Neutron Mirror Optics
and participation of Japan

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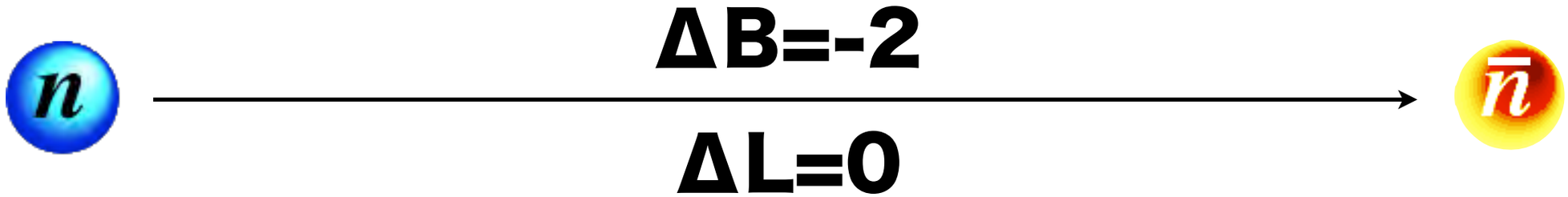
$n\bar{n}$ oscillation



free neutron $\tau_{n\bar{n},\text{free}} > 8.6 \times 10^7 \text{s (CL} = 90\%)$

$$L = \bar{\psi} M \psi$$

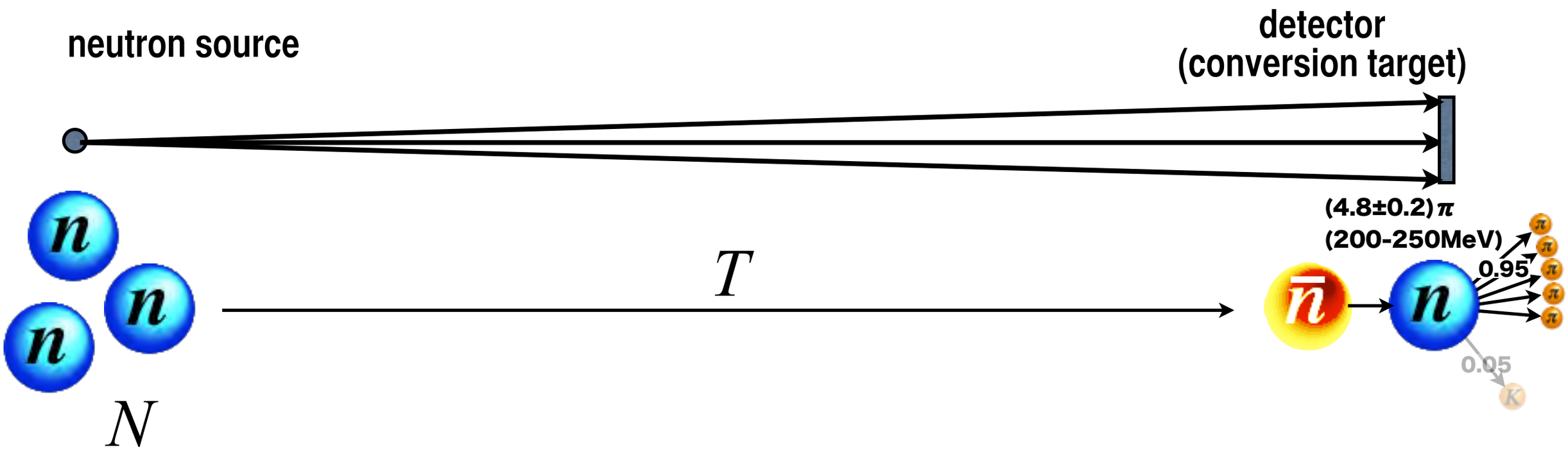
$$\psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad M = \begin{pmatrix} E_0 & c^2 \delta m \\ c^2 \delta m & E_0 \end{pmatrix}$$

$$|n_{1,2}\rangle = \frac{1}{\sqrt{2}}\left(|n\rangle \pm |\bar{n}\rangle\right) \qquad m_{1,2} = m_n \pm \delta m$$

$$I(t) = I(0) \sin^2 \frac{c^2 \delta m}{\hbar} t$$

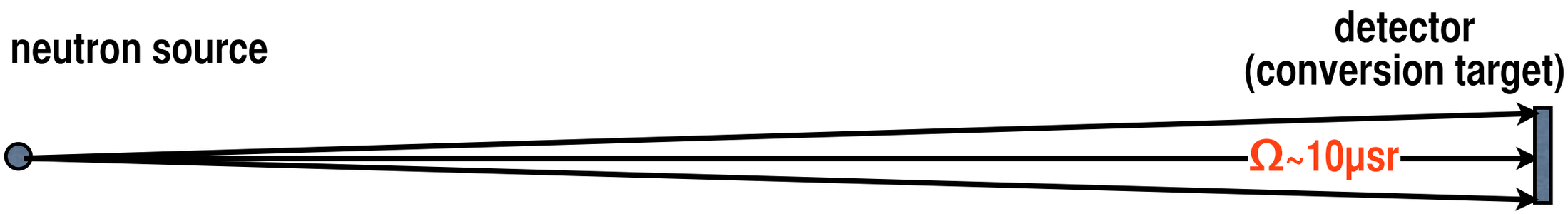
$n\bar{n}$ oscillation measurement

$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$



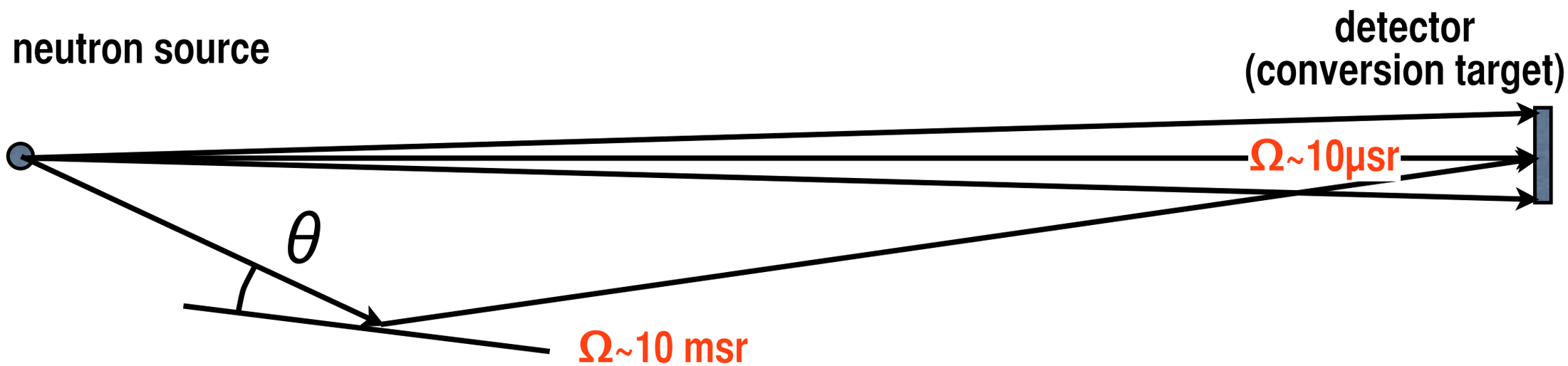
simple flight path

$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$

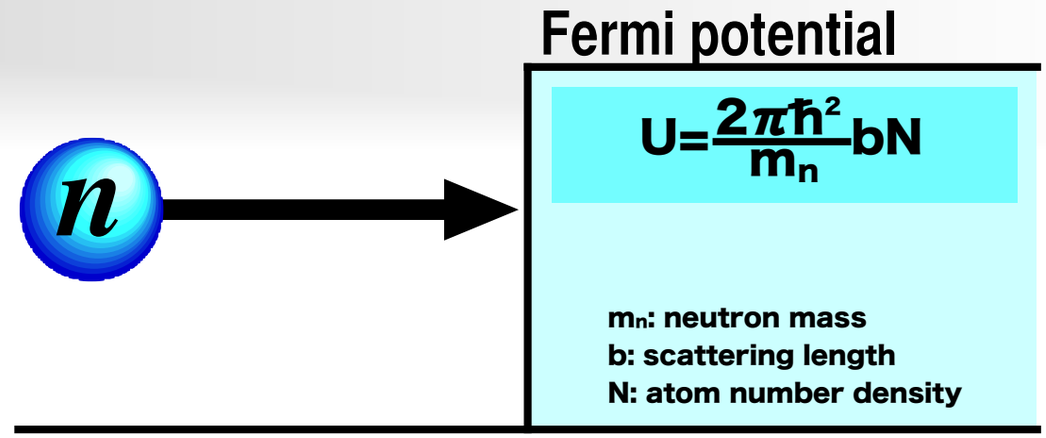


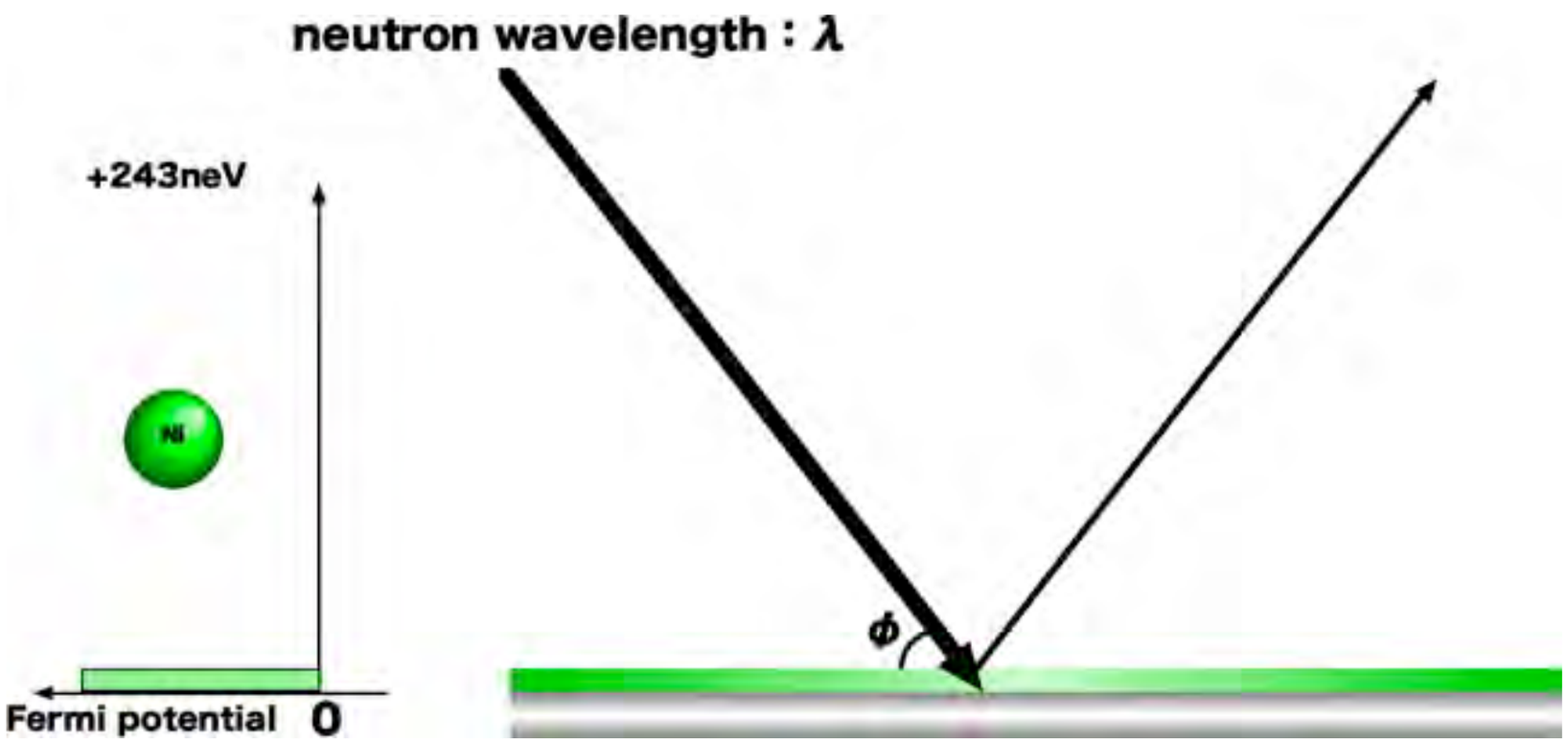
additional acceptance with focusing optics

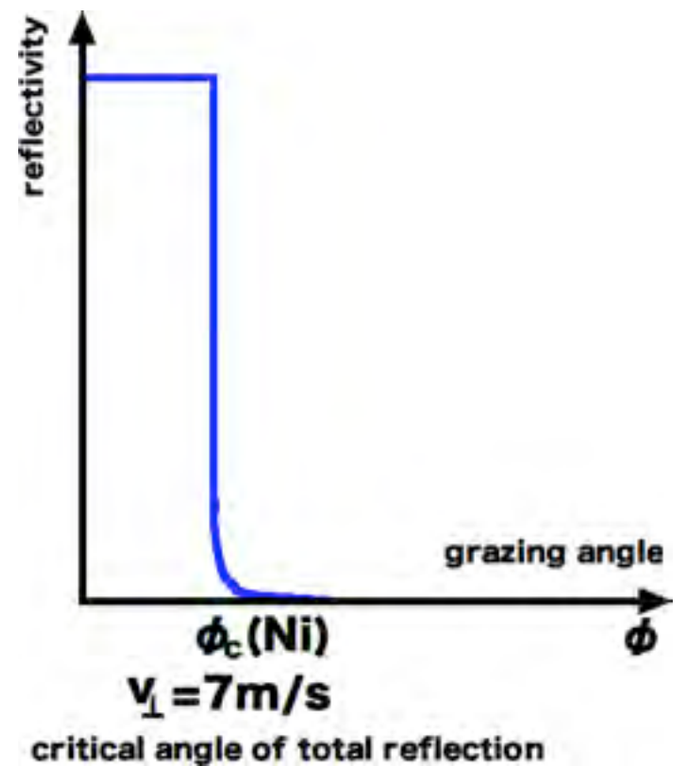
$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$



Neutron Reflection

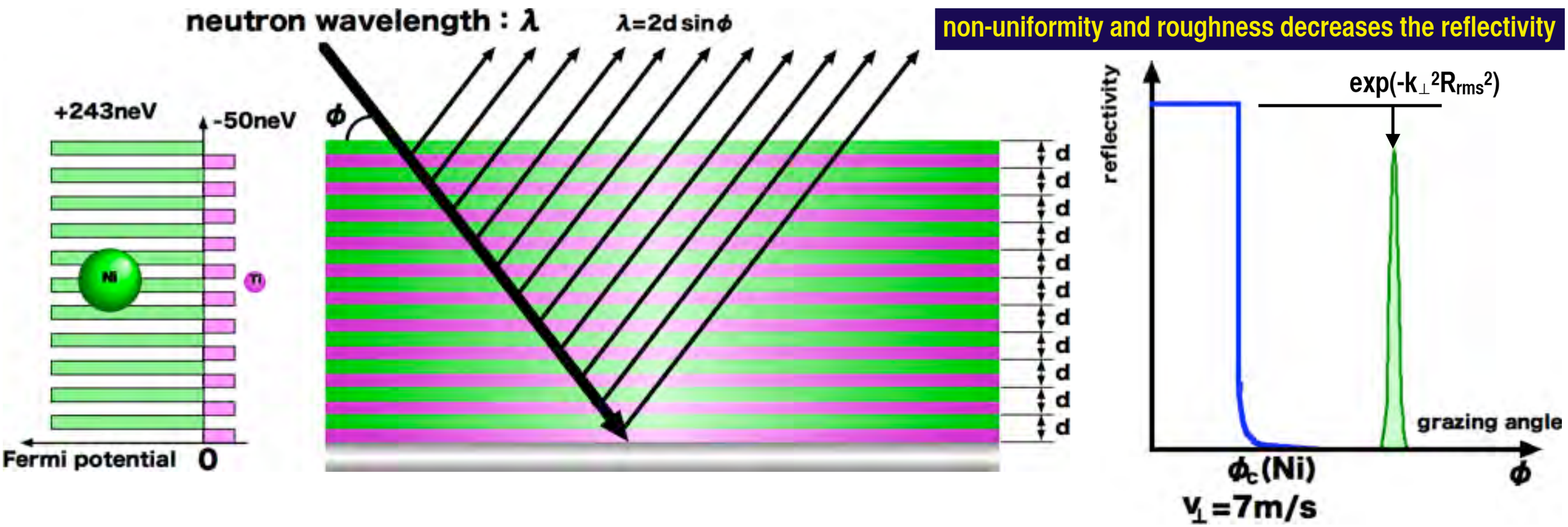






$\phi_c(Ni)/\lambda$=1.7 mrad/Å
$v_\perp(Ni)$=7 m/s

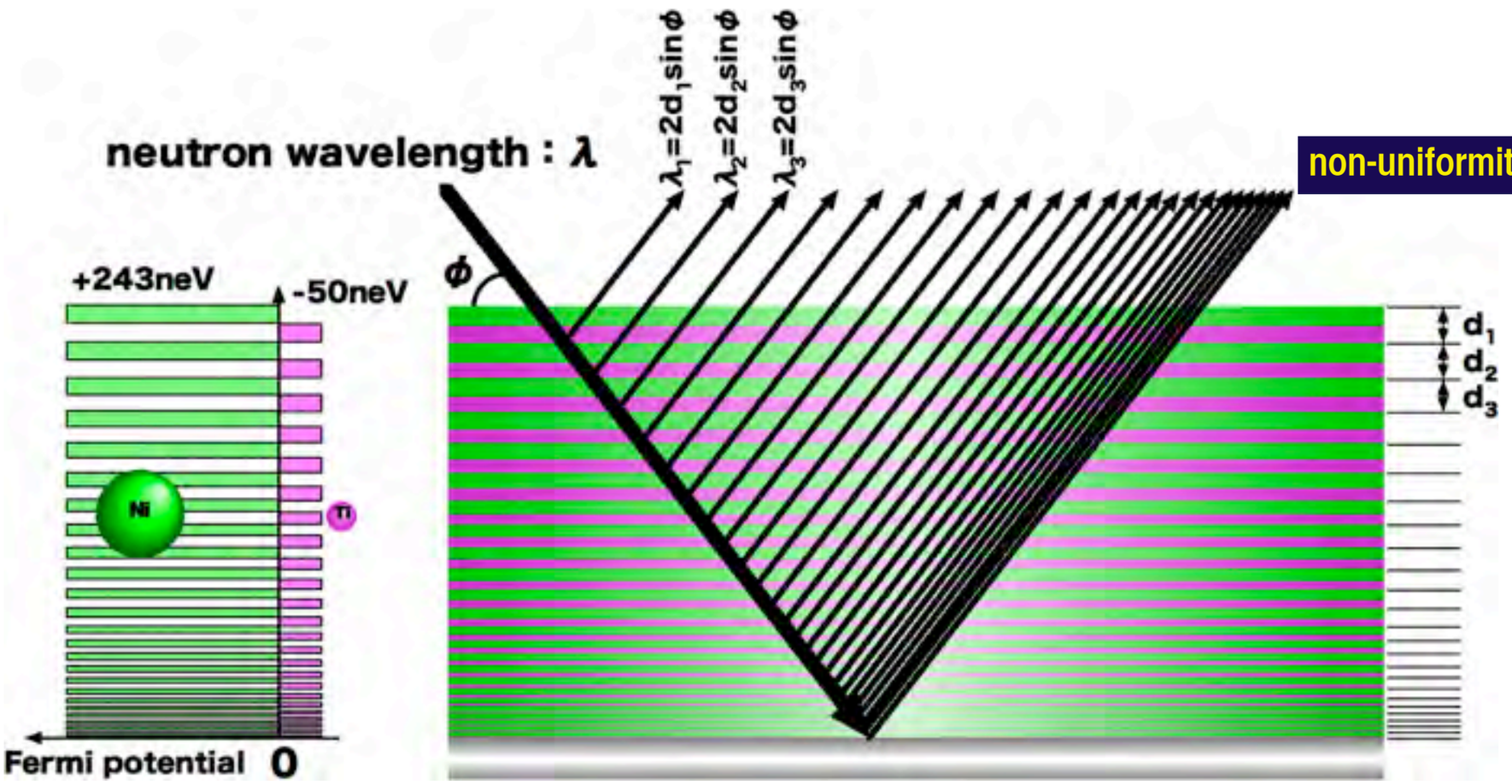
Multilayer Mirror (Monochromatic)



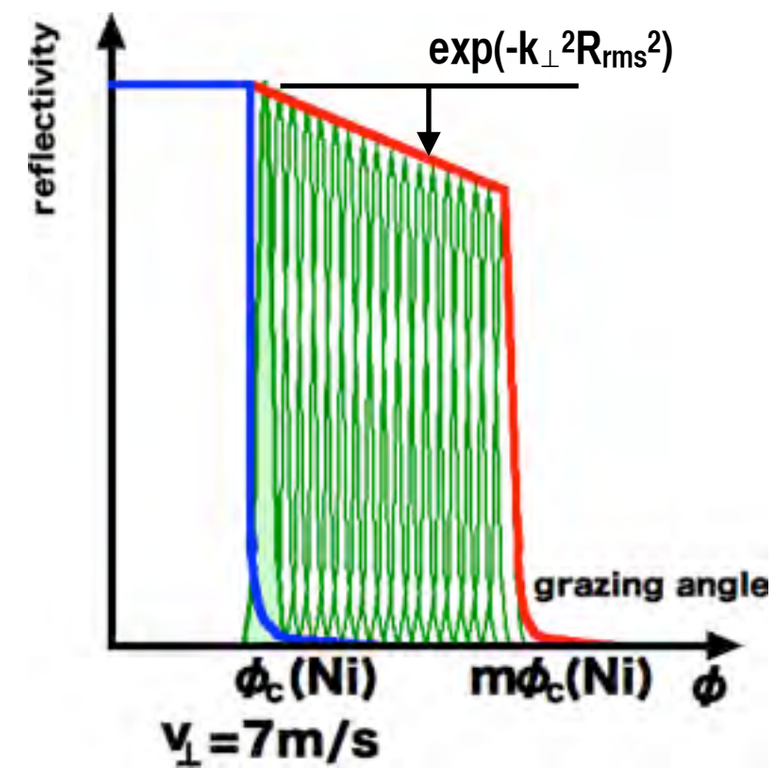
$\phi_c(Ni)/\lambda = 1.7$ mrad/Å

$v_\perp(Ni) = 7$ m/s

Supermirror



non-uniformity and roughness decreases the reflectivity



$m = \phi_c / \phi_c(Ni) = v_c(Ni)/v_c$

$\phi_c(Ni)/\lambda = 1.7$ mrad/Å

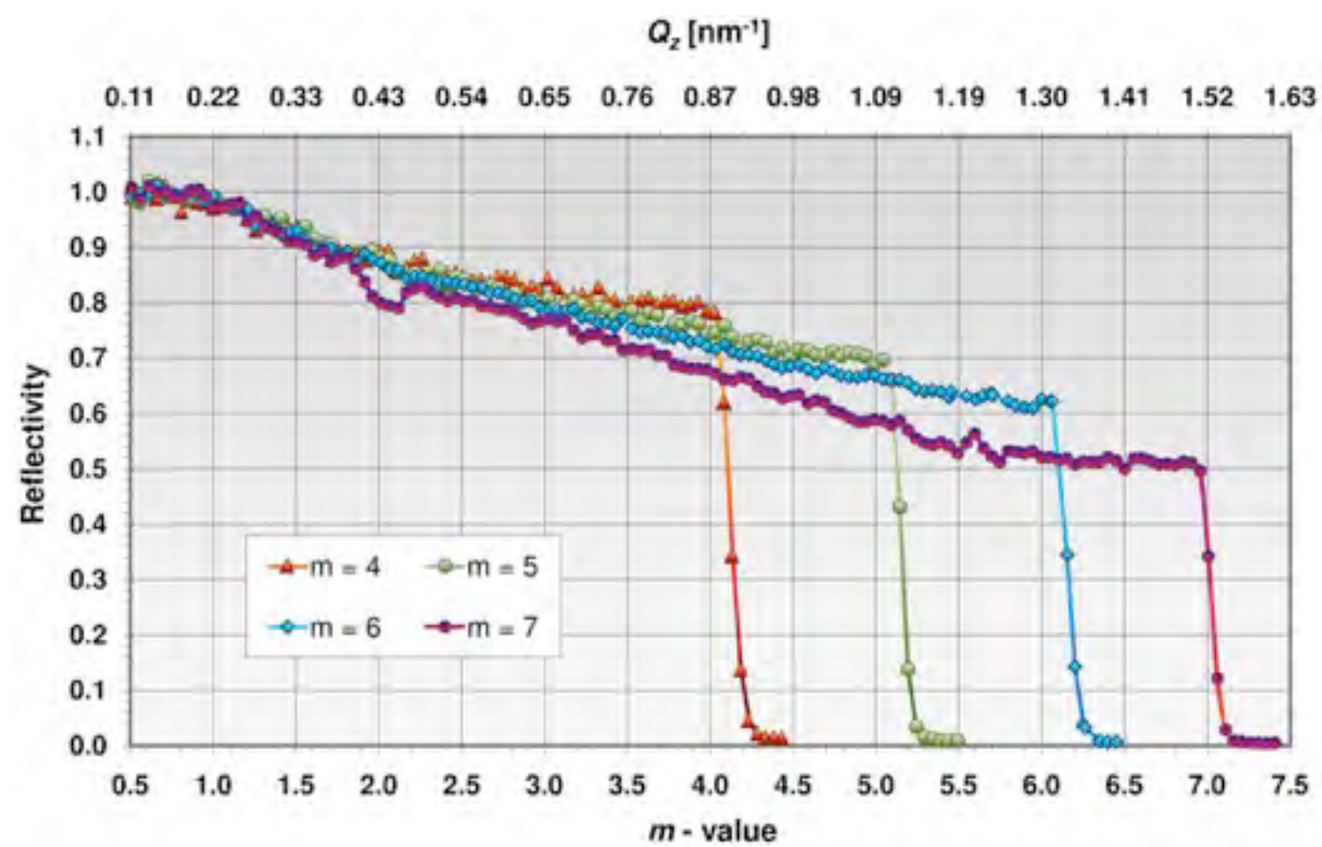
$v_\perp(Ni) = 7$ m/s

supermirrors m≤7

m=4-7 Supermirrors

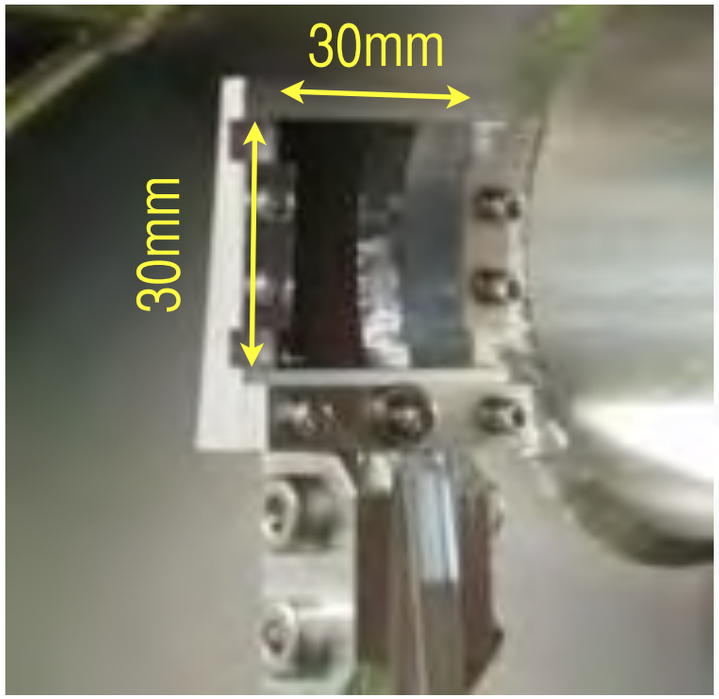
http://www.swissneutronics.ch/

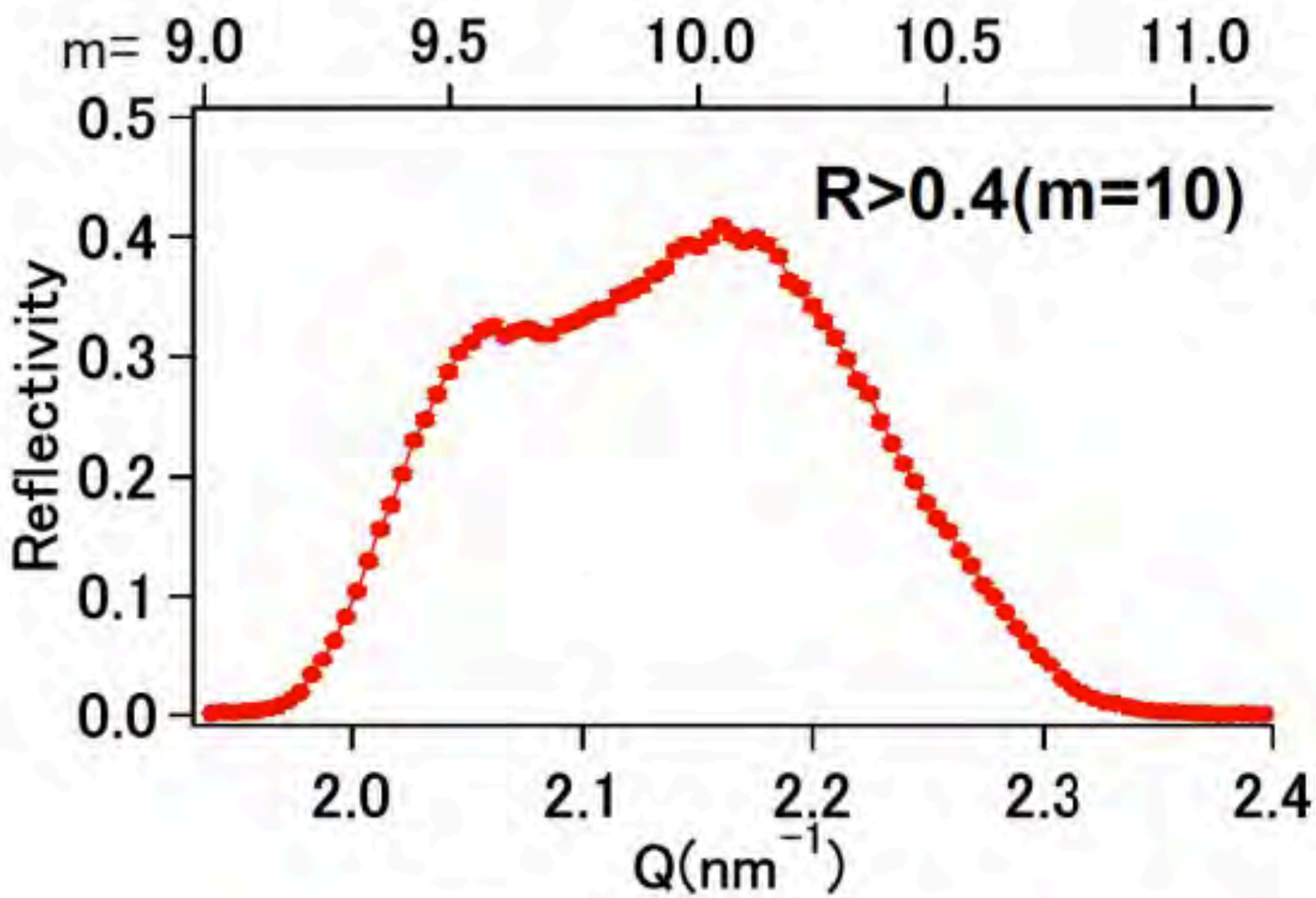
Supermirror: commercially available up to m=7 ($v_\perp$=50m/s)



wide-band multilayer (quasi-monochromatic) reflectors m≤10

m=10 NiC/Ti wide-band quadruple-stack multilayer

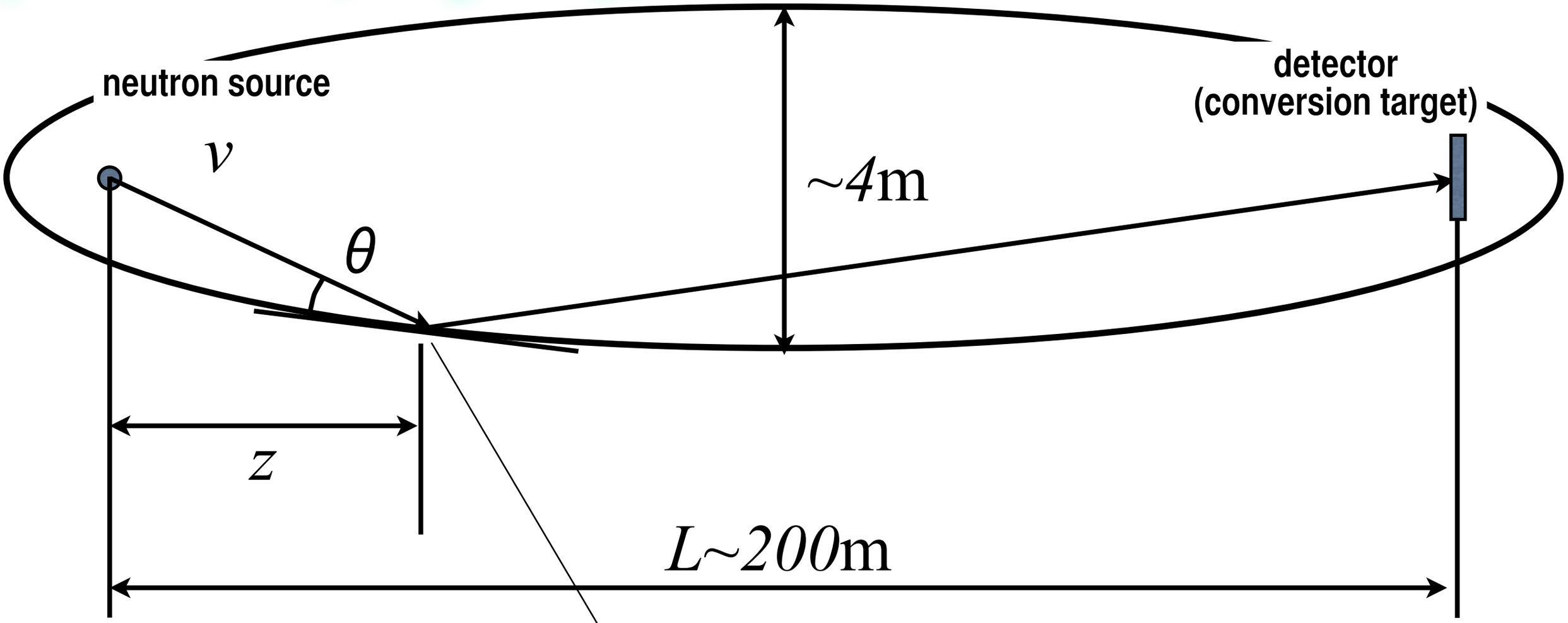


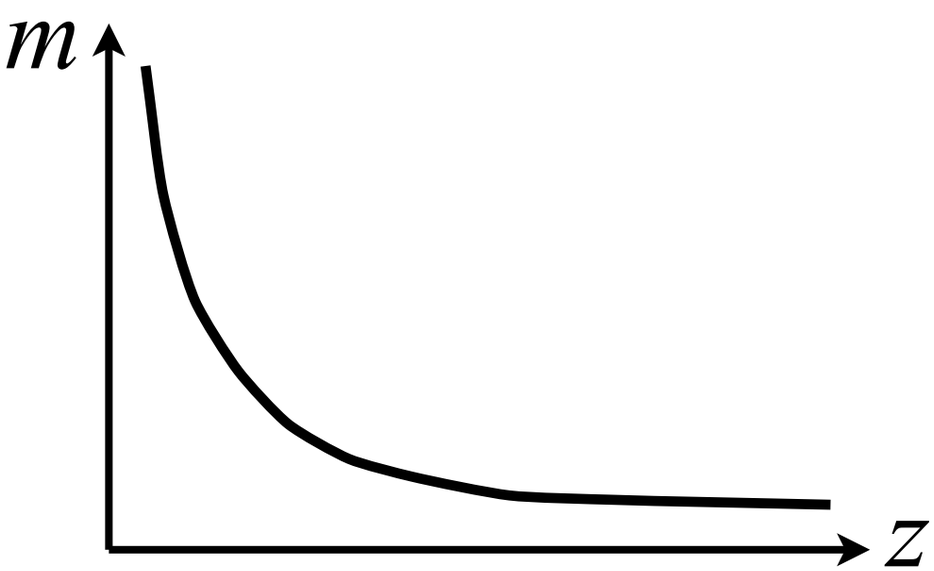


85060 bilayers in total = 4×(10336+10929 bilayers)
quadruple-stack of double-sided multilayer mirrors

point source, no gravity, monochromatic

$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$



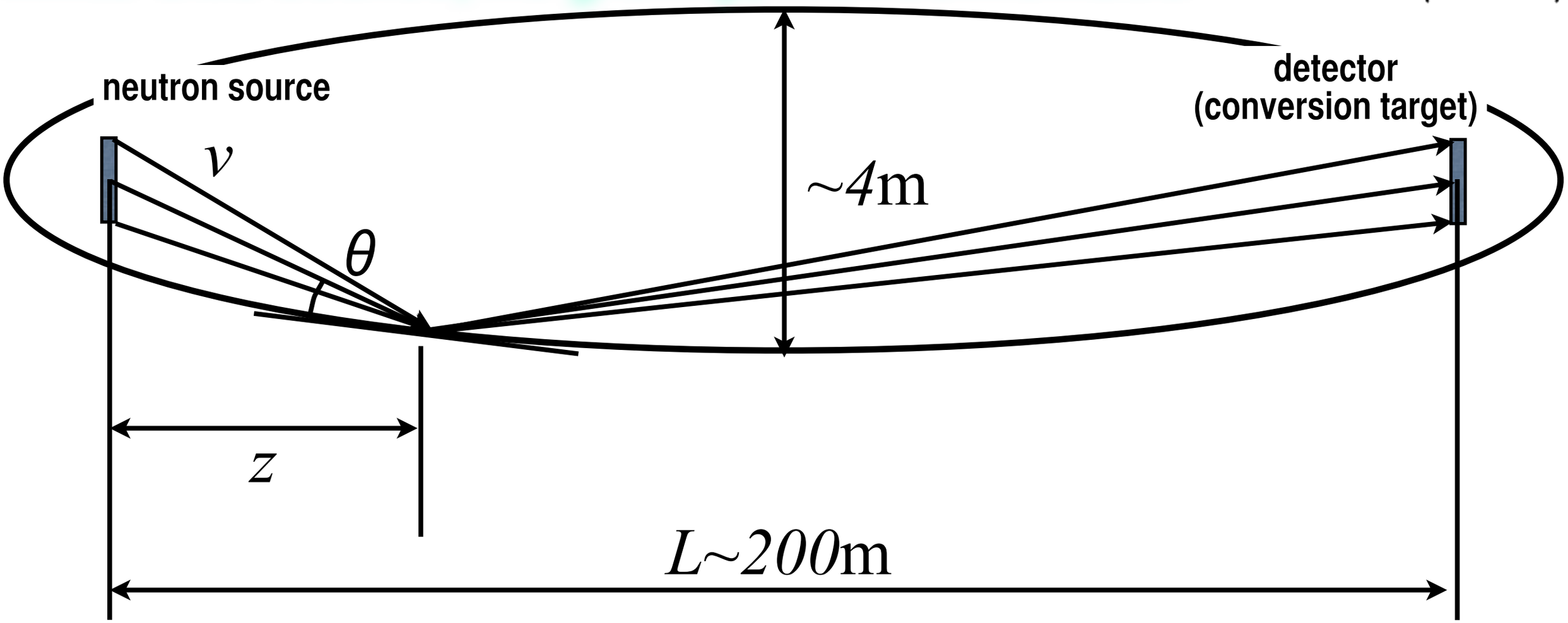


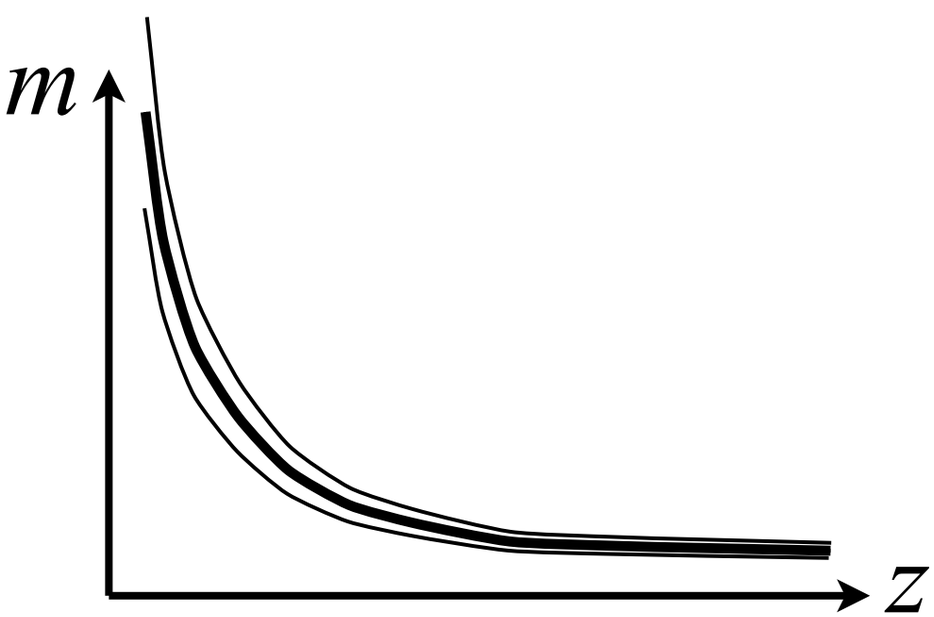
$$m(z) = \frac{v \sin\theta(z)}{7[\mathrm{m/s}]}$$

← critical velocity of total reflection of natural Ni

We need multilayer mirror to go beyond m~1.

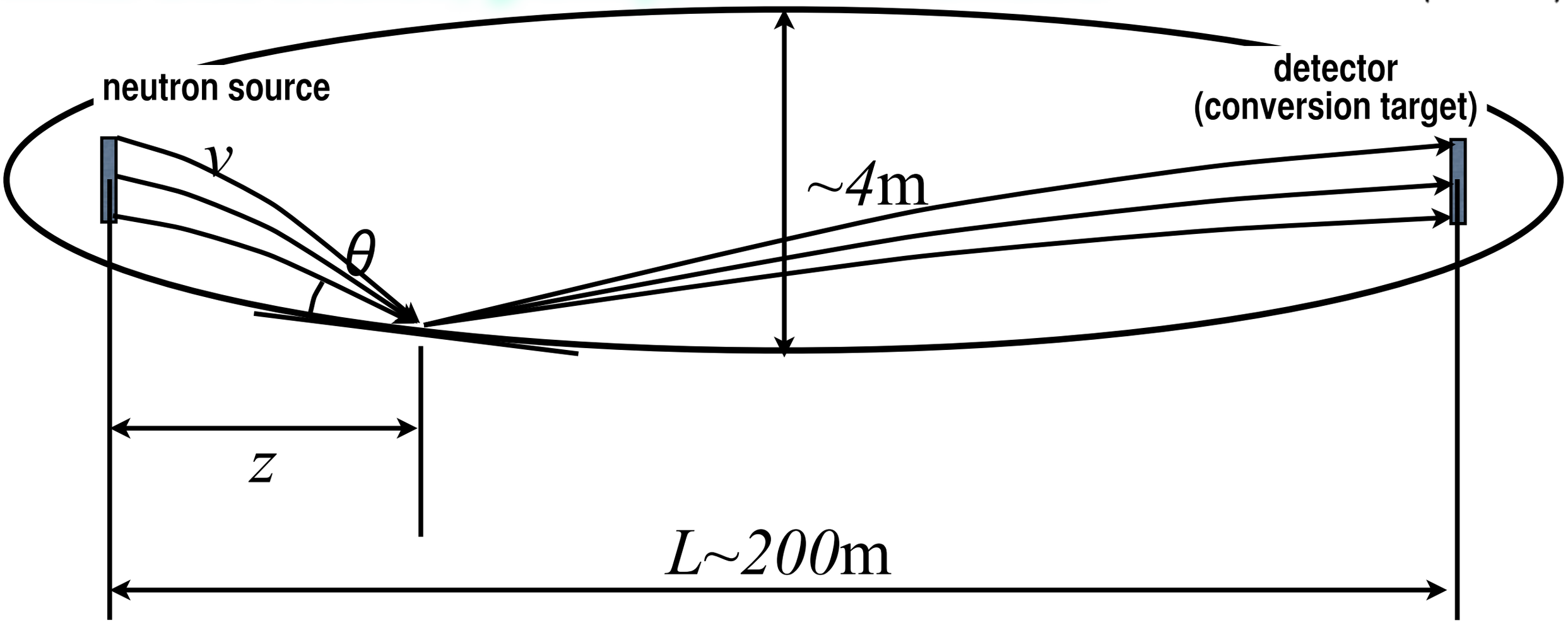
finite-size source, no gravity, monochromatic $\mathrm{FOM} \equiv \langle NT^2 \rangle$

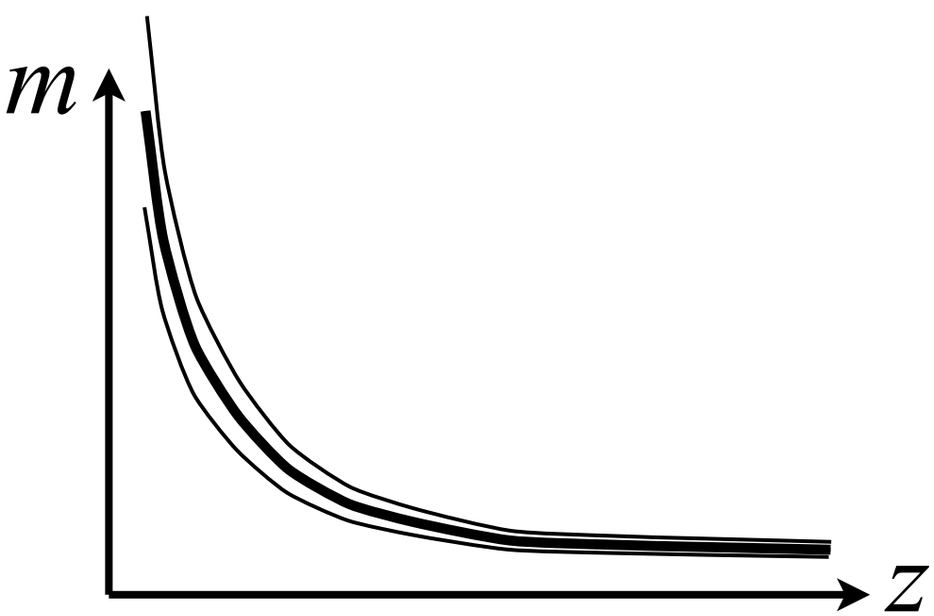




finite-size source, gravity, monochromatic

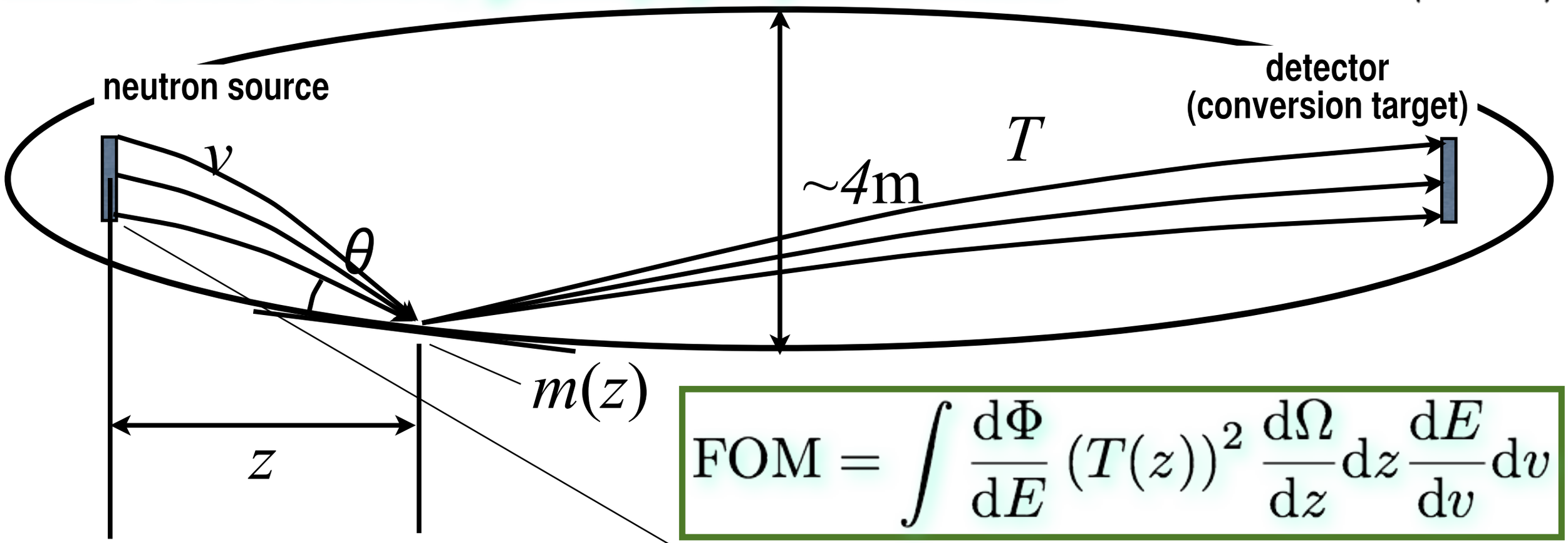
$$\mathrm{FOM} \equiv \langle NT^2 \rangle$$



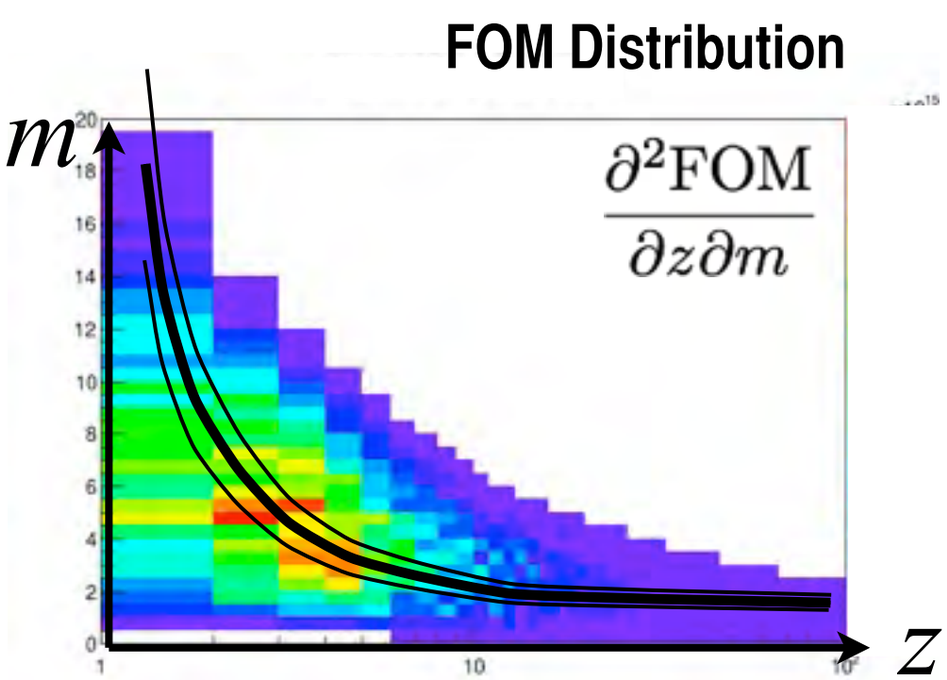


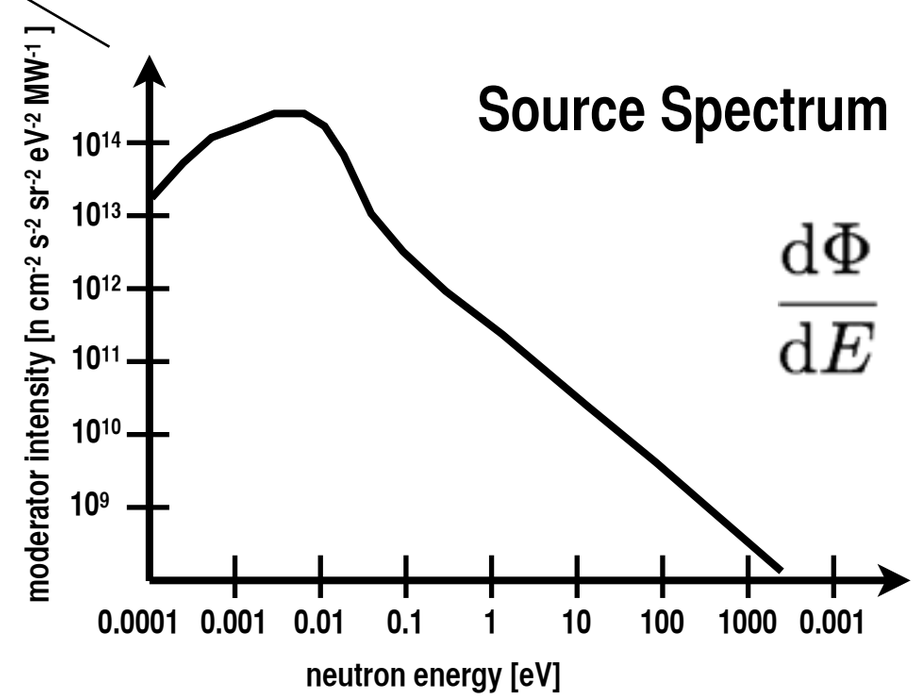
finite-size source, gravity, polychromatic

$$\mathrm{FOM} \equiv \langle N T^2 \rangle$$

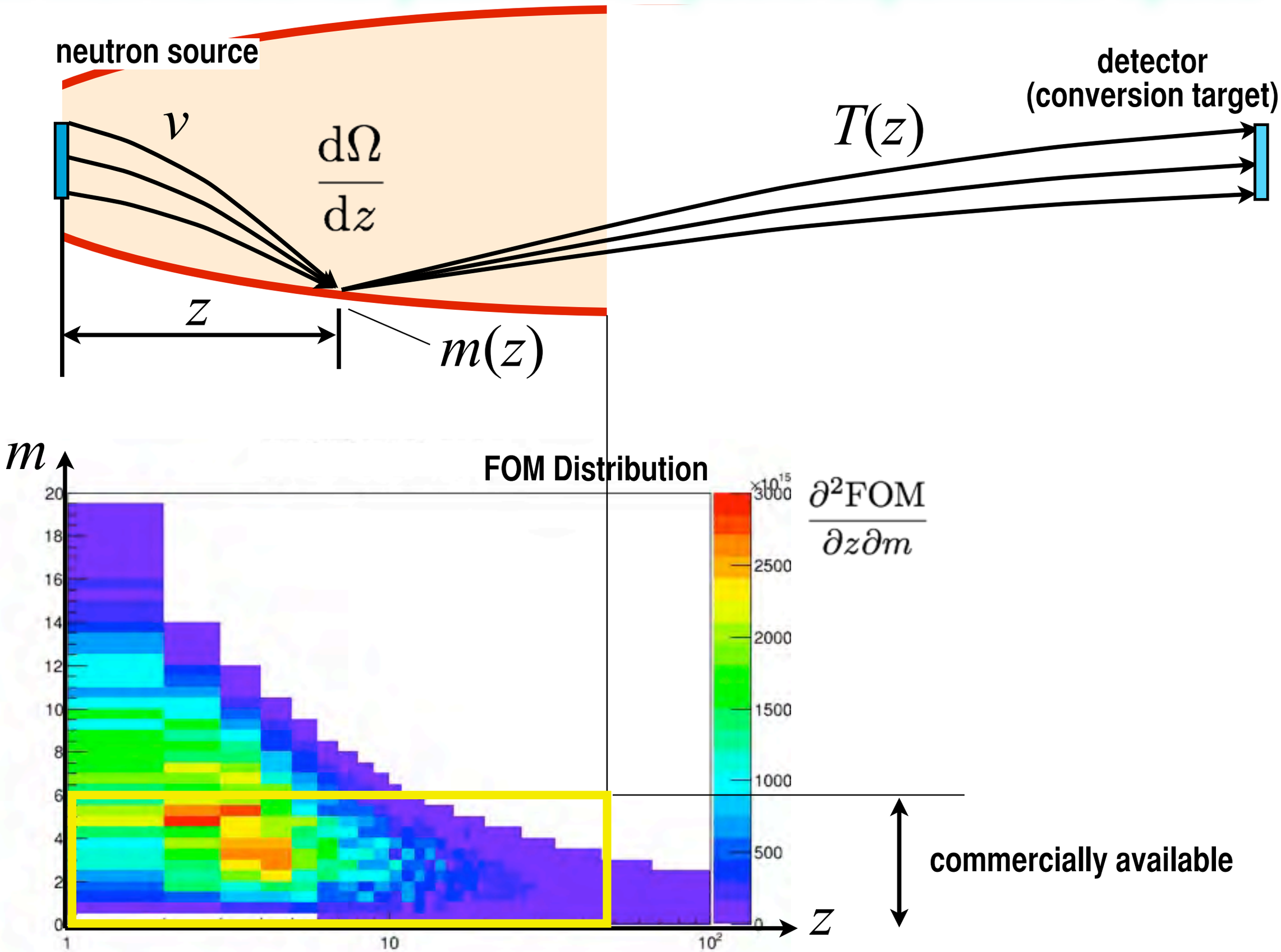


$$\mathrm{FOM} = \int \frac{\mathrm{d}\Phi}{\mathrm{d}E} \left(T(z)\right)^2 \frac{\mathrm{d}\Omega}{\mathrm{d}z} \mathrm{d}z \frac{\mathrm{d}E}{\mathrm{d}v} \mathrm{d}v$$

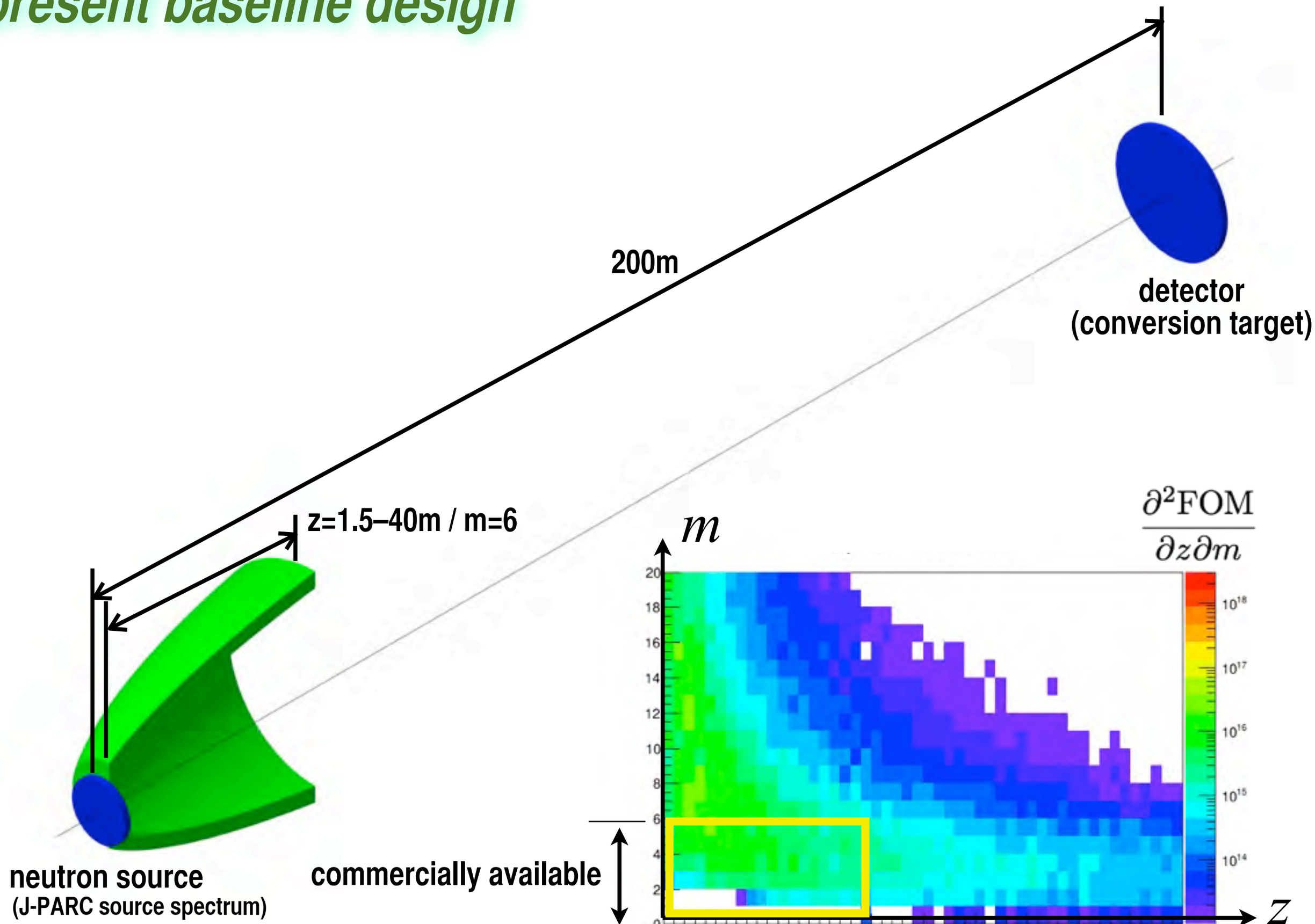




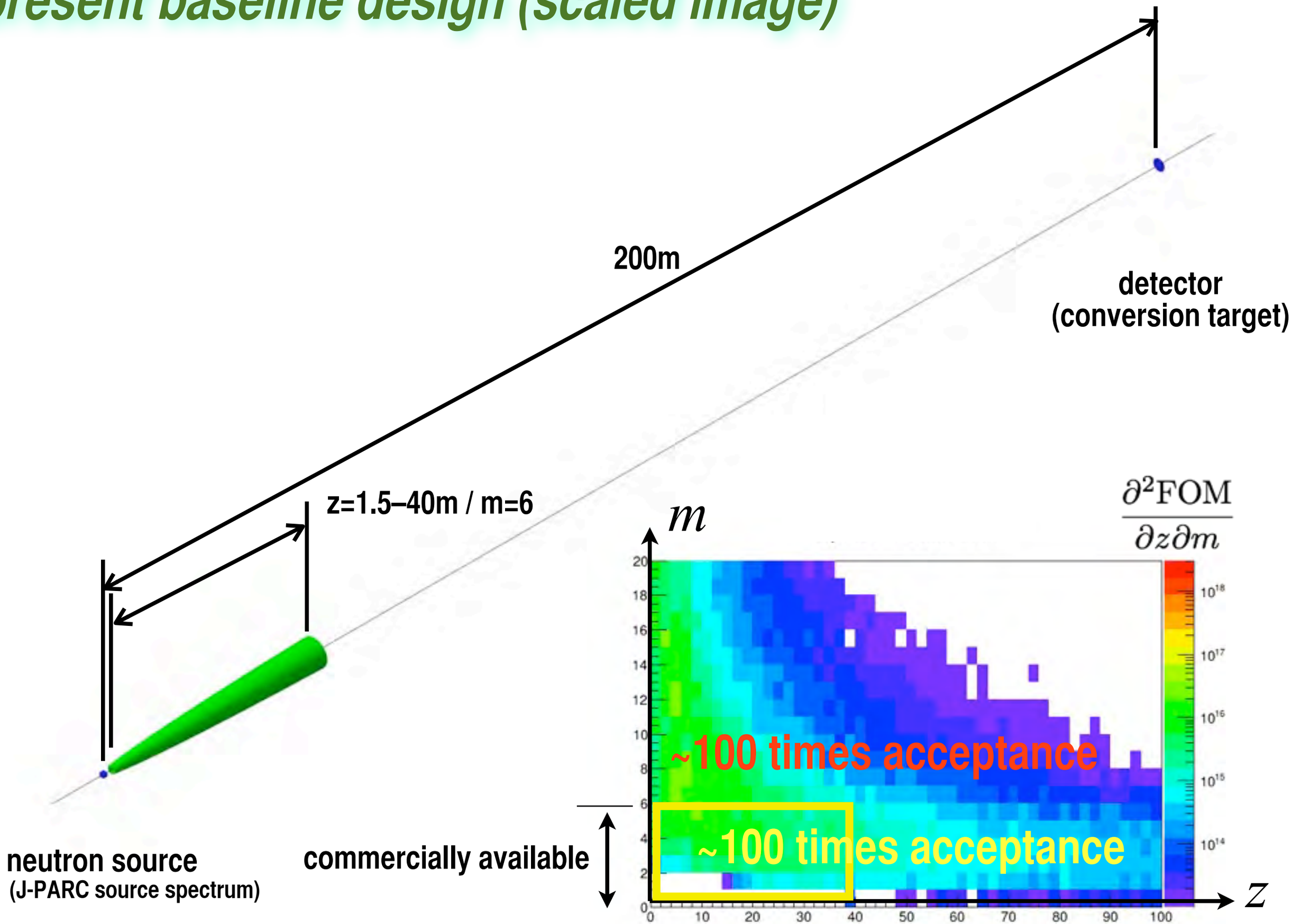
$n\bar{n}$ with horizontal path and ellipsoid supermirror optics



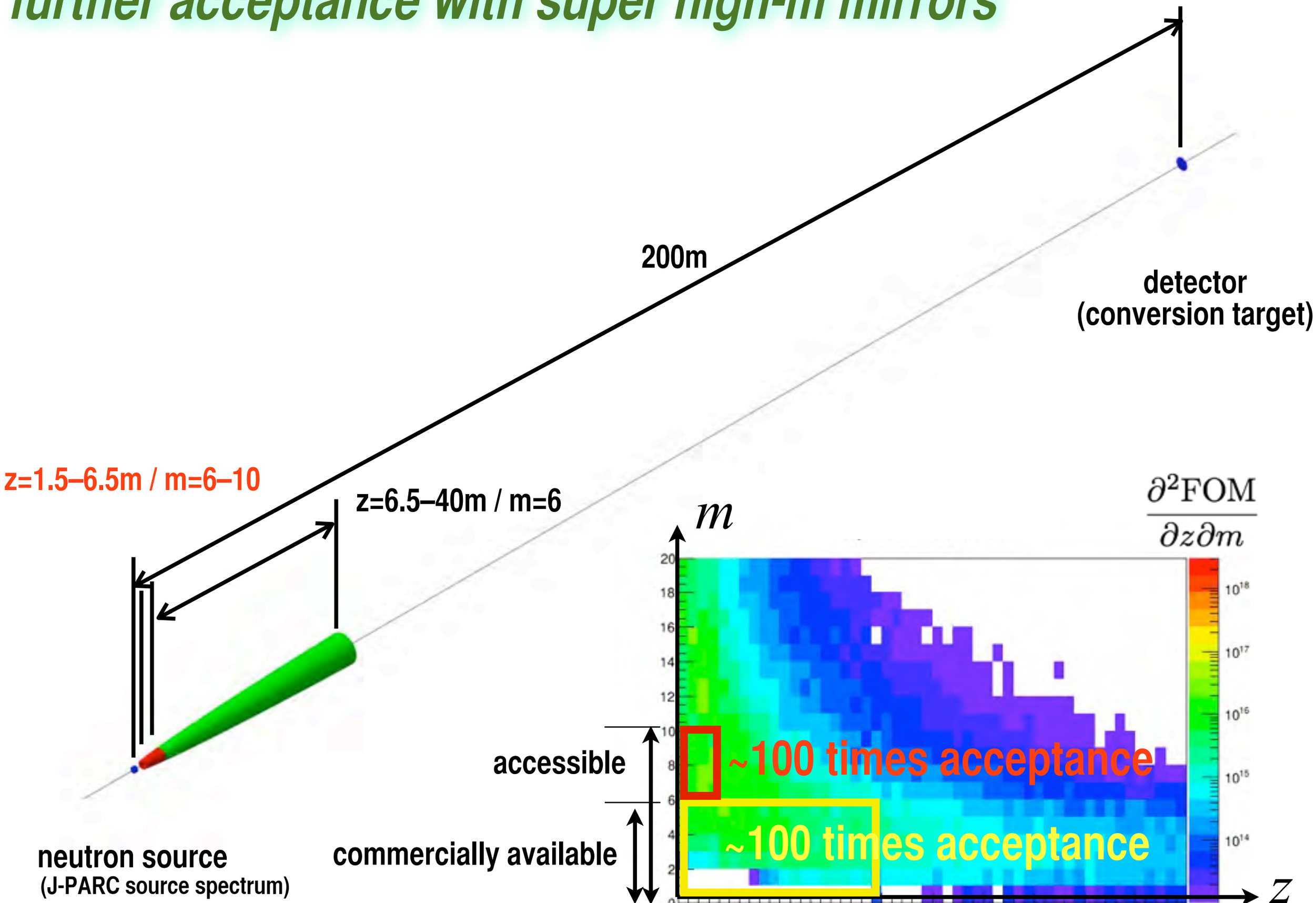
present baseline design



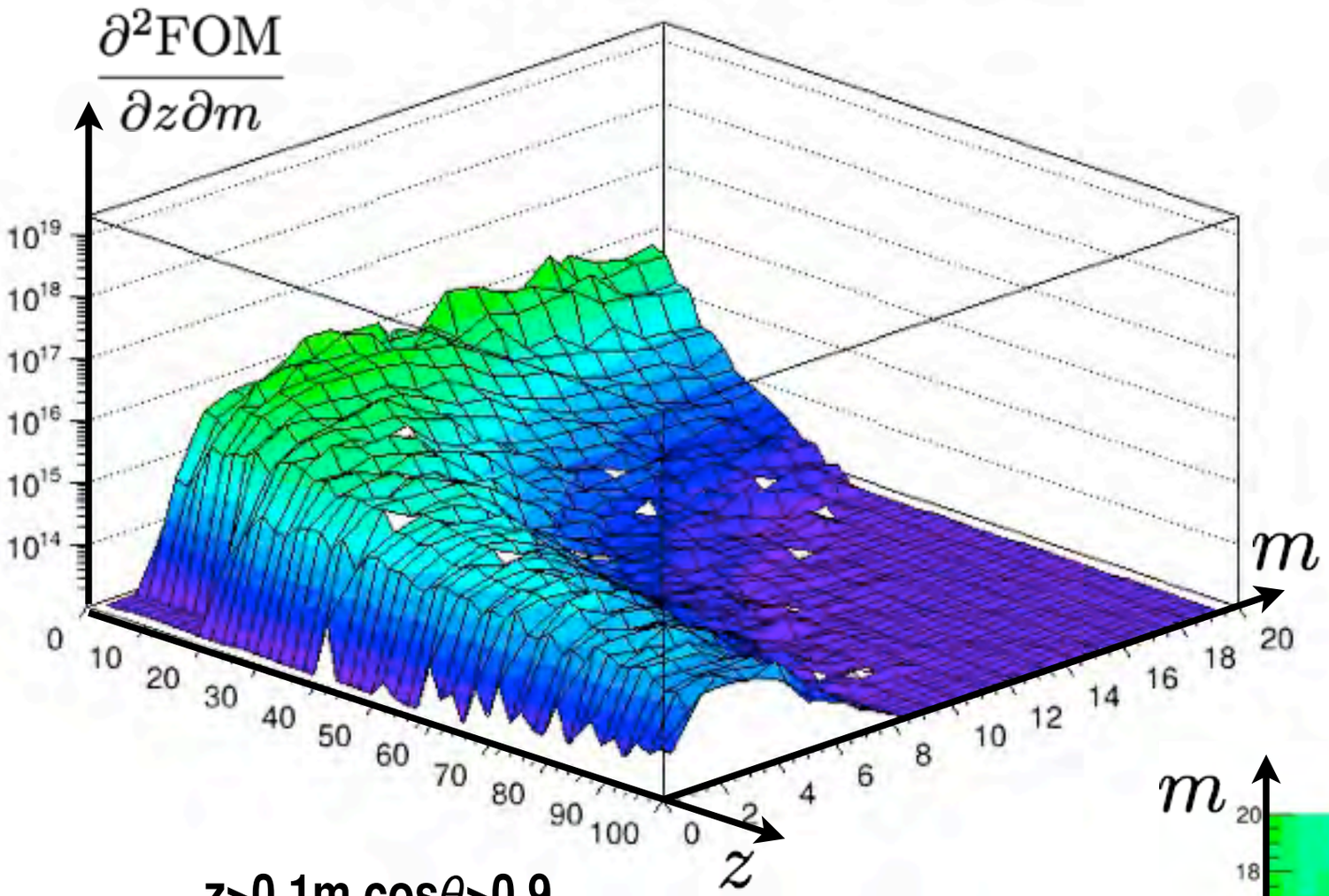
present baseline design (scaled image)



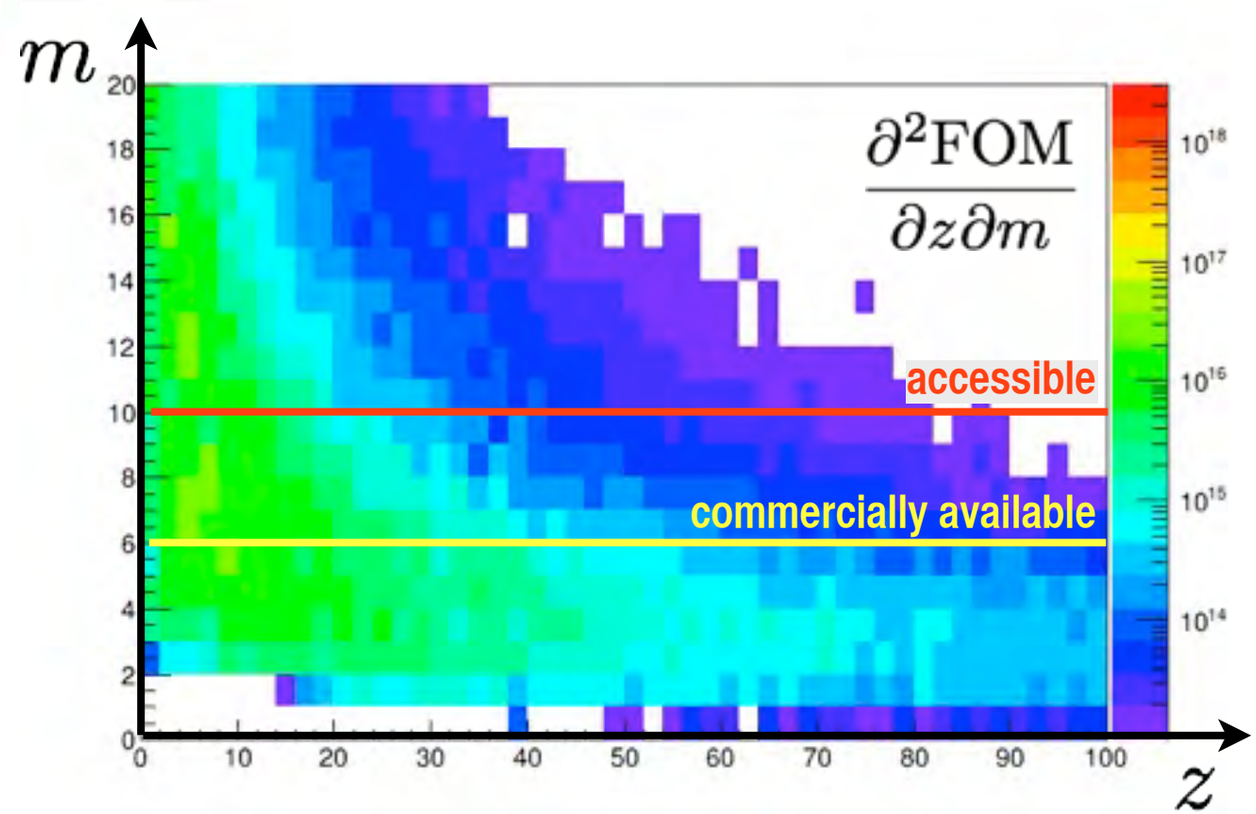
further acceptance with super high-m mirrors



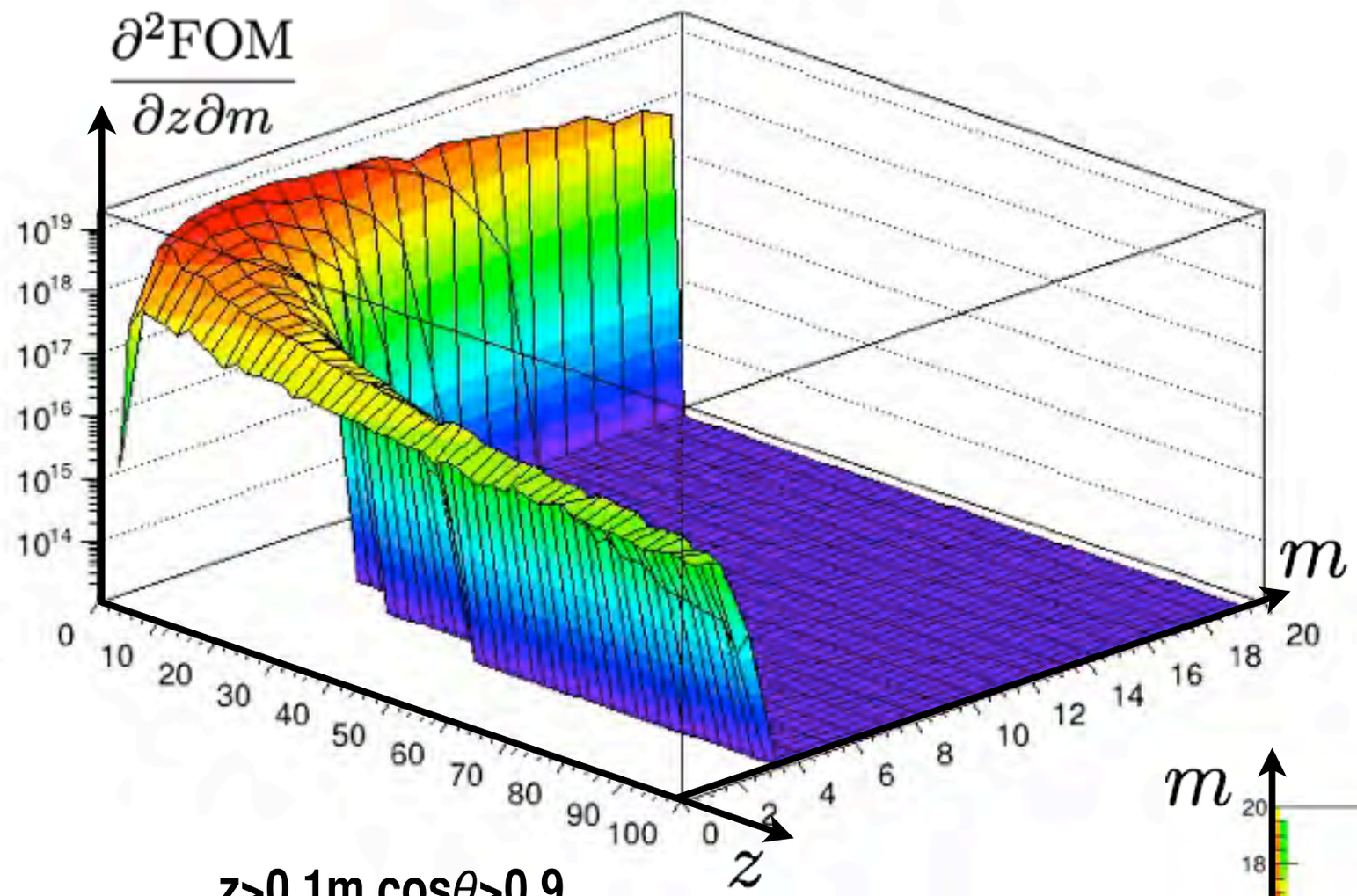
visualization of the acceptance of horizontal flight path



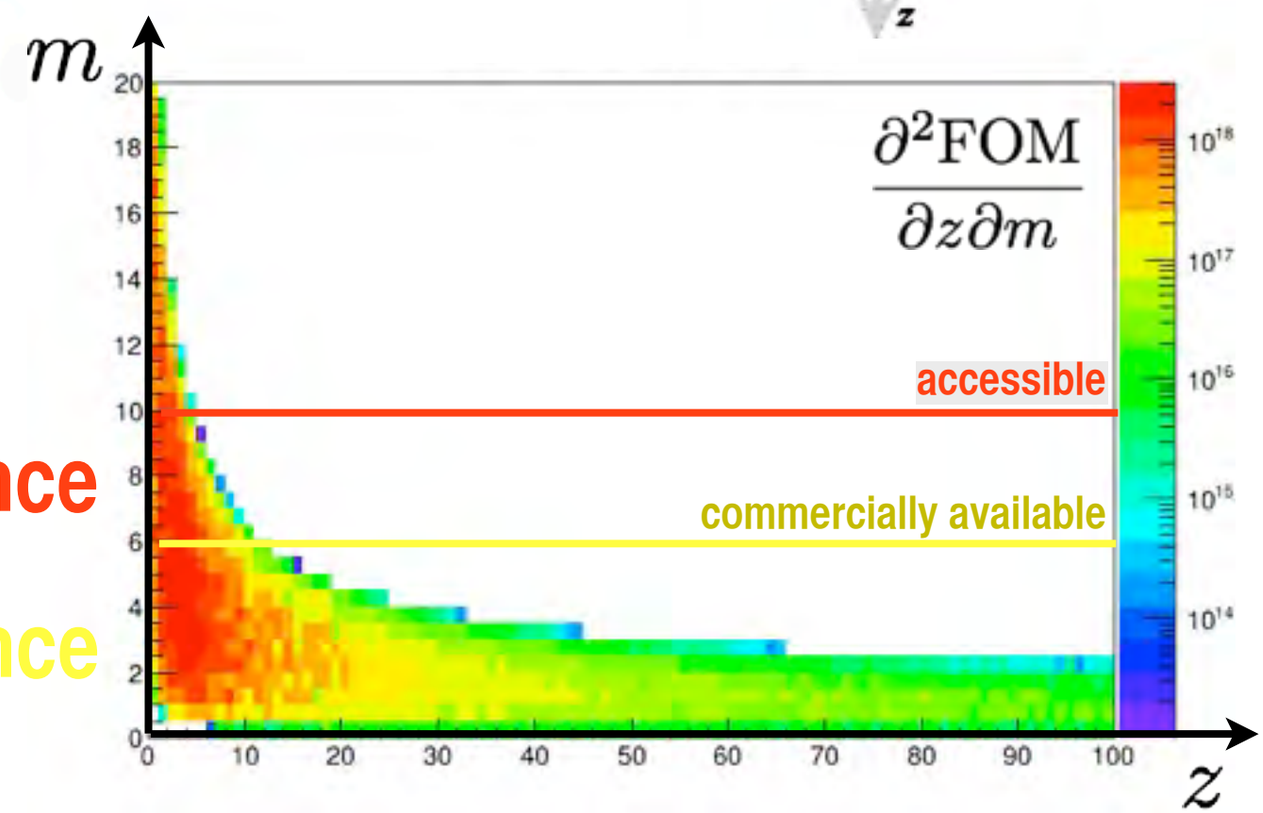
z>0.1m cosθ>0.9



visualization of the acceptance of veritical flight path



z>0.1m cosθ>0.9

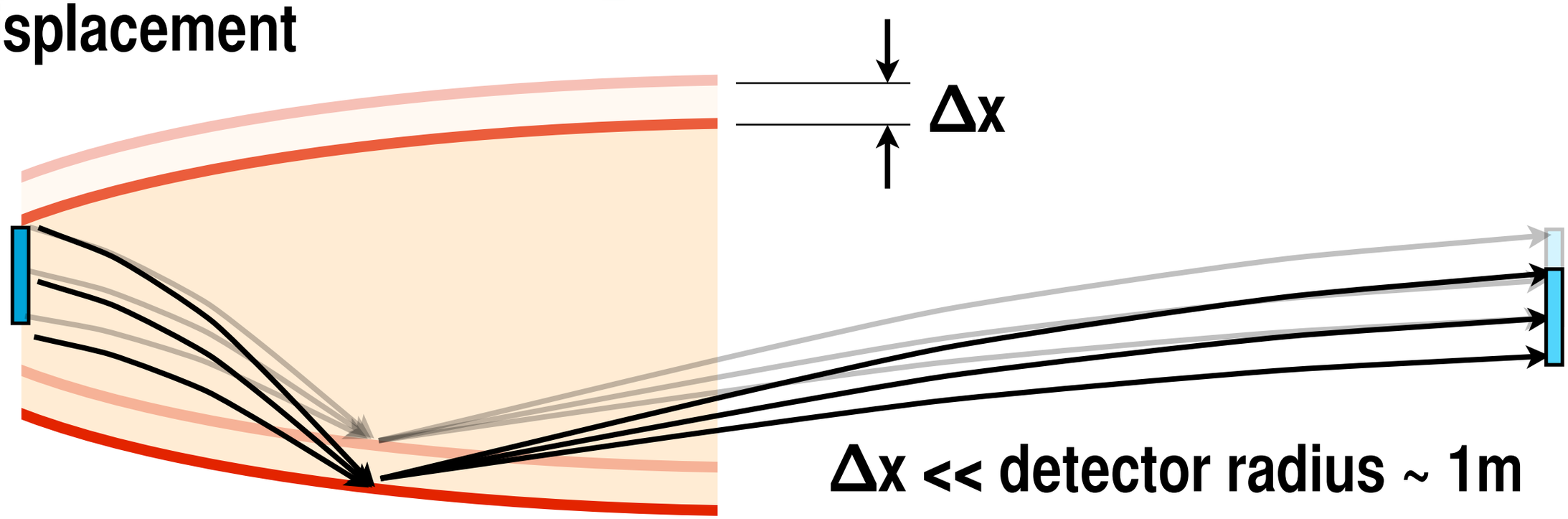


~1000 times acceptance

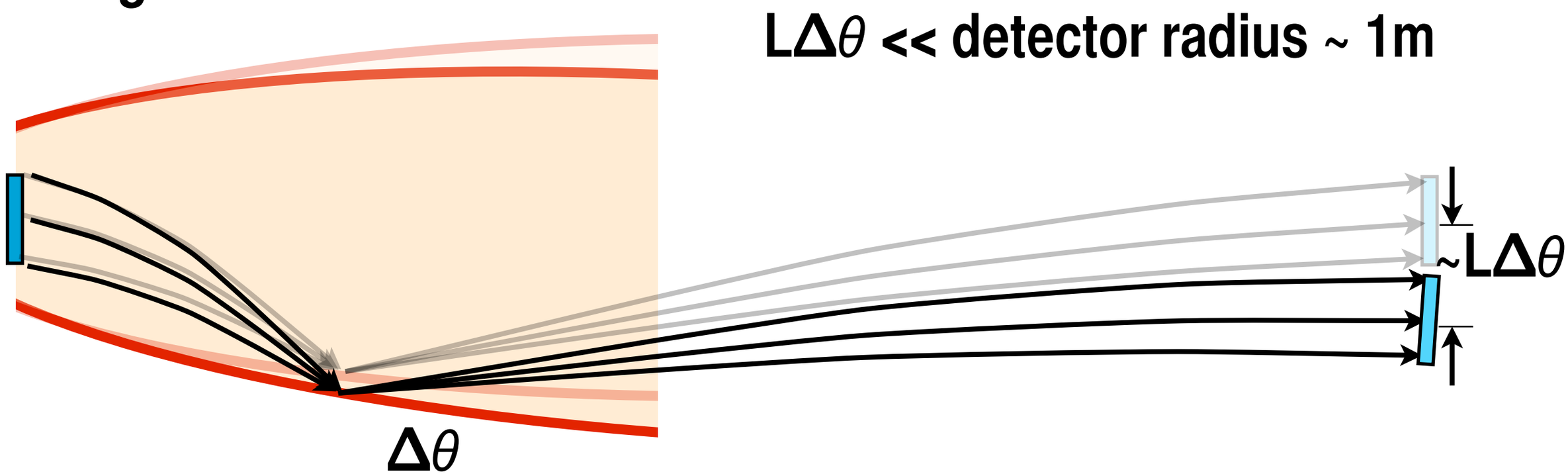
~1000 times acceptance

required mirror accuracy

displacement

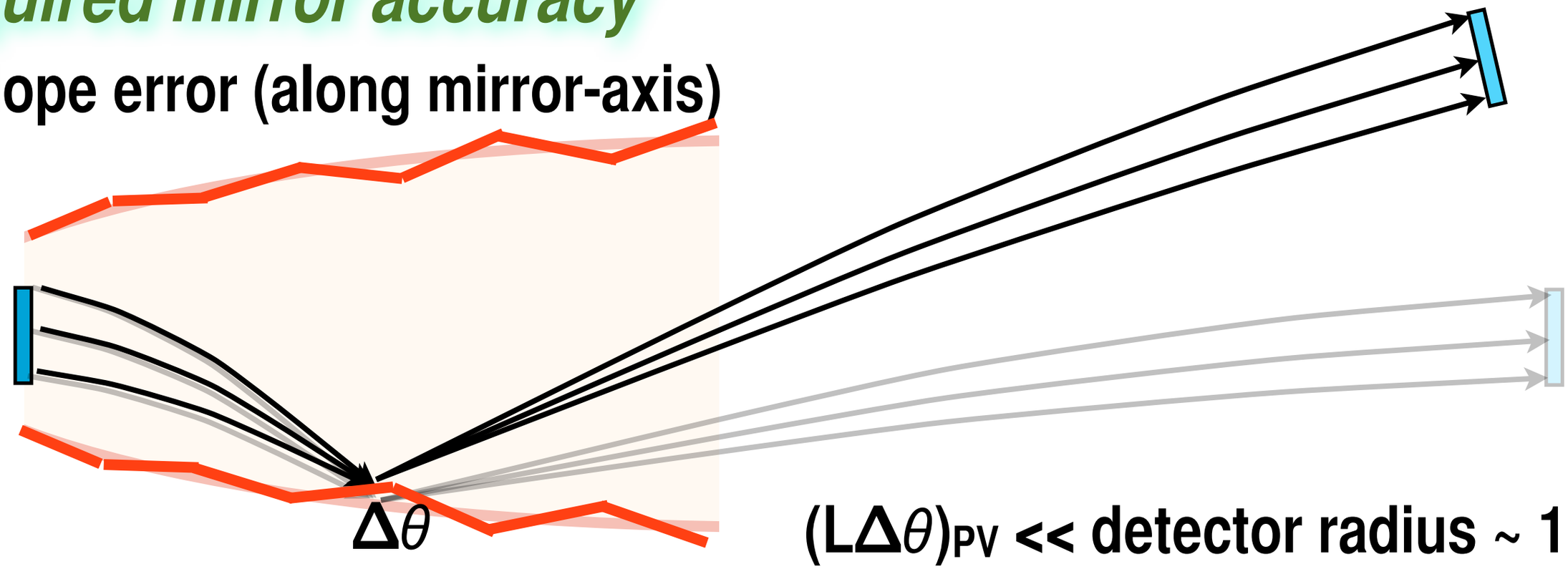


pointing error



required mirror accuracy

slope error (along mirror-axis)



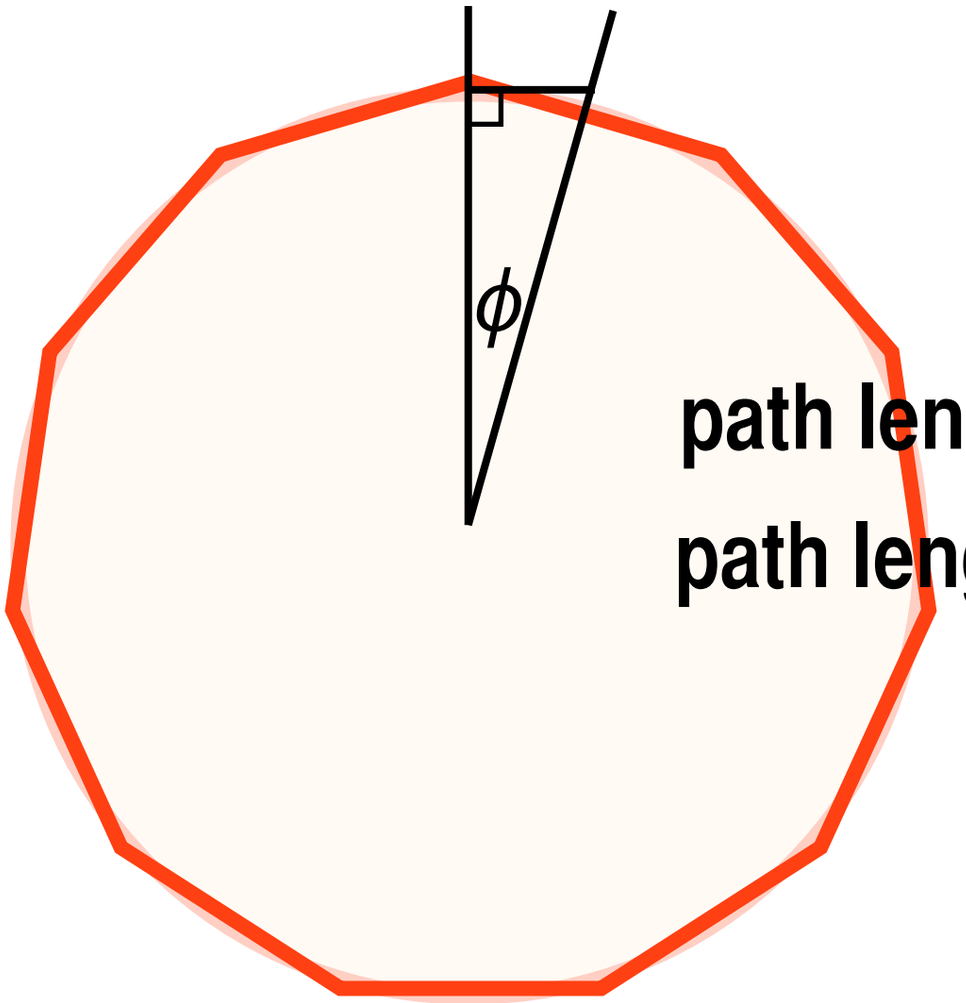
$(L\Delta\theta)_{PV}$ << detector radius ~ 1m

path length = 200m ⟶ $(\Delta\theta)_{PV}$ < 1/200 = 5 mrad

path length = 1000m ⟶ $(\Delta\theta)_{PV}$ < 1/1000 = 1 mrad

required mirror accuracy

limitation to the azimuthal mosaic segmentation



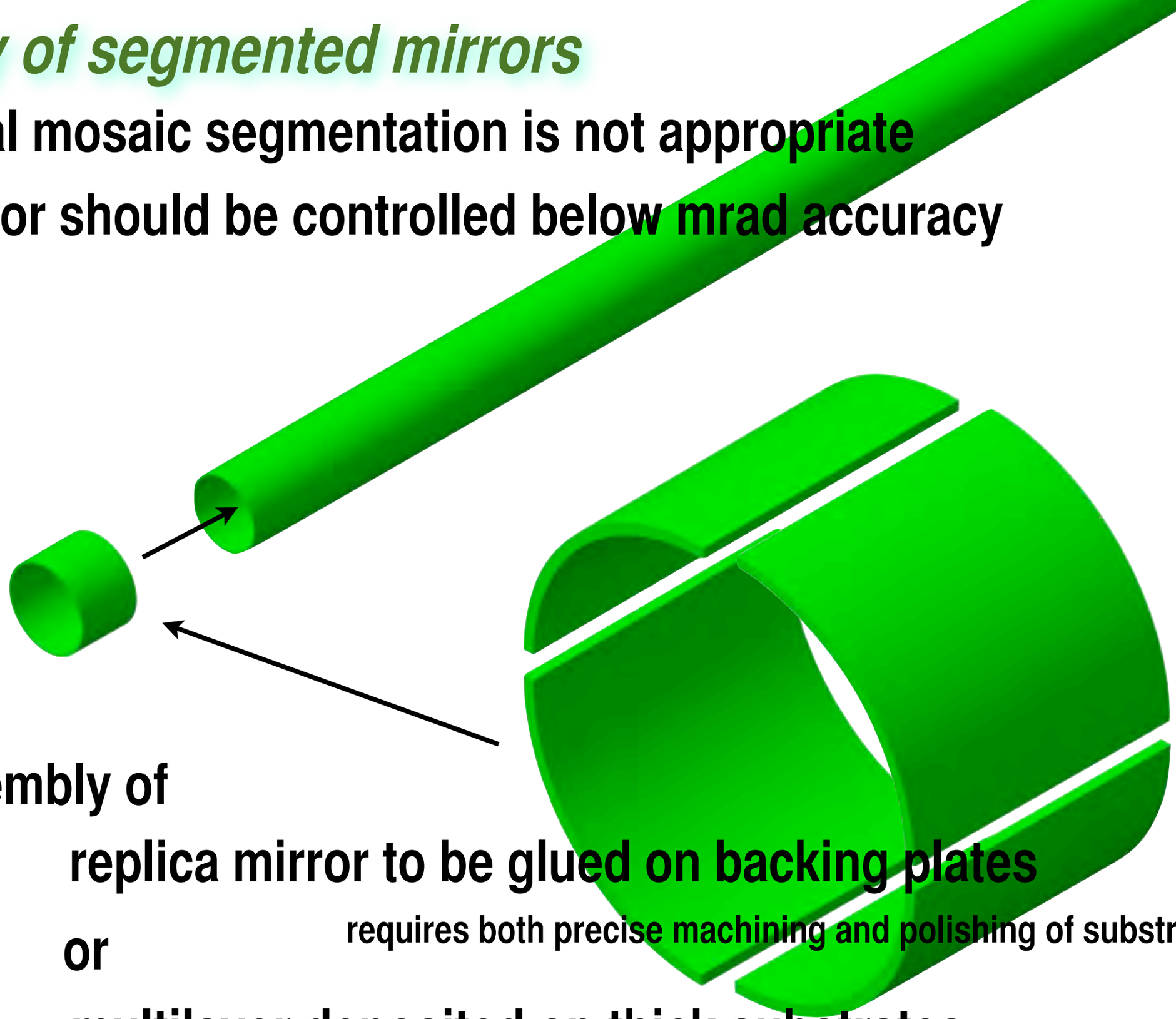
path length = 200m $\longrightarrow$ ϕ < 1/200 = 5 mrad

path length = 1000m $\longrightarrow$ ϕ < 1/1000 = 1 mrad

assembly of segmented mirrors

azimuthal mosaic segmentation is not appropriate

slope error should be controlled below mrad accuracy



assembly of

replica mirror to be glued on backing plates

requires both precise machining and polishing of substrates

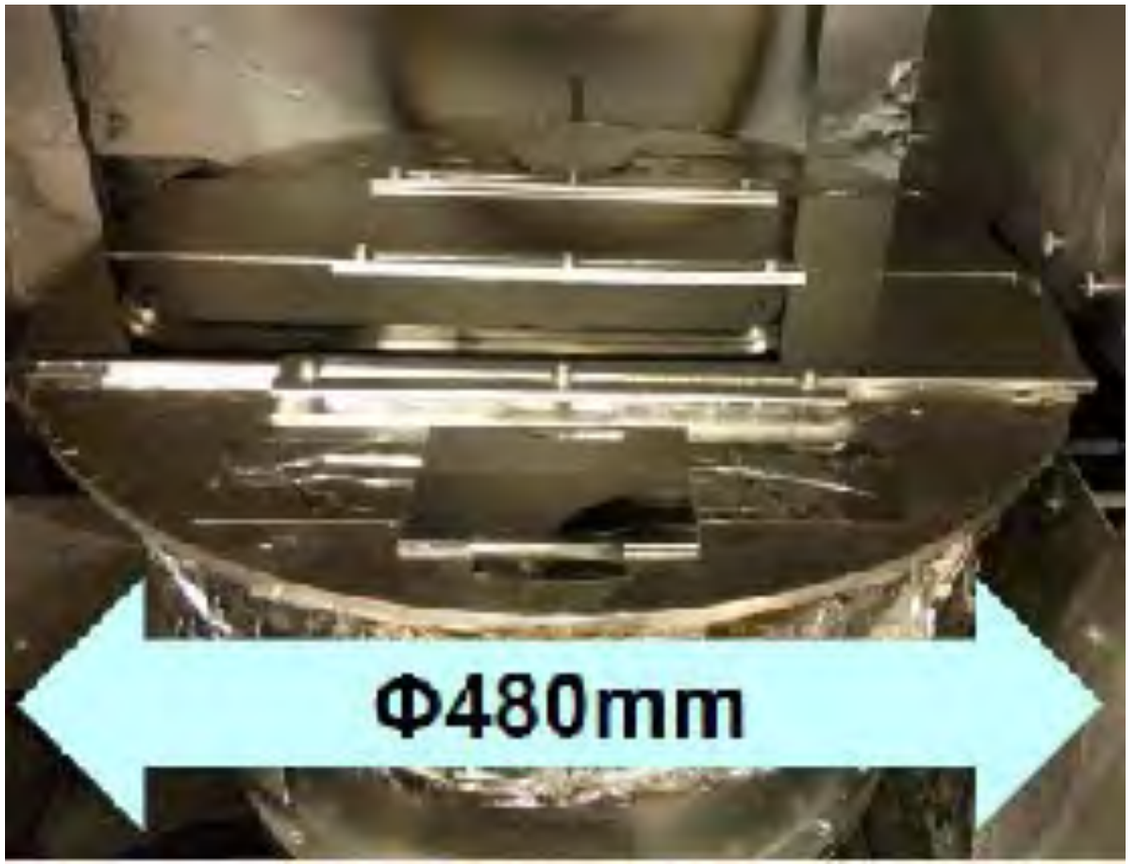
or

multilayer deposited on thick substrates

requires relatively less precise machining
requires replica fabrication technique

production of super high-m multilayer mirrors

Ion Beam Sputter @ Kyoto Univ. Research Reactor Inst.



0.1m²/batch

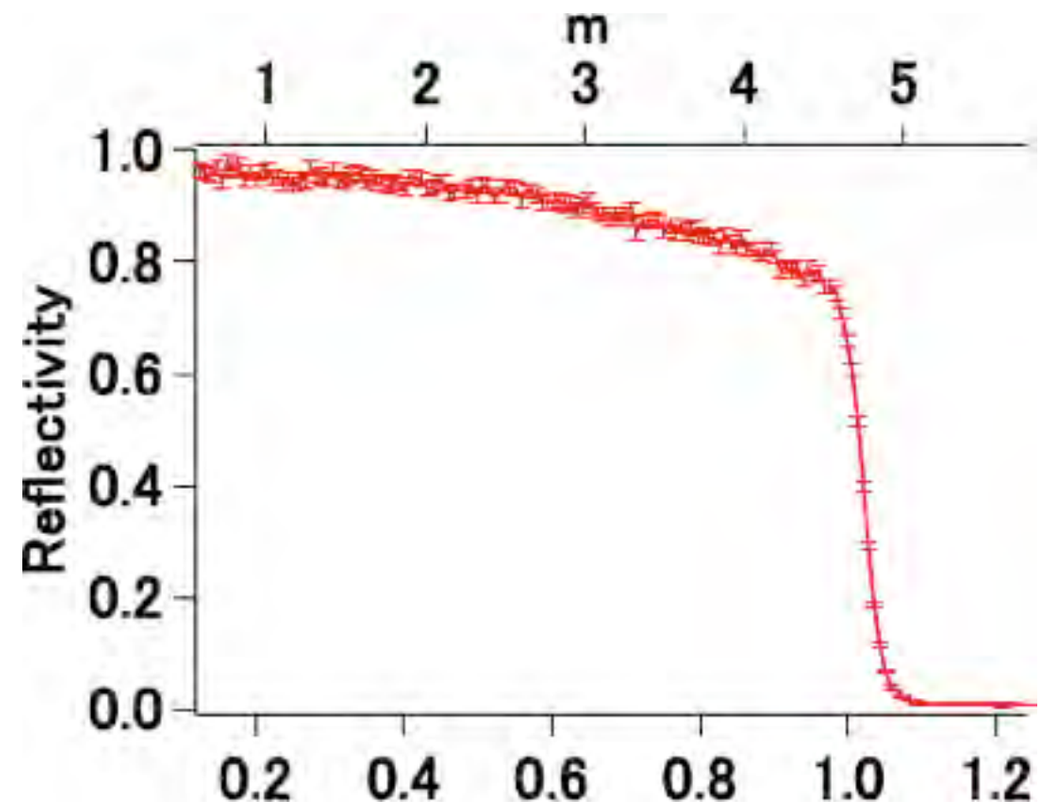
2 batch/day (m=3)

0.2 m²/day/fab.machine

Ion Beam Sputter @ Japan Atomic Energy Agency

(RF Magnetron Sputter for Quicker Mass Production)

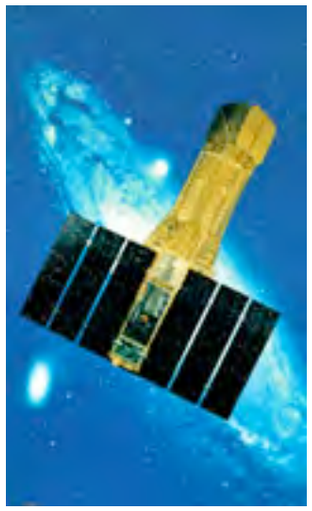
self-sustaining substrateless mirror (replica mirror)

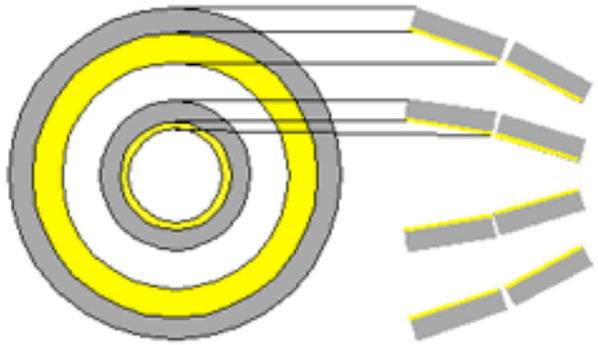


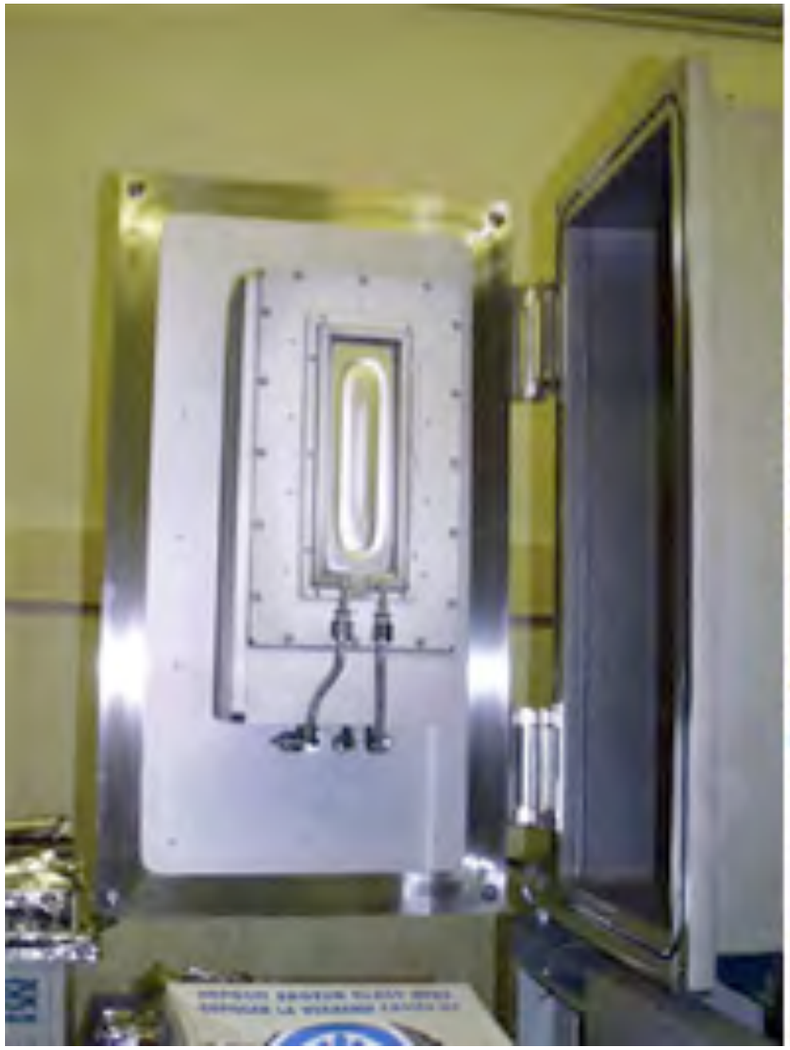
no substrate (radiation hardness expected)

X-ray telescope fabrication skills (replica multilayers)

(Ux-lab. Nagoya Univ.)







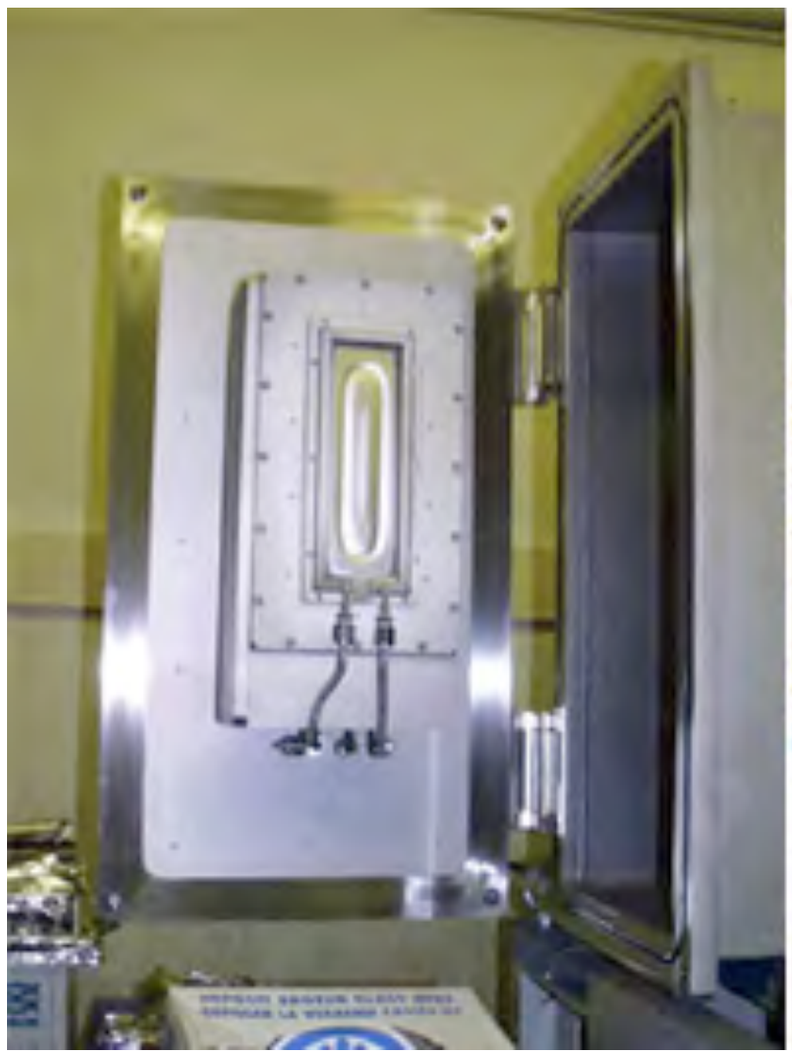
X-ray telescope fabrication skills (replica multilayers)

(Ux-lab. Nagoya Univ.)

3 production units and 2 R&D units

DC Magnetron Sputter

Ni-alloy deposition is currently under study.



Summary

optics enhances experimental sensitivity to nnbar oscillation

optimization, assembly design, alignment strategy, mass production of mirrors, ...

adjusting multilayer mirror fabrication skills (in Japan) for mass production

currently man-power limited

Nagoya Univ., Faculty of Science — (proton 2.8MeV)

Hokkaido Univ., Faculty of Engineering — electron 45MeV

for R&D, education

Kyoto Univ., Faculty of Science — proton 3.5MeV

for education

RIKEN, Innovation Center — proton 7MeV

for engineering and industrial applications

KEK, J-PARC — proton 400MeV (3GeV)

for special sources (medical use and UCN)