The 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08), Mito, 5-7 Mar 2008

Search for Medium Range Force by a Precision Measurement of Neutron Scattering Cross Section

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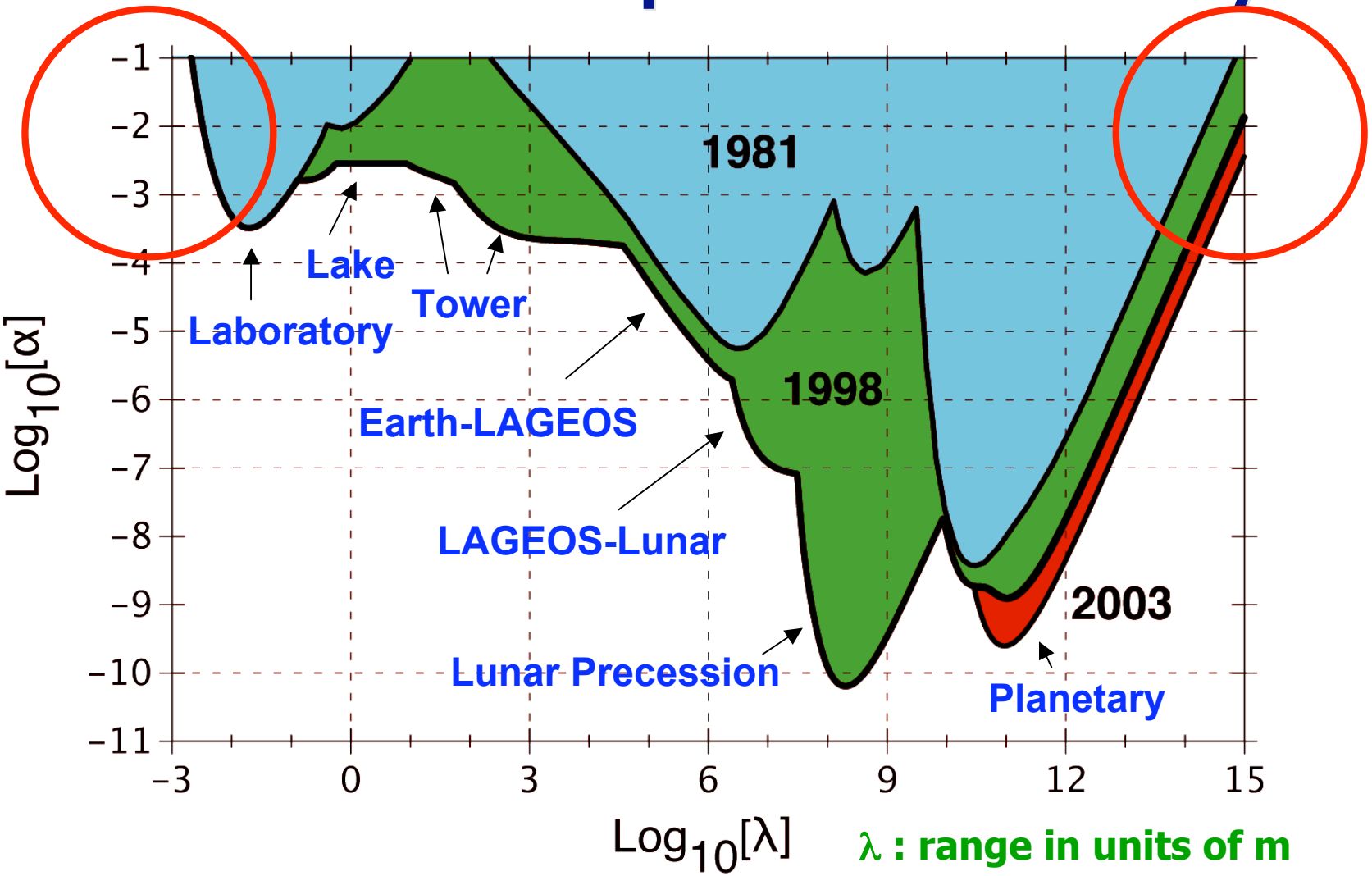
- Introduction
- Why neutron?
- Small angle scattering with gas target
- Simulations
- Summary

Test of Inverse-Square Law of Gravity



λ : range in units of m

Reference: Coy, Fischbach, Hellings, Standish, & Talmadge (2003)

Potential

Newtonian

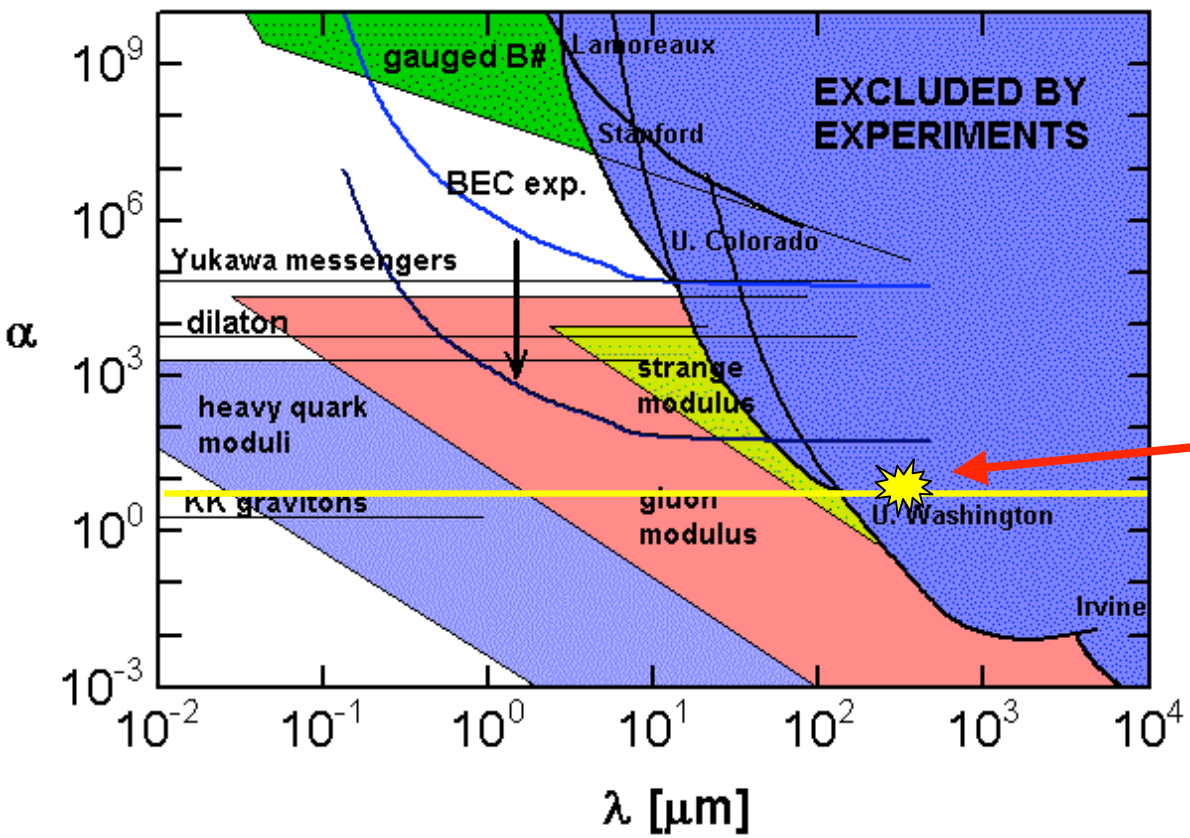
exotic interaction (Yukawa-type)

$$V_G(r) = V_g(r) \cdot (1 + \alpha \exp(-r/\lambda)) \qquad \left(V_g(r) = -G\frac{M \cdot m}{r} \right)$$

Theoretical models:

- Large Extra Dimension (**A**lkani-Hamed, **D**imopoulos, **D**vali)
- Radion-mediated force
- Moduli coupling (exchange of string-theory scalars)
- Axion exchange
- Multi-particle exchange (axions, ν-ν, etc.)
- Vacuum-energy scenarios ("fat graviton" model)

Constraint on Non-Newtonian Gravity in Sub-millimeter Range



$$V_G = V_g(1 + \alpha \exp(-l/\lambda))$$

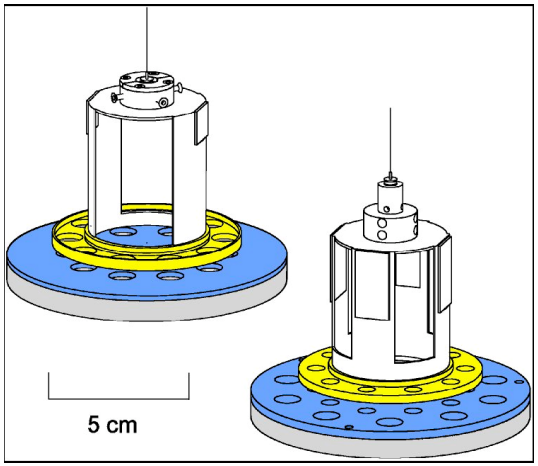
$$\left(V_g = -G\frac{M \cdot m}{l}\right)$$

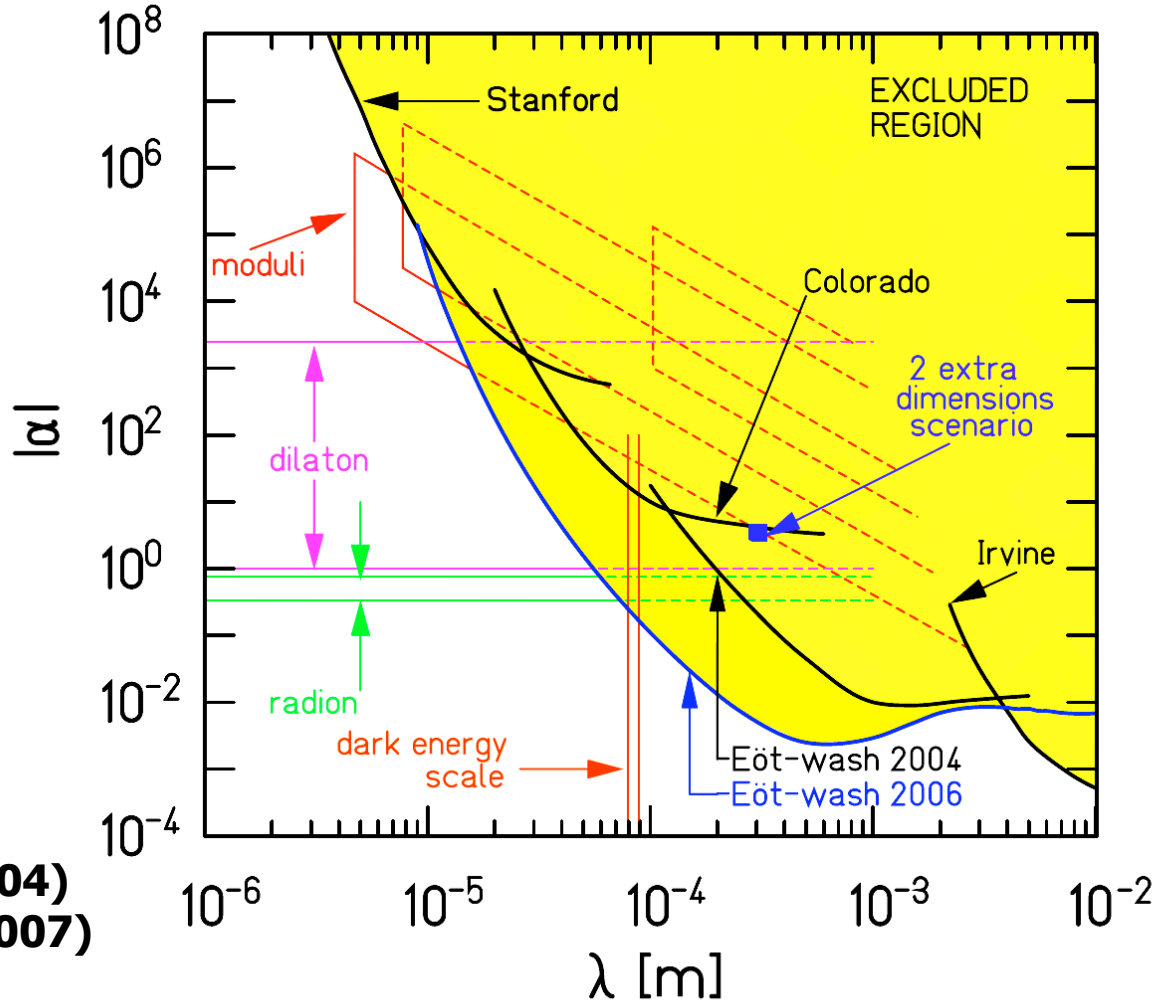
ADD (n=2, M_N=1TeV)

$$n = 3 \Rightarrow \lambda \approx 1.5\,[\mu\mathrm{m}]$$

$$n = 4 \Rightarrow \lambda \approx 3.2\,[\mathrm{pm}]$$

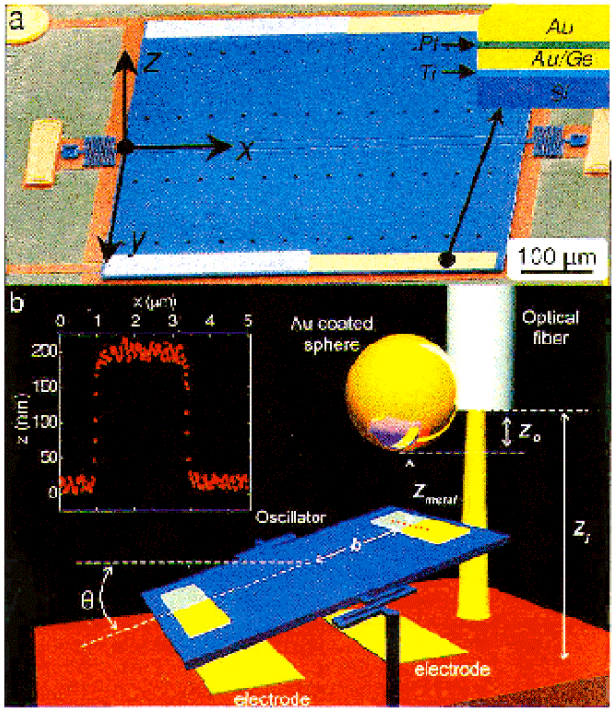
Torsion-balance experiments

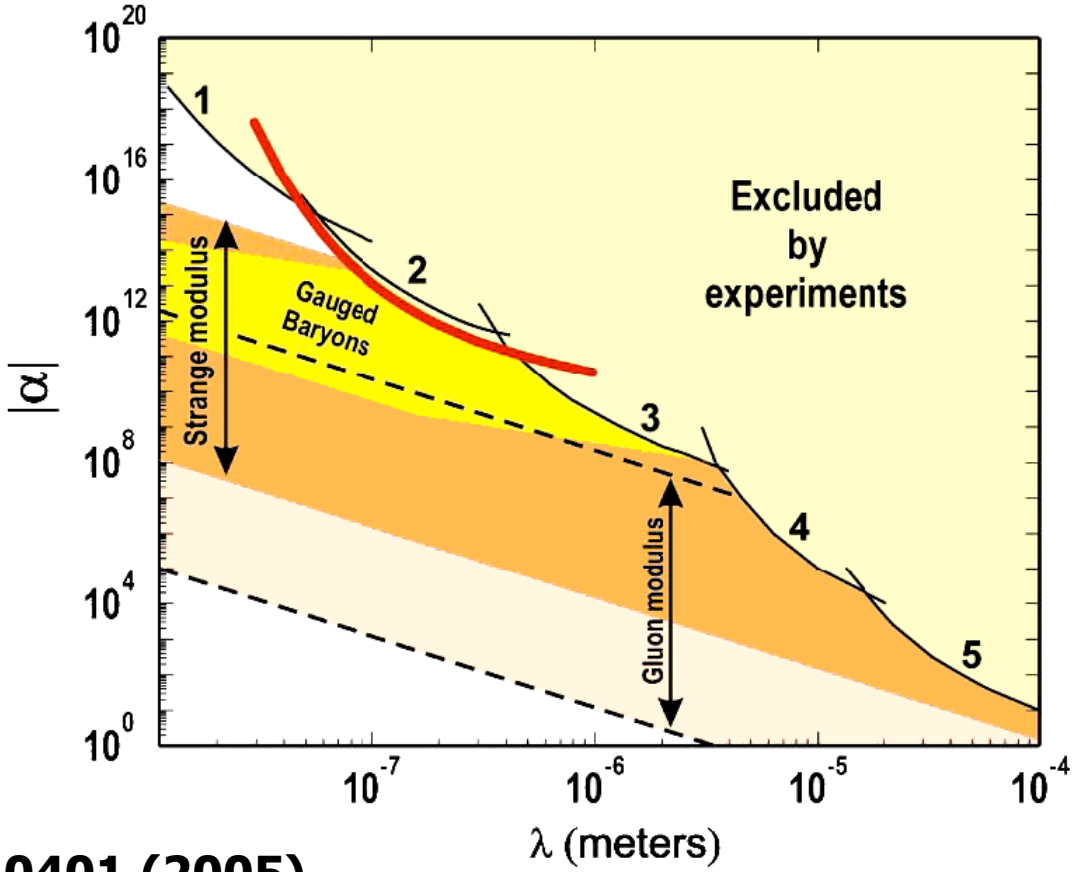




Hoyle et al. PRD70, 042004 (2004)
Kapner et al. PRL98, 021101 (2007)

Atomic Force Microscopy





R.S. Decca et al. PRL94, 240401 (2005)

Background

Van der Waals force is dominant at l < ~10μm ;
(Casimir-Polder)

$$U_C = -\frac{3\hbar c}{8\pi}\frac{\alpha_0}{l^4}$$

Electric polarizability of atoms; α_0 ~ 10^{-24} cm^3

Neutron ; α_n ~ 10^{-42} cm^3

Search for New Intermediate-range Force via Neutron Scattering

Greene & Gudkov
Zimmer & Kaiser
Frank, Isacker & Gómez-Camacho

$$\frac{d\sigma(\theta)}{d\Omega} = \left[a_N + a_{ne} Z F_e(\theta) + a_G F_G(\theta)\right]^2$$

$$\cong a_N^{\ 2} + 2 a_N a_{ne} Z F_e(\theta) + a_{ne}^{\ 2} Z^2 F_e(\theta)^2 + 2 a_N a_G F_G(\theta)$$

$a_G \propto \alpha$

a_N	;	nuclear scattering amplitude
a_{ne}	;	neutron-electron scattering amplitude
a_G	;	gravitational scattering length
Z	;	atomic number of target
$F_e(\theta)$	;	form factor for atomic electron
$F_G(\theta)$	;	gravitational form factor

Cross Section

$$\frac{d\sigma_G(\theta)}{d\Omega} = \alpha^2 \left(\frac{G \cdot m_n \cdot M}{4} \right)^2 \cdot \left(\frac{1}{\frac{1}{m_n c^2} \left(\frac{\hbar c}{\lambda} \right)^2 + 8E_n \sin^2 \frac{\theta}{2}} \right)^2$$

G : coupling constant of Newtonian gravity

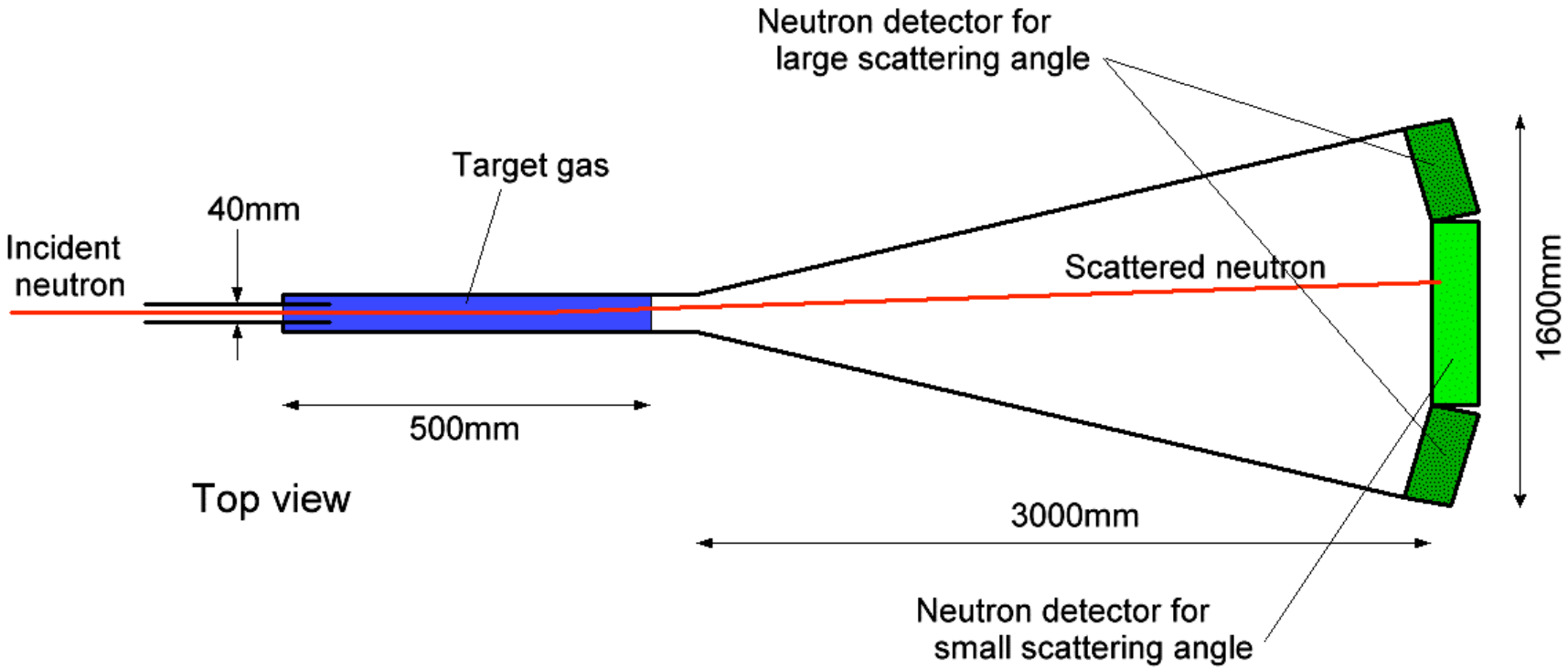
α : coupling constant of LED gravity

λ : range of non-Newtonian gravity

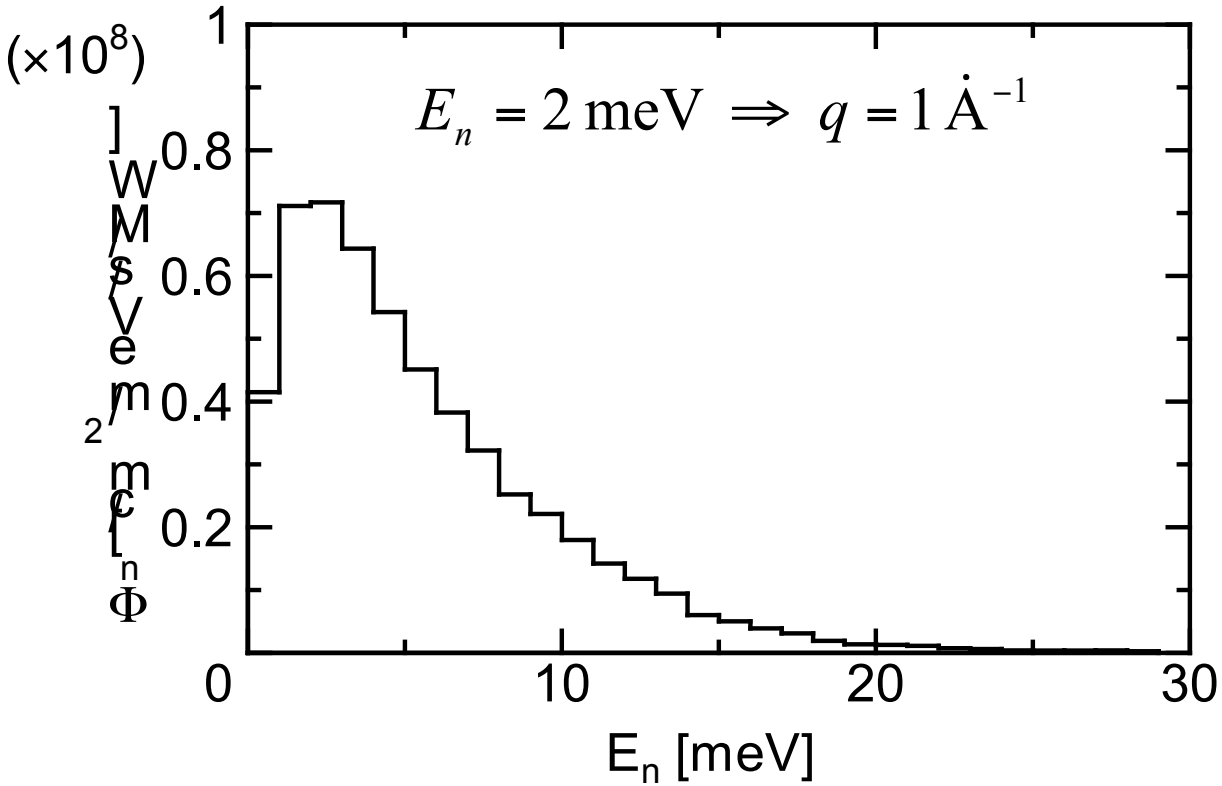
M : target mass

m_n : neutron rest mass

Experimental Setup

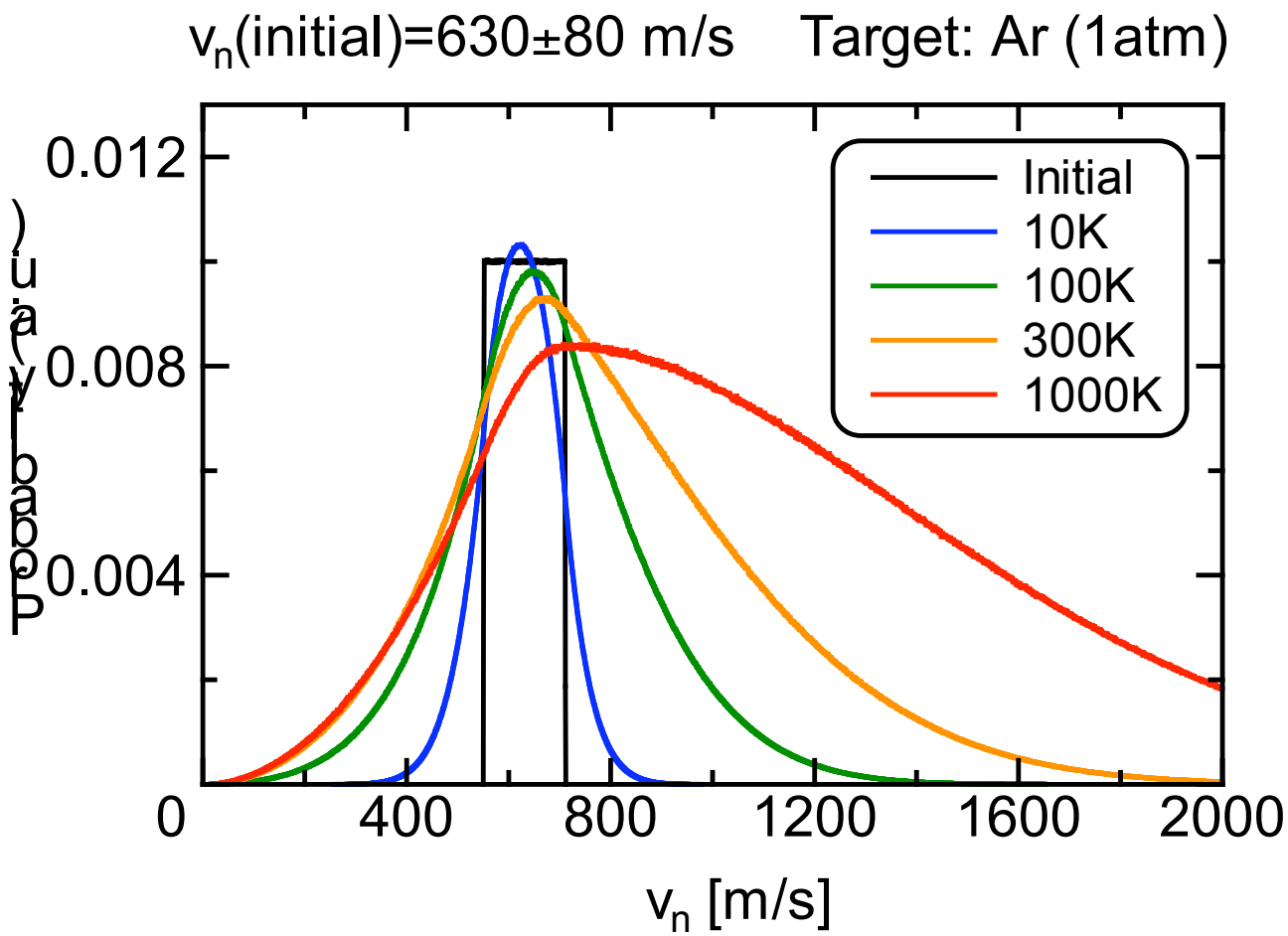


Neutron Energy Spectrum at J-PARC/JSNS/BL05/High-intensity branch



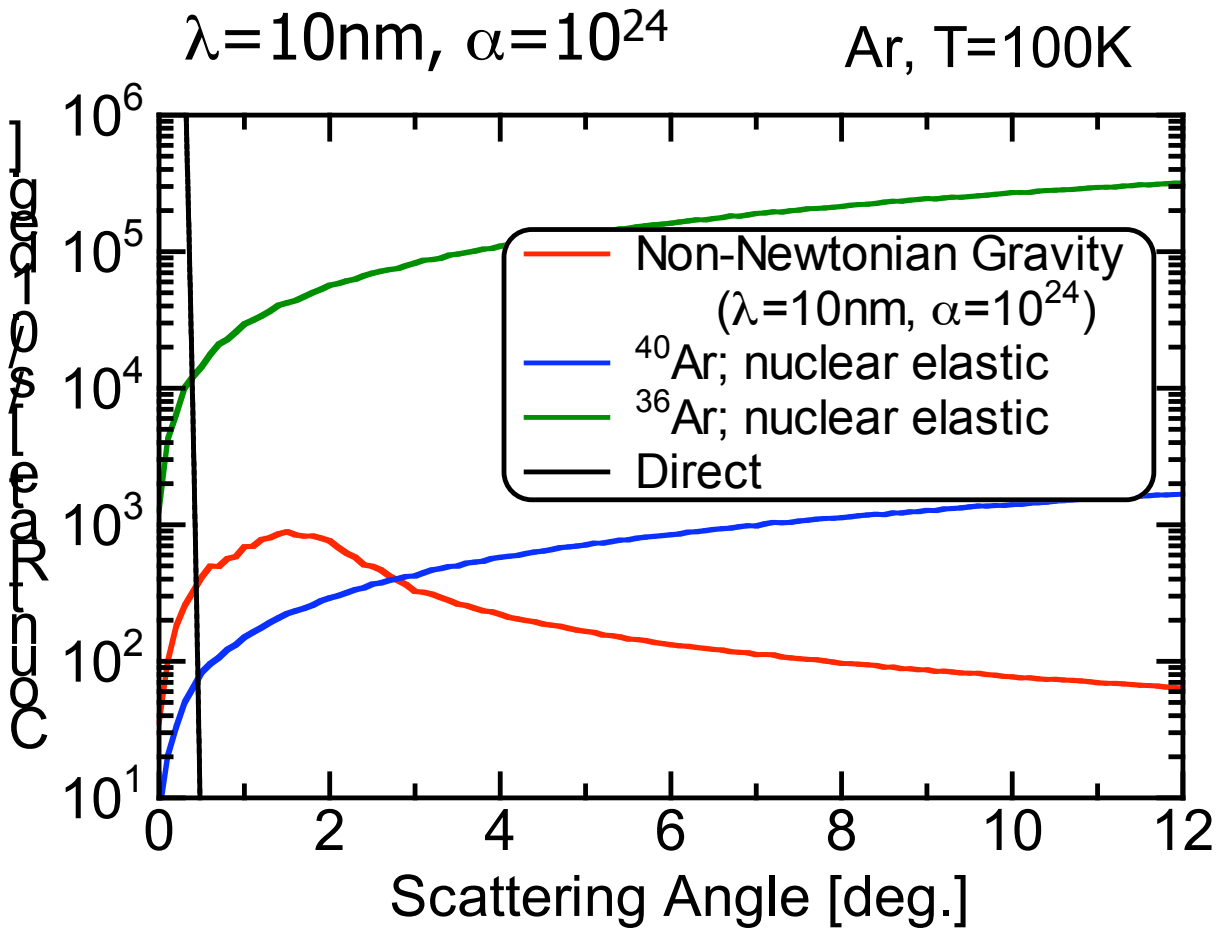
Forward scattering ($\Delta q \sim 0.01 \mathrm{Å}^{-1}$) $\Rightarrow \lambda \sim 10\mathrm{nm}$

Monte Carlo Simulation;
Velocity Distribution of Scattered Neutrons



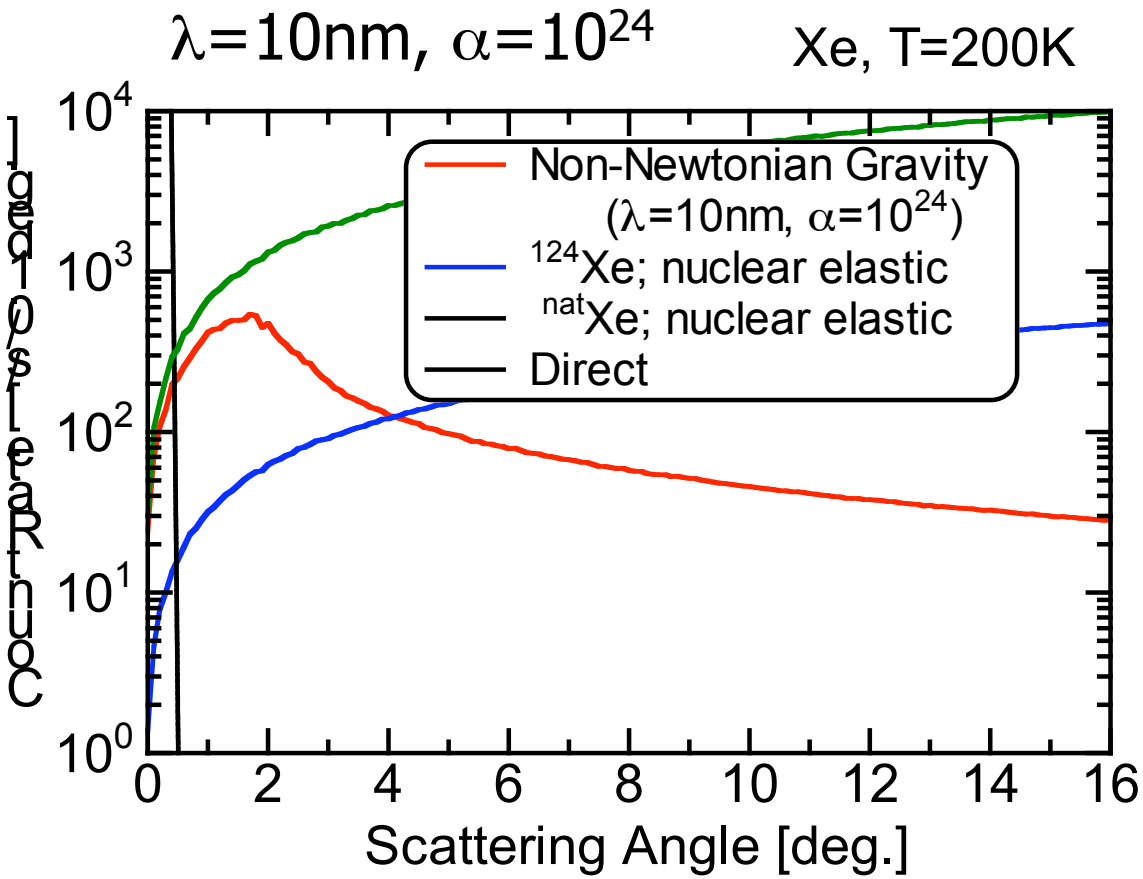
Counting rate; Ar

$\sigma_N(^{36}Ar)=77.90$ b
$\sigma_N(^{40}Ar)=0.421$ b

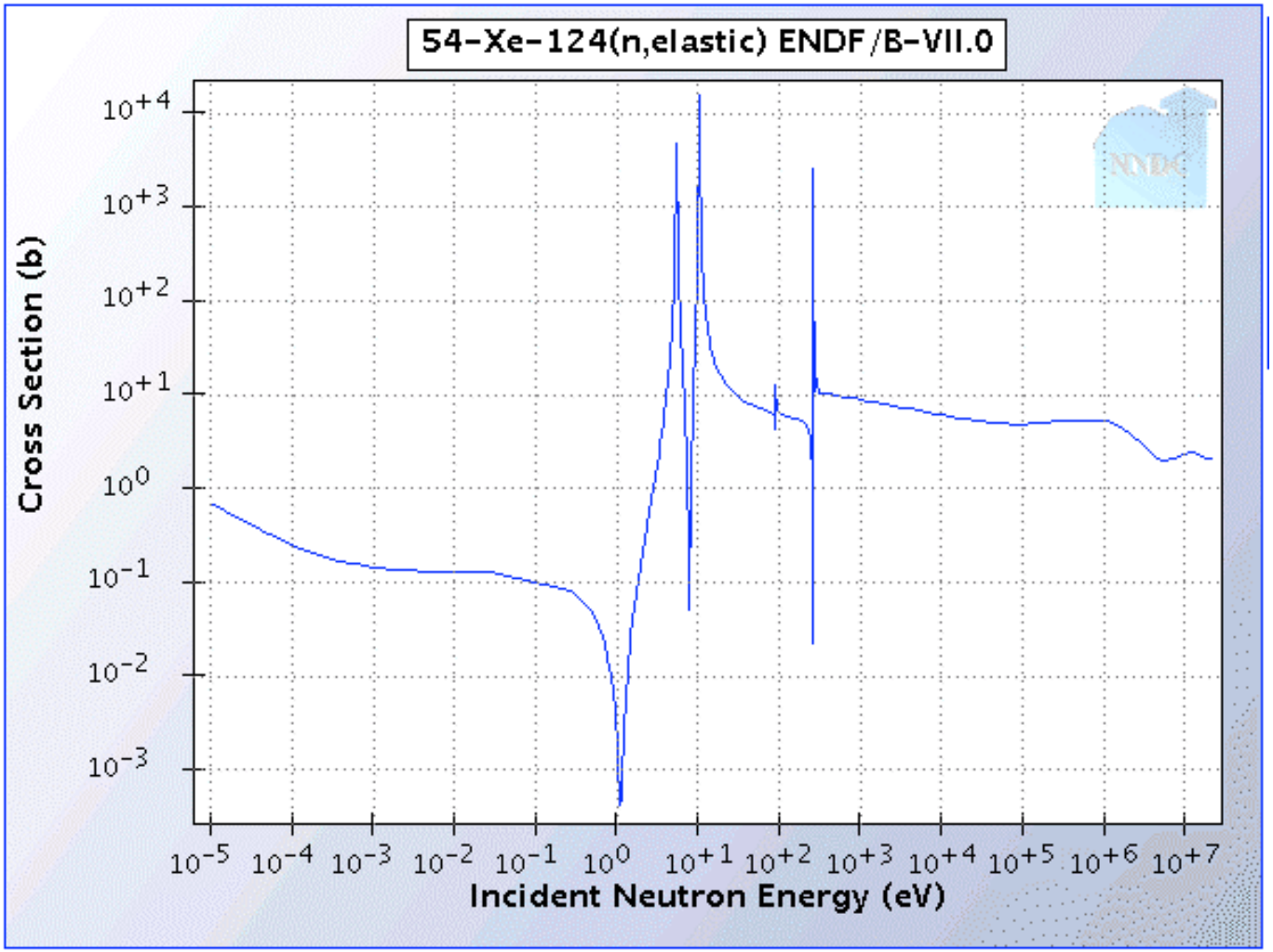


Counting rate; Xe

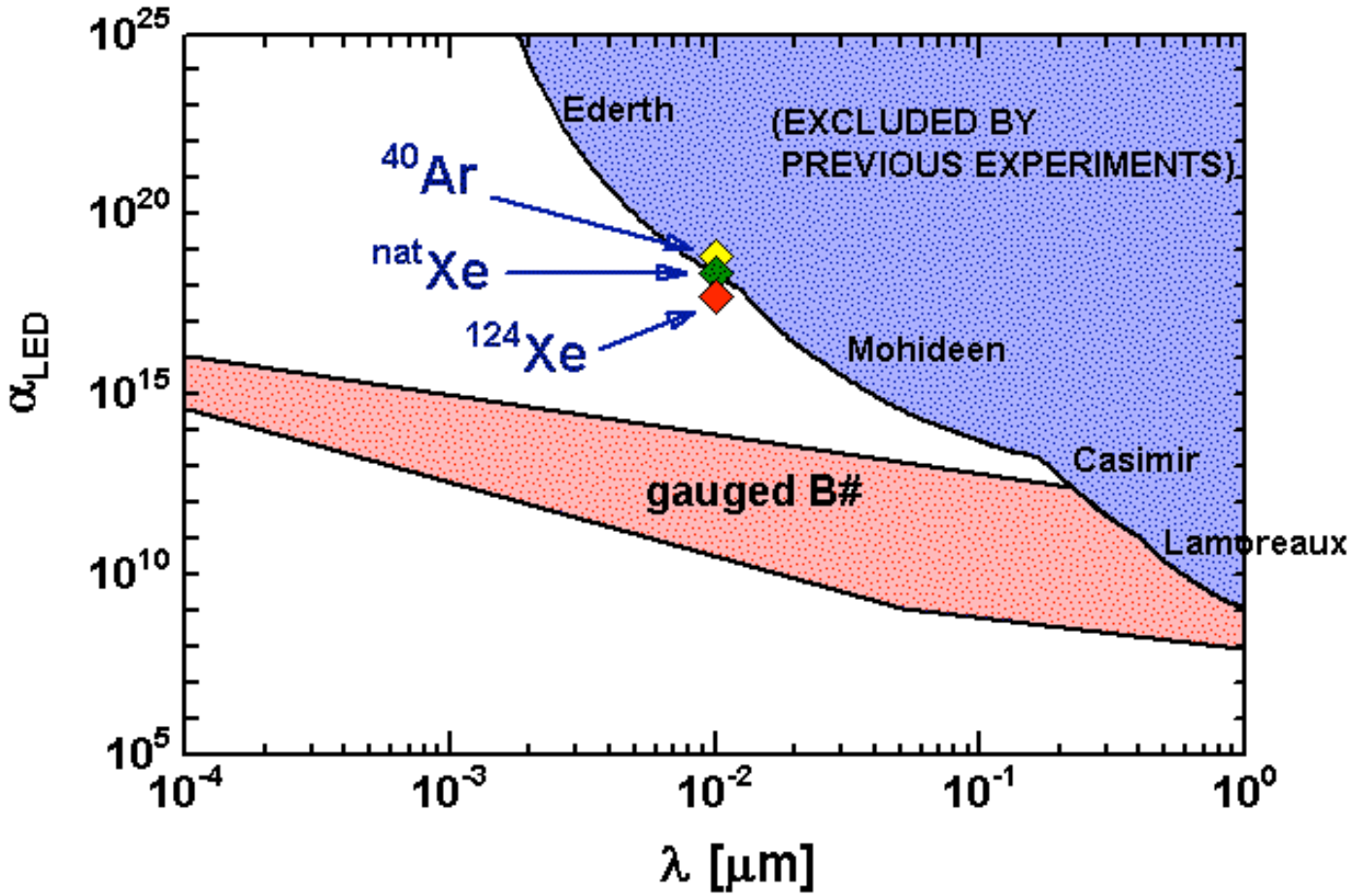
$\sigma_N(^{nat}Xe)=2.96$ b
$\sigma_N(^{124}Xe)=0.141$ b



^{124}Xe(n,n) cross section



Sensitivity (2year measurement, 95% C.L.)



Summary

- Slow neutron is an ideal probe for testing the inverse-square law of the Newtonian gravity in the sub-micrometer range.
- Small-angle scattering of slow neutron with noble gas atom is a simple way to search for exotic intermediate-range forces.
- Experiments with enriched targets of ^{36,40}Ar and ^{124,nat}Xe are planned at the high-intensity branch of the J-PARC/JSNS/BL05 beam line.

Models of Exotic Intermediate-Range Forces

- Large Extra Dimension (Alkani-Hamed, Dimopoulos, Dvali)
- Radion-mediated force
- Moduli coupling (exchange of string-theory scalars)
- Axion exchange
- Multi-particle exchange (axions, ν-$\bar{\nu}$, etc.)

  $\Rightarrow$ power-law potential
- Vacuum-energy scenarios ("fat graviton" model)

Large Extra Dimension model

Alkani-Hamed, Dimopoulos, Dvali (ADD)

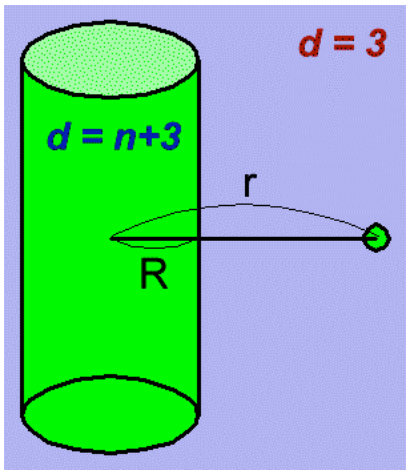
Hierarchy problems ;
- $M_{EW} \sim 100\text{GeV} \Leftrightarrow M_{Pl} \sim 10^{19}\text{GeV}$
- $G \sim 10^{-36}\ \alpha_{EM}$

Gravity in *d=N* space ;

$$F_N(r) = -G_N \frac{m_1 \cdot m_2}{r^{N-1}}, \quad G_N = \frac{hc}{M^{N-1}}$$

Continuity at *r=R* ;

$$G_3 = G_{n+3}\left(\frac{R_{Plank}}{R}\right)^n$$



Size of compact space R is so large as $G_3 << G_N$,
but is smaller than experimentally surveyed range (~1mm).

Atomic Form Factor

$$F_e(q) \cong \begin{cases} 1 & \text{for} \quad q << 0.01\,\text{Å}^{-1} \\ 0 & \text{for} \quad q >> 10\,\text{Å}^{-1} \end{cases}$$

More precisely,

$$F_e(q) \cong 0.998 \quad \text{at } q = 0.01\,\text{Å}^{-1}$$