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

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

Special Things about Gravity

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

$\boxed{\text{Q1}}$

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)

This feature is a base for general relativity.

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

Q3

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

Q2

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

There were not so many.

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

Story Line

Q1

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

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"Constraints on New Gravitylike Forces in the Nanometer Range"

Main topic of this talk!

Q2

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

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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!

Q3

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-coupled 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, and the new interaction appears to violate the inverse square law of gravity.

→ gravity-like force

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

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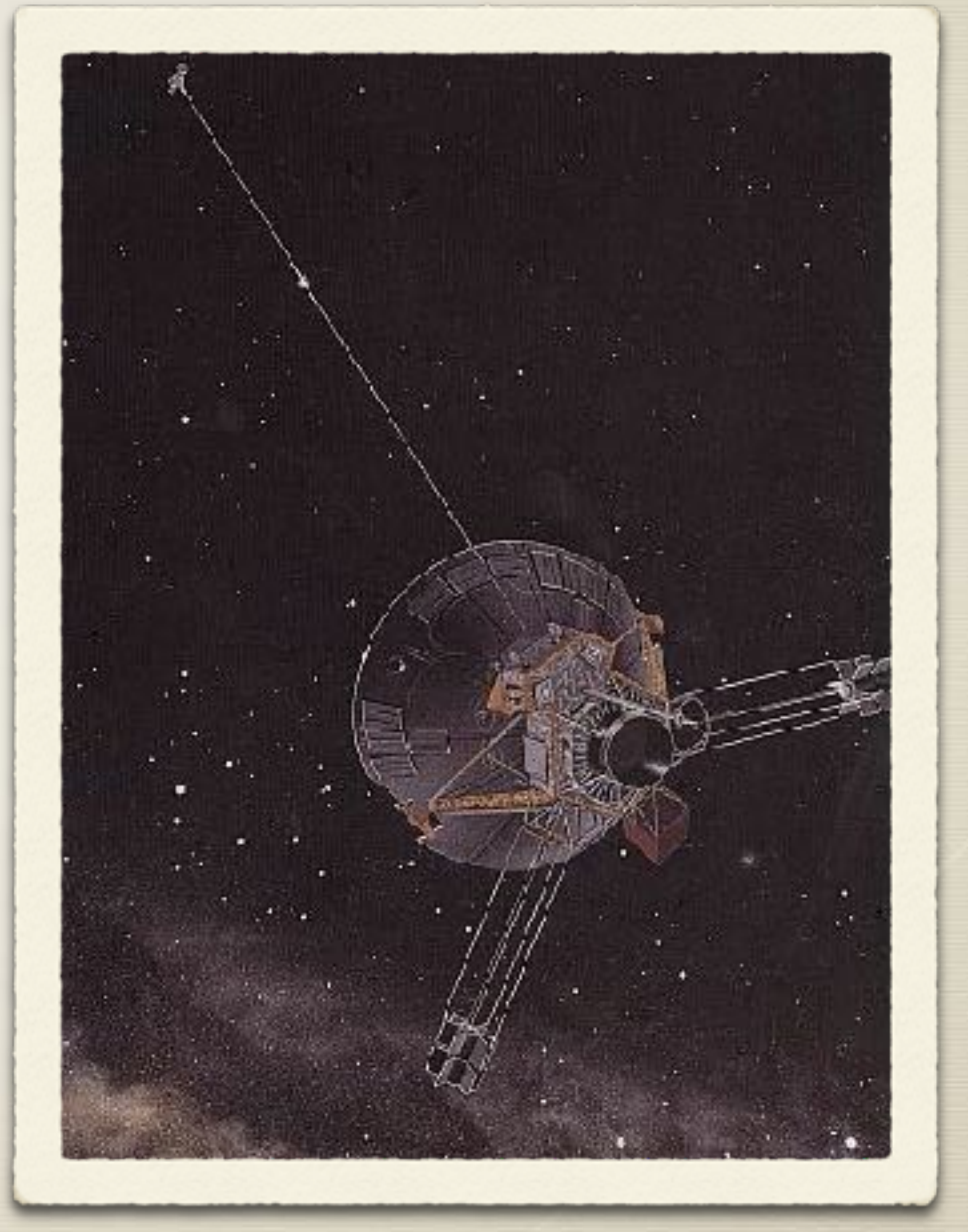
Testing Gravity at the Cosmological Scale

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, only on trajectories out of the Solar System. (1980)

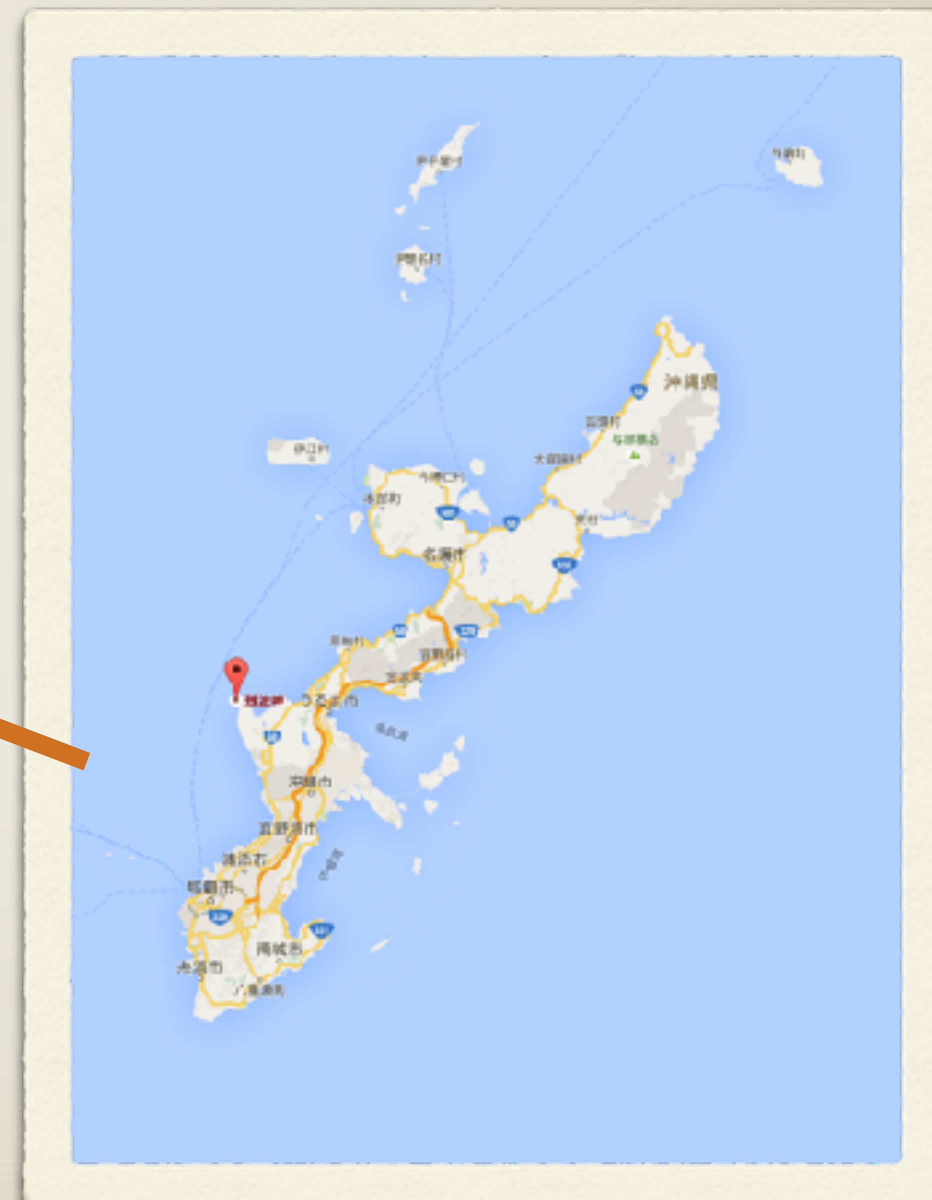
causes discussions including modified gravity

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



Testing Gravity at the scale of < 1 mm

For shorter scale, there are also many experimental tests.

No significant deviation from the Newtonian inverse square law was observed, at the moment.

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

coupling charges

mass

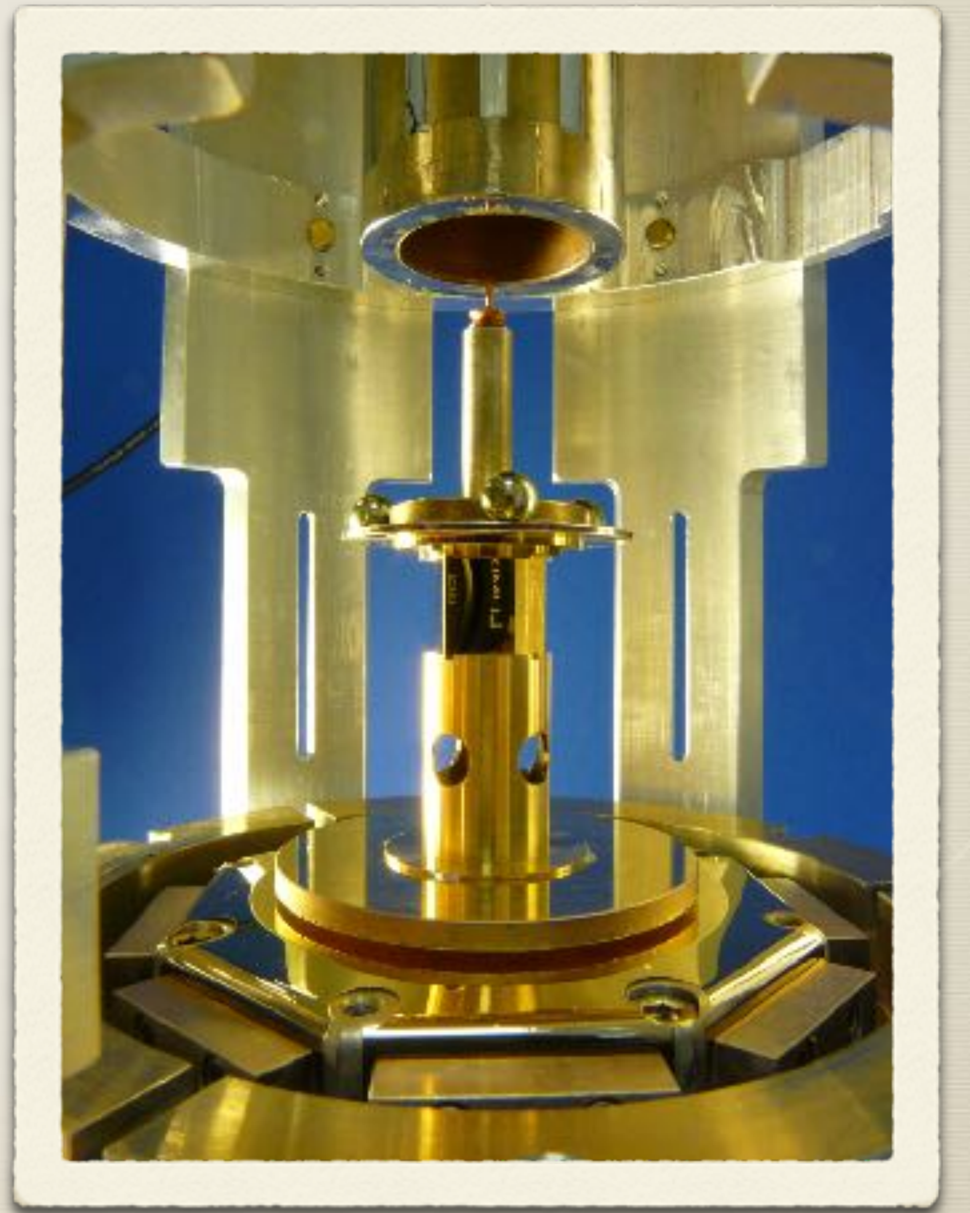
$$V_\phi(r) = -\frac{1}{4\pi} g^2 m_1 m_2 \frac{e^{-m_\phi r}}{r}$$

coupling strength

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

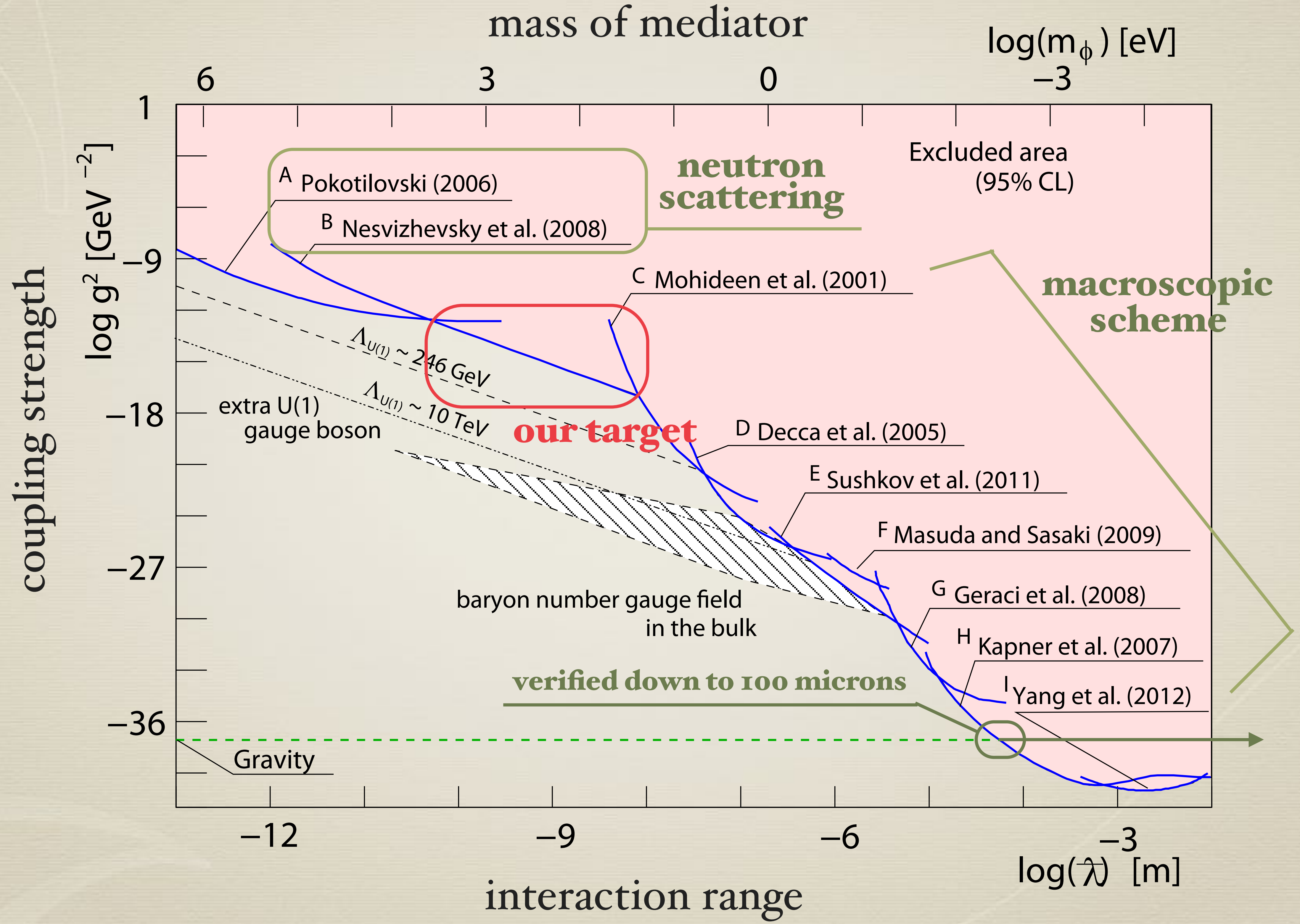
parameter space: (g^2, m_ϕ) or $(g^2, \lambda = 1/m_\phi)$

interaction range



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

Experimental Constraints



Experimental Constraints

PRL 116, 131101 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

New Test of the Gravitational Inverse-Square Law at the Submillimeter Range with Dual Modulation and Compensation

Wen-Hai Tan,[1] Shan-Qing Yang,[1,*] Cheng-Gang Shao,[1] Jia Li,[1] An-Bin Du,[1] Bi-Fu Zhan,[2] Qing-Lan Wang,[3] Peng-Shun Luo,[1] Liang-Cheng Tu,[1] and Jun Luo[1,4,†]
[1]*MOE Key Laboratory of Fundamental Physical Quantities Measurements, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China*
[2]*School of Electrical and Electronic Engineering, Wuhan Polytechnic University, Wuhan 430000, People's Republic of China*
[3]*School of Science, Hubei University of Automotive Technology, Shiyan 442002, People's Republic of China*
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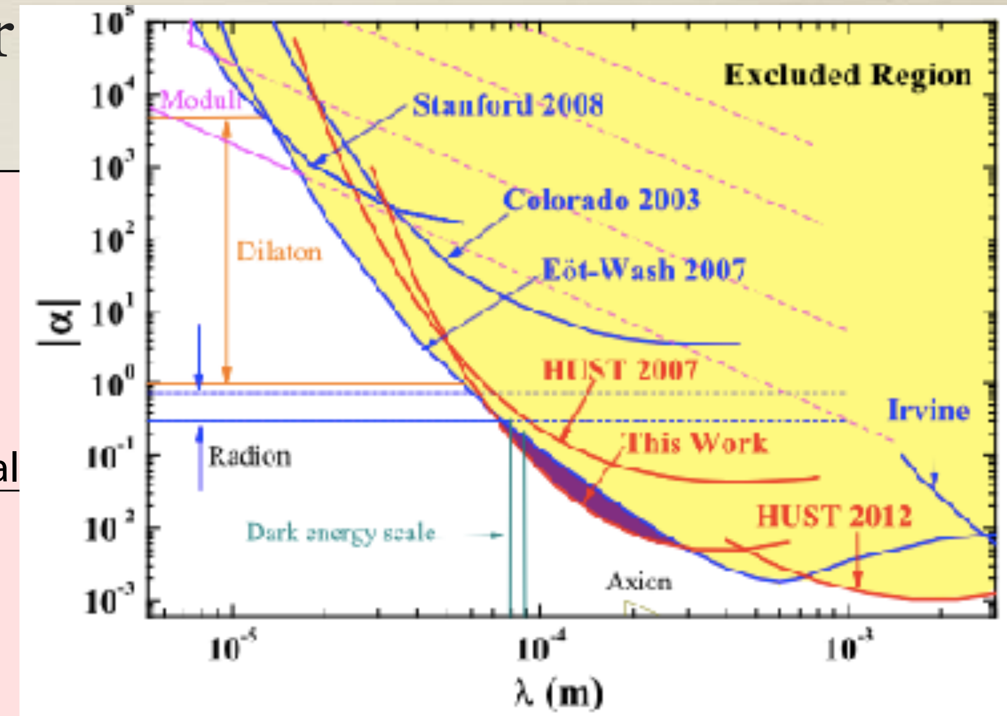
(Received 17 August 2015; revised manuscript received 27 January 2016; published 30 March 2016)

By using a torsion pendulum and a rotating eightfold symmetric attractor with dual modulation of both the interested signal and the gravitational calibration signal, a new test of the gravitational inverse-square law at separations down to 295 μm is presented. A dual-compensation design by adding masses on both the pendulum and the attractor was adopted to realize a null experiment. The experimental result shows that, at a 95% confidence level, the gravitational inverse-square law holds ($|\alpha| \leq 1$) down to a length scale $\lambda = 59$ μm. This work establishes the strongest bound on the magnitude α of Yukawa-type deviations from Newtonian gravity in the range of 70–300 μm, and improves the previous bounds by up to a factor of 2 at the length scale $\lambda \approx 160$ μm.



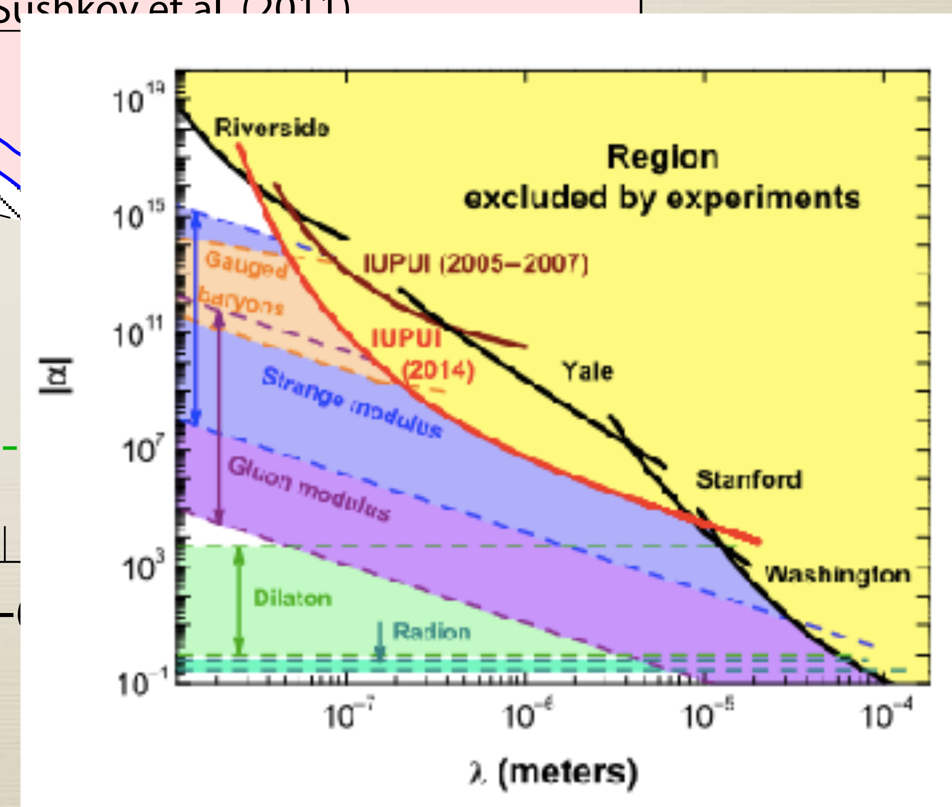
PRL 116, 221102 (2016) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2016

Stronger Limits on Hypothetical Yukawa Interactions in the 30–8000 nm Range

Y.-J. Chen,[1,2] W. K. Tham,[1] D. E. Krause,[3,4] D. López,[5] E. Fischbach,[4] and R. S. Decca[1,*]
[1]*Department of Physics, Indiana University-Purdue University Indianapolis, Indianapolis, Indiana 46202, USA*
[2]*Section 3, N16 Process Integration Department 1, Taiwan Semiconductor Manufacturing Company, HsinChu 30078, Taiwan*
[3]*Physics Department, Wabash College, Crawfordsville, Indiana 47933, USA*
[4]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
[5]*Center for Nanoscale Materials, Argonne National Laboratories, Argonne, Illinois 60439, USA*

(Received 4 November 2014; revised manuscript received 3 January 2016; published 2 June 2016)

We report the results of new differential force measurements between a test mass and rotating source masses of gold and silicon to search for forces beyond Newtonian gravity at short separations. The technique employed subtracts the otherwise dominant Casimir force at the outset and, when combined with a lock-in amplification technique, leads to a significant improvement (up to a factor of 10^3) over existing limits on the strength (relative to gravity) of a putative force in the 40–8000 nm interaction range.



or
et al
ecca et al. (2005)
E Sushkov et al. (2011)
upling

Testing using Cold Neutron Beam

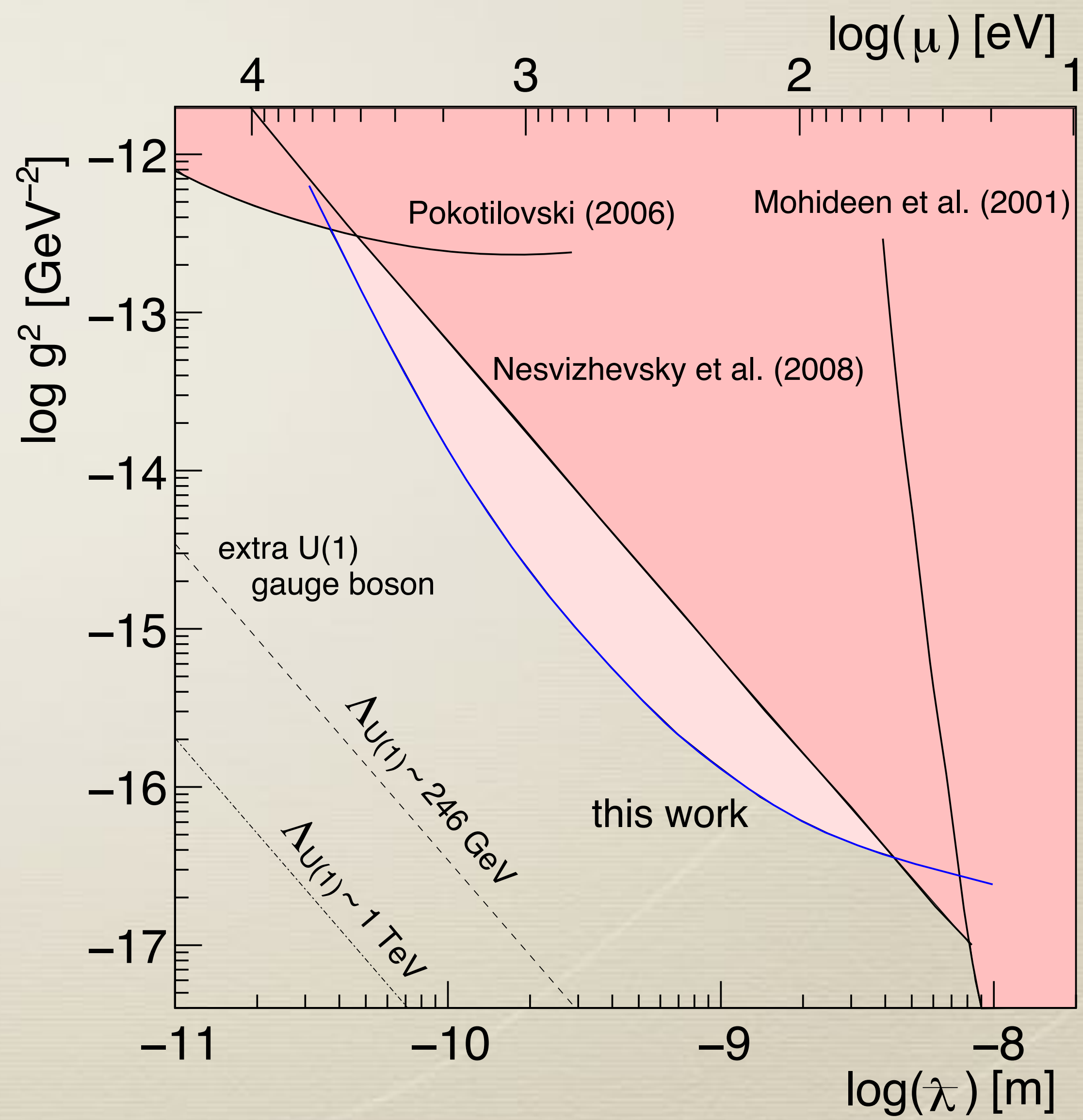
1) measure the angular distribution of cold neutrons scattered off Xenon gas

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,

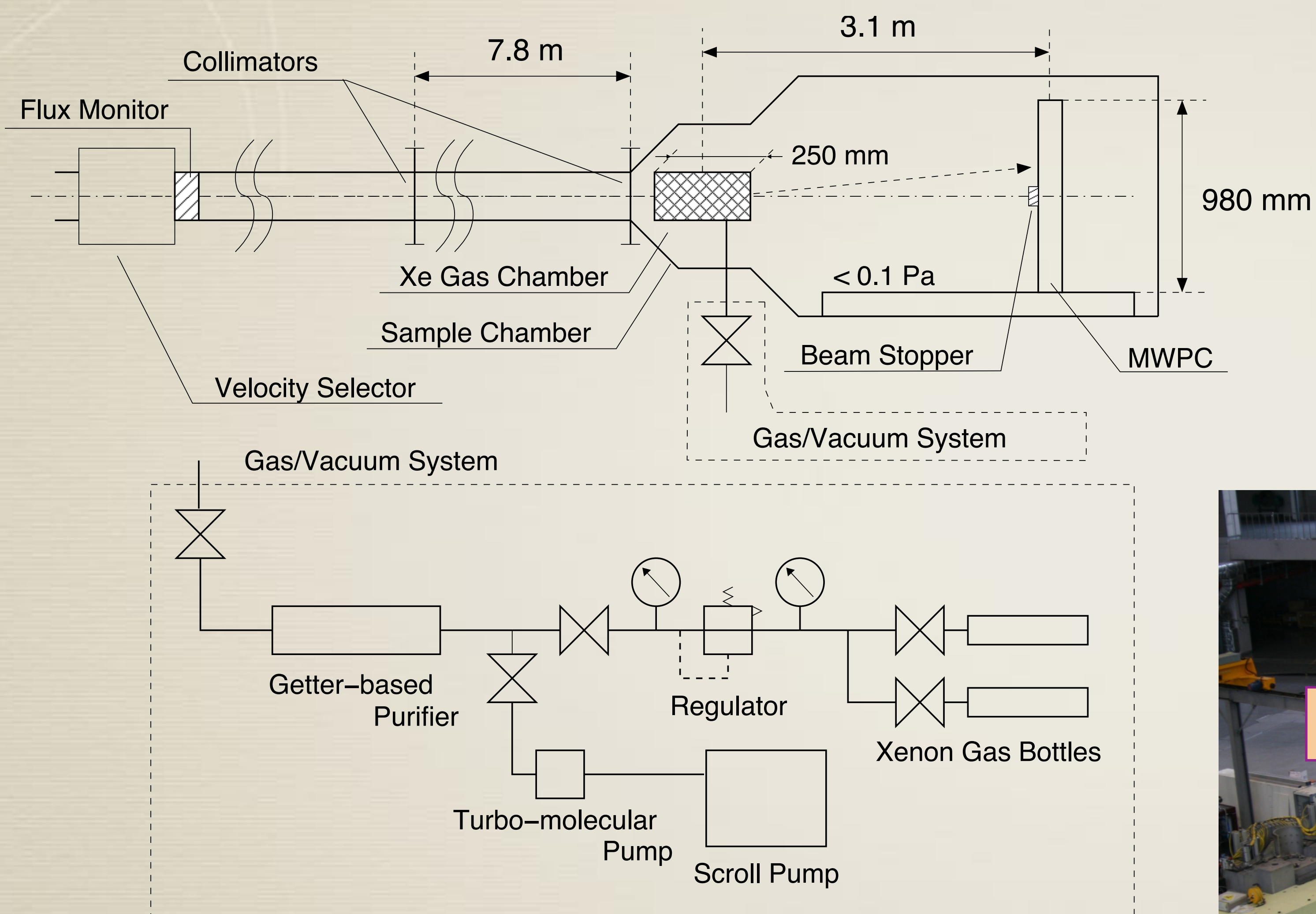
We have finally succeeded to improve previous constraints for gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10

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

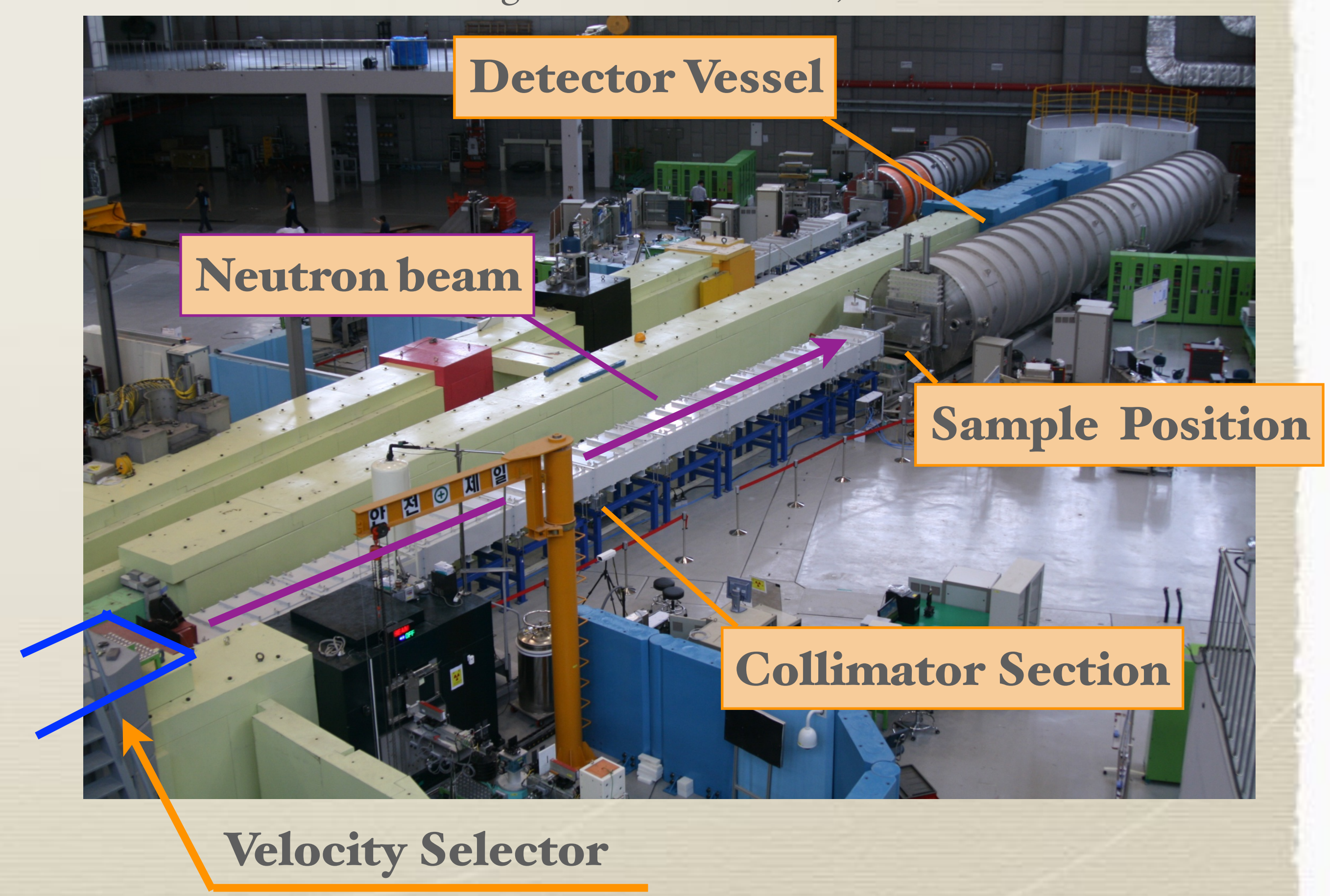
Experimental Site

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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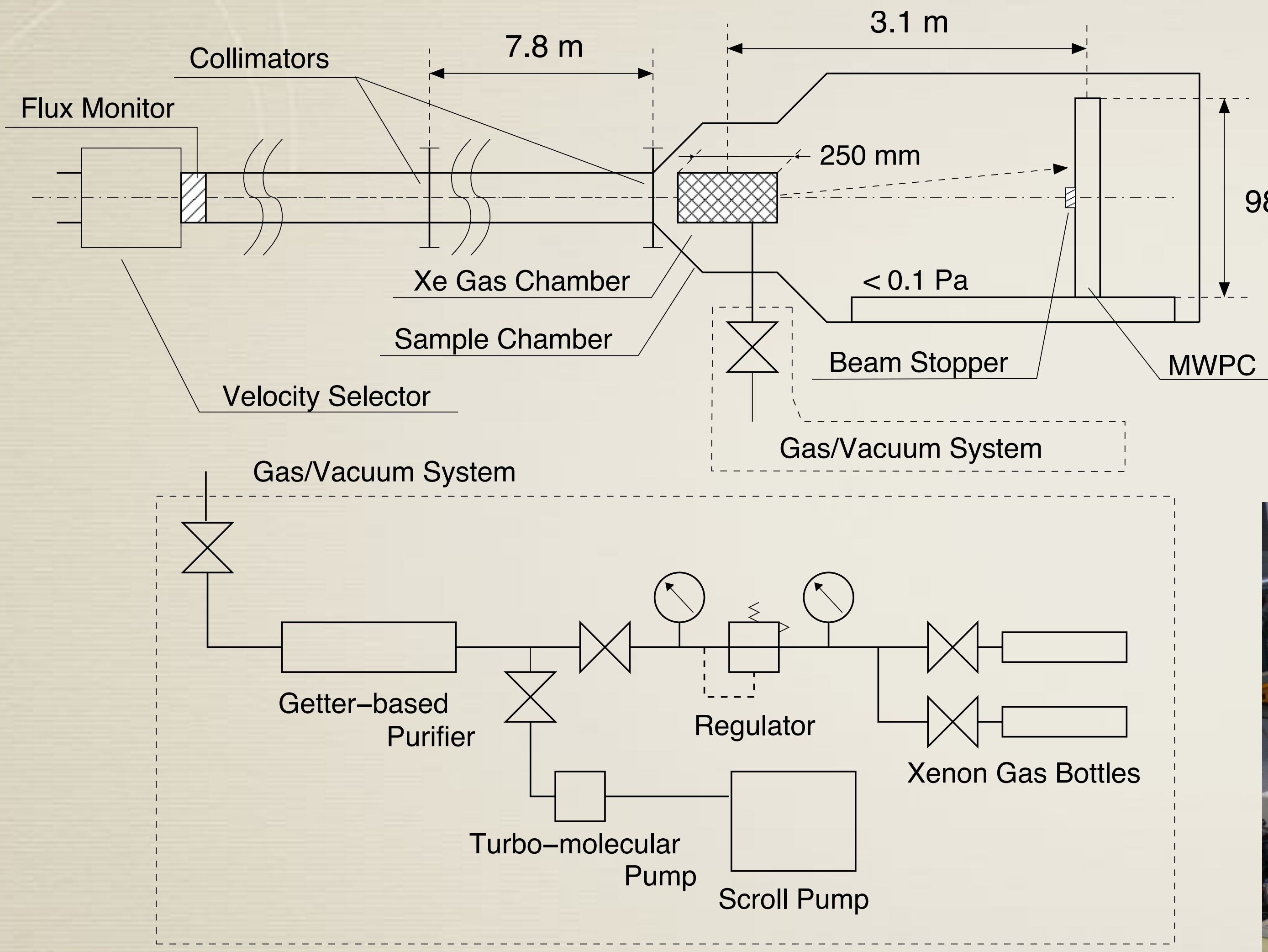
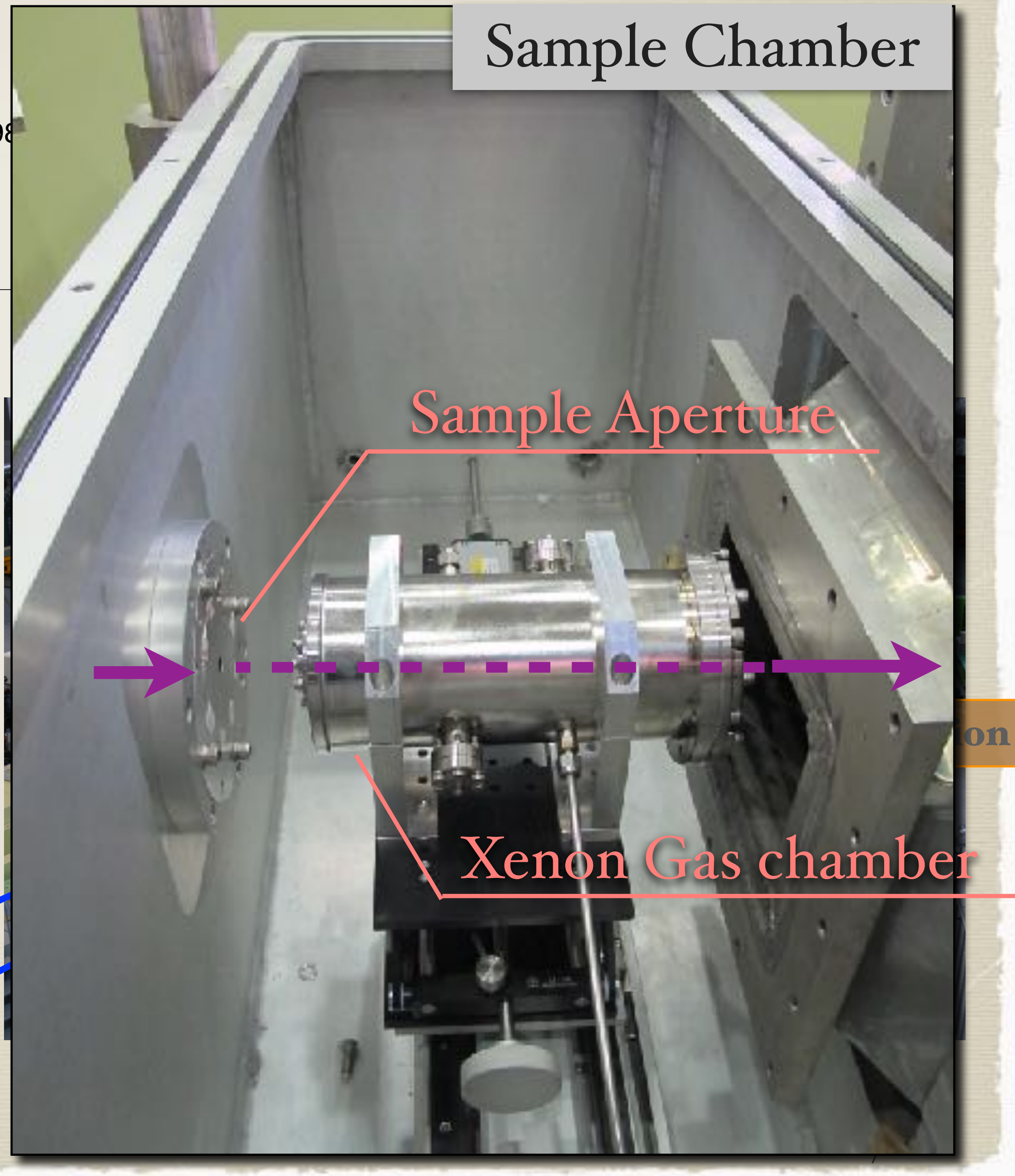




- Wavelength: 5 Å
- Beam size: 22 mm in diameter
- Divergence: ~ 3 mrad
- Intensity: ~ 1.4 x 10^5 neutrons/sec

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)

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

+ 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 $\perp$ scattering plane

atomic form factor:

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

$q_0 \sim 7$ 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.)

$$b_c(q) = \underbrace{(b_{Nc}+b_p)}_{\sim 5\text{ fm}} - \underbrace{(b_F+b_I)}_{\sim -1\times 10^{-1}\text{ fm}} Z[1-f(q)]$$

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

$$\chi \equiv -\frac{b_F+b_I}{b_{Nc}+b_p}Z \quad \sim 3\times 10^{-2}$$

+ coherent scattering length with the new forces

$$b_c(q) = (b_{Nc}+b_p)\{1+\chi[1-f(q)] + \underbrace{\chi_y\frac{m_\phi^2}{q^2+m_\phi^2}}_{\text{via the Born approximation}}\}$$

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

→ 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,

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

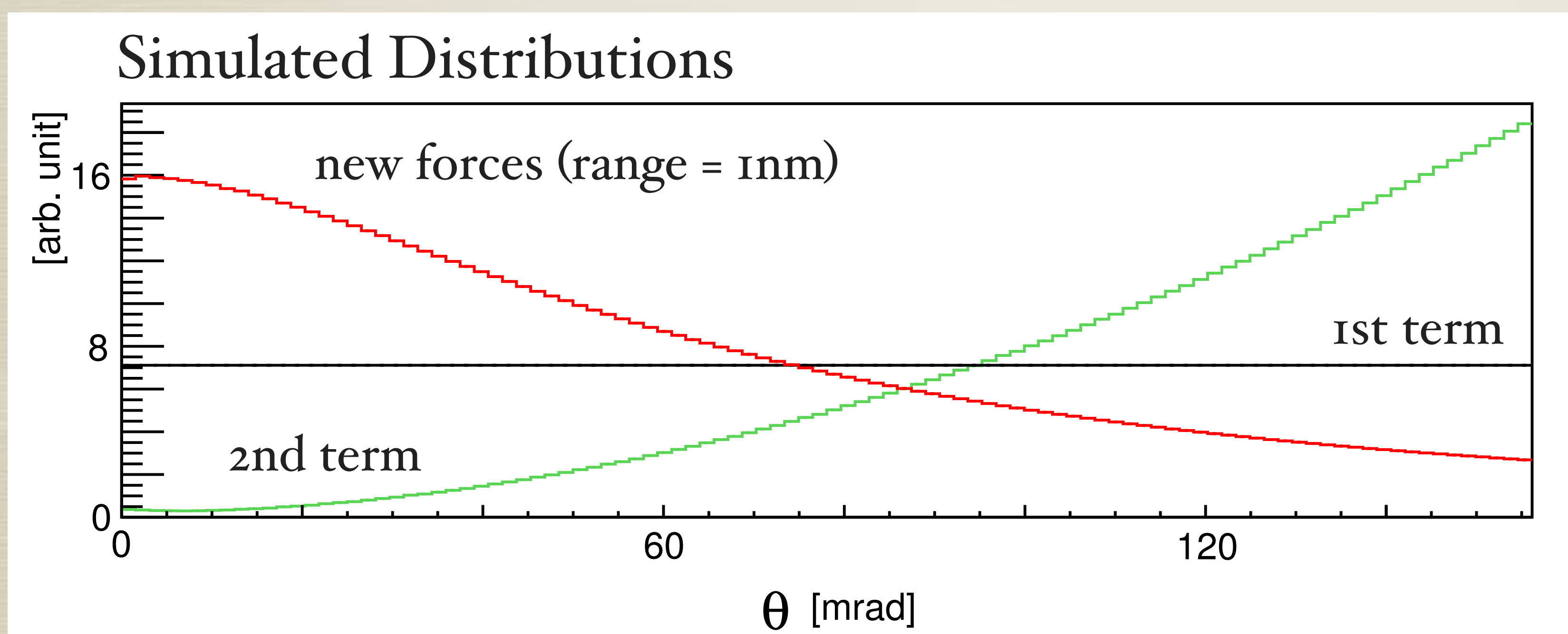
f(q): structure function

(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.

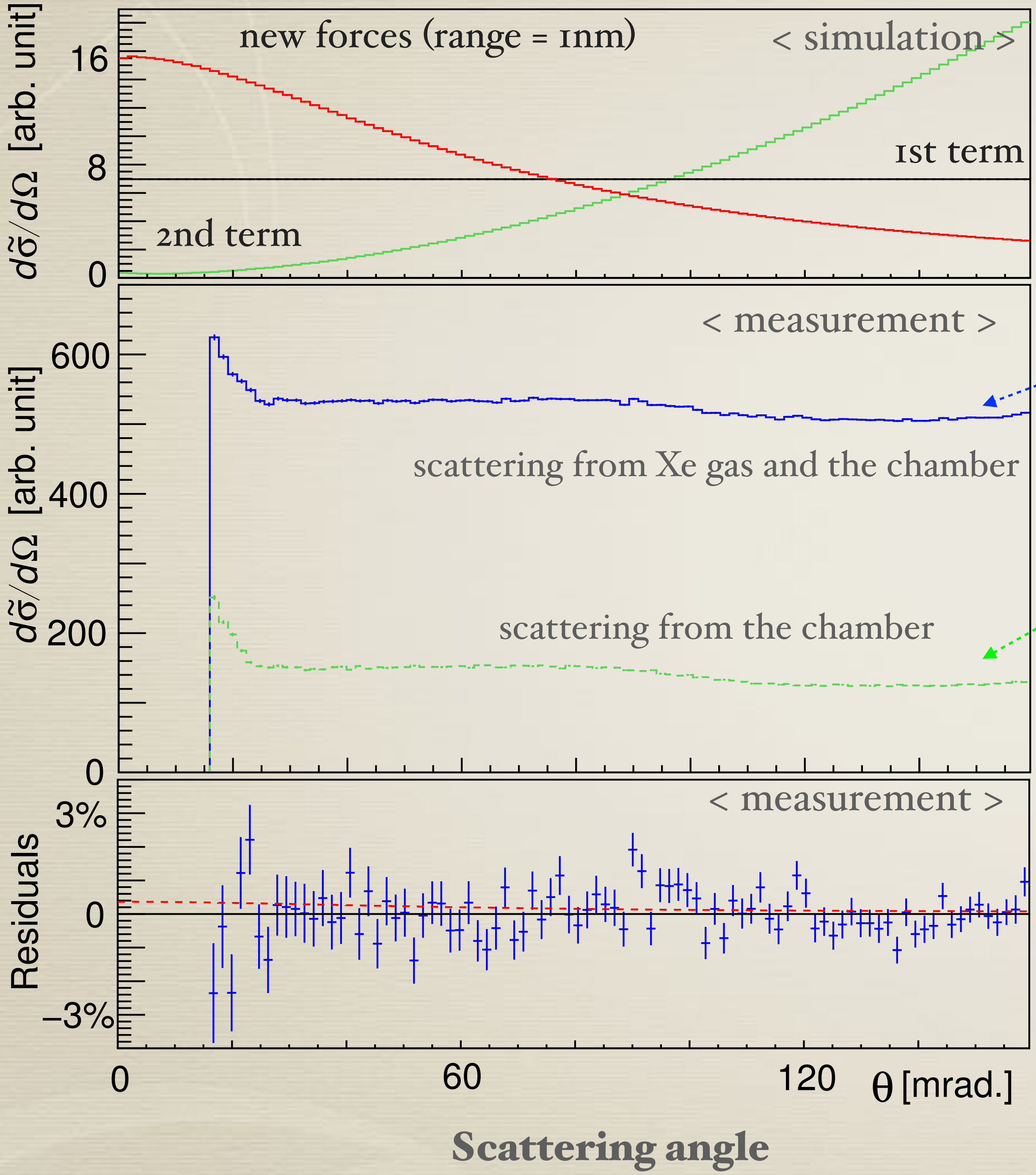
$$\frac{d\tilde{\sigma}}{d\Omega}(\theta) = N\left\{(1-\alpha^*)(1-\beta)h_1(\theta) + \alpha^*(1-\beta)h_2(\theta) + \beta h_y(\theta; m_\phi)\right\}$$



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 by the function and estimate the β

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

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

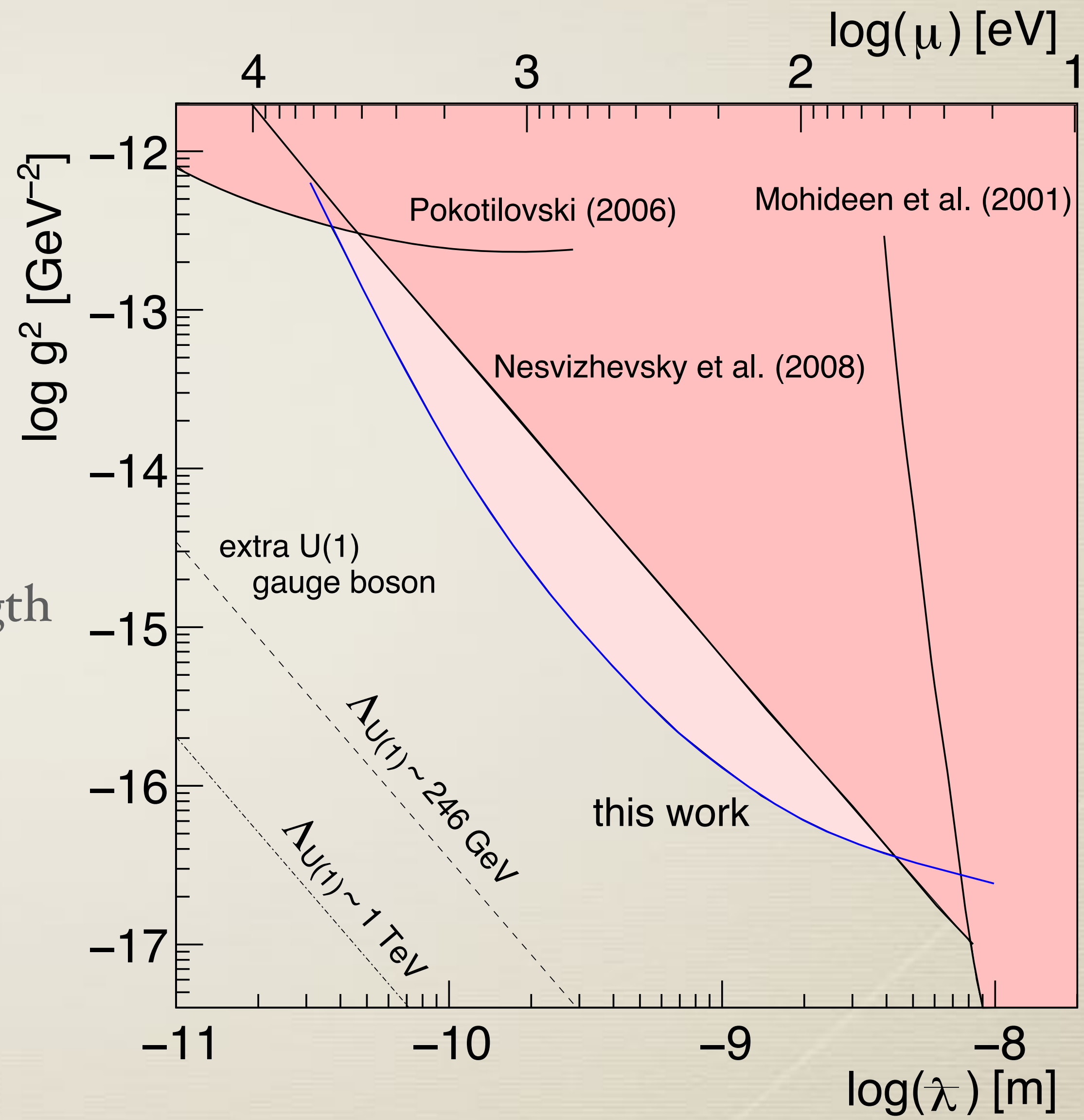
     possible using neutron lenses

     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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→ gravity-like force

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

Chameleon Field

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

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(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

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

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

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

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

<u>features</u>

1) cannot go out of materials - interaction charge cannot be integrated - 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 been defeated experimentally.

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

Constraints on the Chameleon Field

To be add

Story Line

Q1

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

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

"Constraints on New Gravitylike Forces in the Nanometer Range"

Main topic of this talk!

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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.

degenerate

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

"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!

Q3

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

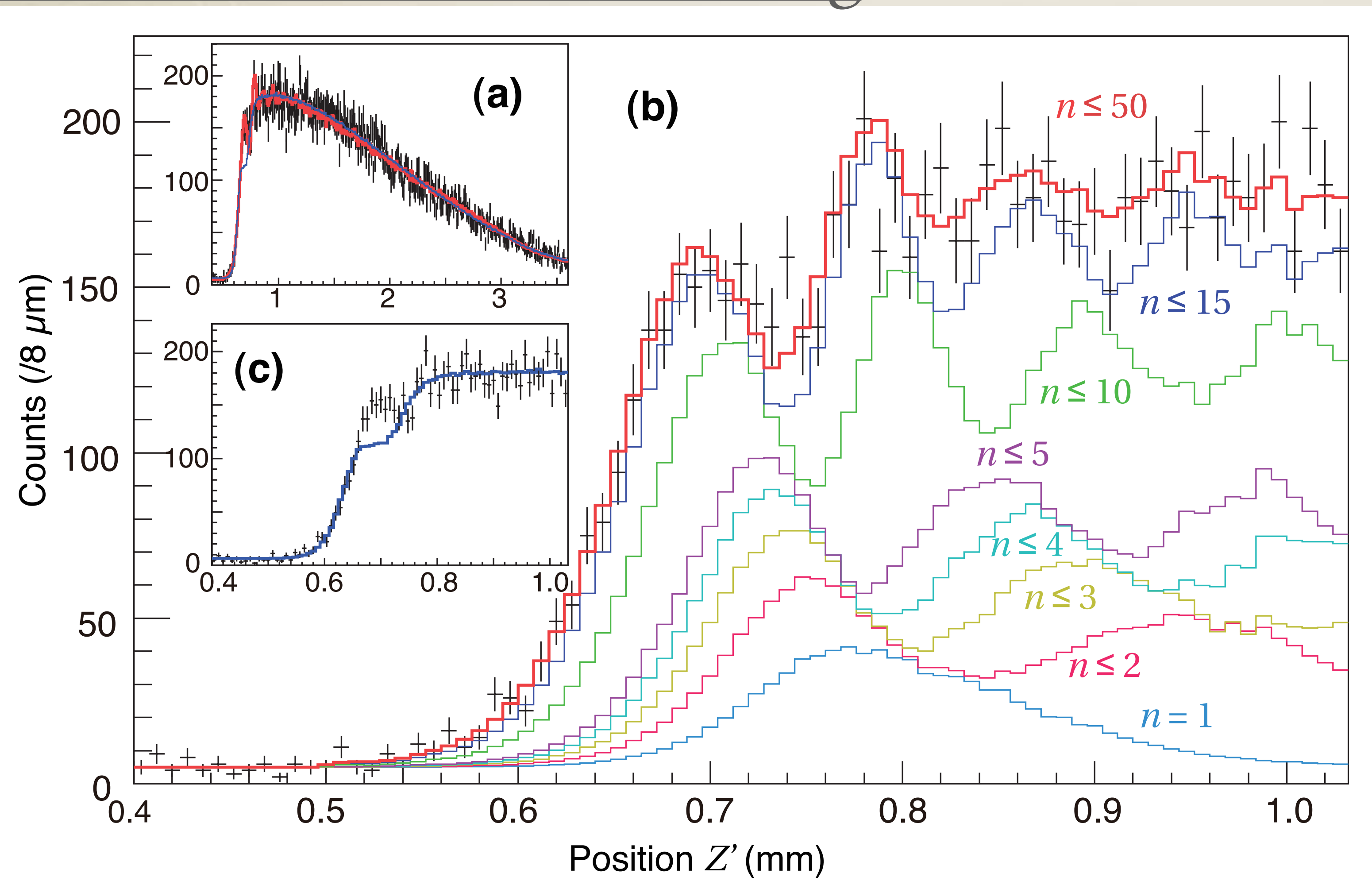
now designing an experiment

Fifth force might violate the WEP at the microscopic range!

Quantum Bouncing of UCNs

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

measurement and model fitting



scales of the system

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

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

modulation of 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 $\chi^2/\text{NDF} = 0.96$

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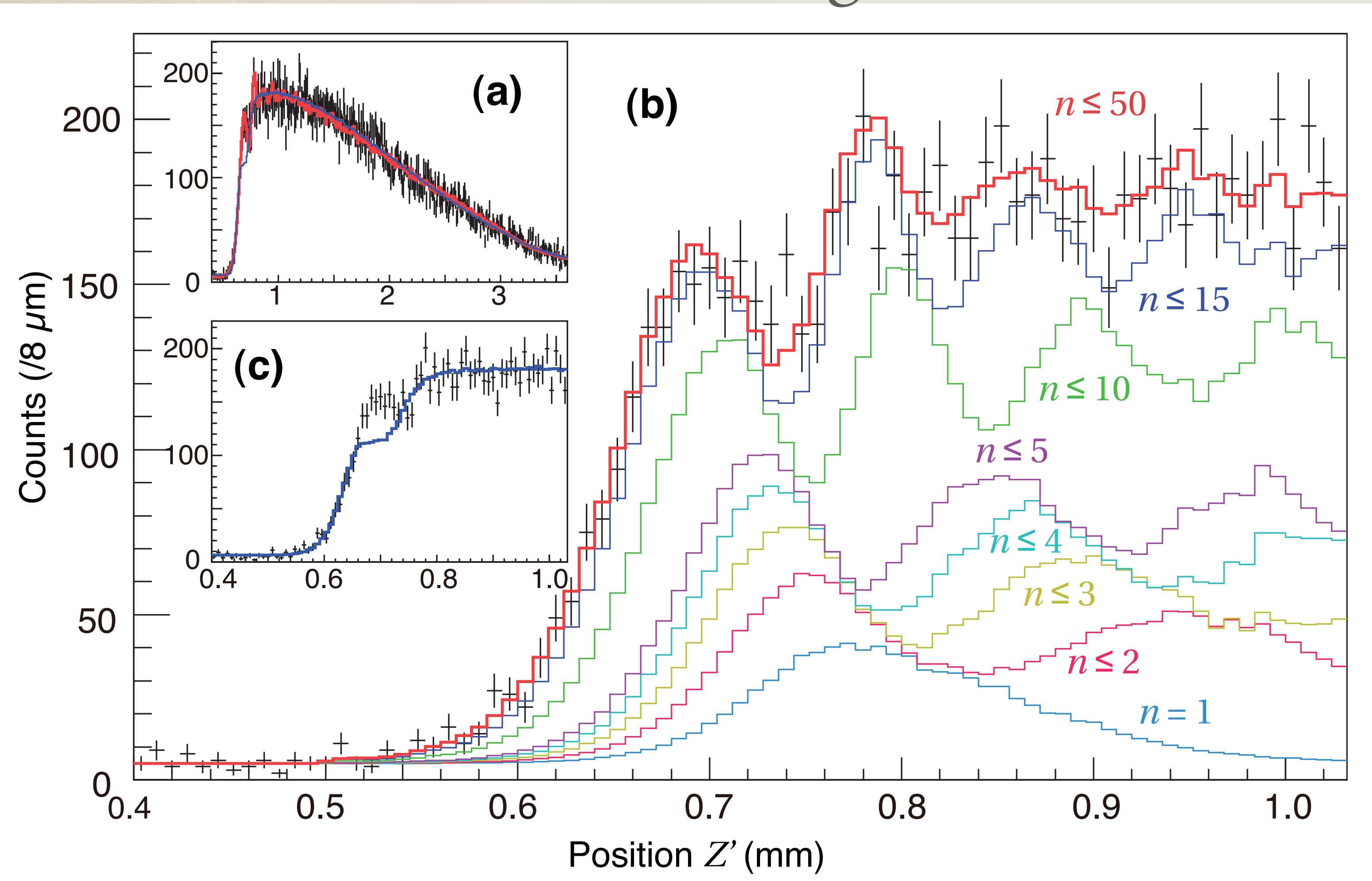

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modulation of neutron distribution due to quantum effect was clearly observed!

You can use this quantum system as a probe of a test of the weak equivalence principle in quantum regime!

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

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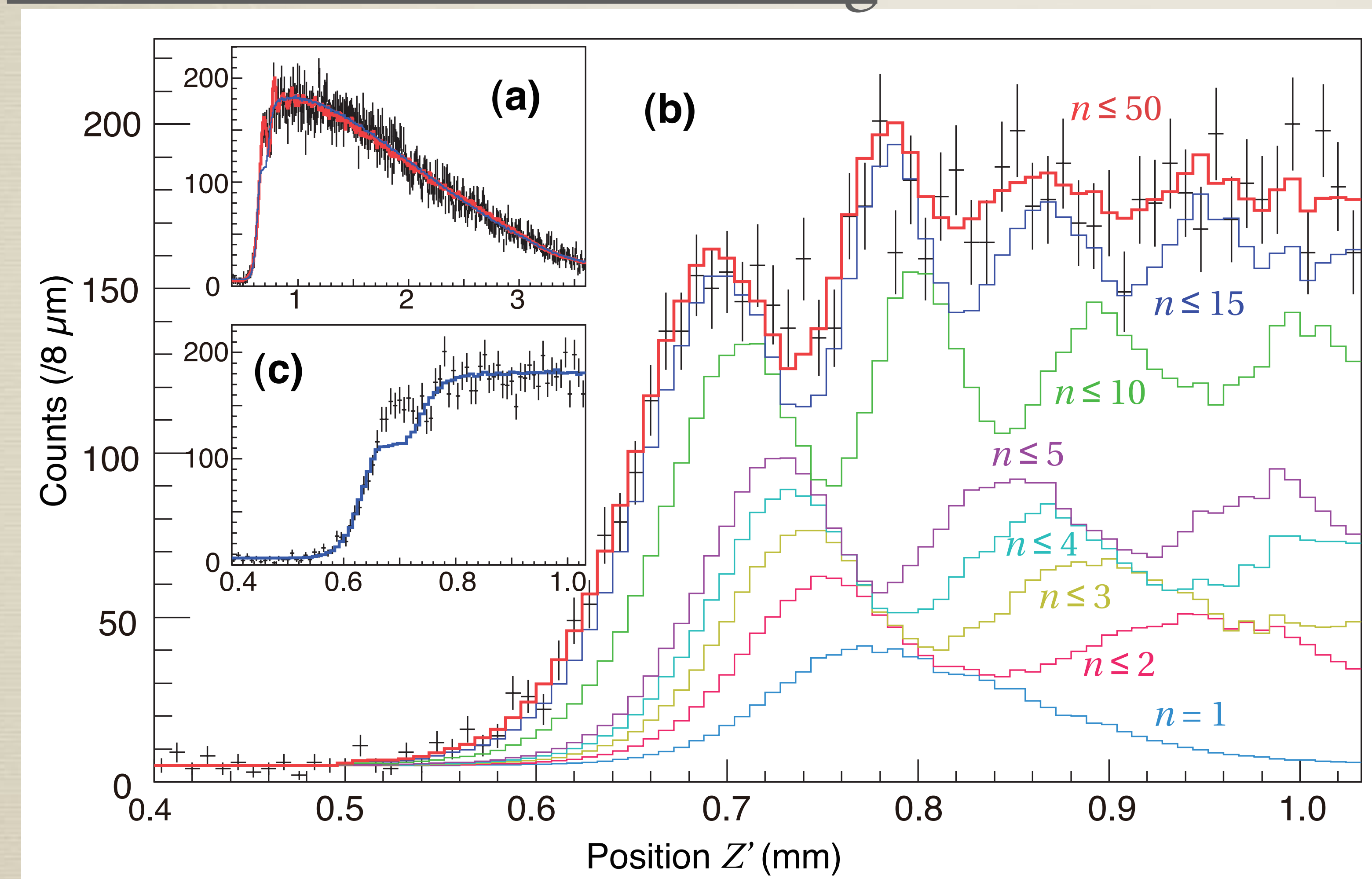

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$$E_0 = \left(\frac{m g^2 \hbar^2}{2}\right)^{1/3} \sim 0.6\ \mathrm{peV}$$

$$\Downarrow$$

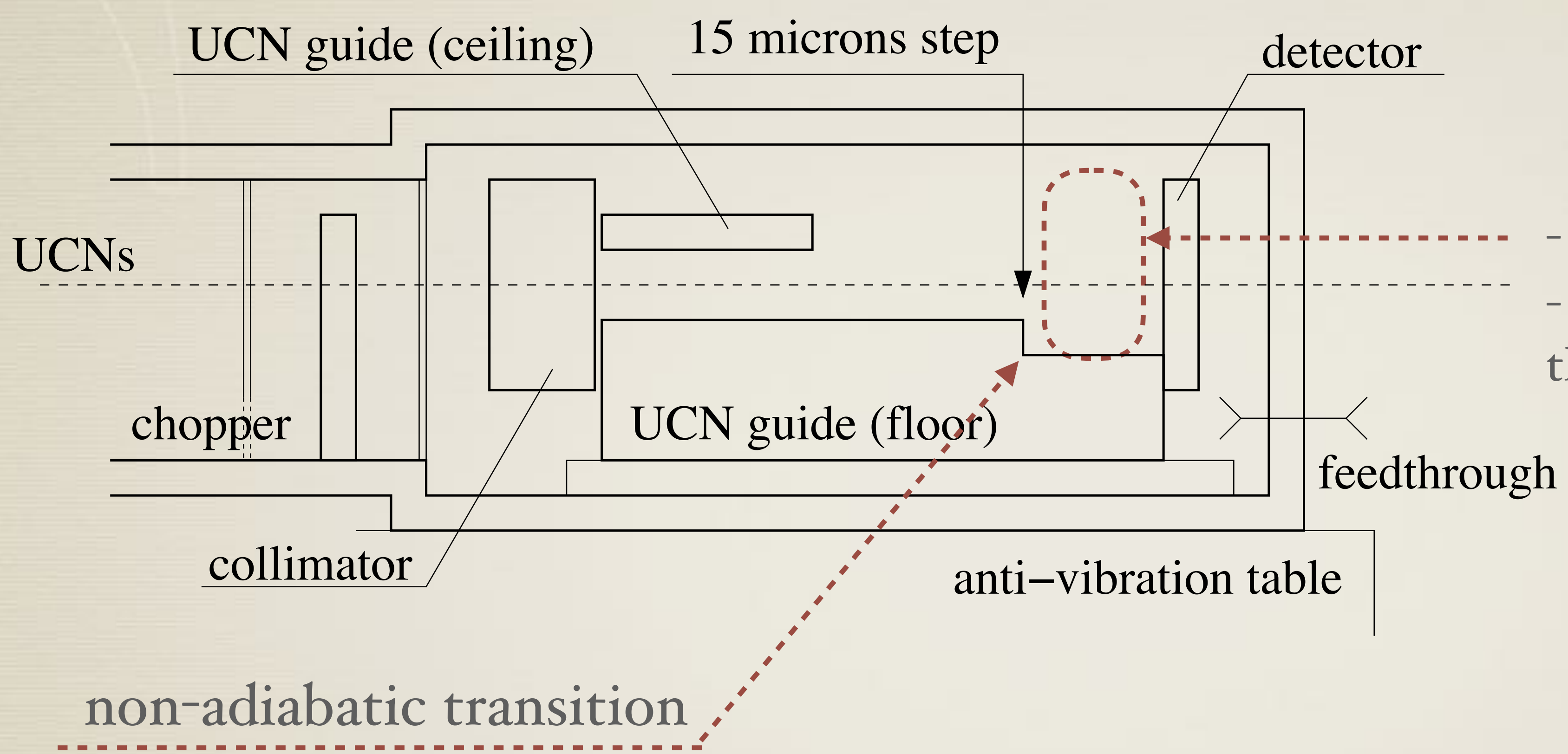
$$z_0 = \left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3} \sim 6\ \mu\mathrm{m}$$

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

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

Testing WEP using the gravitationally bound state of UCNs

now designing an experiment for the test



- start to oscillate between the state
- energy scale can be evaluated by the oscillation frequency

make a state

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

time evolution

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

Testing the Weak Equivalence Principle

Classical Regime:

Lunar Laser Ranging Tests:	10^-13 level	PRL 93, 261101 (2004)
Torsion Balance:	10^-13 level	PRL 100, 041101 (2008)
Atom Interferometer:	10^-8 level	PRL 115, 013004 (2015)

Quantum Regime:

Neutron Interferometer:	10^-3 level	PRA 21, 1419 (1980)

However, some bias in analysis was pointed out by collaboration members.

Physica B151, 22 (1988)

Our target of 1st-stage experiment is 10^-3 level.

Summary

Neutron is one of the powerful tool to search a gravity-related new physics!

Designing is still under way, so I'm very happy if we can collaborate each other at any points of developments. Please let me know, if you are interested in the experiments.

Thank you for your attention.

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

— William M. Snow (Indiana Univ.)