Present/Future Neutron Optics

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Phase Space Density (Brilliance)

ESS, SNS-STS, J-PARC TS-2

J-PARC MLF 2nd Target Station

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

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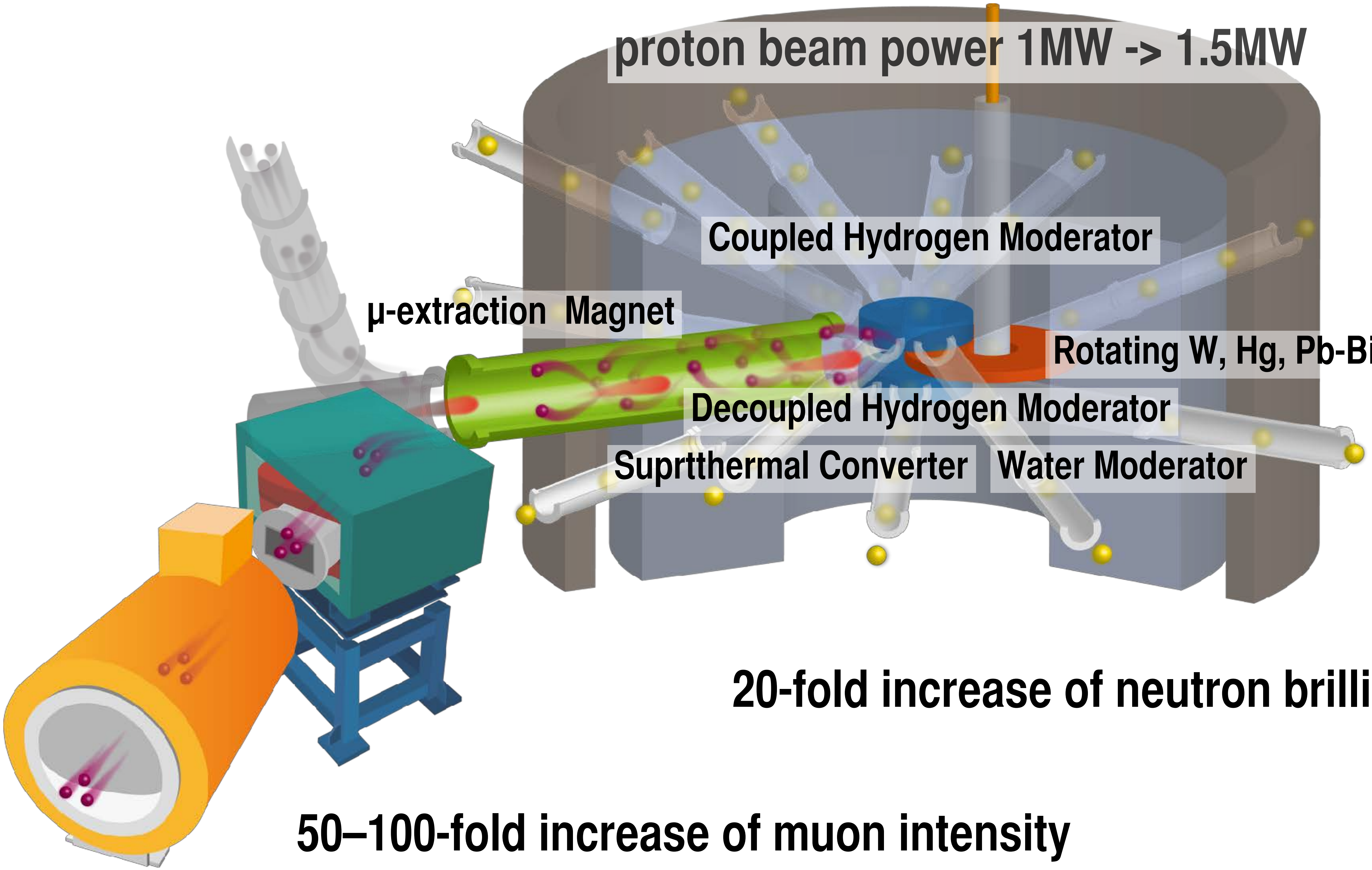


20-fold increase of neutron brilliance

50–100-fold increase of muon intensity

muon science

Material and Life Science

Negative-muon μSR

Chemical Analysis with Muon-characteristic X-rays

Ultra-slow Muons

- Surface Science
- Micro-muon Beam for 2d- and 3d-scanning Imaging
- Transmission Muon MIcroscopy
- Soft- and Hard-error of Electronic Devices

Muon g-2/EDM

Hyperfine Structure of Muonium

Proton Radius

Muon-decay Parameters

Muon Rare Decays

Nuclear Study with Muons

neutron science

Material and Life Science

- Elastic Scattering & Diffraction
- Hydrogen Collective Dynamics
- Vibrational and Magnetic Excitations
- Softmatters
- Holography for Active Sites
- Imaging
  - Neutron Transmission Microscope
- Materials under High-pressures
  - Metallic Hydrogen   Planetary Science   Pressurized Ice
- Materials under High Magnetic Fields

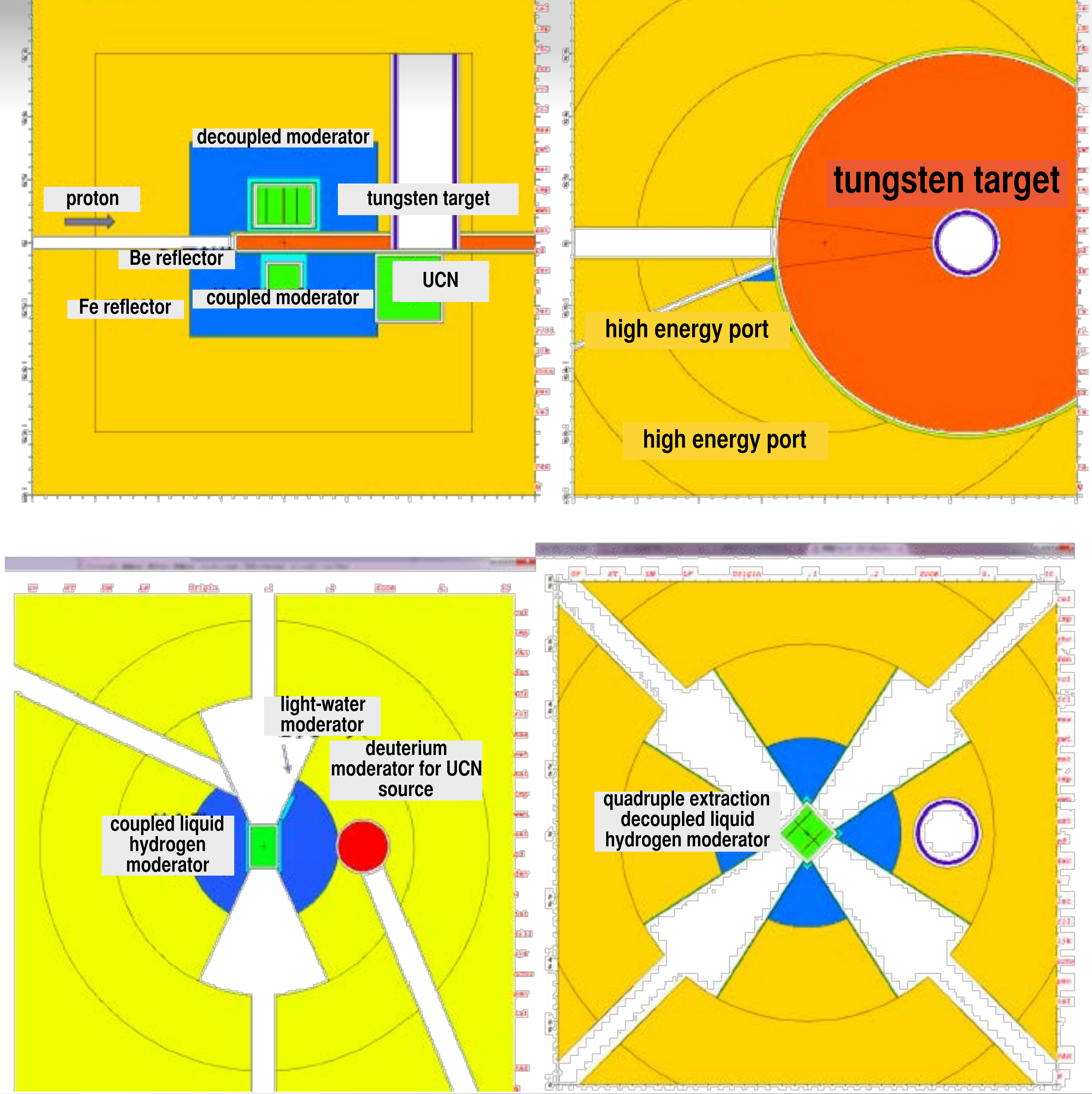
small-crystals (0.5mm -> 0.2mm)
sample environment (T<50mK, P>10GPa)
transient phenomena (sub-msec)
microscopic diffraction
Protein Structural Analysis

Fundamental Physics

UCN	EDM	Gravitational Levels	β-decay Parameters	
VCN	New Interaction Search	Scattering Lengths	Dark Energy Search	
VCN	Neutron-Antineutron Oscillation			
ETN (eV)	Discrete Symmetry Violations in Compound Nuclei -> TS1			

Nuclear Engineering

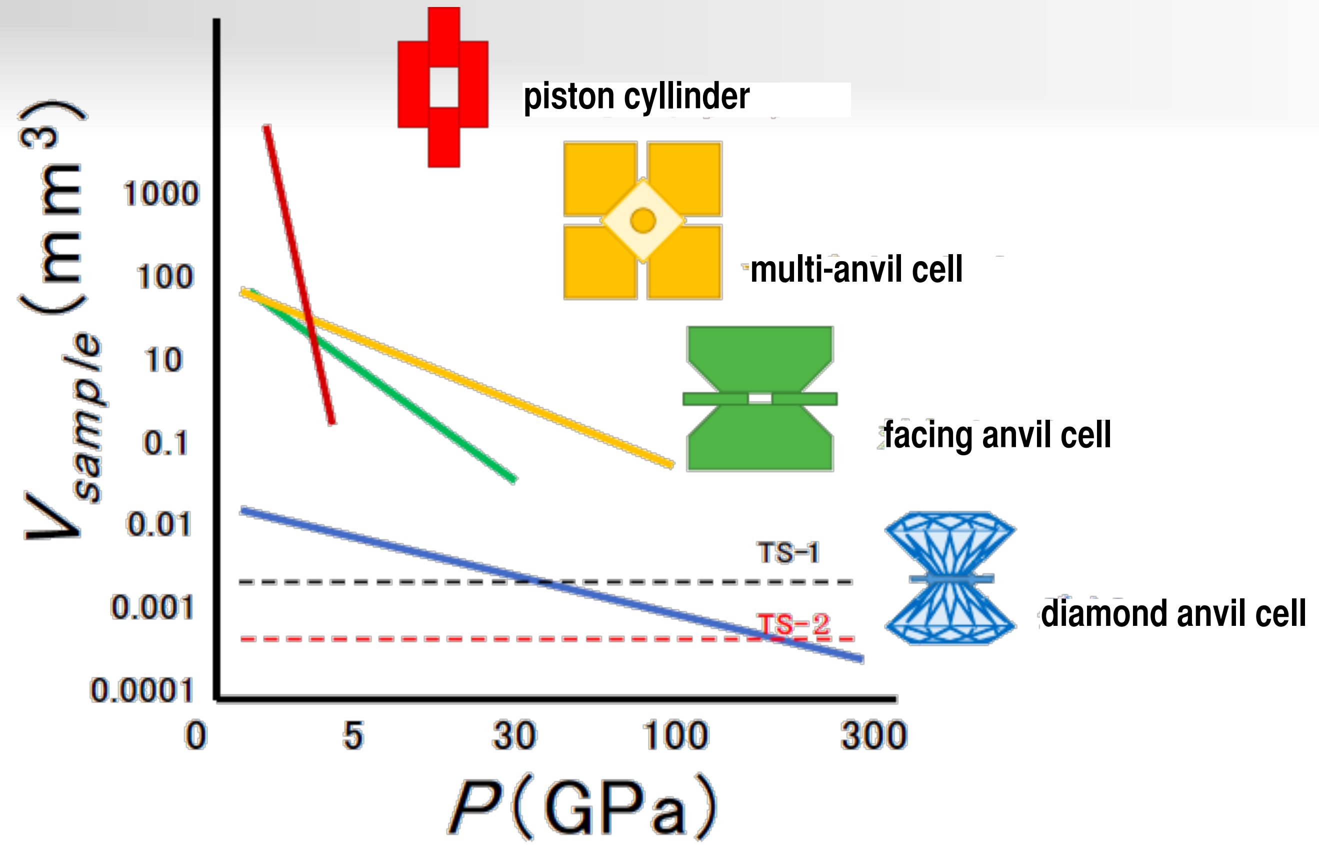
FN (MeV)   Nuclear Data   MeV Transmission Imaging


decoupled moderator
proton
tungsten target
Be reflector
UCN
coupled moderator
Fe reflector
tungsten target
high energy port
high energy port
light-water moderator
deuterium moderator for UCN source
coupled liquid hydrogen moderator
quadruple extraction decoupled liquid hydrogen moderator

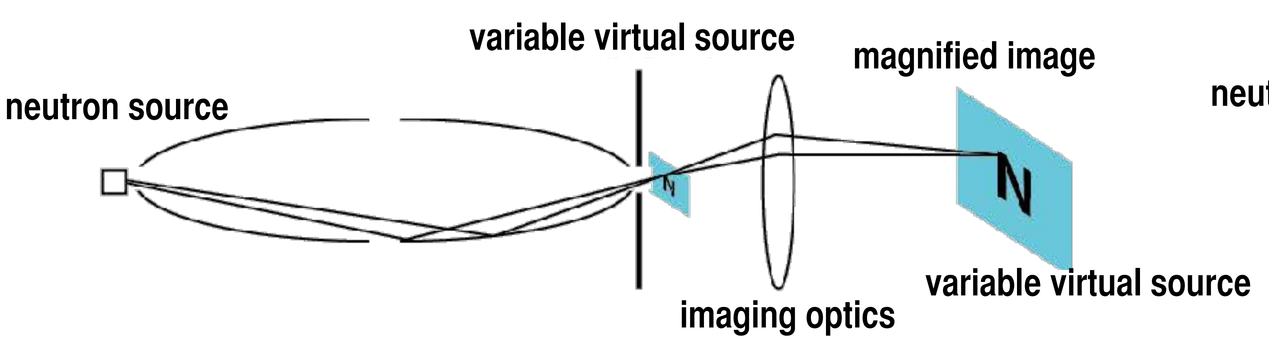
brilliant neutron beam

high phase-space-density

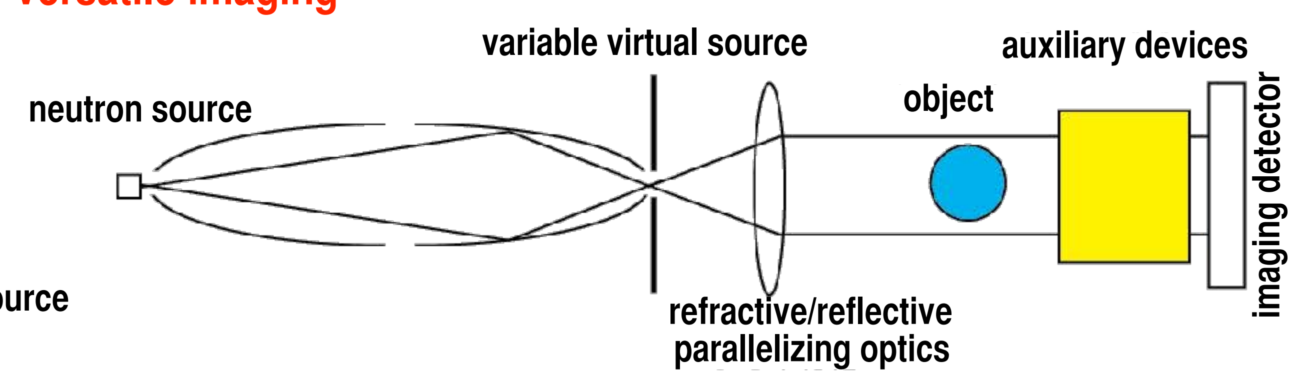
enables flexible optical control similar to photon optics



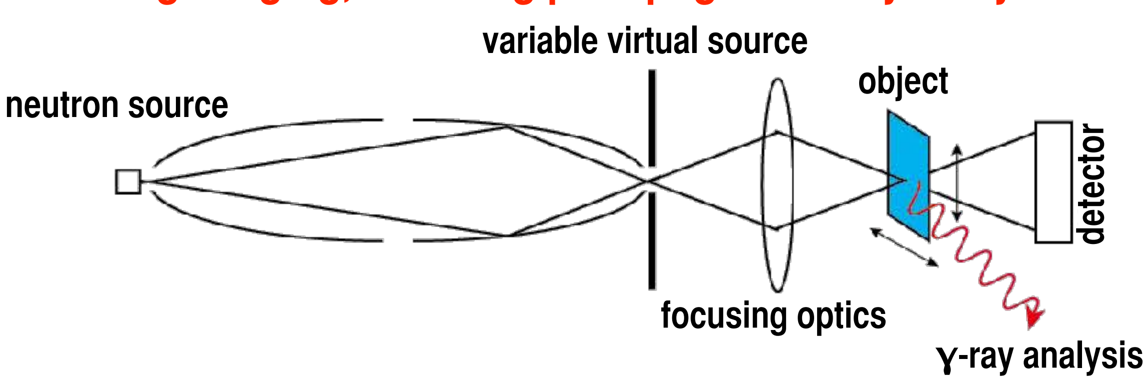
high-resolution imaging



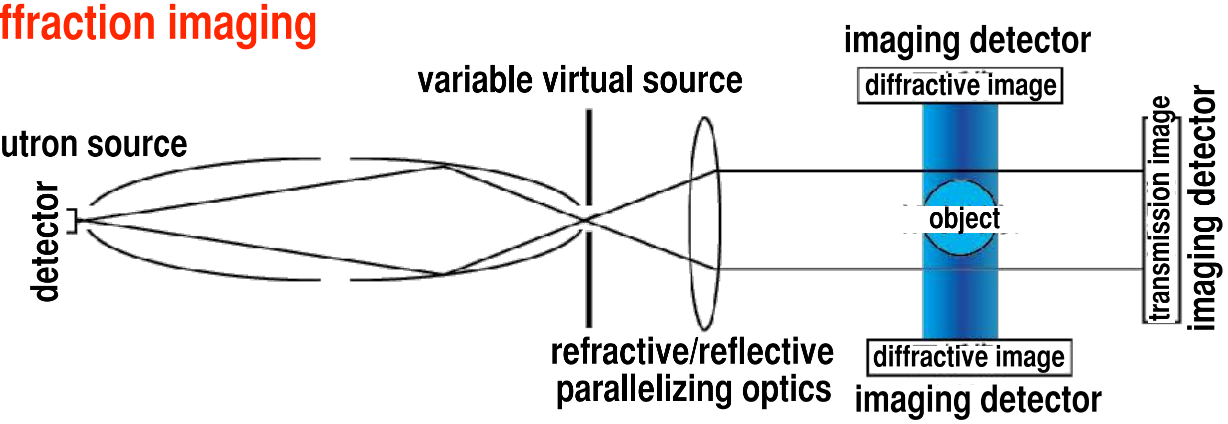
versatile imaging



scanning imaging, scanning prompt gamma-ray analysis

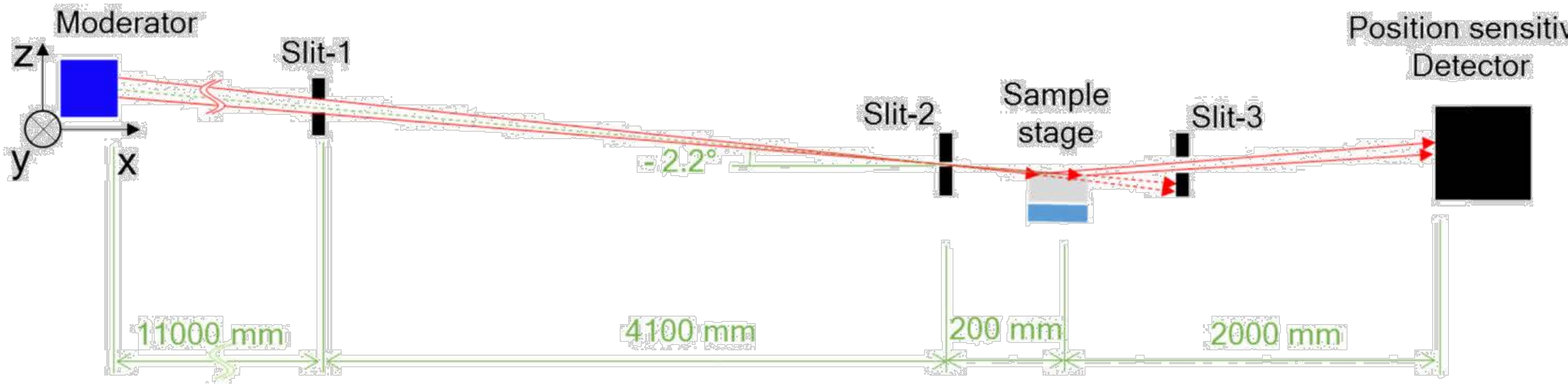


diffraction imaging

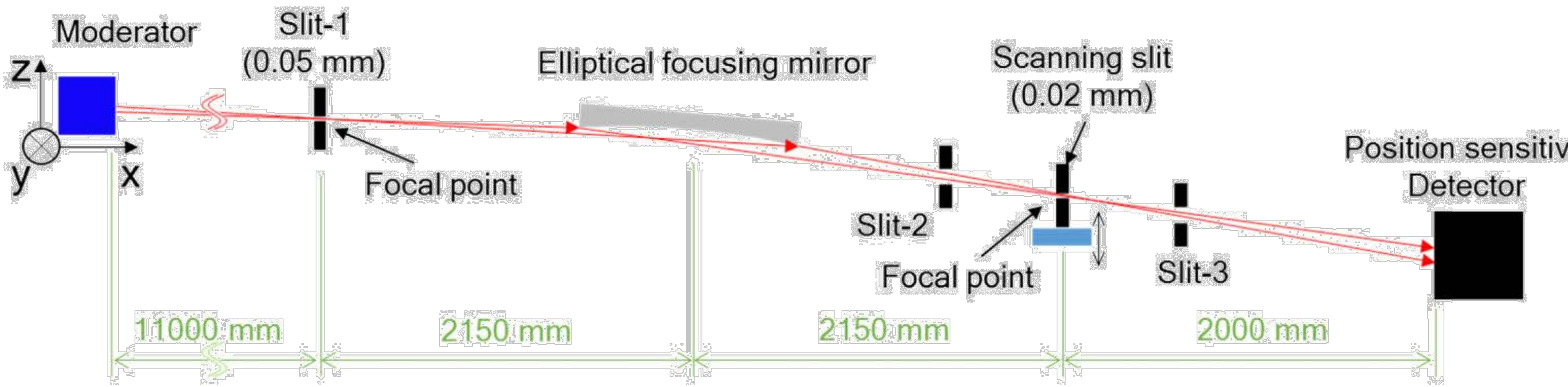


S,Takeda et al., Vol. 24, No. 12 | DOI:10.1364/OE.24.012478 | OPTICS EXPRESS 12478

focusing optics for reflectometry

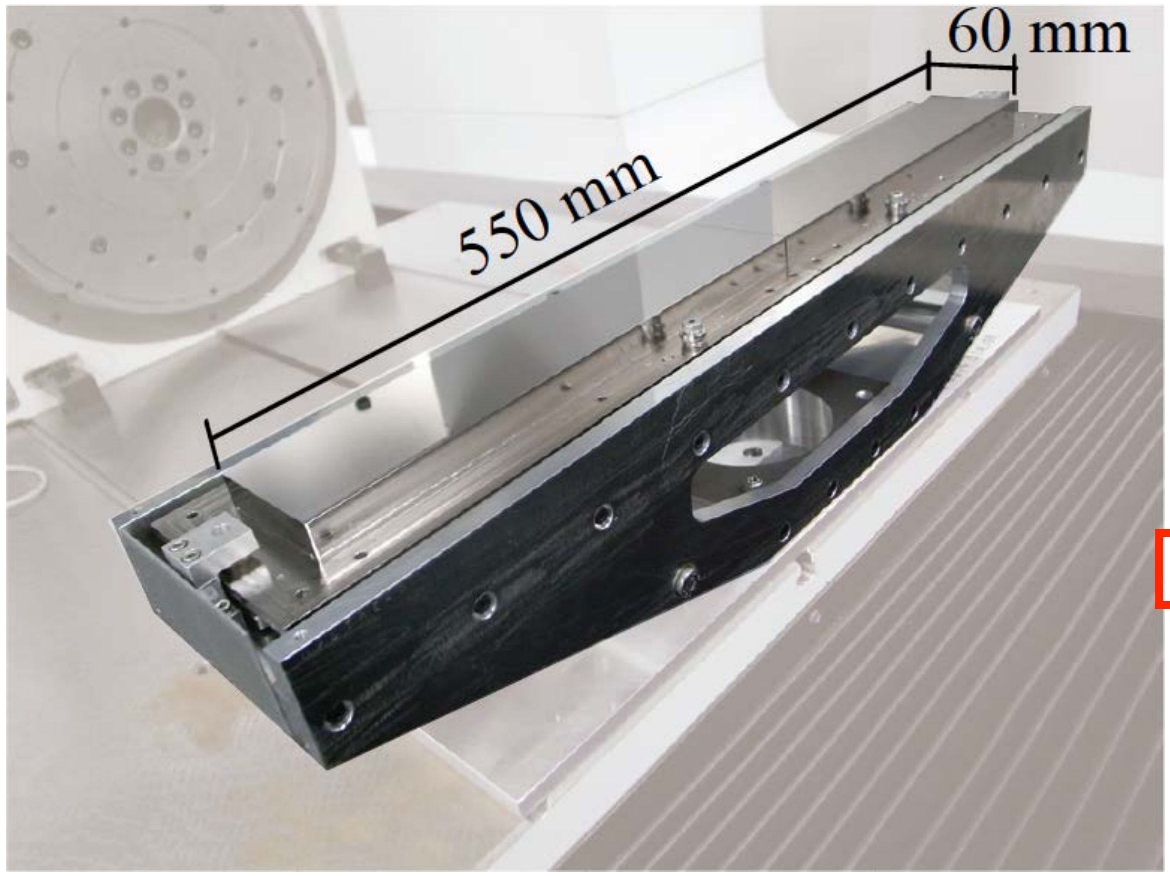


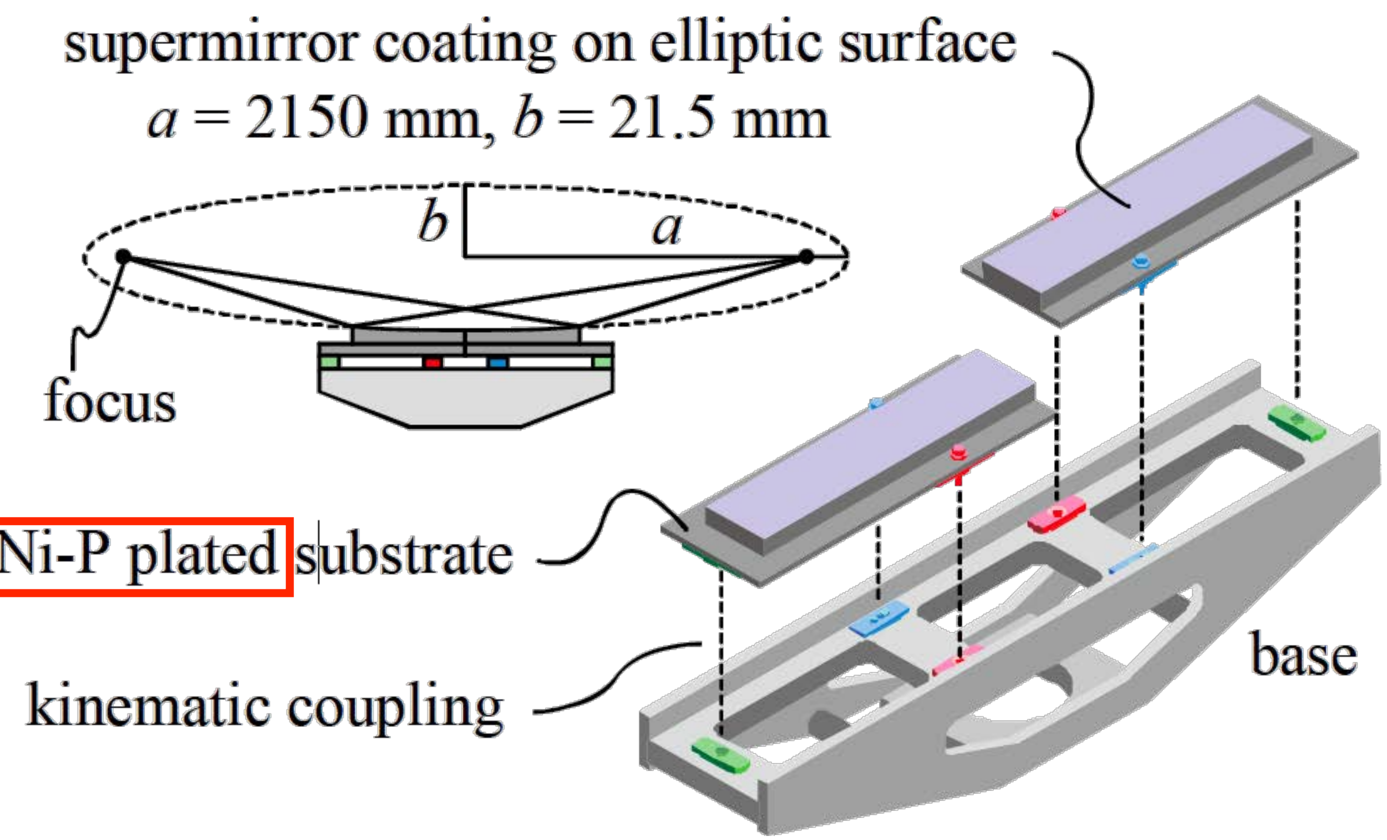
Schematic layout of SOFIA for the 2.2° inclined beamline.



SOFIA with focusing optics

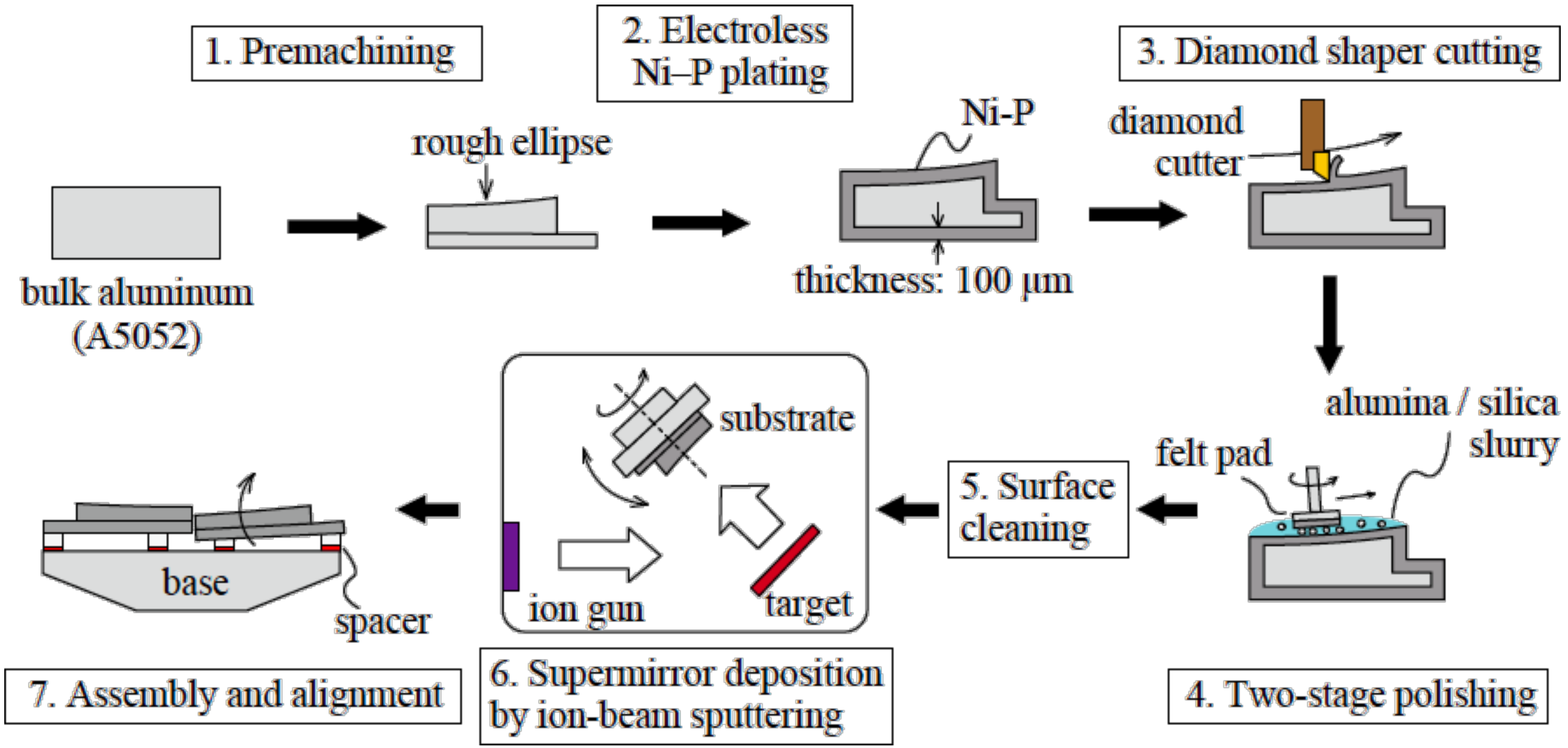
focusing optics for reflectometry



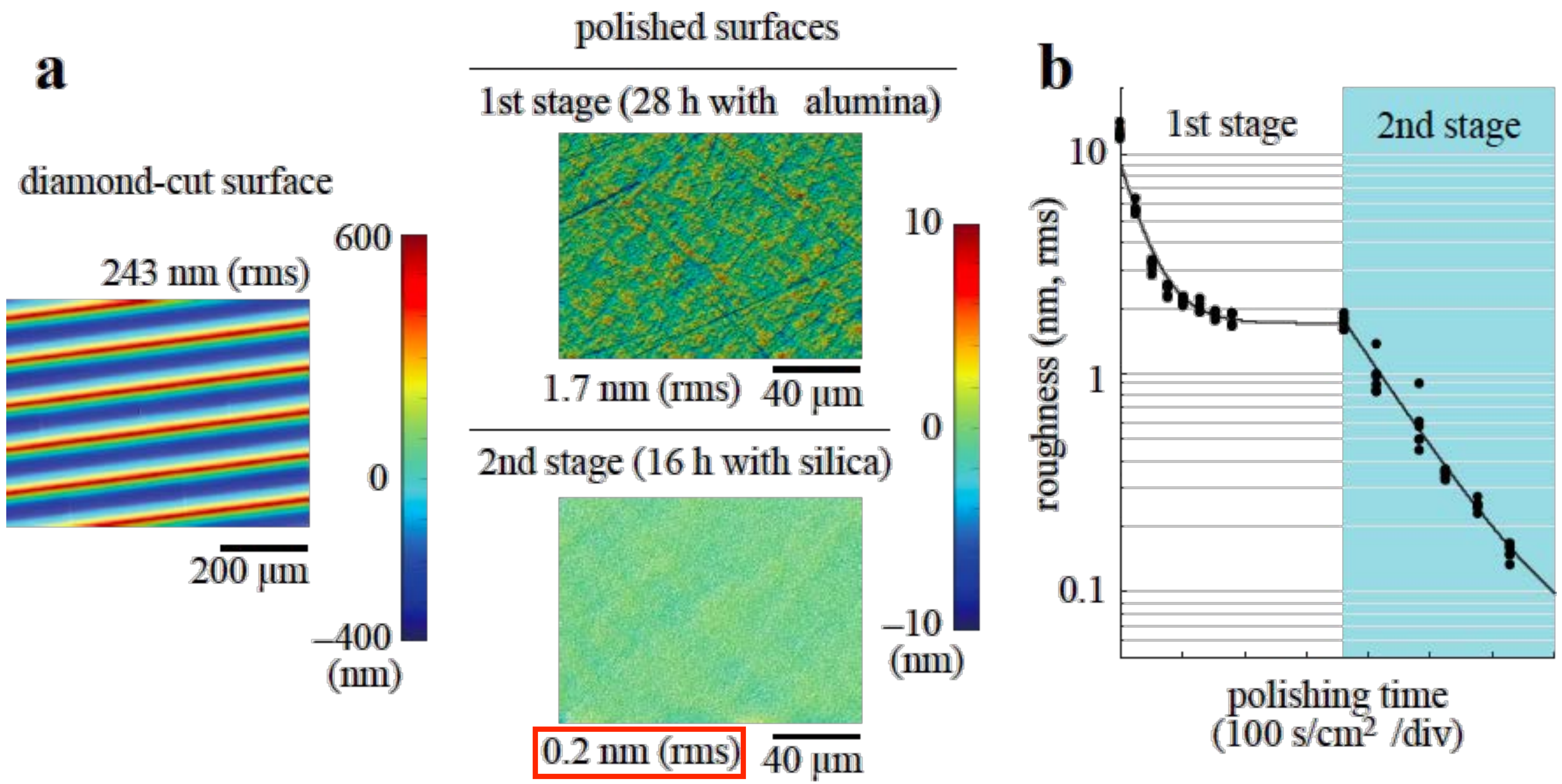


metal substrate super mirrors (MSSM)

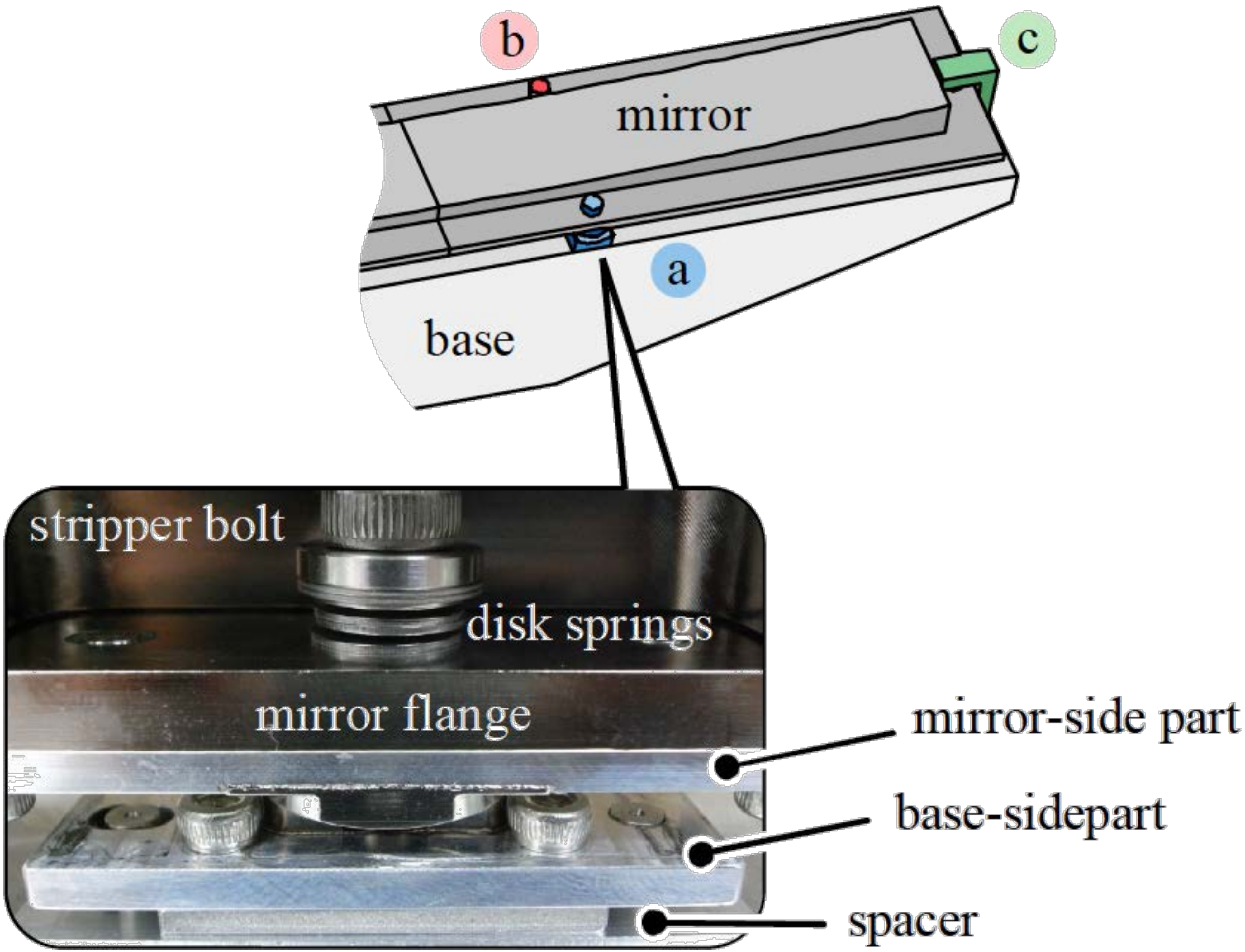
fabrication of metal substrates



polishing of Ni-P plated surface

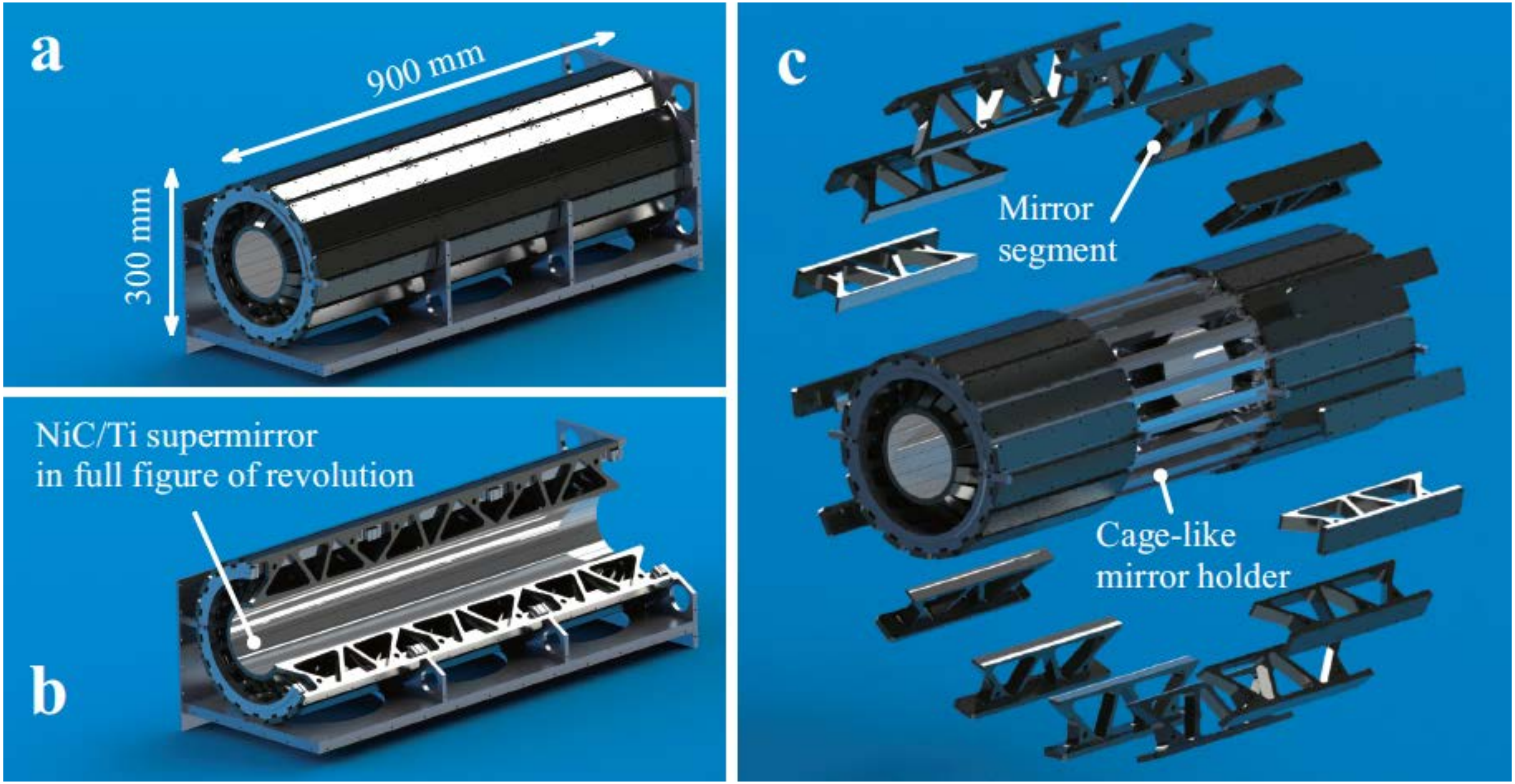


precision assembling metal-substrate mirrors



T.Hosobata et al., JPS Conf. Proc. , 011010 (2018), Proc. Int. Conf. Neutron Optics (NOP2017)
https://doi.org/10.7566/JPSCP.22.011010

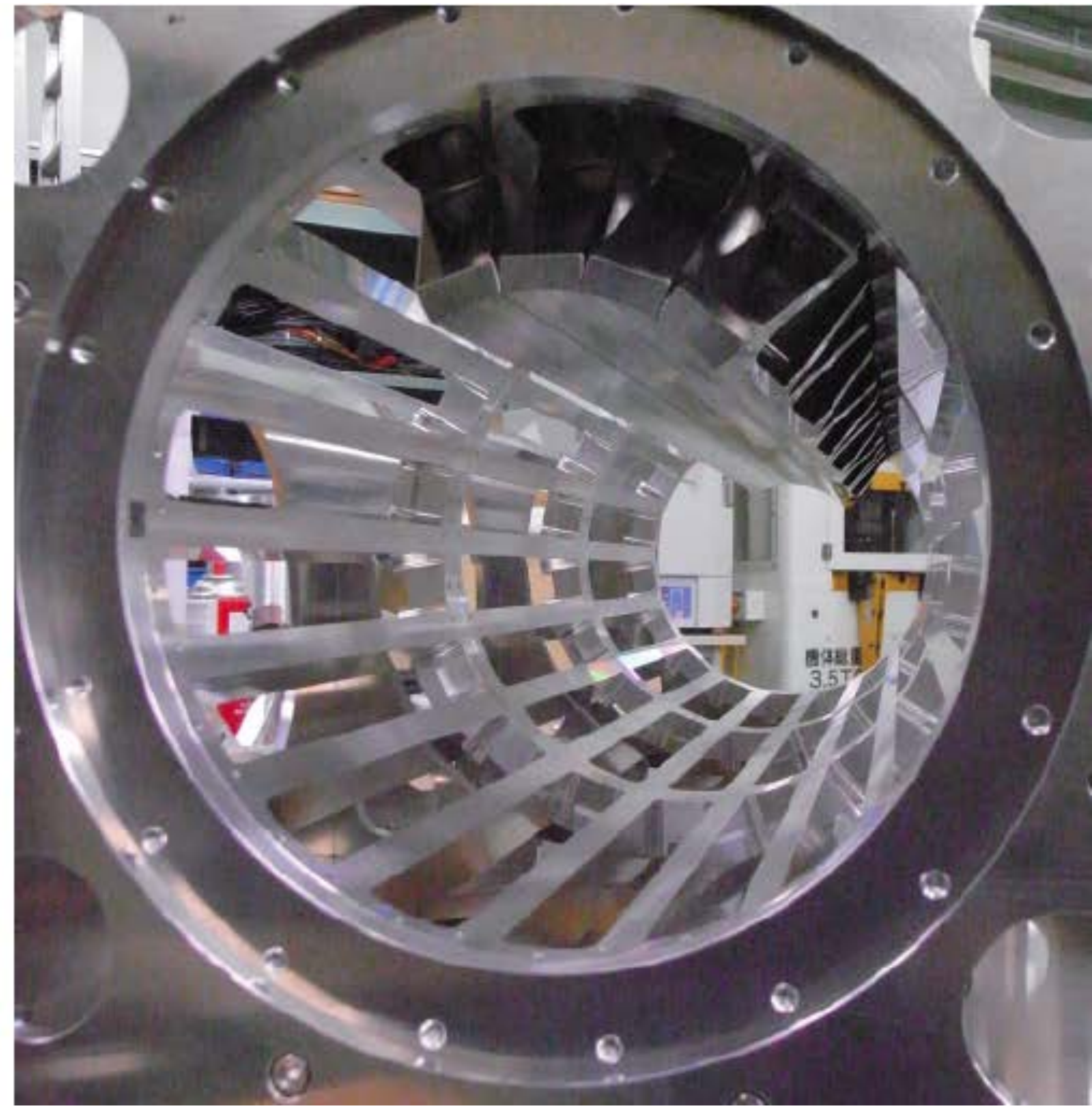
reflective focusing unit



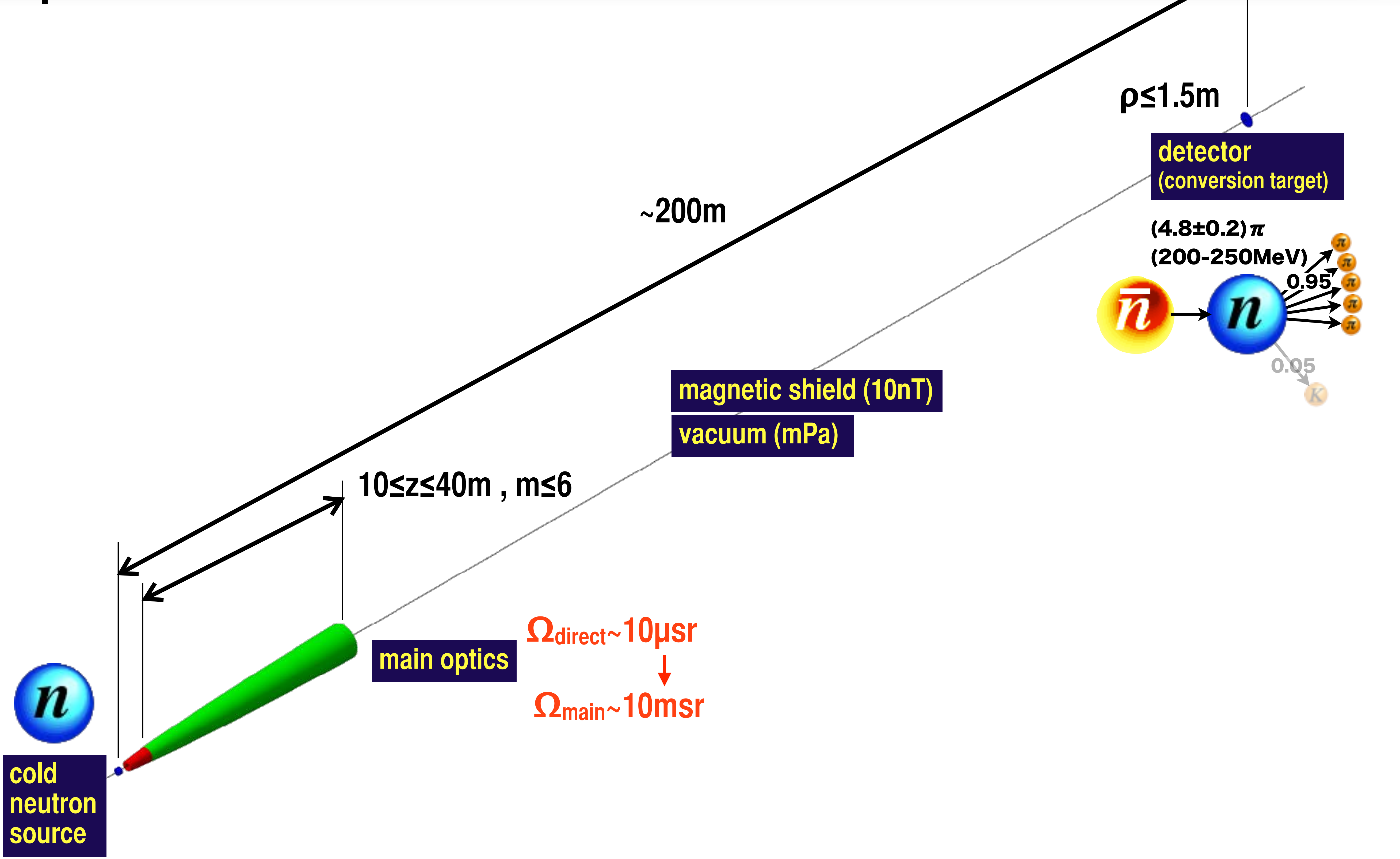
fully metallic -> radiation-hard

T.Hosobata et al., JPS Conf. Proc. , 011010 (2018), Proc. Int. Conf. Neutron Optics (NOP2017)
https://doi.org/10.7566/JPSCP.22.011010

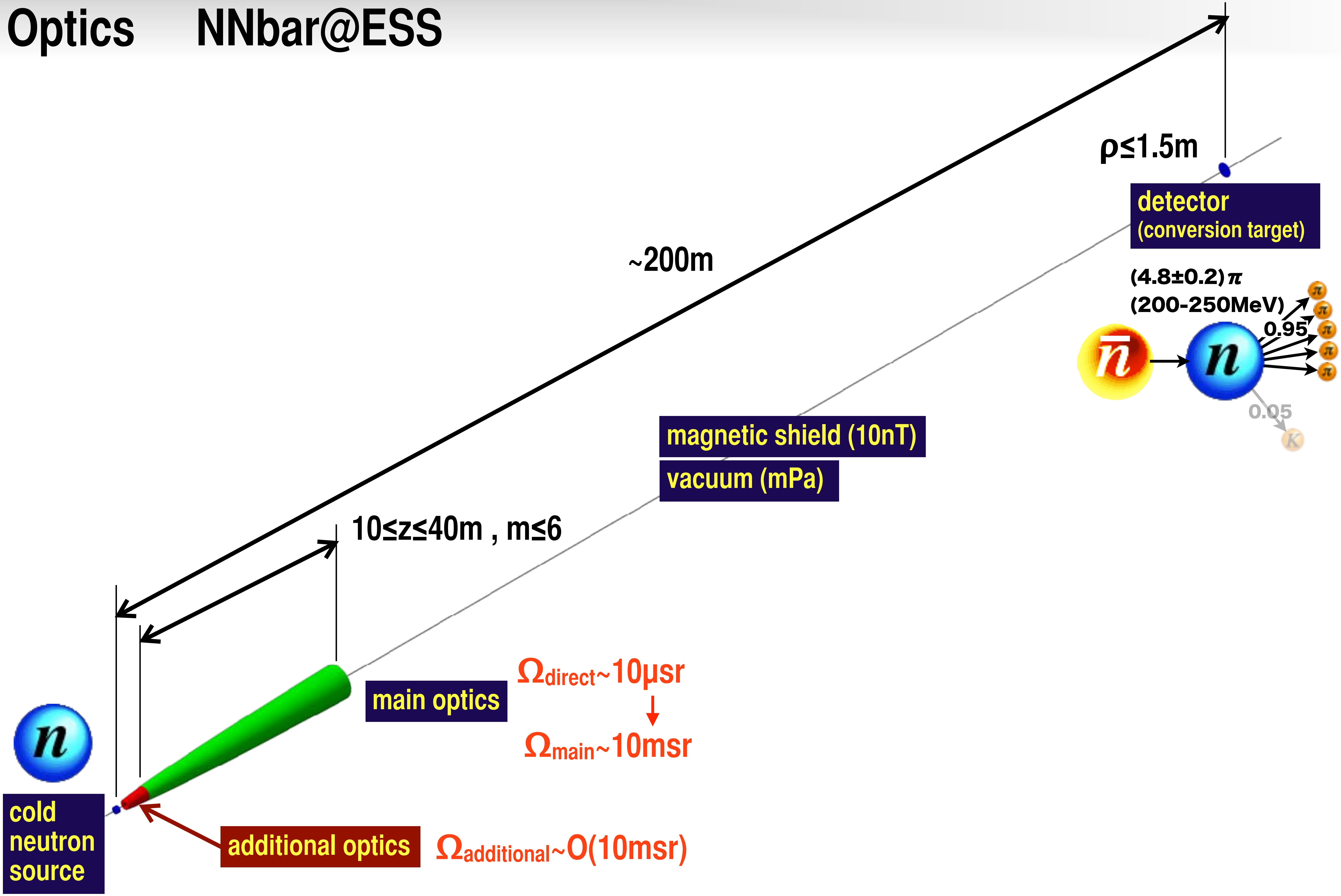
reflective focusing unit



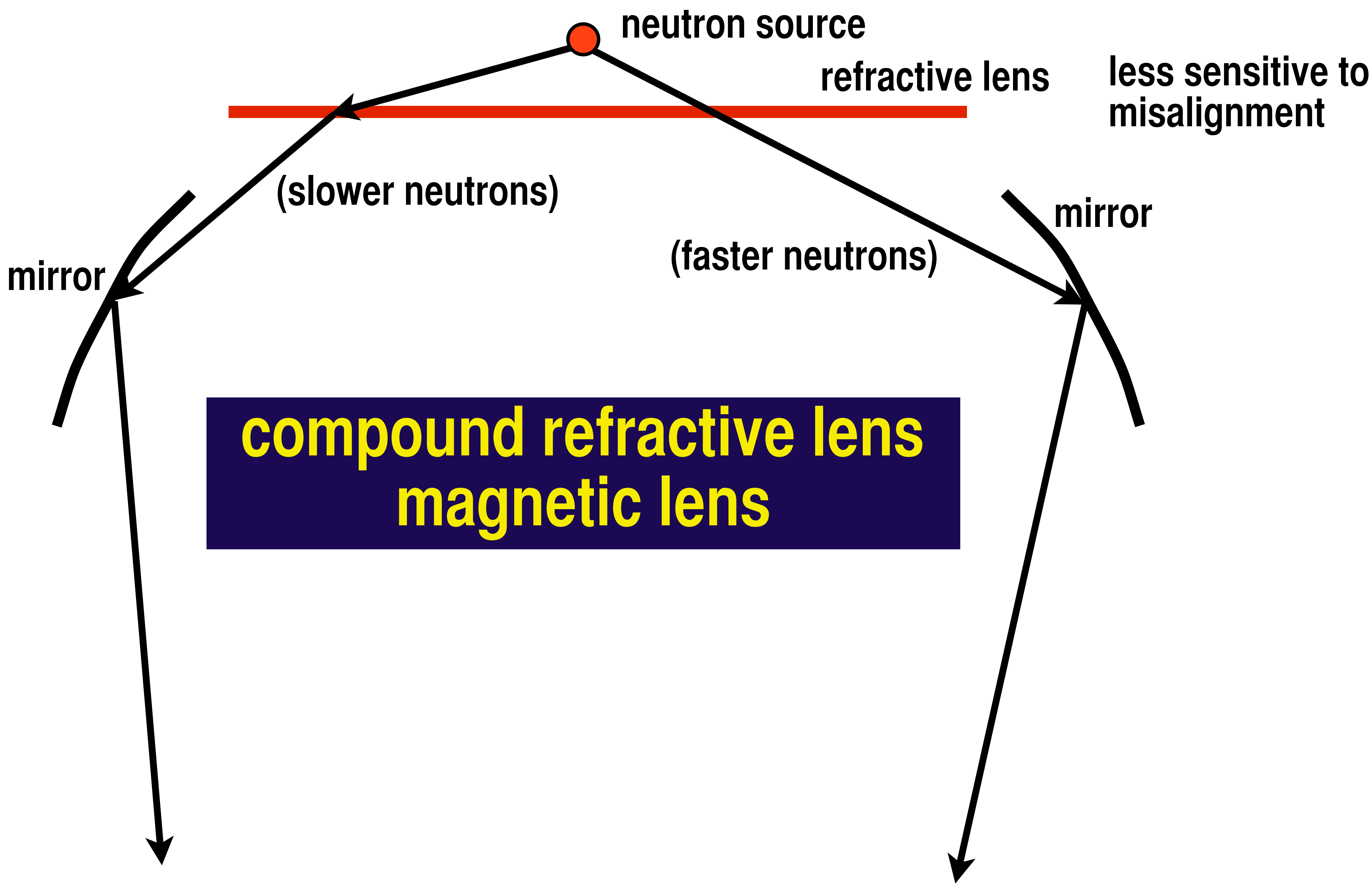
Optics NNbar@ESS



Optics NNbar@ESS



Refractive Lens for Enlarging Effective Acceptance



Refractive Lens
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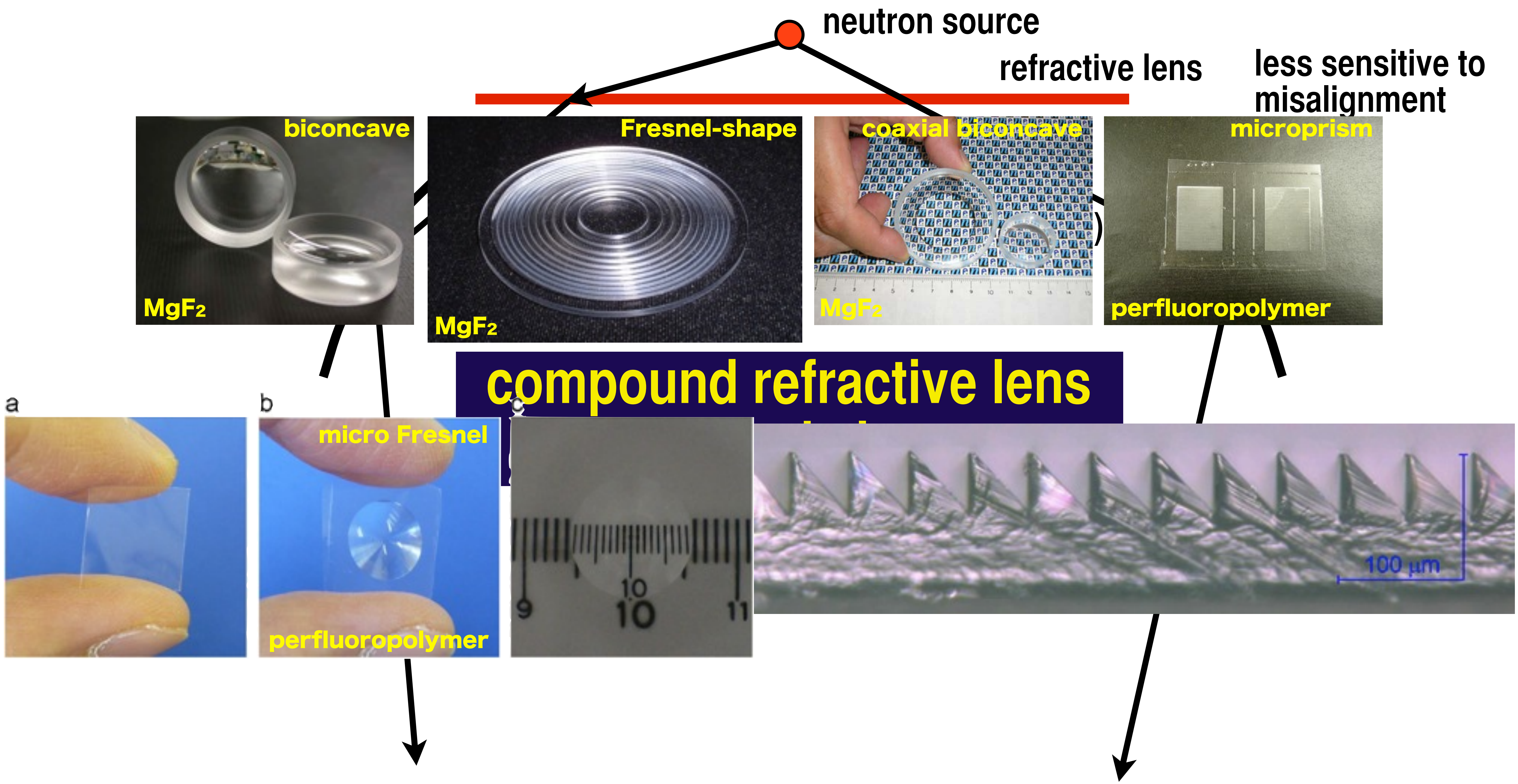
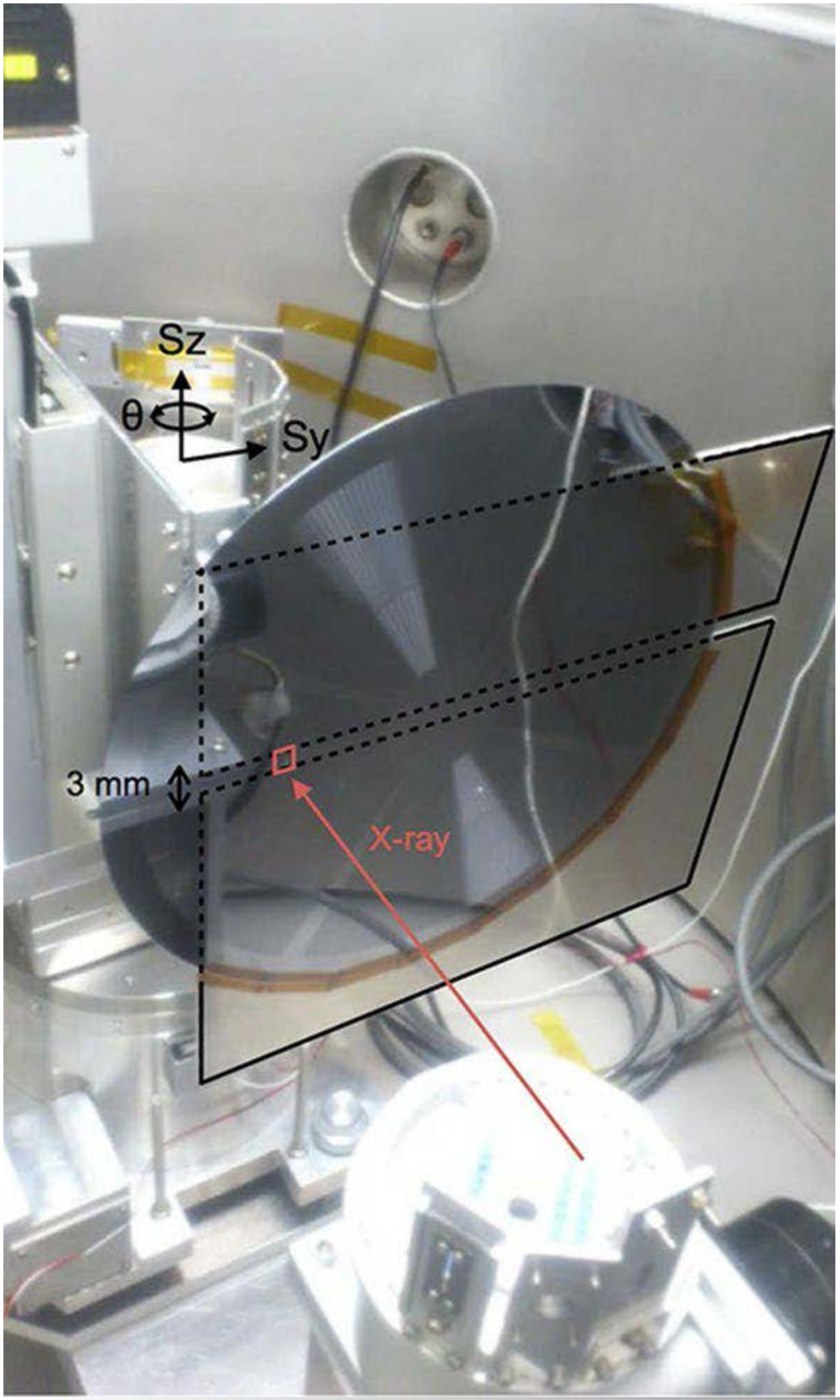
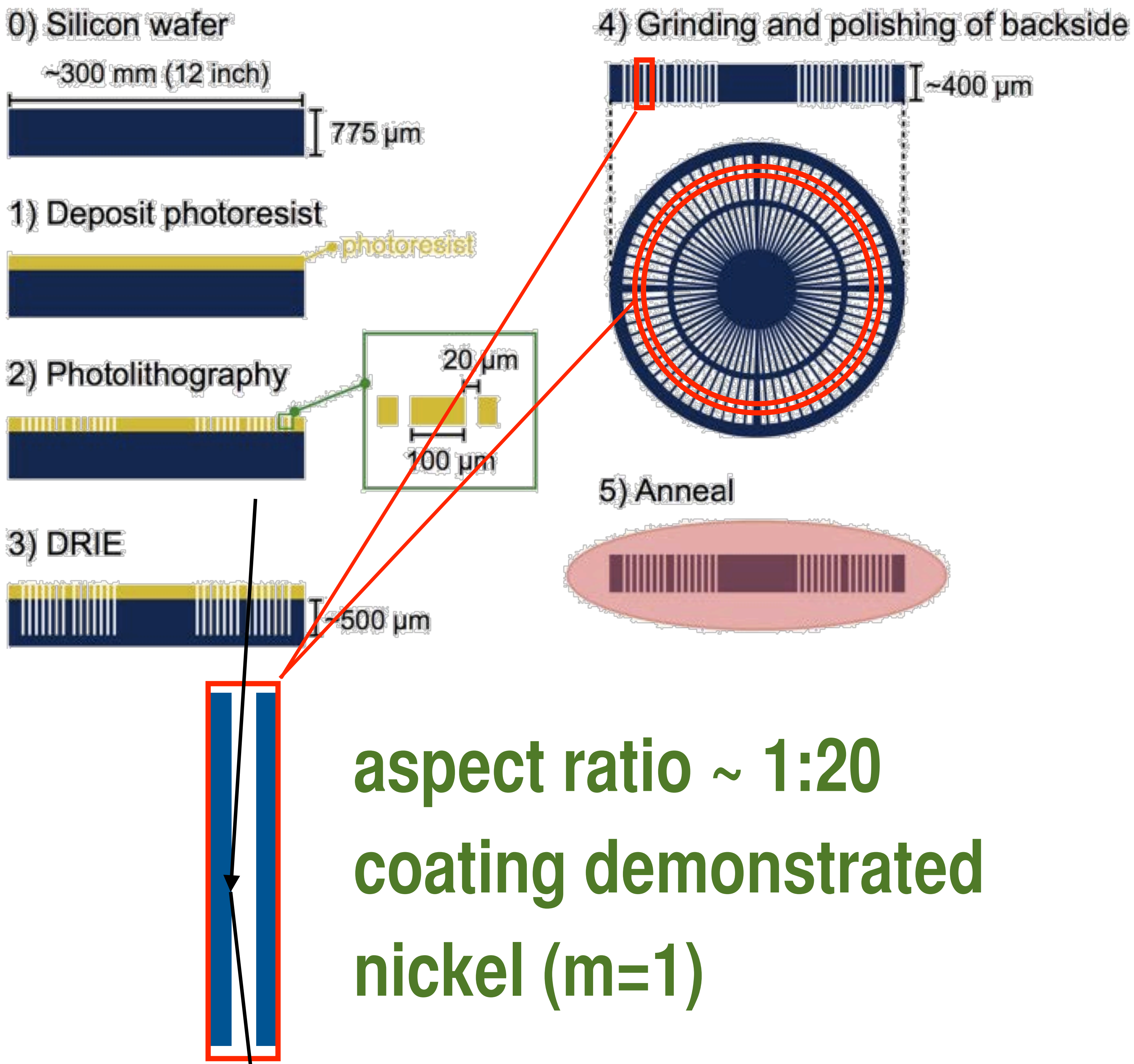


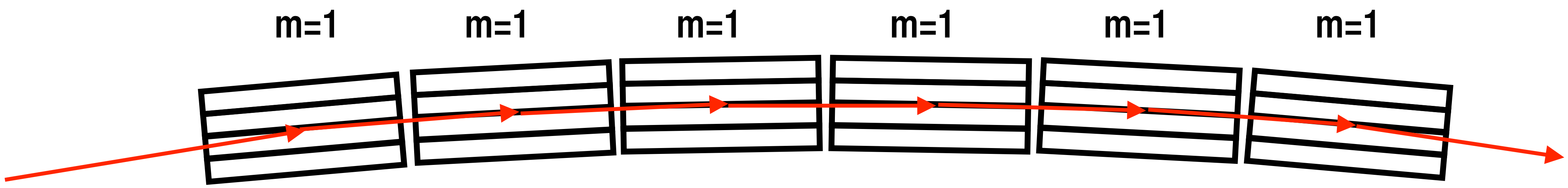
MEMS X-ray Lens

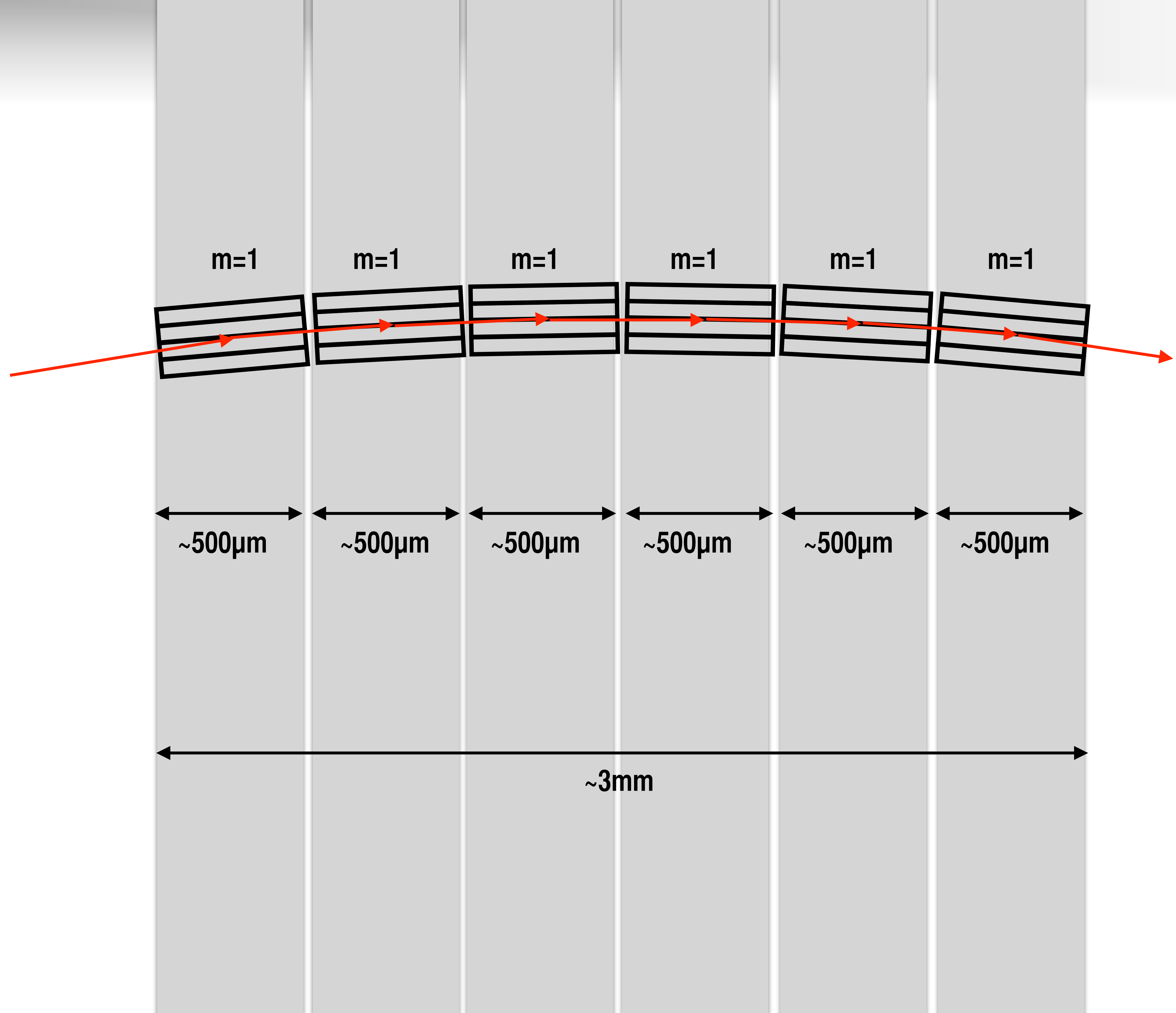
K.Ishikawa, Y.Ezoe et al., DOI 10.1007/s00542–016–2980–6 Microsyst. Technol. (2016)

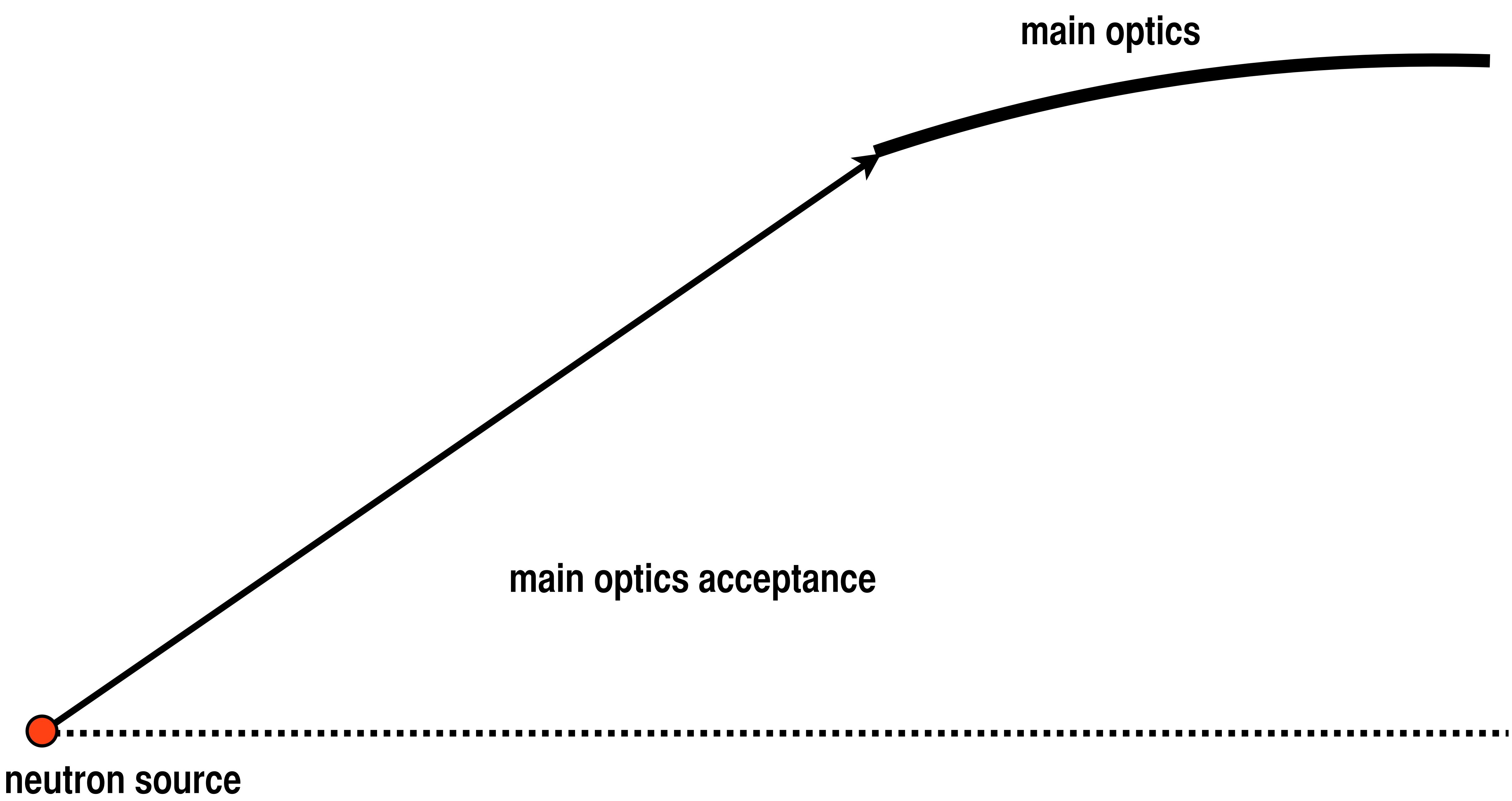


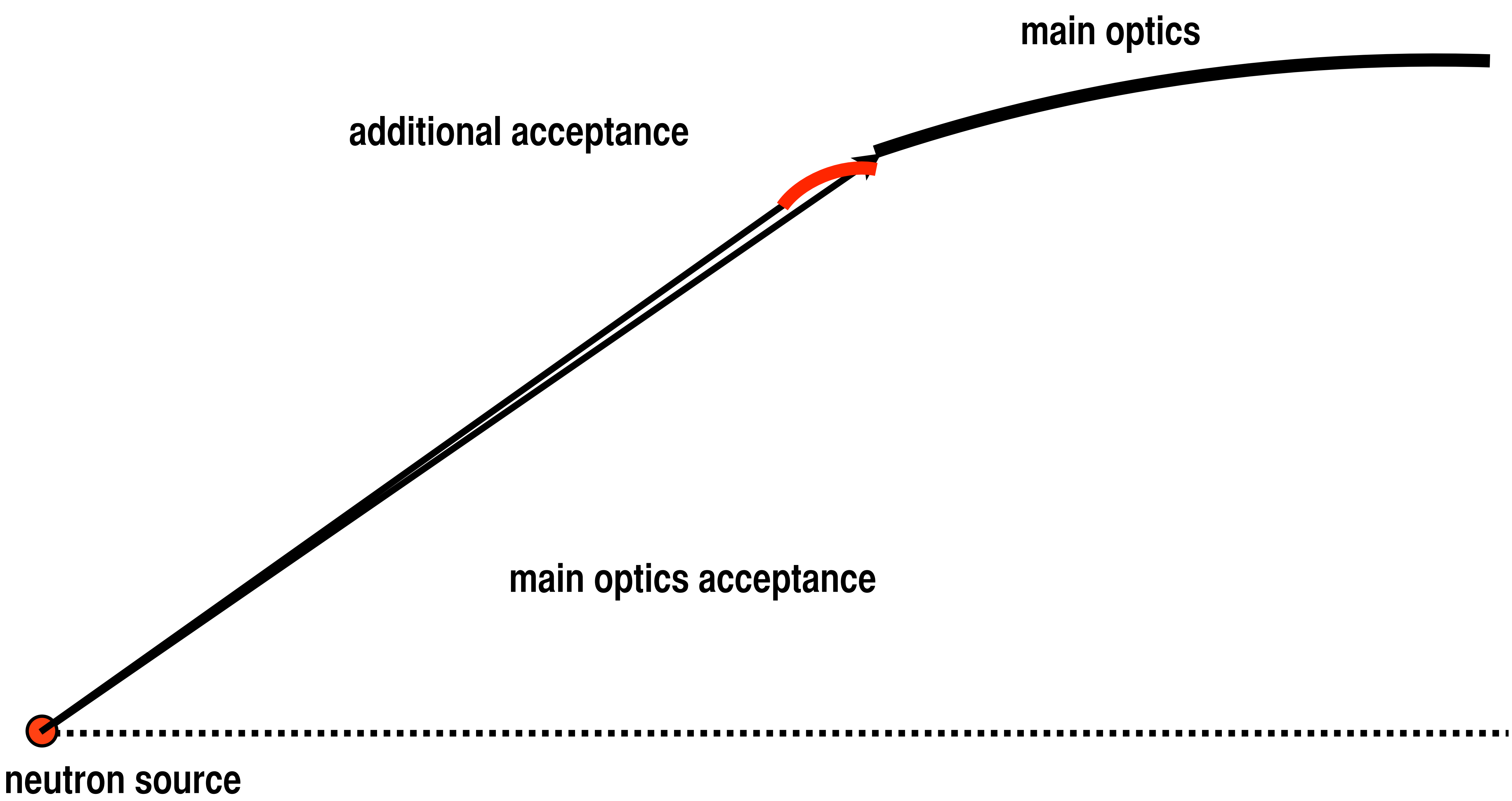


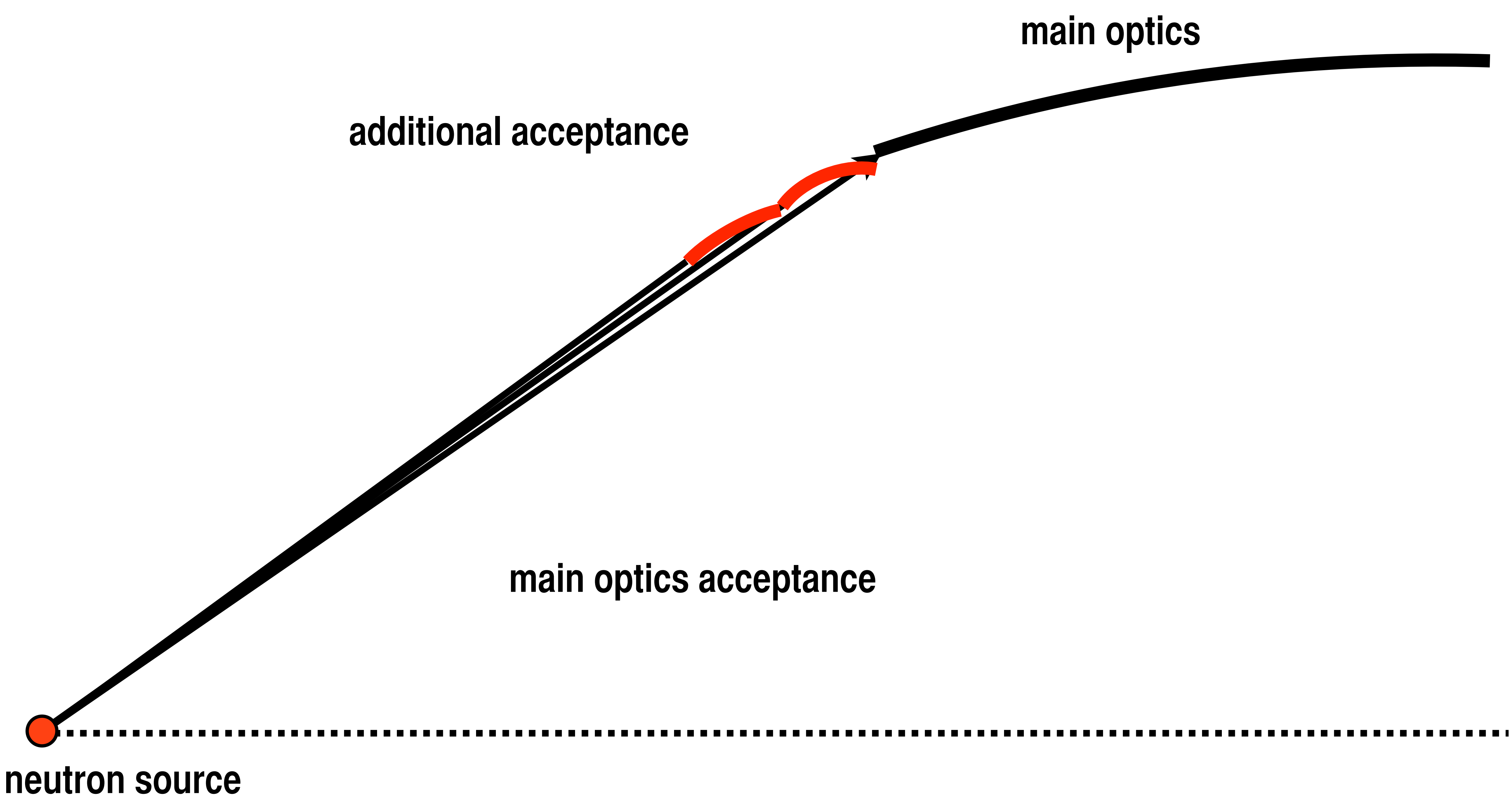
aspect ratio ~ 1:20
coating demonstrated
nickel (m=1)


m=1
m=1
m=1
m=1
m=1
m=1


m=1
m=1
m=1
m=1
m=1
m=1
~500μm
~500μm
~500μm
~500μm
~500μm
~500μm
~3mm


main optics
main optics acceptance
neutron source


main optics
additional acceptance
main optics acceptance
neutron source


main optics
additional acceptance
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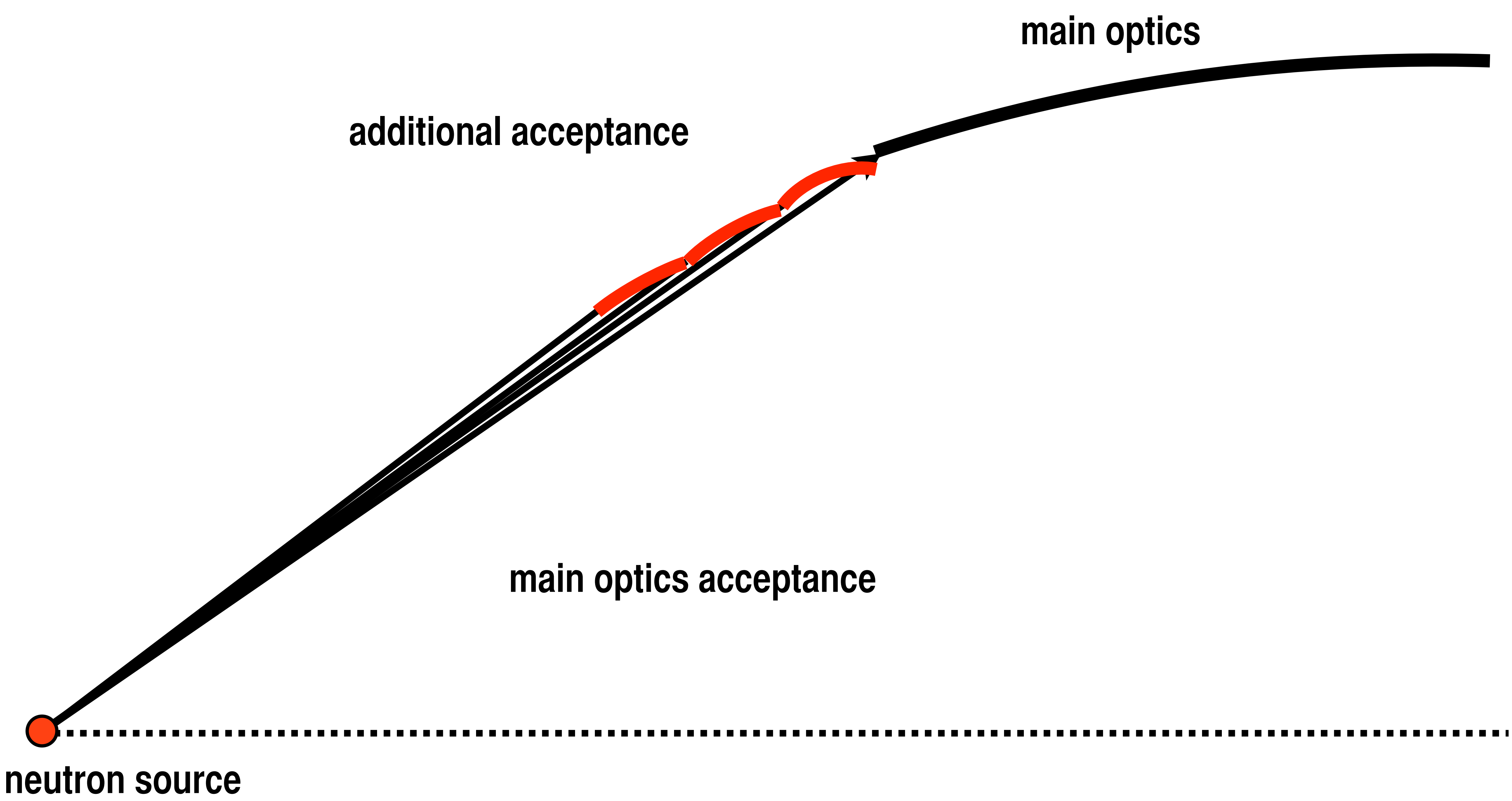
neutron source


main optics
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neutron source

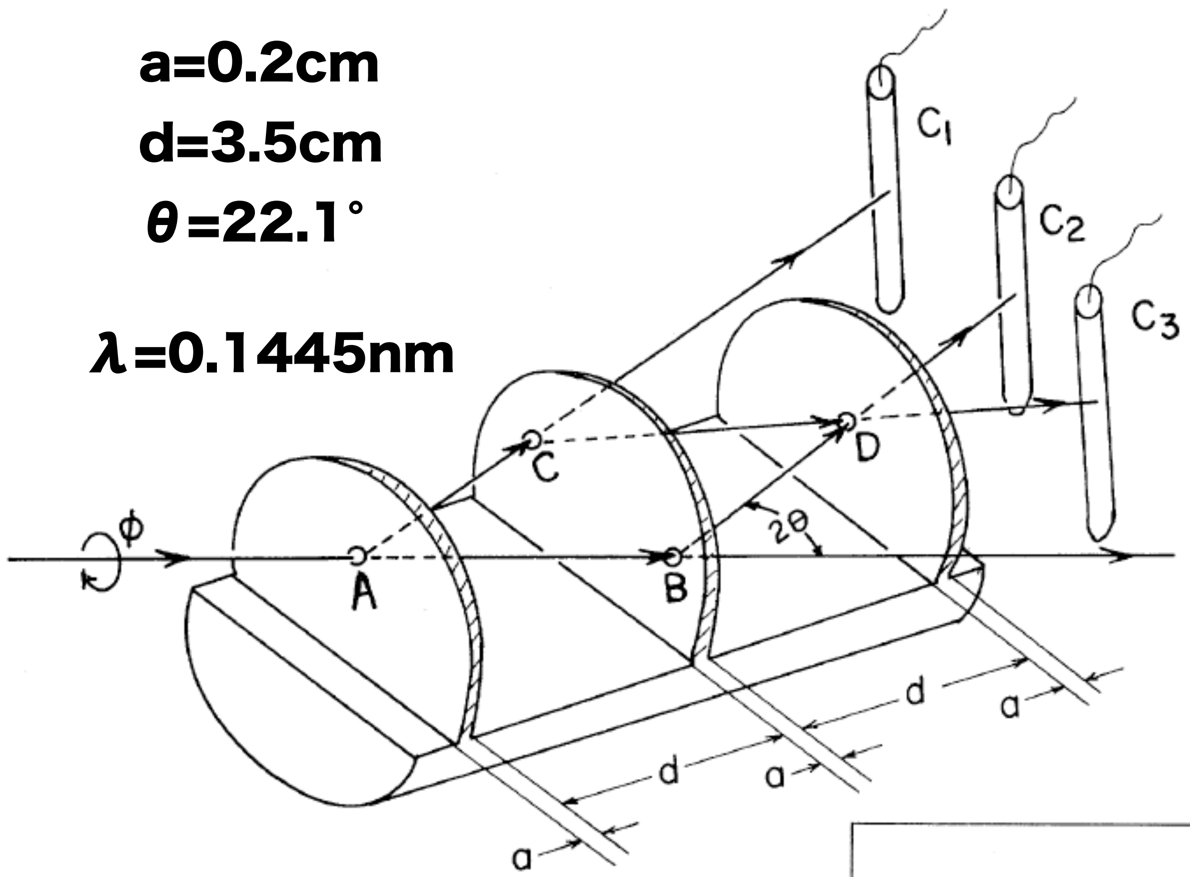
Neutron Interferometry

Neutron Phase induced by Earth's Gravity

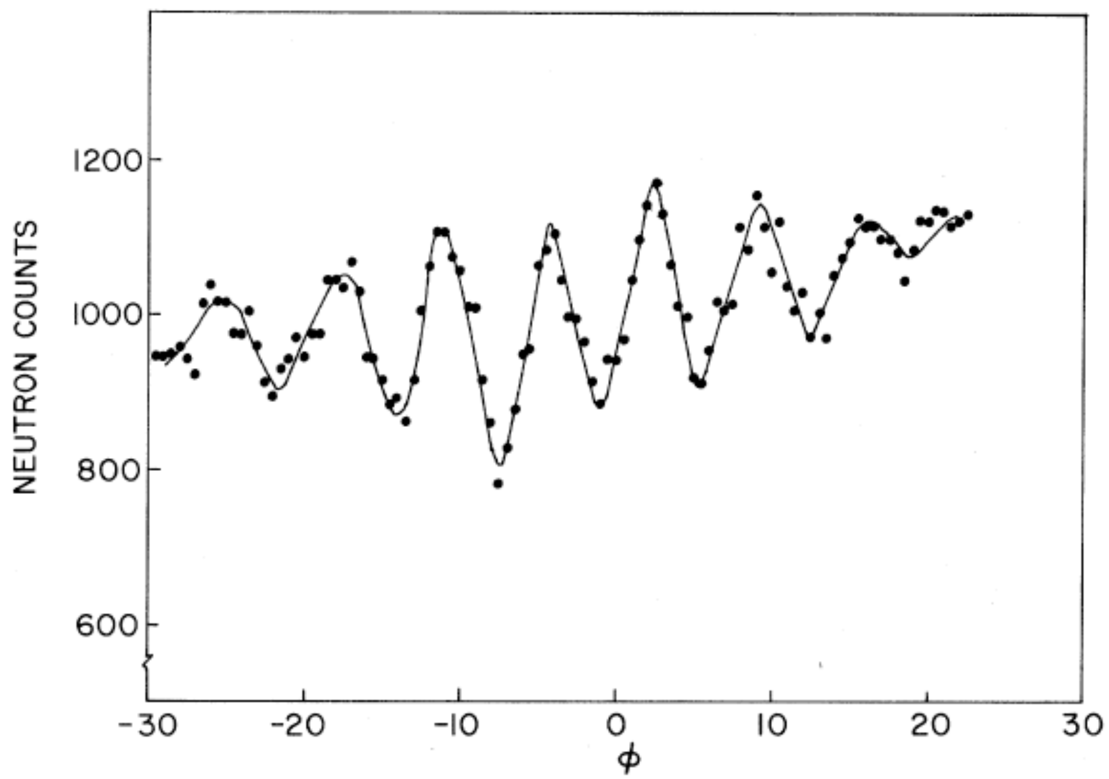
Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

a=0.2cm
d=3.5cm
θ=22.1°

λ=0.1445nm



COW expertment



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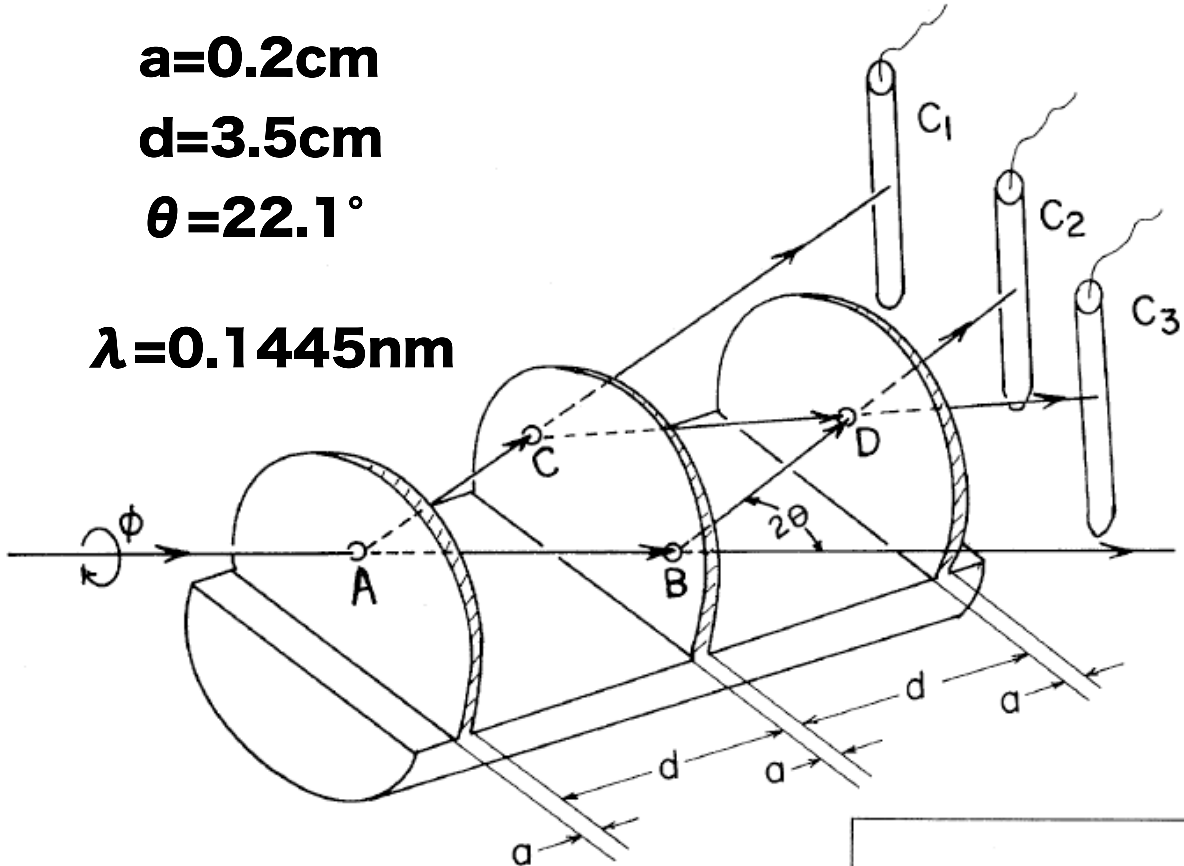

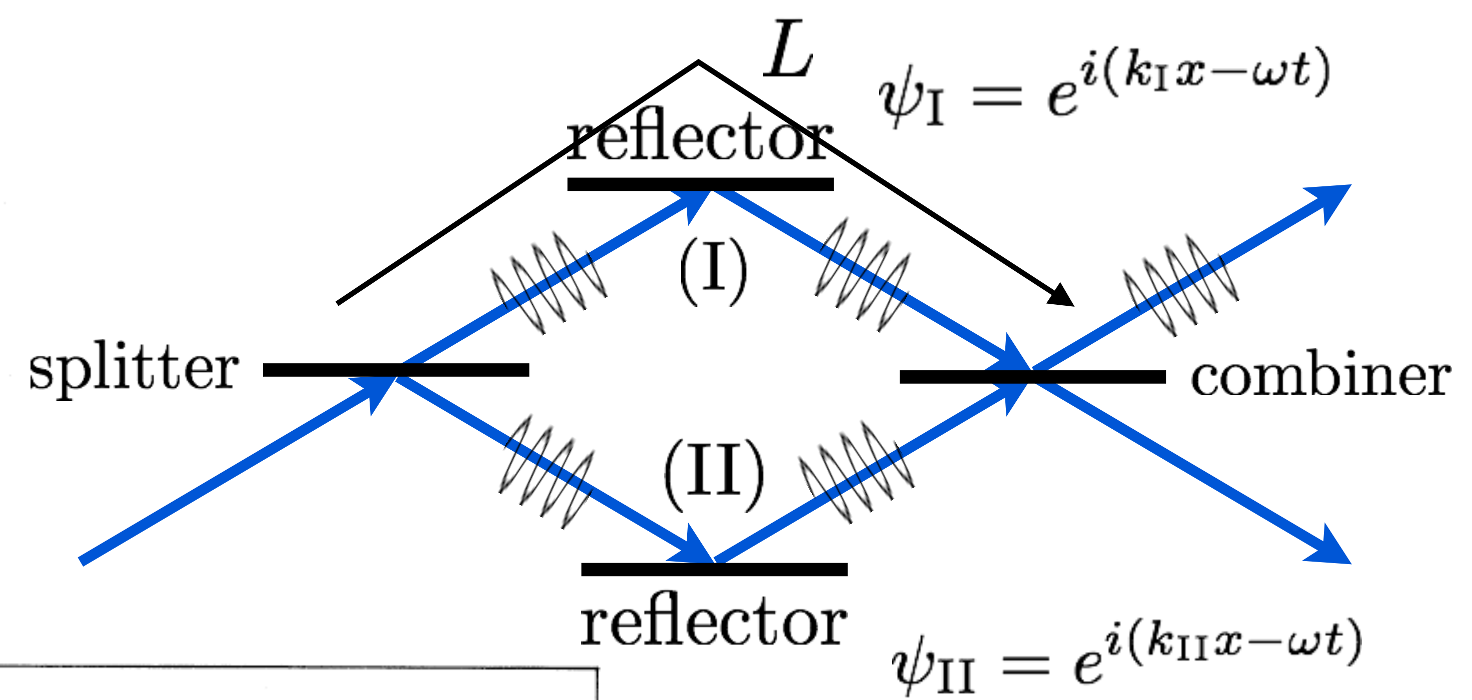

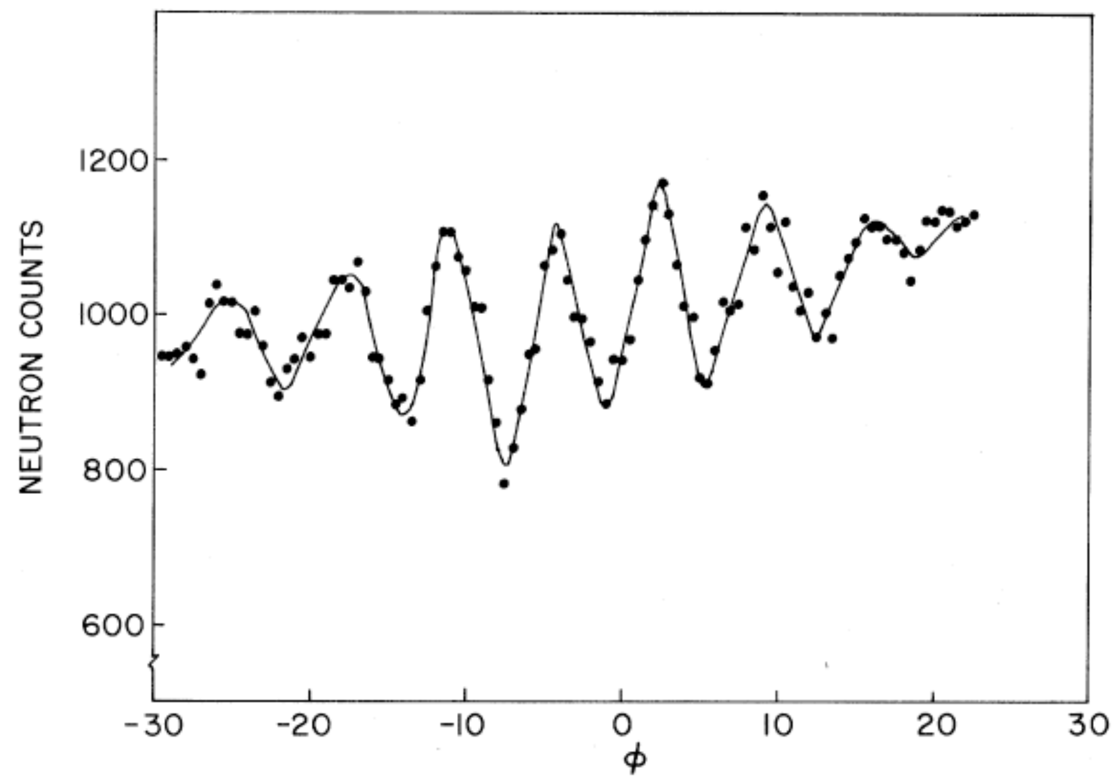

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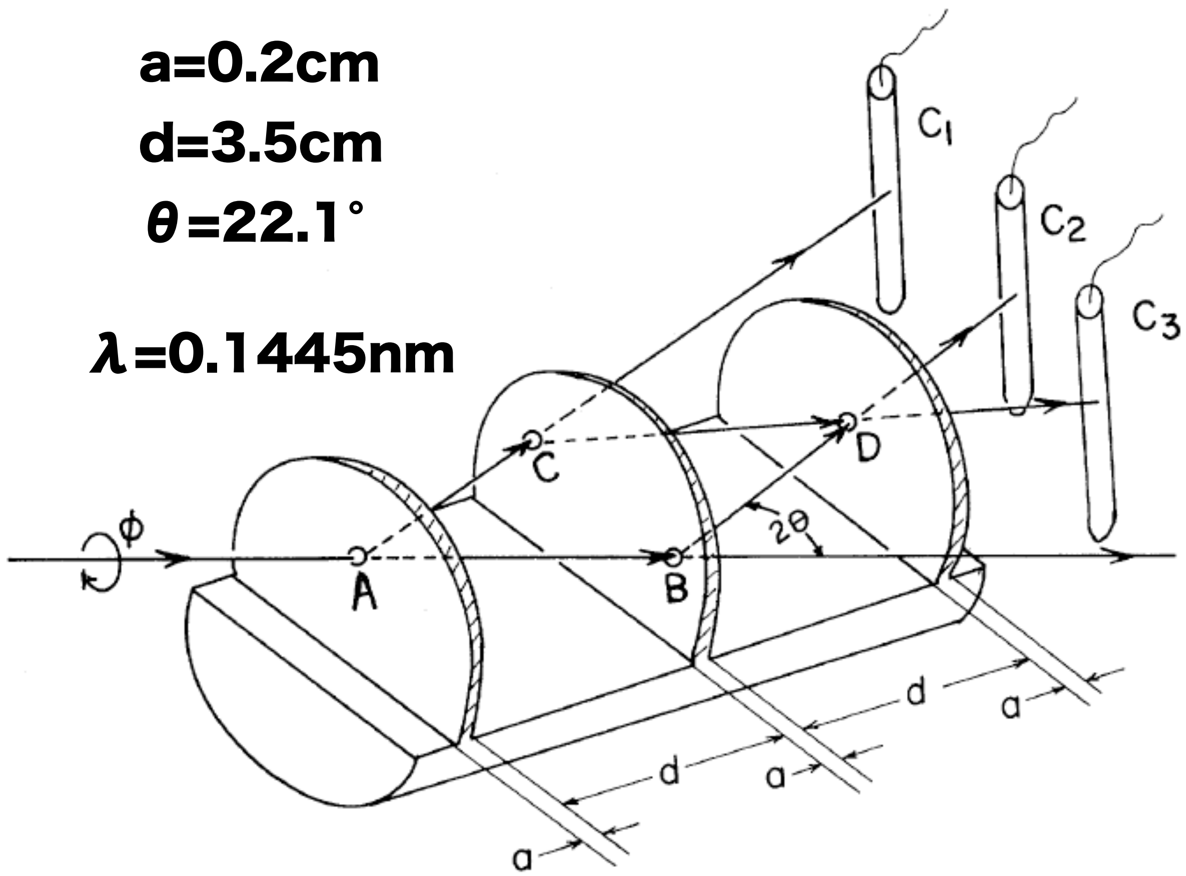

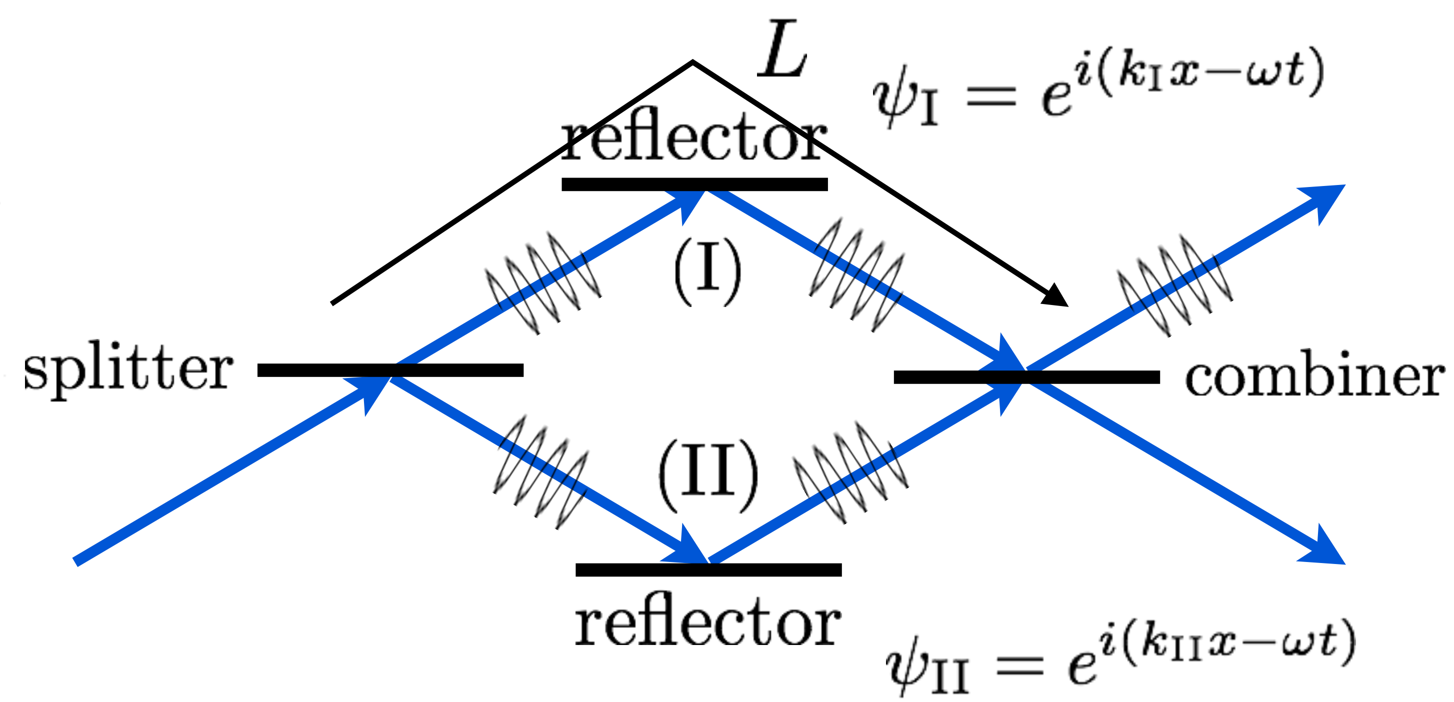

$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0 + U)}}{\hbar}$$

$$\phi_{\mathrm{I}} = k_{\mathrm{I}} L$$

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

$$\phi_{\mathrm{II}} = k_{\mathrm{II}} L$$

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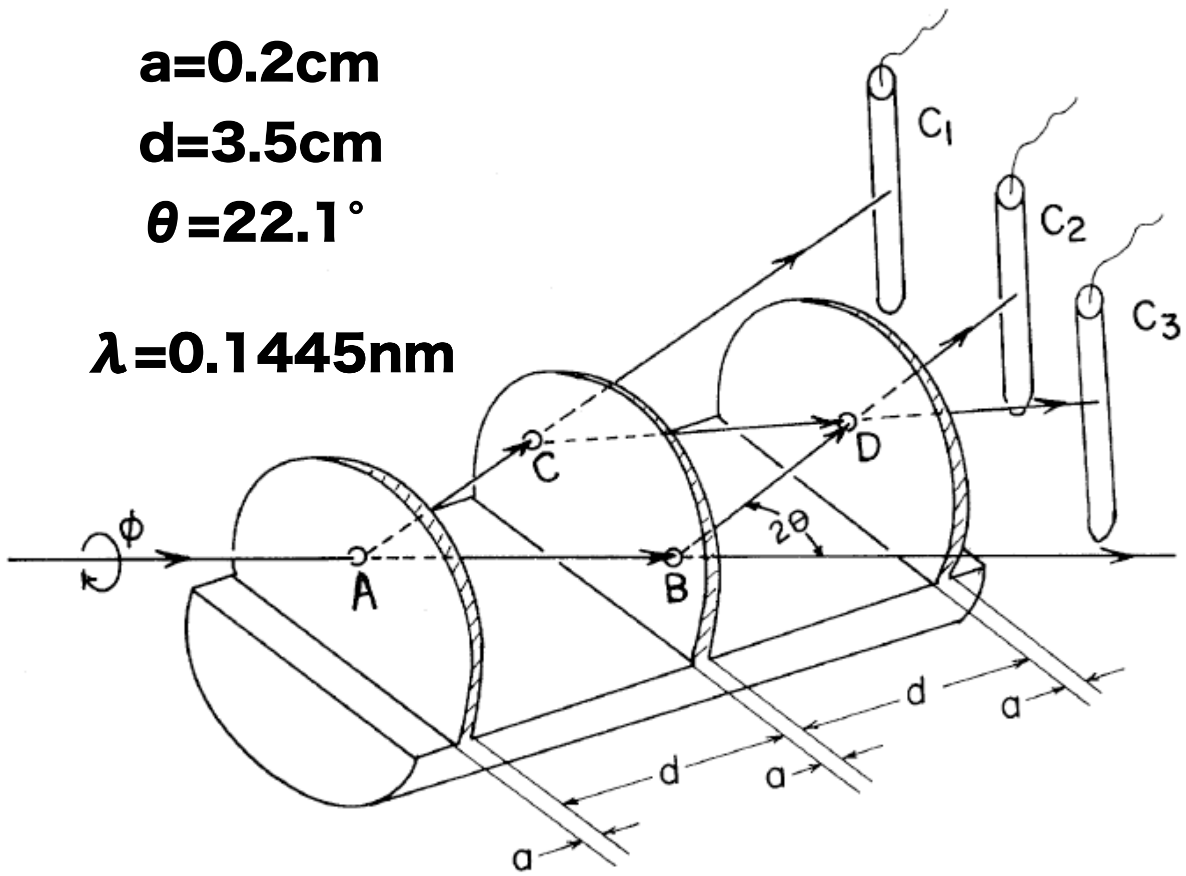

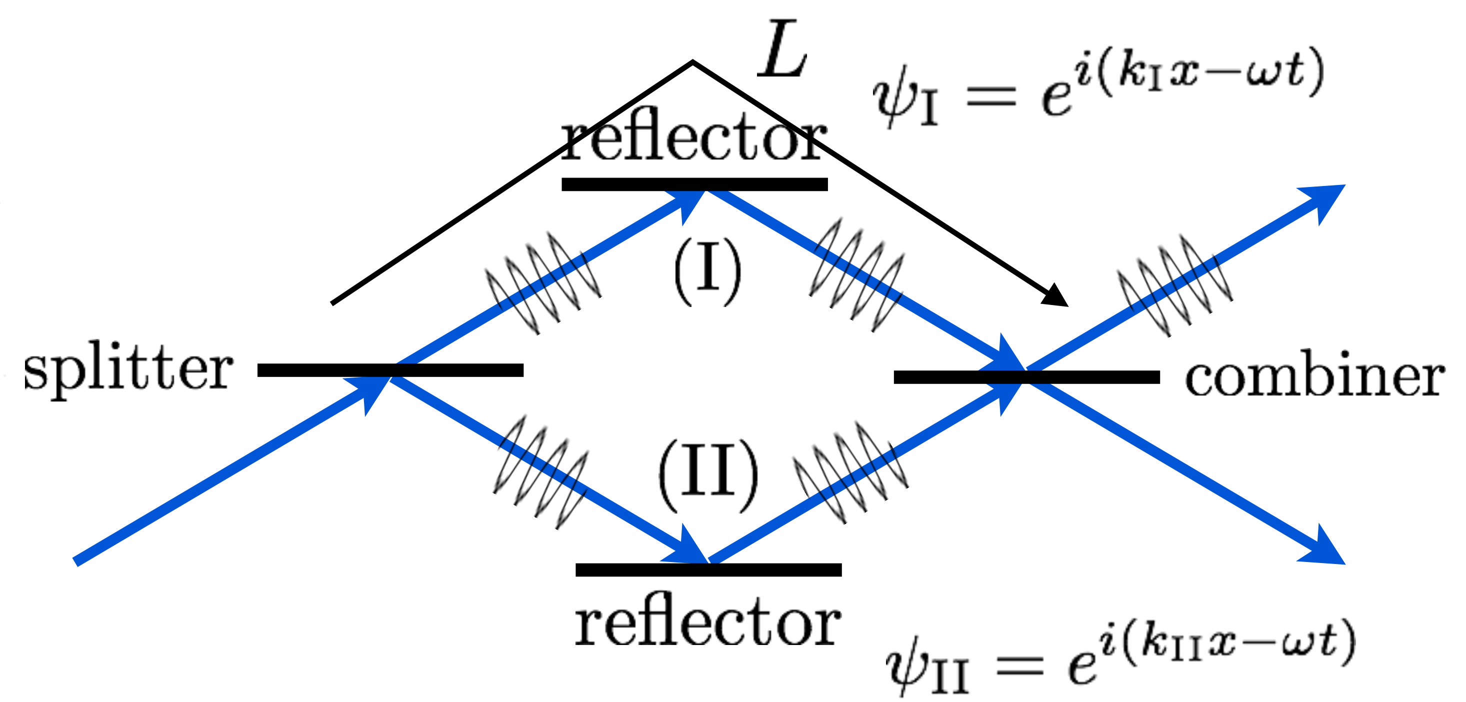

$$k_{\rm I} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\rm I} = k_{\rm I}L$$

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

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

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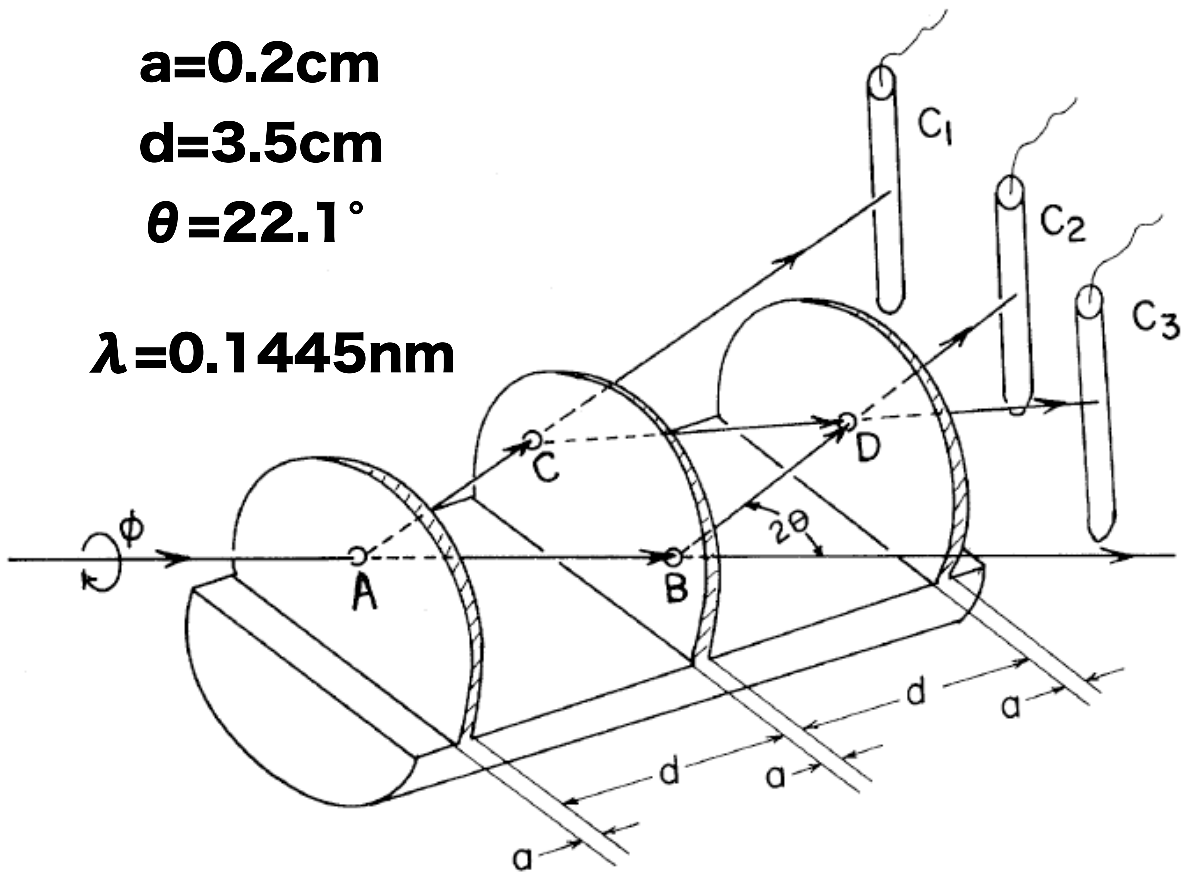
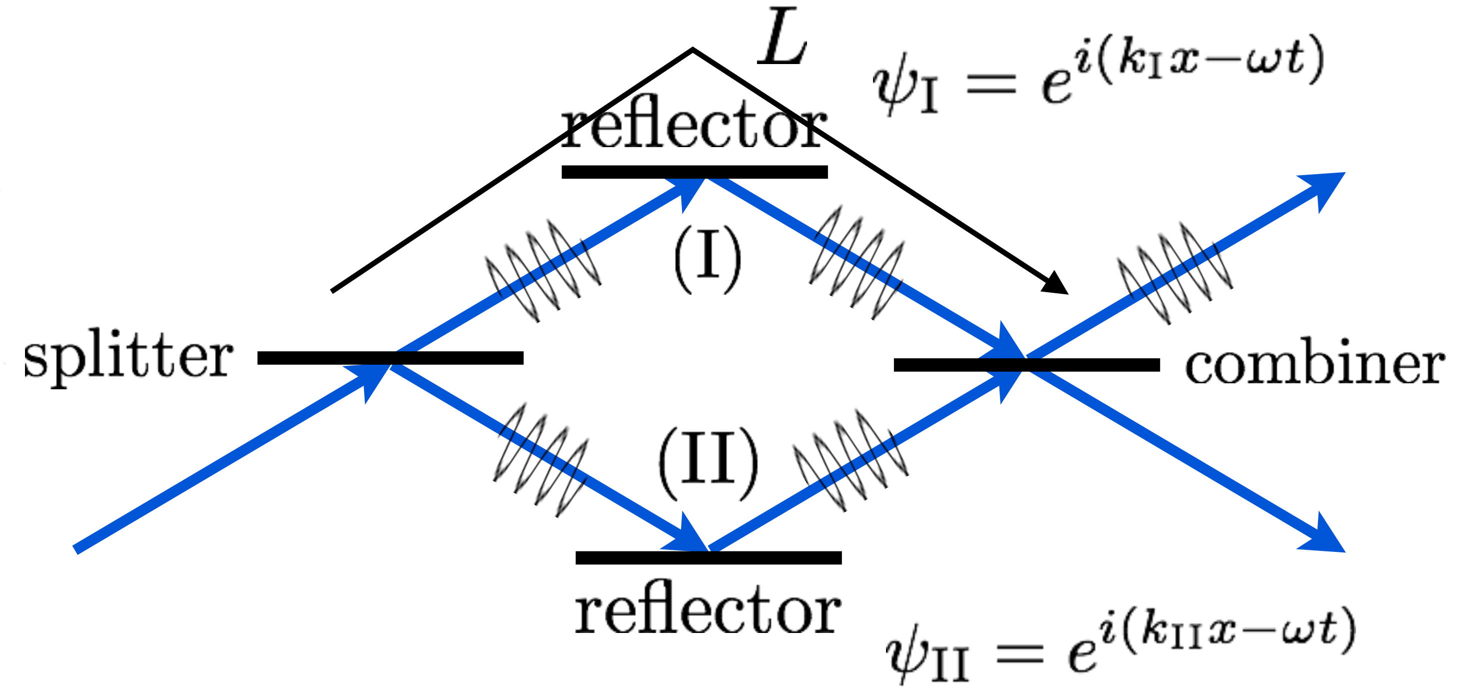




$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0 + U)}}{\hbar} \qquad \phi_{\mathrm{I}} = k_{\mathrm{I}}L$$

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

larger interferometer

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

better statistics

slower neutron

Neutron Phase induced by Earth's Gravity

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

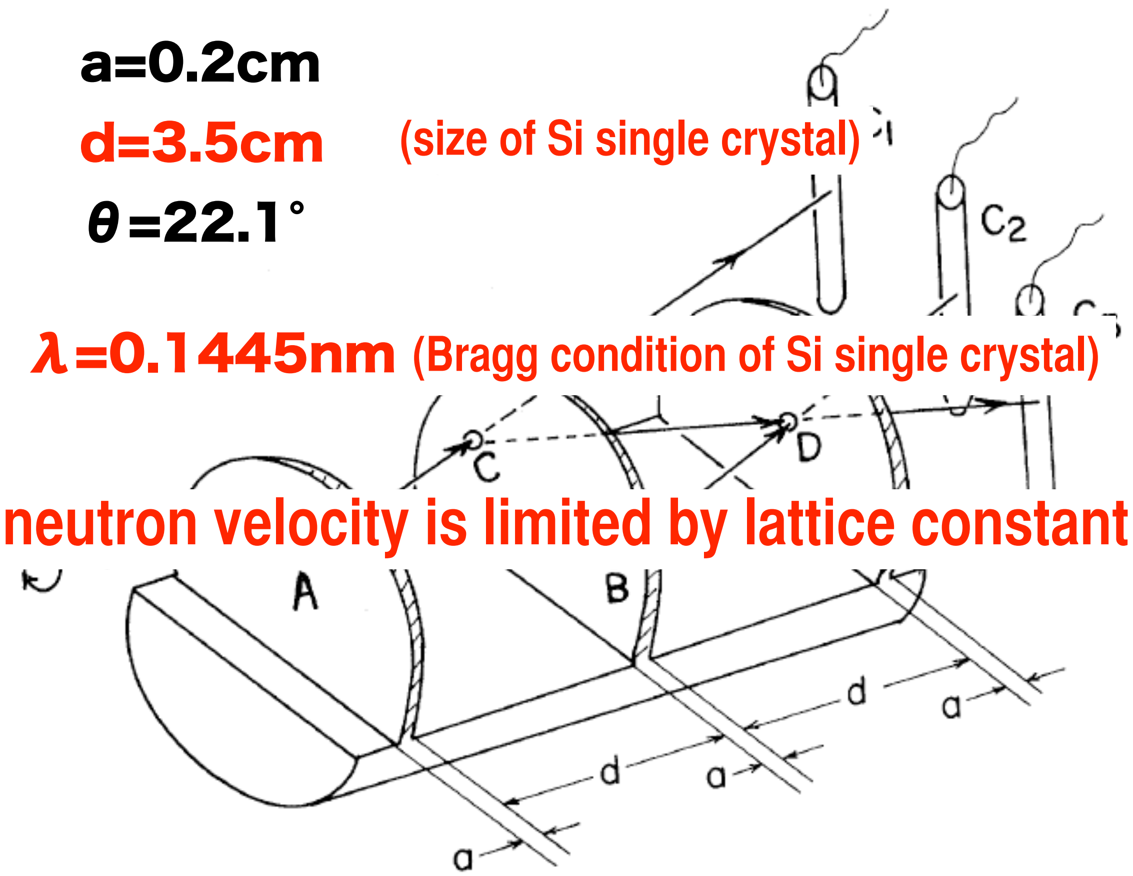
a=0.2cm

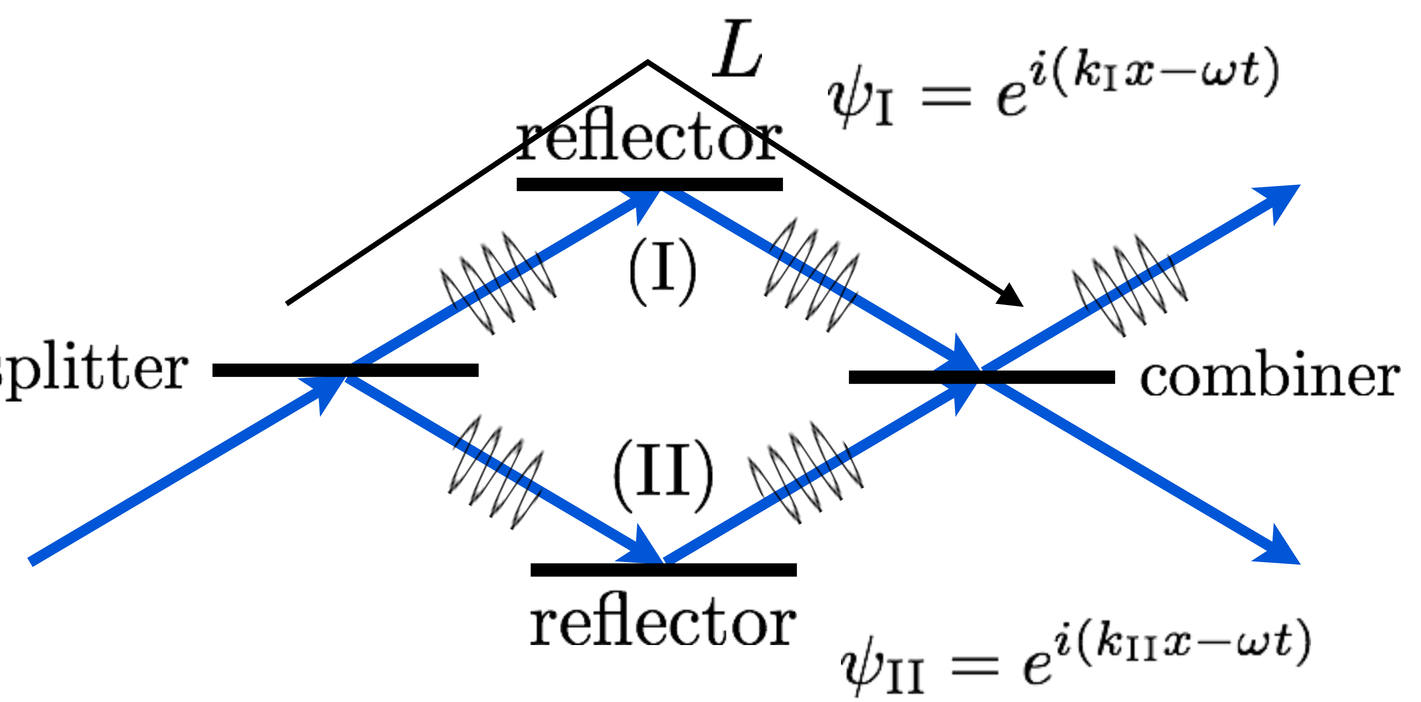
d=3.5cm (size of Si single crystal)

θ=22.1°

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

neutron velocity is limited by lattice constant





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

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

larger interferometer

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

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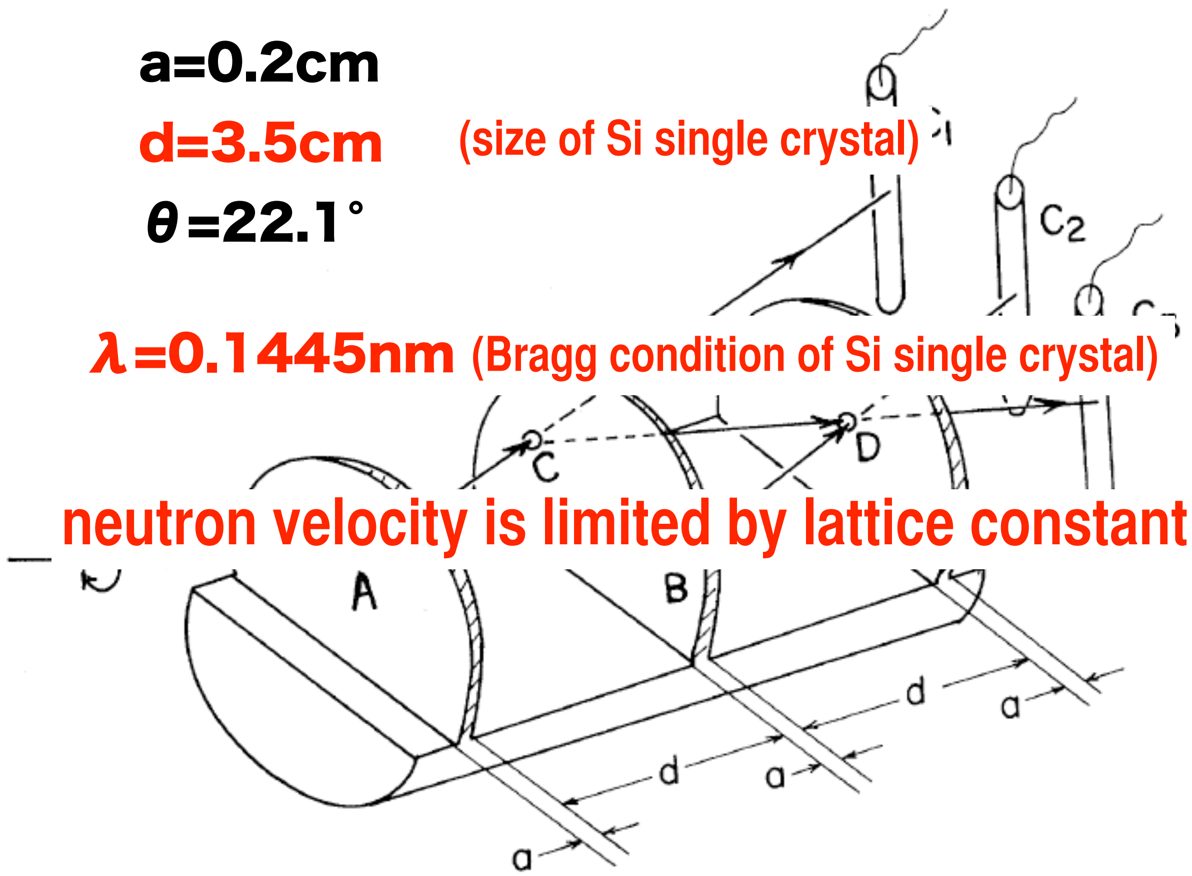
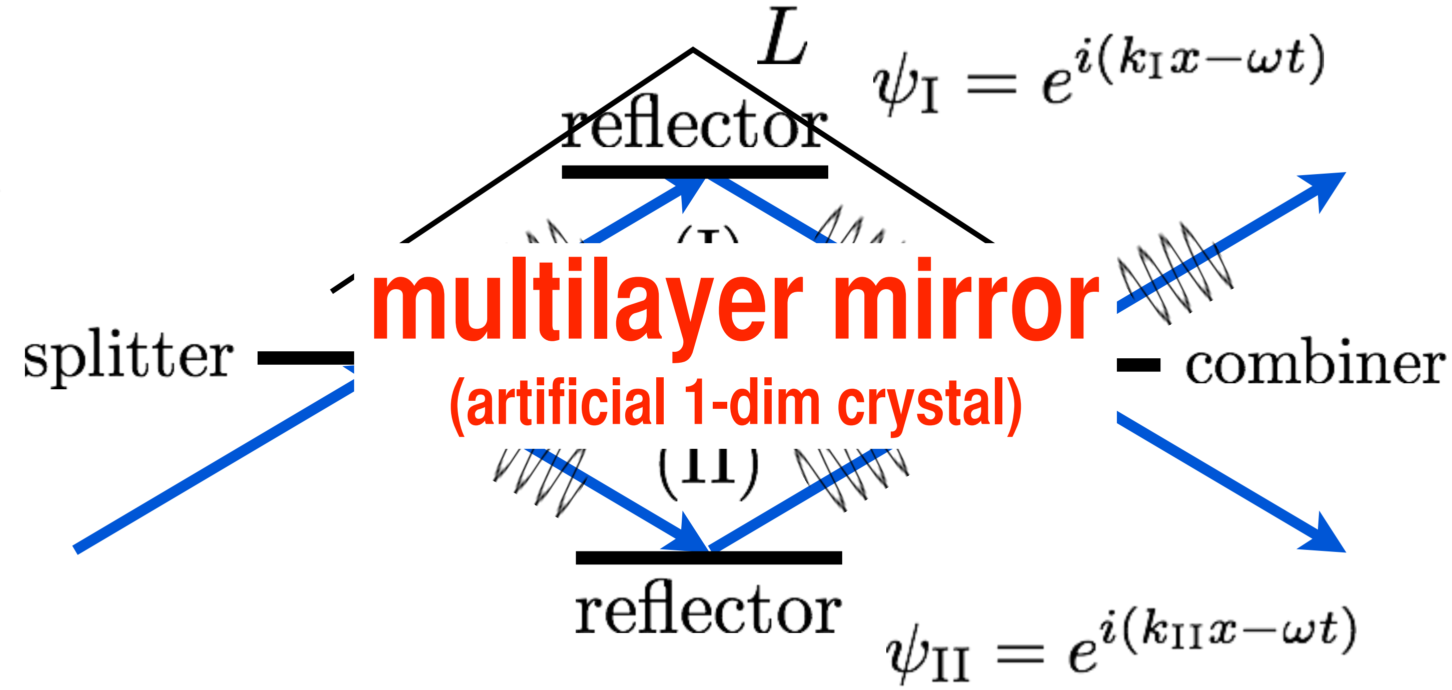


multilayer mirror

(artificial 1-dim crystal)



$$\psi_I = e^{i(k_I x - \omega t)}$$

$$\psi_{II} = e^{i(k_{II} x - \omega t)}$$

$$k_I = \frac{\sqrt{2m_n(E_0 + U)}}{\hbar} \qquad \phi_I = k_I L$$

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

larger interferometer

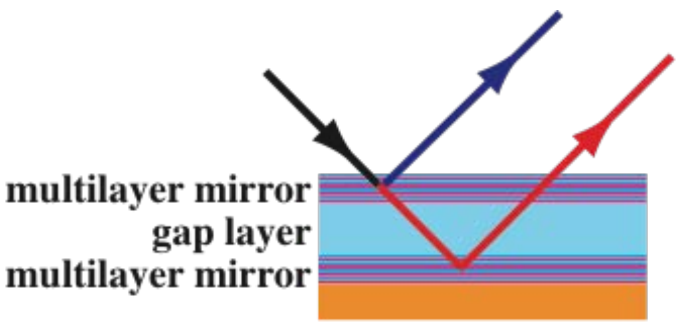
$$\Delta\phi = \phi_{II} - \phi_I \simeq \sqrt{\frac{m_n c^2}{2E}} \frac{L \Delta U}{\hbar c}$$

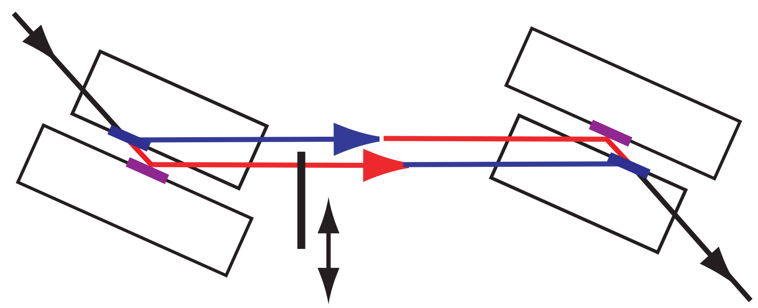
better statistics

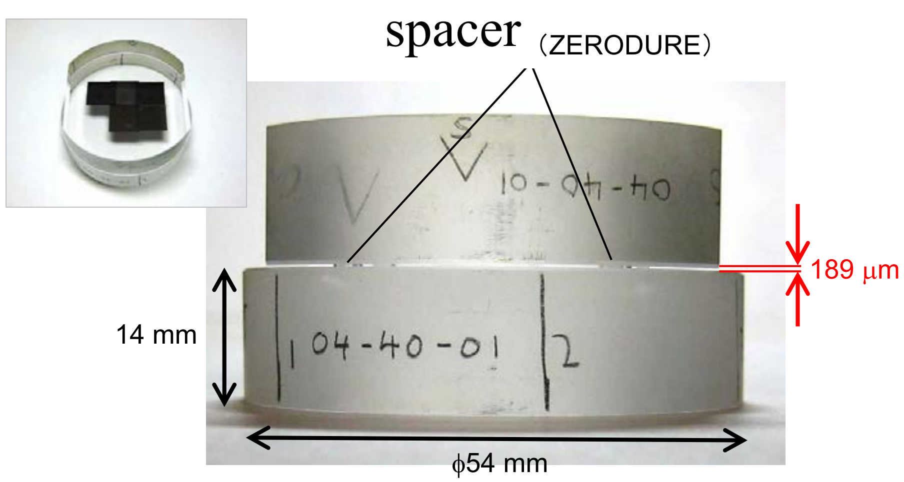
slower neutron

Mirror Alignment

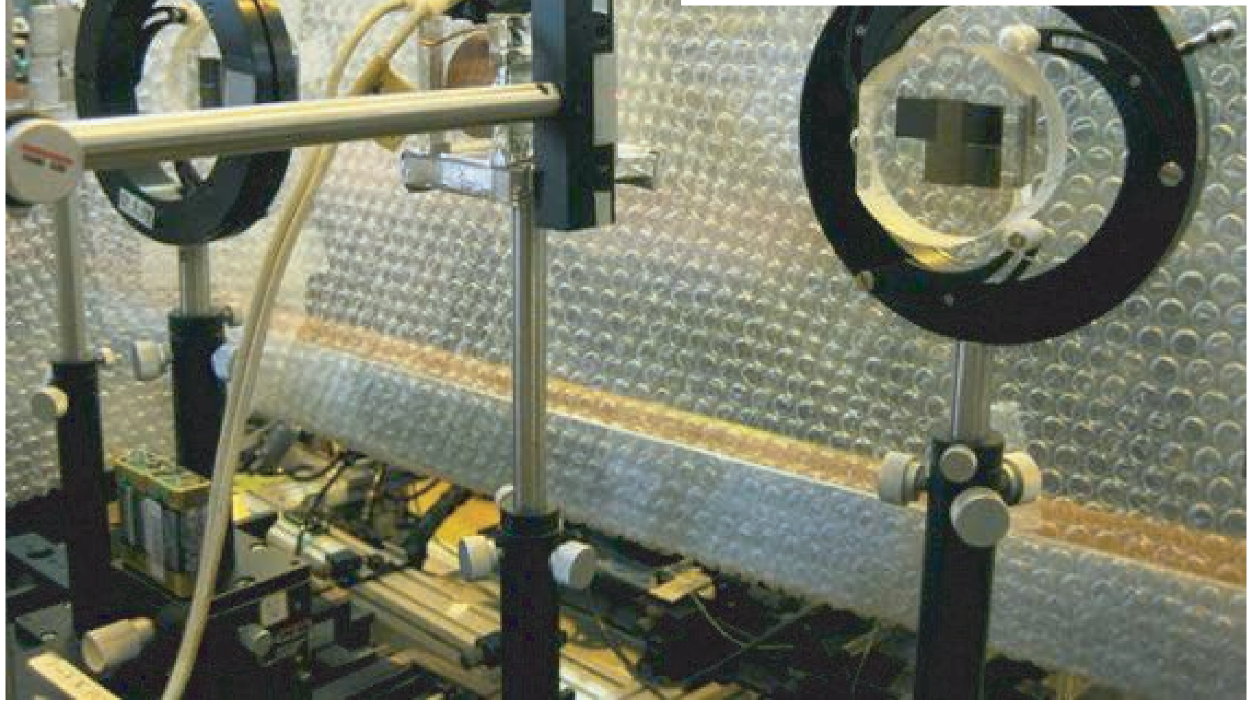
Y. Seki et al., J. Phys. Soc. Jpn. 79 (2010) 124201.

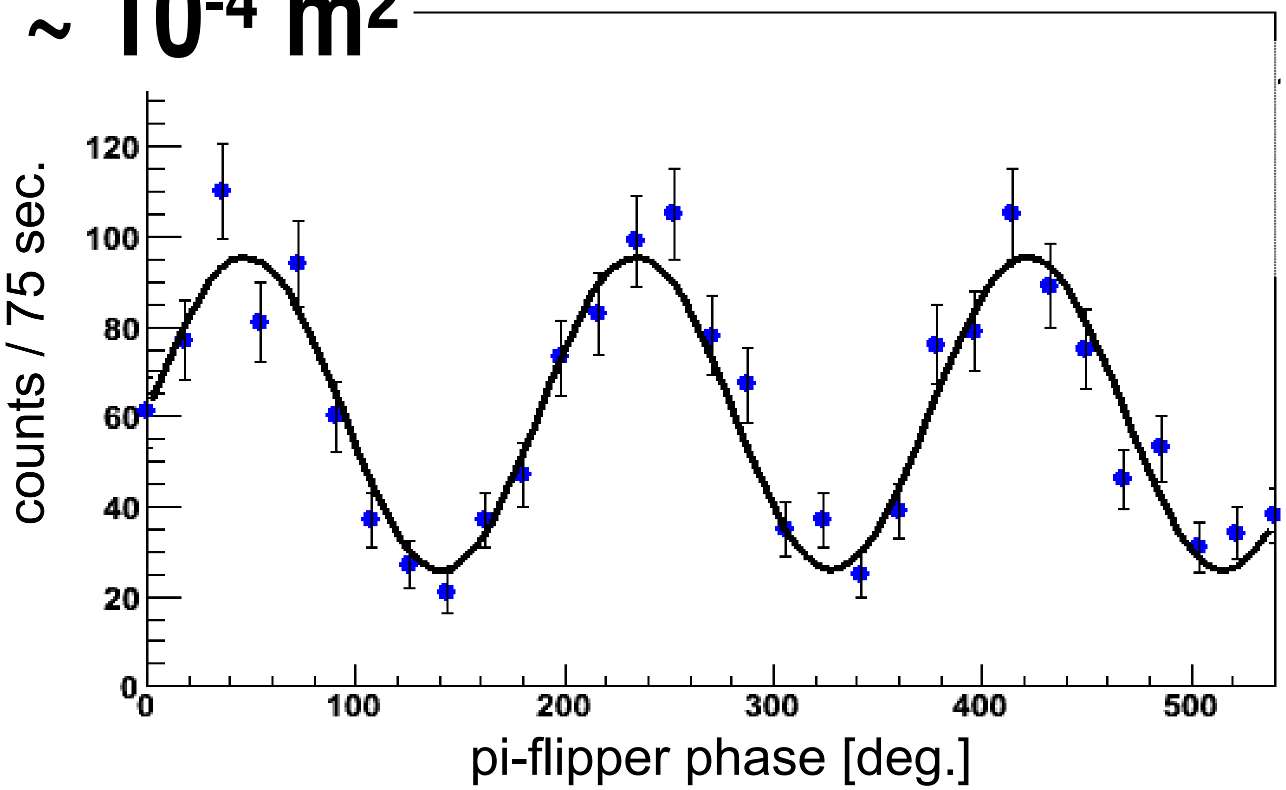




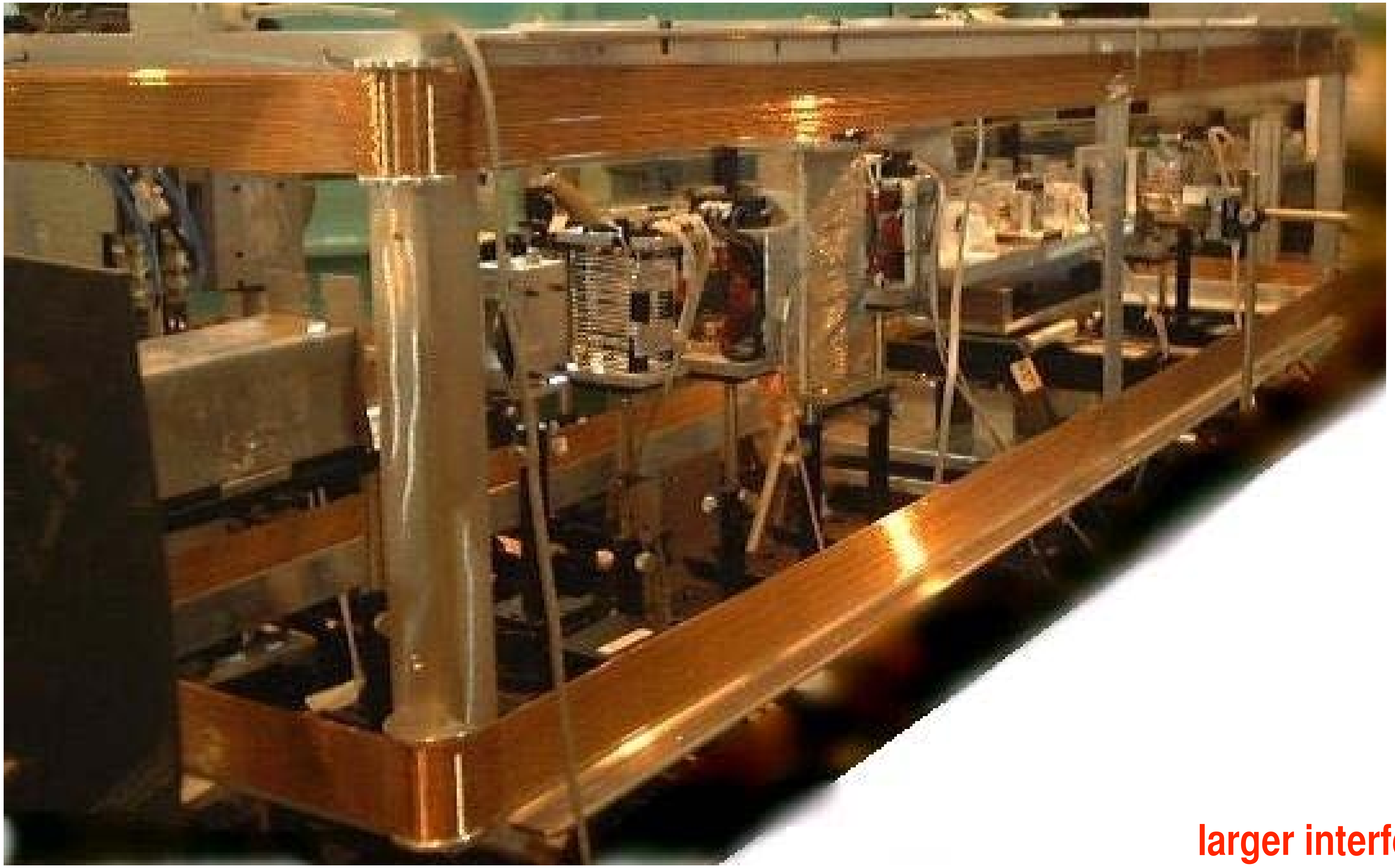


30cm x 0.2mm ~ 10^{-4} m^2





Multilayer Neutron Interferometer



larger interferometer

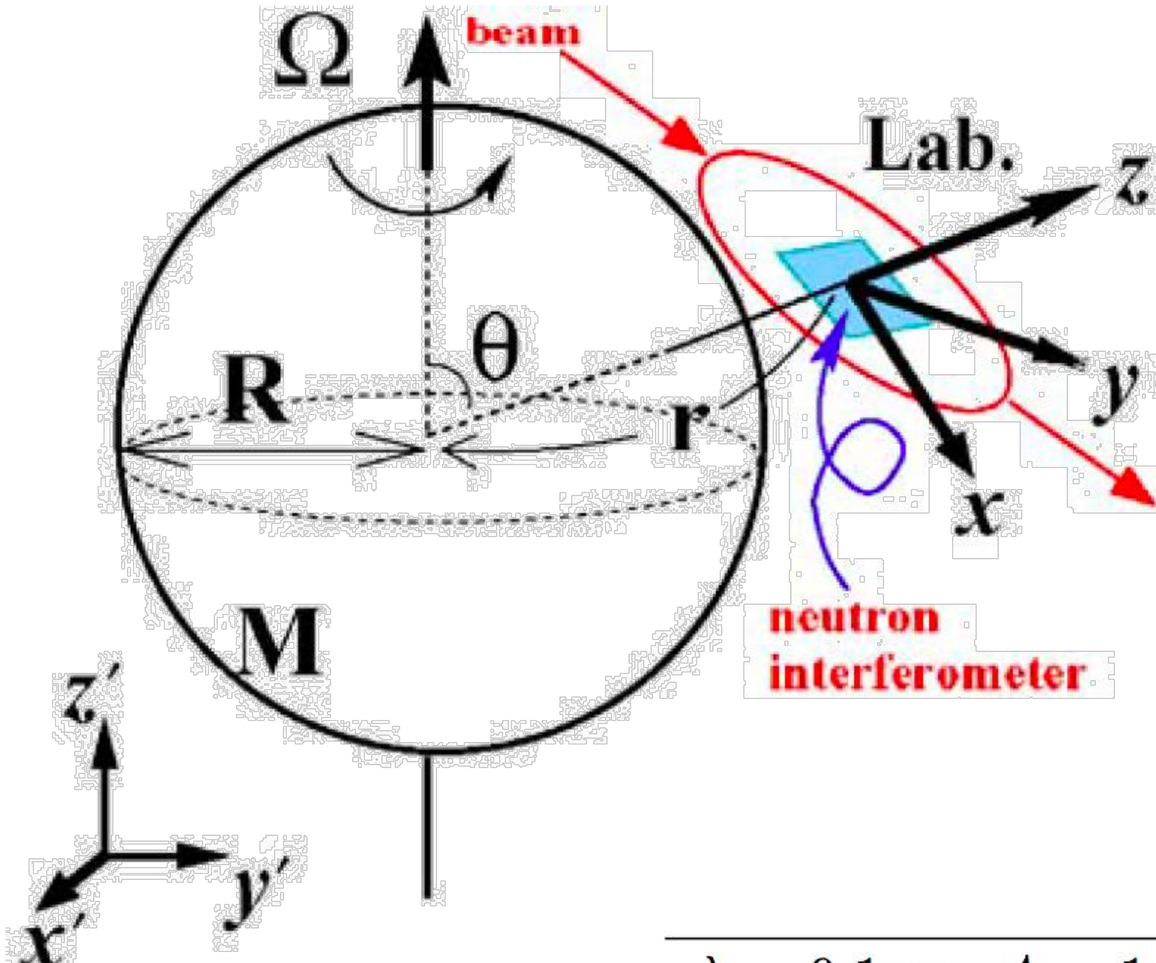
$$\Delta\phi = \phi_{II} - \phi_{I} \simeq \sqrt{\frac{m_n c^2}{2E}}\frac{L\Delta U}{\hbar c}$$

better statistics

slower neutron

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	10^{-6}

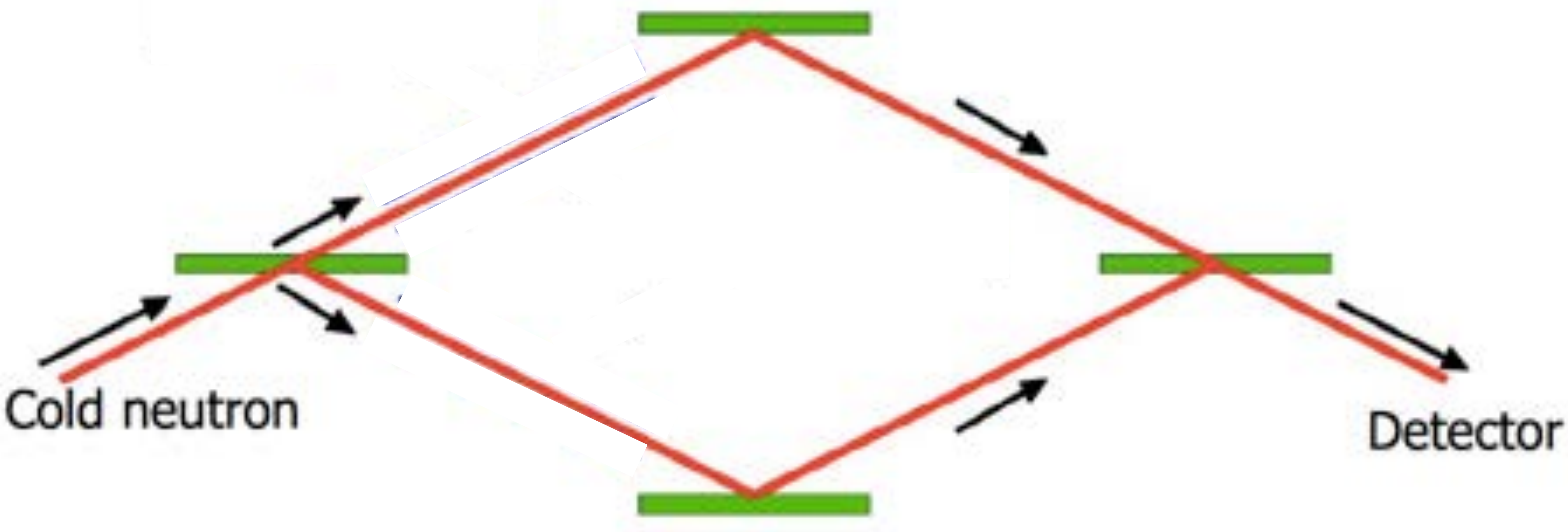
accessible with J-PARC

COW

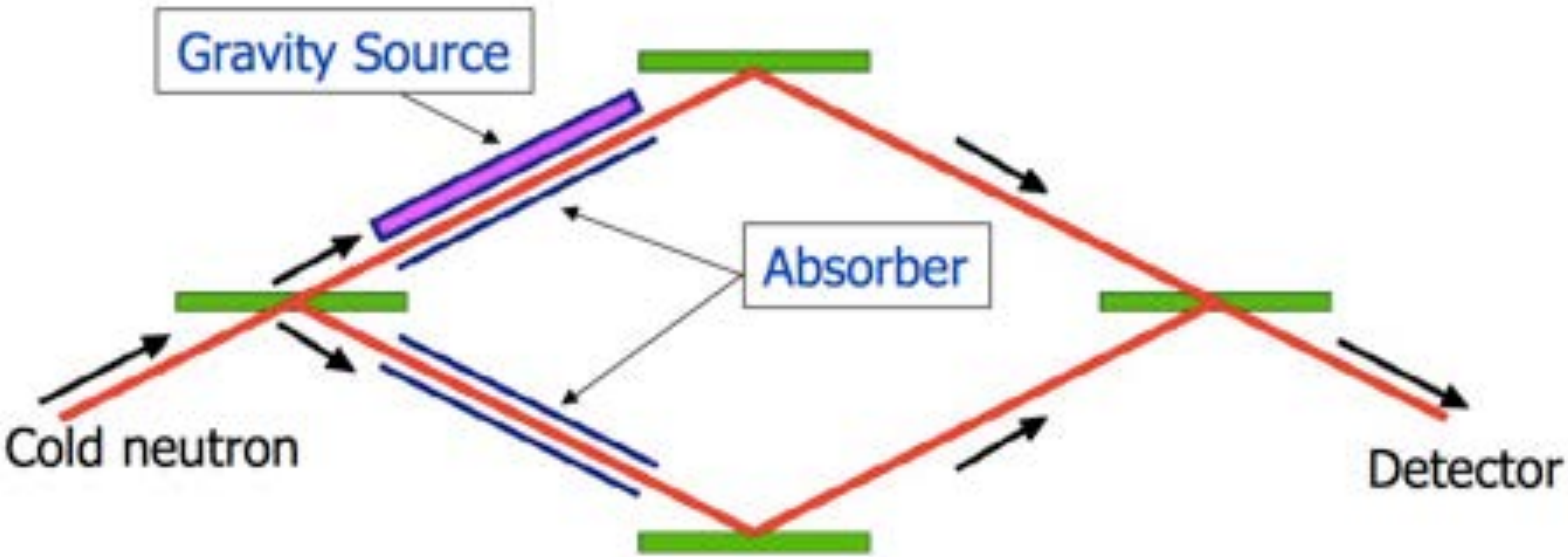
$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + m\phi - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$
$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol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

Lense-Thirring

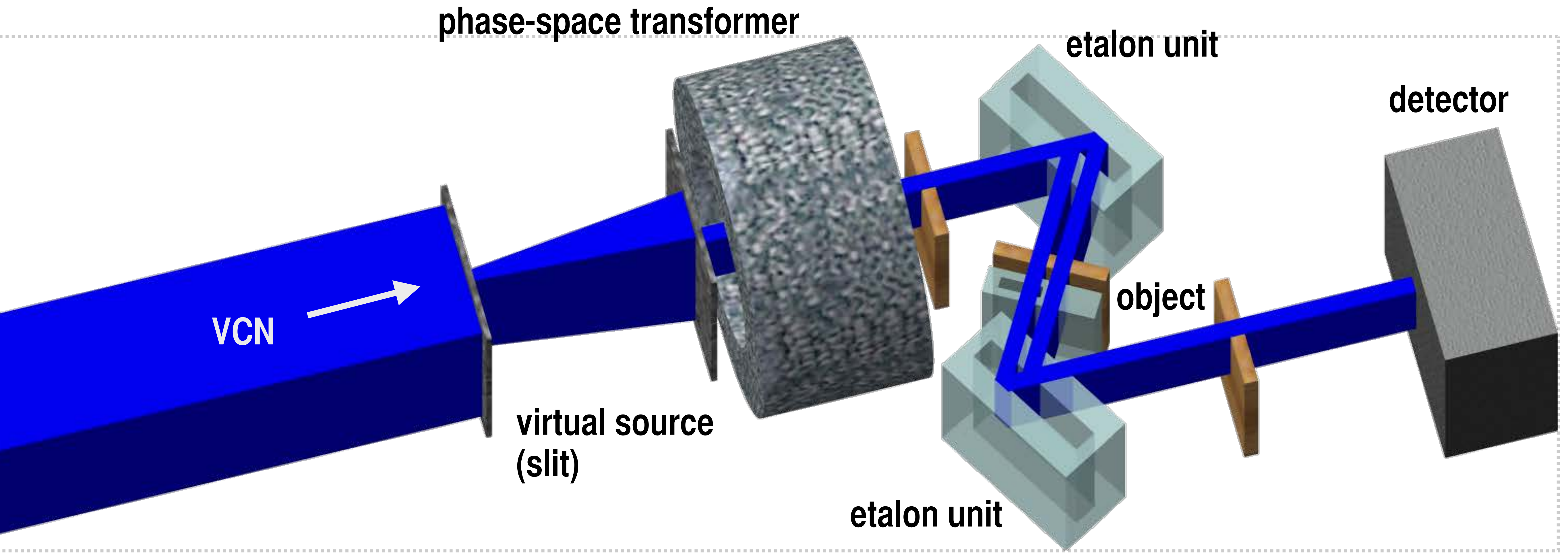
Mach-Zehnder configuration

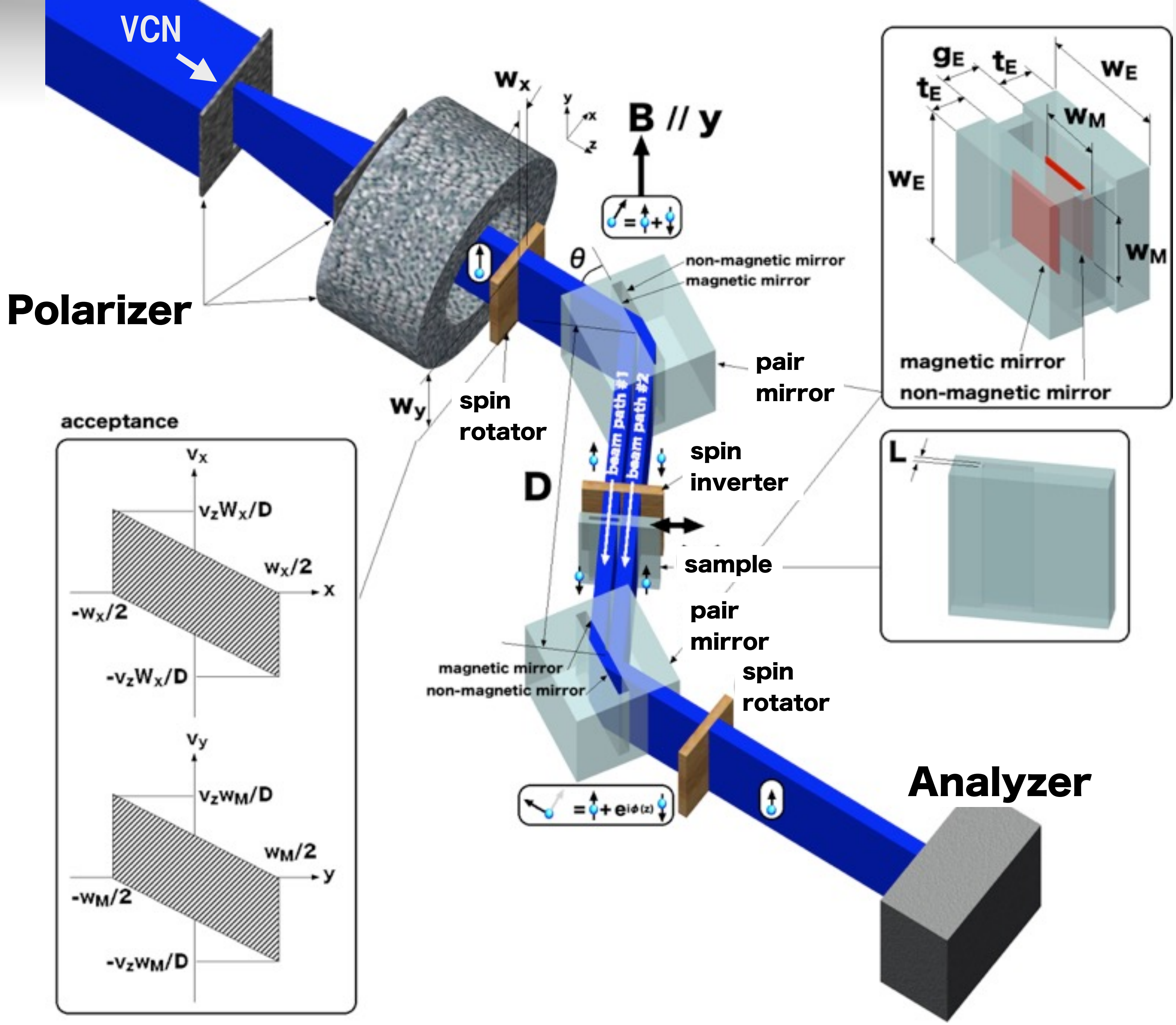


New Interaction Search (mm-range)



VCN Intermetometry




VCN
w_x
B // y
Polarizer
θ
non-magnetic mirror
magnetic mirror
pair mirror
w_y
spin rotator
beam path #1
beam path #2
spin inverter
D
sample
pair mirror
magnetic mirror
non-magnetic mirror
spin rotator
Analyzer
acceptance
v_x
v_zw_x/D
$w_x/2$
x
$-w_x/2$
$-v_zw_x/D$
v_y
v_zw_M/D
$w_M/2$
y
$-w_M/2$
$-v_zw_M/D$
g_E
t_E
t_E
w_E
w_M
w_E
w_M
magnetic mirror
non-magnetic mirror
L

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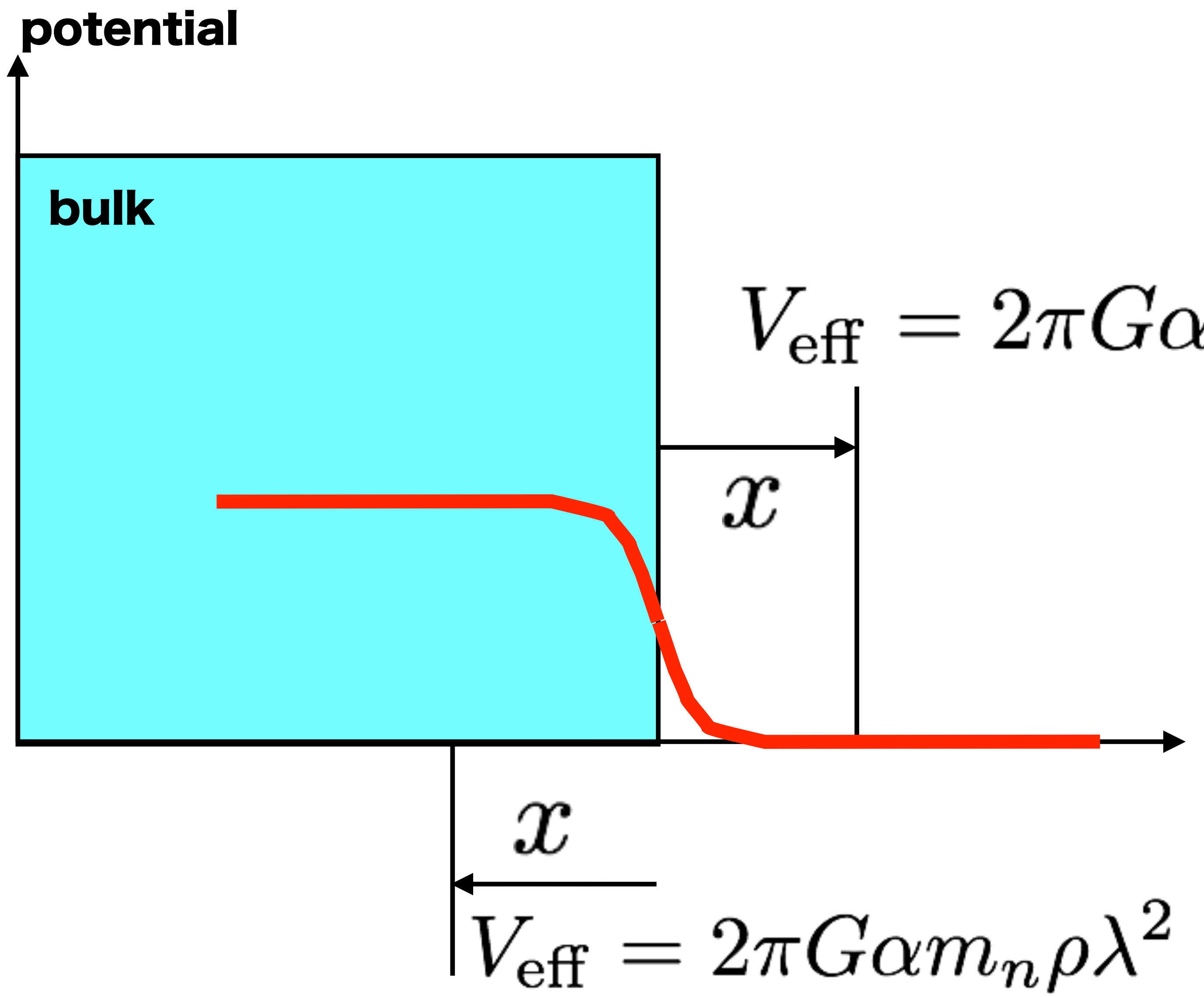
Potential of Hypothetical Yukawa-interactions near the Bulk Surface

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

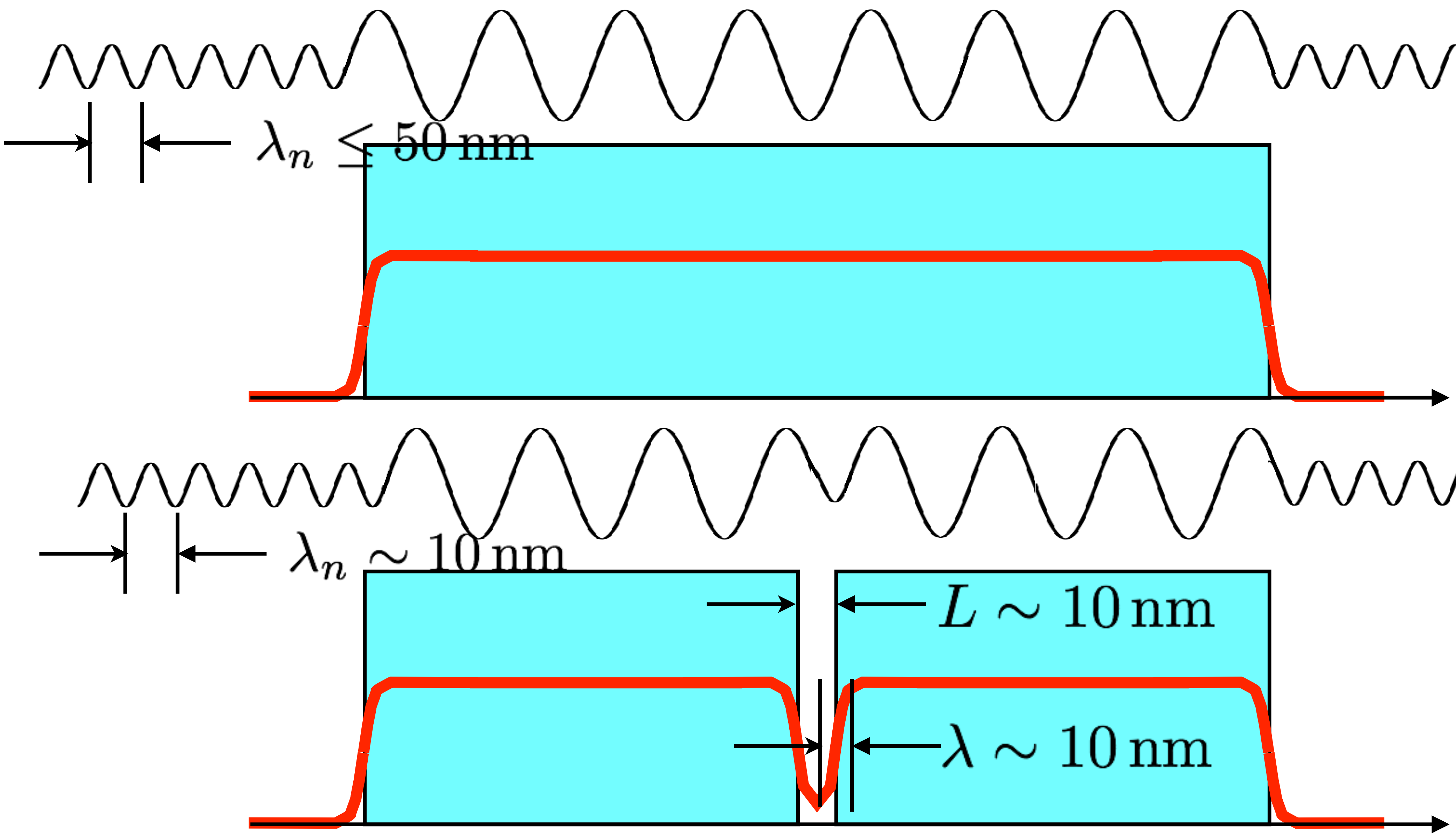


$$V_{\mathrm{eff}} = 2\pi G\alpha m_n \rho \lambda^2 e^{-x/\lambda}$$

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

Parametric Resonance due to the Yukawa Interactions

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



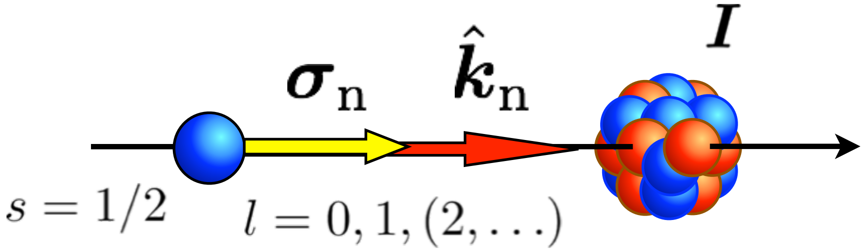
Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

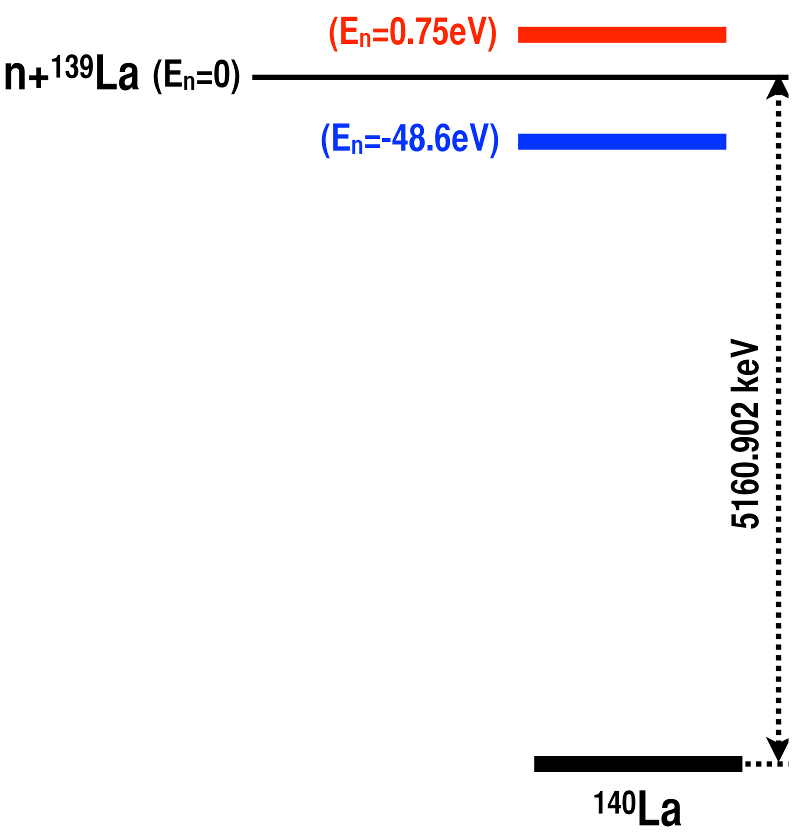
Epithermal Neutron Optics

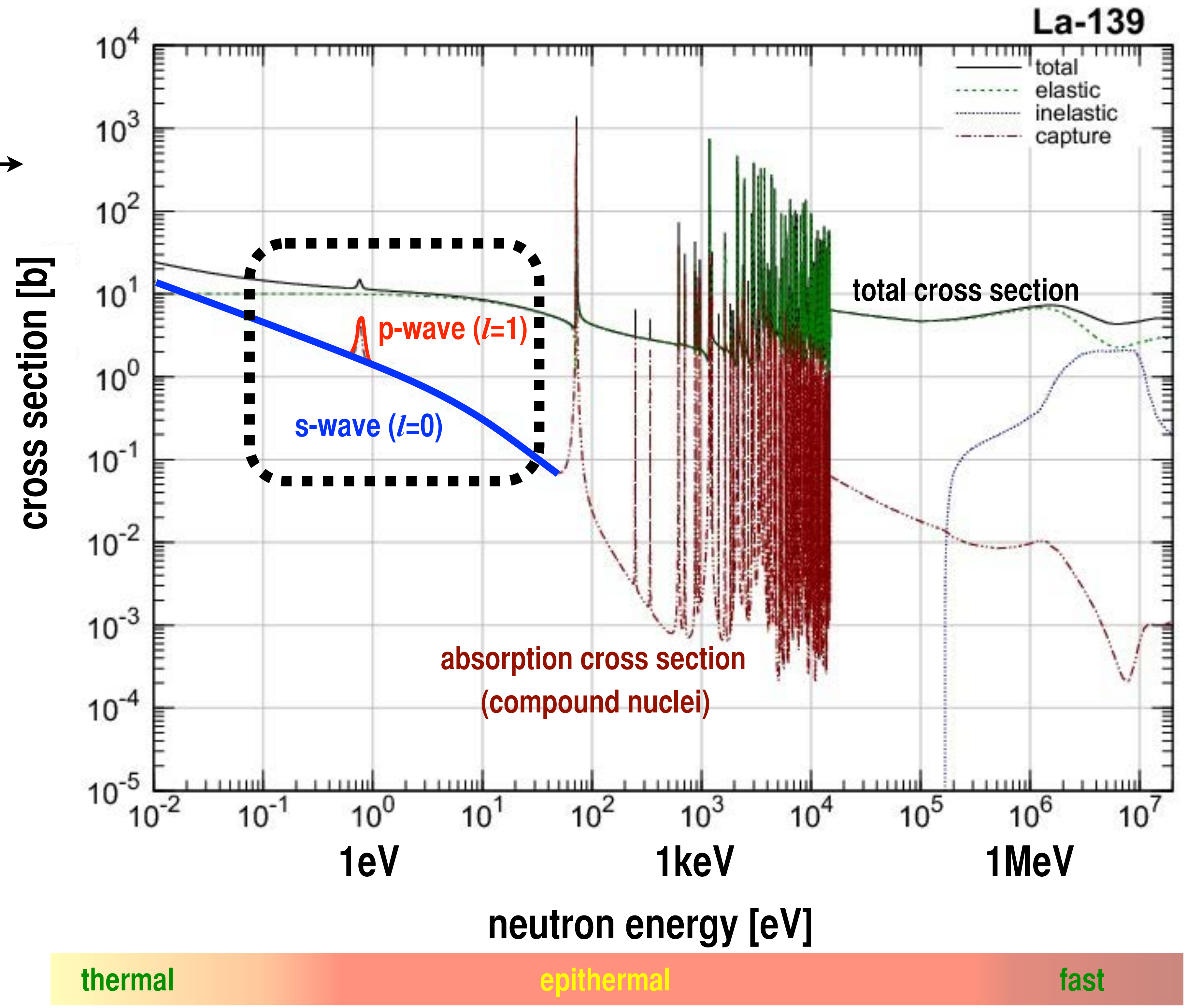
Compound States

P-violation

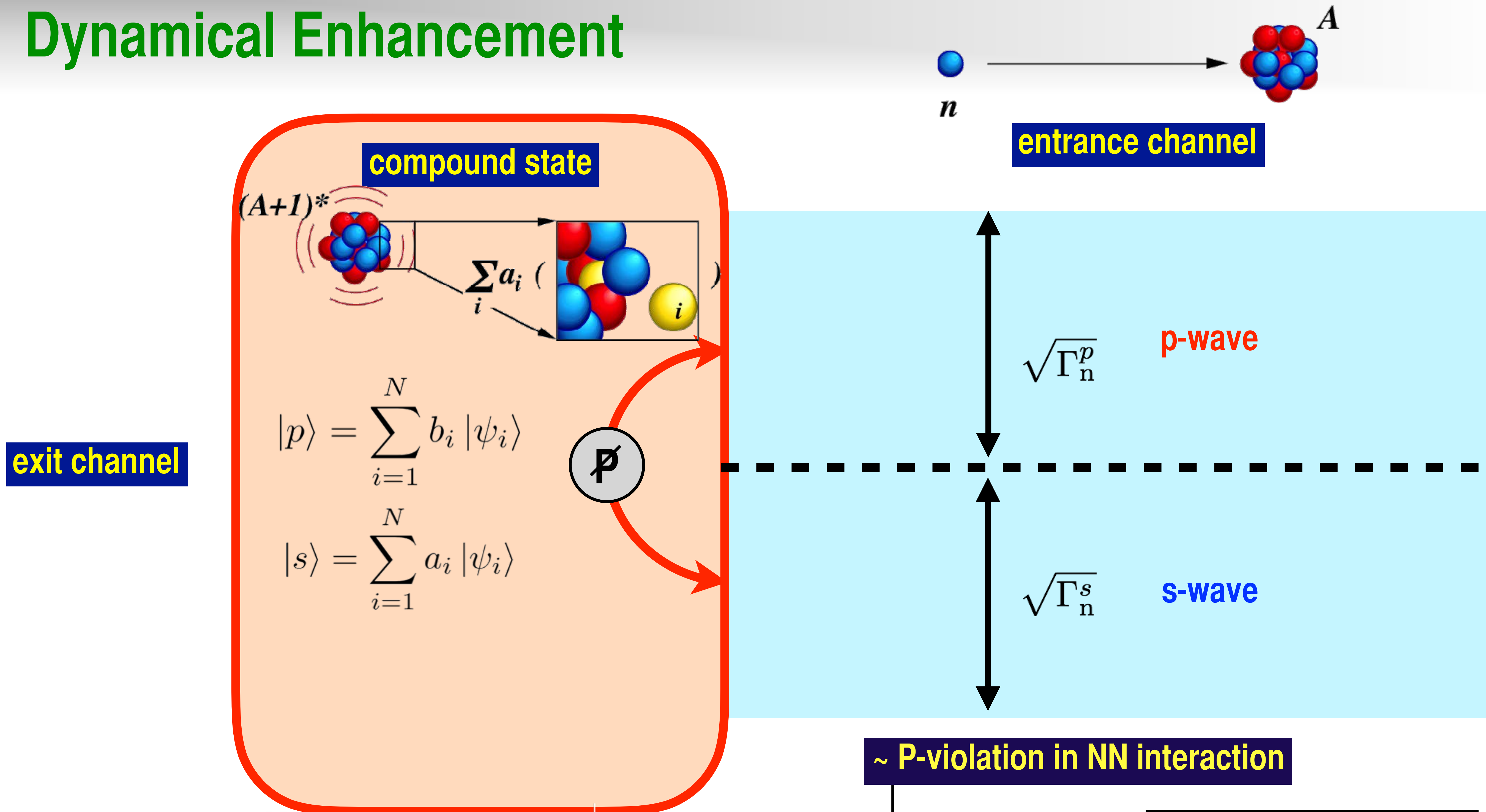
$$\sigma = \sigma_0 + \Delta\sigma(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)$$







Dynamical Enhancement



~ P-violation in NN interaction

$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle\psi_i|W|\psi_j\rangle \sim \frac{1}{\sqrt{N}}\frac{1}{\sqrt{N}}\langle W\rangle\sqrt{N}$$

randomness of expansion coefficients

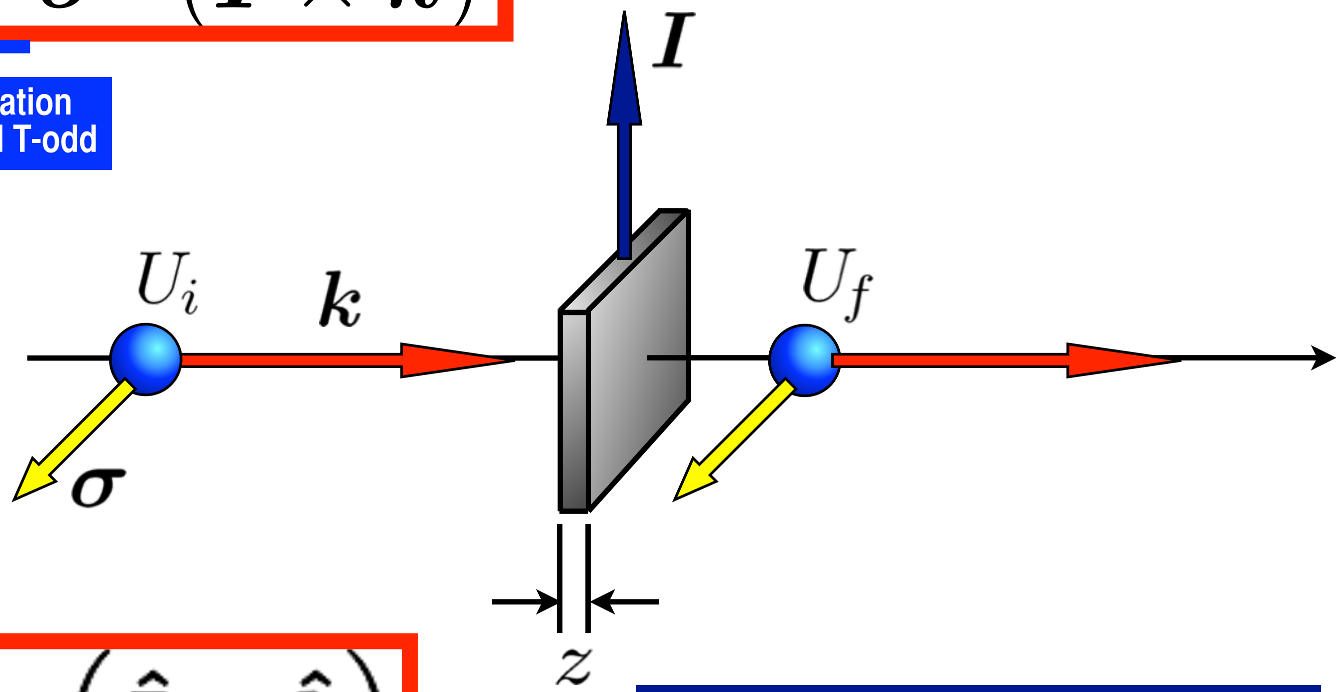
$$N \sim \frac{\Delta E}{D} \sim 10^5$$

ΔE: 10^6 eV, D: 10 eV

T-violation in Neutron Optics

$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

- A': Spin Independent, P-even T-even
- B': Spin Dependent, P-even T-even
- C': P-violation, P-odd T-even
- D': T-violation, P-odd T-odd



$$U_f = \delta U_i$$

$$\delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2} f$$

$$\delta = A + B\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)$$

- A: Spin Independent, P-even T-even
- B: Spin Dependent, P-even T-even
- C: P-violation, P-odd T-even
- D: T-violation, P-odd T-odd

fake T-odd negligible

$$A = e^{iZA'}\cos b \qquad B = ie^{iZA'}\frac{\sin b}{b}ZB'$$

$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$

D≠0 ➡ D'≠0

validity of this description can be checked via the consistency among A, B, C

Present/Future Neutron Optics

Summary

High Phase-space Density (Brilliance)

enables flexible optical control

Optics

Precision machining techniques

are delivering practically applicable new opportunities

with metal substrate super mirrors.

Also control of neutron waves

interferometry and spatial

Epithermal spin optics as a new approach to new physics

(Refractive optics -> afternoon)