A proposed search for spin-velocity-dependent interactions using neutron whispering gallery states

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Hypothetical interaction searches with neutrons

Beyond SM physics predicts new bosons. There may be exotic interactions between fermions. (16 types are categorized with single-boson exchange spin-0 or 1)

L. Cong, et al., Rev. Mod. Phys. 97, 025005 (2025).

We consider **n-N** interactions to exploit the high intensity neutron source at J-PARC!

Neutrons have no net charge and a small electric polarizability.
→ Neutrons can be used as probes in the <μm range without EM backgrounds.

The order of the nm range can be studied using **nm-scale** structures.
→ Nano-particles (coherent neutron scattering)
→ Near-surface quantum states

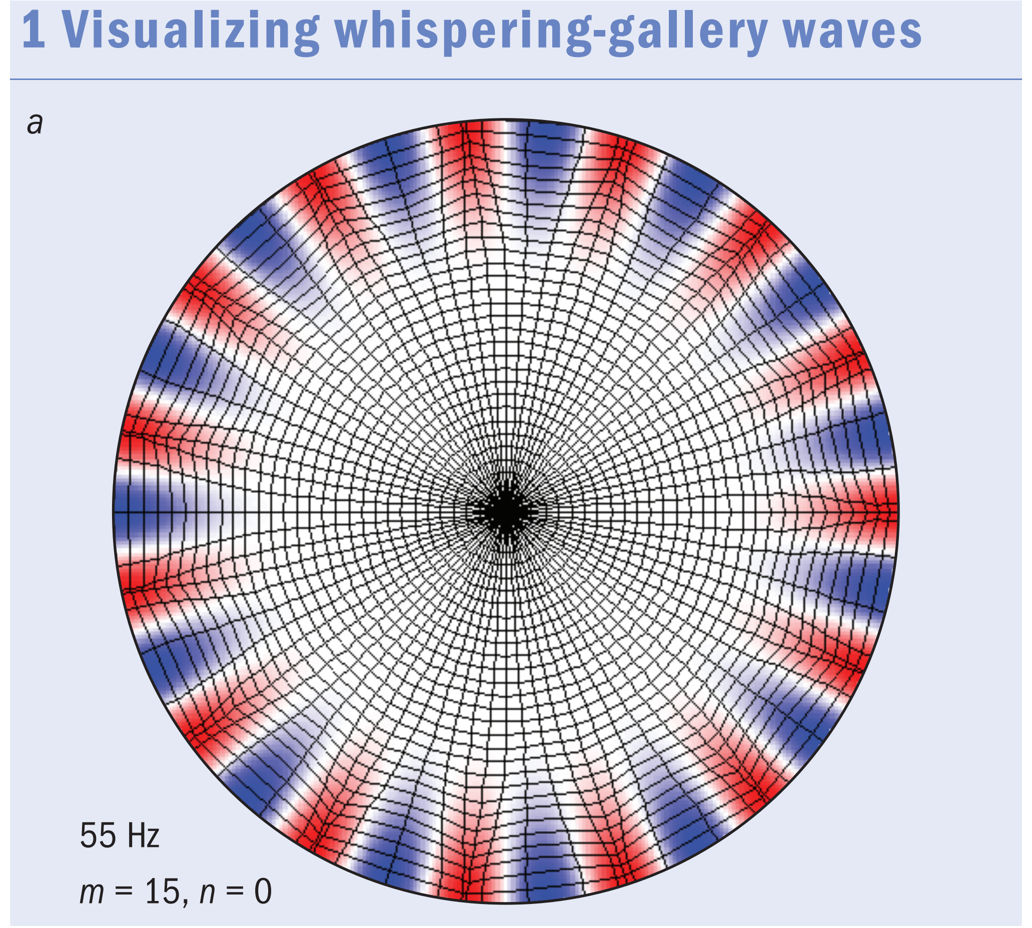
can be created using centrifugal force and the surface of a material.
→ **Neutron whispering gallery**

What is neutron whispering gallery?

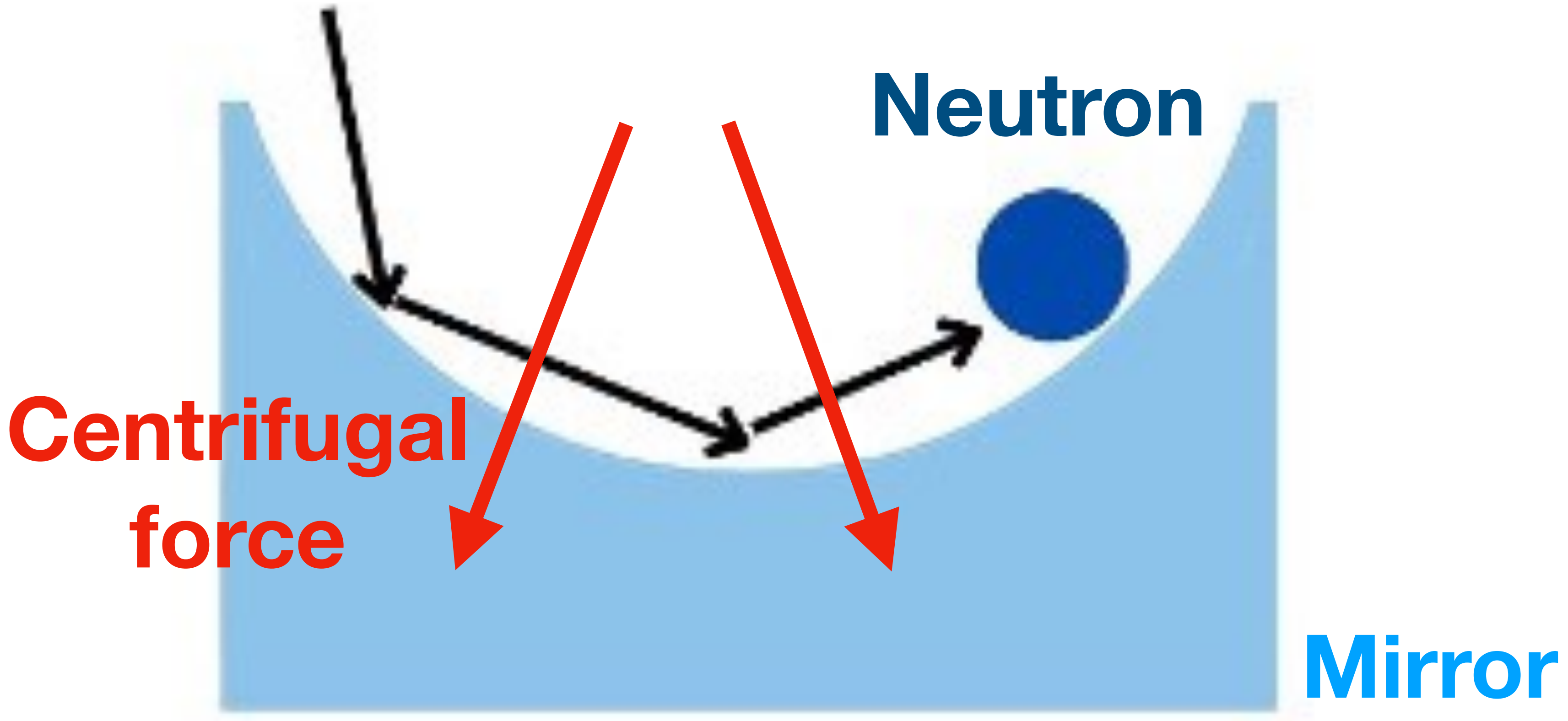
In the whispering gallery of St. Paul's Cathedral, you can hear a whisper from the opposite side.

Photo by Femtoquake, CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:St_Paul%27s_Cathedral_Whispering_Gallery.jpg

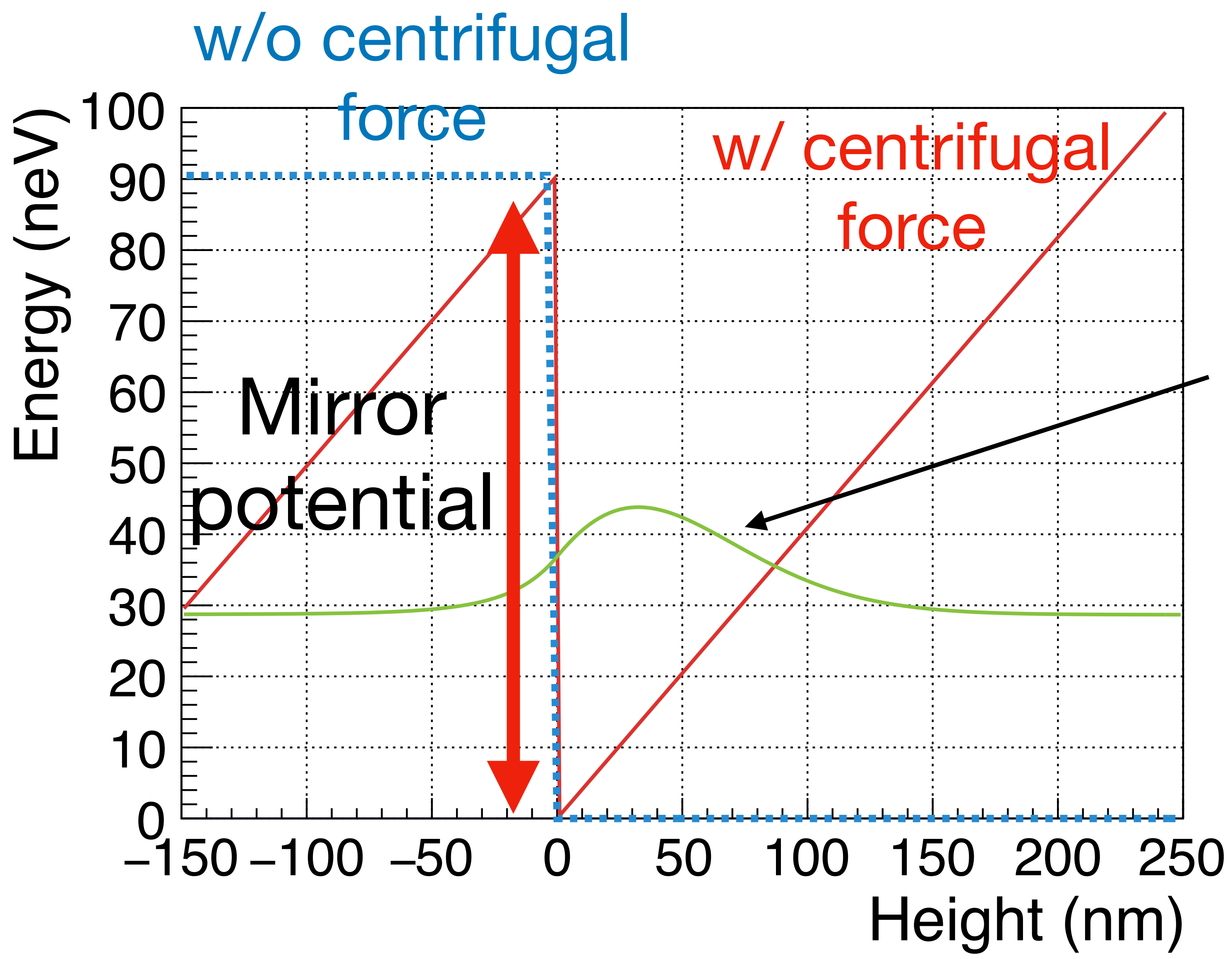
O. Wright 2012 Phys. World **25** (02) 31.



Lord Rayleigh discovered that the phenomenon was due to standing waves (whispering gallery mode).



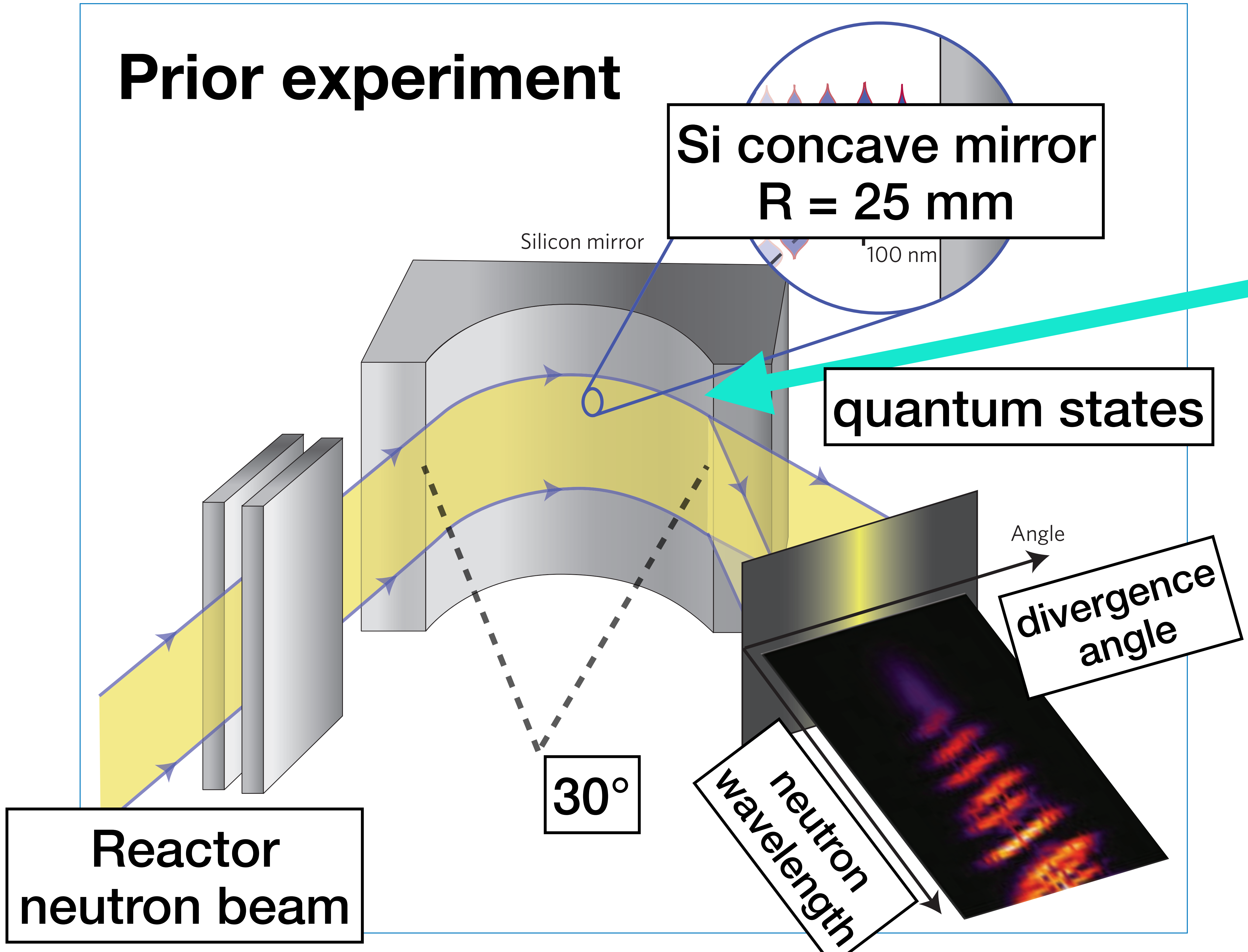
A neutron whispering gallery can be created using a cold neutron beam and a concave mirror.



The quantum state of a neutron whispering gallery is confined between a mirror and the centrifugal force.

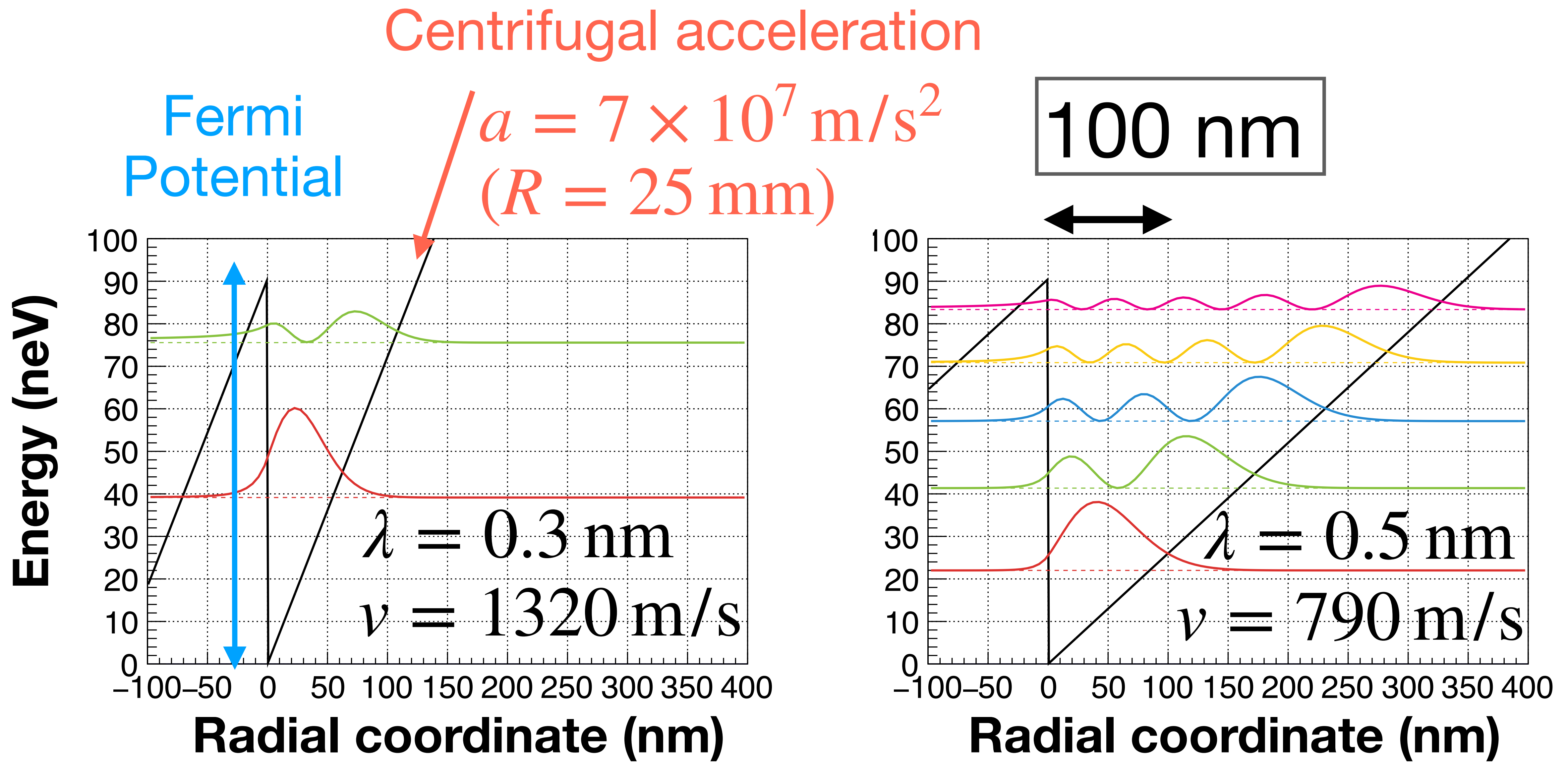
Neutron whispering gallery experiment

V. V. Nesvizhevsky, et al., Nature Phys. 6 (2010) 114-117.



H. Rauch, Nature Phys. 6 (2010) 79.

At ILL reactor PF1B D17 (reflectometer).
peak: λ=5 Å



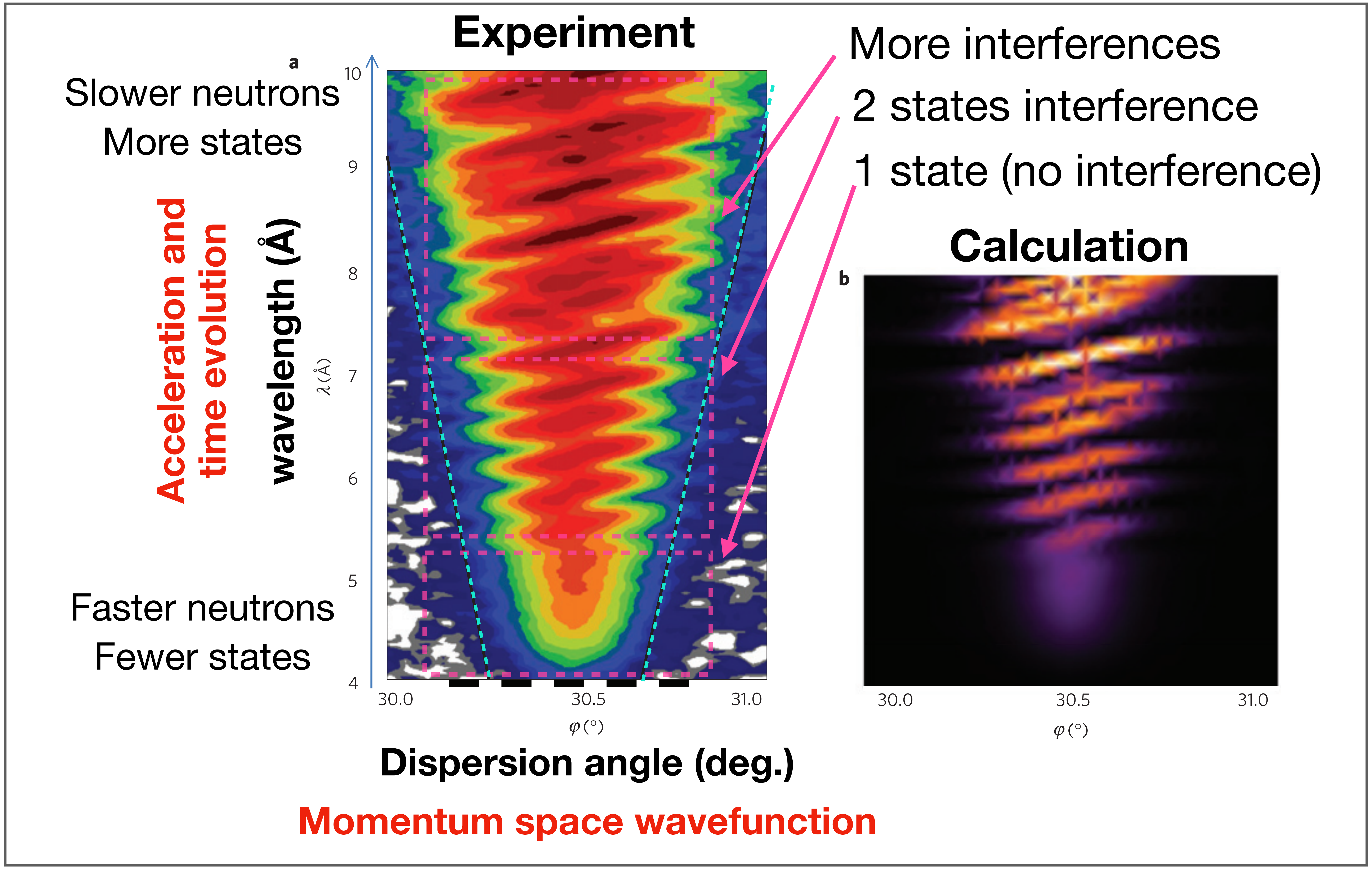
- faster neutrons
- Steep potential slope
- fewer states survive

- slower neutrons
- gentle potential slope
- more states survive

The hypothetical interactions between neutrons and the mirror can be studied.

Discovery of neutron whispering gallery

V. V. Nesvizhevsky, et al., Nature Phys. 6 (2010) 114-117.



The interference fringe wavelength of the two lowest states is defined by $(E_2 - E_1)t/\hbar$. Therefore, we can measure the energy difference.

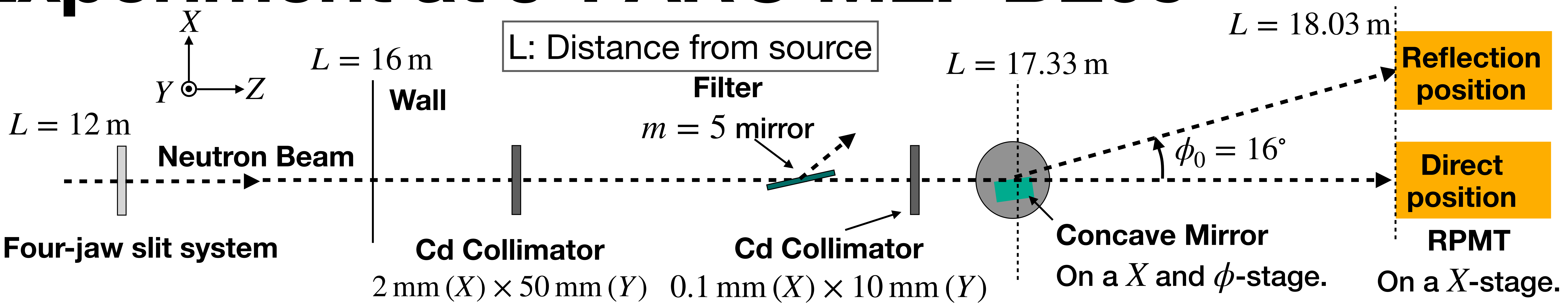
The quantitative results were not achieved due to the surface oxidation of the Si surface.

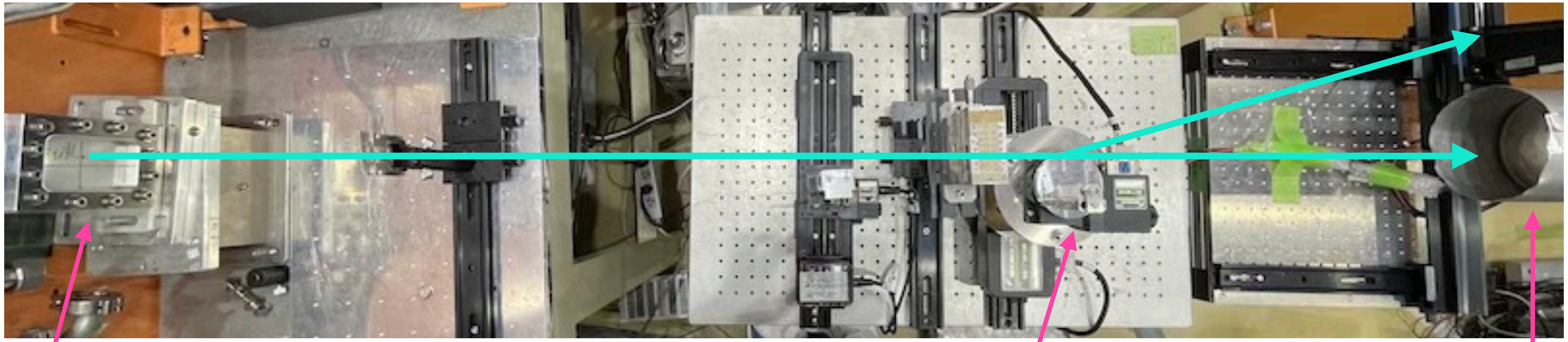
Our experiment at J-PARC

- **40 times neutron intensity**
- **Highly polished SiO_2 mirror**

Experiment at J-PARC MLF BL05

Phys. Rev. D 111, 082008 (2025).



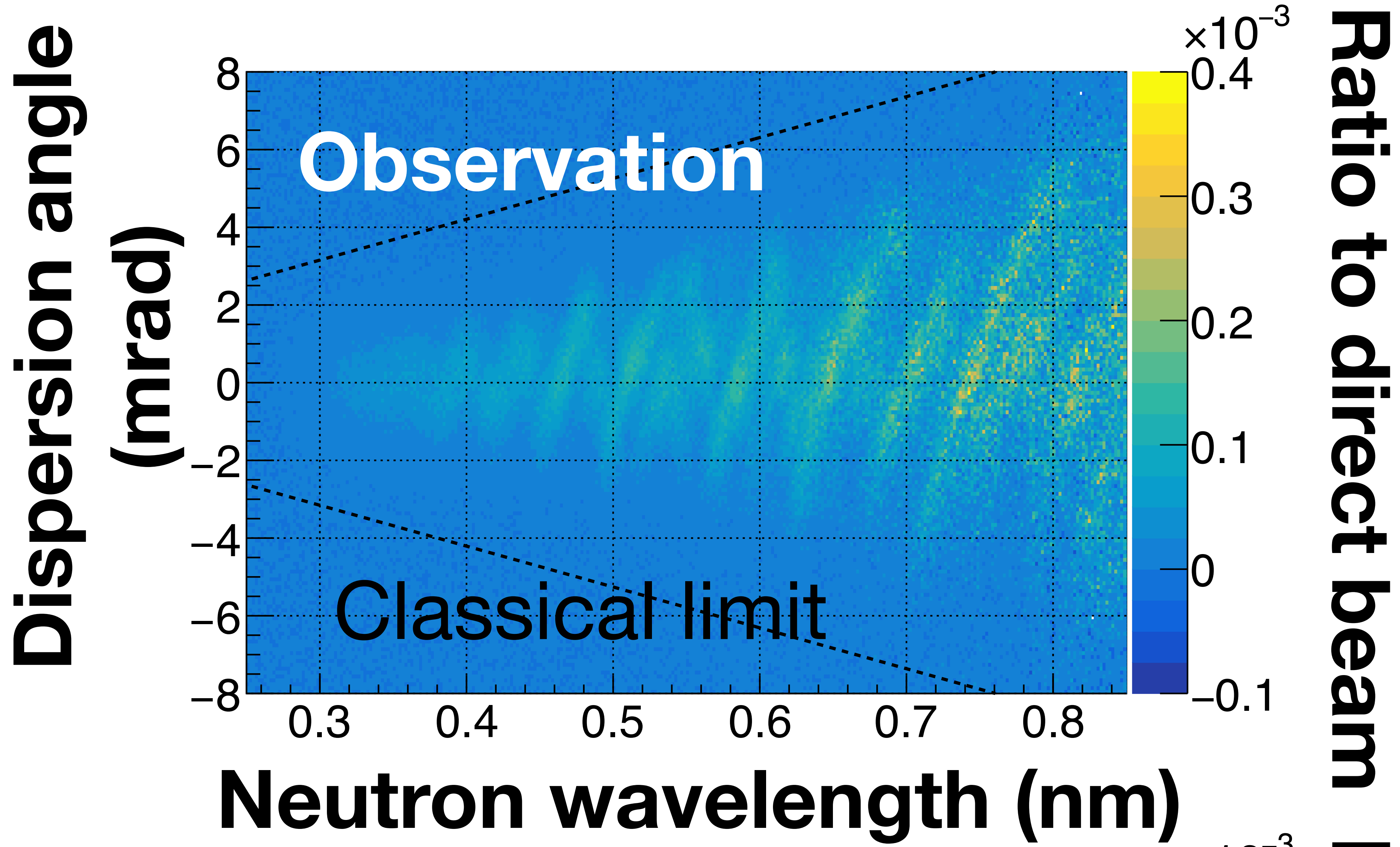


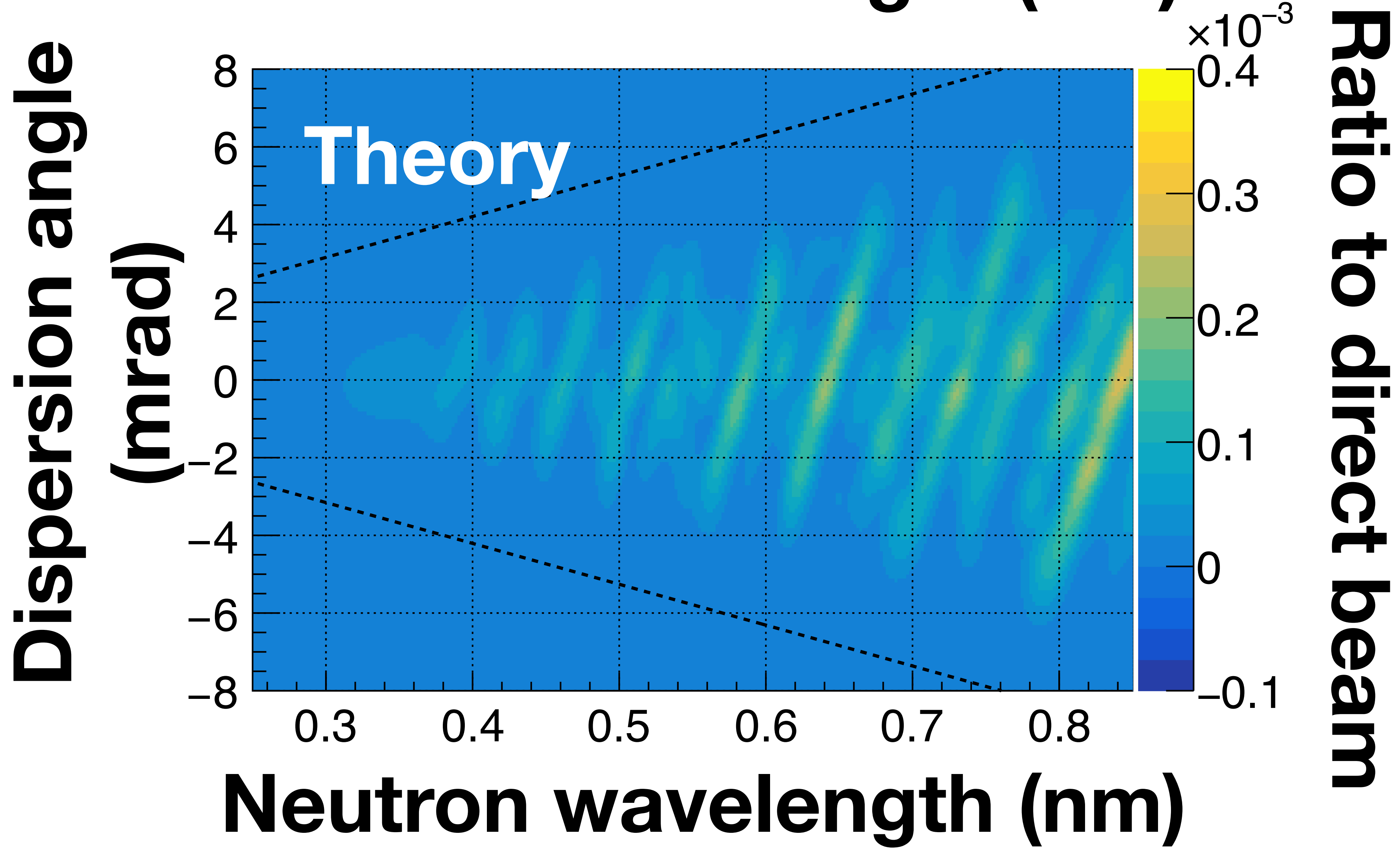
BL05 Low div. branch
MLF cycle: 25 Hz
Horizontal div.
σ_H=0.090 mrad.

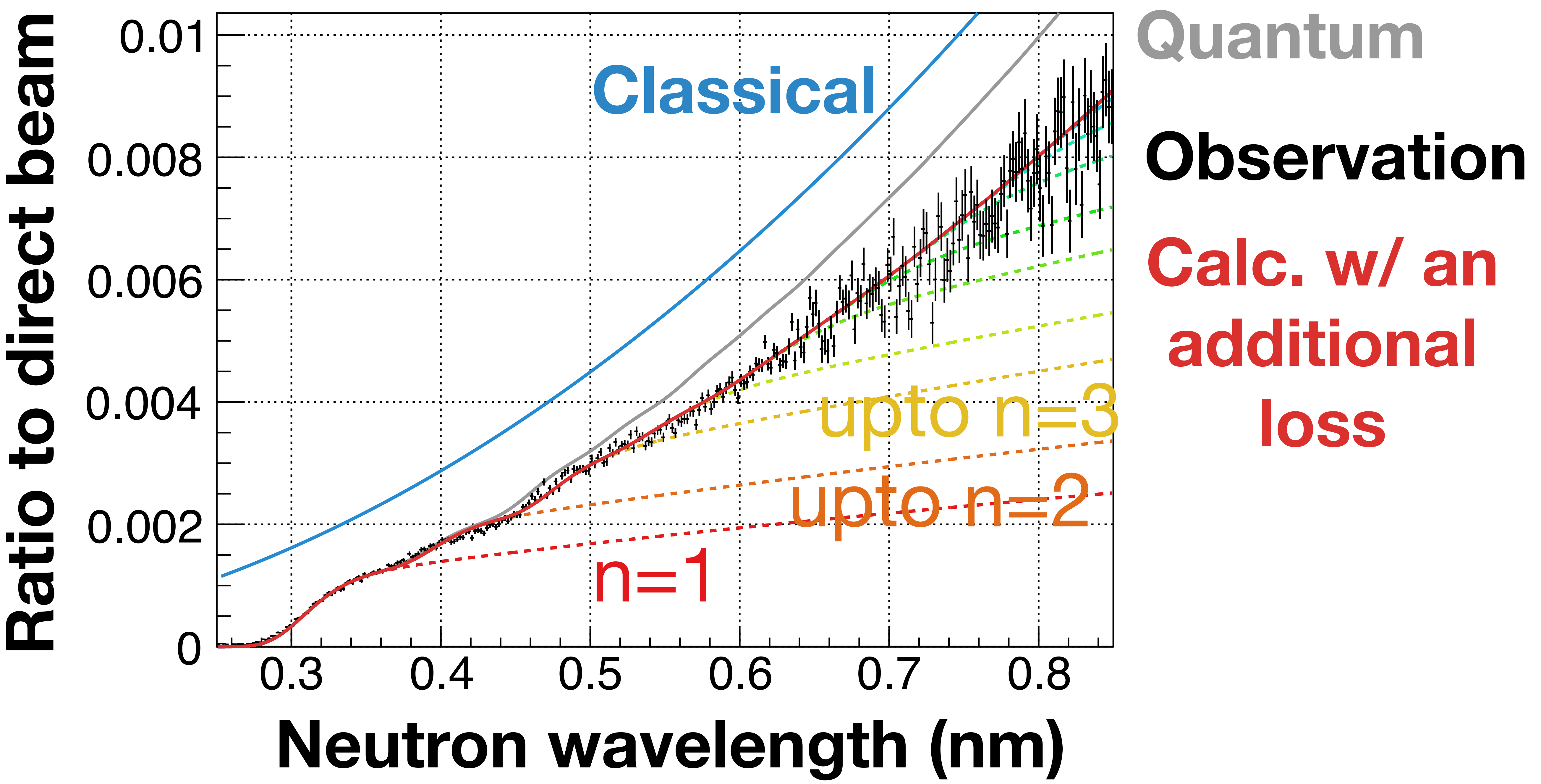
Concave mirror
(Crystal optics)
15×25×40, R=25, ϕ_0=16°
Roughness RMS=0.58 nm
(0.08×0.08 mm^2)

RPMT detector
ZnS(Ag)/^{6}LiF
σ=0.1 mm with time resolution
detection radius < 25 mm

Result of neutron whispering gallery measurement





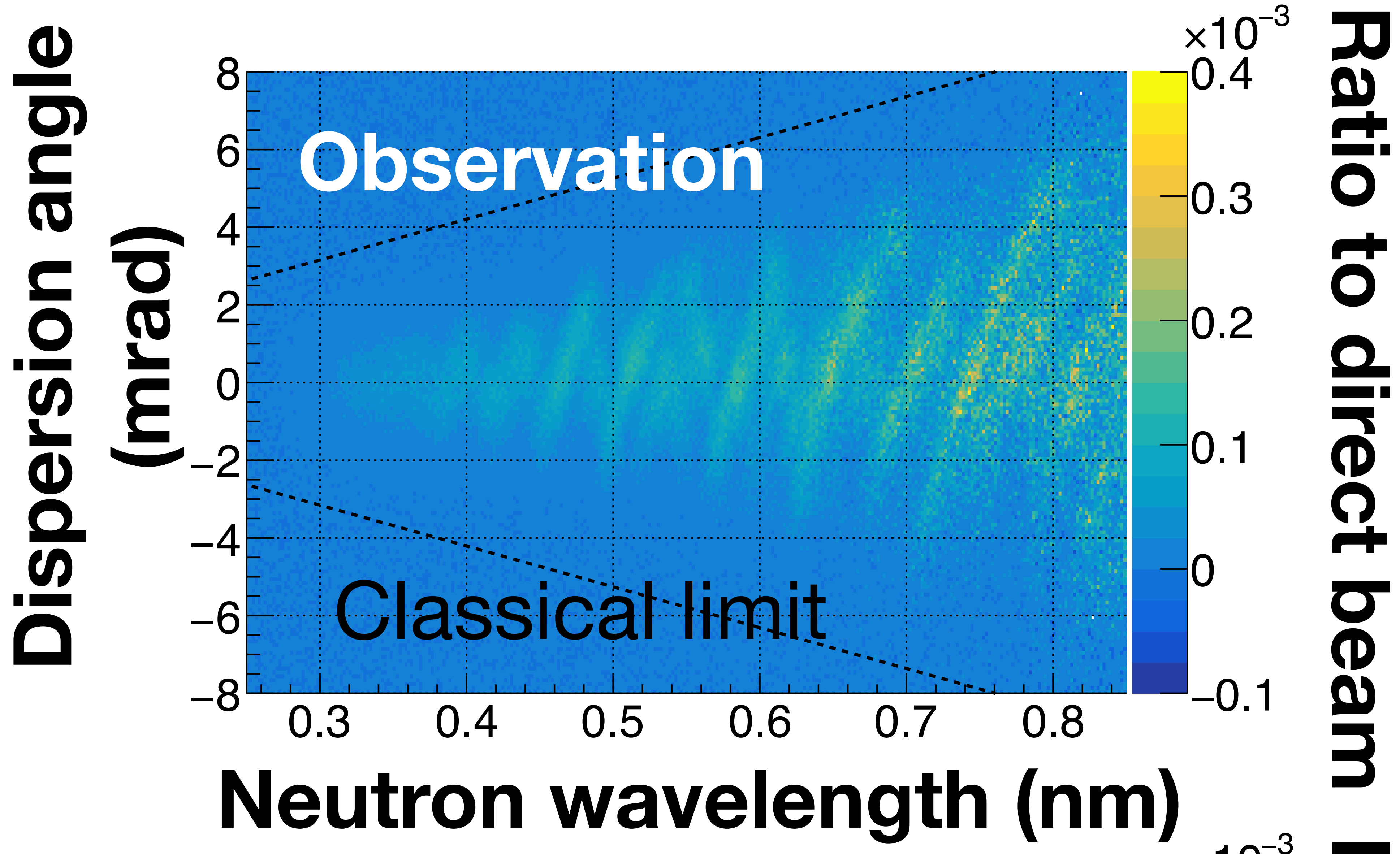


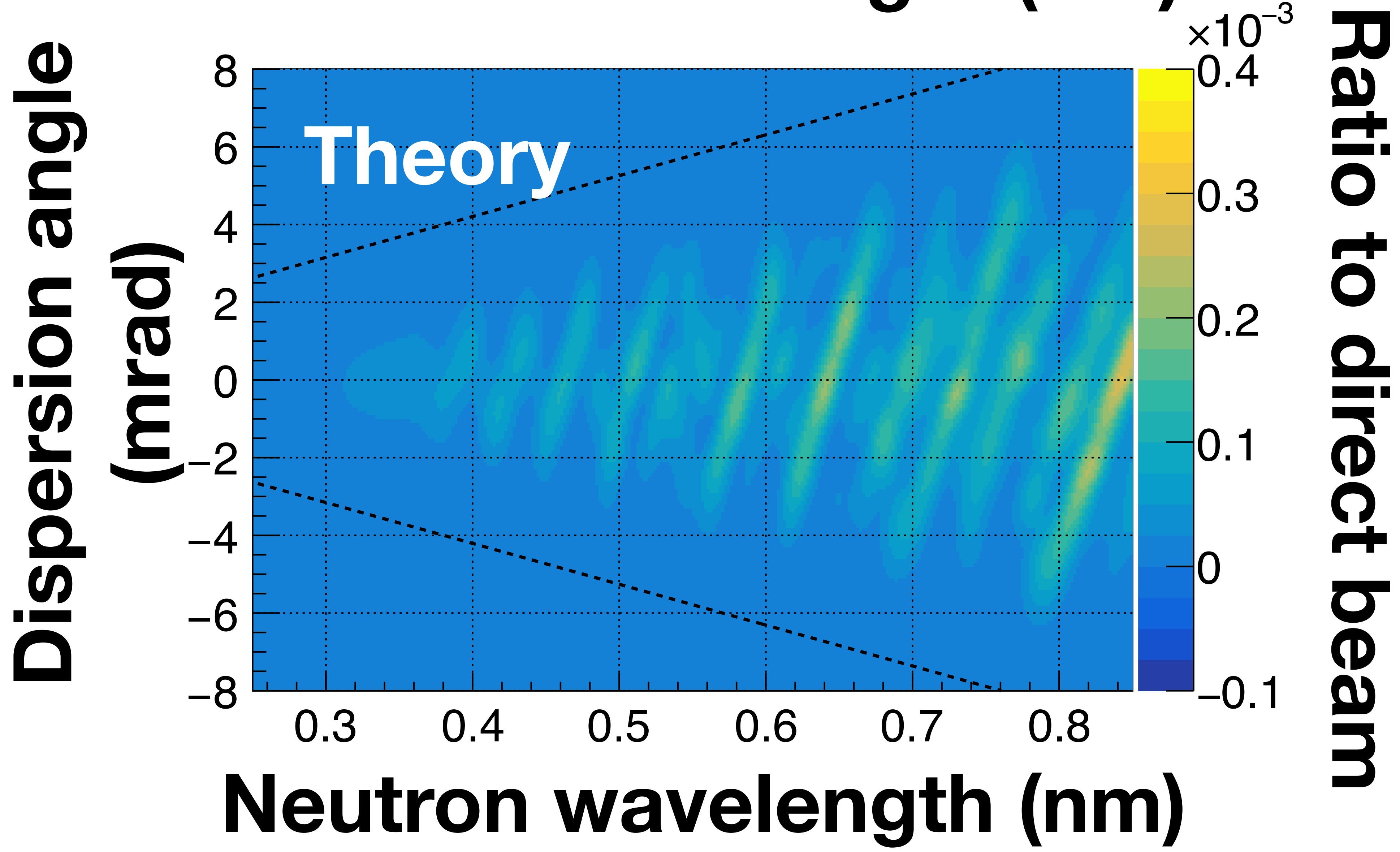
The number of counts increases in steps along the wavelength. The observed value is smaller than the quantum calculation value in the long wavelength region. With additional loss, the results become consistent.

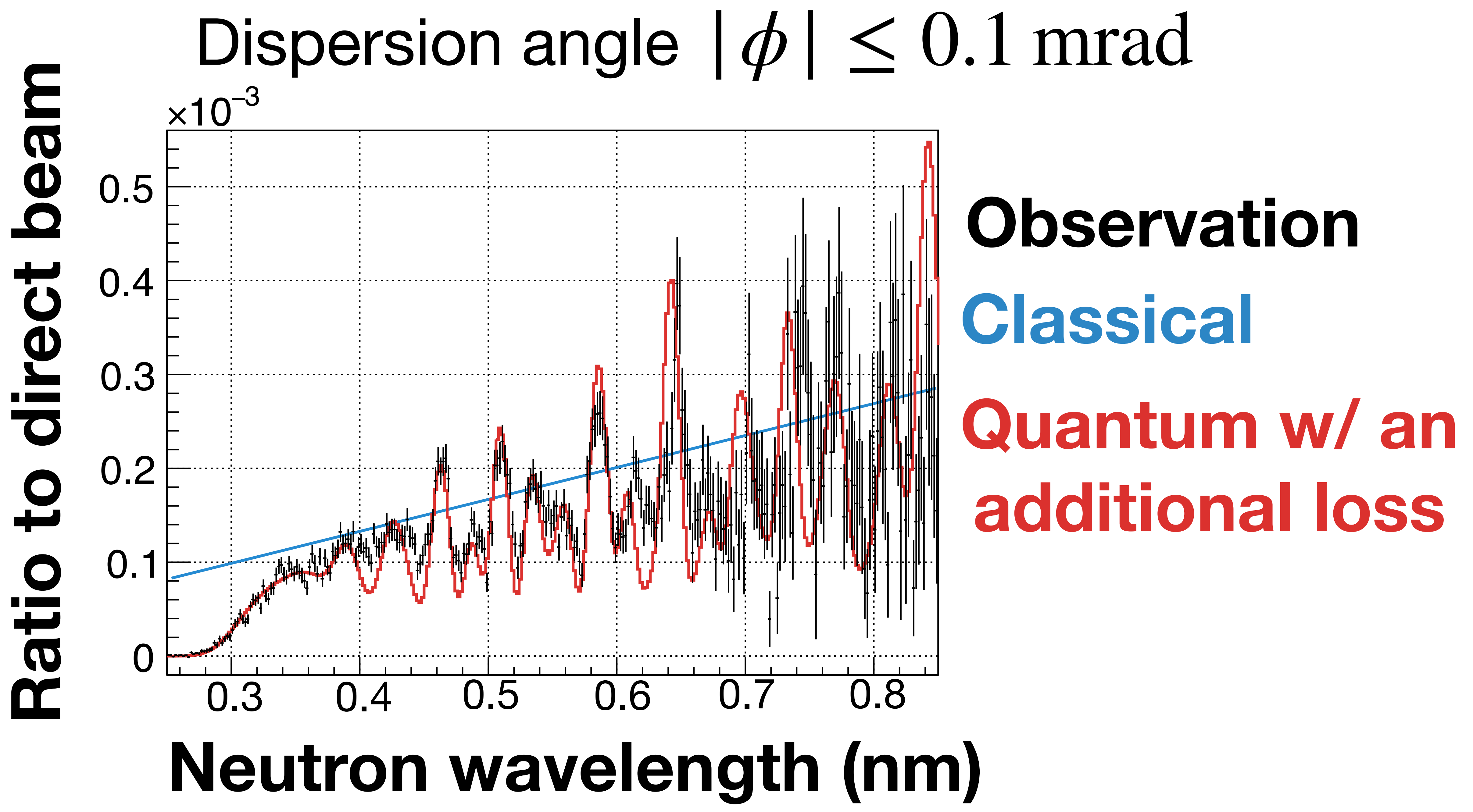
$$\mu_n \propto \int_{U_0-E_n}^{\infty} \mathrm{d}E \frac{k}{\sqrt{2\pi}\Delta} \exp\left(-\frac{E^2}{2\Delta^2}\right)$$

$U_0 - E_n$: Potential difference
k: Loss coefficient.
Δ: Fluctuation of wall potential

Fitting of the interference fringes



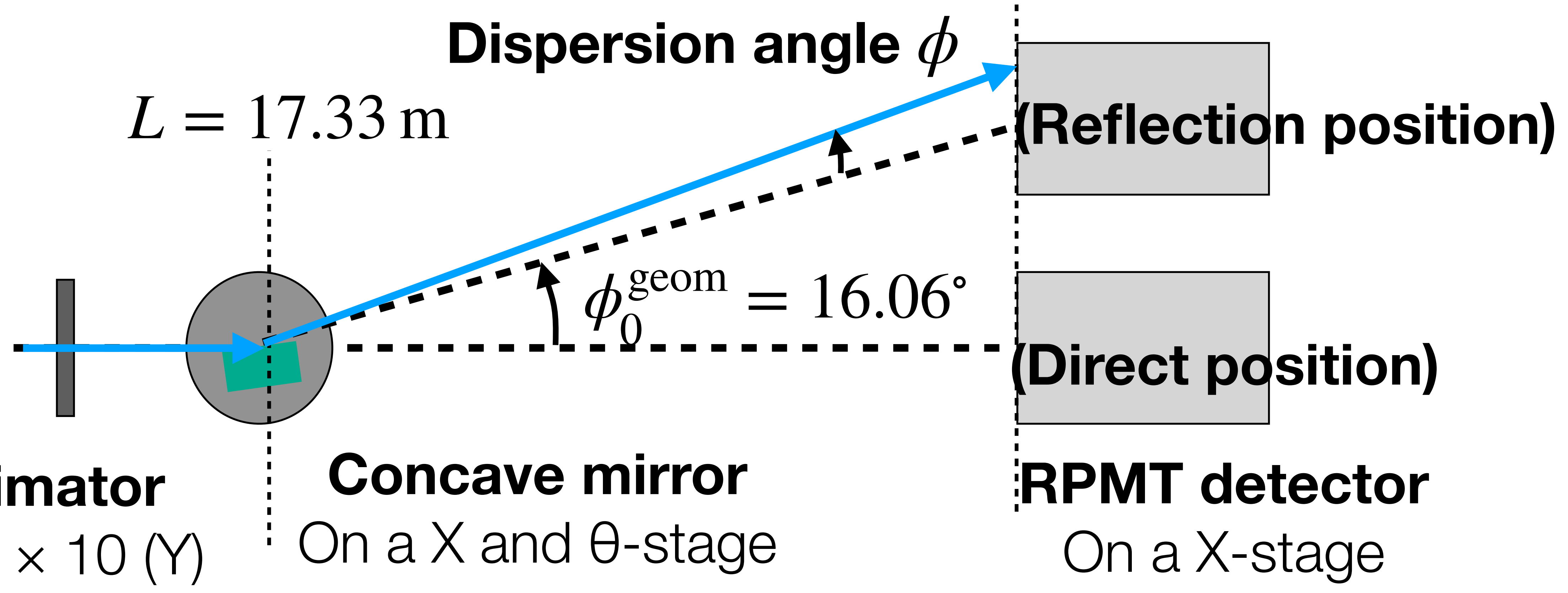




The shape of the interference fringes depends on the energy difference between the states and the evolution time on the concave mirror. Fitting can be used to determine the angle span.

$\rightarrow \phi_0^{\mathrm{fit}} = 16.004(1)^\circ$.

Consistency and sensitivity



Method	Angle span
(A) Scattering angle	16.06(2)°
(B) Surface measurement	15.86(2)°
(C) Interference fringe fitting	16.004(1)°

The angle span of the concave mirror can be determined by the neutron's dispersion angle. →$\phi_0^{\mathrm{geom}} = 16.06(2)^\circ$

The surface measurement of the mirror also determines the angle span. →$\phi_0^{\mathrm{surf}} = 15.86(2)^\circ$.

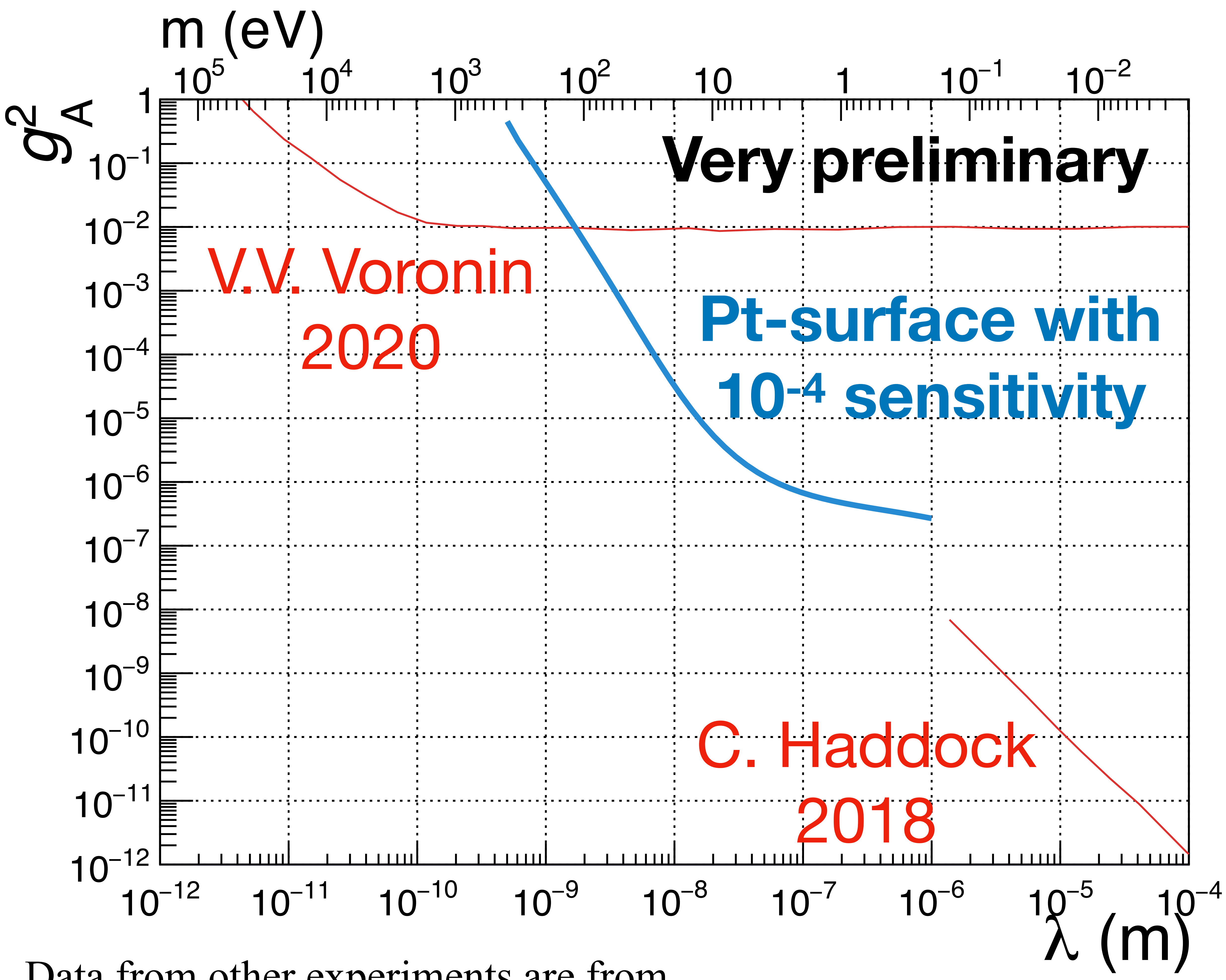
This discrepancy may be caused by the mirror surface deviating from the ideal.

(C) lies between (A) and (B).
The agreement between the observation and the theory was verified to an accuracy of **2%** in terms of centrifugal acceleration.
(Difference between (A) and (B).)
The sensitivity is **10^{-4}** for the fitting result (C).

Search for spin-velocity dependent interactions

$$V_{4+5} \propto \frac{g_A^n g_A^N}{m_n} \overrightarrow{\sigma_n} \cdot (\vec{v} \times \hat{r}) \left(\frac{1}{\lambda_C} + \frac{1}{r} \right) \frac{e^{-r/\lambda_C}}{r}$$

We can exploit the sensitivity of 10^{-4} in a search for spin-velocity dependent interactions.
The difference in the neutron interference fringes between up-spin and down-spin can be observed without displacing any items.
A very preliminary sensitivity estimation is shown on the right.
→**The nm-scale search is unique!**



Data from other experiments are from
L. Cong, et al., Rev. Mod. Phys. 97, 025005 (2025).

Summary

- Neutrons can be confined near a cylindrical surface by material potential and centrifugal force. (Neutron whispering gallery)

- Neutron whispering gallery can be a probe for nm-scale hypothetical interactions.

- We measure the neutron whispering gallery at J-PARC. The result is consistent with the theory within 2% and the experimental sensitivity is 10^{-4}.

- A search for spin-velocity-dependent interactions can exploit the sensitivity of the neutron whispering gallery measurement.