Gravitational effects in muon/neutron experiments

Workshop on Gravitational physics with particle accelerators 2017

2017/11/30

Kyushu University,

Research Center for Advanced Particle Physics

Tamaki Yoshioka

Test of inverse square law of gravity

Test of Inverse Square Law of Gravity

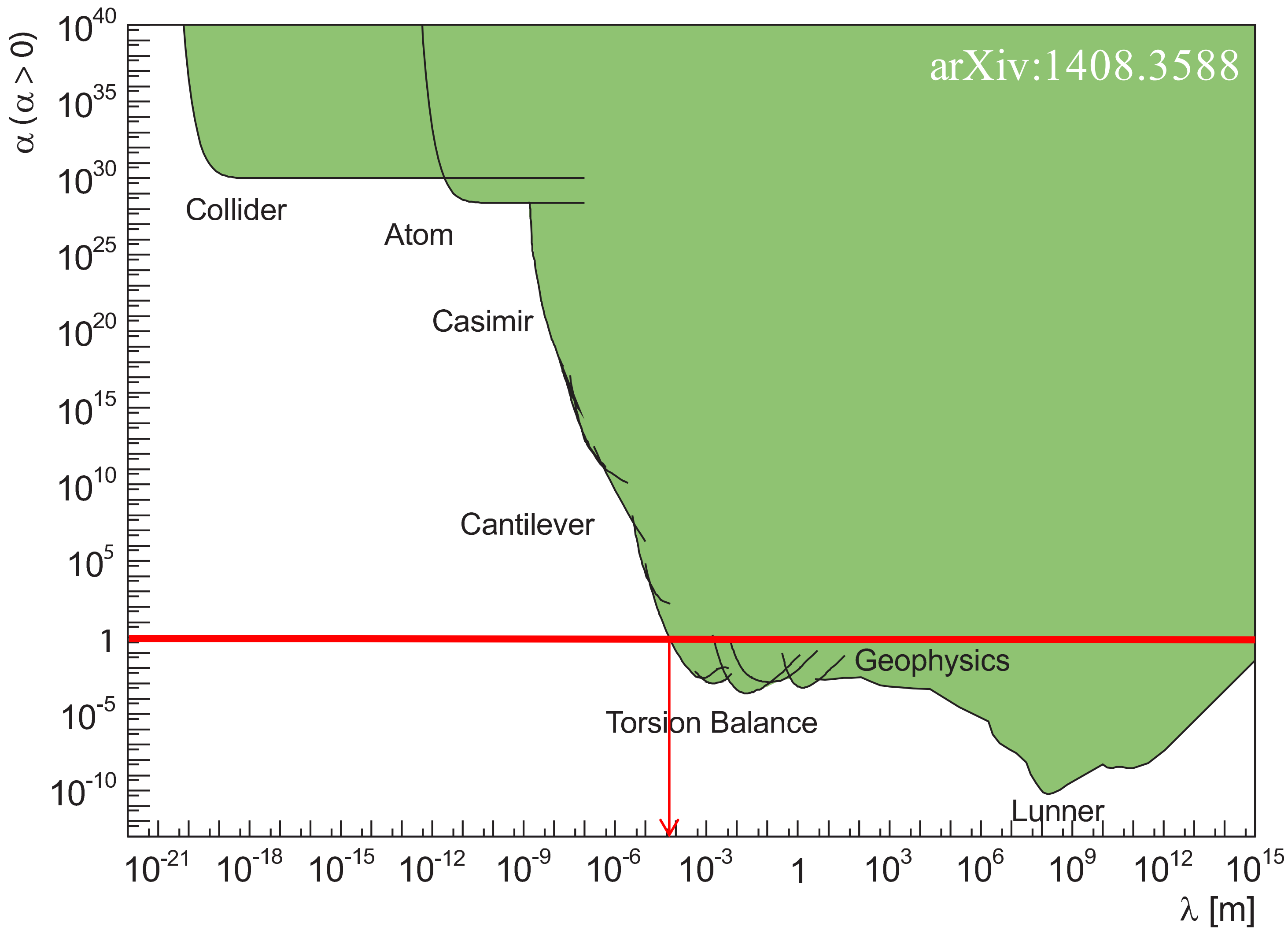
- Gravity is extremely weak compared to the other forces
  - Can be naturally explained by assuming extra dimensions.
  - Deviation from inverse square law is expected if extra dimensions exist.
  - Model-independent search is performed by assuming Yukawa-type force with coupling constant α and Compton wavelength λ.

$$V = -G_N \frac{mM}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

Newtonian potential

Yukawa potential

Test of Inverse Square Law of Gravity



ADD model

Physics Letters B 429 (1998) 263–272

The hierarchy problem and new dimensions at a millimeter

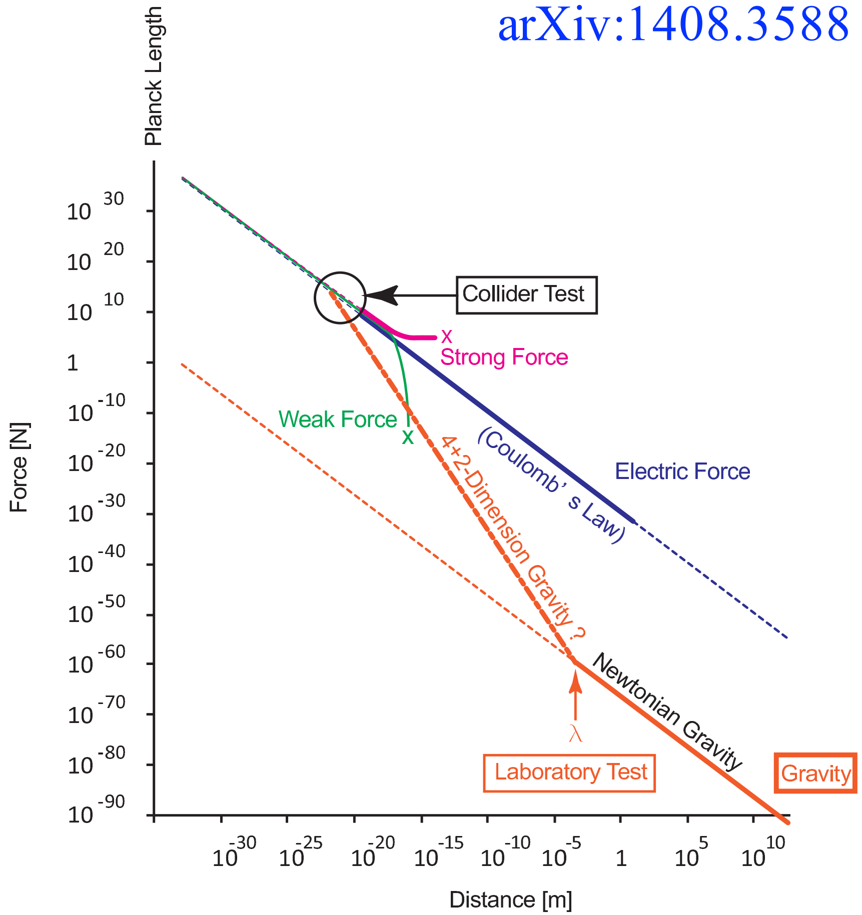
Nima Arkani–Hamed [a], Savas Dimopoulos [b], Gia Dvali [c]

[a] SLAC, Stanford University, Stanford, CA 94309, USA
[b] Physics Department, Stanford University, Stanford, CA 94305, USA
[c] ICTP, Trieste 34100, Italy

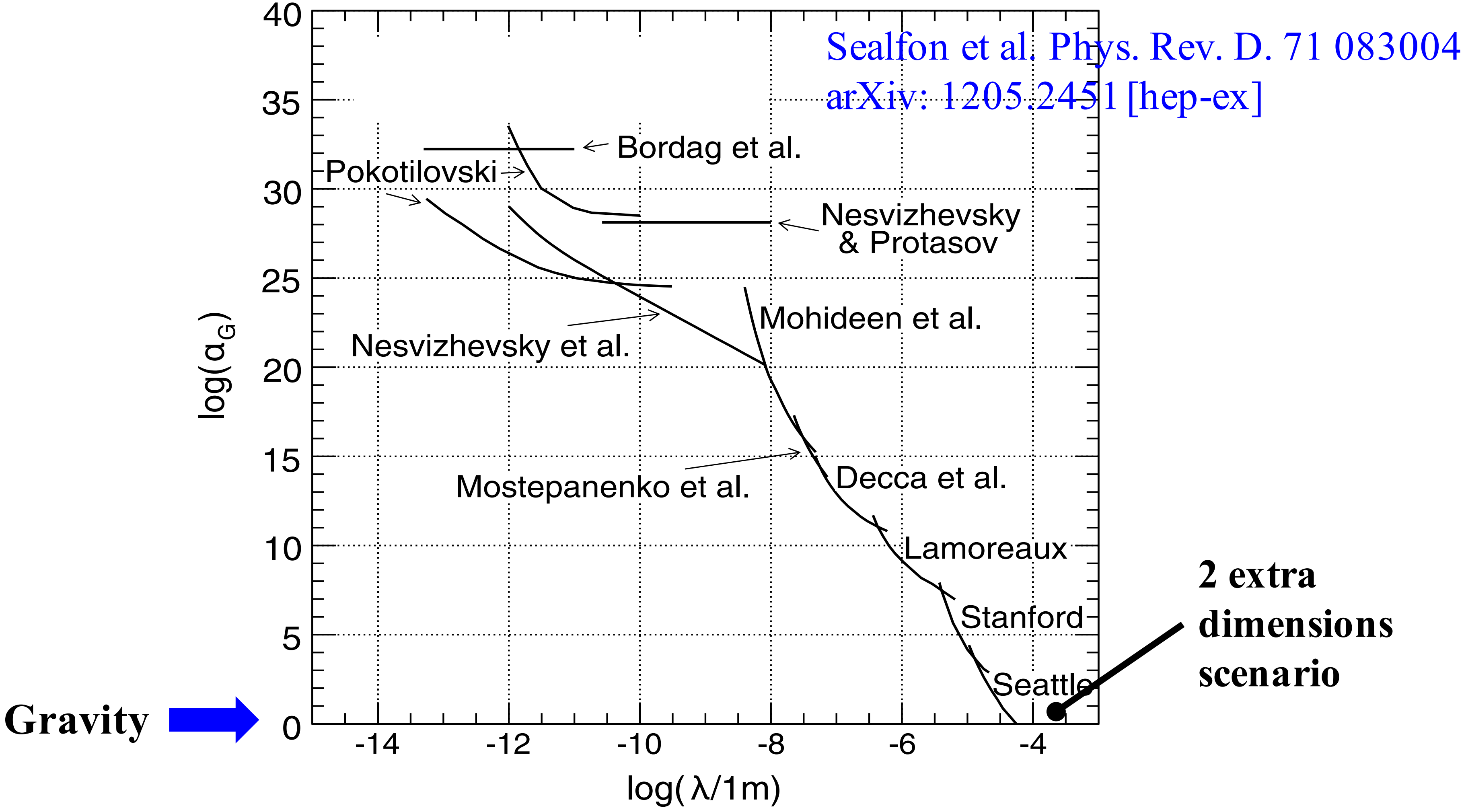
arXiv:1408.3588

- Gravity has only been accurately measured in ~1cm range.
- Assuming the gravity become same order of other forces at TeV scale. Λ=0.1mm for n=2.
- Should be continuous at $r = \Lambda$.

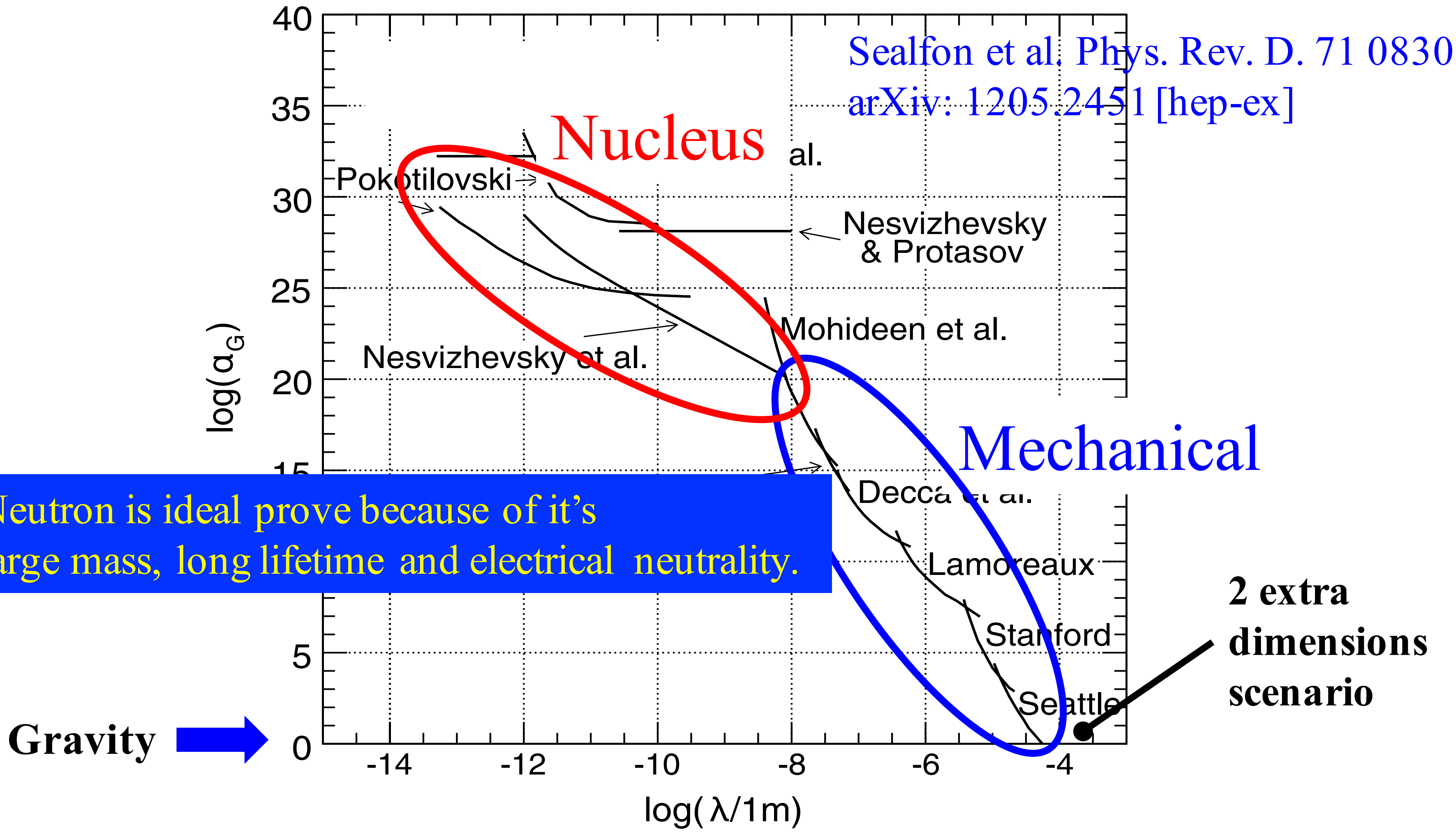
$$F = \begin{cases} G\dfrac{Mm}{r^2} & (r > \Lambda) \\ G_{4+n}\dfrac{Mm}{r^{2+n}} & (r < \Lambda) \end{cases}$$



α-λ Exclusion plot



α-λ Exclusion plot



Neutron is ideal prove because of it's large mass, long lifetime and electrical neutrality.

α-λ Exclusion plot

Main background is Van der Waals force

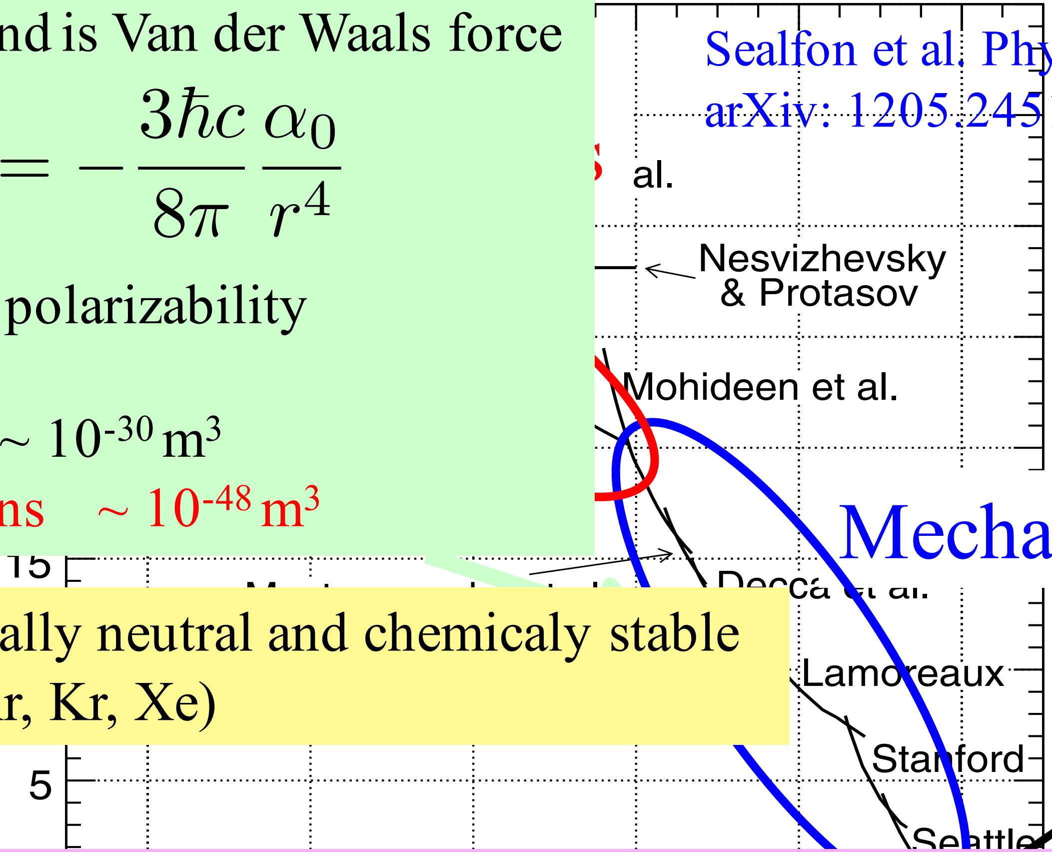
$$U = -\frac{3\hbar c}{8\pi}\frac{\alpha_0}{r^4}$$

α_0 : electric polarizability

Atoms ~ 10^{-30} m^3

Neutrons ~ 10^{-48} m^3

Sealfon et al. Phys. Rev. D. 71 083004
arXiv: 1205.2451 [hep-ex]



Mechanical

2 extra dimensions scenario

Target : electrically neutral and chemicaly stable
→Noble gas (Ar, Kr, Xe)

Gravity

Searching for deviations from inverse square law of gravity at nm range via neutron-noble gas scattering

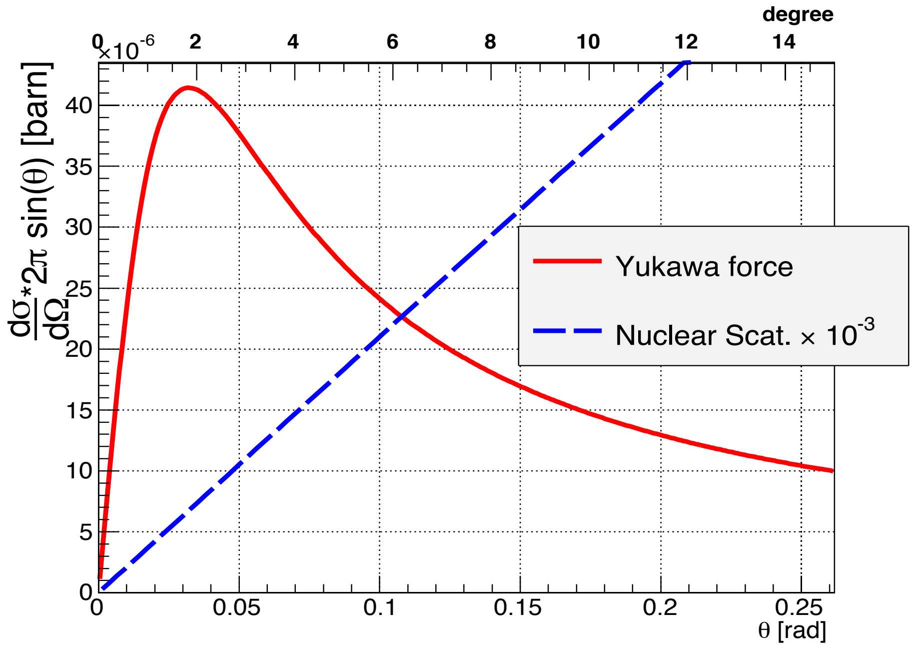
Experimental Principle

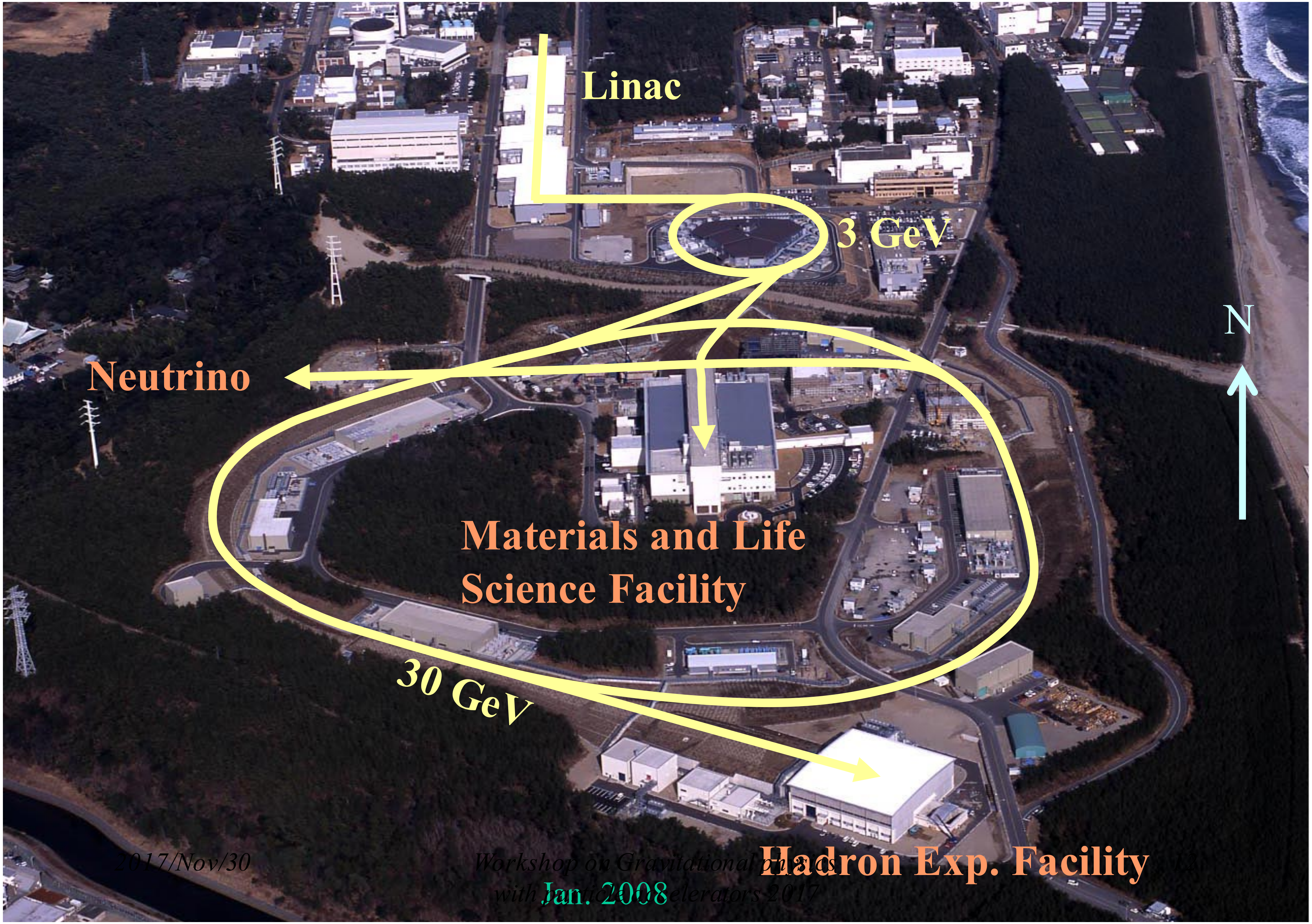
- Differential cross section of Yukawa force is evaluated with Born approximation.

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_Y \propto \sqrt{\sigma_{\mathrm{Nuclear}}}\,\alpha m_{\mathrm{T}}\lambda^2 \left(\frac{1}{1 + C\sin^2\left(\frac{\theta}{2}\right)}\right)$$

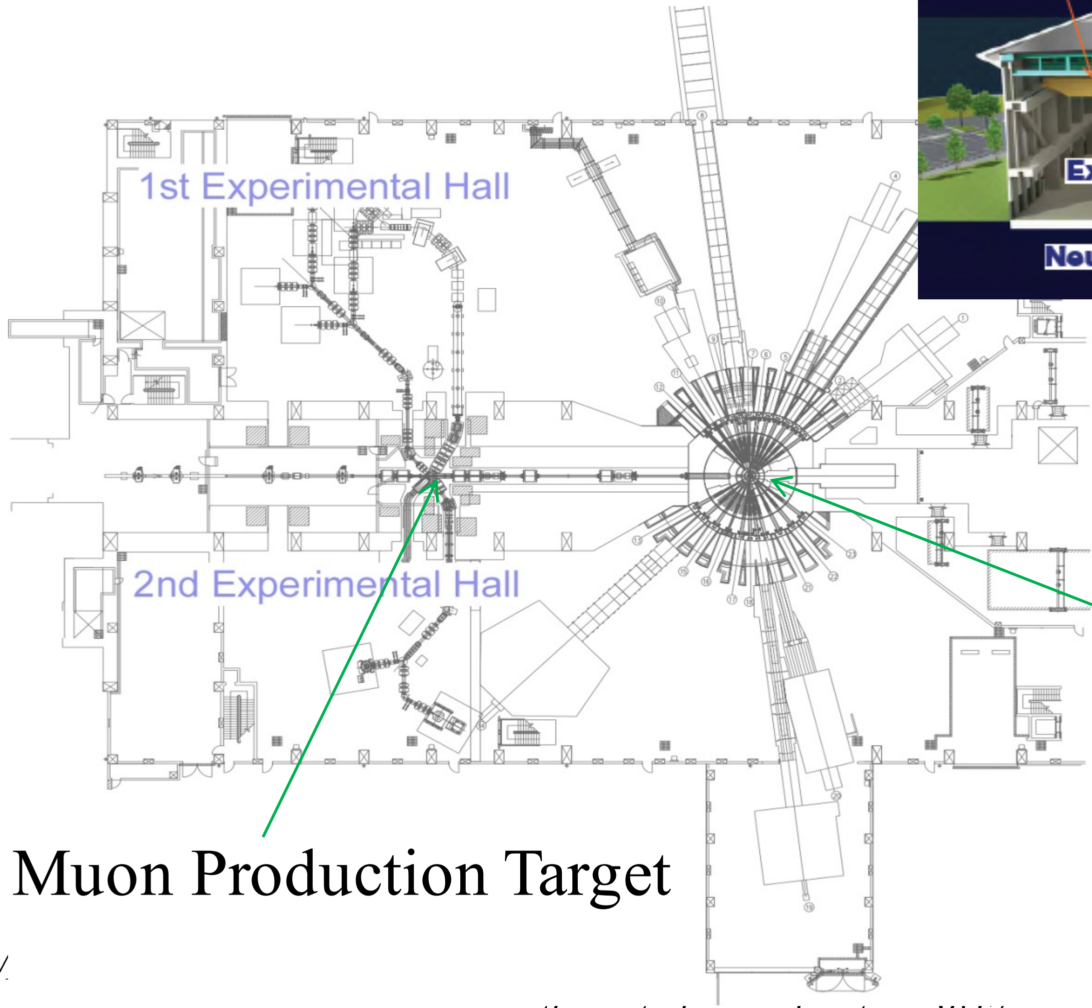
m_{T} : Target mass
$\sigma_{\mathrm{Nuclear}}$: nuclear scattering cross section

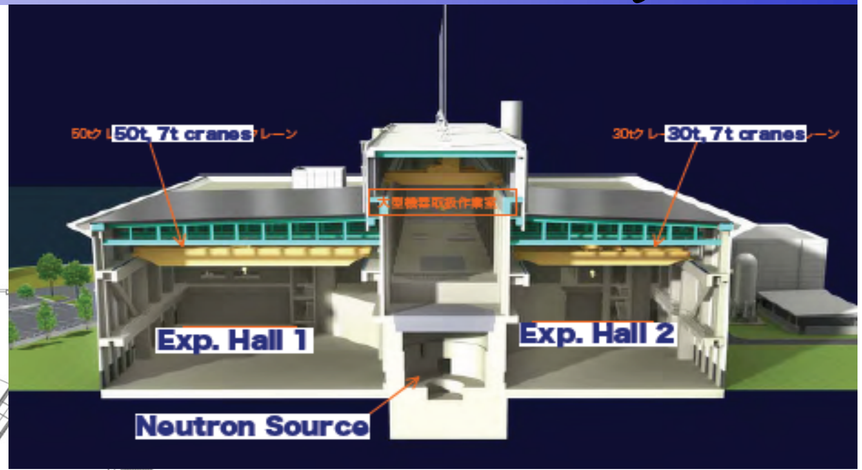
- Nuclear scattering → Isotropic
- Yukawa force → strong angular dependence in the forward region




Linac
3 GeV
N
Neutrino
Materials and Life
Science Facility
30 GeV
Hadron Exp. Facility
Jan. 2008

Material and Life Science Facility

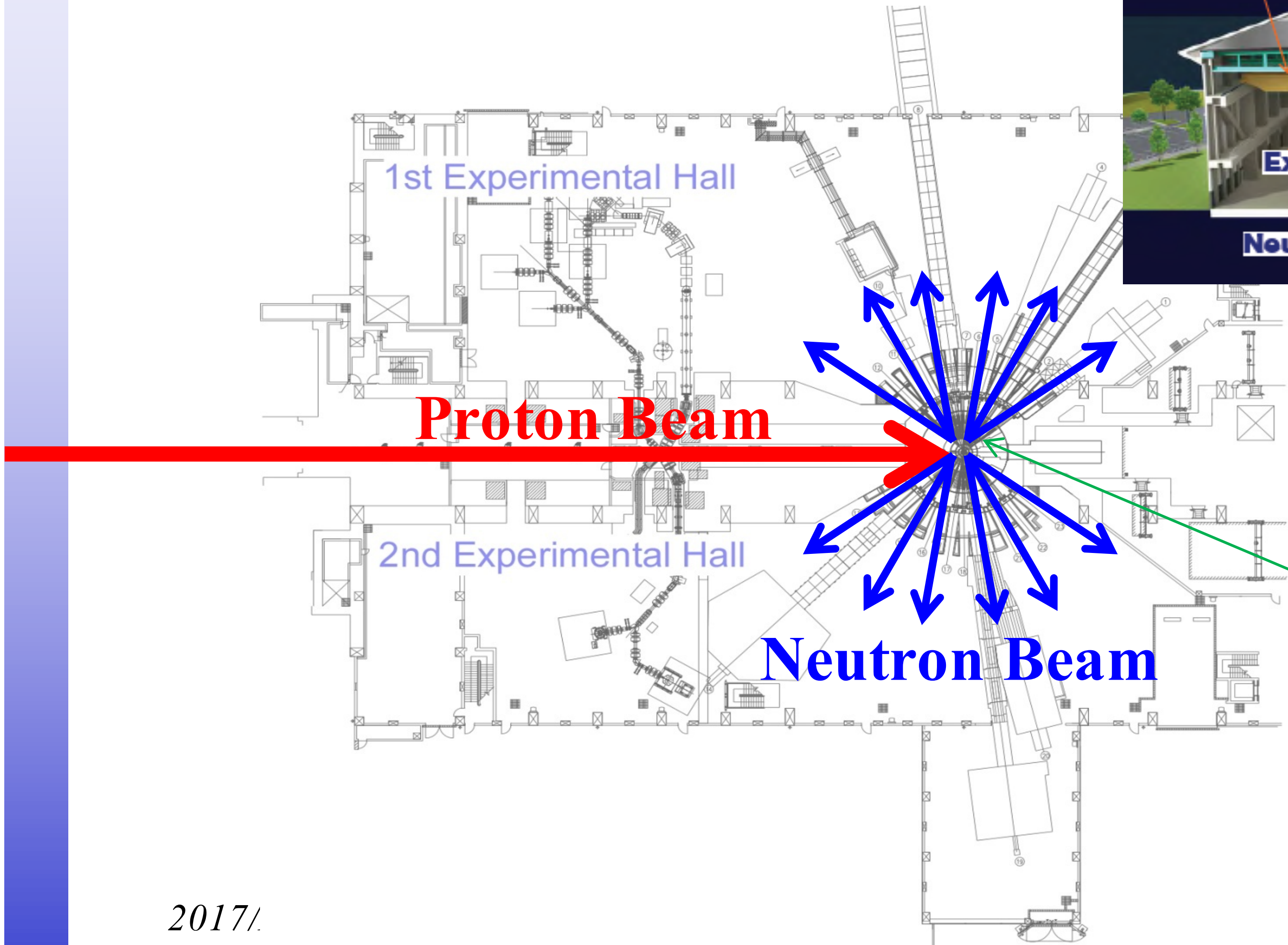


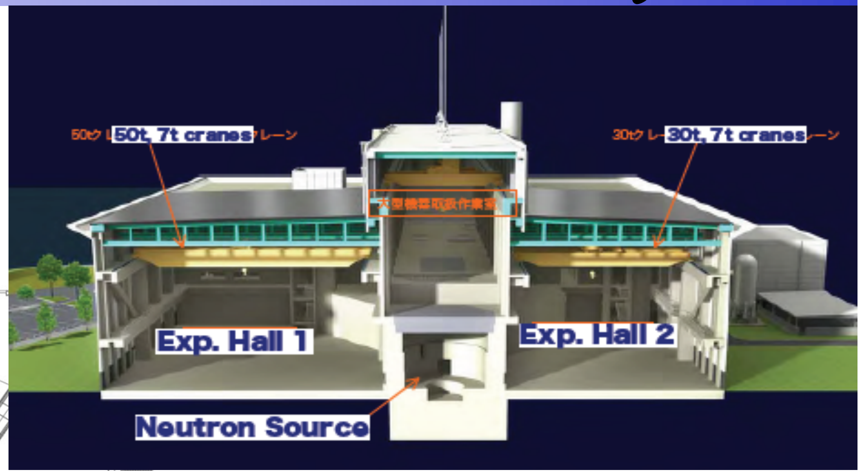


Mercury Target
for neutron production

Muon Production Target

Material and Life Science Facility





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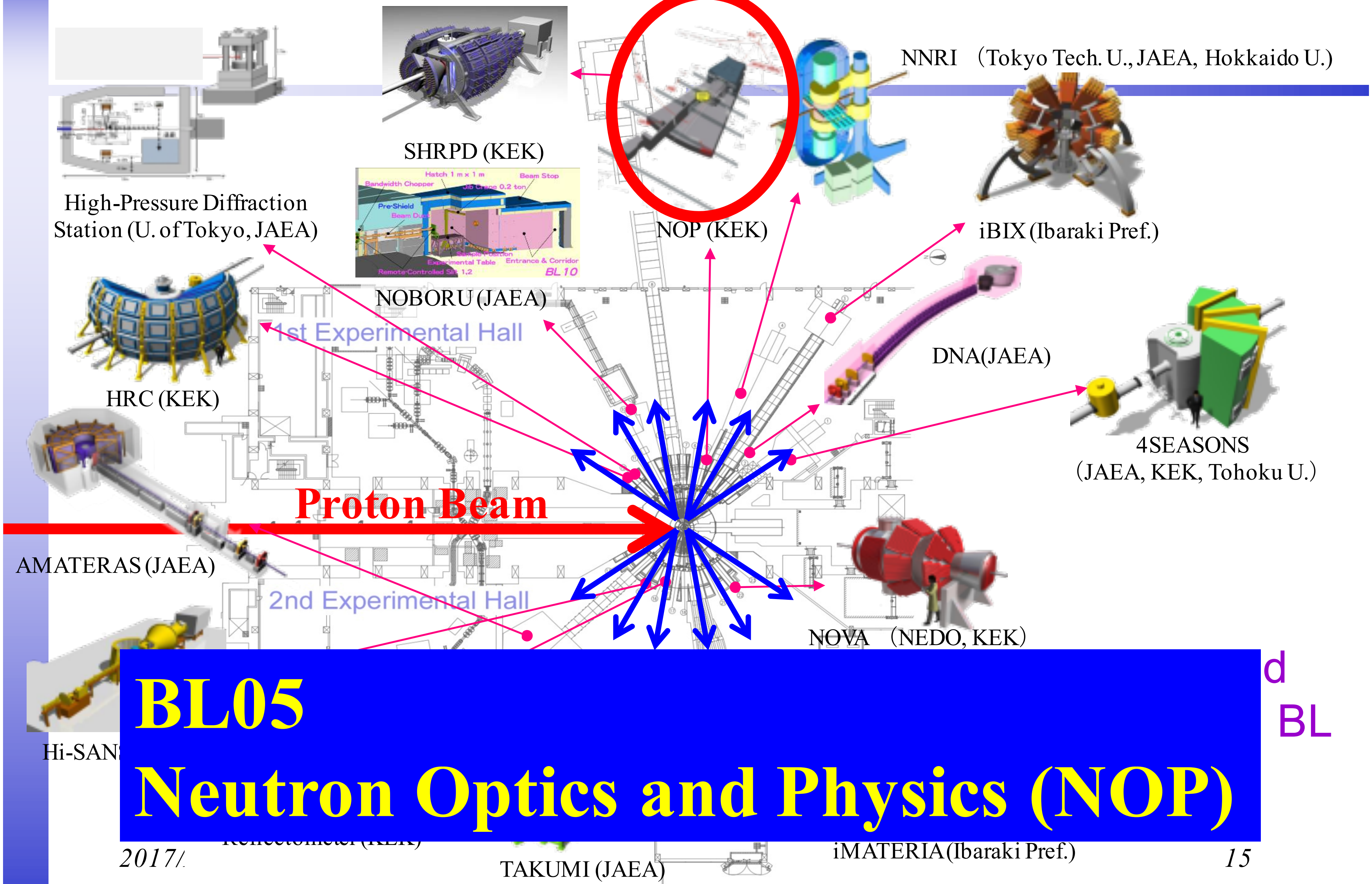
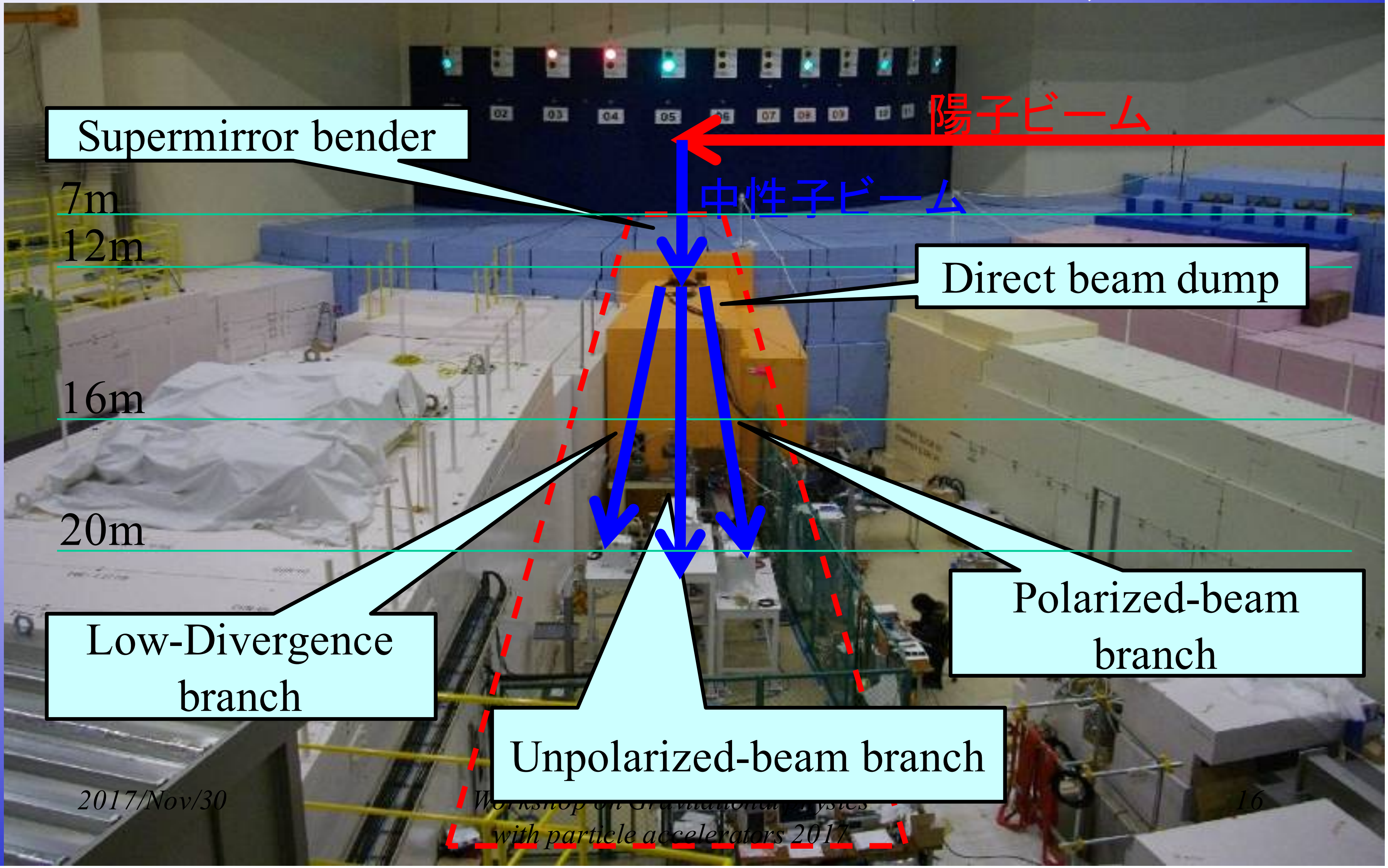
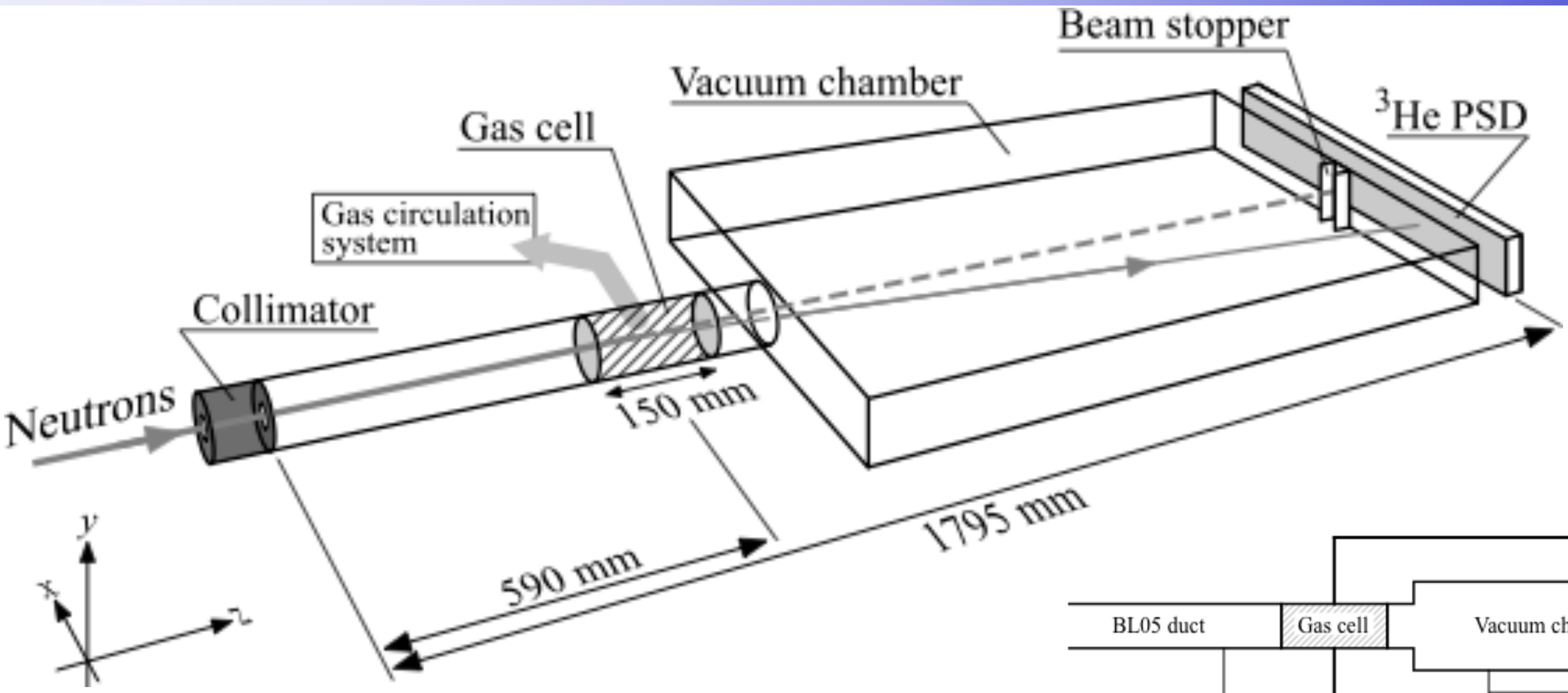


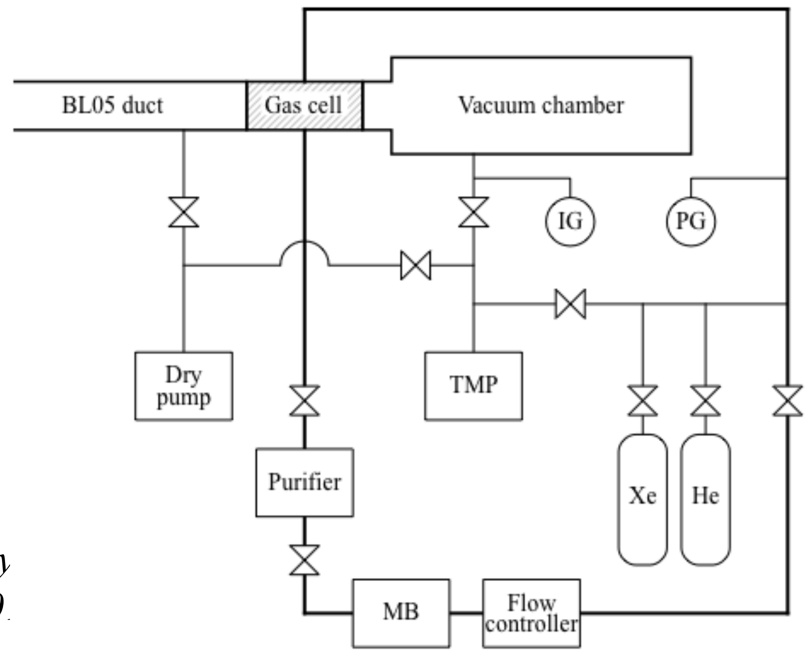
BL05
Neutron Optics and Physics (NOP)

J-PARC/MLF/BL05(NOP)

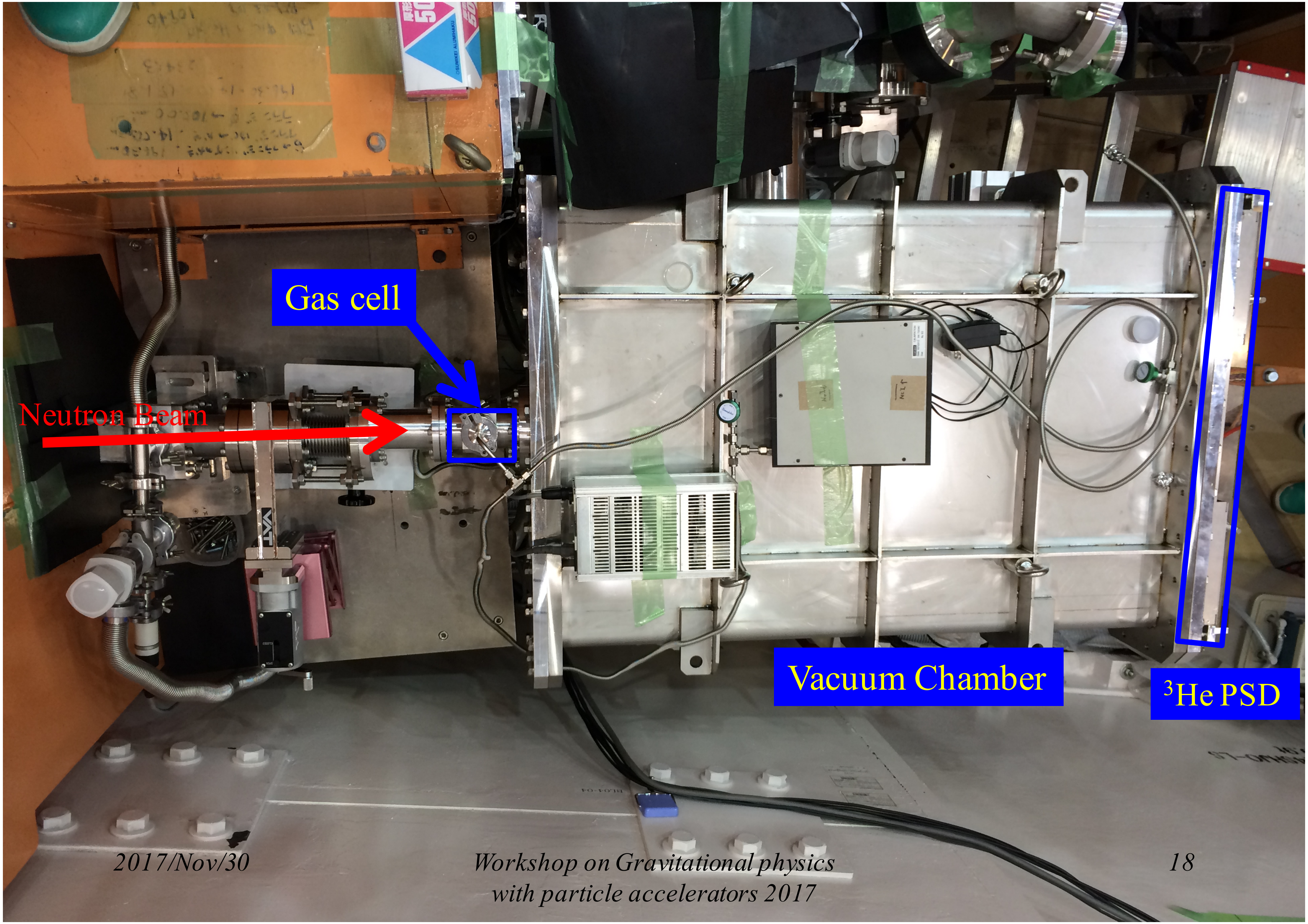


Experimental Setup

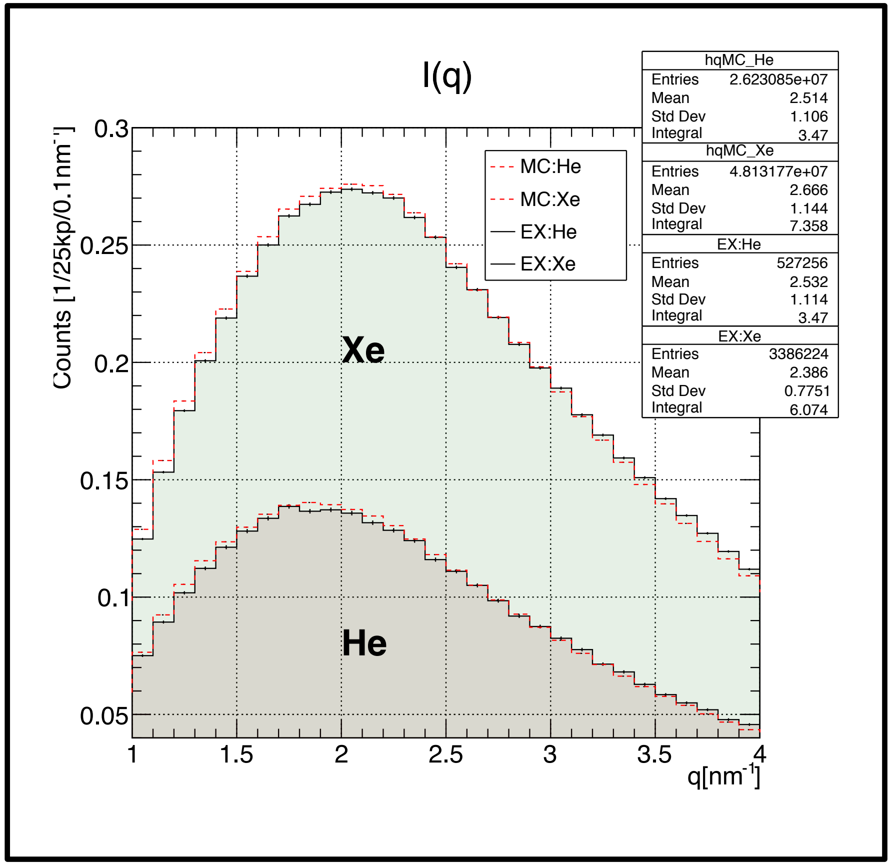


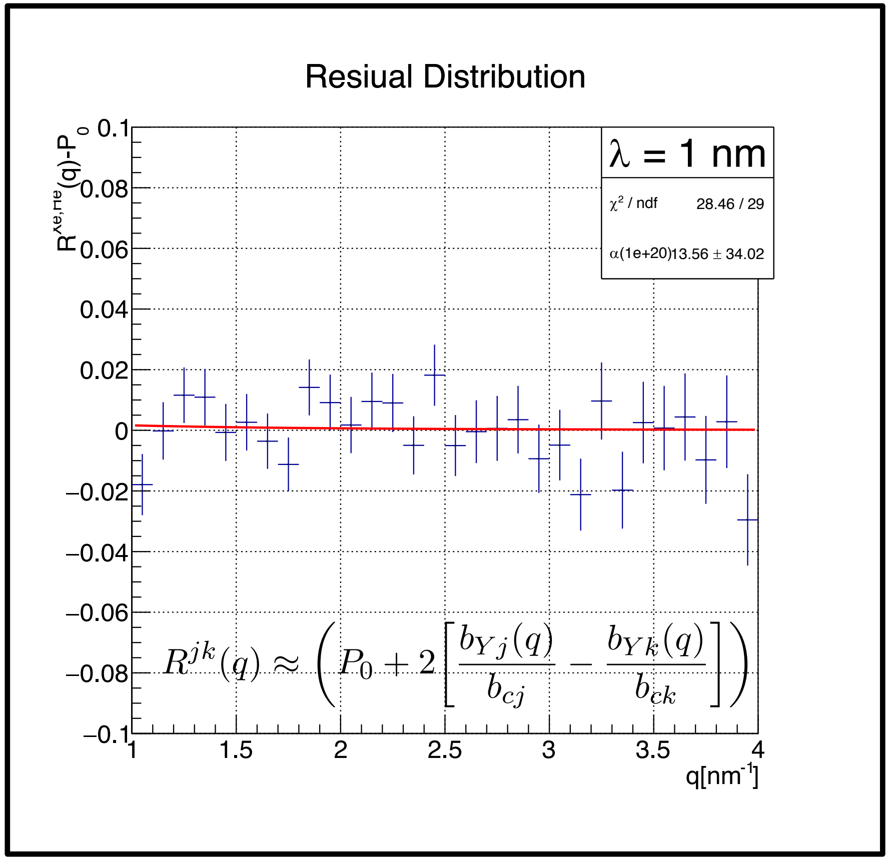


Physics run has been started in 2016.


Gas cell
Neutron Beam
Vacuum Chamber
^{3}He PSD

Results



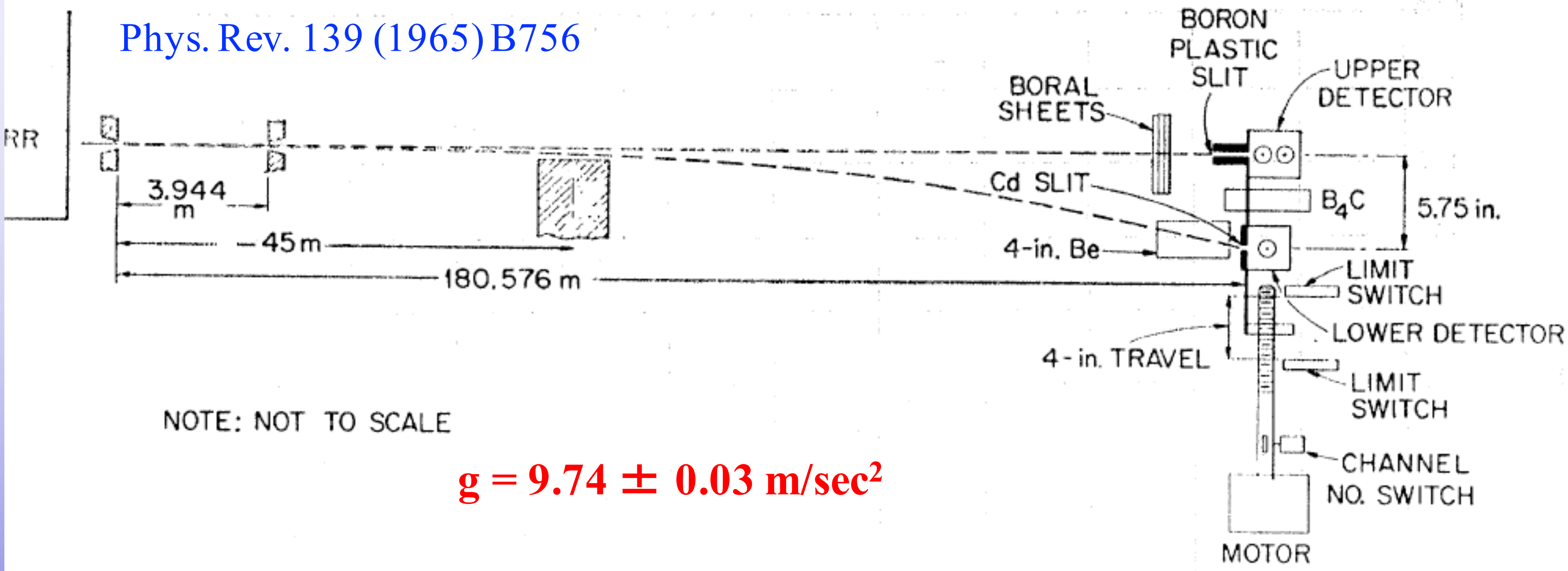


Journal paper is currently being prepared. Final results will be appeared rather soon.

Weak equivalence principle
Antimatter gravity

Gravitational Acceleration of Free Neutron

Phys. Rev. 139 (1965) B756



$g = 9.74 \pm 0.03$ m/sec^2

- Test of subatomic equivalence principle.
  - ← Use of interferometer greatly improved the precision.
    Nucl. Instrum. Meth. A440 (2000) 568
- How about elementary particle/lepton?

Gravitational Acceleration of Electrons

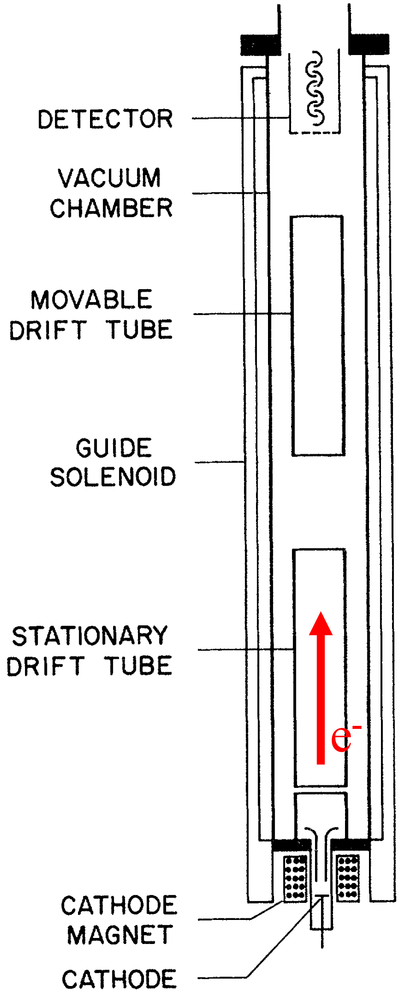
Phys. Rev. Lett. 19 (1967)

VOLUME 19, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1967

EXPERIMENTAL COMPARISON OF THE GRAVITATIONAL FORCE ON FREELY FALLING ELECTRONS AND METALLIC ELECTRONS*

F. C. Witteborn and W. M. Fairbank
Physics Department, Stanford University, Stanford, California
(Received 2 October 1967)

A free-fall technique has been used to measure the net vertical component of force on electrons in a vacuum enclosed by a copper tube. This force was shown to be less than $0.09mg$, where m is the inertial mass of the electron and g is 980 cm/sec^2. This supports the contention that gravity induces an electric field outside a metal surface, of magnitude and direction such that the gravitational force on electrons is cancelled.



- First direct test of gravitational acceleration of electron.
- Inject electrons from cathode and measure time of flight by detector at top.
- Results are controversial and remain inconclusive.
- Another type of experiment is desired.

Gravitational Acceleration of Muonium

- Other candidates : electron, muon, positronium …
- Muonium (μ^+e^- atom, denoted as Mu hereafter) is appropriate candidate because of it's large mass, long lifetime and electrical neutrality.
- Consideration for free drop experiment of Mu

t (ms)	Free drop (nm) $1/2gt^2$	Thermal motion (cm) $t\sqrt{2E/m}$
25	2.5	$1 \times \sqrt{T}$
50	12	$2 \times \sqrt{T}$
75	30	$2.5 \times \sqrt{T}$

- Free drop experiment of Mu seems difficult in straightforward way.
- Completely new idea is necessary.
  → Interferometer

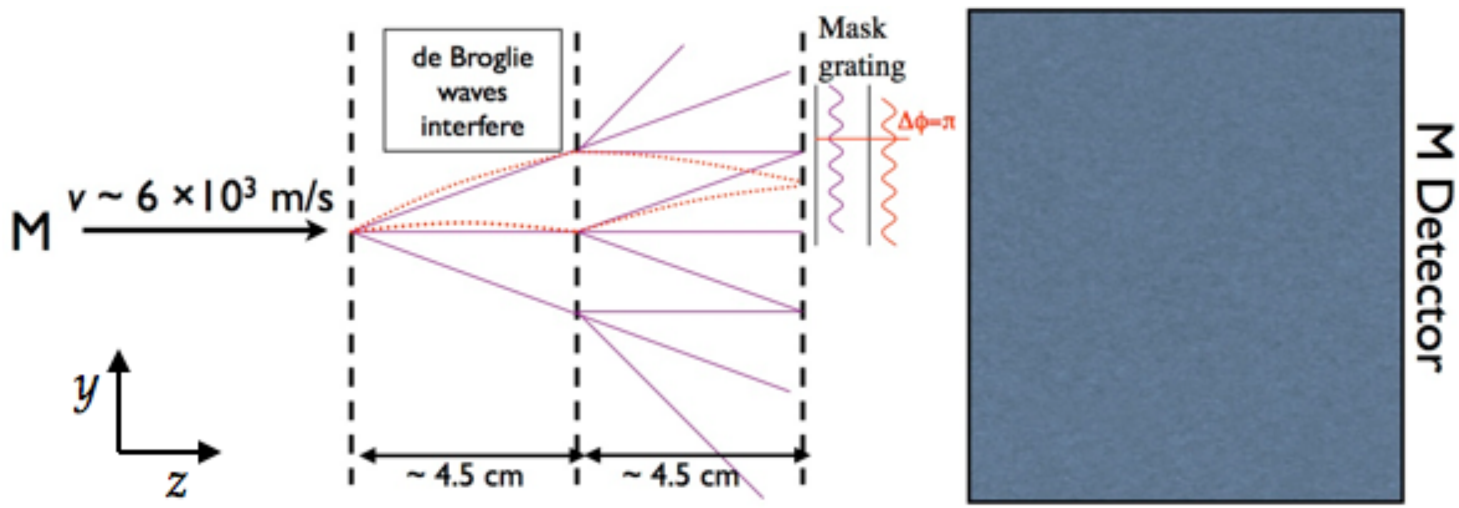
Introductory Muon Science,
Kanetada Nagamine
Cambridge University Press

Antimatter Gravity

- Antimatter gravity has never been directly measured.
- Result of indirect test:
  - g/g - 1 < 10^{-7} , arXiv:0907.4110
- Direct limit of antihydrogen:
  - -65 < g/g < 110 , Nature Commun. 4 (2013) 1785 by ALPHA collaboration
- Again, Mu is suitable for testing antimatter gravity as of it's mass is dominated by μ^+.
- Also, it will be a test for purely leptonic system/second generation.

Antimatter Gravity

- Application of Mach-Zehnder type interferometer originally developed for atom/neutron.
- Three equally spaced identical gratings; first two for producing interference pattern which is scanned by moving third one. The grating pitch is 100nm.
- The experiment is planned to perform at PSI. Precision is 0.03g in 100days by assuming 10^5 Mu/sec.



arXiv:physics/0702143 [physics.atom-ph]
arXiv:1601.07222 [physics.ins-det]

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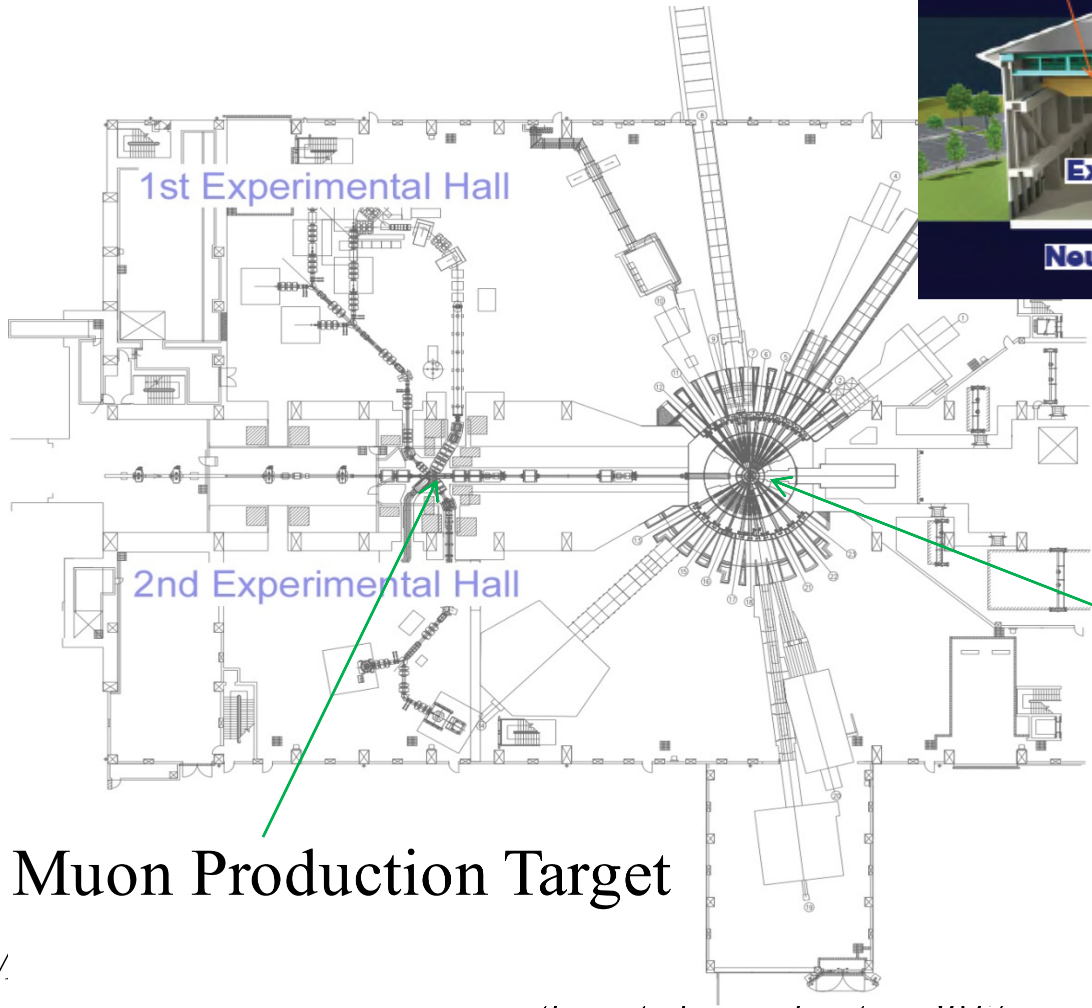

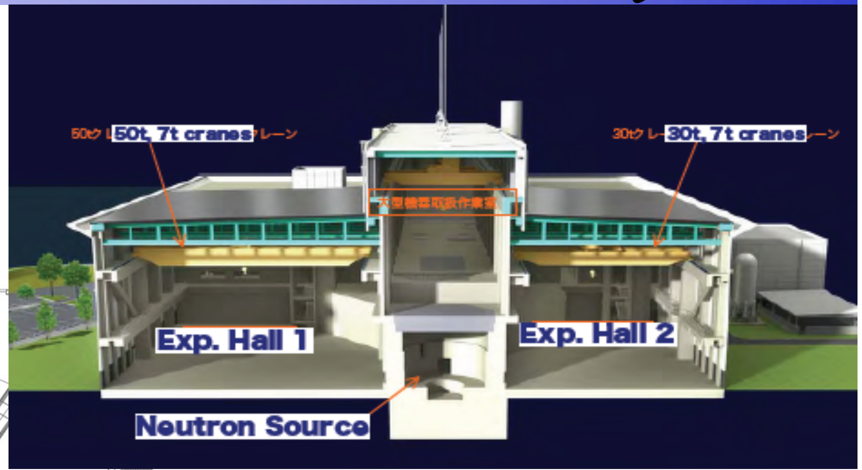

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for neutron production

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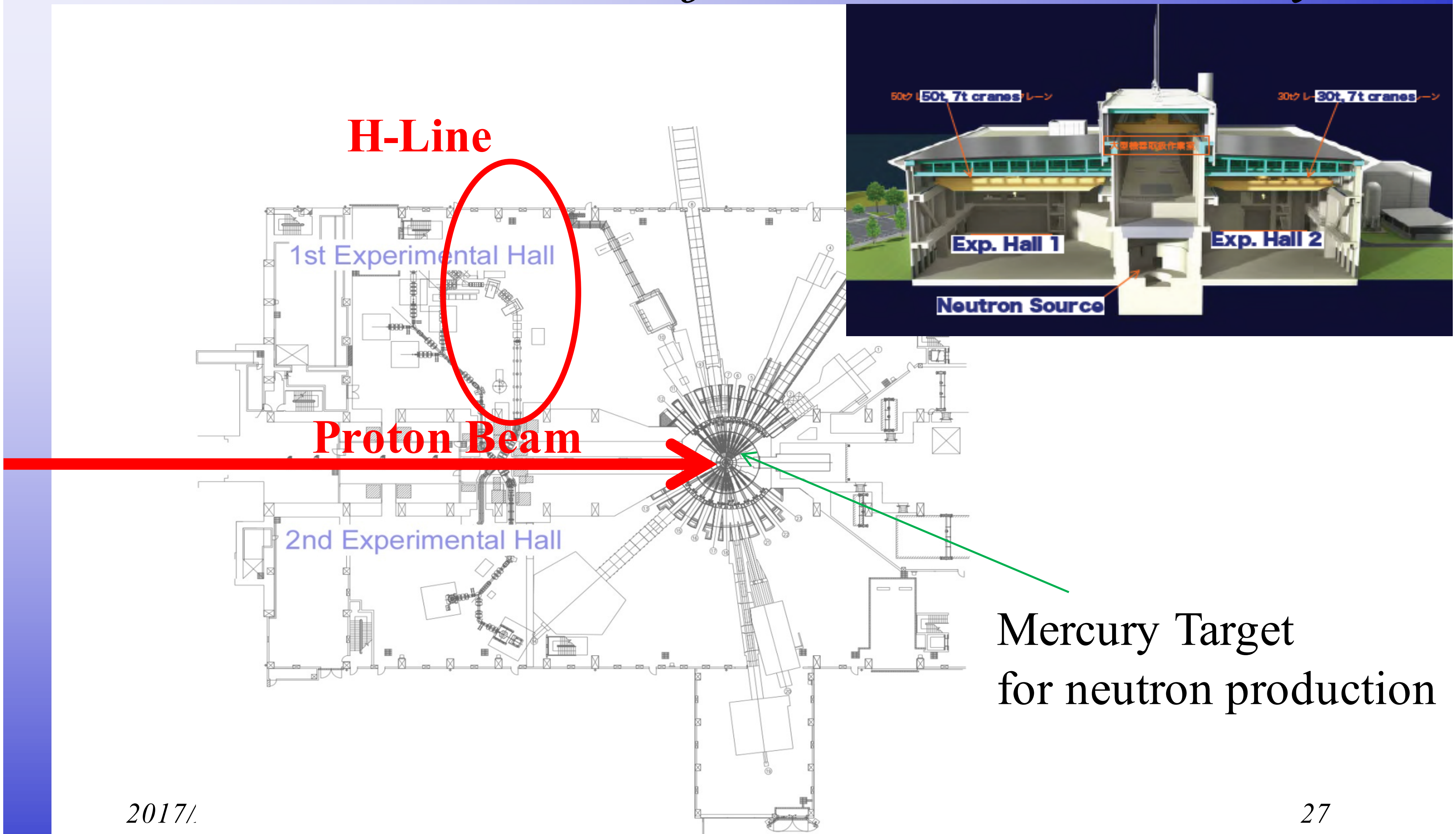
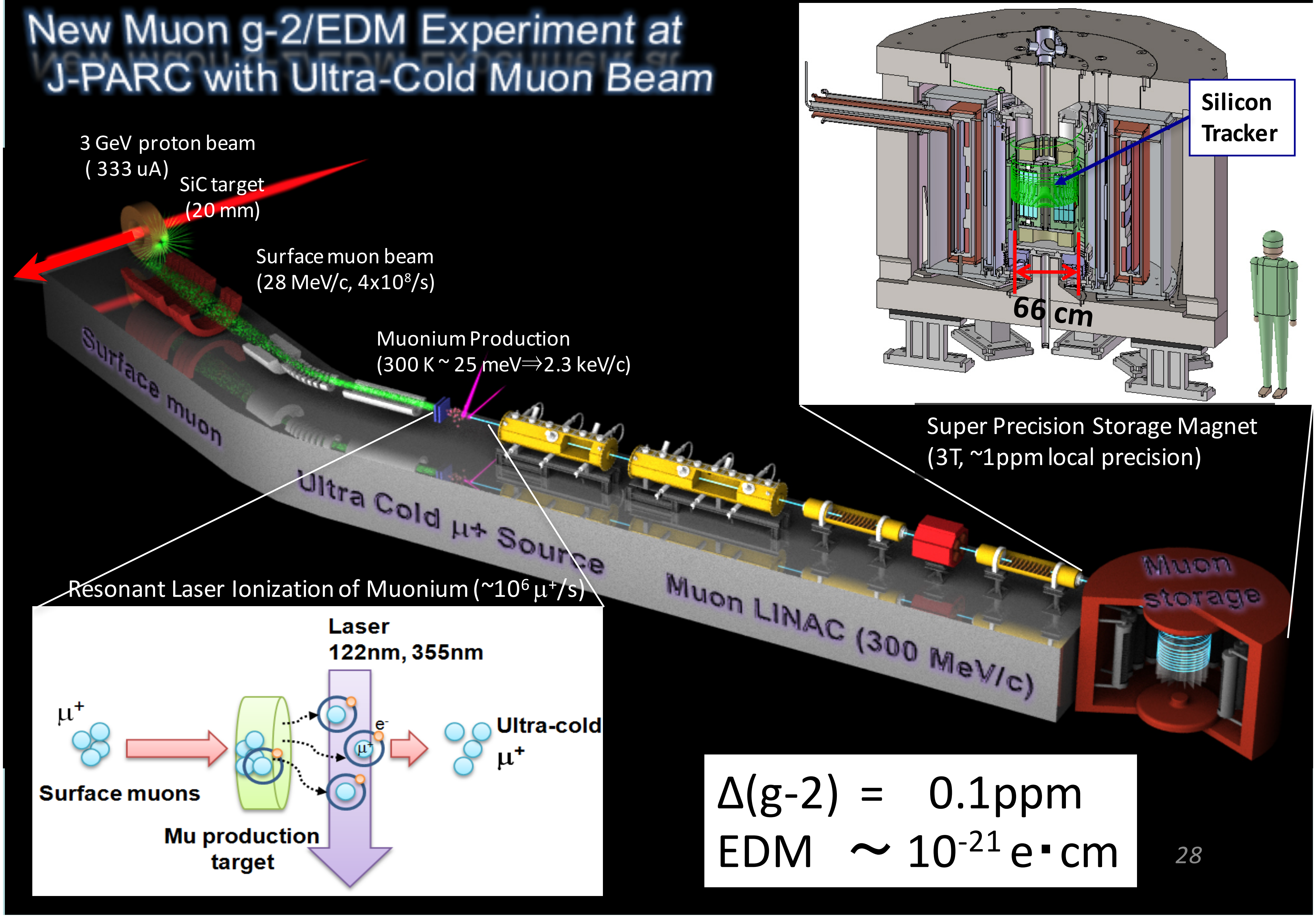
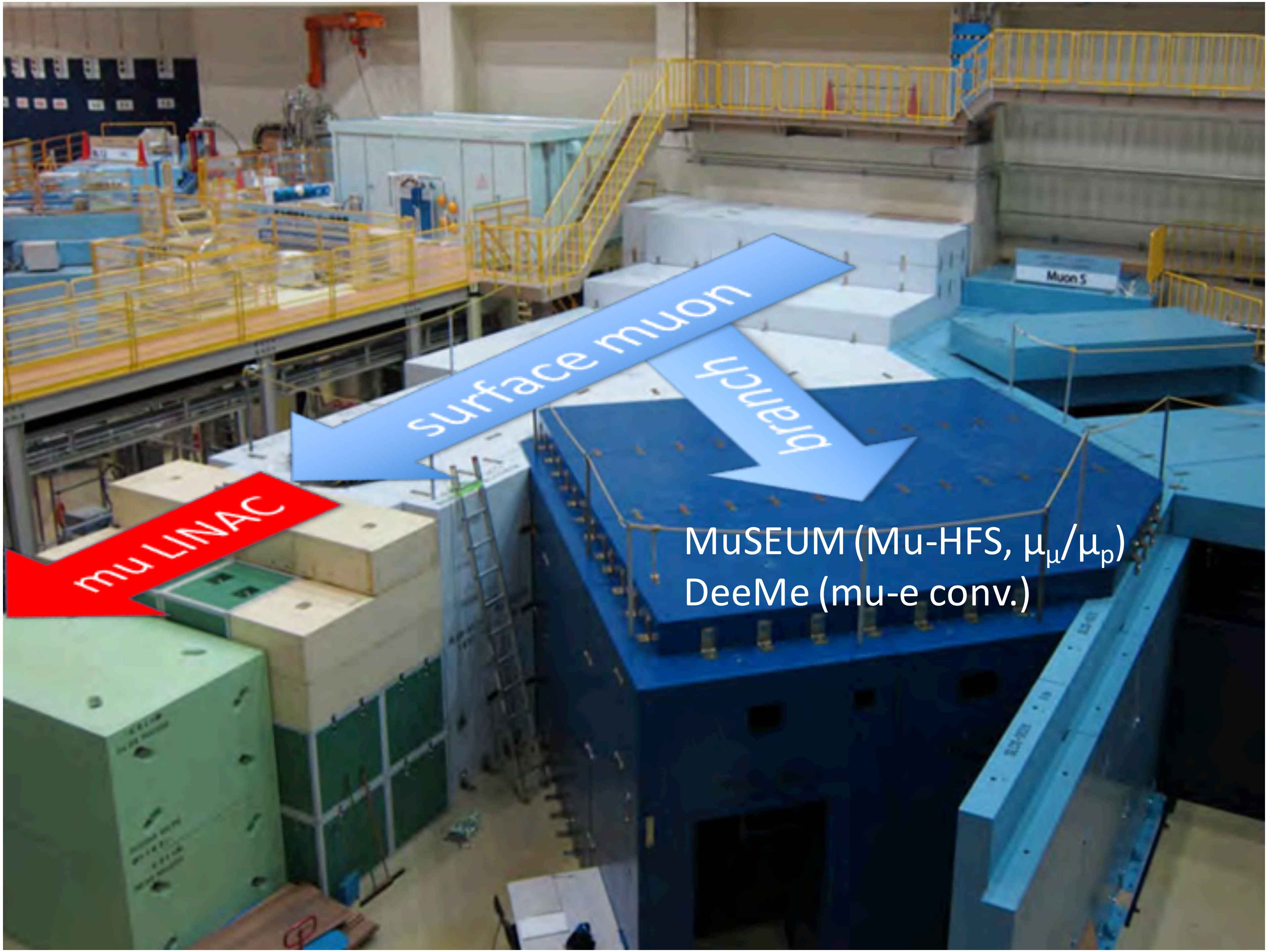


New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

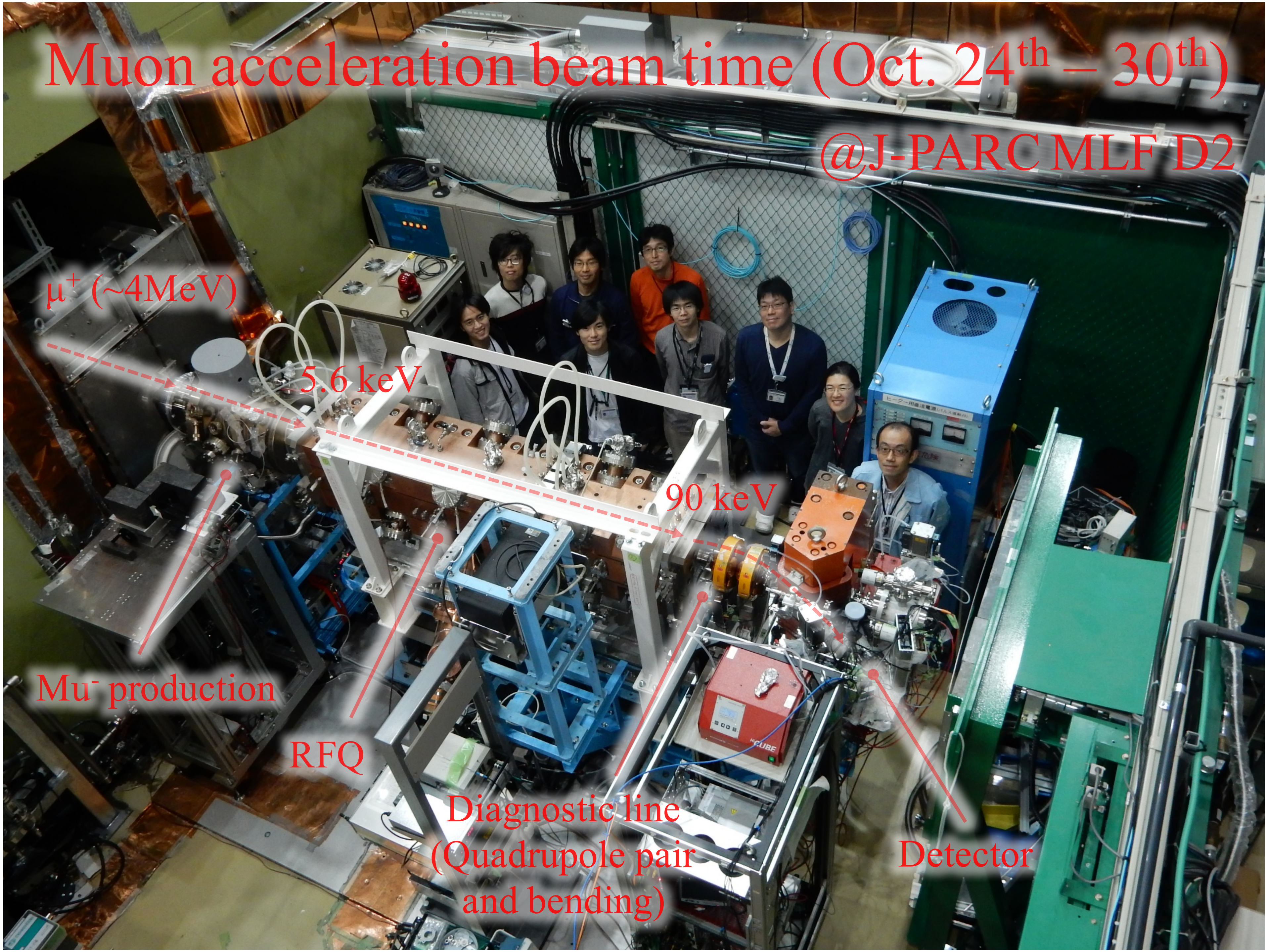


$\Delta(g\text{-}2) = 0.1\text{ppm}$

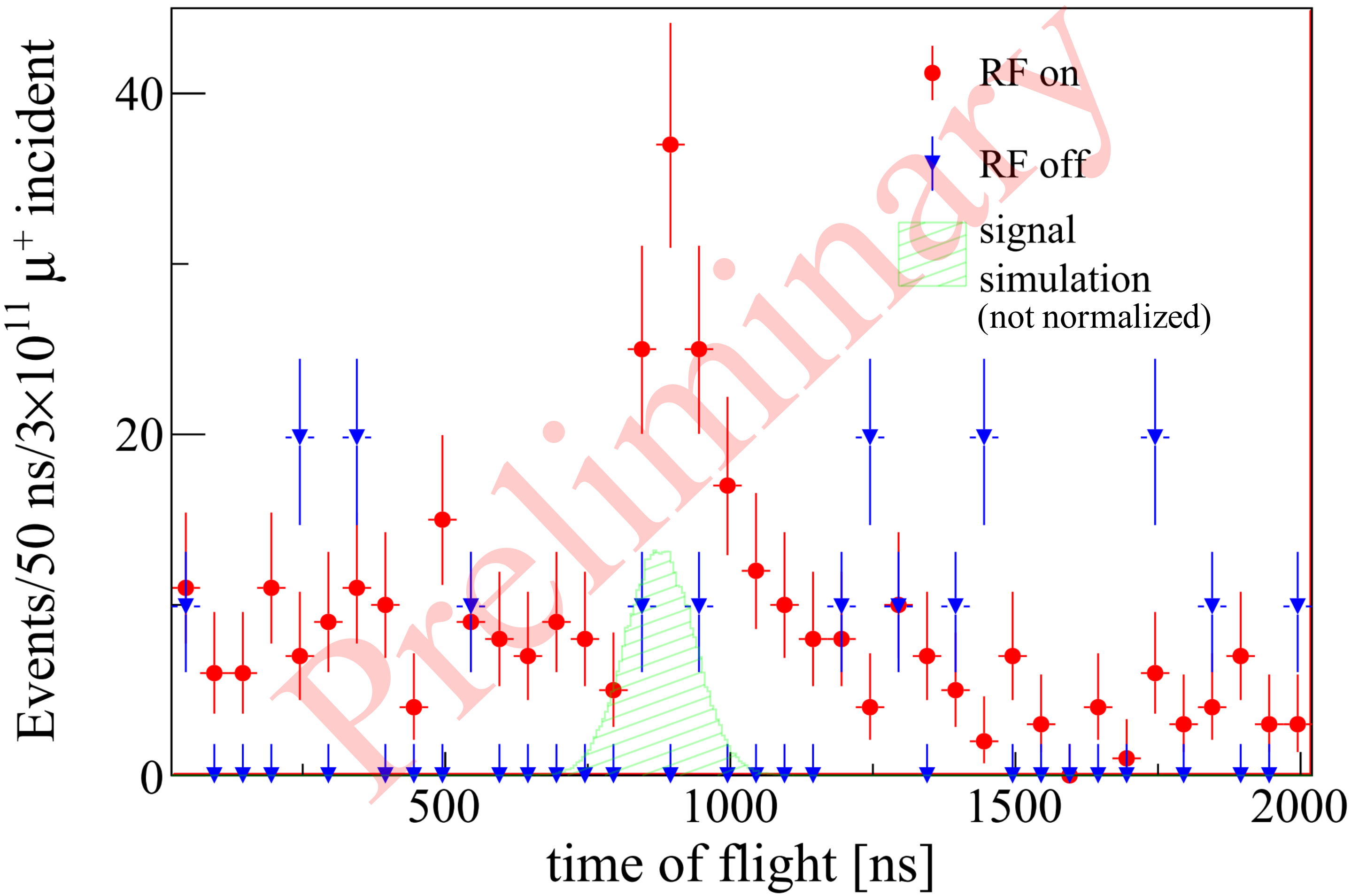
EDM $\sim 10^{-21}\, e \cdot \text{cm}$



surface muon
branch
mu LINAC
MuSEUM (Mu-HFS, μ_μ/μ_p)
DeeMe (mu-e conv.)
Muon S


Muon acceleration beam time (Oct. 24th – 30th)
@J-PARC MLF D2
μ+ (~4MeV)
5.6 keV
90 keV
Mu- production
RFQ
Diagnostic line
(Quadrupole pair
and bending)
Detector

Result



the world's first muon rf linear acceleration!

Summary

- Low energy neutron and muon/Mu are ideal probe to study gravity effect because of their large mass, long lifetime and electrical neutrality.
- J-PARC provide high intense neutron and muon beam.
  - Unique experimental environment.
    - BL05 for neutron fundamental physics.
    - H-Line for muon physics.
  - Pulsed feature may be utilized.
- Any theoretical input will be highly welcomed for design of future experiment.