Slow Neutron at J-PARC

Hirohiko M. SHIMIZU

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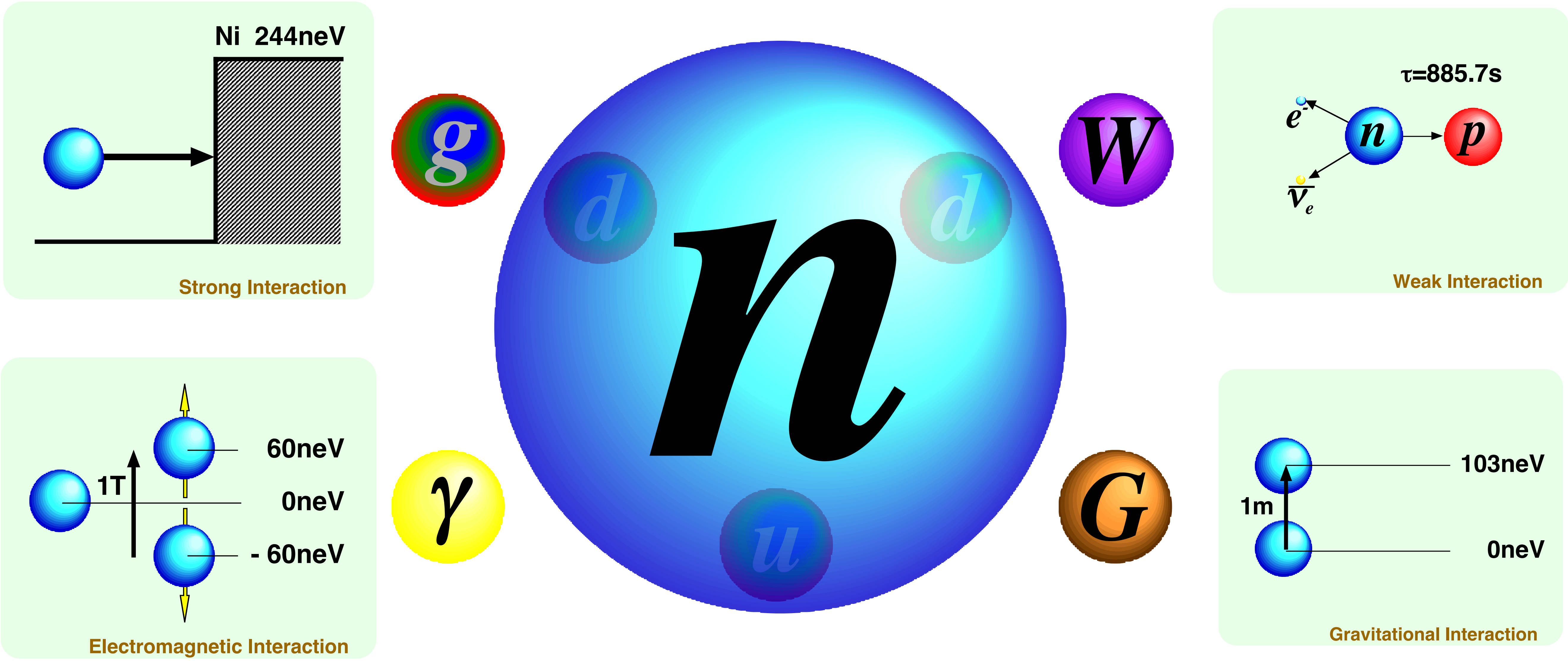
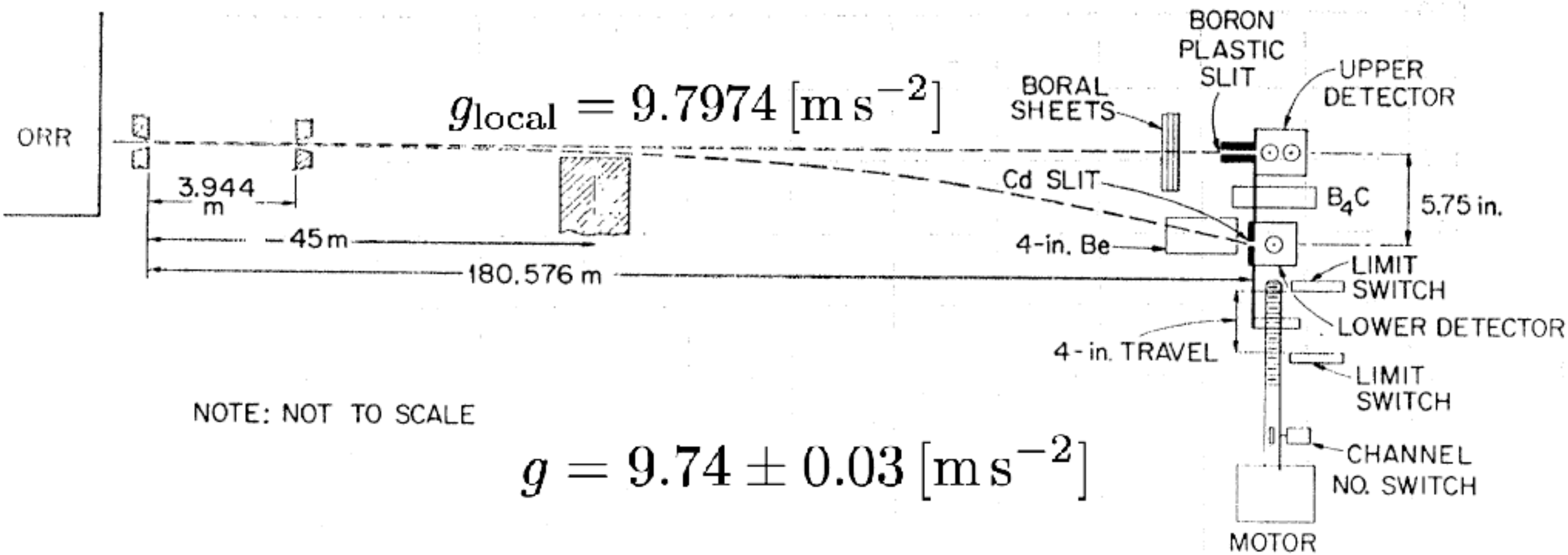

Ni 244neV
Strong Interaction
g
d
d
n
u
W
τ=885.7s
e
n
p
ν
e
Weak Interaction
60neV
1T
0neV
- 60neV
Electromagnetic Interaction
γ
G
103neV
1m
0neV
Gravitational Interaction

Gravitational Fall

Dabbs et al., Phys. Rev. 139 (1965) B756

$$g_{\mathrm{local}} = 9.7974\,[\mathrm{m\,s^{-2}}]$$



$$g = 9.74 \pm 0.03\,[\mathrm{m\,s^{-2}}]$$

Gregoriev et al., Proc. 1st Int. Conf. Neutr. Phys., Kiev, 1 (1988) 60

$$g = 9.801 \pm 0.013\,[\mathrm{m\,s^{-2}}]$$
$$g_{\mathrm{local}} = 9.814\,[\mathrm{m\,s^{-2}}]$$

Gravitational Fall

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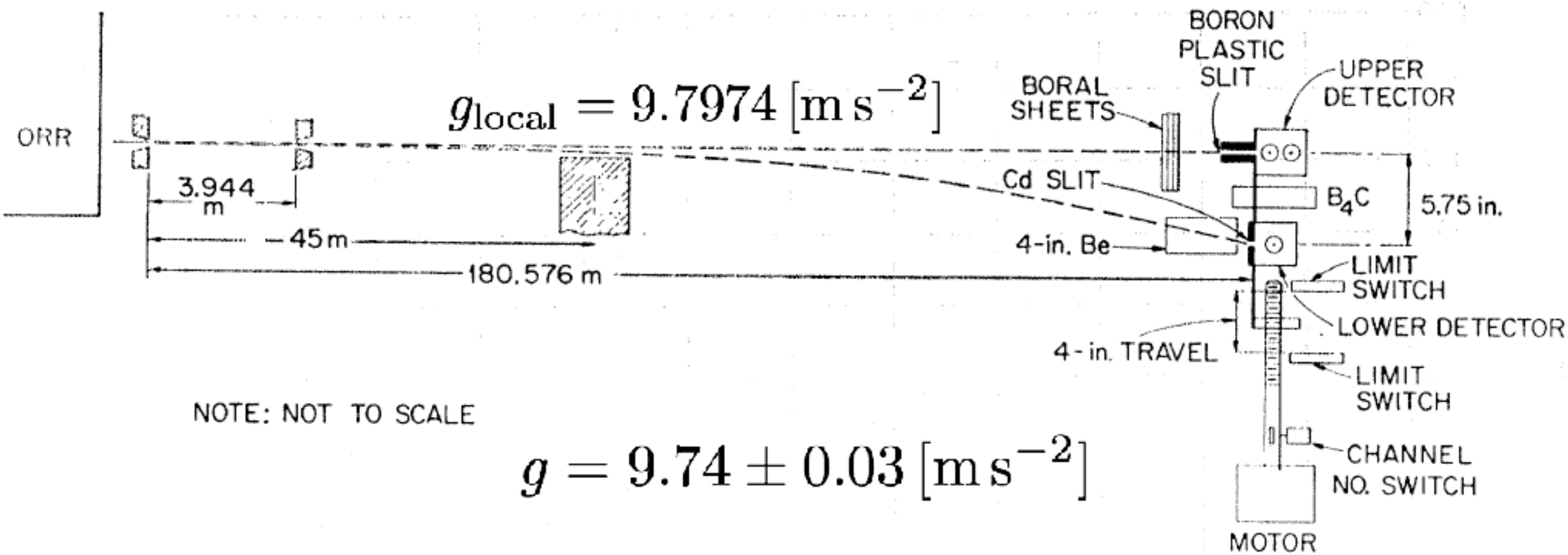

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McReynolds, Bull. Am. Phys. Soc. 12 (1967) 105

$$|\Delta g| < 5 \times 10^{-13} g_0 \qquad g = g_0 + \Delta g(\boldsymbol{\sigma} \cdot \boldsymbol{g})$$

Gravity is extremely weak.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

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Why is the gravity so weak?
Gravity is not renormalizable.
Gravity is the nature of space time.

Gravity is essential at the Planck scale.

"hierarchy problem": $M_{GUT}\sim10^{24}$eV ⇔ $M_{SU(2)\times U(1)}\sim10^{11}$eV

Phenomena out of the standard model is existing.

<u>**Neutrino Oscillation, Dark Energy, Dark Matter**</u>

Super-K, SNO, KamLAND WMAP

Gravity is extremely weak.

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$$U = -G\frac{M m_{\mathrm{n}}}{R}$$

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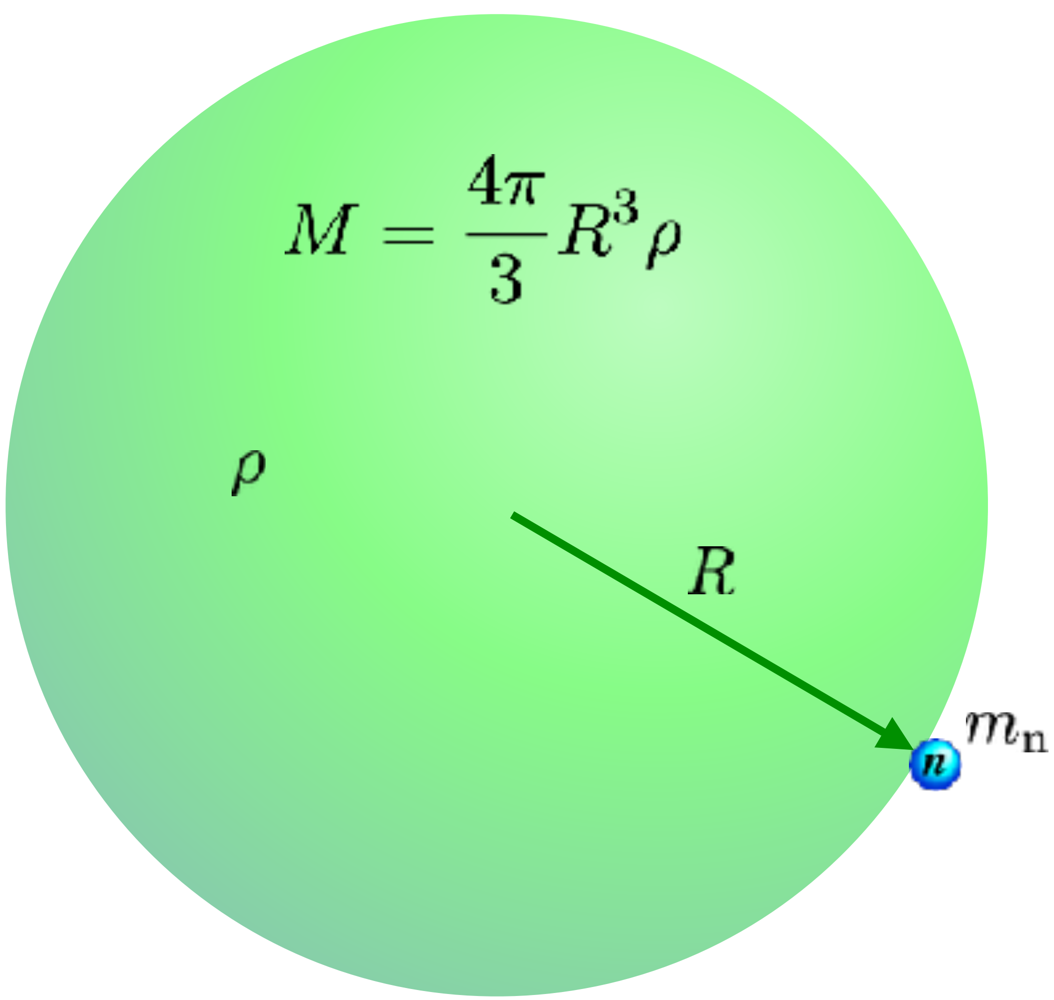
$$= -3.1 \times 10^{-15}[\mathrm{eV}] \times \left(\frac{R}{1\,\mathrm{m}}\right)^2 \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



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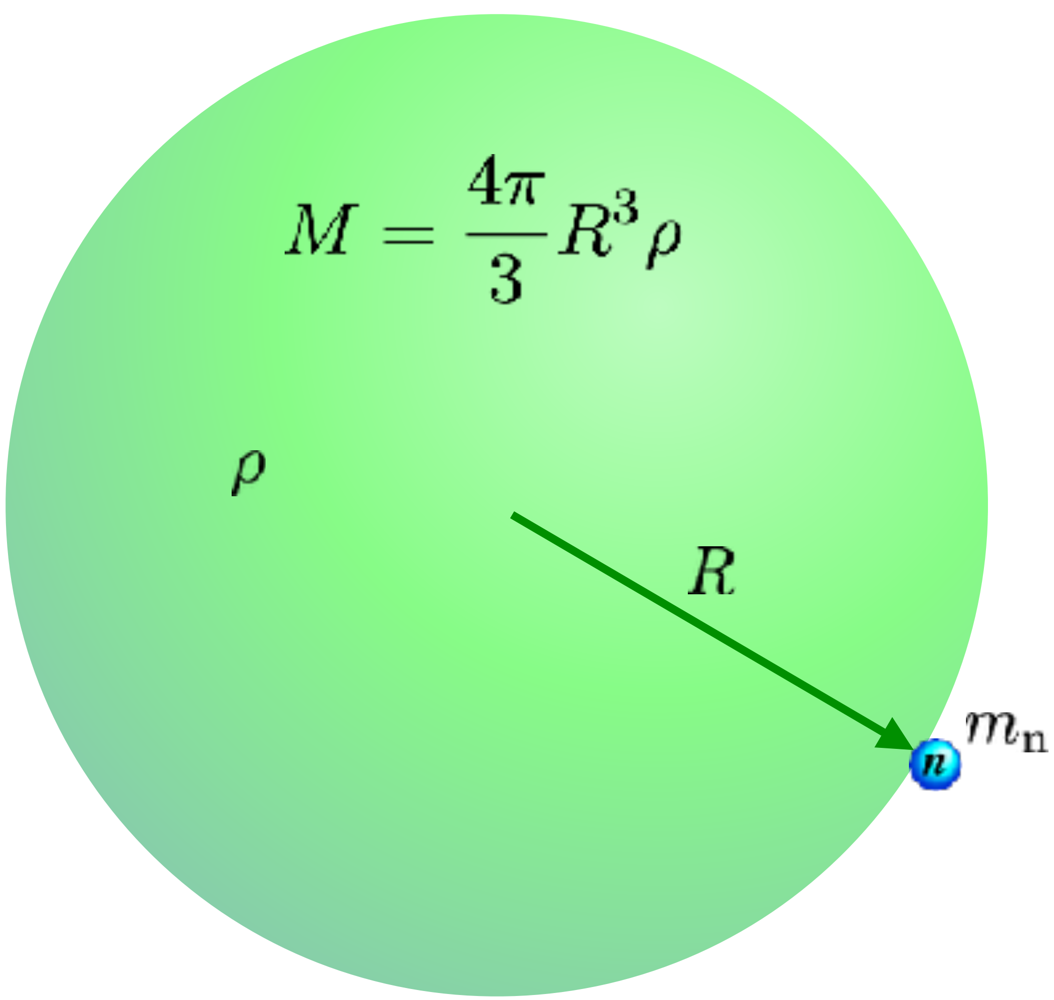
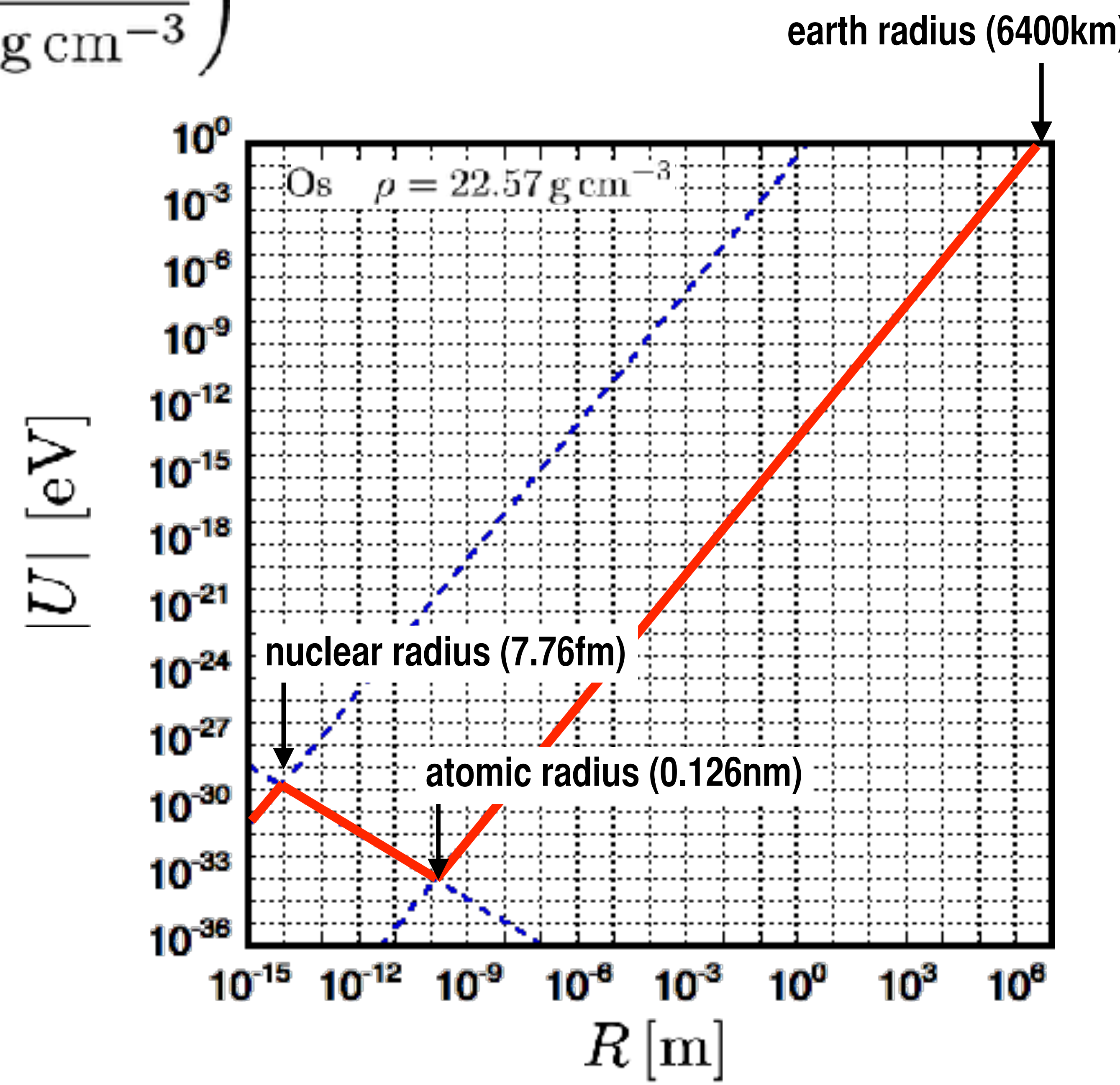
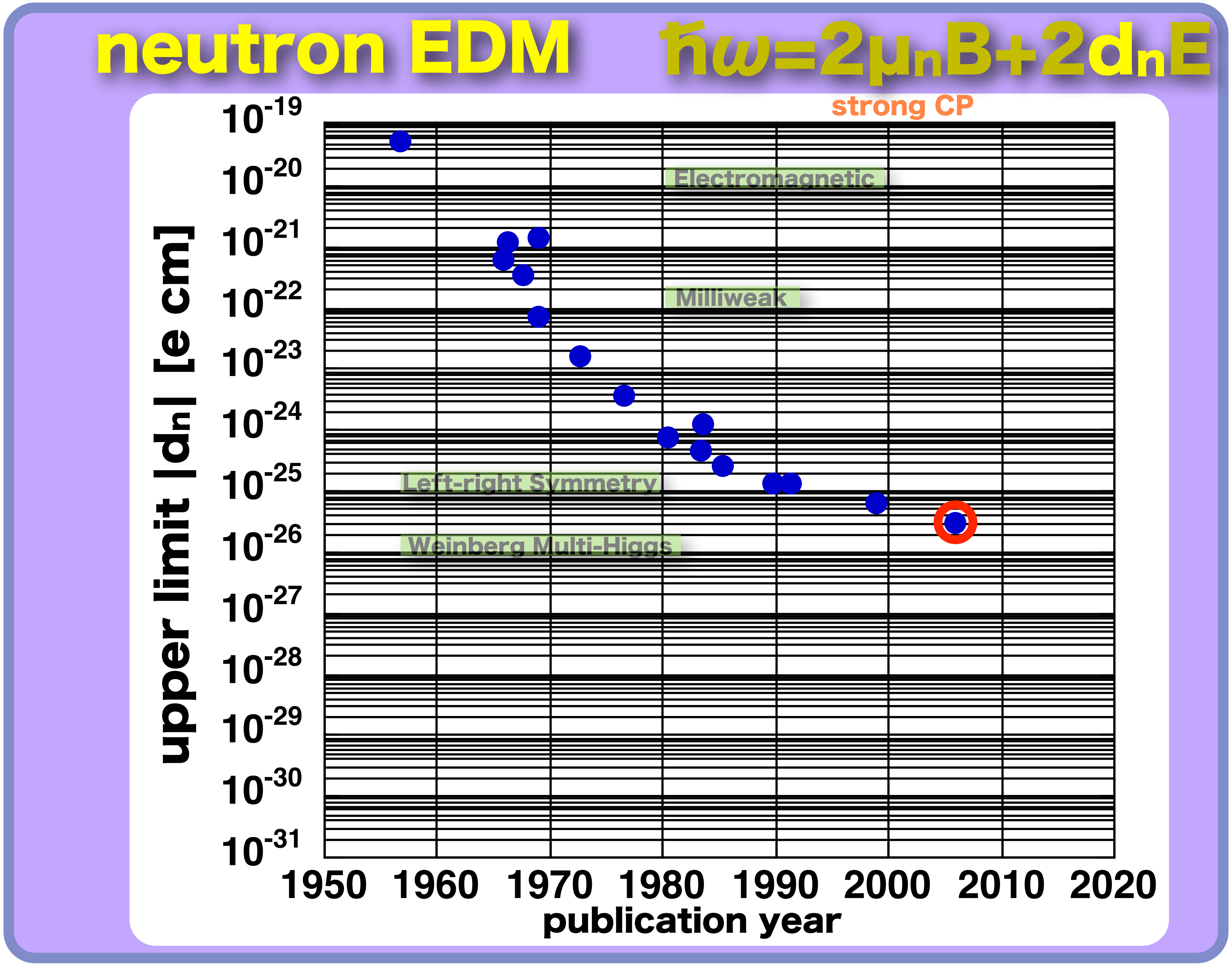




Neutron Electric Dipole Moment

$|d_n| < 3\times10^{-26}$ e cm
(90%C.L.)

Baker et al., PRL97 (2006)131801



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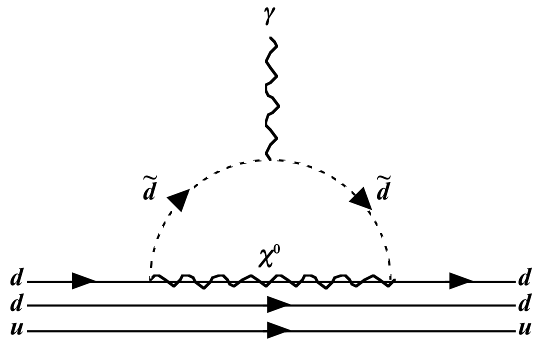
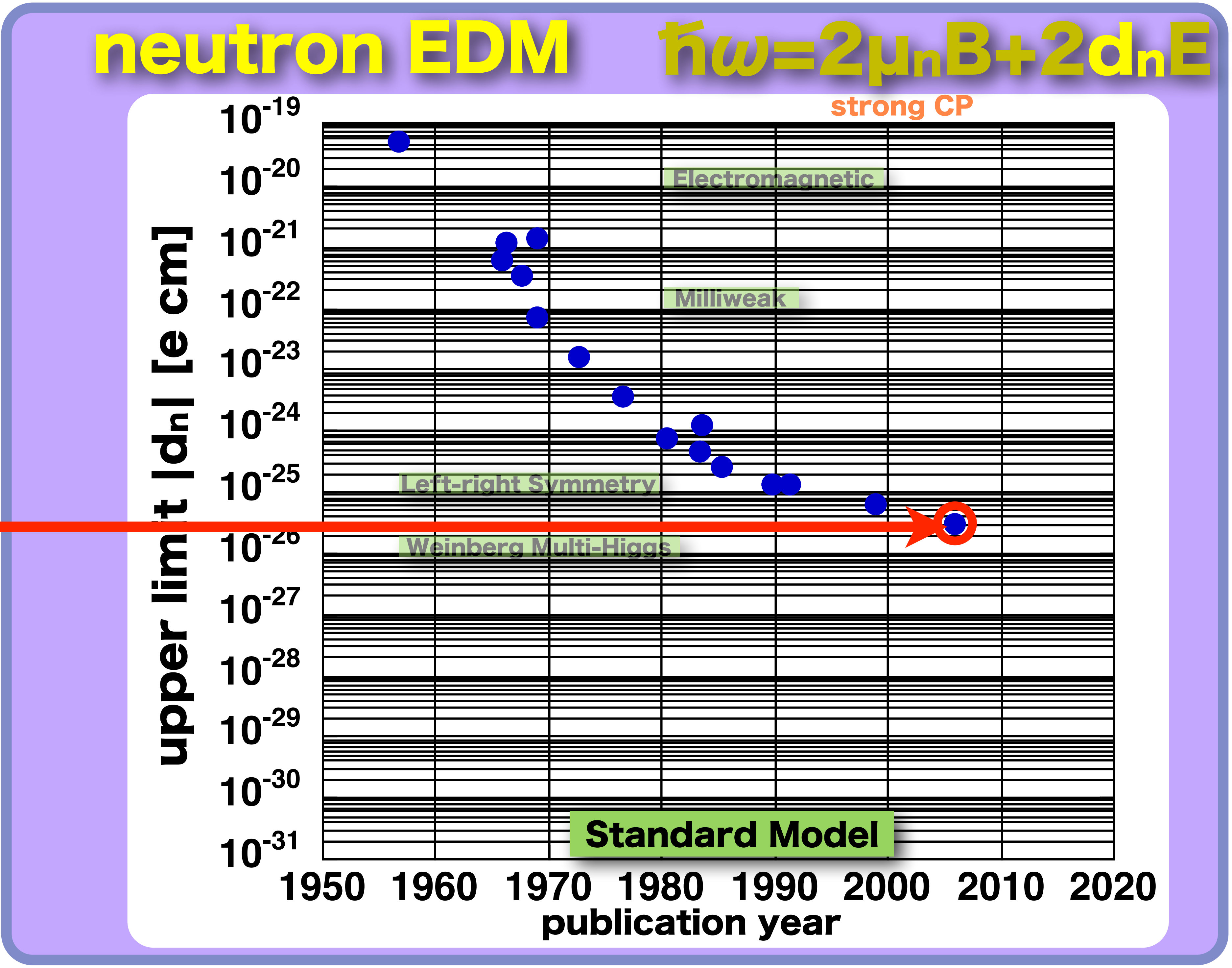
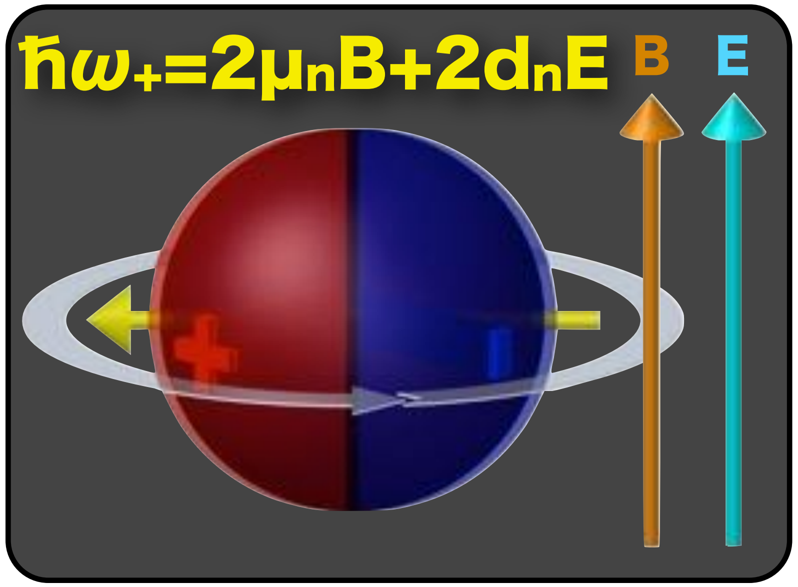




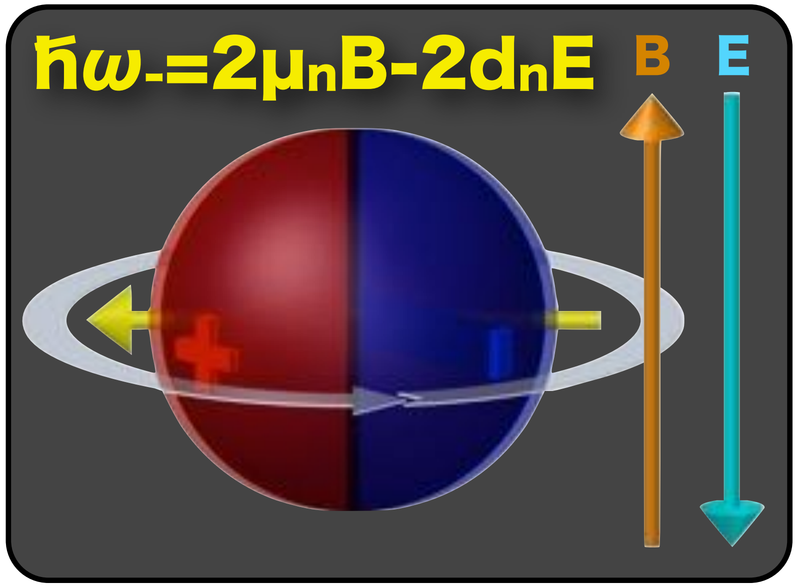
Measurement of Neutron Electric Dipole Moment

search for the phase change when the electric field is reversed

$$\hbar\omega_+ = 2d_n E + 2\mu_n B$$



$$\hbar\omega_- = 2d_n E - 2\mu_n B$$



$$\Delta\phi = \int(\omega_+ - \omega_-)\mathrm{d}t = \frac{2d_n ET}{\hbar}$$

$$\Delta d_n = \frac{\hbar/2}{ET\sqrt{N}}$$

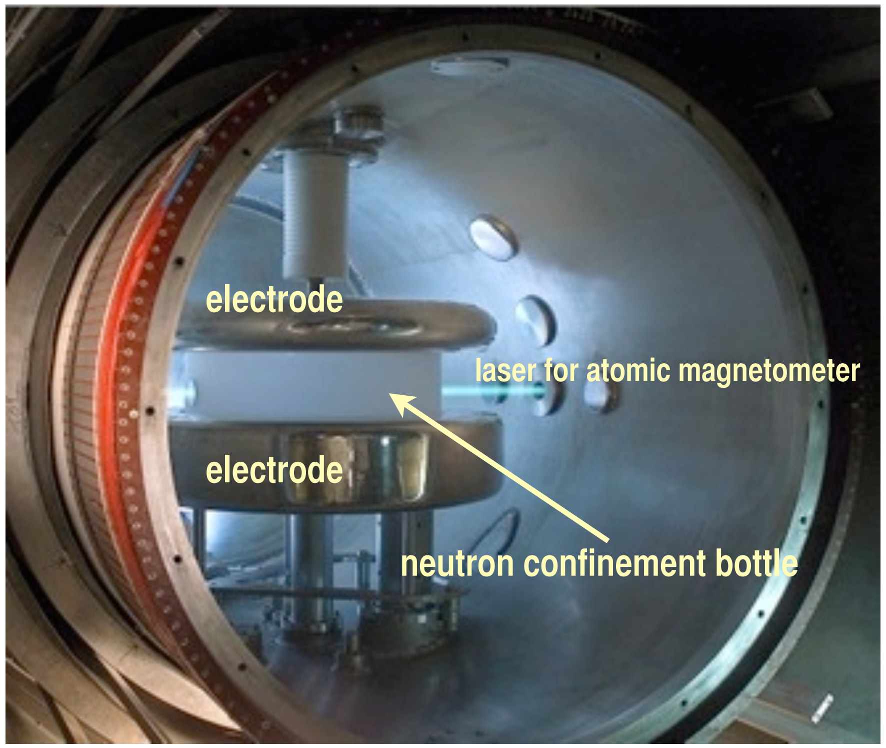
long precession time

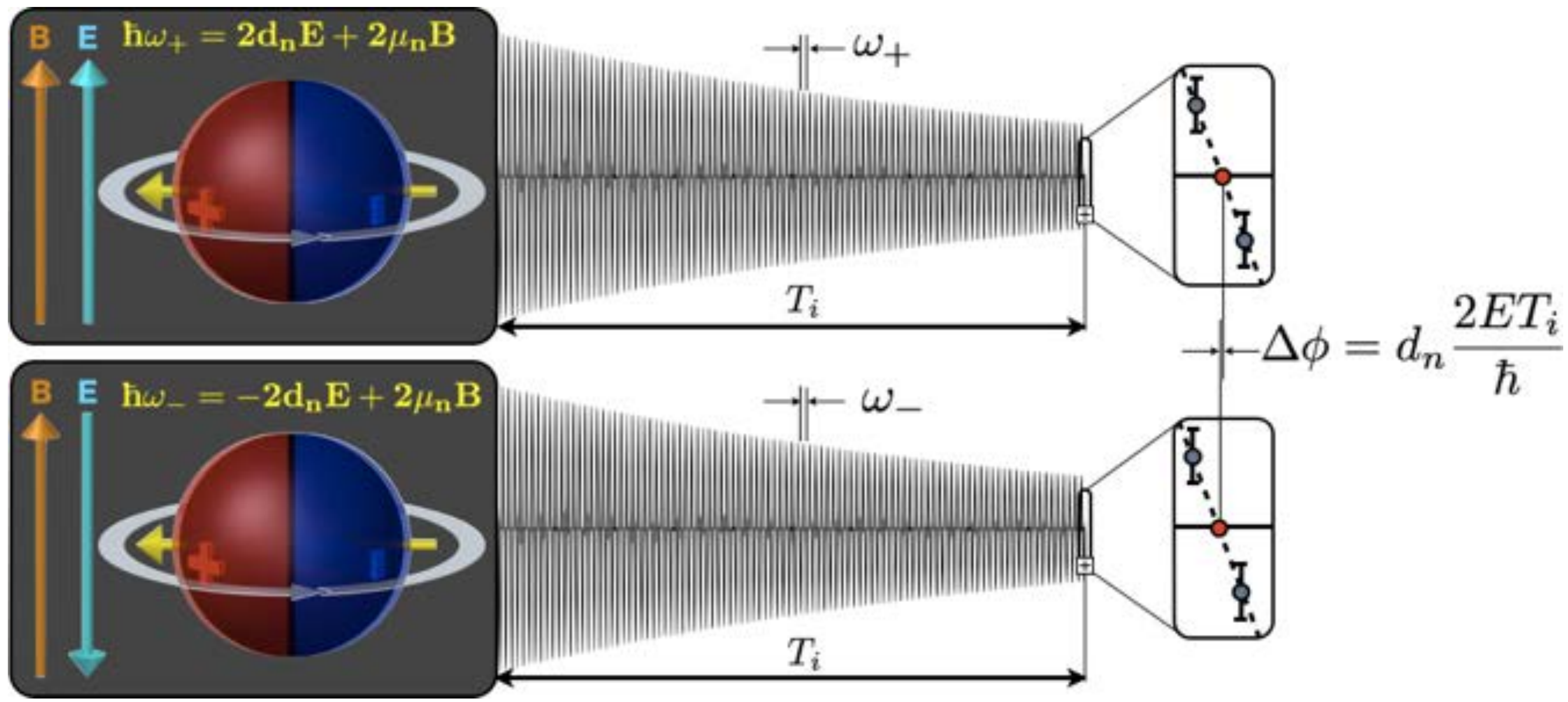
Confined Ultracold Neutron

$E=10^4$ V/cm, $T=100$s

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency



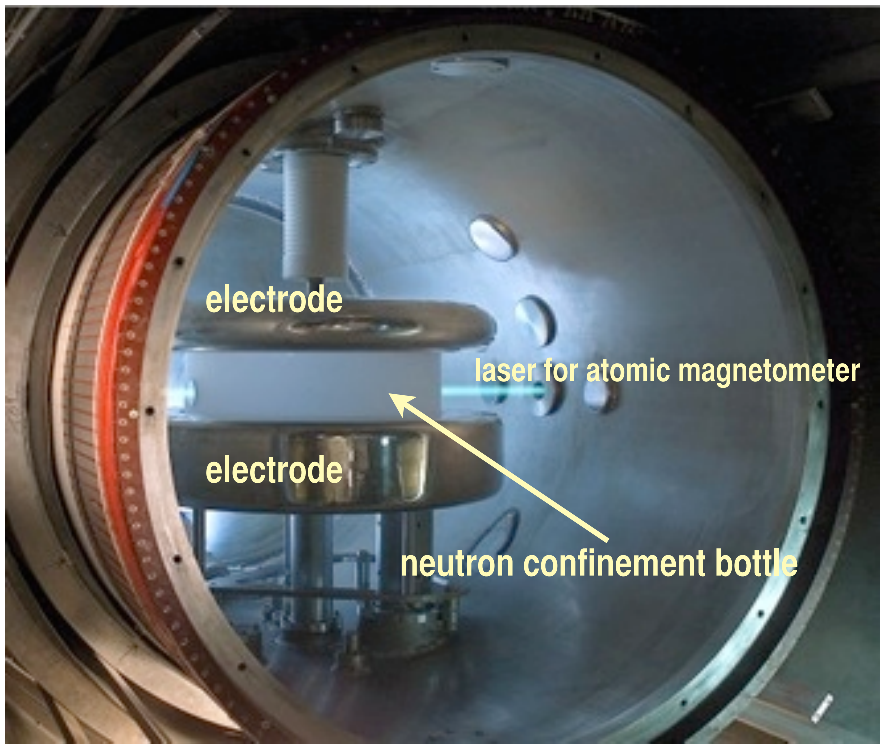


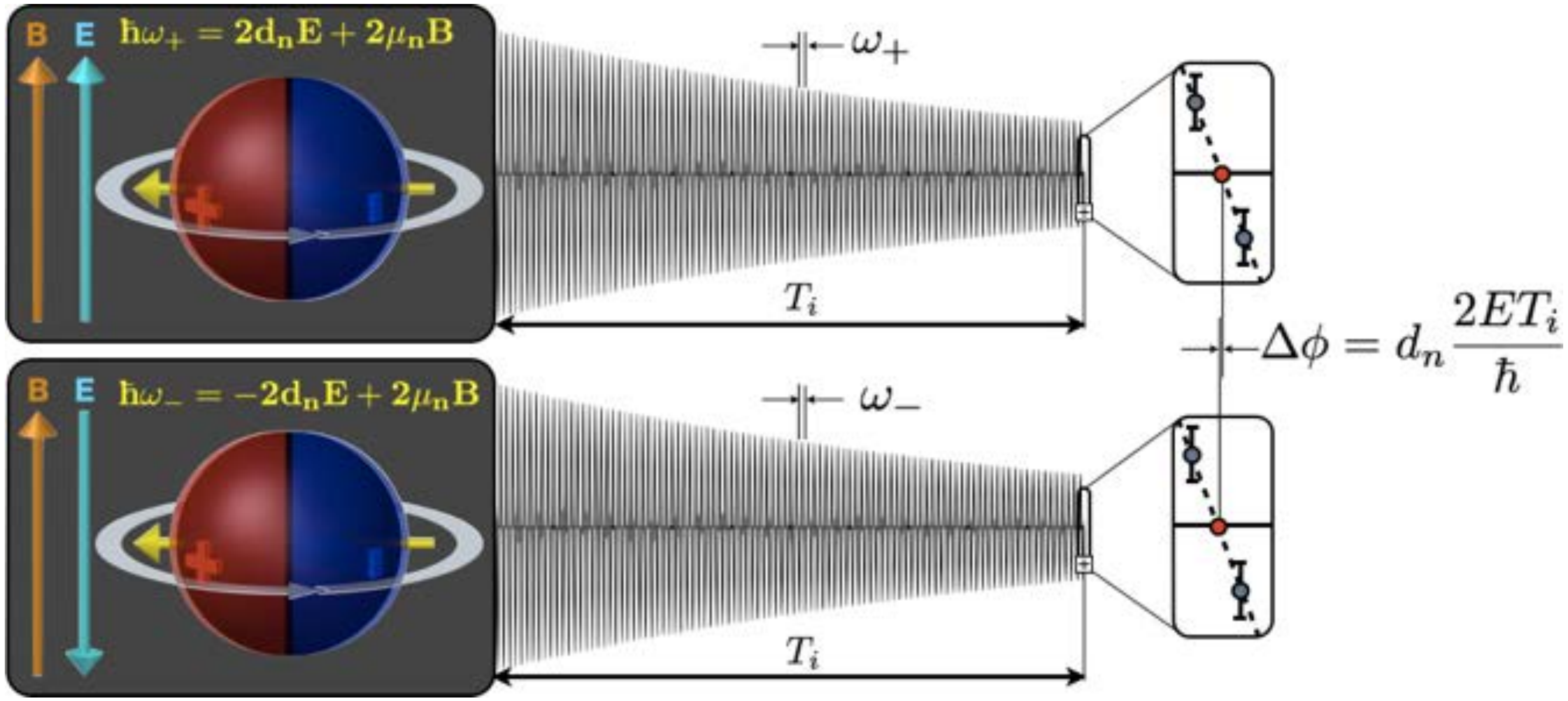
$$\frac{\omega_\pm}{2\pi} = \boxed{30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]}} \pm \boxed{5\times10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}}$$

magnetic field **1μT** electric field **1fT equiv.**

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency





$$\Delta U = 2d_n E = 2 \times (3 \times 10^{-26}\,[e \cdot \mathrm{cm}]) \times 10\,[\mathrm{kV/cm}]$$
$$= 6 \times 10^{-22}\,\mathrm{eV}$$

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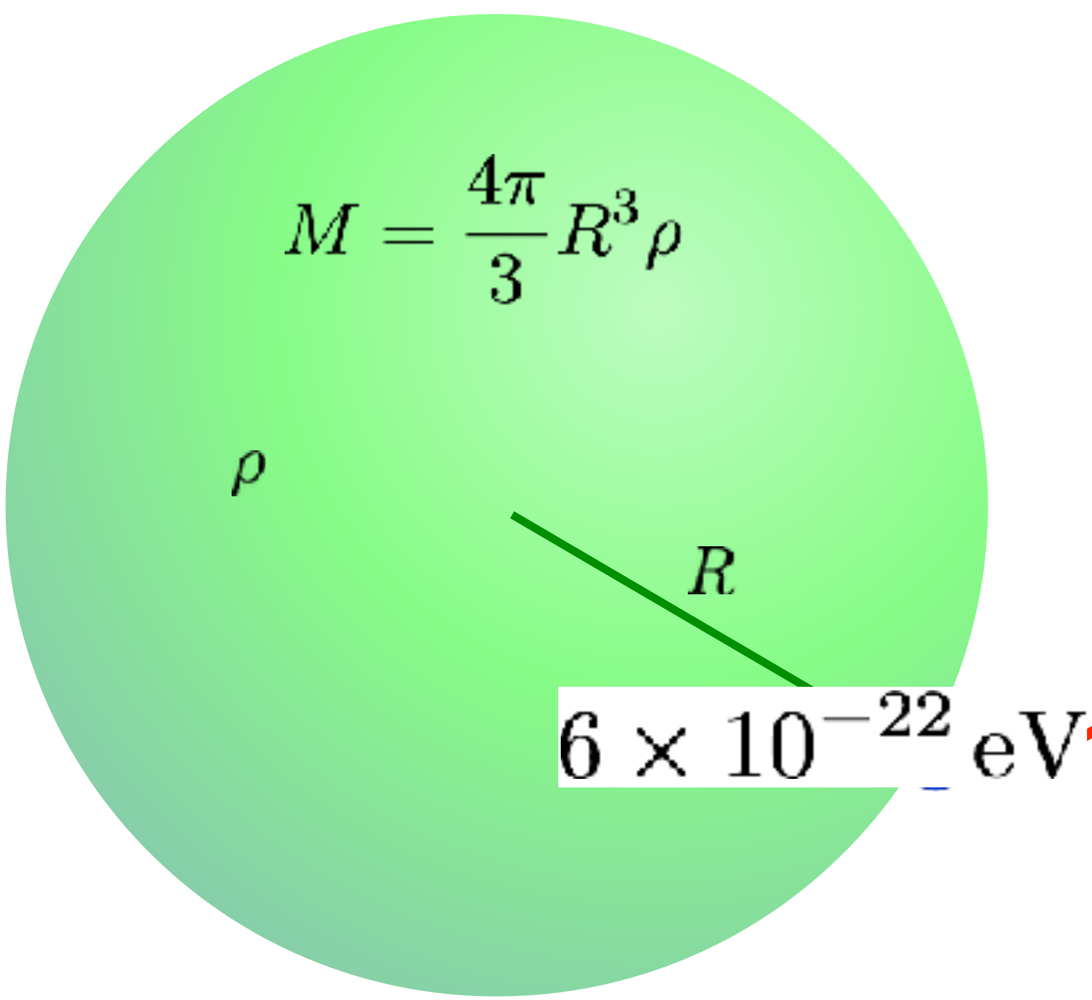
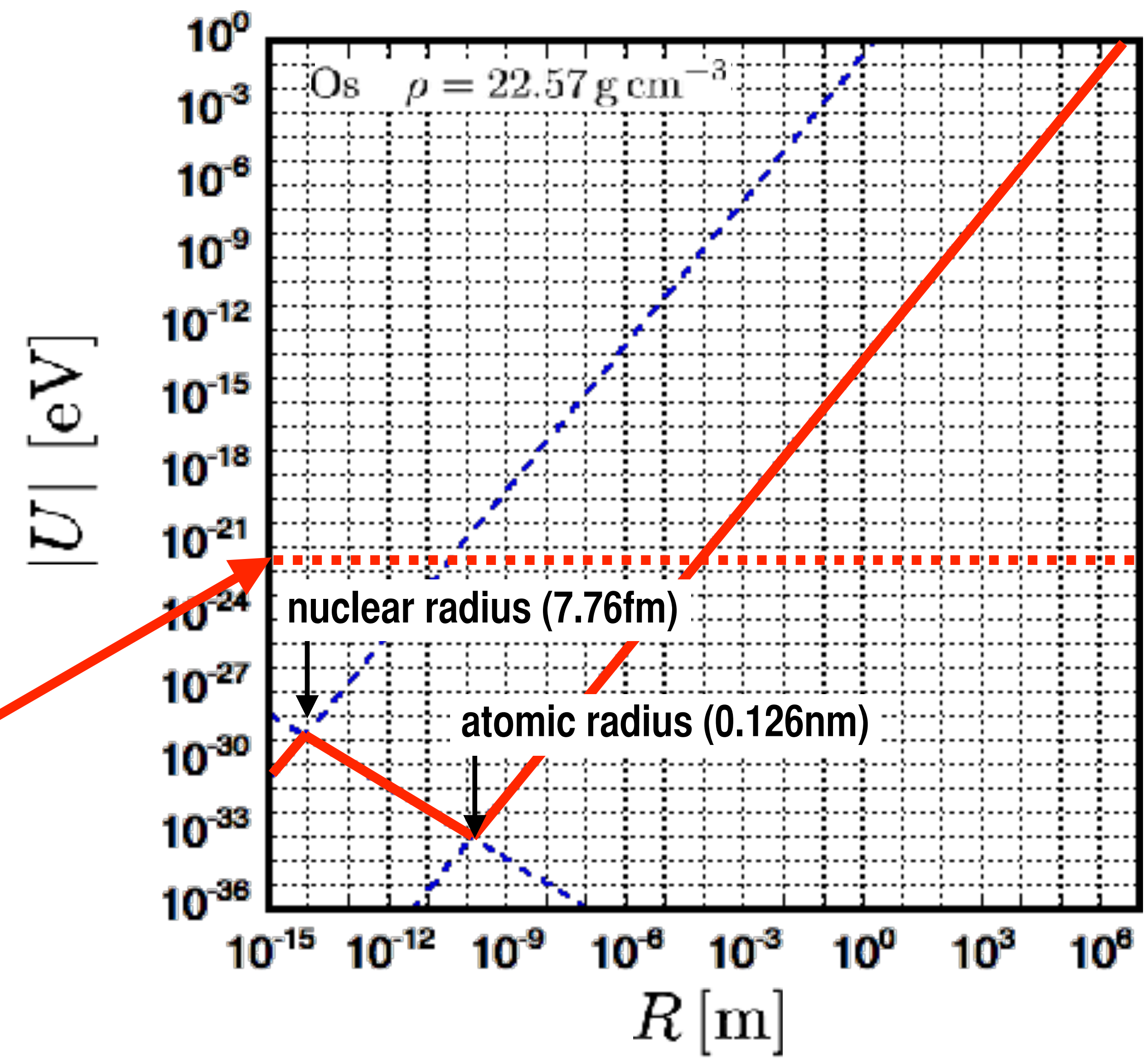
$$U = -G\frac{M m_\mathrm{n}}{R}$$

$$= -3.1 \times 10^{-15}[\mathrm{eV}] \times \left(\frac{R}{1\,\mathrm{m}}\right)^2 \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$





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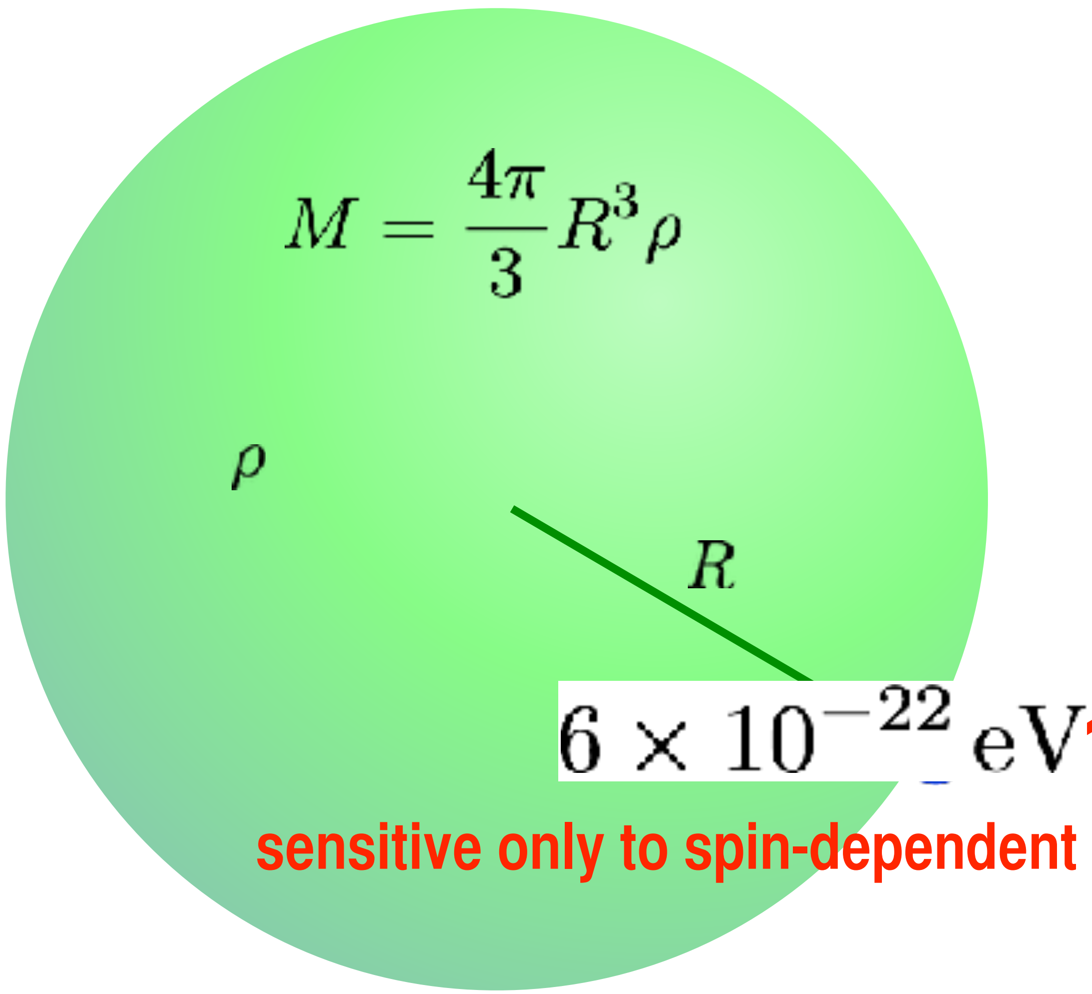
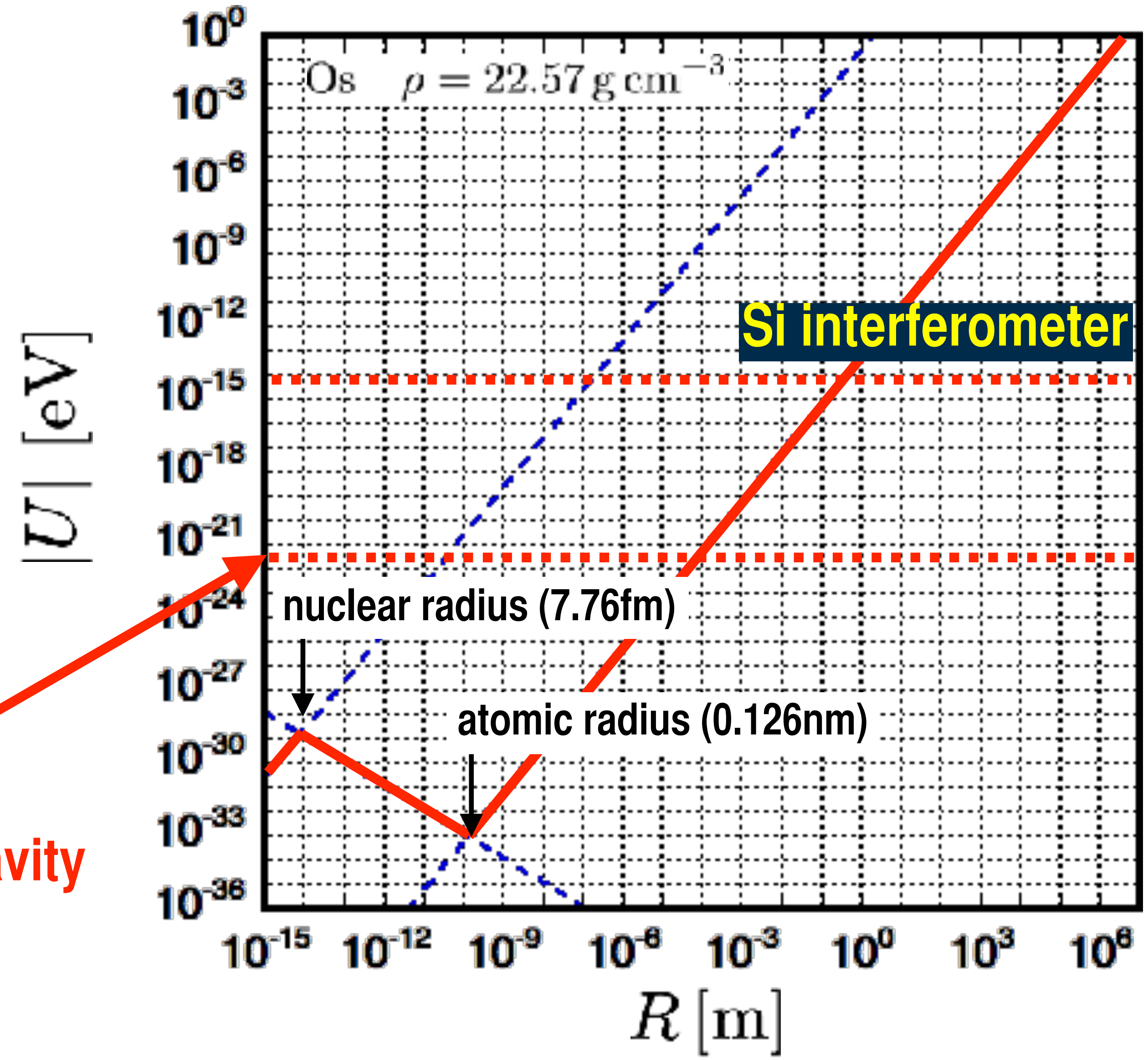


sensitive only to spin-dependent gravity

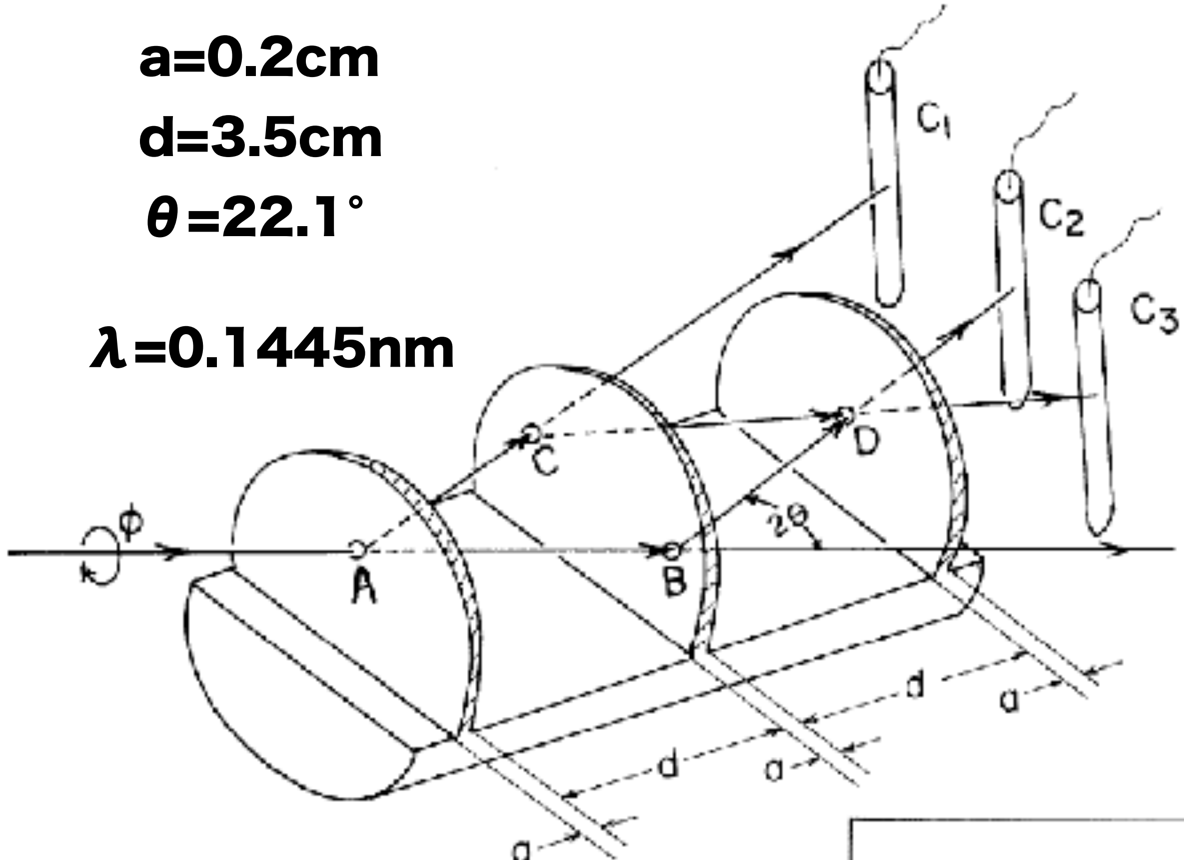


Neutron Phase induced by Earth’s Gravity

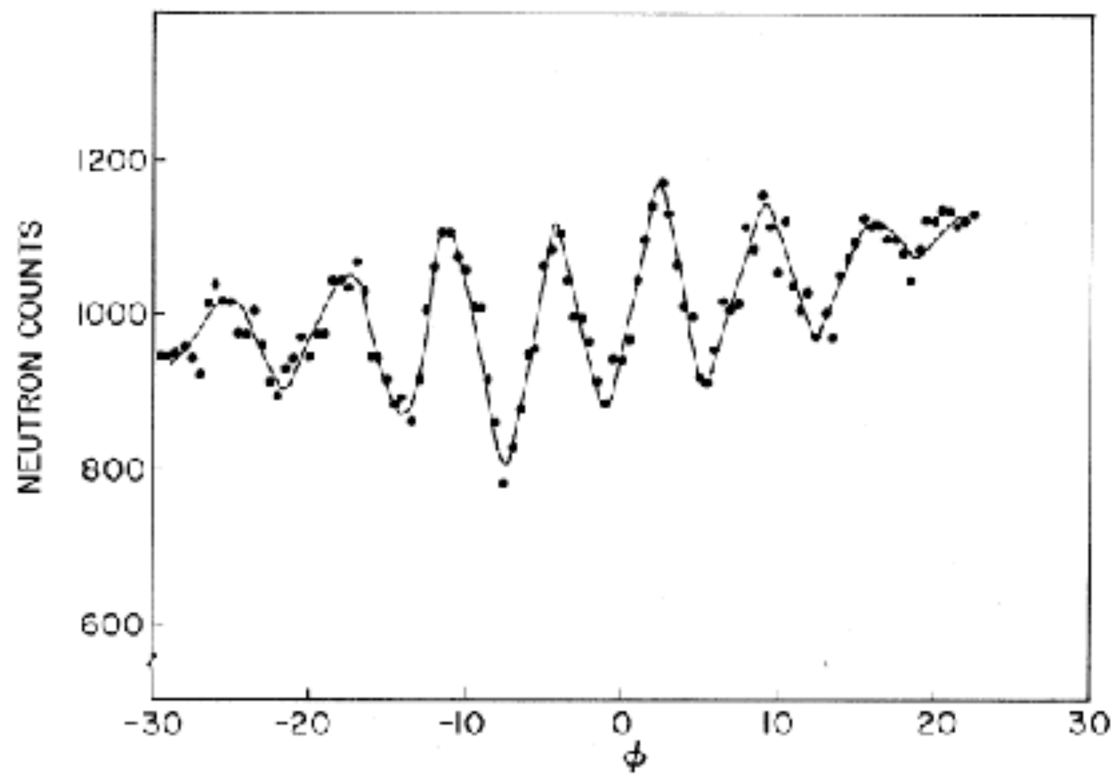
Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

a=0.2cm
d=3.5cm
θ=22.1°

λ=0.1445nm



COW expertment



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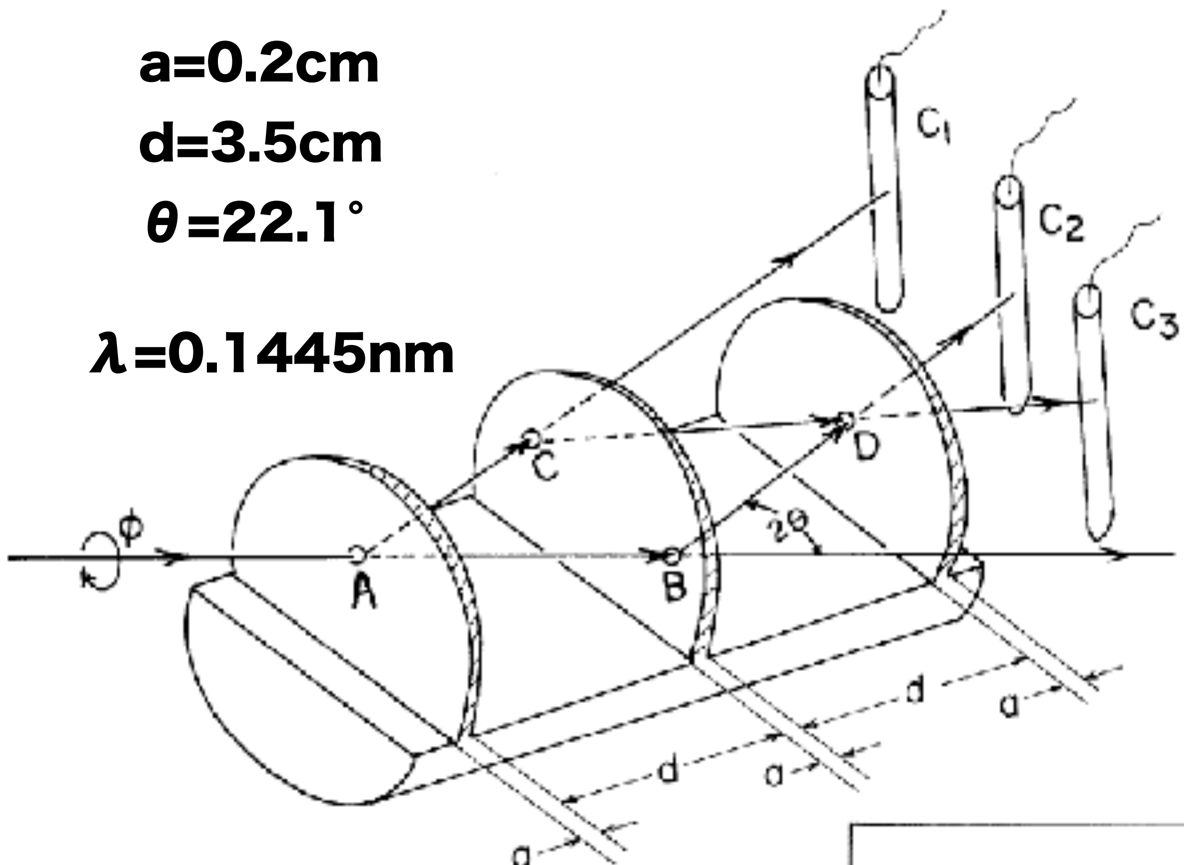

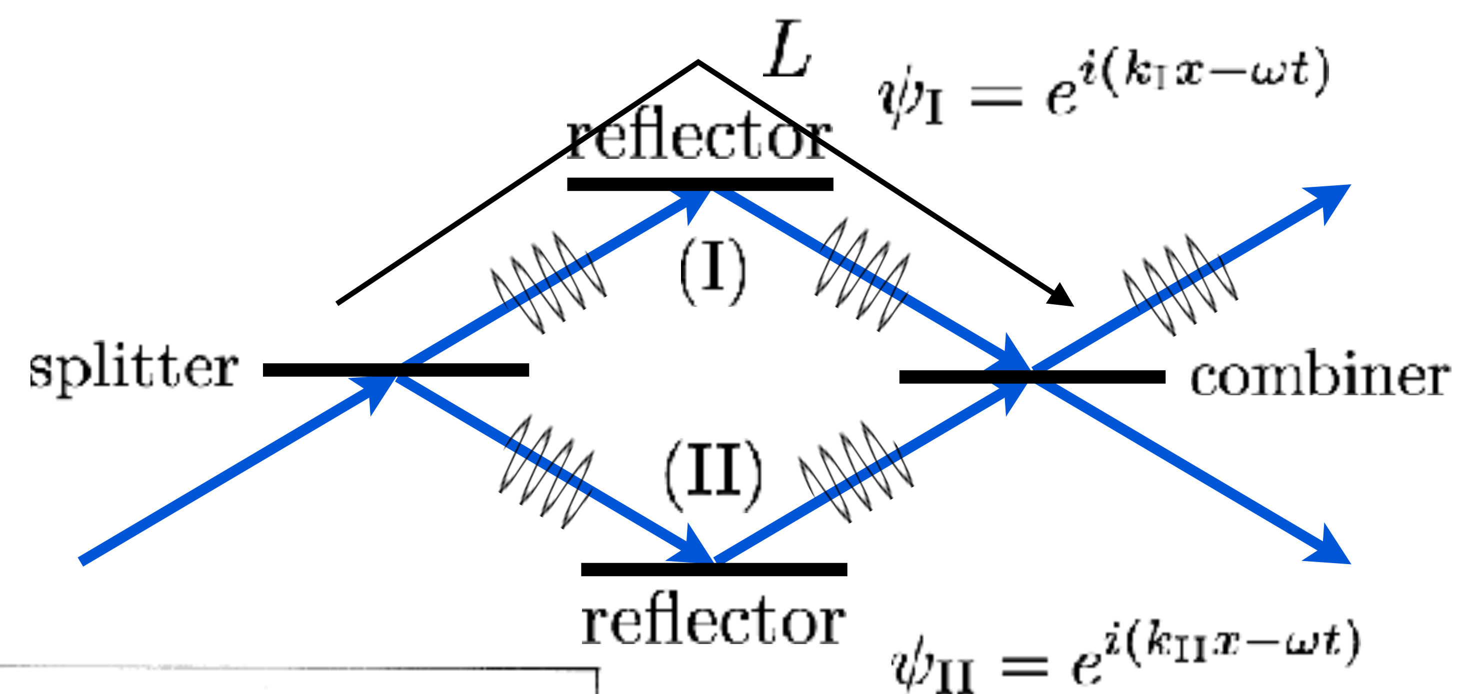

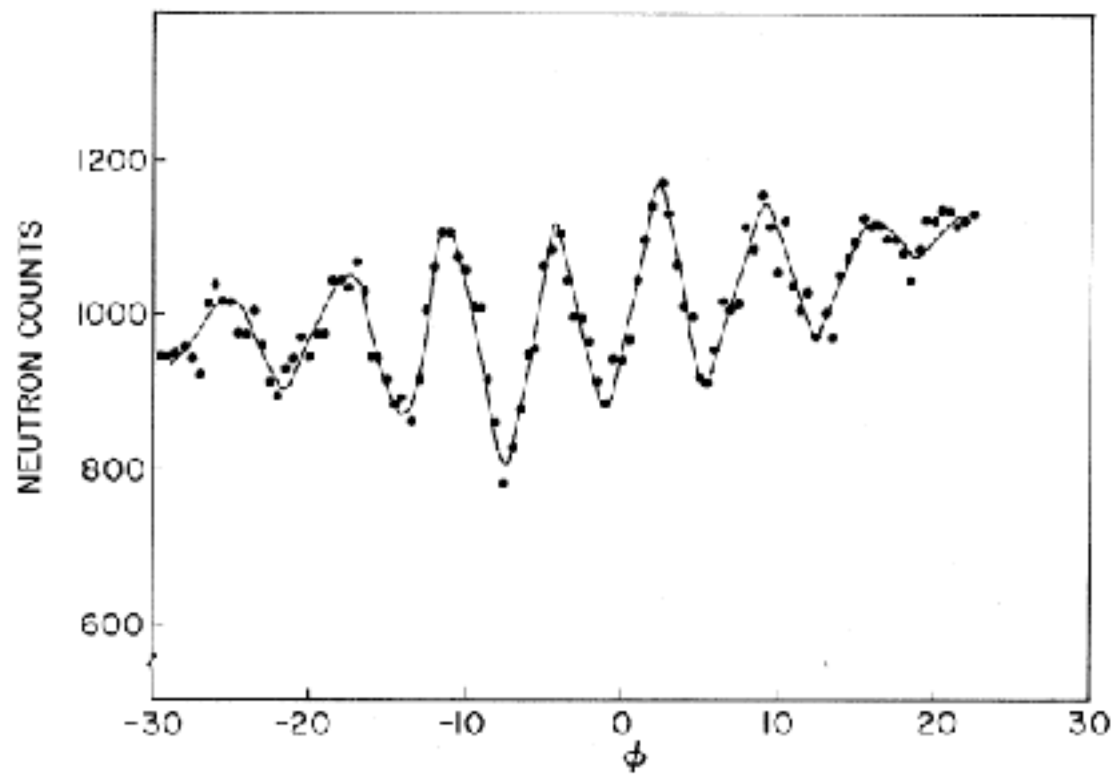

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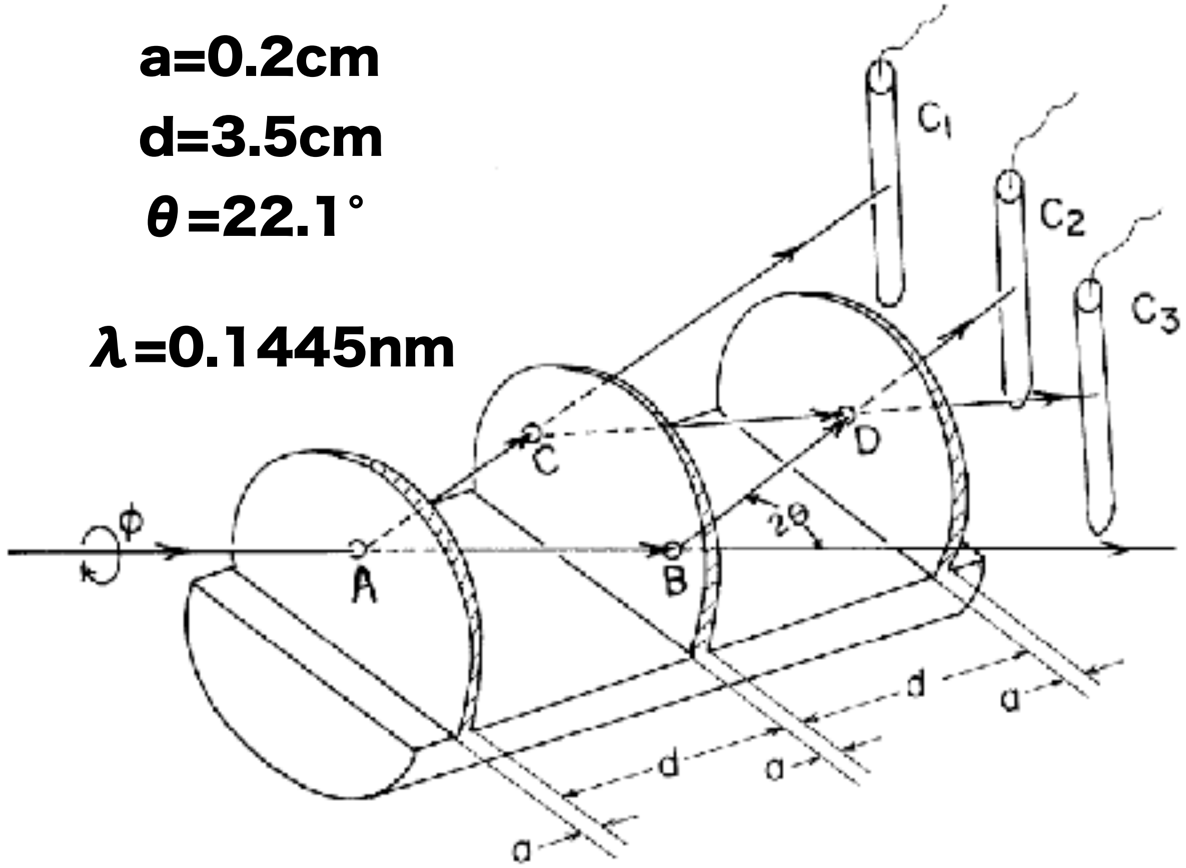

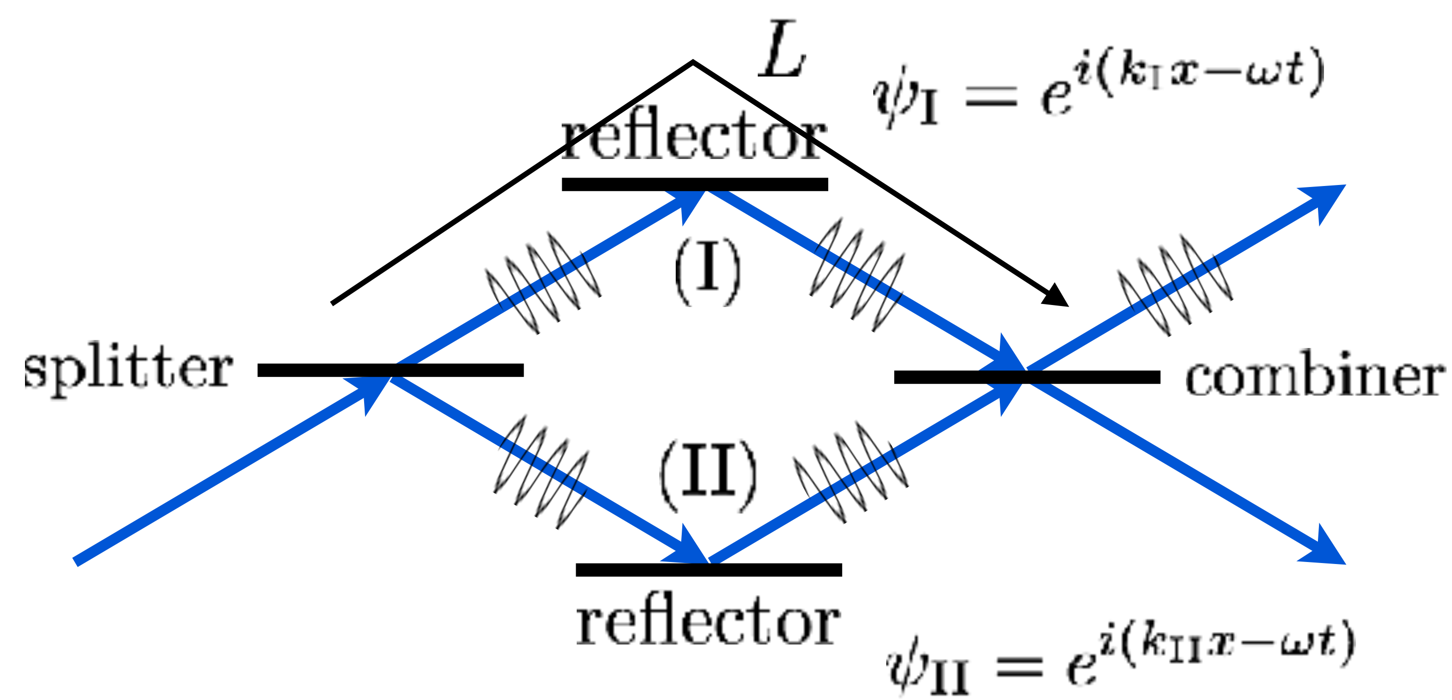

$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\mathrm{I}} = k_{\mathrm{I}}L$$

$$k_{\mathrm{II}} = \frac{\sqrt{2m_n(E_0+U+\Delta U)}}{\hbar} \qquad \phi_{\mathrm{II}} = k_{\mathrm{II}}L$$

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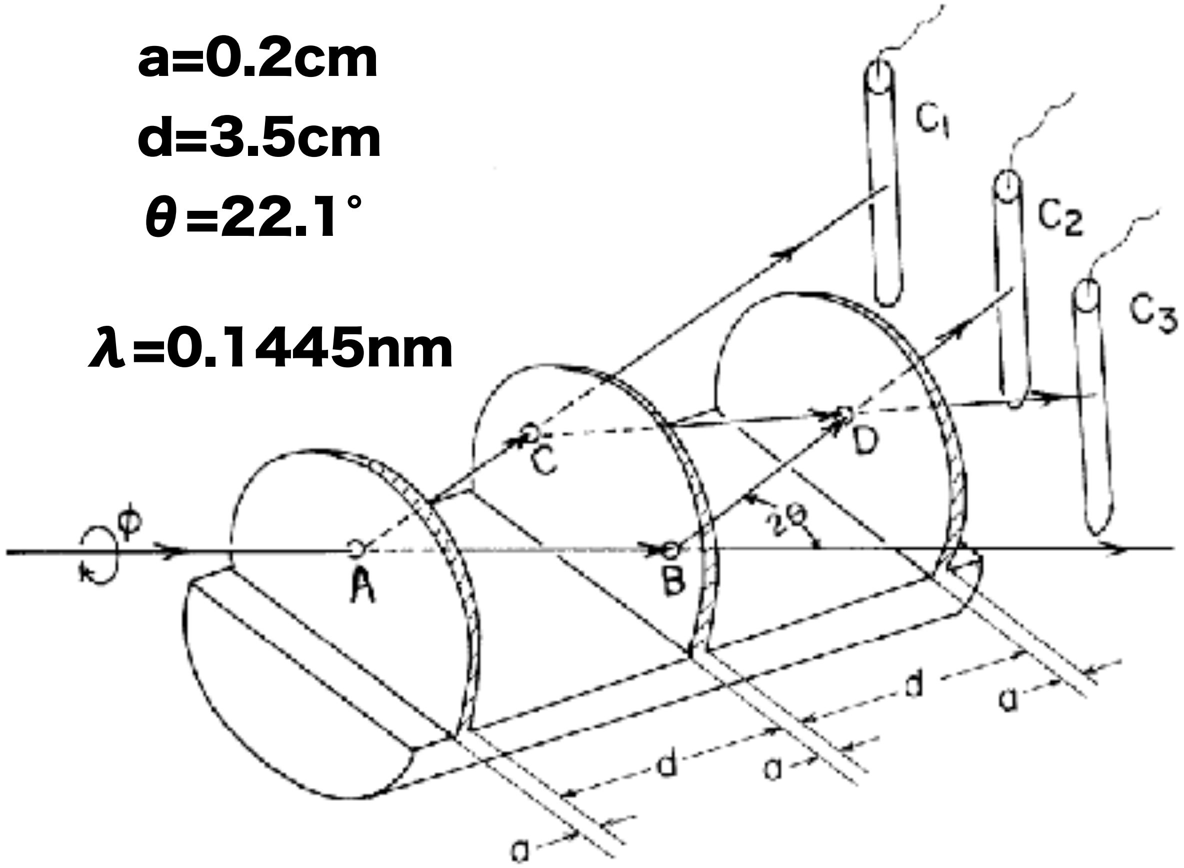

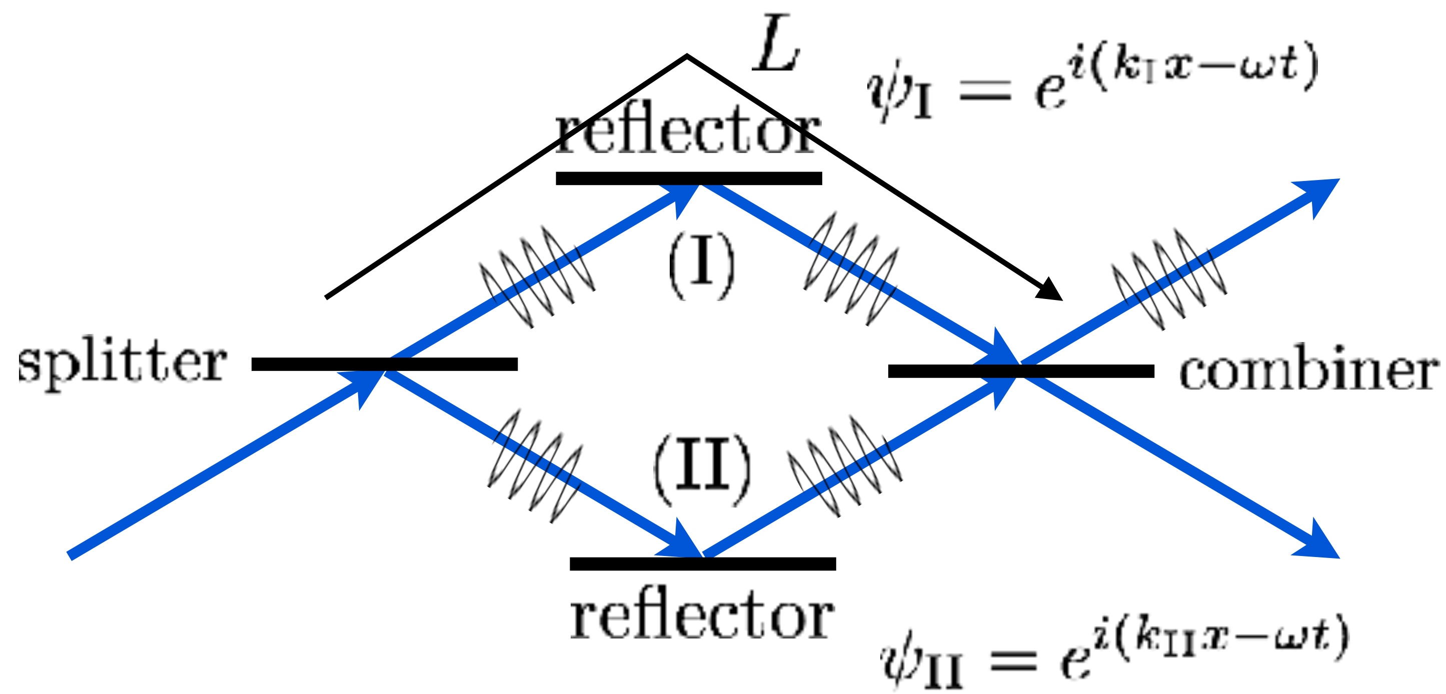

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larger interferometer

$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\frac{\boxed{L}\Delta U}{\hbar c}$$

better statistics

slower neutron

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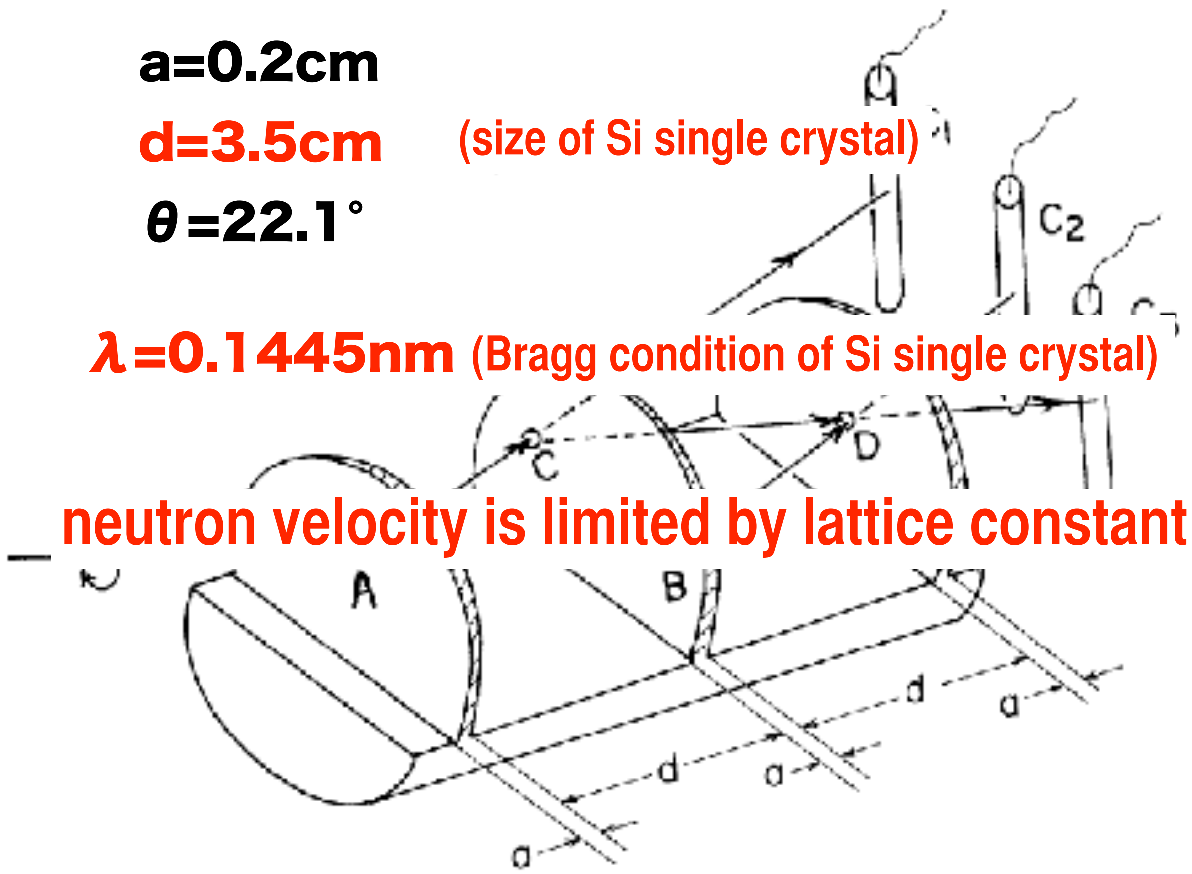
a=0.2cm

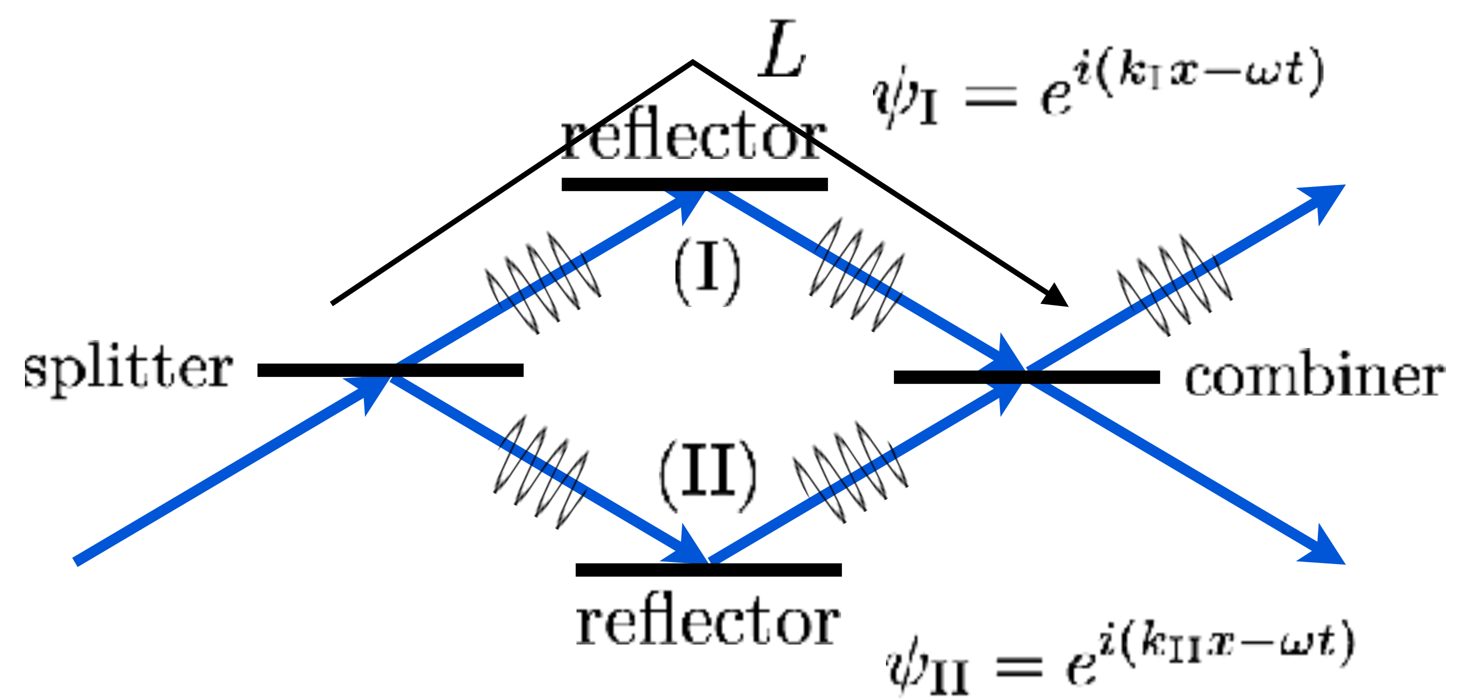
d=3.5cm (size of Si single crystal)

θ=22.1°

λ=0.1445nm (Bragg condition of Si single crystal)

neutron velocity is limited by lattice constant





$$k_{\rm I} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\rm I} = k_{\rm I} L$$

$$k_{\rm II} = \frac{\sqrt{2m_n(E_0+U+\Delta U)}}{\hbar} \qquad \phi_{\rm II} = k_{\rm II} L$$

larger interferometer

$$\boxed{\Delta\phi} = \phi_{\rm II} - \phi_{\rm I} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}} \frac{\boxed{L}\Delta U}{\hbar c}$$

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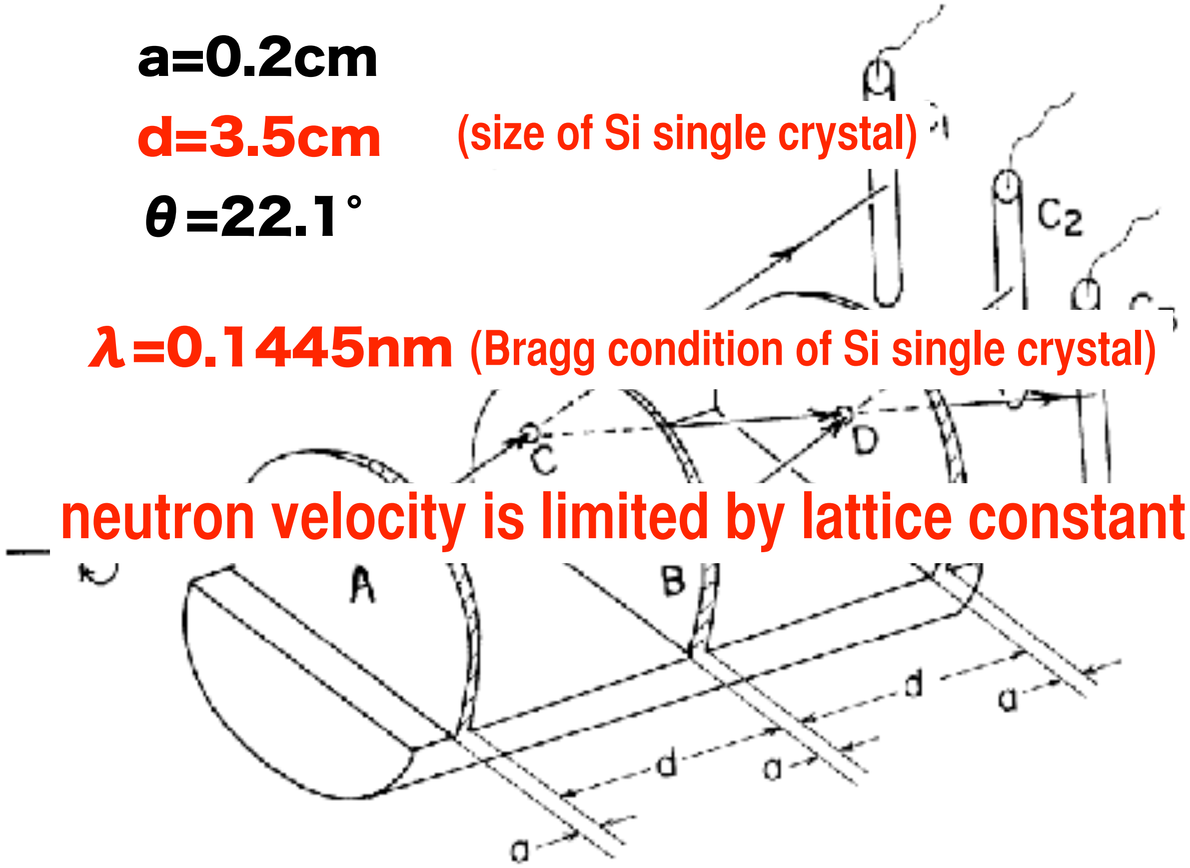

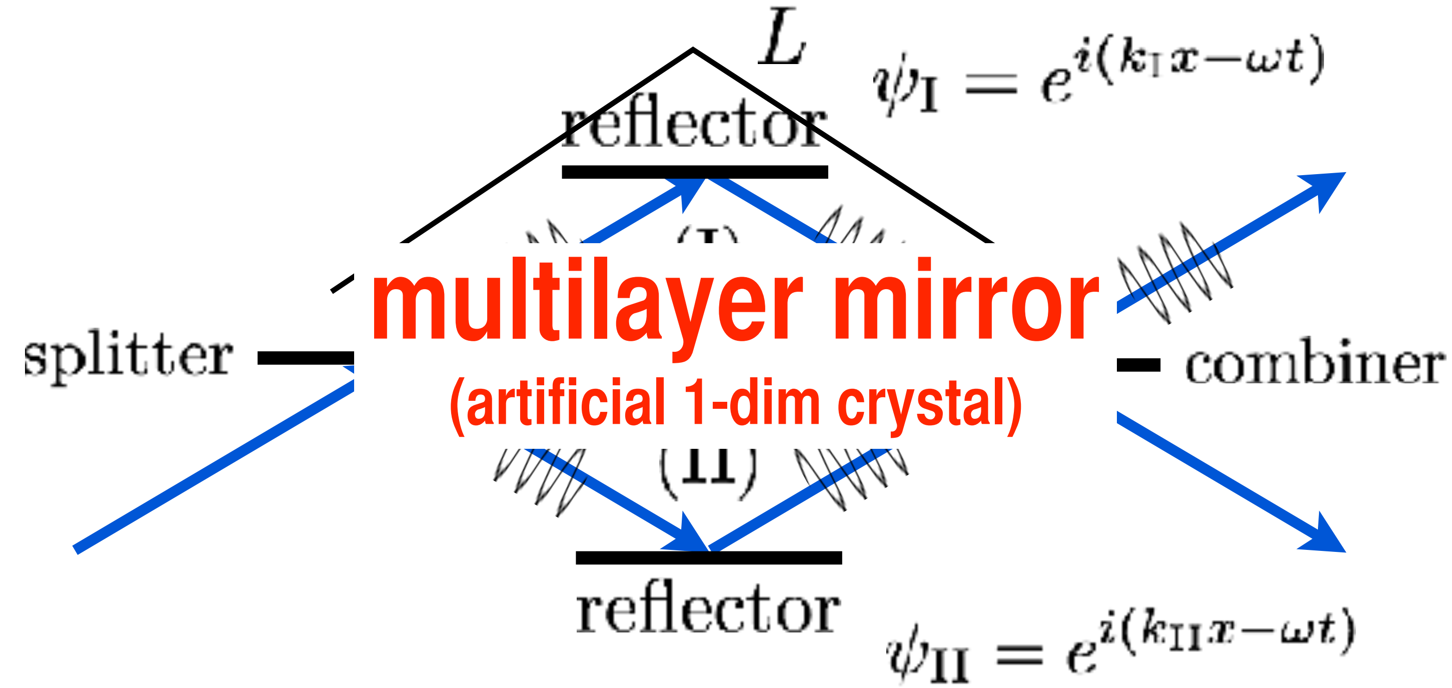

multilayer mirror

(artificial 1-dim crystal)

$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0 + U)}}{\hbar} \qquad \phi_{\mathrm{I}} = k_{\mathrm{I}} L$$

$$k_{\mathrm{II}} = \frac{\sqrt{2m_n(E_0 + U + \Delta U)}}{\hbar} \qquad \phi_{\mathrm{II}} = k_{\mathrm{II}} L$$

larger interferometer

$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\frac{\boxed{L}\Delta U}{\hbar c}$$

better statistics

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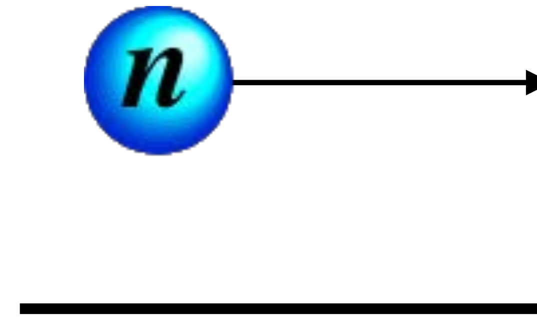
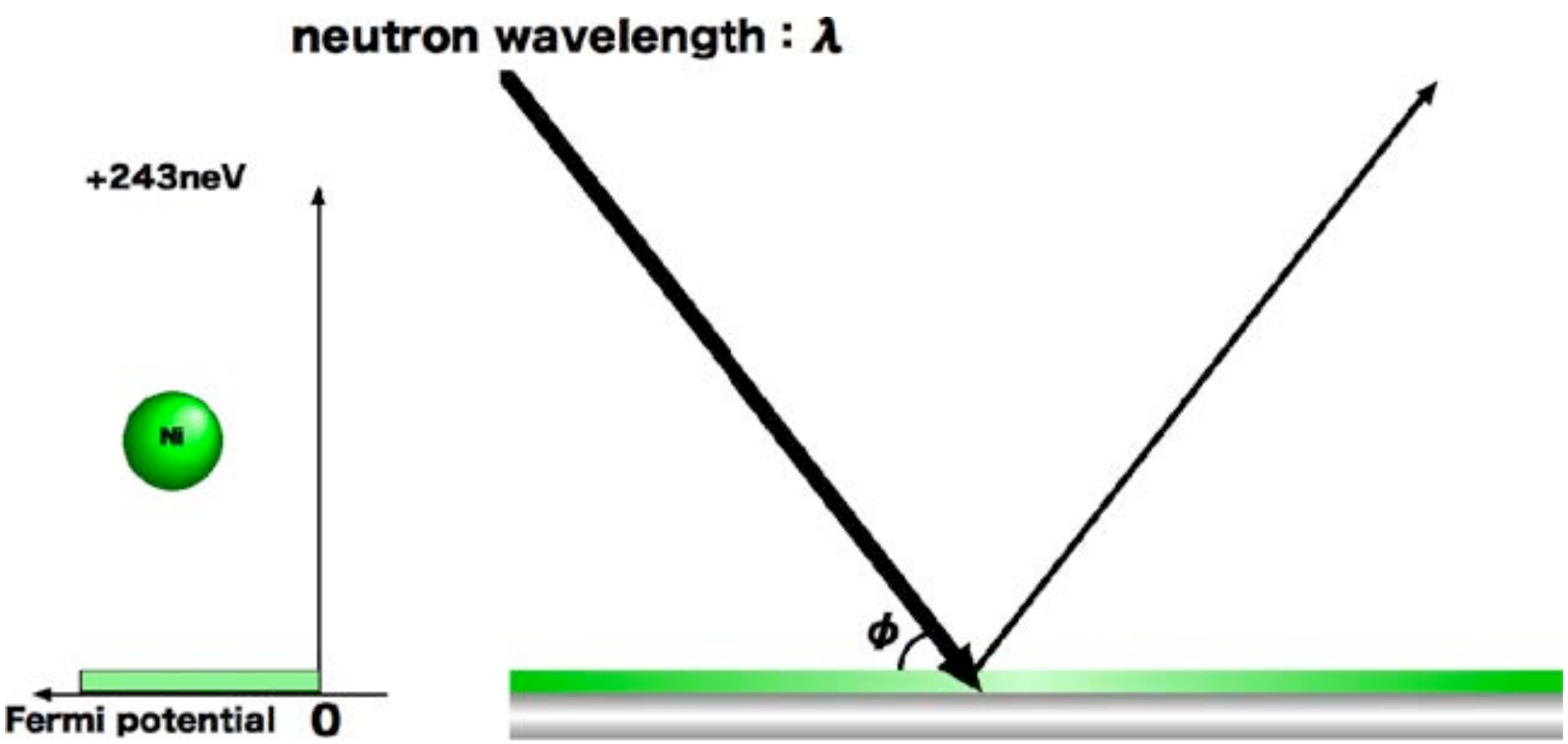
Neutron Reflection

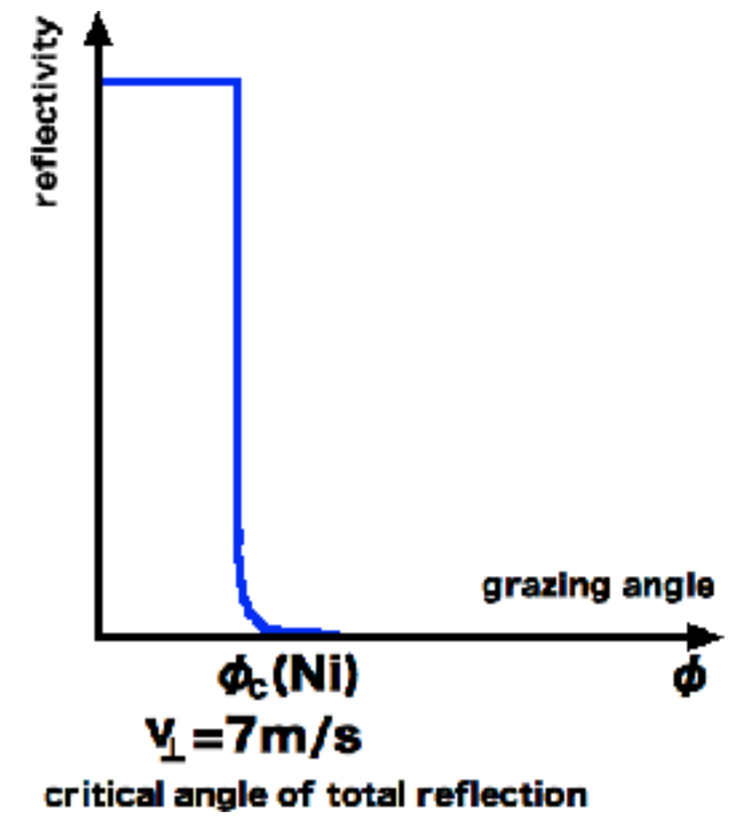
Fermi pseudopotential



$$U = \frac{2\pi\hbar^2}{m_{\rm n}} bN$$

$m_{\rm n}$: neutron mass
b : scattering length
N : atomicnumber density

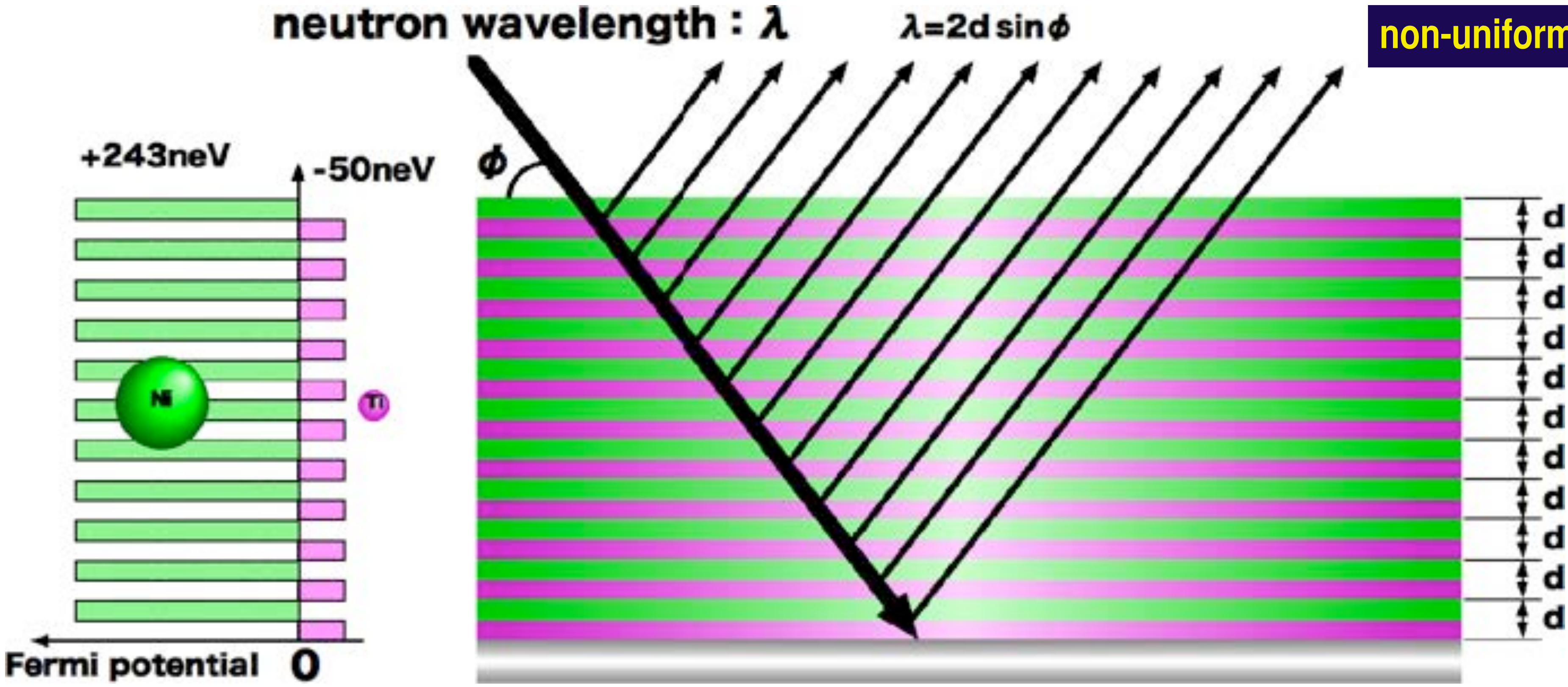




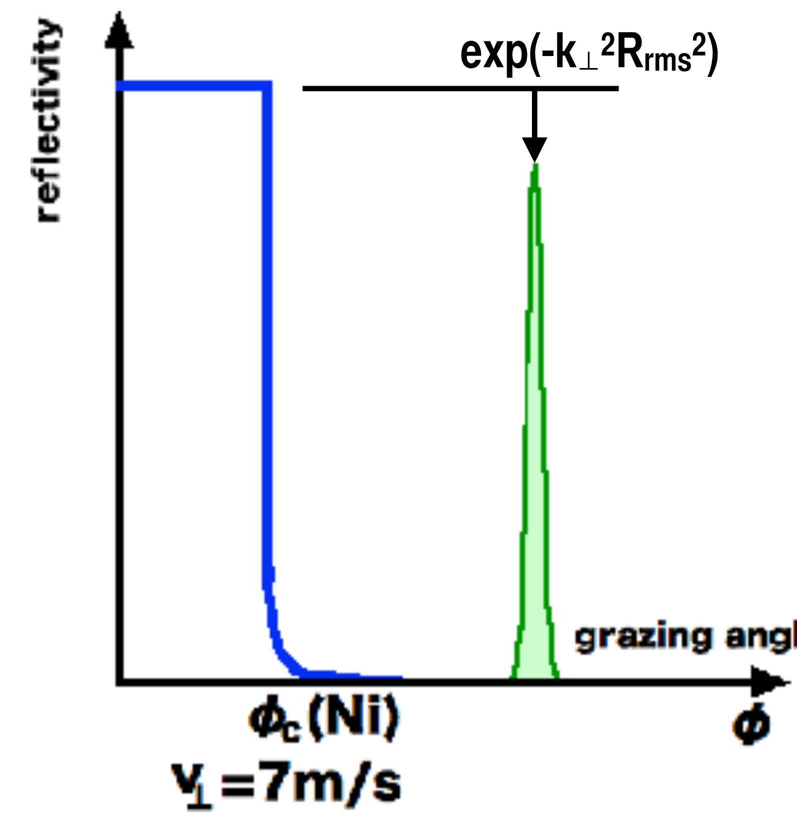
$$\frac{\phi_{\rm c}({\rm Ni})}{\lambda_{\rm n}} = 1.7\,[{\rm mrad}\,\text{Å}^{-1}]$$

$$v_{\perp}({\rm Ni}) = 7\,{\rm m/s}$$

Multilayer Mirror



non-uniformity and roughness decreases the reflectivity

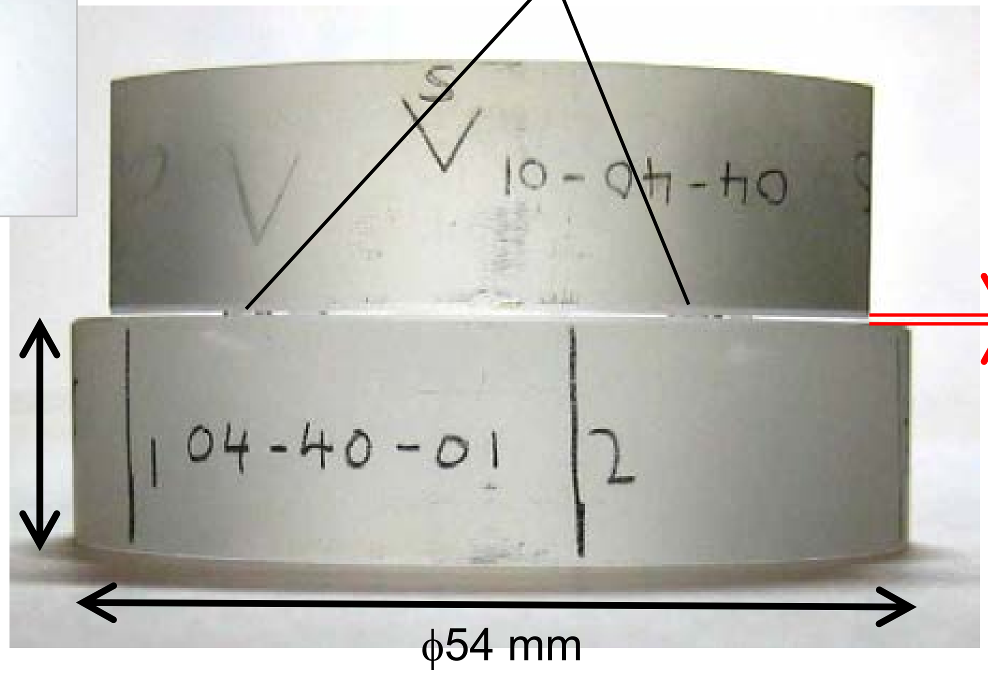


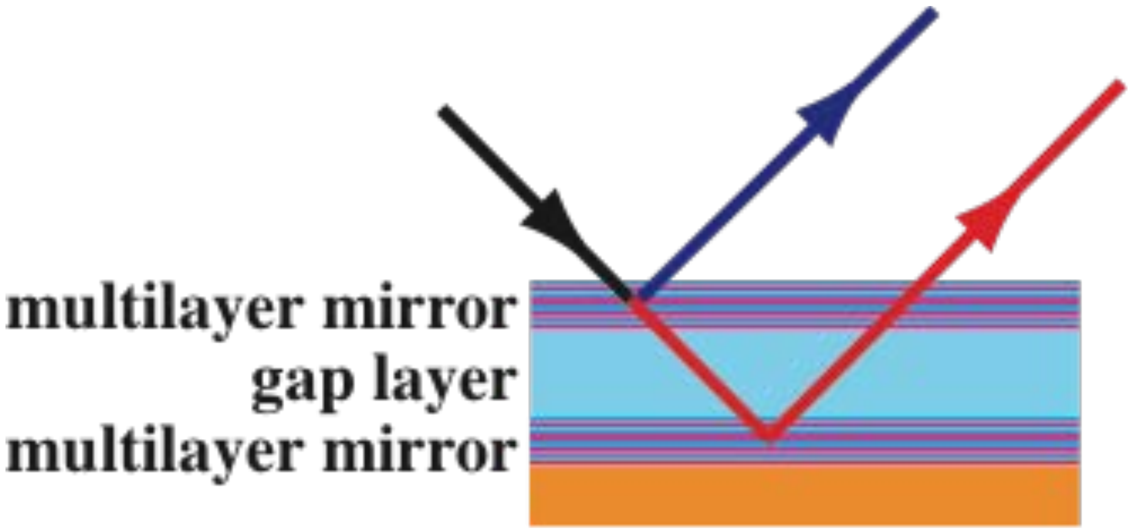
$$\frac{\phi_c(\mathrm{Ni})}{\lambda_n} = 1.7\,[\mathrm{mrad}\,\mathrm{\AA}^{-1}]$$

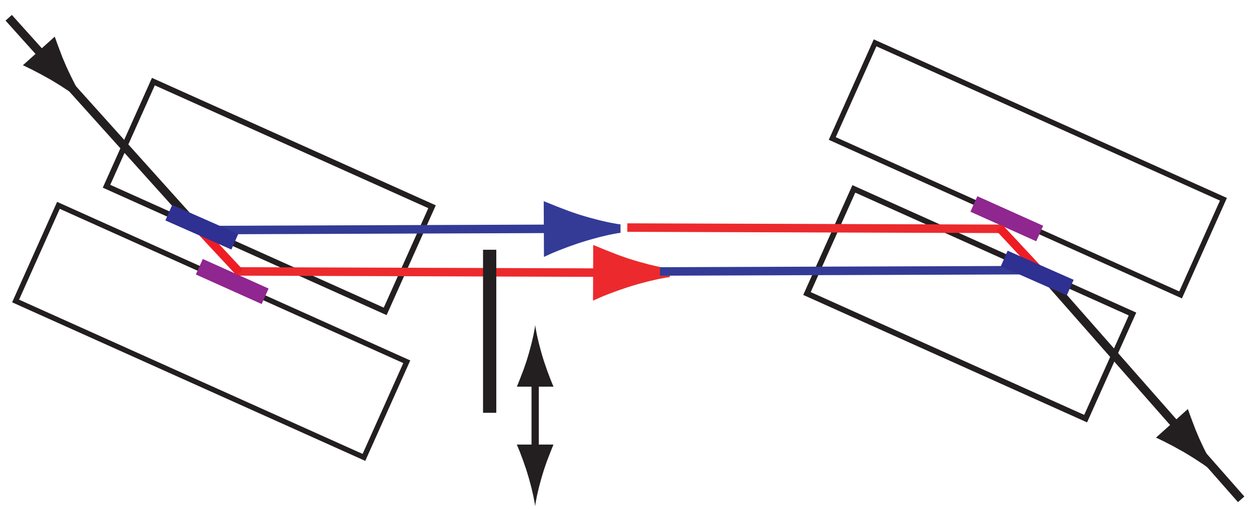
$$v_\perp(\mathrm{Ni}) = 7\,\mathrm{m/s}$$

Mirror Alignment

Y. Seki et al., J. Phys. Soc. Jpn. 79 (2010) 124201.







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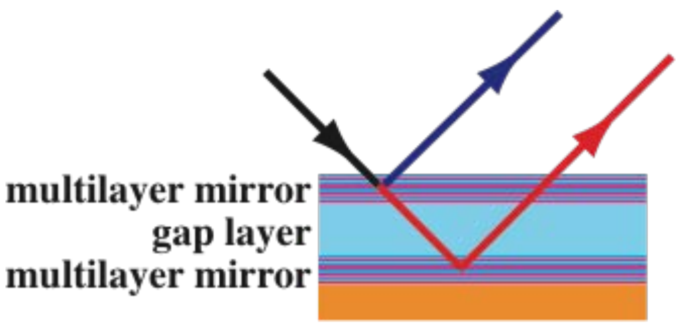

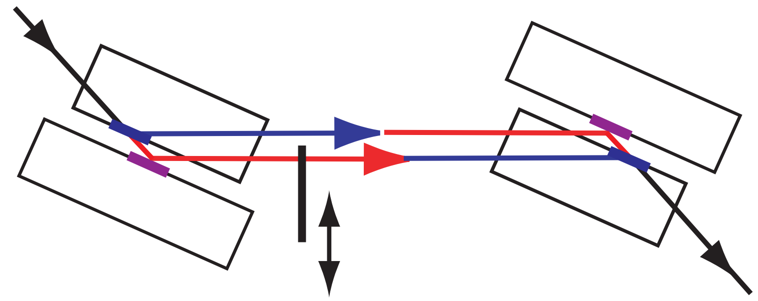

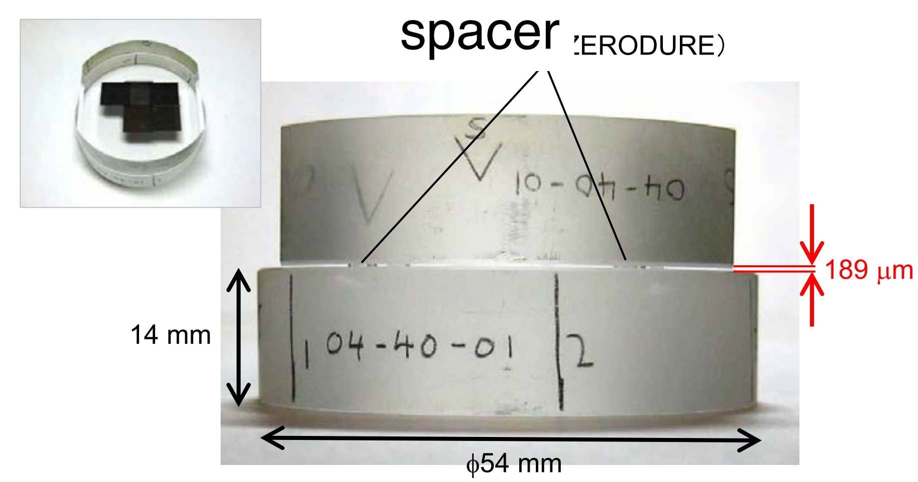

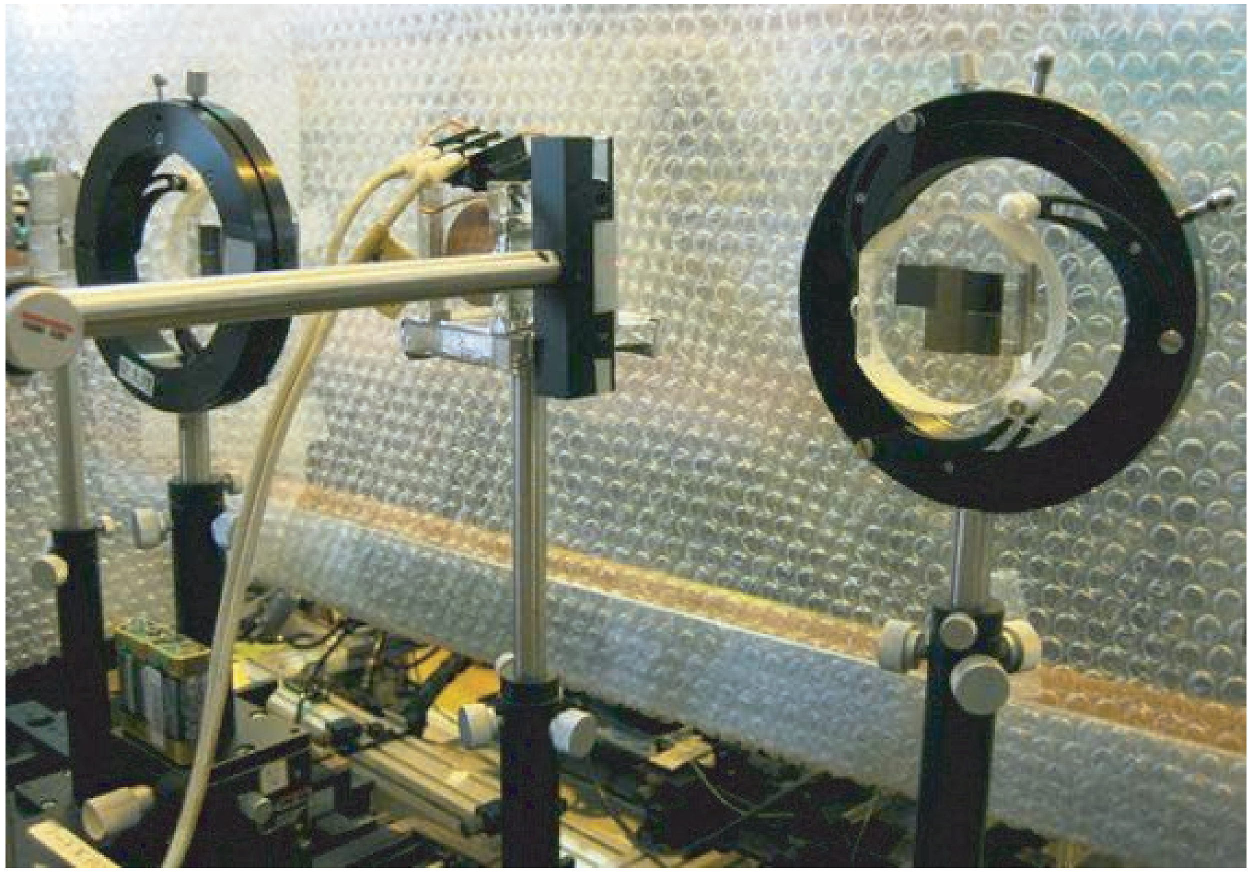

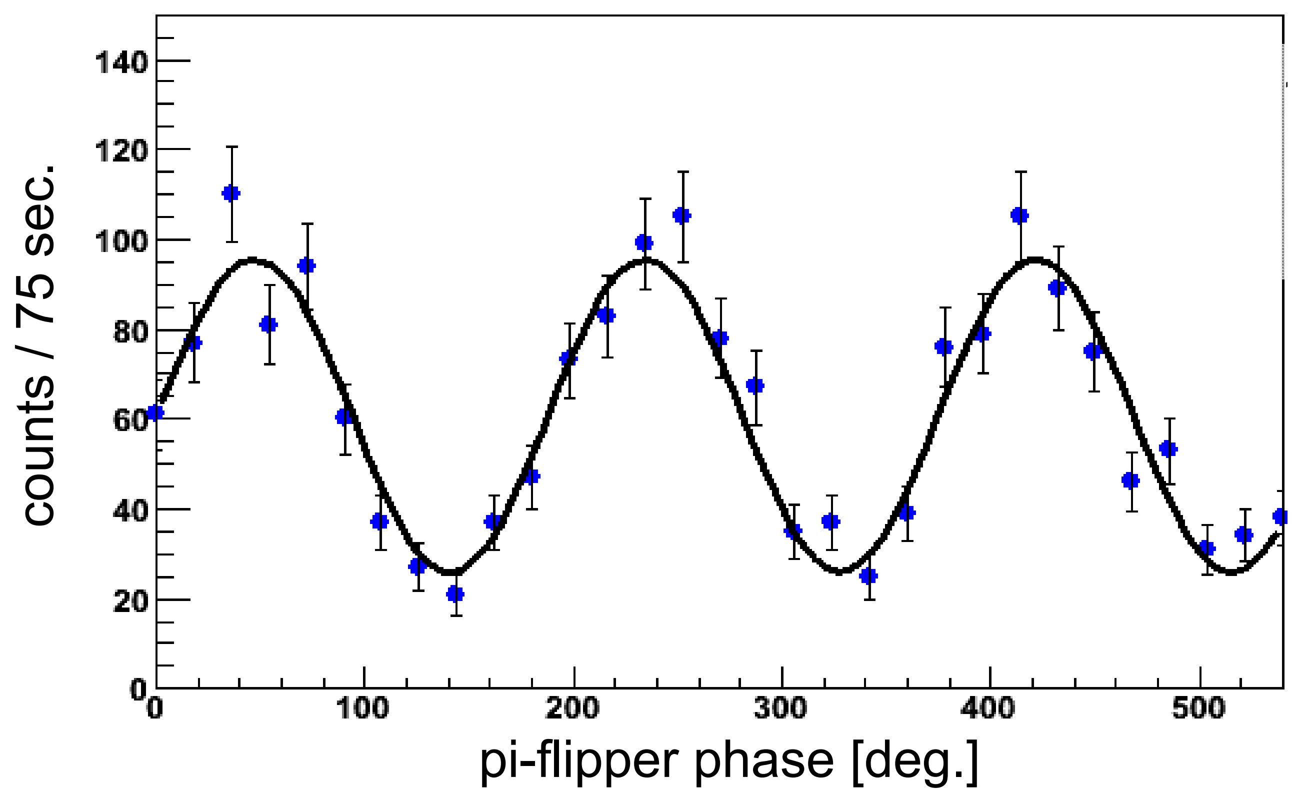

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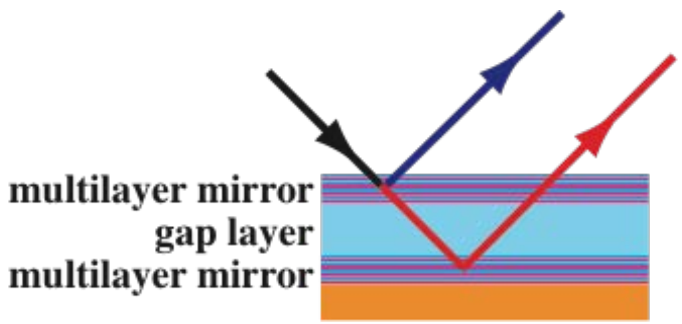
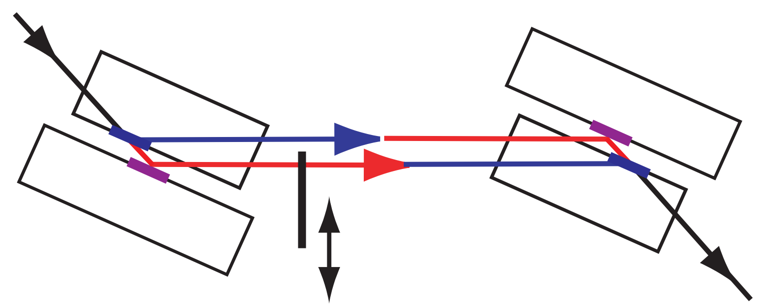
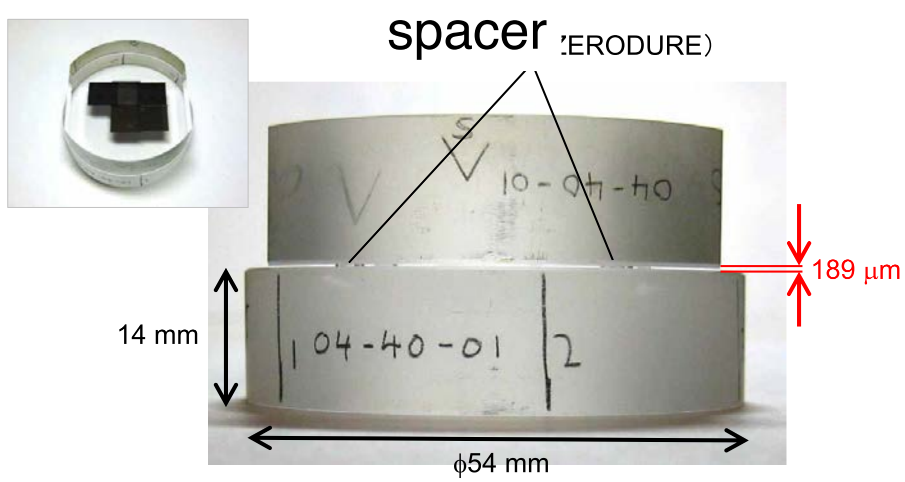
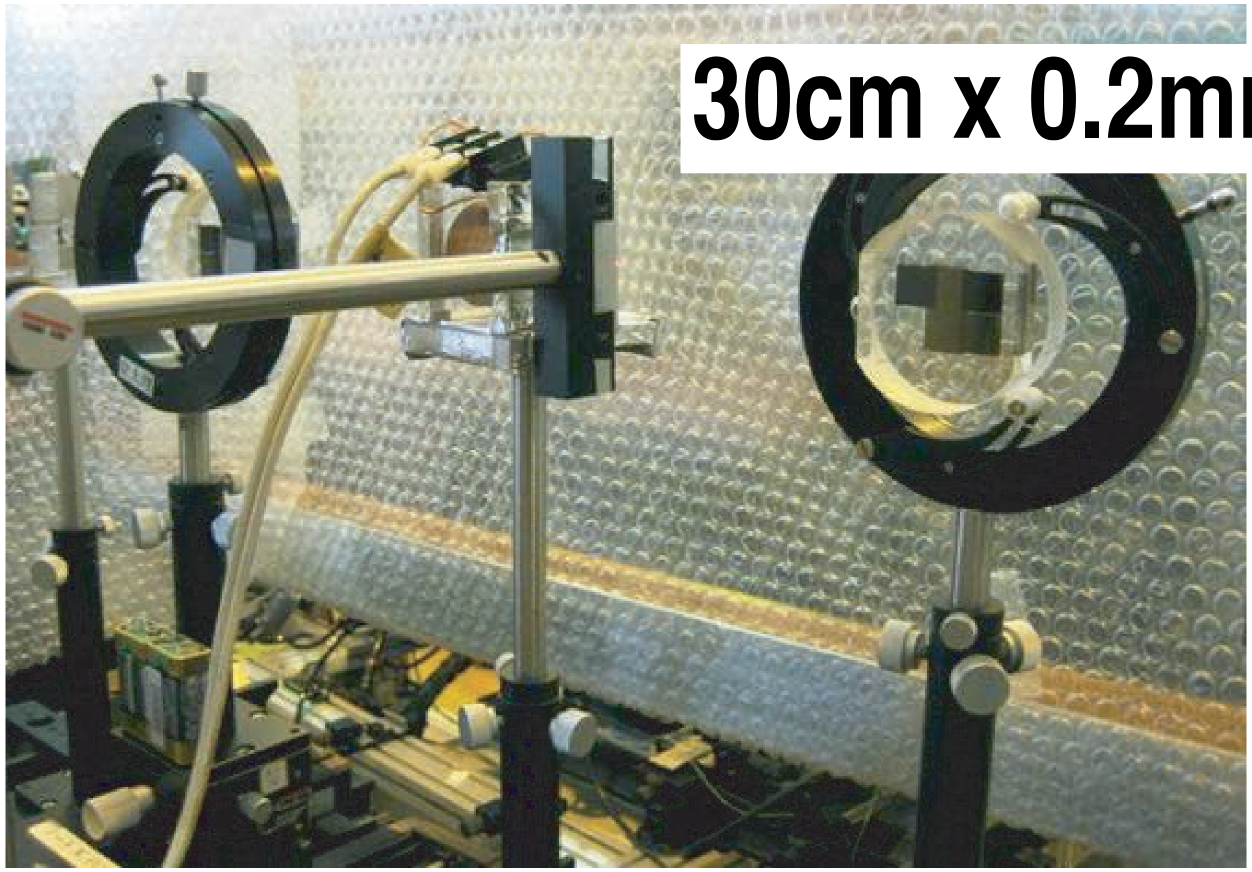
Y. Seki et al., J. Phys. Soc. Jpn. 79 (2010) 124201.

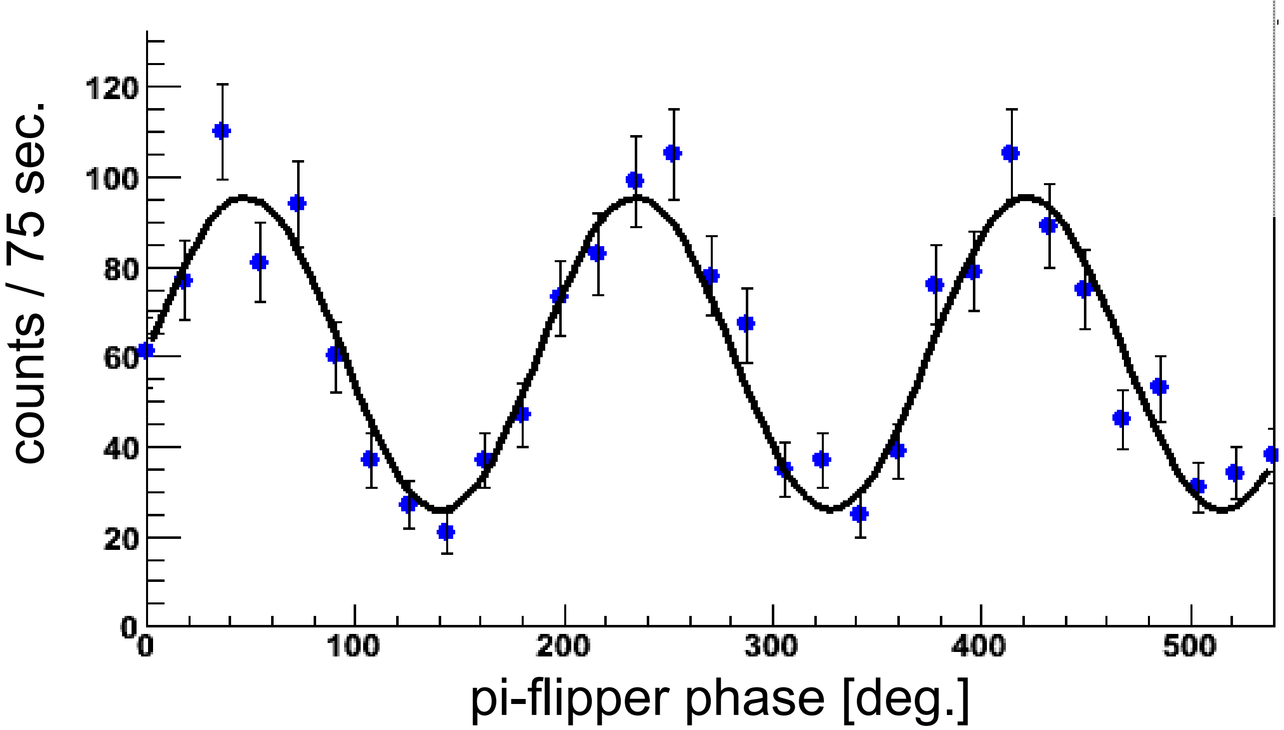




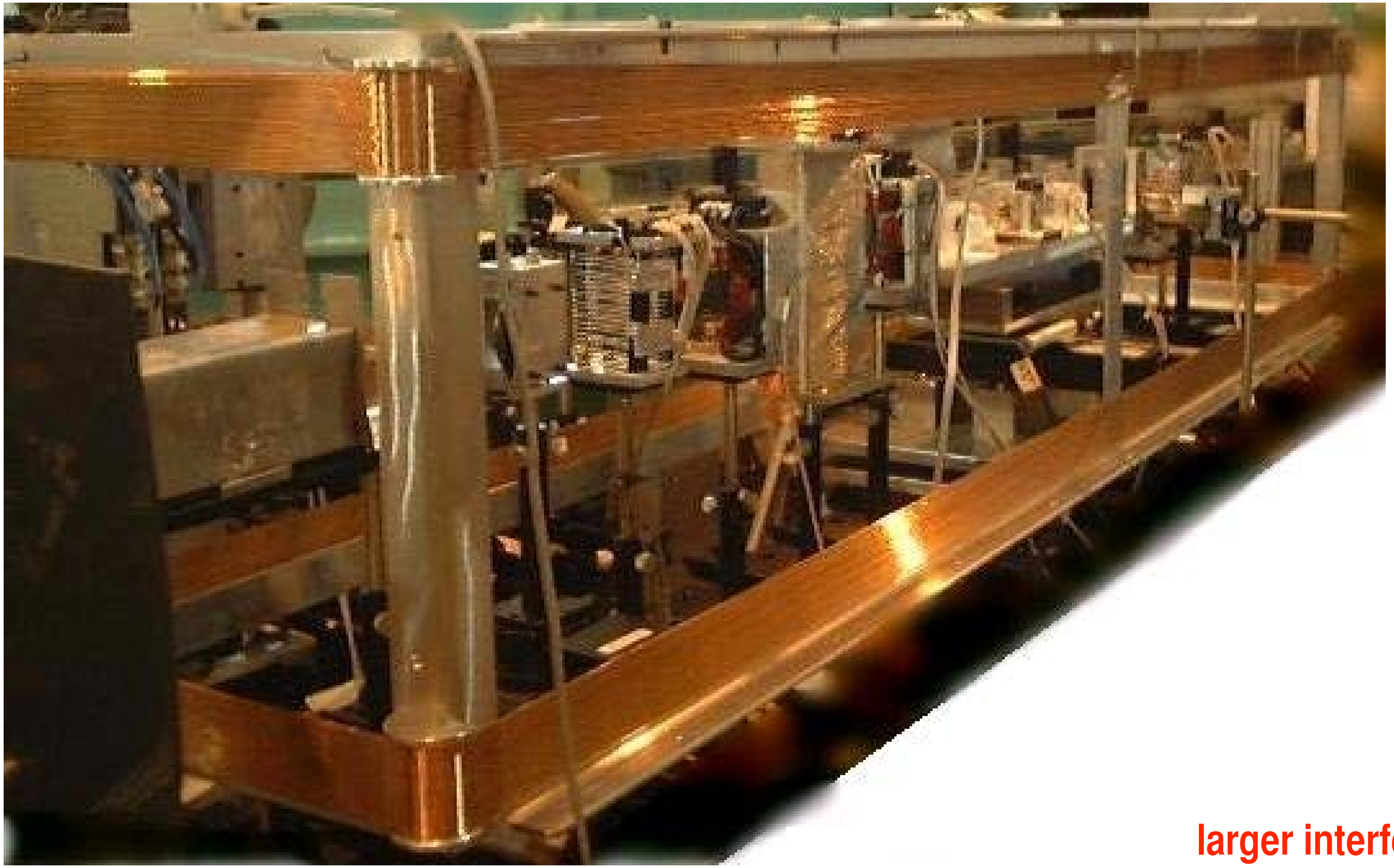




30cm x 0.2mm ~ 10^{-4} m^2



Multilayer Neutron Interferometer



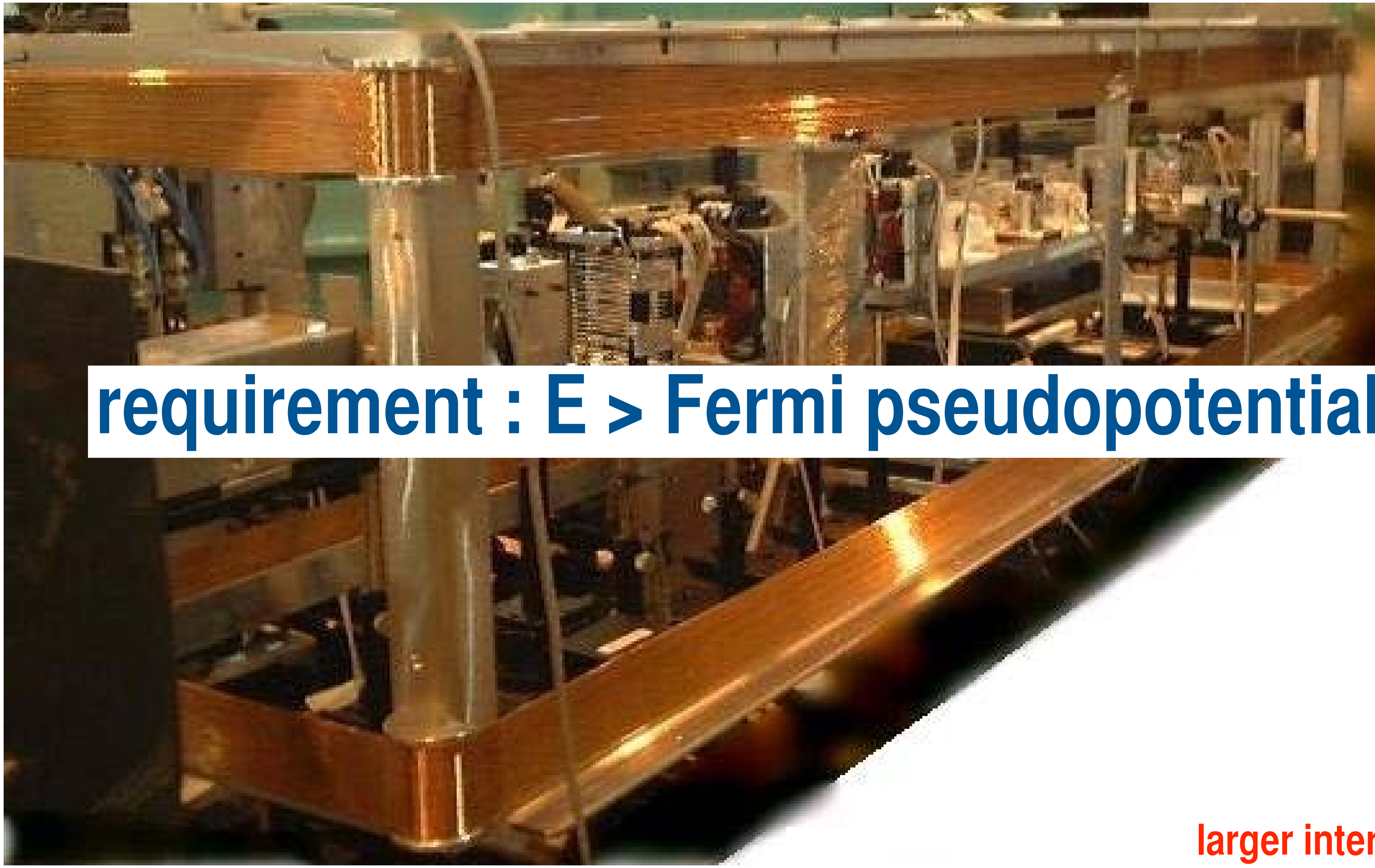
larger interferometer

$$\boxed{\Delta\phi} = \phi_{\rm II} - \phi_{\rm I} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\frac{\boxed{L}\Delta U}{\hbar c}$$

better statistics

slower neutron

Multilayer Neutron Interferometer



requirement : E > Fermi pseudopotential (0.25μeV)

λ<0.5nm

larger interferometer

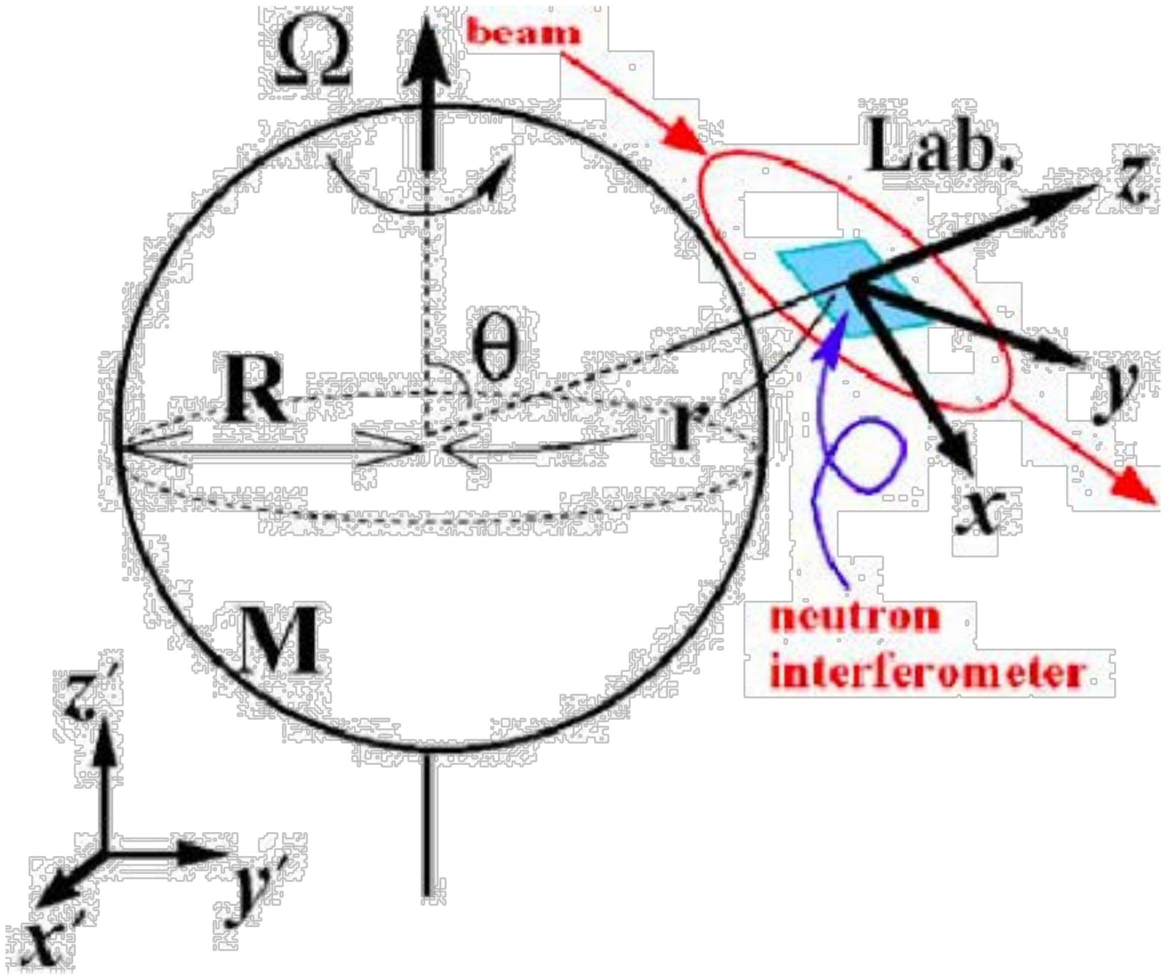
$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\,\Delta U}{\hbar c}$$

better statistics

slower neutron

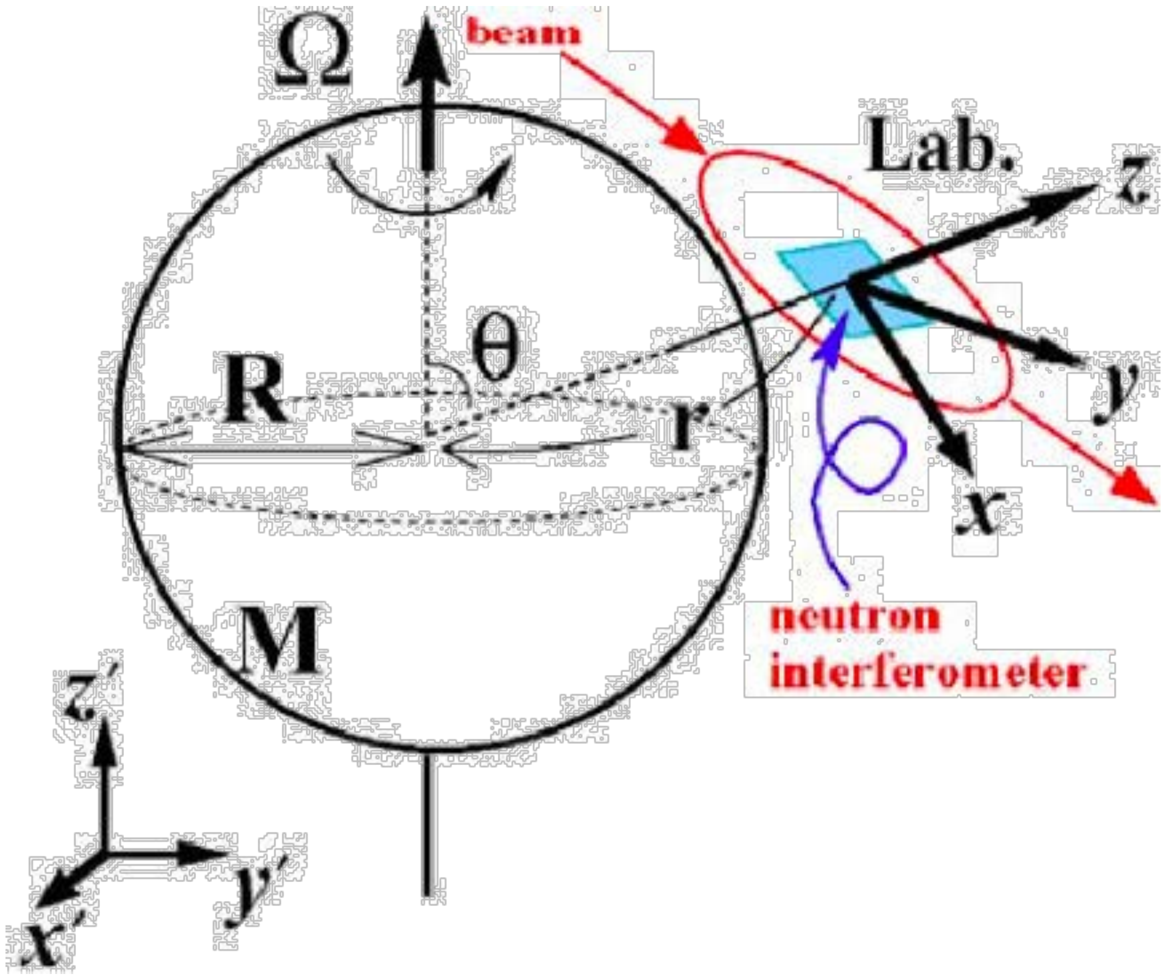
Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



$$\phi = -\frac{GM}{r}$$

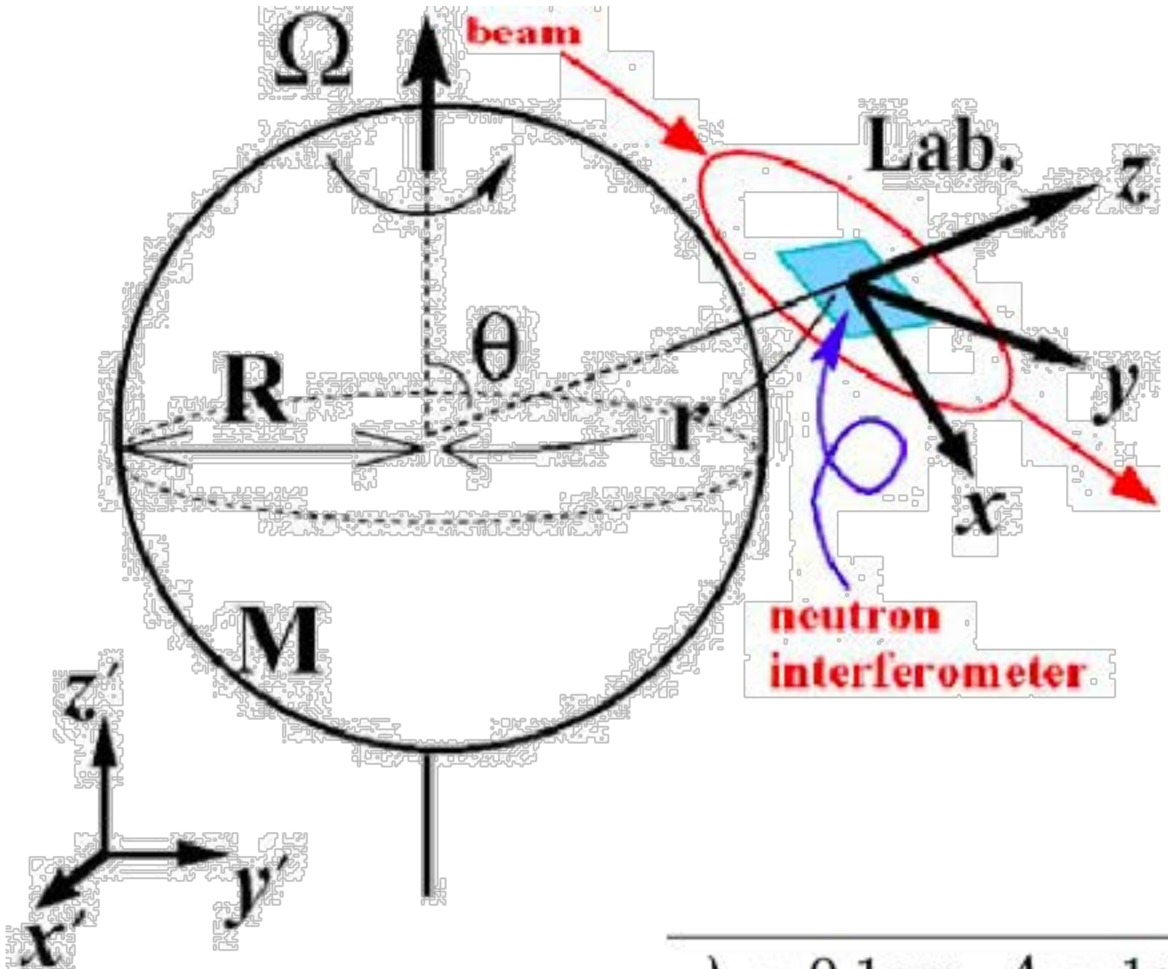
$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + m\phi - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$
$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S}) + \frac{6GMR^2}{5r^5}\boldsymbol{S}\cdot(\boldsymbol{r}\times(\boldsymbol{r}\times\boldsymbol{\Omega}))\right)$$

Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



$$\phi = -\frac{GM}{r}$$

$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$

	$m\phi$	$4GMR^2\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})/5r^3c^2$
$\lambda \sim 0.1\mathrm{nm},\ A \sim 1\mathrm{cm} \times 1\mathrm{cm}$	5	10^{-10}
$\lambda \sim 1.0\mathrm{nm},\ A \sim 1\mathrm{m} \times 1\mathrm{m}$	10^5	10^{-6}

COW

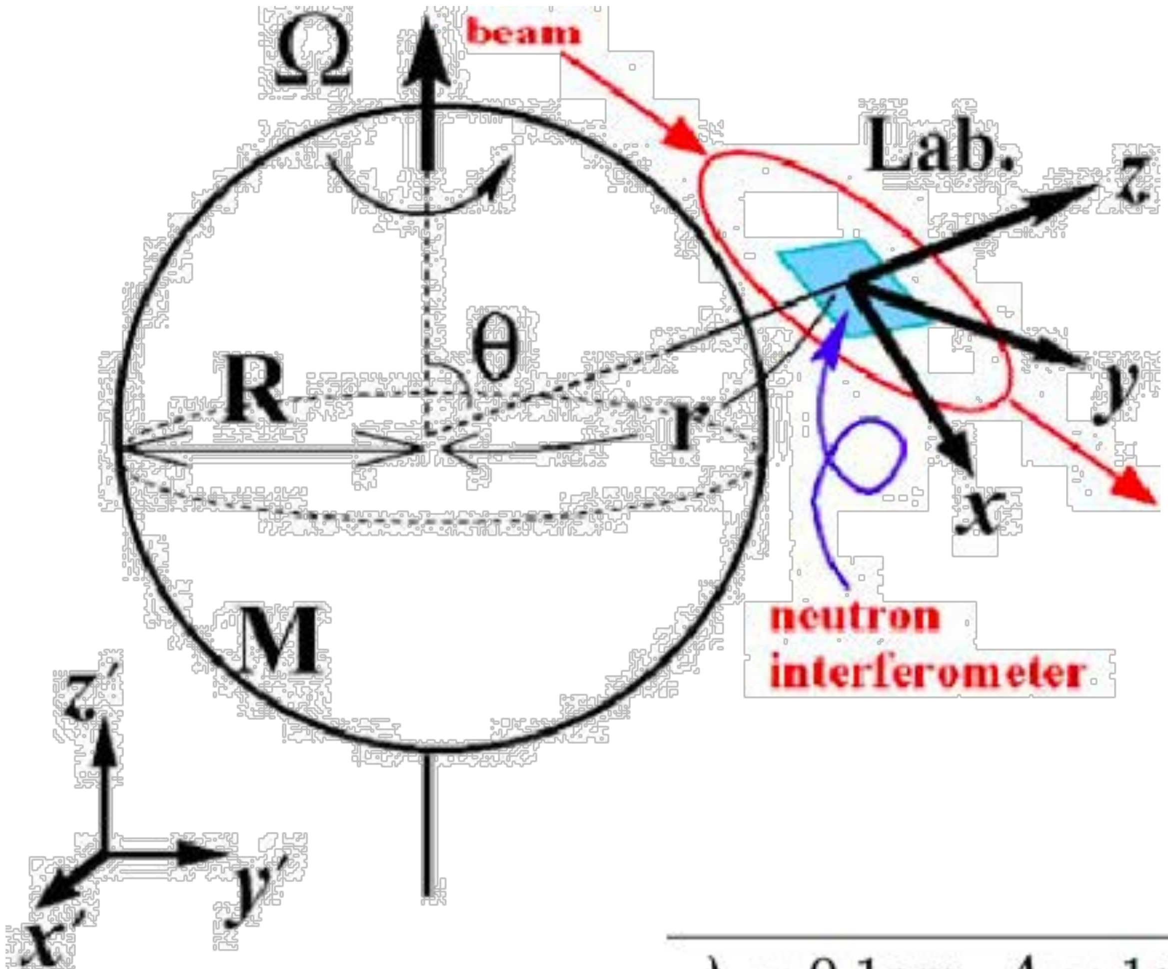
$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + \boxed{m\phi} - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$

$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \boxed{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})} + \frac{6GMR^2}{5r^5}\boldsymbol{S}\cdot(\boldsymbol{r}\times(\boldsymbol{r}\times\boldsymbol{\Omega}))\right)$$

Lense-Thirring

Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



$$\phi = -\frac{GM}{r}$$

$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$

	$m\phi$	$4GMR^2\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})/5r^3c^2$
$\lambda \sim 0.1\text{nm},\ A \sim 1\text{cm} \times 1\text{cm}$	5	10^{-10}
$\lambda \sim 1.0\text{nm},\ A \sim 1\text{m} \times 1\text{m}$	10^5	$\boxed{10^{-6}}$

accessible with J-PARC

COW

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + \boxed{m\phi} - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$

$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \boxed{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})} + \frac{6GMR^2}{5r^5}\boldsymbol{S}\cdot(\boldsymbol{r}\times(\boldsymbol{r}\times\boldsymbol{\Omega}))\right)$$

Lense-Thirring

Neutrons for General Relativity

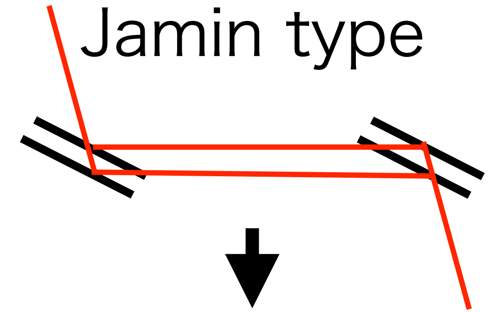
post-Newtonian terms

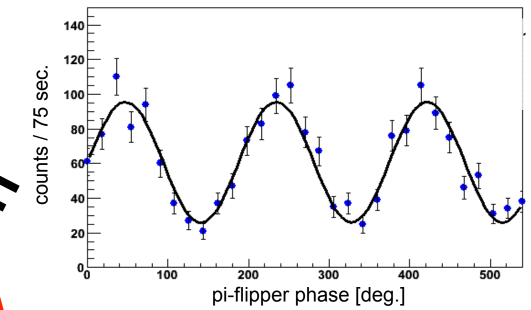
$$
\begin{aligned}
\mathcal{H} \;=\; & \frac{\boldsymbol{p}}{2m_n} + \underline{m\phi} + \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S}) \\
& + \frac{1}{c^2}\Bigg(\underline{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})} - \frac{\boldsymbol{p}^4}{8m^3} + \frac{m\phi^2}{2} + \frac{3\boldsymbol{p}\cdot\phi\boldsymbol{p}}{2m} \\
& + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{6GMR^3}{5r^5}\boldsymbol{S}\cdot[r\times(r\times\Omega)]\Bigg)
\end{aligned}
$$

	COW $m\phi$	Lense-Thirring $4GMR^2\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})/5r^3c^2$
$\lambda \sim 0.1\mathrm{nm},\ A \sim 1\mathrm{cm}\times 1\mathrm{cm}$	5	10^{-10}
$\lambda \sim 1.0\mathrm{nm},\ A \sim 1\mathrm{m}\times 1\mathrm{m}$	10^5	10^{-6}

$1\mathrm{m}^2$, long-wavelength interferometer
can search the effect of General Relativity.

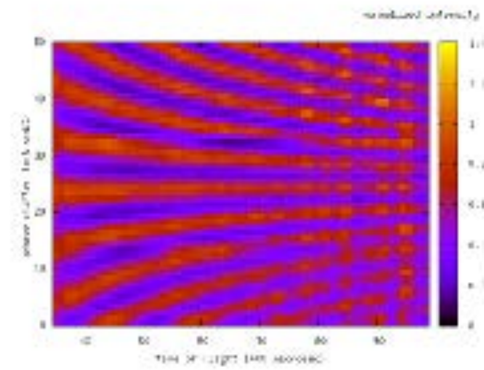
Jamin type





pulsed neutron

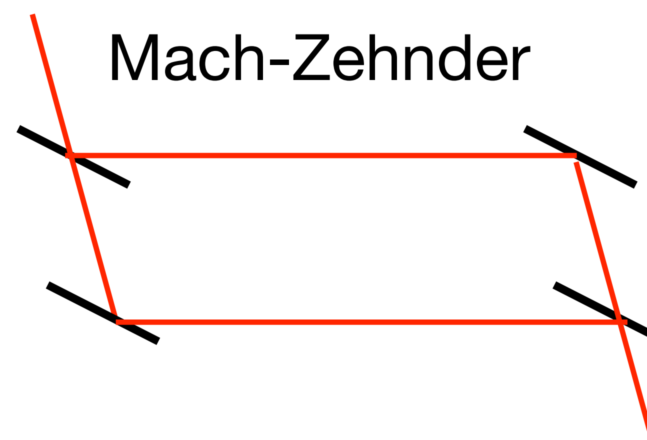
COW exp.



Slower
Larger

λ~100μm
S~1m²

Mach-Zehnder



post-Newtonian

Aromalous Gravity?

3-dim. Gravity

$$F_3(r) = G_3 \frac{m_1 m_2}{r^2}$$

N-dim. Gravity

$$F_N(r) = G_N \frac{m_1 m_2}{r^{N-1}}$$

continuity at r=R*

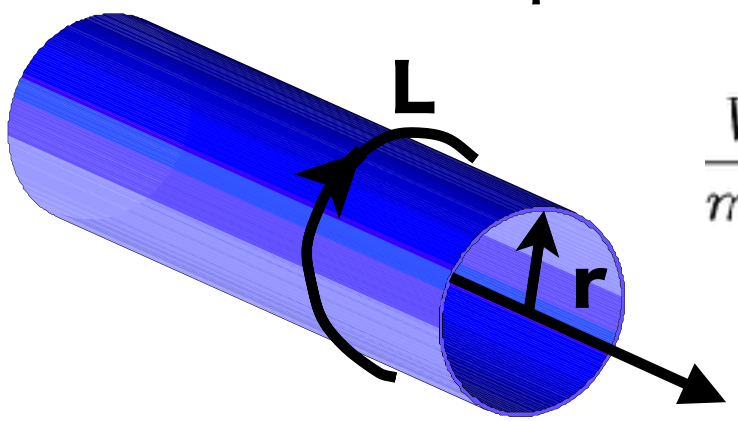
$$\frac{G_3}{R^{*2}} = \frac{G_N}{R^{*N-1}} \Rightarrow G_3 = \frac{G_N}{R^{*N-3}}$$

If R* is longer than the Planck's length, G_3 becomes smaller.

Parametrization: $$V(r) = -\frac{GM}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

KK-graviton, which is emitted off our brane with the momentum (q_1, q_2, ...,q_n) along the extradimension, looks having the mass |q|.

momentum is quantized in the unit of 2π/L in the extra-dimension



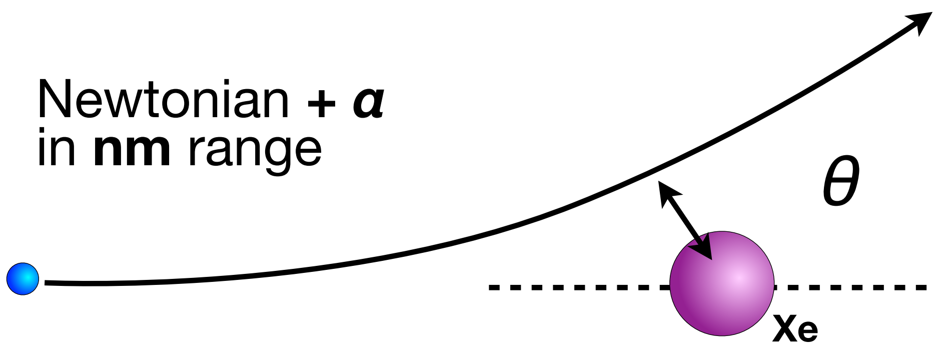
$$\frac{V(r)}{m_1 m_2} = G_3 \sum_{(k_1,\ldots,k_n)} \frac{e^{-\frac{2\pi|k|}{L}r}}{r} \xrightarrow[r \ll L]{} G_3 \frac{1}{r}\left(\frac{L}{2\pi r}\right)^n \int e^{-|u|} \mathrm{d}^n u$$

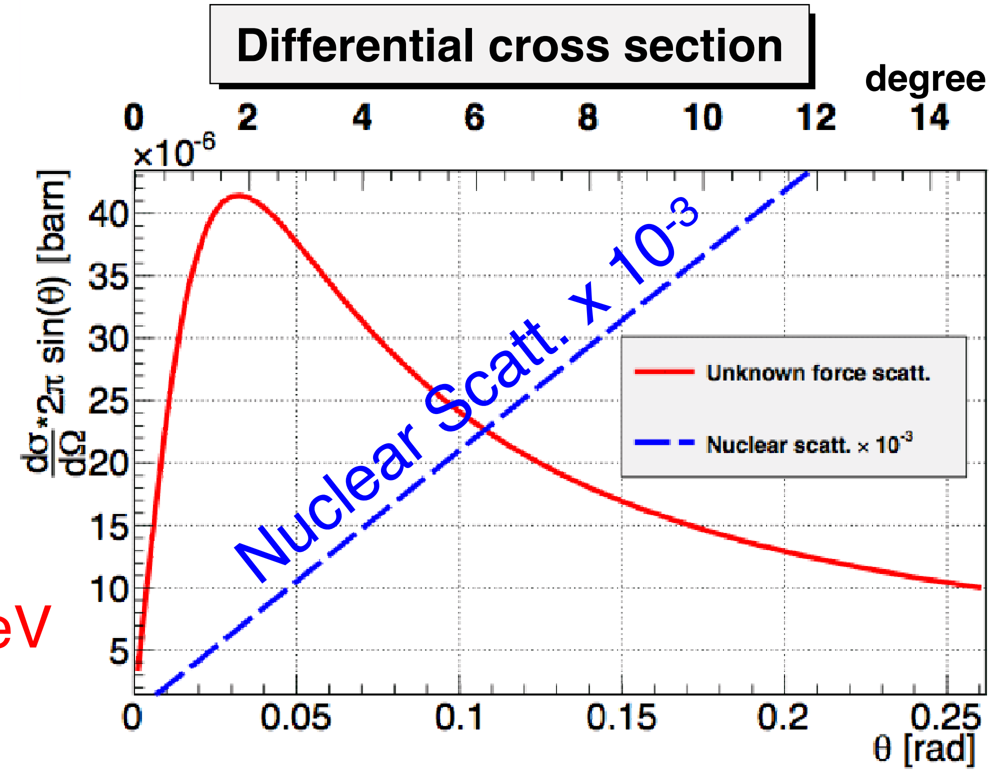
Scattering Experiment to study Intermediate-range Force

T.Yoshioka

Neutron Scattering by Noble Gas Atoms

search for deviations from nuclear scattering

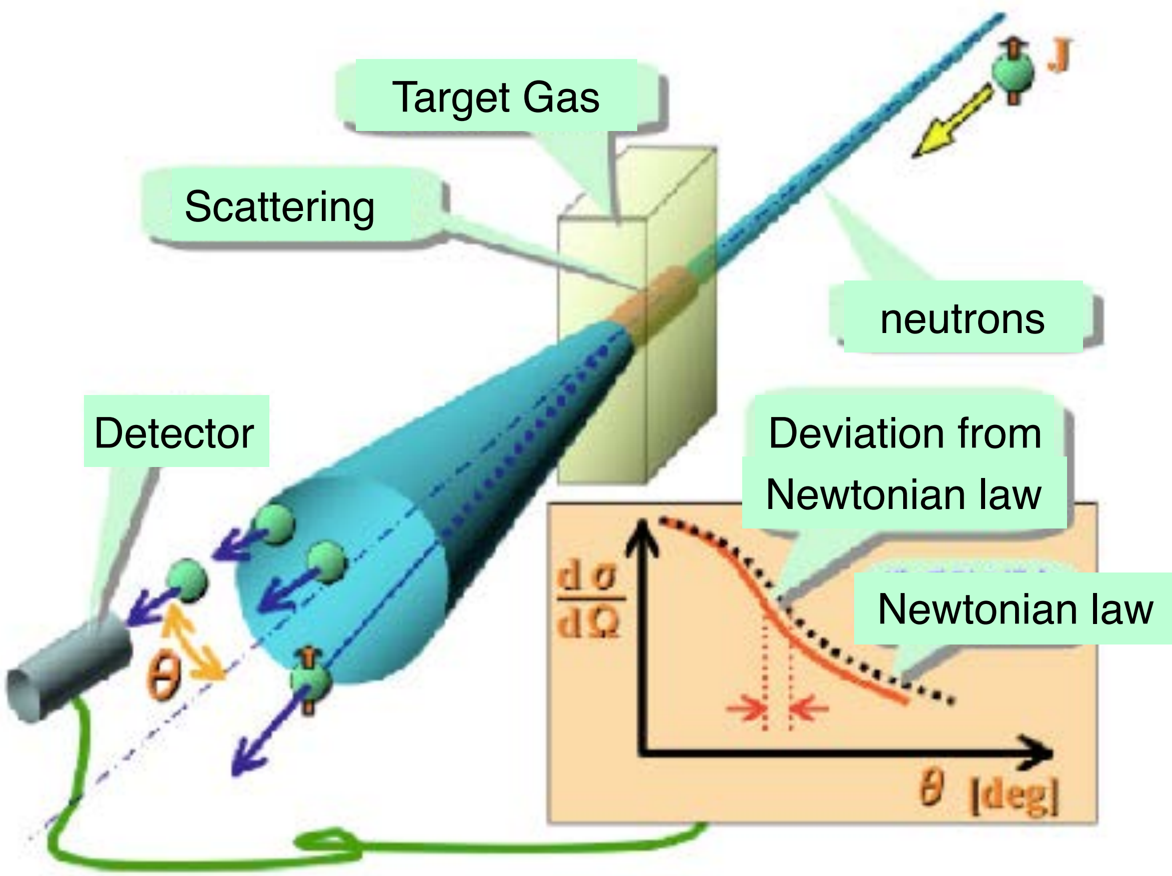




α=10^23

λ=0.5 nm

E_n=20 meV



$a_G \propto \alpha$

$$\frac{d\sigma(\theta)}{d\Omega} = [a_N + a_{ne} Z F_e(\theta) + a_G F_G(\theta)]^2$$

$$\simeq a_N^2 + 2a_N a_{ne} Z F_e(\theta) + a_{ne}^2 Z^2 F_e(\theta)^2 + 2 a_N a_G F_G(\theta)$$

$$\frac{d\sigma_G(\theta)}{d\Omega} = 2\cdot\sigma_N^{1/2}\cdot\alpha\cdot\left(\frac{G\cdot m_n\cdot M}{4}\right)\cdot\left(\frac{1}{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n\sin^2\frac{\theta}{2}}\right)$$

Scattering Experiment to study Intermediate-range Force

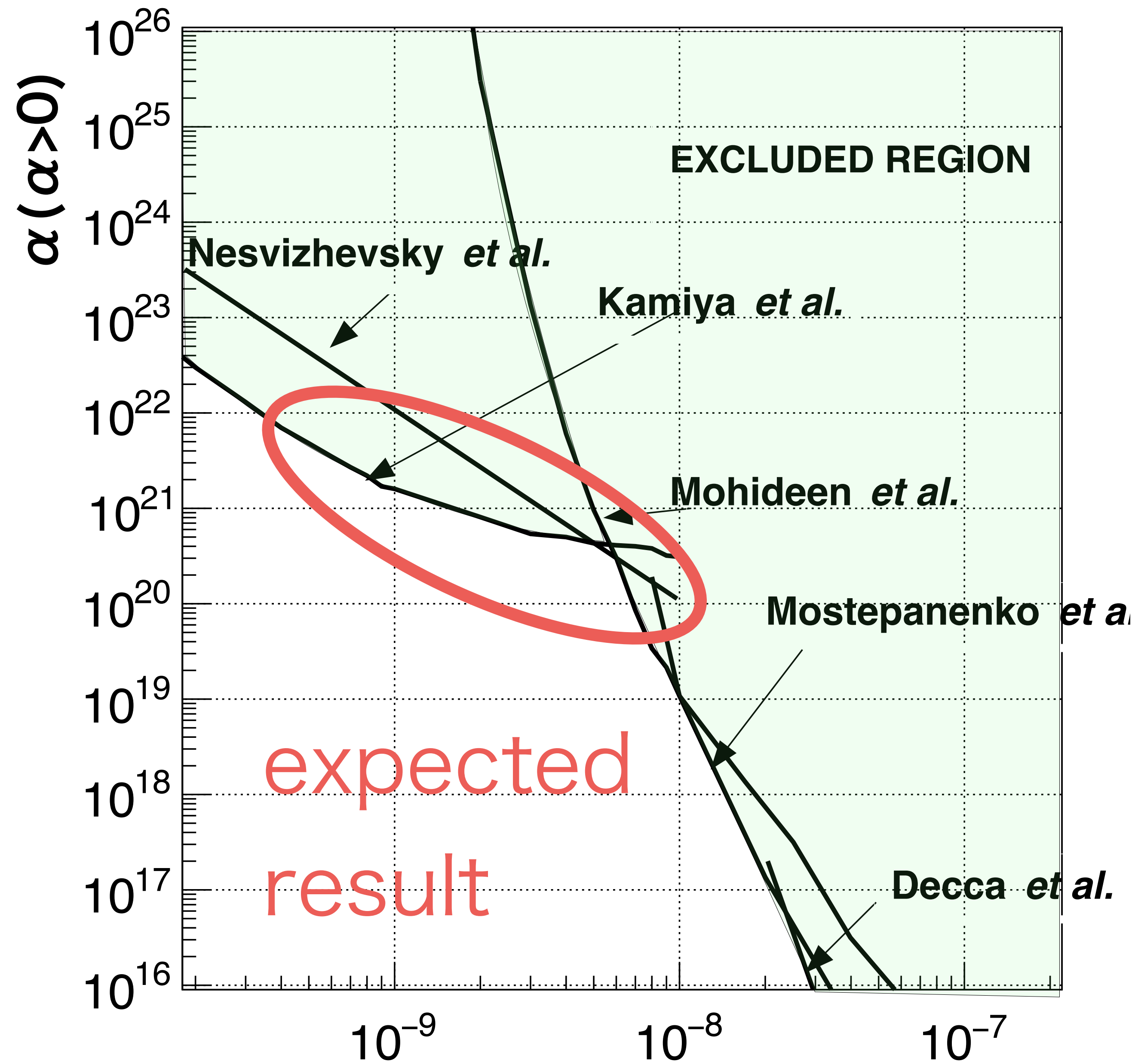
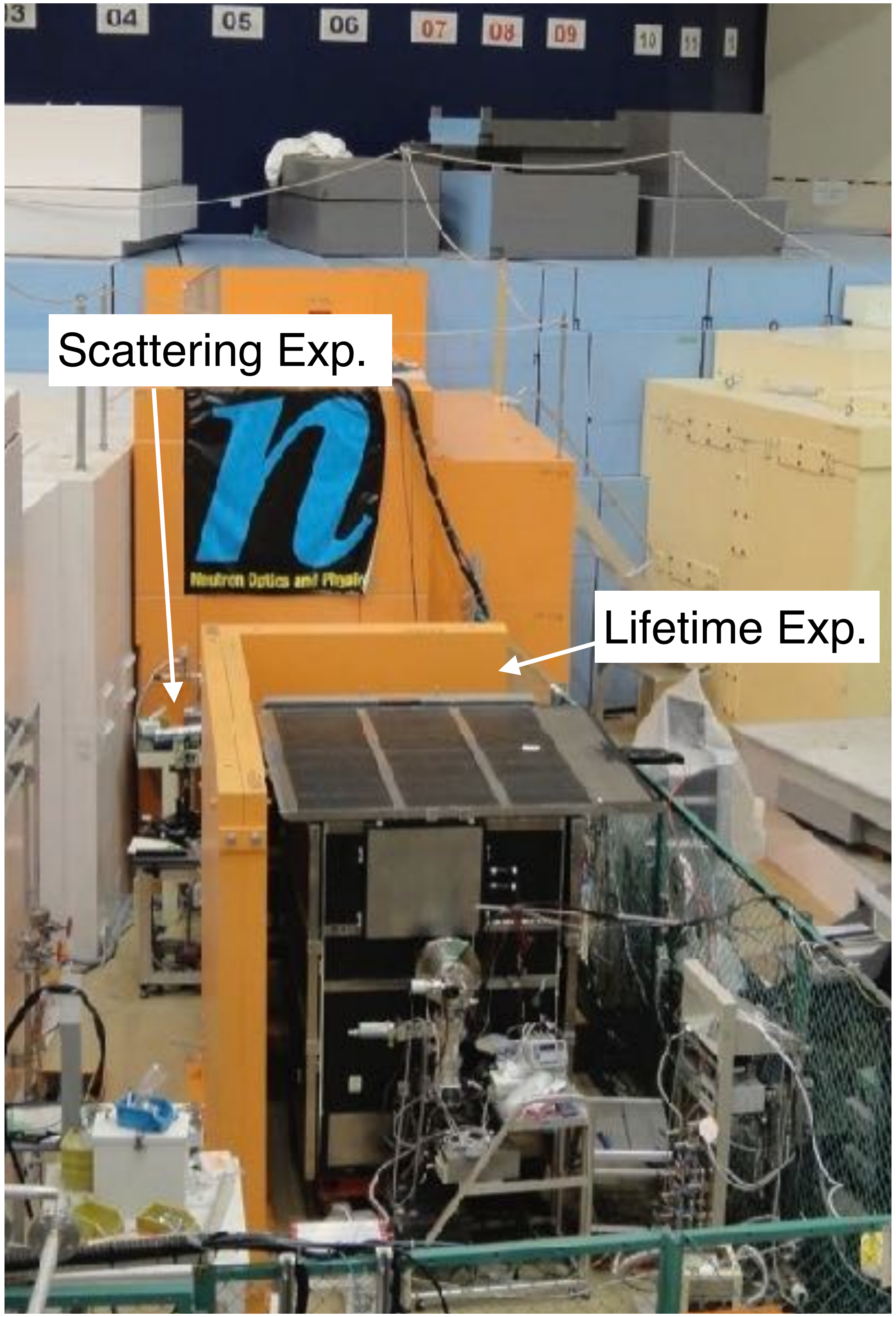
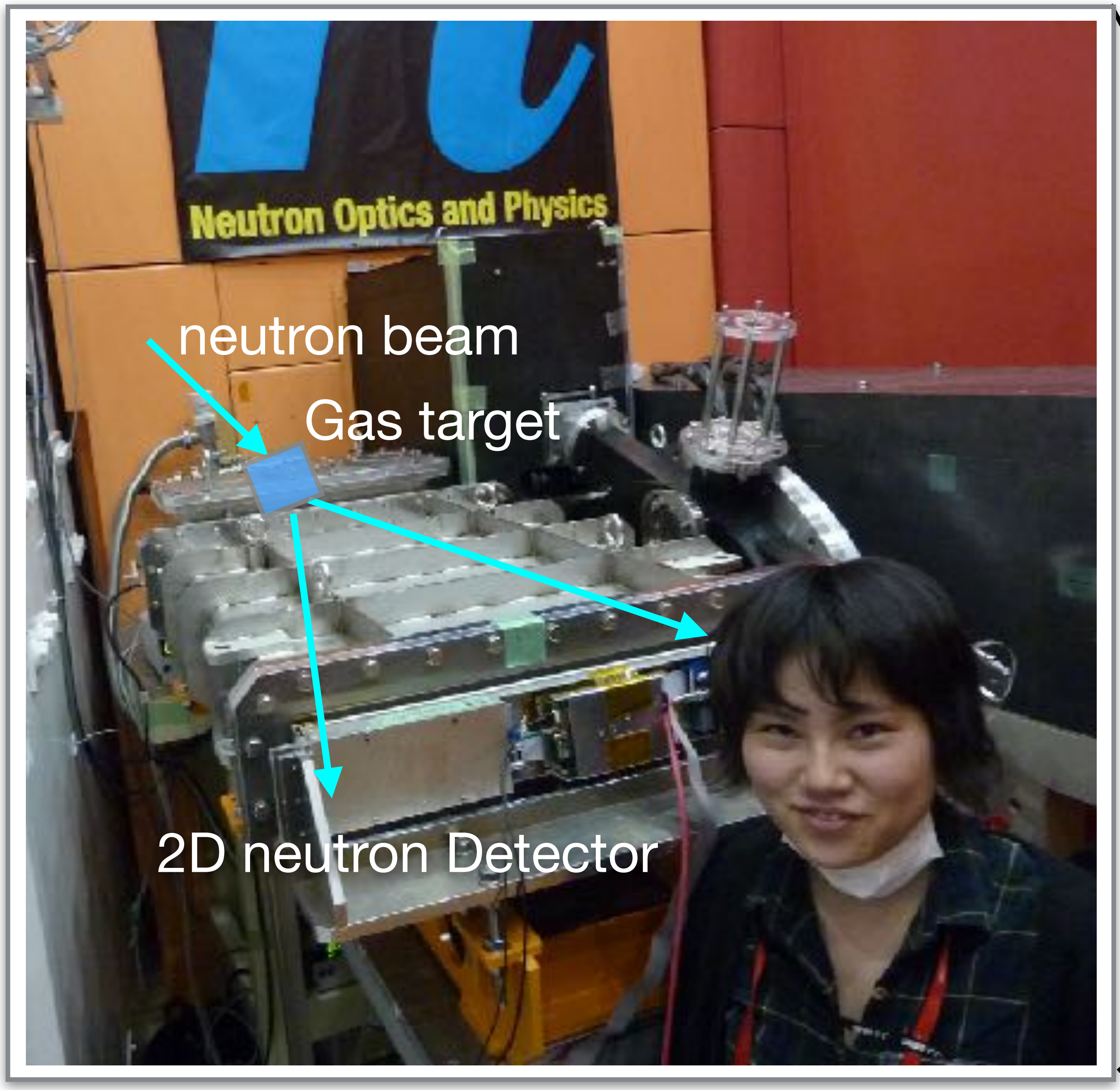
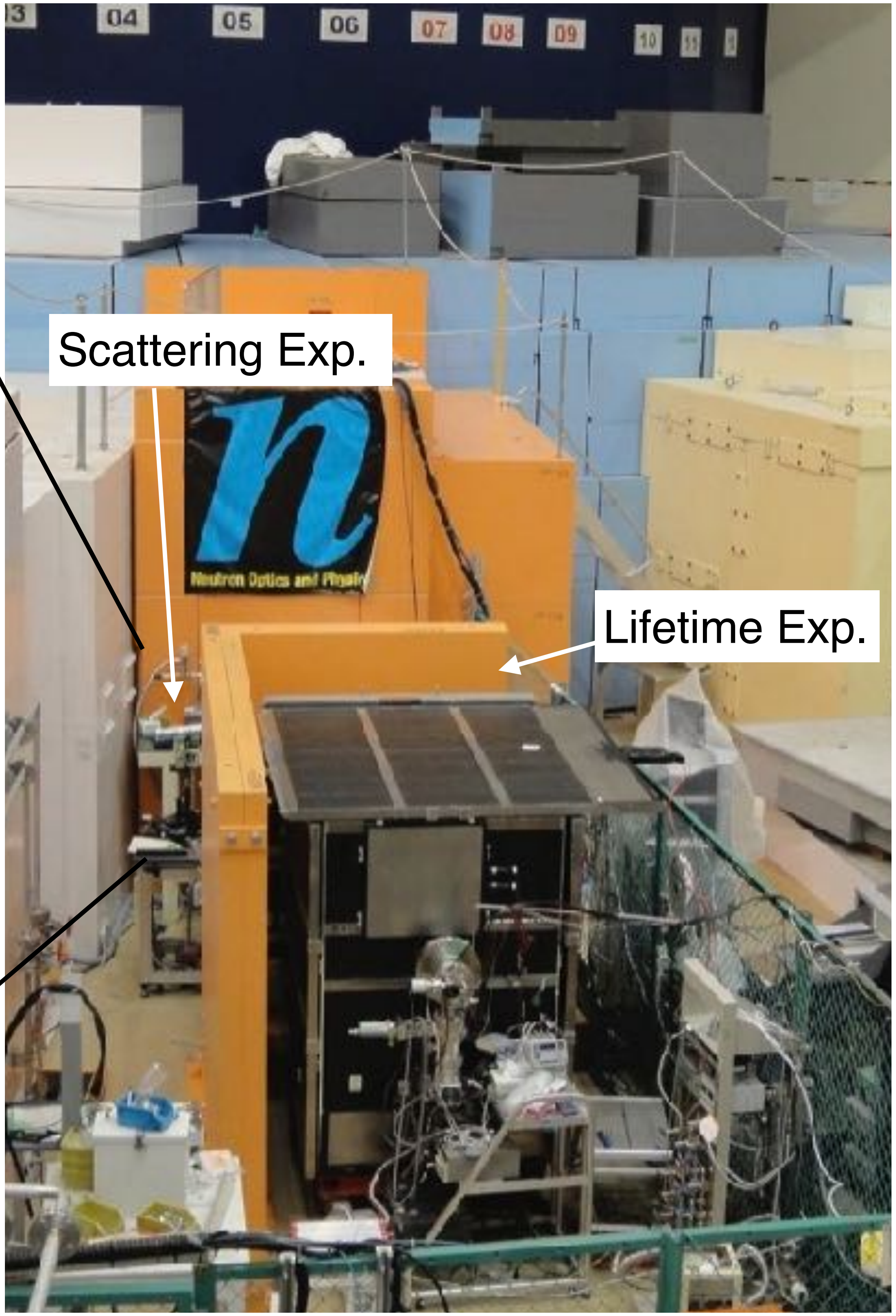


Fig 1. Exclusion map for an unknown interaction



Scattering Experiment to study Intermediate-range Force

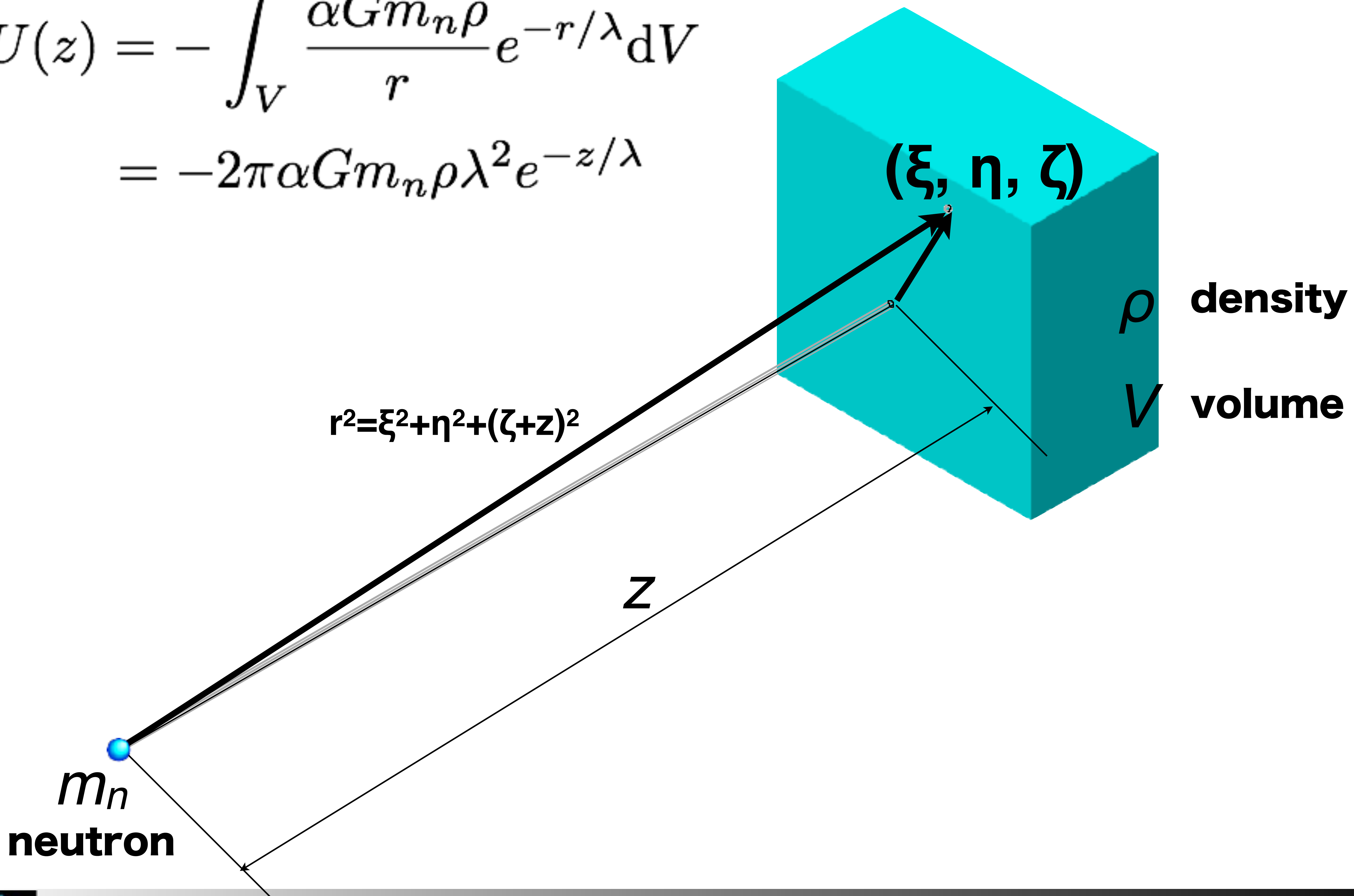




in progress at BL05 in J-PARC MLF

Interferemetric Search for Intermediate-range Forces

$$U(z) = -\int_V \frac{\alpha G m_n \rho}{r} e^{-r/\lambda} \mathrm{d}V$$
$$= -2\pi\alpha G m_n \rho \lambda^2 e^{-z/\lambda}$$



Interferemetric Search for Intermediate-range Forces

$$U(z) = -2\pi\alpha G m_n \rho \lambda^2 e^{-z/\lambda}$$

N=2 **α=16/3**

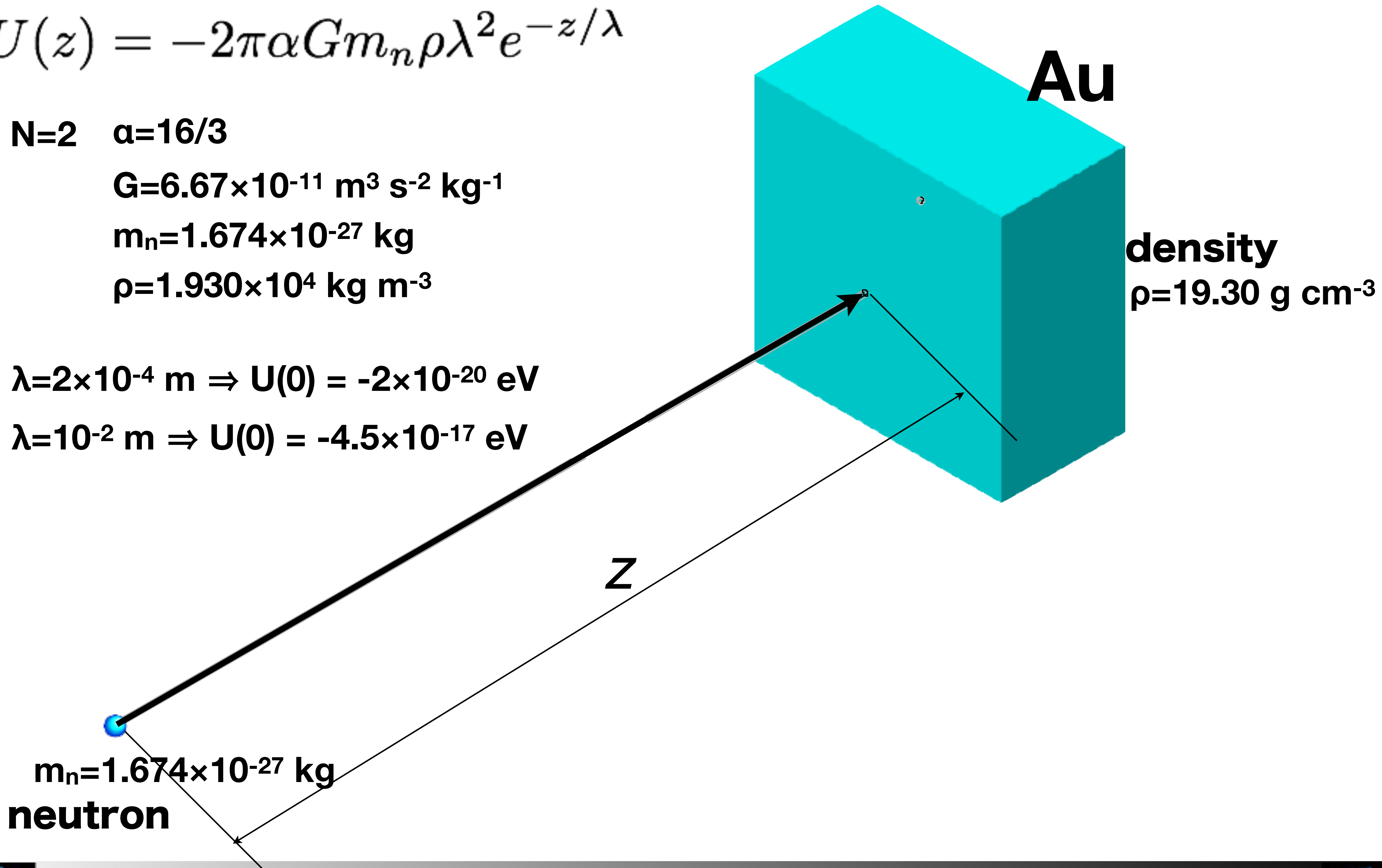
$G=6.67\times10^{-11}$ m^3 s^{-2} kg^{-1}

$m_n=1.674\times10^{-27}$ kg

$\rho=1.930\times10^4$ kg m^{-3}

$\lambda=2\times10^{-4}$ m $\Rightarrow$ U(0) = -2×10^{-20} eV

$\lambda=10^{-2}$ m $\Rightarrow$ U(0) = -4.5×10^{-17} eV



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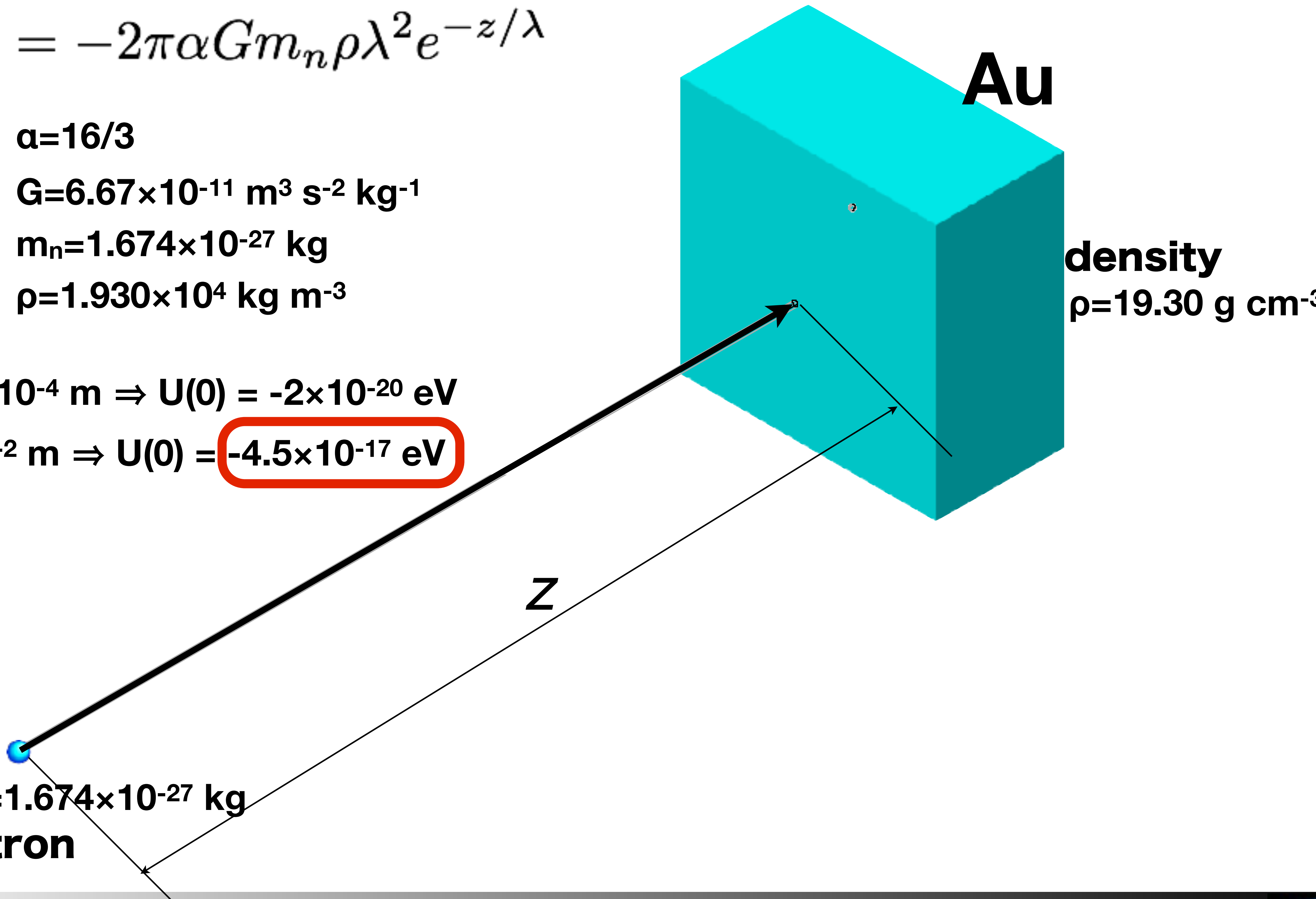
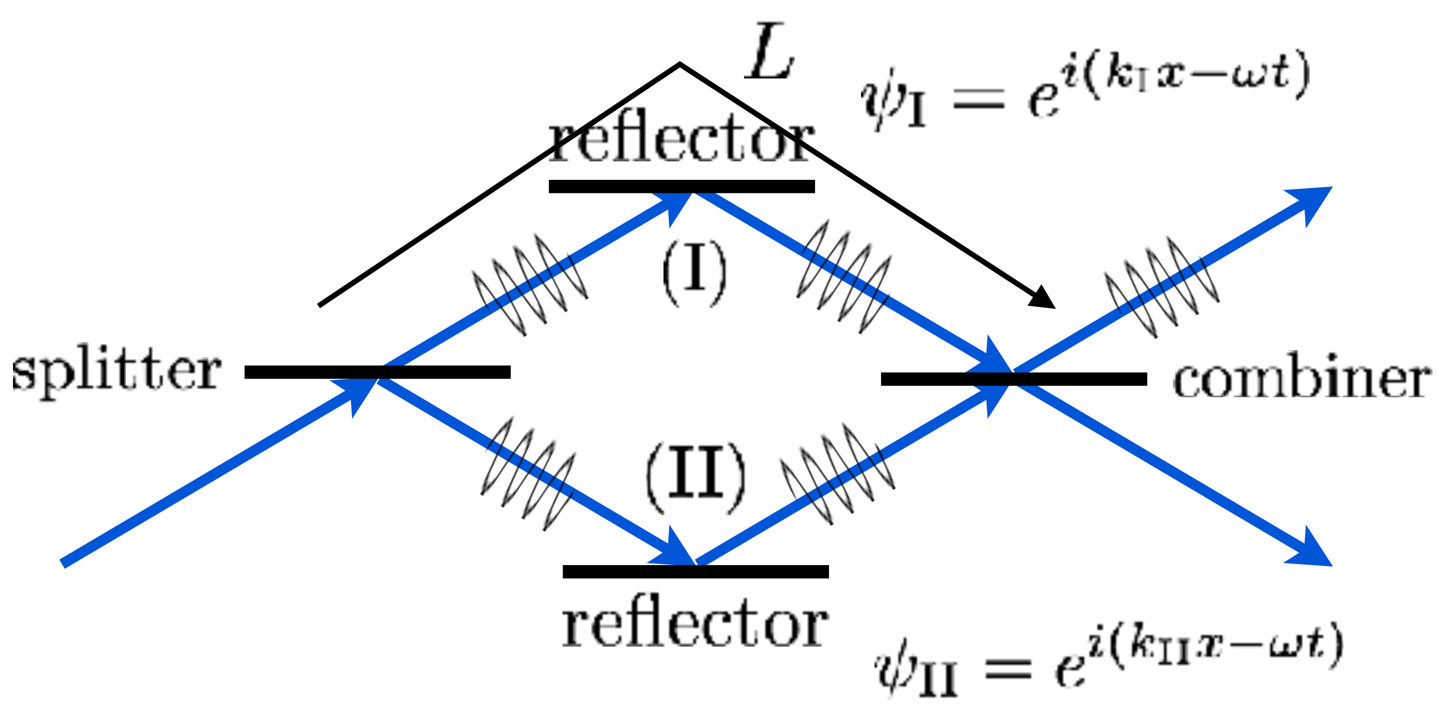
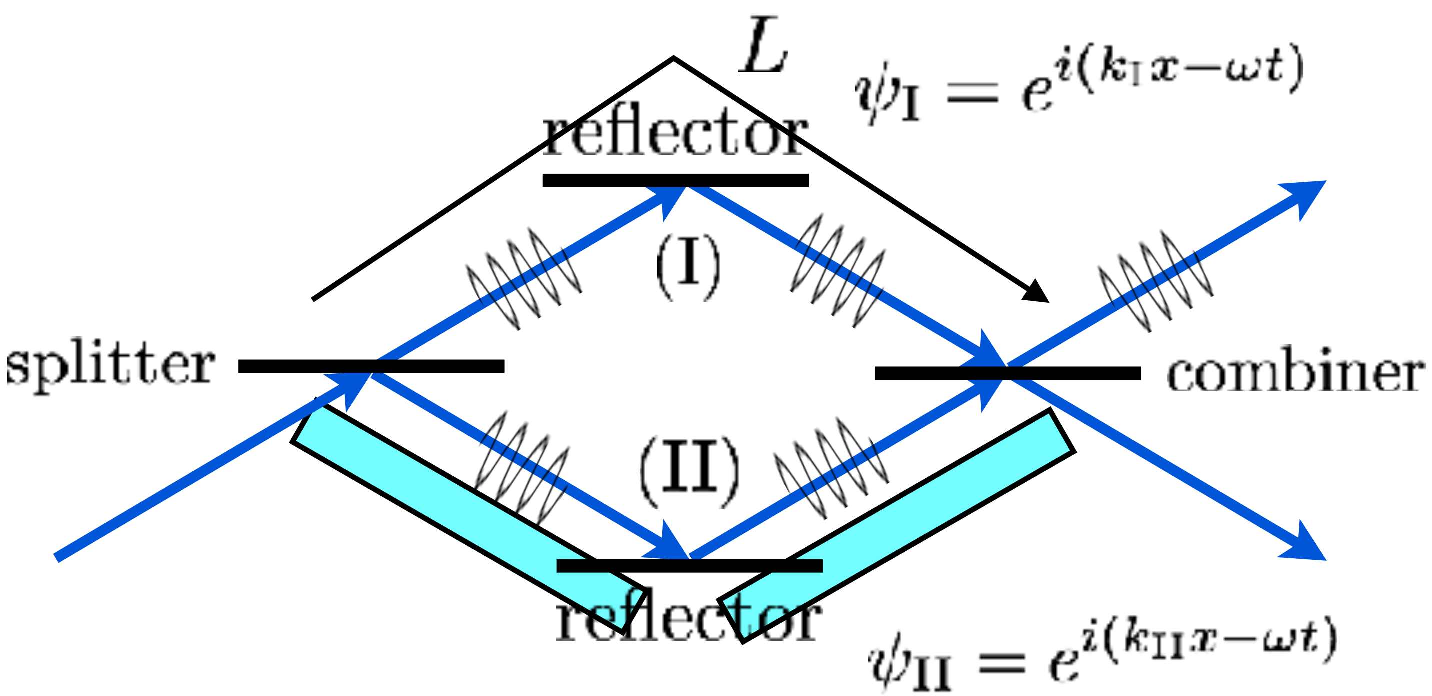




$$\Delta\phi = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2E}} \frac{L\Delta U}{\hbar c}$$

$$1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$$
$$m_n c^2 = 9.4 \times 10^8 \mathrm{eV}$$
$$\hbar c = 1.97 \times 10^{-7} \mathrm{eV\,m}\,(= 197\,\mathrm{MeV\,fm})$$

E	L	Δφ	ΔU	$\Delta U/(m_n g)$
25 meV	0.1 m	1 rad	10^{-14} eV	1 mm



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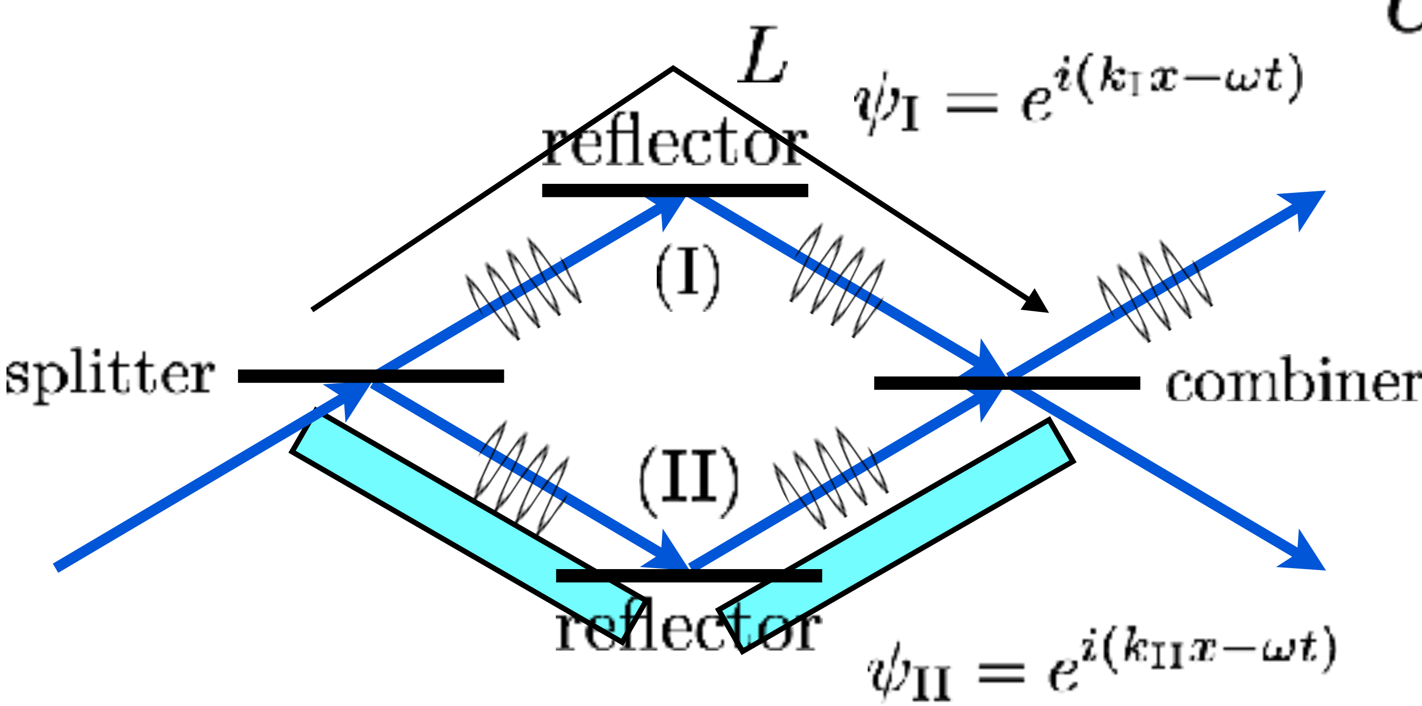

$$U(z) = -2\pi\alpha G m_n \rho \lambda^2 e^{-z/\lambda}$$

N=2 $\quad \alpha$=16/3

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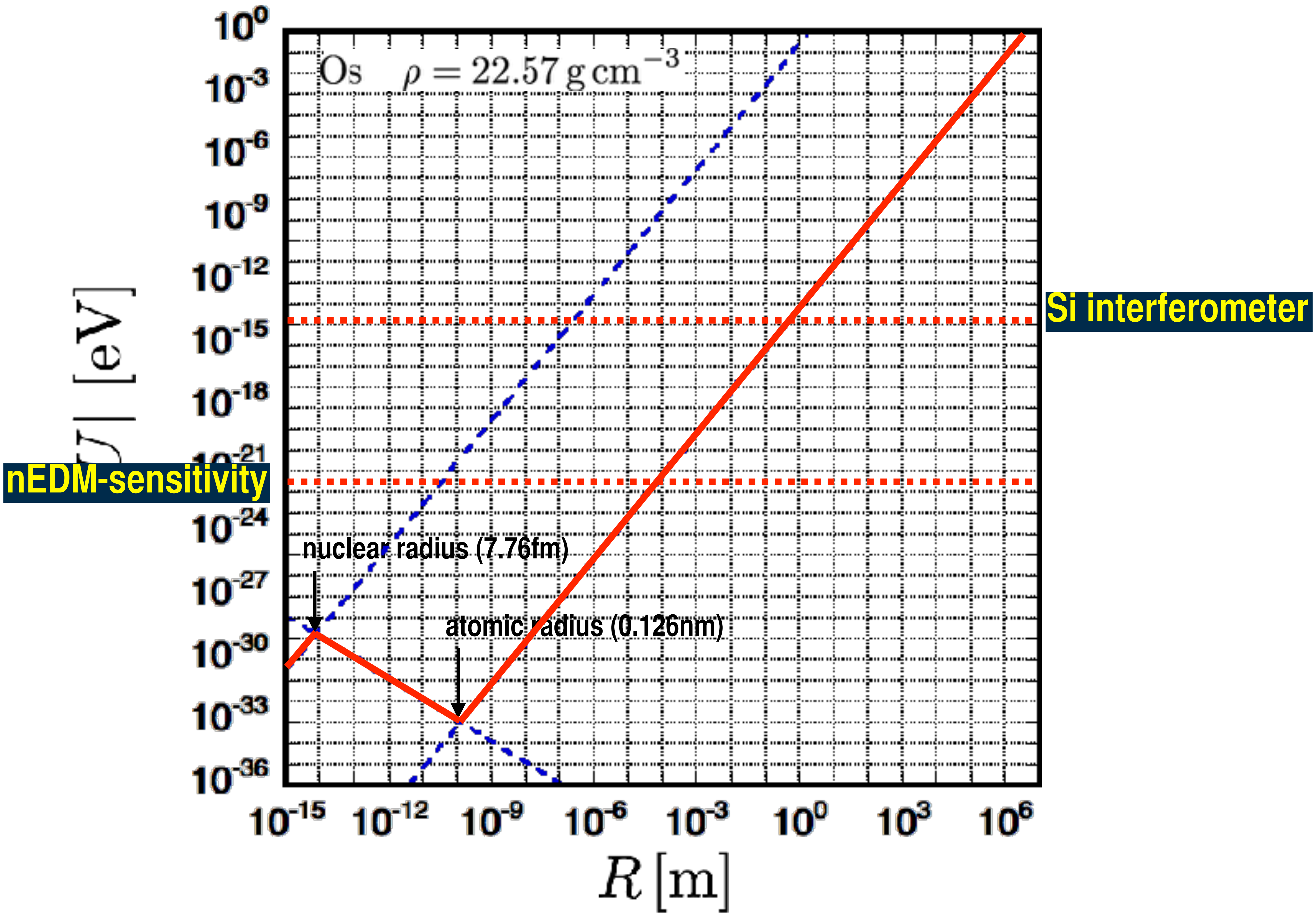
E	L	Δϕ	ΔU	ΔU/(m_ng)
25 meV	0.1 m	1 rad	10^{-14} eV	1 mm
10 meV	**1 m**	**10^{-3} rad**	**9×10^{-16} eV**	**9 nm**
250 neV	**1 m**	**10^{-3} rad**	**5×10^{-18} eV**	**40 pm**

$$U = -G\frac{M m_{\mathrm{n}}}{R} = -3.1\times10^{-15}[\mathrm{eV}]\times\left(\frac{R}{1\,\mathrm{m}}\right)^{2}\left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



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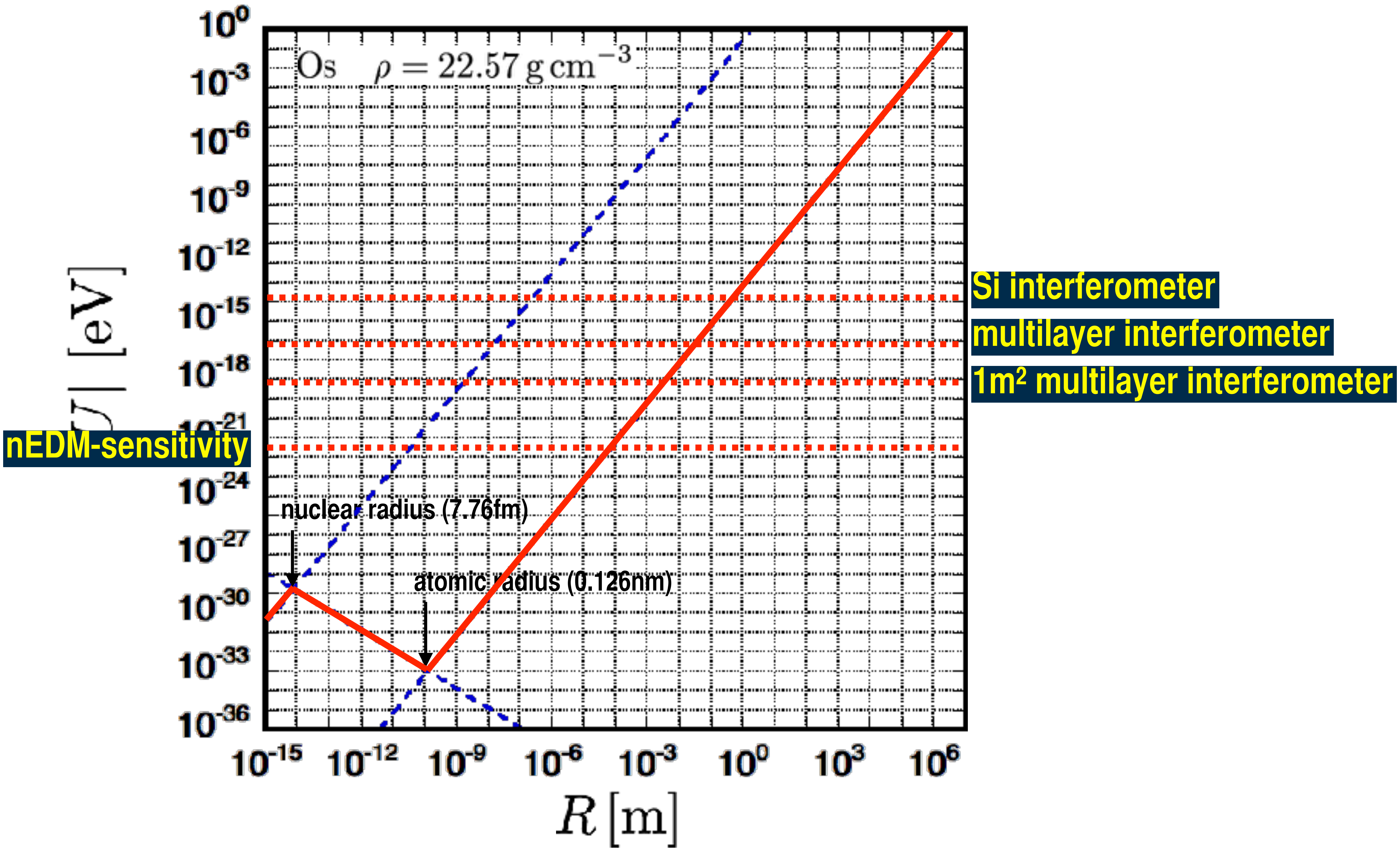


Summary

Precise measurement of the spin precession of ultracold neutrons

for spin-dependent gravity $\sigma \cdot g$

Enlarged multilayer interferometer for pulsed cold and very-cold neutrons

for post-Newtonian terms

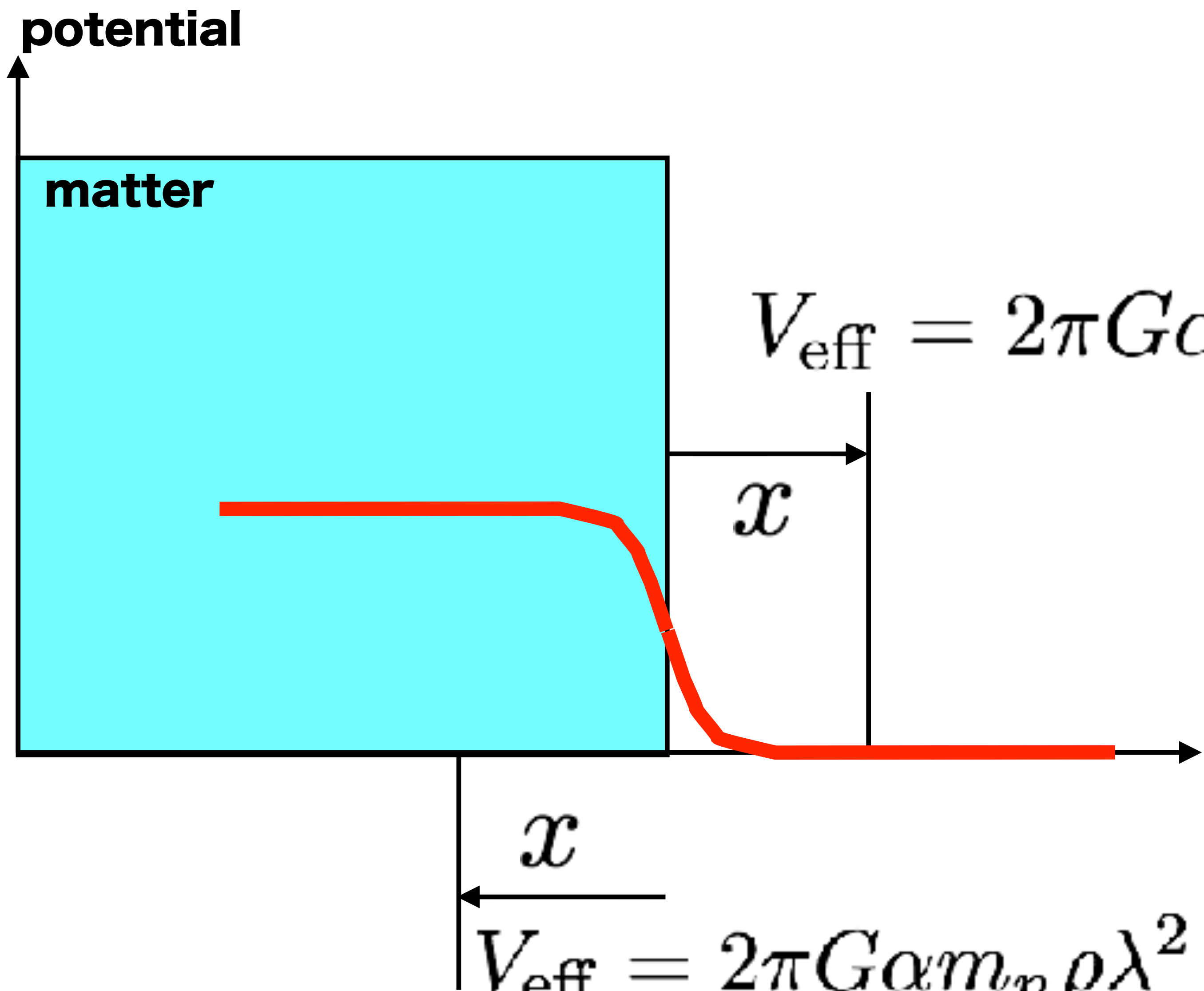
For anomalous gravity in short-distance

neutron scattering, neutron interferometry

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_{\mathrm{G}}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



$$V_{\mathrm{eff}} = 2\pi G\alpha m_n \rho \lambda^2 e^{-x/\lambda}$$

$$V_{\mathrm{eff}} = 2\pi G\alpha m_n \rho \lambda^2 \left(2 - e^{-x/\lambda}\right)$$

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_{\mathrm{G}}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$

$$V_{\mathrm{eff}} = k_0^2 + 2\alpha^2 e^{-L/2\lambda}\cosh\left(\frac{x}{\lambda}\right)$$

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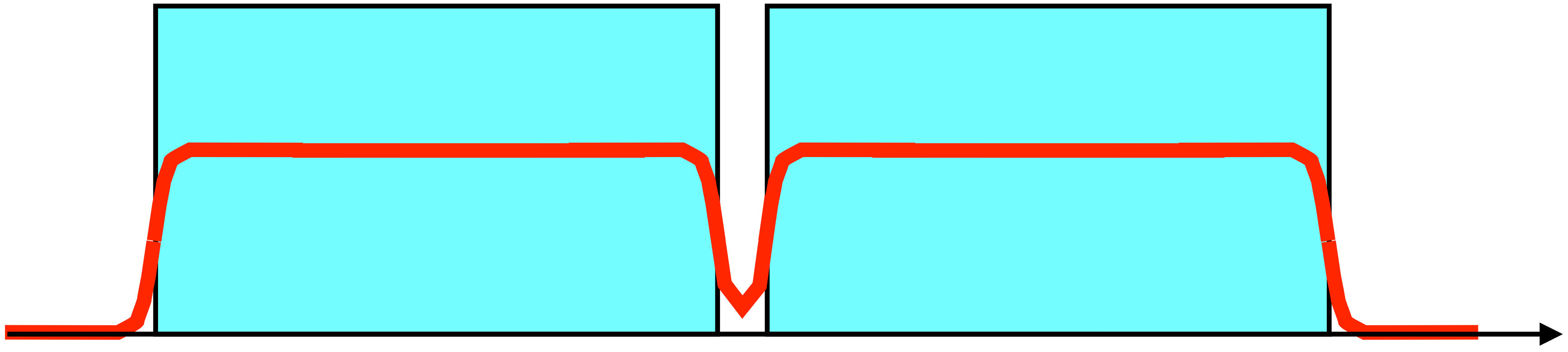

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_{\rm eff} = k_0^2 + 2\alpha^2 e^{-L/2\lambda} \cosh\left(\frac{x}{\lambda}\right)$$

$$\cosh\left(\frac{x}{\lambda}\right) = \frac{\sinh(L/\lambda)}{L/\lambda} + \sum_{n=1}^{\infty}\left[\frac{2(-1)^n (L/\lambda)\sinh(L/\lambda)}{(L/\lambda)^2 + n^2\pi^2}\cos\left(\frac{n\pi x}{L}\right)\right]$$

pamametric resonance

$$\frac{2k_0}{1 + \frac{2\alpha^2}{k_0^2}\exp(-L/\lambda)\frac{\sinh(L/\lambda)}{L/\lambda}} = \frac{n\pi}{L} \qquad \lambda_n \simeq \frac{4L}{n} \quad (\eta \to 0)$$

$$\gamma \simeq \frac{\alpha^2\lambda_n^2}{\pi^2}\frac{(L/\lambda)\sinh(L/\lambda)}{(L/\lambda)^2 + 16\pi^2(L/\lambda)^2} e^{-L/(2\lambda)}$$

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

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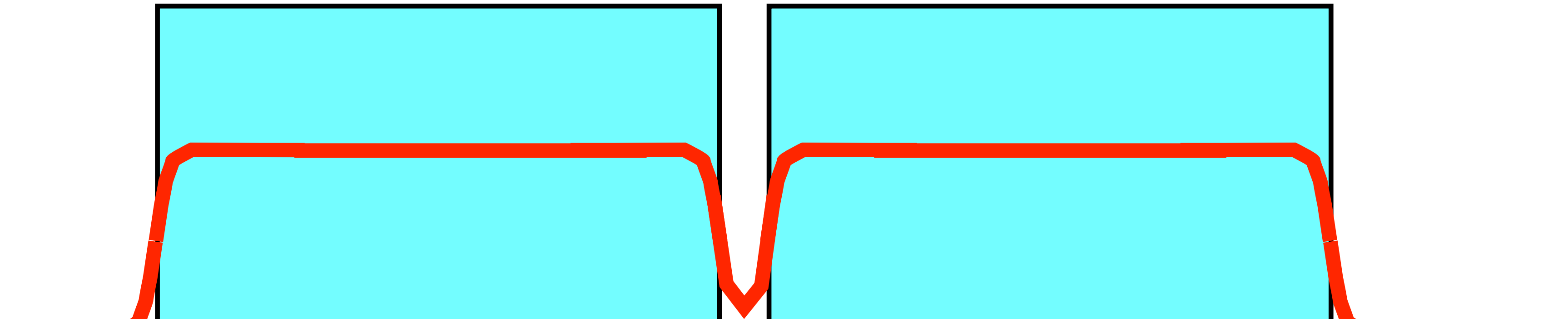
pamametric resonance

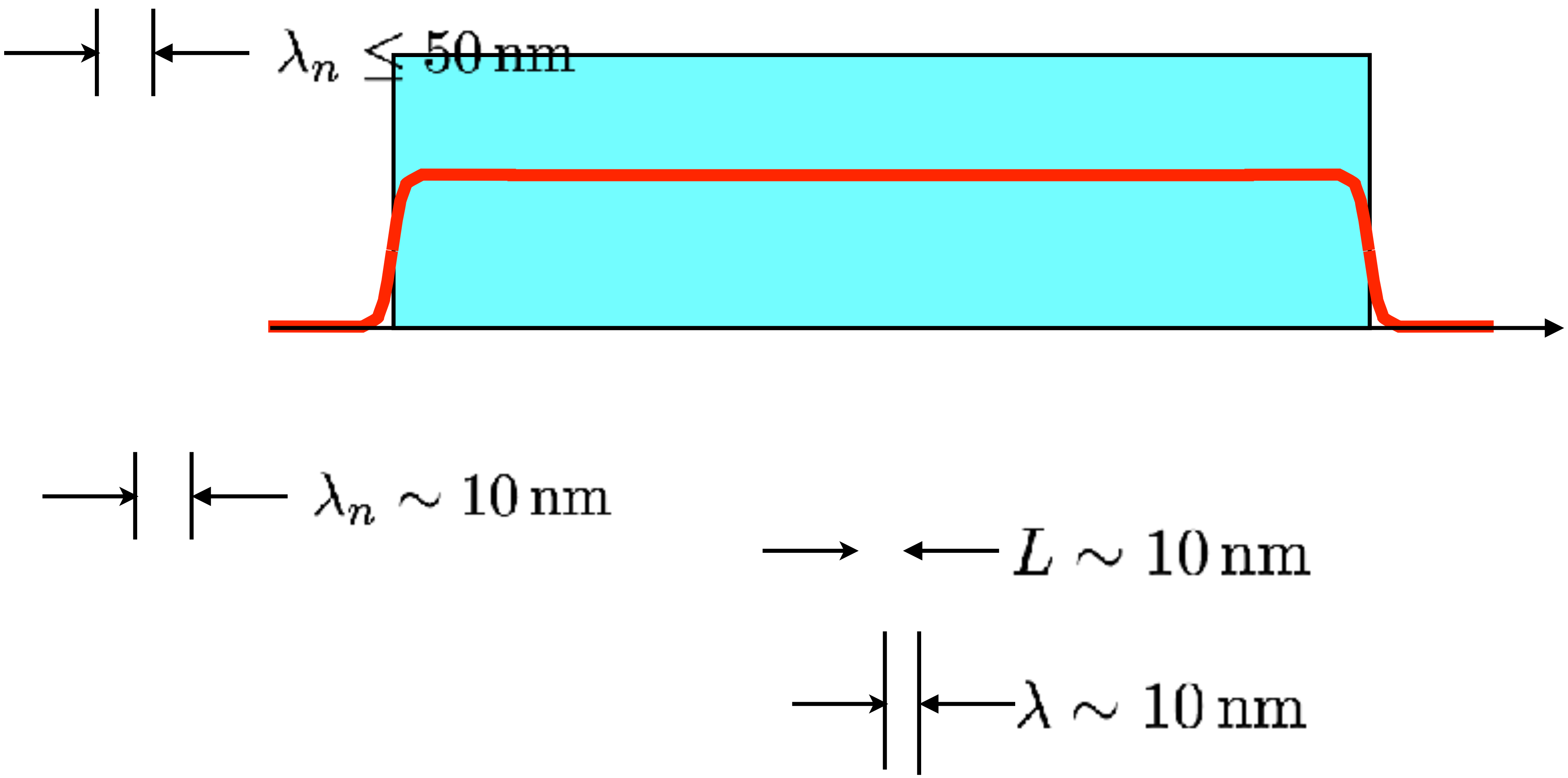
$$\frac{2k_0}{1+\frac{2\alpha^2}{k_0^2}\exp(-L/\lambda)\frac{\sinh(L/\lambda)}{L/\lambda}} = \frac{n\pi}{L} \qquad \lambda_n \simeq \frac{4L}{n} \quad (\eta \to 0)$$

$$\gamma \simeq \frac{\alpha^2\lambda_n^2}{\pi^2}\frac{(L/\lambda)\sinh(L/\lambda)}{(L/\lambda)^2+16\pi^2(L/\lambda)^2}e^{-L/(2\lambda)}$$



Parametric Resonance in 1-dim Potential

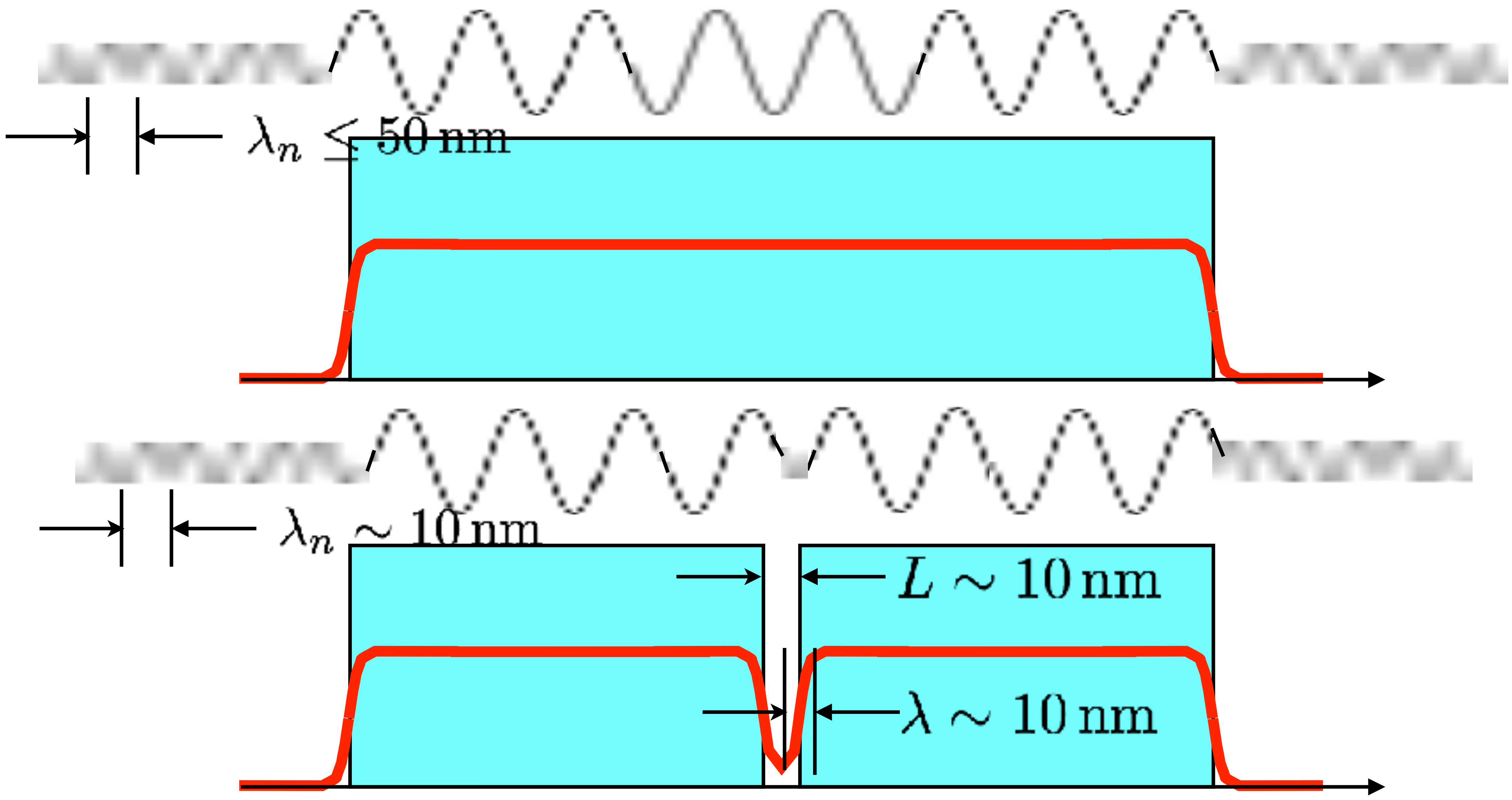
$$V_{\mathrm{G}}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

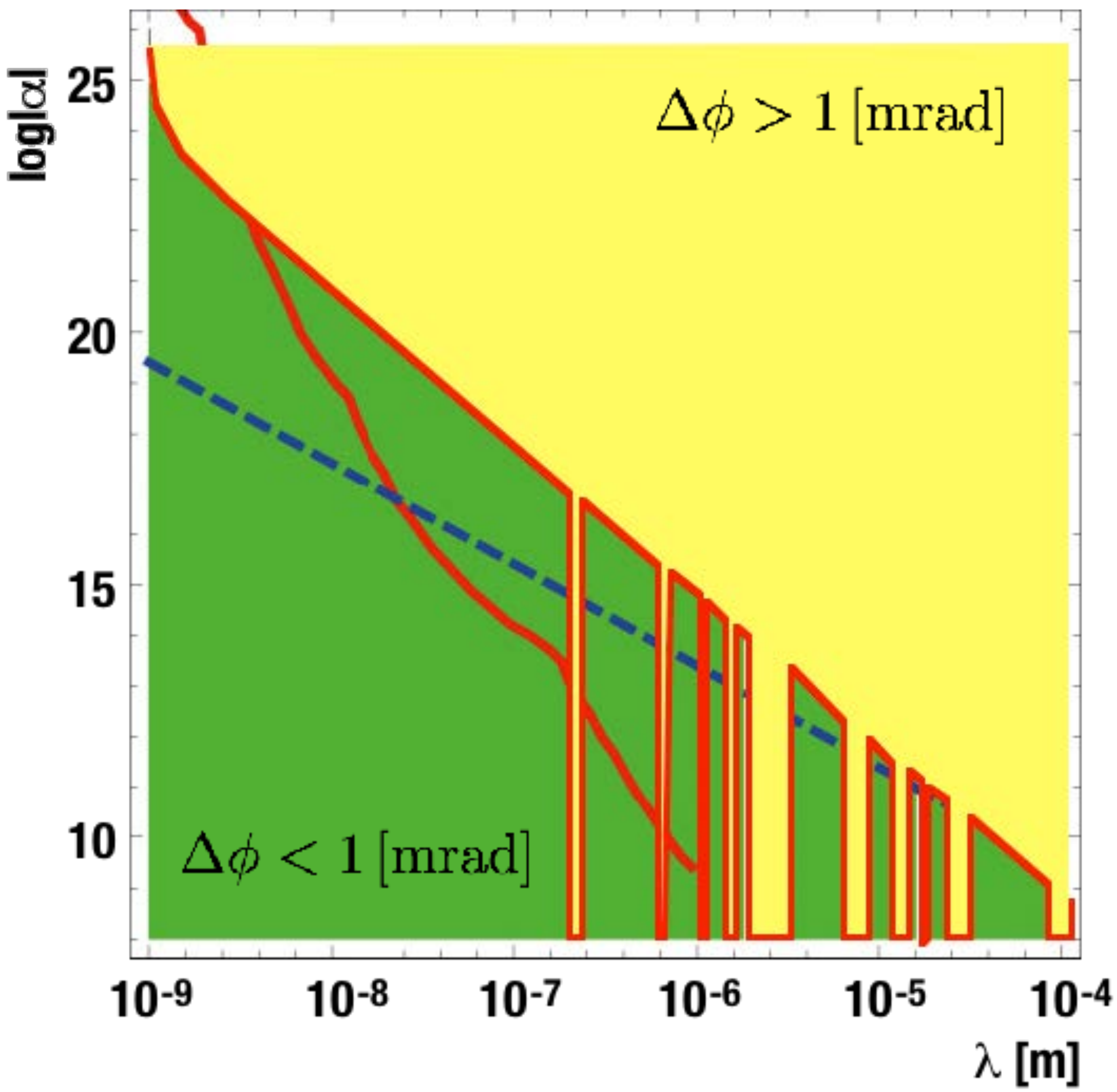
Parametric Resonance in 1-dim Potential

$$V_{\rm G}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

Parametric Resonance in 1-dim Potential



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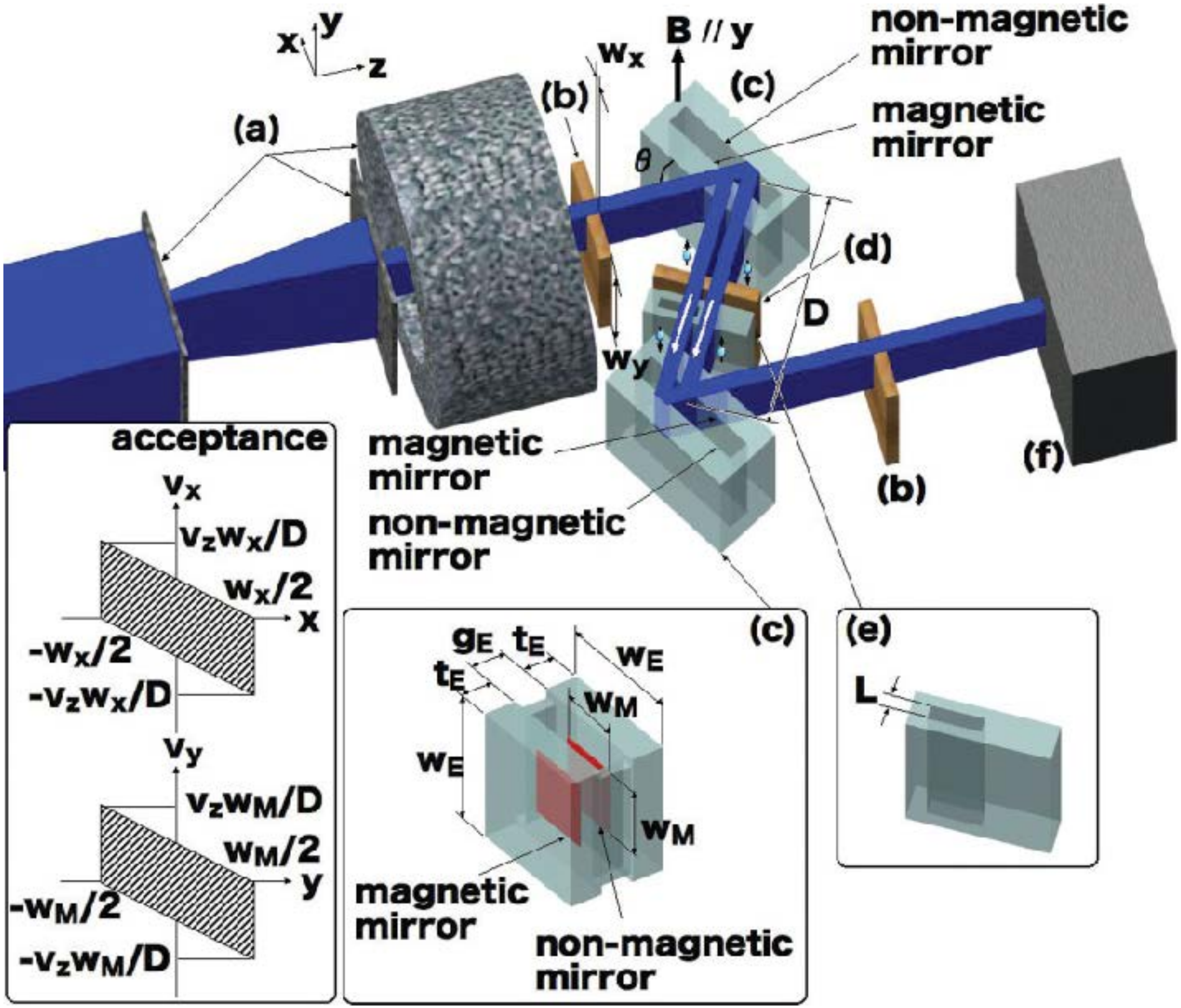
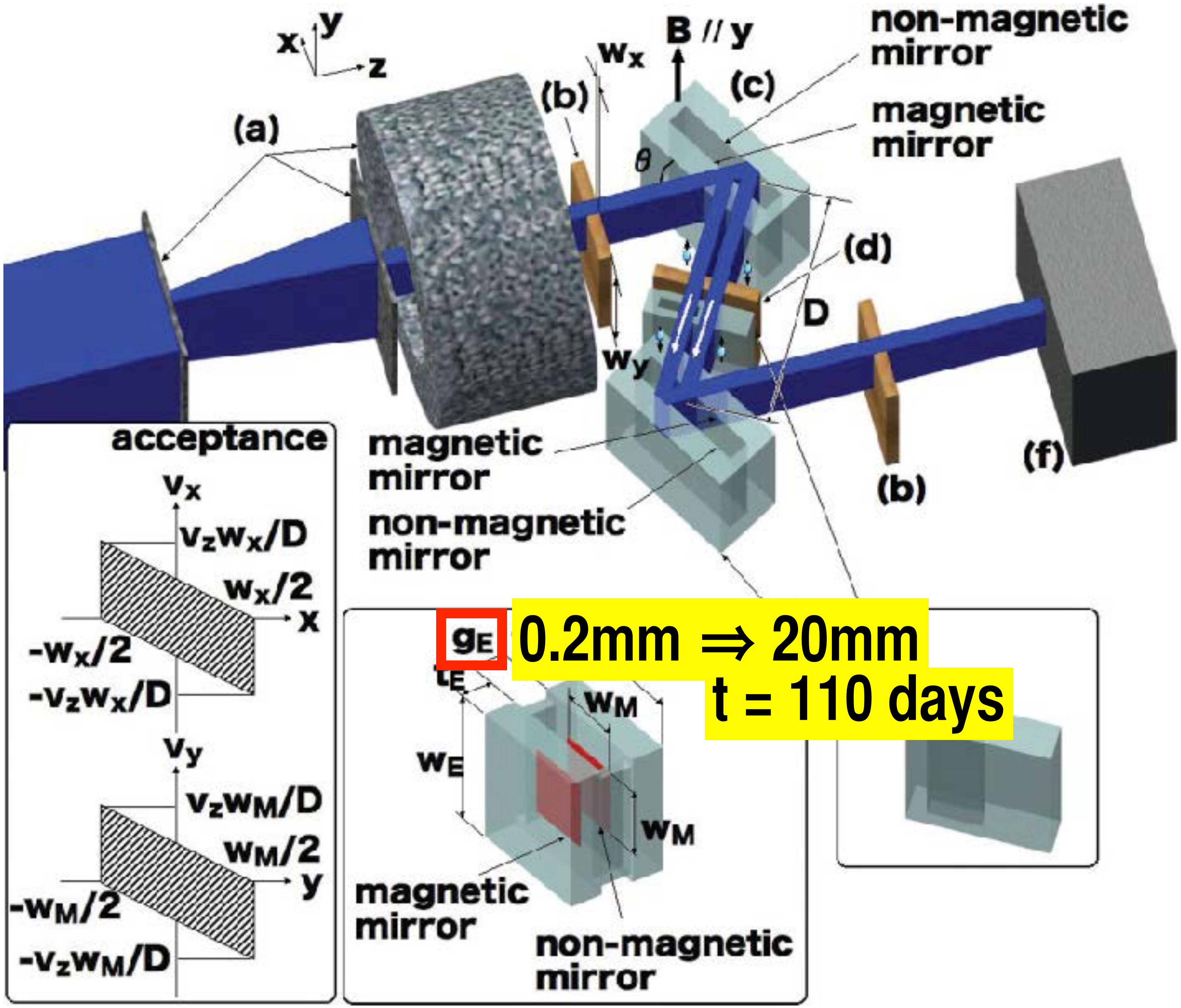
Experimental Apparatus of the Search for Parametric Resonance

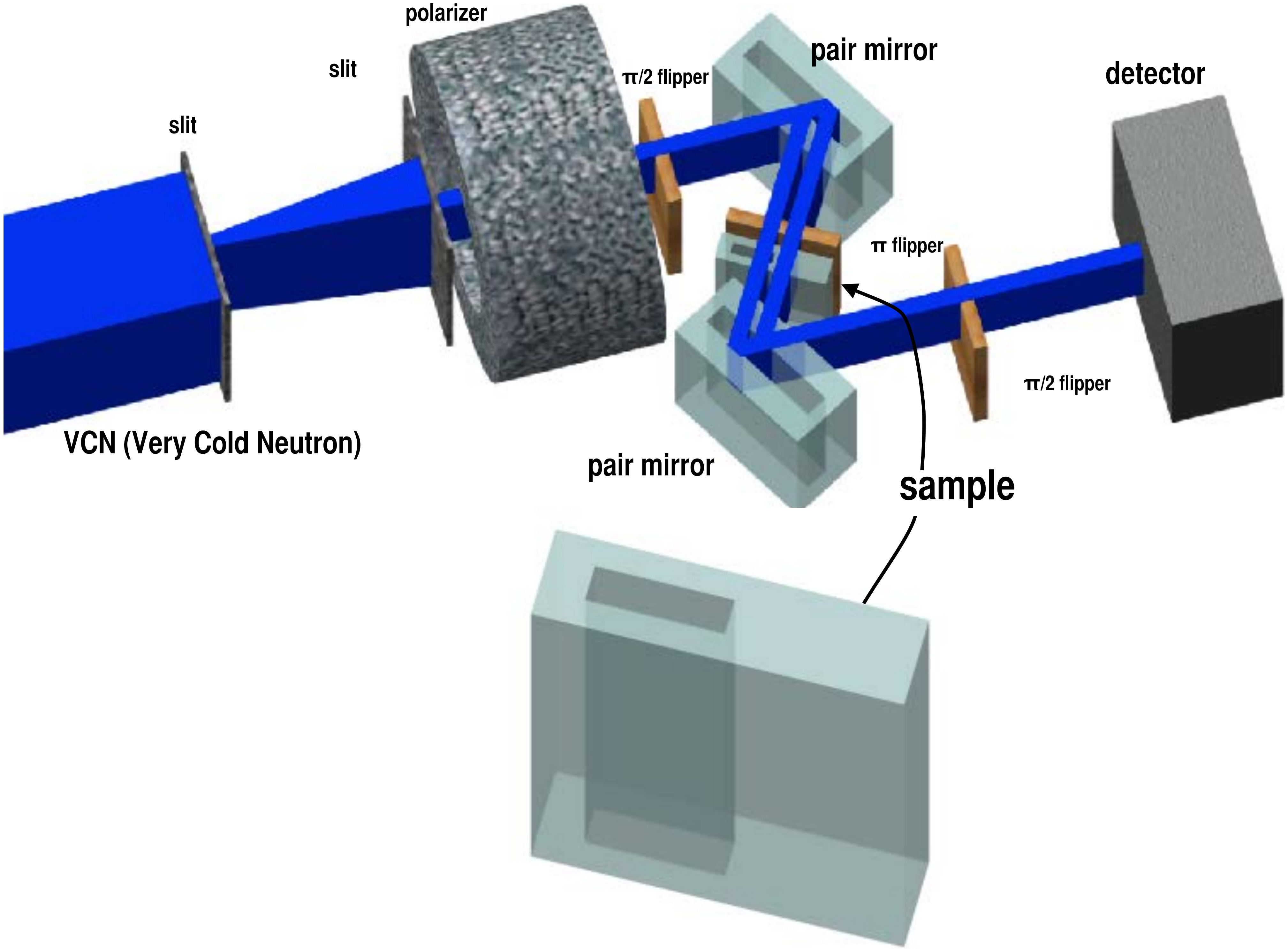


Experimental Apparatus of the Search for Parametric Resonance



0.2mm ⇒ 20mm
t = 110 days

Experimental Apparatus of the Search for Parametric Resonance



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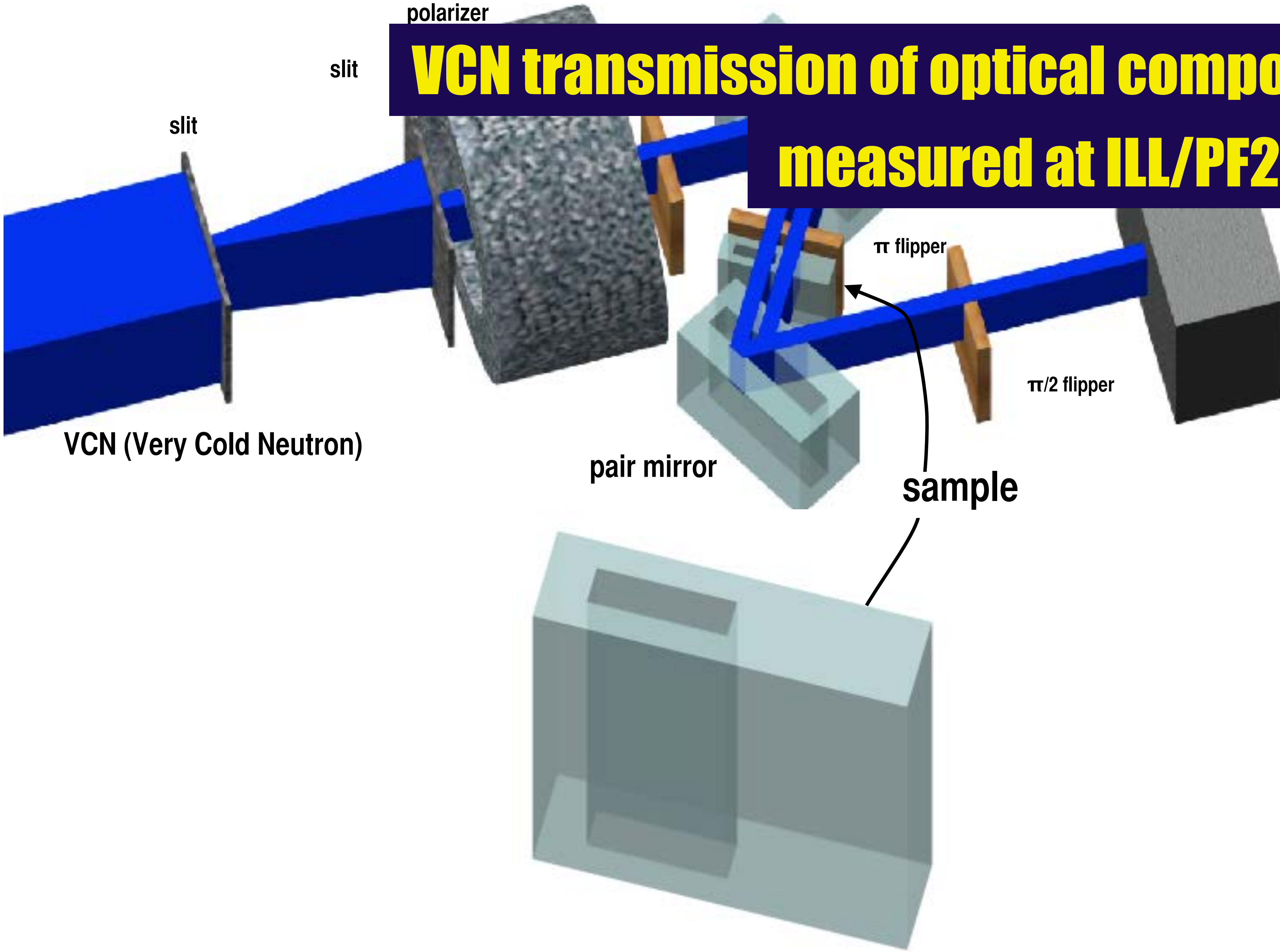
Experimental Apparatus of the Search for Parametric Resonance

VCN transmission of optical component measured at ILL/PF2-VCN



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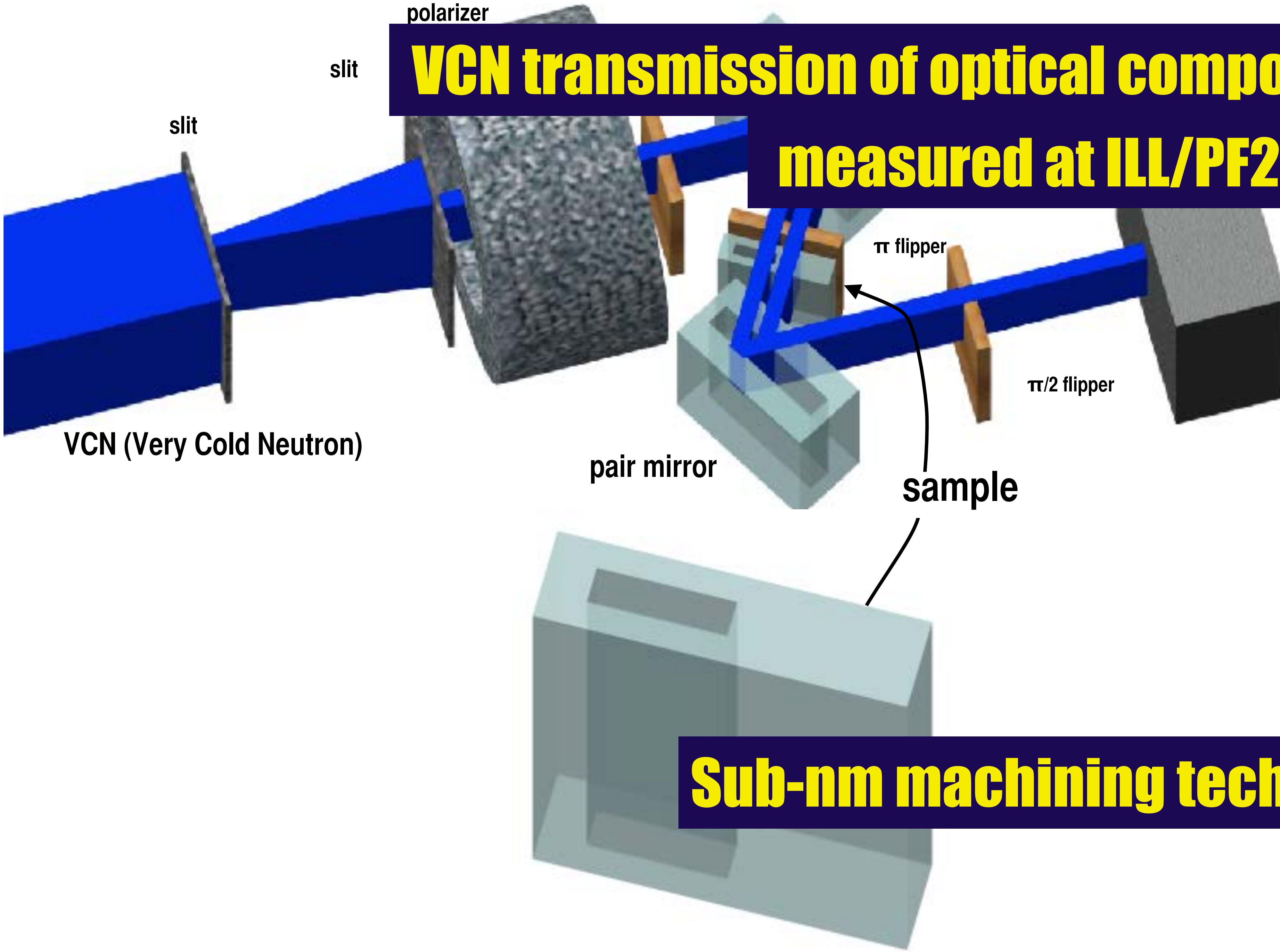
Experimental Apparatus of the Search for Parametric Resonance



VCN transmission of optical component measured at ILL/PF2-VCN

Sub-nm machining technique

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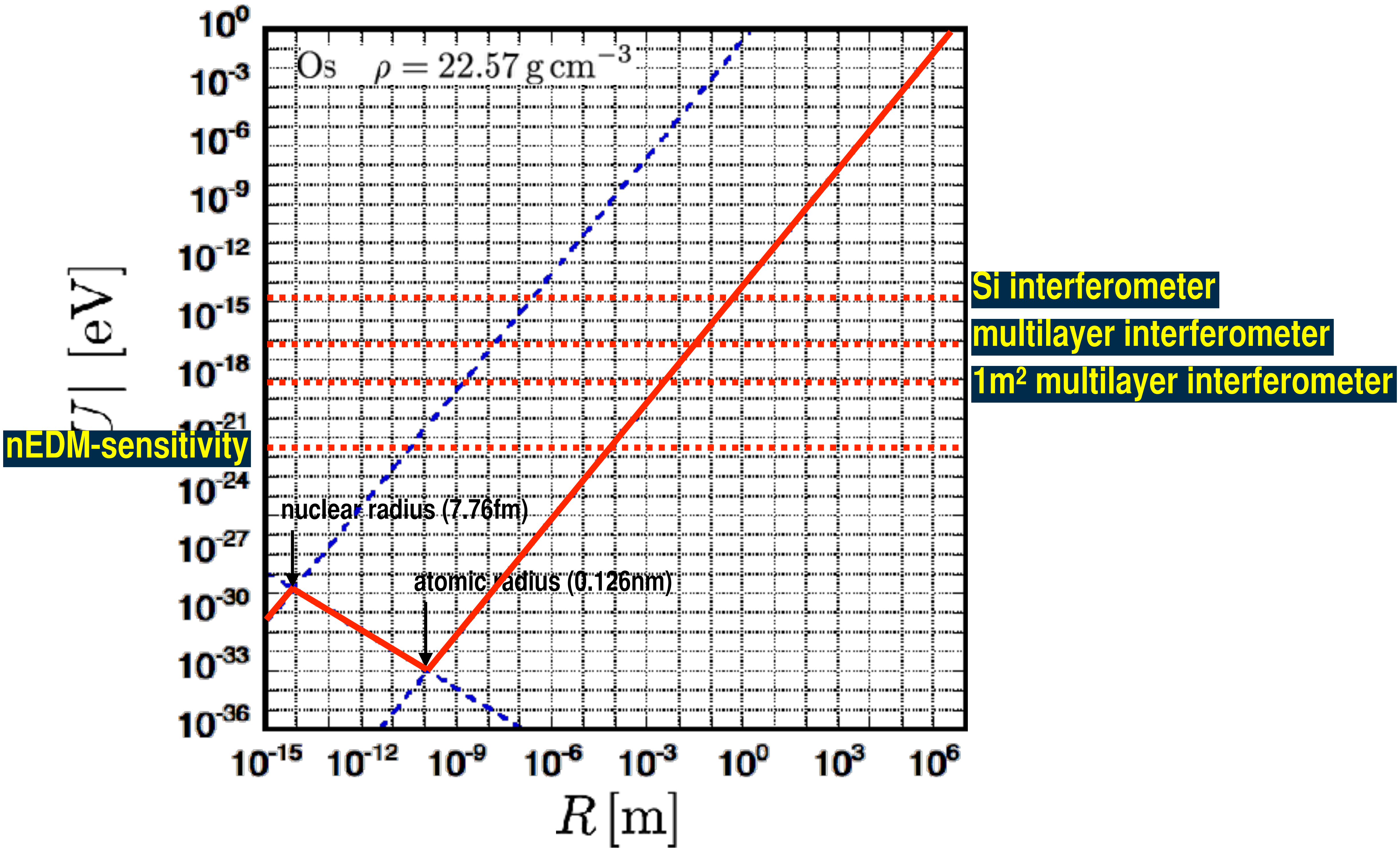
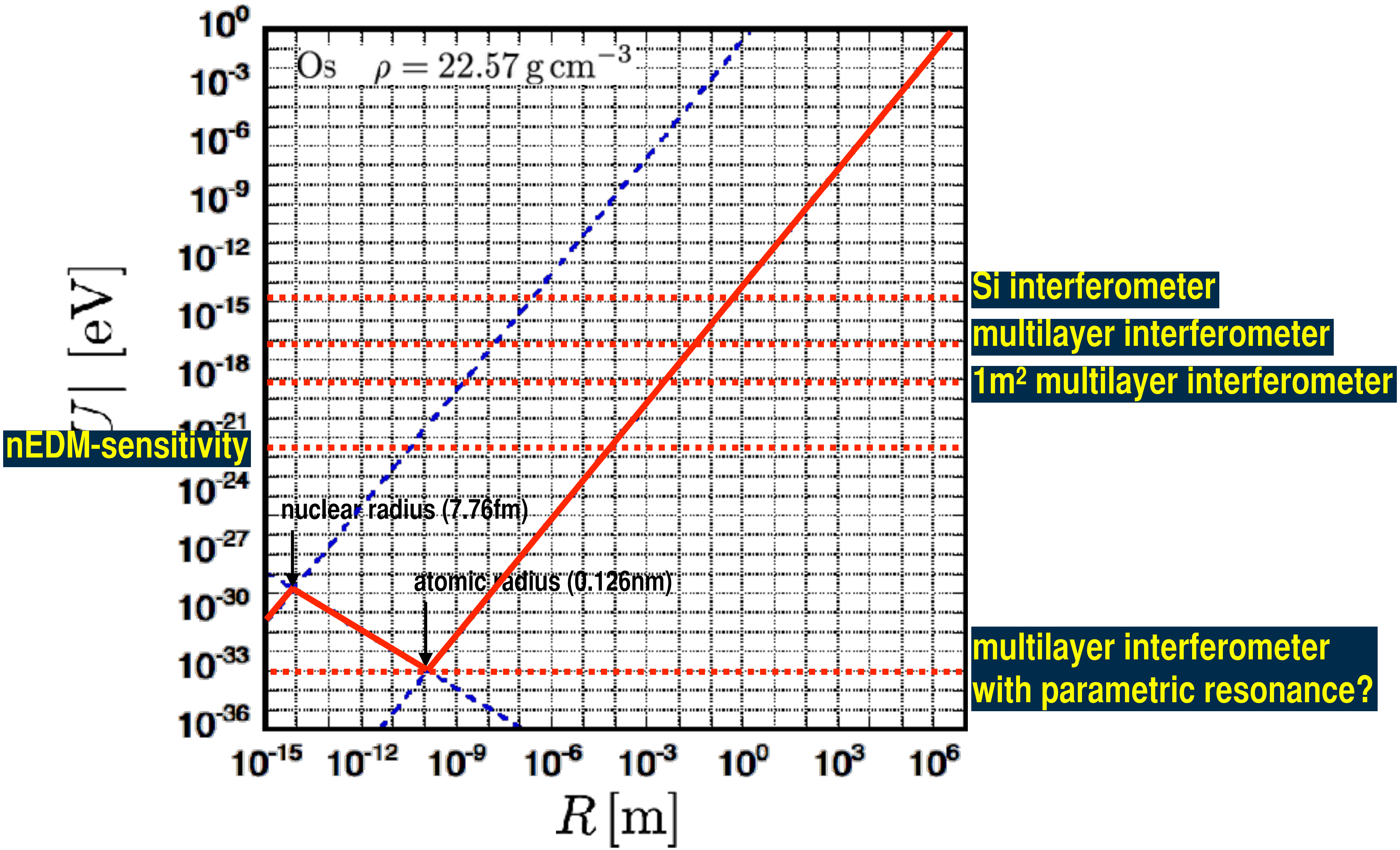
$$U = -G\frac{M m_{\mathrm{n}}}{R} = -3.1 \times 10^{-15}[\mathrm{eV}] \times \left(\frac{R}{1\,\mathrm{m}}\right)^2 \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



$$U = -G\frac{M m_{\mathrm{n}}}{R} = -3.1\times10^{-15}[\mathrm{eV}]\times\left(\frac{R}{1\,\mathrm{m}}\right)^2\left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



Summary

Precise measurement of the spin precession of ultracold neutrons

for spin-dependent gravity $\boldsymbol{\sigma} \cdot \boldsymbol{g}$

Enlarged multilayer interferometer for pulsed cold and very-cold neutrons

for post-Newtonian terms

For anomalous gravity in short-distance

neutron scattering, neutron interferometry

parametric resonance?