Search for new gravity-like short-range forces in neutron-Xe scattering

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New Interactions (5th forces)

think new interactions mediated by a scalar, here after

Lagrangian as a starting point of following discussions

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

- $m_\phi^2 = -\mu^2$, $n = -4$, $\xi = \lambda/4!$, $\eta_i/M_{Pl} = 1/v$

==> Higgs

- $\xi = 0$, $\eta_i = \eta$ (universal)

the equation of motion become an inhomogeneous Klein-Gordon equation, and the new interaction is described by the simple Yukawa-type scattering potential

Yukawa-type Scattering Potential

use a notation of the strength of the Yukawa interaction term as

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

where *m* is a fermion mass and *g* is a proportional constant,
then, scattering potential between two objects is obtained 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

Here the coupling charge is mass, this new interaction appears to violate the Newtonian, inverse square law of the universal gravity.

→ called as gravity-like interaction

Testing Gravity ~ 10^12 m

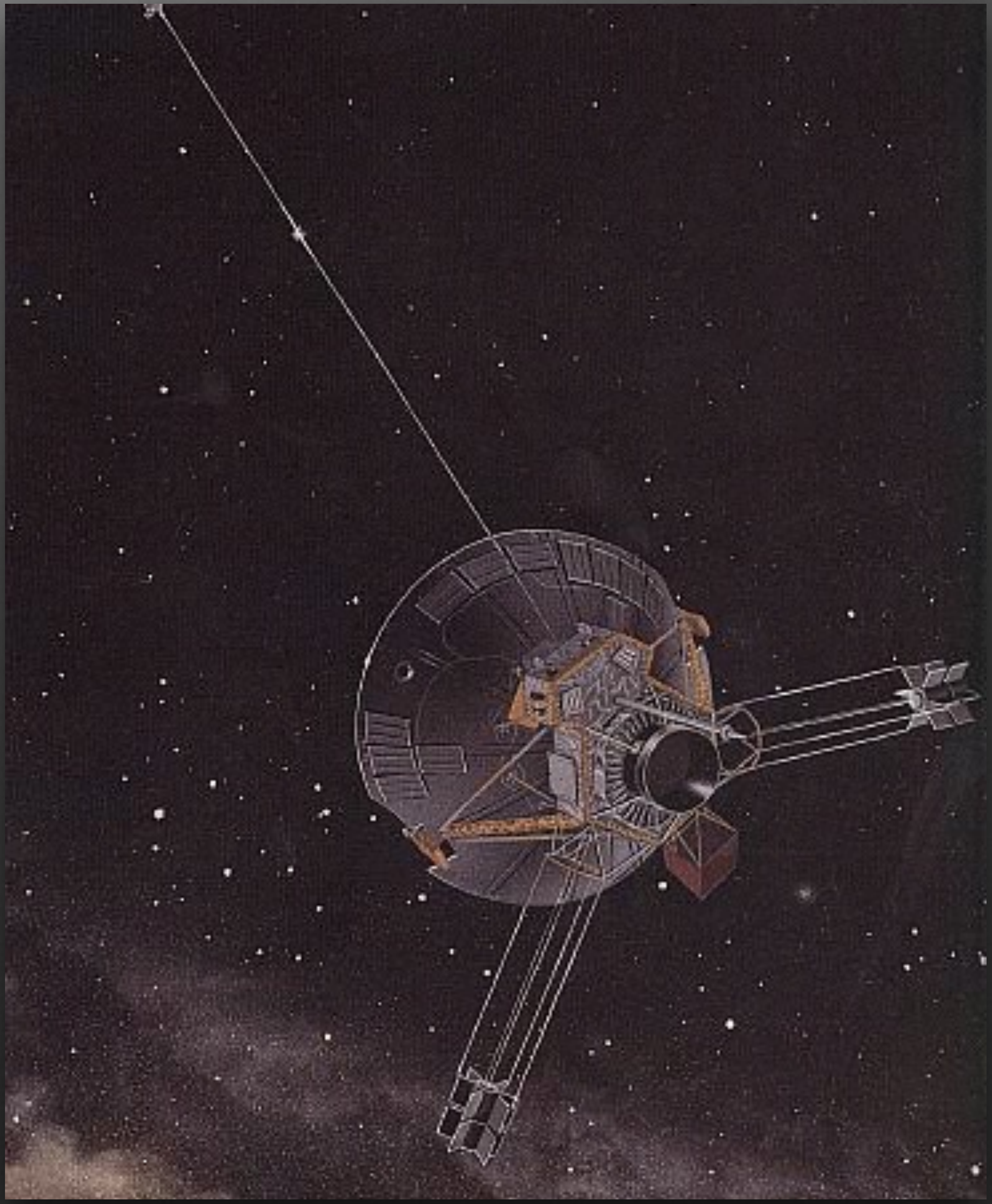
Verified by analyzing planetary and lunar movements

(exception) Pioneer Anomaly

The Pioneer 10/11 spacecrafts were observed to be pulled by the Sun a little bit stronger than the expectation on trajectories out of the Solar System. (1980)

It is now “tentatively" solved by taking into account an anisotropic thermal radiation precisely.

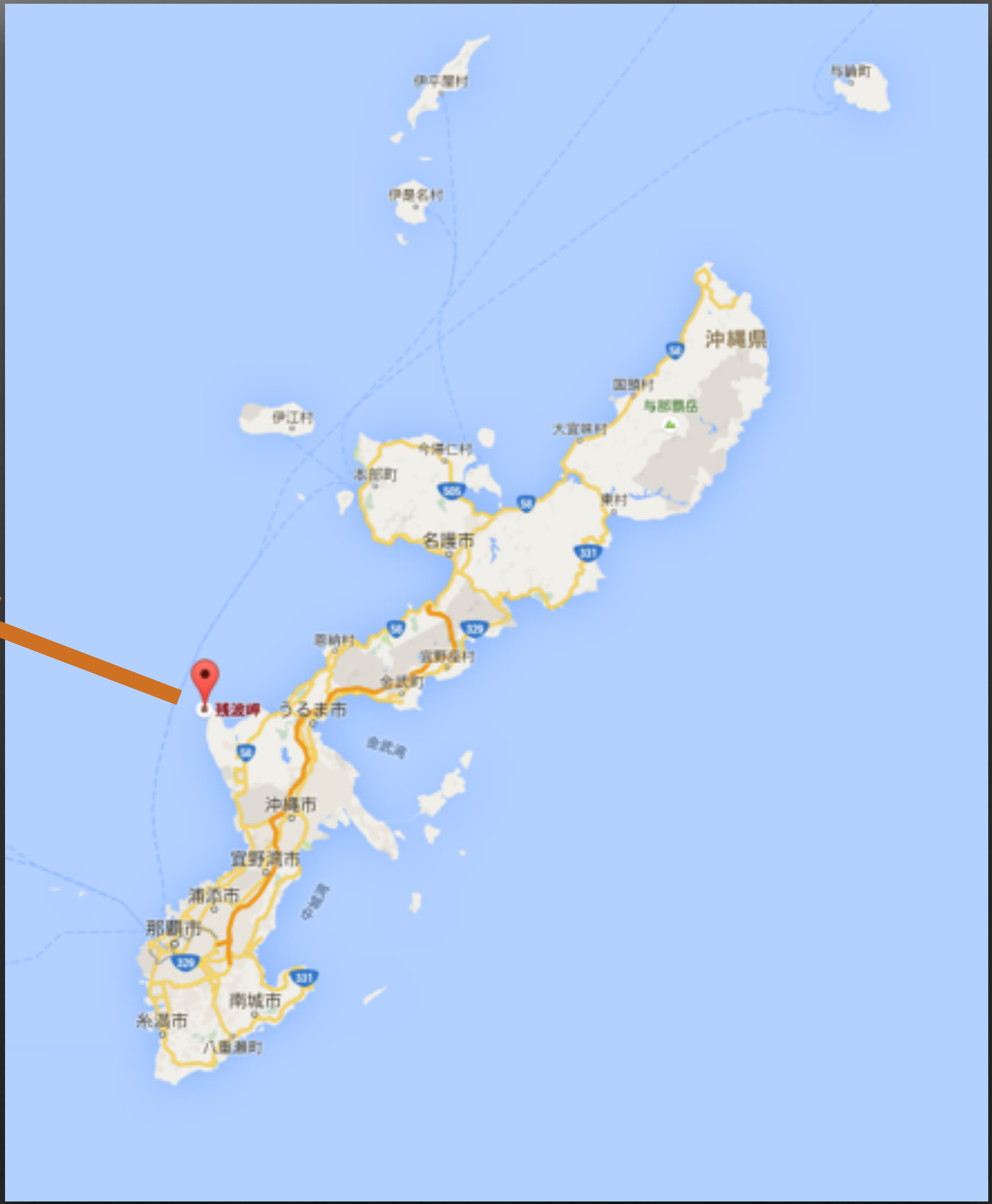
--- PRL108, 241101(2012)



Testing Gravity ~ 10^1 m

verified in the field of Geophysics

Daiki Goto / Zanpa cape



Testing Gravity < 1 m

No significant deviation from the Newtonian Gravity has been observed down to 100 micron ranges.

Many Gravity tests at shorter range have been conducted in several institute.

Deviation is evaluated by the Yukawa

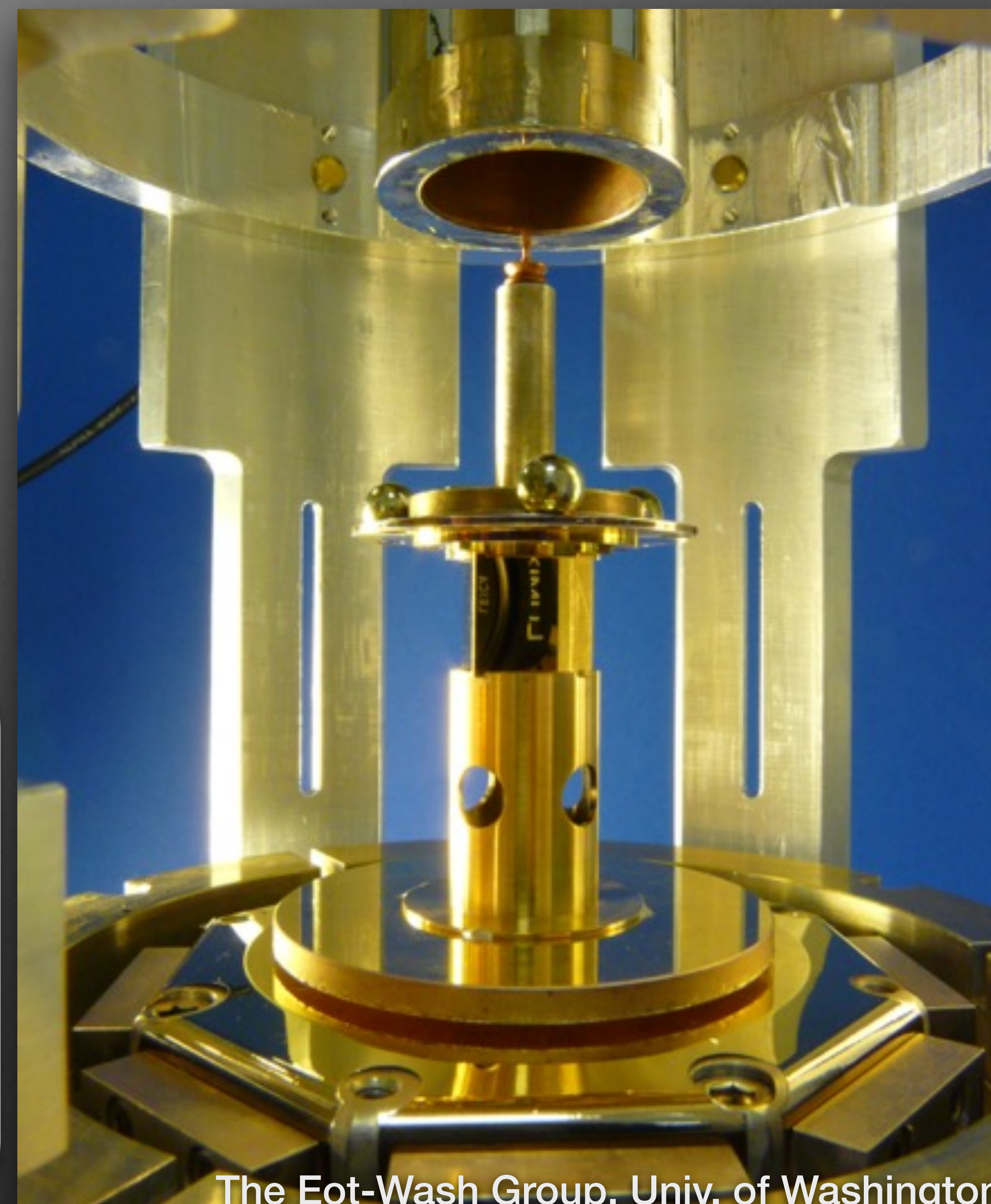
coupling charges

mass

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

coupling strength

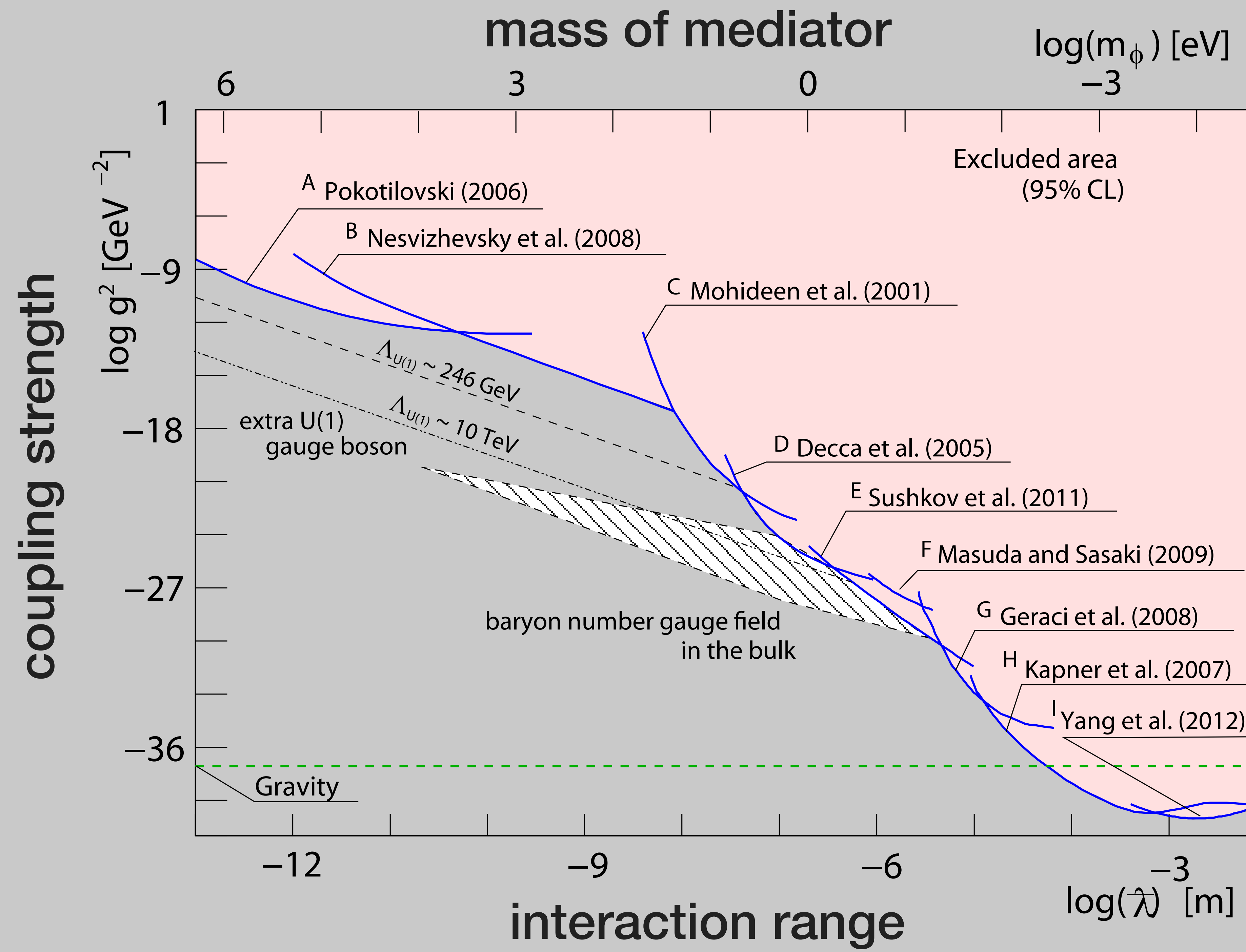
parameter space: (g^2, m_ϕ) or $(g^2, \bar{\lambda} = 1/m_\phi)$



The Eot-Wash Group, Univ. of Washington

http://www.npl.washington.edu/eotwash/sr

Experimental Constraints on the Yukawa-type Parametrization



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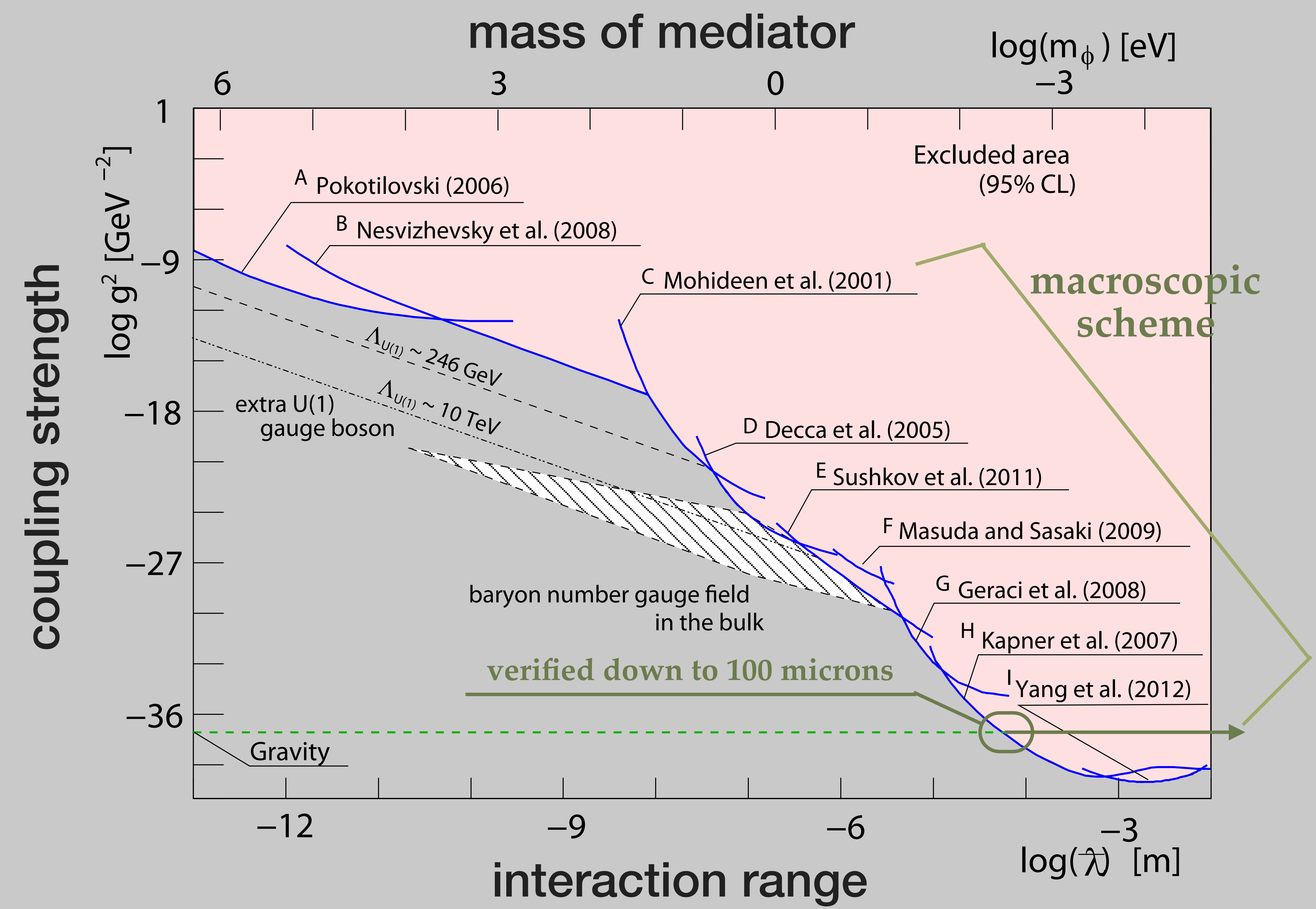

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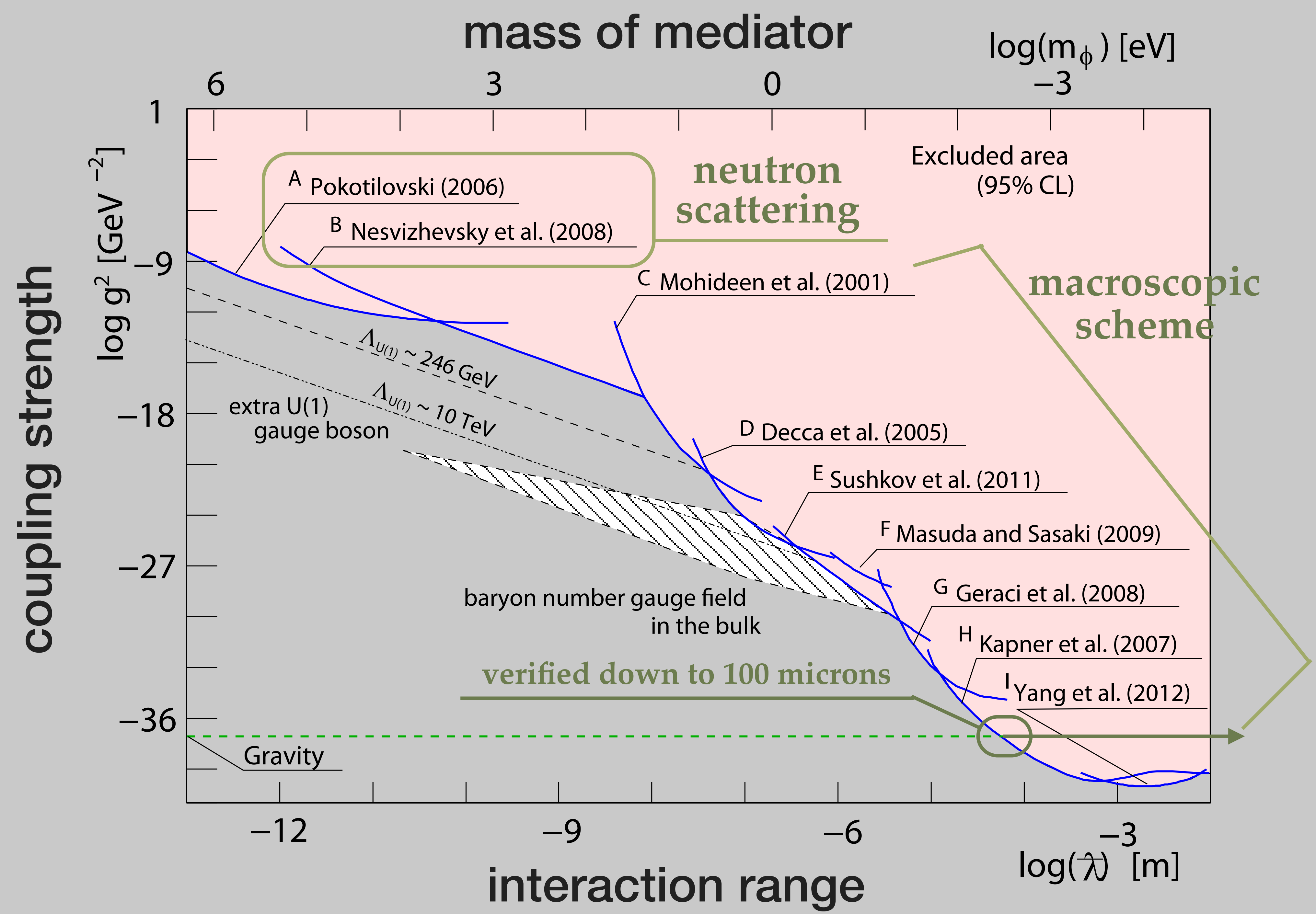

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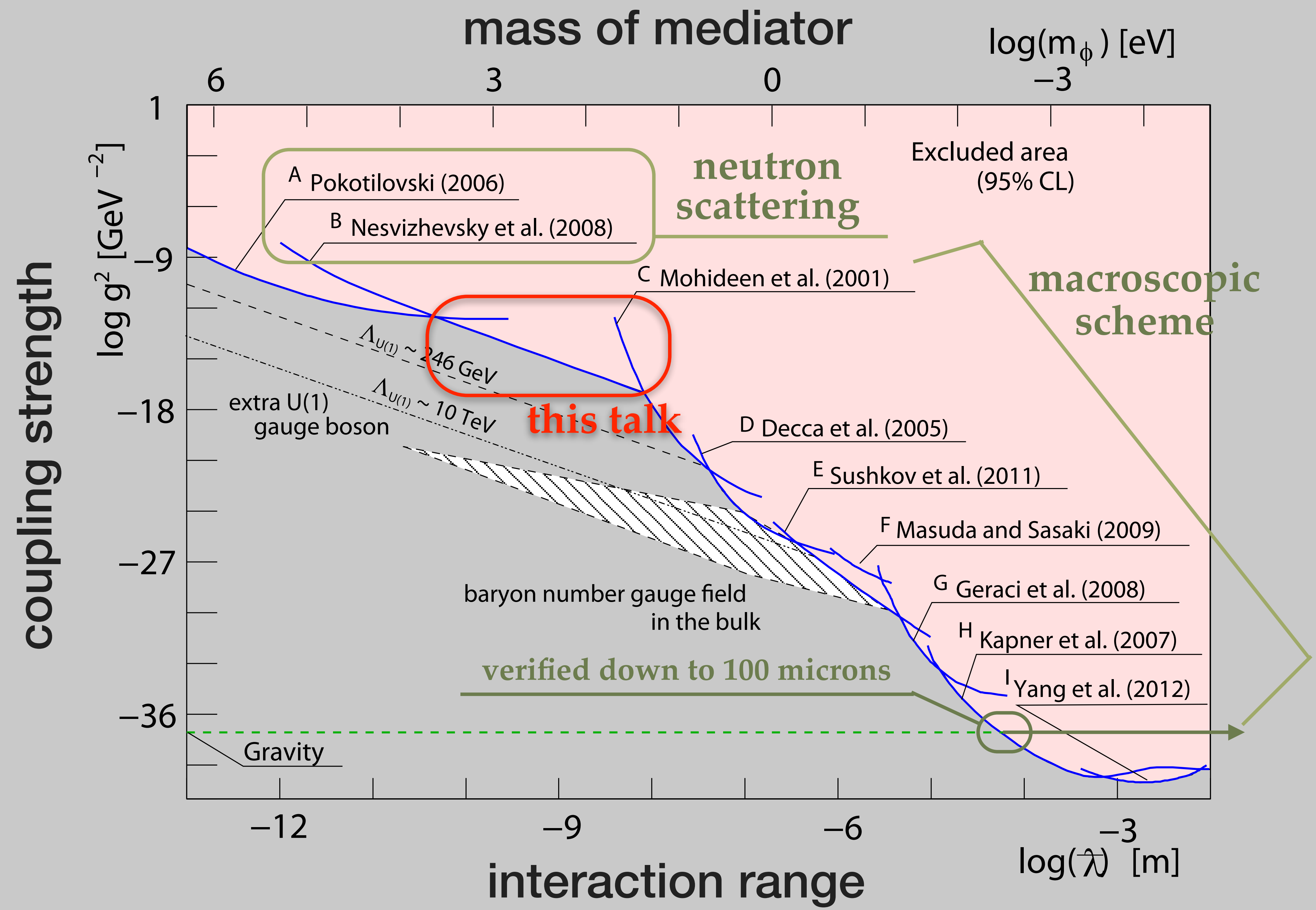
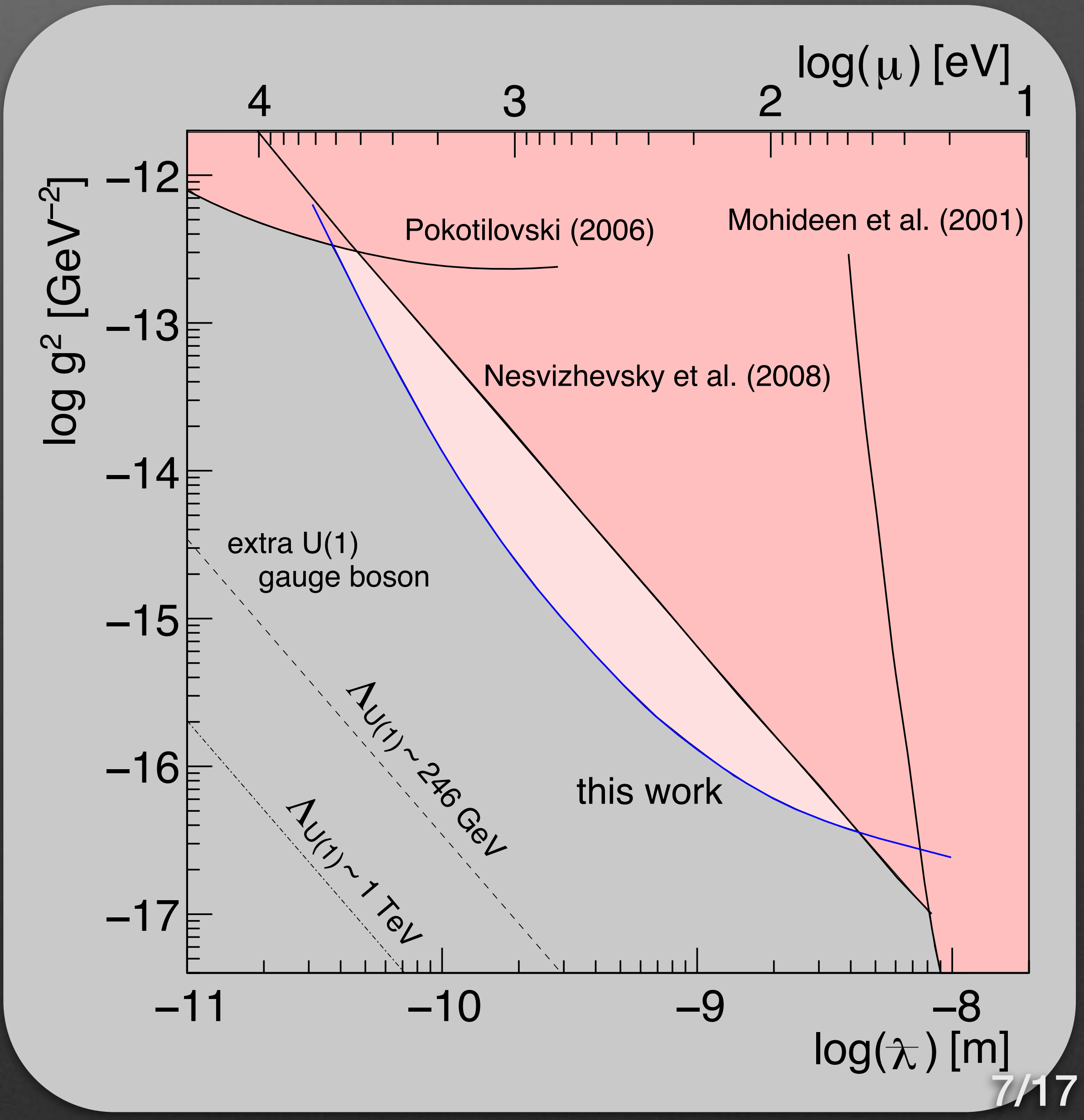


New Force Search using Neutron Scattering

1) measure the angular distribution of 5 A neutrons scattering off atomic xenon gas

2) evaluate deviations from the expectations from know interactions to set limits on additional, unknown interactions



New Force Search using Neutron Scattering

1) measure the angular distribution of 5 A neutrons scattering off atomic xenon gas

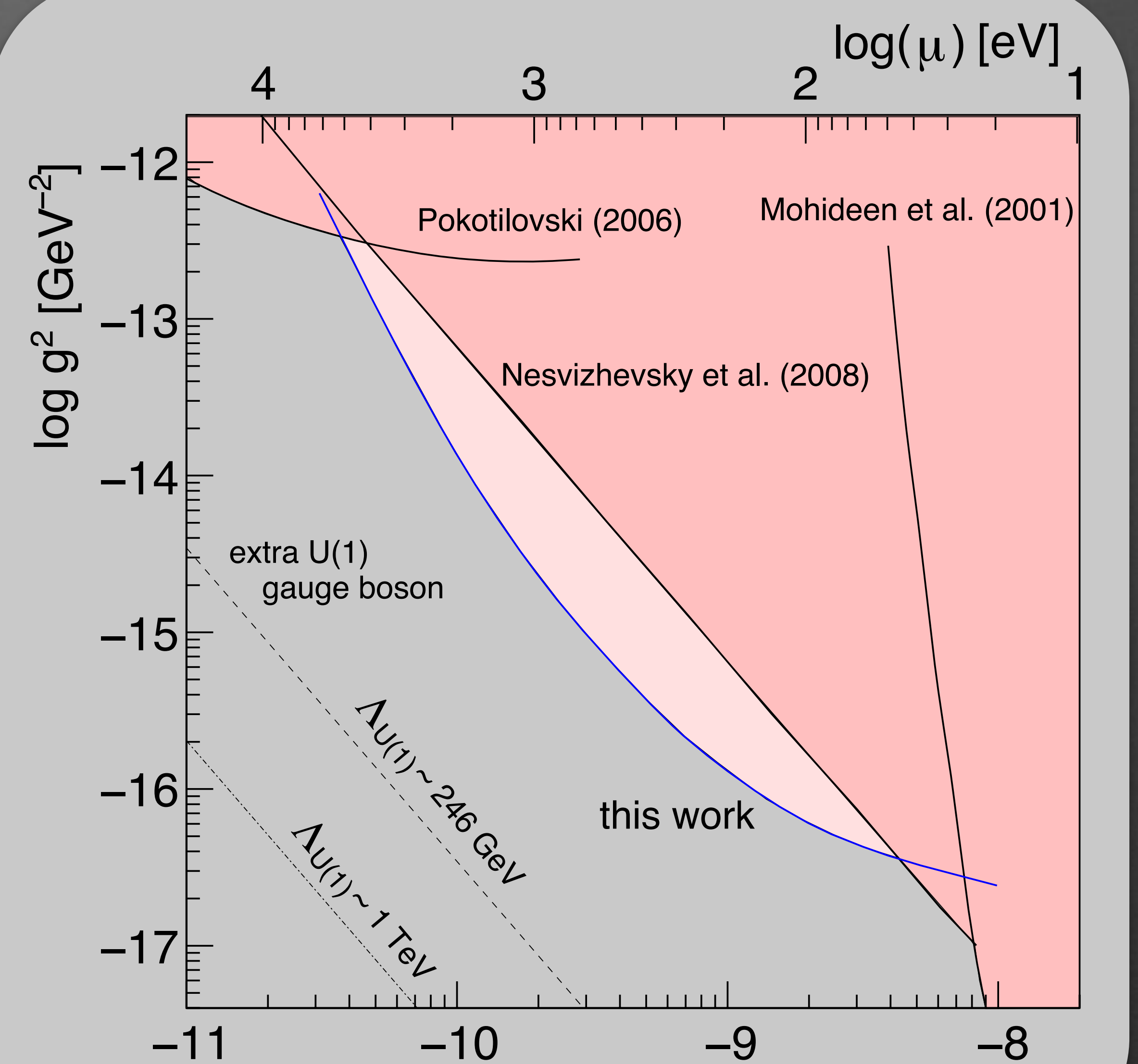
2) evaluate deviations from the expectations from know interactions to set limits on additional, unknown interactions

This experiment started with the presentation in PFUA12 workshop.

Thanks to useful discussions at that time, 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.

— Phys. Rev. Lett. 114, 161101 (2015)

This talk is mostly about this paper.



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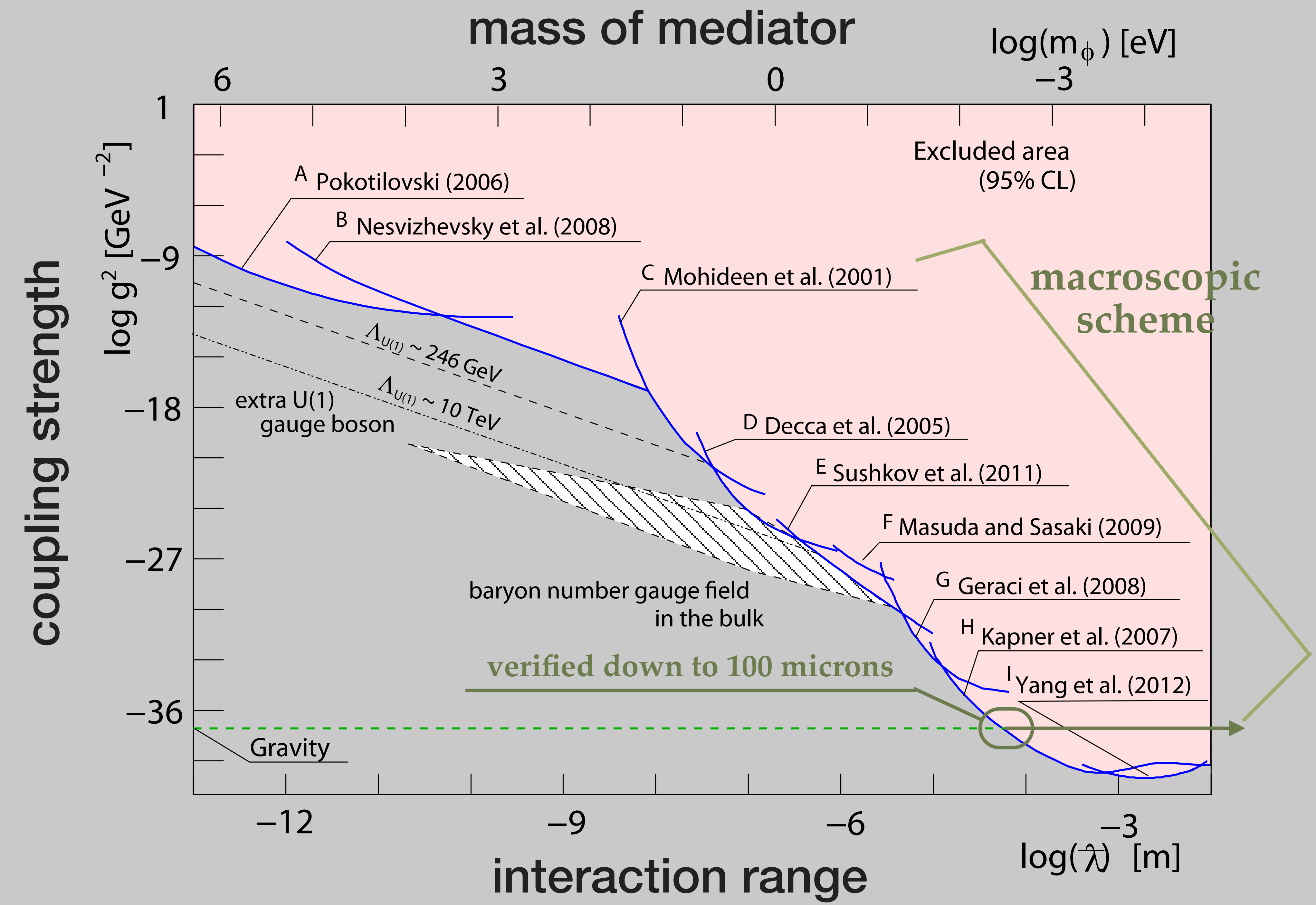

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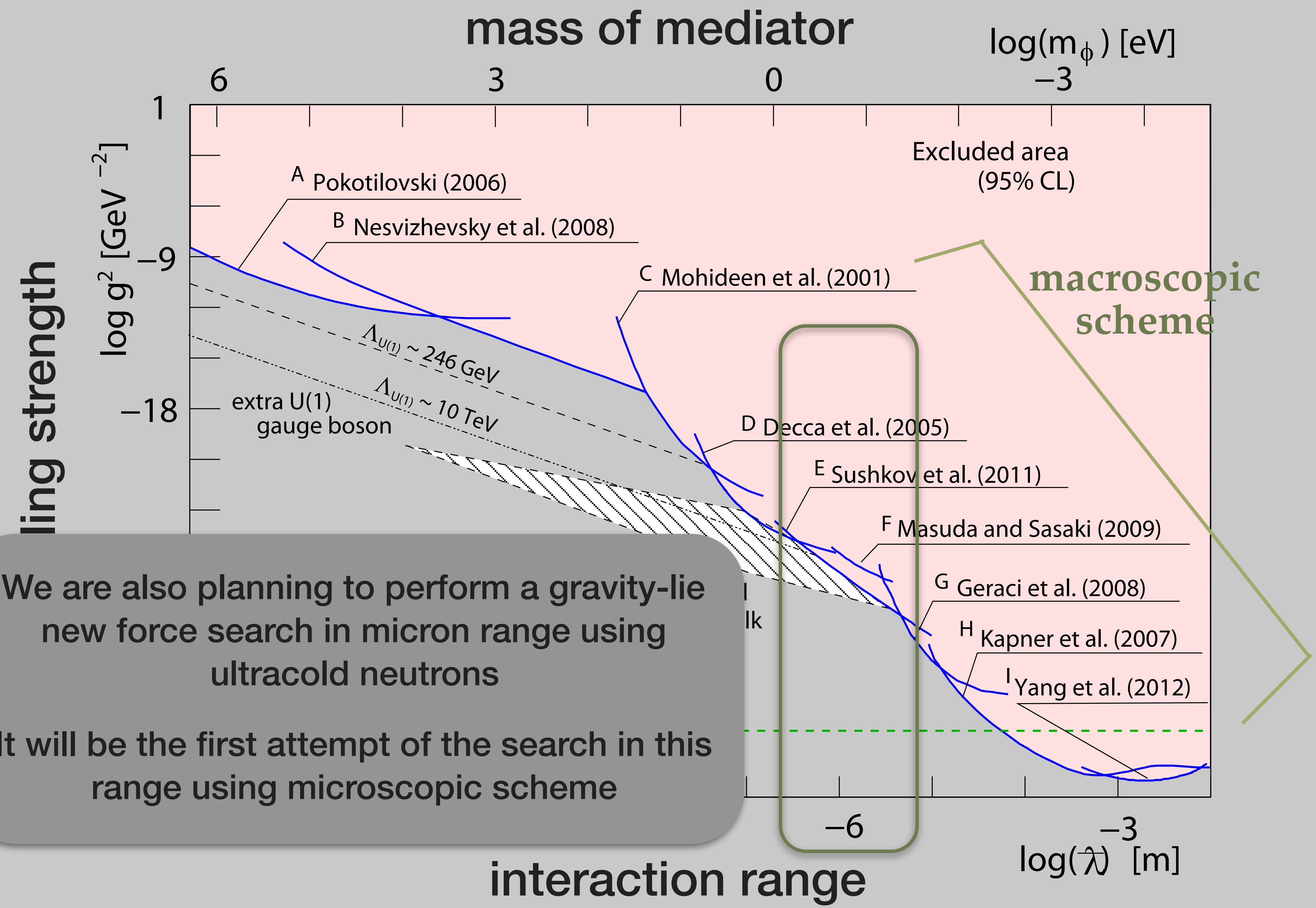


We are also planning to perform a gravity-lie new force search in micron range using ultracold neutrons

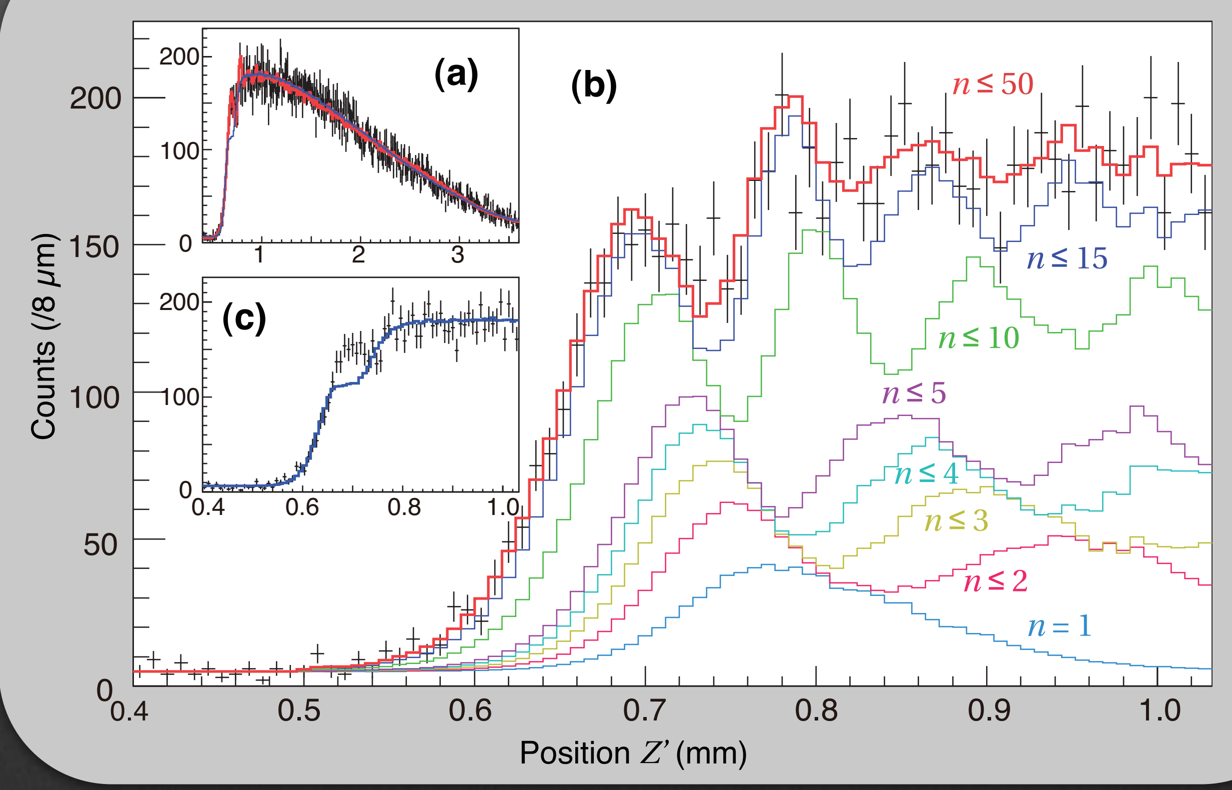
It will be the first attempt of the search in this range using microscopic scheme

Experiment using Ultracold Neutrons

Gravitationally bound quantum states of ultracold neutrons will be a nice probe of the new force search in micrometer range.

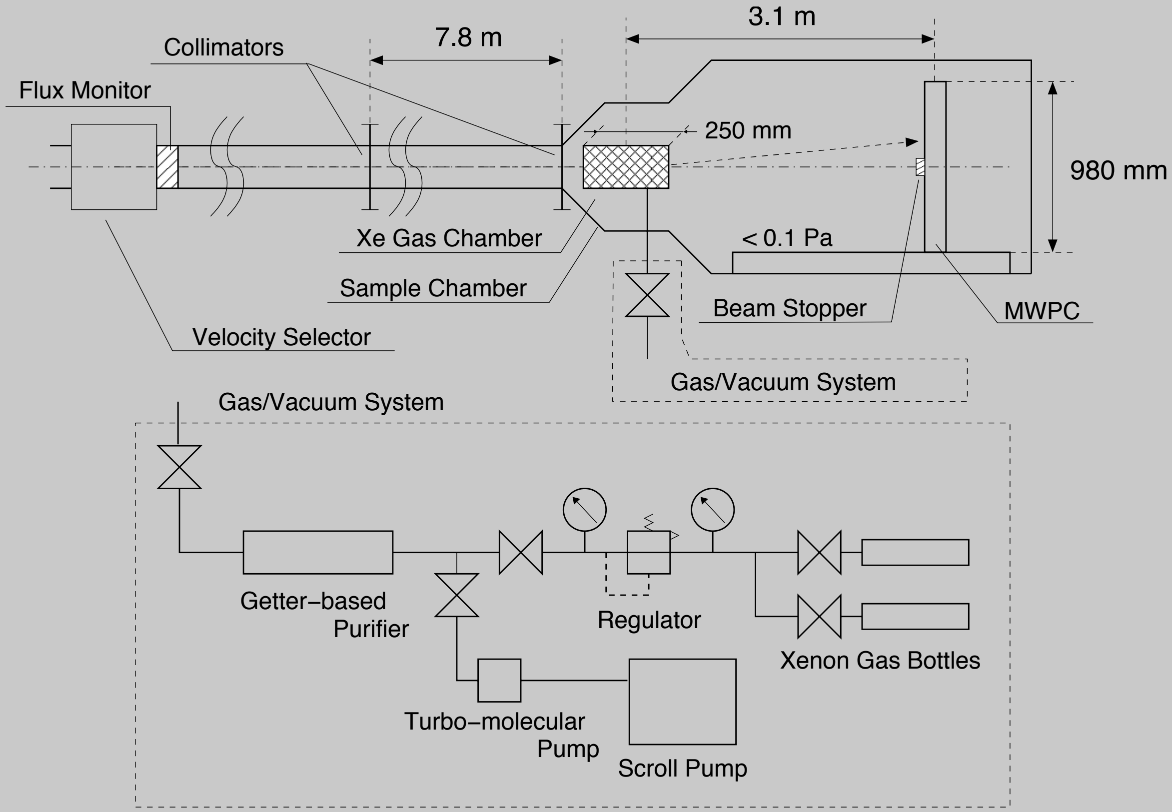
- Scale of the bound states is 5 microns
- We had validated the gravitationally bound states with in sub-micron resolution.

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

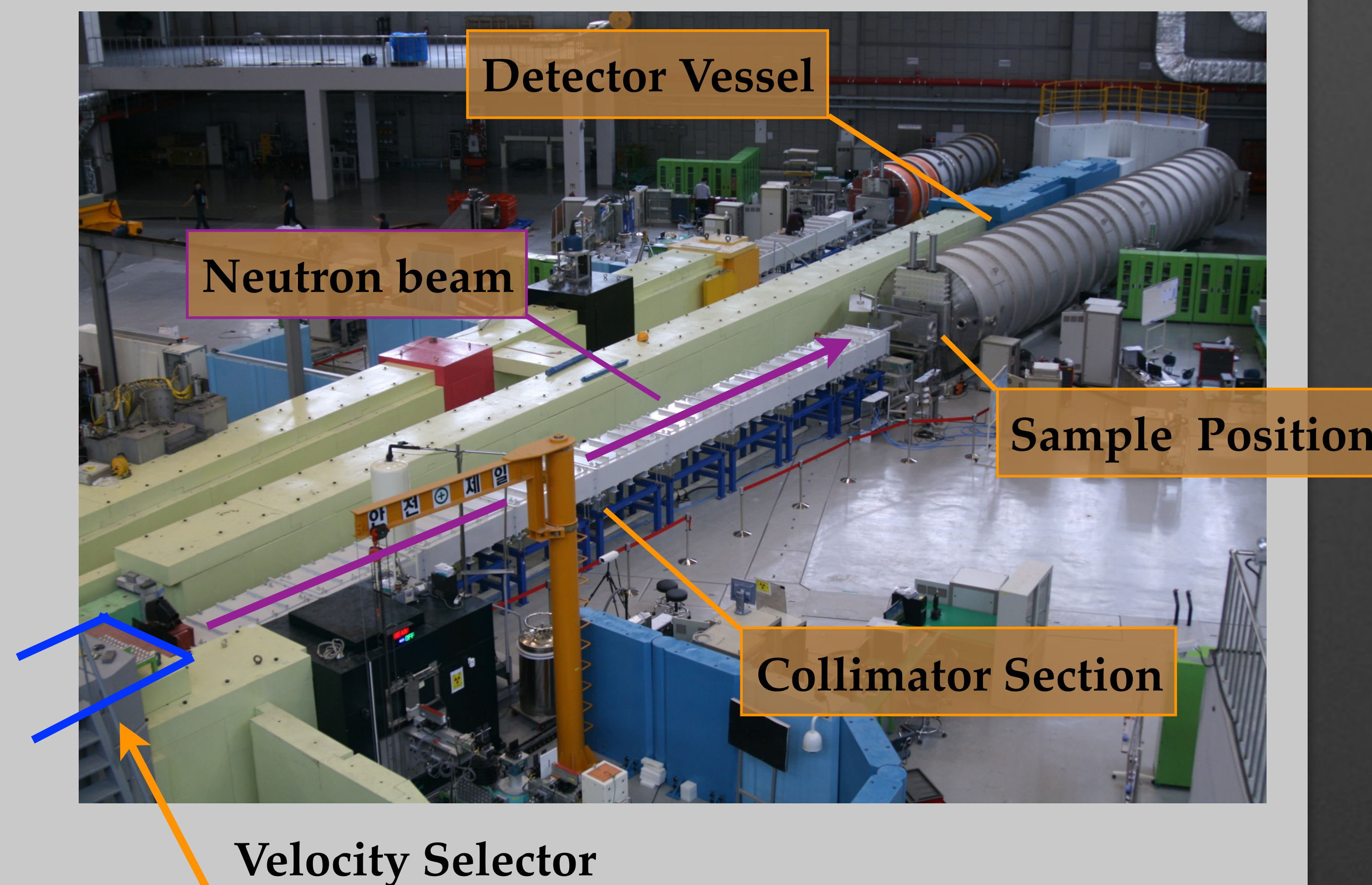


Experimental Site

40 m small angle neutron scattering beam line at HANARO, Korea



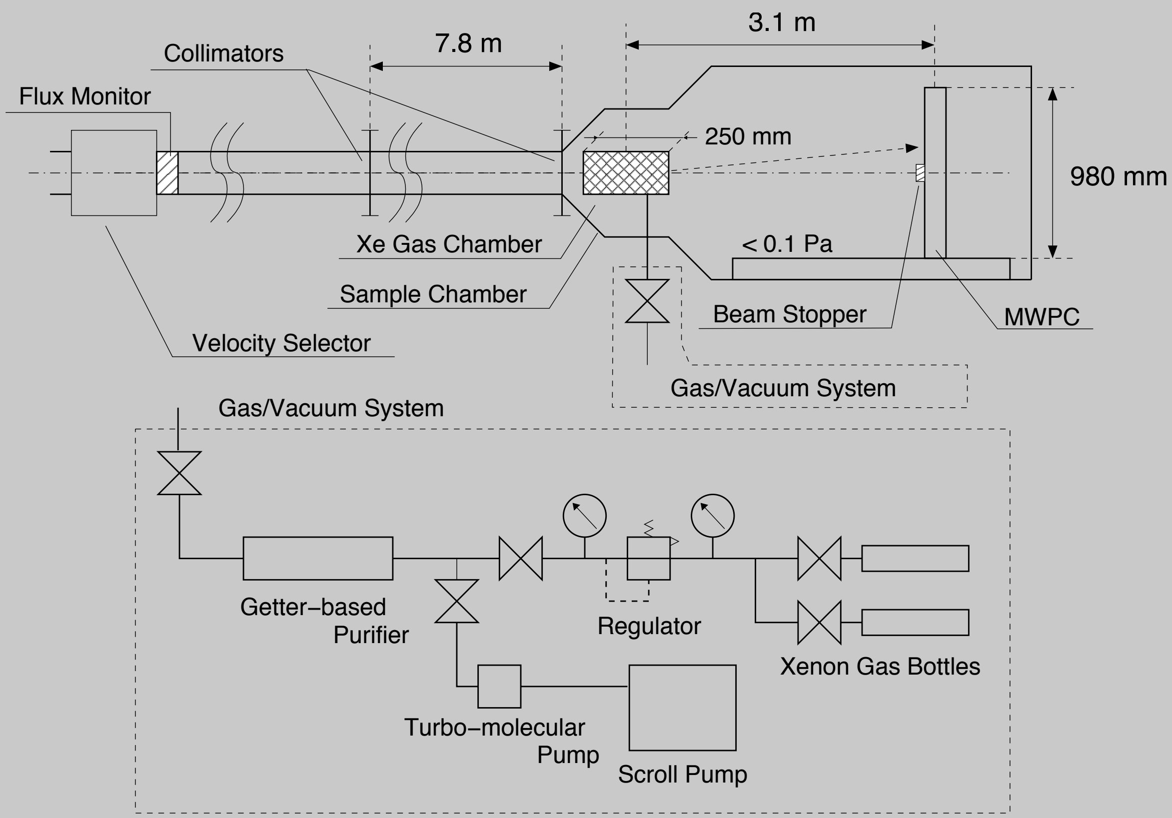
figs. from Young-Soo Han et.al, The 11th Japan-Korea Meeting on Neutron Science, I01 (2011)

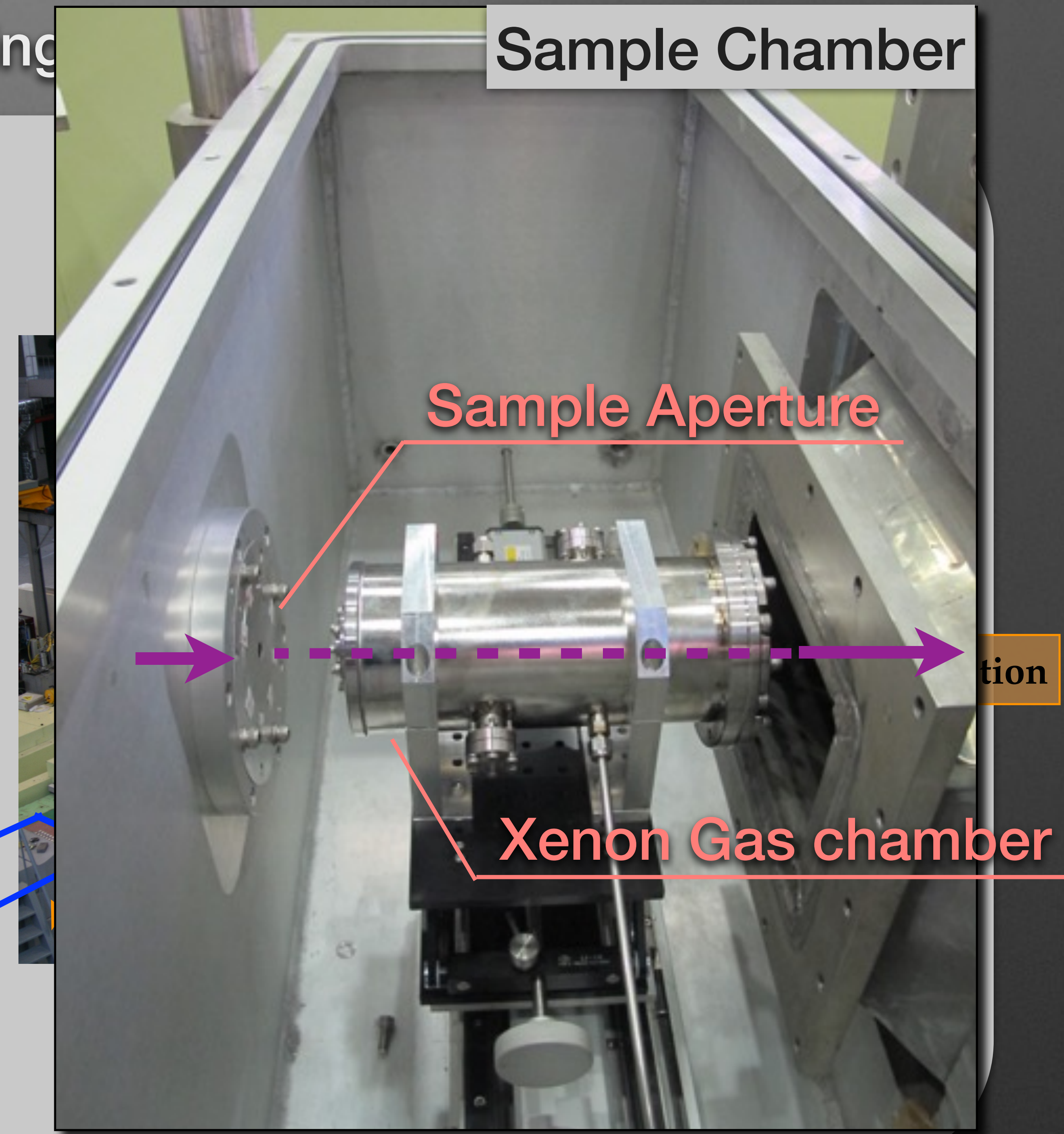


- Wavelength: 5 Å
- Beam size: 22 ϕ
- Divergence: ~ 3 mrad
- Intensity: ~ 1.4×10^5 neutrons/sec

Experimental Site

40 m small angle neutron scattering





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Scattering Length

Scattering Length is divided into
coherent/incoherent/Schwinger scatt. Length

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

+ coherent scattering length

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

+ incoherent scattering length

$$\boldsymbol{b}_i(\boldsymbol{q}) = \underbrace{b_{Ni}}_{\sim 0\ \mathrm{fm}}\boldsymbol{1} - \sqrt{I(I+1)}\,\underbrace{g b_F}_{\sim -1\mathrm{x}10^{-3}\ \mathrm{fm}}(\boldsymbol{1} - \hat{\boldsymbol{q}}\hat{\boldsymbol{q}})$$

+ Schwinger scattering length

$$b_s = \underbrace{b_F}_{\sim -1\mathrm{x}10^{-1}\ \mathrm{fm}} Z[1 - f(\boldsymbol{q})]\cot\theta$$

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

atomic form factor:

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

$q_0 \sim 7$ A^{-1}

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

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$$= (b_{Nc} + b_p)\ \{1 + \chi[1 - f(\boldsymbol{q})]\} \qquad \chi \equiv -\frac{b_F + b_I}{b_{Nc} + b_p} Z \sim 3\mathrm{x}10^{-2}$$

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+ coherent scattering length with the new forces

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

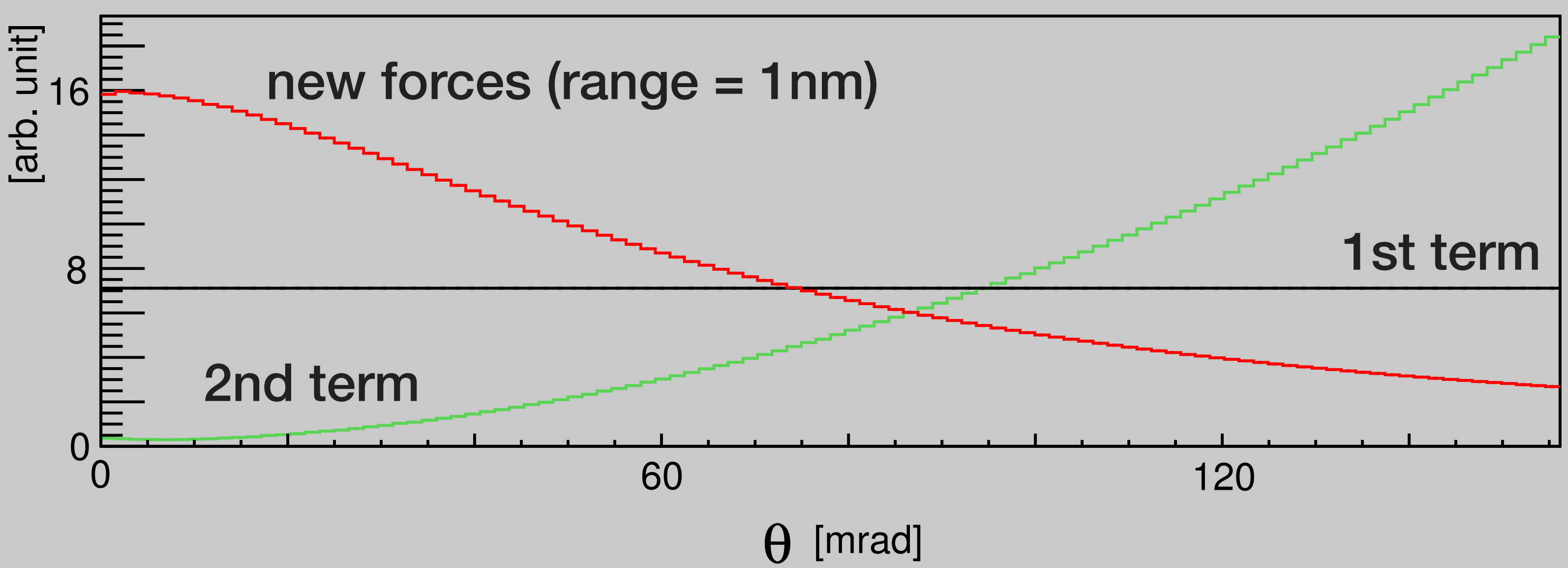
$$\chi_y \equiv \frac{m_n}{2\pi} g^2 m_1 m_2 \frac{1}{(b_{Nc} + b_p) m_\phi^2}$$

Differential Cross Section

$$\frac{d\sigma}{d\Omega} \simeq (b_{Nc} + b_p)^2 \; (1 + 2\chi[1 - f(\boldsymbol{q})] + 2\chi_y[(\frac{q}{\mu})^2 + 1]^{-1})$$

Expected angular scattering distribution to be measured was derived from this differential cross section convoluted with the finite beam size, the length of the scattering chamber, and the thermal motion of the xenon gas.

Simulated Distributions



distributions are clearly distinguished each other

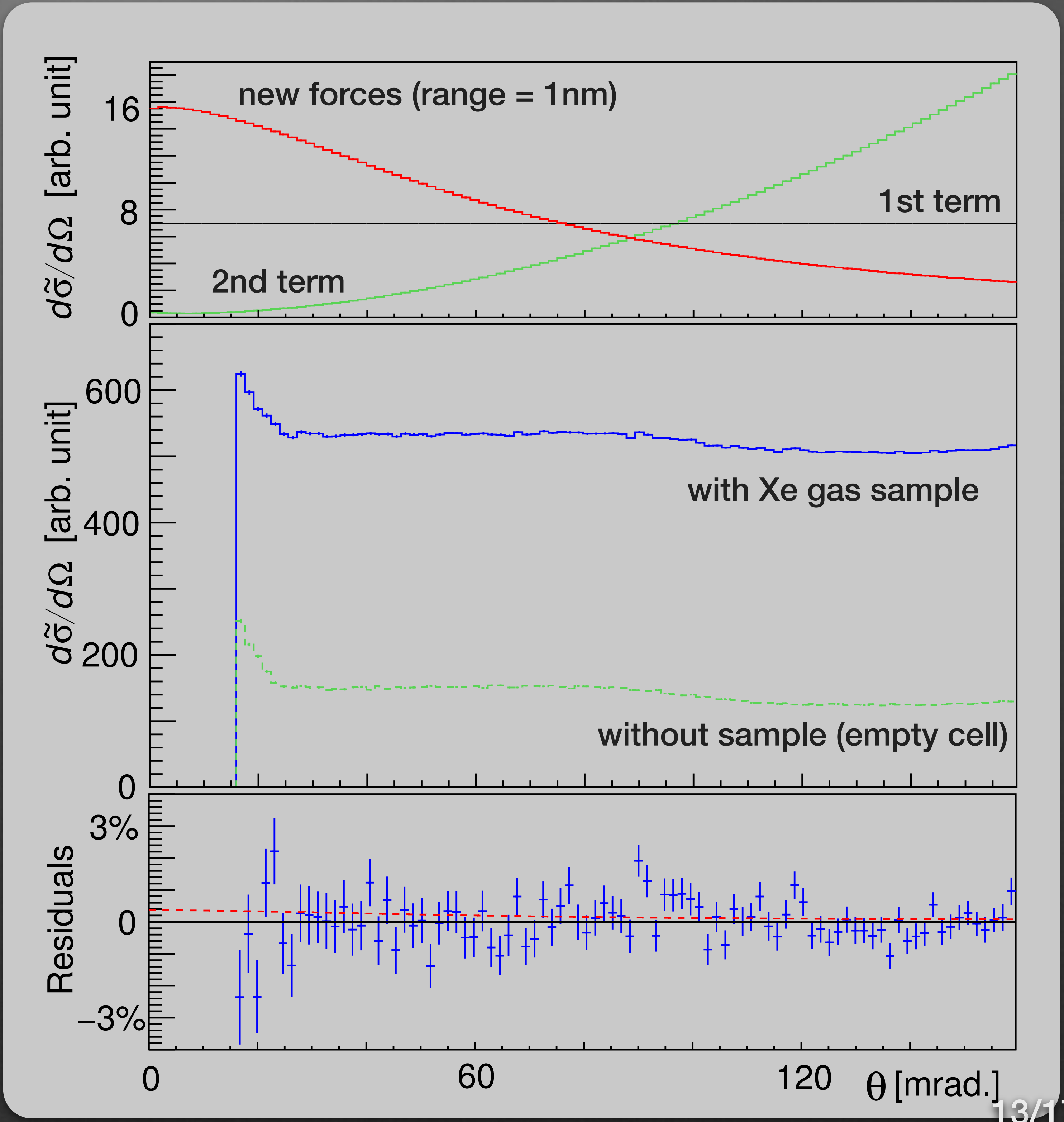
fitting using the shape is effective

Measured Distribution

Measured scattering distributions
w/ Xe gas sample
and w/o sample

The residual distribution from the known interactions is obtained.

No additional non-Newtonian forces are observed within this sensitivity.



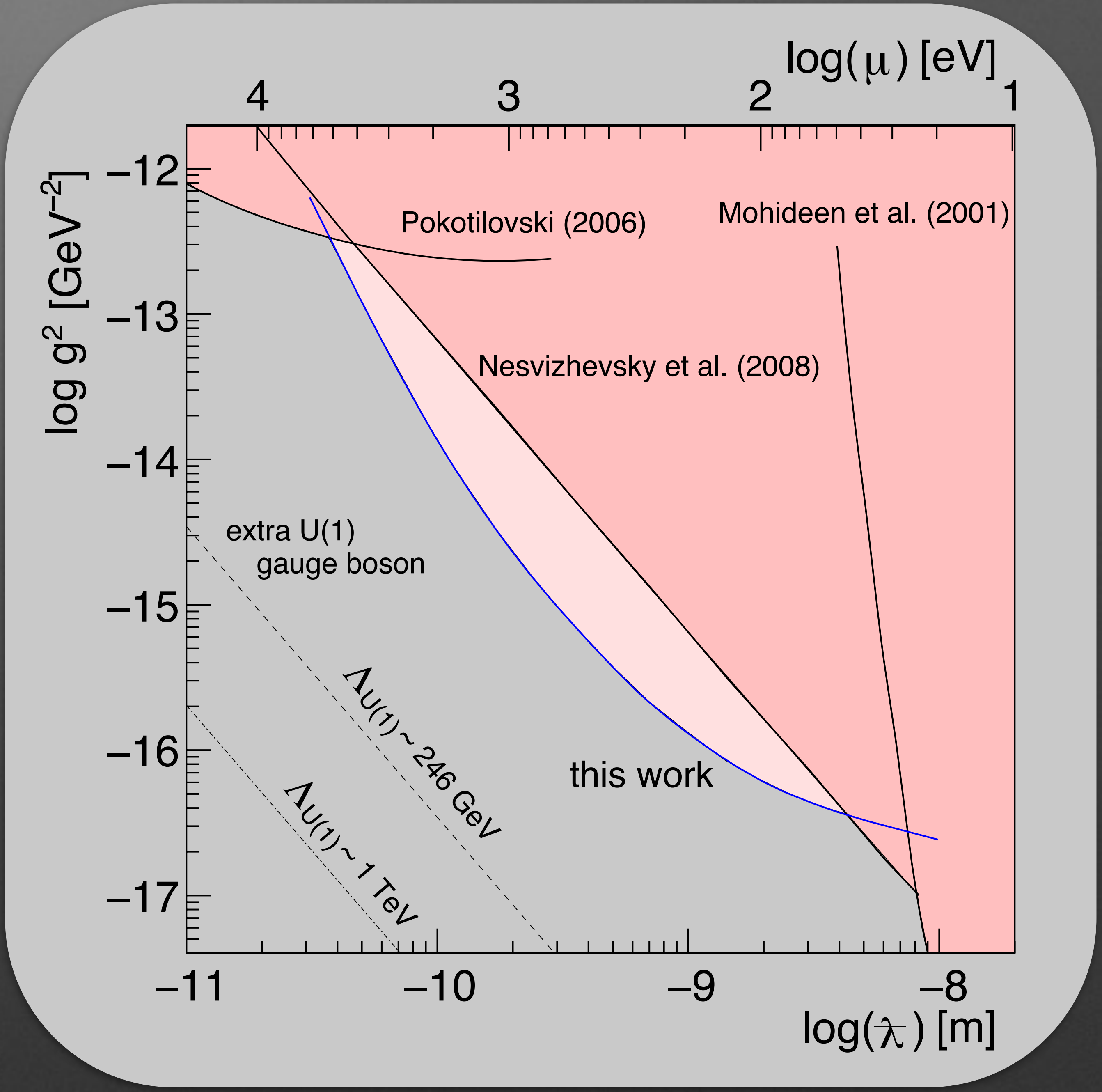
New Constraints

Limits of g^2 at 95% C.L. are evaluated using the Feldman Cousins approach

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

(Discussions)

- to longer range?
  - — possible with neutron lenses
    21pDF-10 Sasayama (JPS2015 spring)
- for other type of new foces?
  - — Next slide



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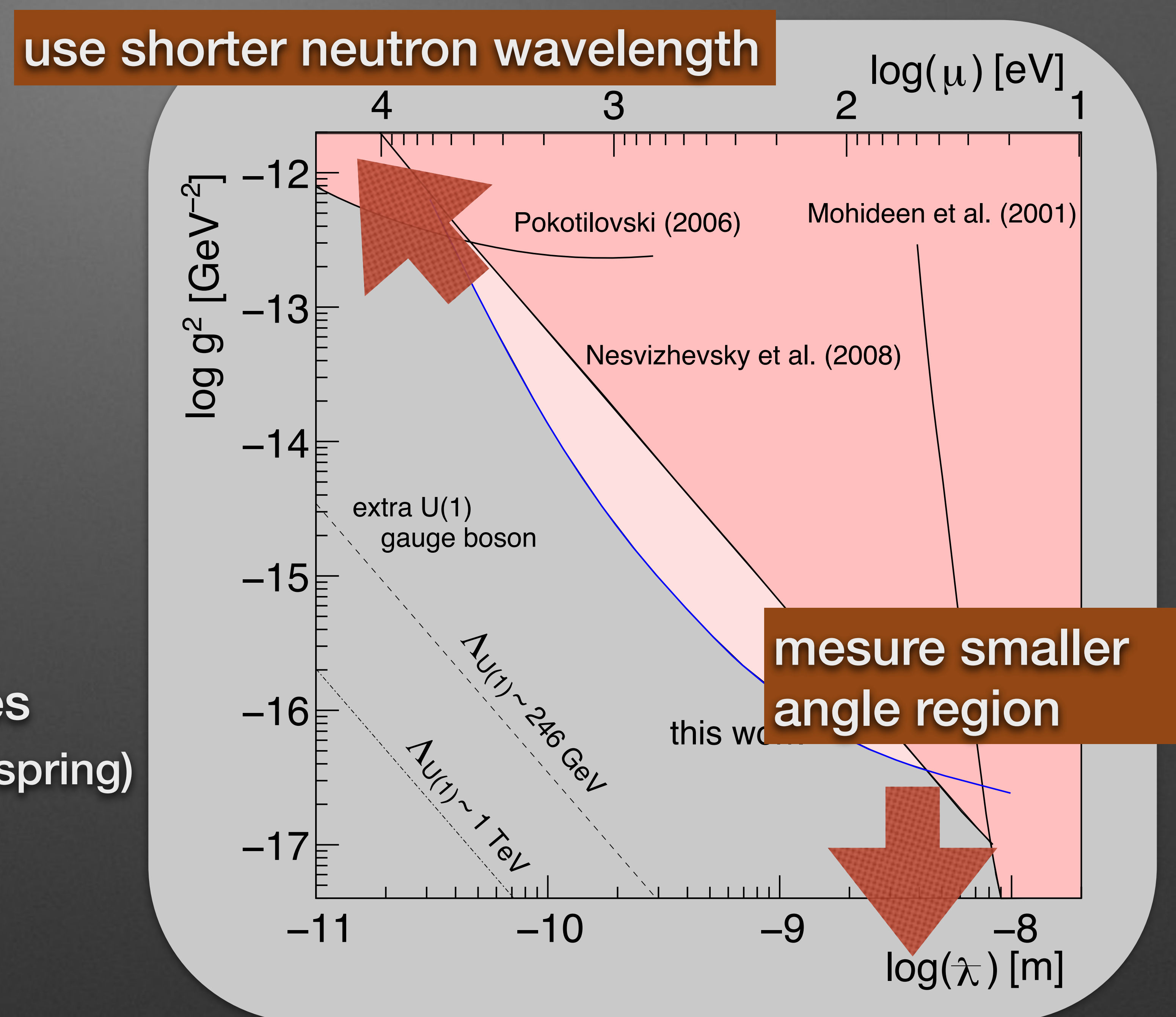

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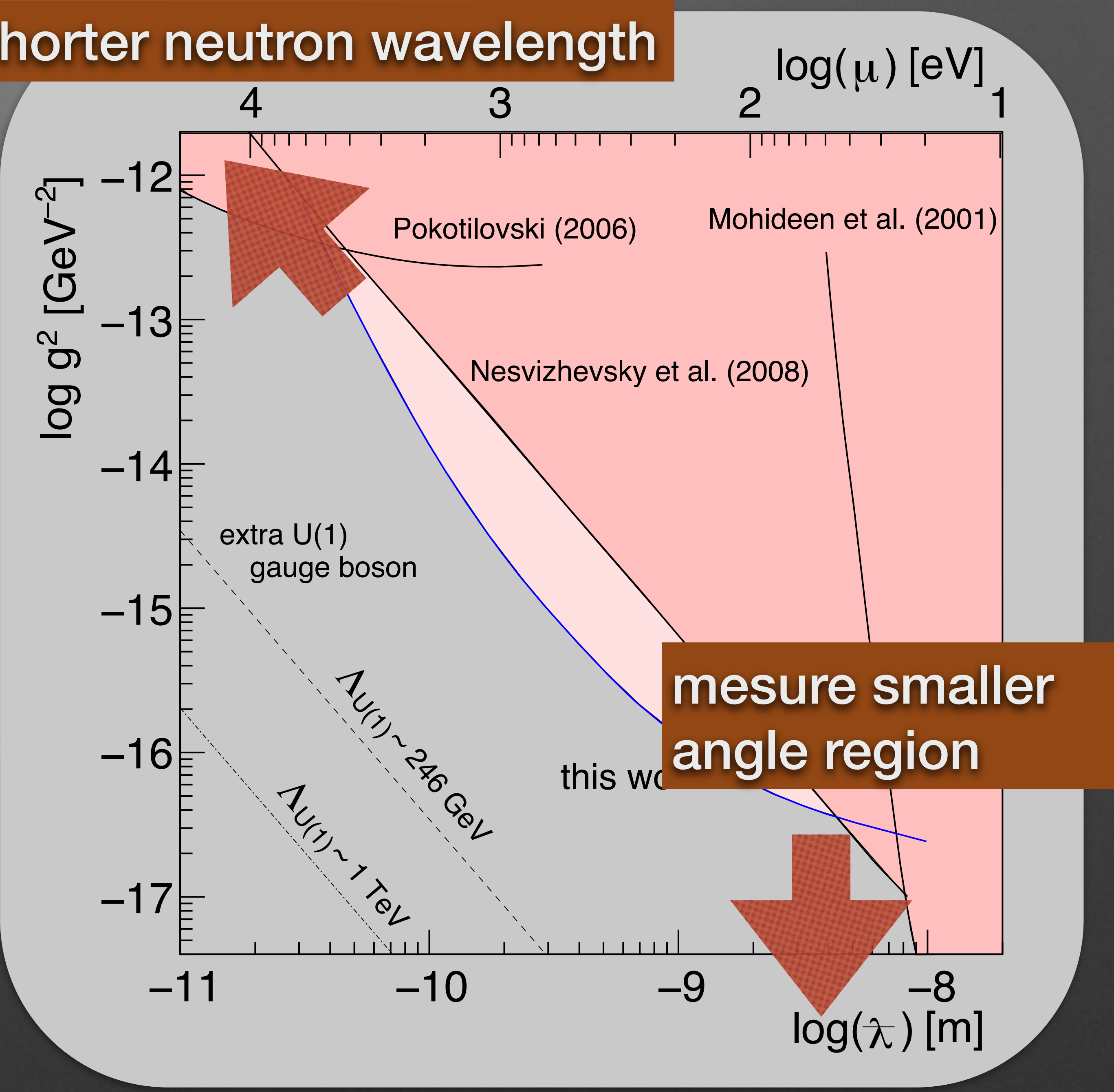
    — just introduction



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Chameleon Fields

think new interactions mediated by a scalar, here after

Lagrangian as a starting point of following discussions

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

- $m_\phi^2 = 0 \quad \eta_i = \eta$ (universal) —> Nonlinearity will be of particular note

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

depends on fermion surround

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

Chameleon Fields

(example) $n = -4$, $\xi \sim 1$, $\eta \sim 1$

In the Universe

$\rho = 10^{-24}$ g/cm^3 $\quad 1/m_{vac} \sim 100$ km

In usual material

$\rho = 1$ g/cm^3 $\quad 1/m_{vac} \sim 0.1$ mm

Interaction charge can not be accumulated (Thin-shell Effect)
range is order of 100 km in the Universe

$\longrightarrow$ hard to see the effect by cosmological observations

$\longrightarrow$ experiments at shorter ranges are effective

The Chameleon partially contribute to solve
the cosmological constant problem!

Summary

・ Searches for new gravity-like short-range forces have been performed at many institutes.

・ We made new limits for the Yukawa-type gravity-like forces in the 4 to 0.04 nm range by a factor of up to 10.

Y. Kamiya, K. Itagaki, M. Tani, G. N. Kim, and S. Komamiya, Phys. Rev. Lett. 144, 161101 (2015)

・ There are plenty parameter space remained to new physics.

・ The field is still active and exciting. Possibility of the connection to the cosmological constant or dark energy have been discussed.

Thank you for your attention.

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

— William M. Snow (Indiana Univ.)