# Synergies in the high-power and muon programs in Japan

Koichiro Shimomura KEK-IMSS,J-PARC

# What is muon ?
# Today's understanding

- Mass 1/9 of proton 200 of electron
- Positive muon ~ light proton
- Negative muon ~ heavy electron
- Spin 1/2
- 2nd generation of charged lepton
- Electro-Weak Interaction ○
- Strong Interaction ×
- Spin polarized in birth
- Relatively long life time (2.2μs) parity non conserving decay
- High transmission capability (useful for imaging)

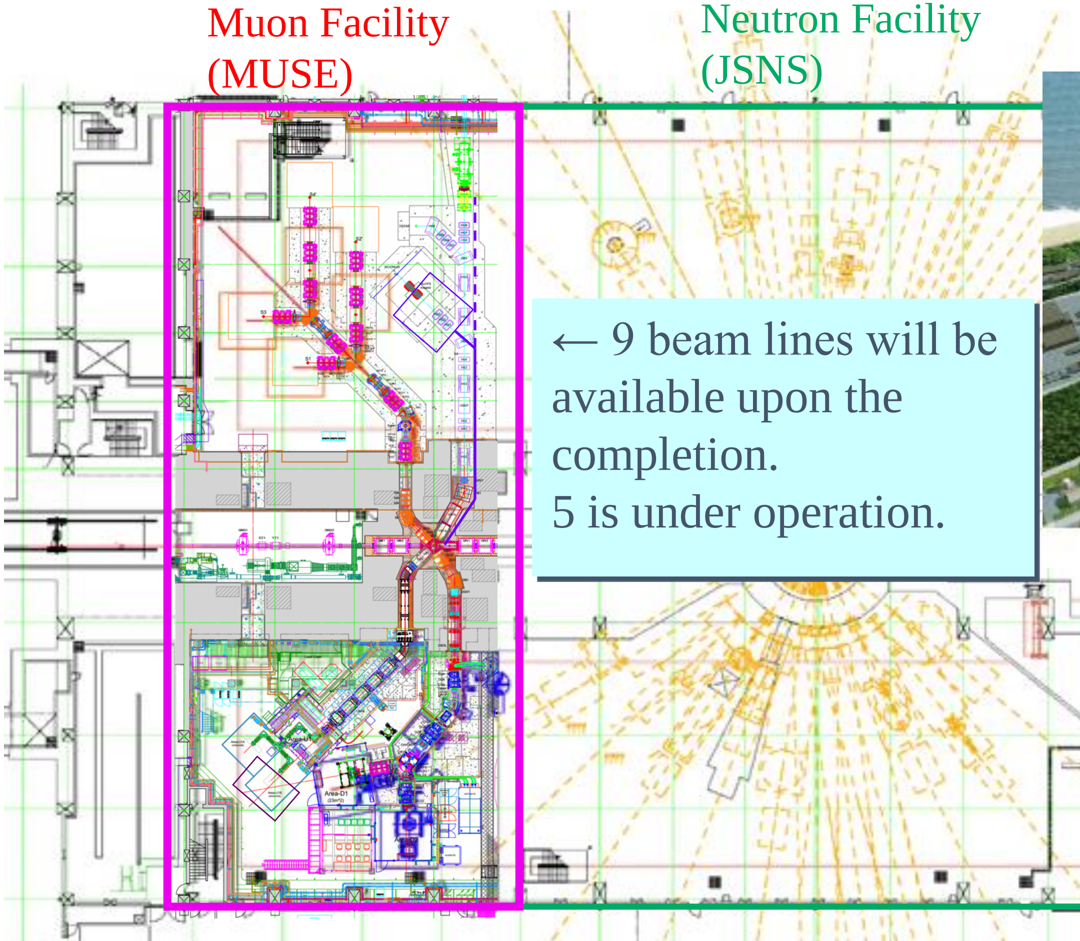
⇒These unique feature enable us to produce various applications

# Muon Facility @J-PARC

## MUSE="Muon Science Establishment"

Muon Facility (MUSE)

Neutron Facility (JSNS)

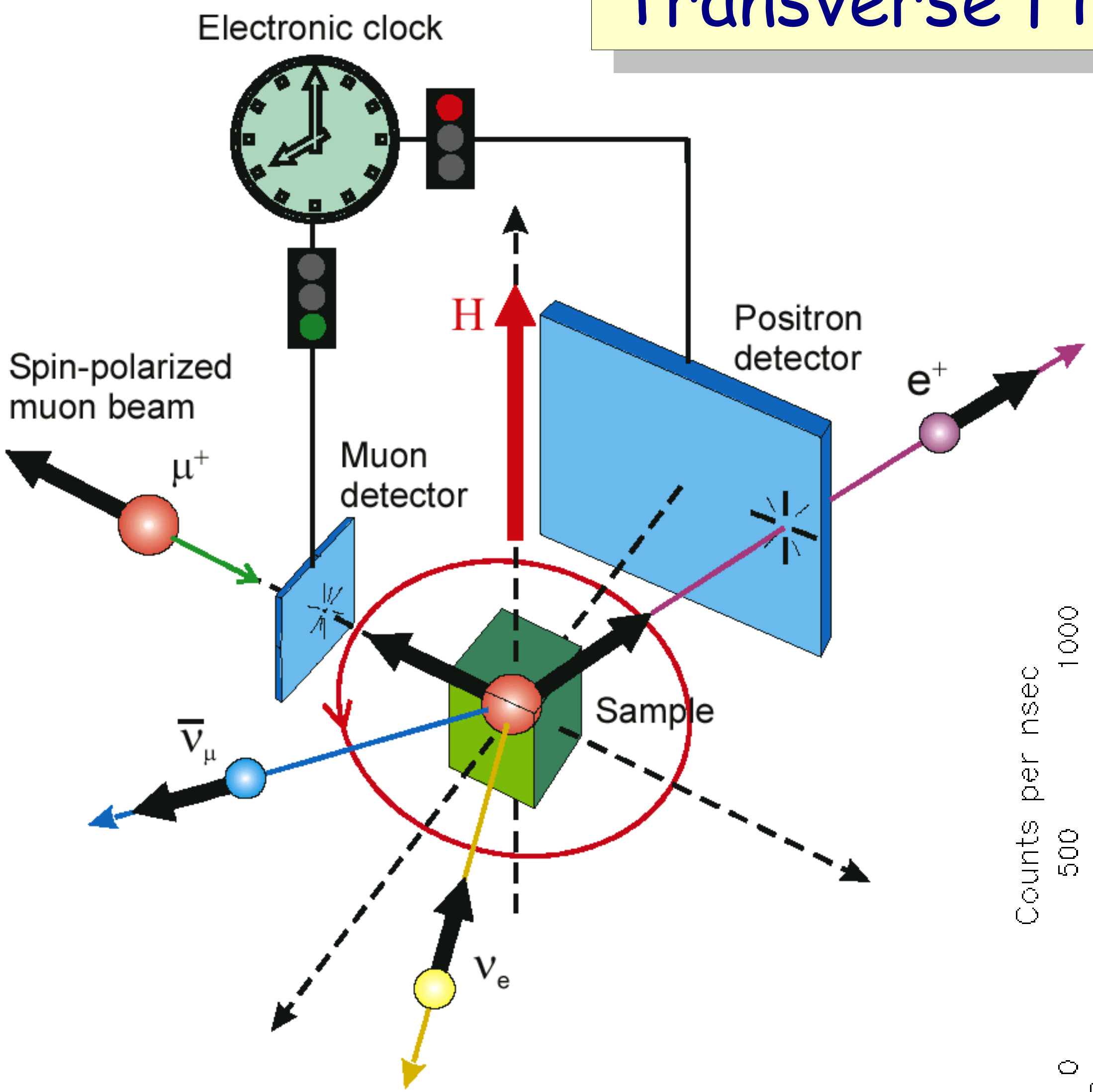


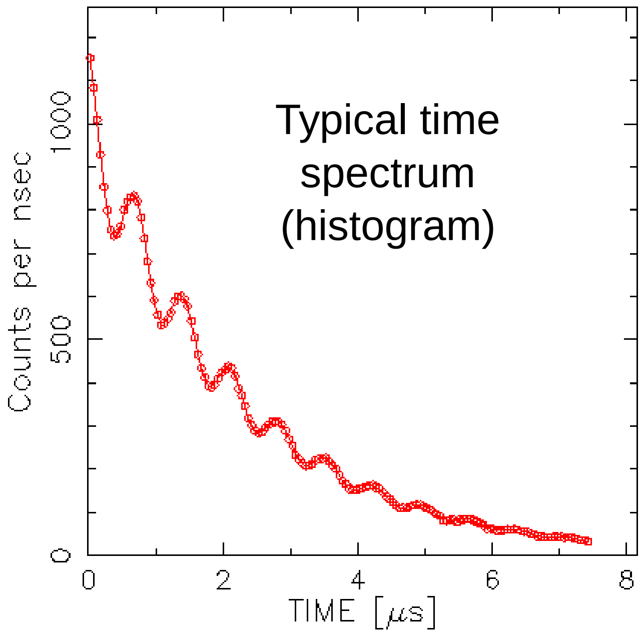
← 9 beam lines will be available upon the completion.
5 is under operation.


Joint Project between KEK and JAEA

Materials and Life Science Experiment Facility

# Transverse Field (TF) $\mu^{+}SR$



# How about muon g factor ?

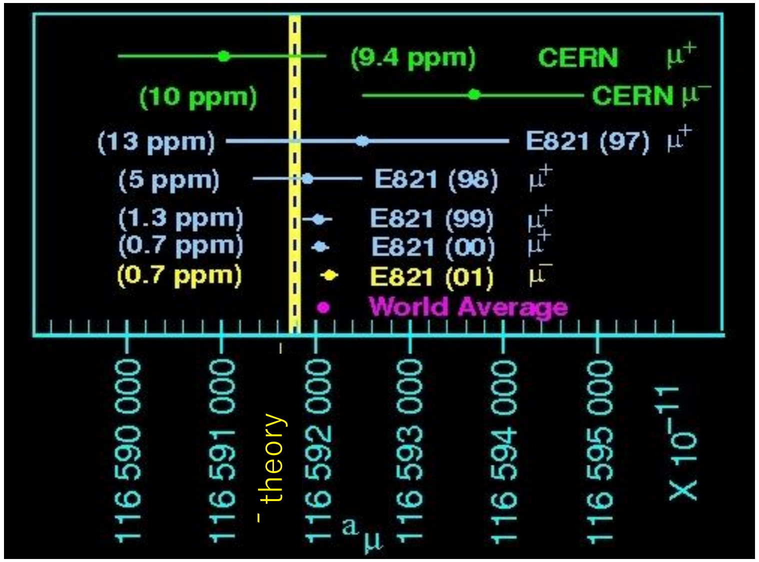
$$g = 2(1 + a);$$

$$a_\mu^{exp} = 116\,592\,089(54)_{st}(33)_{sy}(63)_{tot} \times 10^{-11}$$

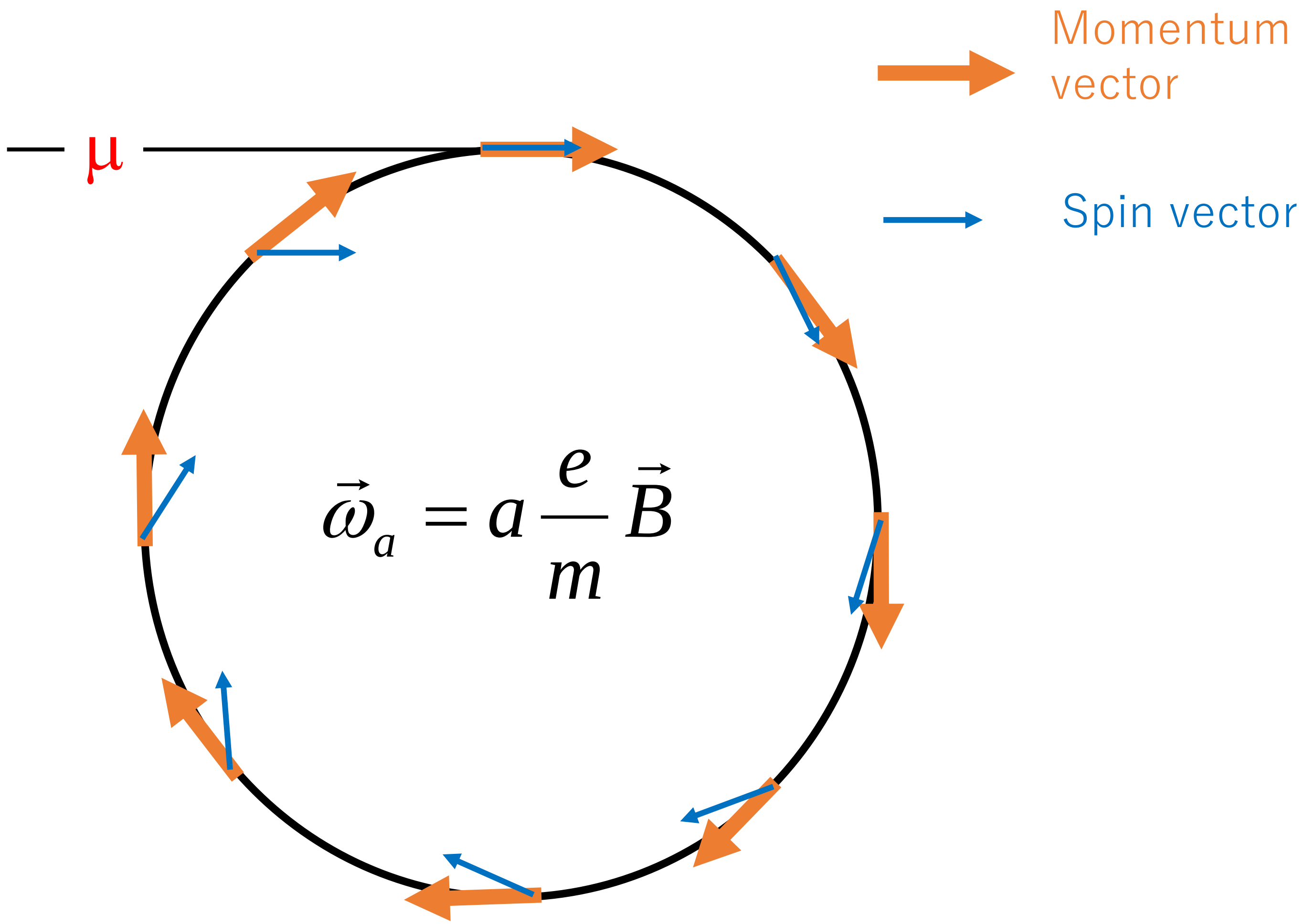
$$a_\mu^{SM} = 116\,591\,820.5 \pm 36 \times 10^{-11}$$

$$\Delta a_\mu^{\rm today} = (269 \pm 72) \times 10^{-11}$$

$$3.7\sigma$$

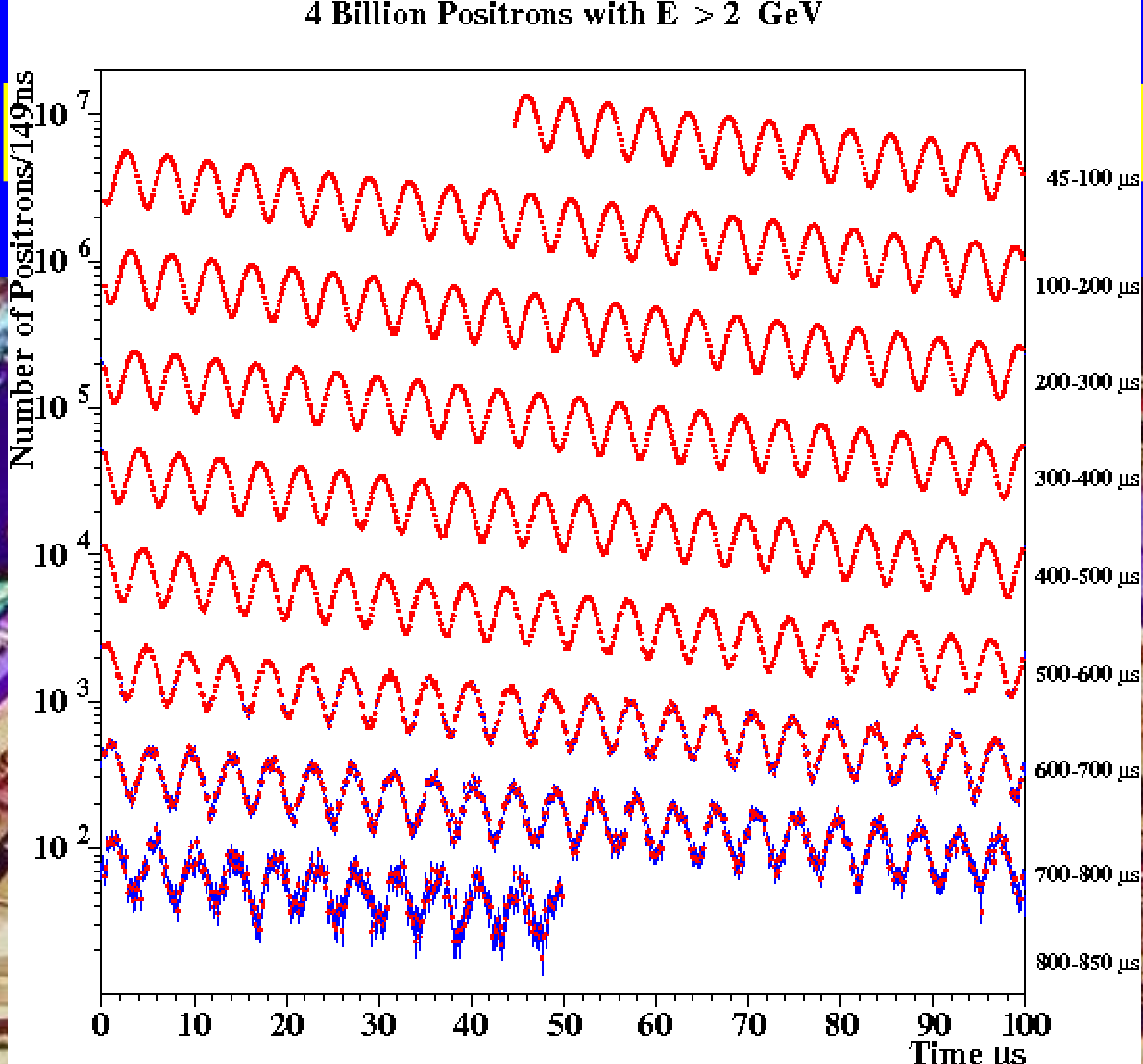


# Muon Spin Precession in Ring
# if g~~≒~~2 (a=0)




$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

# T L)



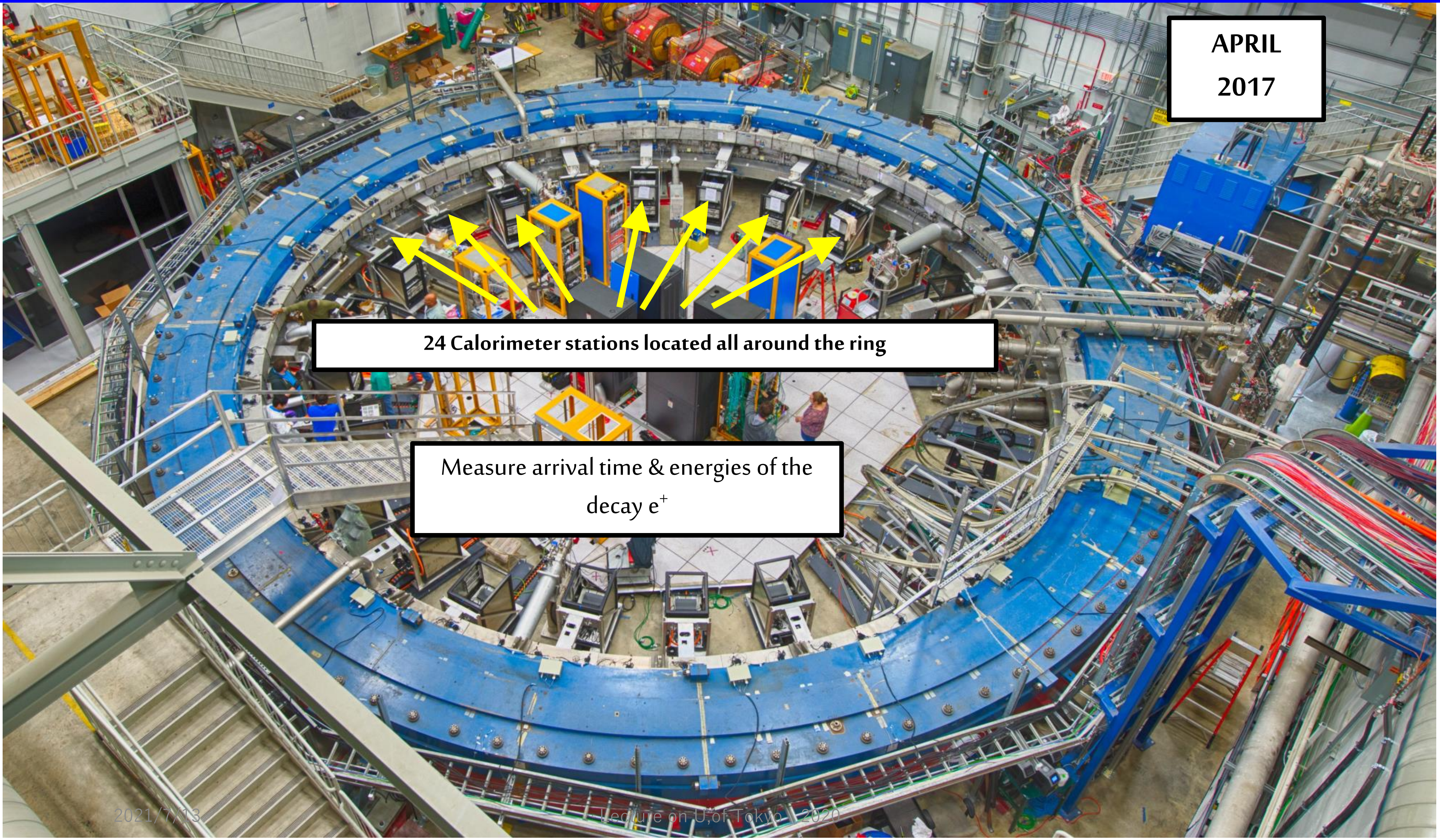

Muon lifetime $\gamma\tau_\mu$ = 64.4 µs

(g-2) period $\tau_a$ = 4.37 µs

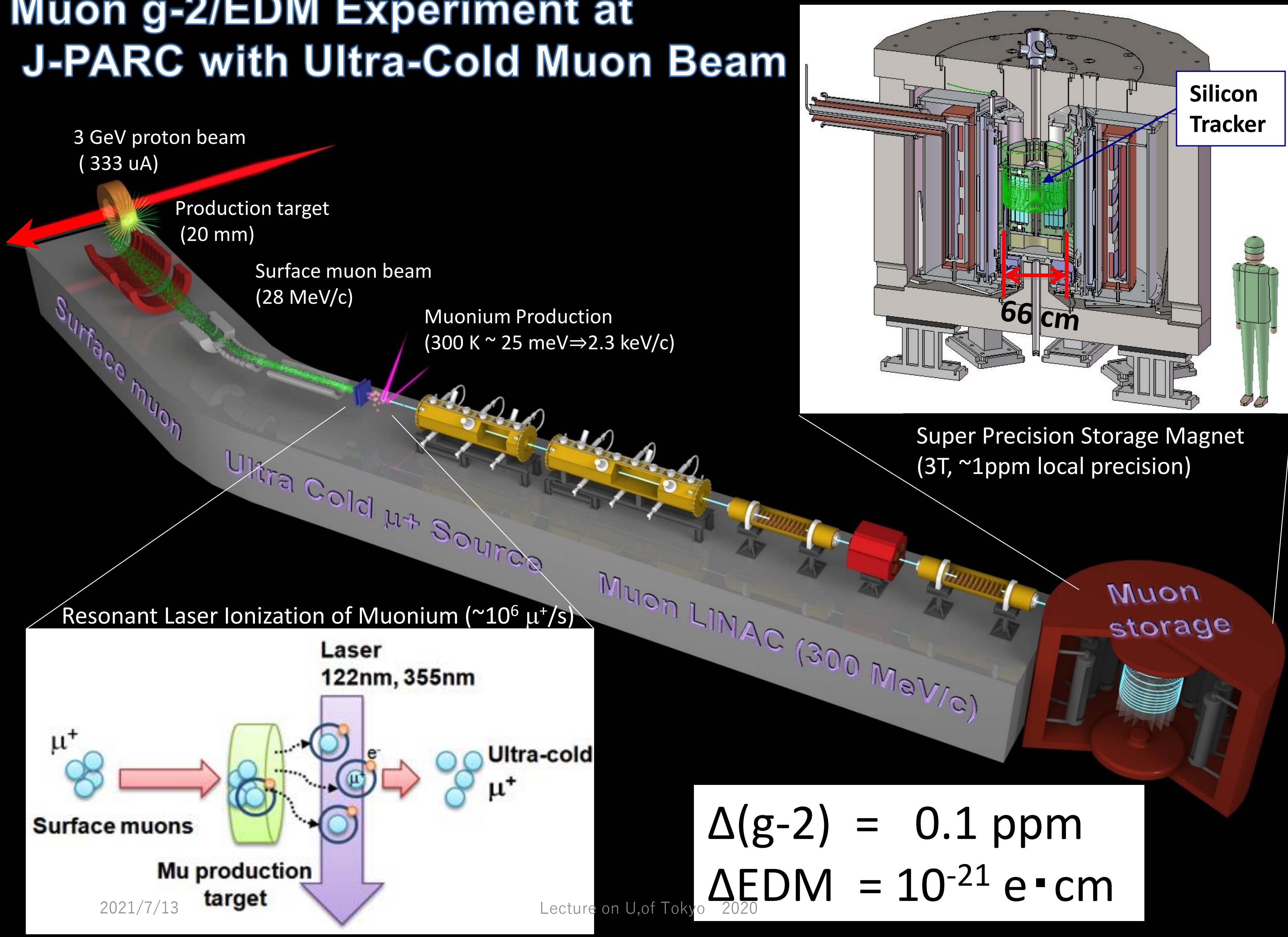
Cyclotron period $\tau_c$ = 149 ns

# The muon ring moved to Fermilab (22 June – 25 July 2013)

# The Magnet (at Fermlab)



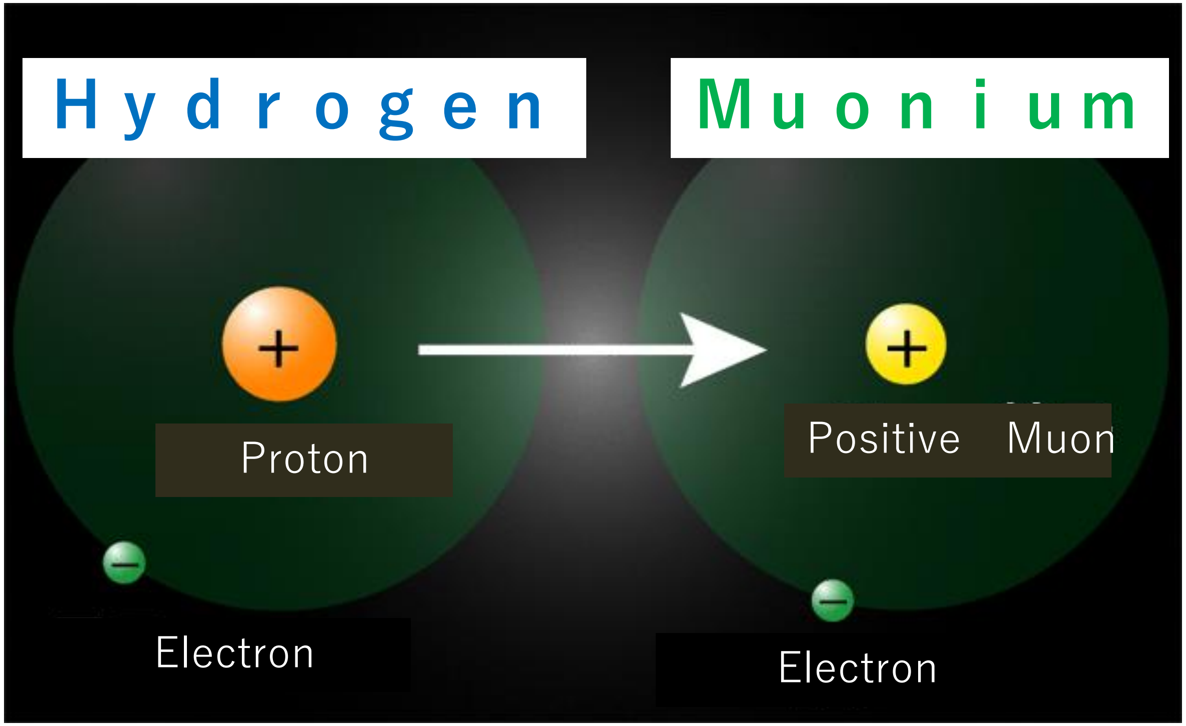
# Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam




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

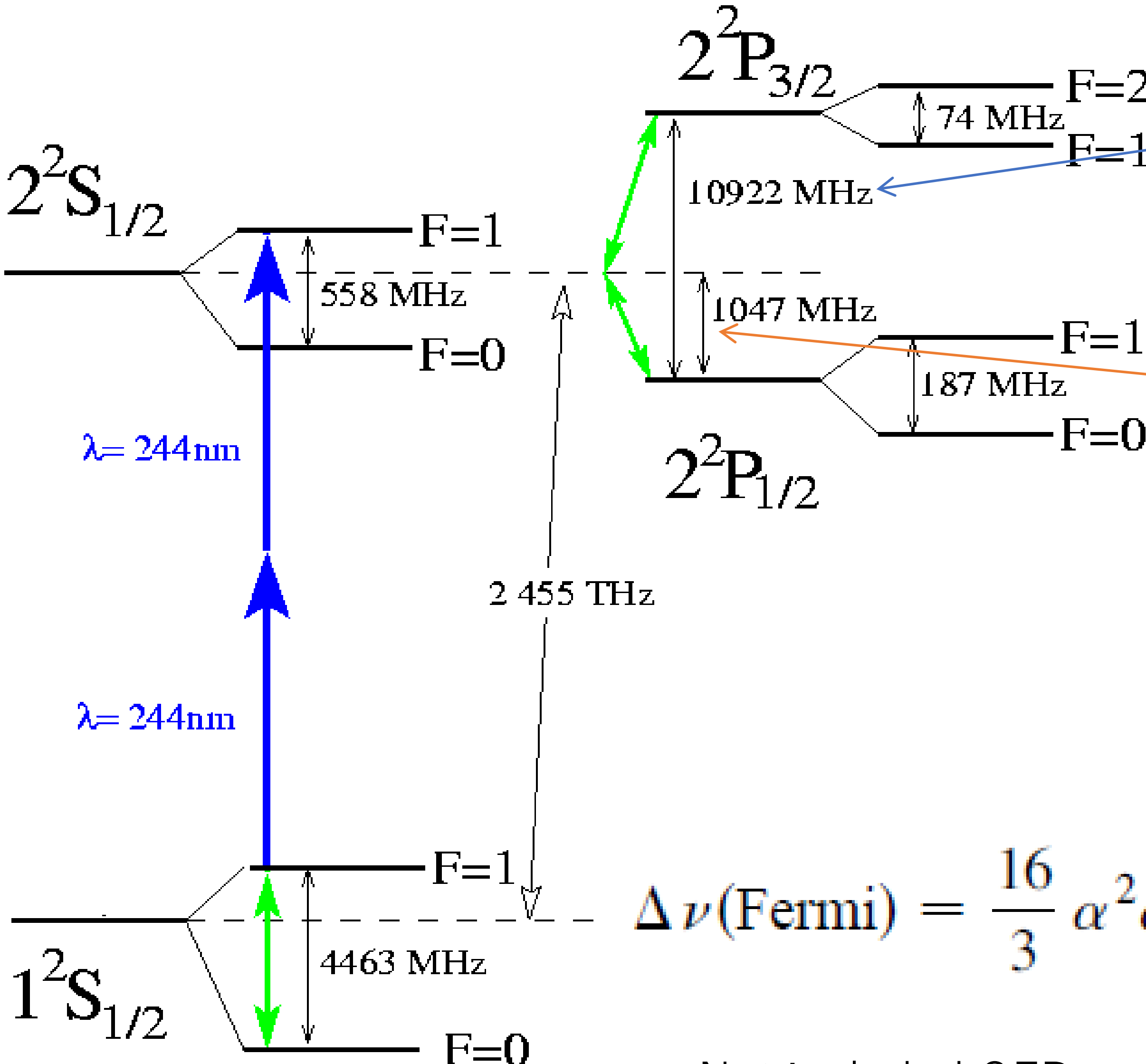
$\Delta EDM = 10^{-21}\ e\cdot cm$

# Muonium




- Pure leptonic bound system, free from finite size effect.
- Good example for testing QED,
- HFS,1s-2s, Lamb shift
- Muonium is also useful in condensed matter physics and chemistry
- Reduced mass of electron in hydrogen and muonium differ only 0.5%

# Mu(H) Energy Diagram




Fine Structure
explained by Dirac

Classical Lamb Shift
QED
Tomonaga, Shwinger,
Feynman

$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1+\frac{m_e}{m_\mu}\right]^{-3}.$$

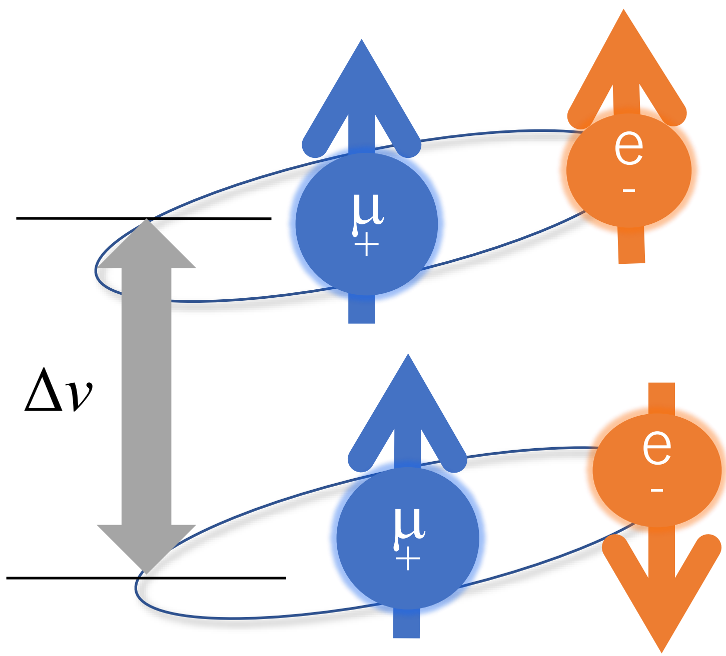
Not included QED weak hadronic correction

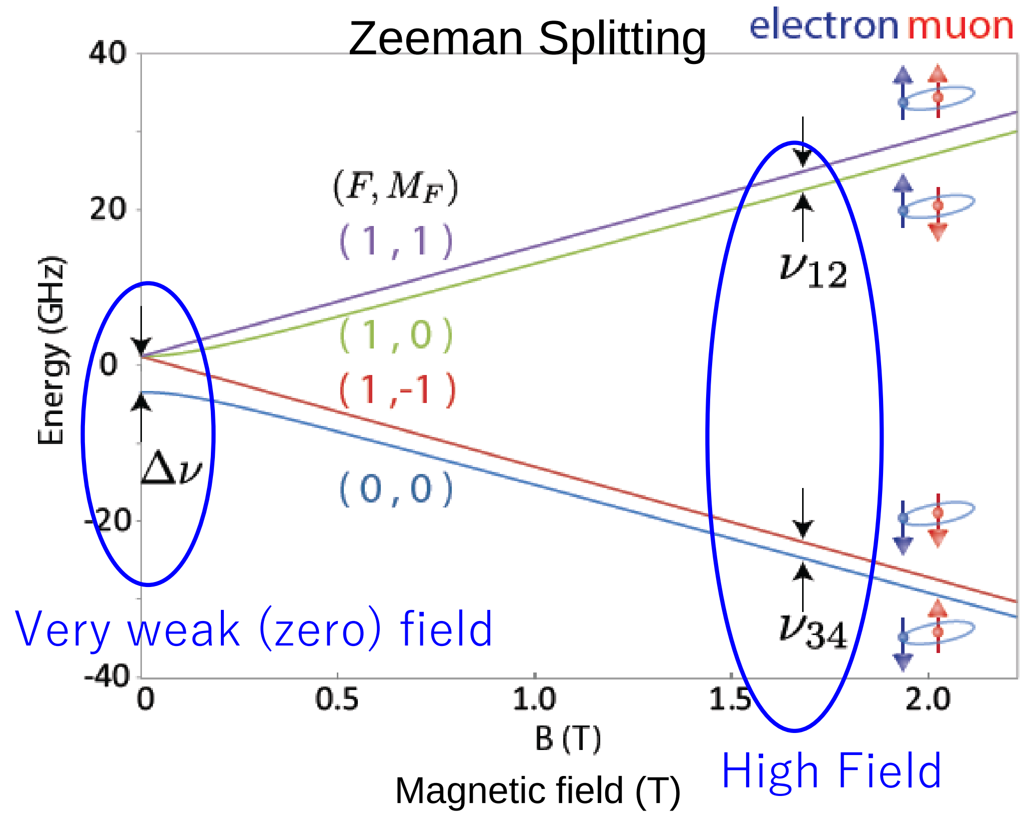
# Muonium Hyperfine Structure

$$\mathcal{H} = h\Delta\nu \mathbf{I}_{\mu} \cdot \mathbf{J} - \mu_B^{\mu} g'_{\mu} \mathbf{I}_{\mu} \cdot \mathbf{H} + \mu_B^{e} g_J \mathbf{J} \cdot \mathbf{H}$$

- Hamiltonian of muonium

$\Delta\nu$: Mu Hyperfine Structure




$\nu_{12}+\nu_{34}=\Delta\nu \qquad \nu_{12}-\nu_{34} \propto \mu_{\mu}/\mu_p$

# Precise measurement of Mu HFS

- The most rigorous validation of the bound-state QED

$\nu_{HFS}$(exp) 4463.302 765(53) MHz (12 ppb) LAMPF1999

$\mu_\mu / \mu_p$ =3.18334524(37) (120ppb)

$m_\mu / m_e$=206.768277(24) (120ppb)

$\nu_{HFS}$(theory) 4463.302 891 (272) MHz (63 ppb) D. Nomura (2013)

$\nu_{HFS}$(QED) 4463.302 720 (253) (98) (3) MHz($m_\mu/m_e$) (QED) ($\alpha$)

$\nu_{HFS}$(weak) -65 Hz

$\nu_{HFS}$(had v.p) 232(1) Hz

$\nu_{HFS}$(had. h.o) 5 Hz

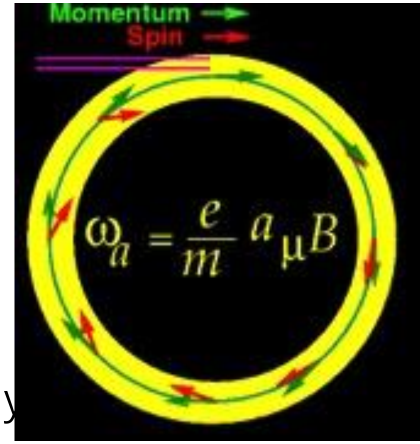
QED calculation →Effort for 10 Hz is in progress by Eides *et al*.

Phys. Rev. A **86**, 024501 (2012), PRL.. 112, 173004 (2014), Phys. Rev. D **89**, 014034 (2014)

# Precise measurement of Mu HFS

- Strong relationship with muon $g-2$
  - 3.7 $\sigma$ deviation btw. theory and experiment
  - Angular frequency of spin precession $\omega$

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right] \qquad a_\mu = \frac{g-2}{2}$$




  - It is important to measure precise **muon mass** independently
  -
  - $\mu_\mu/\mu_p$ accuracy from direct measurement 120ppb

$$a_\mu = \frac{R}{\lambda - R}$$

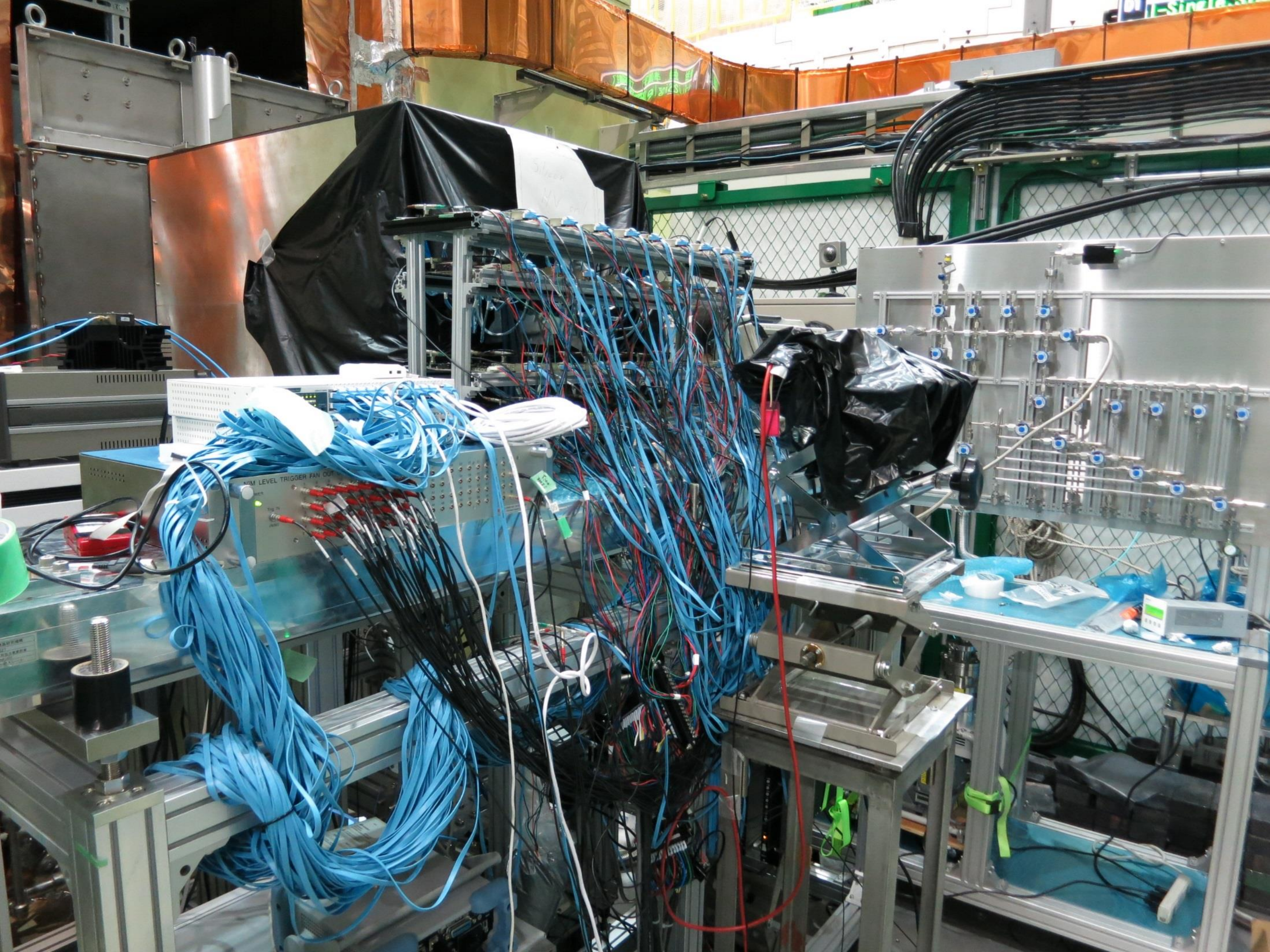
$$R \equiv \frac{\omega_a}{\omega_p}$$

From $g$-2 storage ring

$$\lambda \equiv \frac{\mu_\mu}{\mu_p}$$

From muonium HFS

W. Liu *et al.*, *Phys. Rev. Lett.* ***82***, *711 (1999).*


NIM LEVEL TRIGGER FAN OUT

# What is negative muon?

## Elementary particle

- Charge -*e*
- Spin：1/2
- Lifetime： 2.2 μs

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

- No strong interaction
- Mass: 106 MeV/$c^2$

~207 $m_e$、~1/9 $m_p$

**Muons in material**

$\mu^+$ :  light proton

$\mu^-$ : heavy electron

## Leptons

| | | |
|---|---|---|
| $e$ | $\mu$ | $\tau$ |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |

## Muon production

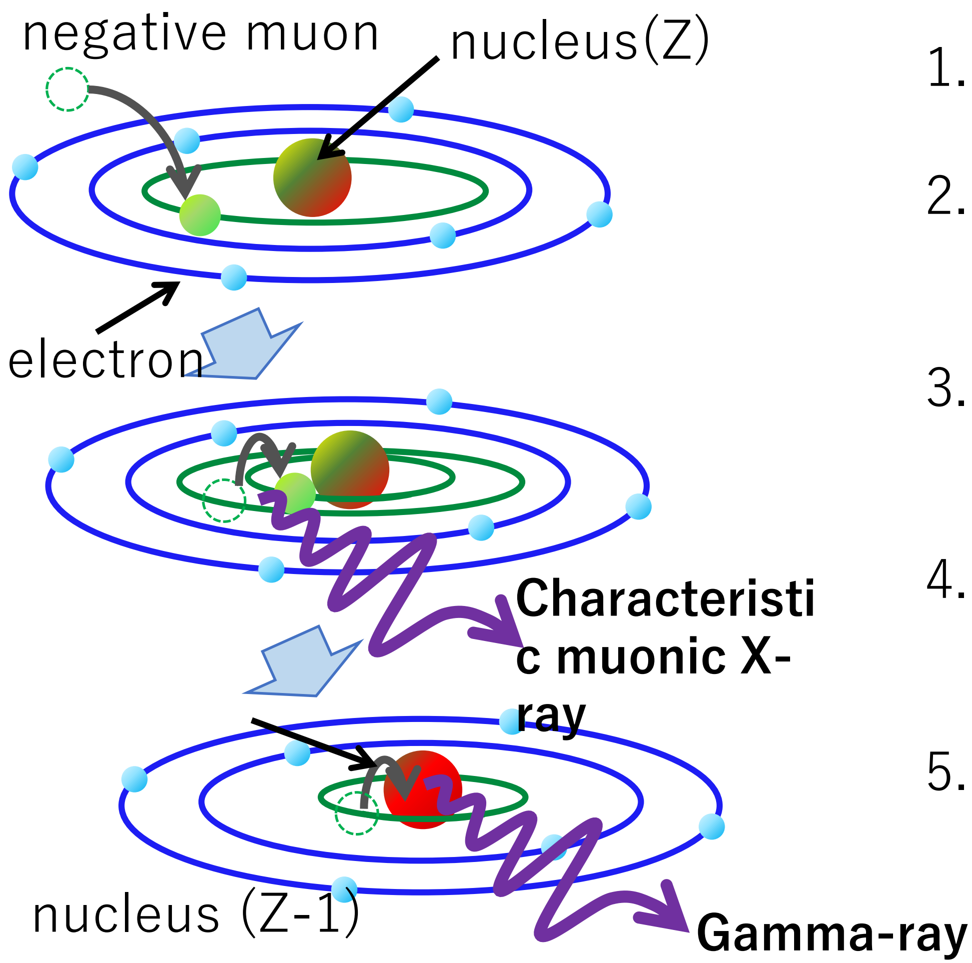
$$\pi^- \xrightarrow[26\ \text{ns}]{} \mu^- + \overline{\nu}_\mu$$

$\pi^\pm$ are produced by

$p^+$ (≥ 280 MeV ) + nucleus

# Negative muon and muonic atom

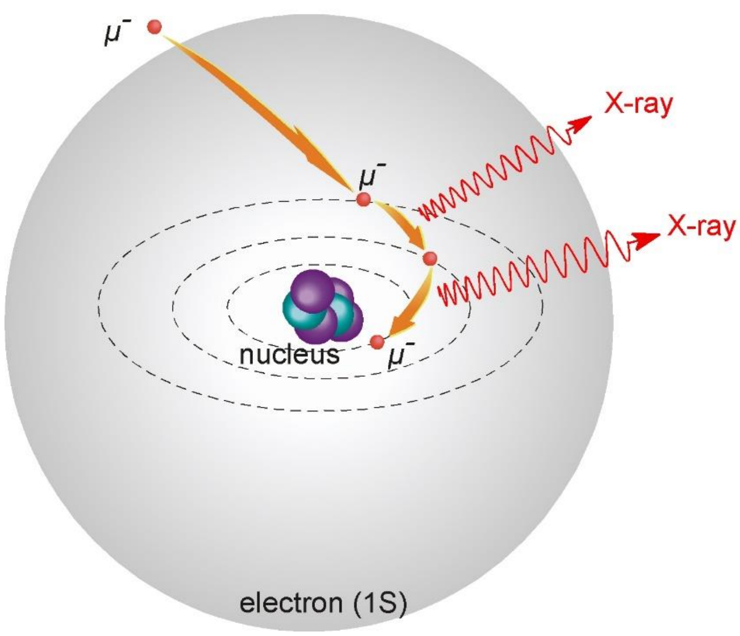
## Muonic atom formation and following processes




1. Energetic muon slows down and stops in material
2. Muonic atom formation
   Muon capture in atomic muonic orbital
3. Muon cascading process
   **Characteristic muonic X-ray emission**
4. Muon in muonic 1s state
   Spends several lifetimes (50-2000 ns)
5. Natural decay or muon capture
   in the nucleus
   **Gamma-ray emission**

# What is muonic X-ray?

Characteristic X-ray emitted during de-excitation process of muonic atom




$$E_n = -\frac{Z^2 m e^4}{8 n^2 \varepsilon_o^2 h^2}$$

$$r_n = -\frac{4\pi\varepsilon_o n^2 \hbar^2}{Z m e^2}$$

$$\frac{m_\mu}{m_e} \approx 207 \approx \frac{E_\mu}{E_e} \approx \frac{r_e}{r_\mu}$$

**Bohr model**

# Composition analysis with negative muons

- **Emission of characteristic muonic X-ray with specific energy to the element**
  - Applicable to every element except for hydrogen
    multi-elemental, simultaneous
  - No need of previous knowledge
  - High energy (0.01- 10 MeV) deep inside, light elements
    Observable from outside of sample
    No need of vacuum huge / porous / bio sample
  - No chemical process non-destructive / damage-less
  - Stopping depth control + beam scan
    depth-selective / 3D mapping
  - More than 1 photons by 1 muon highly efficient

**< Capture probability: proportional to *Z* with slight chemical effects >**

# Asteroid sample

**Multi-elemental** ・ **Non-destructive** ・ **Depth-selective**

Negative muon is the answer

- Wide variety of samples:
  historical, archaeological,,,etc.
  e. g. asteroid sample by MUSES-C probe

(Our research proposal around 2000)

MUSES-C (renamed as Hayabusa) returned in 2010 with a few hundreds of micrograms of dust samples of the asteroid

Hayabusa-2 sample analysis group joined.
H-2 is now traveling to asteroid 1999JC3 supposed to have abundant of B, C, N, O, and returned with samples in Dec 2020

# Measurements are on going