Very Cold Neutrons for Fundamental Physics

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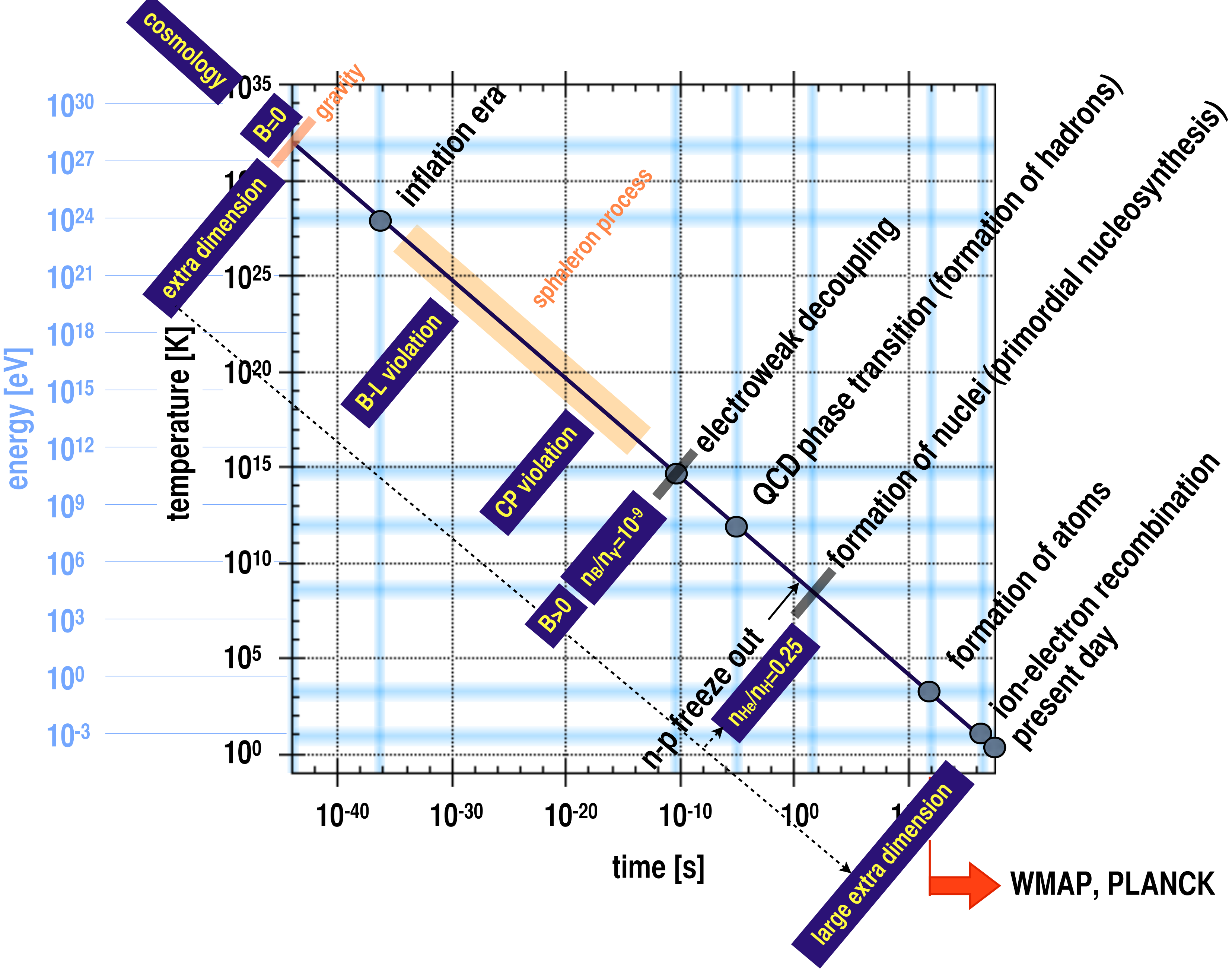
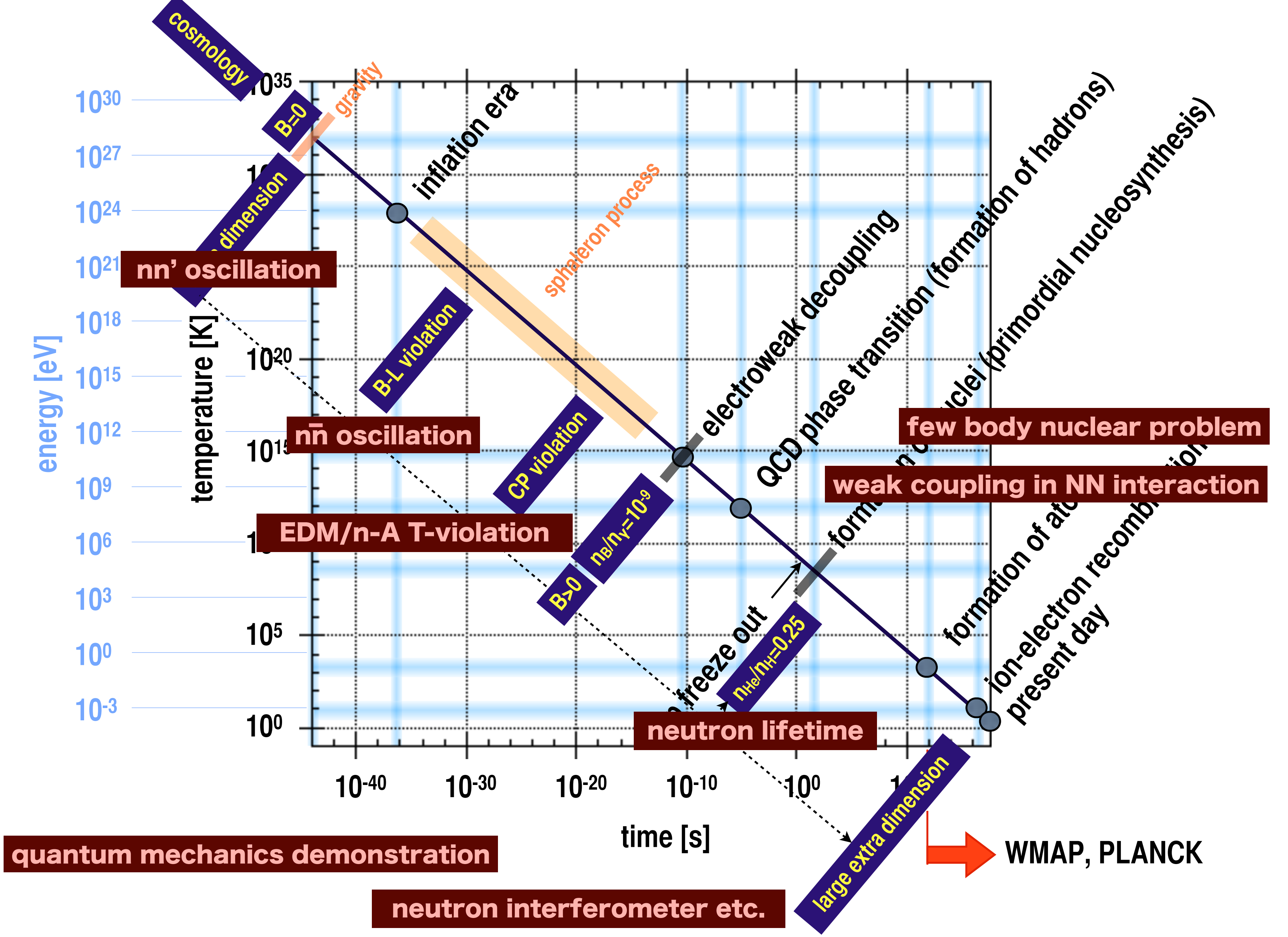

cosmology
gravity
B=0
extra dimension
inflation era
sphaleron process
B-L violation
CP violation
$n_B/n_\gamma=10^{-9}$
B>0
electroweak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-p freeze out
$n_{He}/n_H=0.25$
formation of atoms
ion-electron recombination
present day
large extra dimension
WMAP, PLANCK
energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
temperature [K]
10^{35}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
time [s]
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}



nn’ oscillation

nn̄ oscillation

EDM/n-A T-violation

few body nuclear problem

weak coupling in NN interaction

neutron lifetime

quantum mechanics demonstration

neutron interferometer etc.

physical reality of electromagnetic potential

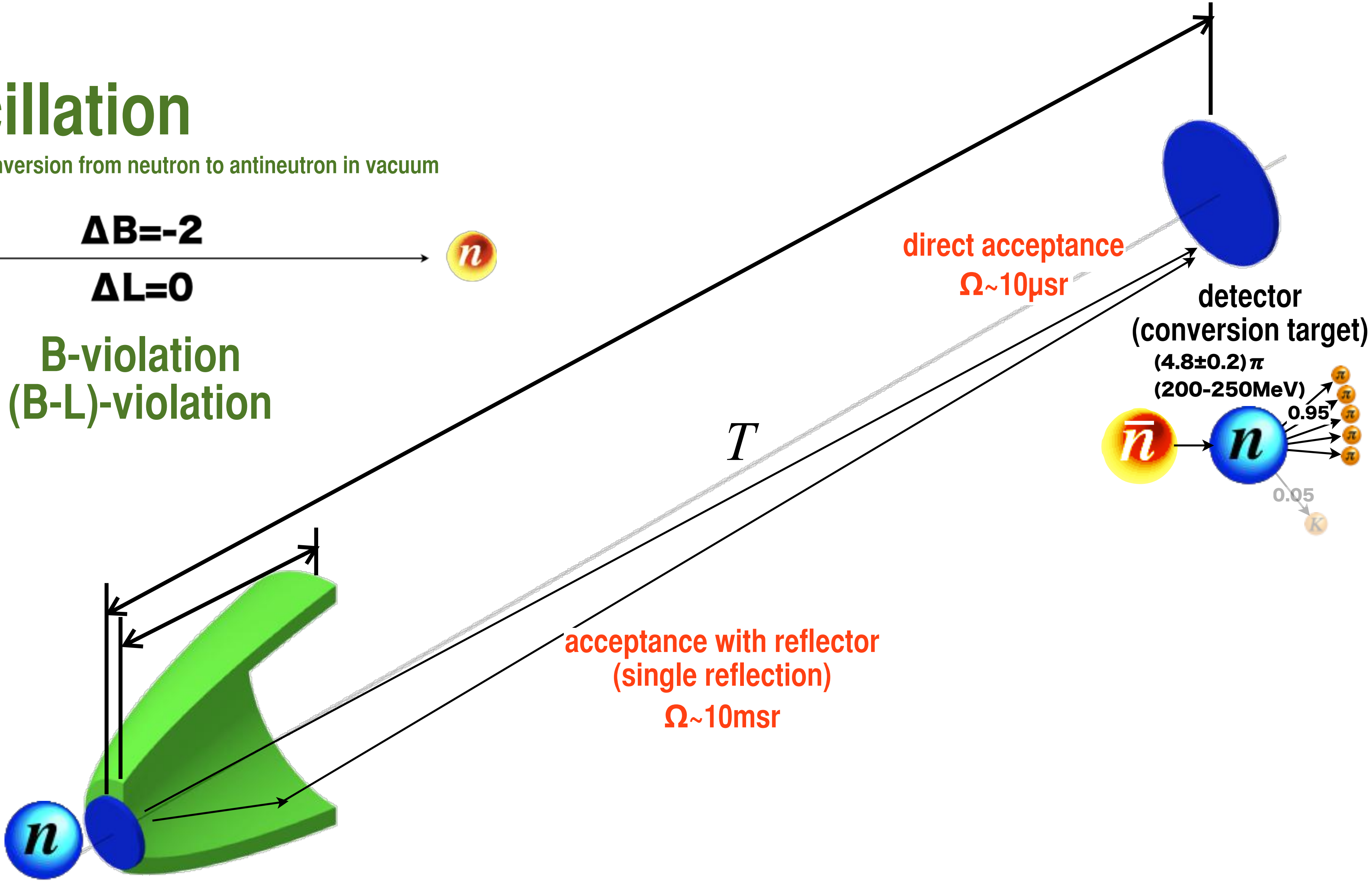
general relativity

n β-decay
nEDM
nn̄ Oscillation

spontaneous conversion from neutron to antineutron in vacuum

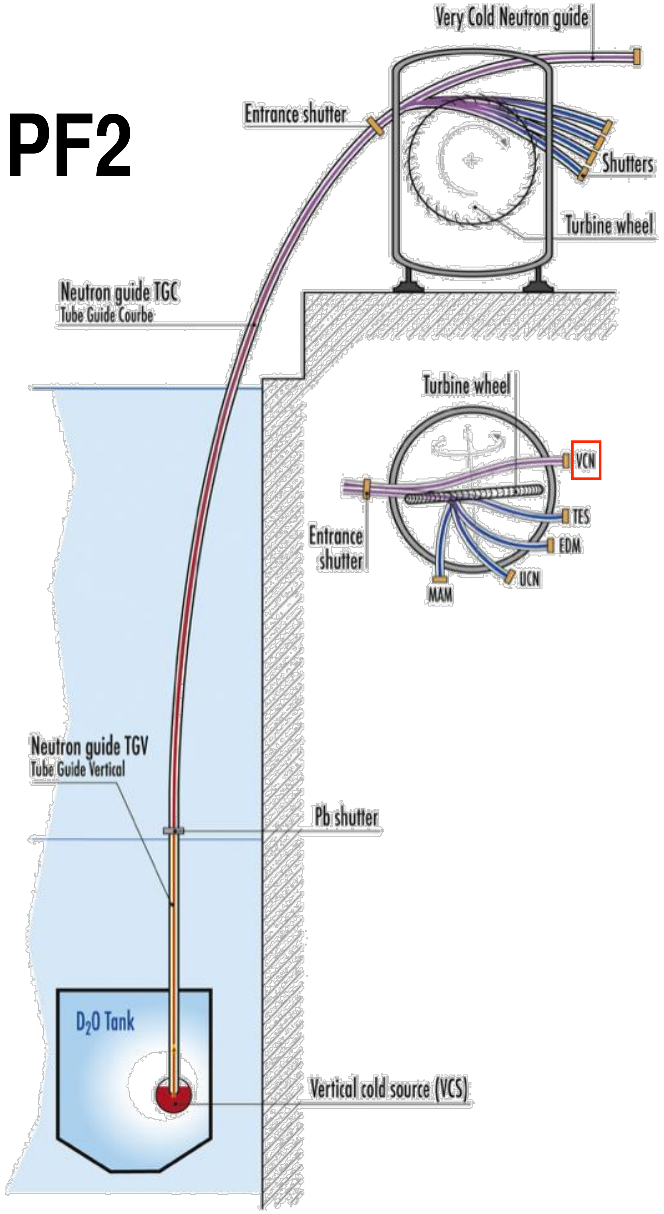
$$n \xrightarrow[\Delta L=0]{\Delta B=-2} n$$

B-violation
(B-L)-violation



Very cold neutrons

ILL PF2



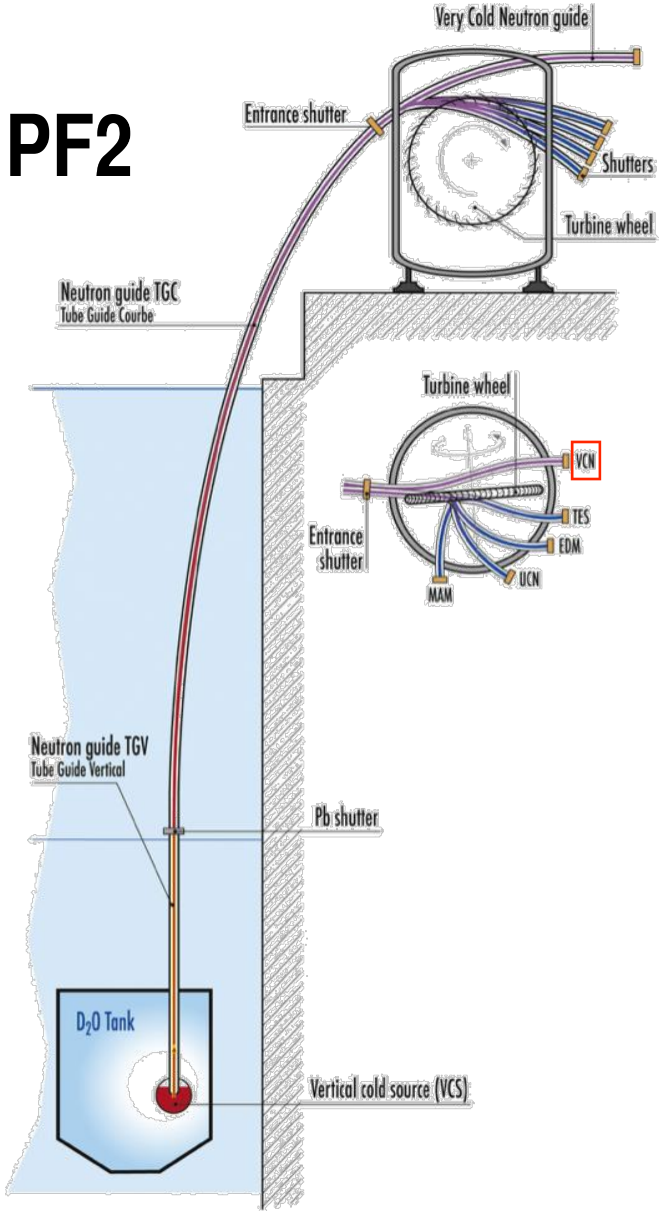
SNS-STS ESS

J-PARC MLF 2nd Target Station

Conceptual Design ver.1.1 (2019/03/22)

Very cold neutrons

ILL PF2



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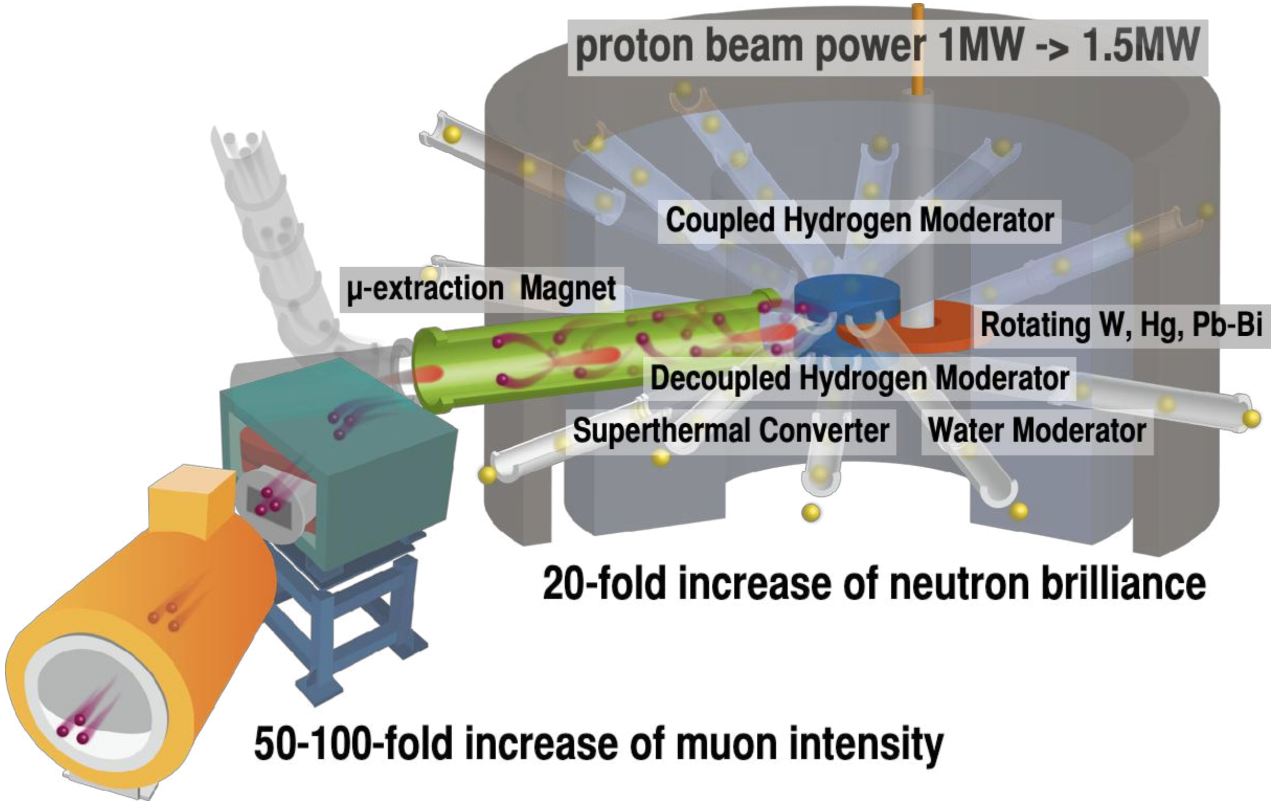


20-fold increase of neutron brilliance

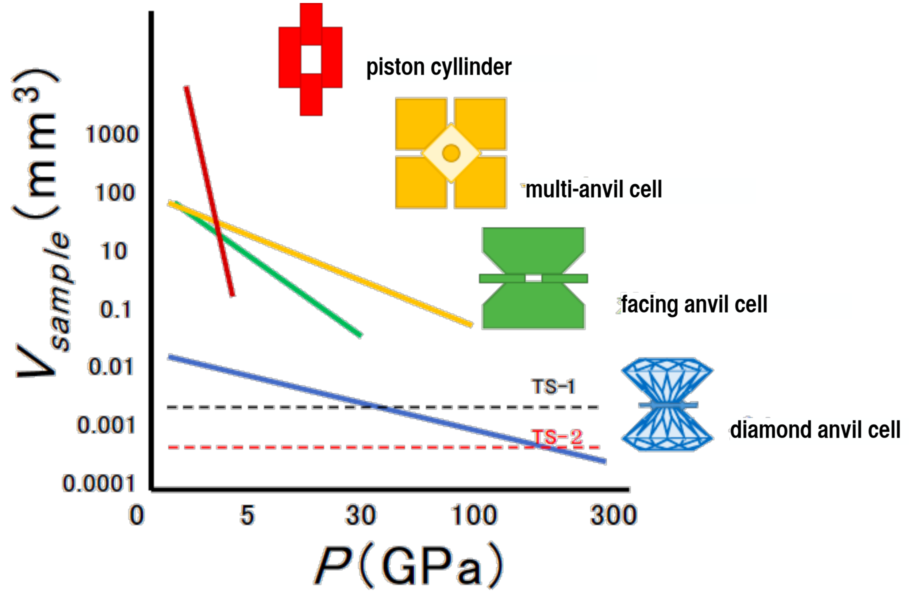
50-100-fold increase of muon intensity

Very cold neutrons

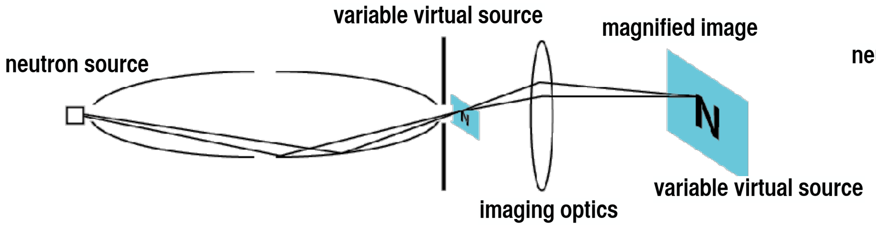
with high phase-space-density

with flexible optical control similar to photon optics

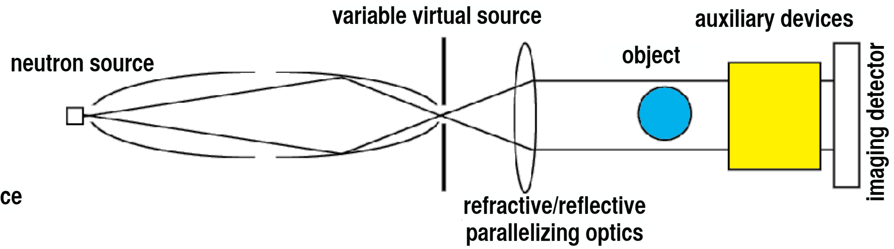
enable various applications.



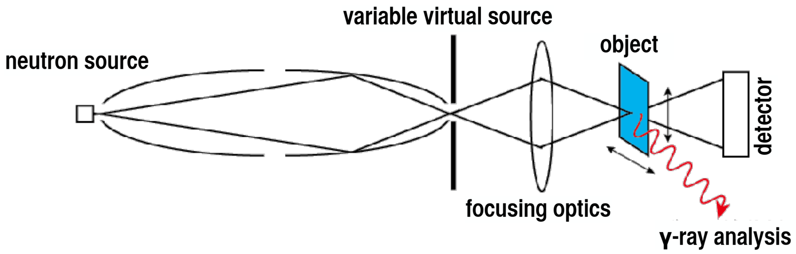
high-resolution imaging



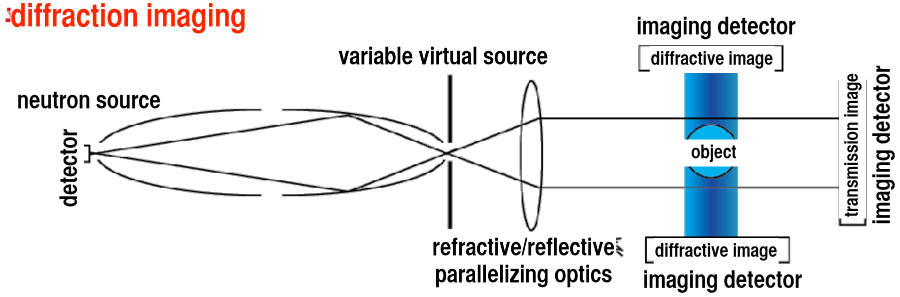
versatile imaging

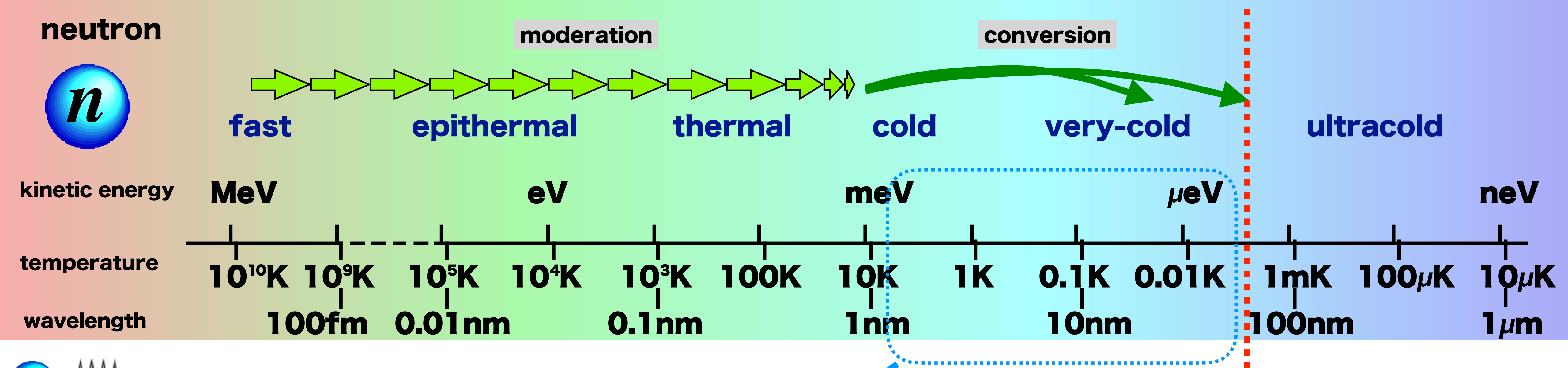


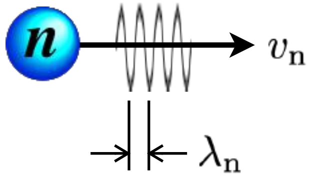
scanning imaging, scanning prompt gamma-ray analysis



diffraction imaging



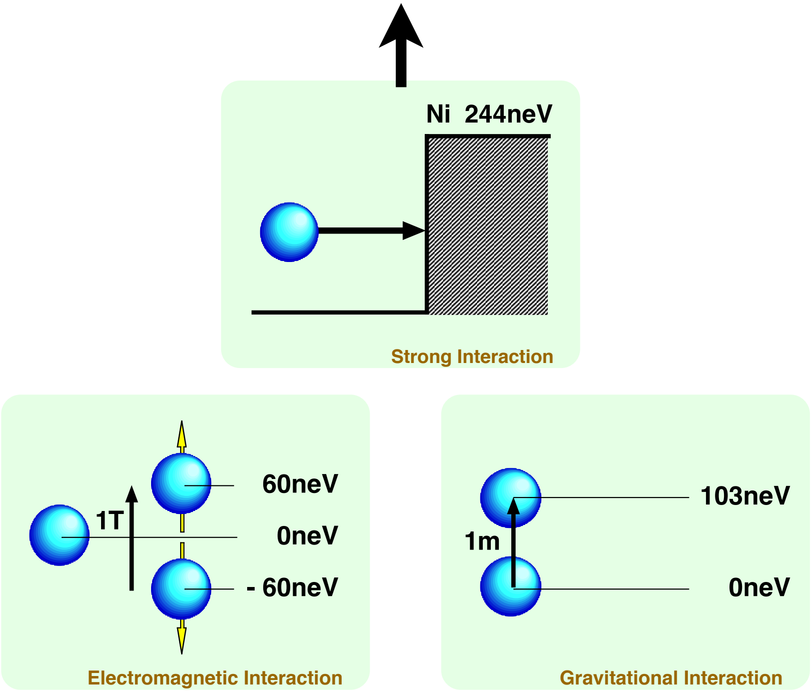




Very cold neutrons

- exhibit significant wave nature,
- can be flexibly controlled by optics,
- can go across material boundaries

neutron interferometry

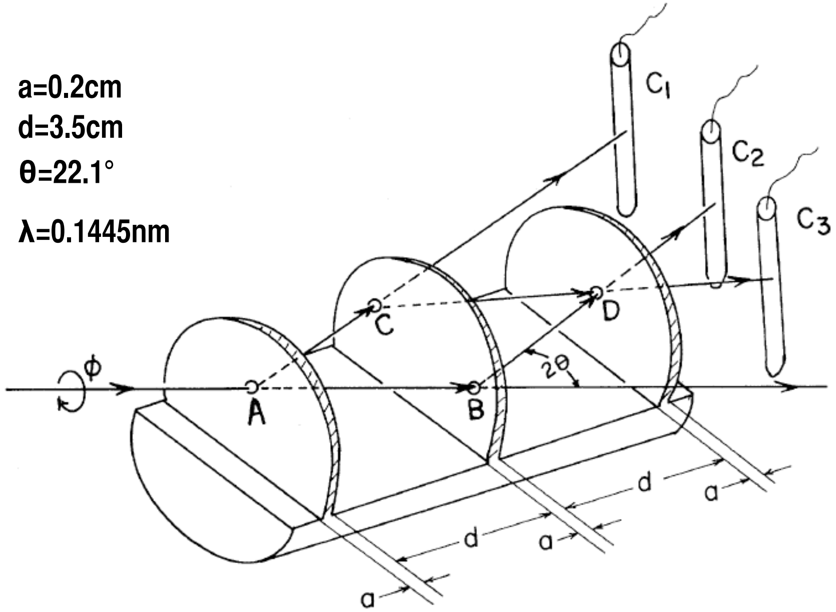


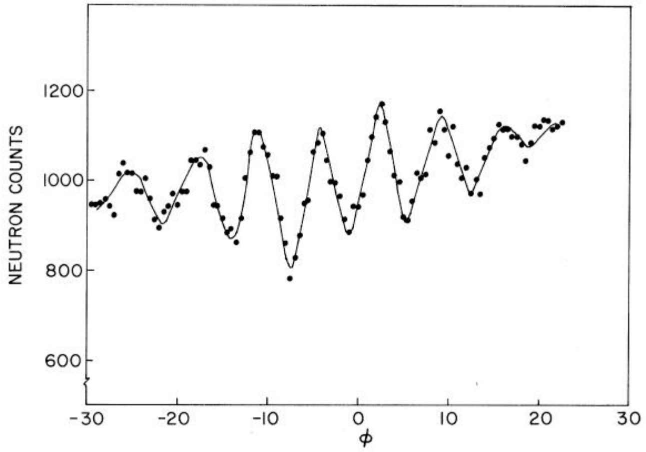
Neutron interferometer

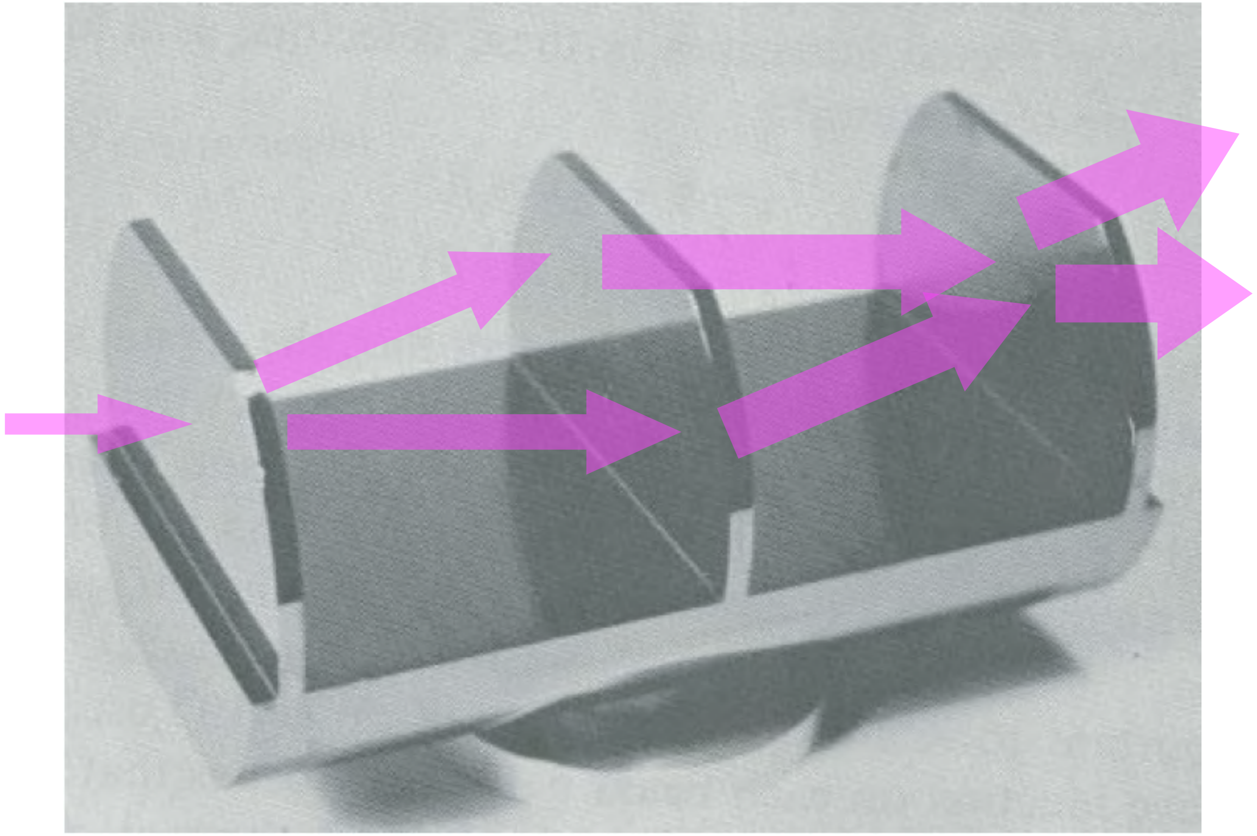
Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

COW experiment (Neutron Phase induced by Earth's Gravity)

a=0.2cm
d=3.5cm
θ=22.1°
λ=0.1445nm

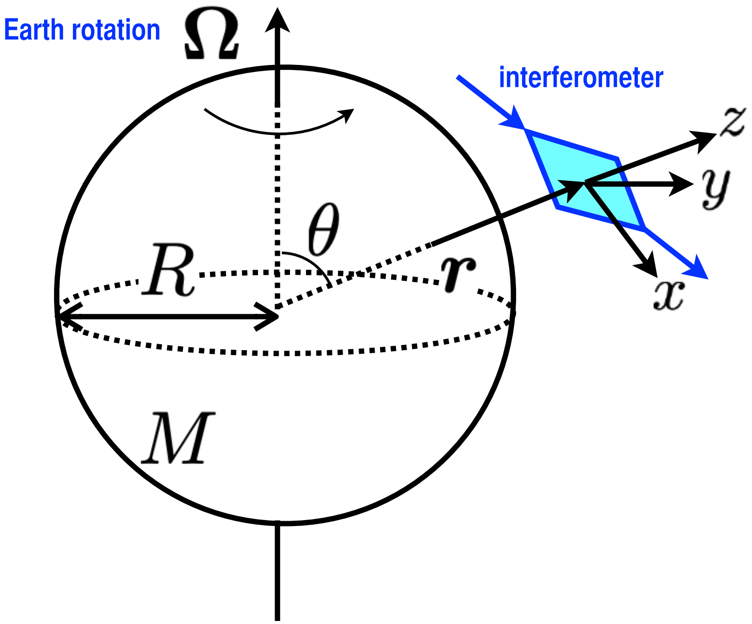






General relativistic effects for neutrons

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



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

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

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

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

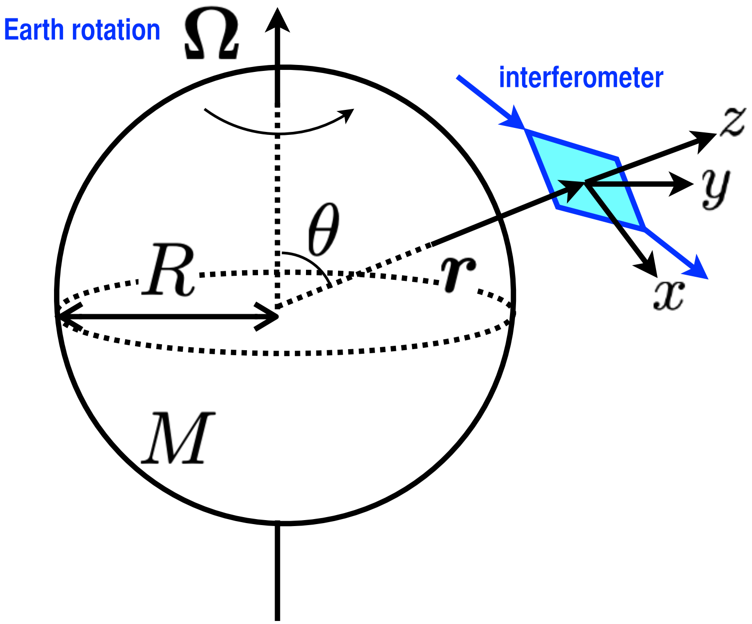
Newtonian terms

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

post-Newtonian terms

General relativistic effects for neutrons

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



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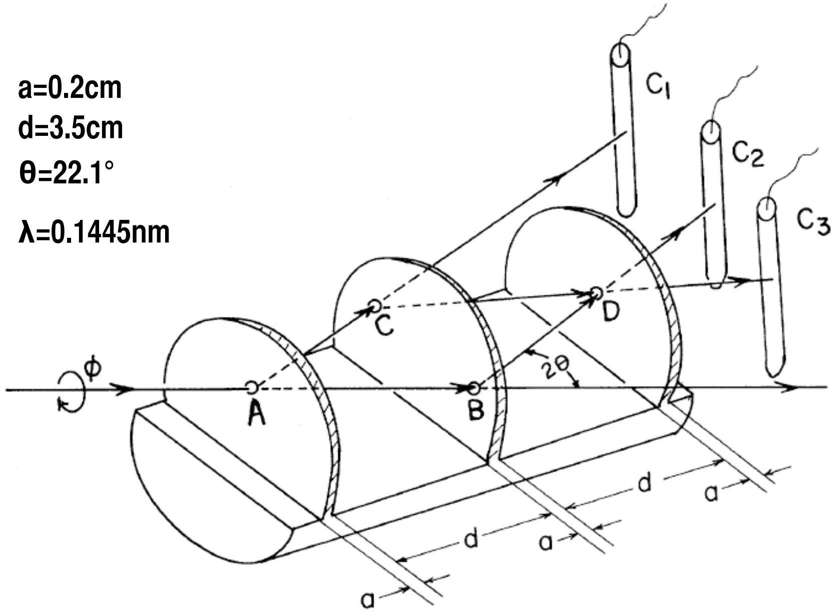
Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

a=0.2cm
d=3.5cm
θ=22.1°
λ=0.1445nm



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

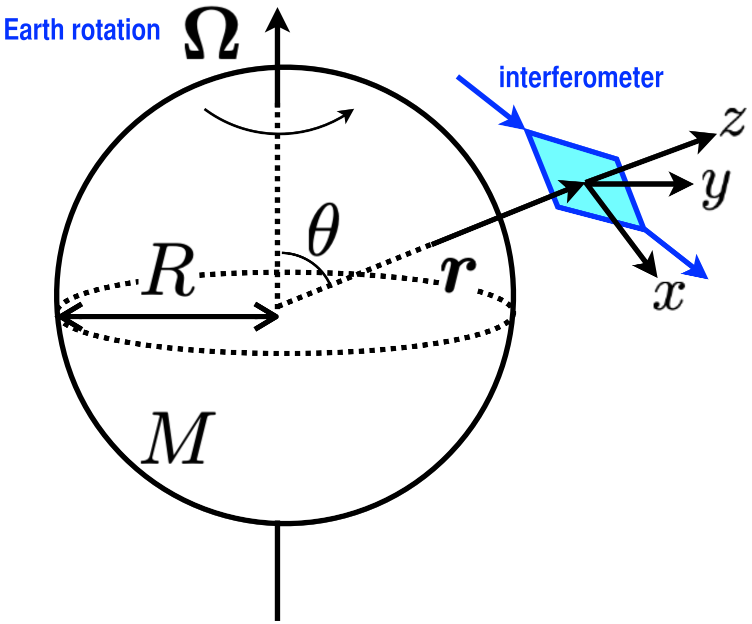
Newtonian terms

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

post-Newtonian terms

General relativistic effects for neutrons

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

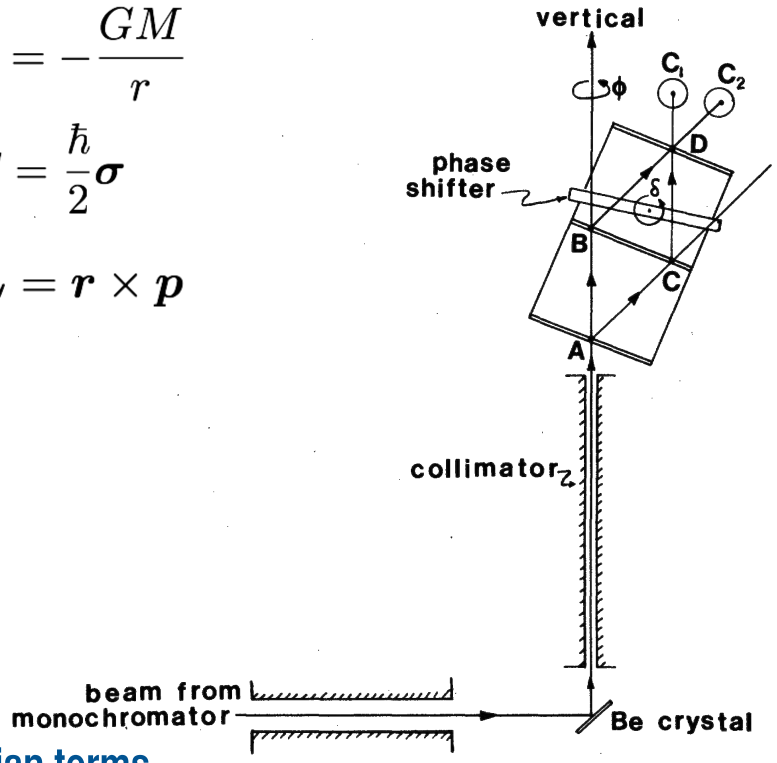


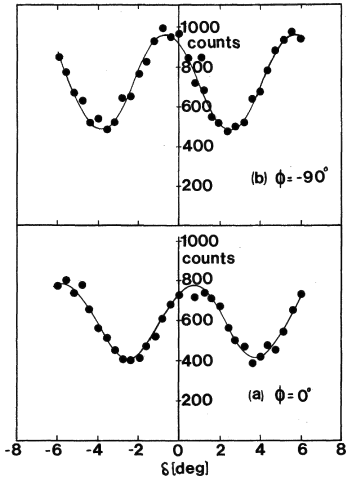
$$\phi = -\frac{GM}{r}$$

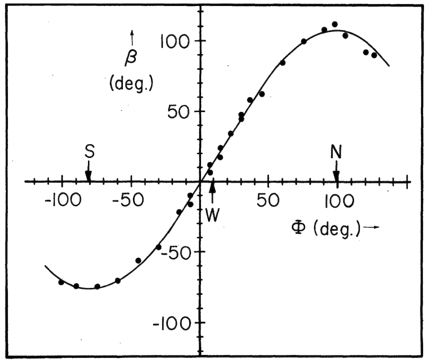
$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

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

S. A. Werner, et. al., Phys. Rev. Lett. 42 (1979) 1103.







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

Newtonian terms

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

post-Newtonian terms

General relativistic effects for neutrons

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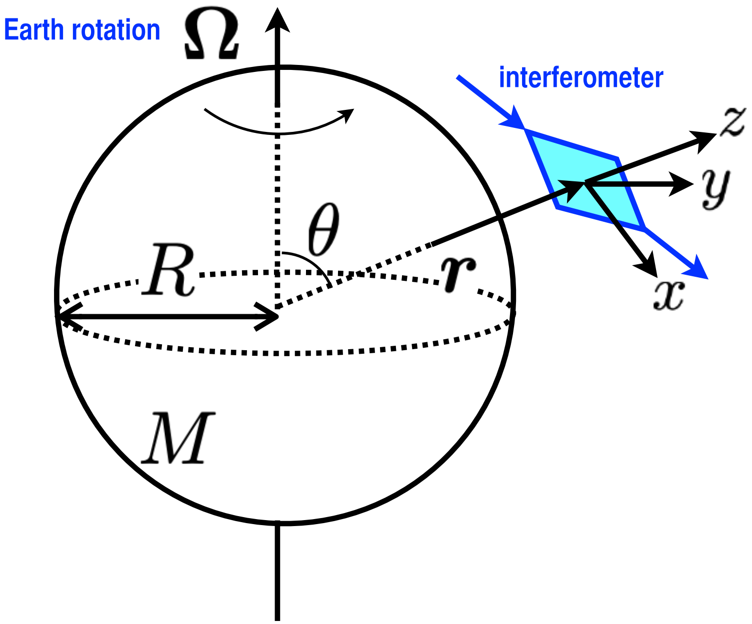


$$\phi = -\frac{GM}{r}$$

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

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

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

Sagnac effect

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

Newtonian terms

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

post-Newtonian terms

Lense-Thirring

Multilayer Neutron Interferometer

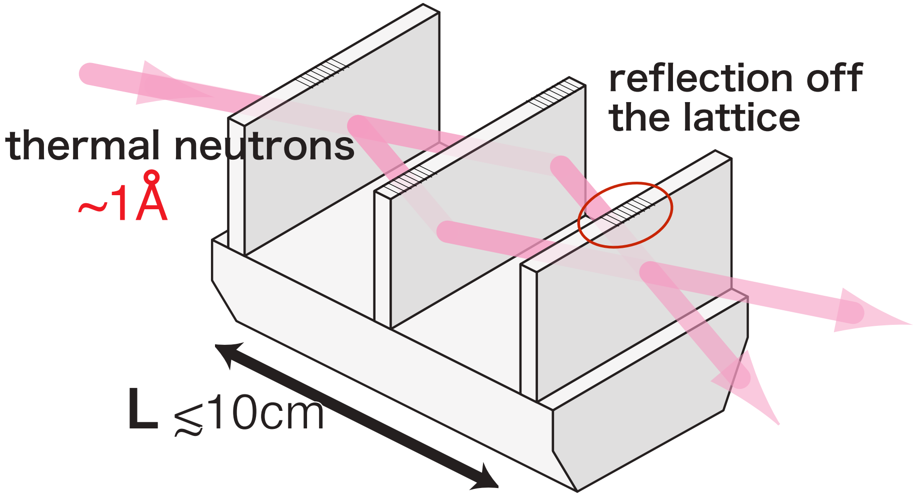
path length

energy difference between two paths

phase change

$$\Delta\varphi = 2\pi \frac{m_\mathrm{n} L}{h^2} \lambda_\mathrm{n} \Delta E$$

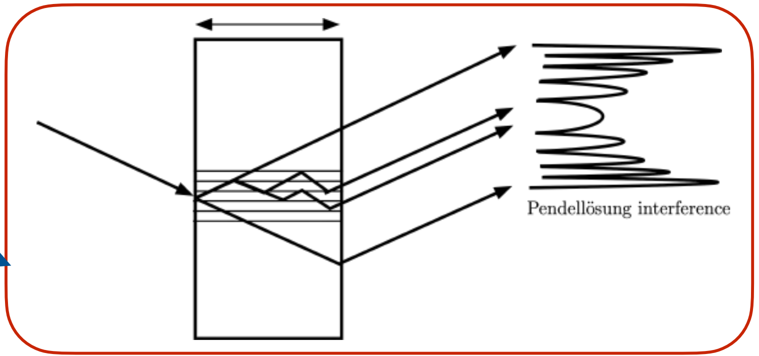
neutron wavelength



λ : limited by the lattice constant

L : limited by the size of available crystal

dynamical diffraction in the diffraction blades



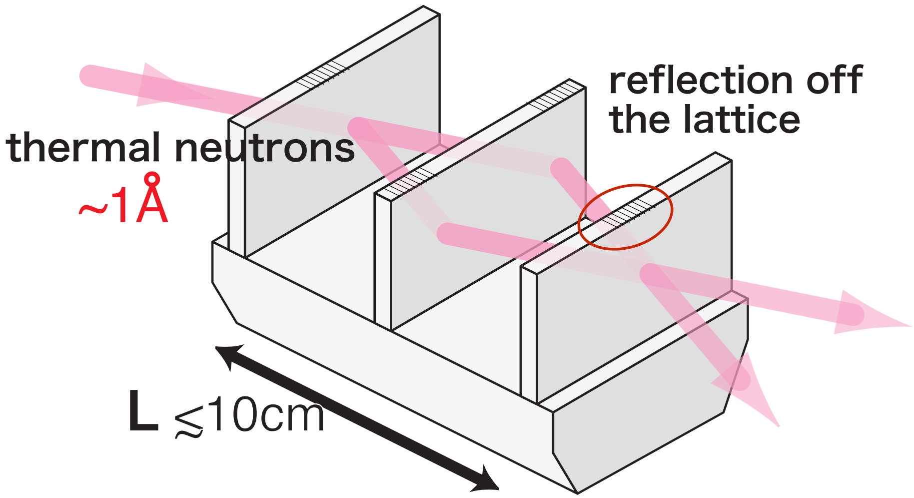
Multilayer Neutron Interferometer

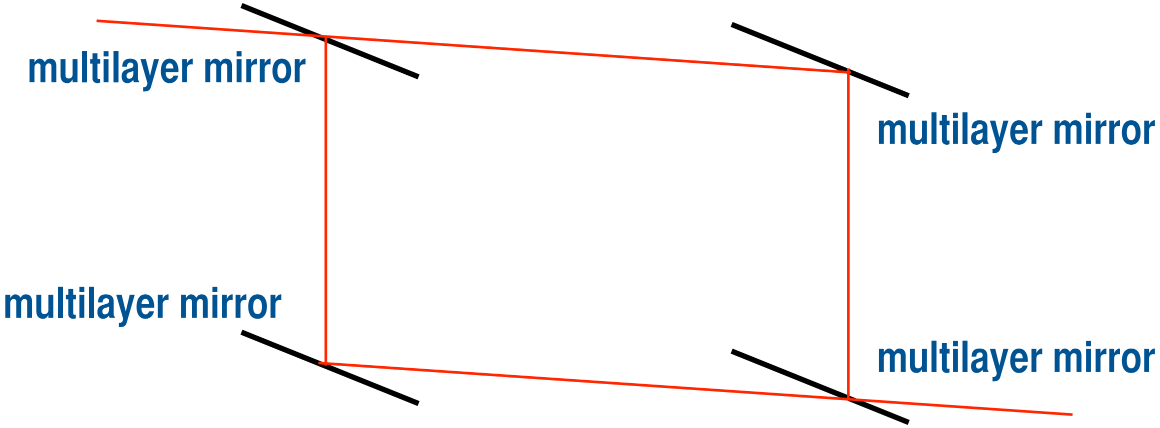
path length

energy difference between two paths

phase change
$$\Delta\varphi = 2\pi \frac{m_{\mathrm{n}} L}{h^2} \lambda_{\mathrm{n}} \Delta E$$

neutron wavelength





λ : limited by the lattice constant

L : limited by the size of available crystal

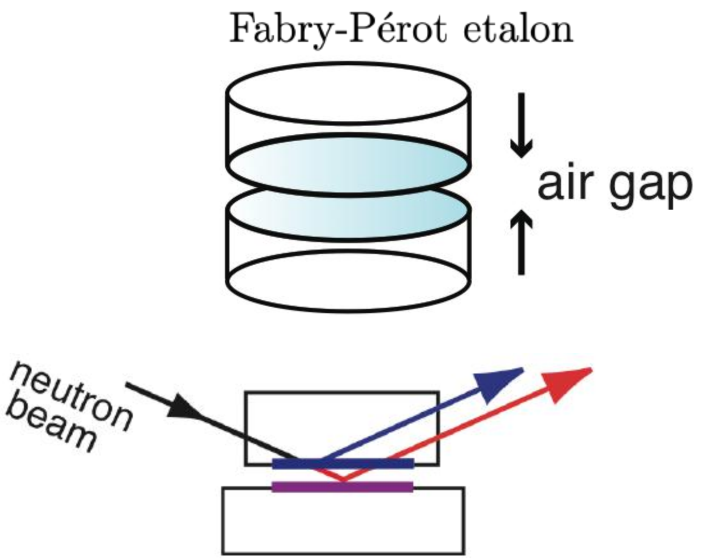
dynamical diffraction in the diffraction blades

λ : not limited by the lattice constant

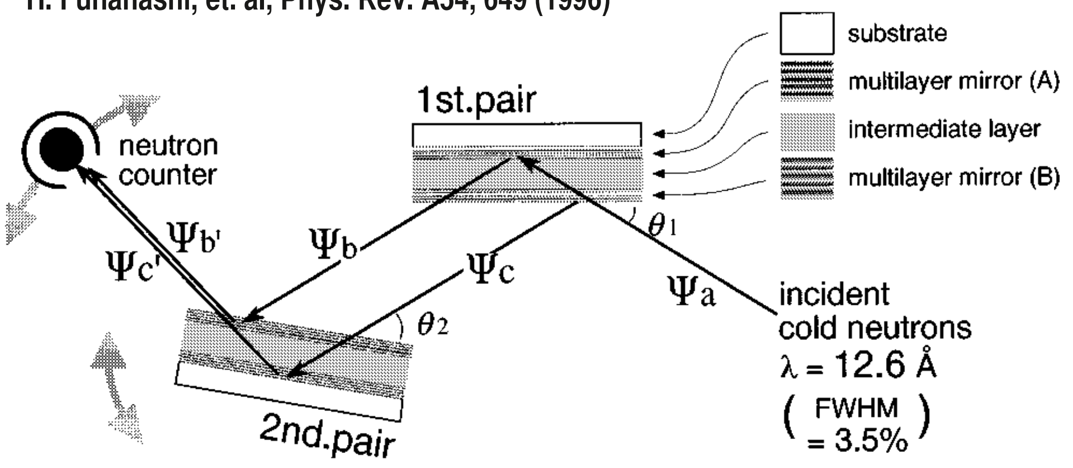
L : not limited by the size of available crystal but mirror alignment

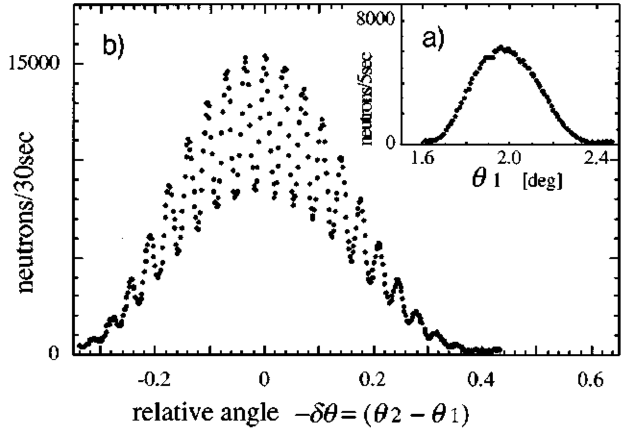
suppressed dynamical diffraction

Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)

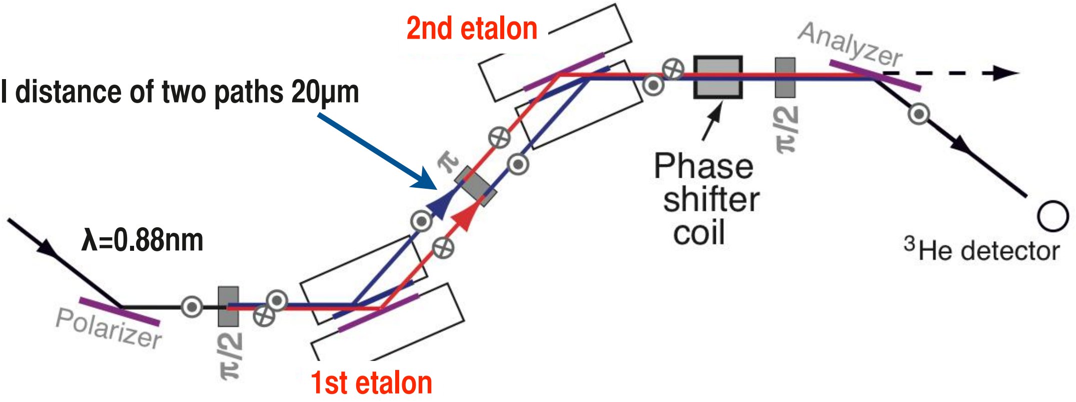


H. Funahashi, et. al, Phys. Rev. A54, 649 (1996)

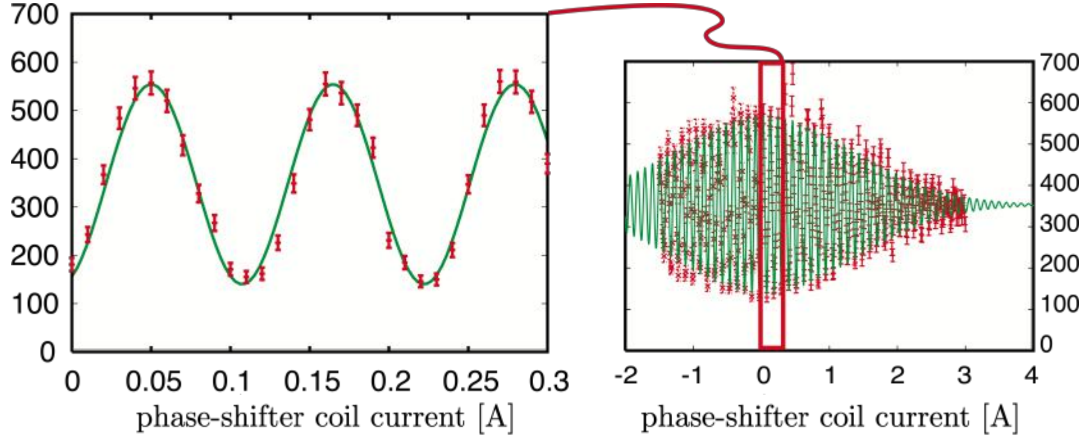




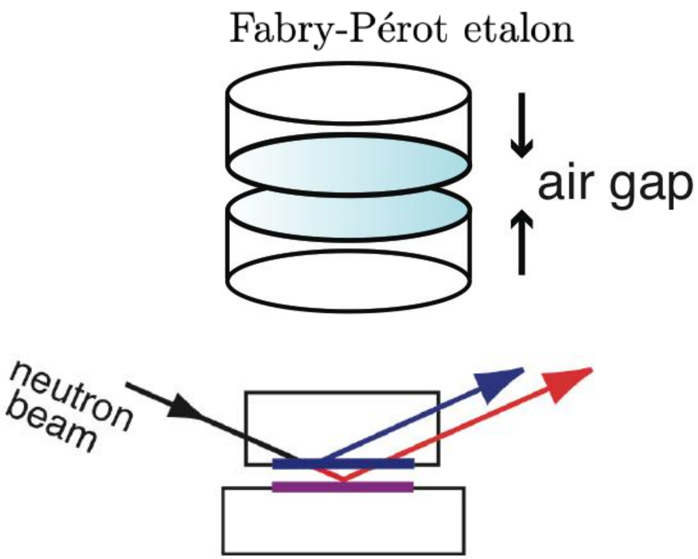
M. Kitaguchi et al., Phys. Rev. A67 033609 (2003).



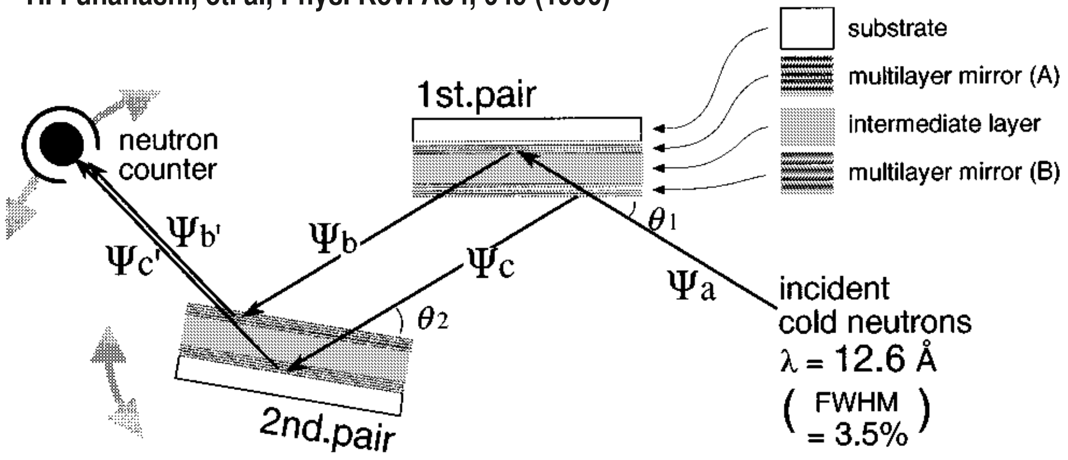
60% contrast

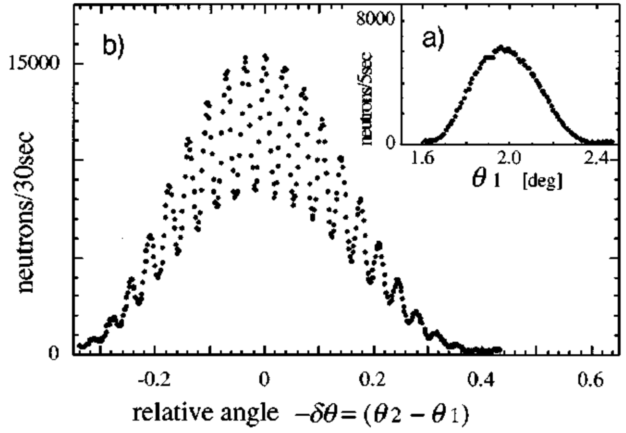


Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)



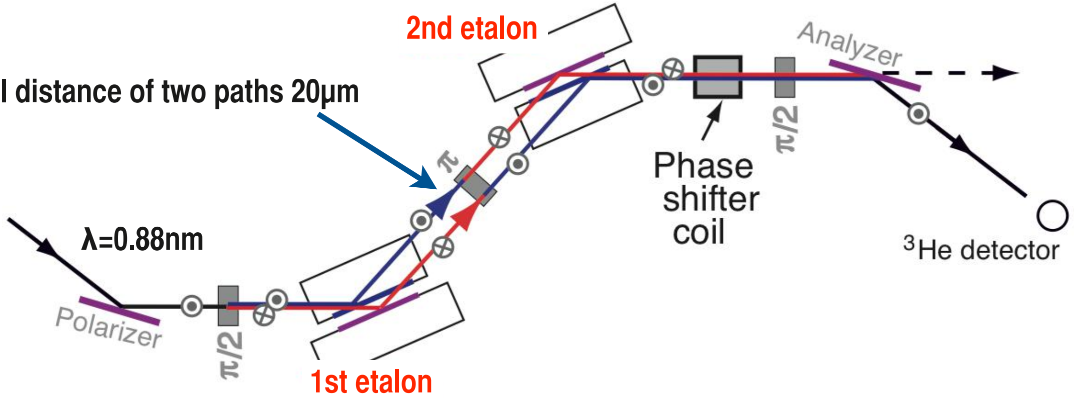
H. Funahashi, et. al, Phys. Rev. A54, 649 (1996)



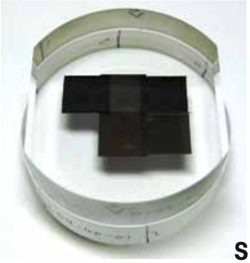


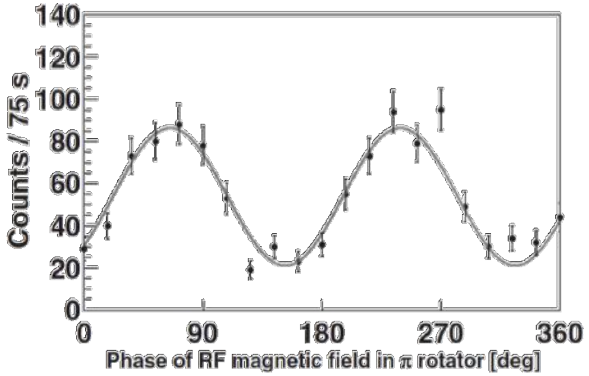
M. Kitaguchi et al., Phys. Rev. A67 033609 (2003).

spatial distance of two paths 20μm



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



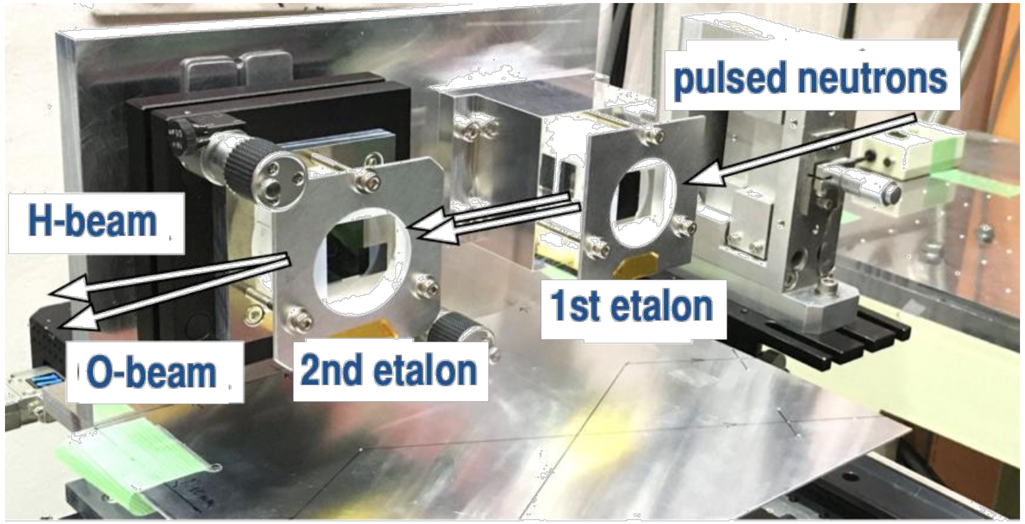


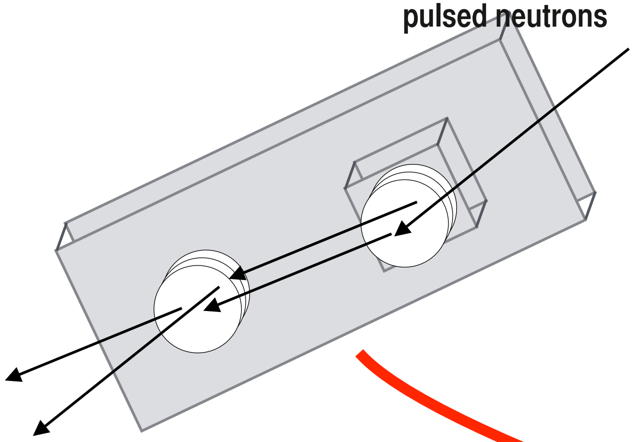
spatial distance of two paths 330μm

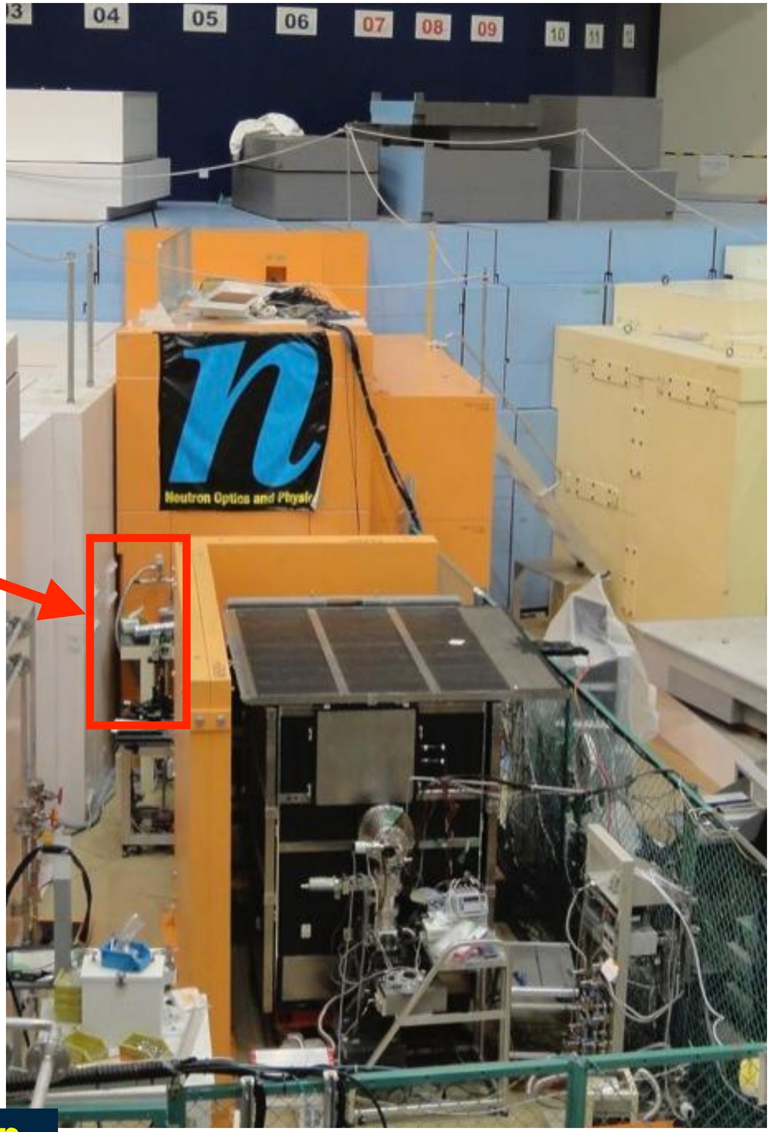
Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)

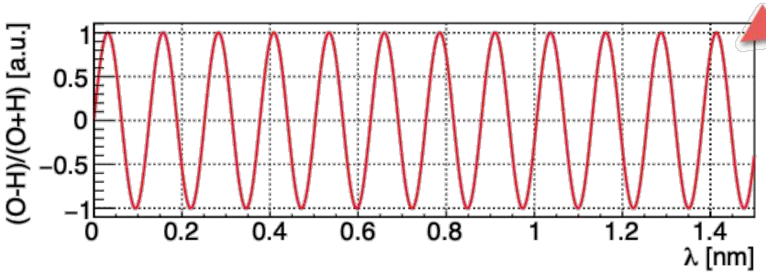
T.Fujiie, M.Hino, T.Hosobata, G.Ichikawa, M.Kitaguchi, K.Mishima, Y.Seki, H.M.Shimizu, Y.Yamagata

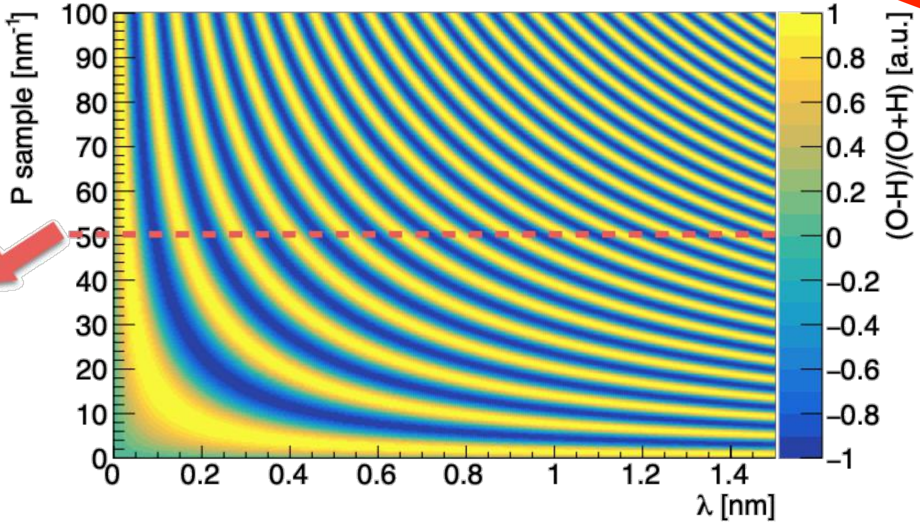
J-PARC MLF BL05 Low Divergence Branch









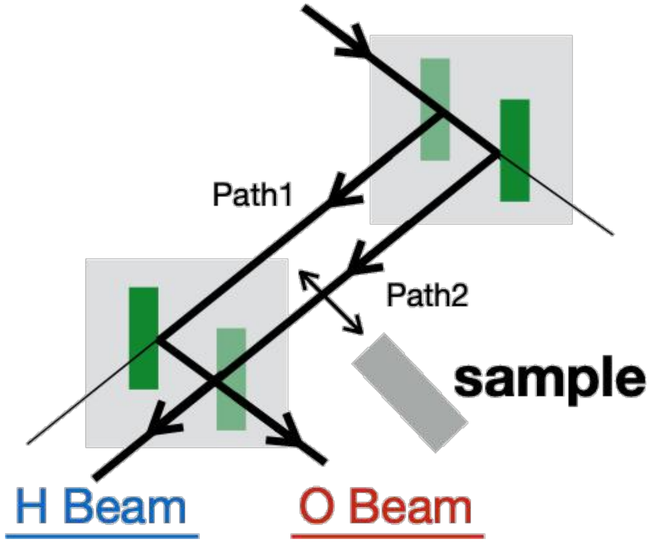


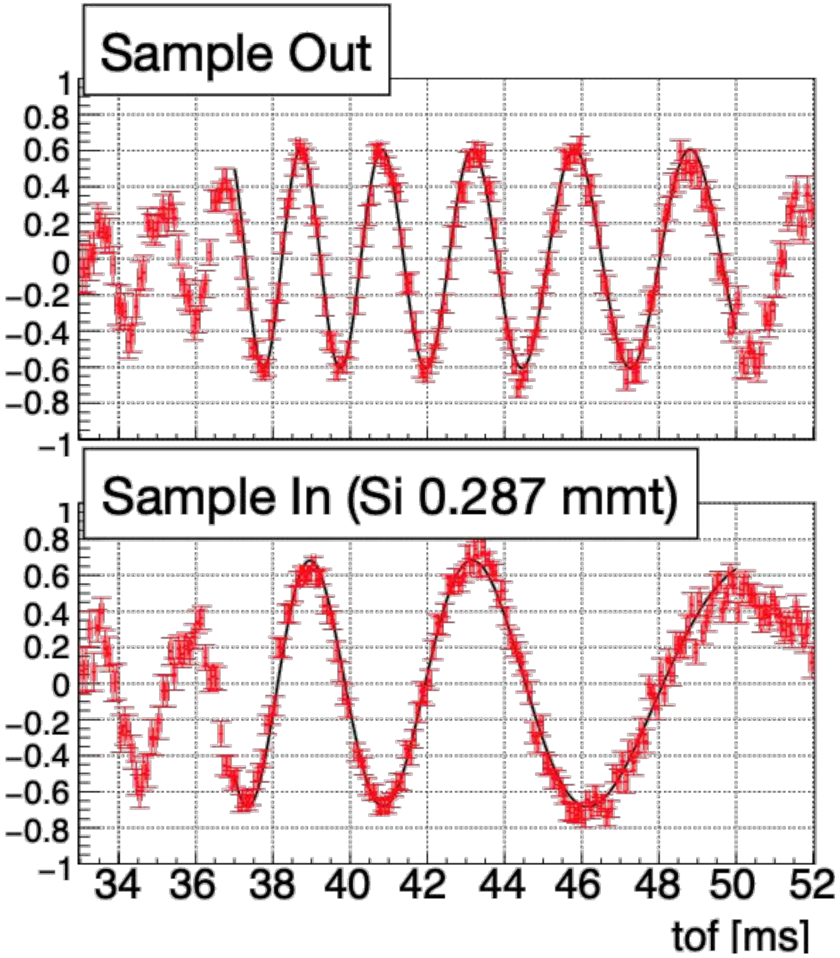
The phase sensitivity is stabled by extracting phase shift in the 2-dim. interference pattern.

Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)

T.Fujiie, M.Hino, T.Hosobata, G.Ichikawa, M.Kitaguchi, K.Mishima, Y.Seki, H.M.Shimizu, Y.Yamagata

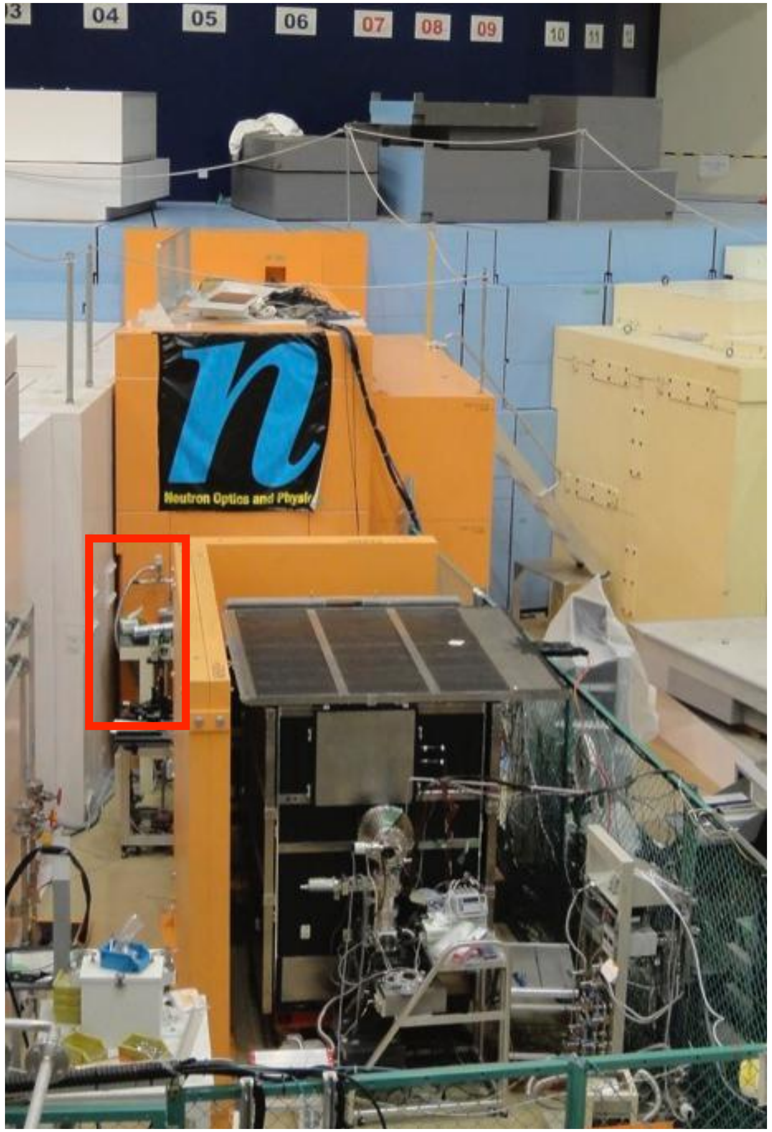
being applied for the measurement of neutron scattering length




Sample Out

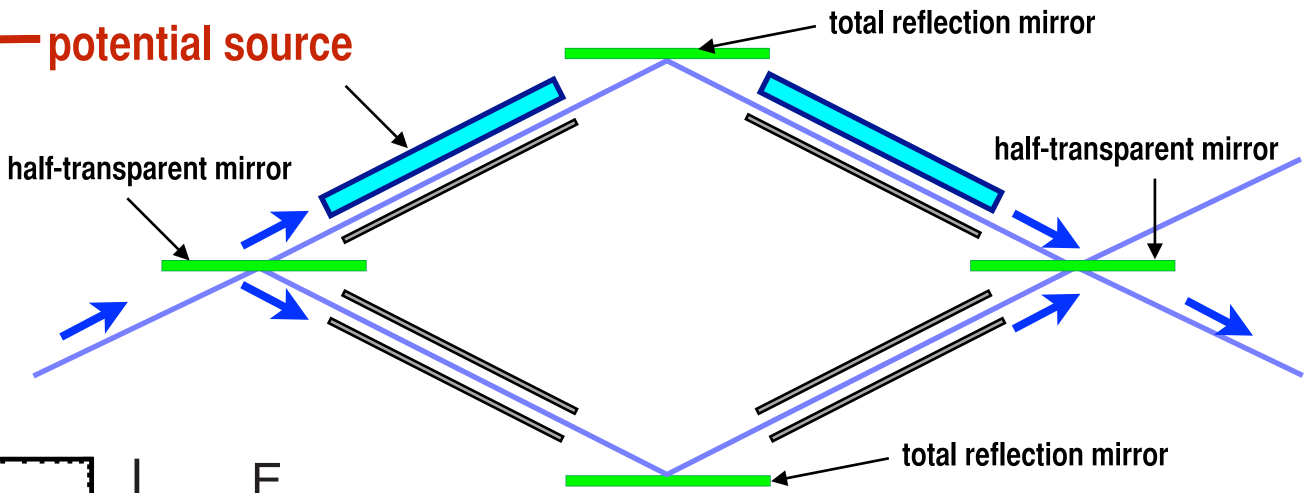
Sample In (Si 0.287 mmt)

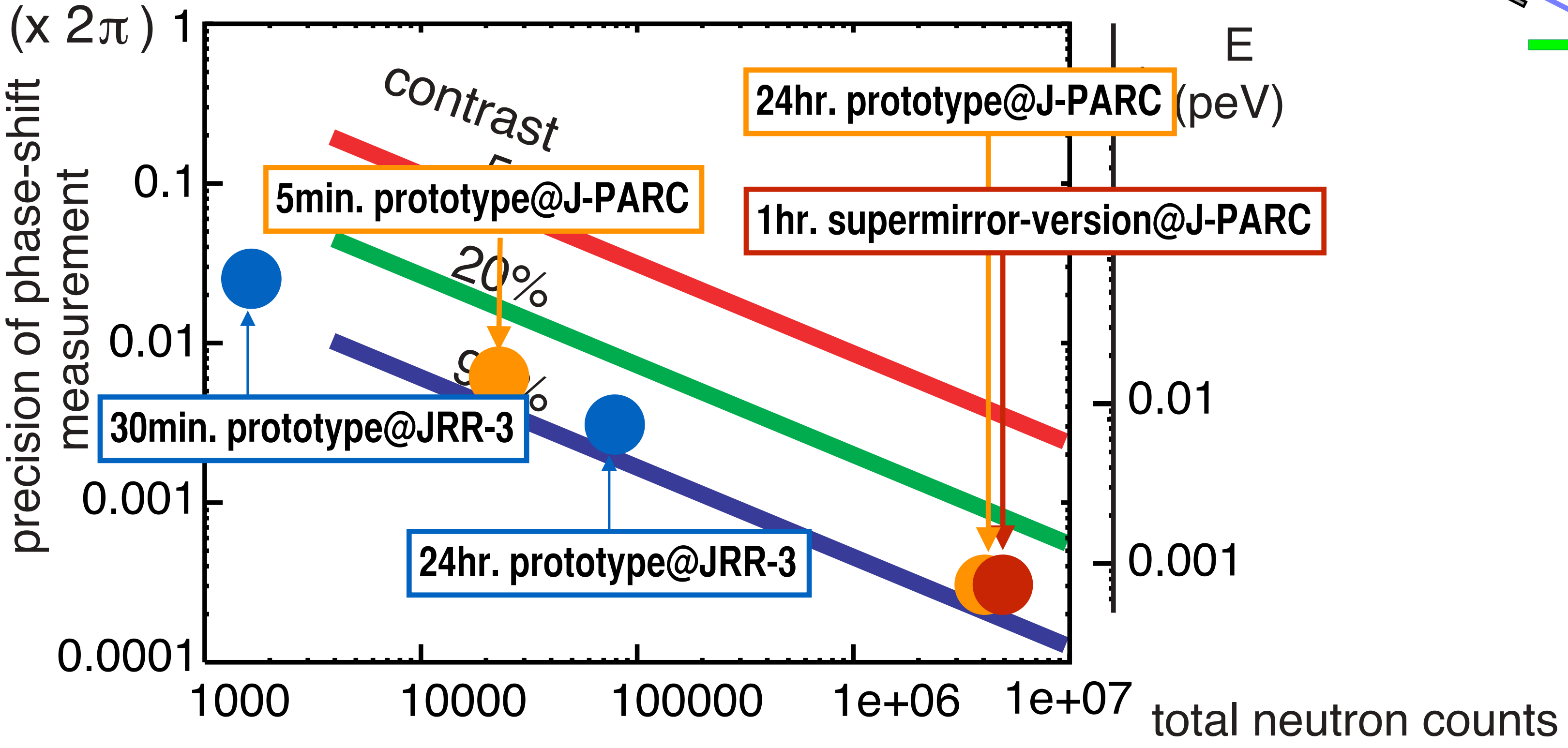
J-PARC MLF BL05 Low Divergence Branch



Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)

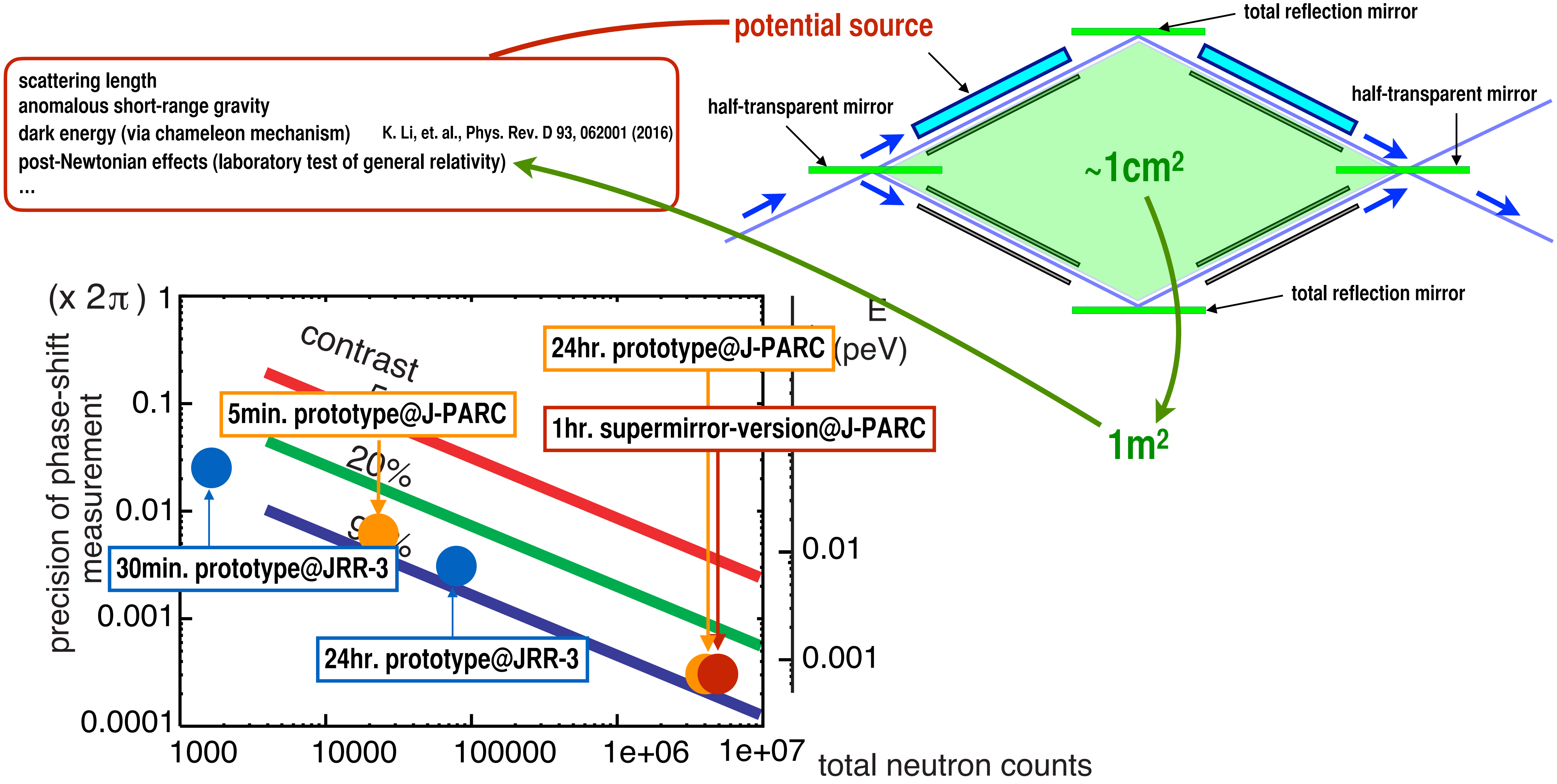
scattering length
anomalous short-range gravity
dark energy (via chameleon mechanism) K. Li, et. al., Phys. Rev. D 93, 062001 (2016)
post-Newtonian effects (laboratory test of general relativity)
...





Multilayer Neutron Interferometer with etalon configuration (BSE: Beam-Splitting Etalon)

scattering length
anomalous short-range gravity
dark energy (via chameleon mechanism) K. Li, et. al., Phys. Rev. D 93, 062001 (2016)
post-Newtonian effects (laboratory test of general relativity)
...

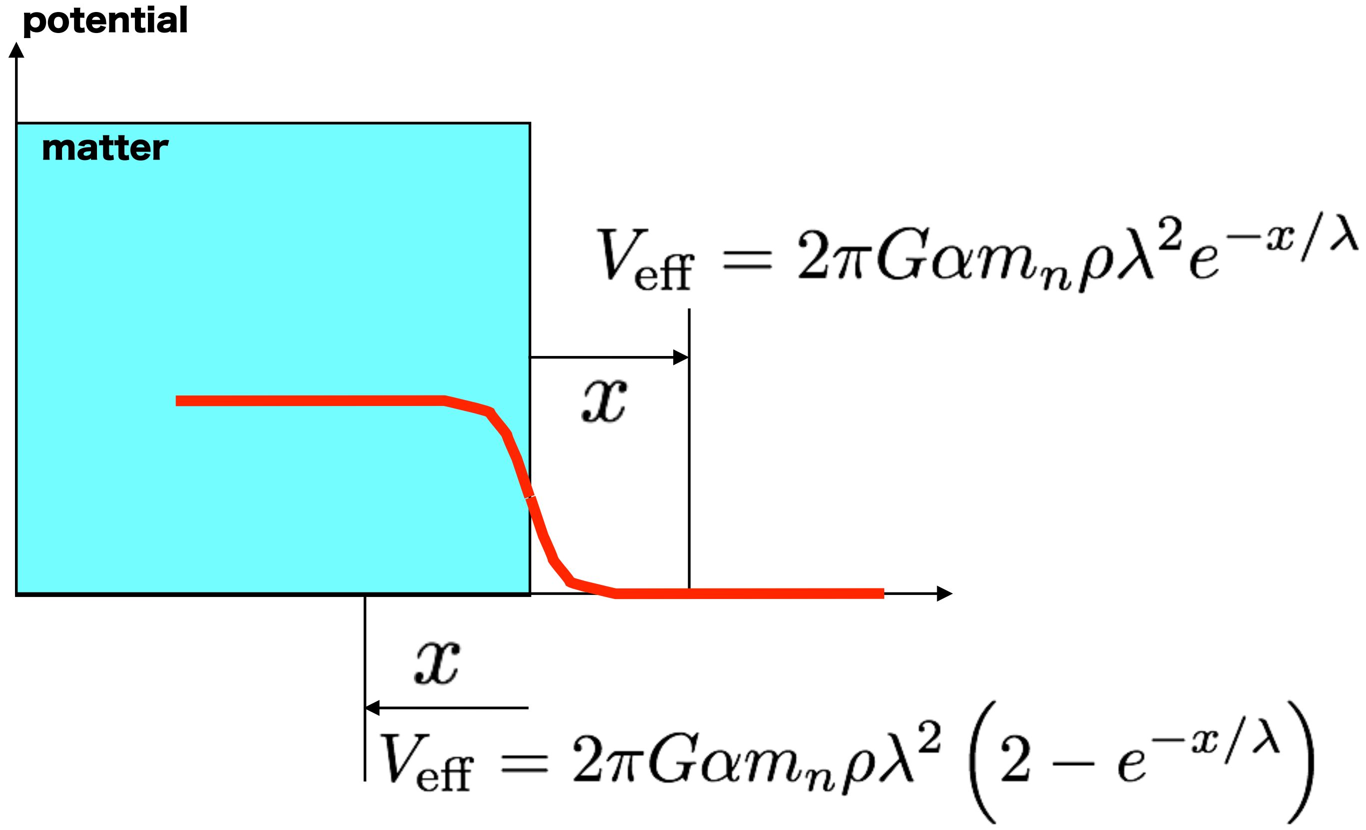


Parametric Resonance

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

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



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

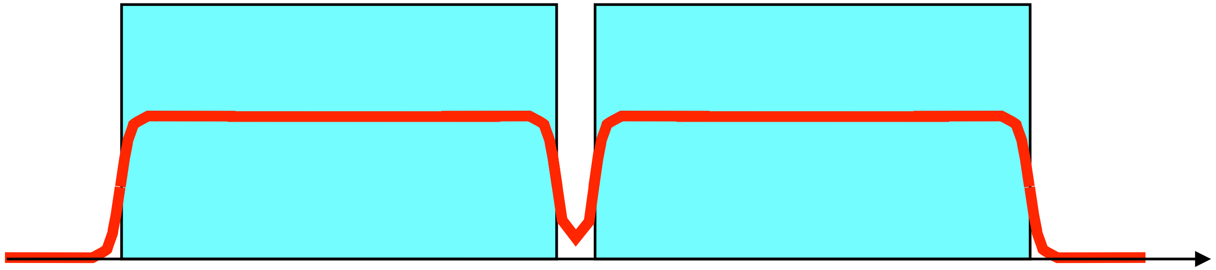
$$V_{\mathrm{eff}} = 2\pi G\alpha m_n \rho \lambda^2 \left(2 - e^{-x/\lambda}\right)$$

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

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

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



Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

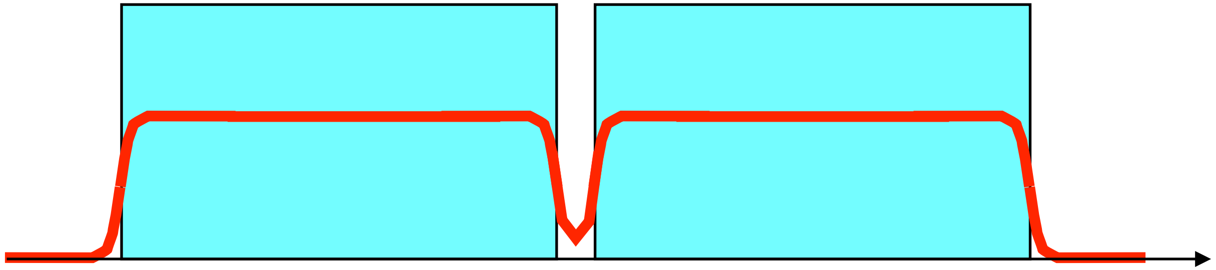
$$V_{\rm eff} = k_0^2 + 2\alpha^2 e^{-L/2\lambda} \cosh\left(\frac{x}{\lambda}\right)$$

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

pamametric resonance

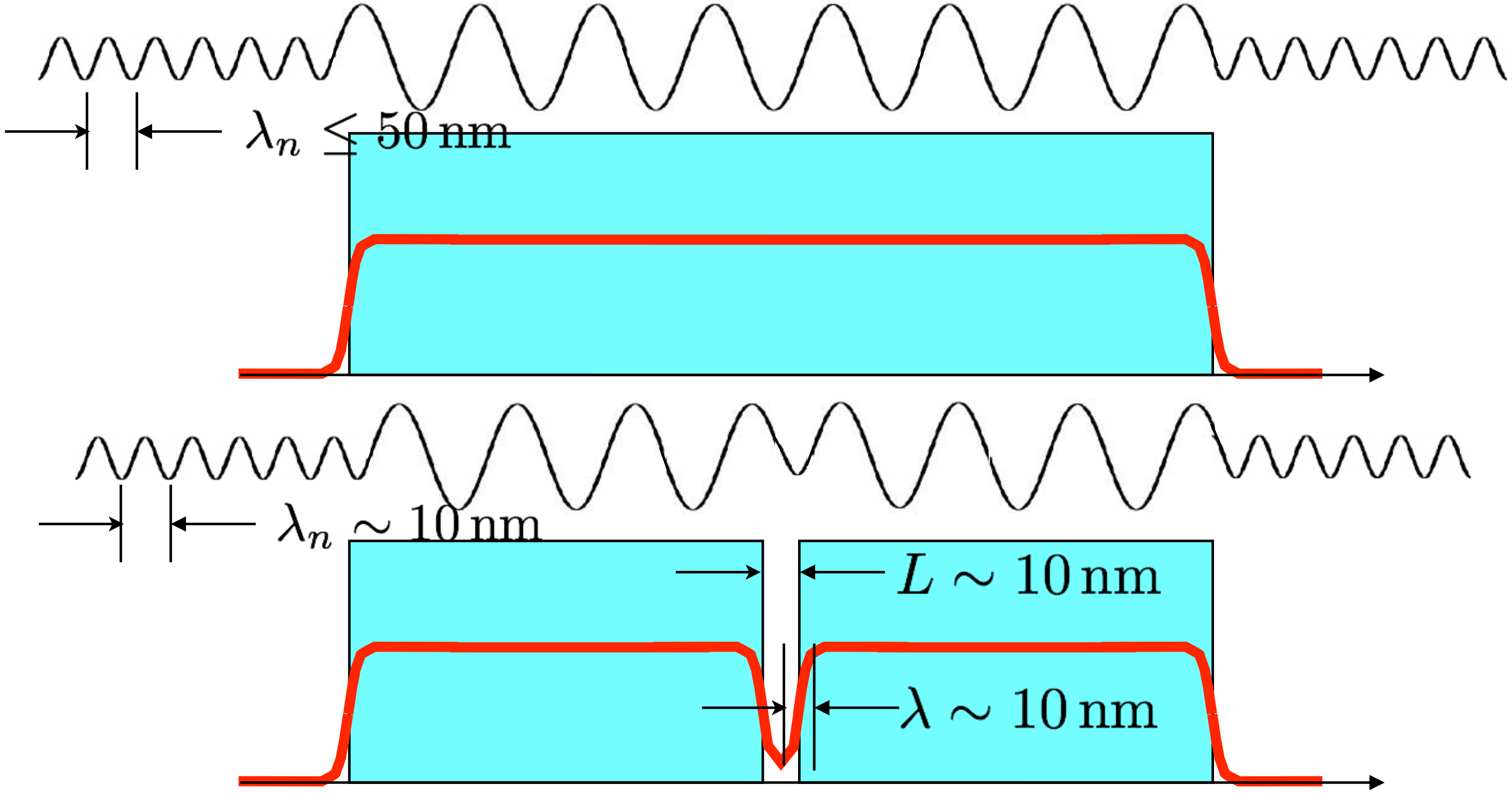
$$\frac{2k_0}{1 + \frac{2\alpha^2}{k_0^2}\exp(-L/\lambda)\frac{\sinh(L/\lambda)}{L/\lambda}} = \frac{n\pi}{L} \qquad \lambda_n \simeq \frac{4L}{n} \quad (\eta \to 0)$$

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



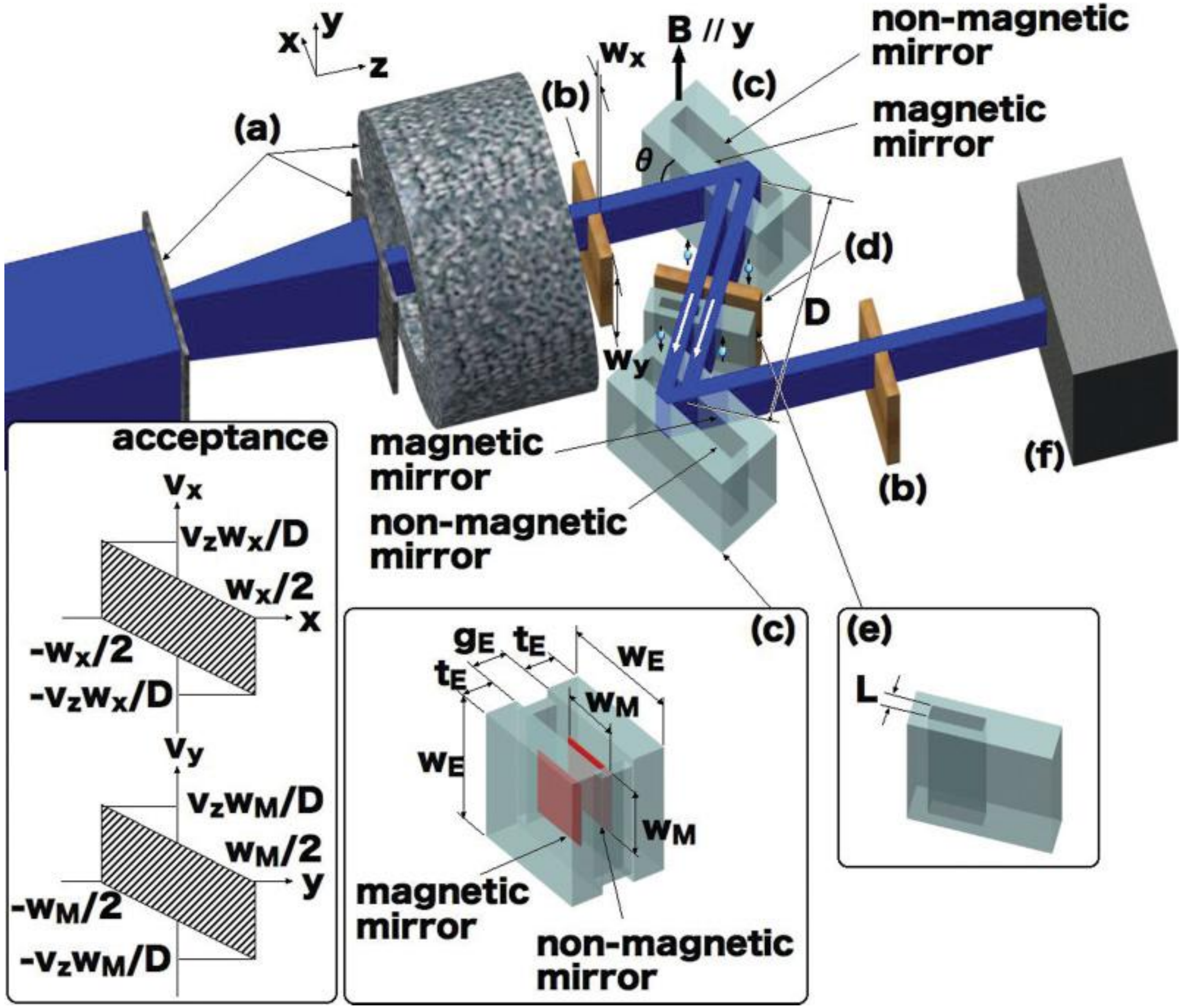
Parametric Resonance in 1-dim Potential

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

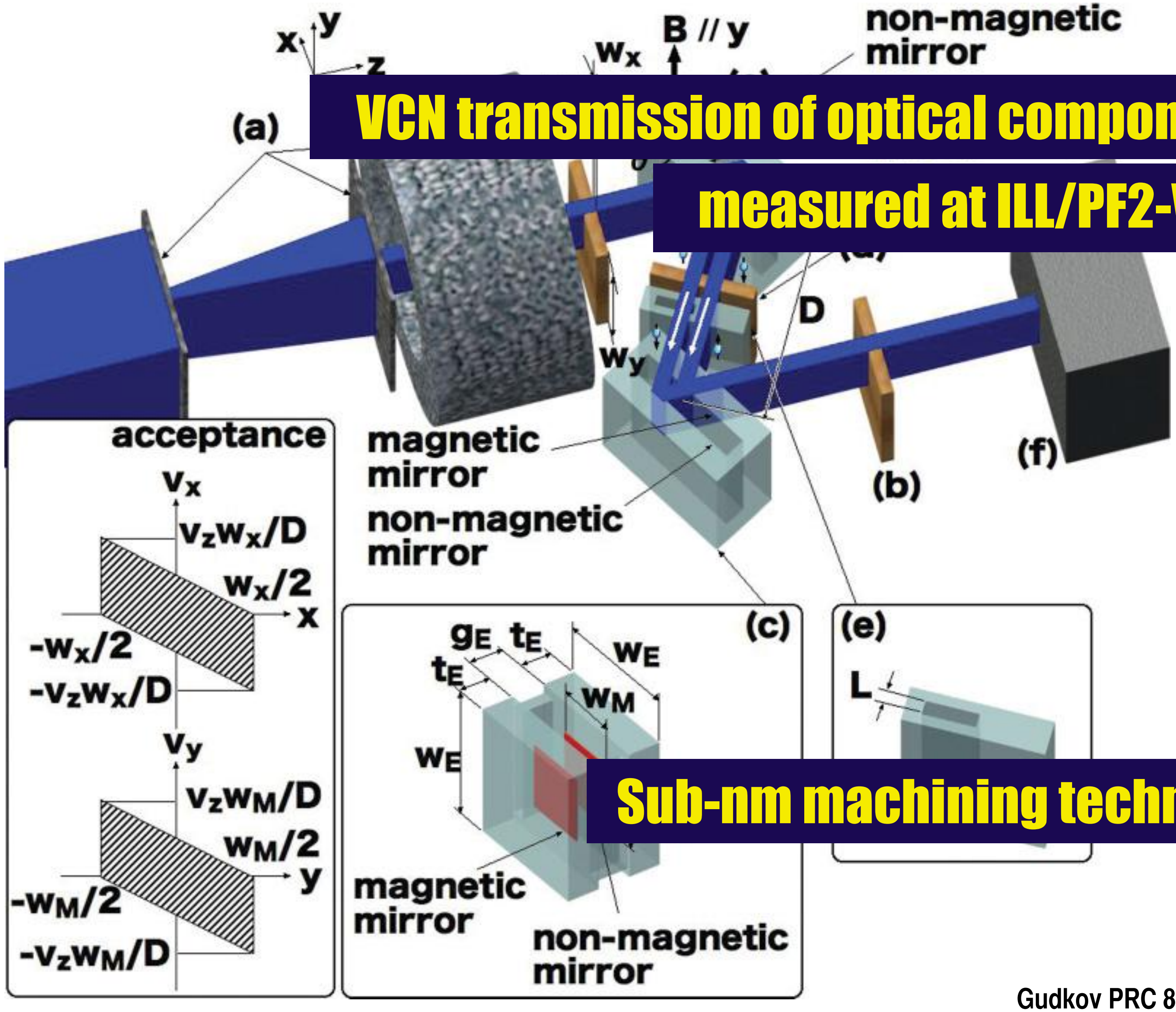


Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

Experimental Apparatus of the Search for Parametric Resonance



Experimental Apparatus of the Search for Parametric Resonance



VCN transmission of optical component

measured at ILL/PF2-VCN

Sub-nm machining technique

Gudkov PRC 83 (2011) 025501

Neutron Velocity Concentrator

M.Kitaguchi, Prog. Theor. Exp. Phys. (2017) 043D01

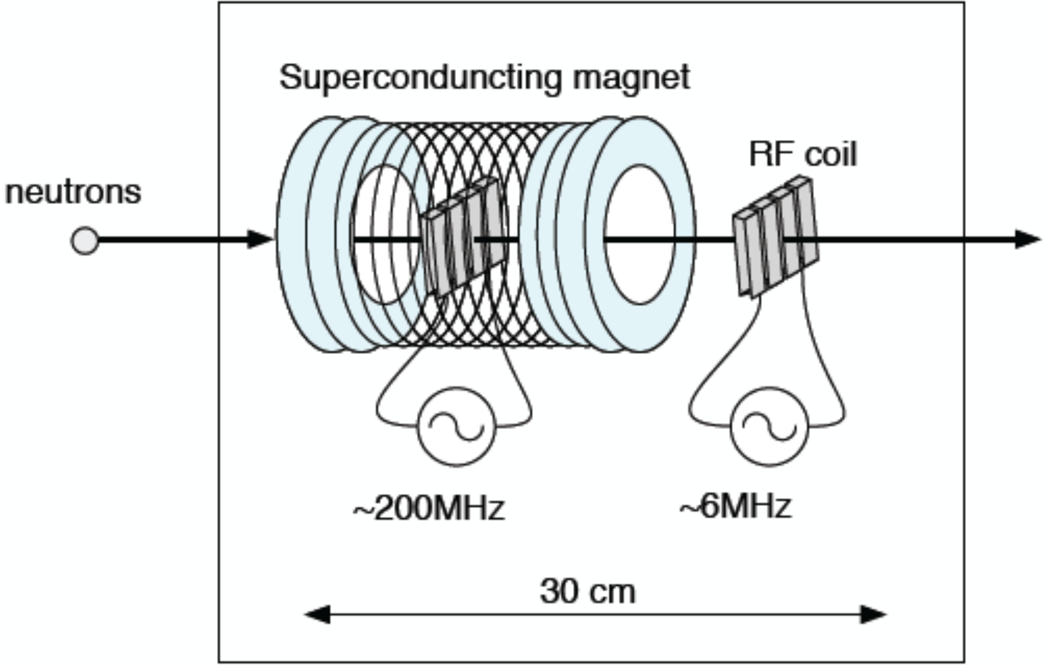
Deceleration and acceleration by spin flip

RF spin flipper

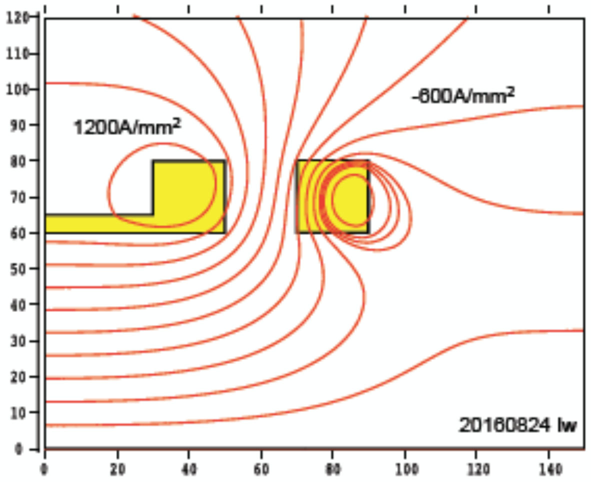
RF spin flipper (RSF) can decelerate and / or accelerate the neutrons.

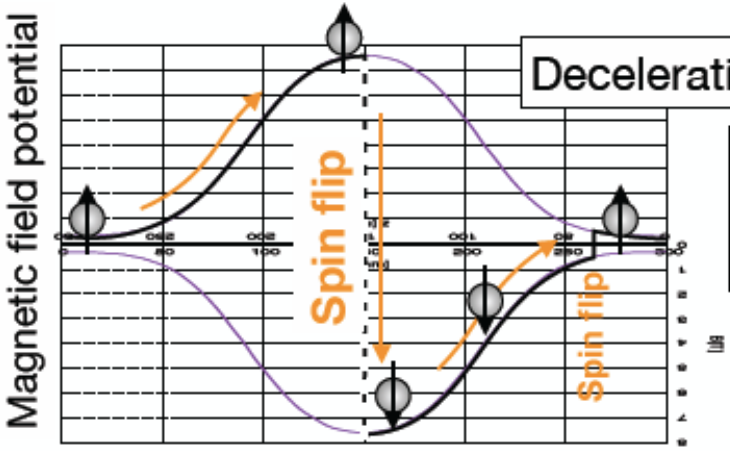
RSF in 7.5 T magnetic field changes the energy of 0.9 μeV.

Flipper unit



Calculation of magnetic field





Deceleration case

A pair of flips conserves the polarity.

Deceleration and acceleration by spin flip

RF spin flipper

RF spin flipper (RSF) can decelerate and / or accelerate the neutrons.

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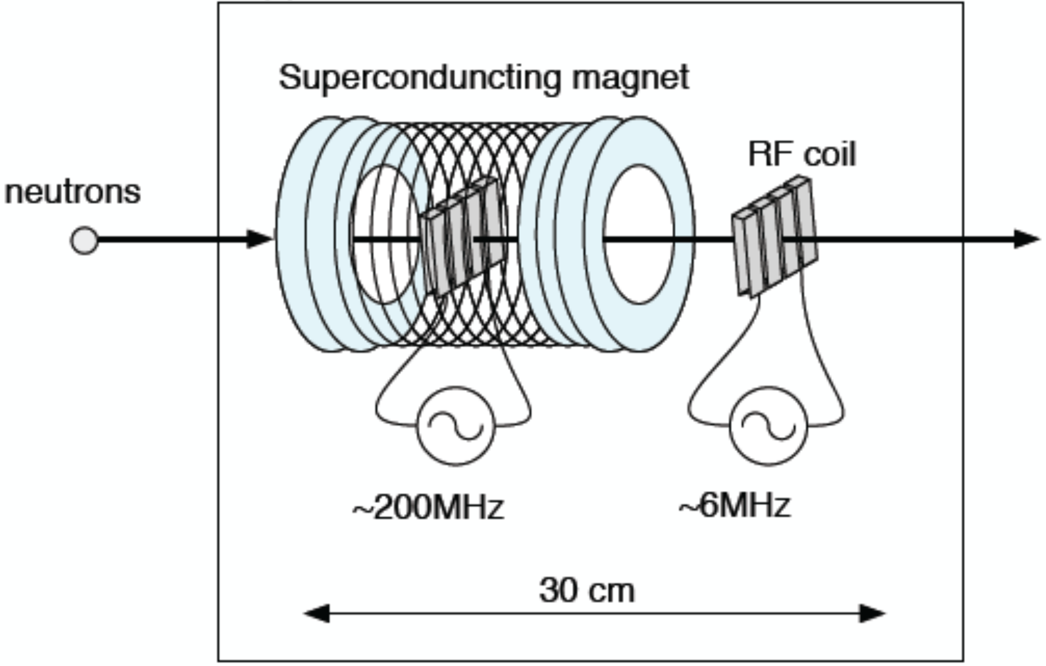
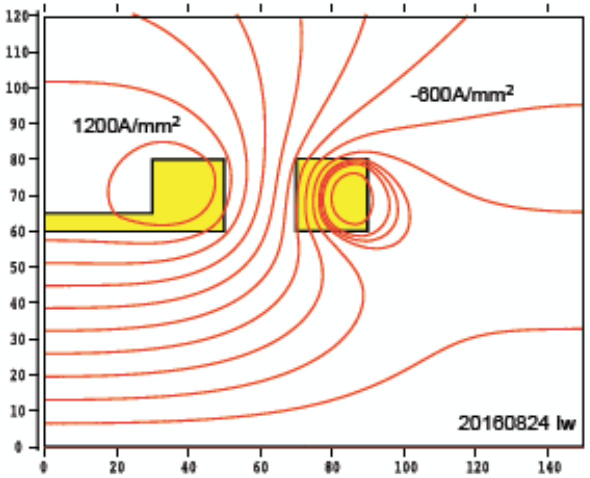
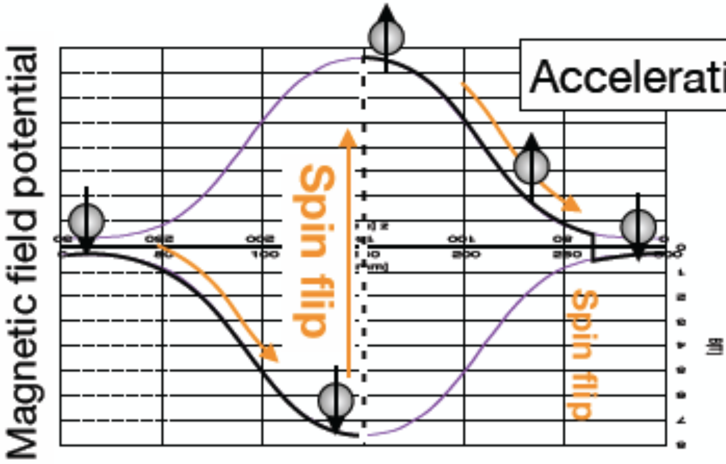
Flipper unit



Calculation of magnetic field





Acceleration case

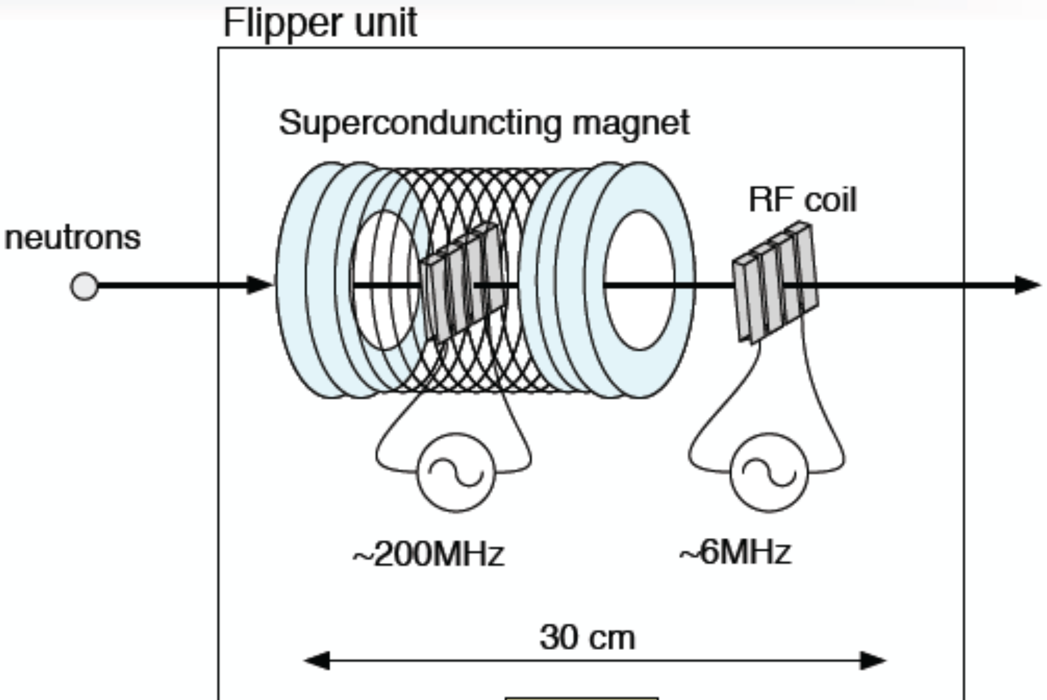
A pair of flips conserves the polarity.

Deceleration and acceleration by spin flip

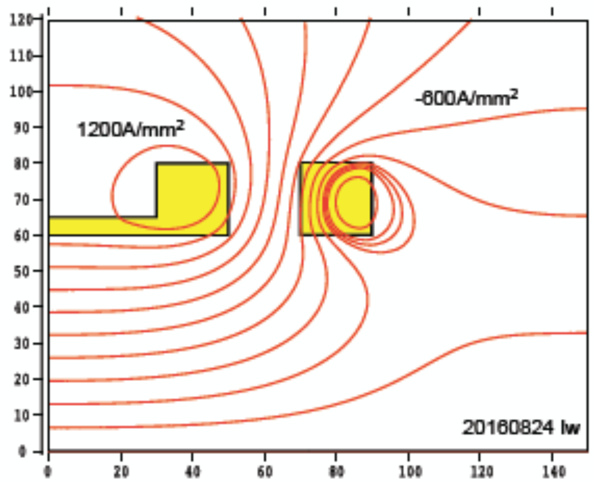
RF spin flipper

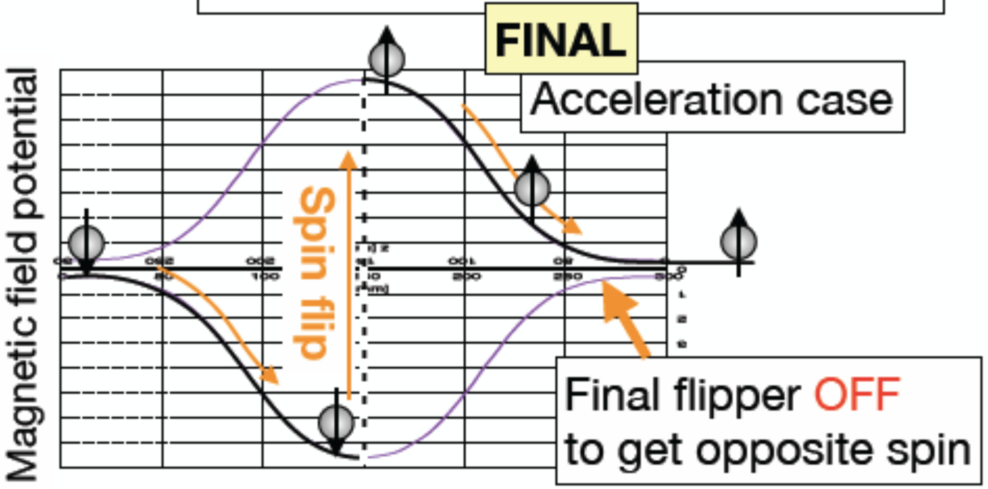
RF spin flipper (RSF) can decelerate and / or accelerate the neutrons.

RSF in 7.5 T magnetic field changes the energy of 0.9 μeV.



Calculation of magnetic field



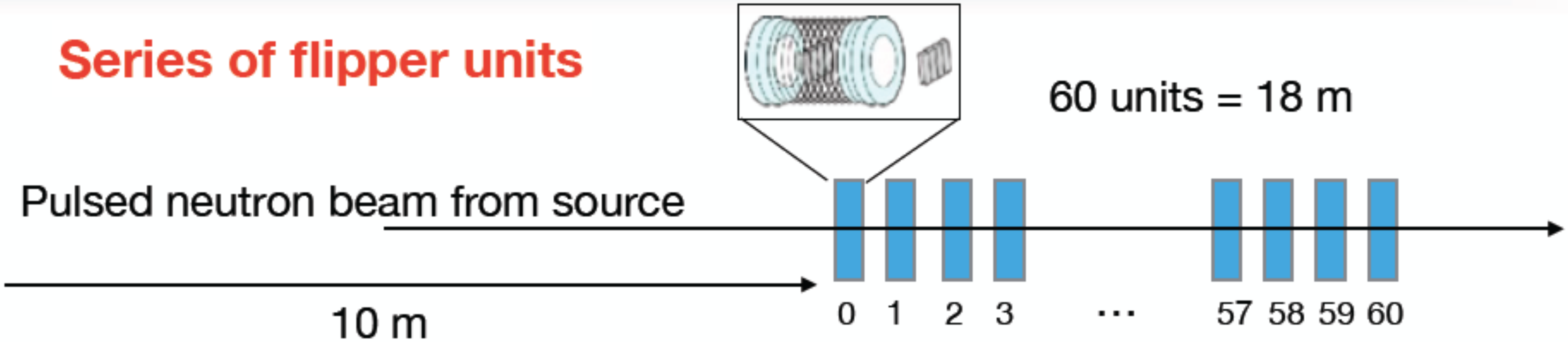


FINAL

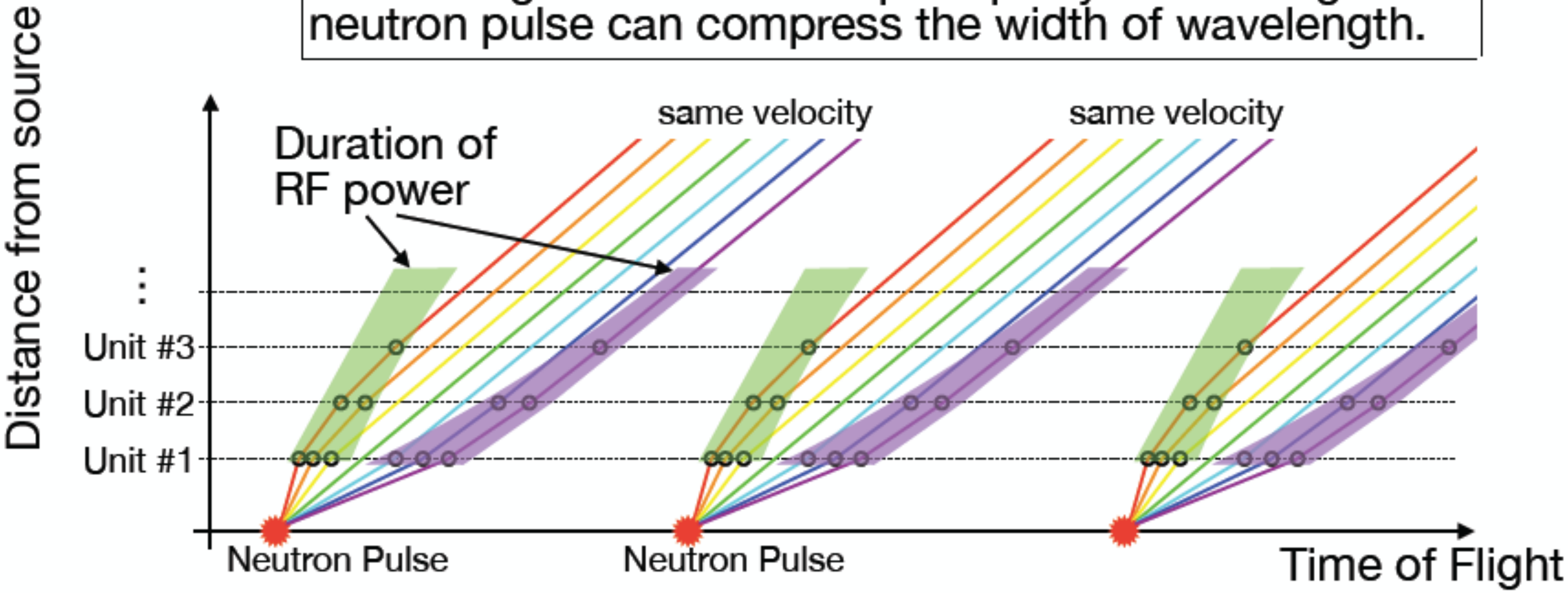
Acceleration case

Final flipper OFF to get opposite spin

Neutron Velocity Concentrator



Controlling the number of spin flips synchronizing with neutron pulse can compress the width of wavelength.

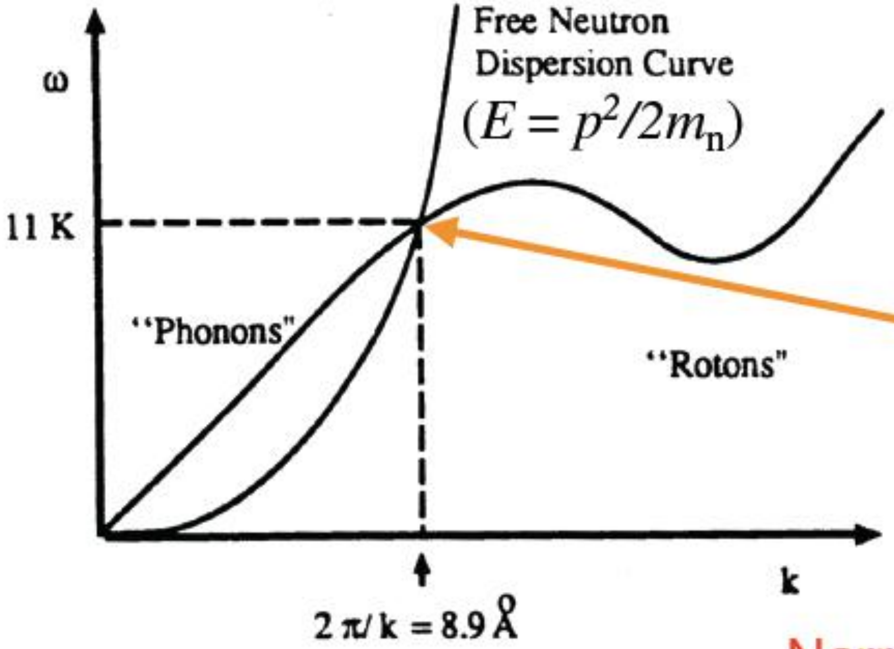


UCN production by superfluid He converter

Superthermal source

Neutron with 1 meV transfers all energy and momentum to phonon and down-scatters to UCNs in superfluid He.

Dispersion curve



UCN production

$$P_{\mathrm{UCN}}(V_c) = N\,\sigma V_c \frac{k_c}{3\pi}\int_0^\infty \frac{\mathrm{d}\phi}{\mathrm{d}\lambda}\, s(\lambda)\,\lambda\,\mathrm{d}\lambda$$

$$s(\lambda) = \hbar \int S(q,\hbar\omega)\delta(\hbar\omega - \hbar^2k^2/2m_{\mathrm{n}})\mathrm{d}\omega$$

Single phonon excitation

$$s_{\mathrm{I}}(\lambda) \;=\; \underline{S^*\delta(\lambda^* - \lambda)}$$

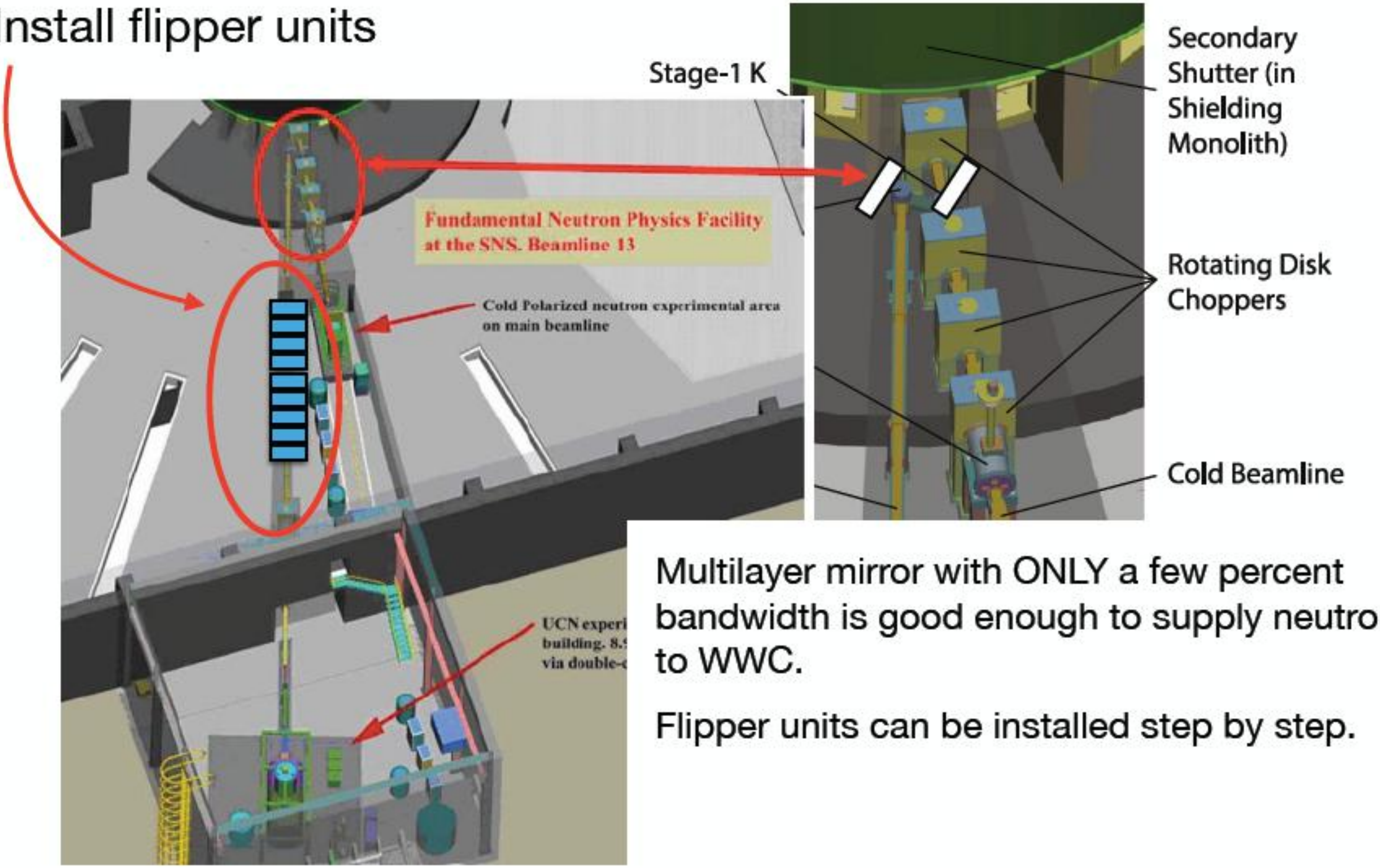
$$\text{where } \lambda^* \;=\; 2\pi/q^*$$

Narrow-bandwidth neutrons are required.

Possible setup for SNS-UCN beamline

N. Fomin et al. / Nuclear Instruments and Methods in Physics Research A 773 (2015) 45–51

Install flipper units



Multilayer mirror with ONLY a few percent bandwidth is good enough to supply neutrons to WWC.

Flipper units can be installed step by step.

Summary

Intense VCN beam introduces NNBAR,

optically controlled applications,

advanced interferometry for

precise determination of scattering length,

search for new interactions,

anomalous short-range gravity, dark energy search via chameleon mechanism

laboratory test of general relativity,

etc.