NEWS colloquium, March 27, 2025, RCNP

B-L symmetry violation and new intermediate-range interaction

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1. Motivation; Mystery of the gravity

Fundamental Interactions in Nature

Interaction	Relative Strength*	Formulation	Quantum theory
Strong	1	1935 (Yukawa)	QCD
Electromagnetic	10^{-2}	1864 (Maxwell)	QED
Weak	10^{-5}	1933 (Fermi)	GWS
Gravity	10^{-39}	1687 (Newton)	N/A

* Ratio of the strength of the force acting between two protons with distance of 1 fm.

Why gravity is so weak ? ("Hierarchy" problem)

Hierarchy problems ; Gravity/Weak ~ 10^{-34}

Weak interaction; Fermi's coupling constant G_F

$$G_F = (\hbar c)^3 \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2} = (\hbar c)^3 \frac{\sqrt{2}}{2} \frac{1}{\langle H \rangle^2}$$

$\langle H \rangle \simeq 246$ [GeV] ; Vacuum expectation value of Higgs field

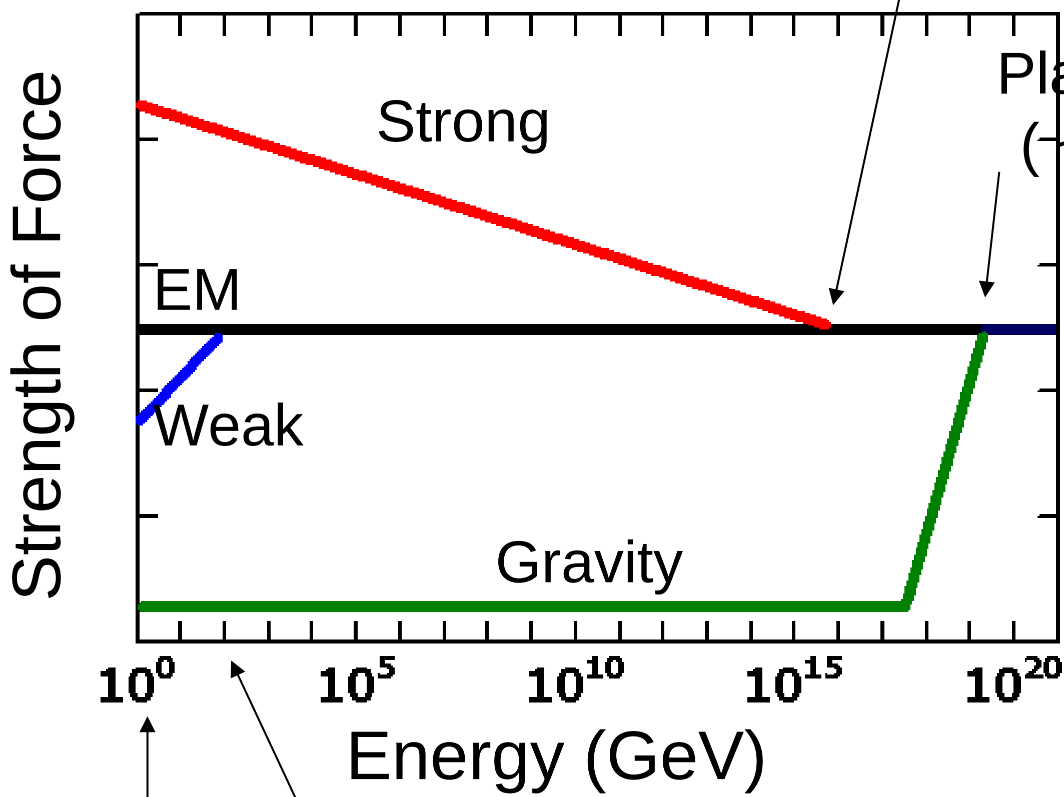
If $\langle H \rangle$ is as large as Planck mass; 10^{19} [GeV], $G_F \sim G_{gravity}$

Why $\langle H \rangle$ is so smaller than M_{Planck} ?

Gap in energy scales

Unification of S, EM, W
(~10^{16} GeV)

Planck Energy
(~10^{19} GeV)

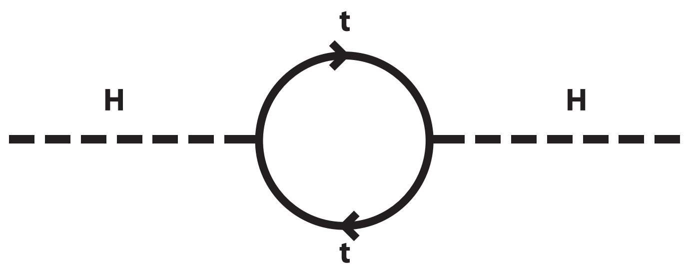


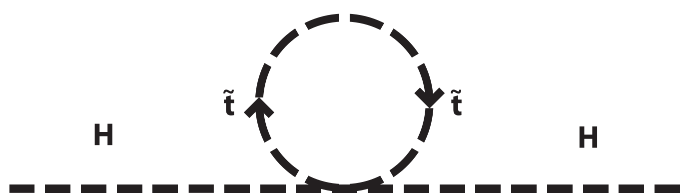
Nucleon mass
(~1GeV)

Unification of EM and Weak
~100GeV << 10^{19} GeV; **fine tuning !**

Super Symmetry (SUSY)

--- Symmetry between boson and fermion



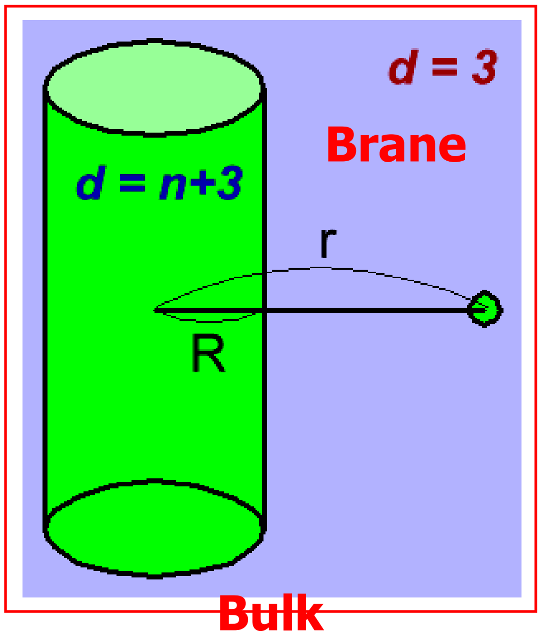


Cancellation between fermion loop and boson loop suppresses the VEV of Higgs field.

Since no evidence was obtained from high-energy experiments, the masses of the susy particles should be above ~10TeV.

Alternative; Large-extra dimension (LED)

N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B429, 263 (1998).



The world is assumed to be

d-dimensional space (bulk, d=n+3),

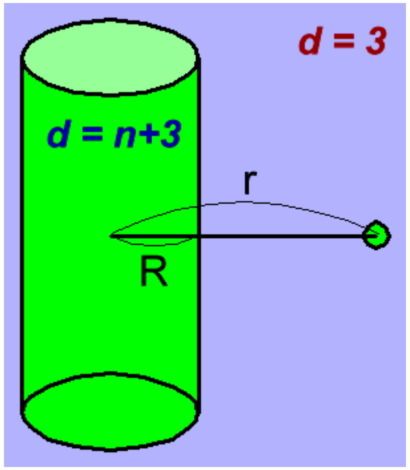
including ordinary 3D space (brane) ,

and only graviton can propagate bulk.

n is the number of extra dimensions.

Then, . . .

Gauss's law in *d*-dimensional space



Gravitational potential in *d*-dimension ;

$$V_d(r) = -G_d \frac{m_1 \cdot m_2}{r^{d-2}}, \qquad G_d = \frac{hc}{M_{Pl(d)}^{d-1}}$$

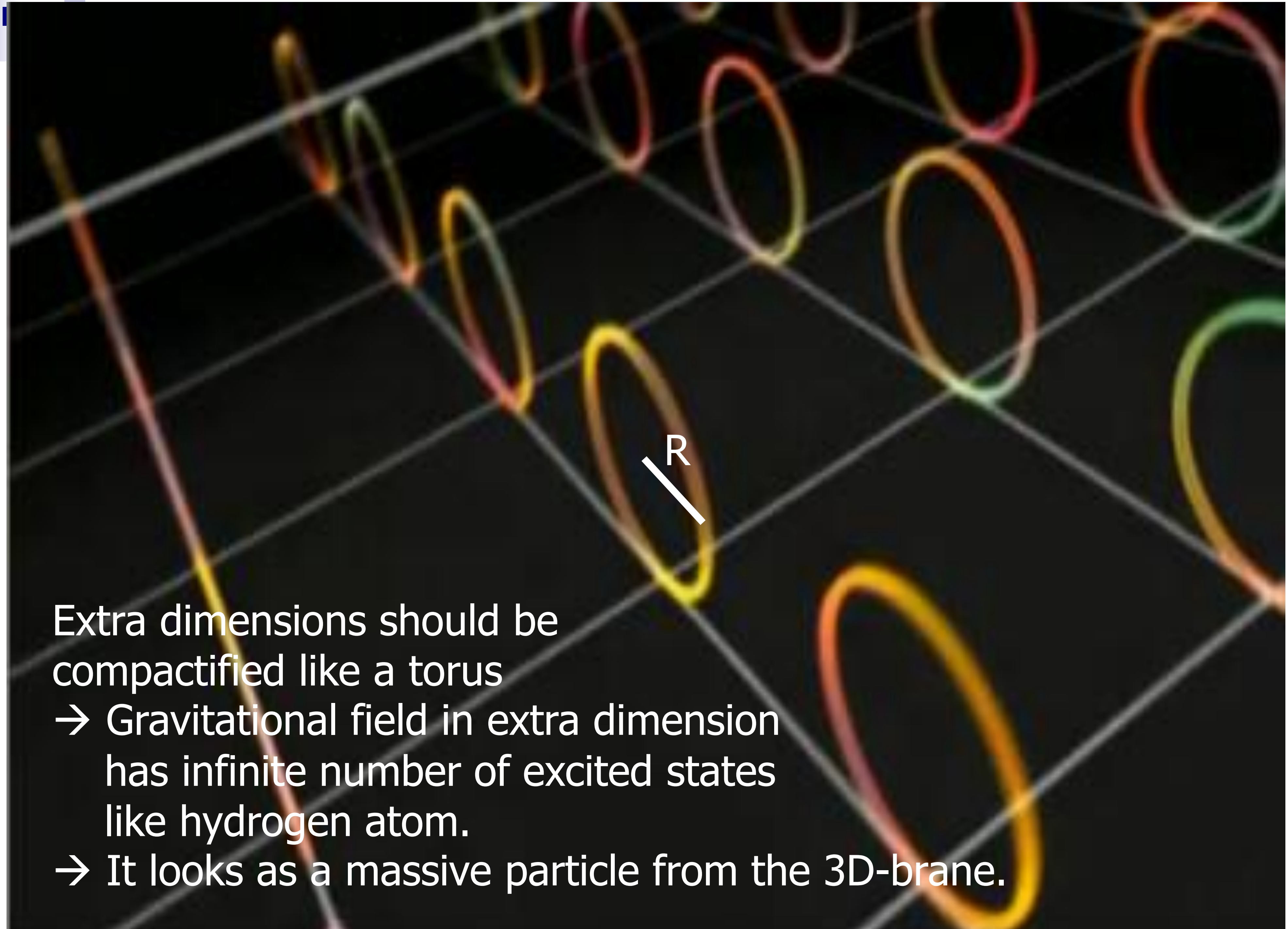
$$r > R \qquad d = 3 \qquad V_3(r) = -G_3 \frac{m_1 \cdot m_2}{r}, \qquad G_3 = \frac{hc}{M_{Pl(3)}^{2}}$$

$$r < R \quad d = n+3 \quad V_{n+3}(r) = -G_{n+3} \frac{m_1 \cdot m_2}{r^{n+1}}, \qquad G_{n+3} = \frac{hc}{M_{Pl(n+3)}^{n+2}}$$

Continuity at *r=R* ; $G_3 = G_{n+3} \frac{1}{R^n} \quad , \quad M_{Pl(3)}^{2} = M_{Pl(n+3)}^{n+2} \cdot R^n$

Possible parameters in terms of Planck energy $M_{Pl(n+3)}$ in bulk

n	R ($M_{Pl(n+3)}$=1TeV)	R ($M_{Pl(n+3)}$=10TeV)
1	~10^{13} m (excluded)	~10^{10} m (excluded)
2	~1 mm (excluded)	~10 μm
3	~10 nm	~0.1 nm
4	~10 pm	~1 pm



Extra dimensions should be compactified like a torus

→ Gravitational field in extra dimension has infinite number of excited states like hydrogen atom.

→ It looks as a massive particle from the 3D-brane.

Potential

Newtonian   New interaction (Yukawa-type)

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

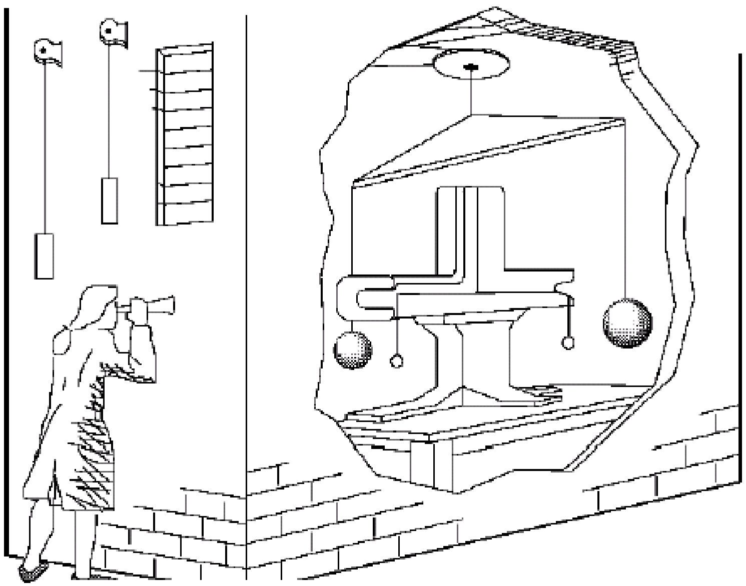
α ; coupling constant (relative to Newtonian gravity)

λ ; range (~ size of compact space (*R*))

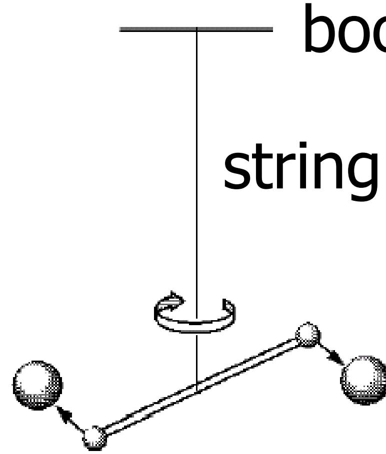
<u>Note.</u> Range λ is equal to the Compton wavelength of the intermediate boson with mass μ, i.e. $\lambda = h/\mu c$

→ Test of the inverse-square law of gravity

Cavendish's experiment (1798)



Experimental Apparatus

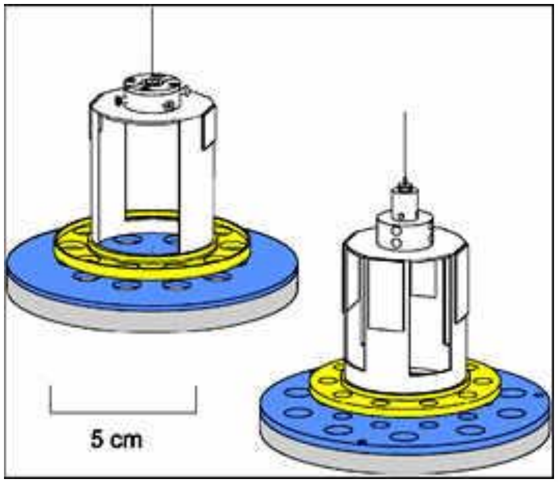


Torsion balance

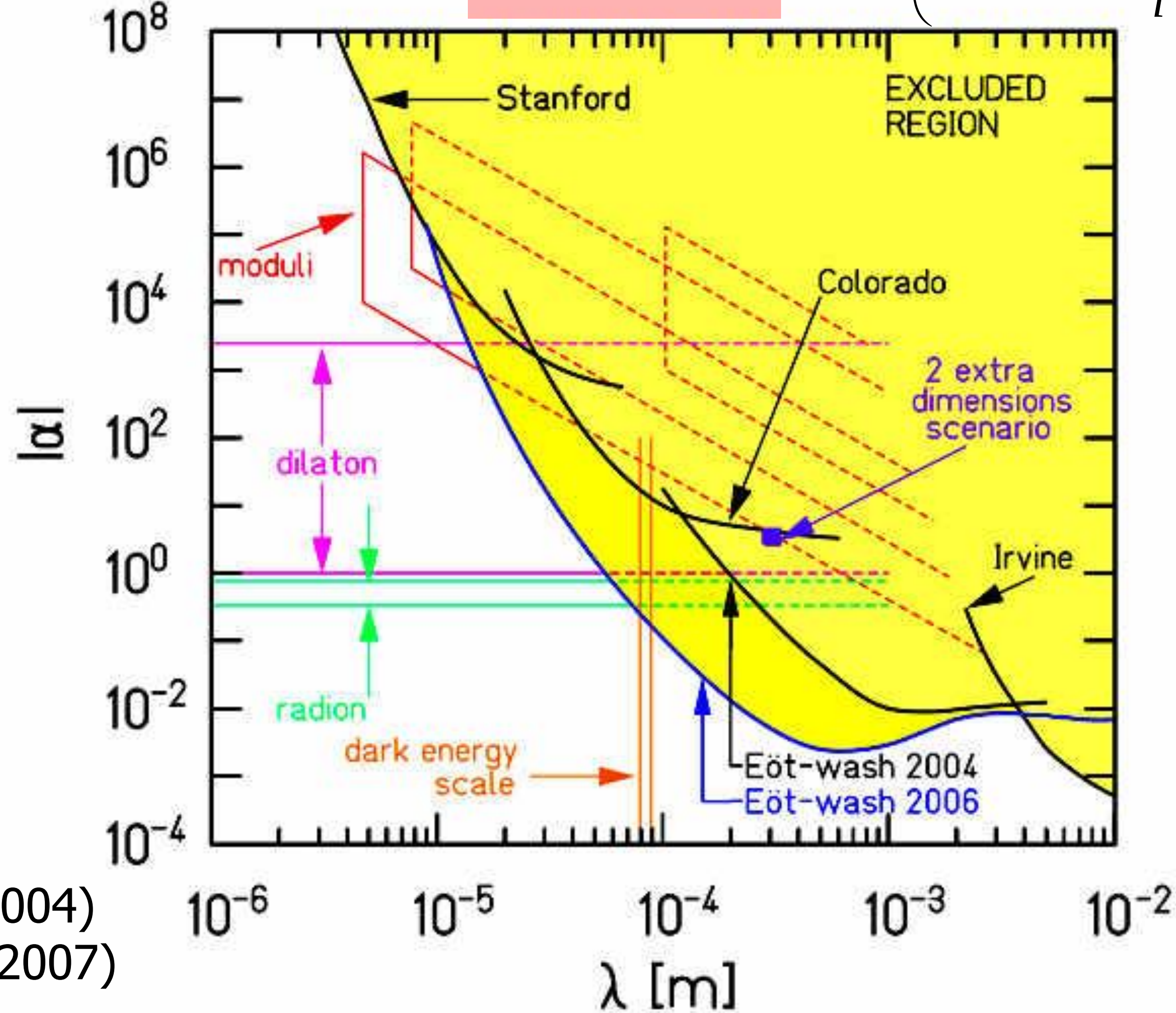
Current status of the experimental search for non-Newtonian gravity in sub-millimeter region

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

Torsion pendulum

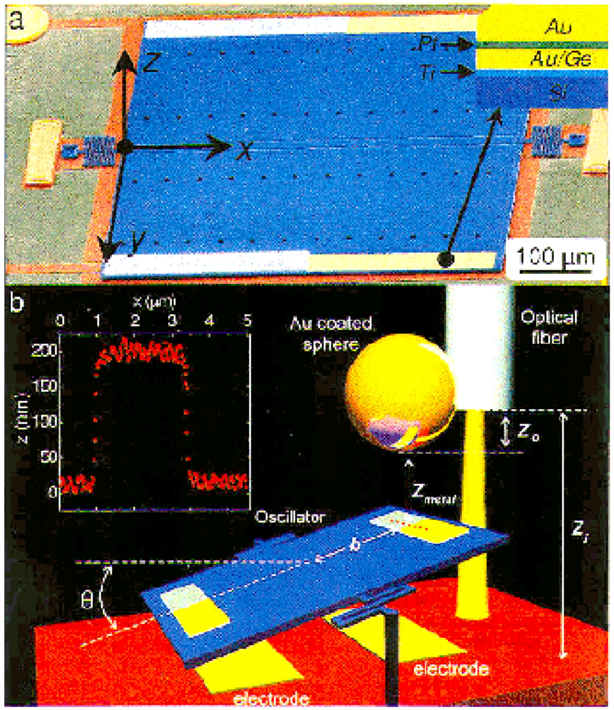


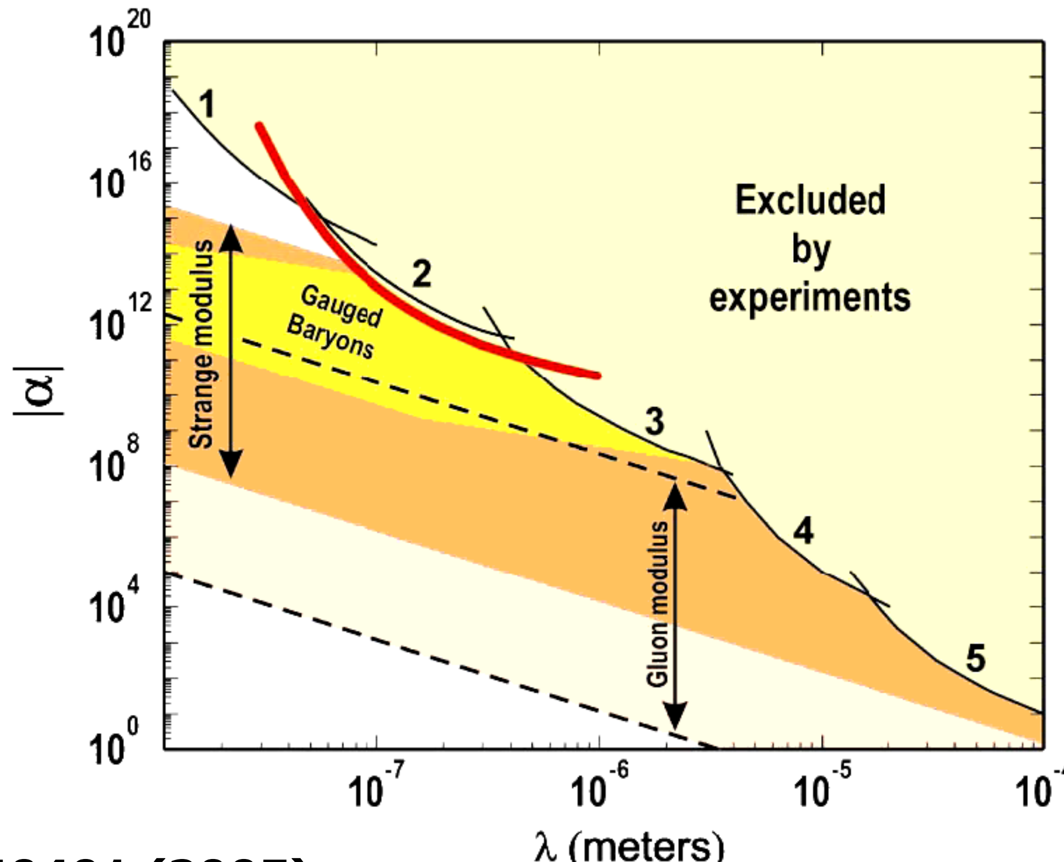
Gravitational force contribute to restoring force.



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

Atomic Force Microscopy





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

Background

In case of ordinary non-charged materials,

Van der Waals force dominates at $l < \sim 1\mu m$;

$$U_L = -\frac{3}{2}\left(\frac{E_A E_B}{E_A + E_B}\right)\frac{\alpha_A \alpha_B}{r^6}$$

E; ionization potential

α ; electric polarizability (London)

Electric polarizability of atoms; $\alpha_0 \sim 10^{-24}$ cm^3

Neutron ; $\alpha_n \sim 10^{-42}$ cm^3

2. Search for New Intermediate-range Force by means of small-angle neutron scattering

T.S., Genshikaku-Kenkyu, Vol.49, p.51 (2004)

A.Frank, P.V.Isacker, J.Gomez-Camacho, Phys. Lett. B582, 15 (2004)

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

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

$a_G \propto \alpha$

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

V_G ⟺ Fourier Transform!

Differential Cross Section (1st Born approx.)

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

G : coupling constant of Newtonian gravity

α : coupling constant of LED gravity

σ_N : nuclear scattering cross section

λ : range of non-Newtonian gravity

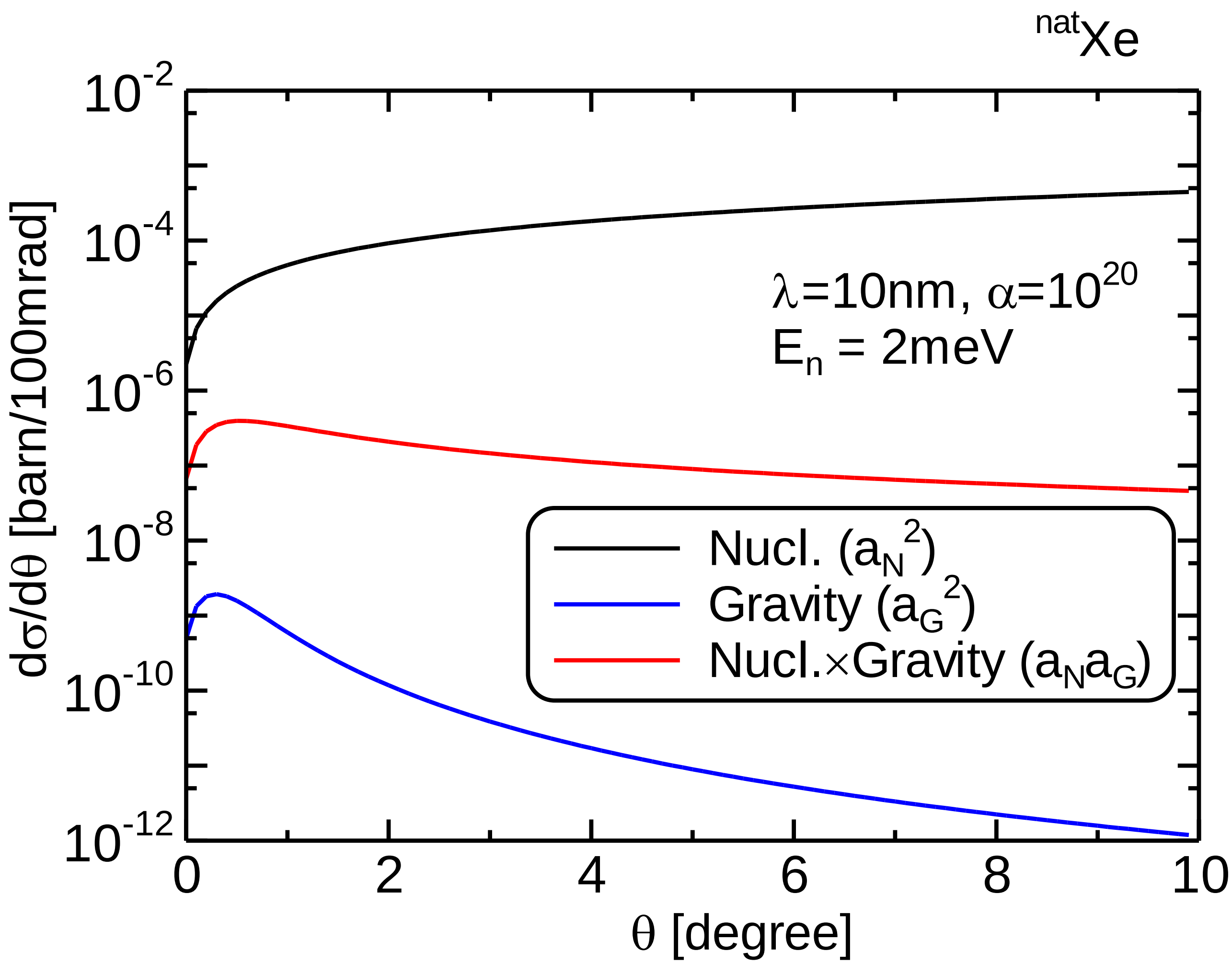
M : target mass

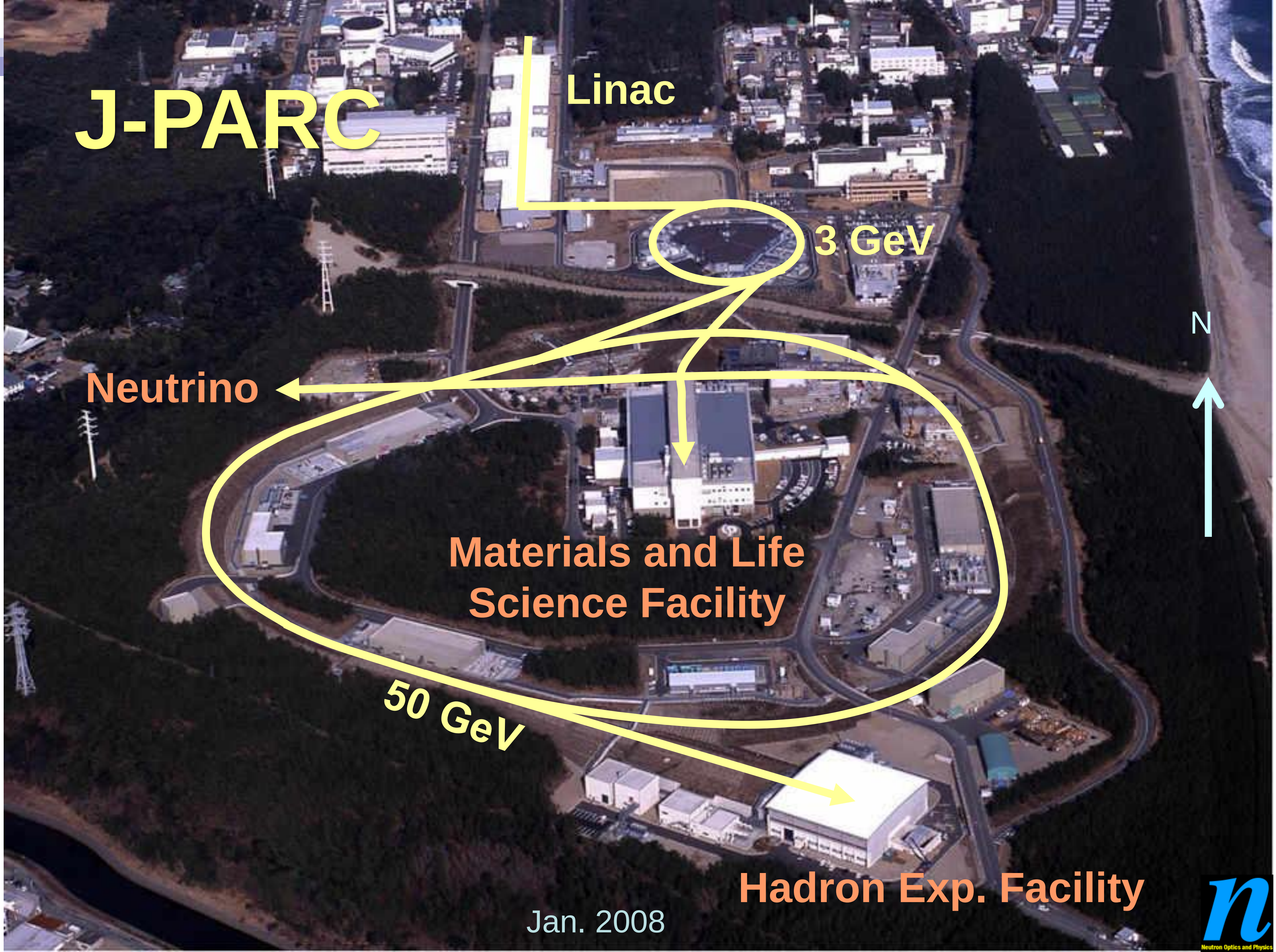
m_n : neutron rest mass

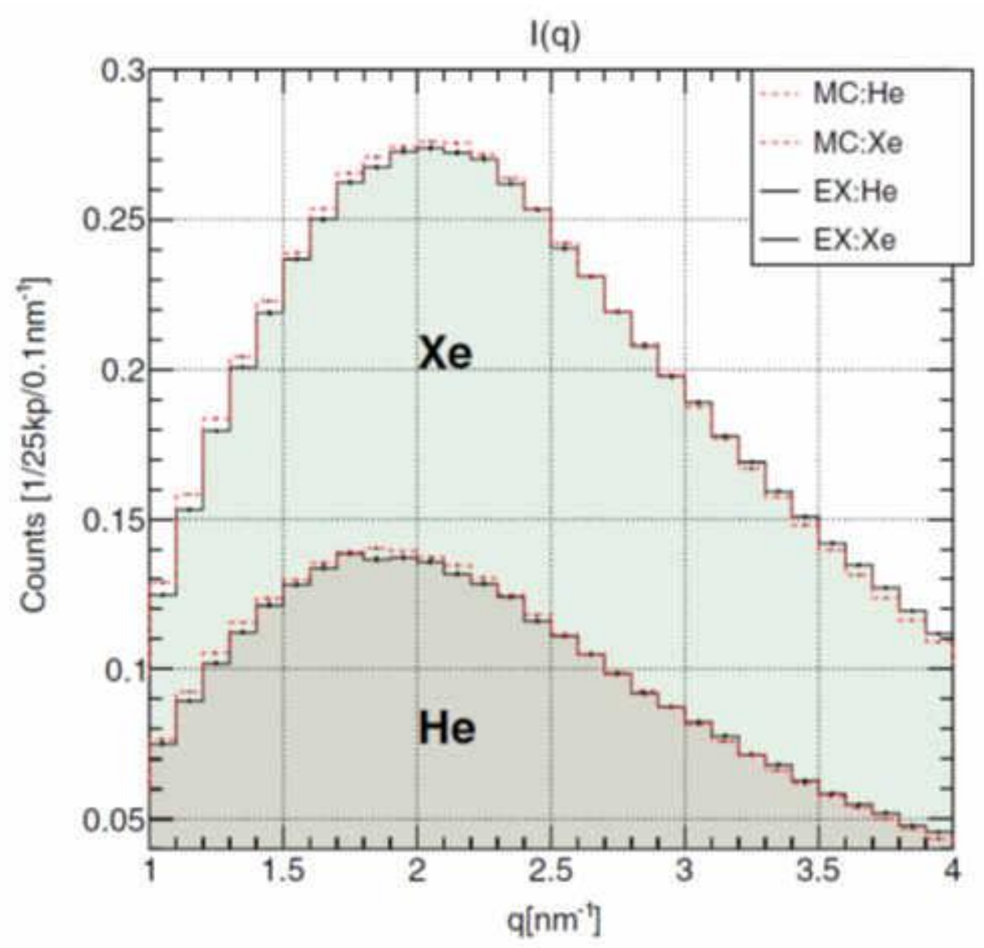
E_n : neutron energy

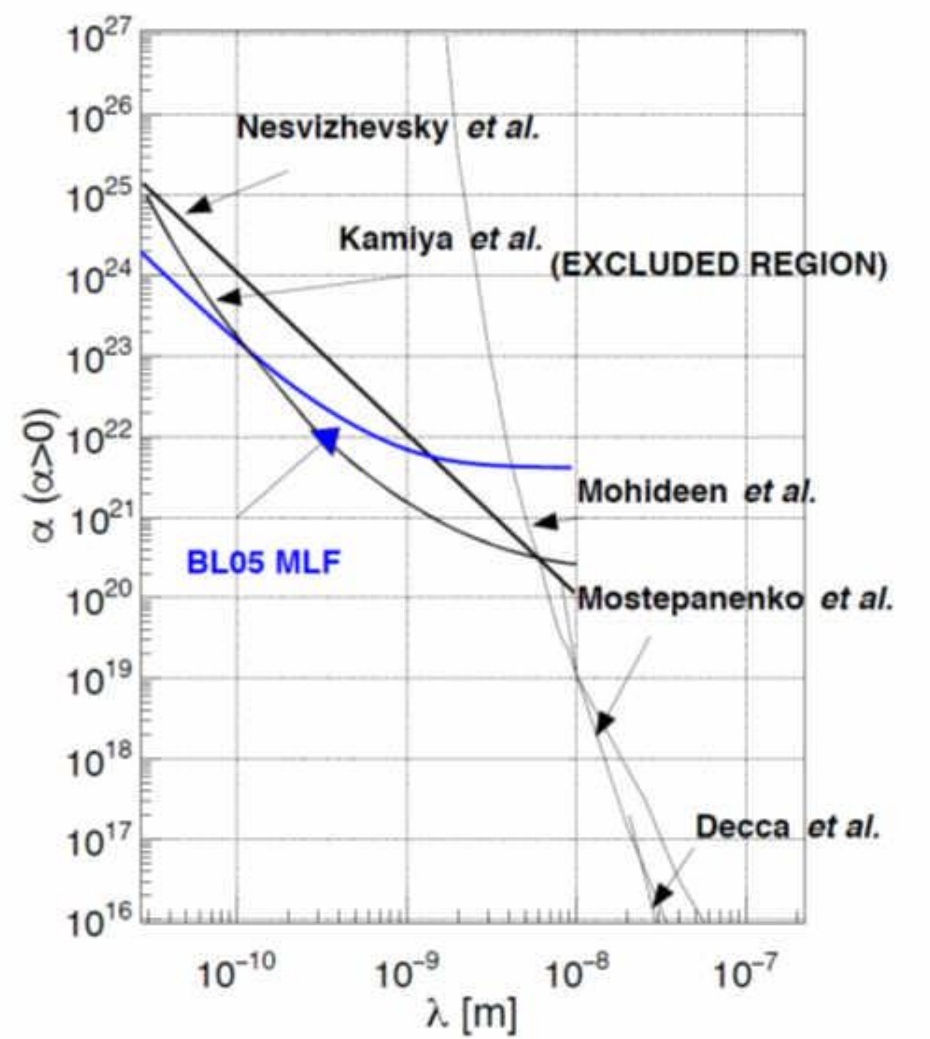
θ : scattering angle

Neutron angular distribution (example)



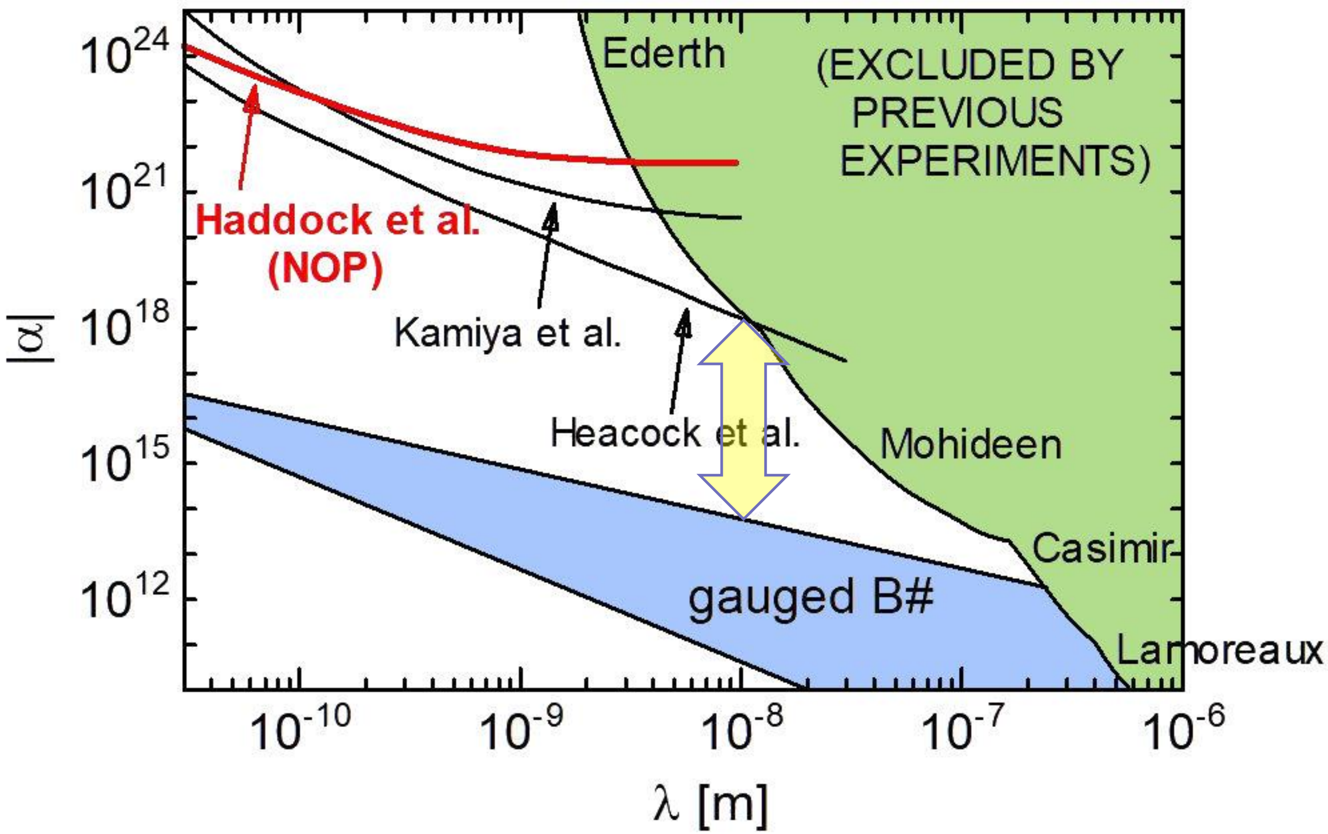

J-PARC
Linac
3 GeV
N
Neutrino
Materials and Life
Science Facility
50 GeV
Hadron Exp. Facility
Jan. 2008
Neutron Optics and Physics





C.C. Haddock, N. Oi, K. Mishima, T.S, H.M. Shimizu, T. Yoshioka et al., Phys. Rev. D97, 062002 (2018)

We need further improvement of experiment…



4~5 orders of magnitude far !

Baryon number conservation

Conservations of baryon number (B) and Lepton number (L) are both global symmetries in SM.

→ We can suppose the conservation of B correspond to U(1) gauge symmetry.

Spontaneous breaking of U(1) symmetry leads to violation of B as well as pseudo-NG boson with very small mass, since the symmetry breaking is expected to be not large. The exchange of the boson generates a new intermediate-range force. Its mass is governed by how large the B violation is.

Leptonic version

We can suppose lepton-number conservation correspond to U(1) gauge symmetries.
Then we can consider a new scaler field χ for $U_L(1)$.

Spontaneous symmetry breaking of $U_L(1)$ symmetry leads to violation of L, as well as massless NG boson, which is called **Majoron**. Its mass is governed by how large the L violation is. SSB of $U_L(1)$ symmetry can also account for Majorana neutrino → See-saw for light neutrinos

B-L symmetry

In principle, B and L are not necessarily related to each other. However, U(1) symmetry for particle-number conservation is naturally contained in SO(10) GUT model, which also naturally provides left-right symmetric model.

$$SO(10)\ (Spin(10)) \supset SO(6) \times SO(4)$$ (decomposition to maximal subgroup)

$$SO(6) \supset SU(4) \supset SU(3)_c \times \mathbf{U(1)}$$

$$SO(4) \supset SU(2) \times SU(2)'$$

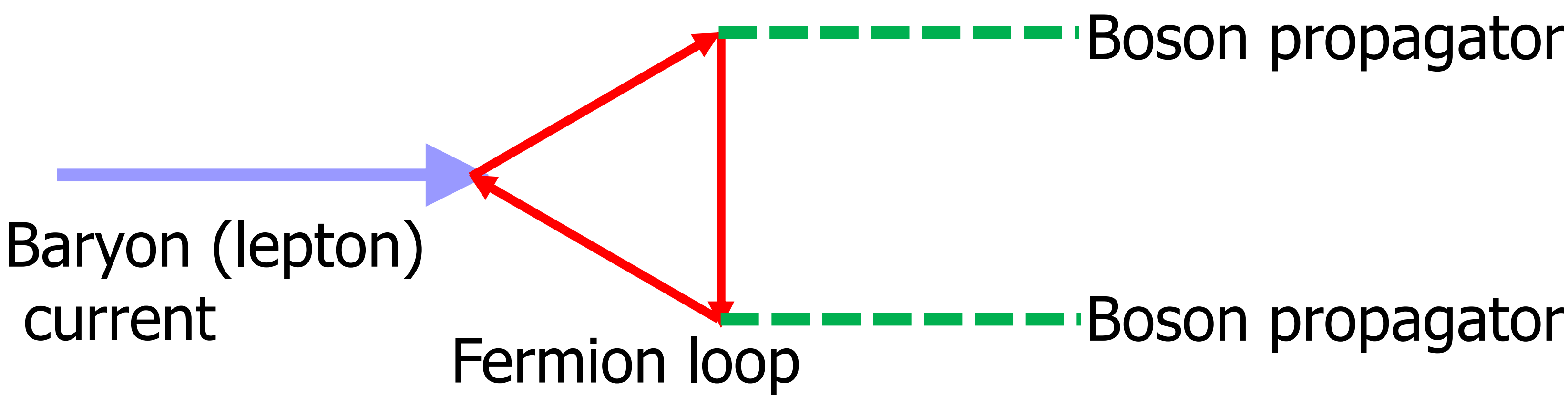
$$\downarrow \qquad \downarrow$$

$$SU(2)_L \quad SU(2)_{\boldsymbol{R}}$$

In SO(10) GUT, all the fermions, baryons and leptons including right-handed neutrino are naturally allocated to 16 irreducible spinor representations. Therefore, it is natural to consider conserved particle number as B+L or B-L.

B ? L? B+L ? or B-L ?

Also, it is known that B alone, L alone, and B+L are violated by the effect of the triangle anomaly, but in the case of B-L,



$$A = \sum_{SU(2)\ doublets} (B-L) \cdot Tr\left(T^a T^b\right)$$

T^a, T^b are generators of the gauge group.

$$= \left[3 \times \frac{1}{3} - 1\right] \times 2 = 0$$

Cancellation between baryon and lepton happens only in B-L!

Gauged baryon number model

We can suppose the conservation of B correspond to local U(1) gauge symmetries.

Spontaneous breaking of U(1) symmetry leads to violation of B as well as a new vector boson (called "baryonphoton") which may couple with neutrinos or dark matter.

Extra-dimensional gauged baryon number model
(of present interest)
--- U(1) scaler field can couple with higher-dimensional massive gravitons.

Extra-dimensional SO(10) GUT model will be interesting.
→ T. Fukuyama, https://doi.org/10.48550/arXiv.1212.3407
B. E. Hanlon, G. C. Joshi
https://doi.org/10.48550/arXiv.hep-ph/9303283

LED determines parameters dynamically

Majorana mass of neutrinos:

N. Alkani-Hamed, S. Dimopoulos, G. Dvali, PRD65, 024032 (2001)

$$m_M \simeq \frac{\langle H \rangle^2 \Delta_n(R)}{M_{Pl(N)}^{n-1}} \sim \frac{\langle H \rangle^2}{M_{Pl(N)}^{n-1}} \frac{\exp(-m_\chi R)}{R^{n-2}}$$

$\langle H \rangle$; vacuum exp. value of Higgs field ~246GeV

$\Delta_n(r)$; propagator of messenger χ in bulk

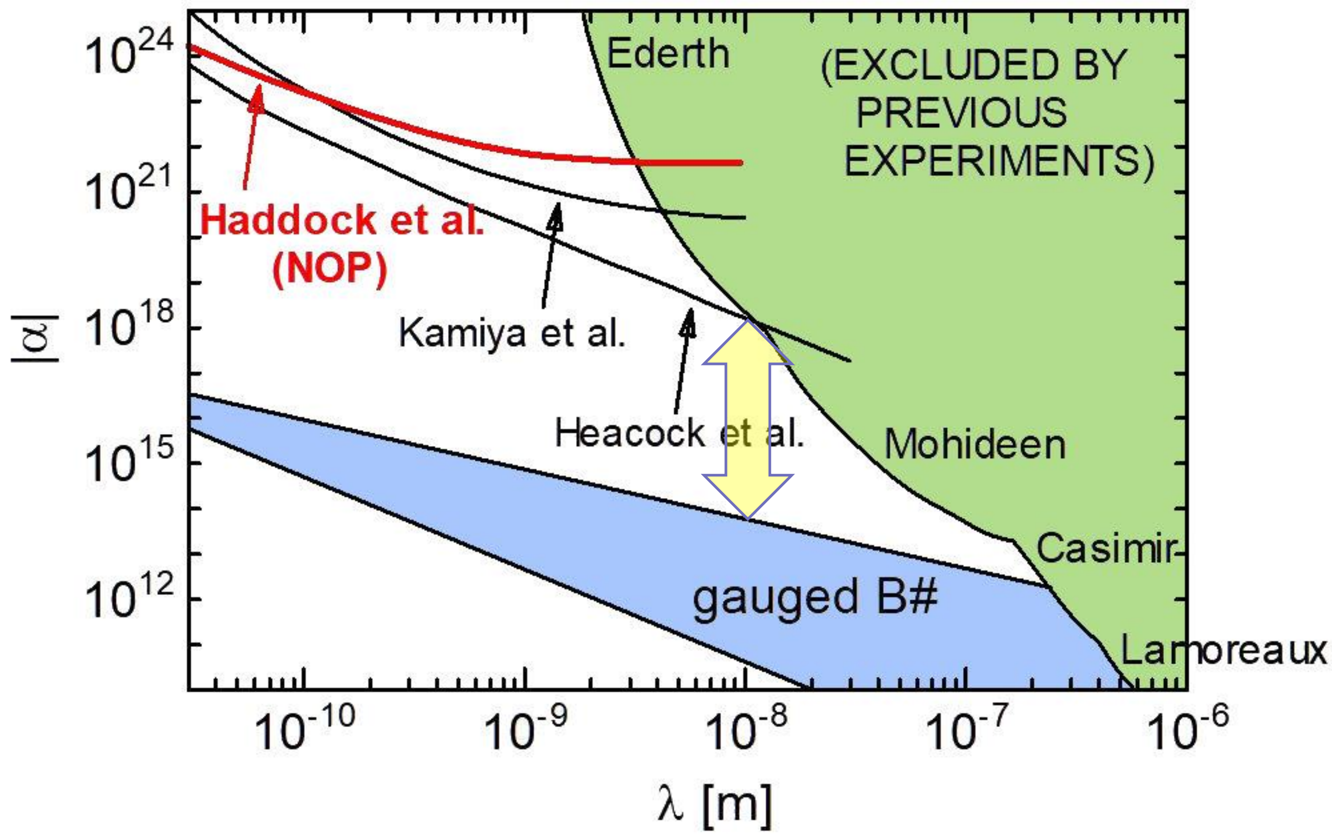
m_χ ; mass of χ which transfer L violation

For example, in case of *R*~1μm, n=2, and m_χ=1.5keV,

$m_M \simeq 50\ \mathrm{meV}$ - - - alternative to See-Saw with ν_R

H. Päs and W. Rodejohann 2015 *New J. Phys.* **17** 115010

We need further improvement of experiment…



4~5 orders of magnitude far !

To increase the experimental sensitivity…

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

M : target mass

Diam. of Xe atom; 216 pm << range of LED gravity; λ=1-100 nm

- - - Xe atom is too small as a target !

Diameter of target particle can be as large as λ ; nanoparticle!

➡ > 10^6 improvement thanks to coherent neutron scattering !!

This is the case of the coherent neutron scattering.

Side effect; coherent nuclear scattering is also enhanced …

$$\sigma_{coh}^{nuclear} = 4\pi \left[n \sum_{i=1} p_i a_i \right]^2$$

n : # of target nuclei
p_i : mixing ratio of i-th isotope
a_i : scattering length of i-th isotope

	Coherent Scattering Length [fm]
^{nat}Ni	10.3
^{nat}Ti	-3.438
^{nat}V	-0.3824*
^{nat}Mn	-3.73
^{62}Ni	-8.7
^{64}Ni	-0.37

* -0.55 [fm] by interferometer T. Fujiie et al.