Cold Neutron Reflective Optics for nnbar

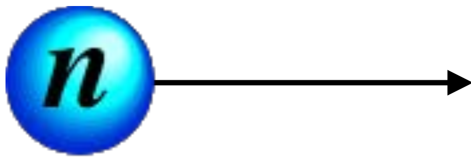
Kosuke NAGAMOTO, Takahiro MORISHIMA, Go ICHIKAWA,
Masaaki KITAGUCHI and Hirohiko M. SHIMIZU

Department of Physics, Nagoya University

neutron reflection

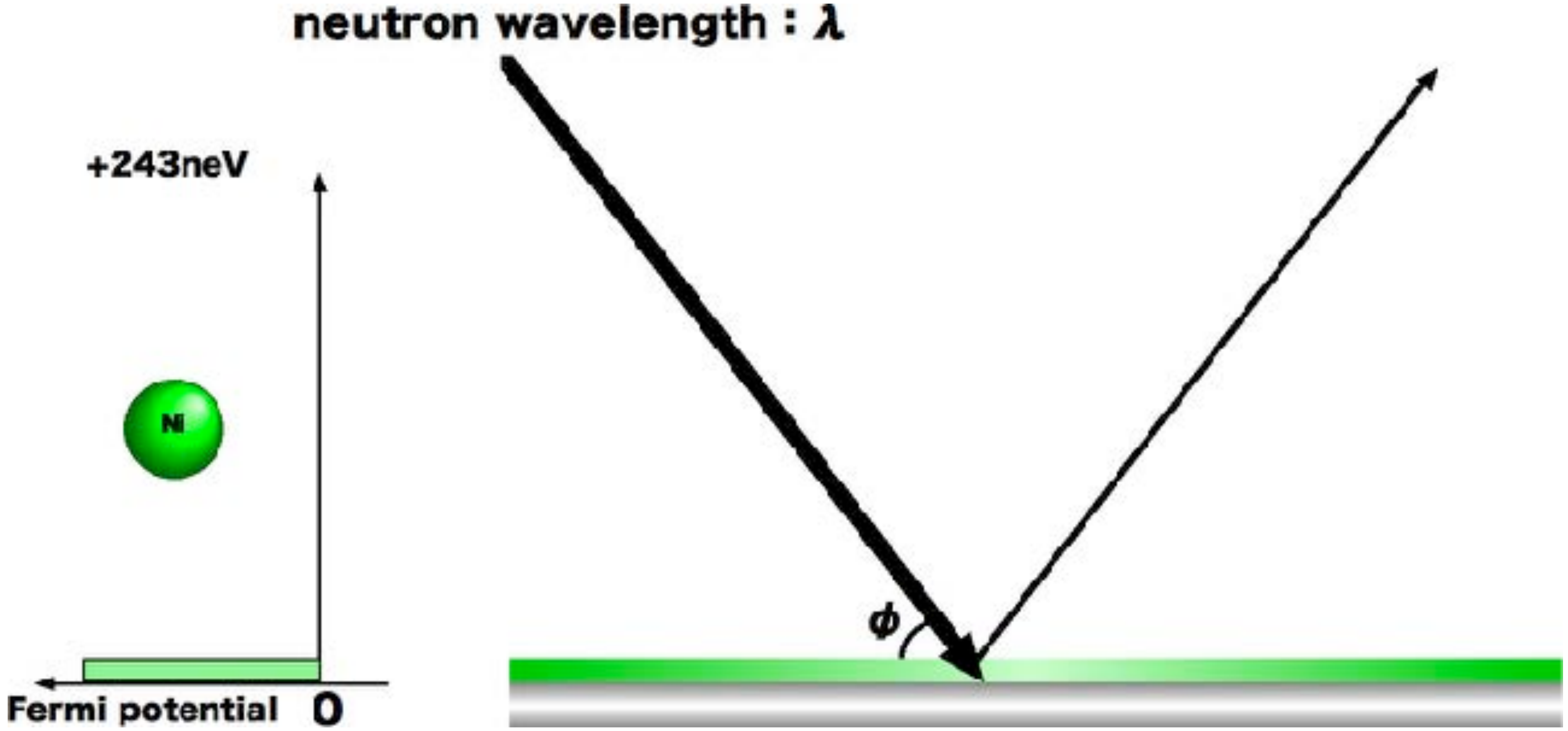
Fermi pseudopotential

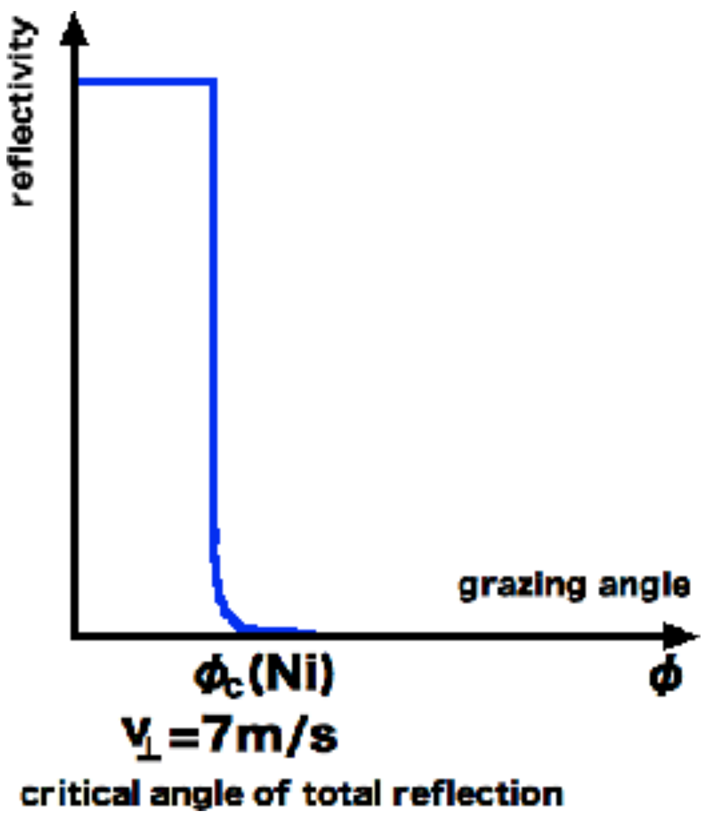
Neutron Reflection



$$U = \frac{2\pi\hbar^2}{m_n} bN$$

m_n : neutron mass
b : scattering length
N : atomic number density

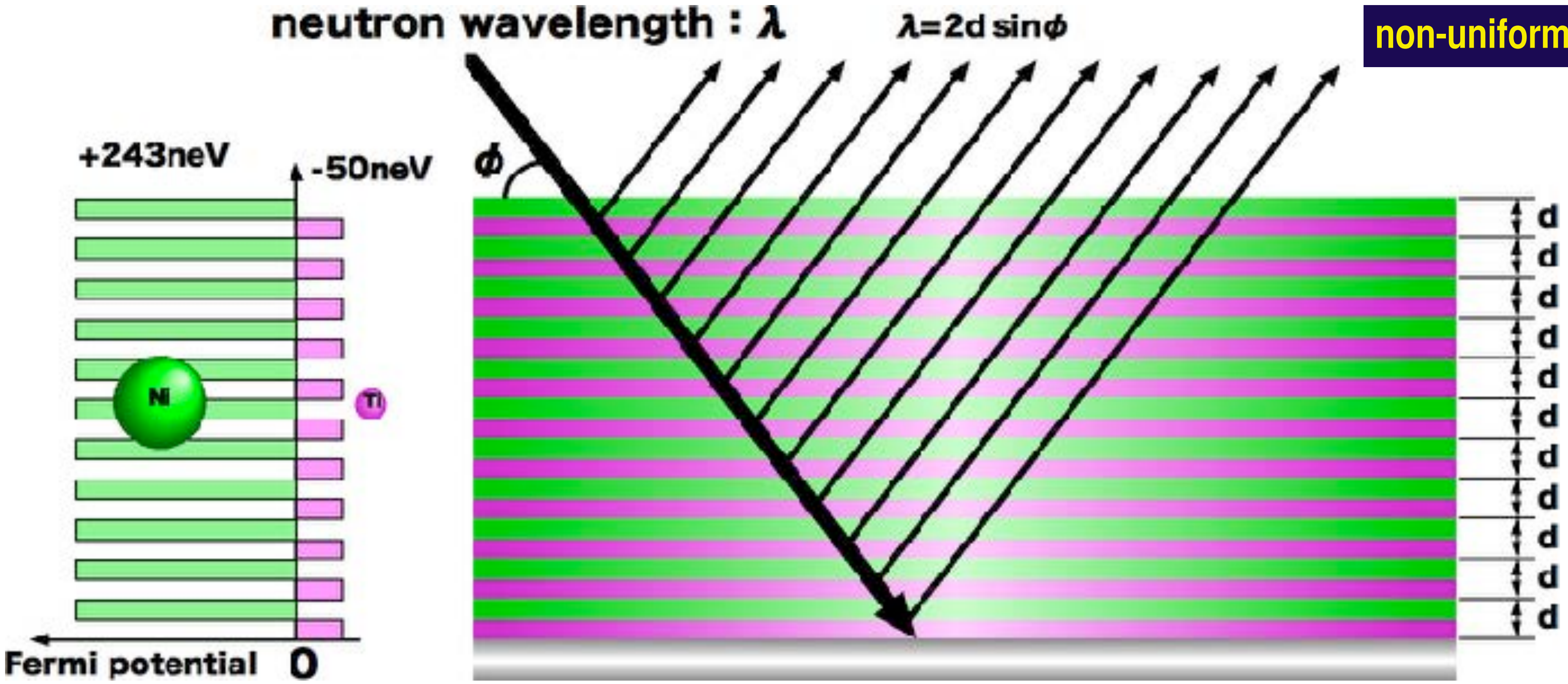


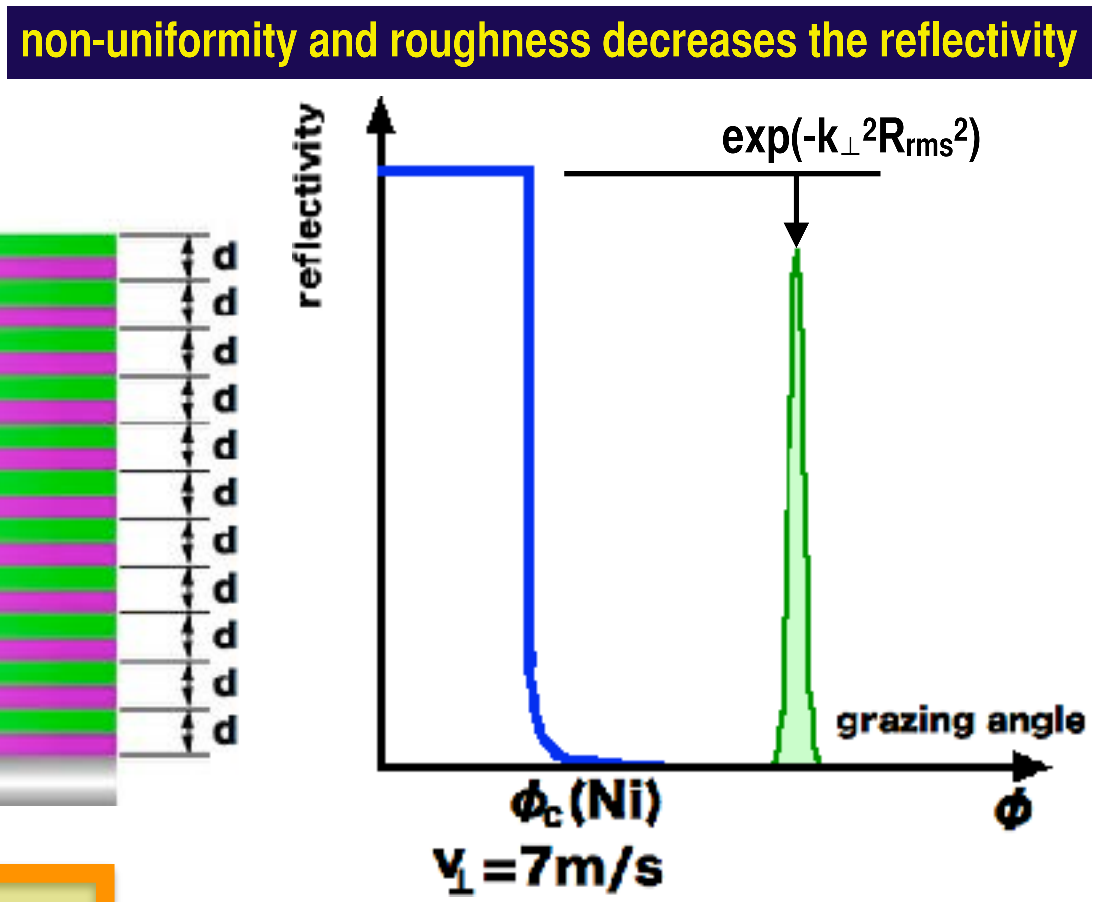


$$\frac{\phi_c(\mathrm{Ni})}{\lambda_n} = 1.7\,[\mathrm{mrad}\,\mathrm{\AA}^{-1}]$$

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

Multilayer Mirror

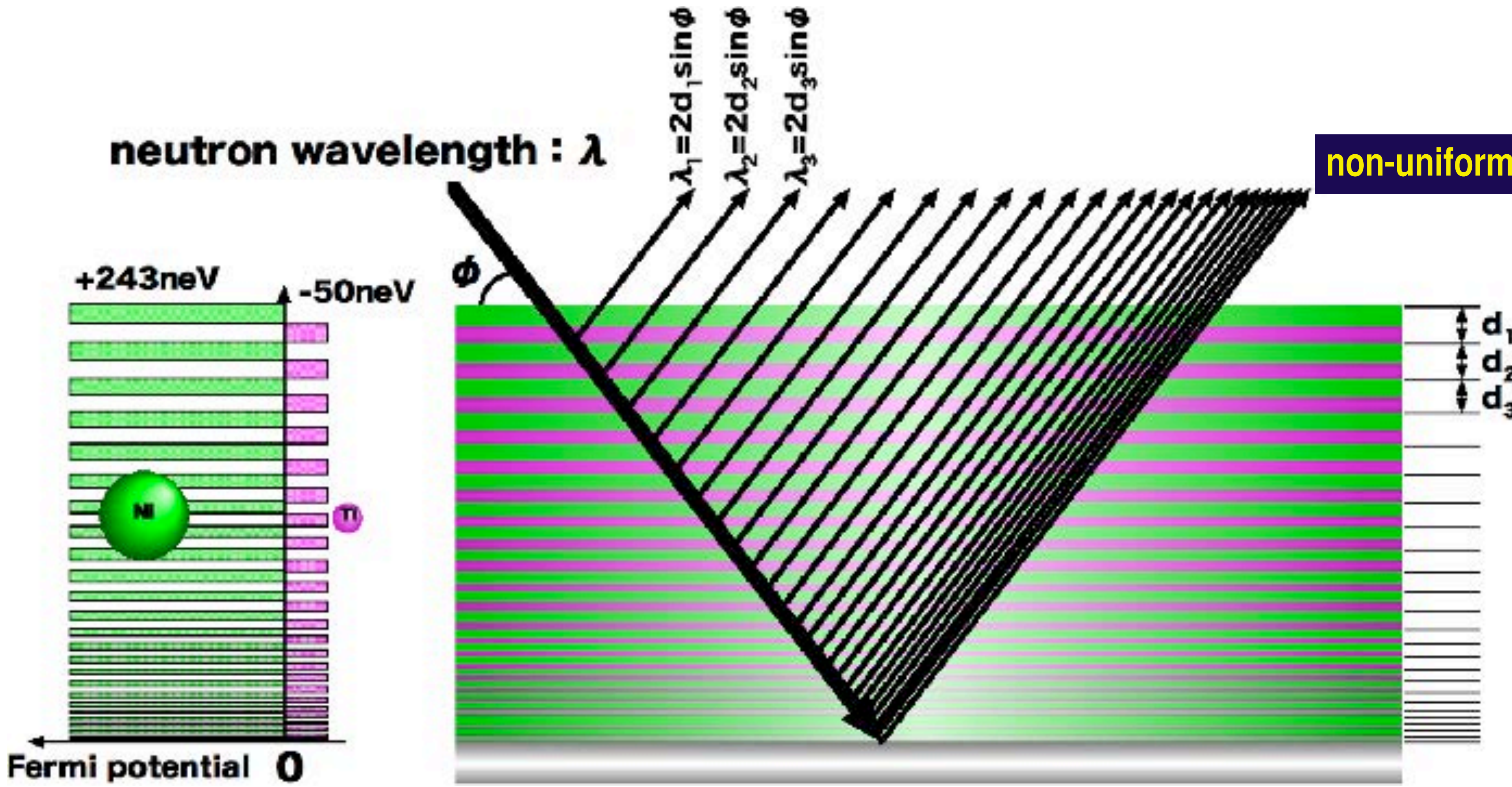




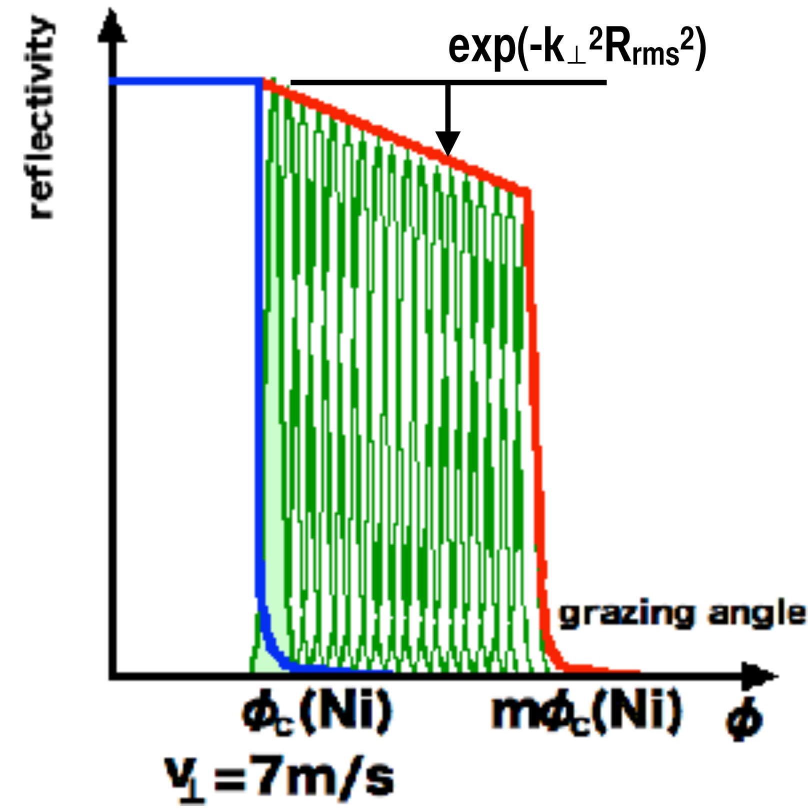
$$\frac{\phi_c(\mathrm{Ni})}{\lambda_n} = 1.7\,[\mathrm{mrad}\,\text{Å}^{-1}]$$

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

Supermirror



non-uniformity and roughness decreases the reflectivity

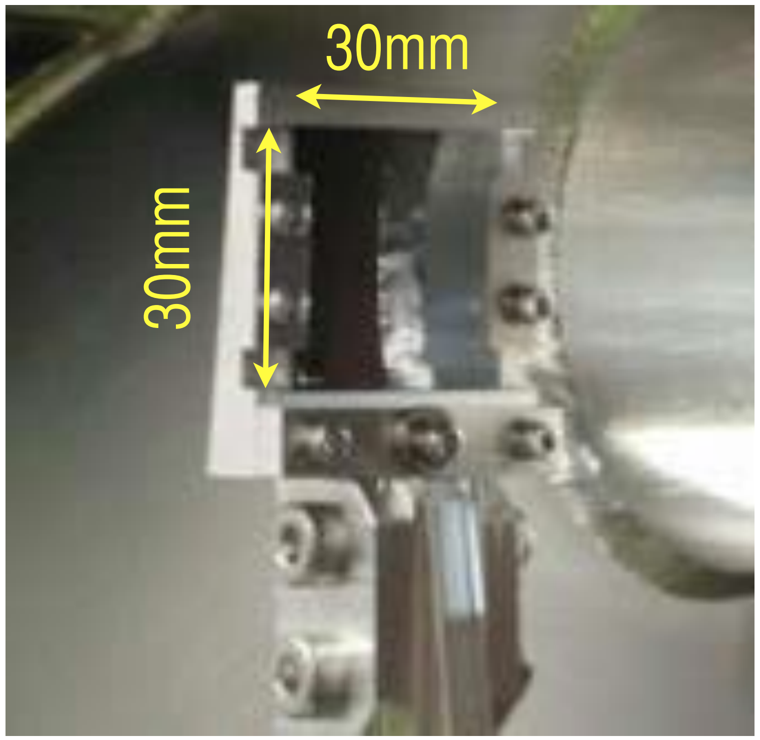


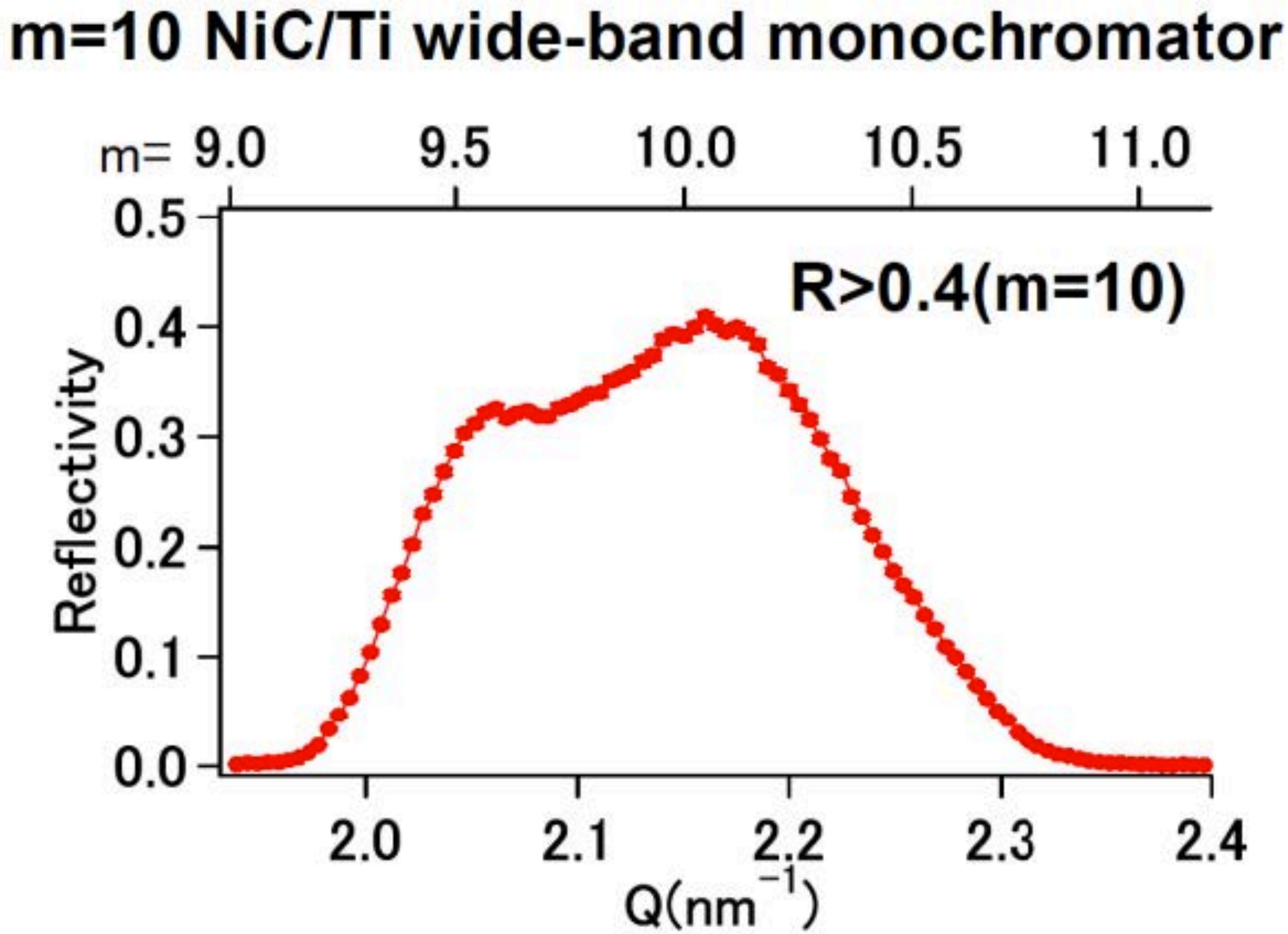
$$\frac{\phi_c(\mathrm{Ni})}{\lambda_n} = 1.7\,[\mathrm{mrad}\,\text{Å}^{-1}]$$

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

$$m = \frac{\phi_c}{\phi_c(\mathrm{Ni})} = \frac{v_\perp}{v_\perp(\mathrm{Ni})}$$

Quadruple-stack Multilayer m=10
the highest m-value ever realized

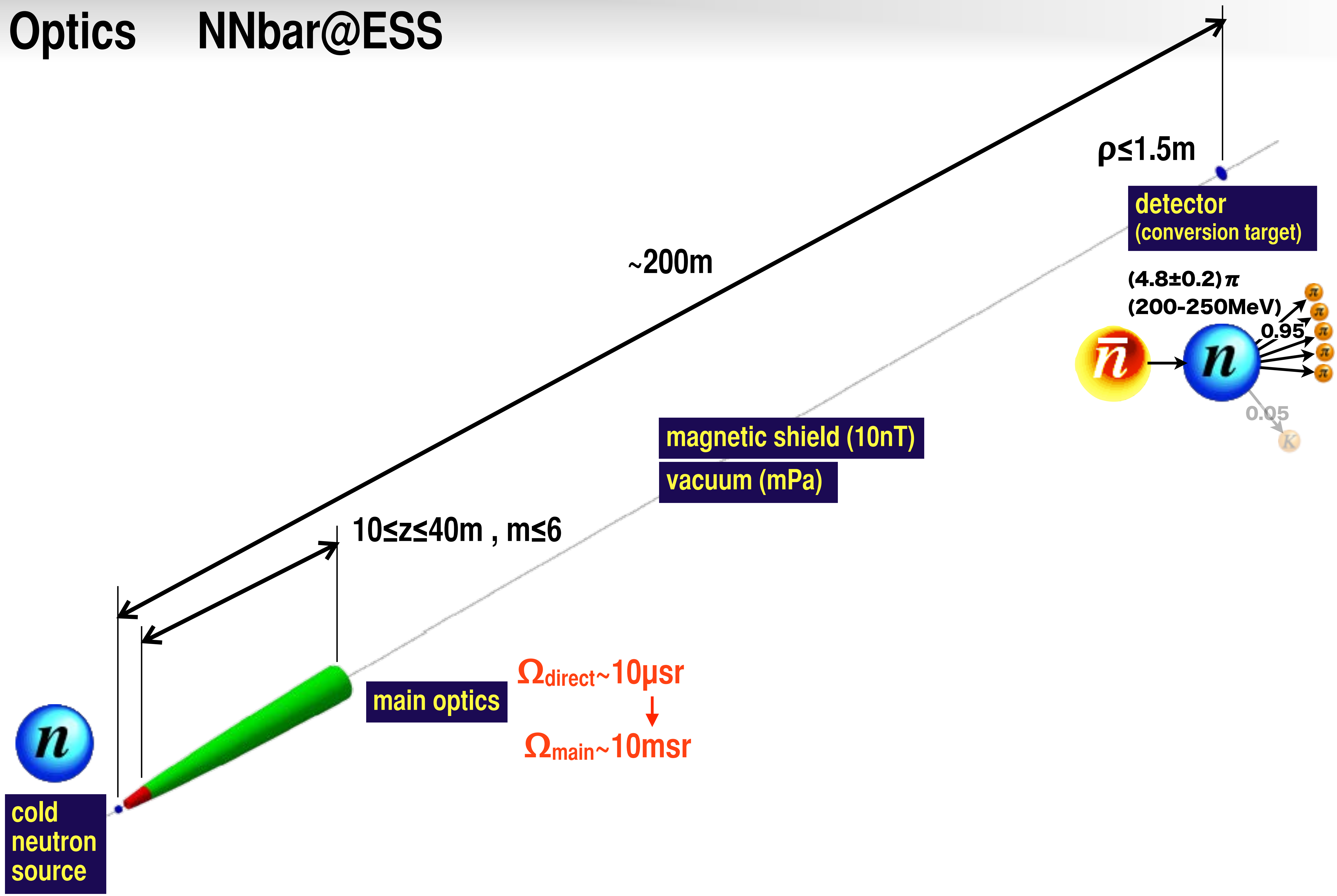




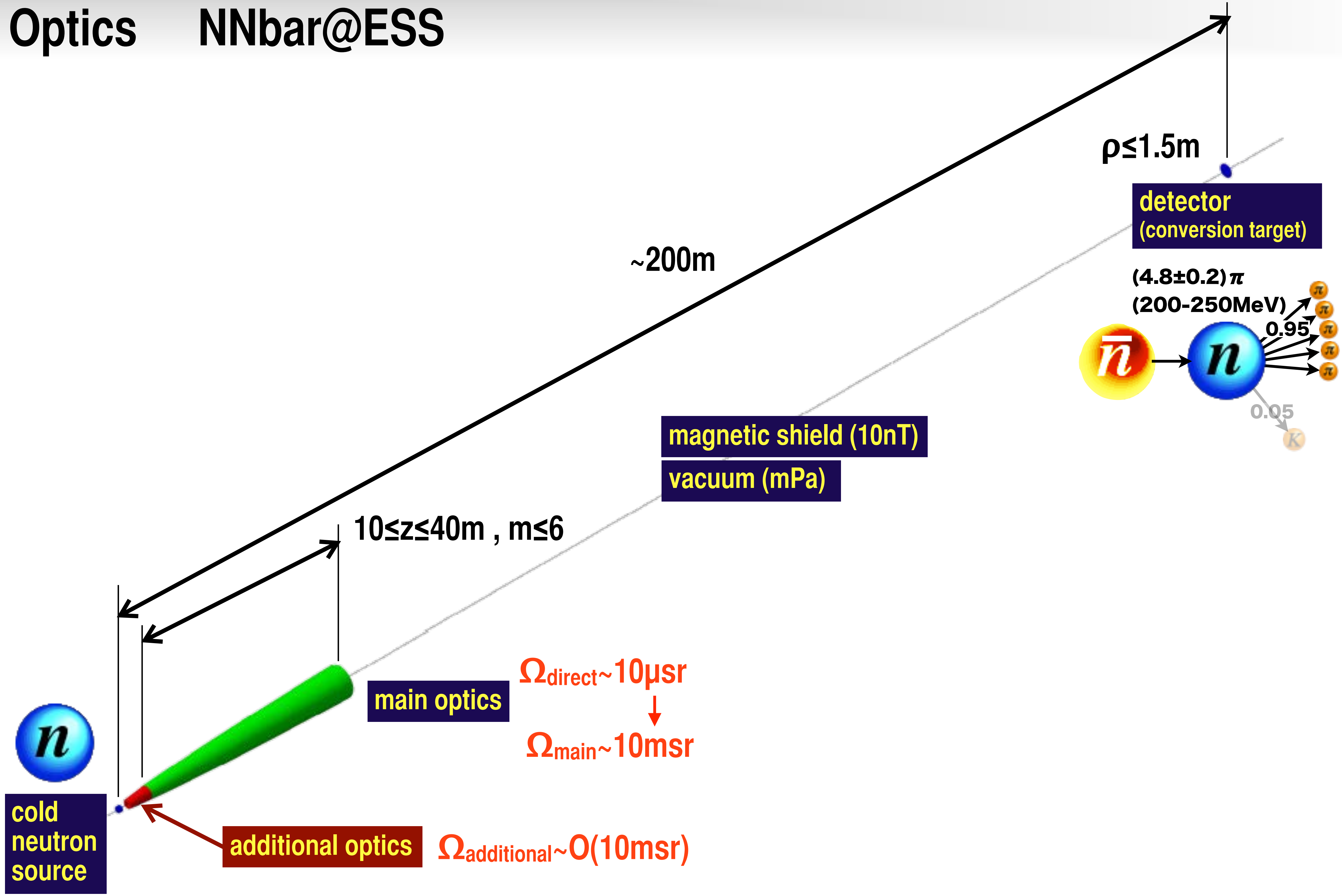
85060 bilayers in total = 4×(10336+10929 bilayers)
quadruple-stack of double-sided multilayer mirrors

baseline optics

Optics NNbar@ESS

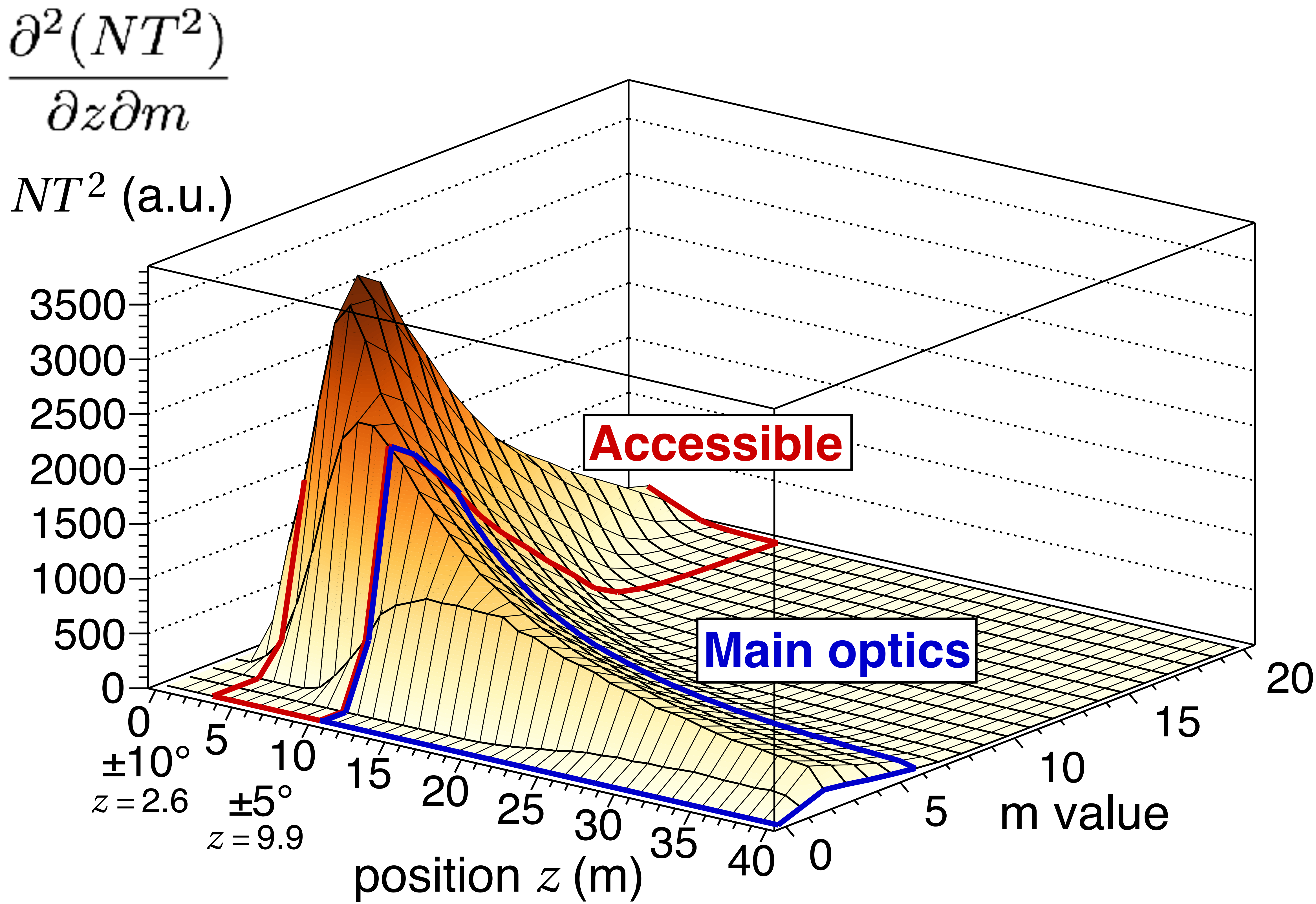


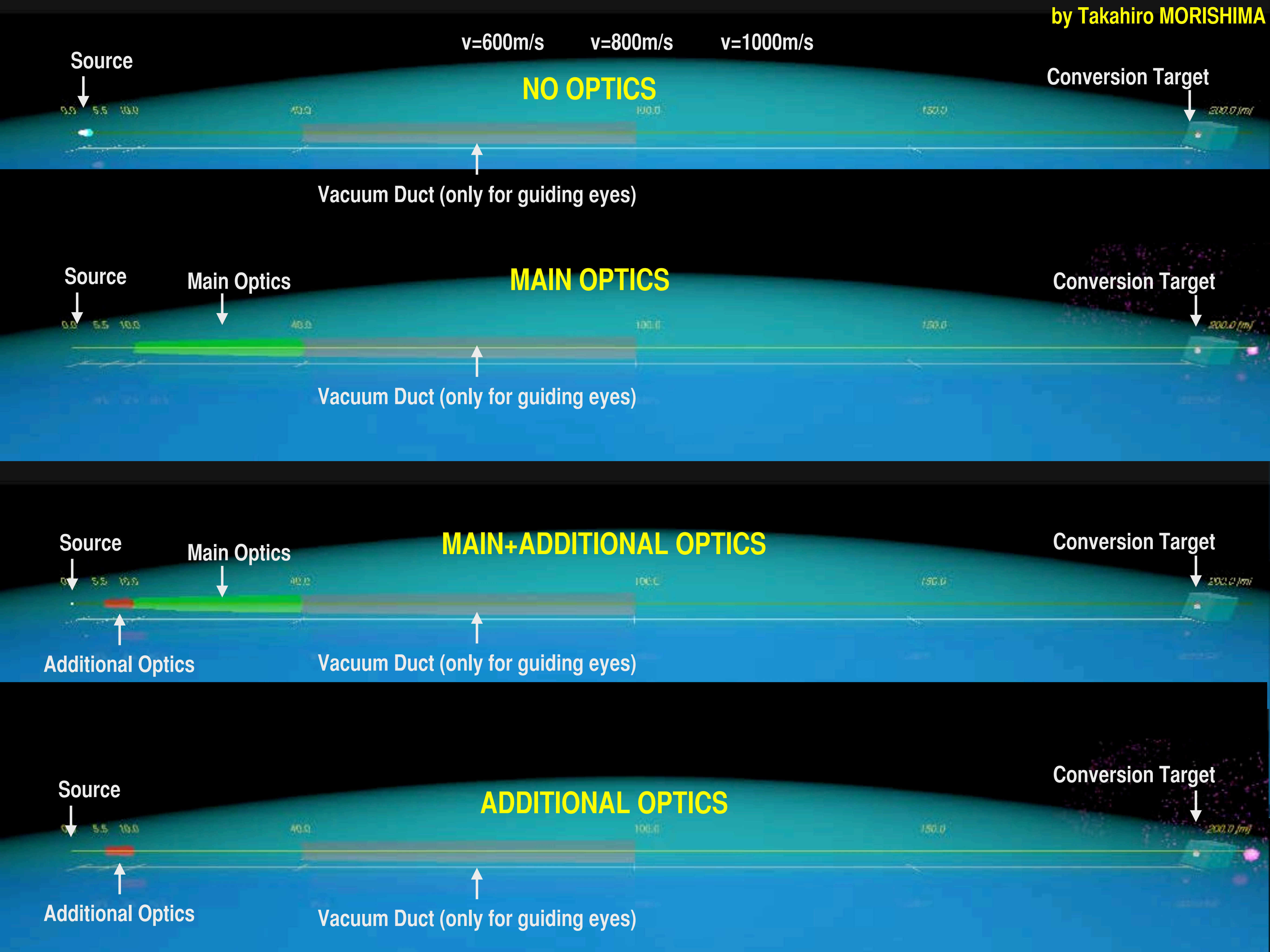
Optics NNbar@ESS



by Go ICHIKAWA

Map of Figure-Of-Merit (NT^2)




by Takahiro MORISHIMA
v=600m/s
v=800m/s
v=1000m/s
Source
NO OPTICS
Conversion Target
Vacuum Duct (only for guiding eyes)
Source
Main Optics
MAIN OPTICS
Conversion Target
Vacuum Duct (only for guiding eyes)
Source
Main Optics
MAIN+ADDITIONAL OPTICS
Conversion Target
Additional Optics
Vacuum Duct (only for guiding eyes)
Source
ADDITIONAL OPTICS
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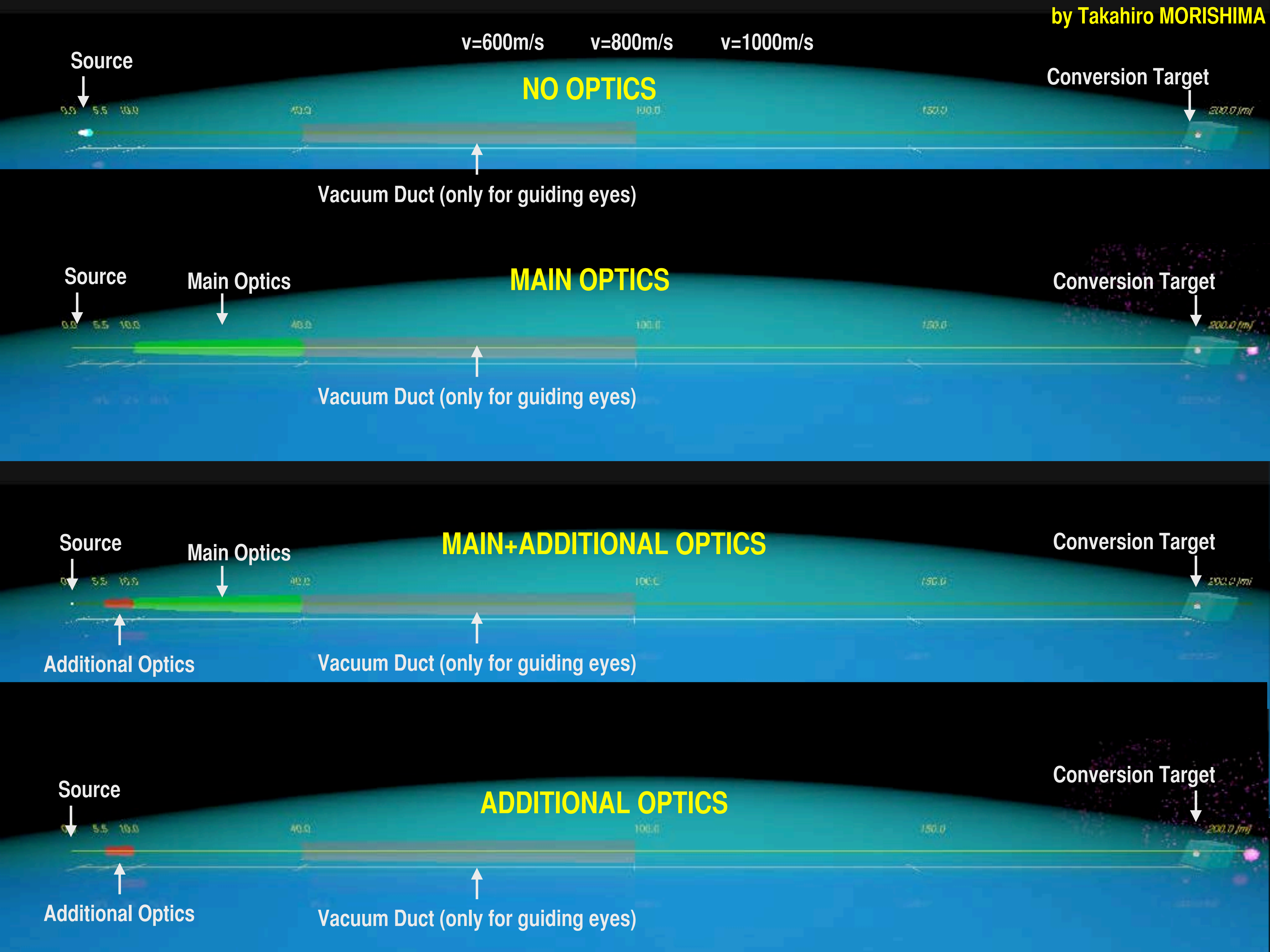

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Source
ADDITIONAL OPTICS
Conversion Target
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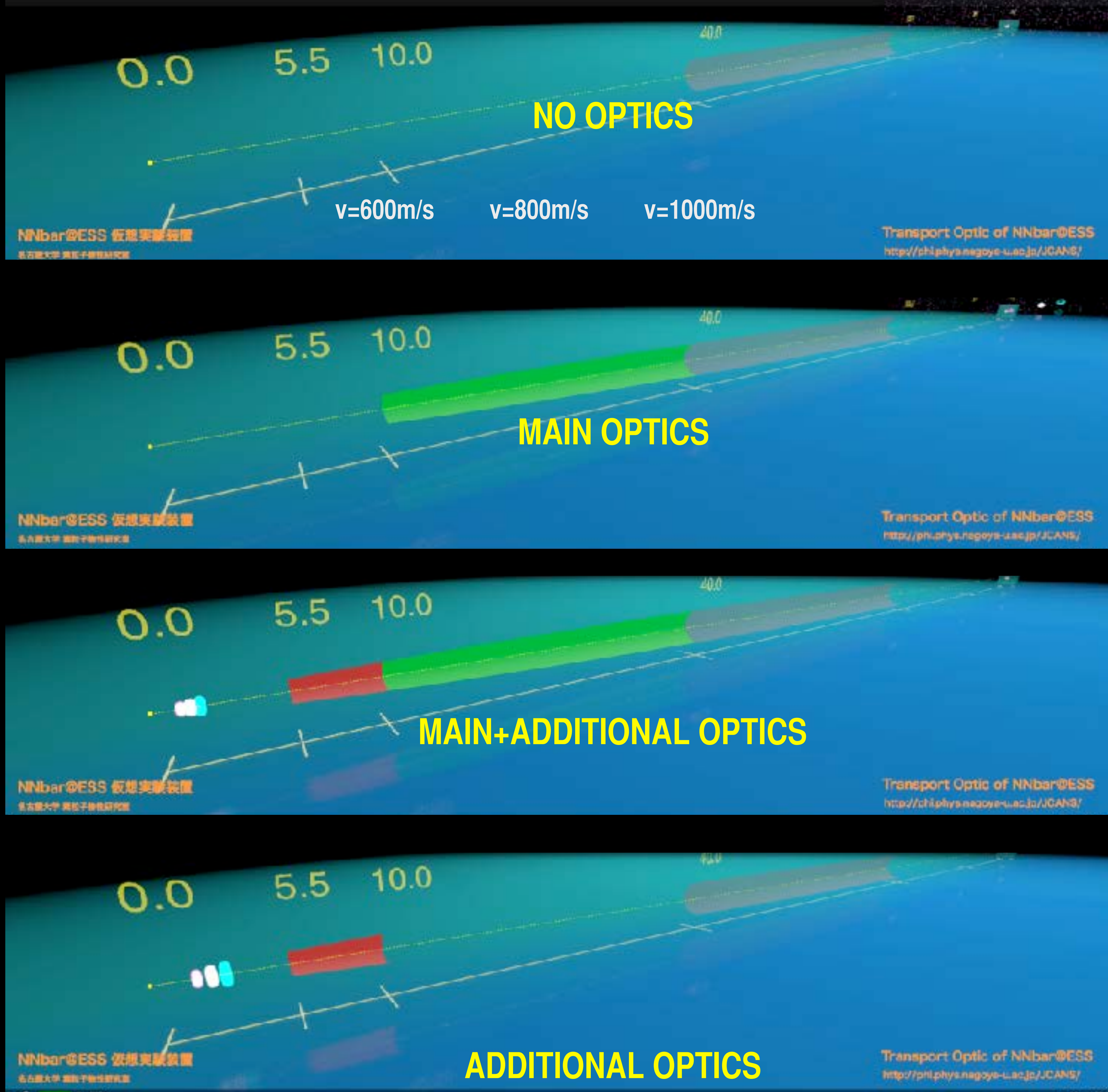
Vacuum Duct (only for guiding eyes)

Viewing from the Source

by Takahiro MORISHIMA



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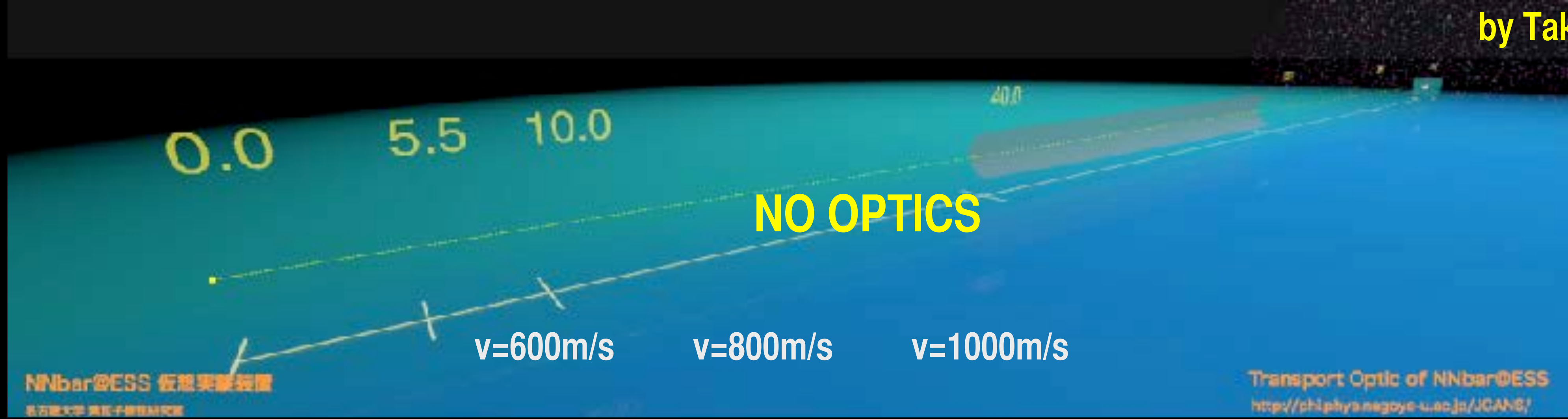

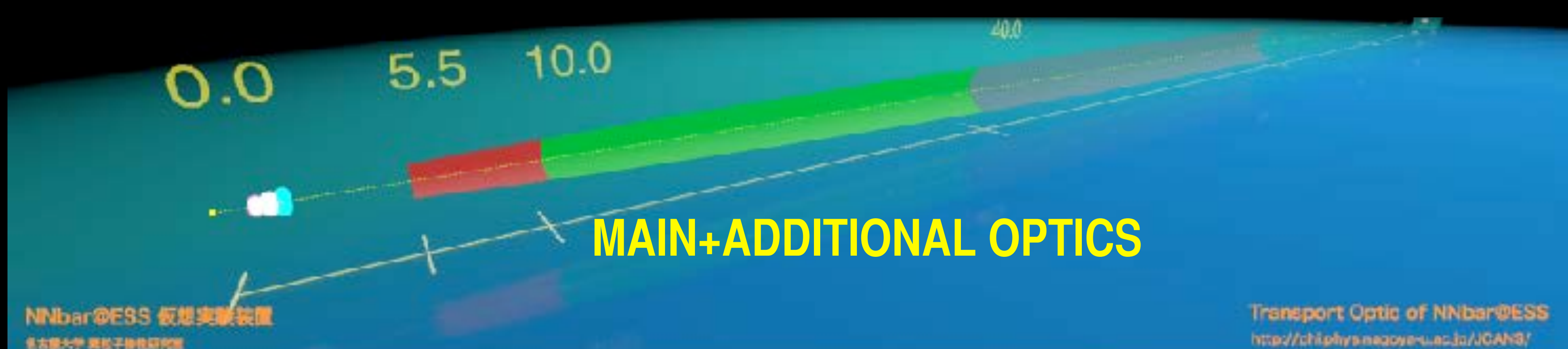

Viewing from the Detector

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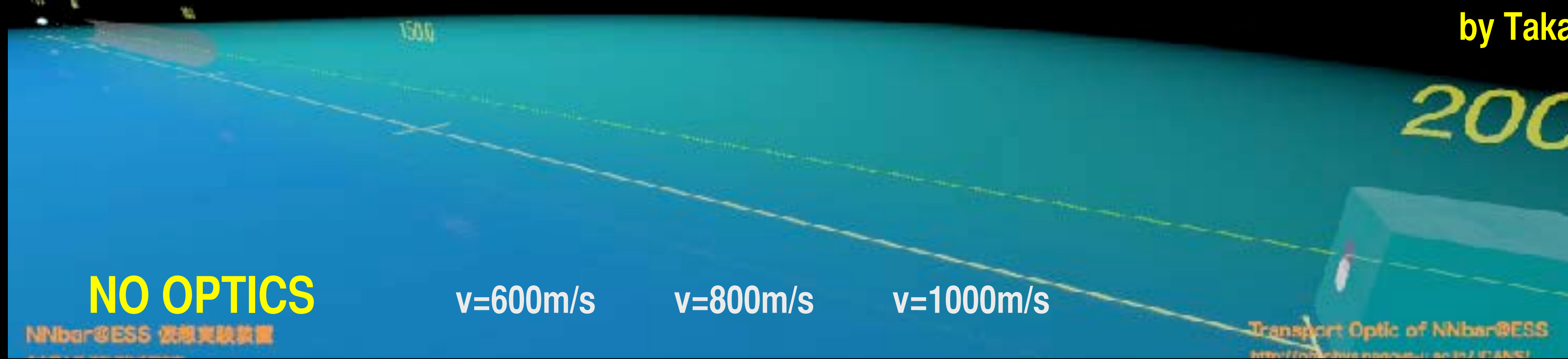

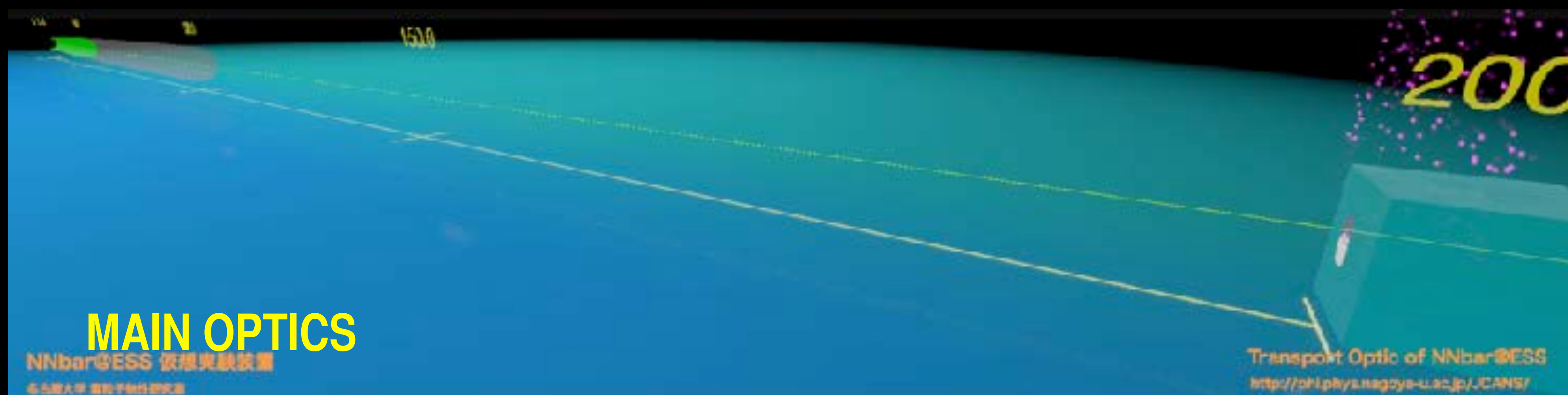

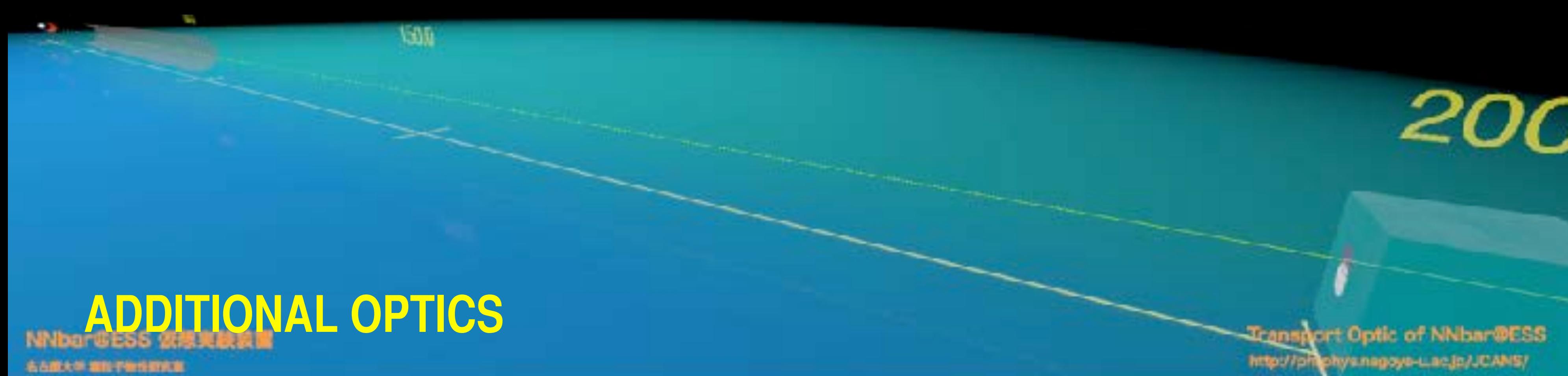

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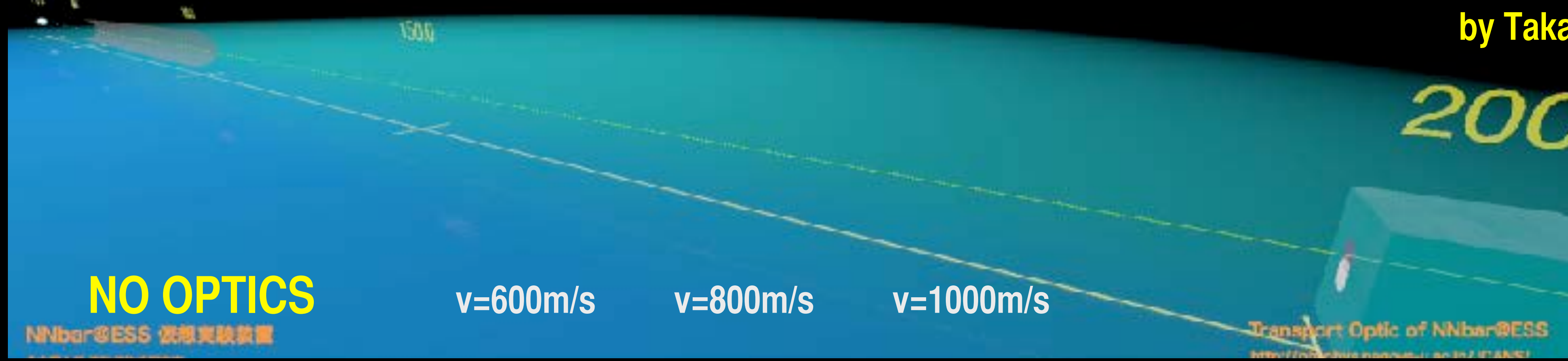
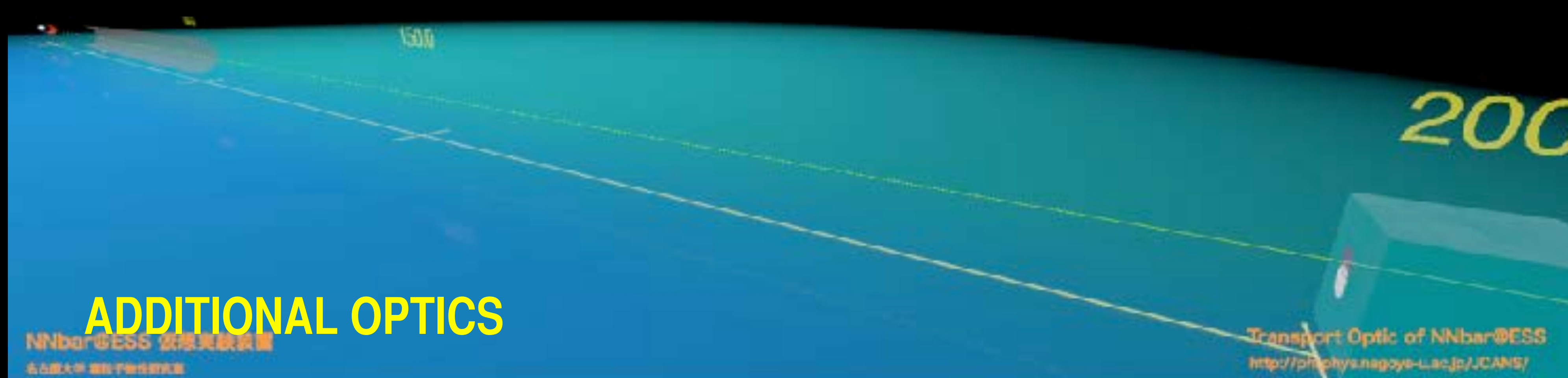
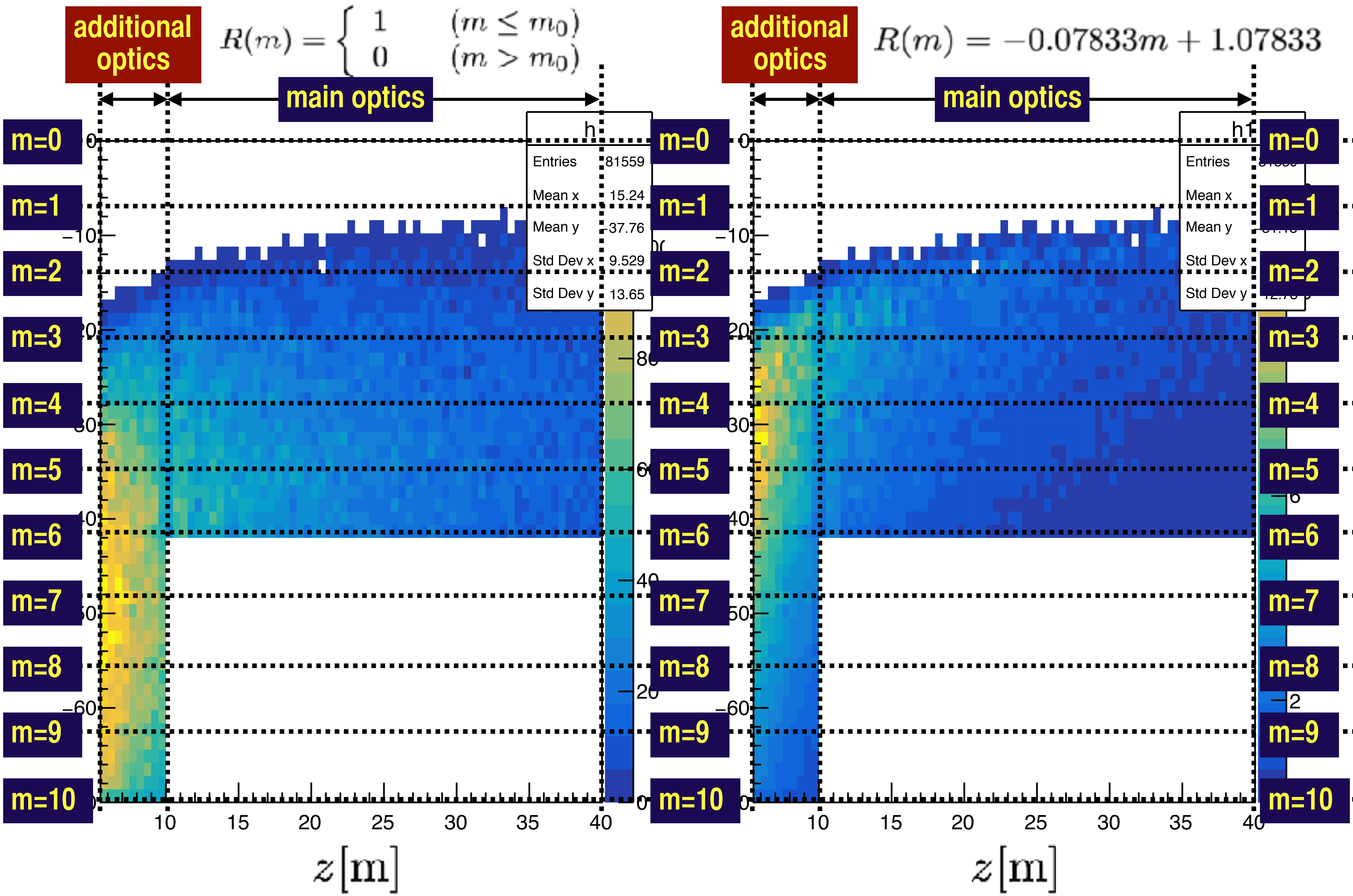




by Kosuke NAGAMOTO

Map of Figure-Of-Merit (NT^2) $\frac{\partial^2(NT^2)}{\partial z \partial m}$



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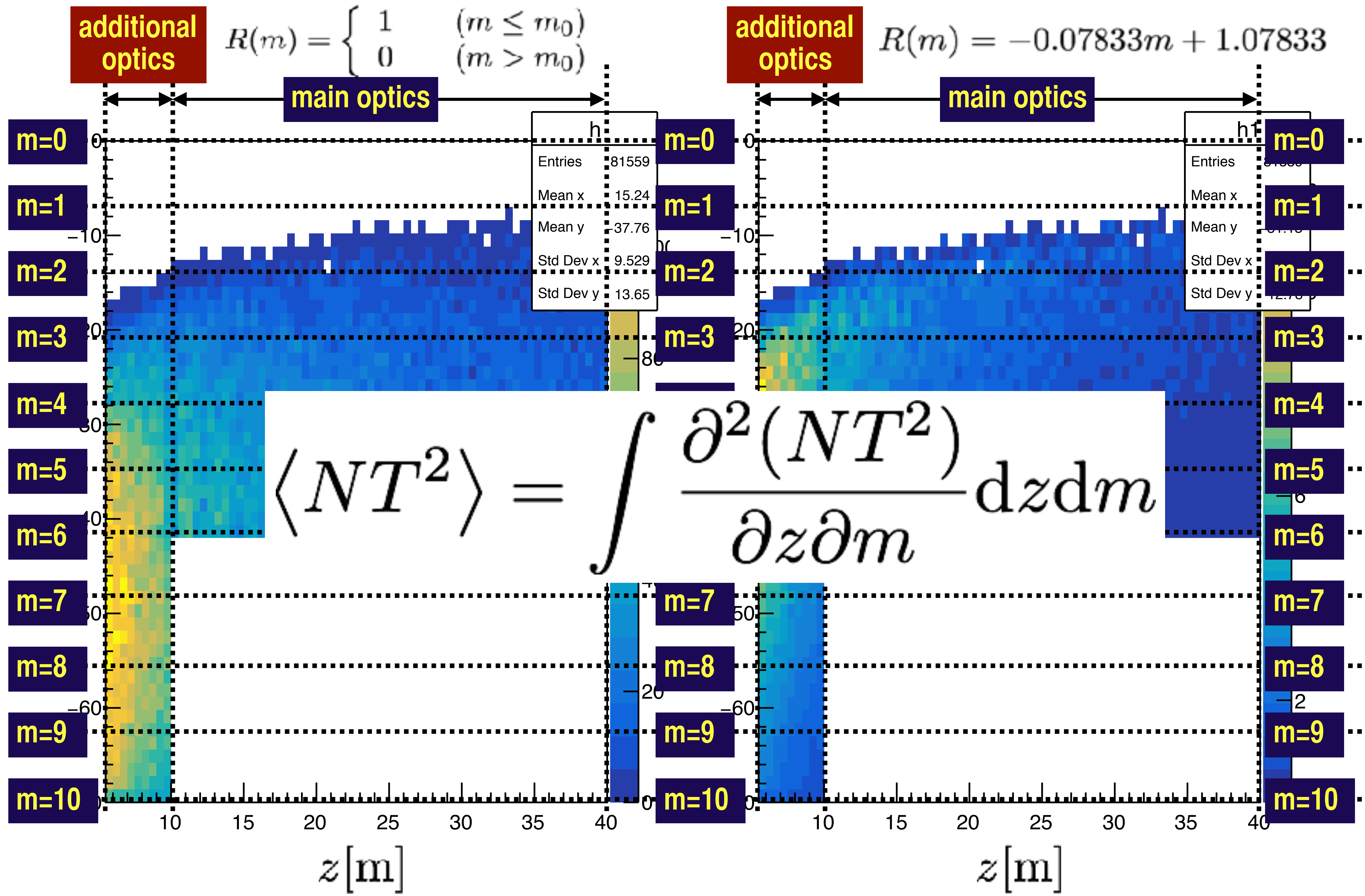


$$\langle NT^2 \rangle = \int \frac{\partial^2 (NT^2)}{\partial z \partial m} \mathrm{d}z\mathrm{d}m$$

by Kosuke NAGAMOTO

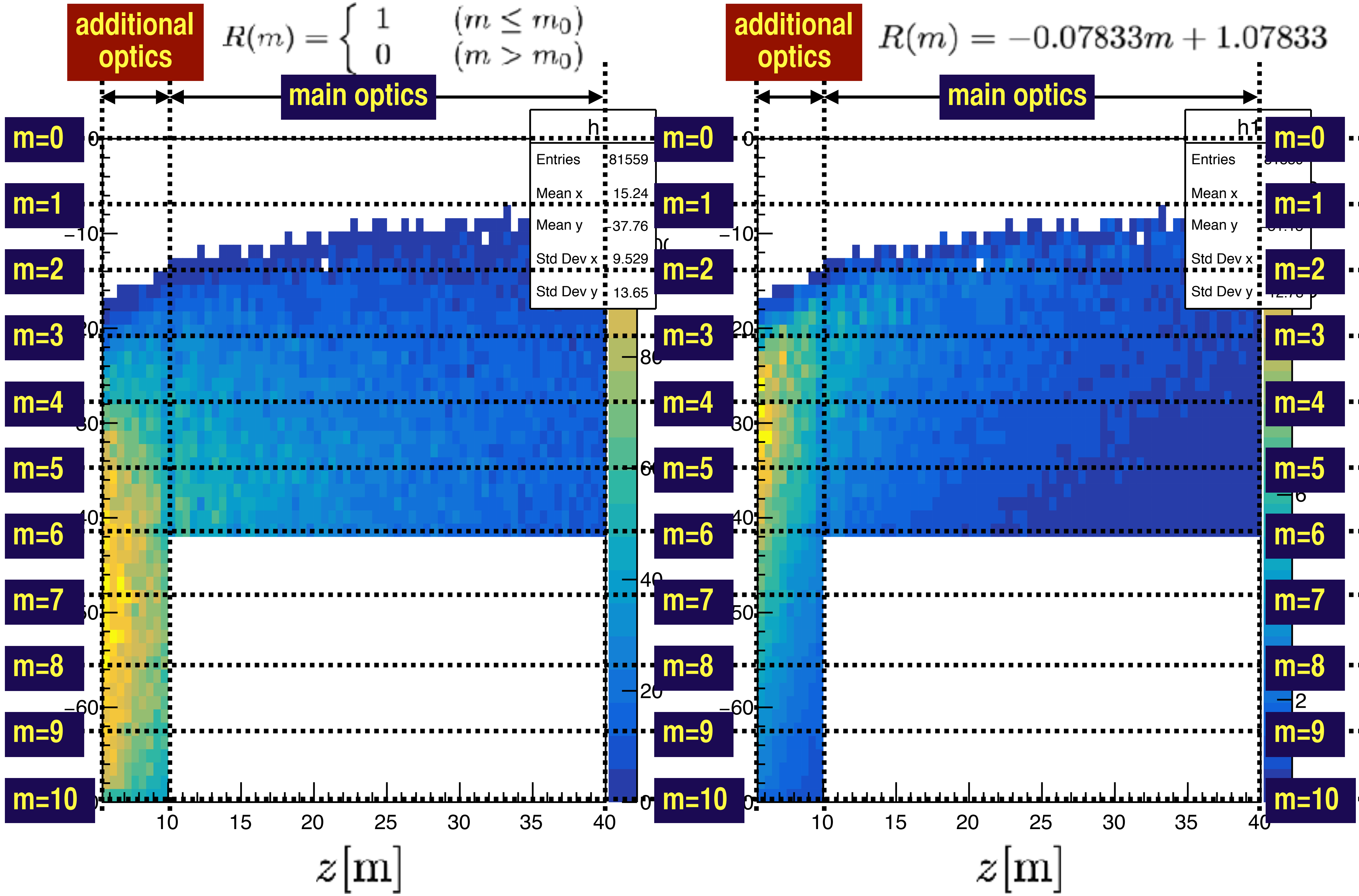
Map of Figure-Of-Merit (NT^2)

$$\frac{\partial^2(NT^2)}{\partial z \partial m}$$

$$\langle NT^2 \rangle = \int \frac{\partial^2(NT^2)}{\partial z \partial m} \mathrm{d}z\mathrm{d}m$$

$$R(m) = \begin{cases} 1 & (m \leq m_0) \\ 0 & (m > m_0) \end{cases}$$

$$R(m) = -0.07833m + 1.07833$$



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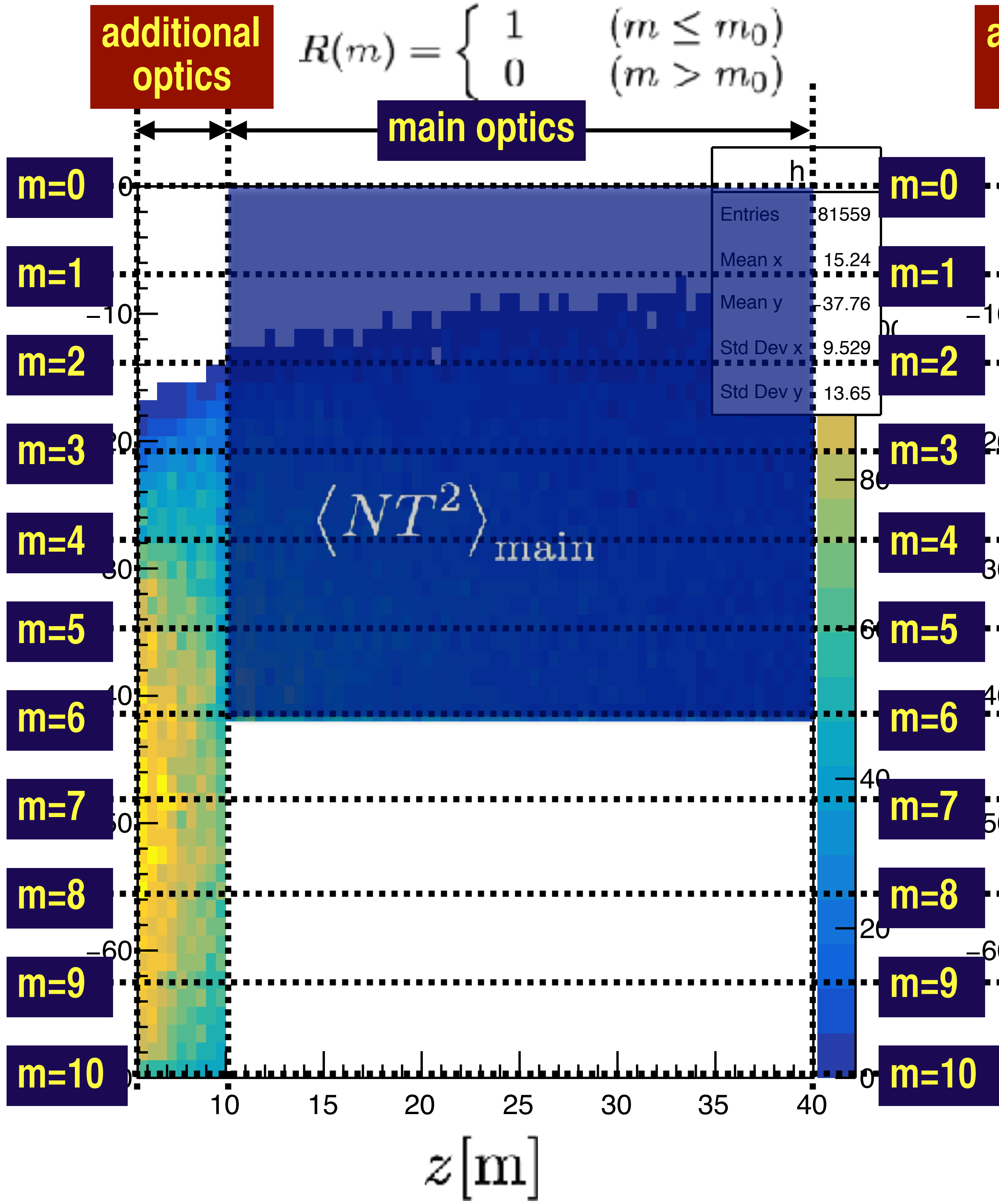

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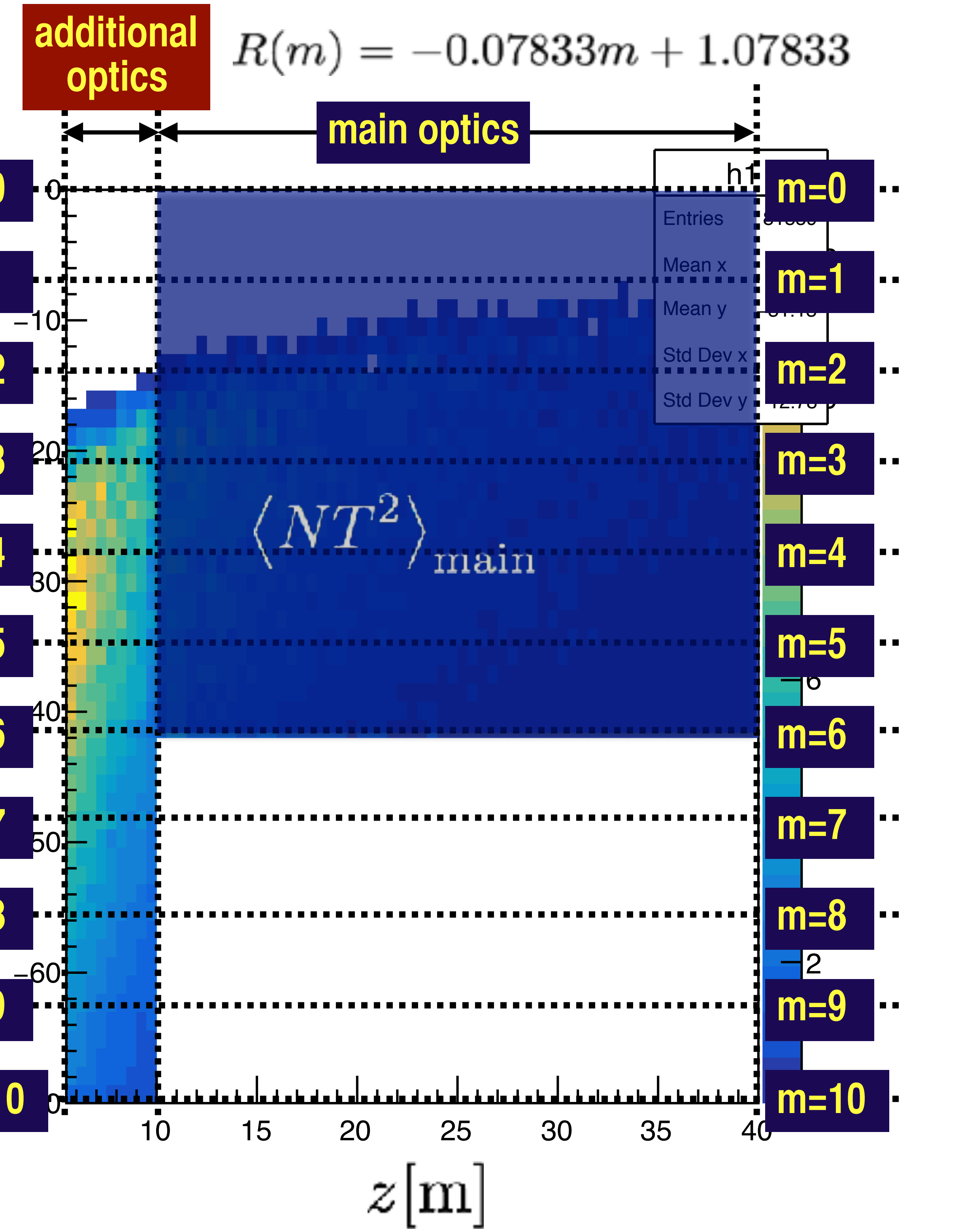

by Kosuke NAGAMOTO

Map of Figure-Of-Merit (NT^2)

$$\frac{\partial^2 (NT^2)}{\partial z \partial m}$$

$$\langle NT^2 \rangle = \int \frac{\partial^2 (NT^2)}{\partial z \partial m} dz dm$$

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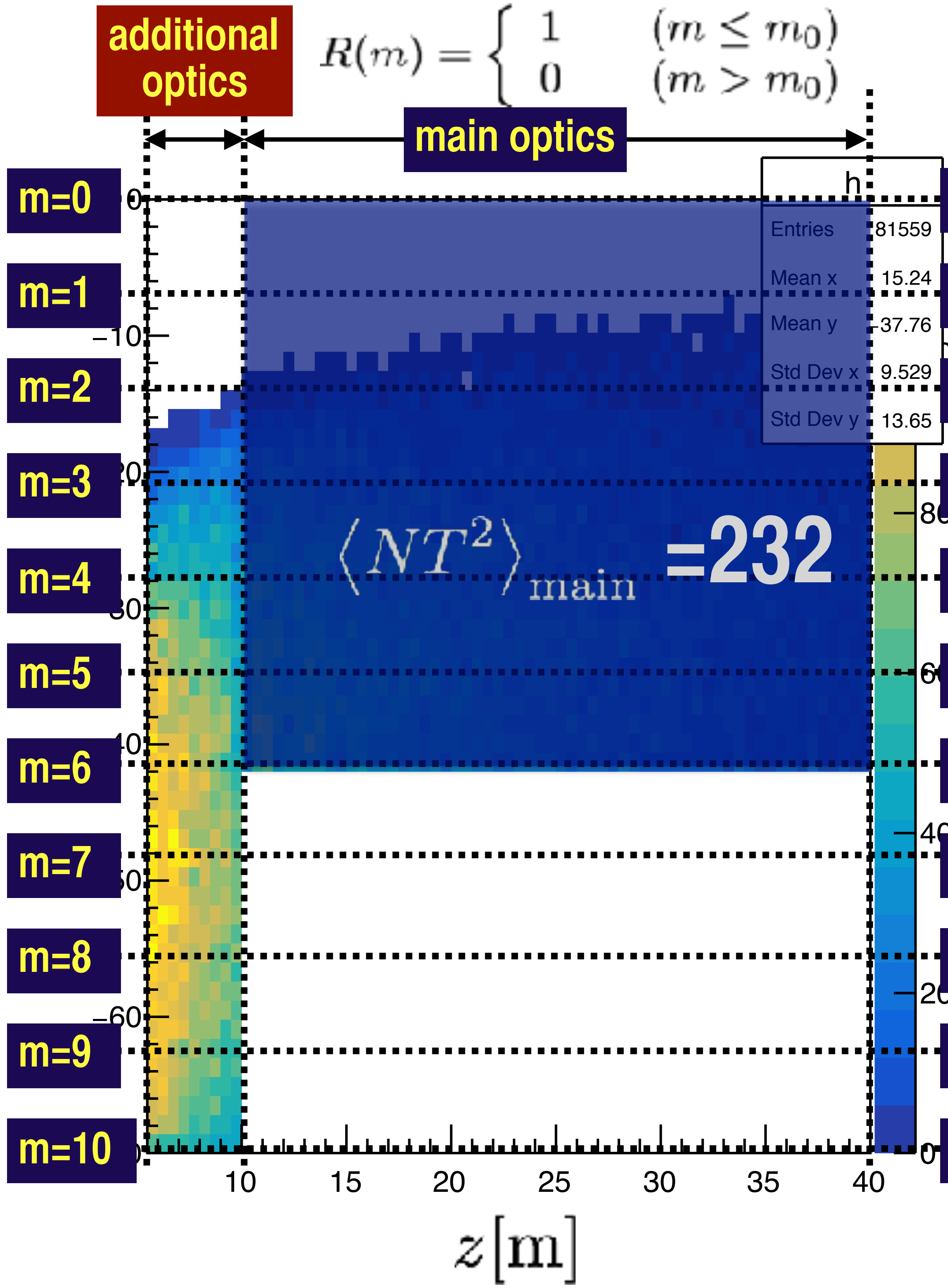

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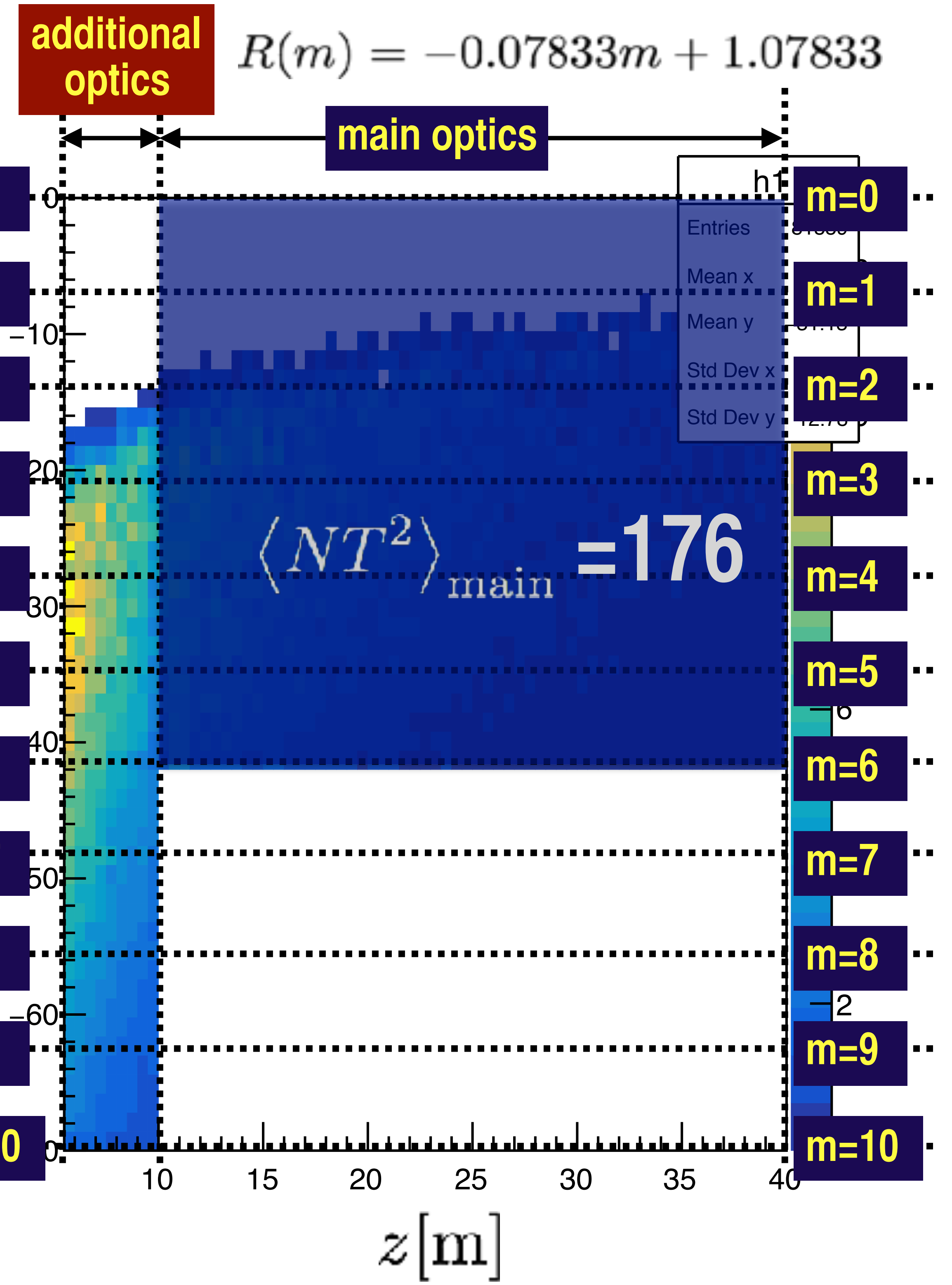

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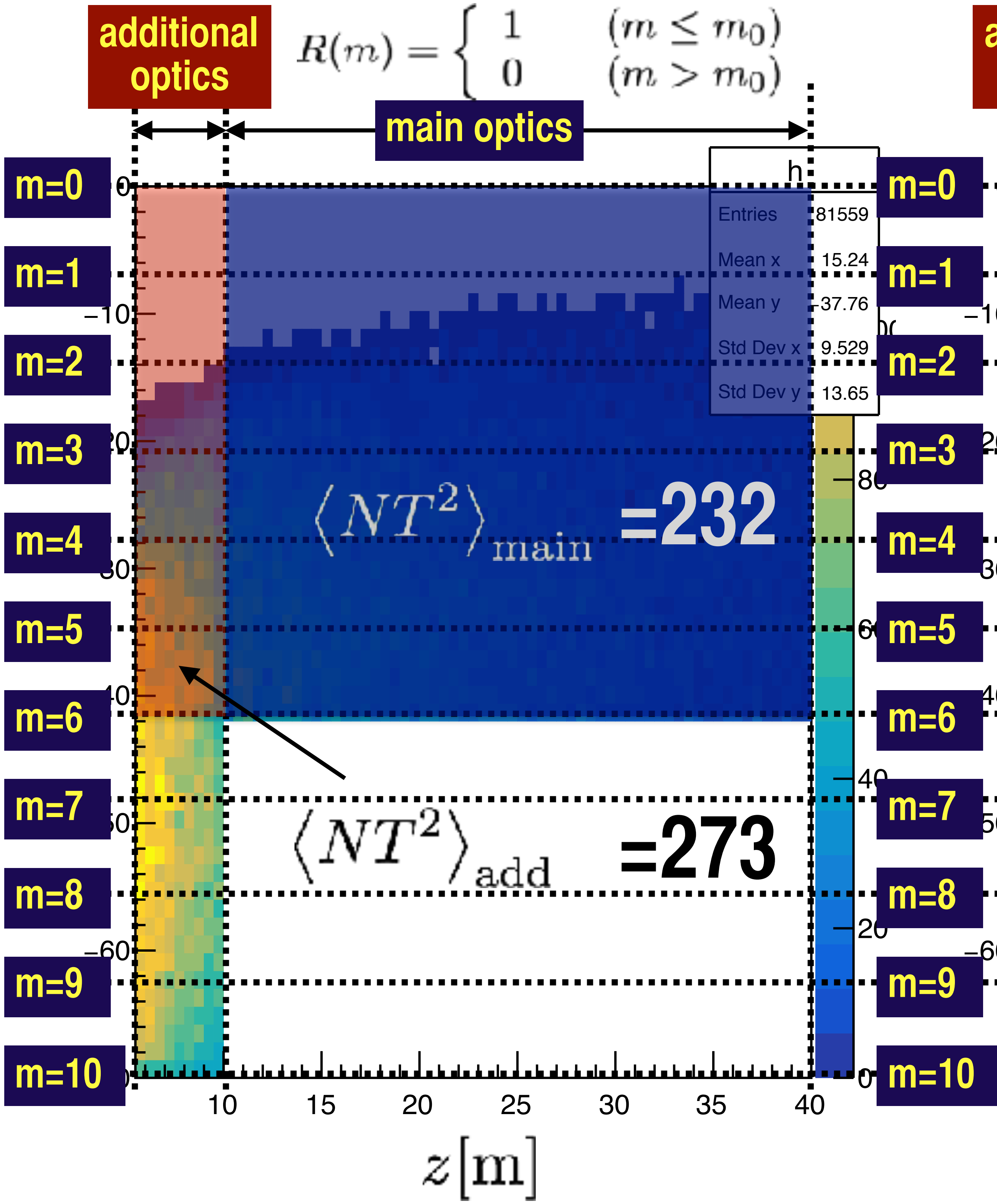

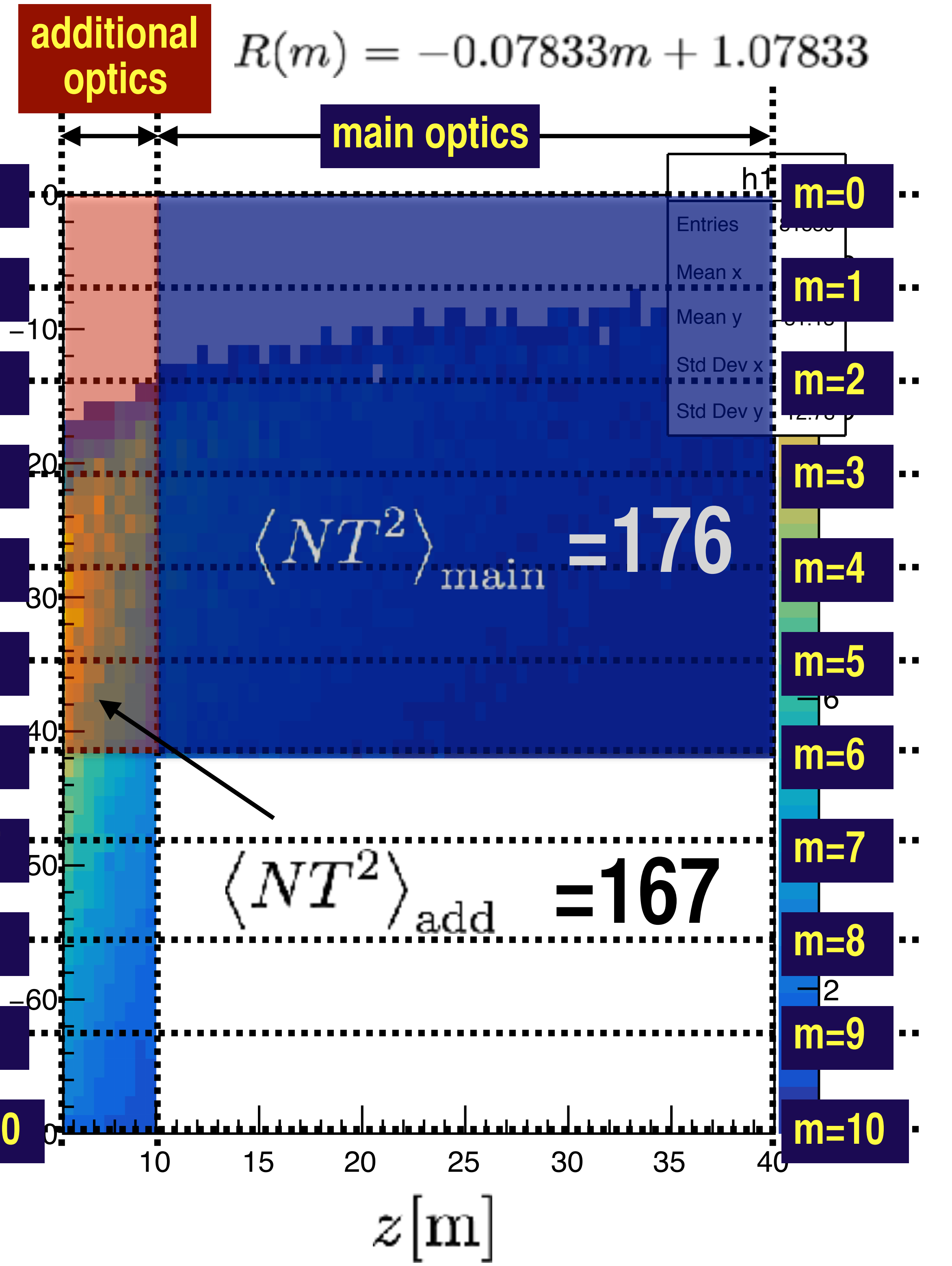

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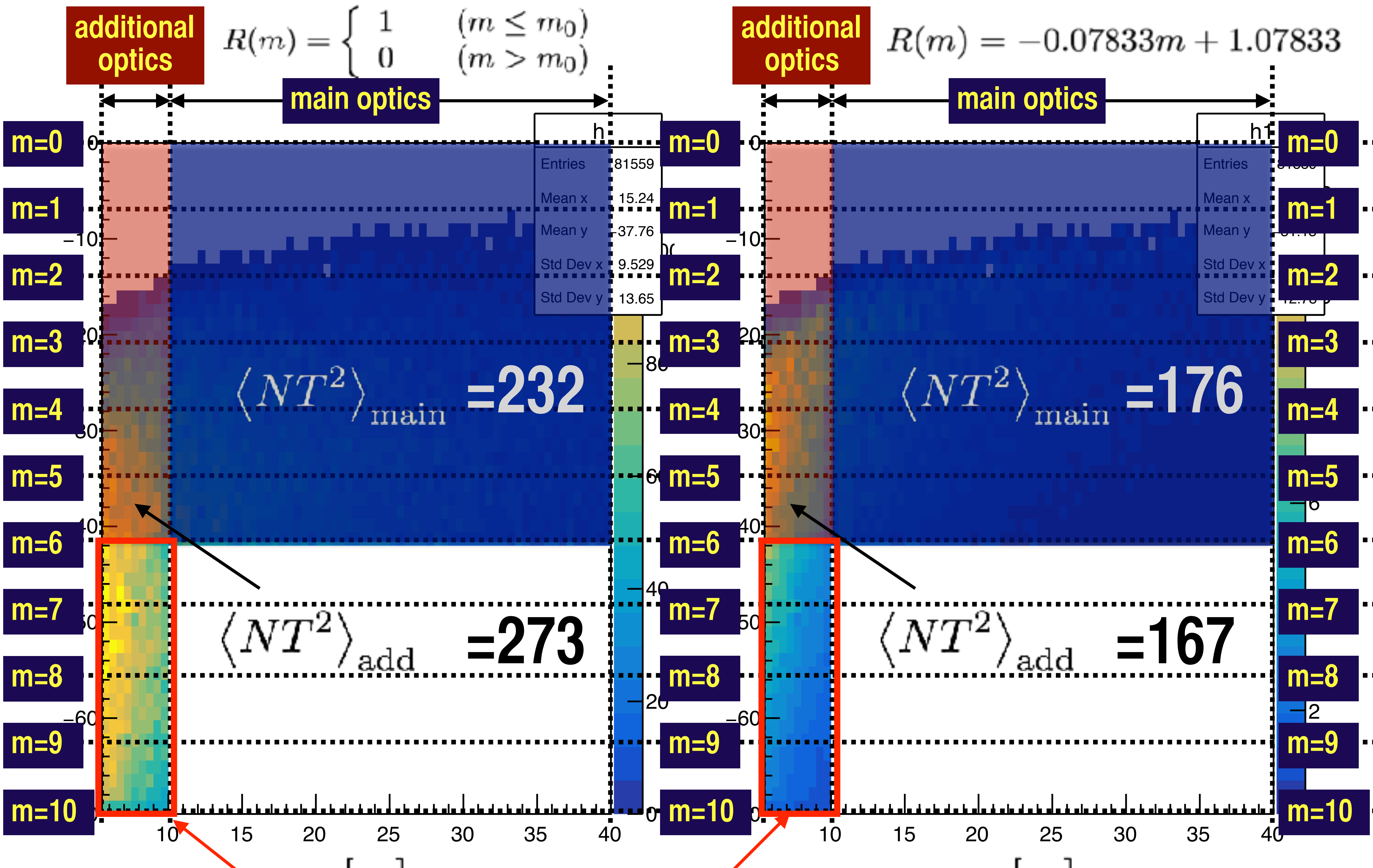

Most of neutrons in this region are fast, they do not contribute to NT² very much.
The contribution of the region of 6≤m≤10 is not very large.

by Kosuke NAGAMOTO

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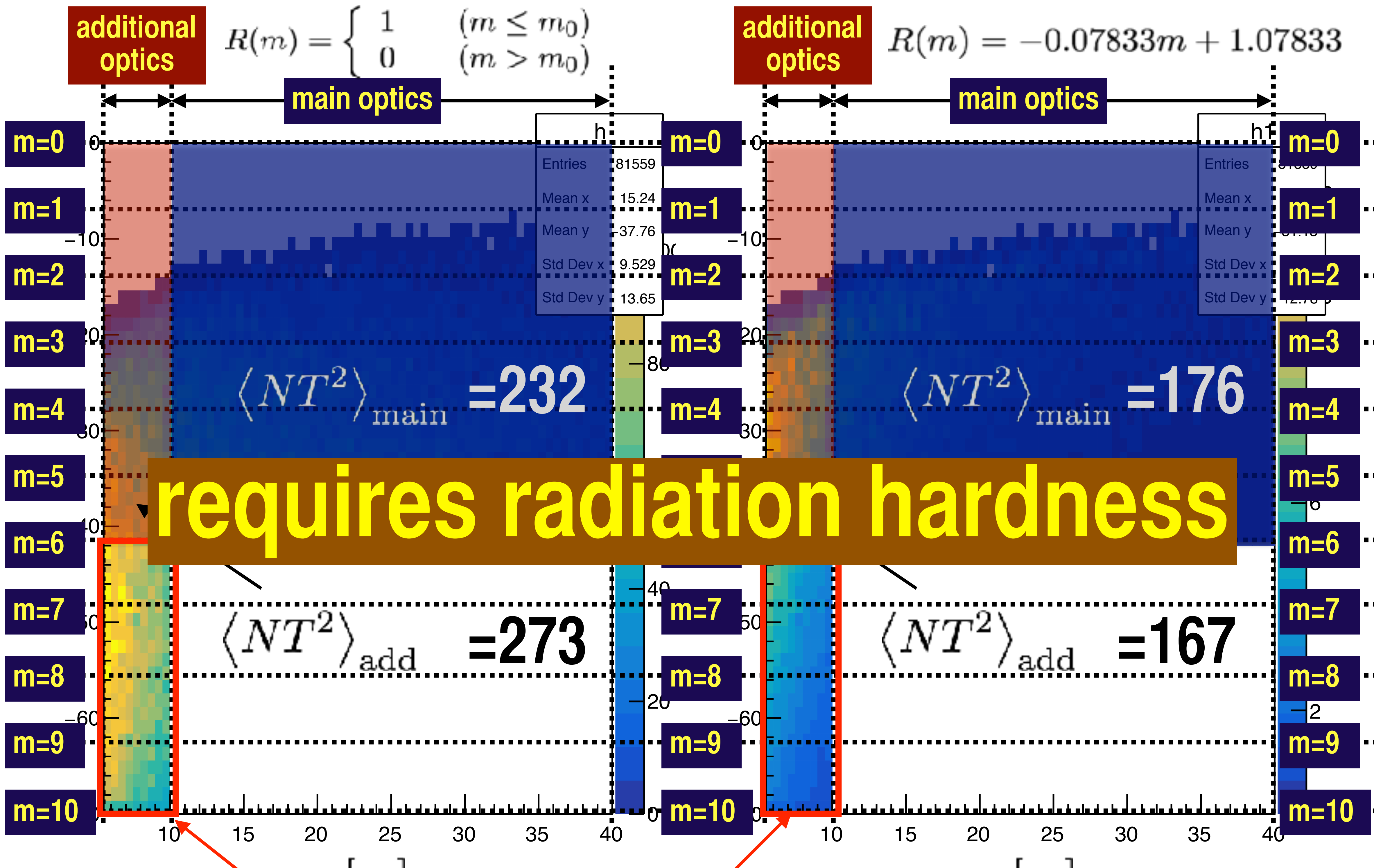

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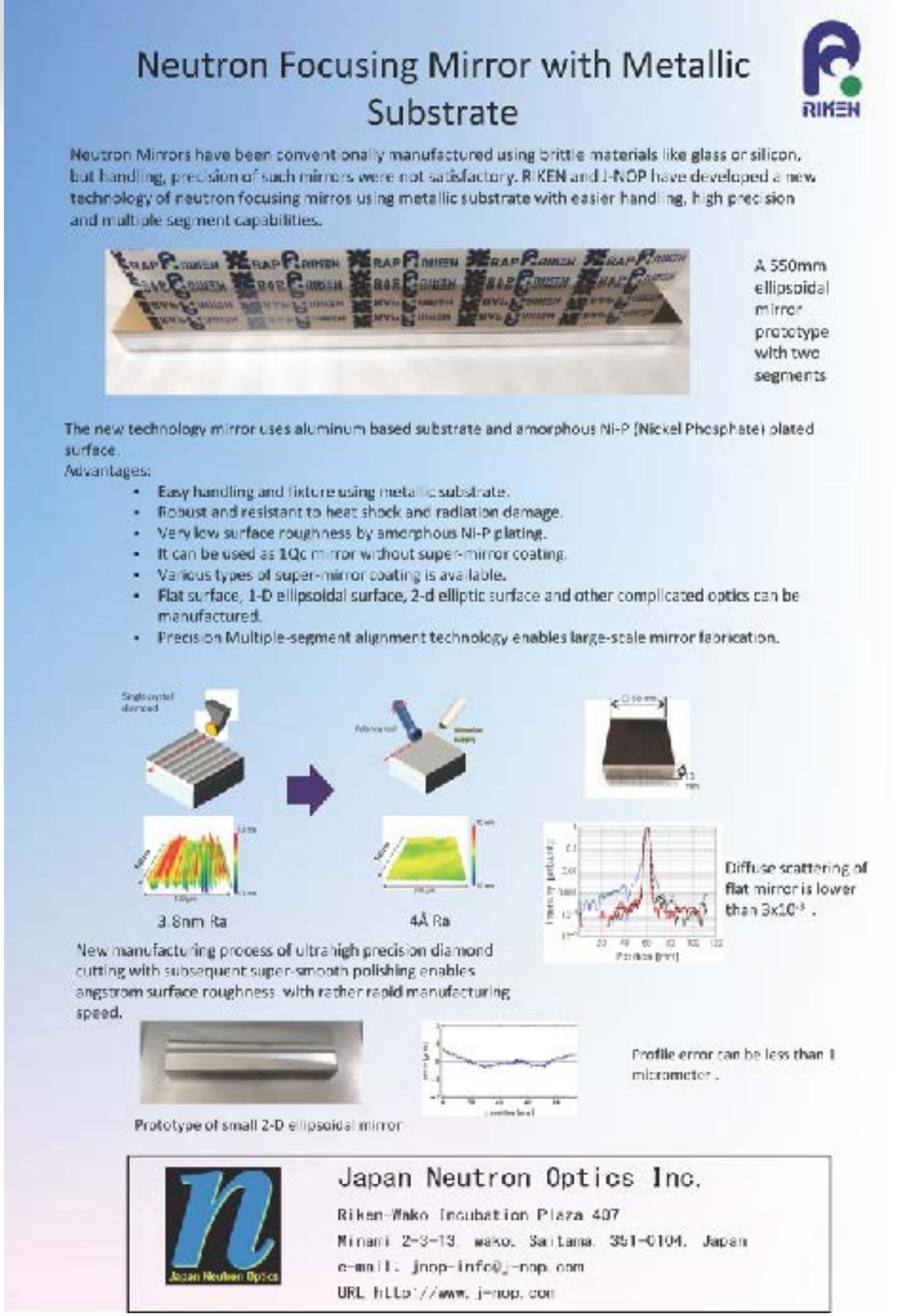
Metal Substrate Multilayer Mirror

Yutaka YAMAGATA*, Jiang GUO*, Shin-ya MORITA*, Jun-ichi KATO*, Katsuya HIROTA*, Yoshie OTAKE**, Atsushi TAKETANI**, Sheng WANG**, Shin TAKEDA****, Masahiro HINO*** and Michihiro FURUSAKA****
*Ultrahigh Precision Optics Technology Team, RIKEN Center for Advanced Photonics (RAP), RIKEN, Japan
yamagata@riken.jp
**Neutron Beam Technology Team, RIKEN Center for Advanced Photonics, RIKEN, Japan
***Kyoto University Research Reactor Institute
**** Hokkaido University

Metal-Substrate Multilayer Mirror
(catalogued by J-NOP Inc.)

Aluminum substrate with amorphous Ni-P plated surface

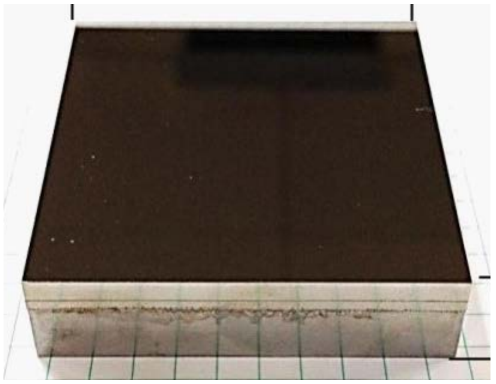
Advantages:
- Easy handling and fixture
- Robust and resistant to heat shock and radiation damage
- Very low surface roughness
- Usable as m=1 mirror without supermirror coating
- **Full numerical control**: flat surface, 1-D ellipsoidal surface, 2-d elliptic surface and other complicated optics
- **Precision multiple-segment alignment technology enables large-scale mirror fabrication**



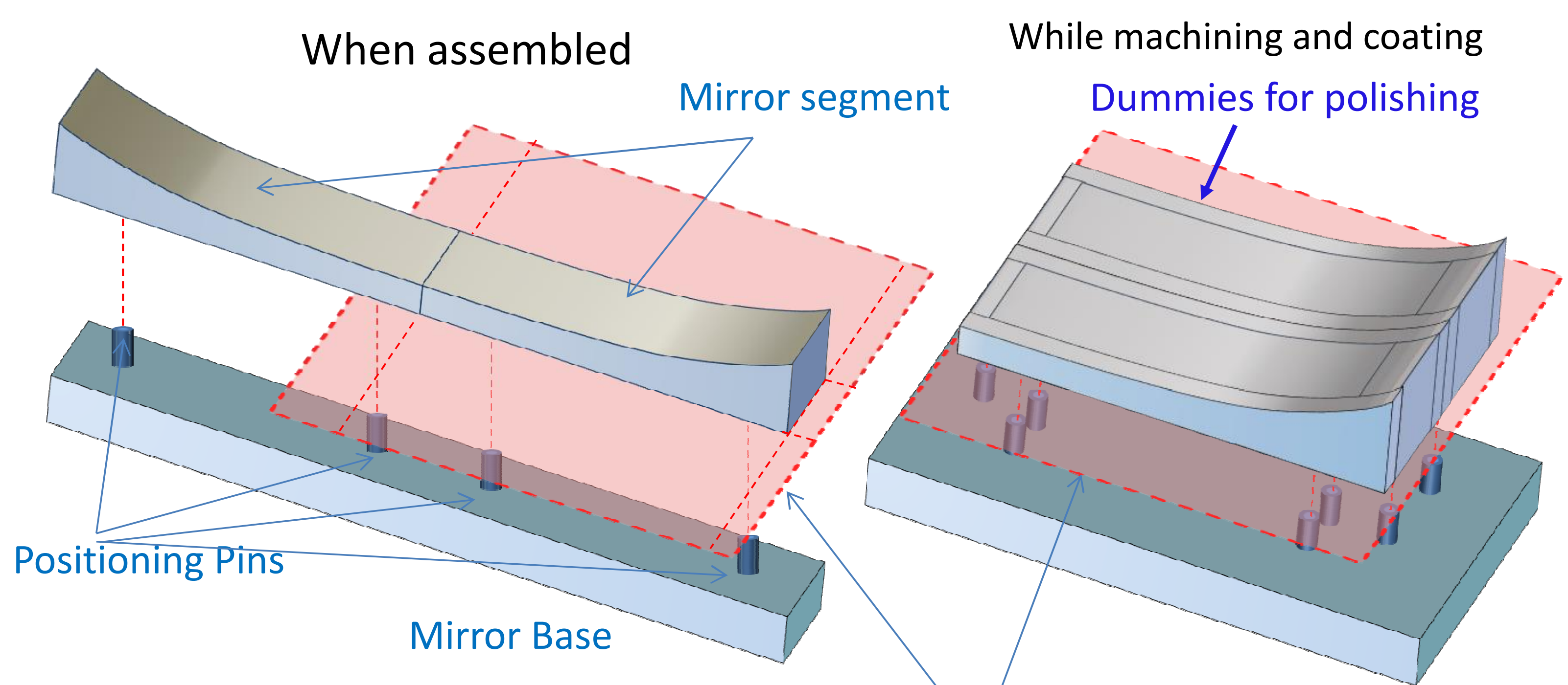
cf.) This technique can be applied to stainless steel substrate, glass substrate, ..., if necessary.

Neutron Optics

Metal substrate mirror

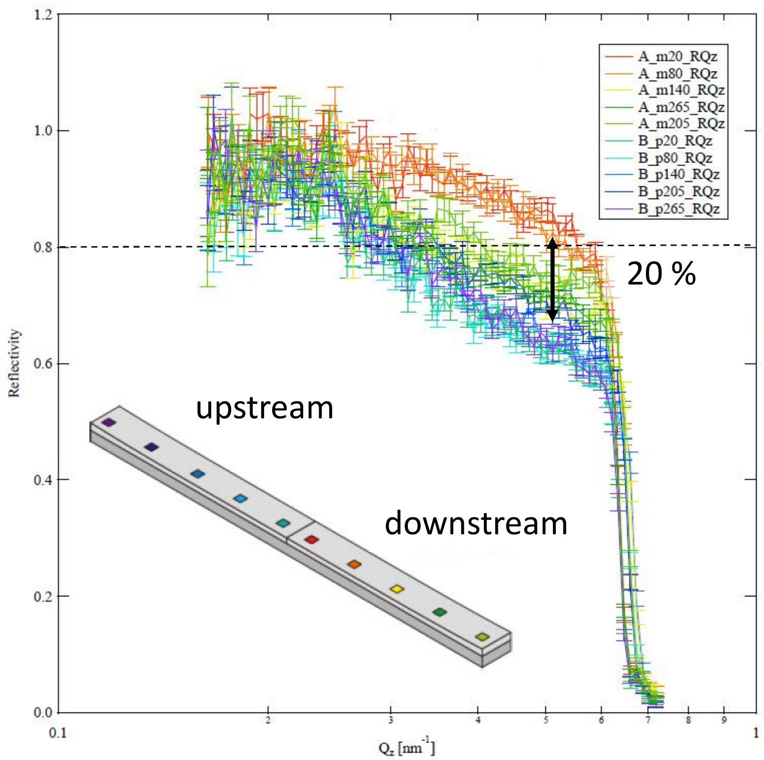


Fabrication method for multi-segmented mirror

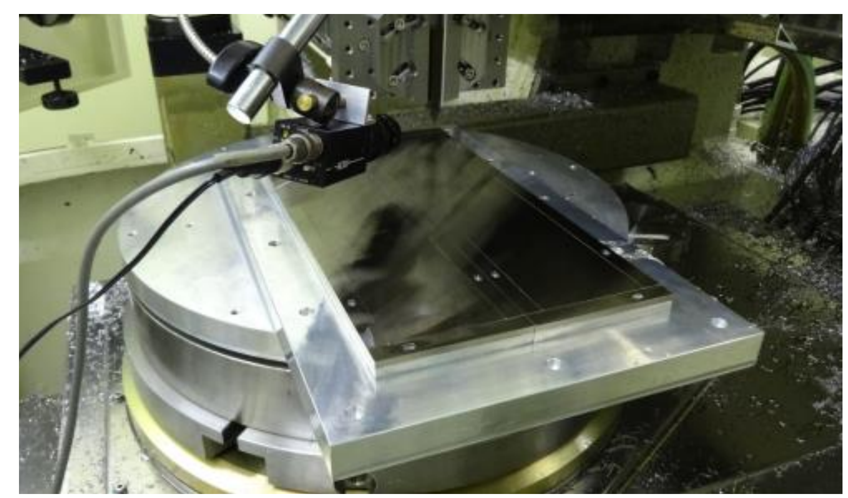


Alignment of mirror segments are controlled by positioning pins

Segment size is limited by coating chamber capacity.



- Reflectivity of several parts showed as high reflectivity as glass substrate mirrors
- Reflectivity decrease are due to surface contamination by polishing abrasives



- **R&D in progress under the collaboration among PSI, RIKEN and KUR.**

Summary 1

Additional optics doubles the FOM.

$<NT^2>_{main} \sim <NT^2>_{add}$

If we use only the additional optics,
the flight-path radius can be reduced.

a thinner vacuum tube

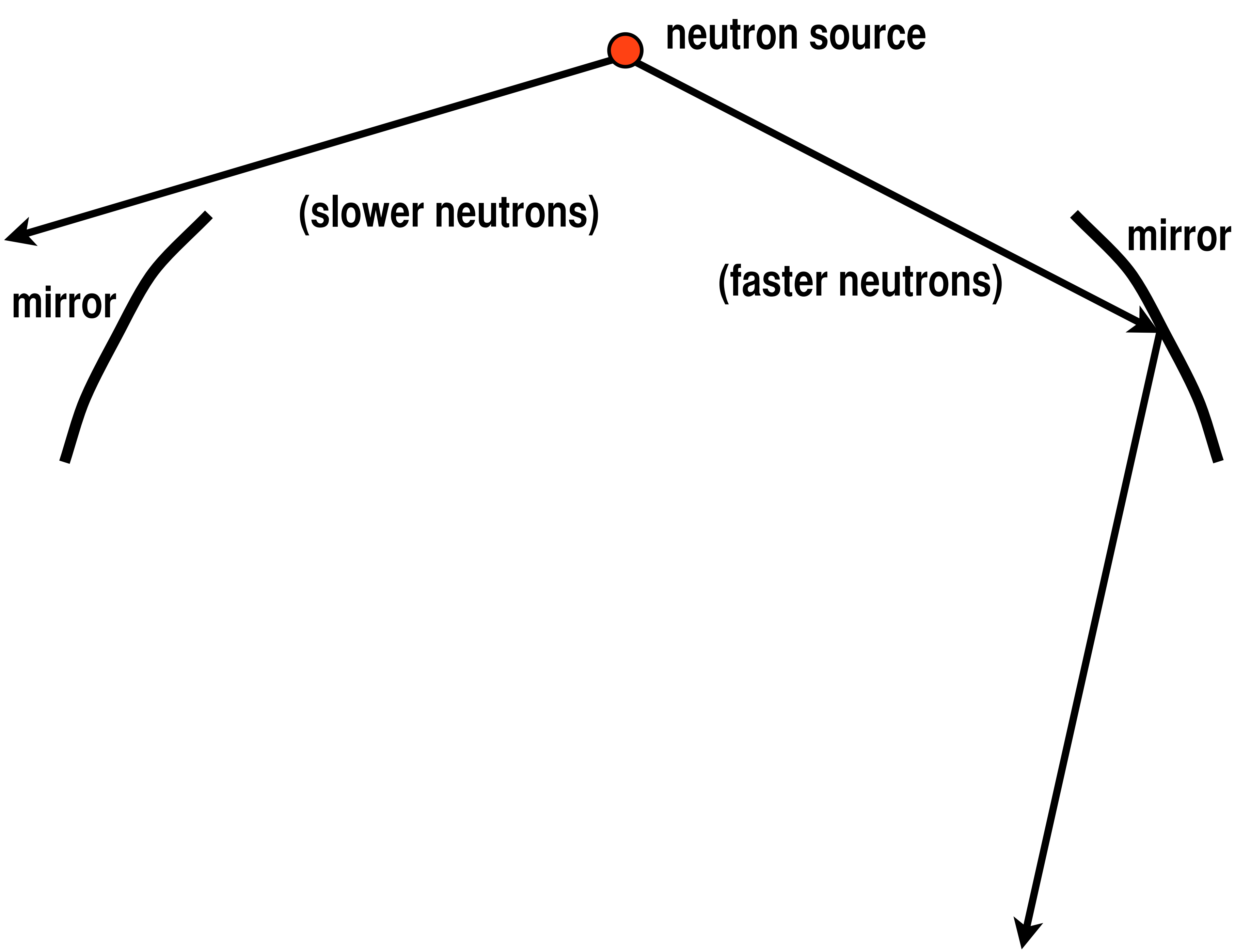
a smaller magnetic shield

cost effective

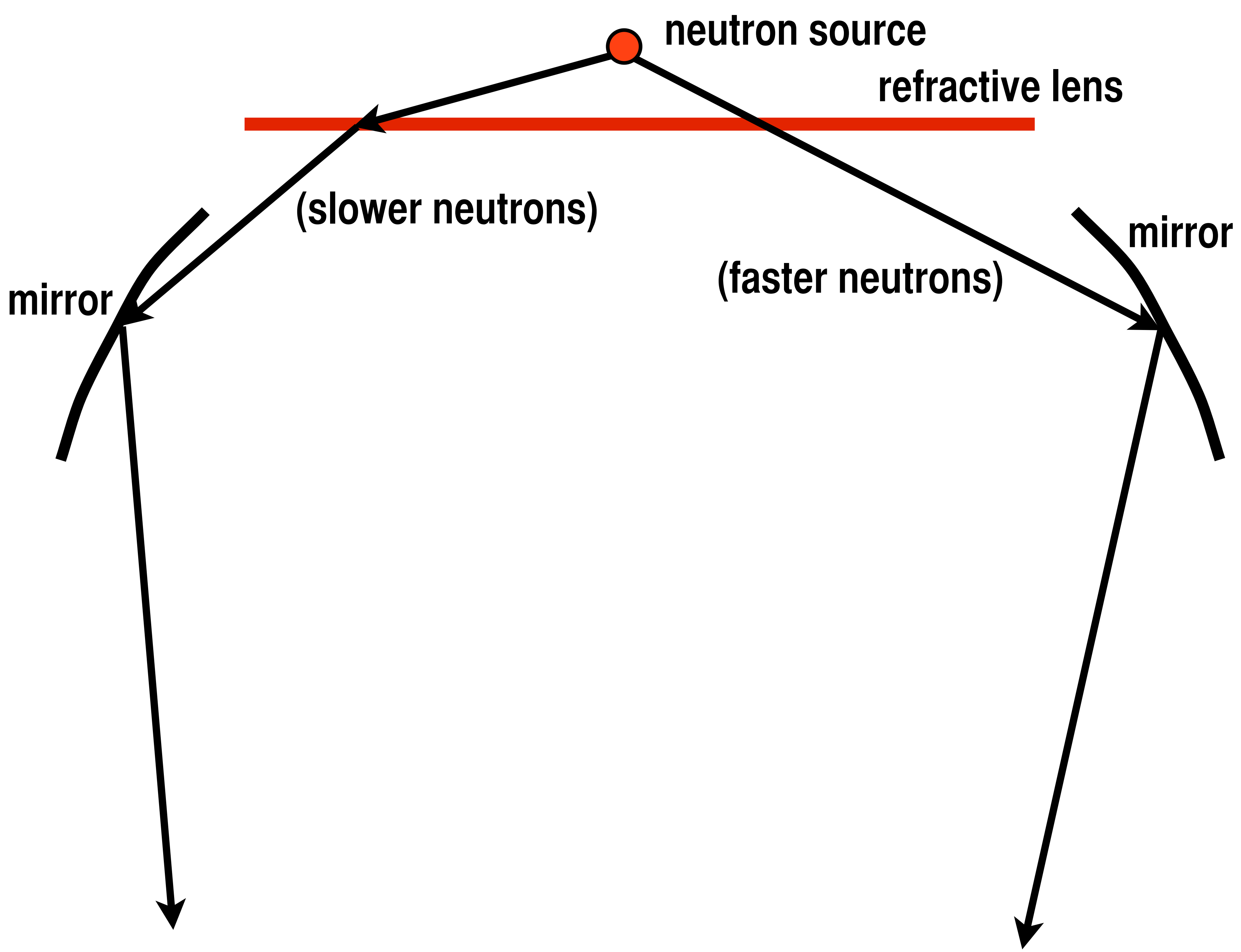
a discussion for more acceptance

Auxiliary Optics
for an additional acceptance

Refractive Lens
for Enlarging Effective Acceptance



Refractive Lens for Enlarging Effective Acceptance



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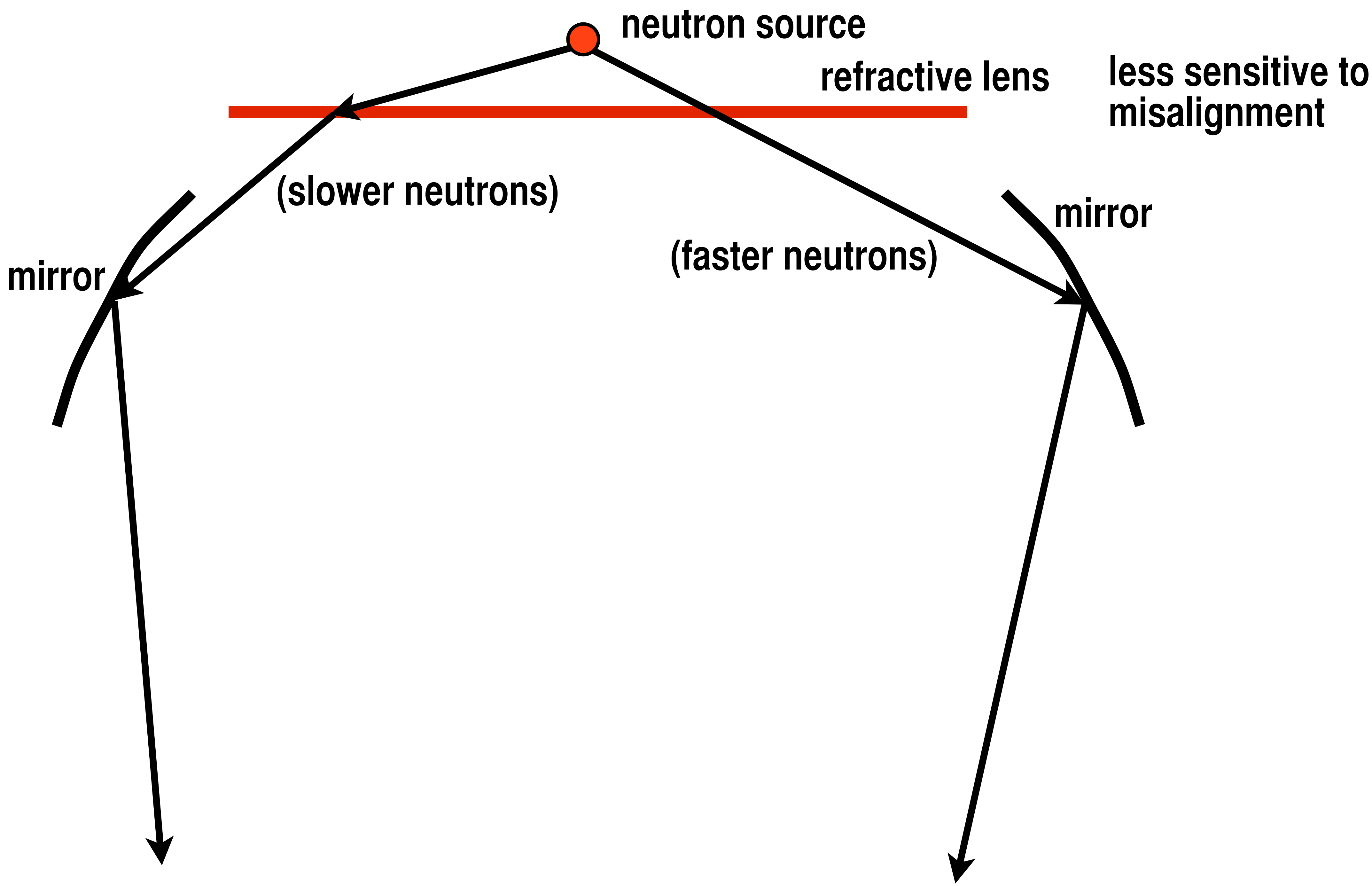

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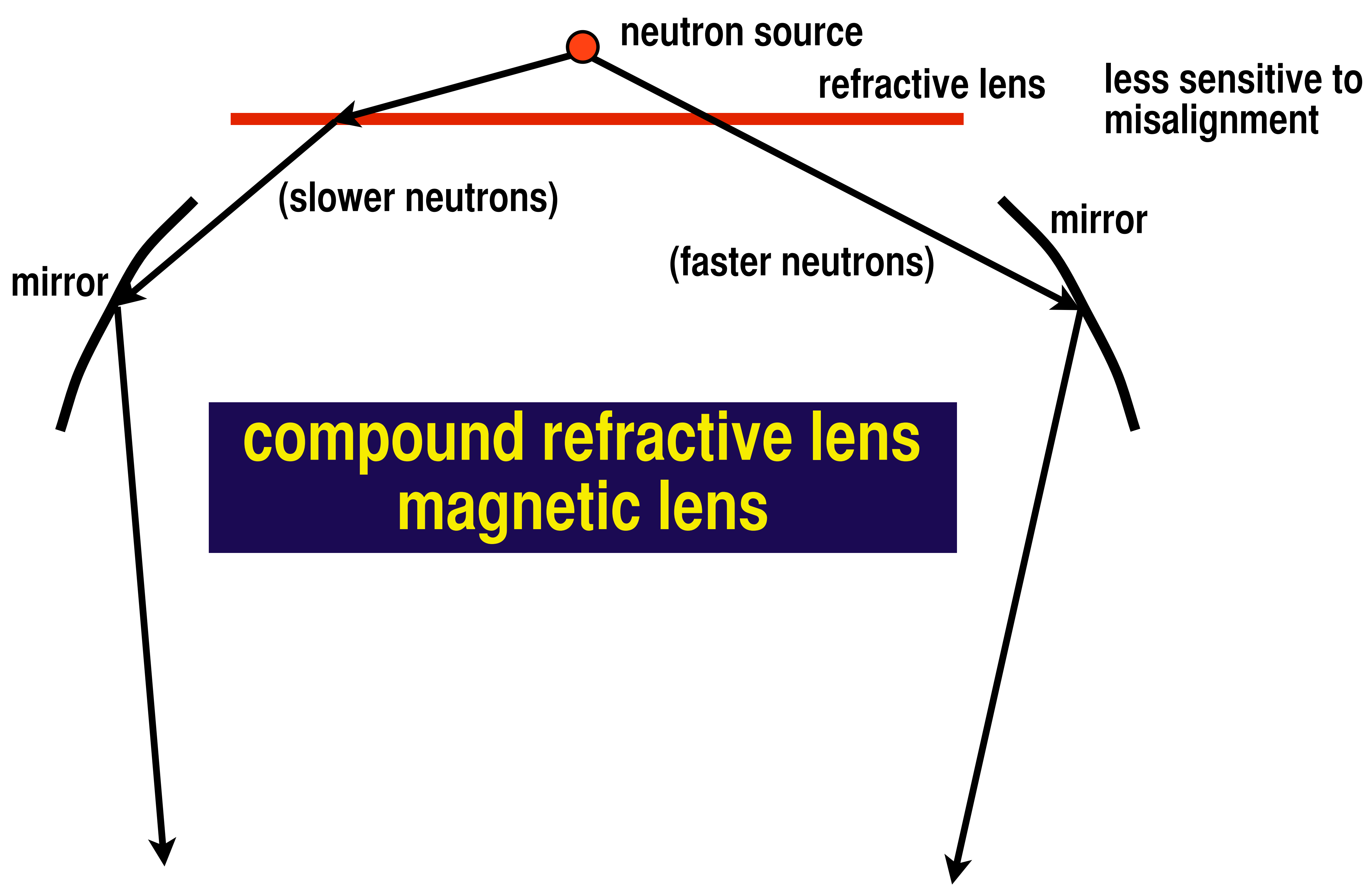

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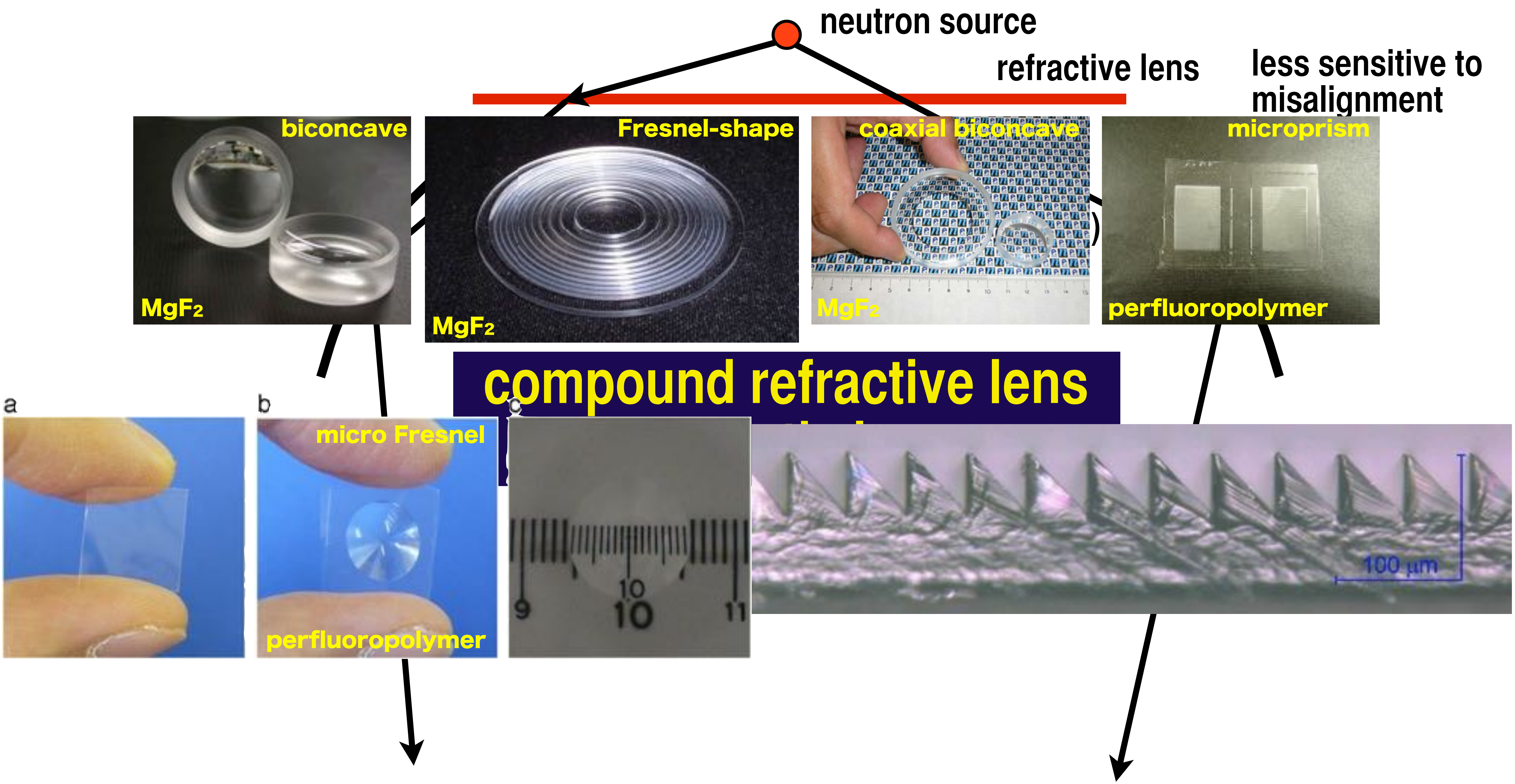
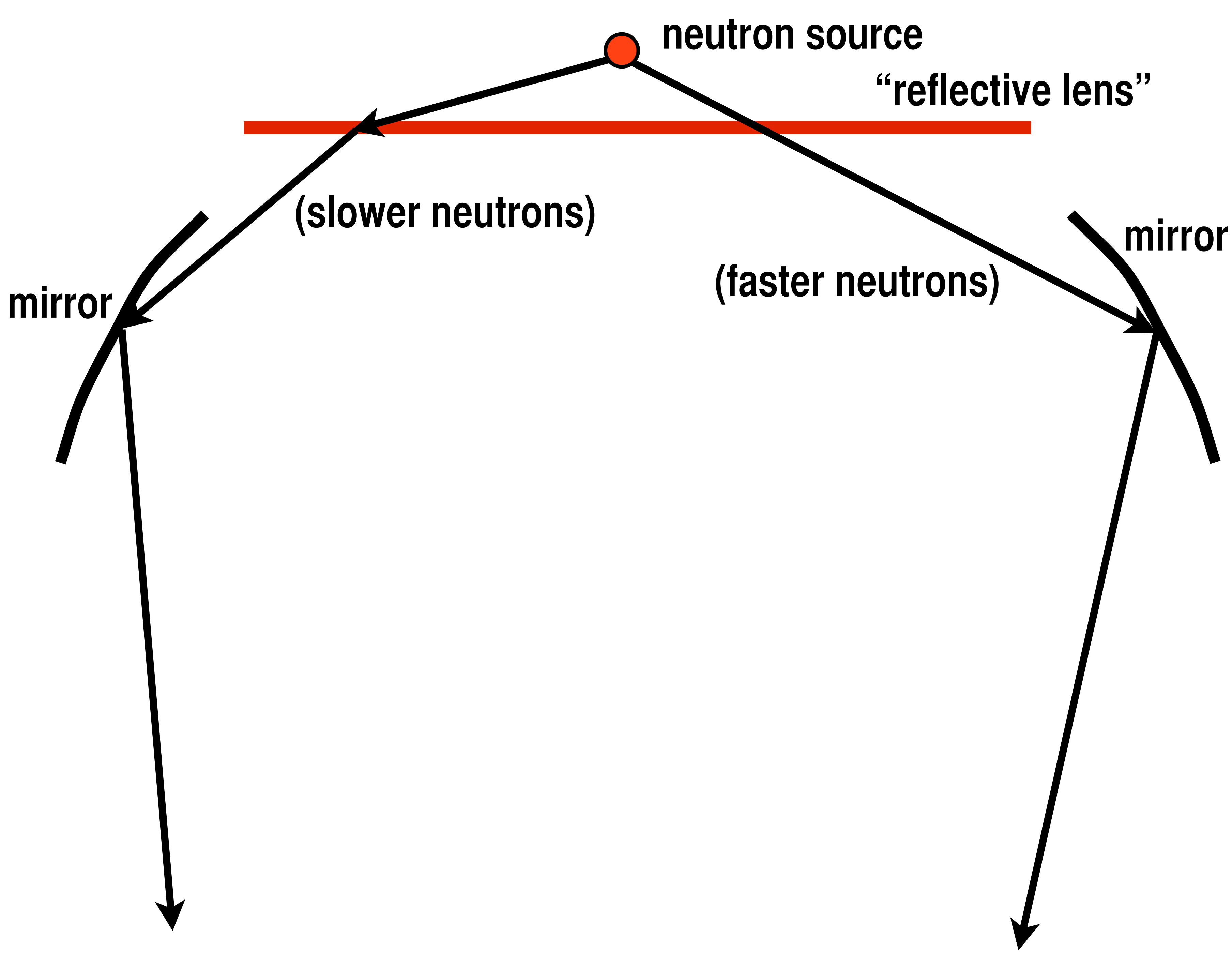
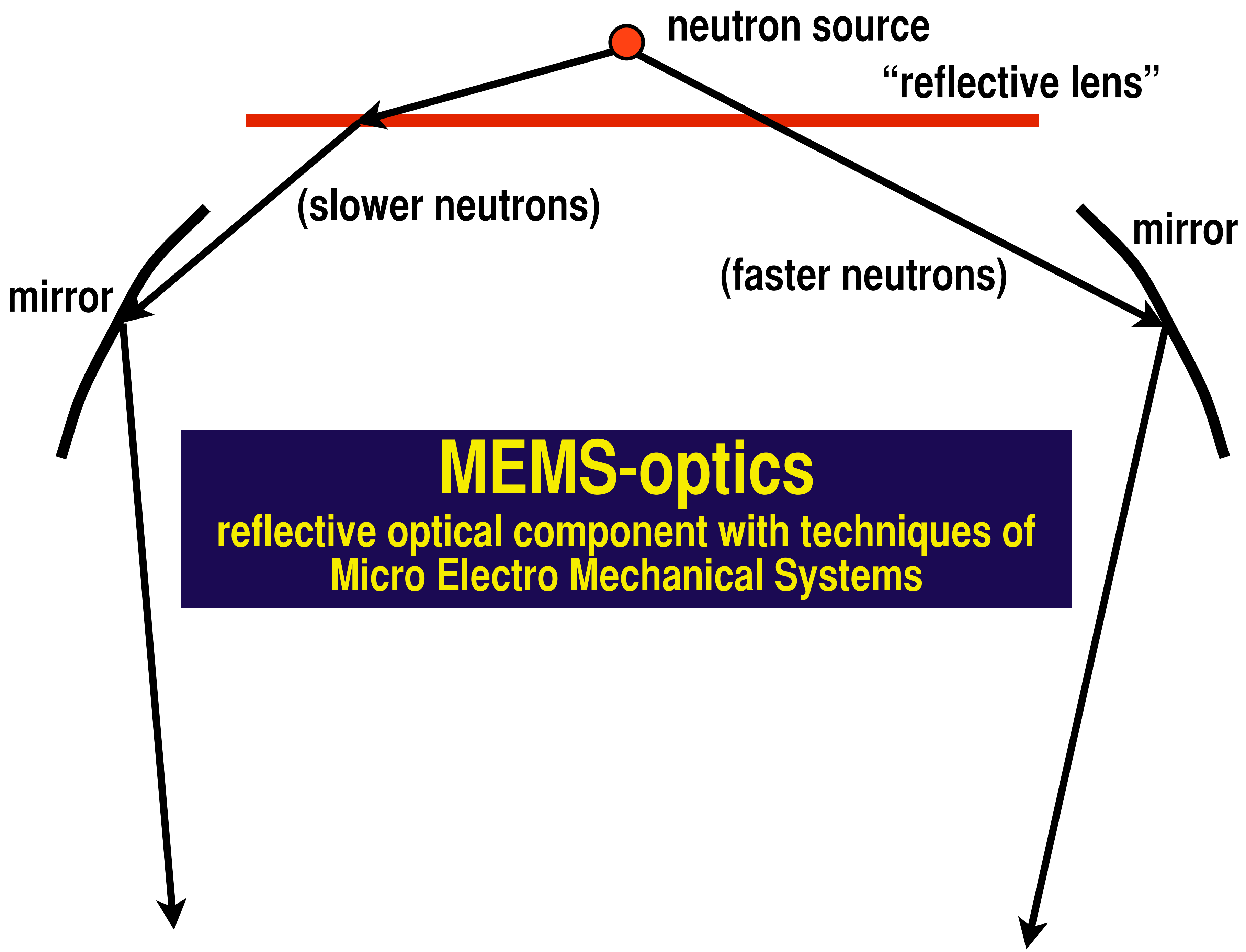


"Reflective Lens" for Enlarging Effective Acceptance

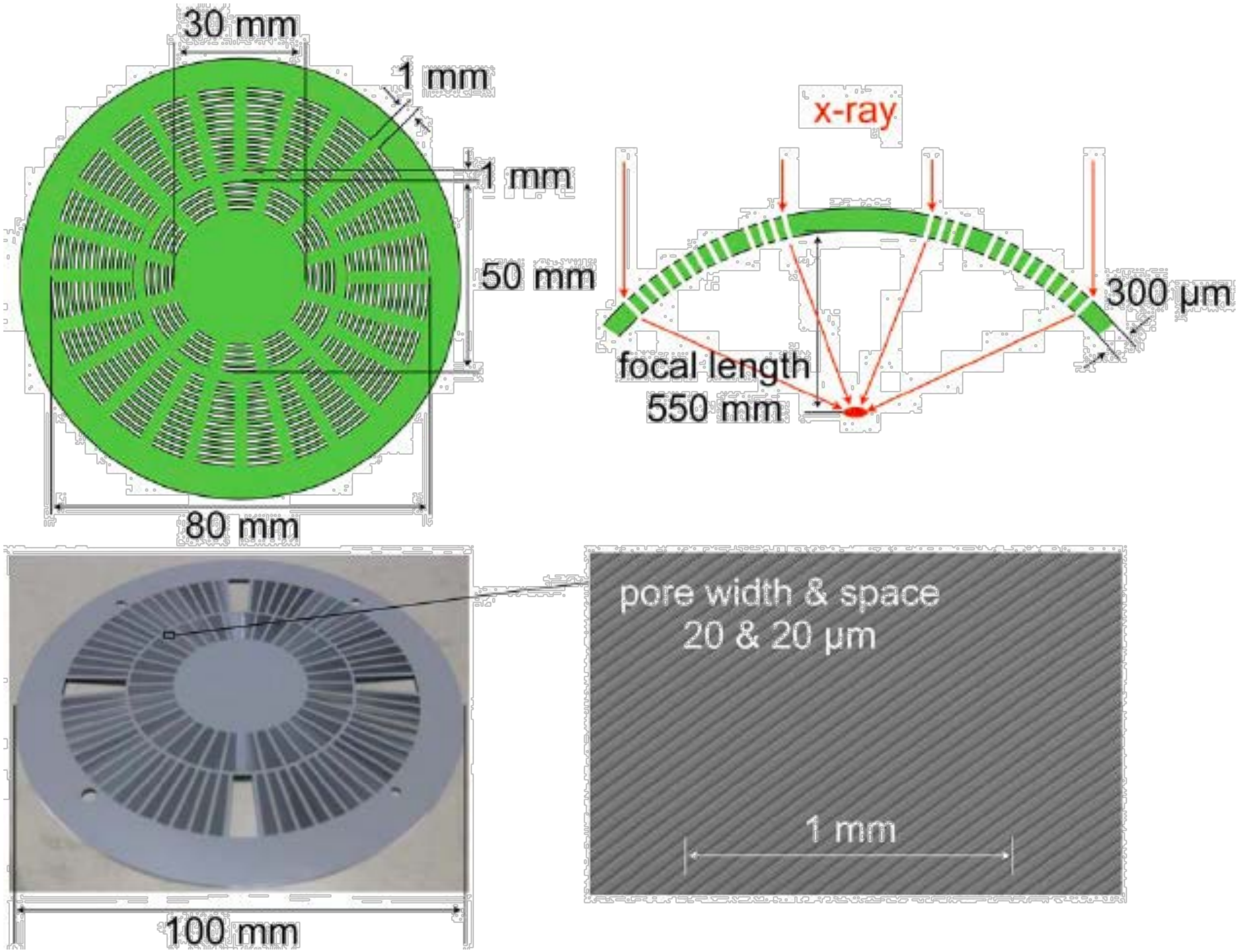


"Reflective Lens" for Enlarging Effective Acceptance



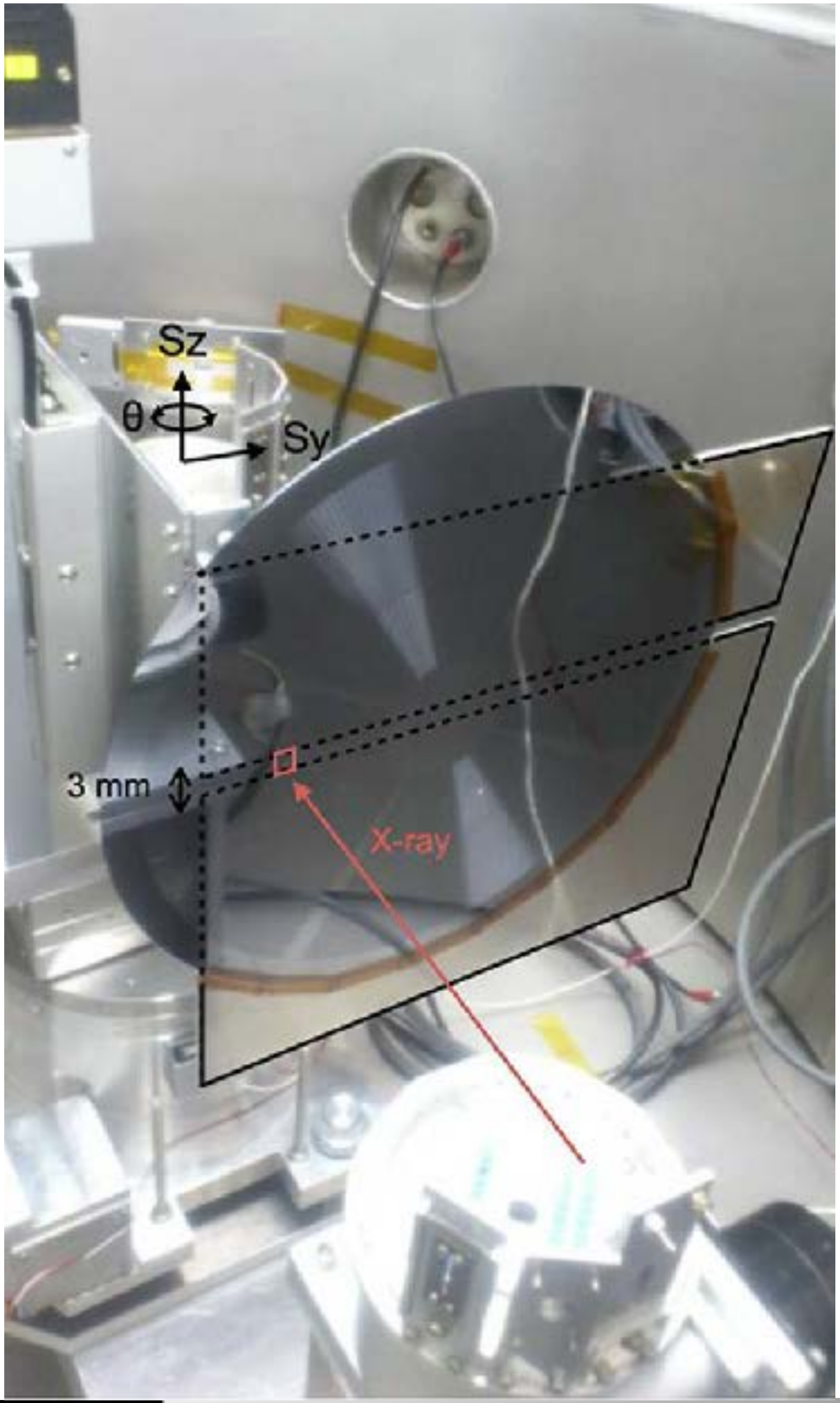
MEMS X-ray Lens

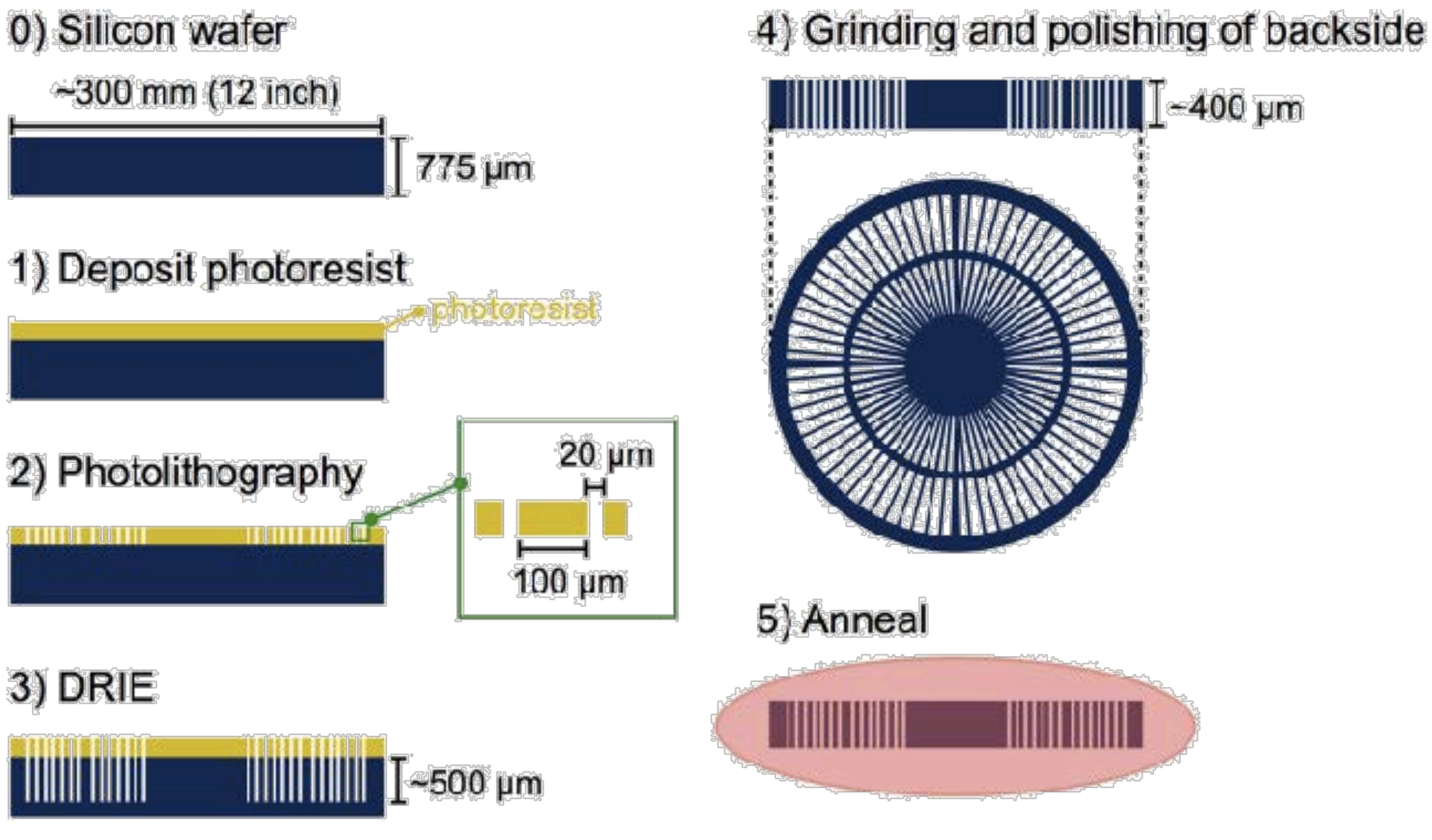
Y.Ezoe et al., Optics Letters 37 (2012) 779



MEMS X-ray Lens

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





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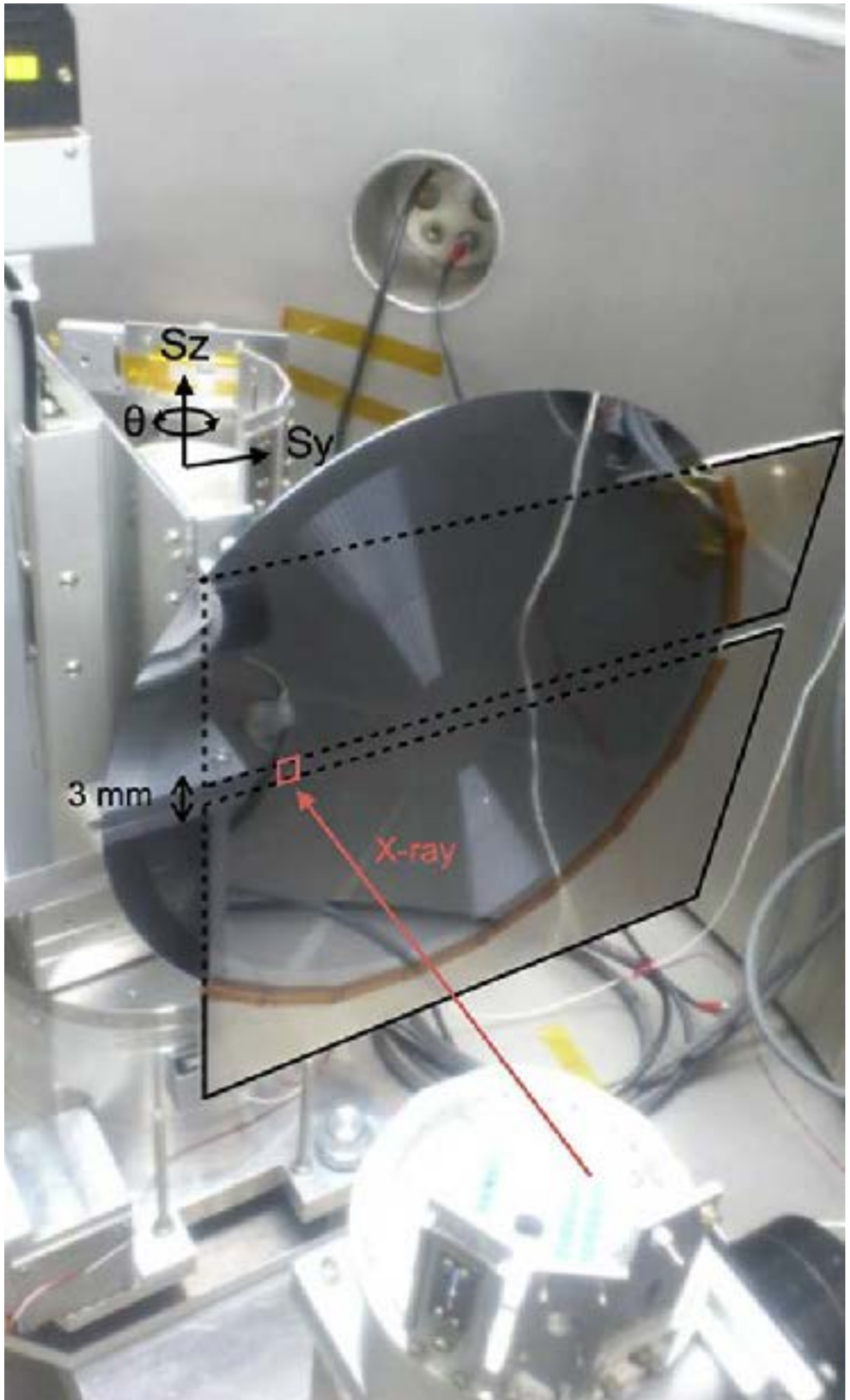

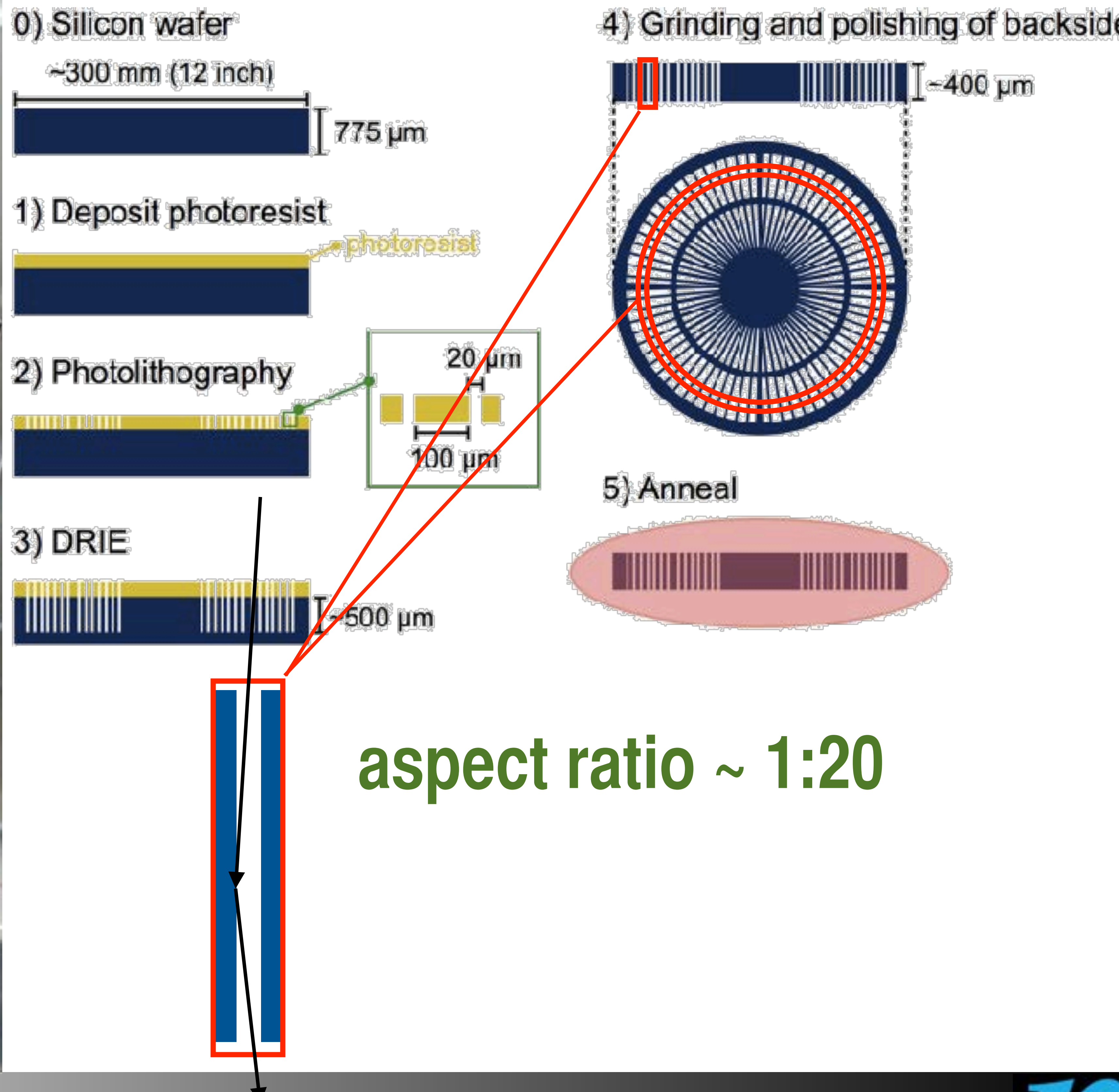

aspect ratio ~ 1:20

MEMS X-ray Lens

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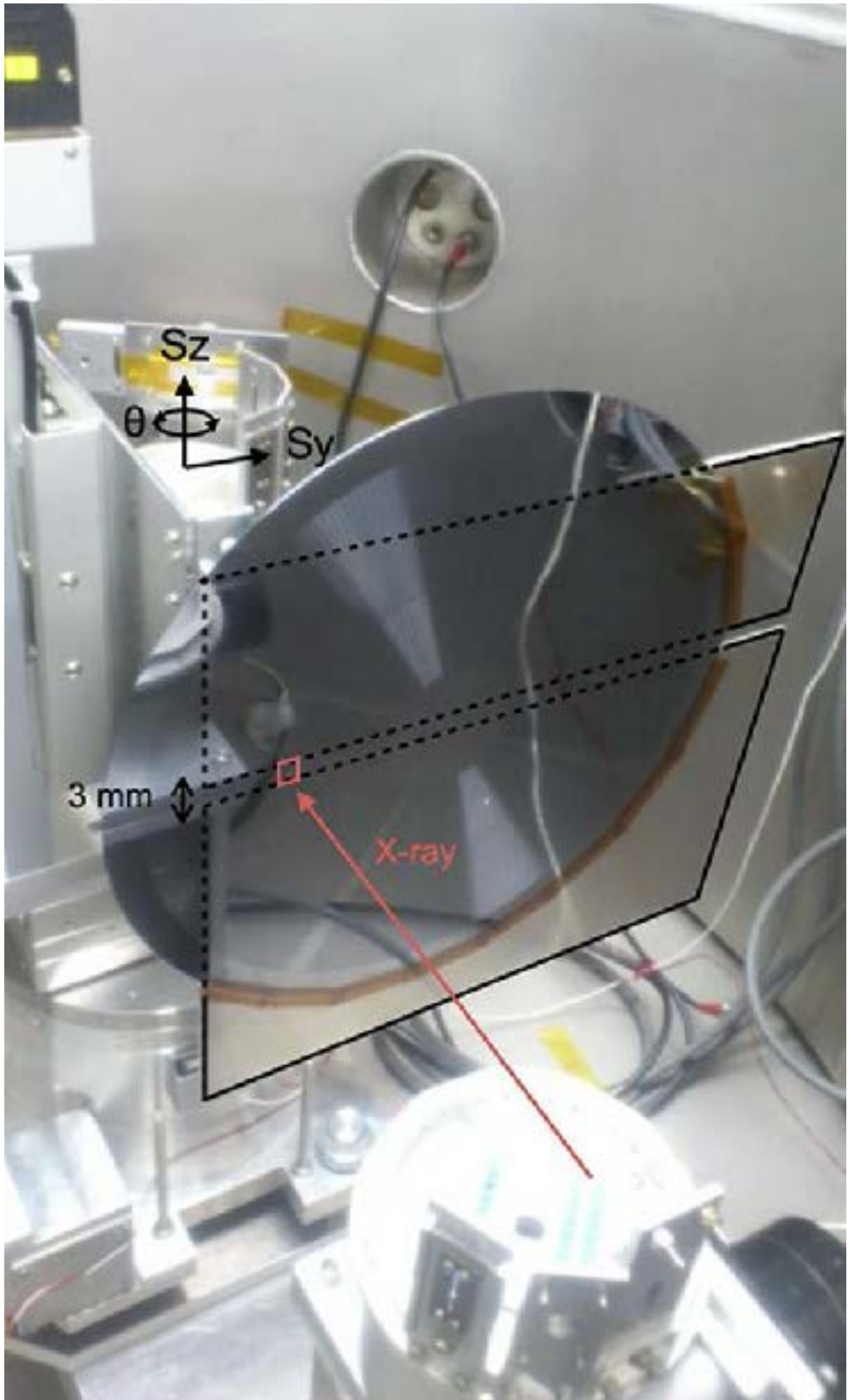
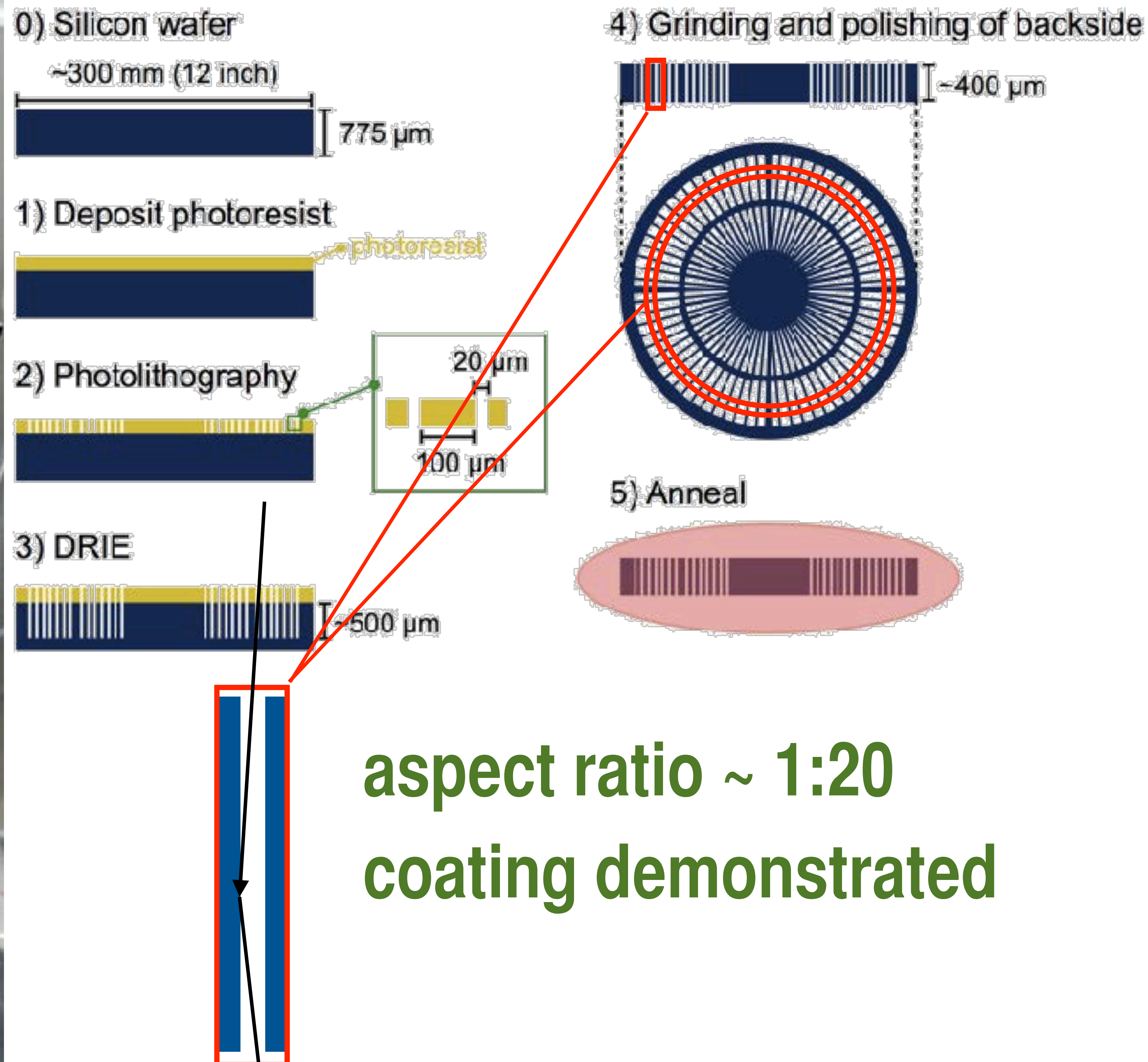
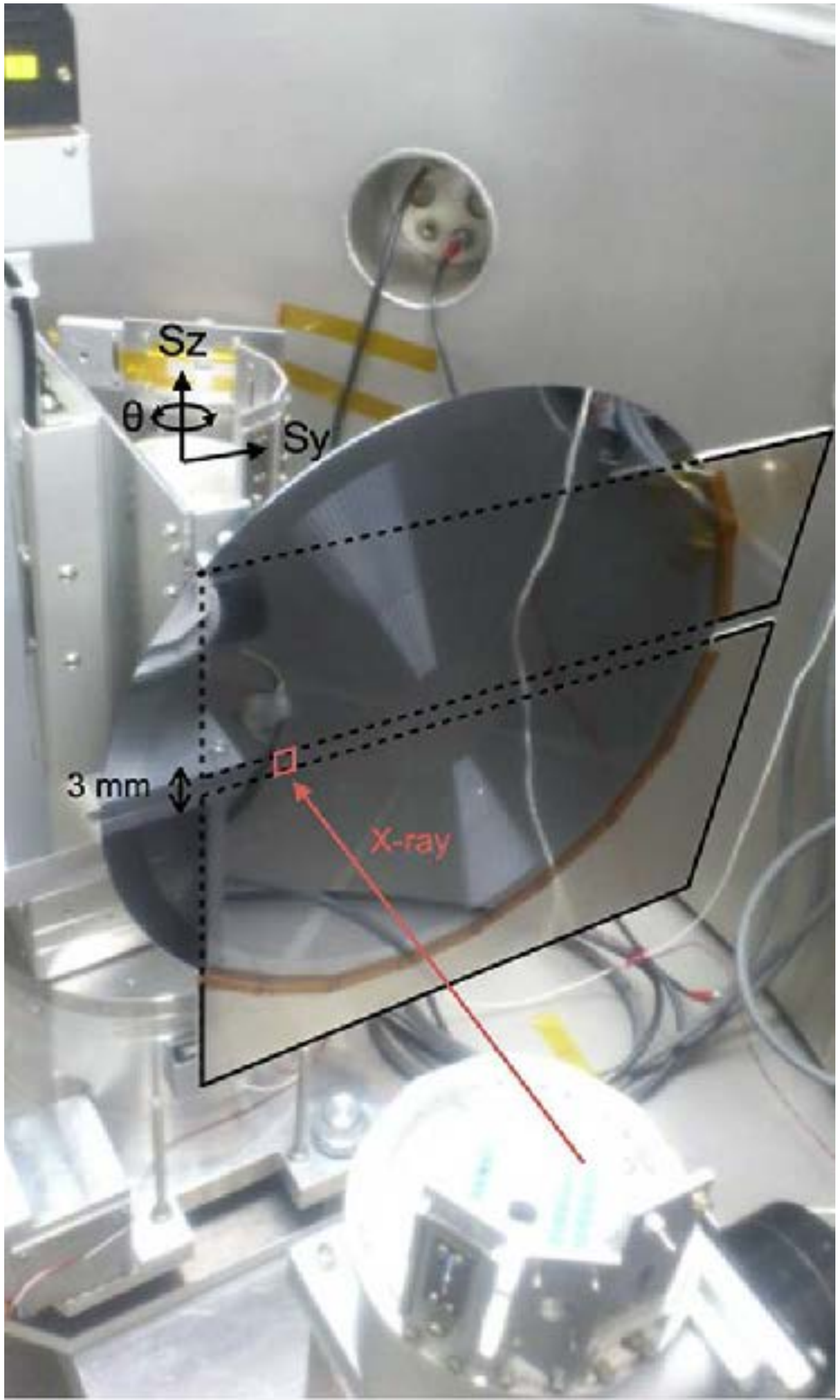


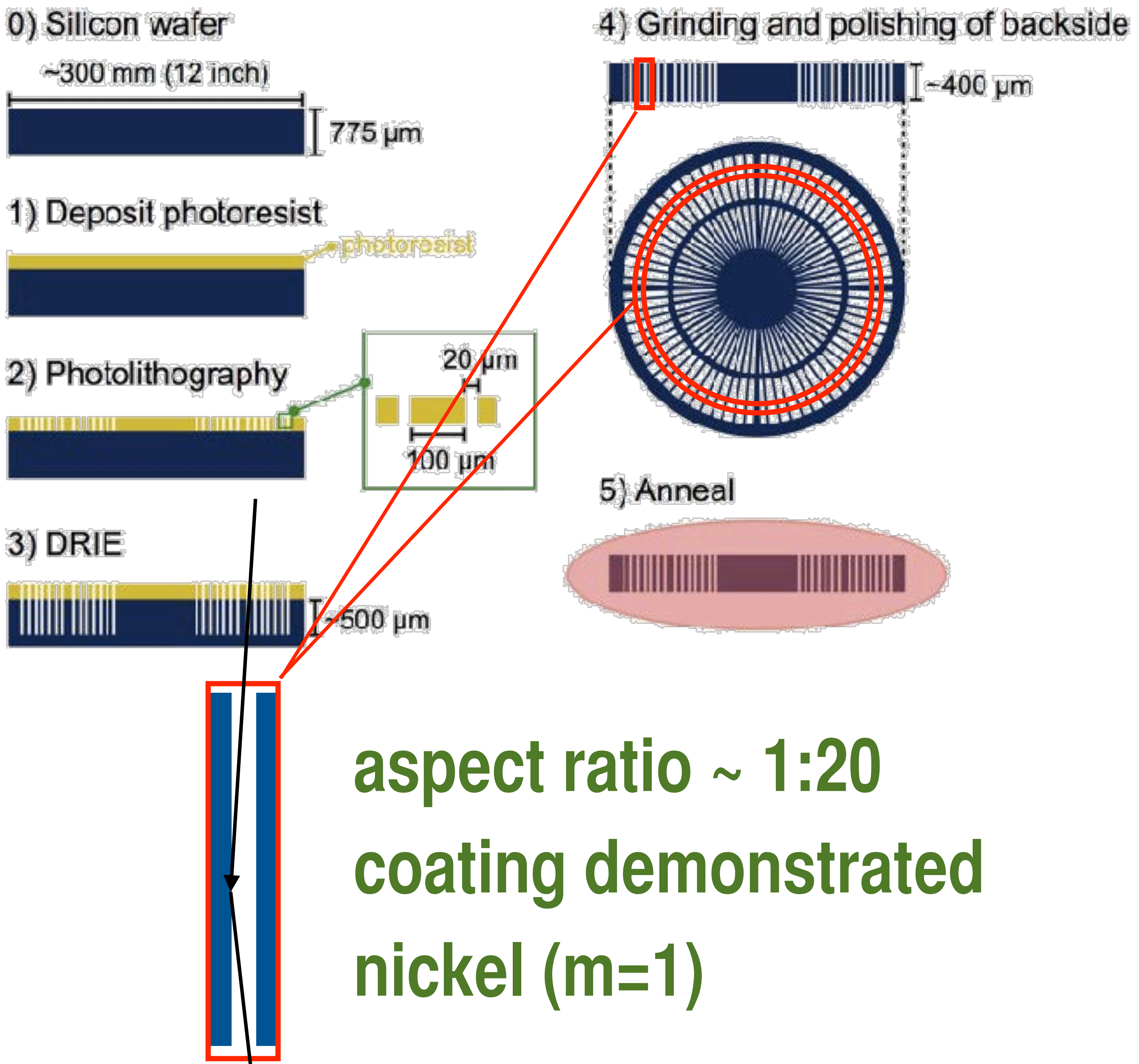


aspect ratio ~ 1:20
coating demonstrated

MEMS X-ray Lens

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

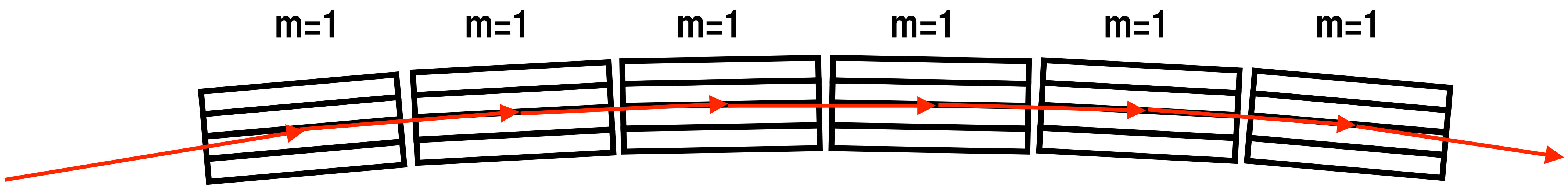


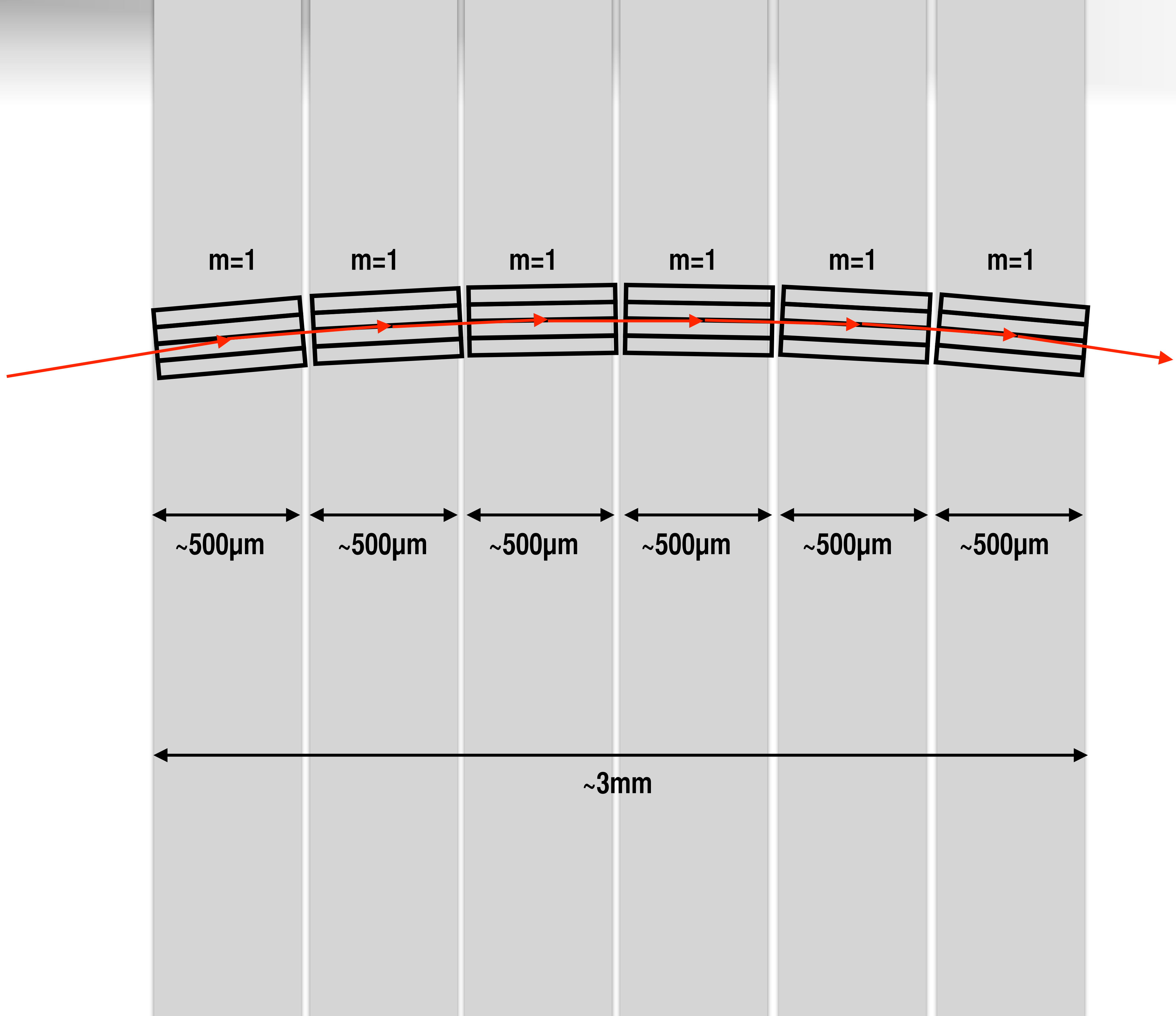


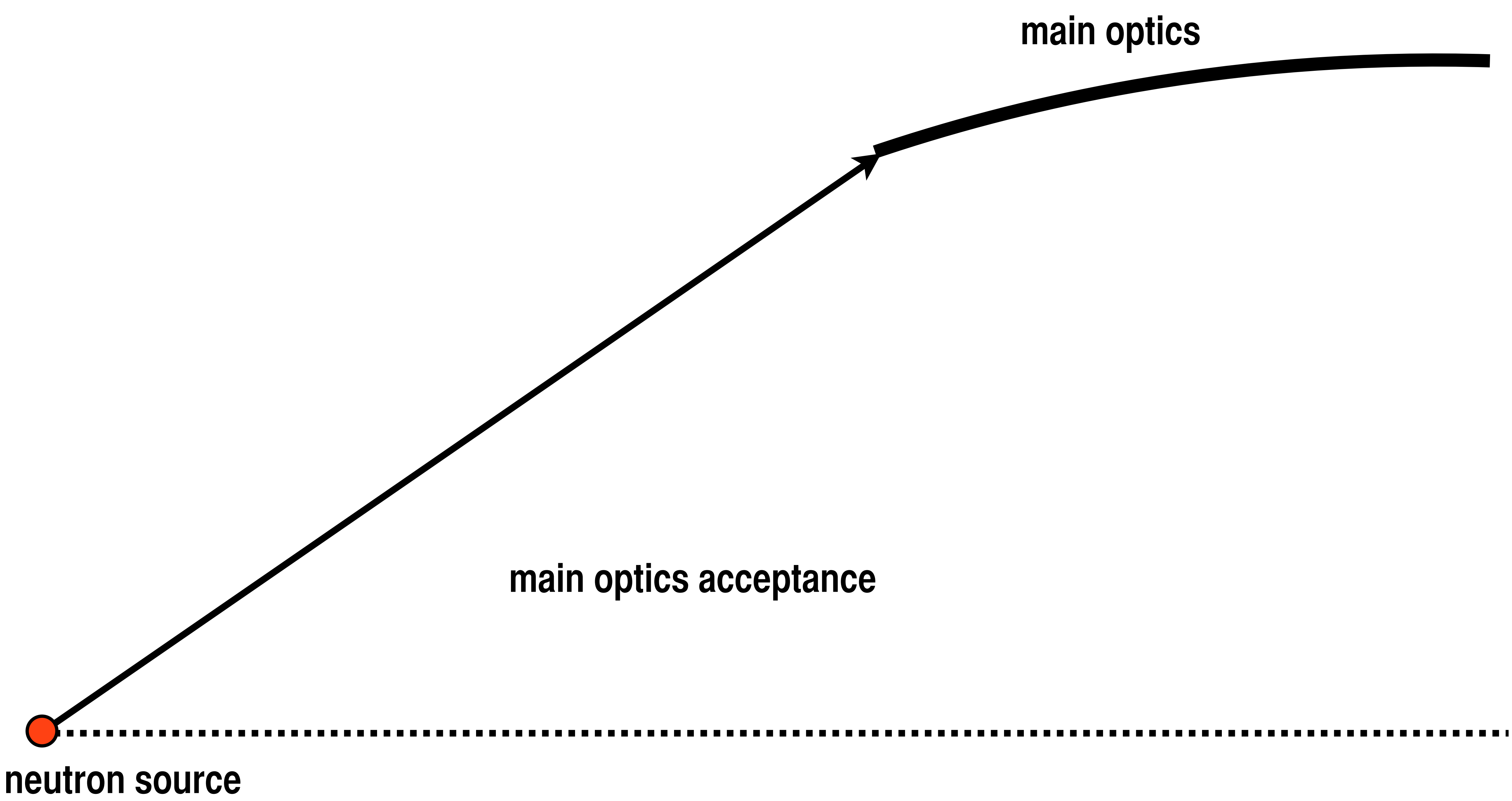
aspect ratio ~ 1:20

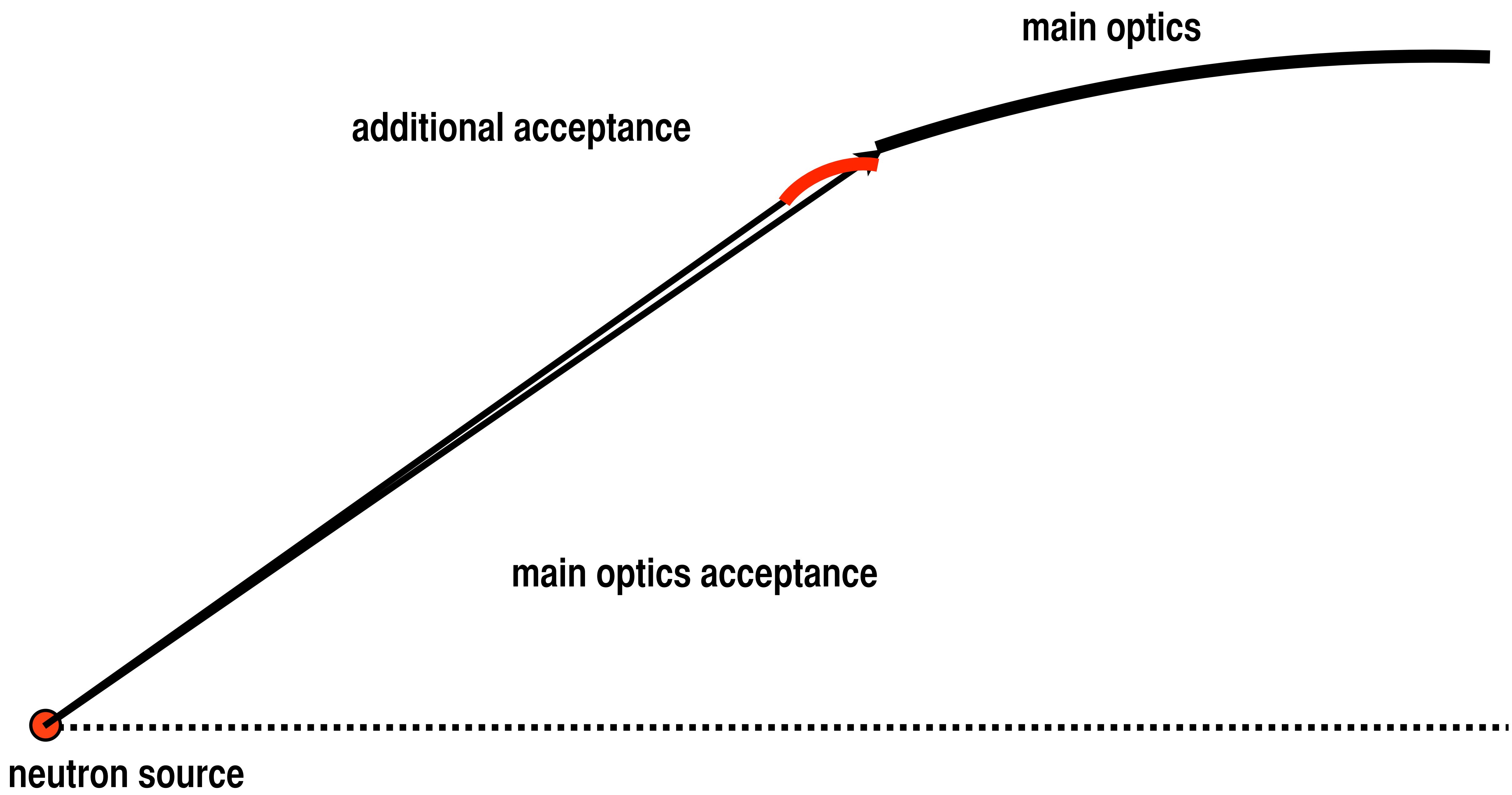
coating demonstrated

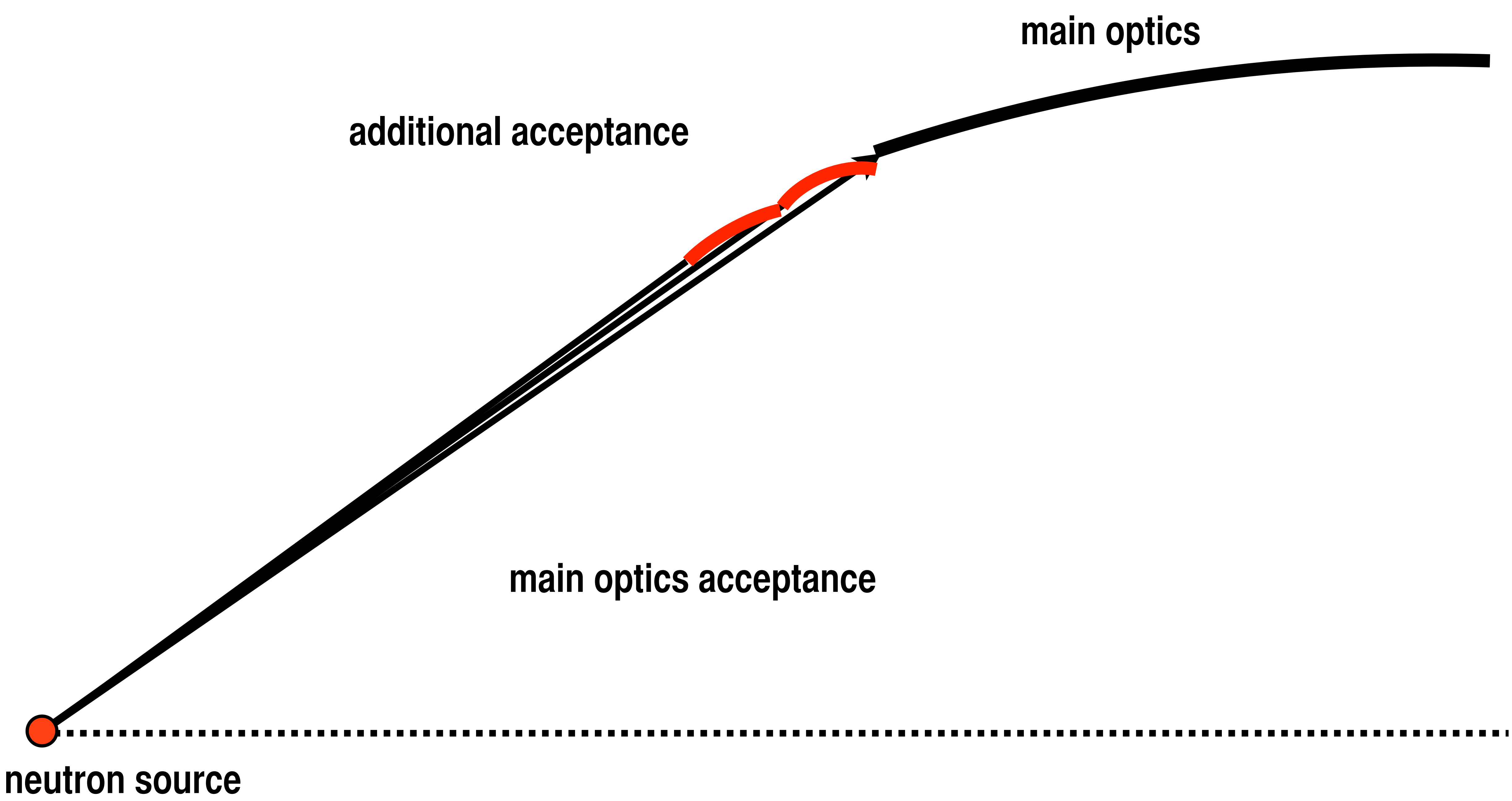
nickel (m=1)

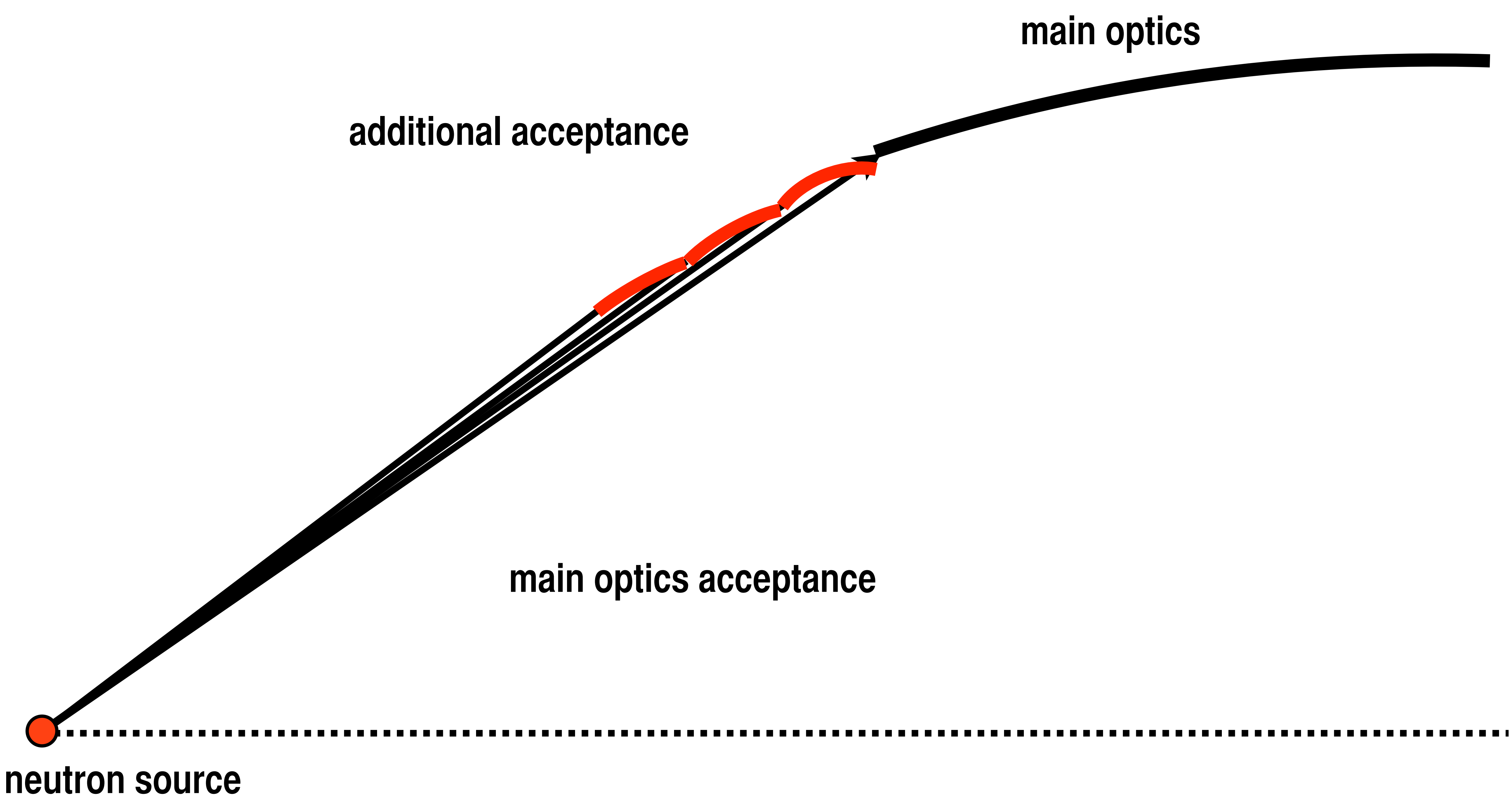

m=1
m=1
m=1
m=1
m=1
m=1


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
main optics acceptance
neutron source


main optics
additional acceptance
main optics acceptance
neutron source

Summary

Radiation hardness is the key

for cost effective apparatus

a thinner vacuum tube
a smaller magnetic shield

and for additional acceptance.