Experimental Search for New Gravity-like Interactions with Slow Neutrons

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Accelerating Universe in the Dark @ Yukawa Institute for Theoretical Physics (Mar. 4-8 2019)

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 weak equivalence principle (WEP)

The WEP have been experimentally confirmed by several tests.

mostly in the classical framework.

How about in the quantum regime, in contrast?

There are not so many.

We are preparing an experiment to test the WEP in the quantum regime using the gravitationally bound neutrons system.

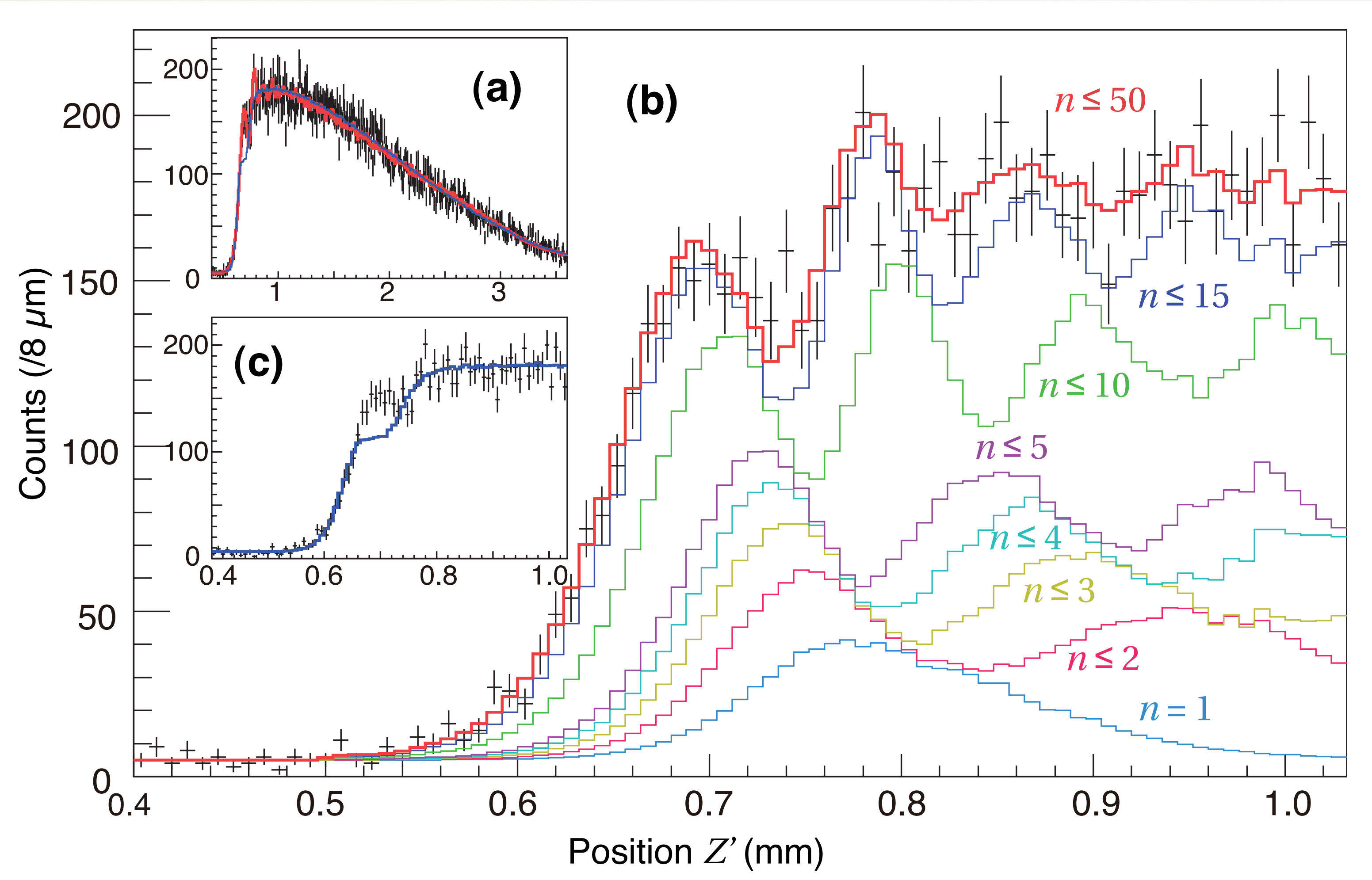
G. Ichikawa, S. Komamiya, YK *et al.*, PRL 112, 071101 (2014)

Gravitationally Bound Neutrons

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

measurement and model fitting

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 $\chi^2/\mathrm{NDF} = 0.96$

scales of the system

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

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

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

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

By measuring both scales simultaneously, we can evaluate the ratio between the masses.

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!

Gravitational constant is too small, compared to the other 3 fundamental forces, to think that the all forces came from the same origin.

$$G = \sqrt{\frac{1}{8\pi M_p^2}}$$

The Reduced Planck Mass

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

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

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

It is natural to think that there might be new physics at a certain scale between the electroweak and the Planck scales.

Testing Tools

Neutron-Atomic Gas scattering processes are clearly understood by V.F. Sears, Phys. Rep. 141, 281 (1985), therefore, precision measurement of the scattering features can provides an experimental search for anomalies from the known interactions in the nanometer range.

What we do:

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

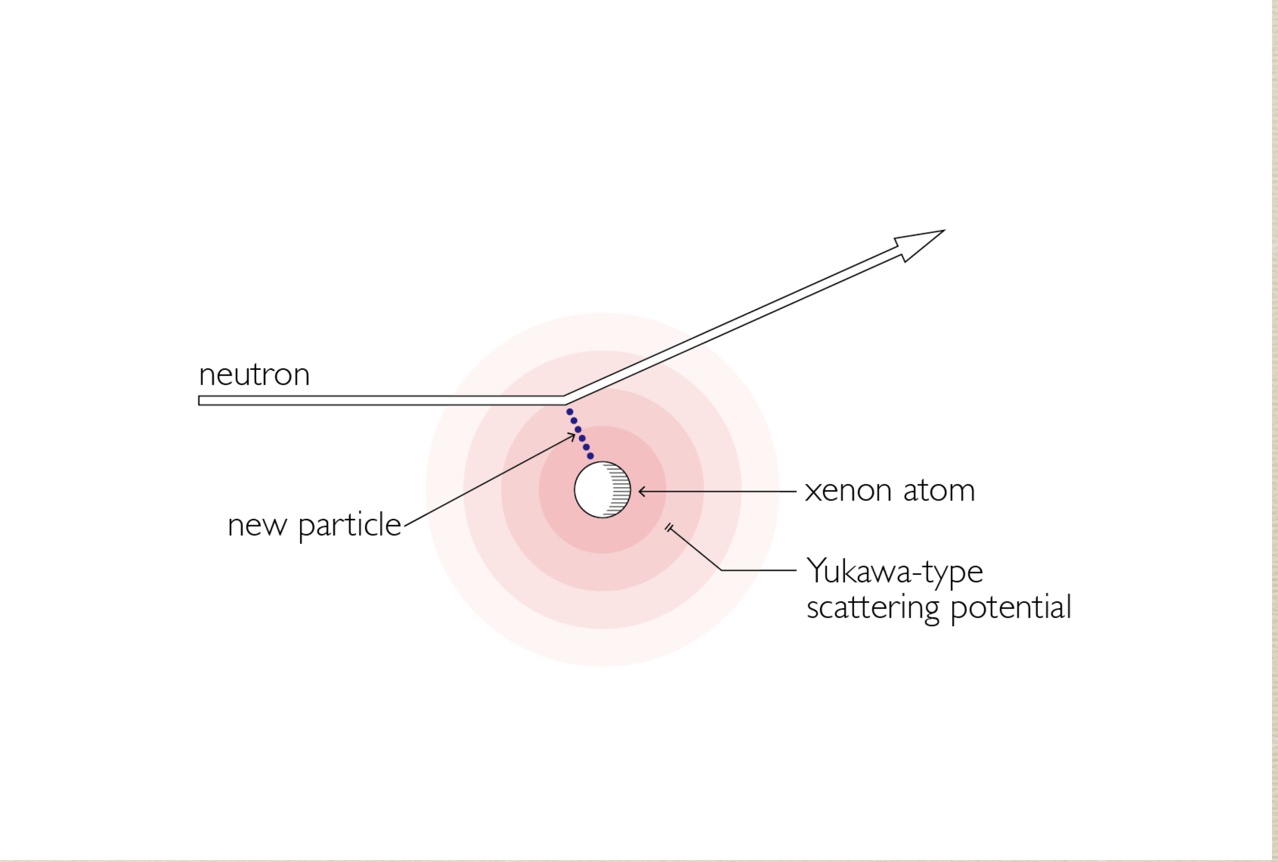
2) evaluate any deviations from known scattering processes using the Yukawa-type parametrization

coupling charges

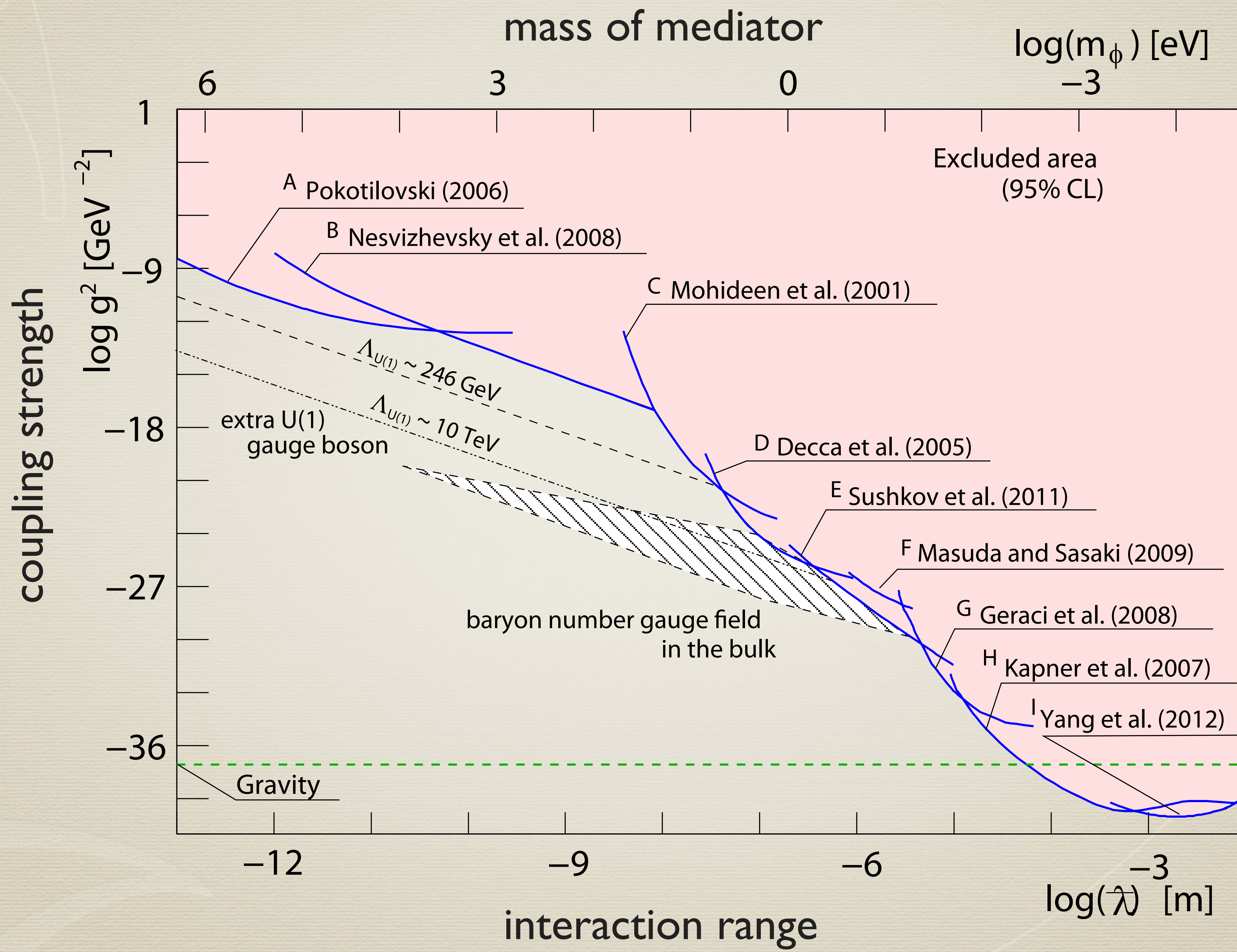
mass

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

coupling strength



Current Limits in the Yukawa-type Parametrization



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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,†]

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[2]*School of Electrical and Electronic Engineering, Wuhan Polytechnic University, Wuhan 430000, People's Republic of China*
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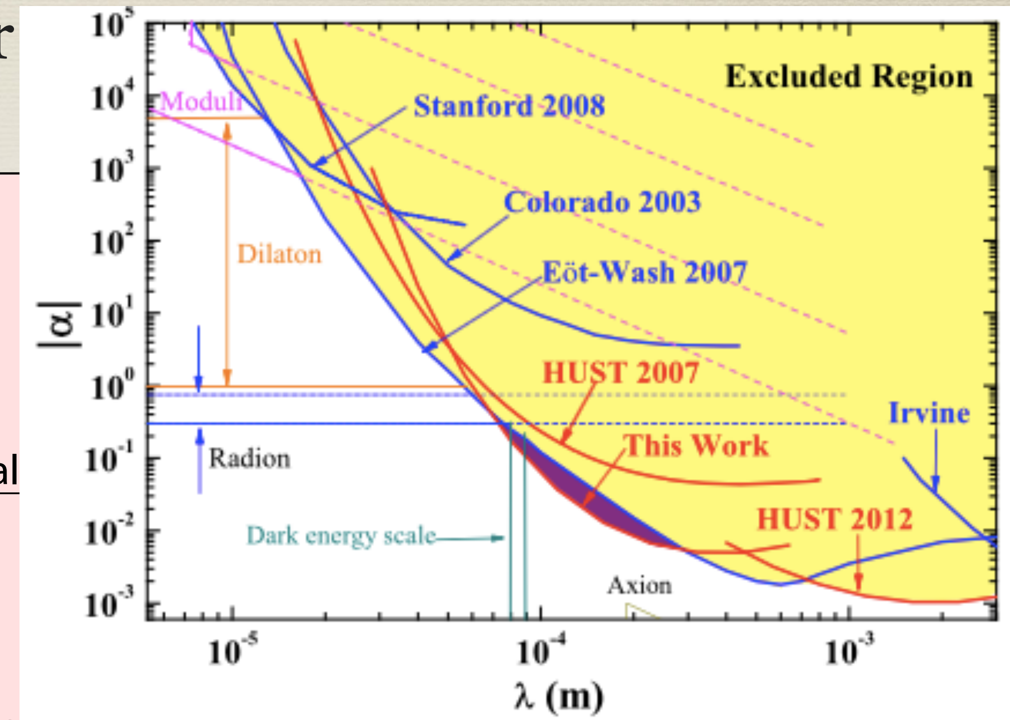
(Received 17 August 2015; revised manuscript received 27 January 2016; published 30 March 2016)

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

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[3]*Physics Department, Wabash College, Crawfordsville, Indiana 47933, USA*
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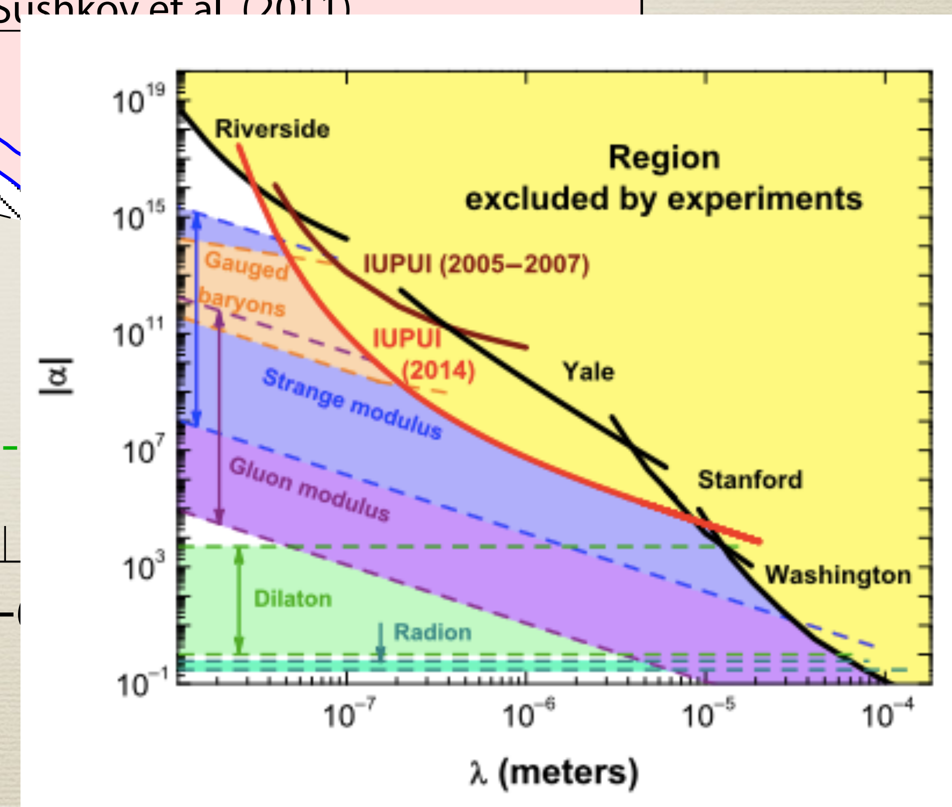
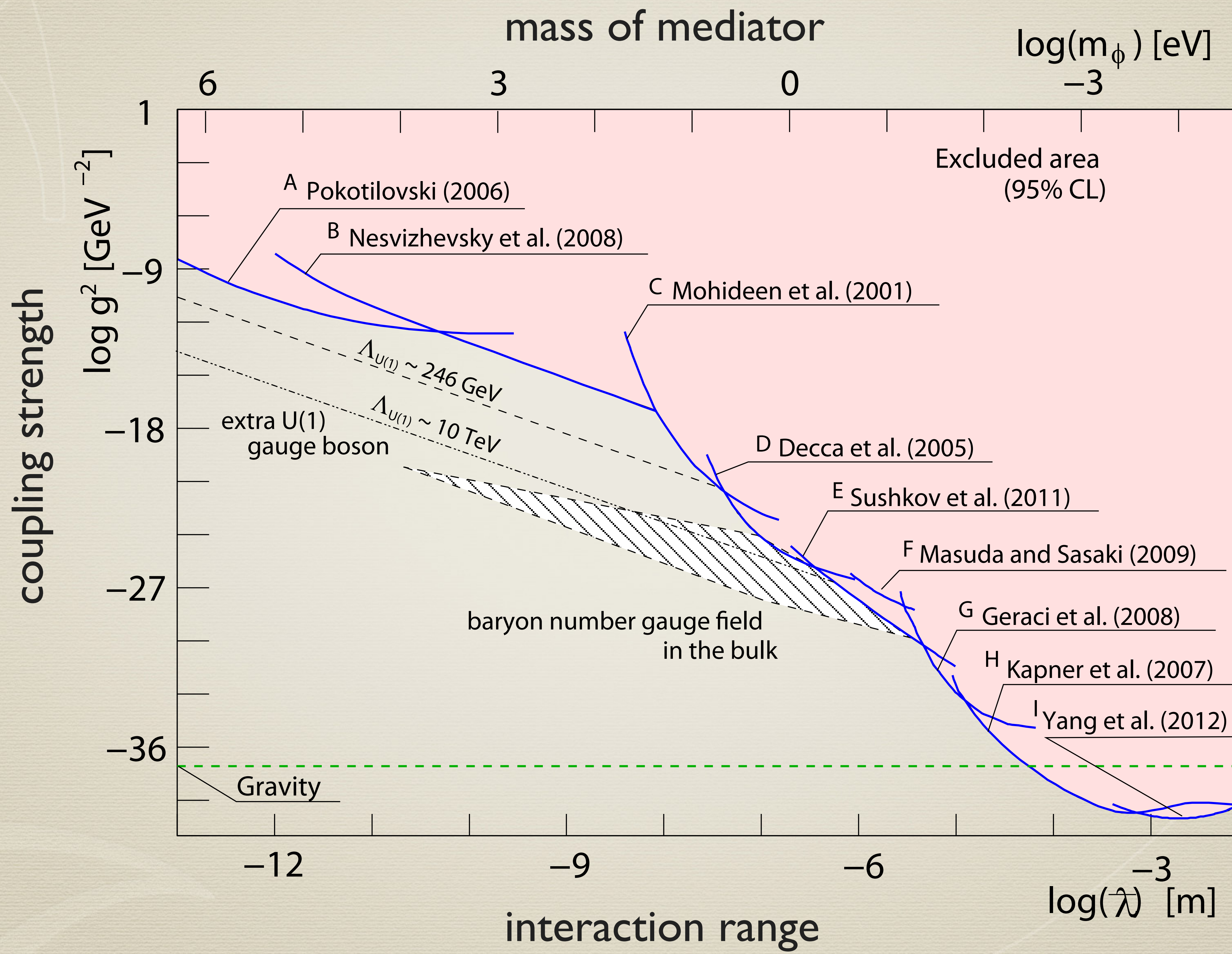
(Received 4 November 2014; revised manuscript received 3 January 2016; published 2 June 2016)

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.



Current Limits in the Yukawa-type Parametrization



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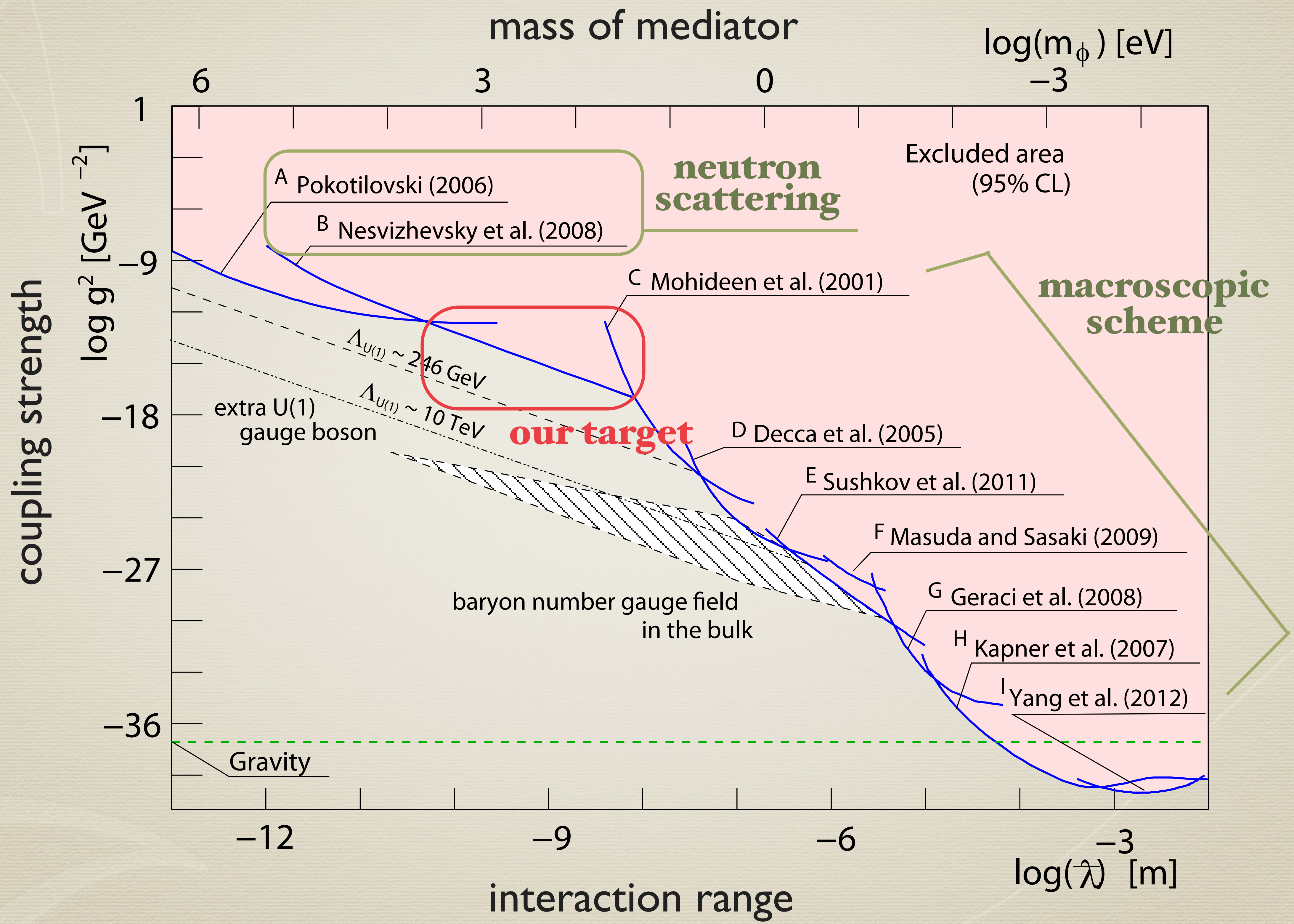

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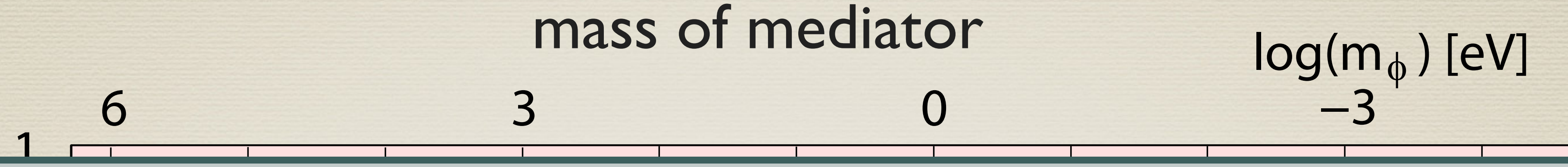
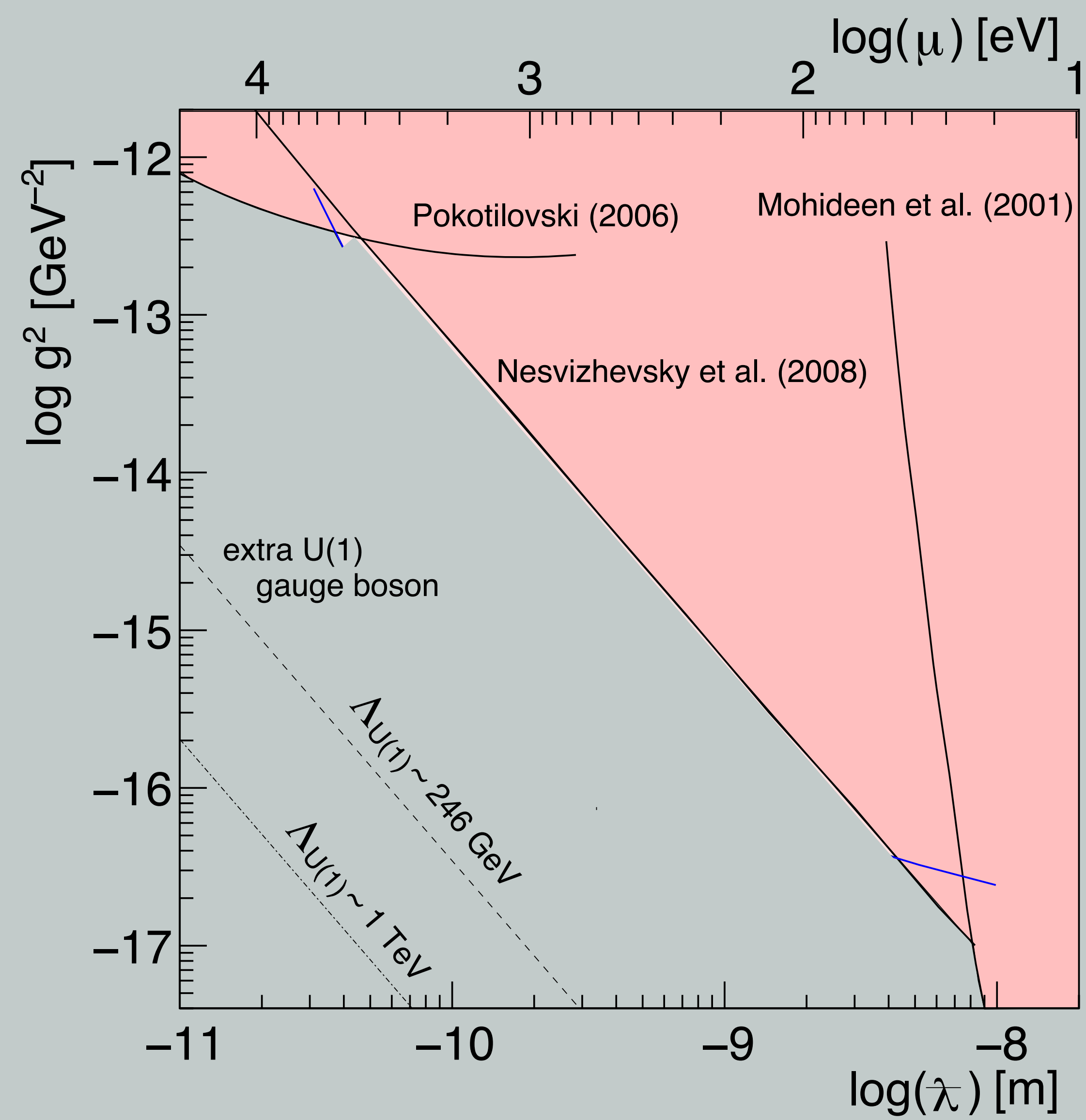


This experiment had started from 2013 with financial support of KAKENHI No. 25870160

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



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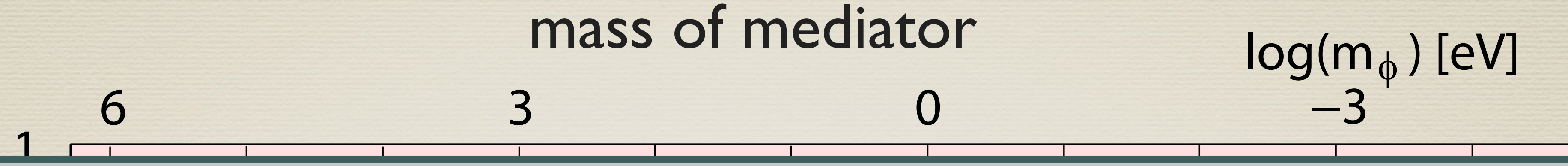

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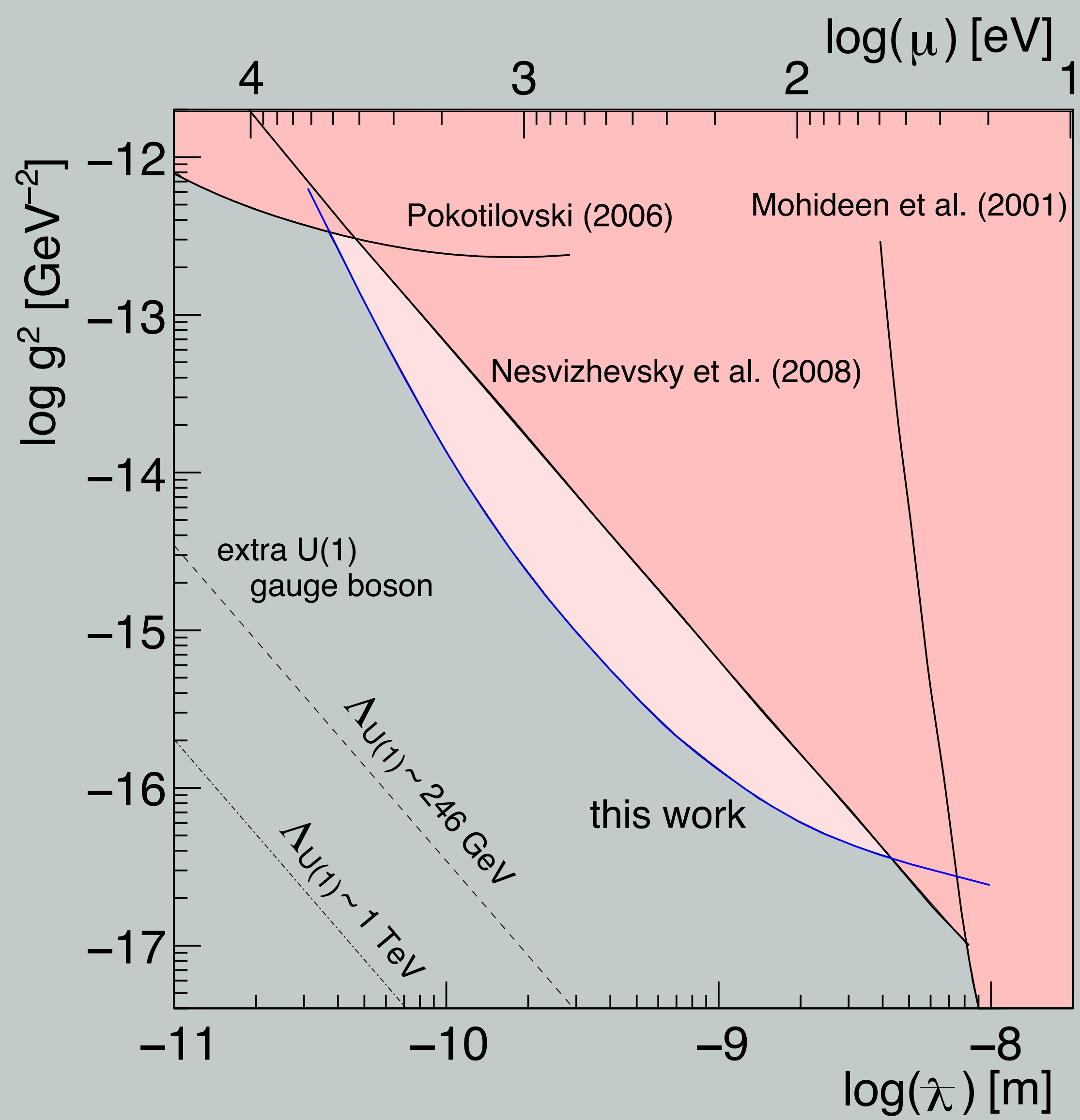

"New schemes at the nanometer range"

THE JOURNAL OF PHYSICAL CHEMISTRY A
Article
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Heavy Element Effects in the Diagonal Born–Oppenheimer Correction within a Relativistic Spin-Free Hamiltonian

Yuji Imafuku,[†] Minori Abe,[*,†] Michael W. Schmidt,[‡] and Masahiko Hada[†]

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[‡]Department of Chemistry and Ames Laboratory (US-DOE), Iowa State University, Ames, Iowa 50011, United States

Tokyo Metropolitan Univ.

Probing Non-Newtonian gravity by photoassociation spectroscopy

M Borkowski[1], A A Buchachenko[2], R Ciuryło[1], P S Julienne[3], H Yamada[4], K Yuu[4], K Takahashi[4], Y Takasu[4], and Y Takahashi[4,5]

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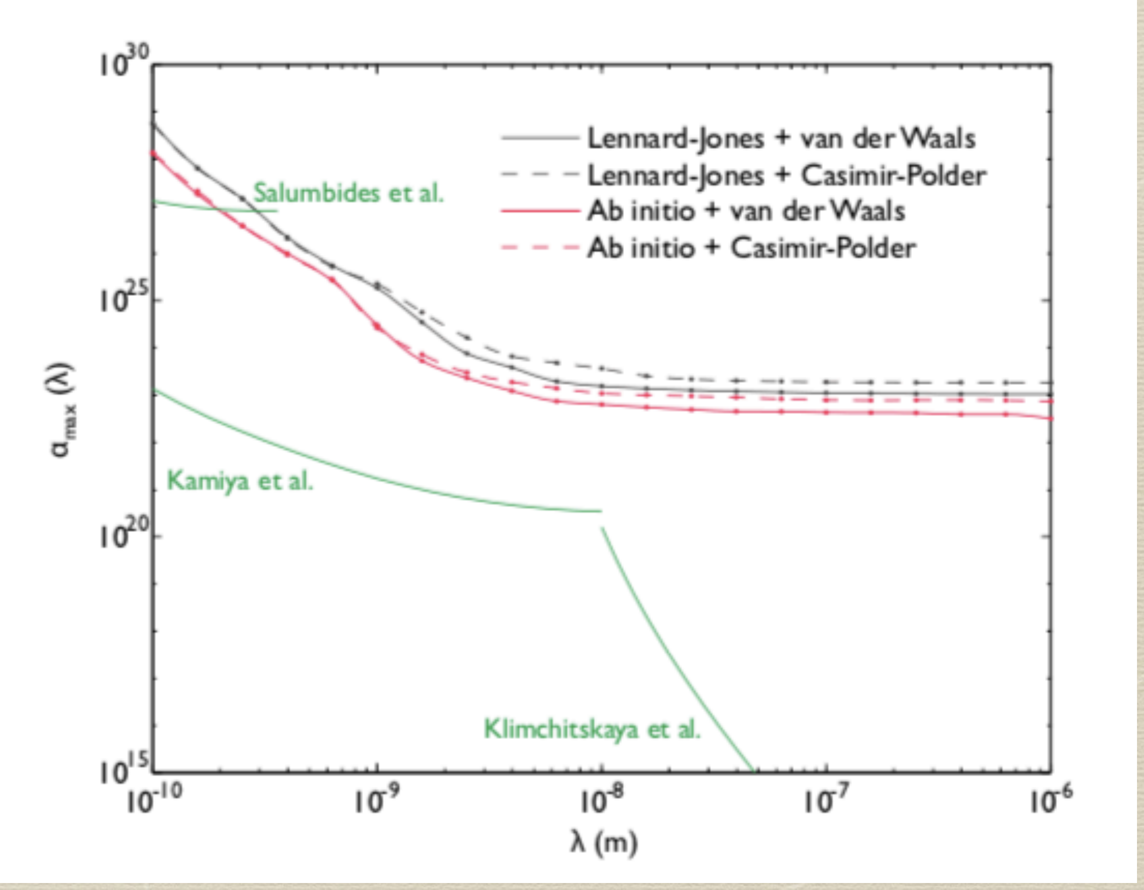
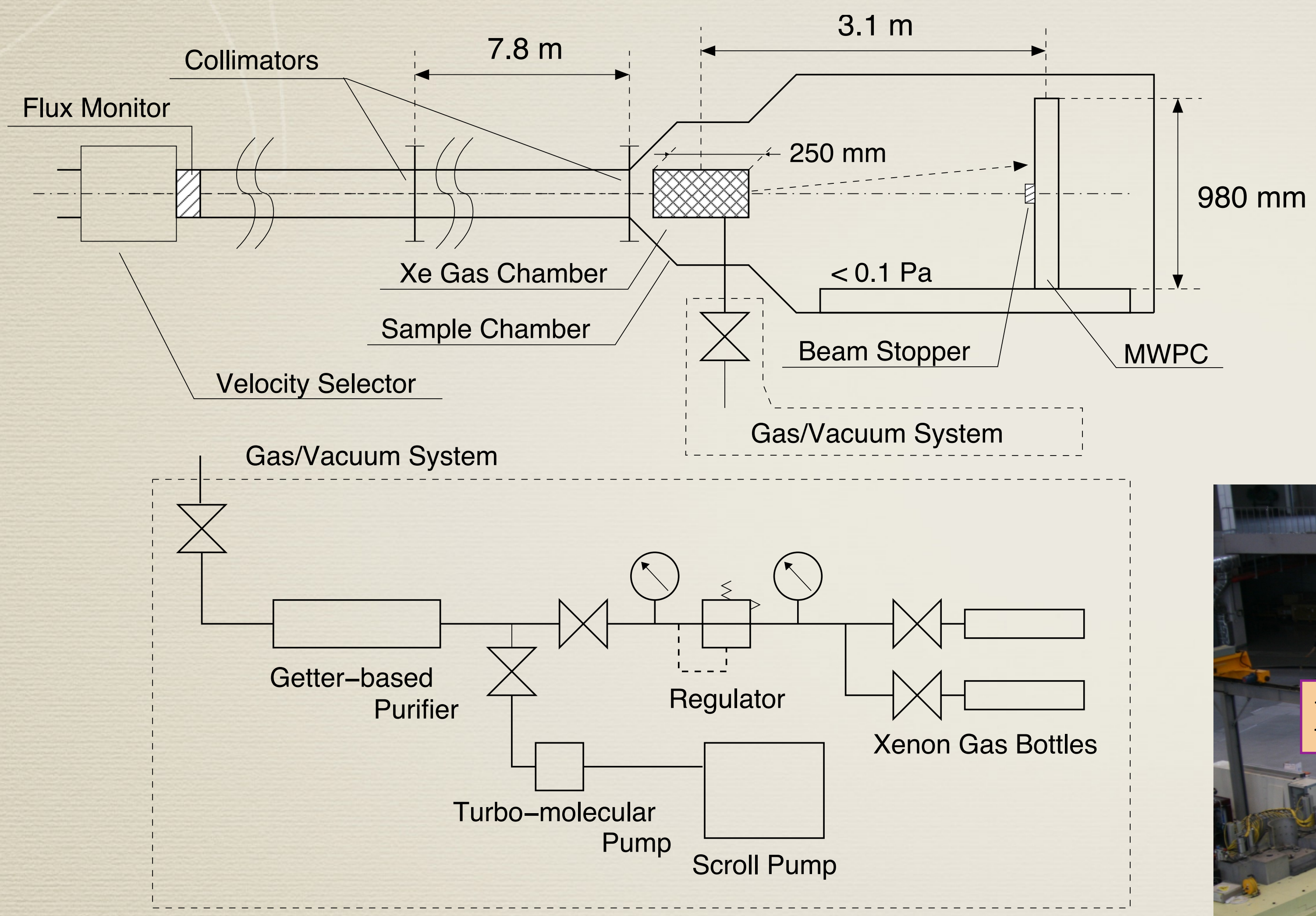
Kyoto Univ.

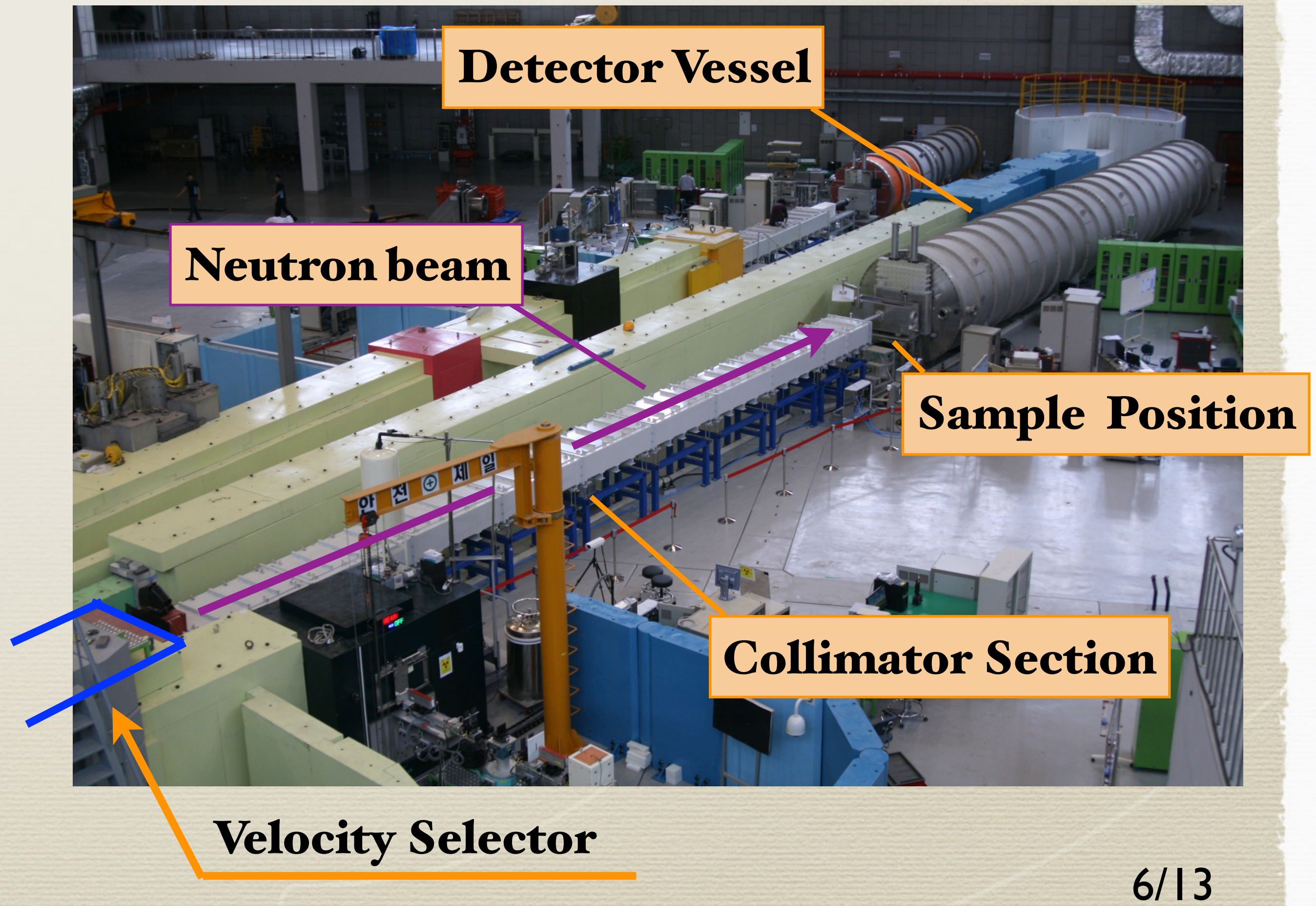


Experimental Site

Small Angle Neutron Scattering Beam Line which is originally designed for material science.



figs. from Young-Soo Han et.al, The 11th Japan-Korea Meeting on Neutron Science, 101 (2011)



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

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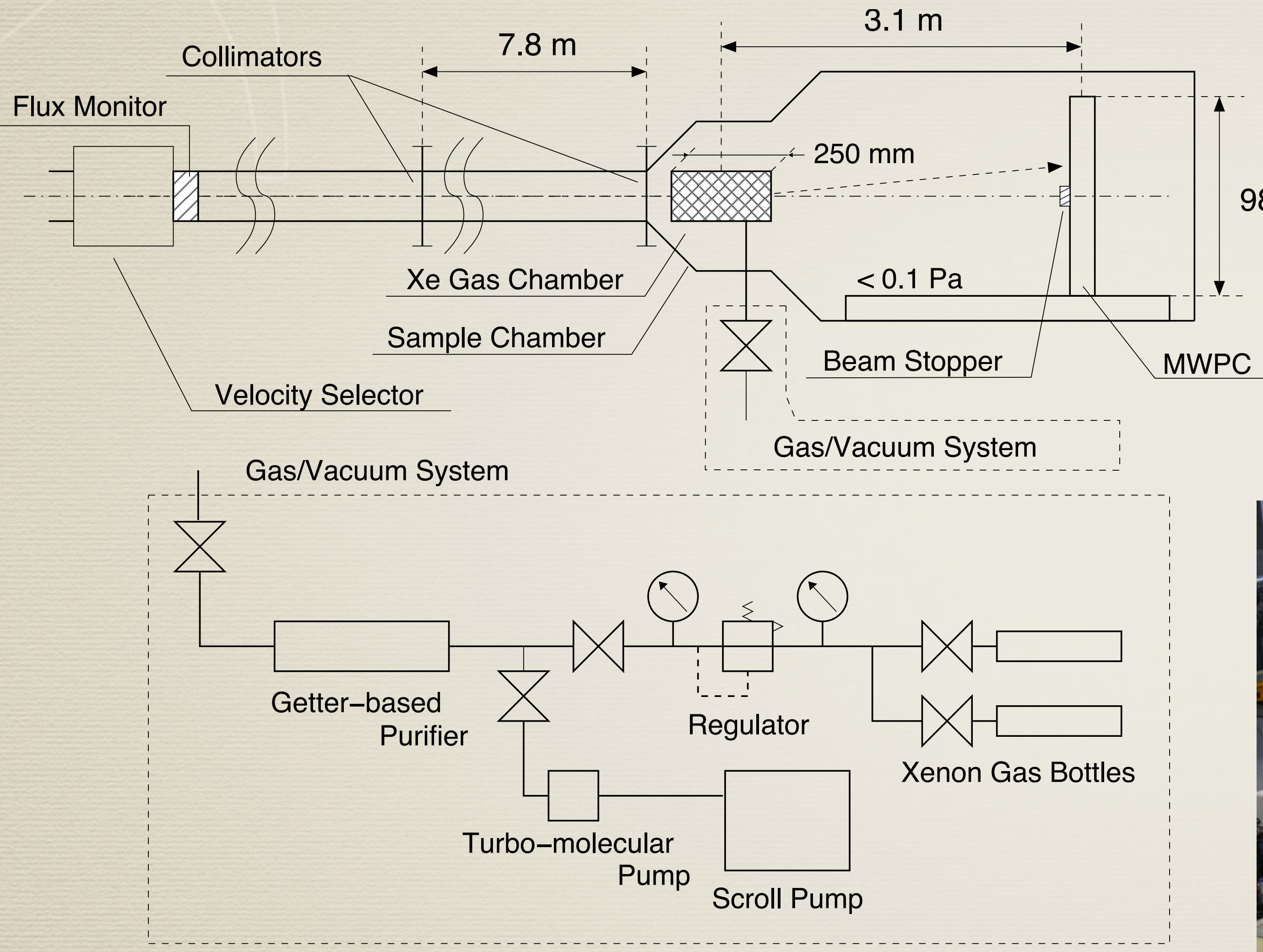

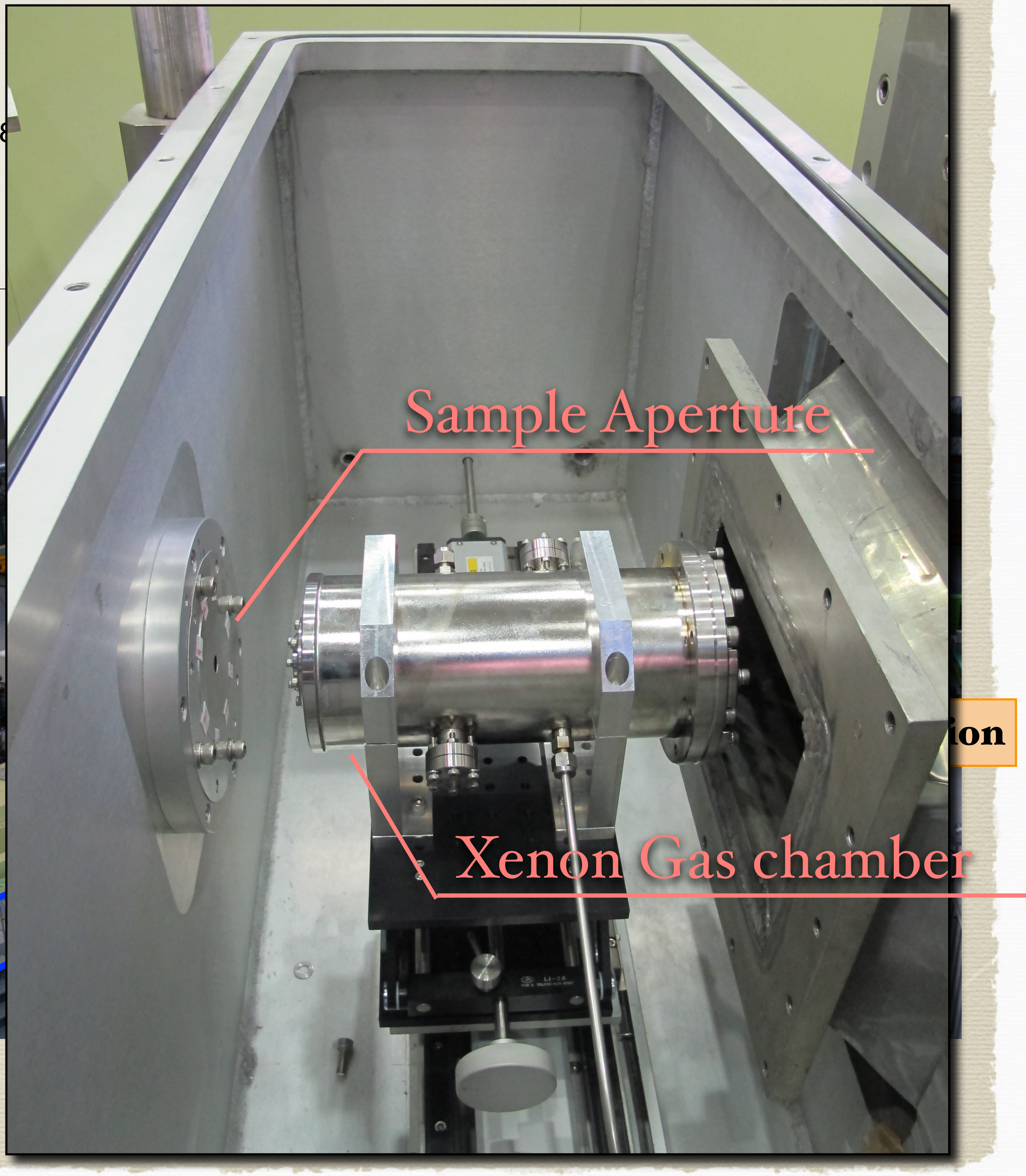

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Scattering Length

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

momentum transfer

coherent scatt.

incoherent scatt.

Schwinger scatt.

→ differential cross section

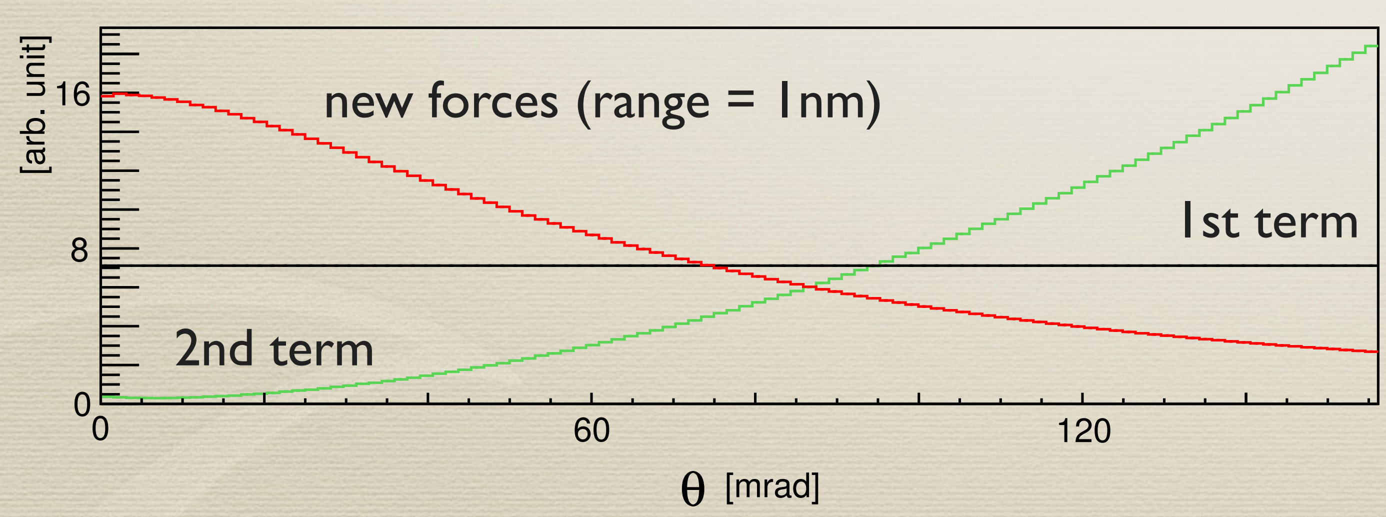
const.

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

non-flat distr.

The expected angular scattering distribution to be measured is derived by convoluting it with the finite beam size, the length of scattering chamber, and the thermal motion of the Xenon gas

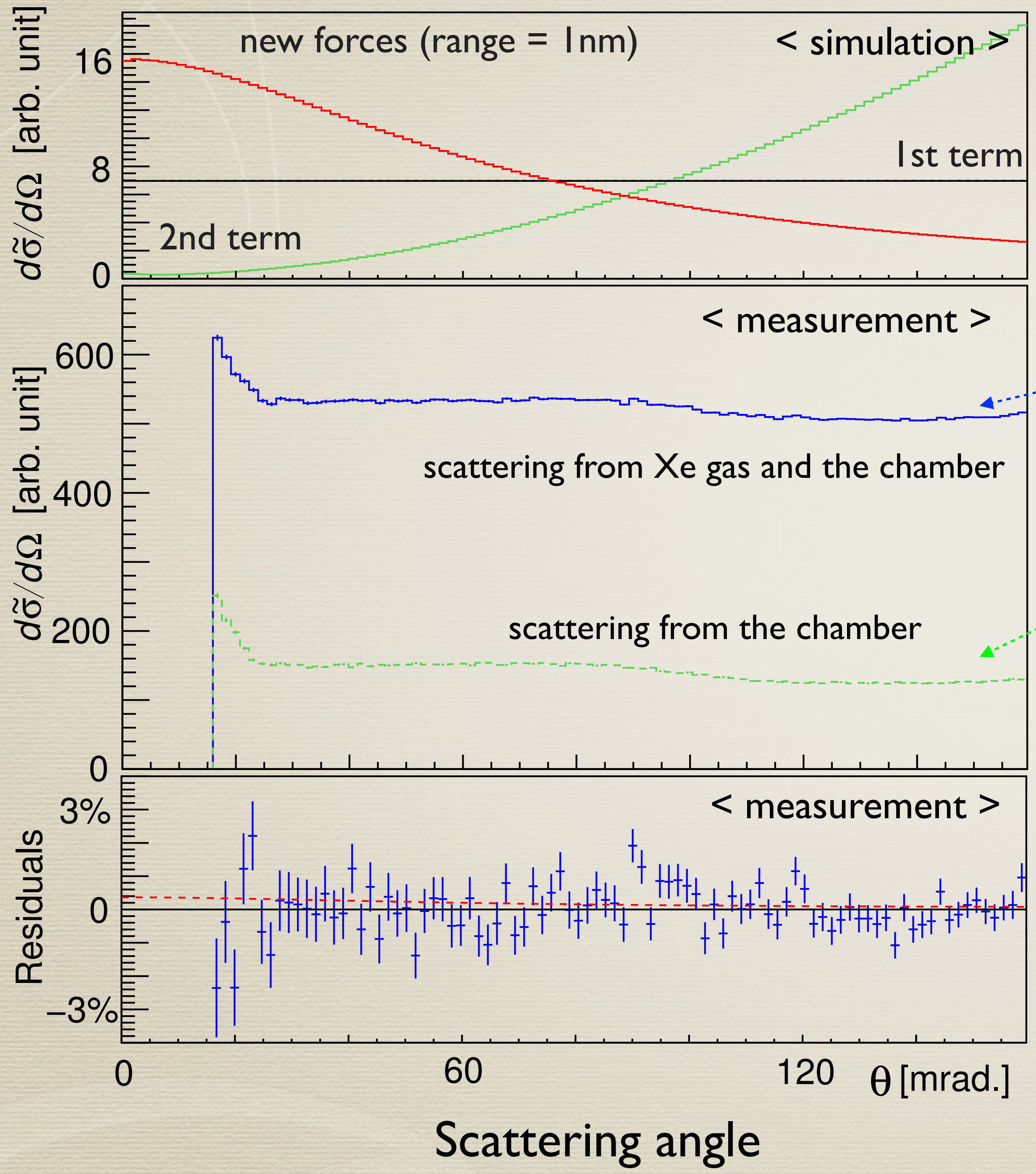
Simulated Distributions



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

We can find the effects from new forces by analyzing a shape of measured distribution.

Measured Distributions



<u>procedure</u>

1. remove contribution 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

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

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

for 1 nm range

3. set 95% confidence interval 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

Discussions)

1. The sensitivity is still limited by statistics.

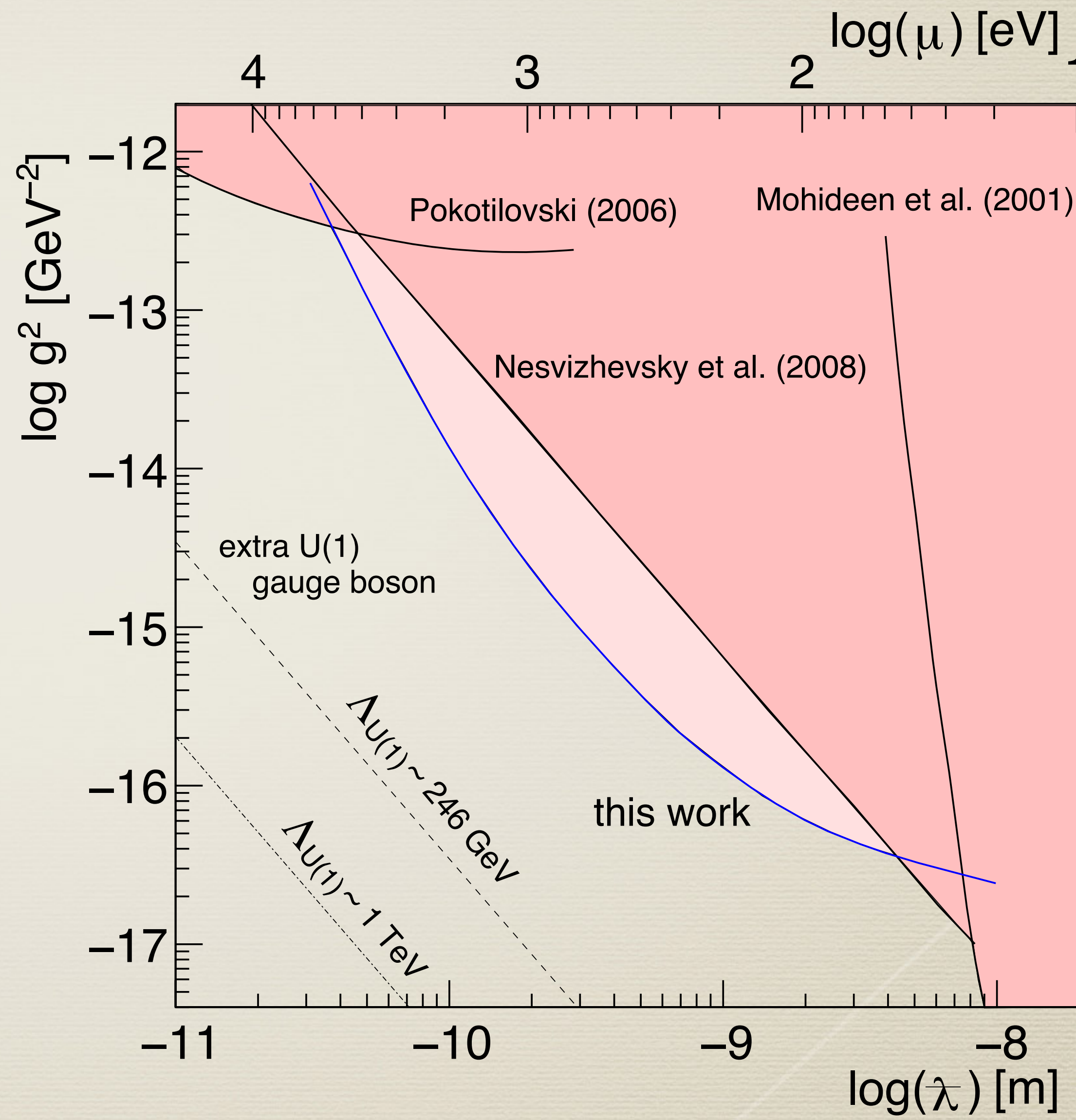
   We are now testing more intense neutron beam lines and investigating systematic effects we would meet.

2. How to expand our experimental reach?

   - use shorter wavelength
   - measure at smaller angle

3. Any sensitivity for other type of forces?

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



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

New Scalar Field

Start with a Lagrangian density for a scalar field

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

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

If a field doesn't show self-coupling feature, the equation of motion will be the Klein-Gordon's 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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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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If a field has a self-coupling term, nonlinearity become significant and the field has its mass as a function of the ambient fermion density.

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

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

Chameleon Field

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

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

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

<u>interesting feature</u>

It cannot go out of materials - interaction charge cannot be integrated - Thin Shell Effect

Lab-scale experiments might have sensitivities for this kind of new models.
Experiment of atomic interferometry set the most stringent limits on this.

M. Jaffe, P. Haslinger, V. Xu et al., Nature Phys. 13, 938 (2017)

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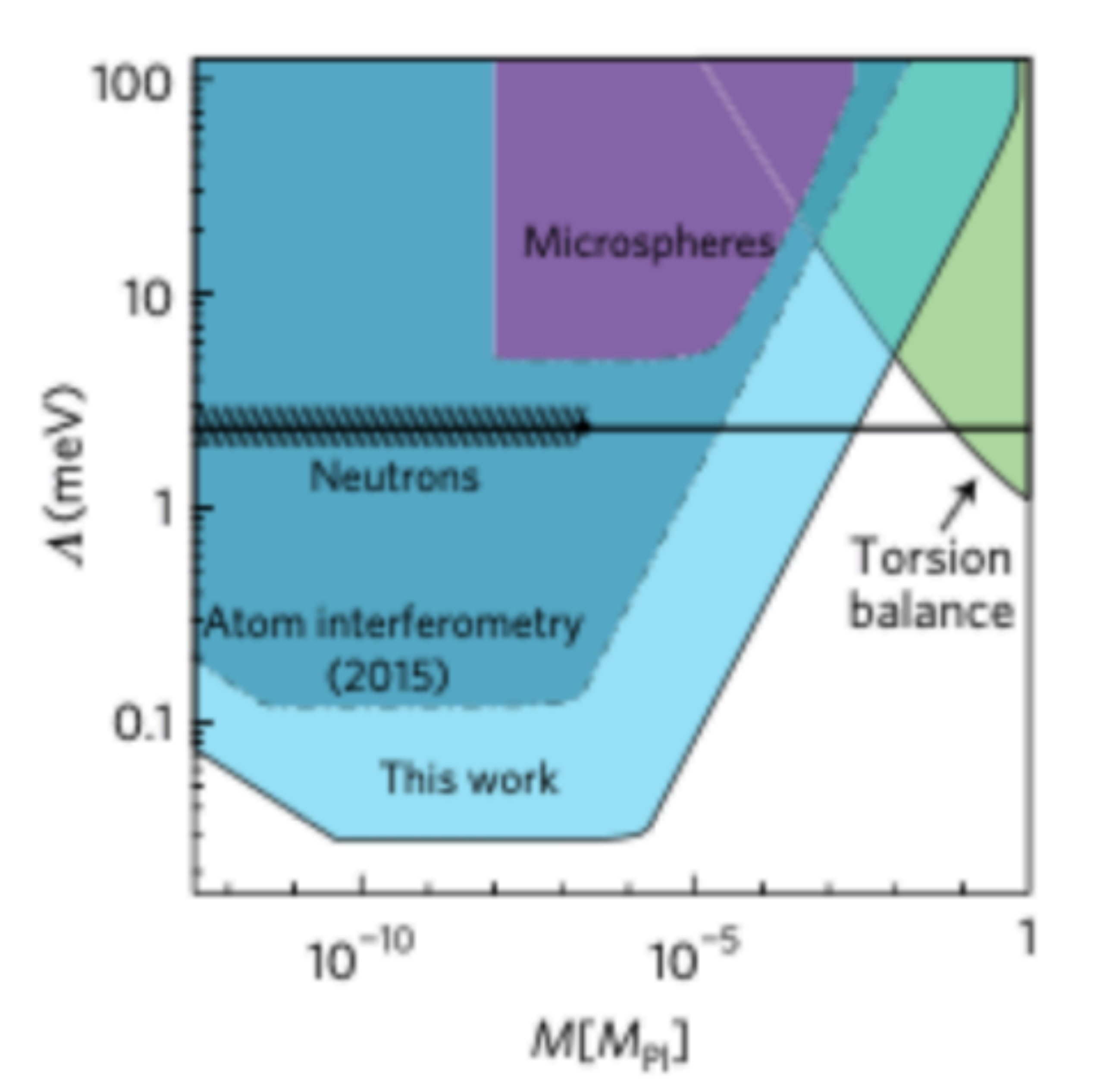
M. Jaffe, P. Has



Summary

1. New gravity-like interaction can be searched by measuring neutron-Xe scattering processes precisely.

2. The sensitivity is limited by statistics.

3. We are now investigating other possible applications of this experimental method.