Fifth Force Search with Neutron Scattering

Gravity-like

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

The Univ. of Tokyo / Kyngpook Nat. Univ.

High Sensitivity Experiments Beyond the Standard Model, Vietnam - 2016 Aug.

Special Things about Gravity

Gravity is the commonest force experienced in every day life, however the most unusual from the view of particle physics. $\longrightarrow$ Very fascinating!

- Extremely weak!

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

(ratios between the other forces are 2 to 3 orders by contrast)

Electroweak scale ~ 1 TeV (Vacuum Expectation Value of the Higgs)

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

Q1

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

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

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Gravity is the commonest force experienced in every day life, however the most unusual from the view of particle physics. → Very fascinating!

- Geometric!

as a result of the weak equivalence principle (WEP)

The principle has been tested in several ways, but most of them are in the classical framework!

Q3

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

now designing an experiment

Q2

Is there any observation of quantum effects due to the gravitational field? — test of quantum effect in gravitationally bound state

There were not so many.

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

Story Line

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"Constraints on New Gravitylike Forces in the Nanometer Range"

Main topic of this talk!

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"Observation of the Spatial Distribution of Gravitationally Bound Quantum States of Ultracold Neutrons and its Derivation using the Wigner Function"

We got new microscopic probe for gravity at the micron range!

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

now designing an experiment

Fifth force might violate the WEP at the microscopic range!

New Scalar Forces

Think about a scalar mediating force for easy discussion

Lagrangian density is written as

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial\phi)^2}_{\text{kinematic term}} - \underbrace{\frac{1}{2}m_\phi^2\phi^2}_{\text{mass term}} - \underbrace{\xi M^4(\frac{\phi}{M})^{-n}}_{\text{self-coupling term}} - \underbrace{\Sigma_i \frac{\eta_i}{M_{Pl}}\rho_i\phi}_{\text{Yukawa-coupling term}}$$

(For the Higgs, $n = -4$, $\eta_i/M_{Pl} = 1/v$)

For no-self-coupling field with universal Yukawa-coupling, ($\xi = 0$, $\eta_i = \eta$) equation of motion is the Klein-Gordon and the interaction potential becomes the Yukawa-type

By changing notation of the Yukawa-coupling strength to g, the interaction potential is written as

coupling charges

mass

$$V_\phi(r) = -\frac{1}{4\pi}g^2 m_1 m_2 \frac{e^{-m_\phi r}}{r}$$

coupling strength

where $\Sigma_i \frac{\eta}{M_{Pl}}\rho_i = gm\delta(x)$

The coupling charge is mass, so the new interaction appears to violate the inverse square law of gravity.

→ gravity-like force

Therefore, basic stance of the experiment is "Testing Gravity"

Current Status of Testing Gravity > 1 mm scale

Gravity is experimentally tested with fine resolution by planetary and lunar motions, and so on.

(exception) Pioneer Anomaly

The Pioneer 10/11 spacecrafts were observed to be strongly pulled by the Sun than the expectation slightly, on trajectories out of the Solar System. (1980)

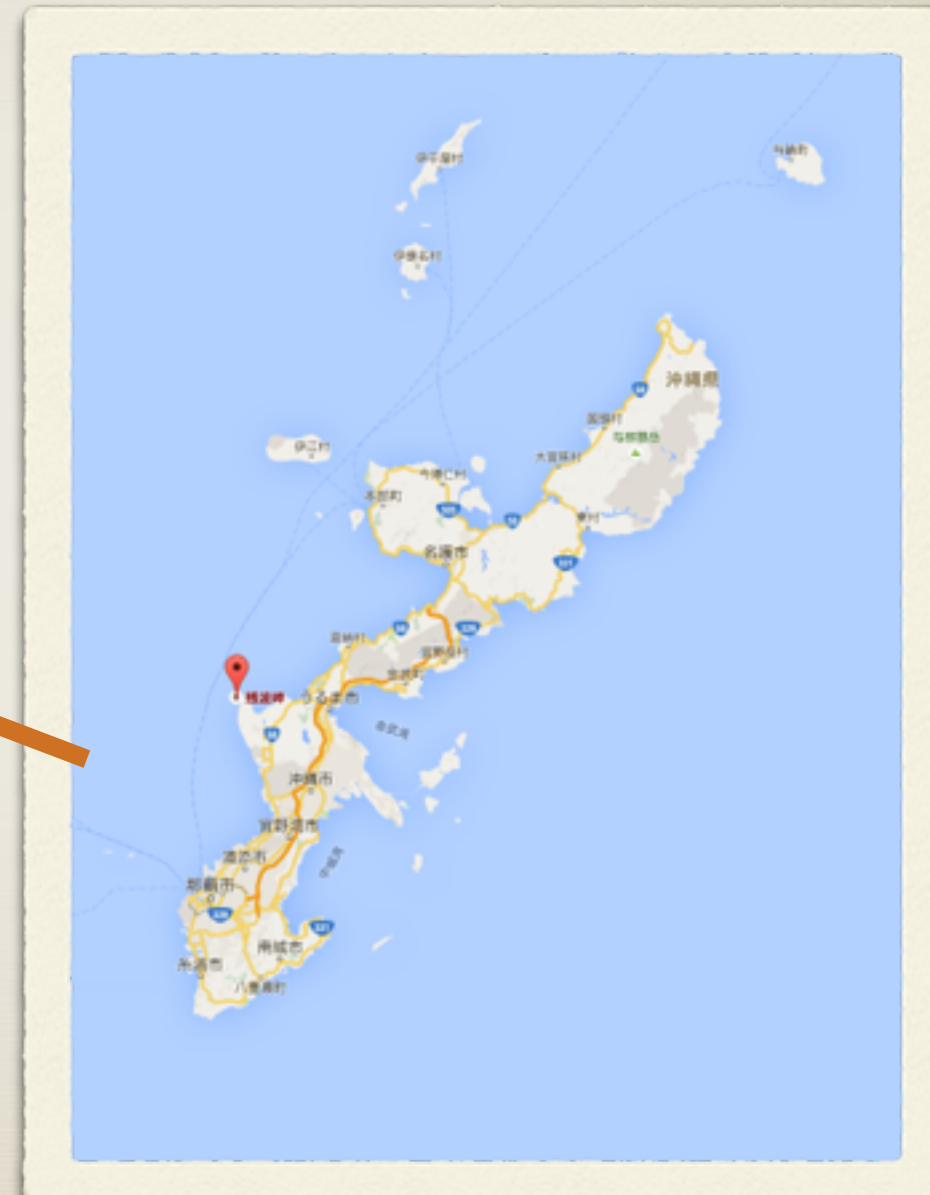
causes discussions including modified gravity

Now the anomaly is explained by an anisotropic thermal radiation forces

--- PRL 108, 241101 (2012)

Testing Gravity at the Human Scale

Daiki Goto / Zanpa cape



Current Status of Testing Gravity < 1 mm scale

For shorter scale, no significant deviation from the Newtonian inverse square law was observed, at the moment.

Many experimental challenges to find any anomaly at shorter distances have been performed by several institutes, with extremely high sensitivities.

Deviation from Newtonian gravity is generally evaluated by the Yukawa-type parametrization

coupling charges

mass

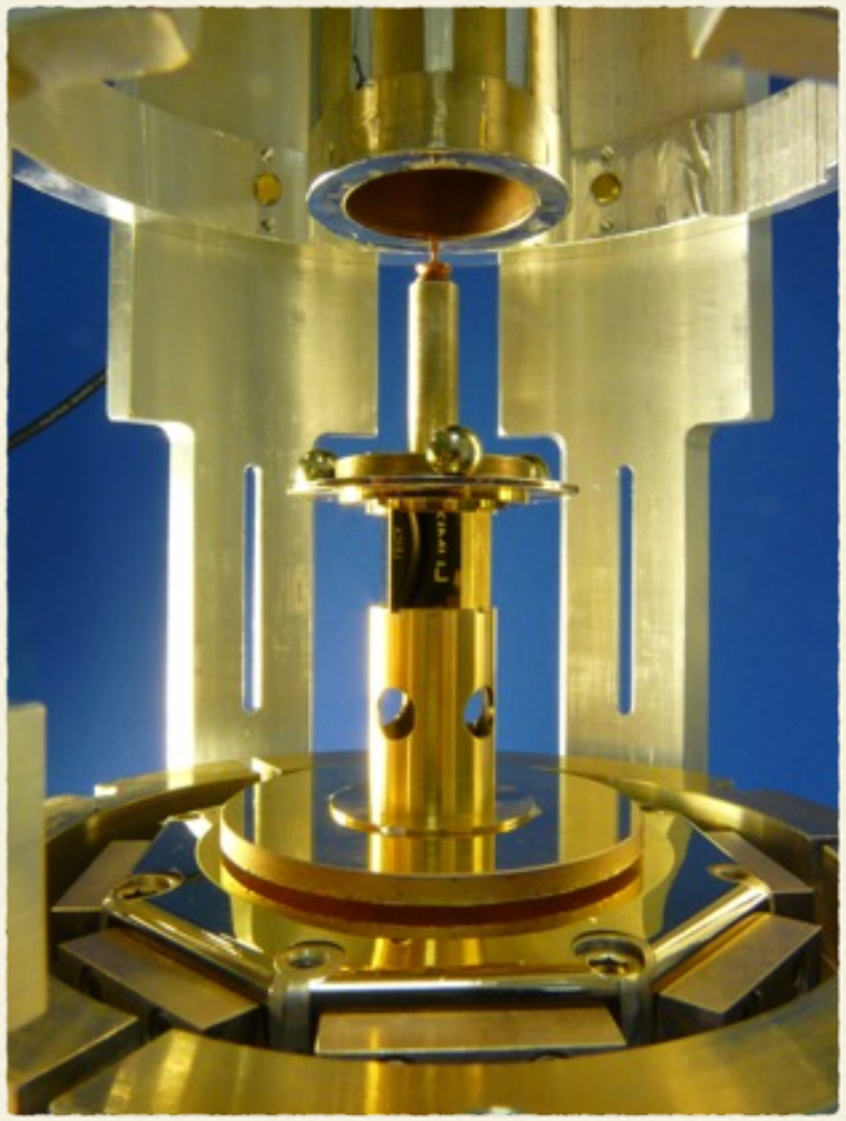
$$V_\phi(r) = -\frac{1}{4\pi} g^2 m_1 m_2 \frac{e^{-m_\phi r}}{r}$$

coupling strength

where $\Sigma_i \frac{\eta}{M_{Pl}} \rho_i = g m \delta(x)$

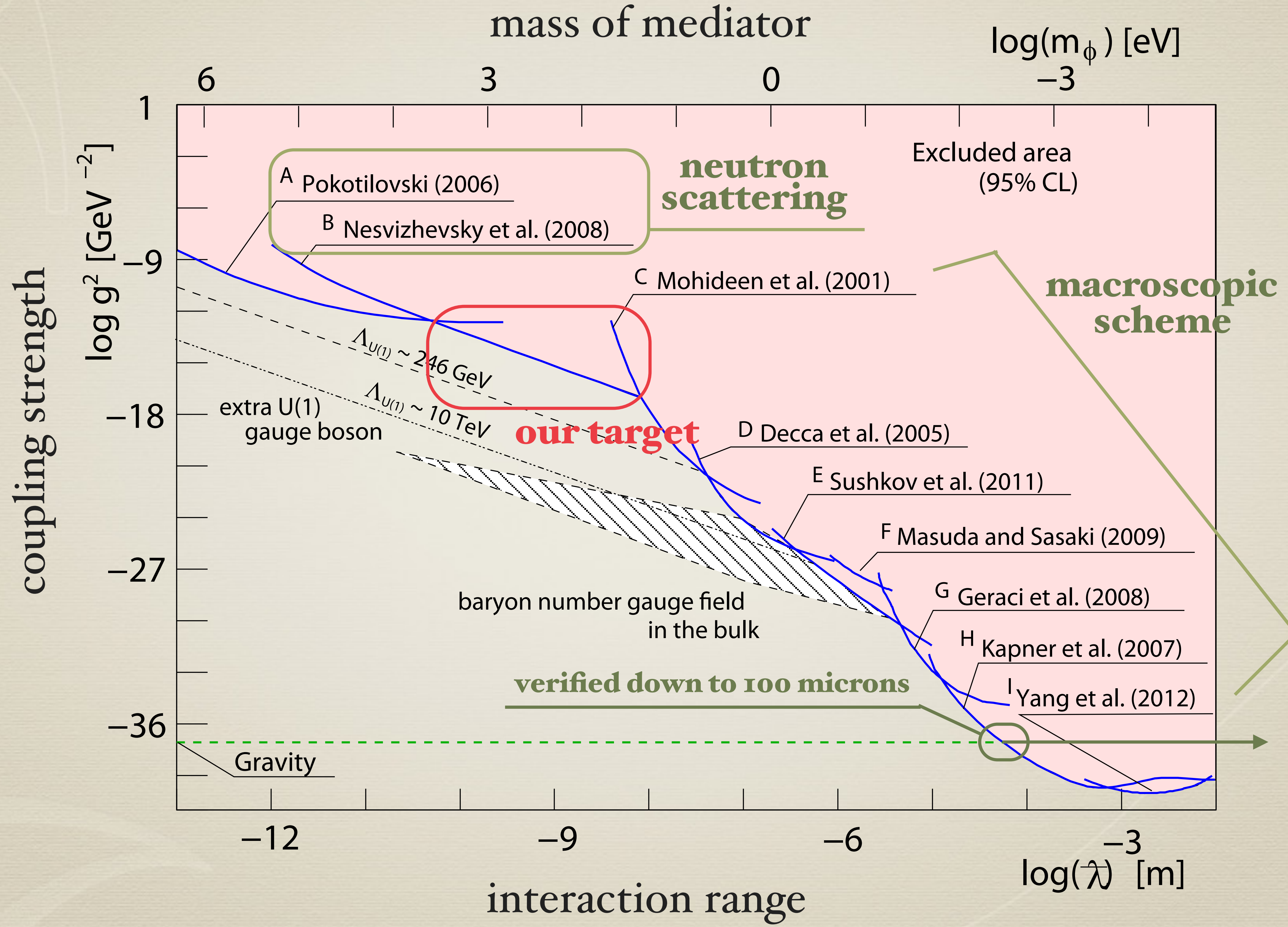
parameter space: (g^2, m_ϕ) or $(g^2, \lambda = 1/m_\phi)$

interaction range



The Eot-Wash Group, Univ. of Washington
http://www.npl.washington.edu/eotwash/sr

Experimental Constraints



Testing using Cold Neutron Beam

1) measure the angular distribution of cold neutrons scattered off Xenon gas

2) evaluate deviations from known scattering processes

Xenon Gas:

large mass — large sensitivity for gravity-like interactions

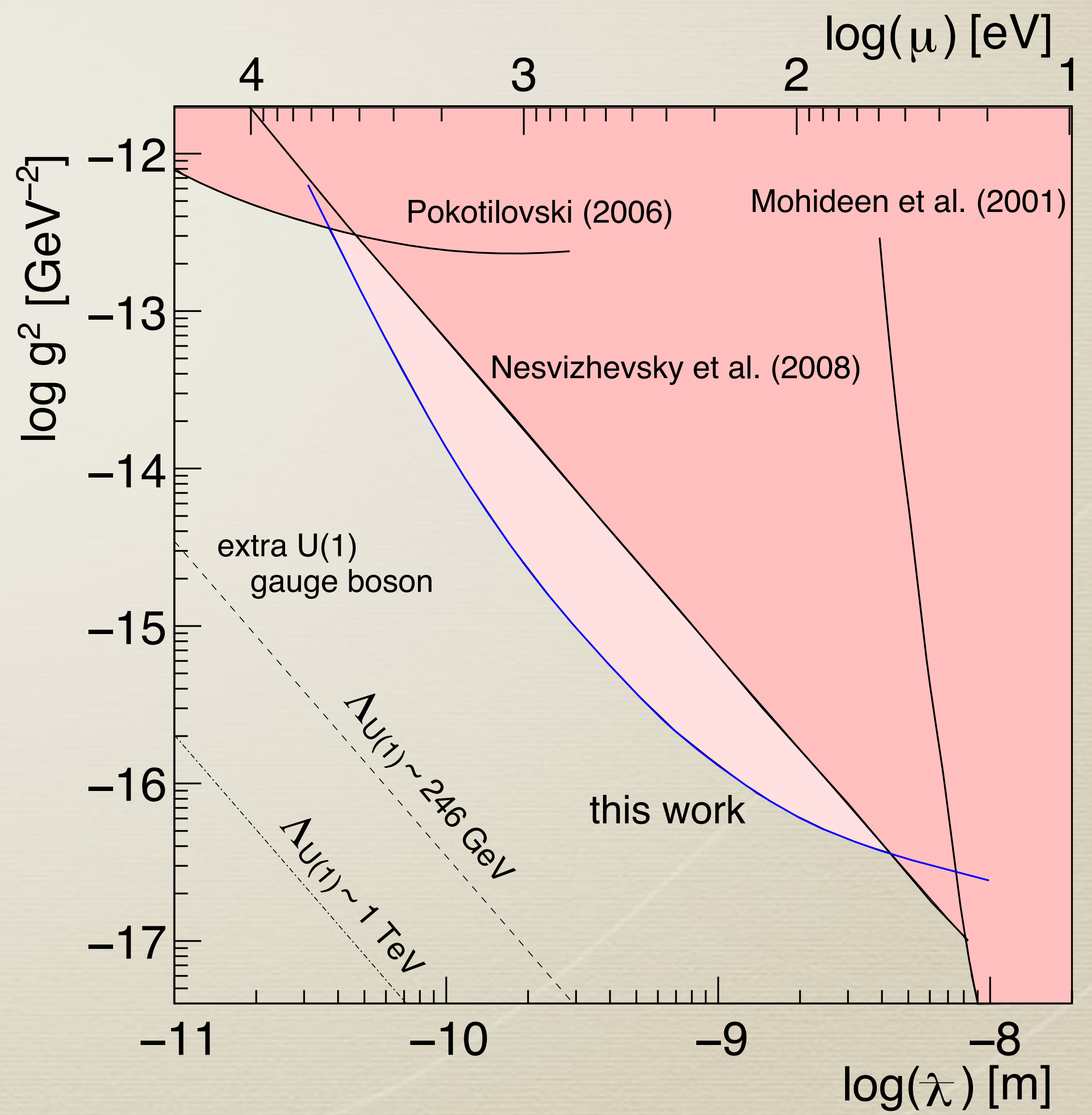
noble gas — EM scattering processes are well understood

This experiment had started from 2013 with financial support of KAKENHI No. 25870160

Two high statistics runs were in 2014,

We have finally succeeded to improve previous constraints for gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10

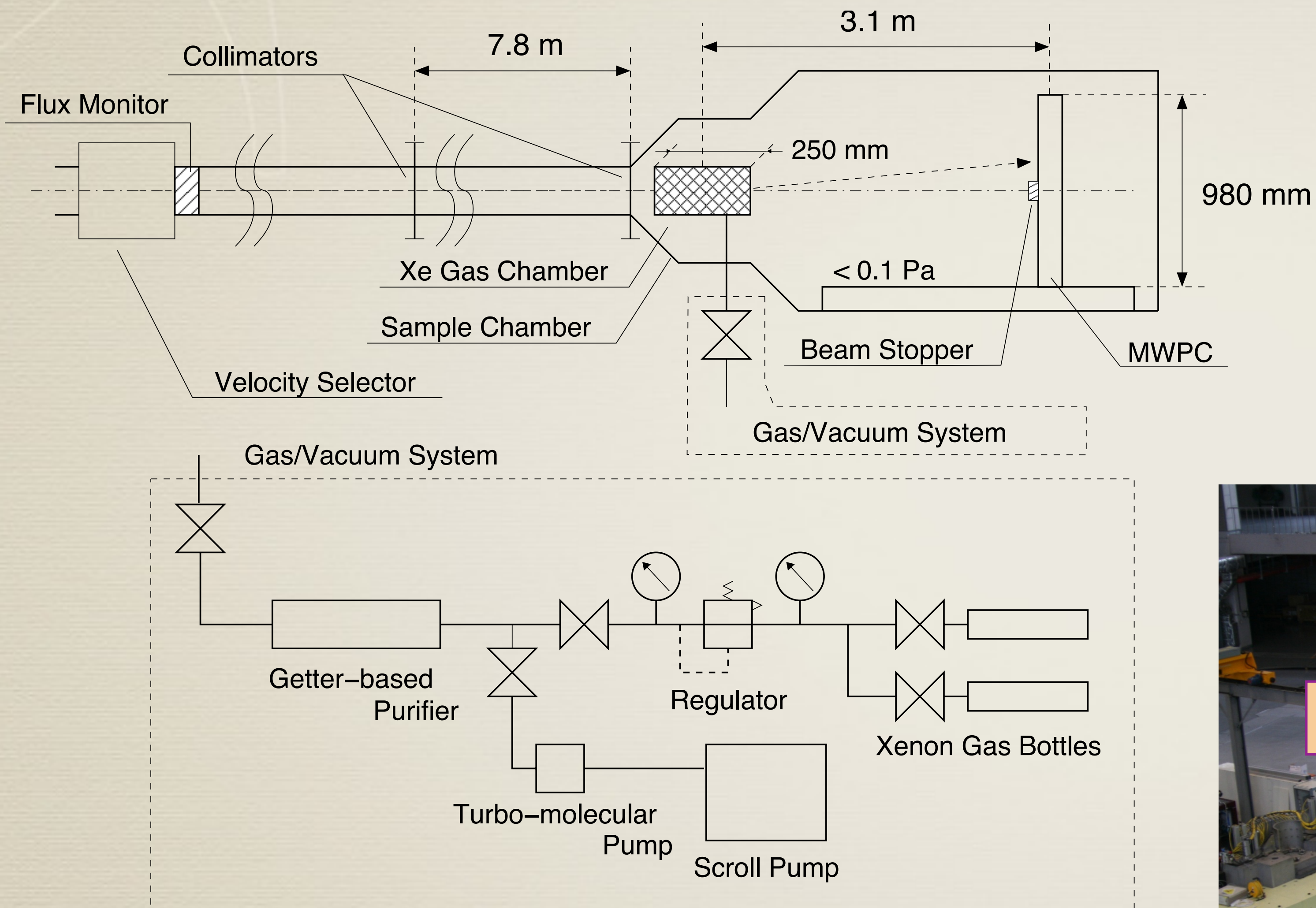
Y. Kamiya, K. Itagaki, M. Tani et al., PRL 114, 161101 (2015)



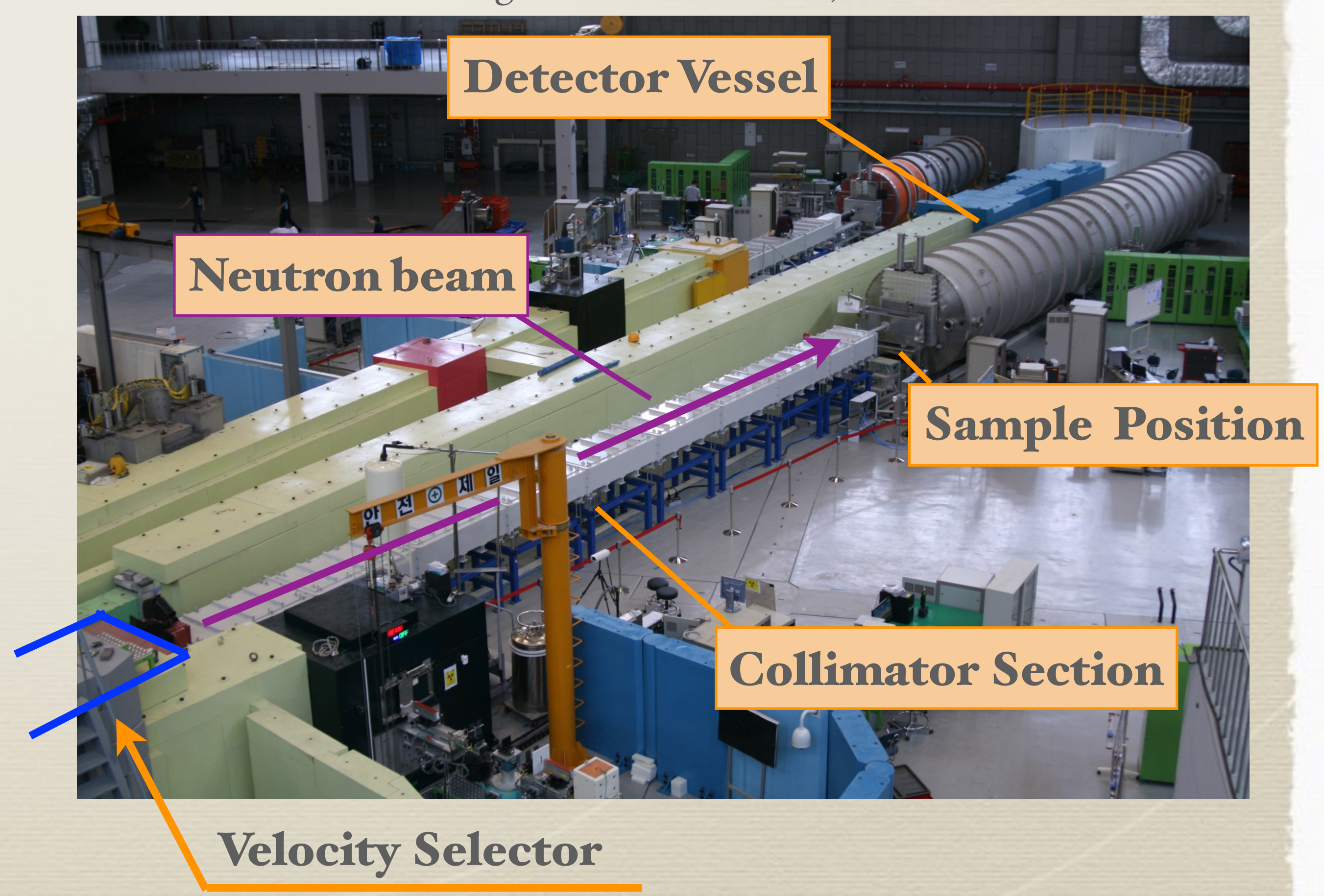
Experimental Site

40 m Small Angle Neutron Scattering Beam Line at the Korean Atomic Energy Research Institute

— nearest research-reactor-based neutron facility



figs. from Young-Soo Han et.al, The 11th Japan-Korea Meeting on Neutron Science, I01 (2011)



- Wavelength: 5 Å
- Beam size: 22 mm in diameter
- Divergence: ~ 3 mrad

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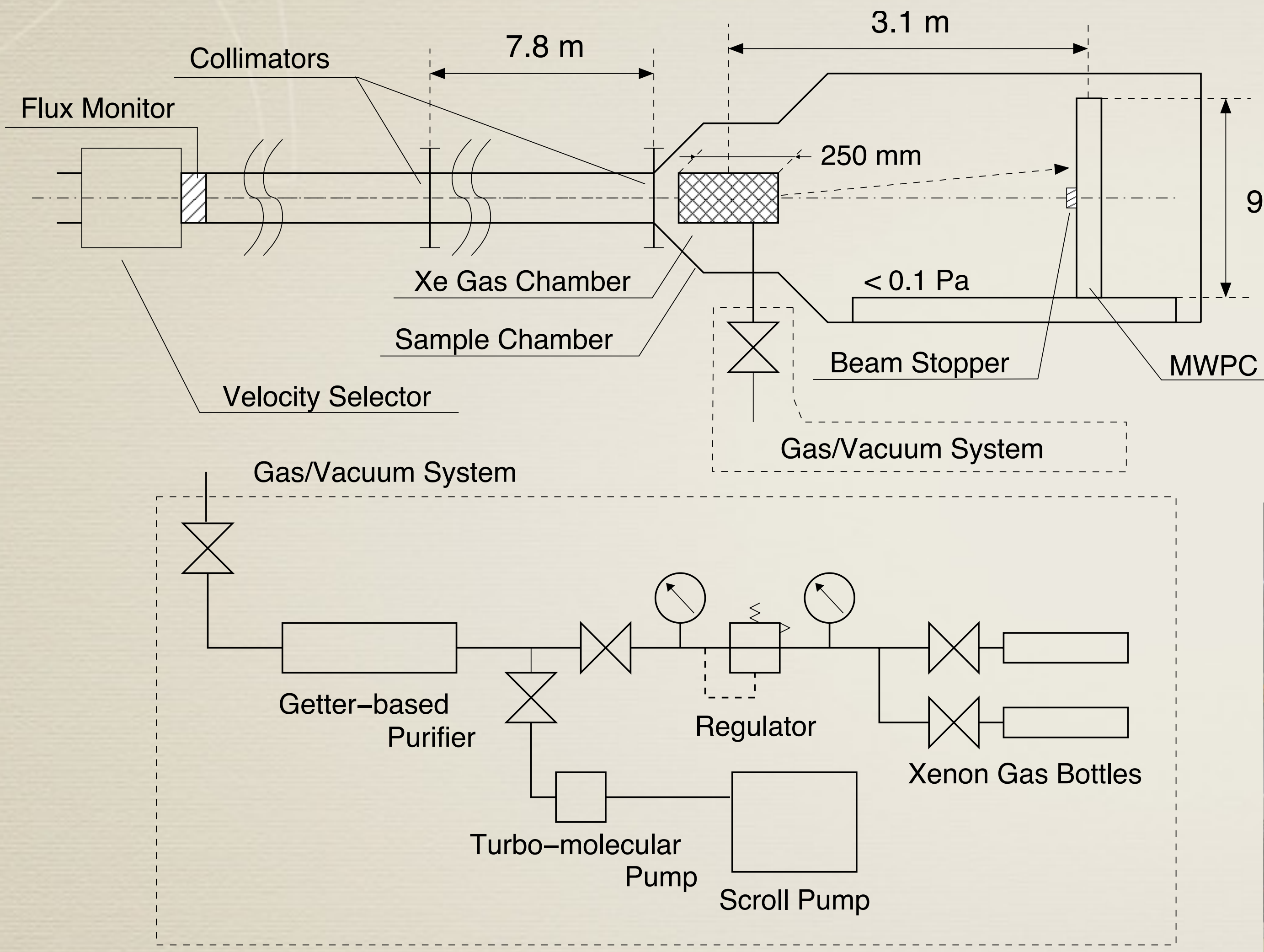

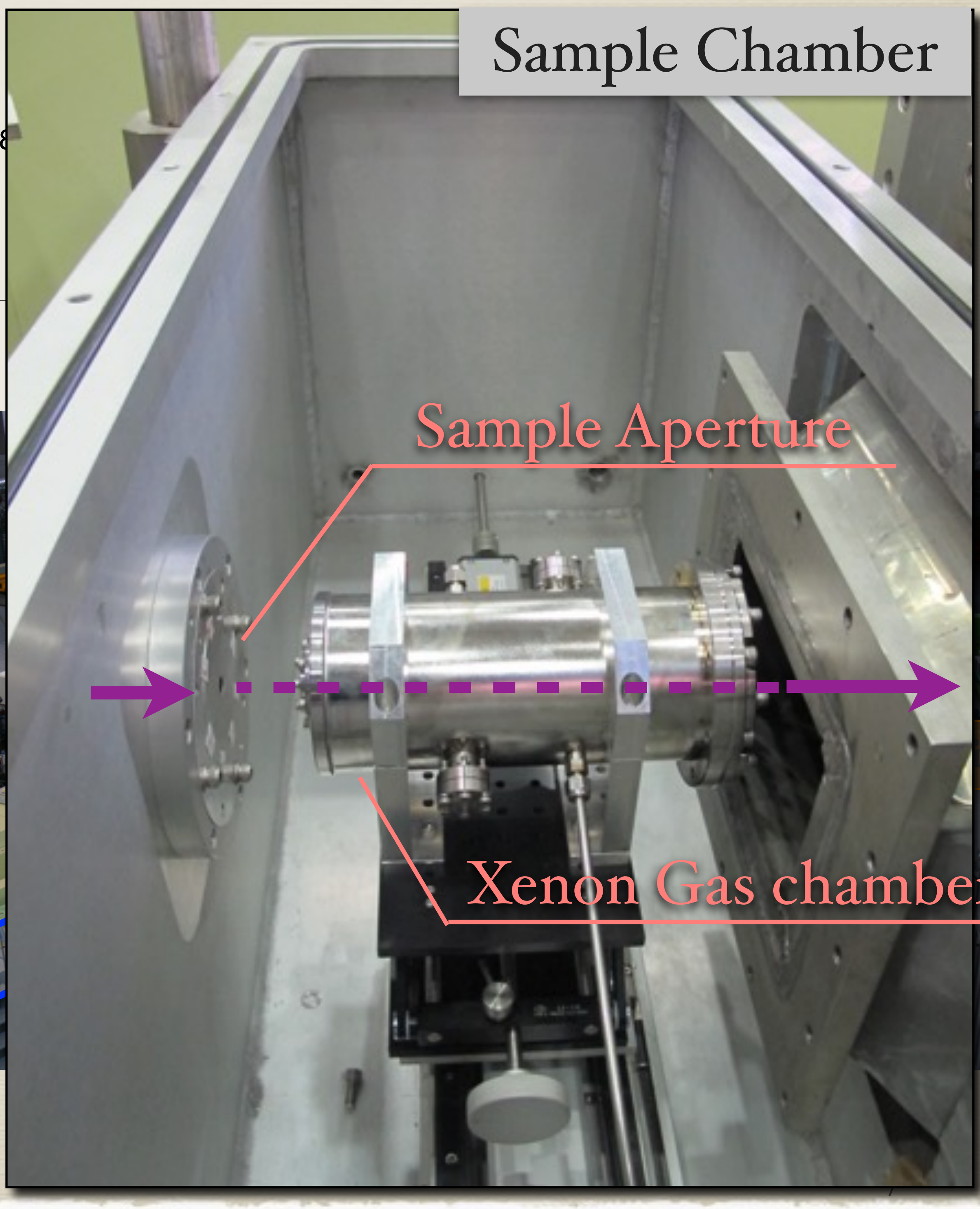

- Wavelength: 5 Å
- Beam size: 22 mm in diameter
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Scattering Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}}\,\boldsymbol{\sigma}\cdot\boldsymbol{b_i}(\boldsymbol{q})\cdot\boldsymbol{I} + ib_s(\boldsymbol{q})\;\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

momentum transfer

coherent scatt.

incoherent scatt.

Schwinger scatt.

+ coherent scattering length (nuclear-nuclear scatt.)

$$b_c(q) = \underbrace{(b_{Nc} + b_p)}_{\sim 5\ \mathrm{fm}} - \underbrace{(b_F + b_I)}_{\sim -1\times10^{-1}\ \mathrm{fm}} Z[1 - f(q)]$$

+ incoherent scattering length (involving an energy exchange)

$$\boldsymbol{b}_i(\boldsymbol{q}) = \underbrace{b_{Ni}}_{\sim 0\ \mathrm{fm}}\mathbf{1} - \sqrt{I(I+1)}\underbrace{g b_F}_{\sim -1\times10^{-3}\ \mathrm{fm}}(\mathbf{1} - \hat{\boldsymbol{q}}\hat{\boldsymbol{q}})$$

+ Schwinger scattering length (an effect of the special relativity)

$$b_s = \underbrace{b_F}_{\sim -1\times10^{-1}\ \mathrm{fm}} Z[1 - f(\boldsymbol{q})]\cot\theta$$

$\sigma/2$: neutron spin
I : nucleus spin
$\hat{n}$: unit vector ⊥ scattering plane

atomic form factor:

$$f(q) = [1 + 3(\frac{q}{q_0})^2]^{-0.5}$$

$q_0 \sim 7\ \mathrm{A}^{-1}$ for Xe

b_{Nc}: coherent nuclear scatt. length
b_p: polarization scatt. length
b_F: Foldy scatt. length
b_I: intrinsic n-e scatt. length
b_{Ni}: incoherent nuclear scatt. length
g: magnetic dipole moment ~ 0.9

Scattering Length

$$b(\boldsymbol{q}) = b_c(\boldsymbol{q}) + \frac{1}{\sqrt{I(I+1)}}\,\boldsymbol{\sigma}\cdot\boldsymbol{b_i}(\boldsymbol{q})\cdot\boldsymbol{I} + ib_s(\boldsymbol{q})\,\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

momentum transfer

coherent scatt. incoherent scatt. Schwinger scatt.

+ coherent scattering length (nuclear-nuclear scatt.)

$$b_c(q) = \underbrace{(b_{Nc} + b_p)}_{\sim 5\ \mathrm{fm}} - \underbrace{(b_F + b_I)}_{\sim -1\times10^{-1}\ \mathrm{fm}} Z[1 - f(q)]$$

$$= (b_{Nc} + b_p)\{1 + \chi[1 - f(q)]\}$$

$$\chi \equiv -\frac{b_F + b_I}{b_{Nc} + b_p}Z \quad \sim 3\times10^{-2}$$

+ coherent scattering length with the new forces

$$b_c(q) = (b_{Nc} + b_p)\{1 + \chi[1 - f(q)] + \chi_y \frac{m_\phi^2}{q^2 + m_\phi^2}\}$$

$$\chi_y \equiv \frac{m_n}{2\pi} g^2 m_n m_{Xe} \frac{1}{(b_{Nc} + b_p)m_\phi^2}$$

via the Born approximation

→ differential cross section

$$\frac{d\sigma}{d\Omega} = < |b(q)|^2 > \simeq (b_{Nc} + b_p)^2 \left\{ \overset{\text{const.}}{1} + 2\chi[1 - f(q)] + 2\chi_y \frac{m_\phi^2}{q^2 + m_\phi^2} \right\}$$

non-flat distr.

Differential Scattering Cross-section

The angular scattering distribution to be measured is derived from this differential scattering cross-section,

$$\frac{d\sigma}{d\Omega} \simeq (b_{Nc} + b_p)^2 \left\{ 1 + 2\chi[1 - f(q)] + 2\chi_y \frac{m_\phi^2}{q^2 + m_\phi^2} \right\}$$

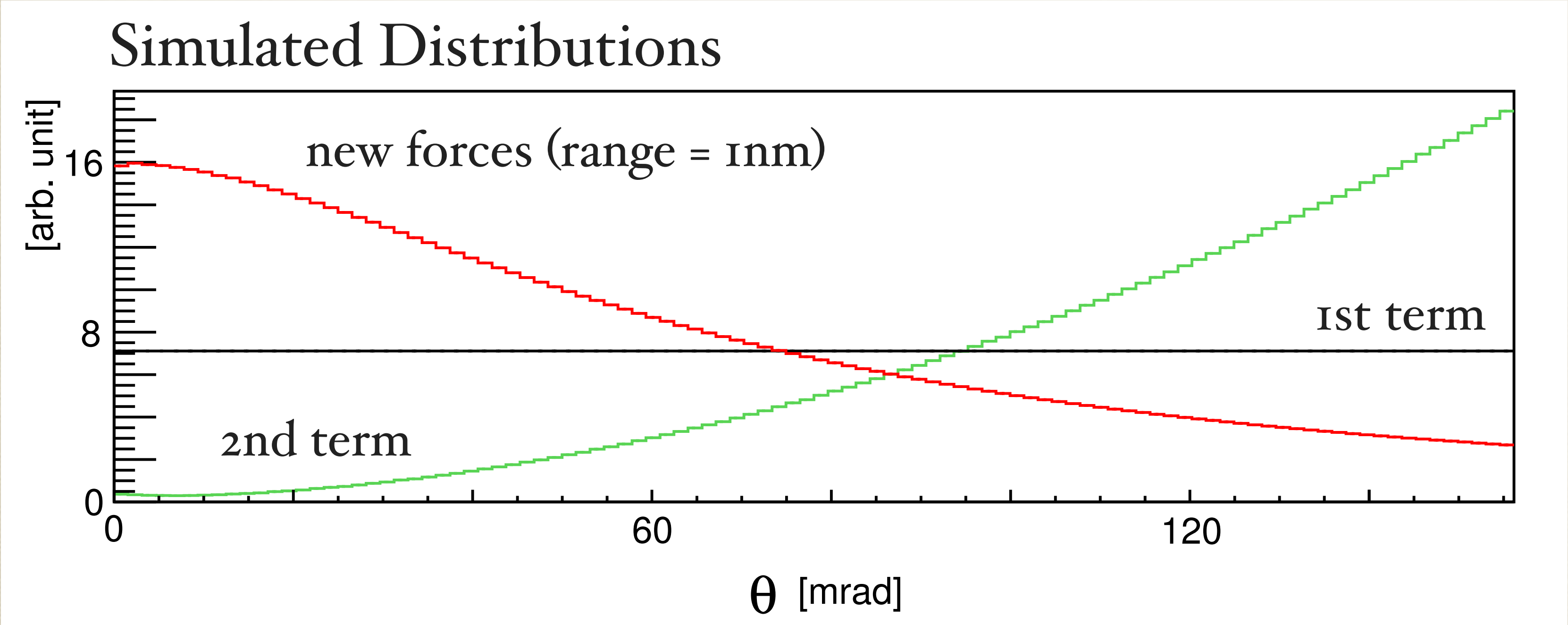
f(q): structure function

(Nuclear scattering + Higher order EM scattering + New interaction)

convoluted with the finite beam size, the length of scattering chamber, and the thermal motion of the Xenon gas

Expected angular scattering distribution is expressed as the sum of three functions, h_1, h_2, h_y, corresponding to the constant, electromagnetic, and new interaction terms.

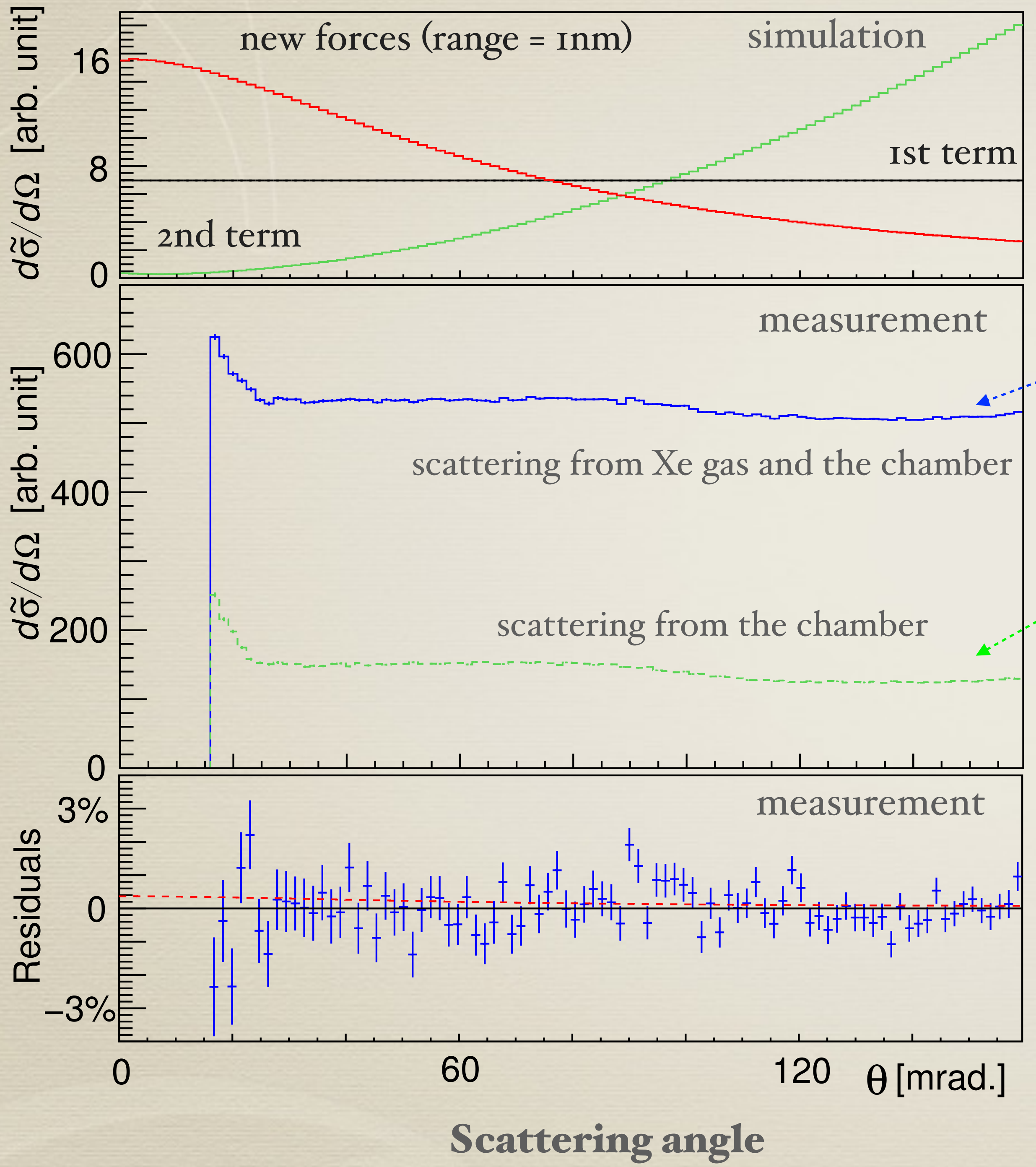
$$\frac{d\tilde{\sigma}}{d\Omega}(\theta) = N\left\{(1-\alpha^*)(1-\beta)h_1(\theta) + \alpha^*(1-\beta)h_2(\theta) + \beta h_y(\theta; m_\phi)\right\}$$



Distribution due to the new interaction term for 1 nm range is clearly different from the known interaction terms

Fitting evaluation using the distributions effectively works!!

Measured Distribution



procedure

1. remove the effect of neutron-Chamber scattering

$$g(\theta) = g_{sam}(\theta) \quad - \quad \gamma \frac{M_{sam}}{M_{emp}} g_{emp}(\theta) \\ -(1-\gamma)\frac{M_{sam}}{M_{bg}} g_{bg}(\theta)$$

neutron transmittance in the Xe gas sample: $\gamma = 0.904 \pm 0.004$

2. fitting with the function and estimate the β

$$\frac{d\tilde{\sigma}}{d\Omega}(\theta) = N\{(1-\alpha^*)(1-\beta)h_1(\theta) \\ +\alpha^*(1-\beta)h_2(\theta) + \beta h_y(\theta; m_\phi)\}$$

estimated to be $\hat{\beta} = (-0.7 \pm 1.2) \times 10^{-3}$
for 1 nm range

3. set 95% Confidence Level using Feldman-Cousins approach

New Constraints

the results improve previous constraints for gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10

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

Discussions)

1. Can we expand the experimental reach?

    - use shorter wavelength

        Todo: re-select an experimental site

    - measure at smaller angle

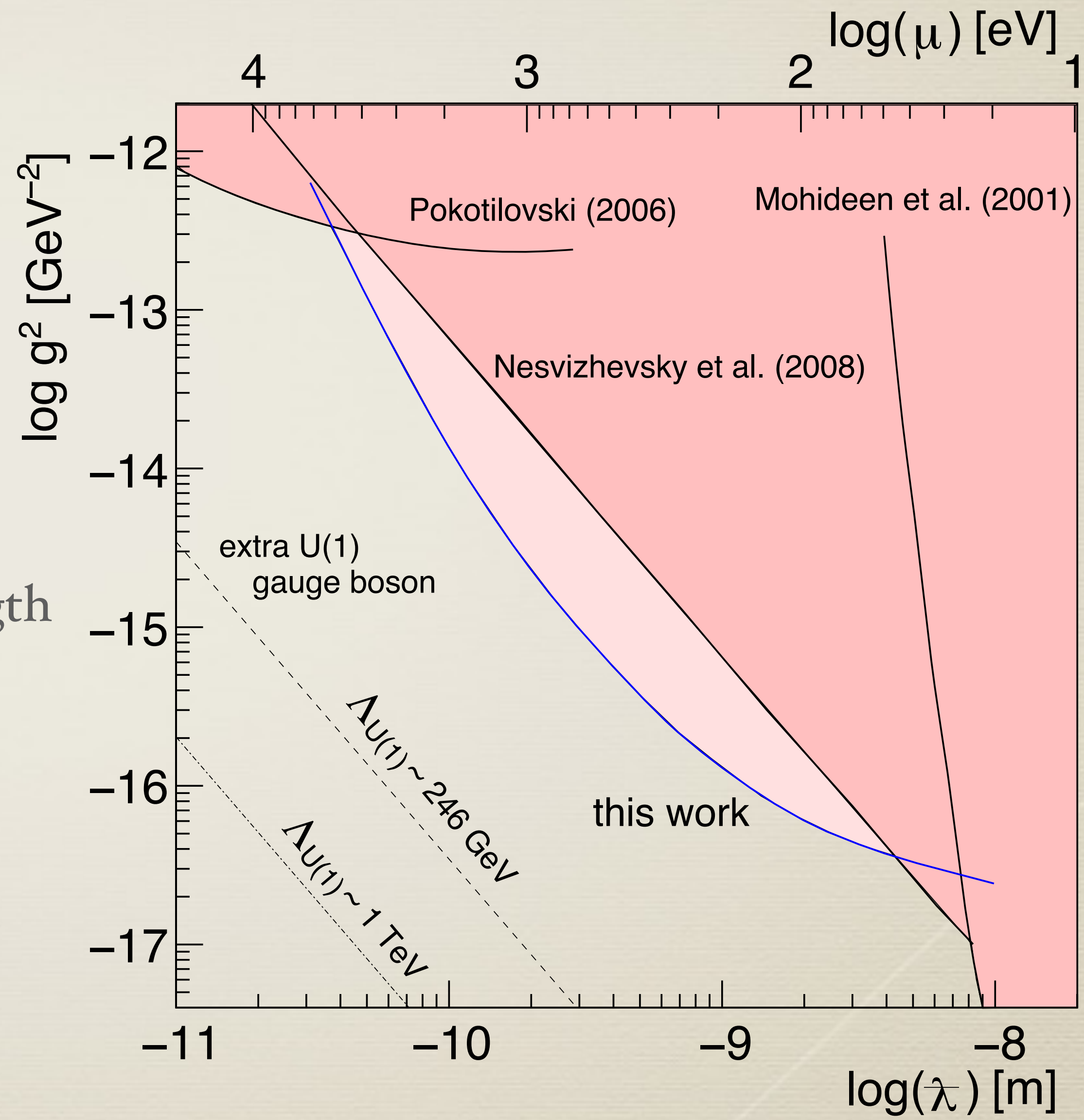
      possible using neutron lenses

        Todo: develop new lenses with 5 m focal length

2. Any sensitivity for other type of forces?

    axion type, radion, diraton, fat graviton, multi-particle exchange, ...

We have some sensitivity for them



example) Chameleon field : will be Yukawa-type in some special condition

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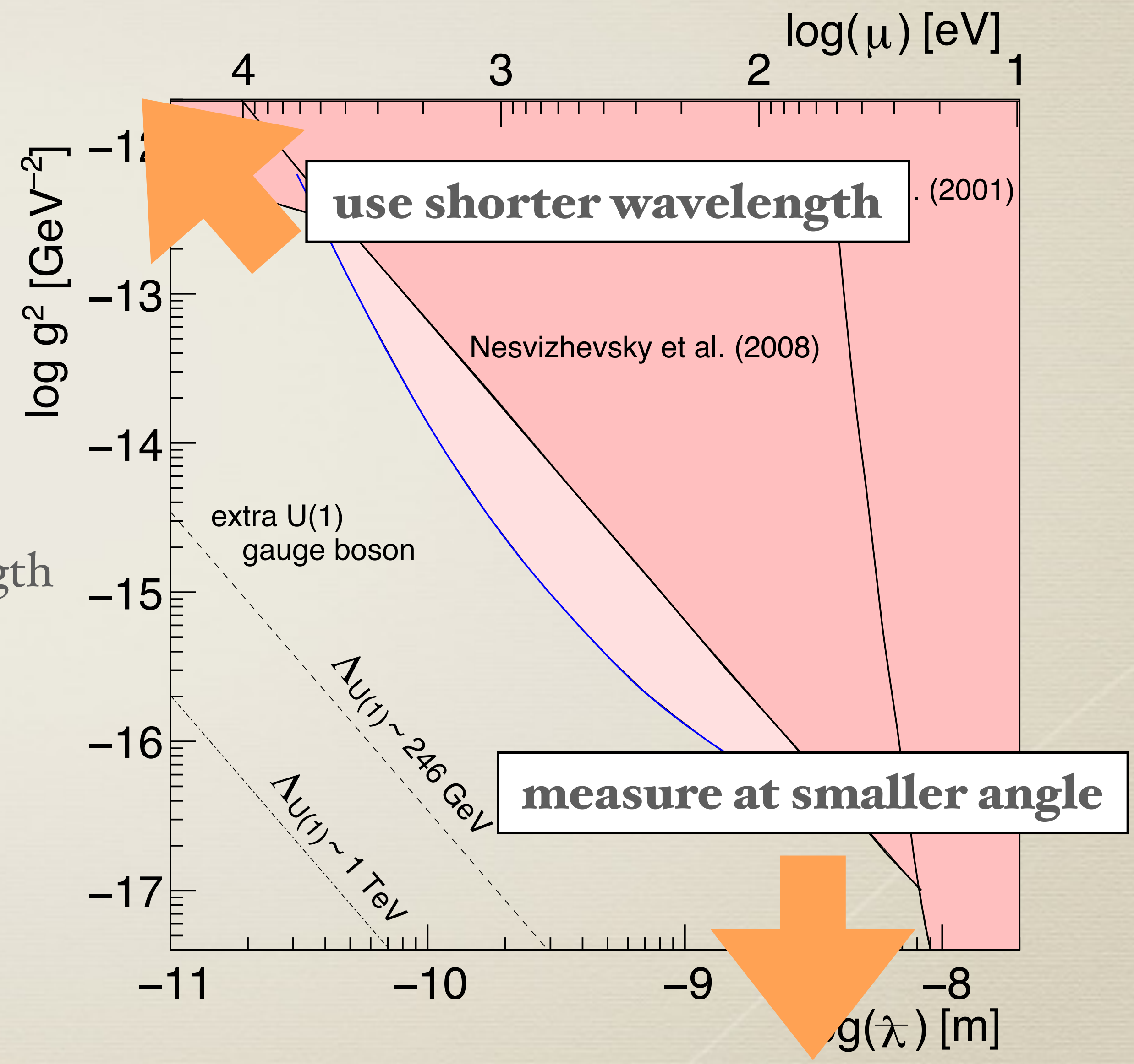

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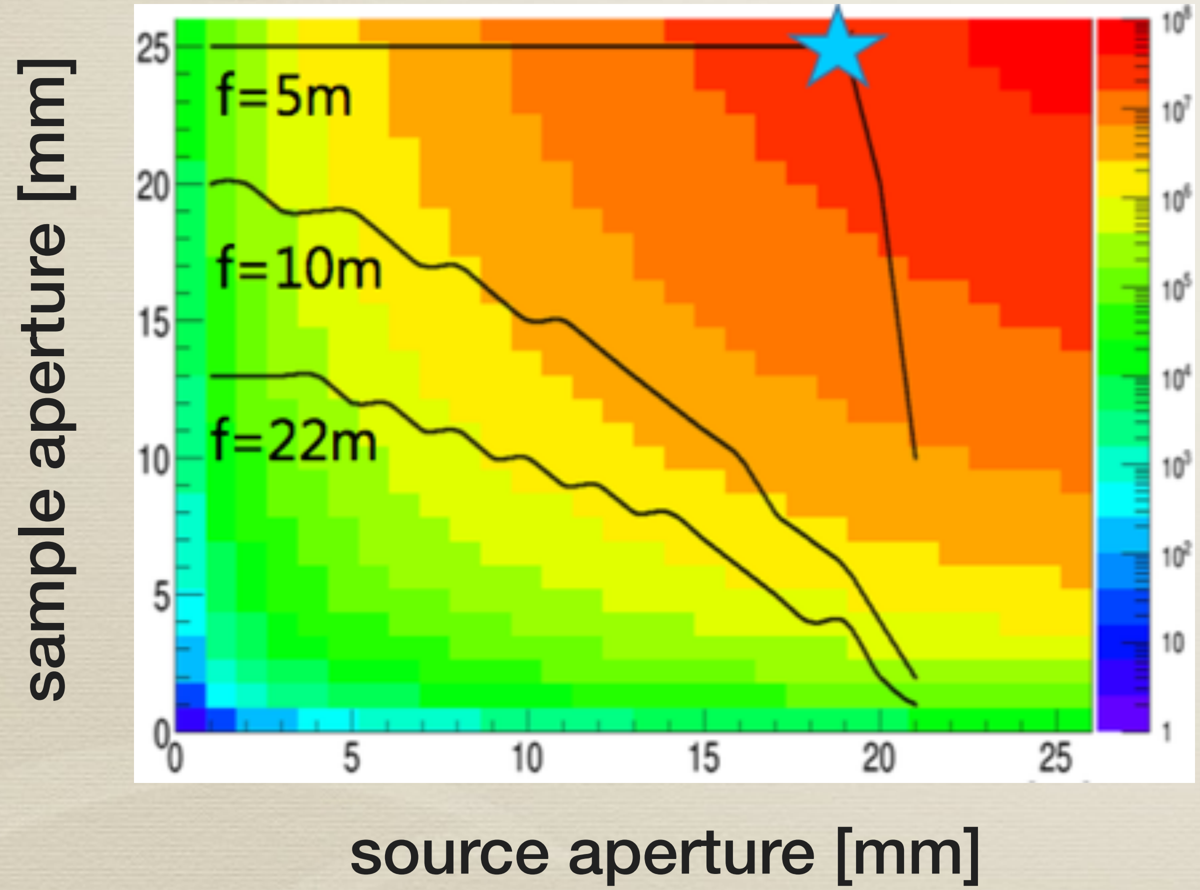
example) Chameleon field : will be Yukawa-type in some special condition

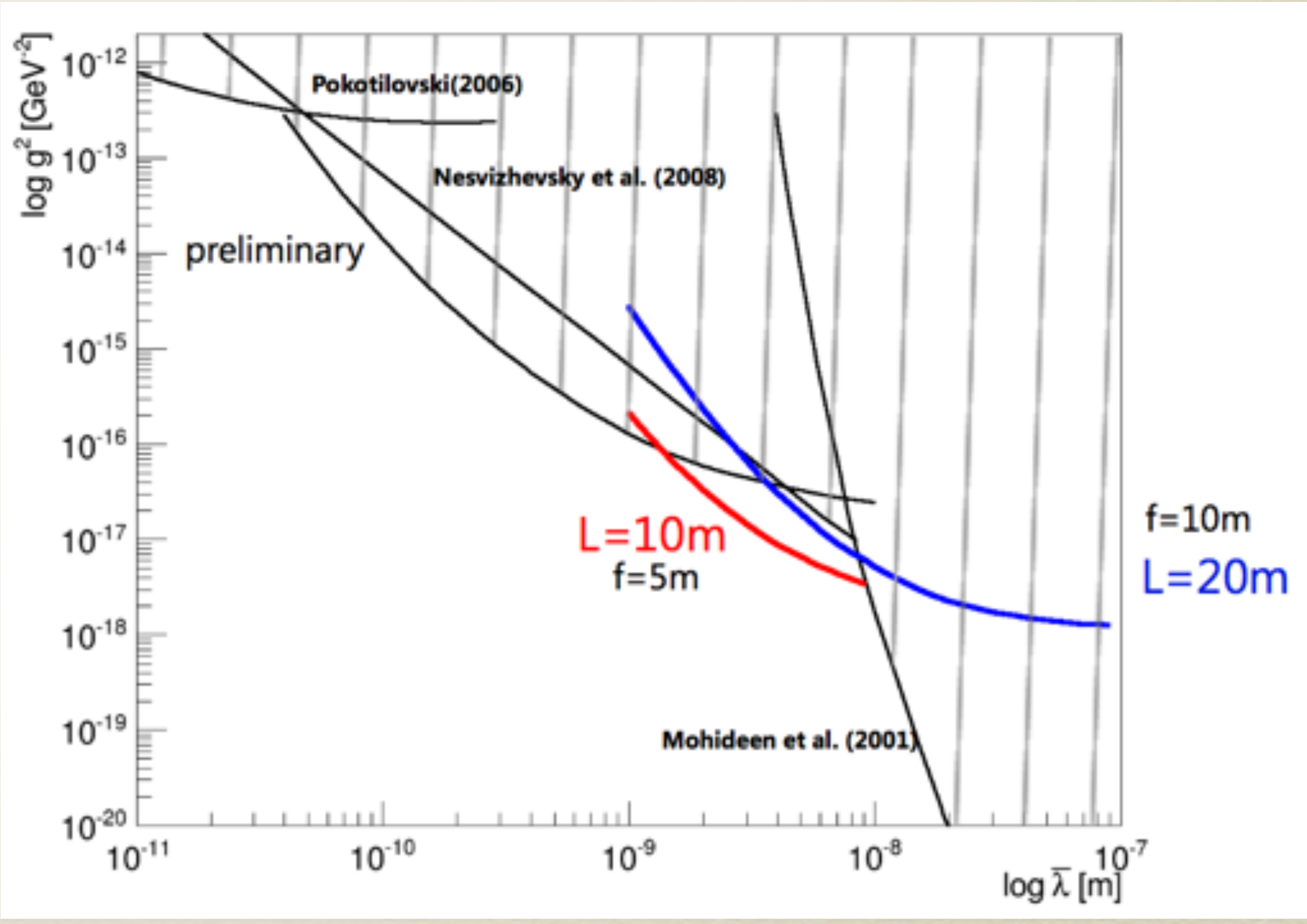
Lens Option Study (preliminary)

Optimized by changing the focal length of the lenses, the sample aperture, and the source aperture.

Source-Sample dist.: 10 m, Sample-Detector dist.: 10 m

Expected Data Statistics





Chameleon Field

J. Khoury and A. Weltman, PRL 93, 171104 (2004)
D. Mota and D. J. Shaw, PRD 75, 063501 (2007)

Think about a scalar mediating force for easy discussion

Lagrangian density is written as

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \xi M^4(\frac{\phi}{M})^{-n} - \Sigma_i \frac{\eta_i}{M_{Pl}}\rho_i\phi$$

kinematic term mass term self-coupling term Yukawa-coupling term

(For the Higgs, $n = -4$, $\eta_i/M_{Pl} = 1/v$)

When the mass term is 0, ($m_\phi = 0, \eta_i = \eta$)

, nonlinearity due to self-coupling becomes significant!

Vacuum Expectation Value : $\phi_{vac} = M(\frac{\eta\rho}{n\xi M_{Pl}M^3})^{-\frac{1}{n+1}}$

Effective Mass : $m_{vac} = \sqrt{n(n+1)\xi}M|\frac{M}{\phi_{vac}}|^{\frac{n}{2}+1}$

The mass changes as ambient Fermion density

→ "Chameleon"

Chameleon Field

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Interaction range for $n = -4\,, \xi \sim 1\,, \eta \sim 1$

$1/m_{vac} \sim 0.1$ mm at $\rho = 1$ g/cm^3 (in usual materials)

$1/m_{vac} \sim 1000$ km at $\rho = 1 \times 10^{-29}$ g/cm^3 (in the Universe)

features

1) cannot go out of materials - interaction charge cannot be integrate - Thin Shell Effect

2) hard to see in planetary and lunar motions, because the range is less than 1000 km

Because of those features, Chameleon has not be defeated.

experiments at the lab-scale still have importance for testing gravity and pseudo-gravity

Story Line

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"Constraints on New Gravitylike Forces in the Nanometer Range"

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Main topic of this talk!

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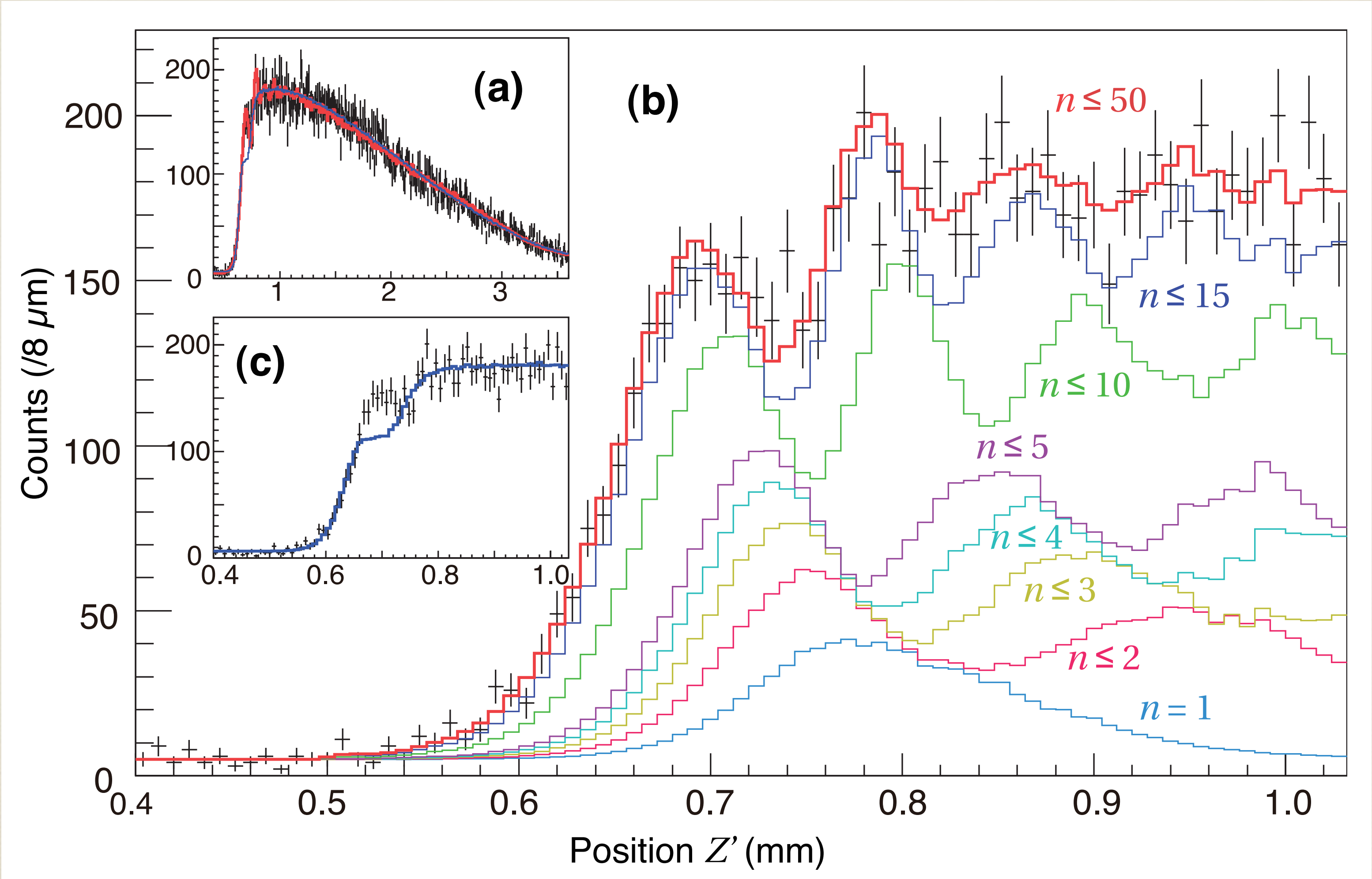
Testing of Gravitationally Bound State of Neutrons

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

measurement and model fitting



modulated neutron distribution due to quantum effect was clearly observed!

(a) expectations from quantum mechanics

(b) expectations from quantum mechanics (zoomed in)

(c) expectations from classical mechanics

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

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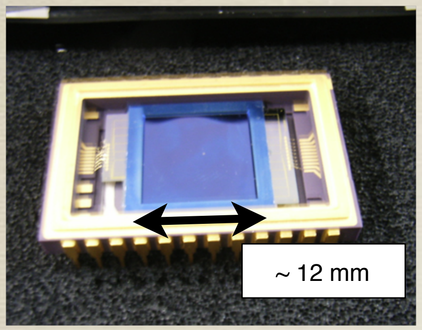
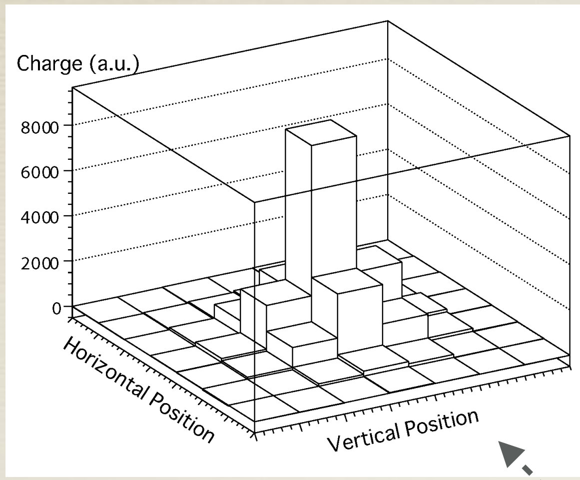
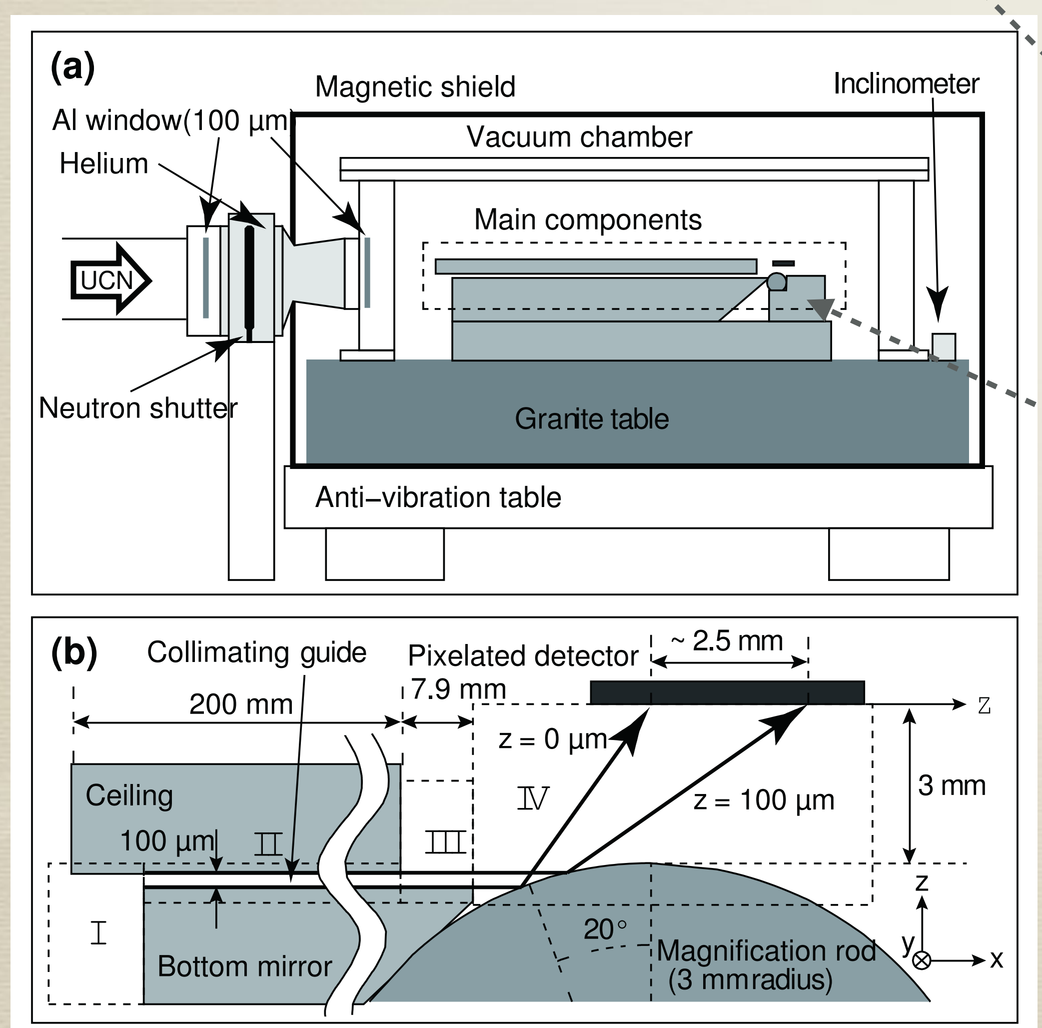




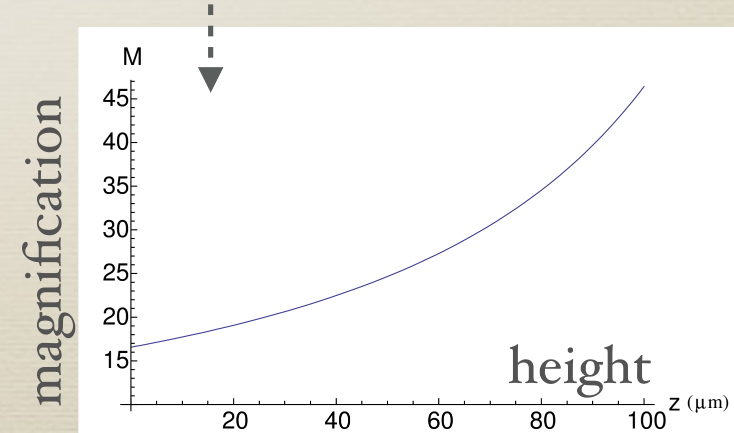
<u>Detector</u> S. Kawasaki, G. Ishikawa, M. Hino et al., NIM A 615,42 (2010)

- back-illuminated CCD with ^{10}B skin of 200 nm thickness
- n + ^{10}B -> ^{4}He + ^{7}Li + γ (Q=2.3 MeV)
  n + ^{10}B -> ^{4}He + ^{7}Li (Q=2.8 MeV)



- typical shape of charge cluster
- evaluate the position by waited center of the cluster

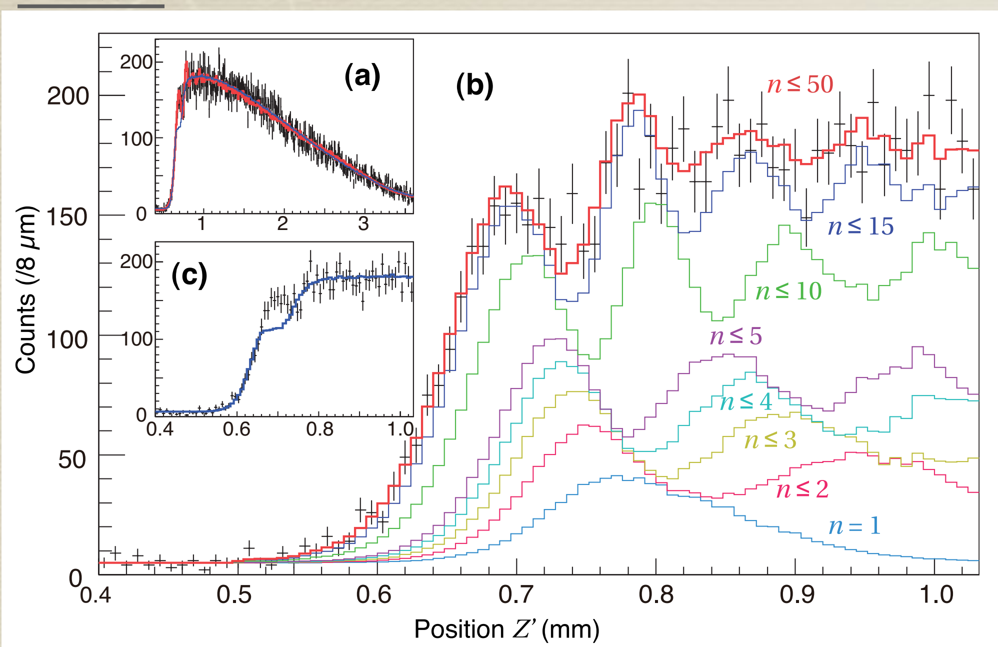
  ➞ 3 micron spacial resolution by 24 micron pixels
- magnify the neutron distribution at the end of the guide using glass rod by 17〜40 times

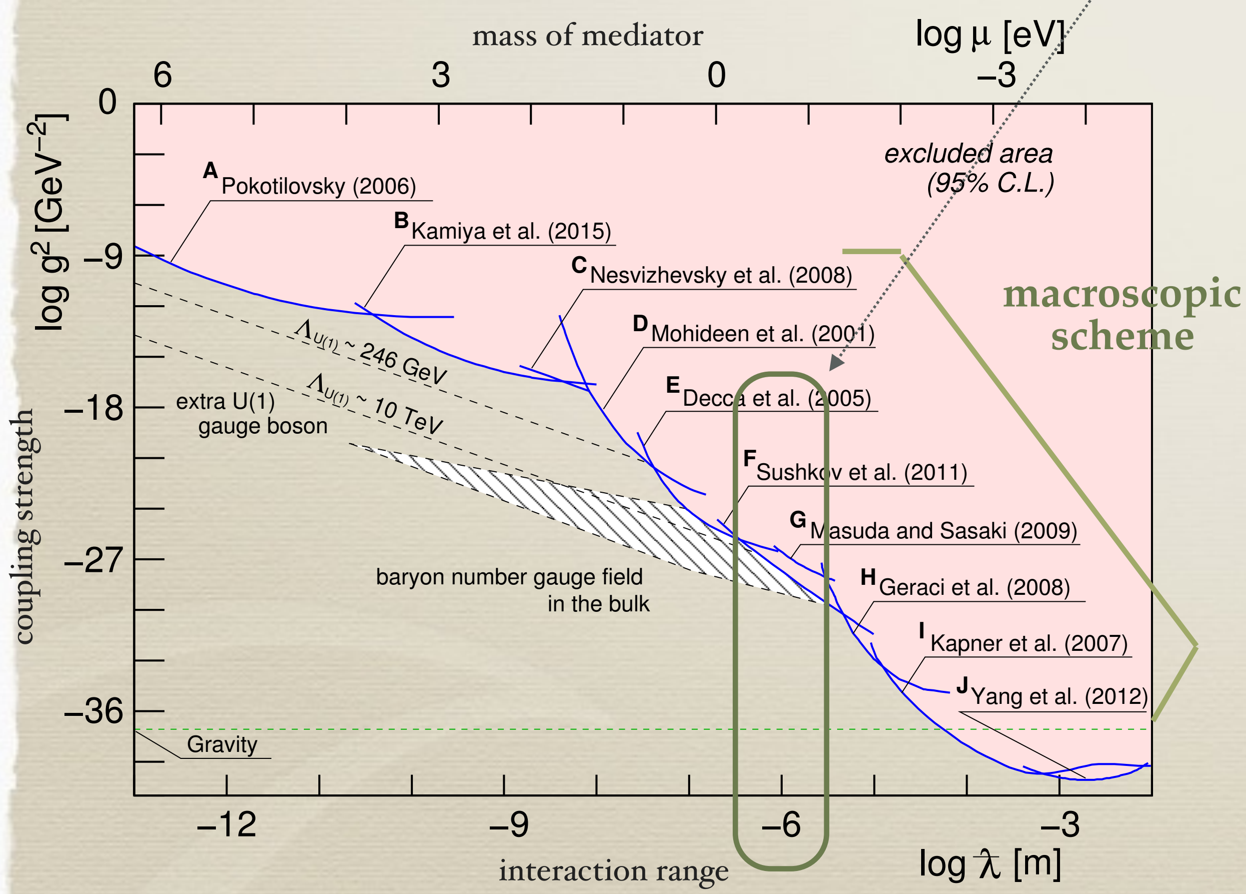


Observation of Gravitationally Bound State of Neutrons

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

<u>results</u>





<u>application</u>

The system has 6 μm scale

- can be used as a prove for μm scale new interactions

1. If there is a new interaction, the distribution is distorted.

2. By evaluating the distortion from know gravitational expectation, we can discuss about new interactions.

First attempt for this scale using microscopic scheme

Competitor:

Several group from UK and USA are interested in the fifth force search using cold atom interferometer at micron or nm range.

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Fifth force might violate the WEP at the microscopic range!

COW Experiment

R. Colella A. W. overhauser, and S. A. Werner, PRL 34, 1472 (1975)

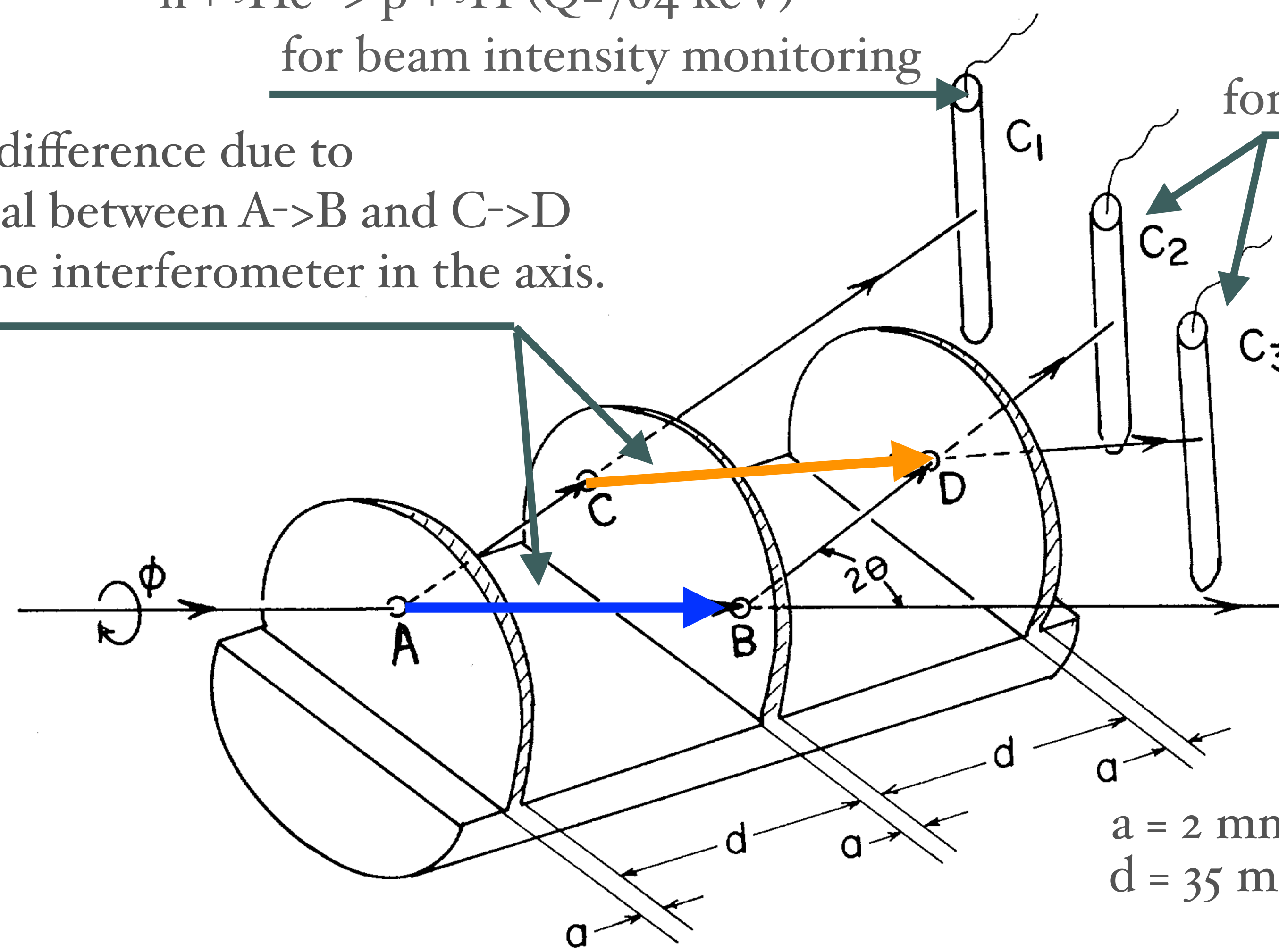
^{3}He neutron counter
n + ^{3}He -> p + ^{3}H (Q=764 keV)
for beam intensity monitoring

for interfered beam

Make phase leading difference due to gravitational potential between A->B and C->D passes, by rotating the interferometer in the axis.

cold neutron beam
$(\lambda = 1.445\ \text{Å})$

Bragg angle
$\theta = 22.1^\circ$



a = 2 mm
d = 35 mm

FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

COW Experiment - newest results -

S. A. Werner et al., Physica B 151, 22-35 (1988)

relative phase $\Delta\beta = \underbrace{-g\lambdabar(\frac{m_n}{\hbar})^2}_{\equiv q_{\rm grav}} S\cdot\sin\phi$ $\quad (S = 2d(d+a)\tan\theta)$ $(\sim 10^3\ \mathrm{mm}^2)$

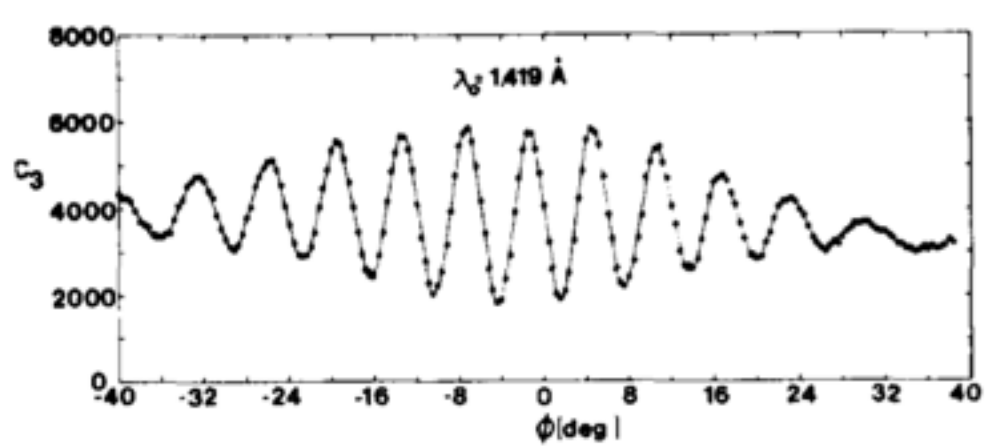


Fig. 1. Gravitationally-induced quantum interference data of Staudenmann et al. [2]. The counting rate (counts/7 mins) in detector 3 (fig. 2) is shown as a function of the interferometer tipping angle ϕ.

Gravity-induced quantum phase was observed!

0.05% systematic uncertainty

$q_{\rm grav} = 58.72 \pm 0.03$ (Exp.)

$q_{\rm grav} = 59.21$ (Calc.)

0.8% difference

$$q^2_{\rm meas} = (q_{\rm grav} + q_{\rm bend})^2 + q^2_{\rm Sagnac}$$

$$q_{\rm bend} = 1.41$$

$$q_{\rm Sagnac} = 1.45$$

J. -L. Staudenmann, S. A. Werner, R. Colella, and A. W. Overhauser, PRA 21, 1419 (1980) is report < 0.4% difference between Exp. and Calc. However, S. A. Werner pointed that there is unwilling bias in analysis.

Testing WEP using Neutron Interferometer

J. -L. Staudenmann et al., PRA 21, 1419 (1980)

(Bias in analysis was pointed out.)

relative phase

$$\Delta\beta = -g\lambda\!\!\!^{-}(\frac{m_n}{\hbar})^2 S \cdot \sin\phi$$

write inertial and gravitational masses explicitly

$$\Delta\beta = -g\lambda\!\!\!^{-}\frac{m_i m_g}{\hbar^2} S \cdot \sin\phi$$

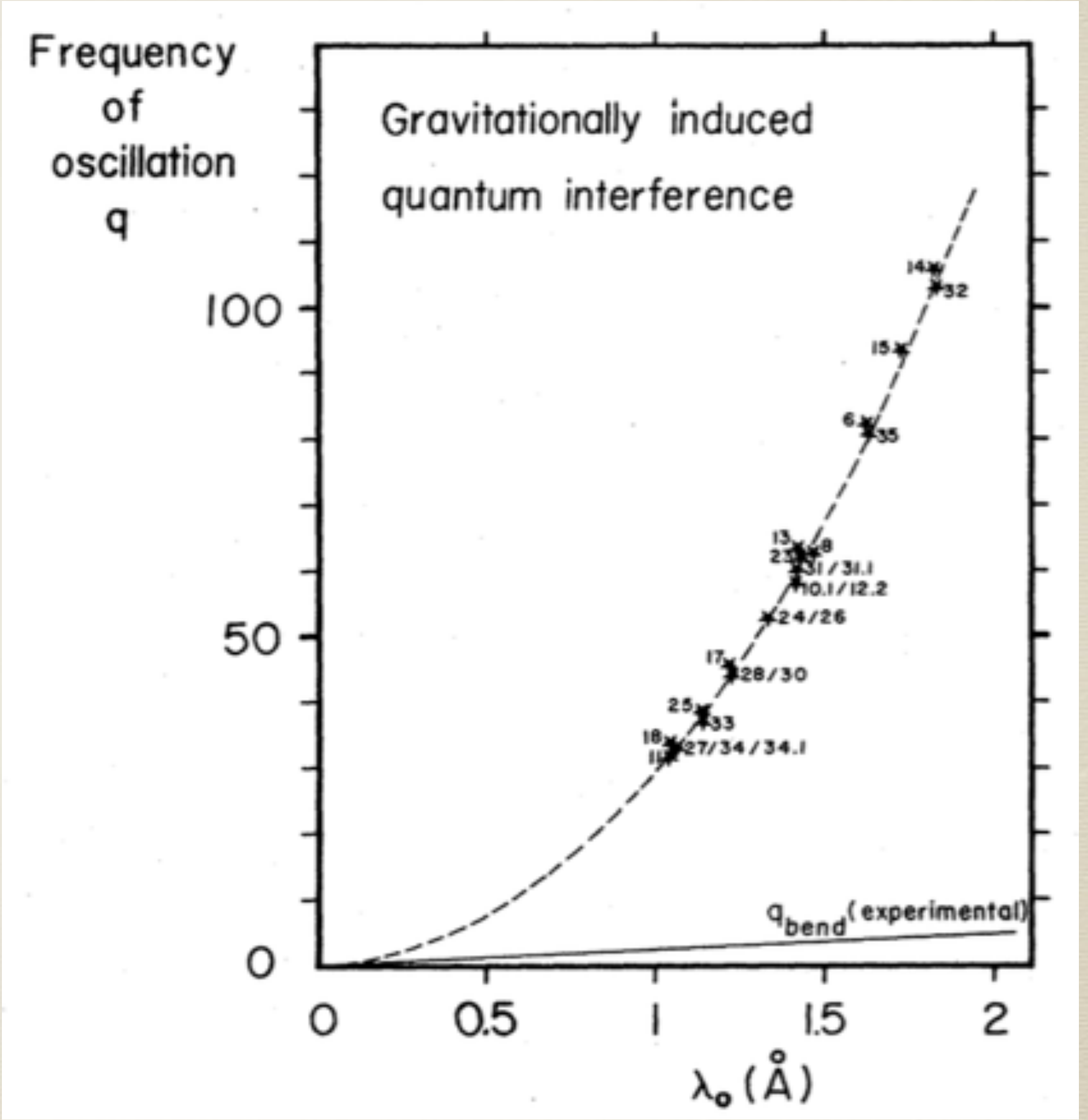
by measuring wavelength dependence of Δβ

$$(m_i m_g)^{1/2} = (1.675 \pm 0.003) \times 10^{-27}\ \mathrm{kg}$$

(Experiment)

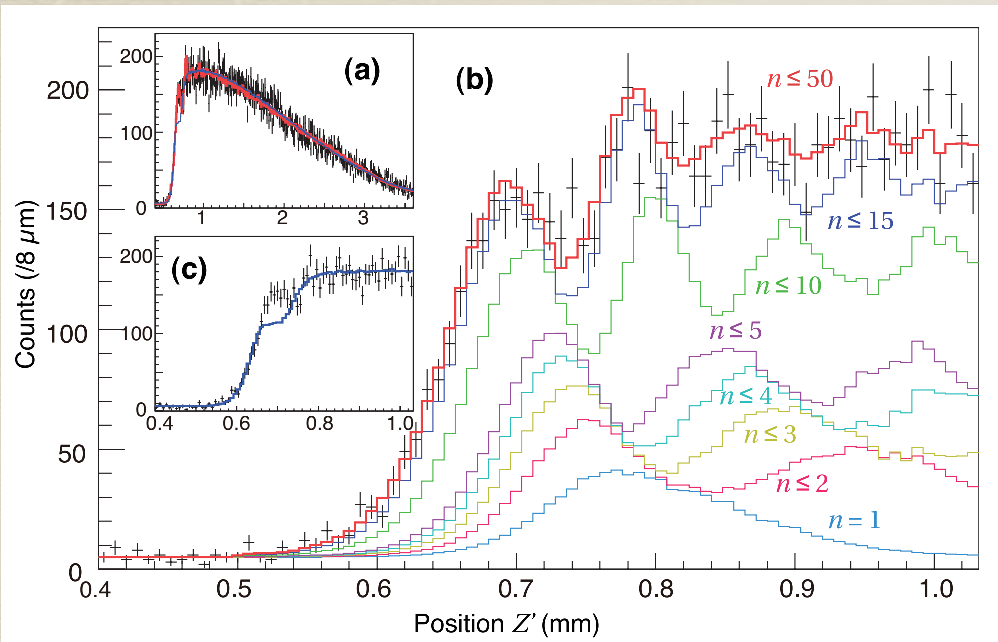
$$m_i = 1.6731 \times 10^{-27}\ \mathrm{kg}$$

(Particle Data Group)



Testing WEP using the gravitationally bound state of neutrons

We can test the WEP by measuring length and energy scales of the system



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

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

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

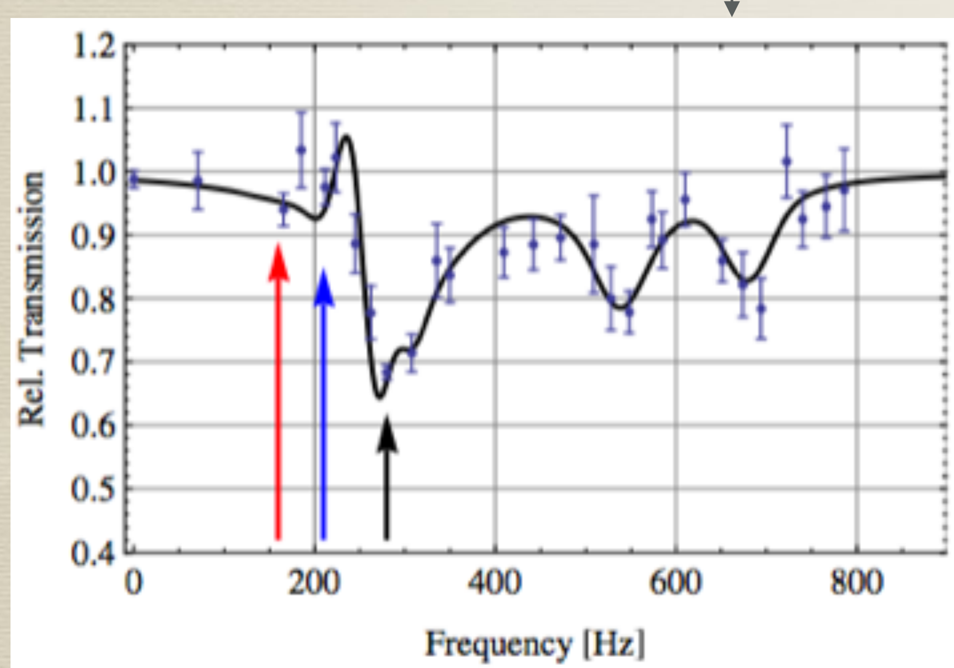
$$z_0 = \left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} \sim 6\ \mu\mathrm{m}$$

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

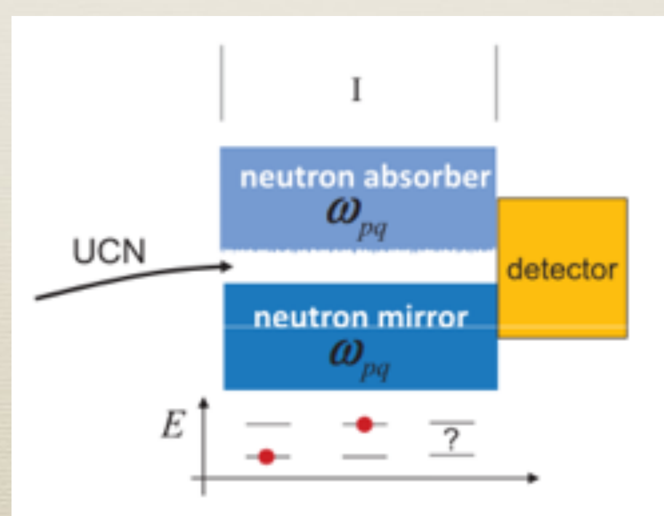
length scale ↑

energy scale ↓

see the resonance transition between the quantum states



T. Jenke, G. Cronenberg, J. Burgdorfer et al., PRL 112, 151105 (2014)
T. Jenke, P. Geltenbort, H. Lemmel, and H. Abele, Nature Phys. 7, 468 (2011)



. . . . .

We are now planning the experiment which can measure the two scales simultaneously.

Summary

Neutron is one of the powerful tool to search and investigate Fifth forces

Thank you for your attention.

"We plan to continue our work until defeated by systematic errors."

—William M. Snow (Indiana Univ.)