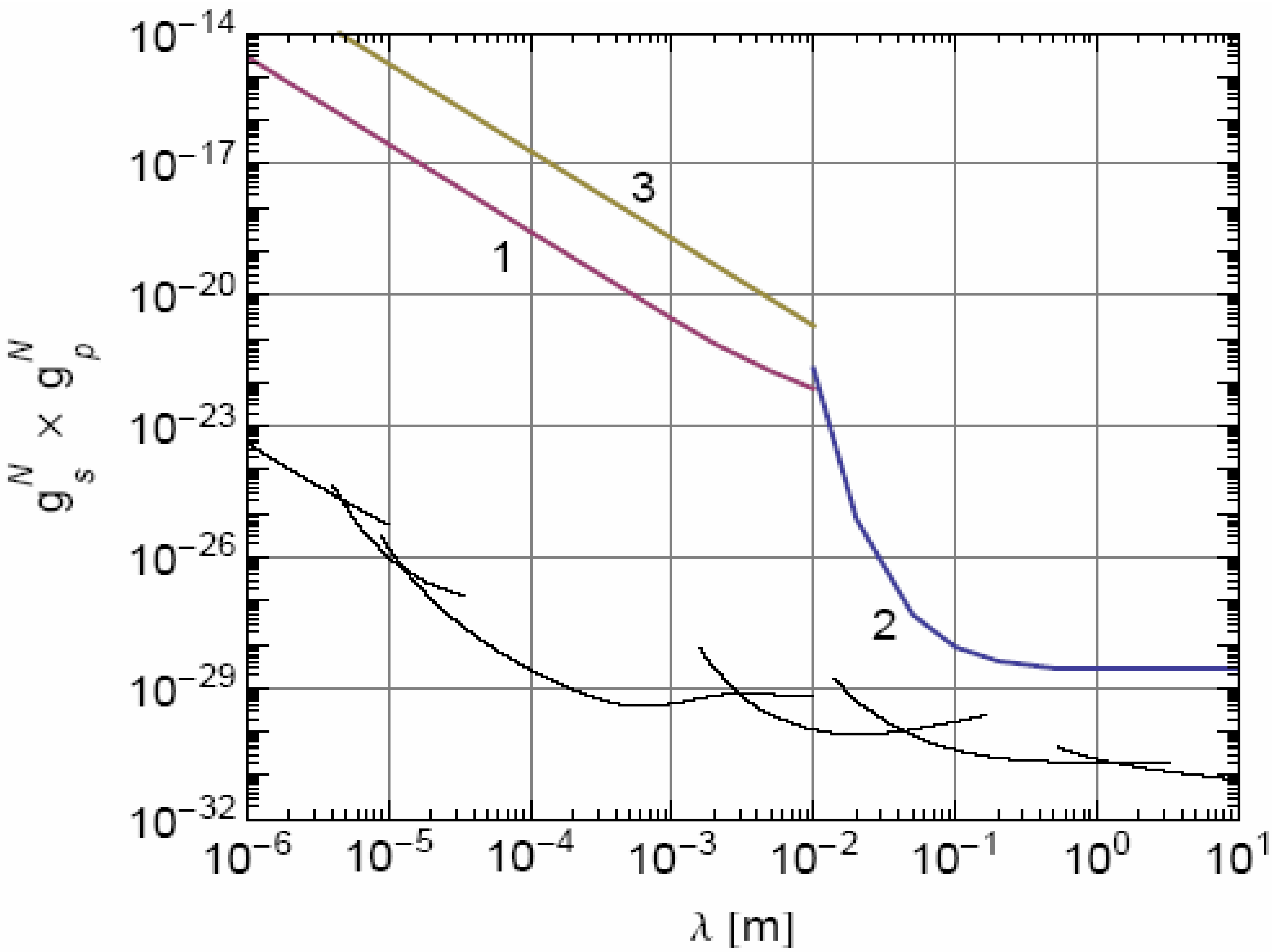
Lloyd mirror, a=0.02 cm, L=100 cm, λ_n=100 A
$g_s g_p$=1*10^{-18}, λ_{int}=0.05 cm
U_0=0
spin-up
spin-down
intensity
1,0
0,8
0,6
0,4
0,2
0,0
0,000
0,005
0,010
0,015
0,020
position (cm)


z
a
b
I
II
0
x
L



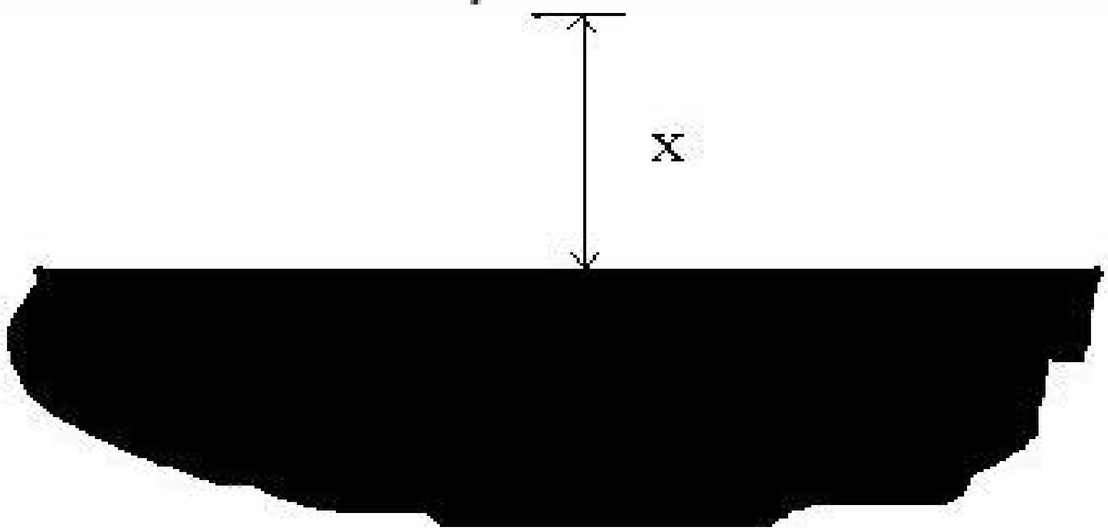
LLoyd's double-mirror, λ_n=100 A, L=1 m
a=0.02 cm, $g_s g_p=10^{-18}$
number of oscill.
λ_{int}=0.02 cm
0.01 cm
0.005 cm
0.003 cm
0.001 cm
gravit., c=5*10^{-5}
refl., $k_b=10^6$ cm^{-1}
phase shift [rad]
1
0,1
0,01
1E-3
1E-4
0,000
0,005
0,010
0,015
0,020
interf. coord. [cm]

G. Raffelt, arxiv:1205.1776 (8 May 2012)

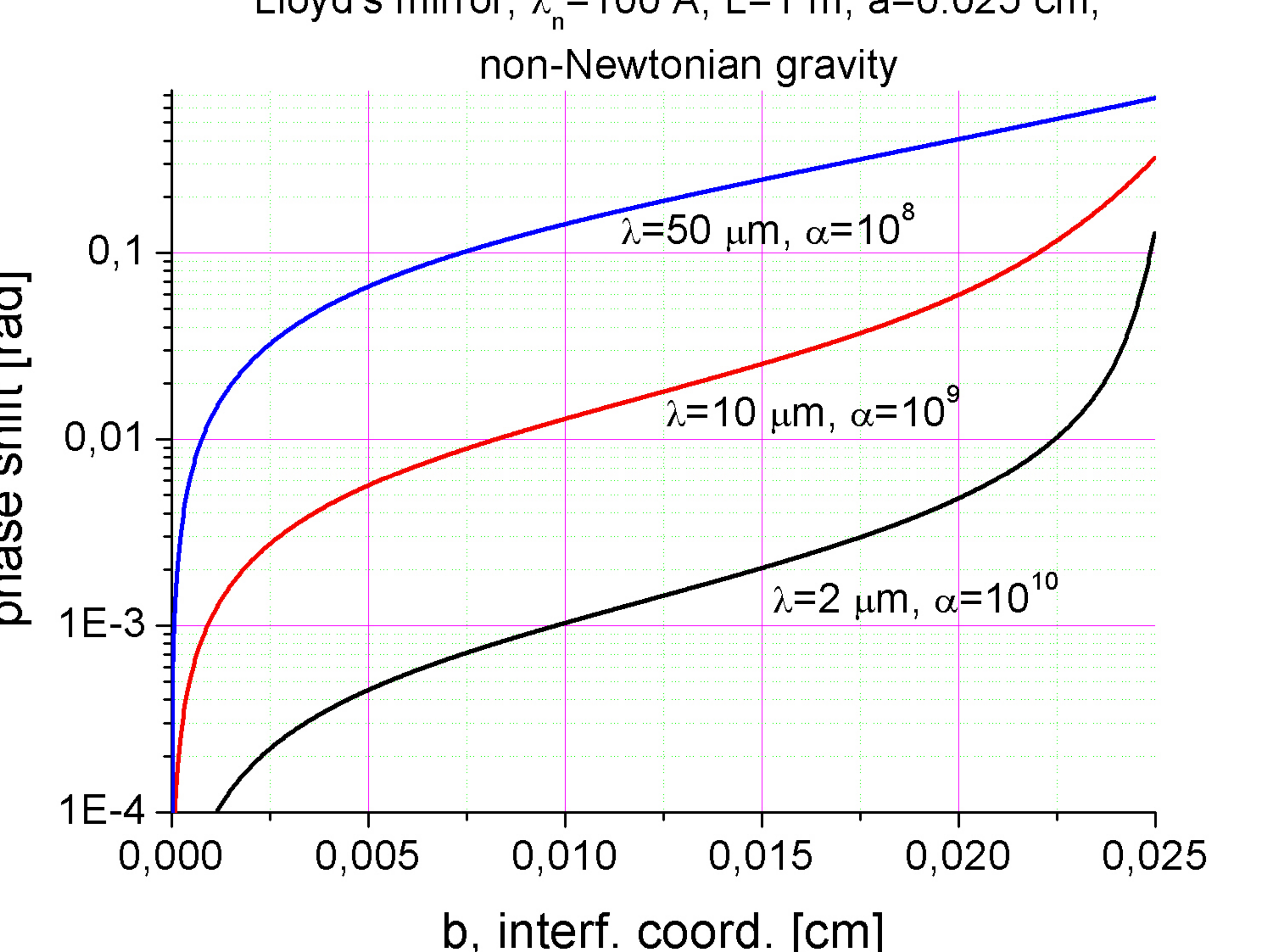


Non-Newtonian gravity at the μm scale

$$V_G(r) = -G\frac{mM}{r}(1+\alpha_G e^{-r/\lambda})$$



$$V(x) = 2\pi\alpha m_n^2 N G \lambda^2 e^{-x/\lambda} = V_0 e^{-x/\lambda}$$


non-Newtonian gravity
phase shift [rad]
0,1
0,01
1E-3
1E-4
λ=50 μm, α=10^8
λ=10 μm, α=10^9
λ=2 μm, α=10^10
0,000
0,005
0,010
0,015
0,020
0,025
b, interf. coord. [cm]

V.V. Nesvizhevsky, Mod. Phys. Lett. A27 (2012) No. 5