Testing the weak equivalence principle using gravitationally bound quantum states of ultracold neutrons

Yoshio Kamiya*

International Center for Elementary Particle Physics, The University of Tokyo

Sachio Komamiya

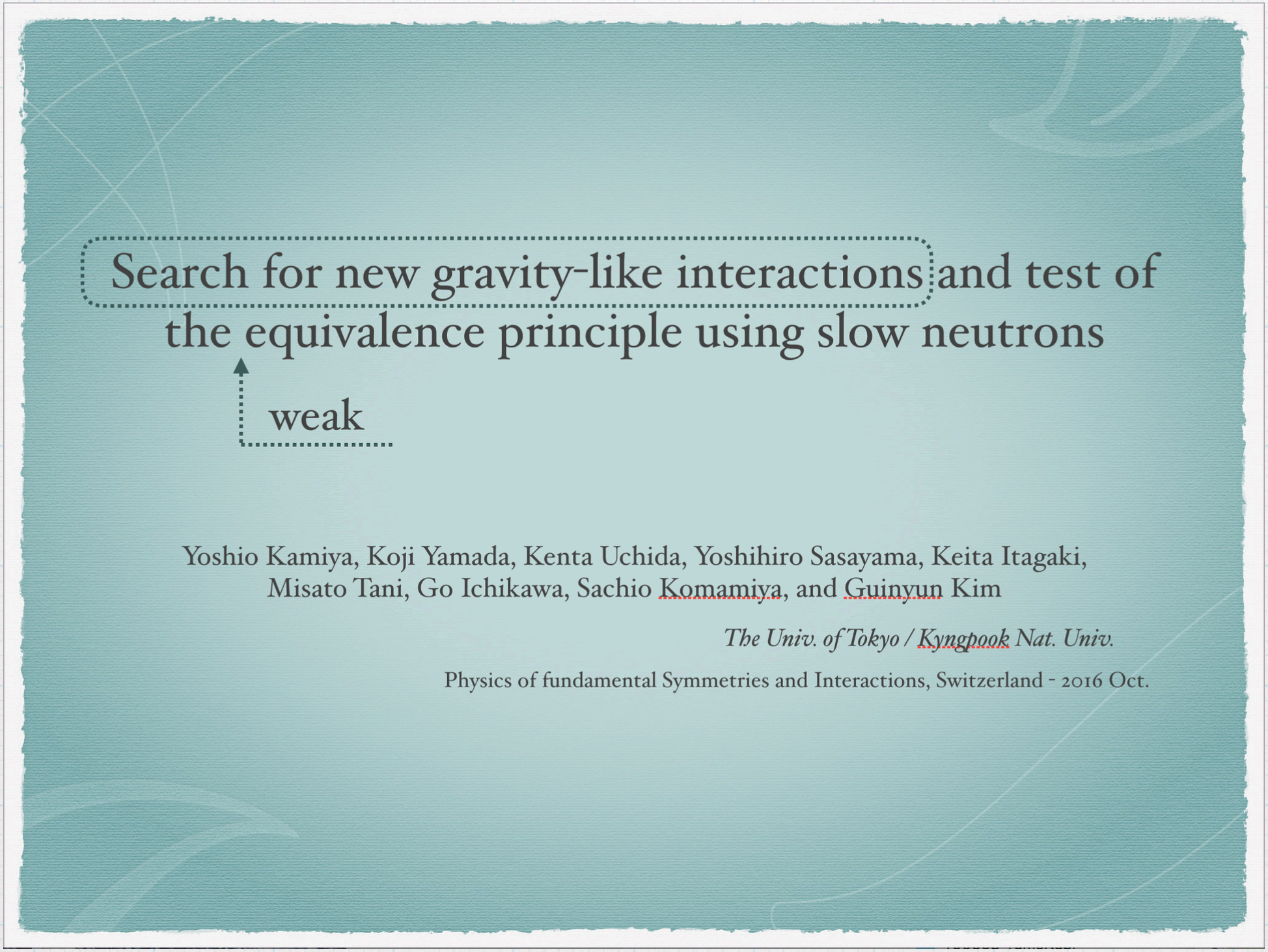
Waseda University

* *kamiya@icepp.s.u-tokyo.ac.jp*

http://www.icepp.s.u-tokyo.ac.jp/~kamiya/

Physics of fundamental Symmetries and Interactions - PSI2019, Switzerland, 20-25 Oct. 2019

In the previous PSI 2016 workshop, I got a chance to make a presentation with the title of



In the previous PSI 2016 workshop, I got a chance to make a presentation with the title of

Search for new gravity-like interactions and test of the equivalence principle using slow neutrons

weak

Yoshio Kamiya, Koji Yamada, Kenta Uchida, Yoshihiro Sasayama, Keita Itagaki, Misato Tani, Go Ichikawa, Sachio Komamiya, and Guinyun Kim

The Univ. of Tokyo / Kyngpook Nat. Univ.

Physics of fundamental Symmetries and Interactions, Switzerland - 2016 Oct.

Equivalence Principle

"main target" It is said Sake "酒"

this talk

It is said Sakana "肴"

Special Things on Gravity

Gravity is the very common force experienced in everyday life, however the most unusual from the view of particle physics. → Very attractive!

- Extremely weak!

Gravity between protons is weaker than Coulomb force by 10^{-36}

Electroweak scale ~ 0.1 TeV (Vacuum Expectation Value of the Higgs)

Gravitational Interaction scale ~ 10^{16} TeV (the Planck mass)

Question 1

Is there any force with intermediate strength? — fifth force search experiment

Y. K, K. Itagaki, M. Tani *et al.*,
PRL 114, 161101 (2015)

Special Things on Gravity

Gravity is the very common force experienced in everyday life, however the most unusual from the view of particle physics. → Very attractive!

- Geometry! as a result of the equivalence between inertial and gravitational mass
  → Weak Equivalence Principle (WEP)

The WEP have been experimentally confirmed by several tests.

Question 3

Is the weak equivalence principle OK in the framework of quantum mechanics? — test of WEP with quantum system

Question 2

Is there any observation of quantum effects due to the gravitational field? — test of quantum effect due to gravity by measuring gravitationally bound quantum state of UCNs

There were not so many.

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

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— test of WEP with quantum system

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— test of quantum effect due to gravity by measuring gravitationally bound quantum state of UCNs

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

How Trapped UCNs in Gravity Look Like?

When you spill UCNs on the floor, they bounce like balls due to their small kinetic energy.

Schrodinger equation for UCNs under the gravity

$$\{-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}z^2} + V(z)\}\psi_n(z) = E_n\psi_n(z),$$

neutron mass

where $V(z) = \begin{cases} mgz, & z \geq 0 \\ \infty, & z \leq 0 \end{cases}$

Dimensionless equation is written as a function of $\xi_n \equiv z/z_0 - E_n/E_0$

$$(\frac{\mathrm{d}^2}{\mathrm{d}\xi_n^2} - \xi_n)\psi_n(\xi_n) = 0$$

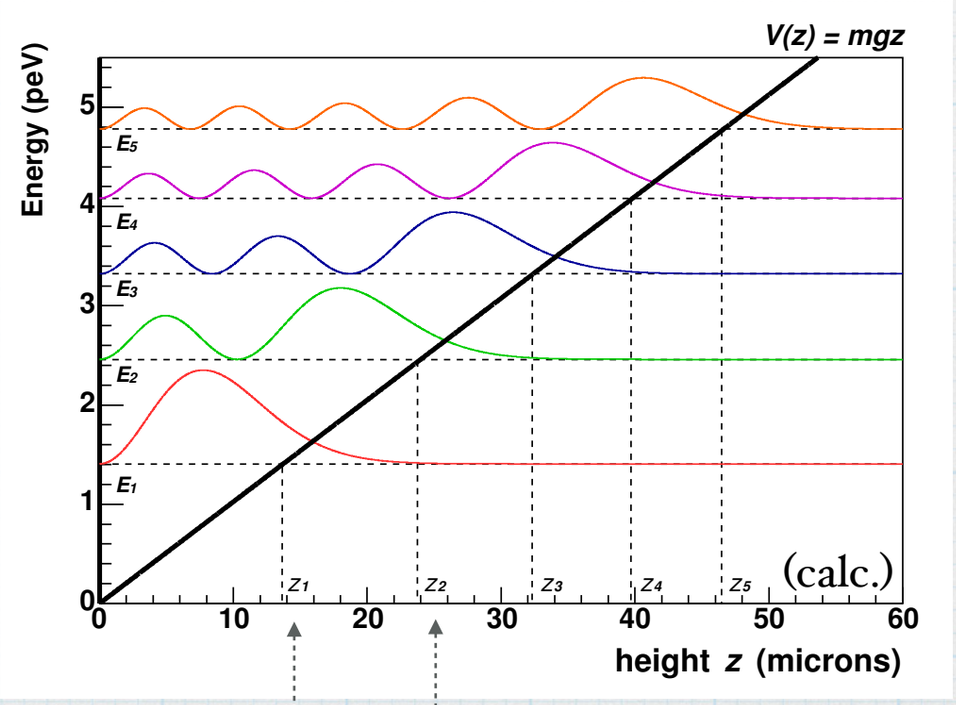
where the system's scales,

$$z_0 = (\frac{\hbar^2}{2m^2 g})^{1/3} \sim 6\ \mu\mathrm{m}$$

$$E_0 = (\frac{mg^2\hbar^2}{2})^{1/3} \sim 0.6\ \mathrm{peV}$$

Classical turning points

$$z_n \equiv z_0 E_n/E_0 \quad (\xi_n = 0)$$



Gravitationally Bound Quantum States of UCNs

V. V. Nesvizhevsky et al., Nature 415, 297 (2002)

Exp. Setup

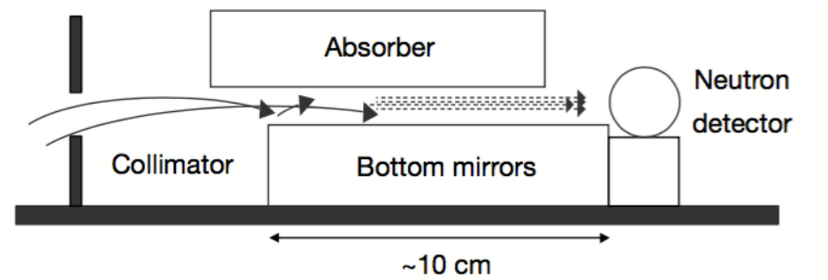


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

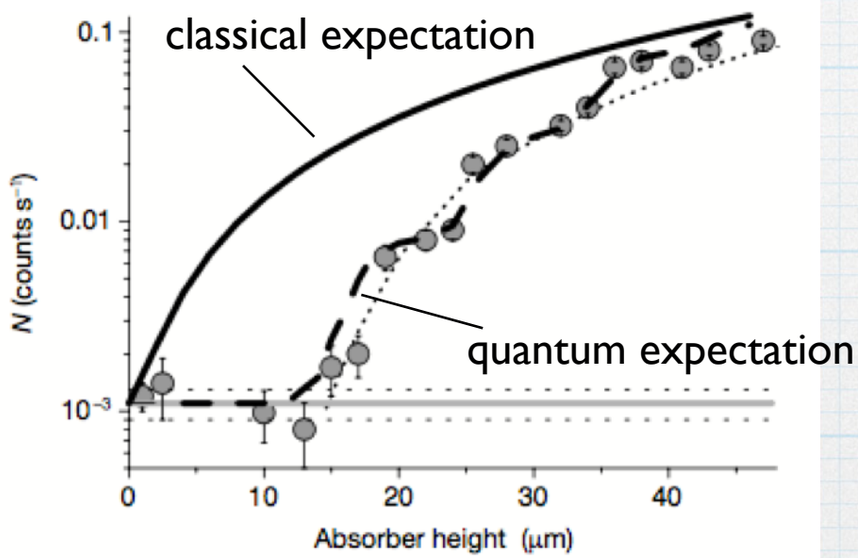


Figure 4 The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 μm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental data. The solid curve is again the full classical treatment. The dotted line is a truncated fit in which it is assumed that only the lowest quantum state—which leads to the first step—exists.

They measured neutron transmission through this thin neutron guide as a function of the height.

Neutron Guide:

length = 10 cm
height = ~ several tens microns

The ceiling scatter neutrons on higher energy states.

If the quantum states are formed in the guide,

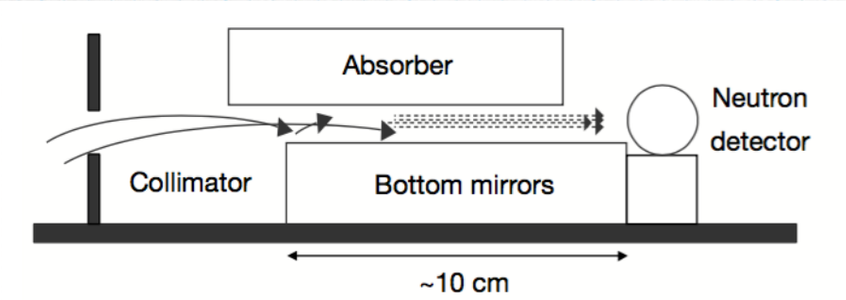
When the height is equal to the spatial width of the lowest quantum state, the transmission would increase sharply.

The data shows a sharp step around 13 micron height

Gravitationally Bound Quantum States of UCNs

V. V. Nesvizhevsky et al., Eur. Phys. J. C 40, 479 (2005)

Exp. Setup



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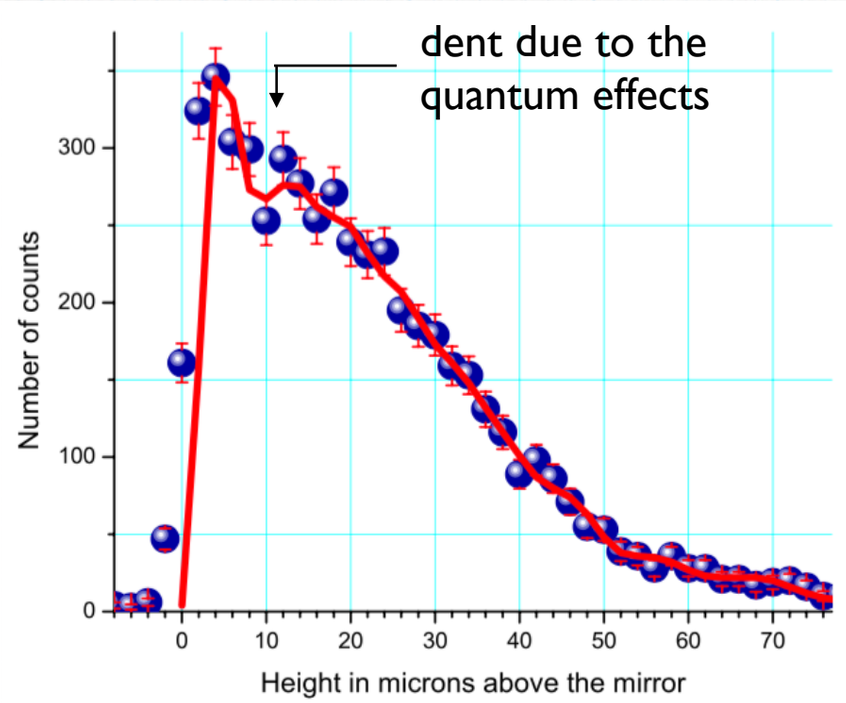
They directly measured neutron distribution using a position sensitive neutron detector with the fixed height.

to avoid uncertainties which come from a modeling of the ceiling



Detector: ^{235}U coated CR39 (plastic)

V.V. Nesvizhevsky et al., NIM A 440, 754 (2000)

<Principle>

Daughter nuclei from nuclear fission are make defects on the CR39.

The defects are enlarged by chemical etching.

Measure the points using microscope.

Spatial resolution is said to be about 1 micron.

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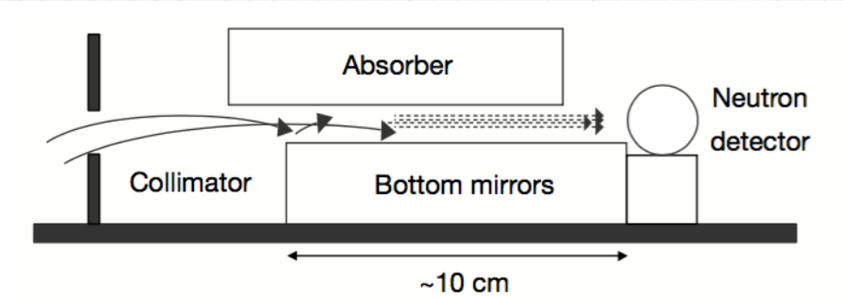

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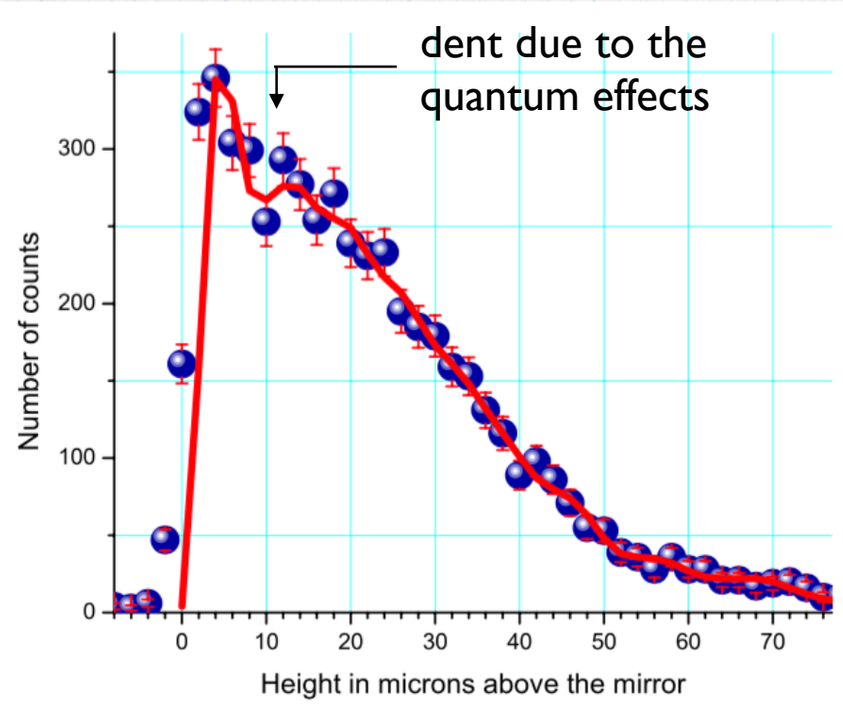

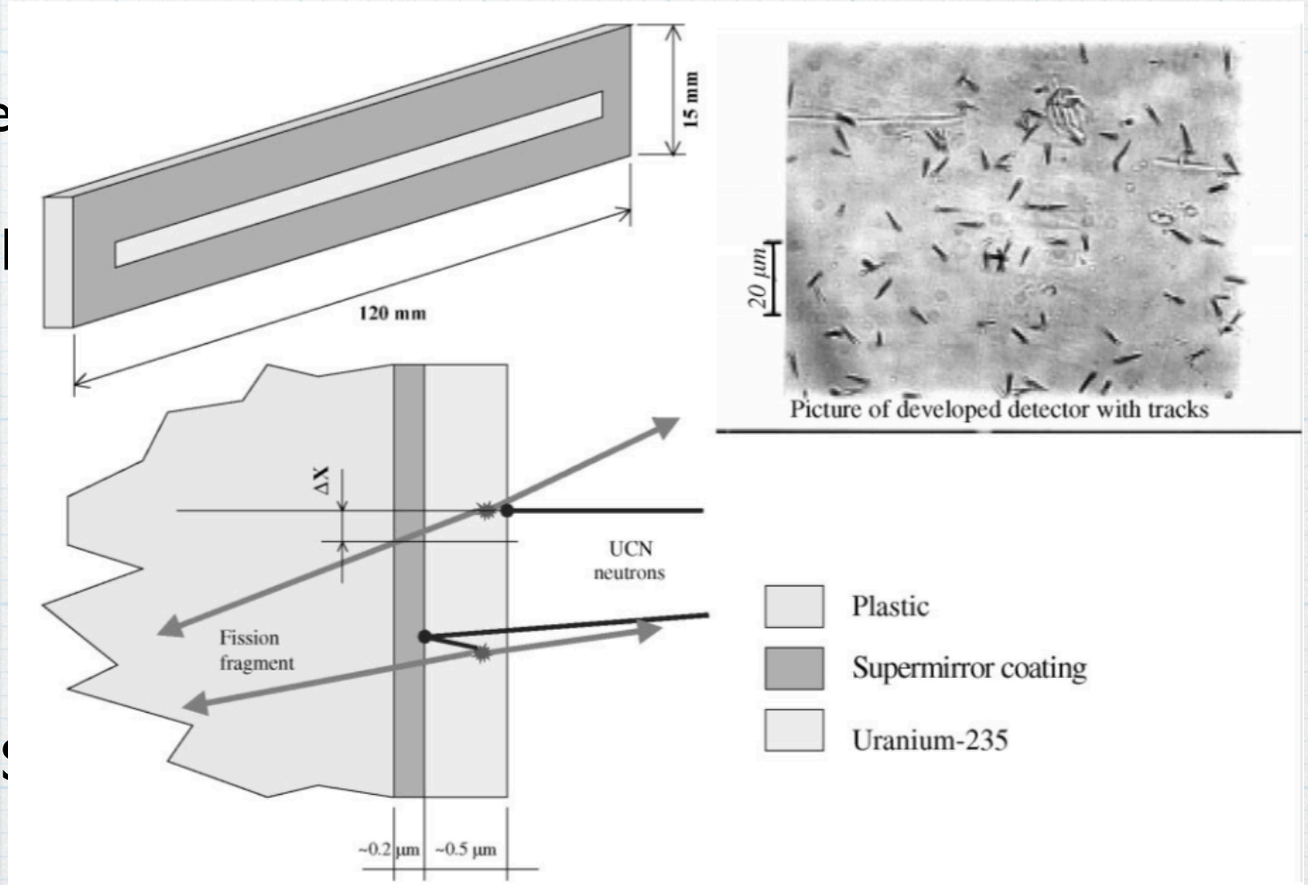

Fig. 4. Position sensitive detector for ultra-cold neutrons.

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V. V. Nesvizhevsky et al., Eur. Phys. J. C 40, 479 (2005)

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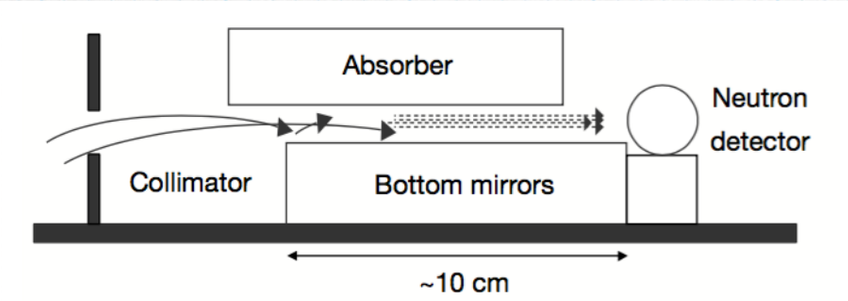

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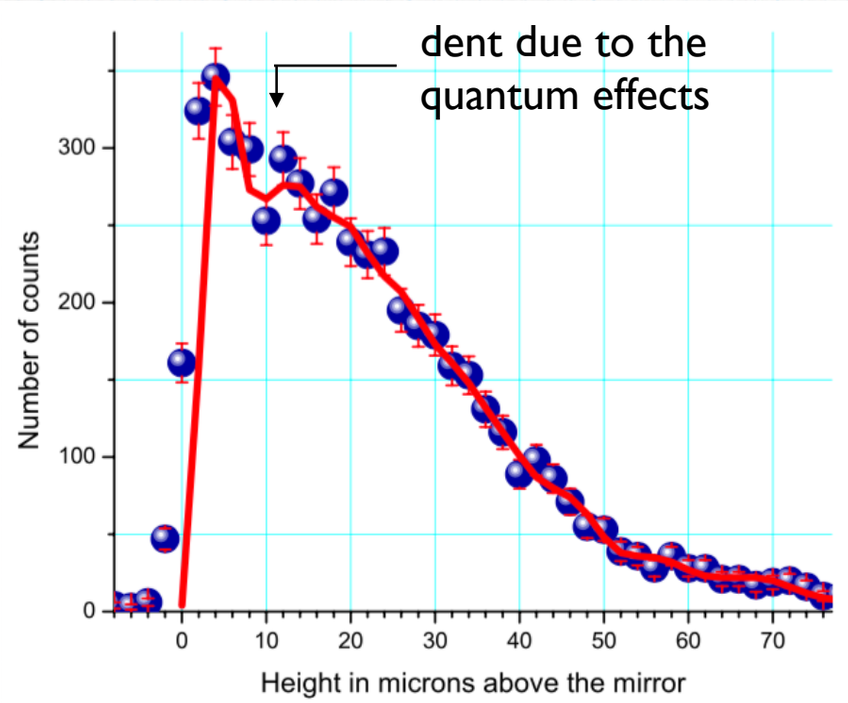

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<Principle>

Daughter nuclei from nuclear fission are make defects on the CR39.

The defects are enlarged by chemical etching.

Measure the points using microscope.

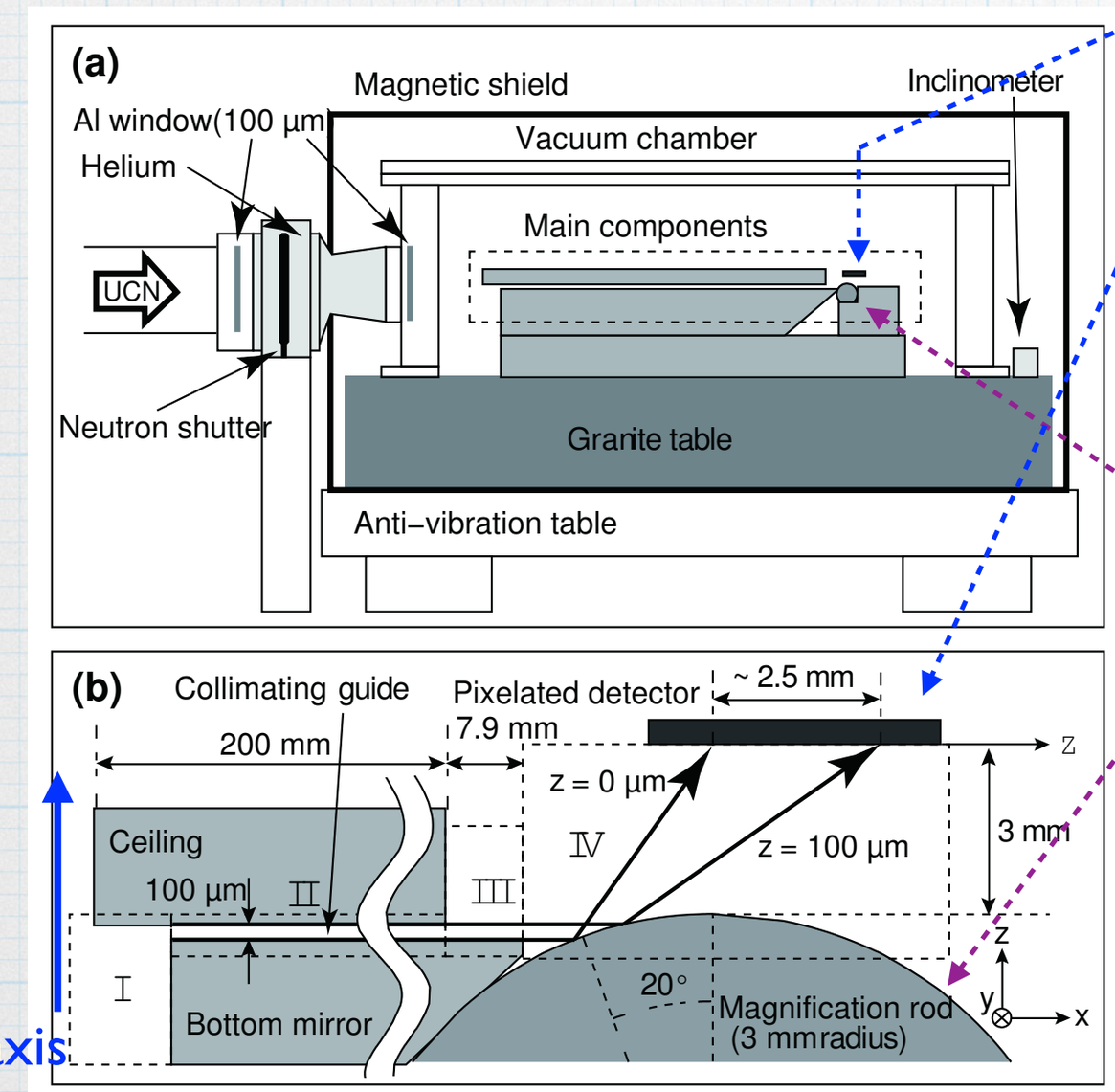
Spatial resolution is said to be about 1 micron.

We have been impressed by these experiments, so we started new attempts to image this UCN distribution.

Measurement of CCD-based Imaging Detector

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

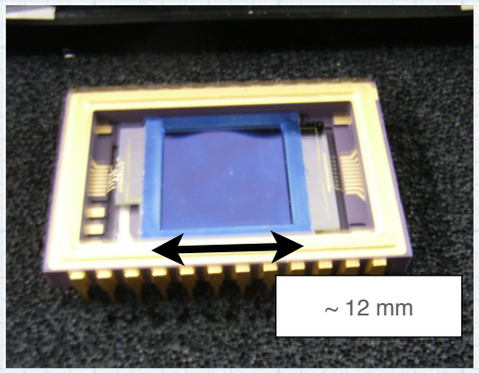
Exp. Setup



(HAMAMATSU)

CCD-based Imaging Detector

S. Kawasaki, G. Ishikawa, M. Hino, YK et al., NIM A 615,42 (2010)

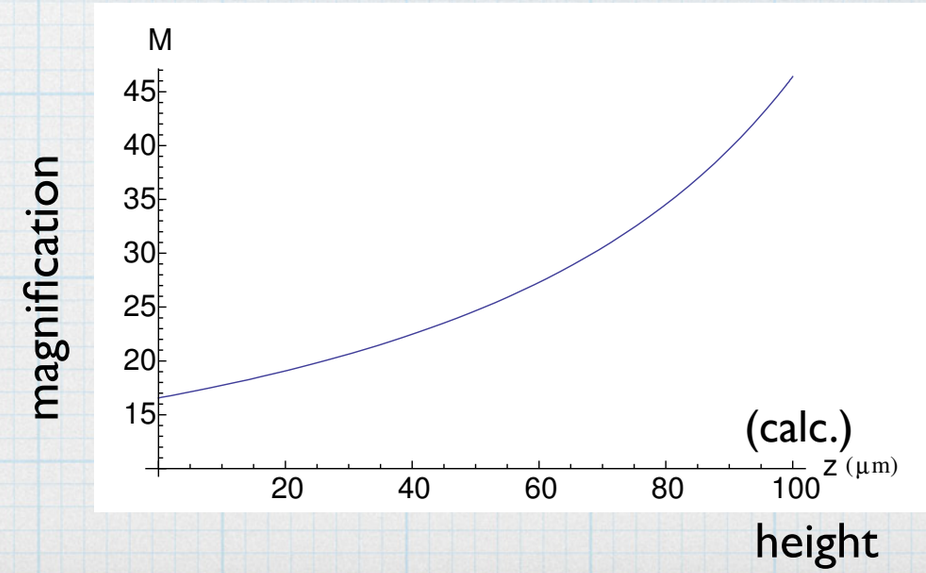


Position meas.: 3 microns

Timing meas.: ~ sec

Magnification Rod

magnify the neutron distribution using glass rod by 17〜40 times



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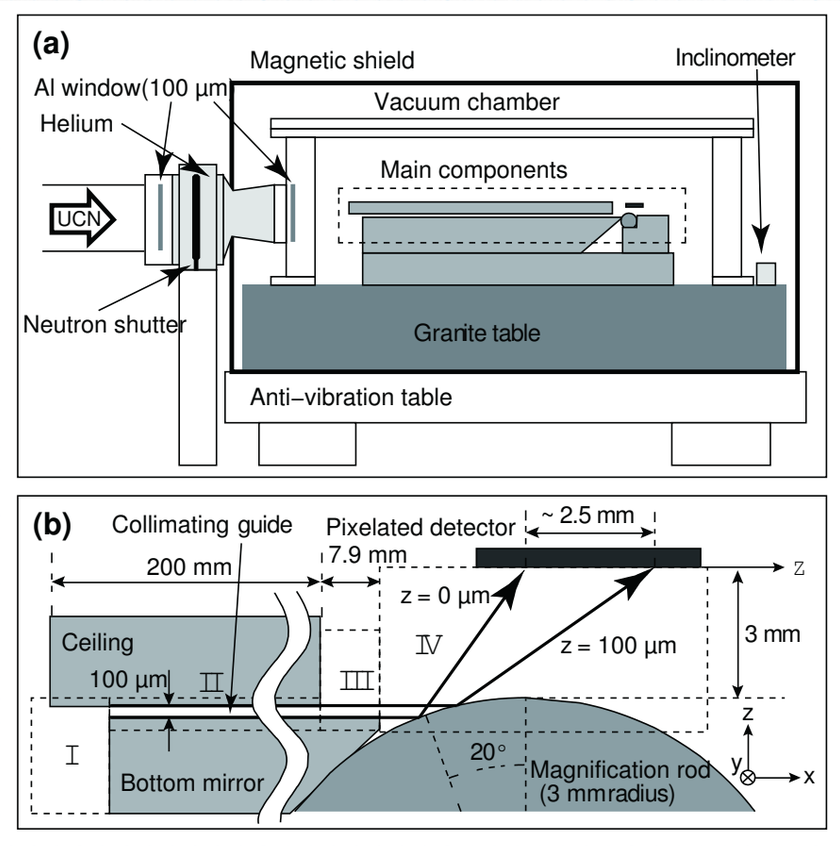

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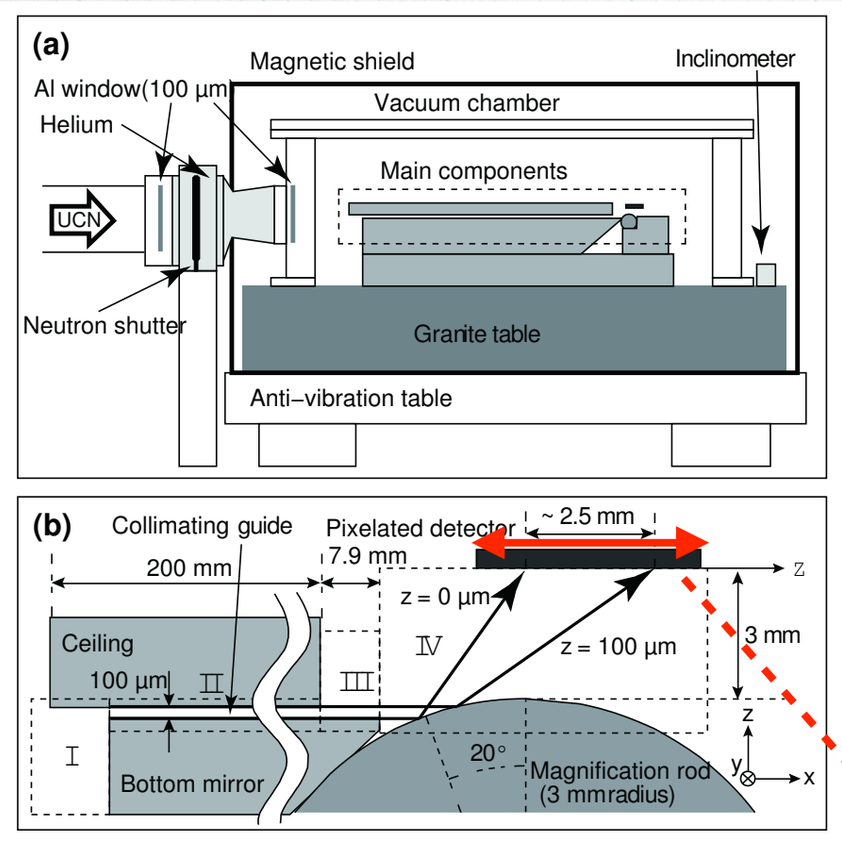
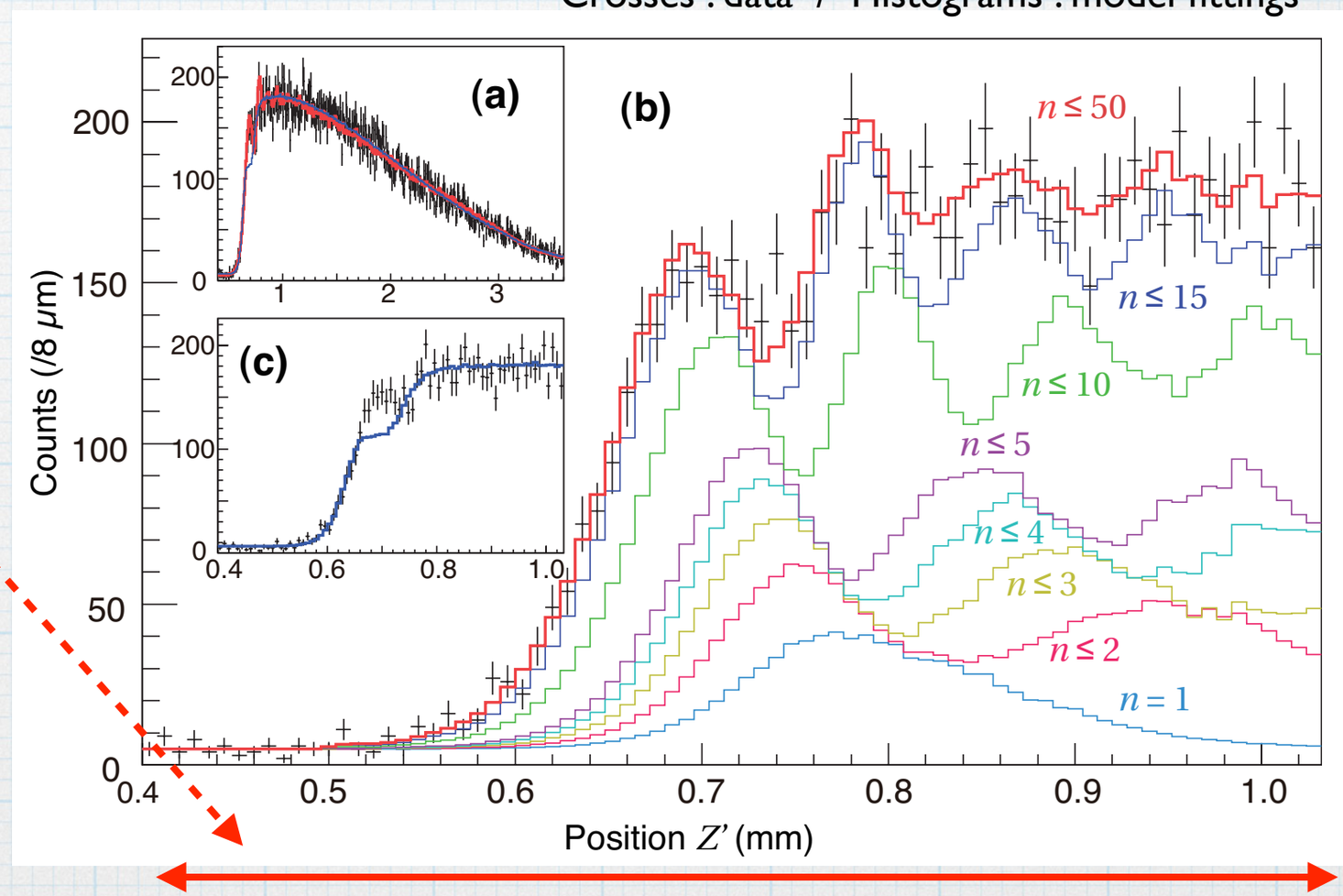
consistent with quantum mechanics $\chi^2/\mathrm{NDF} = 0.96$



Crosses : data / Histograms : model fittings



Modulated distribution due to quantum effects is clearly measured!!

Treatment of Reflection on a Cylindrical Surface

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

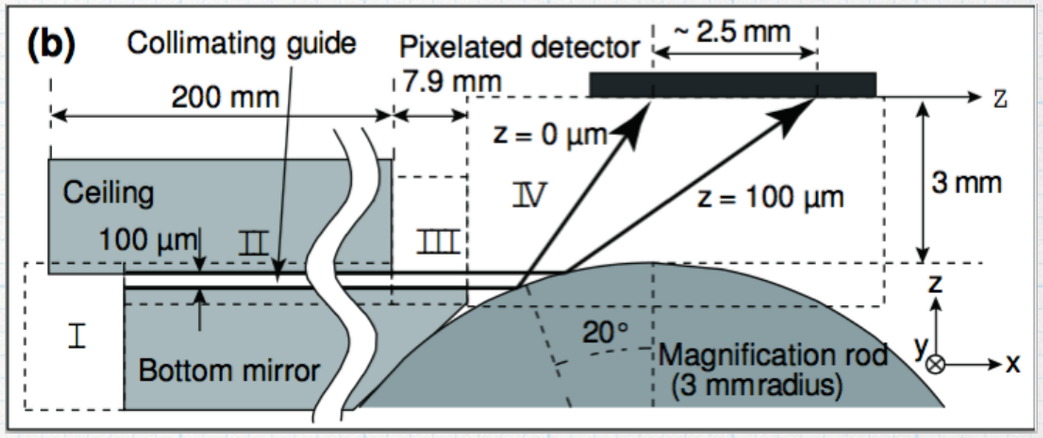
In the classical manner,

Reflection direction is determined by giving an incident position z and momentum (angle) Pz at the same time.

In the quantum manner?

We cannot give z and Pz simultaneously.

(in usual Hilbert space formulation.)



<u>Utilize the Wigner pseudo probability distribution</u>

(another formulation of quantum mechanics in phase space)

<u>Difinision</u>

$$W(z,p_z) \equiv \frac{1}{2\pi\hbar}\int_{-\infty}^{\infty} d\eta\ e^{-\frac{i}{\hbar}p_z\eta} < z+\frac{1}{2}\eta|\hat{\rho}|z-\frac{1}{2}\eta >$$

$\hat{\rho}$: density operator

<u>Characteristics</u>

Probability distribution of the position is given by integrating with momentum (projecting to an axis of position)

$$\int_{-\infty}^{\infty} dp_z W(z,p_z) =< z|\hat{\rho}|z >$$

Expectation value is given by integrated with the weight of the Wigner distribution

$$< \hat{A} >= \mathrm{Tr}(\hat{\rho}\hat{\mathrm{A}})$$

$$= \int_{-\infty}^{\infty} dz \int_{-\infty}^{\infty} dp_z\ A(z,p_z)W(z,p_z)$$

$$\left(A(z,p_z) \equiv \int_{-\infty}^{\infty} d\eta\ e^{-\frac{i}{\hbar}p_z\eta} < z+\frac{1}{2}\eta|\hat{A}|z-\frac{1}{2}\eta > \right)$$

Time Evolution of the Wigner Distribution

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

<u>time evolution of the operator</u>

$$\frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}]$$

Liouville - von Neumann Equation

Evaluating the time evolution of the Wigner distribution with $\hat{H} = \frac{\hat{p_z^2}}{2m} + V(\hat{z})$

$$\left(\frac{\partial}{\partial t} + \frac{p_z}{m}\frac{\partial}{\partial z} - \frac{dV(z)}{dz}\frac{\partial}{\partial p_z}\right) W(z, p_z) = \sum_{l=1}^{\infty} U_l(z, p_z)$$

here, $U_l(z, p_z) \equiv \frac{(-1)^l (\hbar/2)^{2l}}{(2l+1)!} \frac{d^{2l+1}V(z)}{dz^{2l+1}} \frac{\partial^{2l+1}}{\partial p_z^{2l+1}} W(z, p_z)$

Since the right side term contains the higher derivatives of the potential,

in our case, under the gravity of $V(z) = mgz$, $\sum_{l=1}^{\infty} U_l(z, p_z) = 0$

The distribution evolves according to the Liouville equation of classical statistical mechanics.

$$\left(\frac{\partial}{\partial t} + \frac{p_z}{m}\frac{\partial}{\partial z} - \frac{dV(z)}{dz}\frac{\partial}{\partial p_z}\right) W(z, p_z) = 0$$

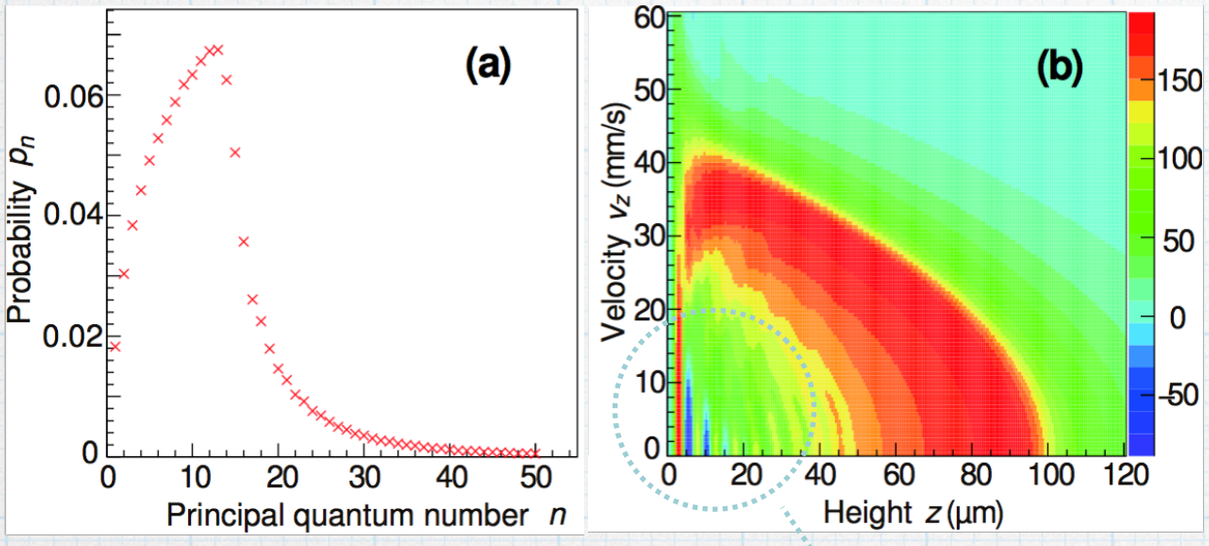
Description of the Quantum System by the Winger Distribution

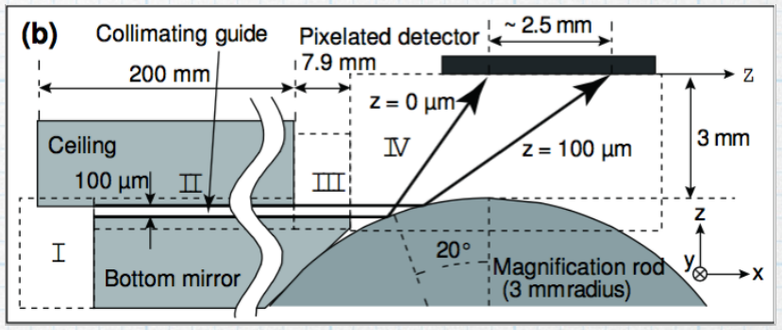
G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

(a) Population distribution of the states

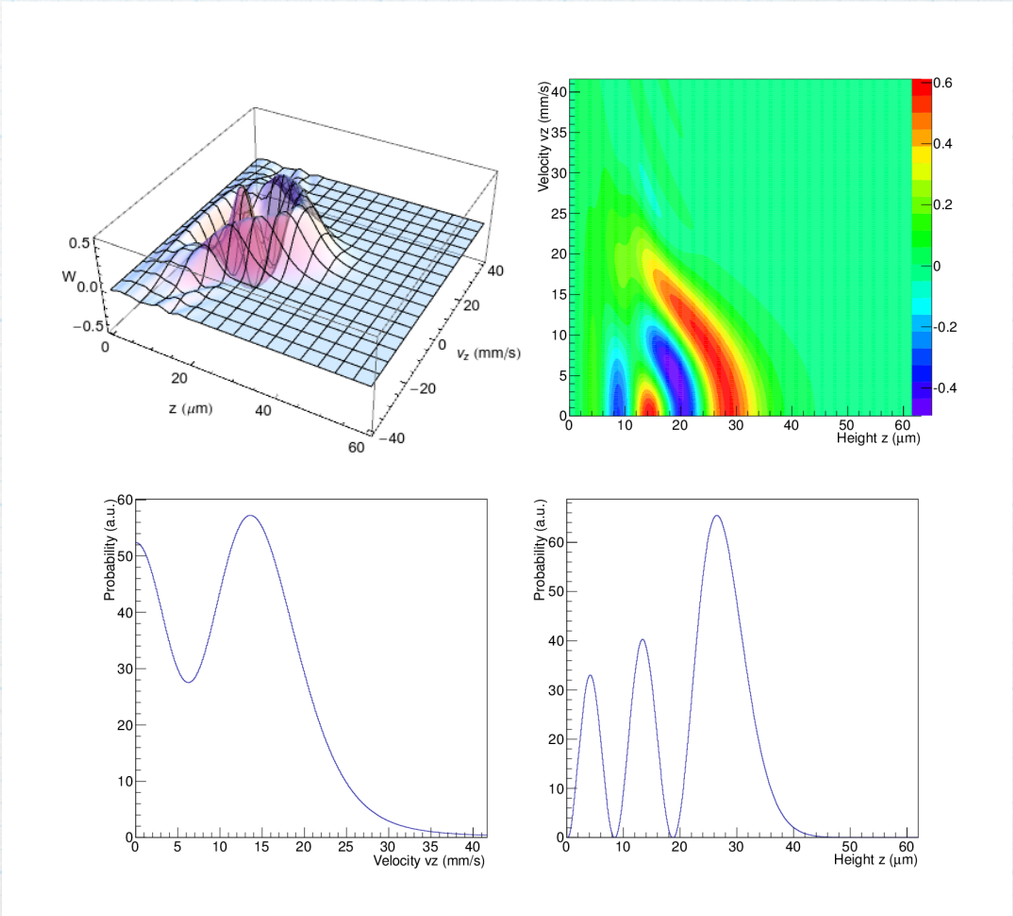
and (b) the Wigner distribution

at the end of the guide (reagion 3)



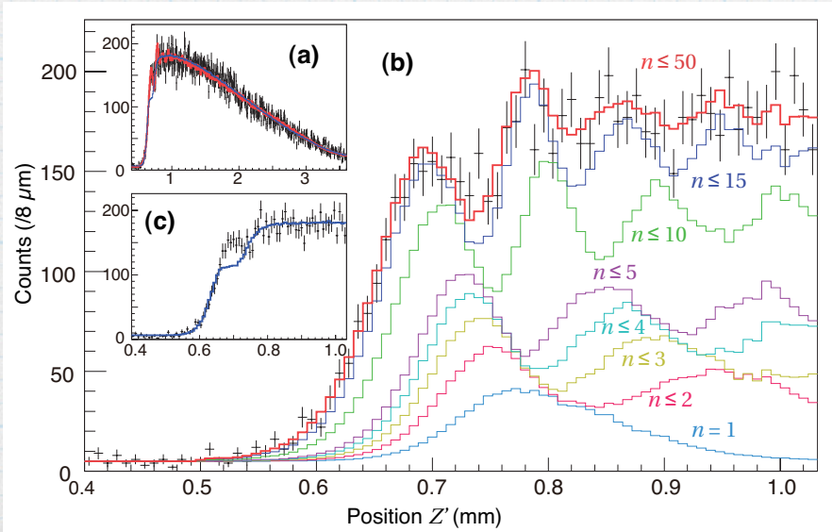


Wigner distribution of the 3rd state



Negative probability reflects quantum effects

The time evolution and projection give the spacial distribution on the detector.



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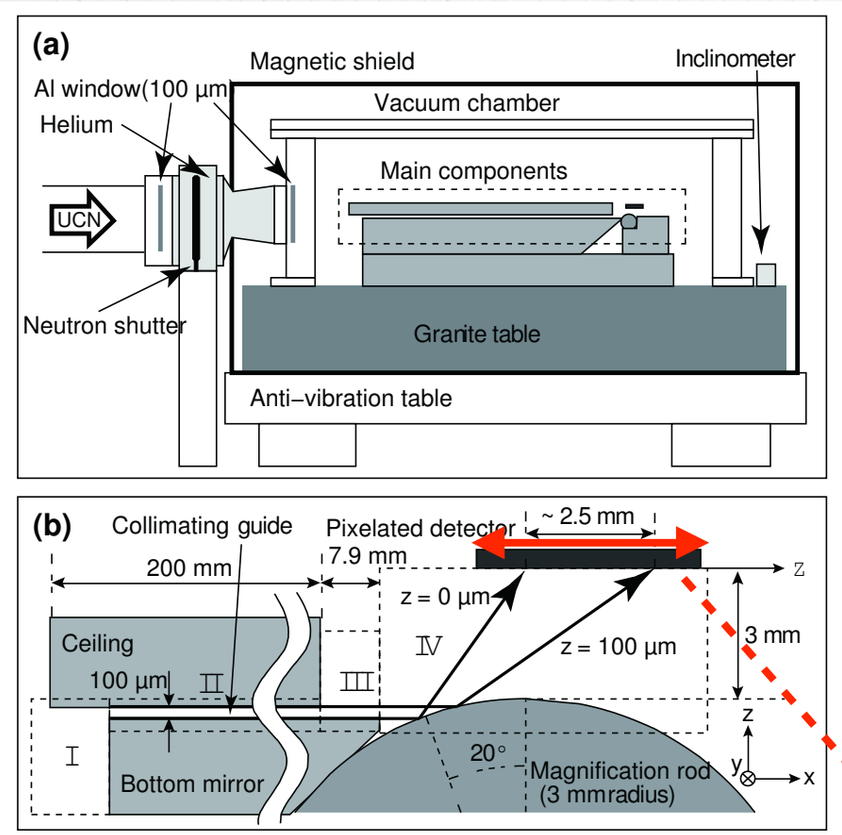

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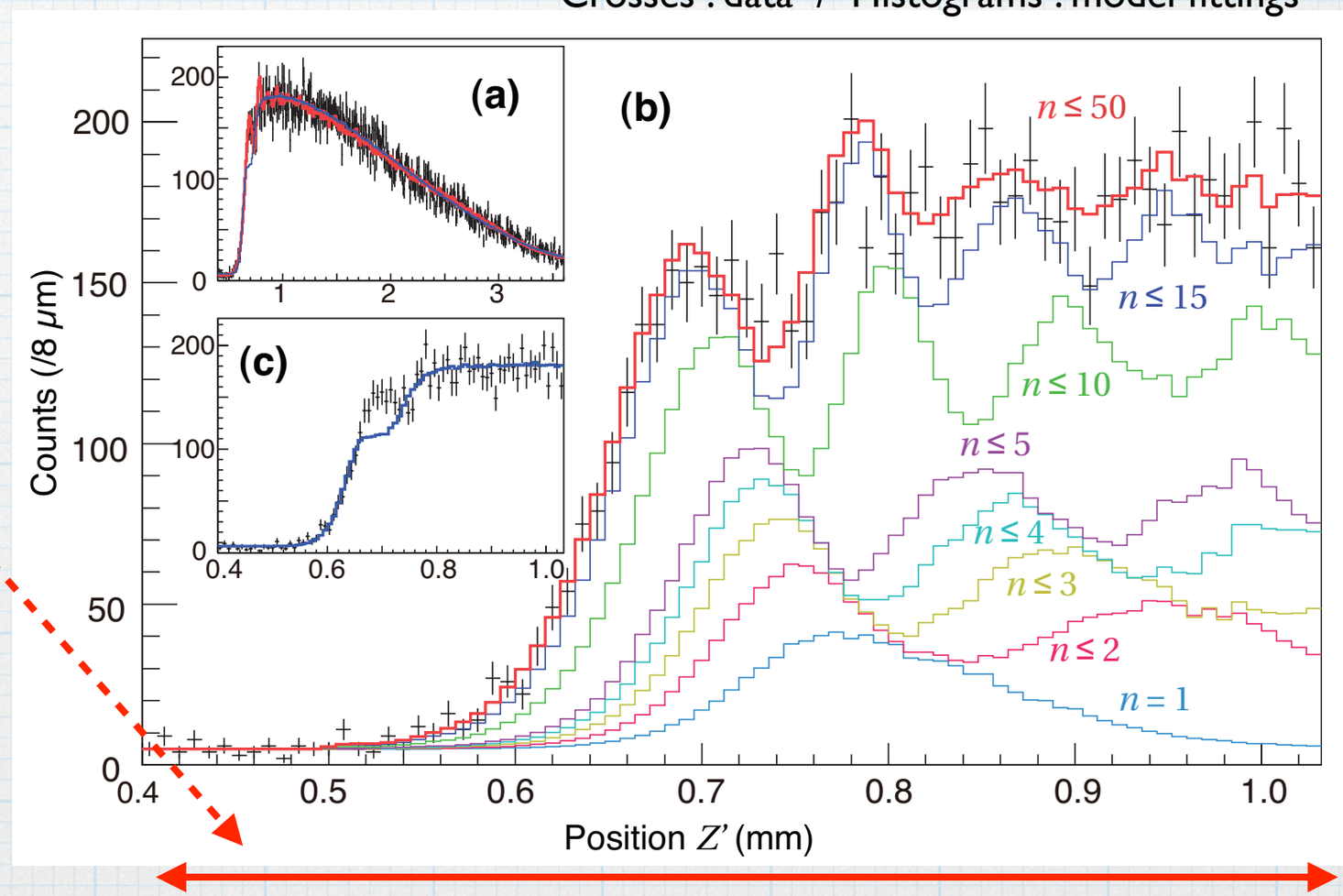

Now we have got a quantum system which couples to gravity!!

Measurement of CCD-based Imaging Detector

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Scales of the system

$$z_0 = \left(\frac{\hbar^2}{2m^2 g}\right)^{1/3} \sim 6\ \mu\mathrm{m}$$

$$E_0 = \left(\frac{mg^2\hbar^2}{2}\right)^{1/3} \sim 0.6\ \mathrm{peV}$$

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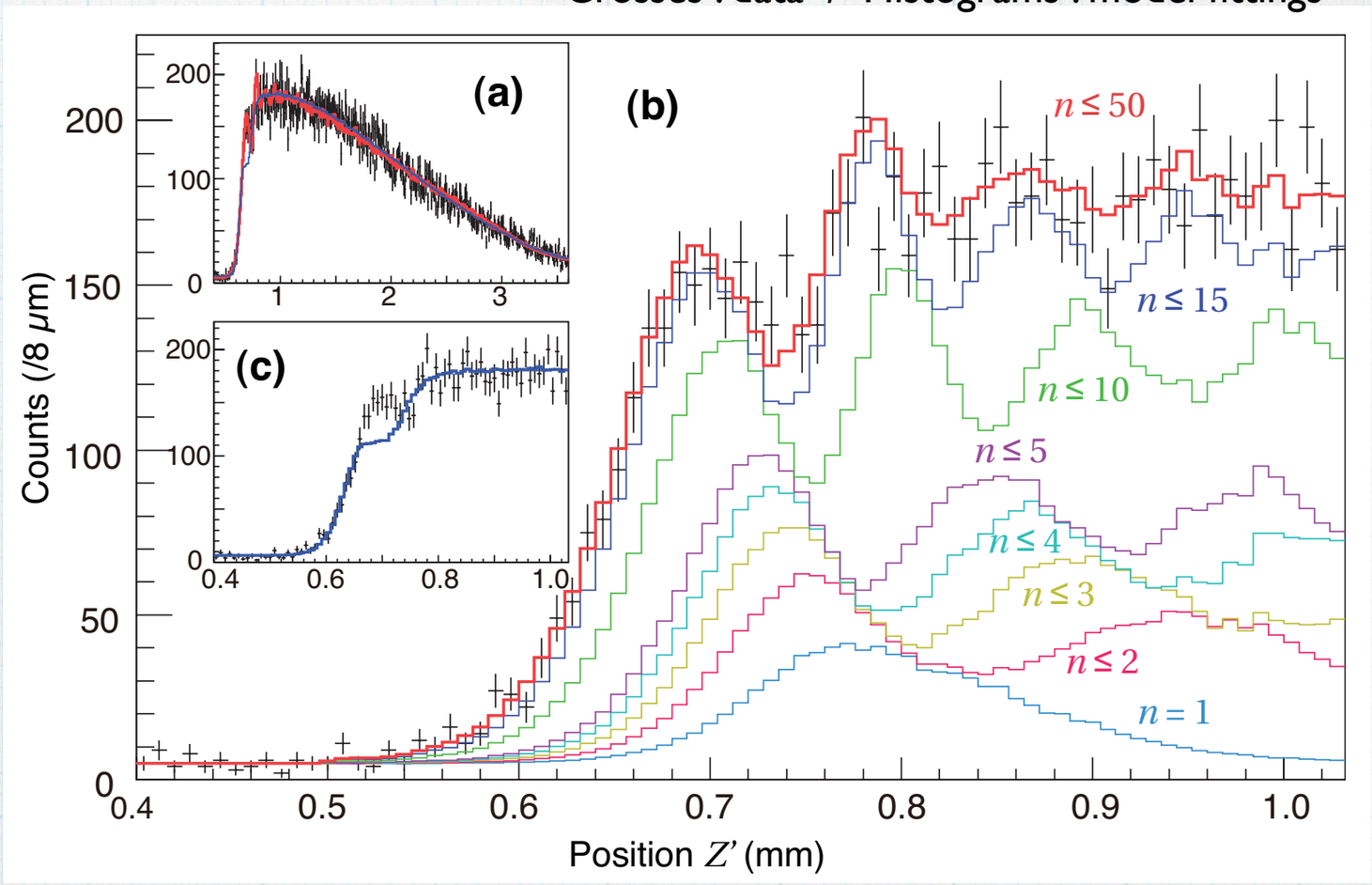

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$$z_0 = \left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} \sim 6\ \mu\mathrm{m}$$

$$E_0 = \left(\frac{m_g^2 g^2 \hbar^2}{2m_i}\right)^{1/3} \sim 0.6\ \mathrm{peV}$$

m_g : gravitational mass
m_i : inertial mass

Measurement

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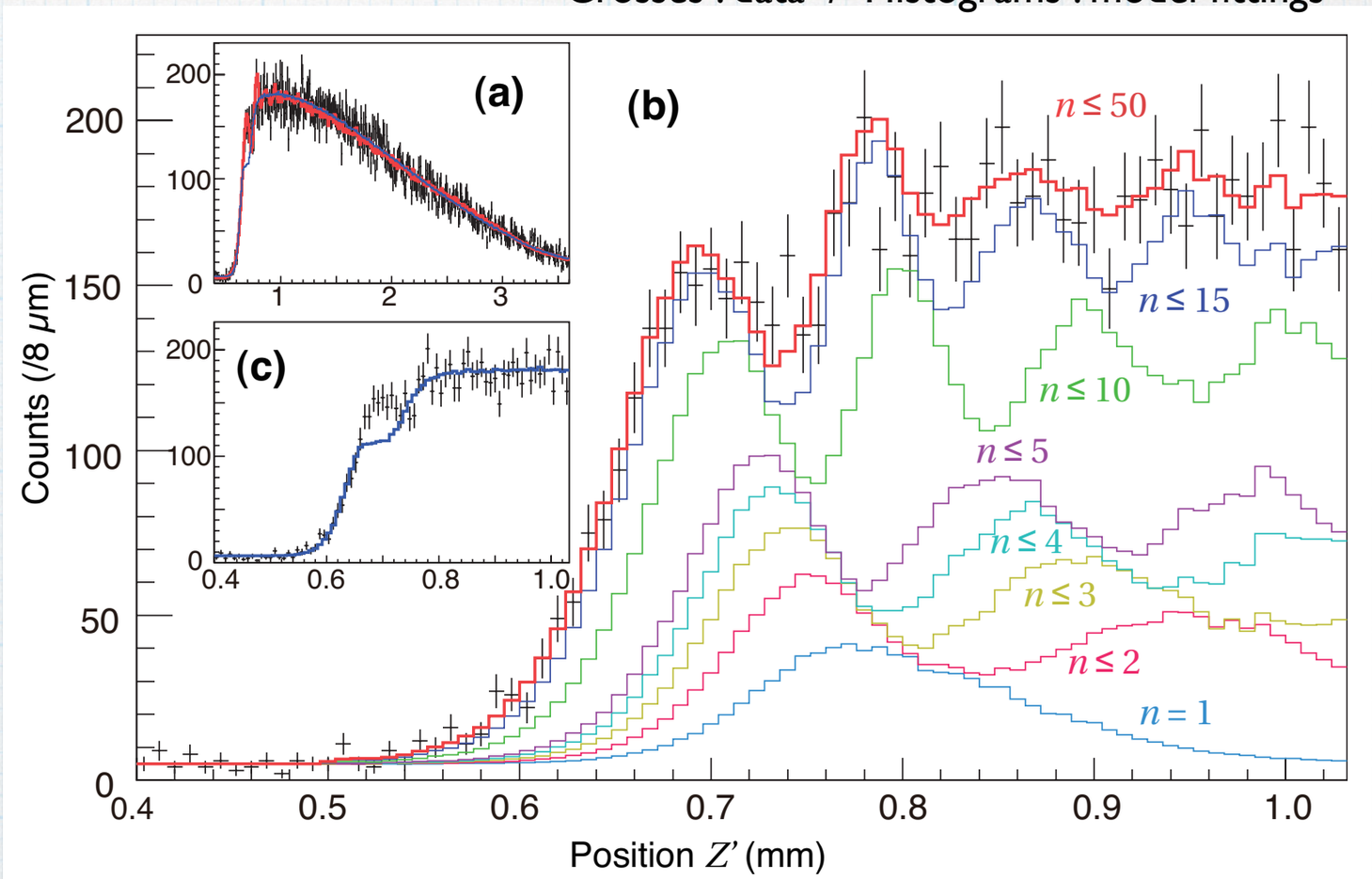
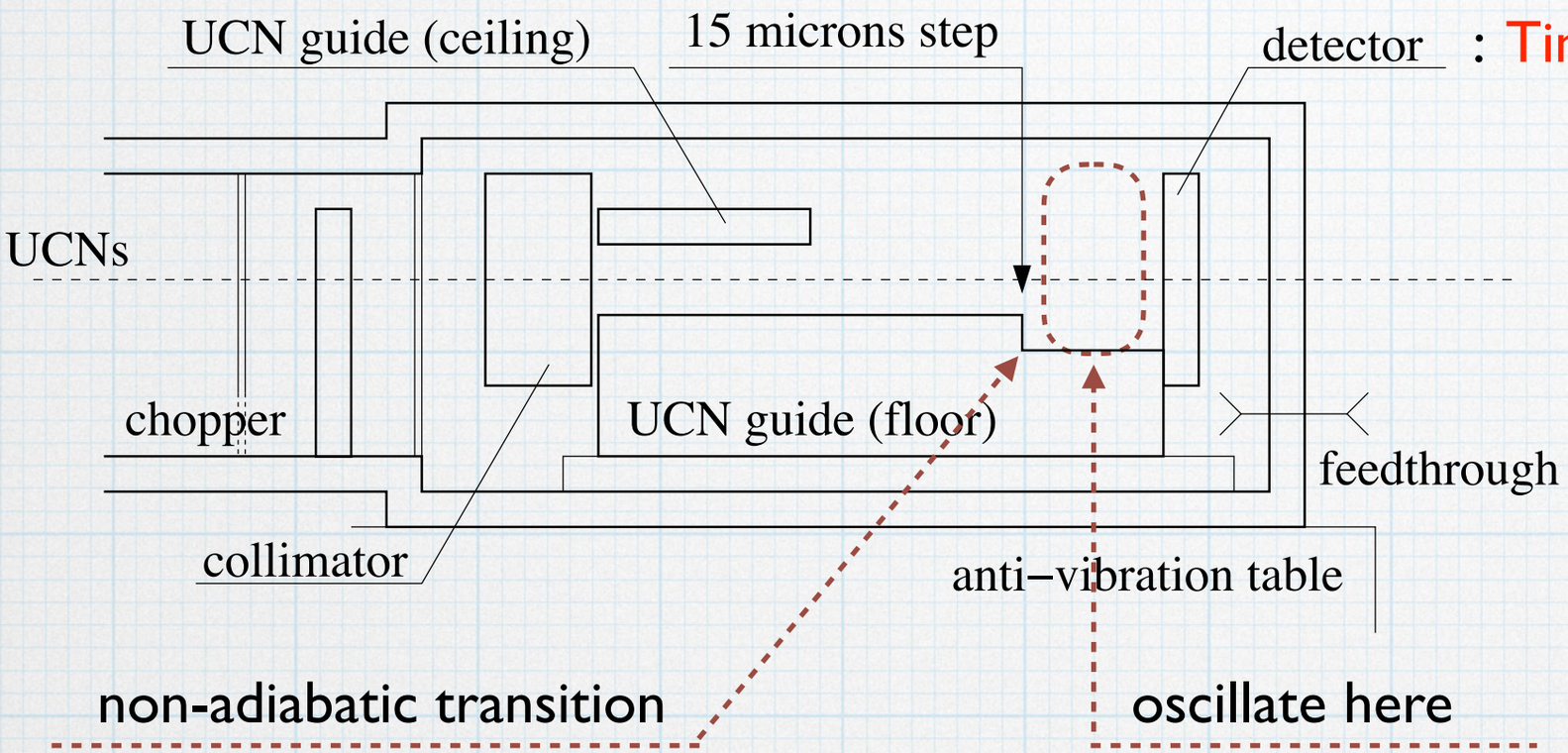


We can evaluate the mass ratio $\eta \equiv \frac{m_g}{m_i}$ by measuring length and energy scales simultaneously!!

How to Measure the Two Scales Simultaneously?



: Time-resolving imaging detector

- length scale is measured by seeing spacial distribution of neutrons directly
- energy scale is evaluated by measuring oscillation frequencies between the states

developing with the group of
Yutaka Yamagata *Riken*

developing with the group of
Giuseppe Iacobucci
The Geneva University

The step changes the eigenstates (basis of the Hilbert space) of this quantum system.

$$\psi_{(z,t=0)} = a_1\phi_{1(z)} + a_2\phi_{2(z)}$$

energy scale

$$|\psi_{(z,t)}|^2 = |\psi_{(z,t=0)}|^2 - \underbrace{4a_1a_2\phi_{1(z)}\phi_{2(z)}\sin^2\frac{(\varepsilon_2-\varepsilon_1)}{2}t}_{\text{oscillating term}}$$

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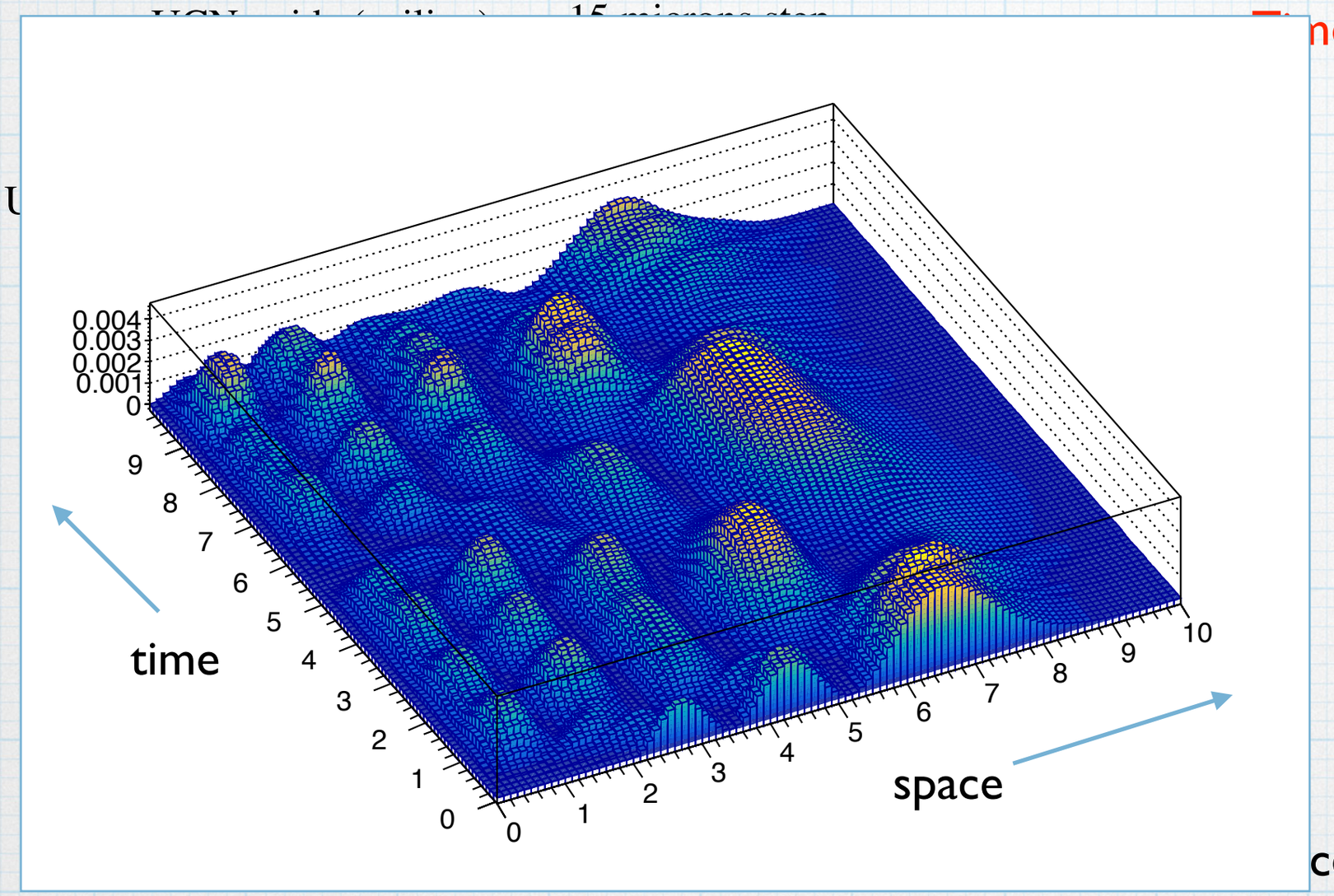

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energy scale

$$|\psi_{(z,t)}|^2 = |\psi_{(z,t=0)}|^2 - 4a_1a_2\phi_{1(z)}\phi_{2(z)}\sin^2\frac{(\varepsilon_2-\varepsilon_1)}{2}t$$

oscillating term

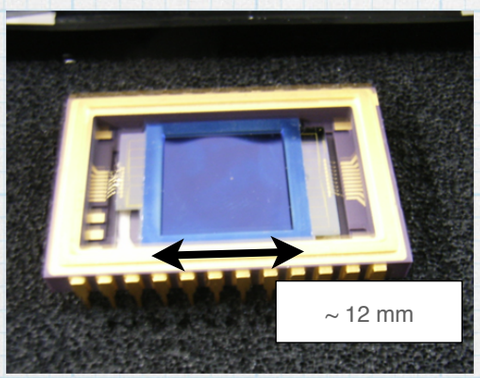
Time-resolving Imaging Detector for UCNs

Our previous detector : CCD based

Position resolution : 3 microns

Readout time : ~ sec

Not enough :-(

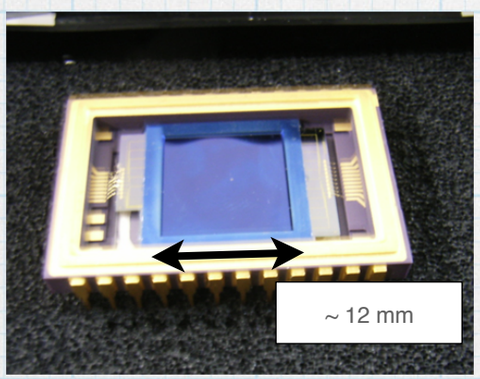


Time-resolving Imaging Detector for UCNs

Our previous detector : CCD based

Position resolution : 3 microns

Readout time : ~ sec

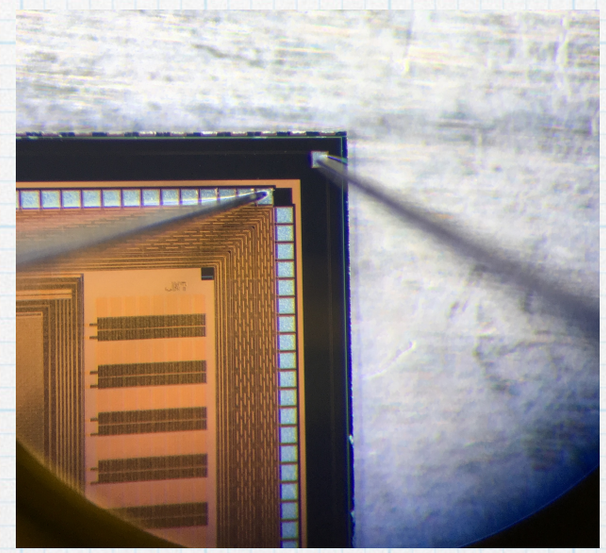


Not enough :-(

New detector design : CMOS based

Position resolution : a few microns (expected.)

Readout time : ~ msec

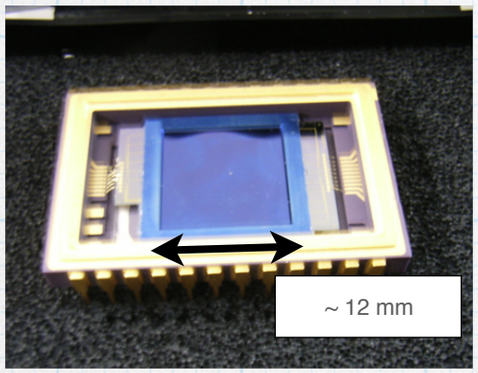


Looks OK! :-)

Charge sharing?
Charge overflow?

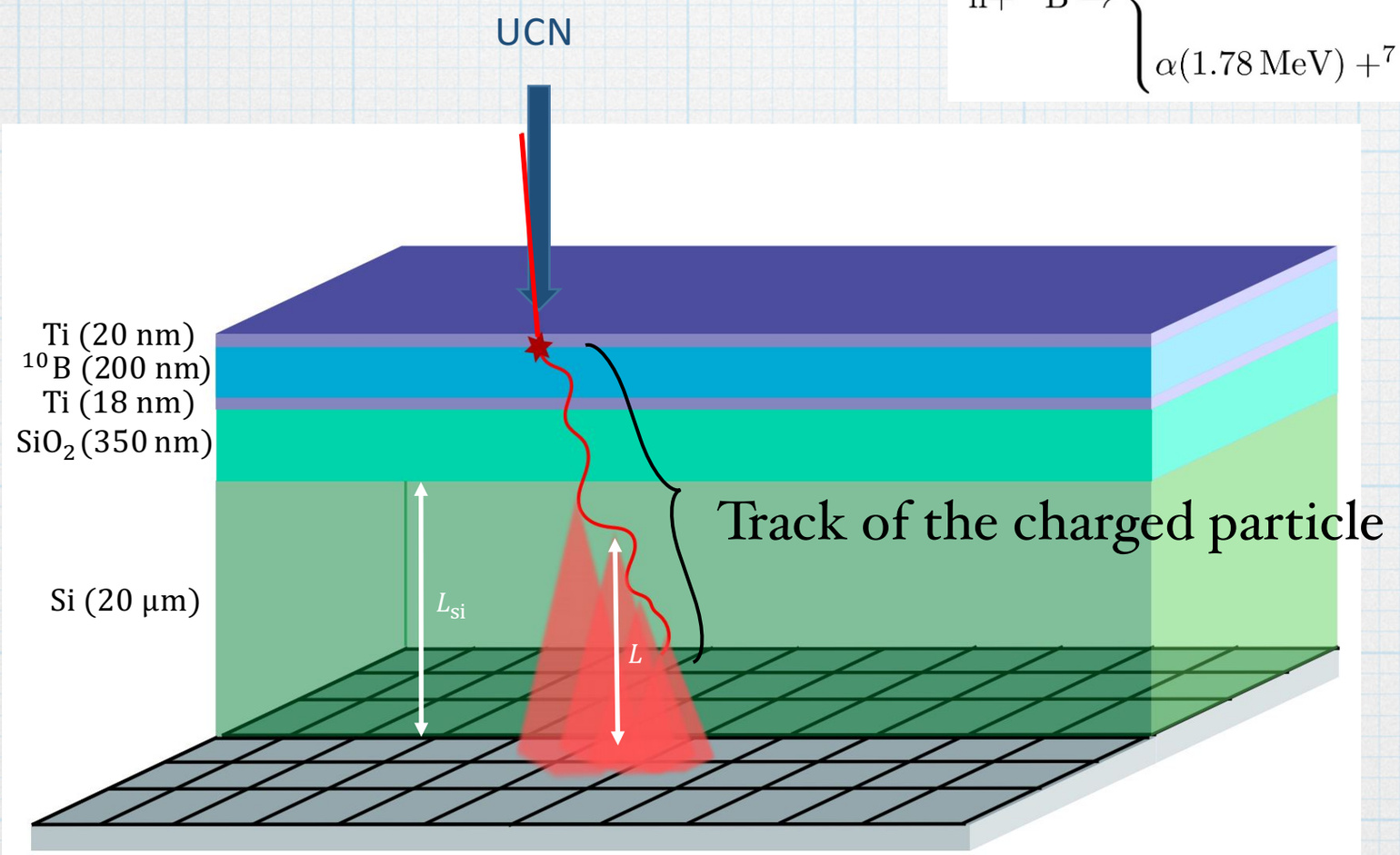
Detector Design

We follow the concepts of
our previous CCD-based detector: ^{10}B coated HAMAMATSU back-illuminated CCD
Pixel size : 24 microns



UCN converts to charged particles in the ^{10}B layer

$$\mathrm{n}+{}^{10}\mathrm{B} \rightarrow \begin{cases} \alpha(1.47\,\mathrm{MeV}) + {}^{7}\mathrm{Li}^{*}(0.84\,\mathrm{MeV}) & (93.9\,\%) \\ \qquad\qquad \hookrightarrow {}^{7}\mathrm{Li}(0.84\,\mathrm{MeV}) + \gamma(0.48\,\mathrm{MeV}) & \\ \alpha(1.78\,\mathrm{MeV}) + {}^{7}\mathrm{Li}(1.01\,\mathrm{MeV}) & (6.1\,\%) \end{cases}$$



Position meas.: 3 microns

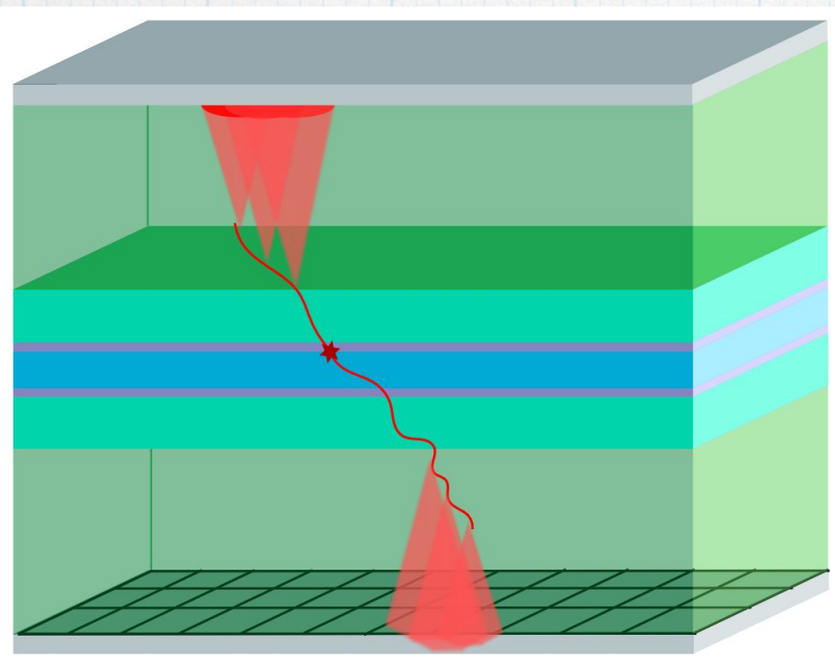
Timing meas.: ~ sec

S. Kawasaki, G. Ishikawa, M. Hino, Y. K. *et al.*, NIM A 615,42 (2010)

G. Ichikawa, S. Komamiya, Y. K. *et al.*, PRL 112, 071101 (2014)

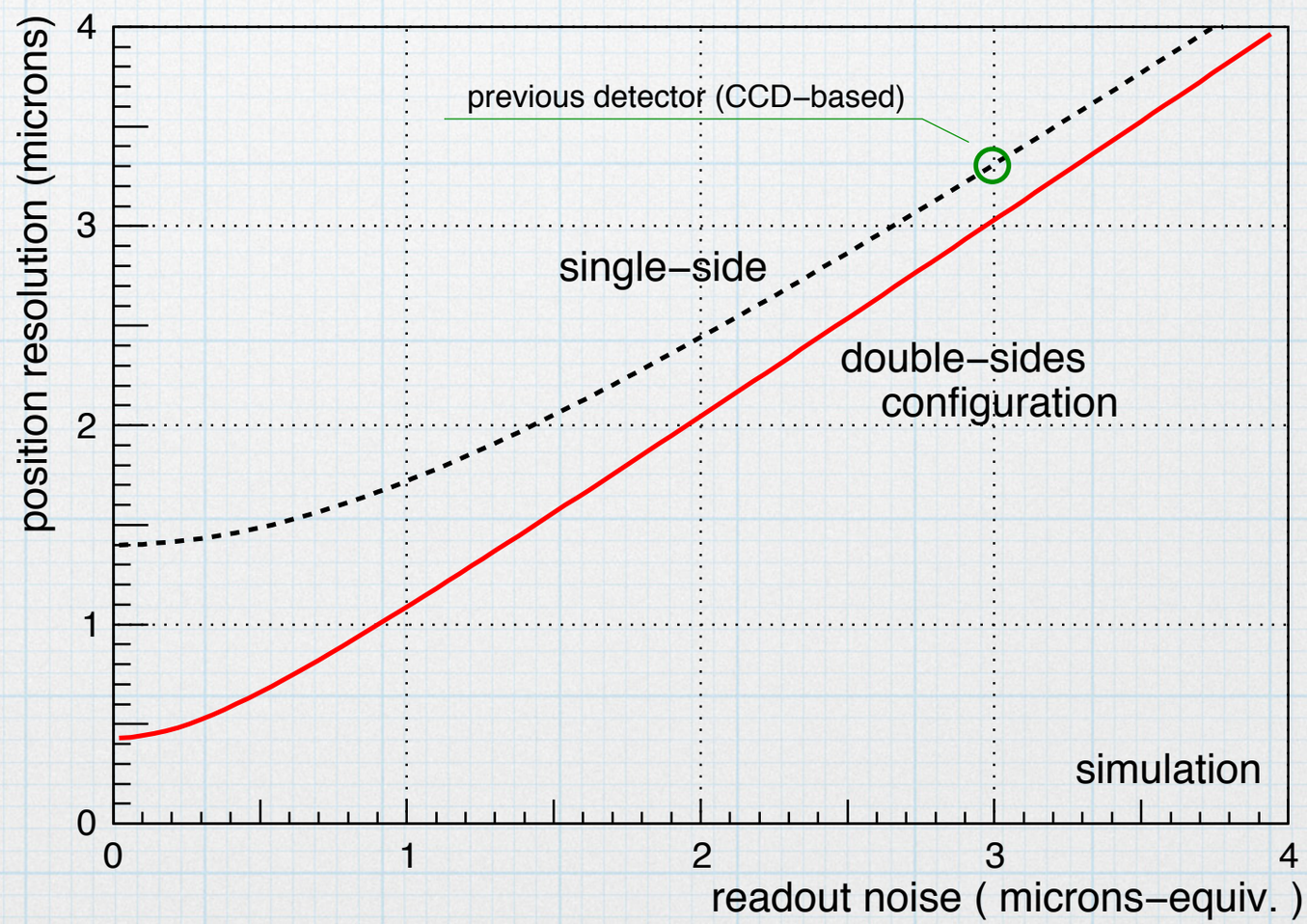
Sandwich (double-sides) Configuration

When you measure the two decay products,
spacial resolution improves.



two body decay

$$\mathrm{n}+{}^{10}\mathrm{B} \rightarrow \begin{cases} \alpha(1.47\,\mathrm{MeV}) + {}^{7}\mathrm{Li}^{*}(0.84\,\mathrm{MeV}) & (93.9\,\%) \\ \qquad\qquad \hookrightarrow {}^{7}\mathrm{Li}(0.84\,\mathrm{MeV}) + \gamma(0.48\,\mathrm{MeV}) & \\ \alpha(1.78\,\mathrm{MeV}) + {}^{7}\mathrm{Li}(1.01\,\mathrm{MeV}) & (6.1\,\%) \end{cases}$$



Thank you!