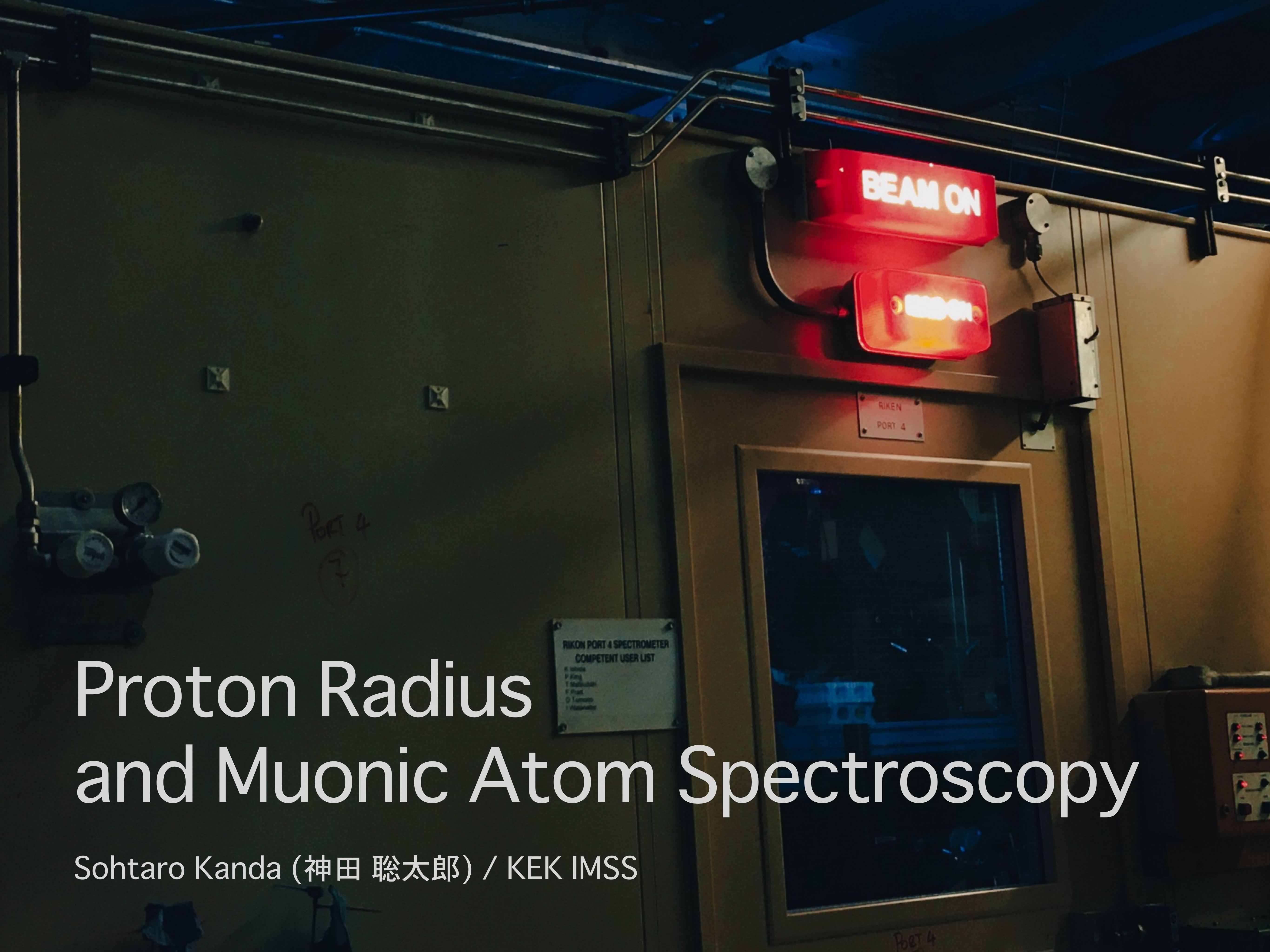
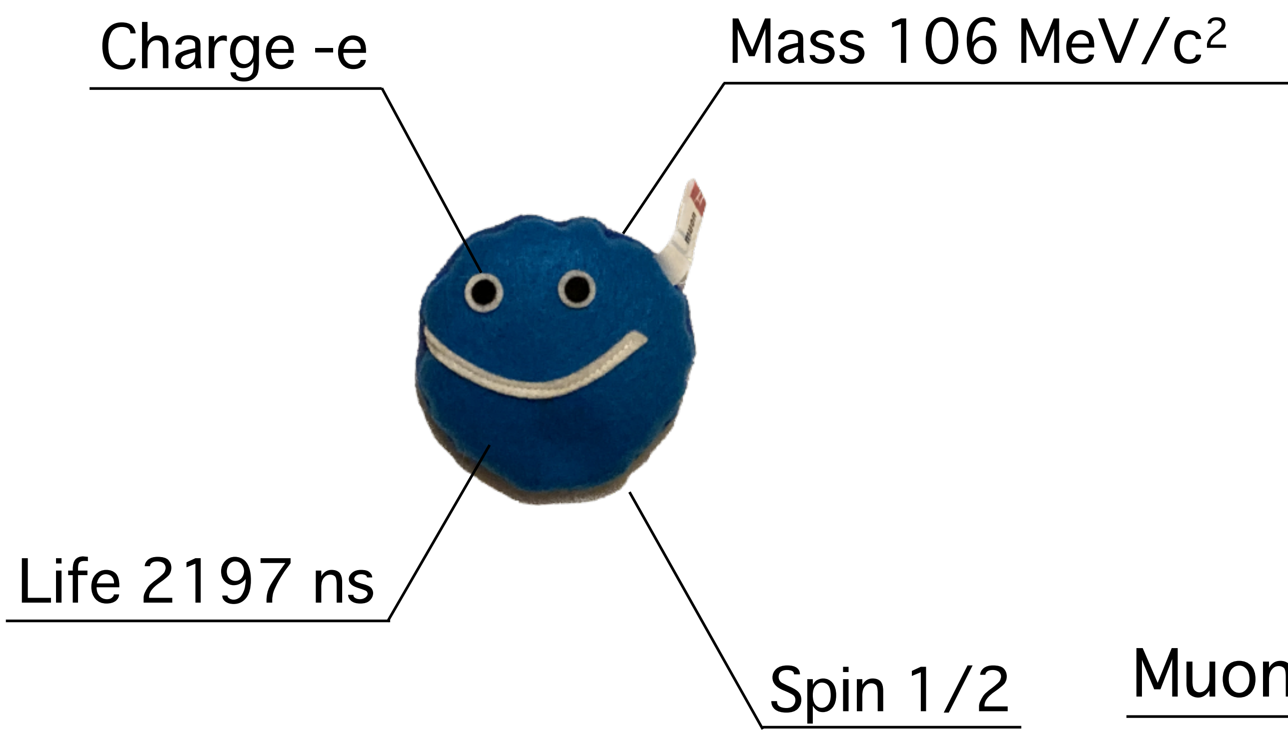



# Proton Radius and Muonic Atom Spectroscopy

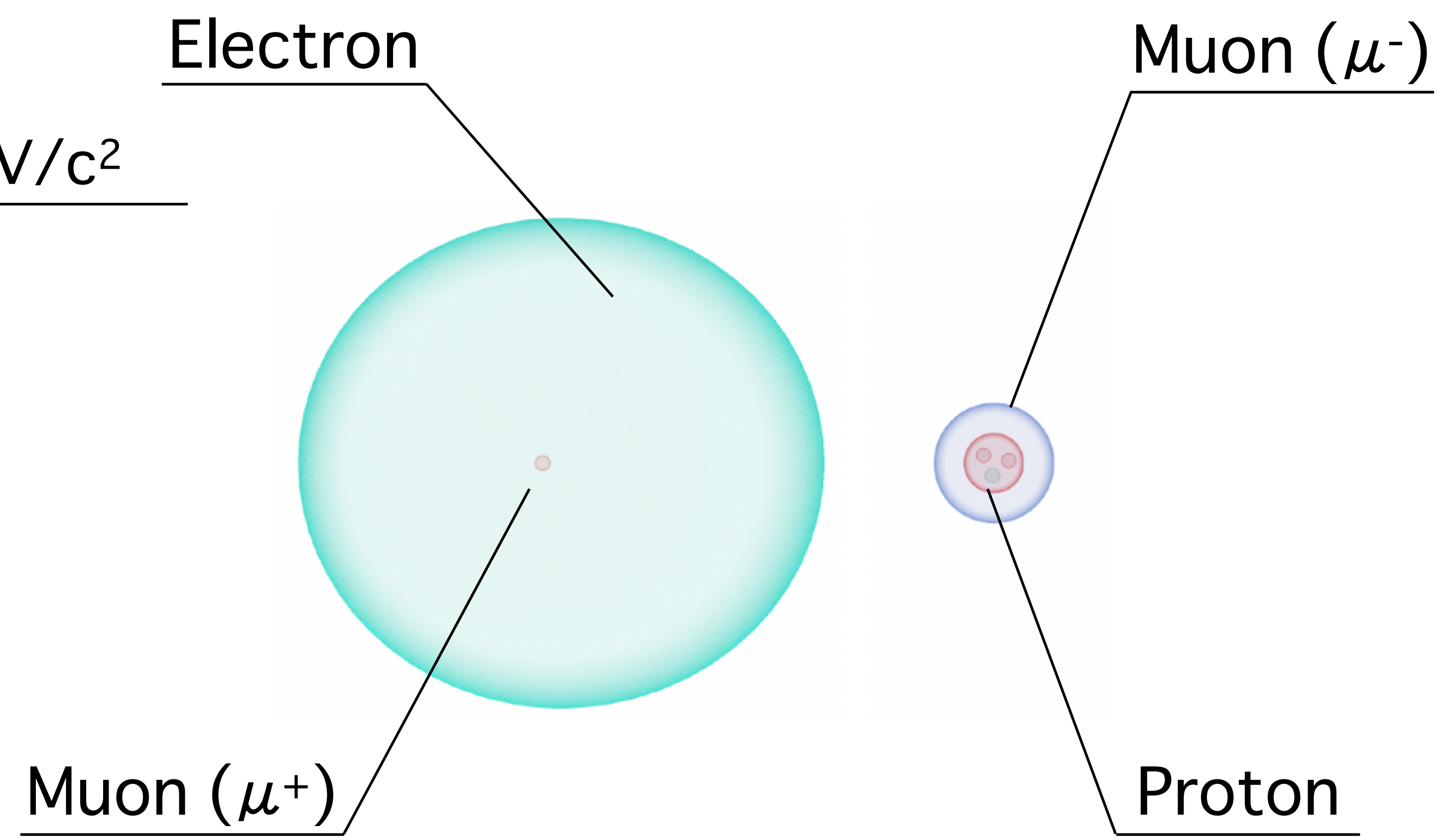
Sohtaro Kanda (神田 聡太郎) / KEK IMSS

# Muons and Muonic Systems

## Second-generation charged-leptons




"Who ordered that?"



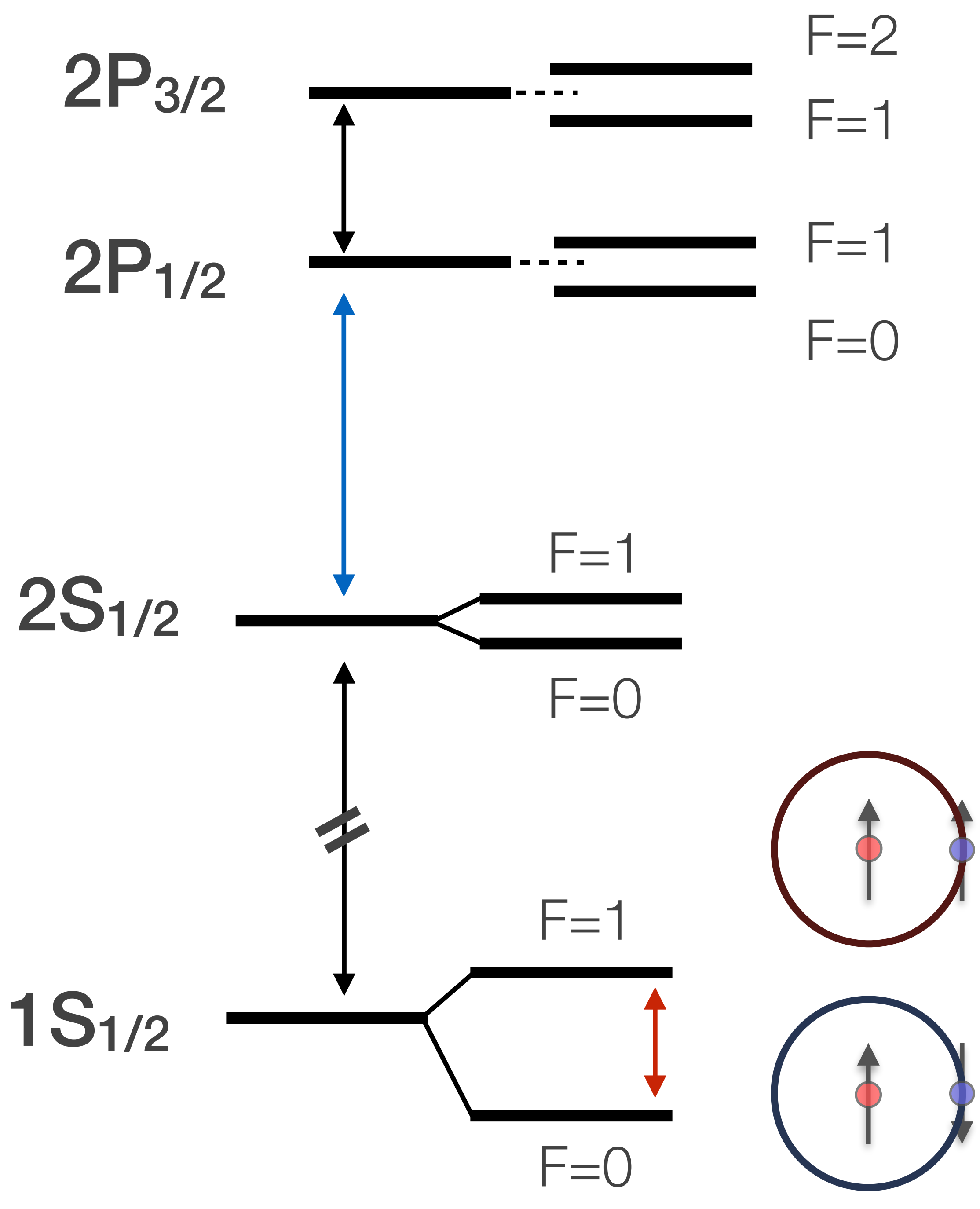

Muonium $r_{\mu p} = 0.532$ Å

Muonic atom $r_{\mu p} = 0.00256$ Å

- Muon is 207 times heavier than electron and decays in 2.2 $\mu$s of the lifetime.
- Muonic systems provide unique opportunities to determine the fundamental physical constants and to search for physics beyond the Standard Model.

# Muonic Hydrogen Spectroscopy

## to determine the proton radius




Lamb Shift : 206 meV=6 $\mu$m

Finite size effect 3.7 meV

→ Charge Radius

1S-HFS : 183 meV=6.8 $\mu$m

Finite size effect 1.3 meV

→Zemach Radius

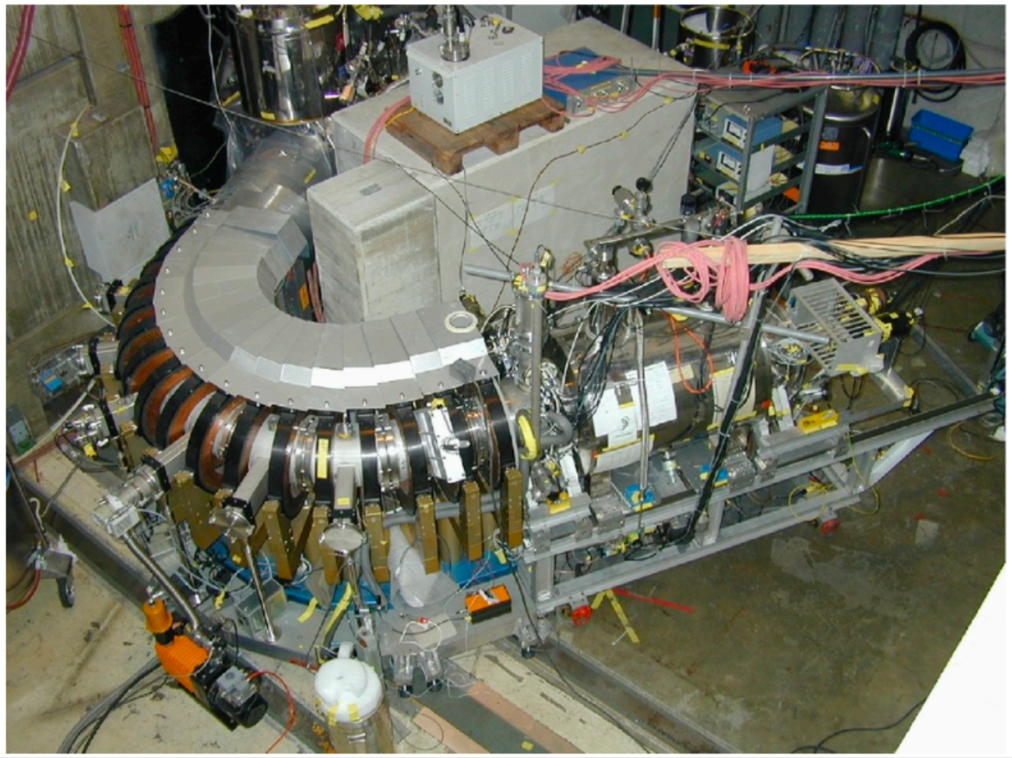
Difference from normal hydrogen spectroscopy:

- Short lifetime of 2.2 μs
- Muon transfer to heavier nuclei
- Irradiation of high-energy beams produced by accelerators onto low-density targets

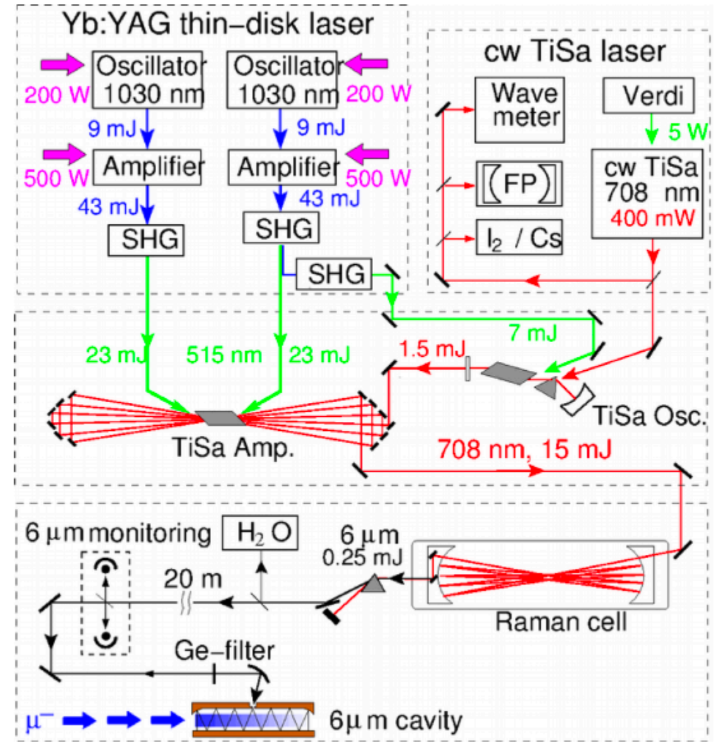
# CREMA

Randolf Pohl, in SSP2018 workshop

## The muon beam line in πE5



## The laser system




Yb:YAG Disk laser
→ fast response on µ

Frequency doubling (SHG)
→ green light to pump Ti:sapphire laser

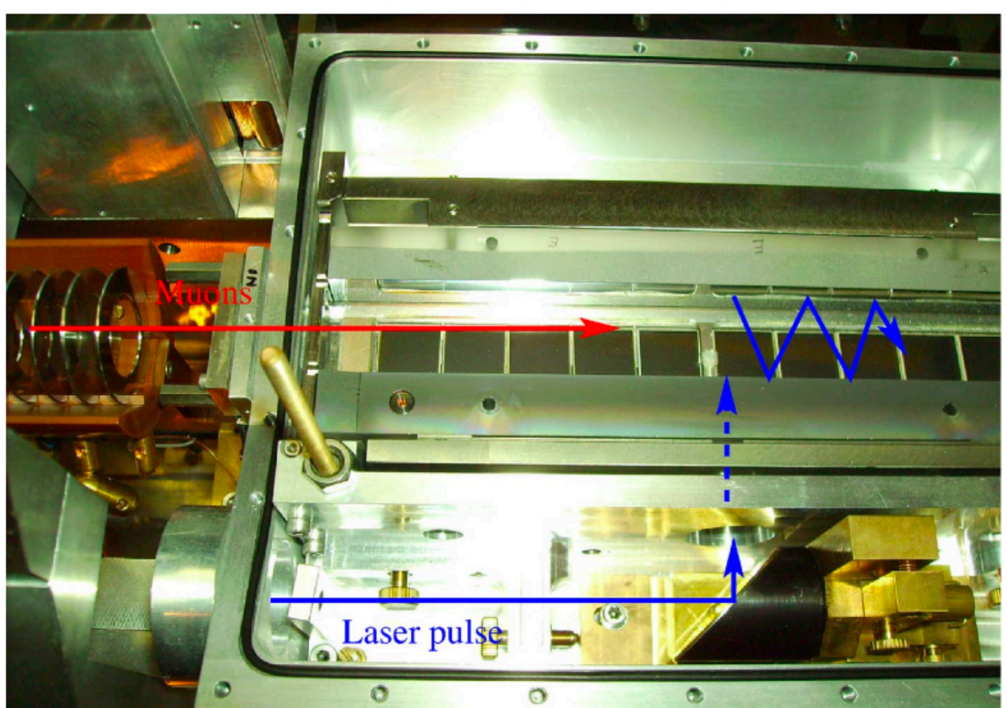
Ti:sapphire cw laser
→ determines laser frequency

Ti:sapphire MOPA
→ high pulse energy (15 mJ)

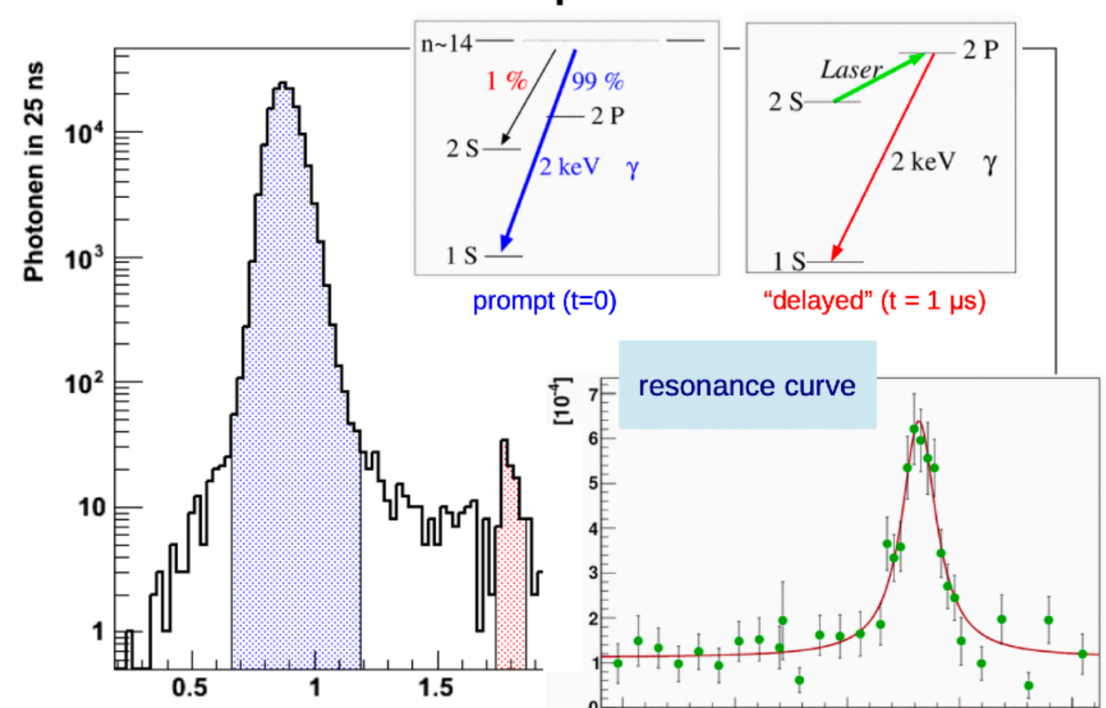
Raman cell
→ 3 sequential stimulated Raman Stokes shifts Laser wave length → 6 µm

Target Cavity
→ Mirror system to fill the muon stop volume ($H_2$)

## The hydrogen target

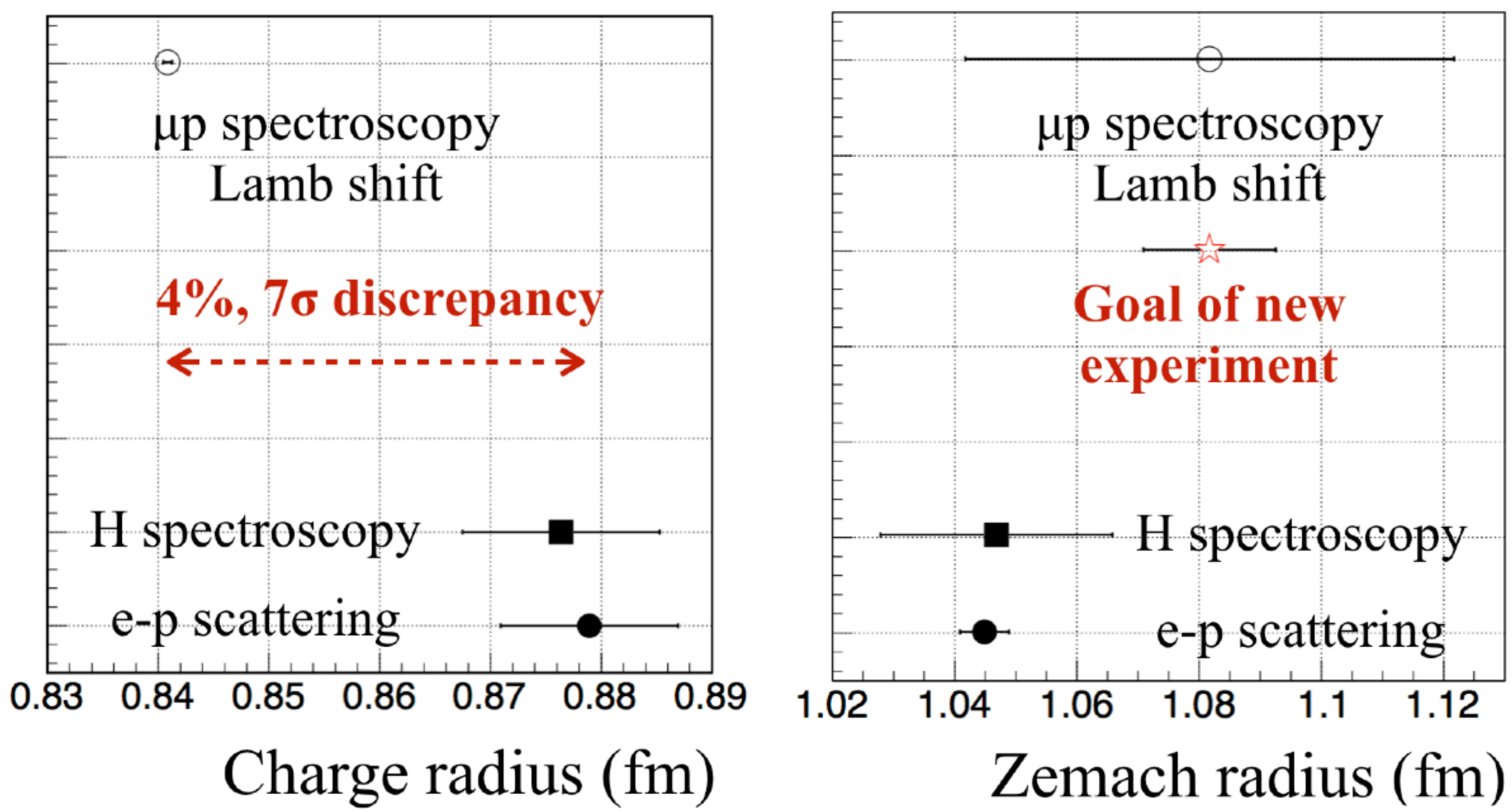



## Time Spectra



# Proton Radius Puzzle

## Unsolved Problem in Subatomic Physics

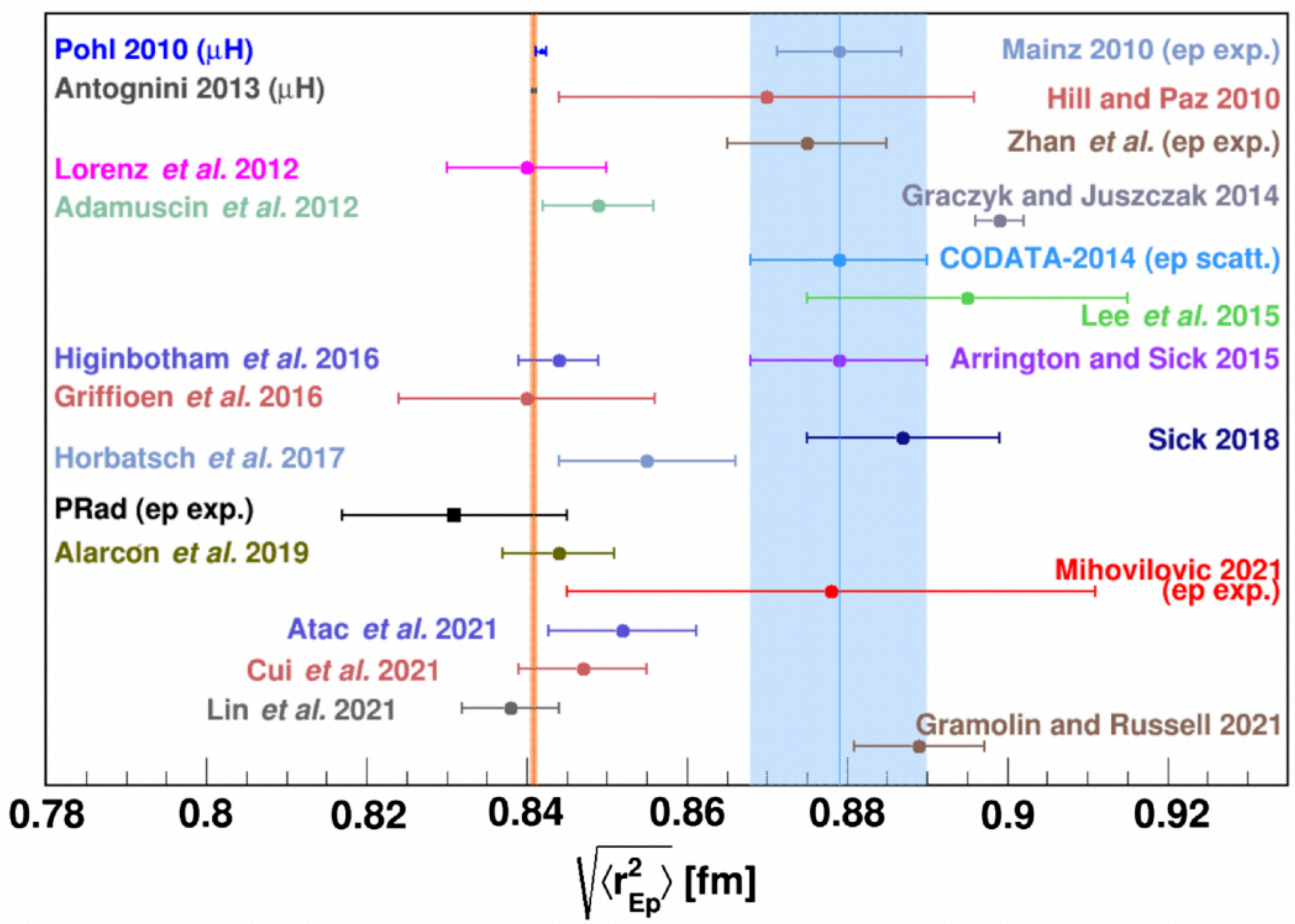


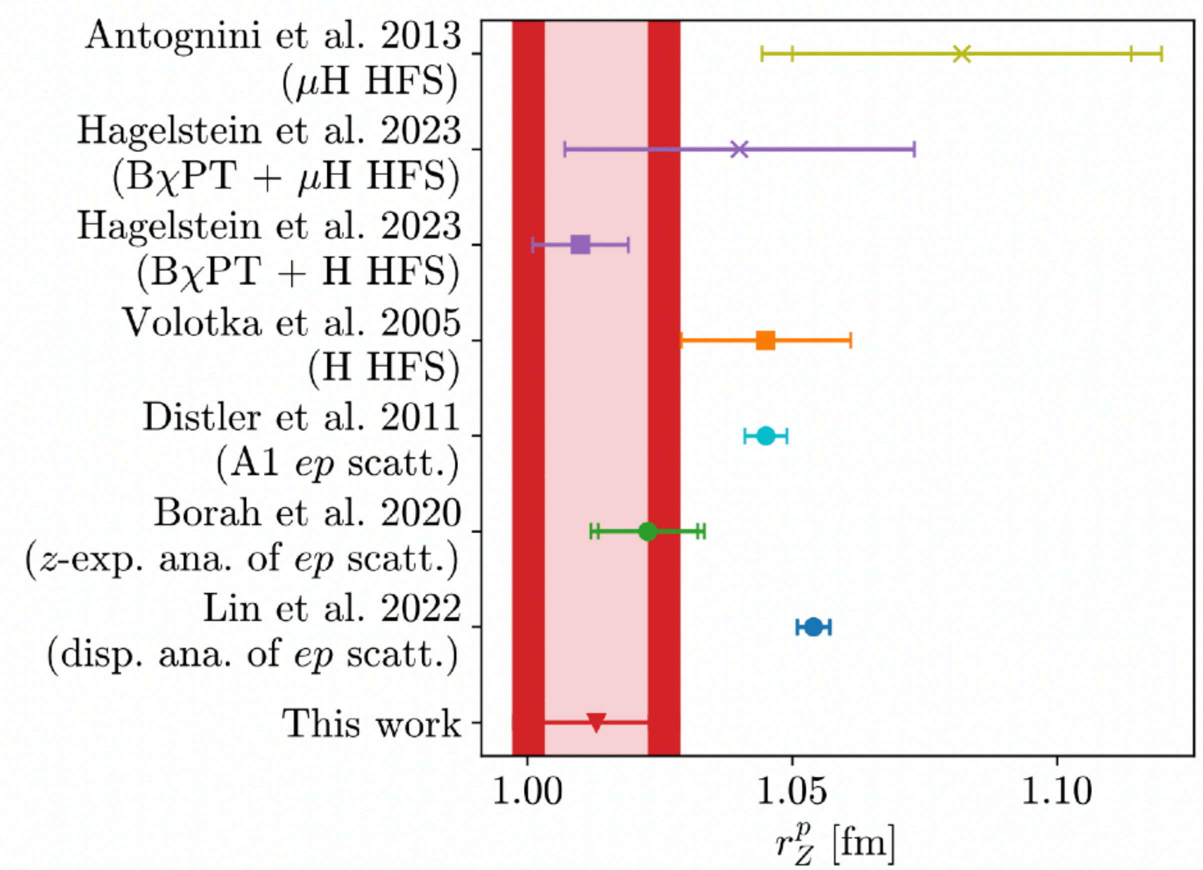

R. Pohl *et al*., Nature 466, 213 (2010).
A. Antognini *et al*., Science 339, 417 (2013).
J. C. Bernauer *et al*., Phys. Rev. C 90 015206 (2014).
A. V. Volotka *et al*., Eur. Phys. J. D33, 23 (2005).

- The proton is fundamental building block of the universe. However, it is a composite particle with a complex structure.
- A large discrepancy in results of the proton's charge radius from electronic and muonic systems has been known since 2010.
- As an alternative approach to this problem, we proposed a measurement of the Zemach radius taking into account the magnetic moment distribution.

# Proton Radius Puzzle

## More recent situation




**The results on charge radius have become more abundant, but there has not been much increase in information about what is happening with the Zemach radius.**

Left: H. Gao and M. Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022).
Right: D. Djukanovic et al., arXiv:2309.17232 [hep-lat].

# Proton Zemach Radius

## Spatial distribution of charge and spin

- Defined by a convolution of the charge distribution with a magnetic moment distribution.

$$R_Z = \int d^3r \int d^3r' \rho_E(r')\rho_M(r-r')$$

A. C. Zemach, Phys. Rev. 104, 1771 (1956).

- Can be obtained by measuring the hyperfine splitting.

$$E_{\mathrm{HFS}} = E_{\mathrm{F}}(1 + \delta_{\mathrm{QED}} + \delta_{\mathrm{Proton}})$$ ($E_F$=182.443 meV)

$$\delta_{\mathrm{Proton}} = \delta_{\mathrm{Rec}}$$ 1.06 meV

$$+ \delta_{\mathrm{Pol}}$$ 0.084 meV

$$+ \delta_{\mathrm{HVP}}$$ 0.004 meV

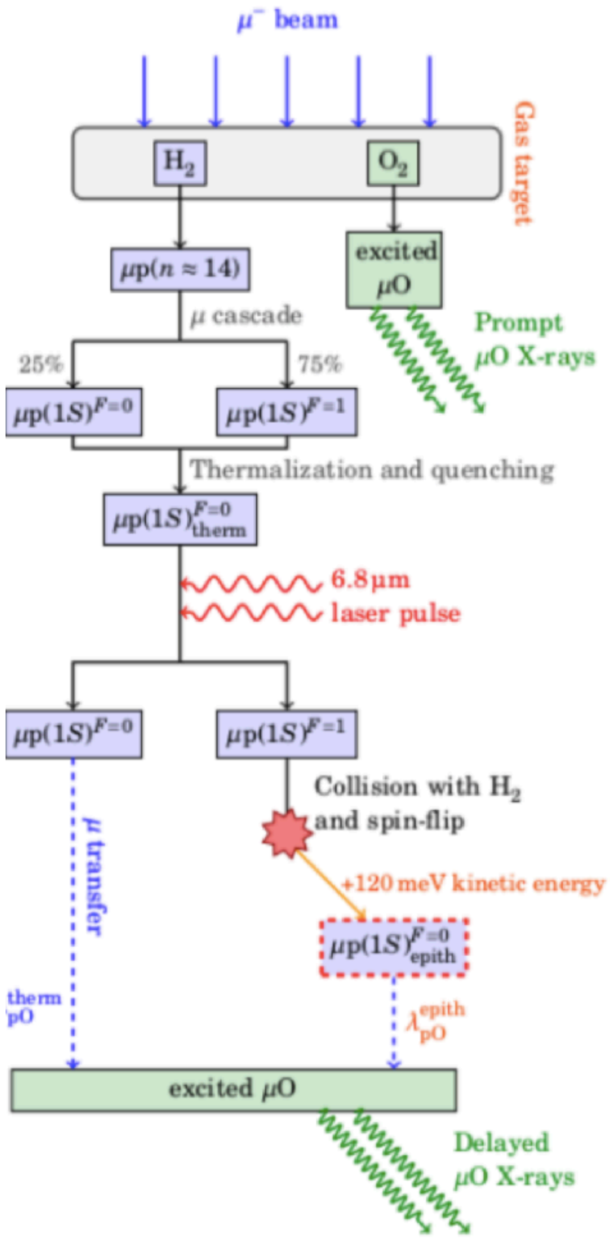
$$+ \delta_{\mathrm{Zemach}}$$ -1.36 meV $\longleftarrow$ $\delta_{\mathrm{Zemach}} = -2\alpha m_{\mu p} R_Z$

R. N. Faustov and A. P. Martynenko, J. Exp. Theor. Phys. 98, 39 (2004).

# Three $\mu$p-HFS Projects

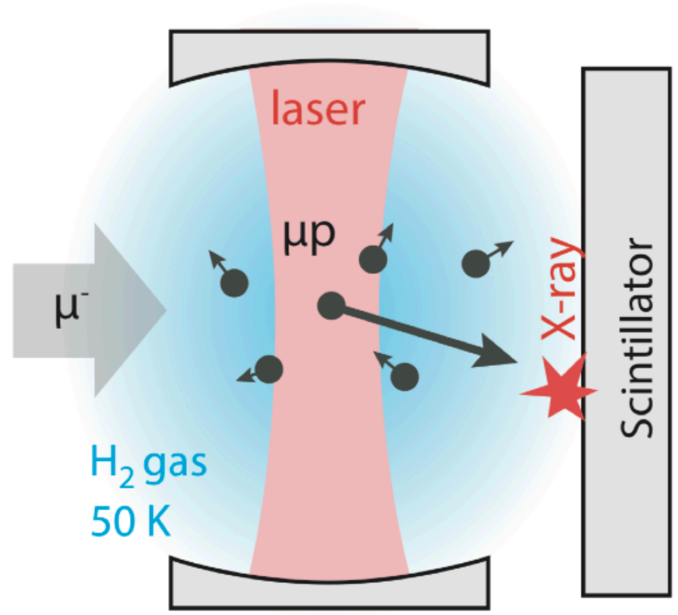
## Independent approaches at RAL, PSI, and RIKEN

FAMU



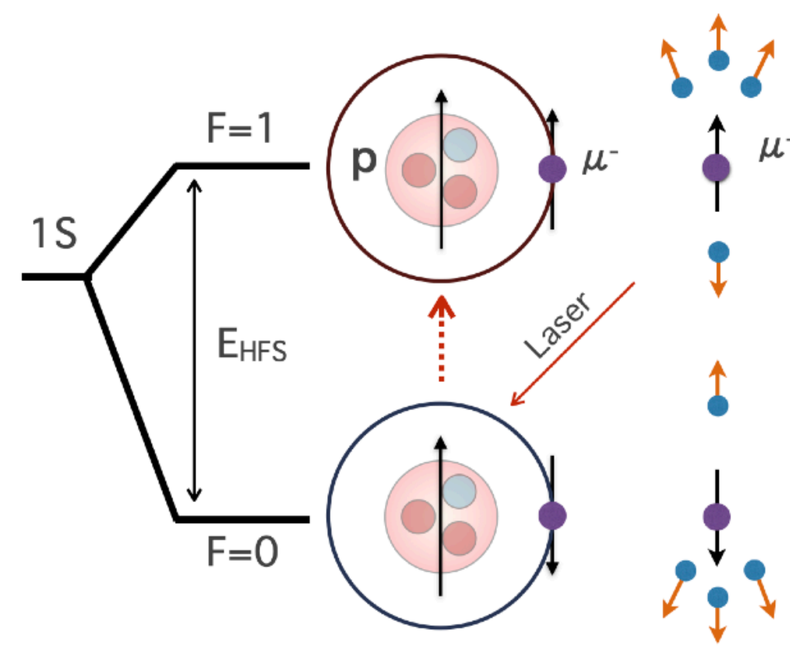

E. Mocchiutti, in PREN2022 workshop

Hyper-Mu




A. Antognini, in PREN2022 workshop

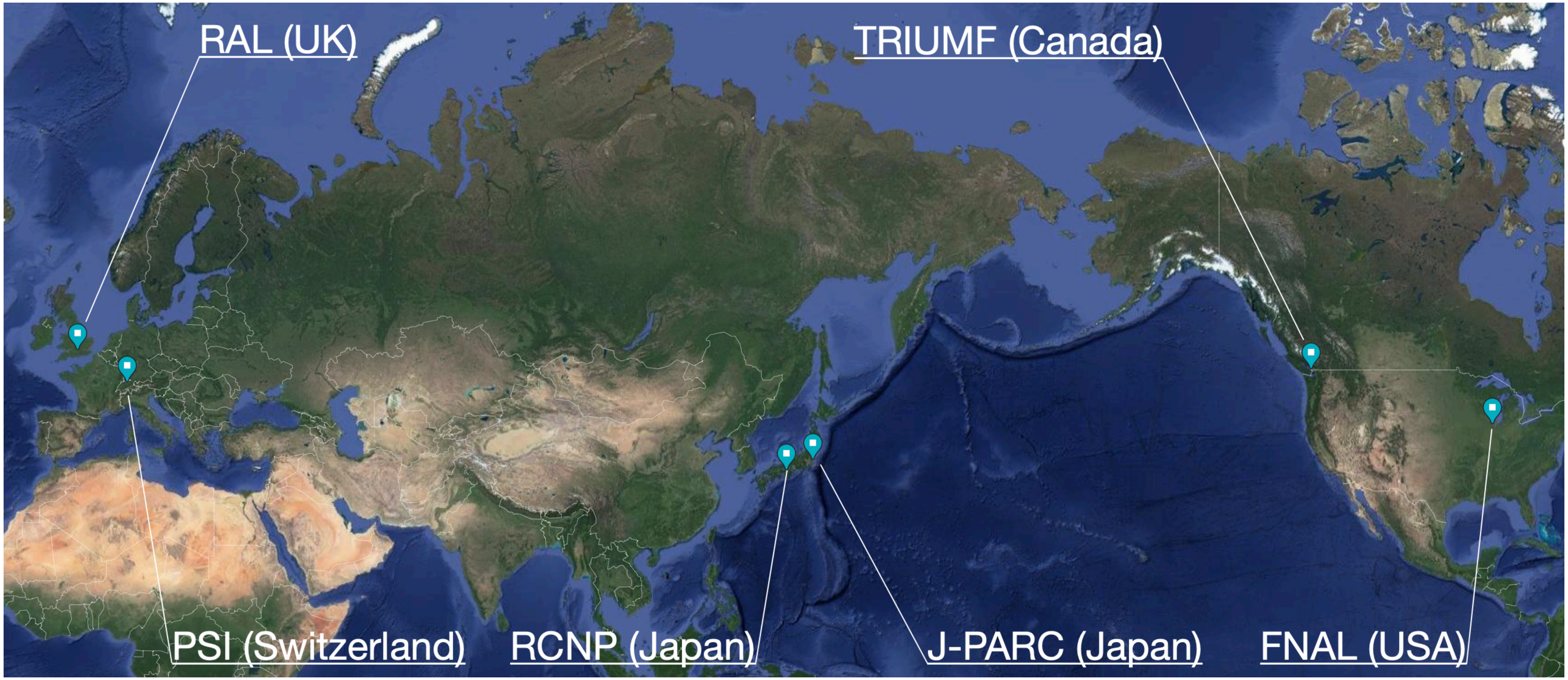
RIKEN/J-PARC



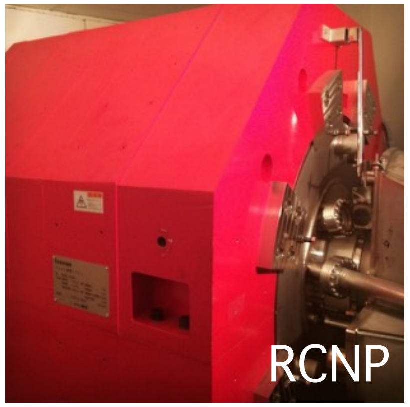

| | FAMU | PSI | RIKEN |
|---|---|---|---|
| Method | Transfer | Diffusion | Asymmetry |
| Detection | X-Rays | X-Rays | Electrons |
| Beam | Pulsed | Contiuous | Pulsed |

# Muon Facilities

## around the world





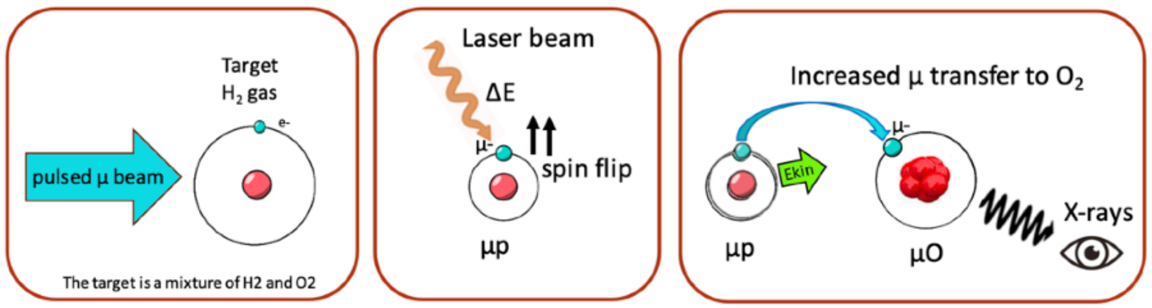





# FAMU Status

Cecilia Pizzolotto, in PSAS2024 workshop

## FAMU method and workflow




- Create muonic hydrogen and wait for its thermalization;
- Shoot laser at the hyperfine splitting energy ($\lambda_0$~6.8μm) and change spin state of μp from $1^1S_0$ to $1^3S_1$, spin is flipped: μ⁻p(↑↓) → μ⁻p(↑↑) ;
- De-excitation and acceleration of μ⁻p (~120 meV)
- If μ⁻p are accelerated, the μ⁻ transfer to Oxygen increases (O2 has an energy-dependent rate);
- The hyperfine splitting energy is determined by varying the wavelength of the laser beam and search the maximum number of oxygen X-rays

Temperature dependence of the μ transfer to Oxygen
https://doi.org/10.1016/j.physleta.2021.127401
https://doi.org/10.1016/j.physleta.2020.126667

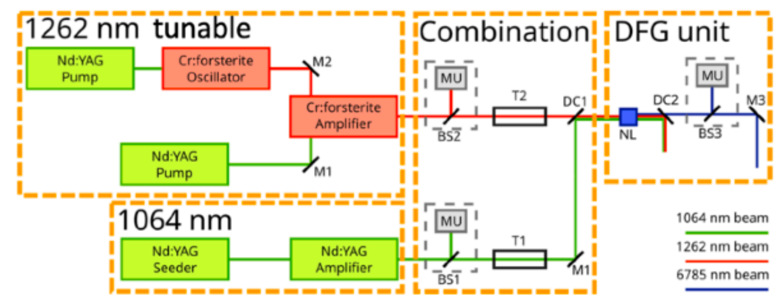


## FAMU Laser

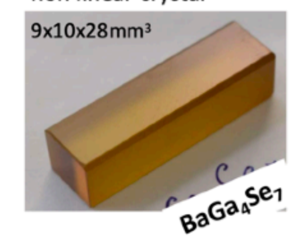
Characteristics:

| | |
|---|---|
| Wavelength range | 6800 ± 50 nm |
| Energy output | > 1 mJ |
| Linewidth | < 30 pm |
| Tunability steps | ~9 pm |
| Pulses duration | 10 ns |
| Repetition rate | 25 Hz |

We reached better values than our goal




non linear crystal




$$\lambda_{DFG}^{-1} = \lambda_1^{-1} - \lambda_2^{-1}$$

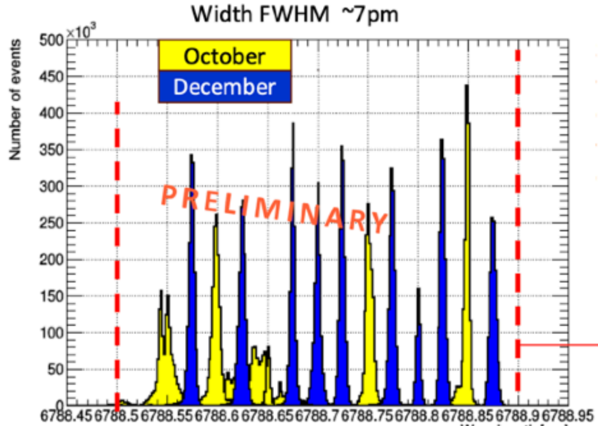
M1 - Mirror HR 1064 nm, M2 - Mirror HR 1262 nm, M3 - Mirror HR 1064&1262&6785 nm, M4 - Mirror HR 6785 nm, T1 and T2 - telescopes, BS1 - beamsplitter/beamsampler 1064 nm, BS2 - beamsplitter/beamsampler 1262 nm, BS3 - beamsplitter/beamsampler 6785 nm, DC1 - dichroic mirror (reflecting 1064 nm, transmitting 1262 nm), DC2 - dichroic mirror (reflecting 1064 nm and 1262 nm, transmitting 6785 nm), NL - nonlinear crystal, MU - measuring units (wavelenght meter, energy meter, dimensions)



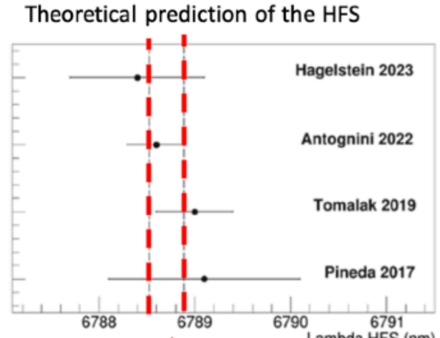
## FAMU investigated regions in 2023

**Laser wavelengths investigated in 2023:**

14 frequencies investigated
in steps of 25 pm
~ 24 h for each frequency
Width FWHM ~7pm

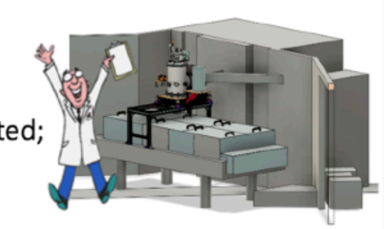



Theoretical prediction of the HFS






## Summary and outlook



- Successful physics data taking in 2023 ;
  - target, detectors, cavity, and laser are performing as expected;
  - 14 frequencies investigated
- The analysis of the 2023 dataset is ongoing
- New physics data taking planned in July and till 2025
  - Improvement: larger coverage from X-rays detectors
  - Enlarge the investigated WL region by 2/3

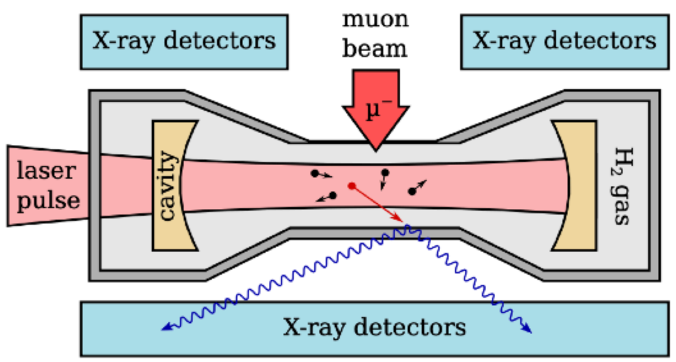
Future:

Working on an improvement of the laser scheme in terms of energy and stability

# Hyper-Mu Status

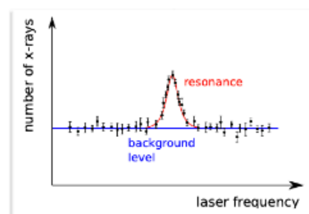
Ahmed Out, in PSAS2024 workshop

## The principle of the experiment



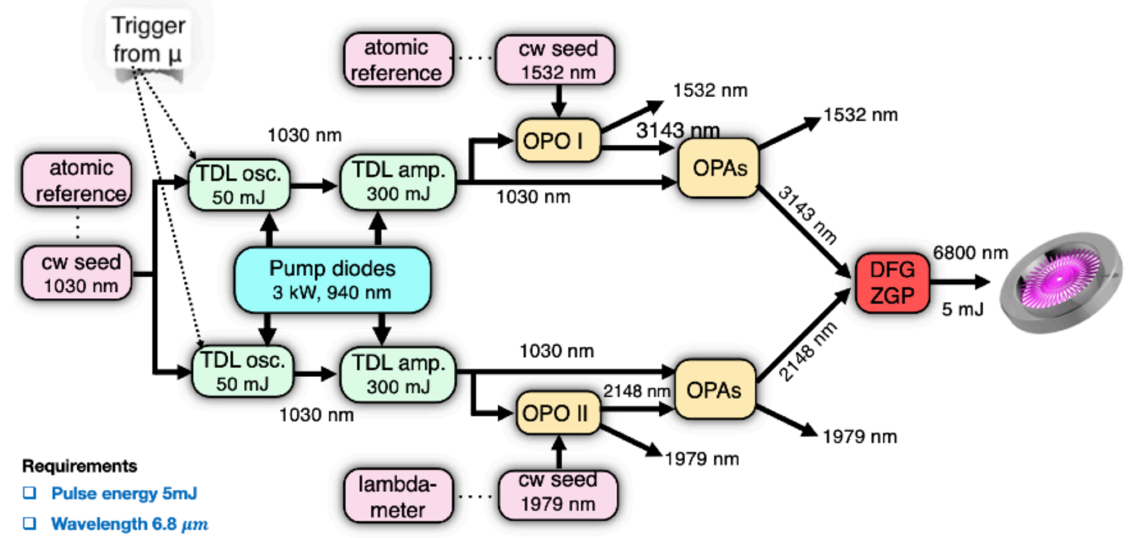

- Diffusion: μp diffuses to Au-coated target walls
- Detection: formed μAu* de-excites producing X-rays
- Resonance: Plot number of X-ray events vs laser frequency

Related Proposals: FAMU at RIKEN/RAL, muonic H at J-PARC




Ahmed Ouf PSAS'2024 Zurich 14.06.2024

## The laser system




**Requirements**

- Pulse energy 5mJ
- Wavelength 6.8 $\mu m$
- Linewidth < 100 MHz
- Stochatic trigger (detected muon)
- Response time 1 $\mu s$
- Tunability 40 GHz

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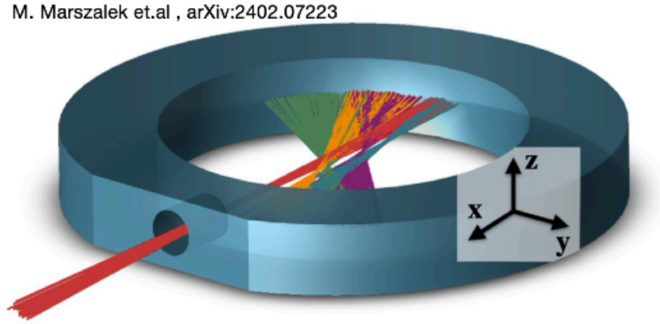
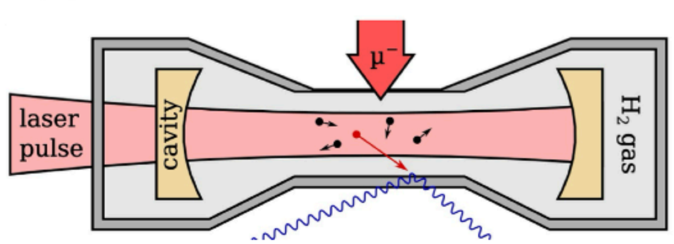
## Enhancement cavity

M. Marszalek , PhD Thesis, ETH 2022
M. Marszalek et.al , arXiv:2402.07223

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## Simulated resonance

**Assuming the resonance has been found and given:**

- Laser pulse 1mJ
- Target length 1.2 mm
- Cavity R = 99.2%
- Detection system: $\epsilon_{\text{Au}} = 70\%$ , $\epsilon_{\text{Au-false}} = 9\%$

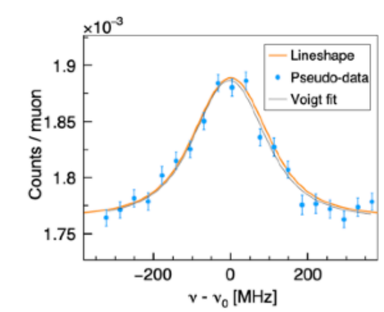
⇩

Determine resonance position with

$$\sigma = 4 \text{ MHz } (1.6 \times 10^{-8} \text{ eV})$$

$$\frac{\sigma}{E_{\text{HFS}}} = \frac{4 \text{ MHz}}{44 \text{ THz}} = 1 \times 10^{-7}$$

→ • **Theory improvement needed**

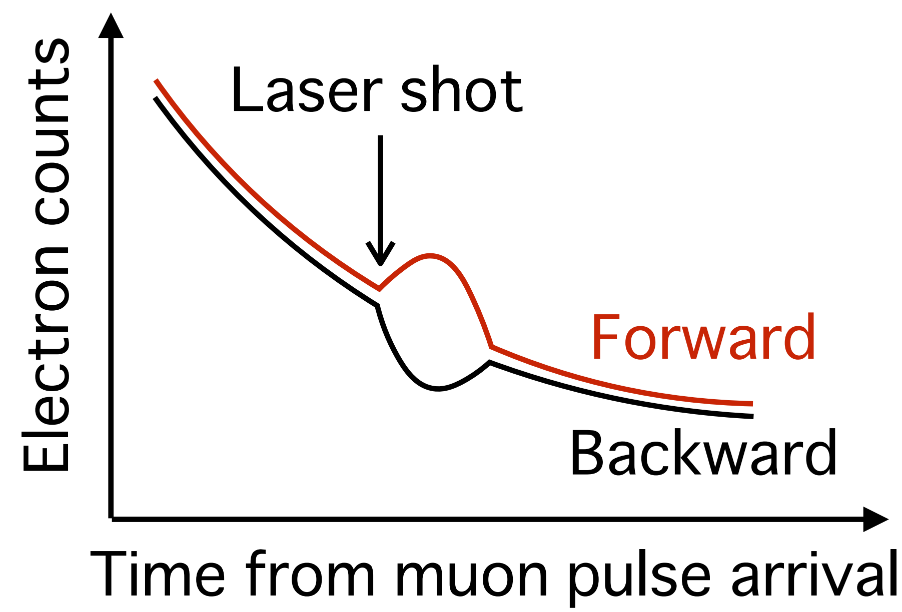


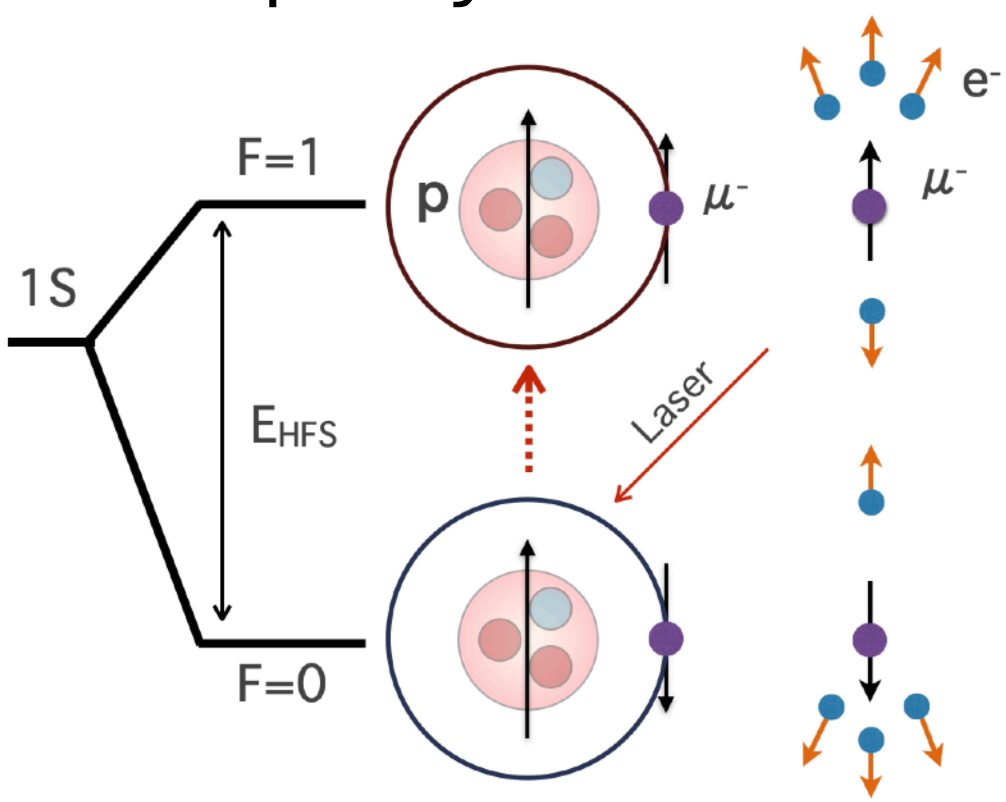

Ahmed Ouf PSAS'2024 Zurich 14.06.2024

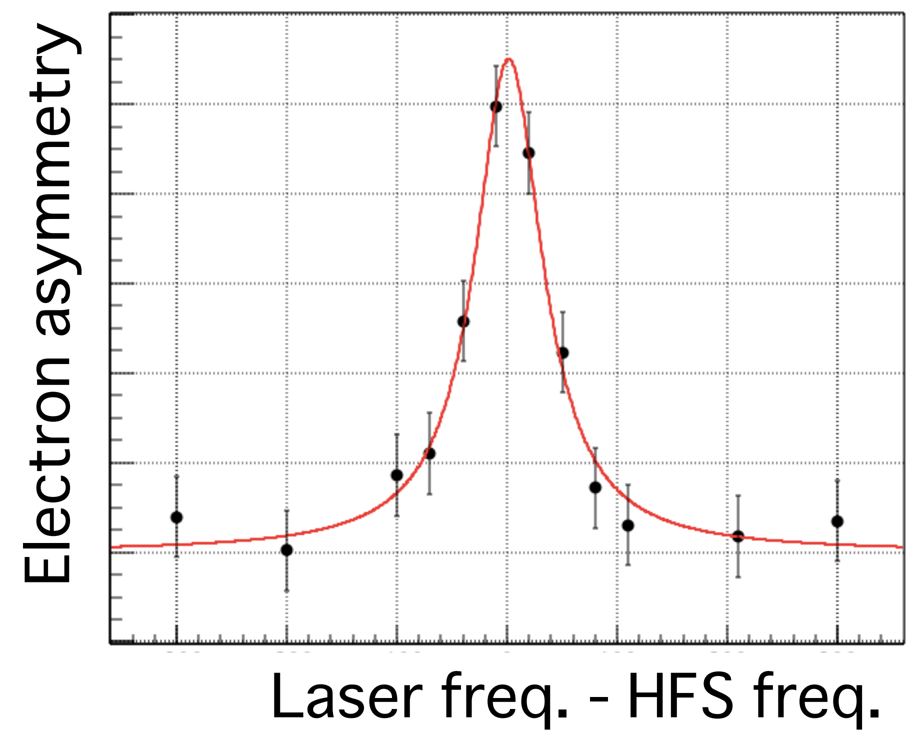
# Laser Spectroscopy of $\mu$p-HFS

## Method of our experiment at J-PARC

- Laser induced hyperfine transition and muon spin flip
- Parity violating muon decay
- Decay electron angular asymmetry
- Laser frequency scan

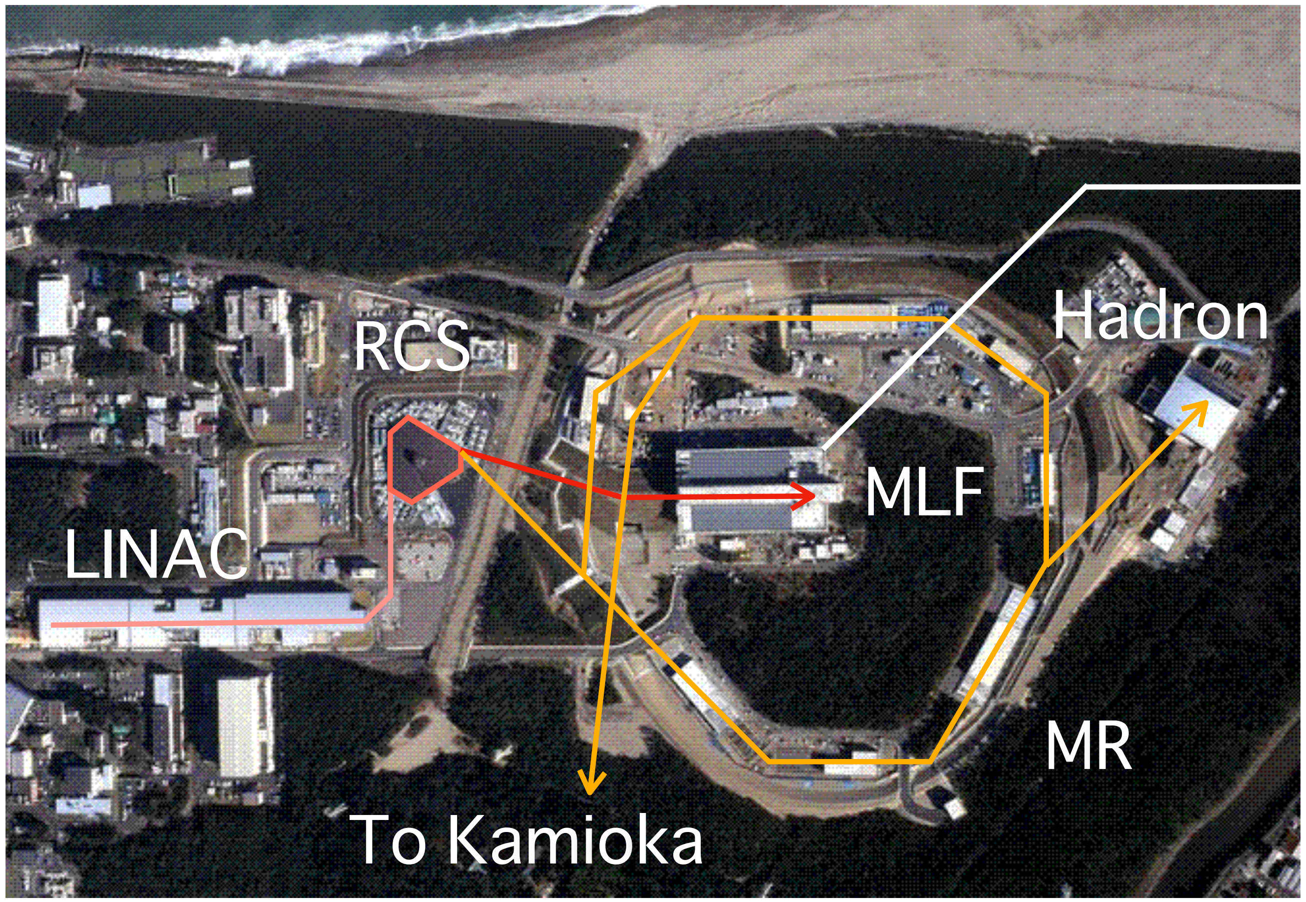


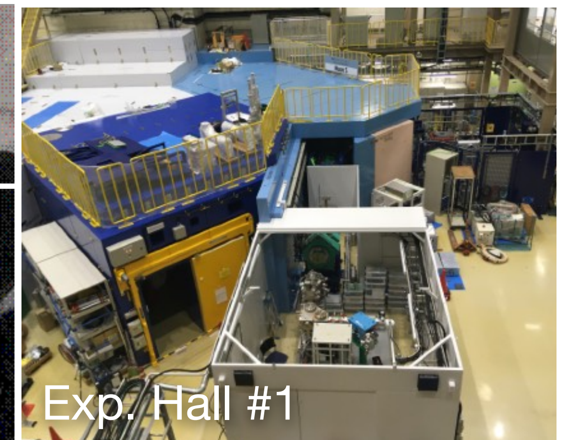



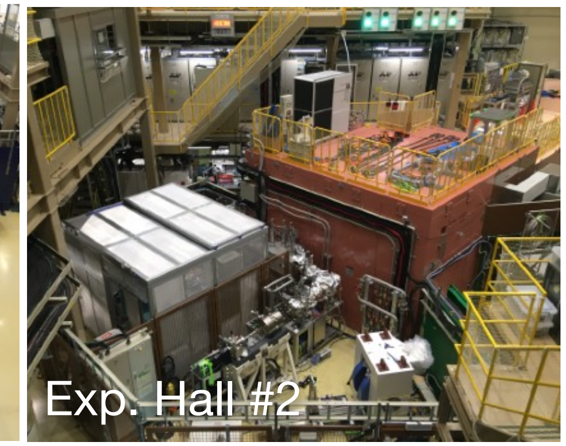



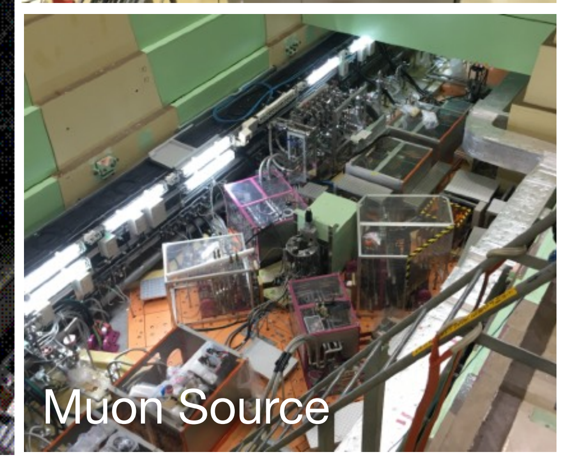
# J-PARC

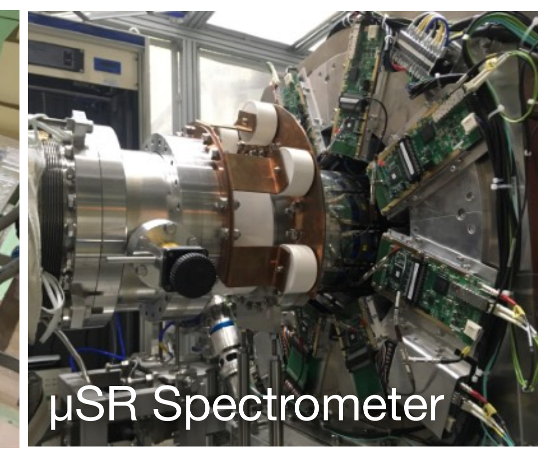
## Japan Proton Accelerator Research Complex



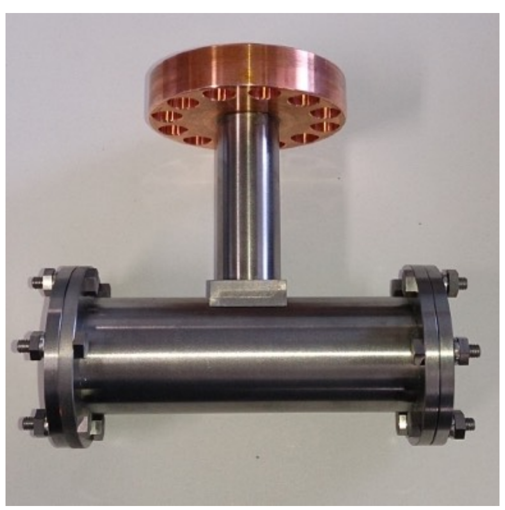




- World most intense pulsed proton driver.
- RCS provides 3 GeV protons for muon production at MLF.
- MR delivers higher energy protons for the COMET, hadron, and neutrino experiments.

# Project Timeline

## Since the experimental proposal

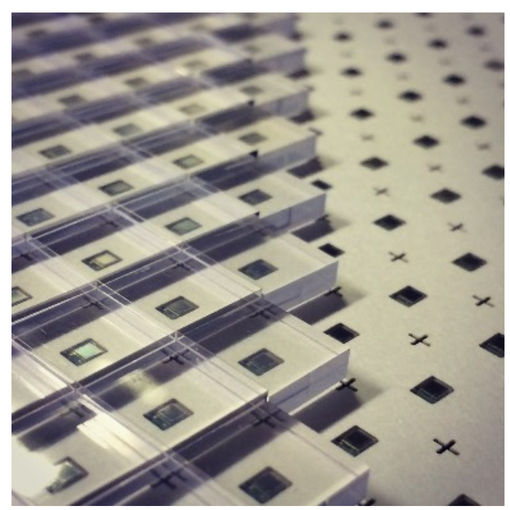
| 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|
| The Puzzle | Proposal Submitted | Target R&D | Target R&D | RAL Test1 | RAL Test2 | RAL Test3 |
| | | Detector R&D | Detector R&D | Detector R&D | J-PARC Test | |
| | | Laser R&D | Laser R&D | Laser R&D | Laser R&D | Laser R&D |



Target Cell

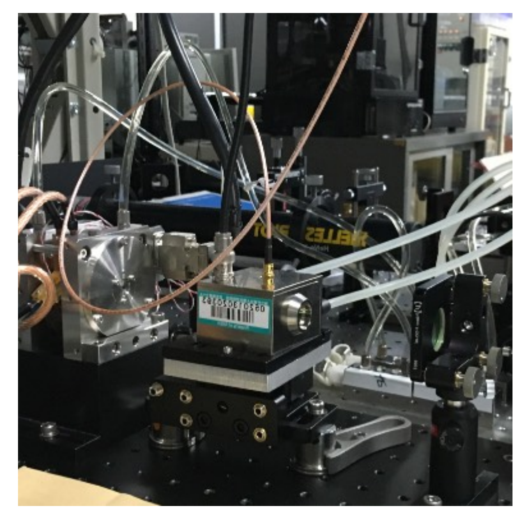
Cryostat

M. Sato, K. Ishida

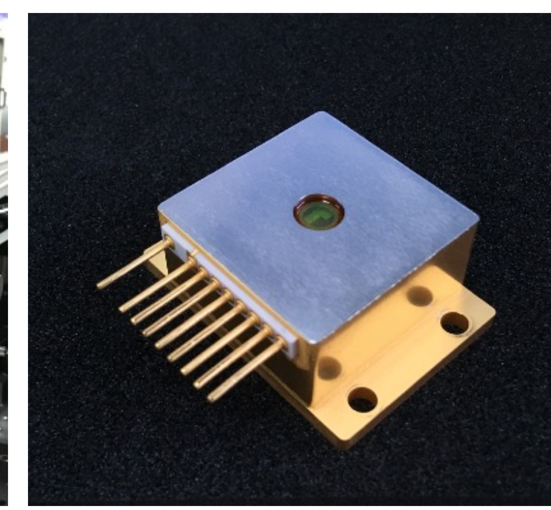


Detector

S. Okada, Y. Ma



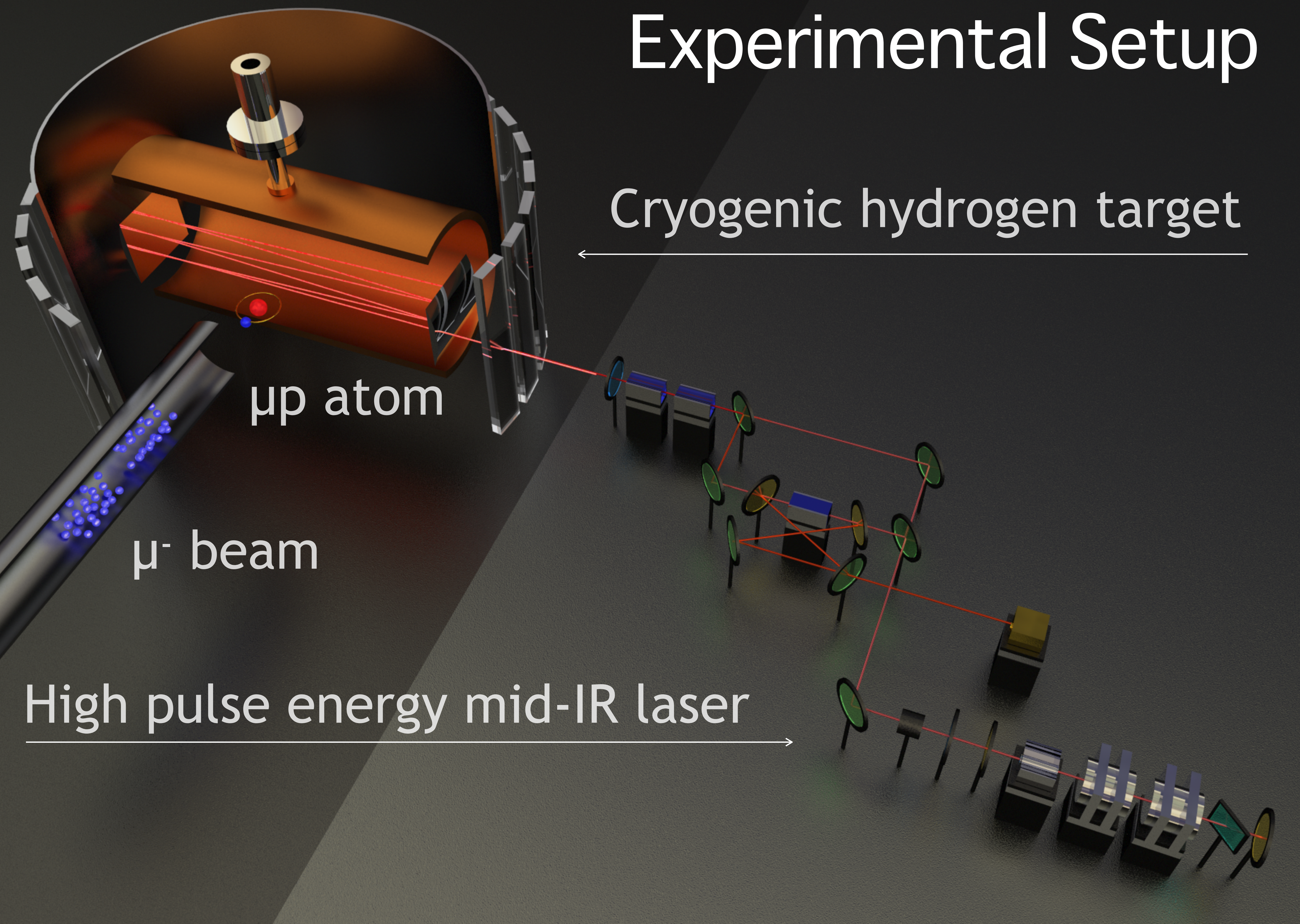
Pump Laser

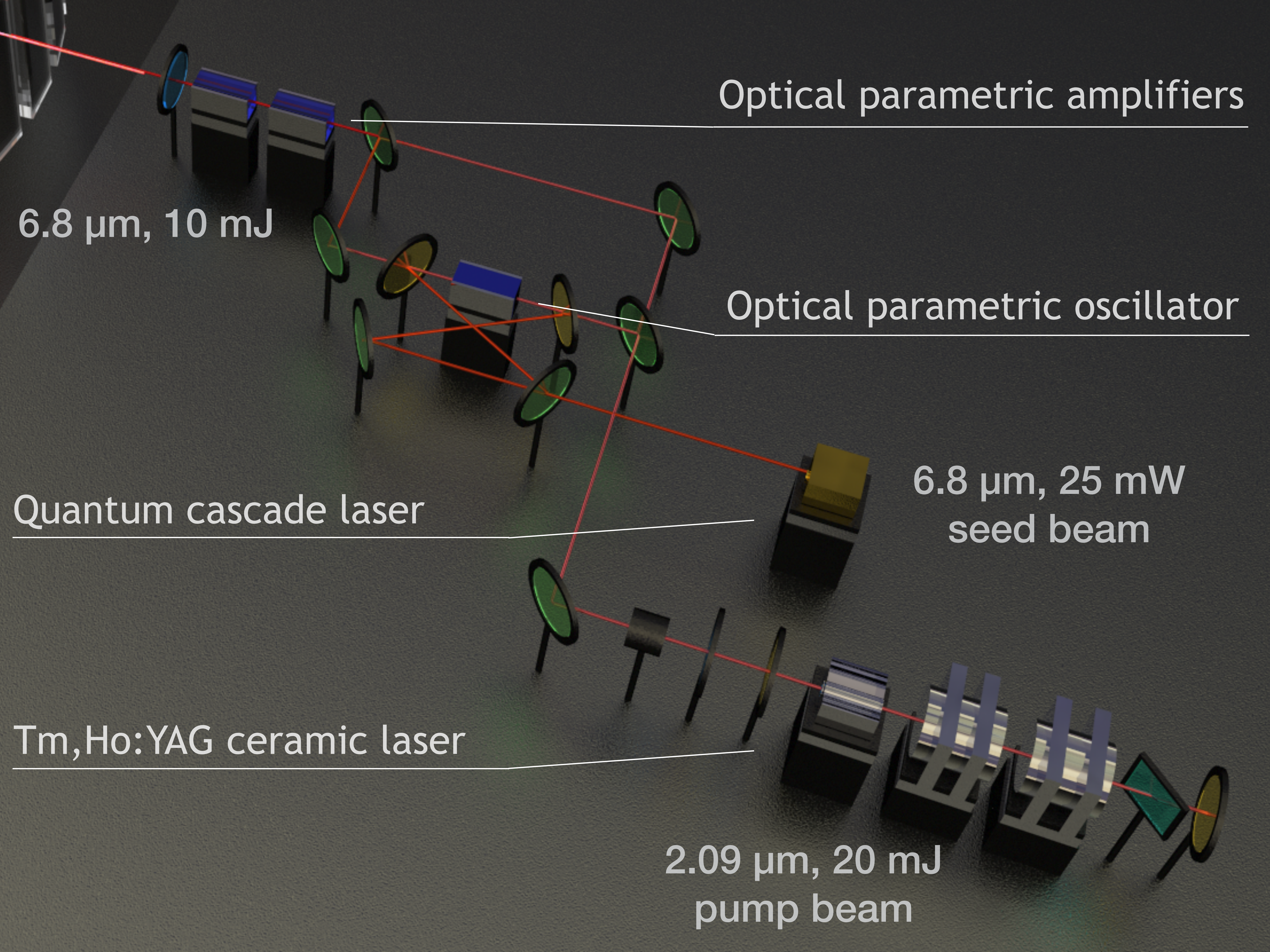


Seed Laser

S. Aikawa, M. Yumoto, N. Saito, Y. Oishi

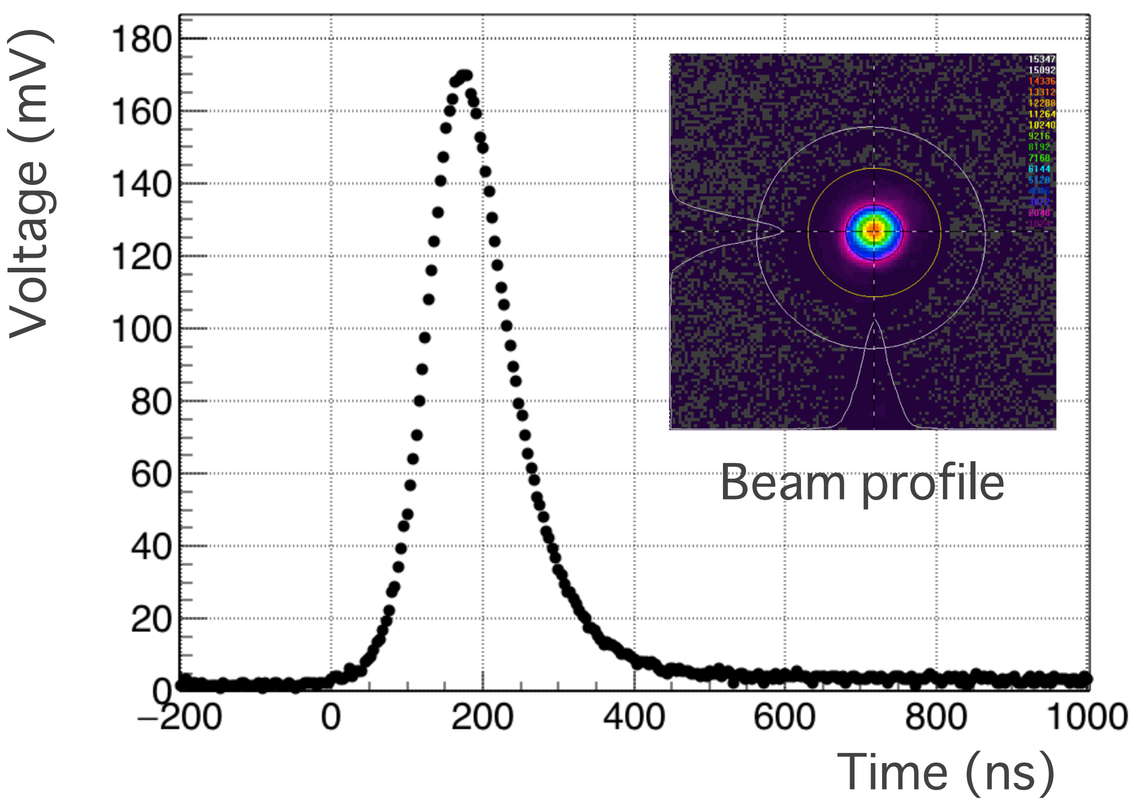
# Experimental Setup

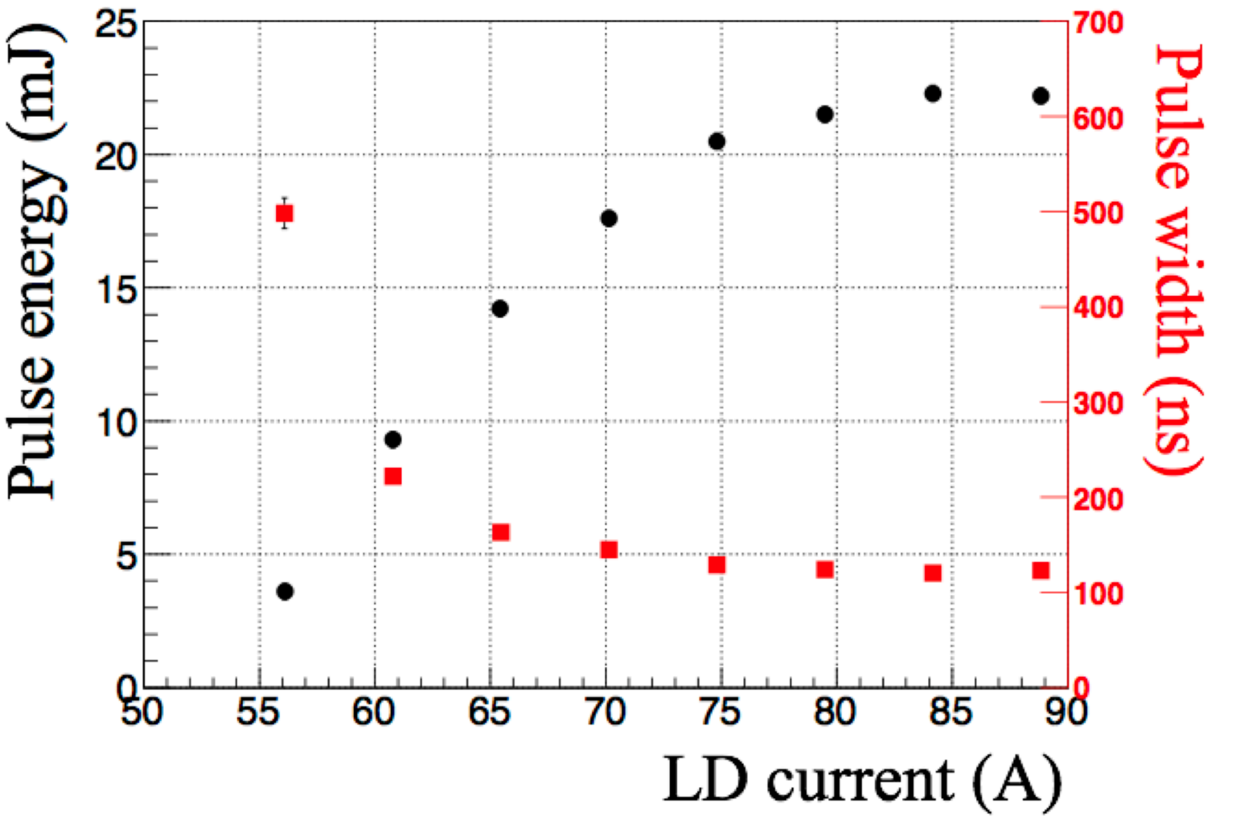



Optical parametric amplifiers
6.8 μm, 10 mJ
Optical parametric oscillator
6.8 μm, 25 mW
seed beam
Quantum cascade laser
Tm,Ho:YAG ceramic laser
2.09 μm, 20 mJ
pump beam

# Tm,Ho: YAG Ceramic Laser

## for a pump beam



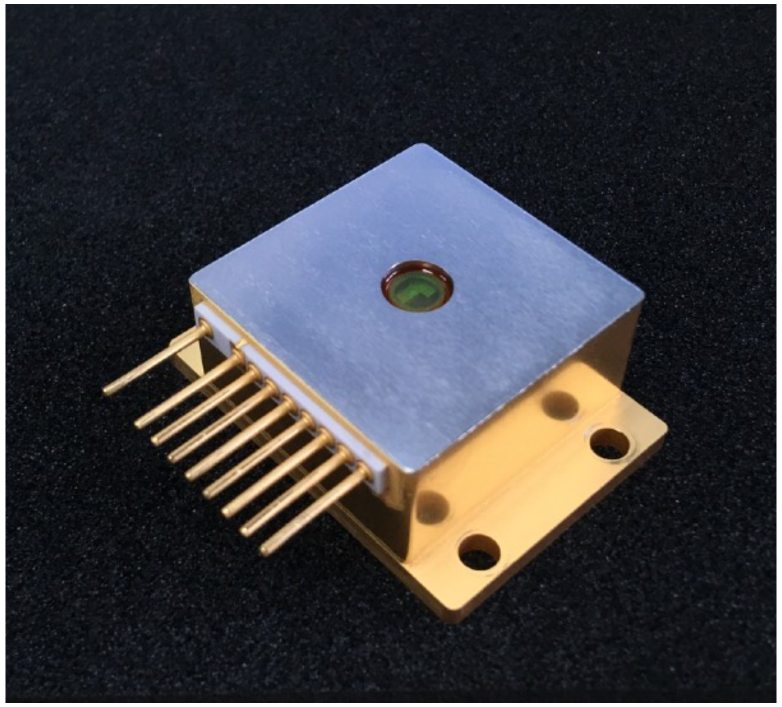



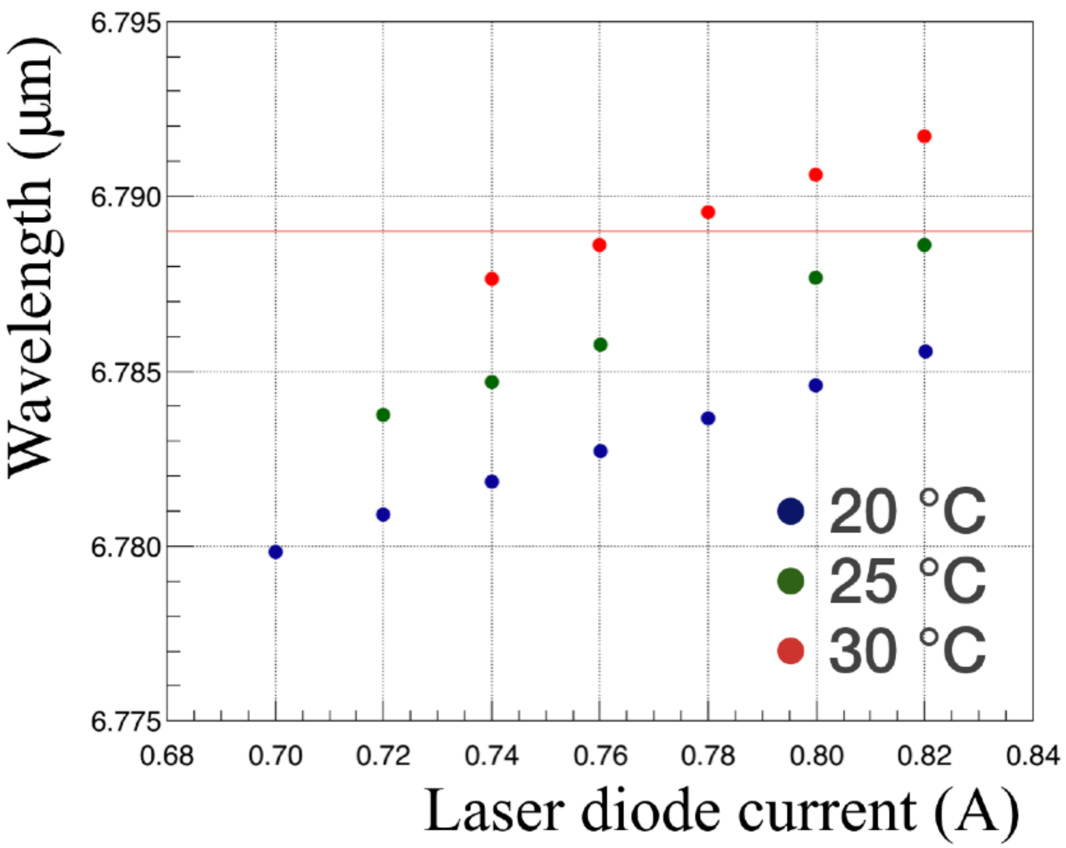

- 2.09 $\mu$m light is necessary for 6.8 $\mu$m light generation via an OPO.
- LD pumped, Q-switching, $Tm^{3+}$,$Ho^{3+}$ co-doped YAG ceramic laser was developed.
- Sufficient performance as a pumping beam for the ZGP-OPO was achieved (E>20 mJ, Width<150 ns).

S. Kanda et al., RIKEN Accelerator Progress Report 51, 214 (2018).

# Quantum Cascade Laser

## for a seed beam

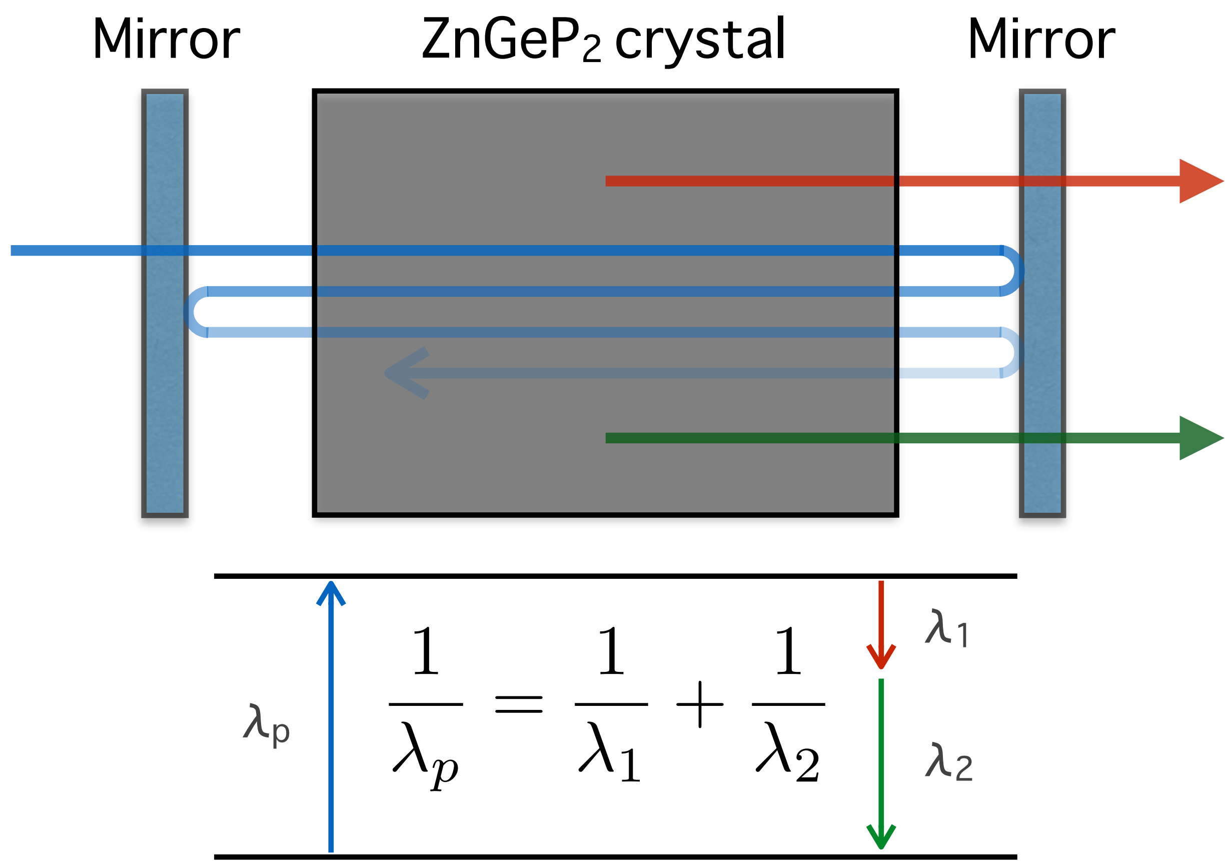


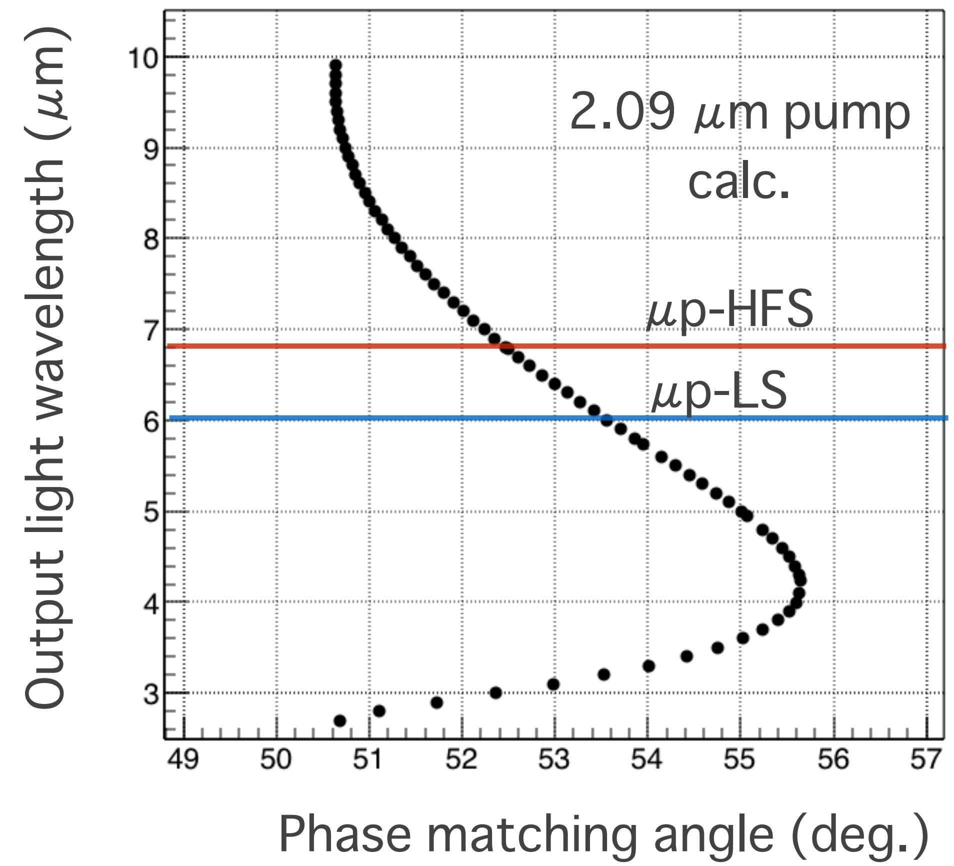



- Quantum cascade laser (QCL) for a seeder was developed.
- Oscillation at 1473.03 cm-1 = 6.778 $\mu$m was confirmed.
- Radiant output power was 25 mW at 6.778 $\mu$m (high enough).

# Optical Parametric Oscillator

## for frequency conversion

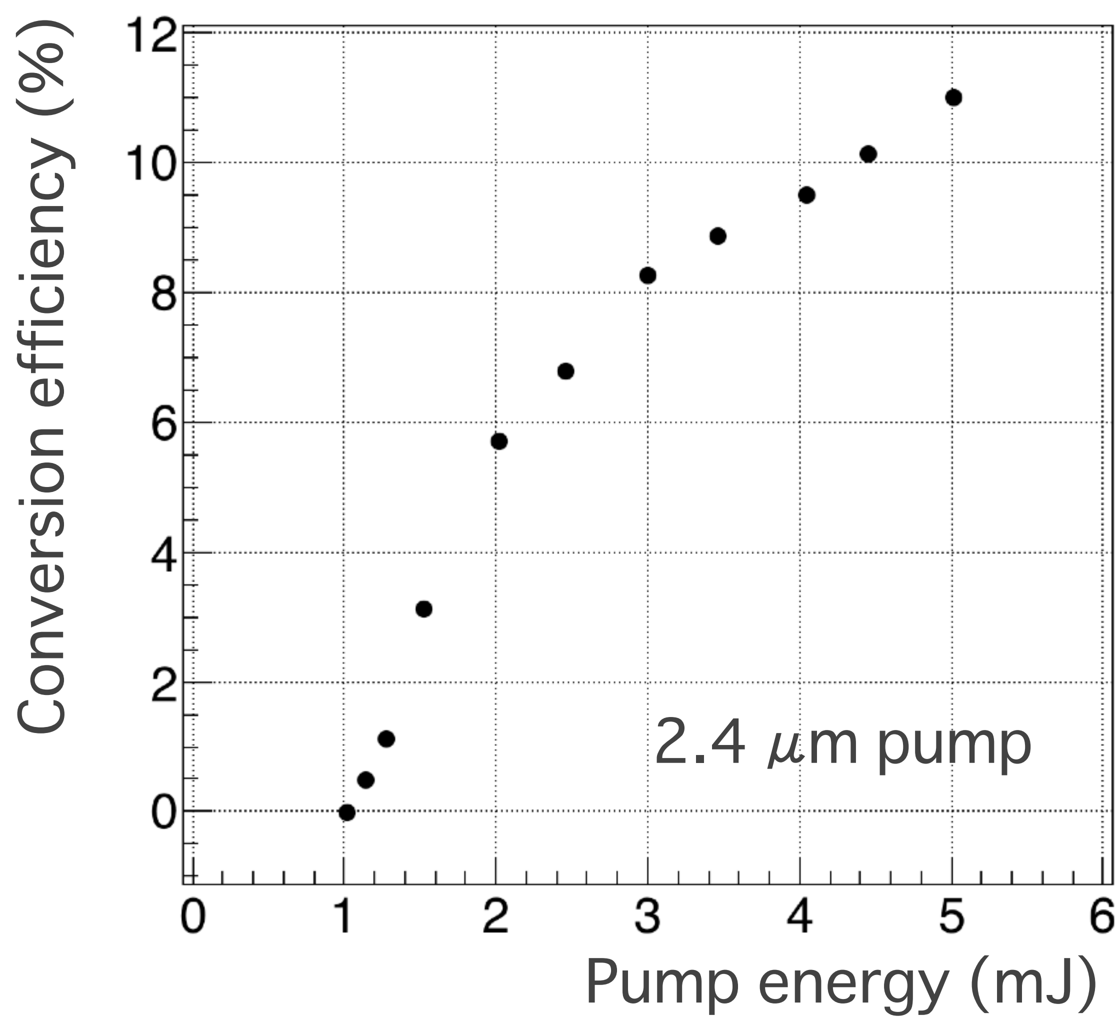


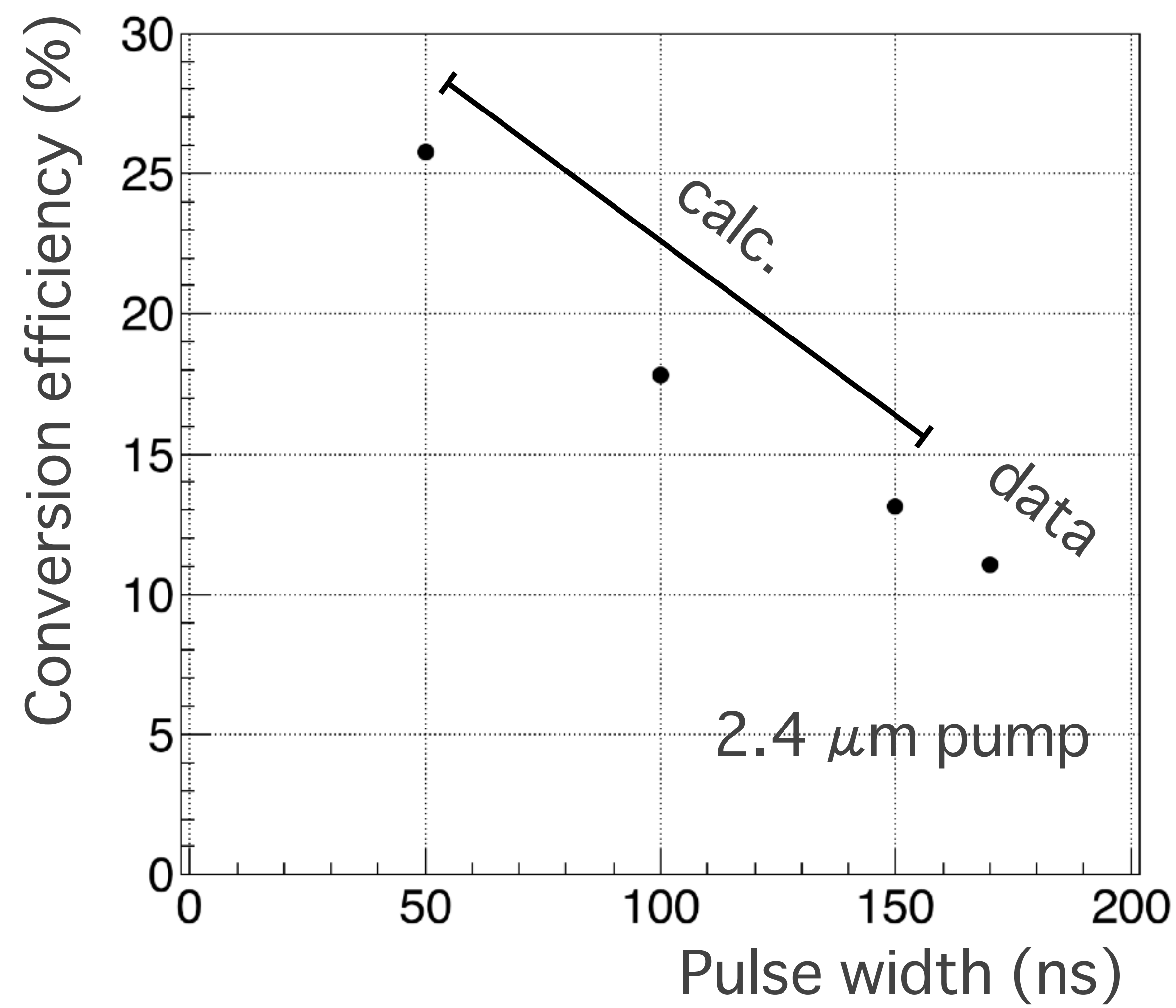




- Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.
- ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.
- The Lamb shift can also be measured by adjusting the phase-matching angle.

# Optical Parametric Oscillator

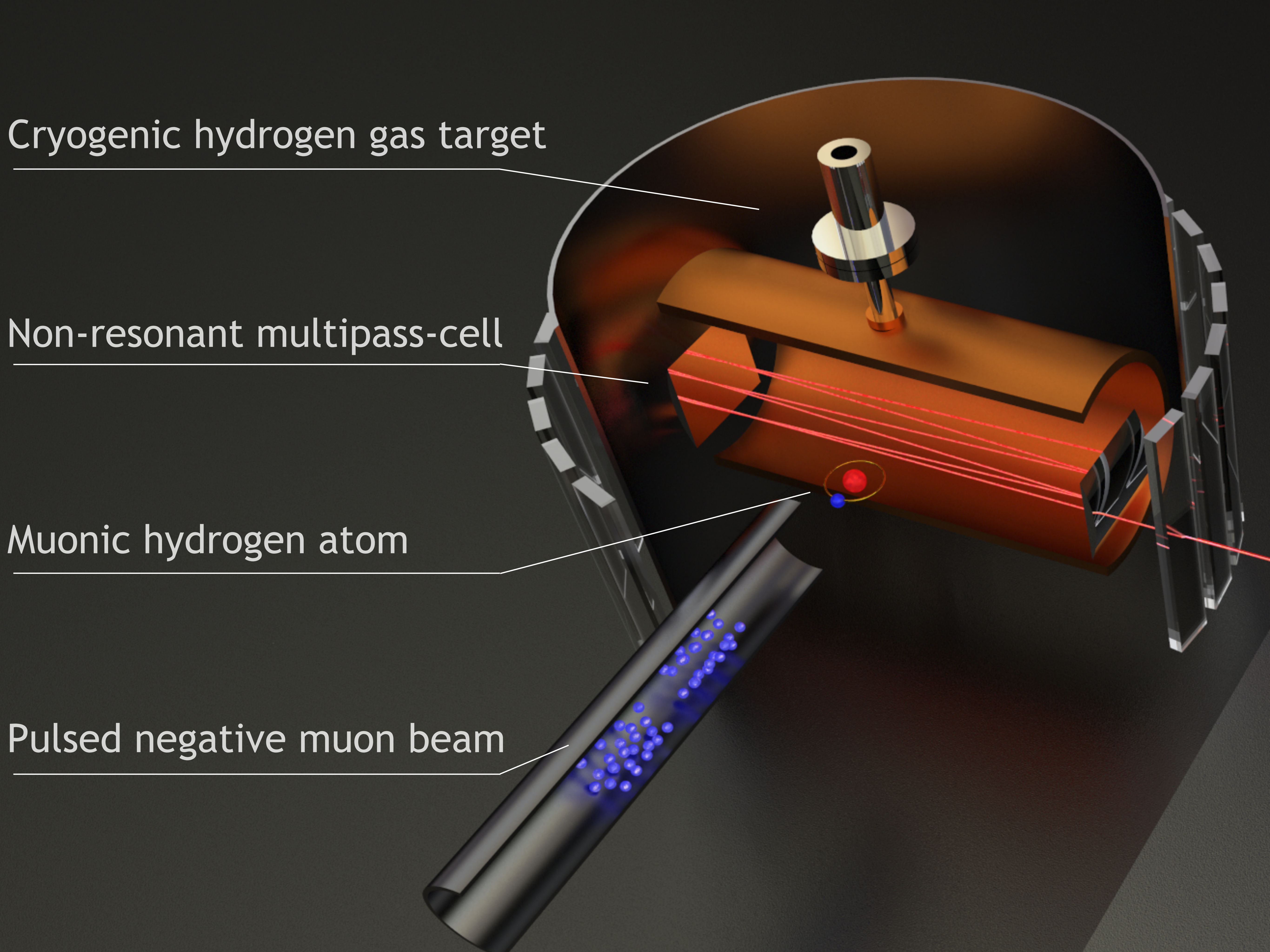
## for frequency conversion



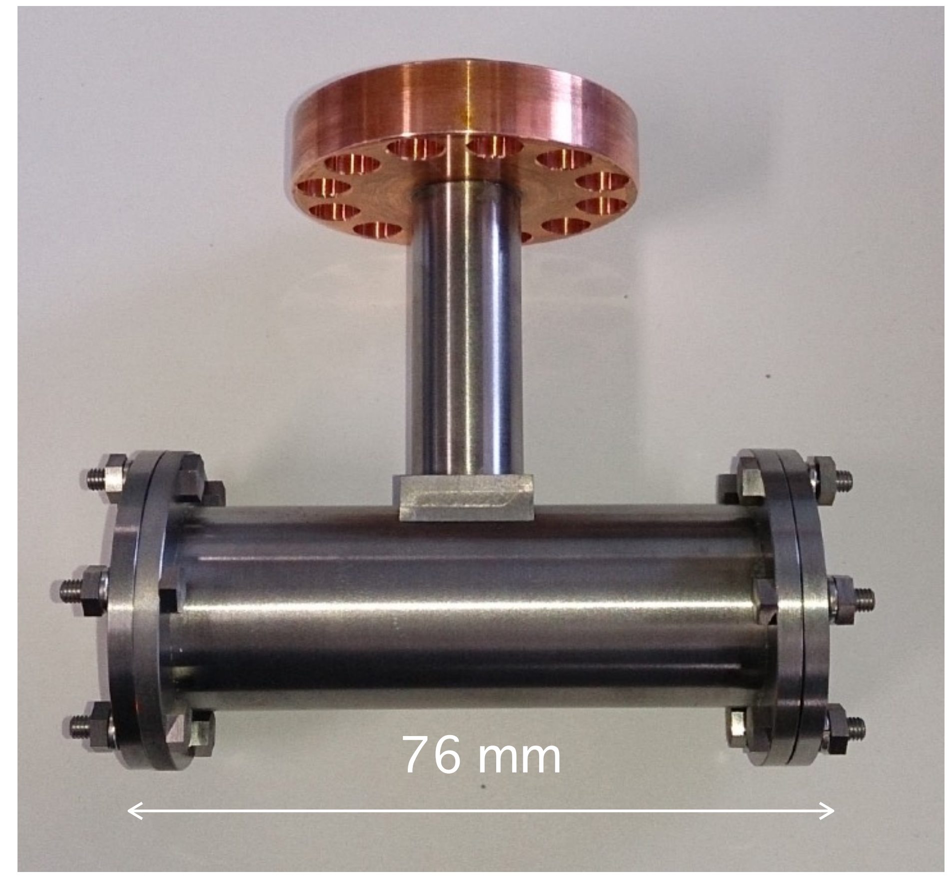

- The ZGP-OPO was demonstrated with Cr:ZnSe laser (2.4 $\mu$m).
- Similar performance is expected with 2.09 $\mu$m pump.
- The conversion efficiency of 13% or above is achievable.

S. Aikawa, Master Thesis, Tokyo Institute of Technology (2016).


Cryogenic hydrogen gas target
Non-resonant multipass-cell
Muonic hydrogen atom
Pulsed negative muon beam

# Hydrogen Gas Target

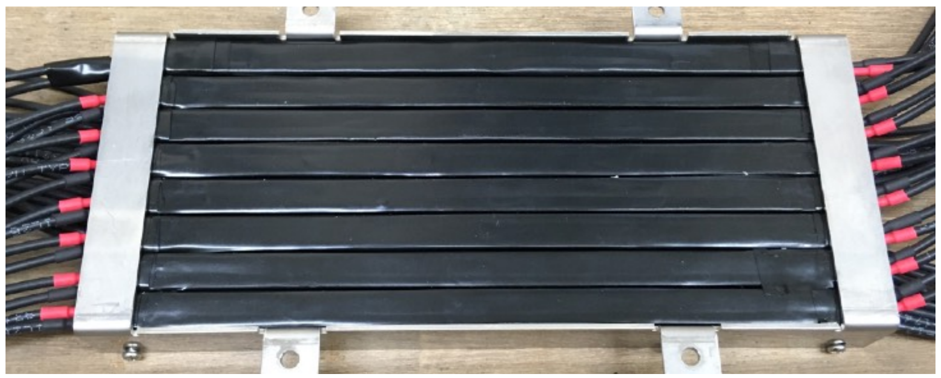
## at cryogenic temperatures

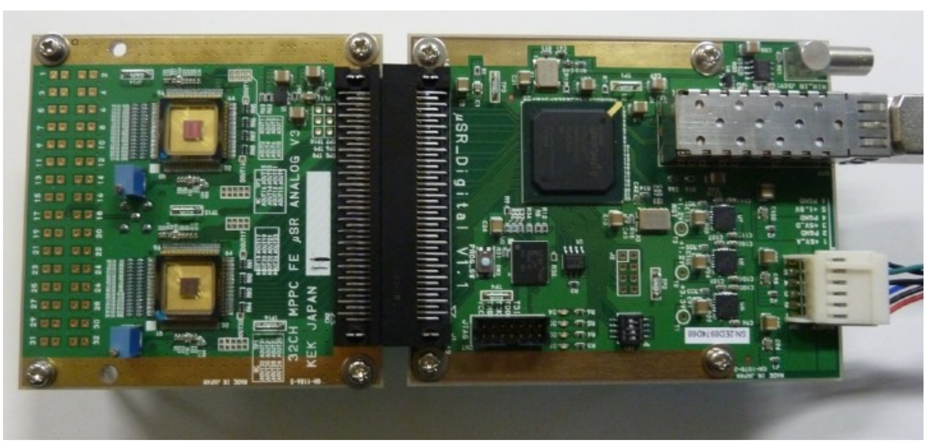


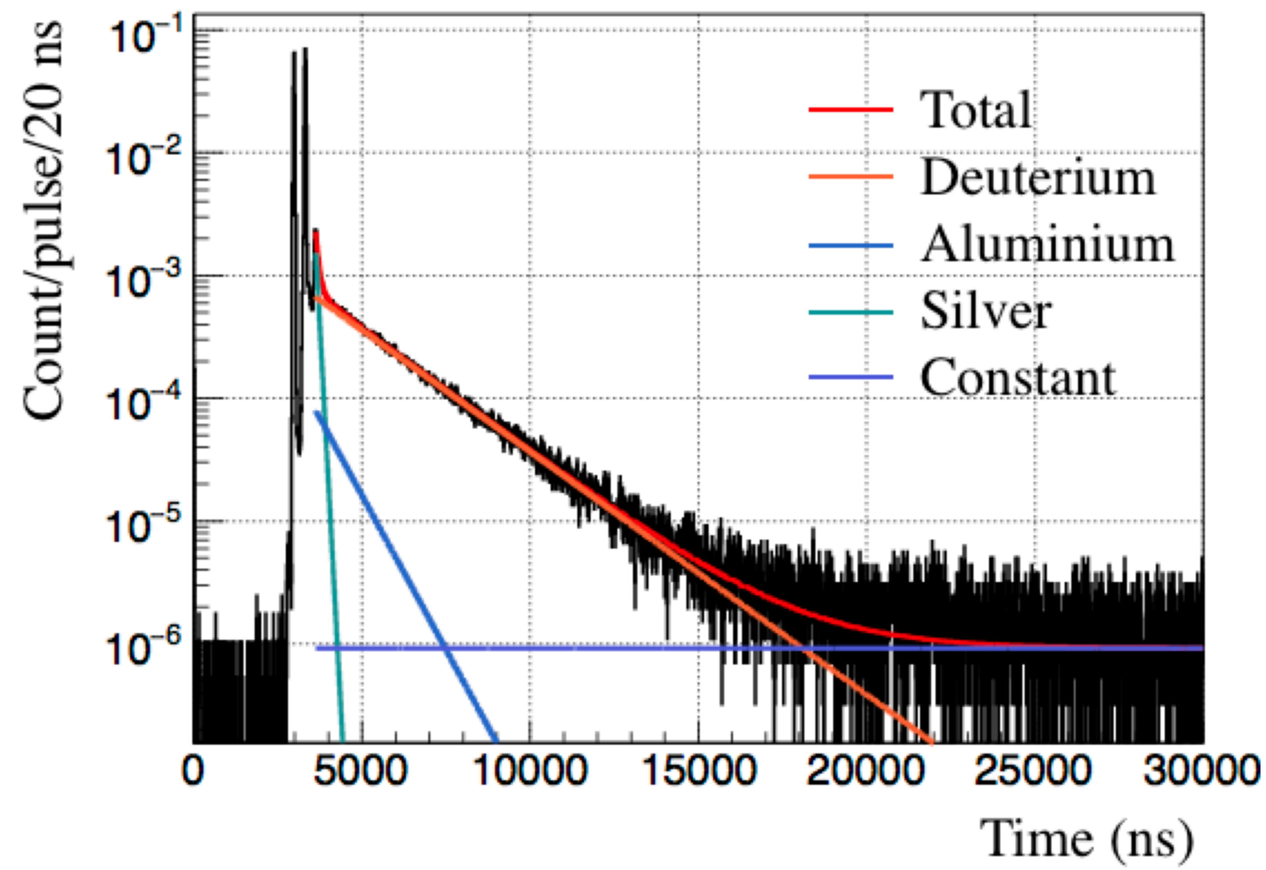

- Target is cooled down to 20 K by using a pulse-tube cryostat.
- Gas density is monitored by a Baratron pressure gauge.
- Target cell is made of tungsten for background suppression.

# Electron Detector

## for a muon spin measurement





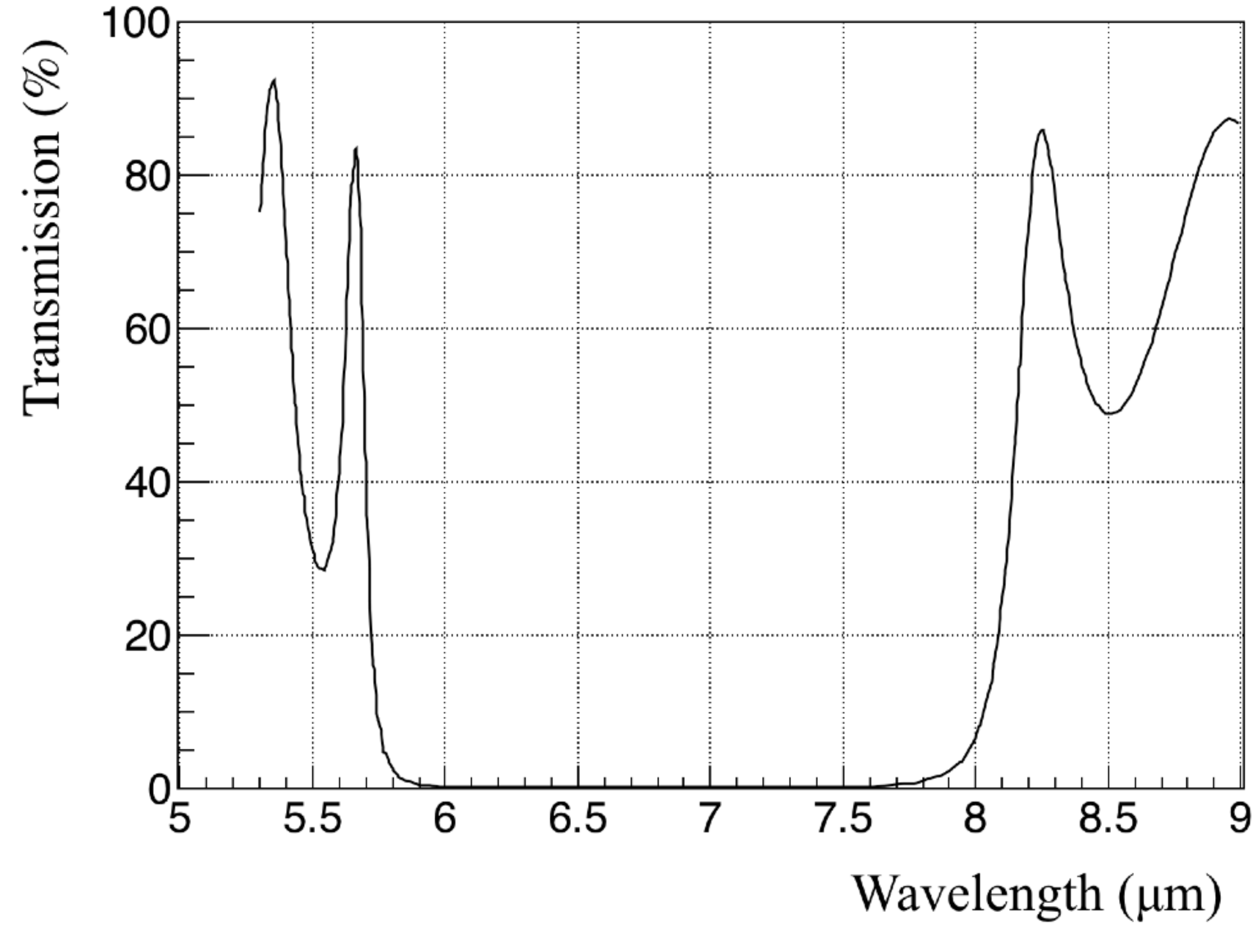



- A segmented scintillation counter consisting of scintillator bars and silicon photomultipliers (SiPMs). A fast frond-end electronics for SiPM readout is used.
- Coincidence analysis for signal-to-noise ratio improvement.
- Tested at RIKEN-RAL muon facility and sufficient performance was confirmed.

S. Kanda et al., RIKEN Accelerator Progress Report 52, 180 (2019).

# Multipass-Cell

## for laser-light reflections

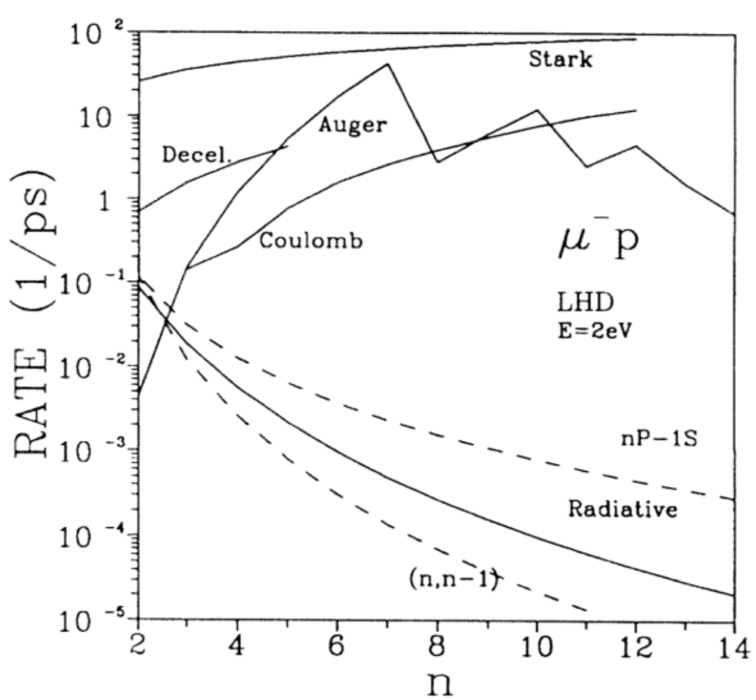




- The reflective index of 99.95% is desirable.
- A pair of prototype mirrors were fabricated and tested.
- A precise measurement of the reflective index is planned.

# Cascade De-excitation

## of muonic atoms in a low-density gas

| Mechanism | Process (Hydrogen case) |
|---|---|
| Radiative transition | $(\mu p)_i \rightarrow (\mu p)_f + \gamma$ |
| External Auger effect | $(\mu p)_I + H_2 \rightarrow (\mu p)_f + e^- + H_2^+$ |
| Stark mixing | $(\mu p)_{nl} + H \rightarrow (\mu p)_{nl'} + H$ |
| Elastic scattering | $(\mu p)_n + H \rightarrow (\mu p)_n + H$ |
| Coulomb de-excitation | $(\mu p)_i + p \rightarrow (\mu p)_f + p$ |



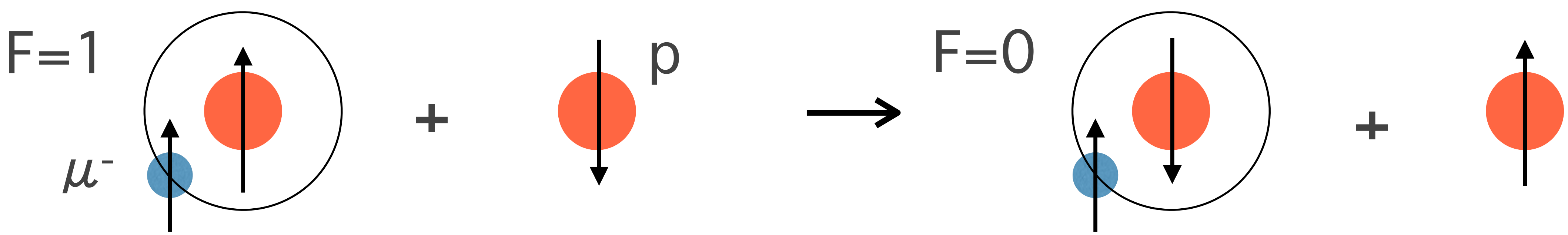

V. A. Markushin, Phys. Rev. A 50, 1137 (1994).

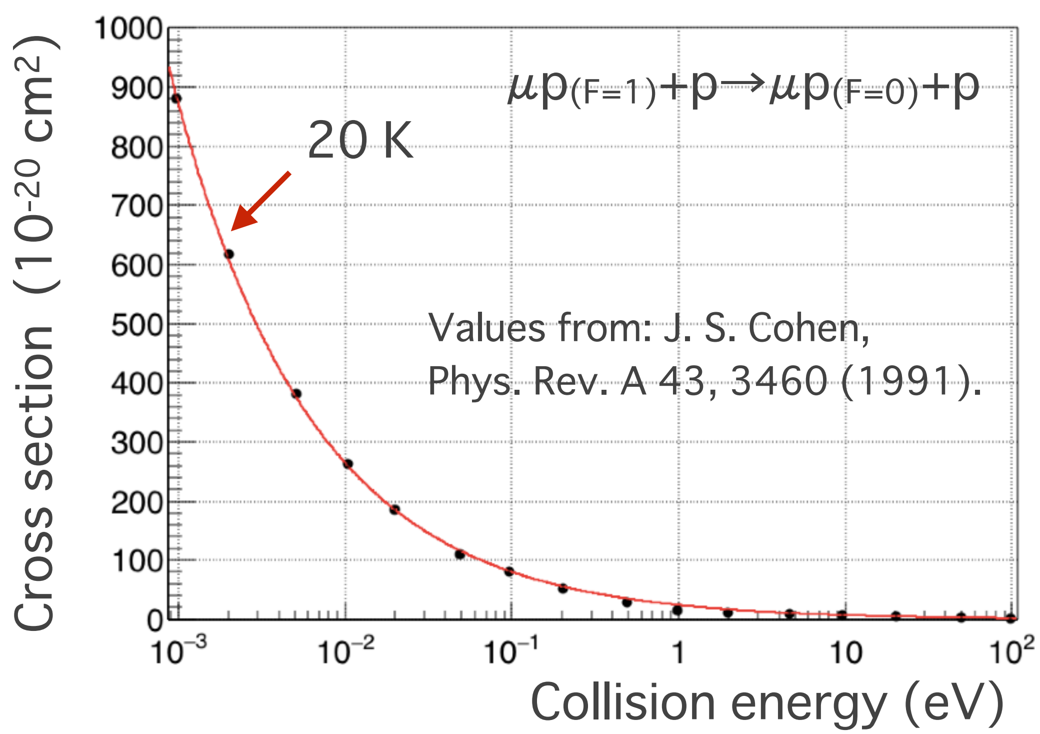
- When a nuclear Coulomb potential captures a negative muon, the muon forms an exotic bound state called muonic atom.
- Initial state is highly excited with the principle quantum number $n \sim 14$ ($\sim\sqrt{m_\mu/m_e}$).
- Muon spin depolarization due to Auger electrons.
- Acceleration by Coulomb de-excitations.
- Coulomb explosion of a molecule.
- Electron refilling from surrounding atoms.
- Too fast to track one-by-one.

# Atomic Collisional Quenching

## De-excitation of the hyperfine triplet

- Collisional quenching of the HFS triplet state
- Inelastic scattering $\mu$p(F=1)+p -> $\mu$p(F=0)+p
- Only theoretical predictions are known and no measurement had been performed.

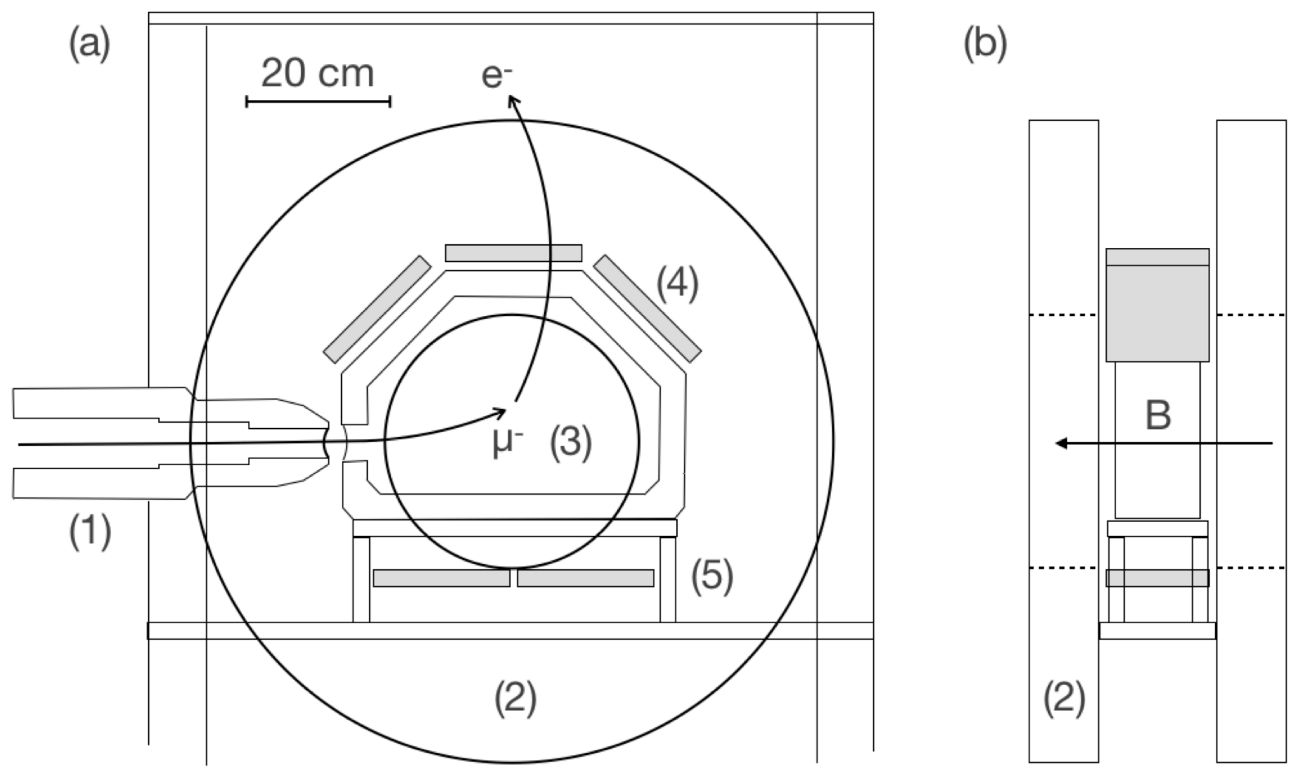


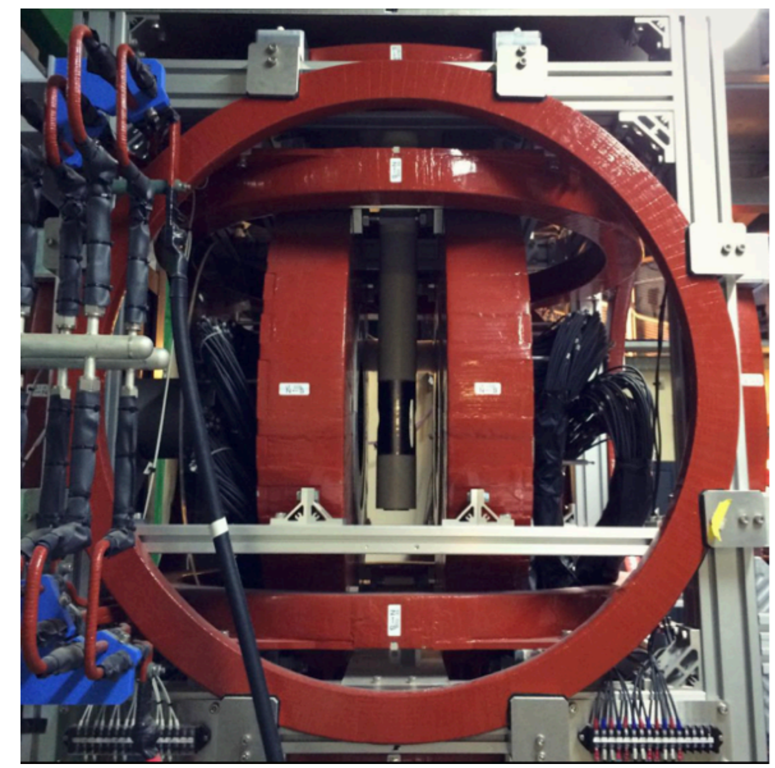

- Quenching rate depends on collision energy and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate was proposed.

# Collisional Quenching Measurement

## at RIKEN-RAL Muon Facility




Experimental setup



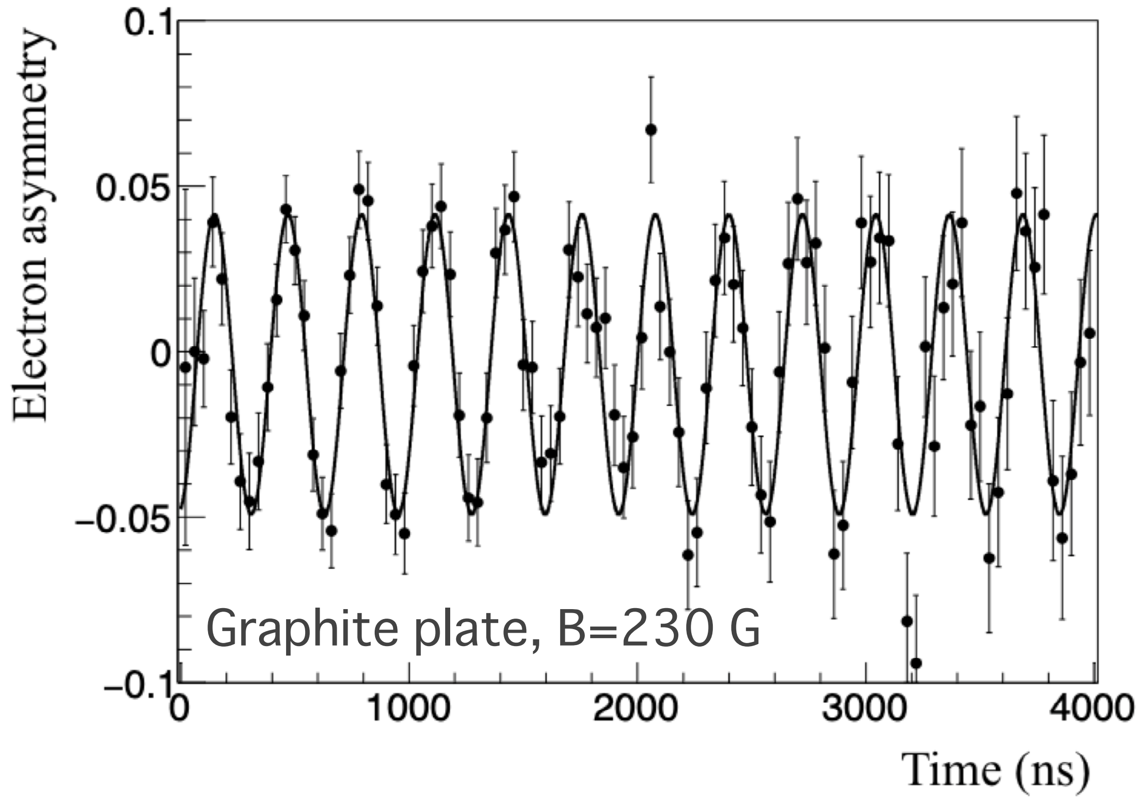
CHRONUS spectrometer

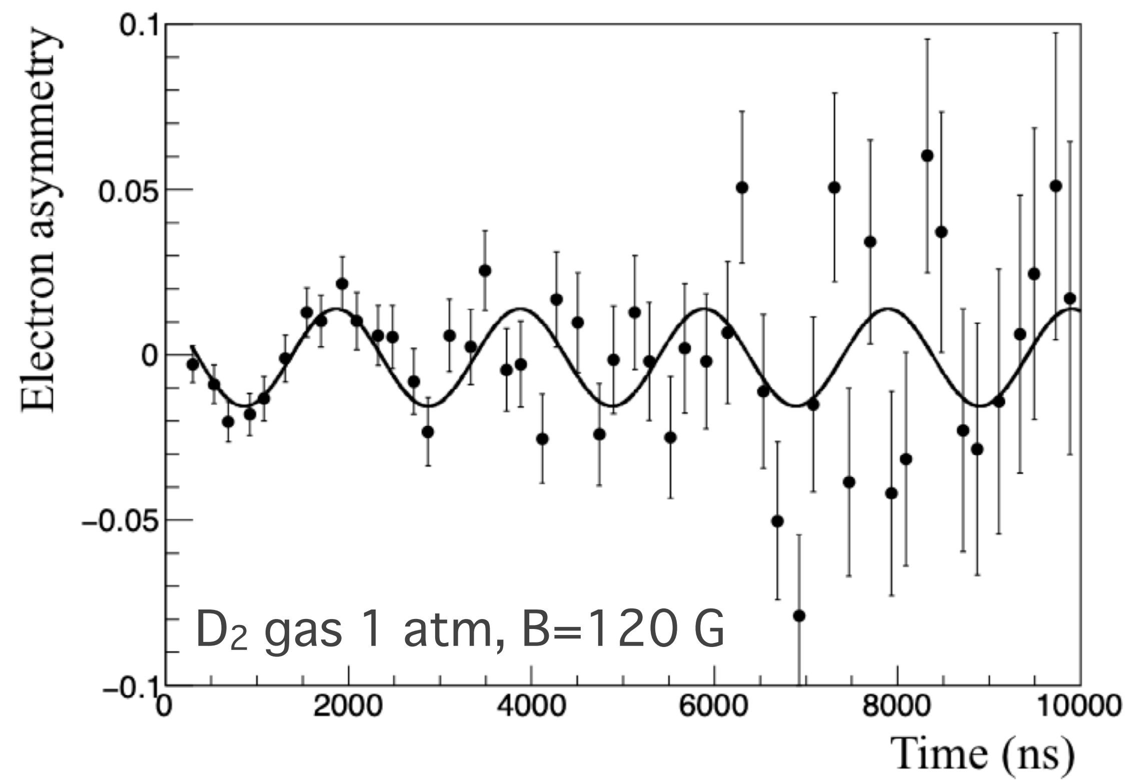
- Initial muon spin is polarized along the beam axis.
- Muon forms a muonic atom after stopping in the target.
- Muon spin rotates under a static magnetic field.
- Angular asymmetry in electron emission from muon decay is measured.

S. Kanda et al., J. of Phys. Conf. Ser., 1138 (2018).

# Negative Muon Spin Rotation

## of muonic carbon and muonic deuterium



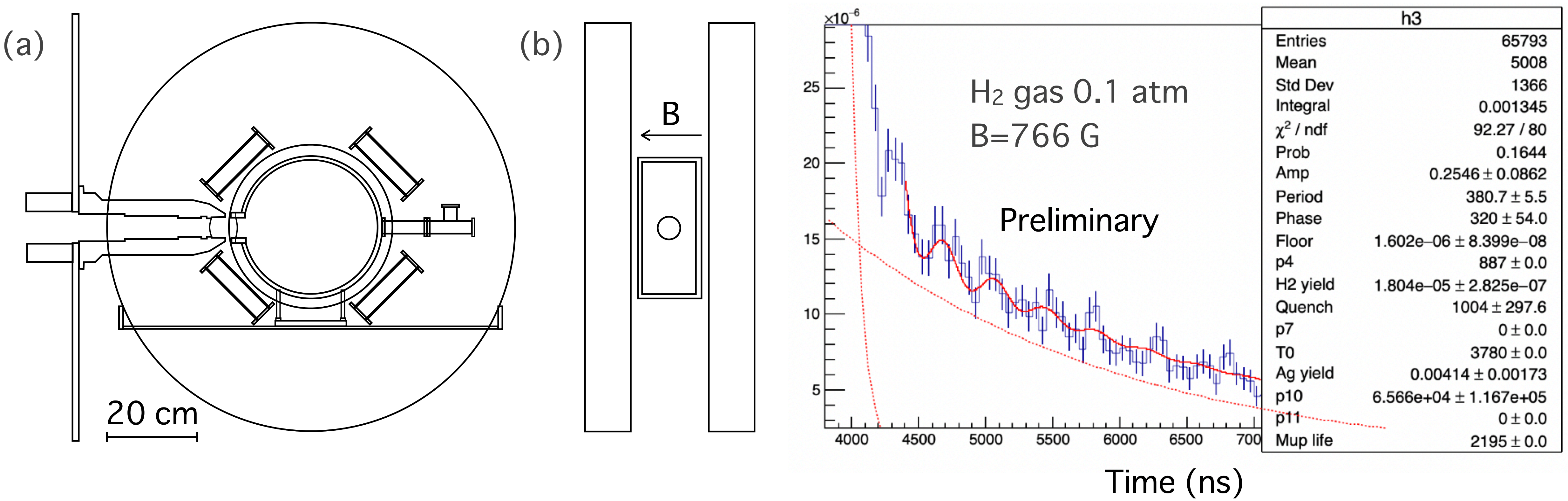




- Muon spin rotation in graphite was measured to calibrate the beam polarization and detector acceptance. The $\mu$SR amplitude was 0.045± 0.002, the beam polarization was estimated to be 95%.
- Using a deuterium gas target, an oscillation amplitude of 0.017±0.003 was obtained, then the residual polarization was 8.3%. Relaxation was too slow to evaluate.

Publication in preparation

# Muonic Protium Spin Rotation

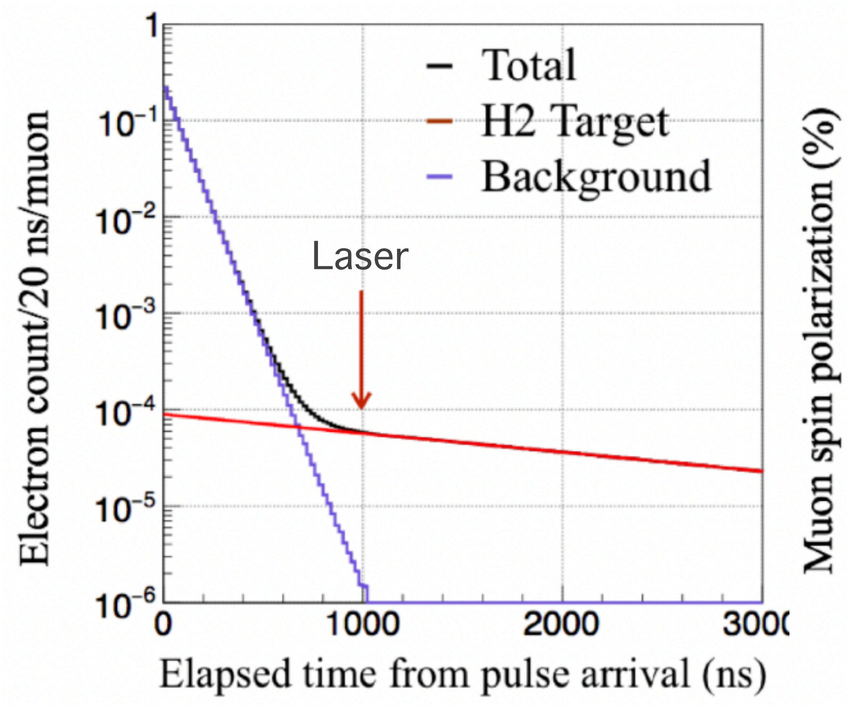
## at RIKEN-RAL Muon Facility

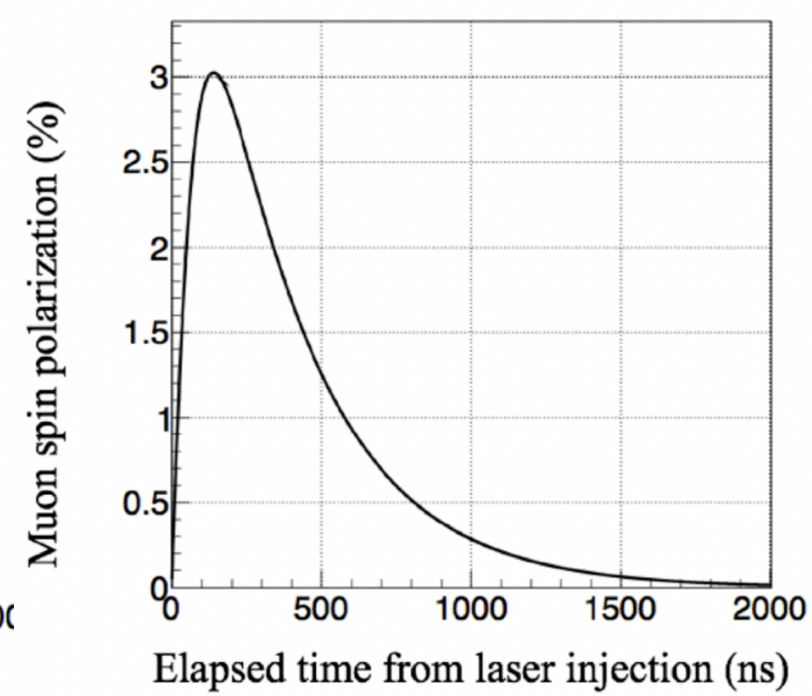


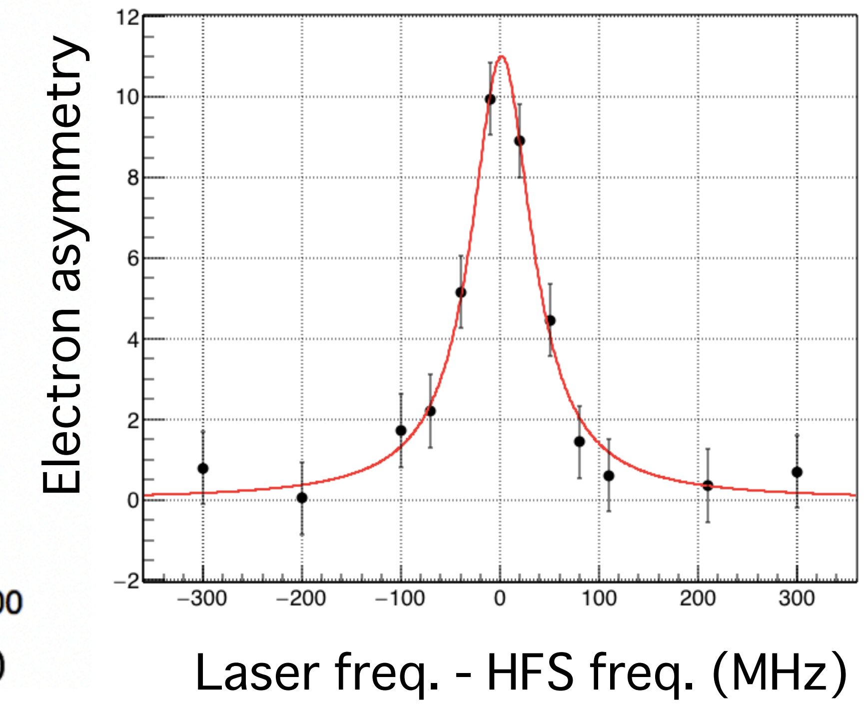

- Muon spin rotation with a low-density hydrogen gas target was performed using a new target chamber for better B-field uniformity.
- The low gas pressure of 0.1 atm was necessary, so the signal-to-noise ratio is small. Nevertheless, a precession-like signal is visible, so careful analysis and detailed simulations are underway.

# Feasibility of the Experiment

## expectation on the statistical precision



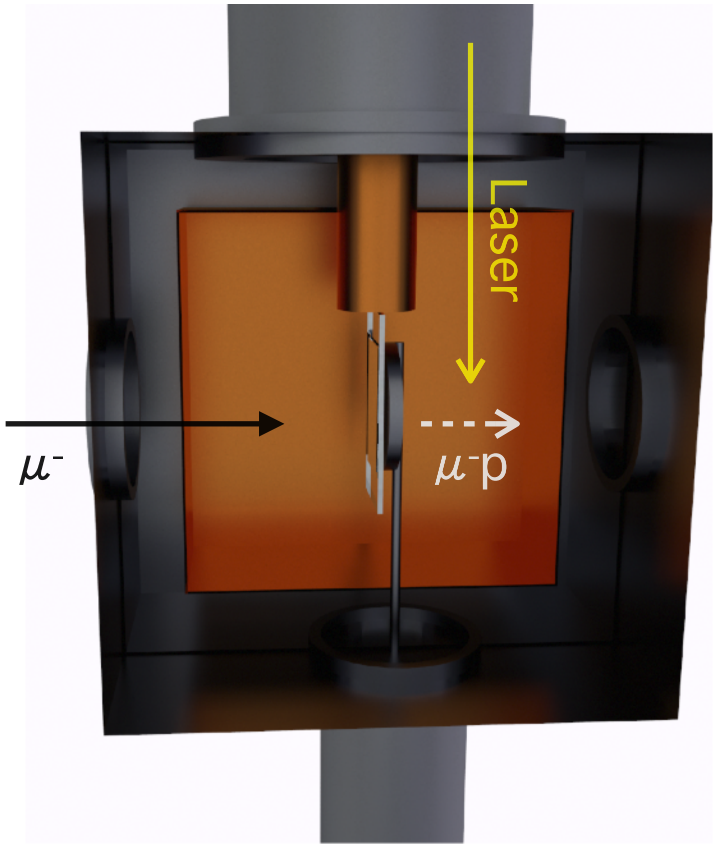



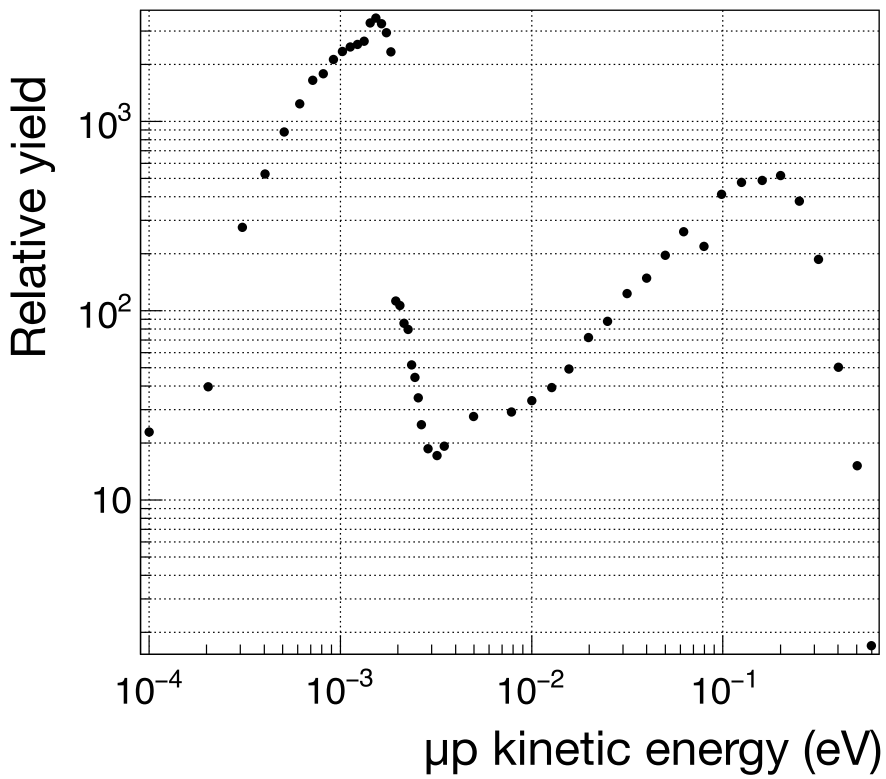

- The beam flux is $1\text{x}10^6$ $\mu$/s with the momentum of 40 MeV/c. About 0.05% of muons stop between the multipass-cell mirrors.
- The laser light is injected 1 $\mu$s after the muon pulse arrival. The averaged muon spin polarization will be 2% with the pulse energy of 20 mJ.
- The signal counting rate will be 0.14/s. A week of measurement is required for frequency scan.
- Completion of the high pulse-energy laser system is necessary. Improvement in the OPO and OPA is essential. Technically possible, mainly a matter of budget.

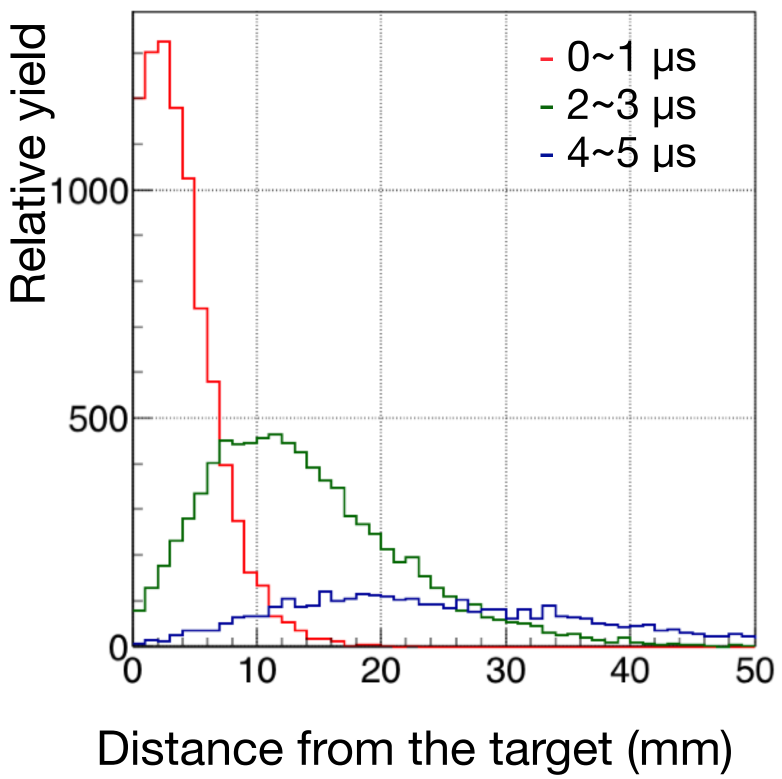
S. Kanda et al., Proceeding of Science, PoS(NuFACT2017)122 (2018).

# Solid Hydrogen Target

## for spectroscopy in vacuum



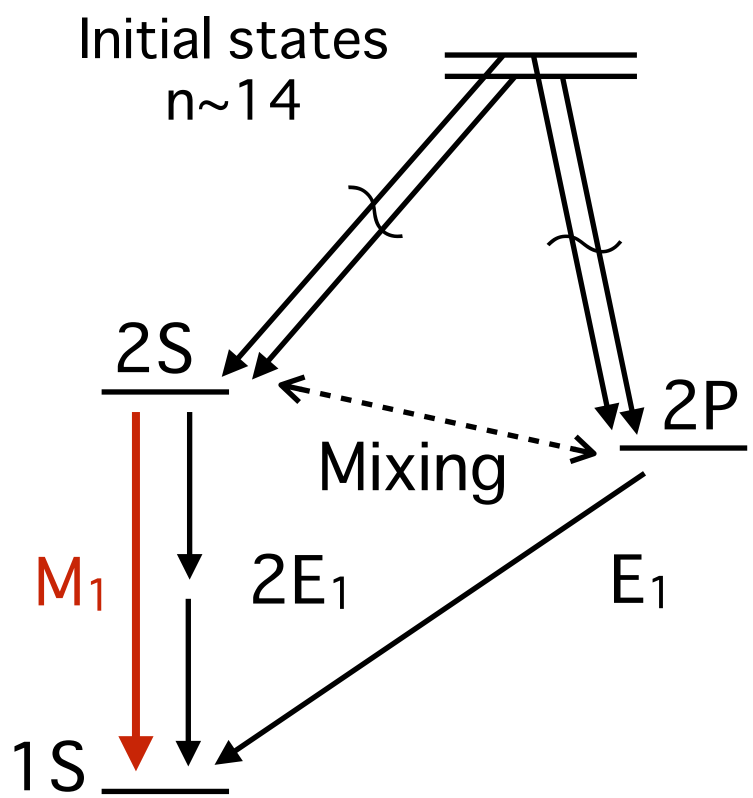



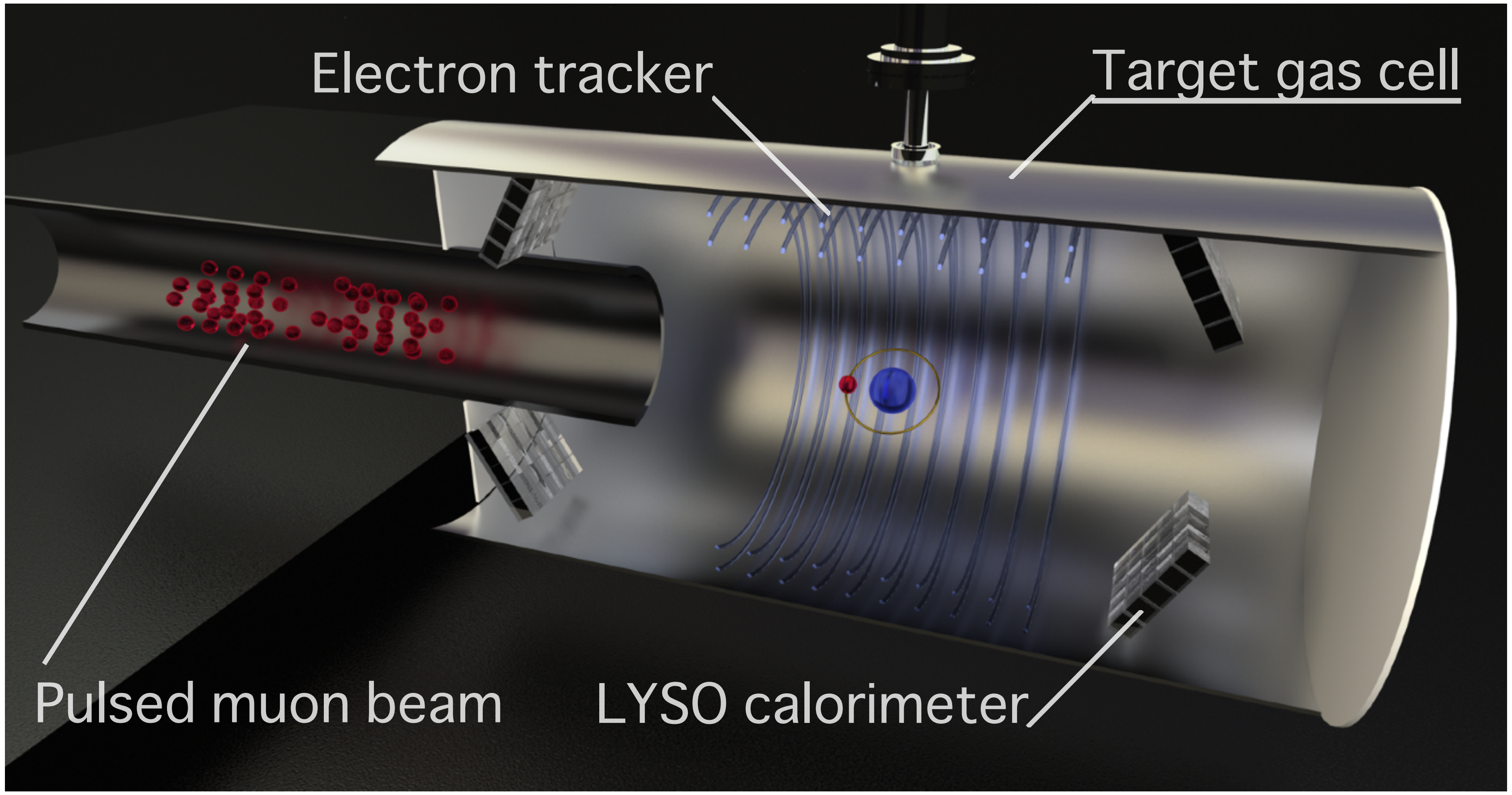

Model: J. Wozniak et al., Phys. Rev. A 68, 062502 (2003).

- Muonic hydrogen atoms are emitted from solid hydrogen in to a vacuum.
- Spectroscopy become possible without collisional quenching.
- Under development as a common system with a solid rare-gas moderator for a muonium interferometer.
- A beam test is scheduled for early next year.

# Atomic Parity Violation

## a spin-off project from $\mu$p-HFS spectroscopy



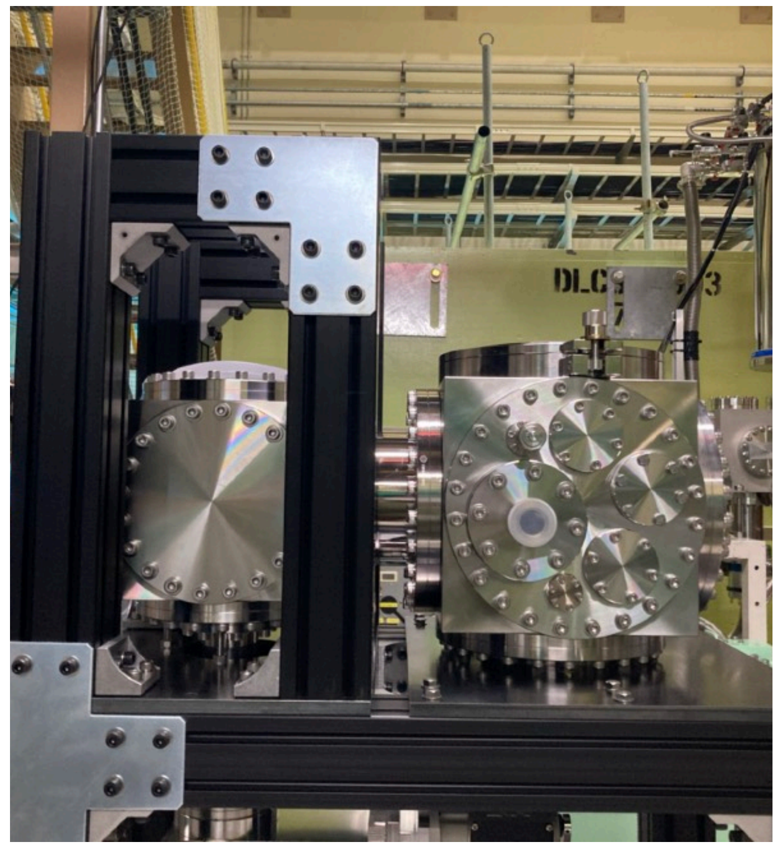



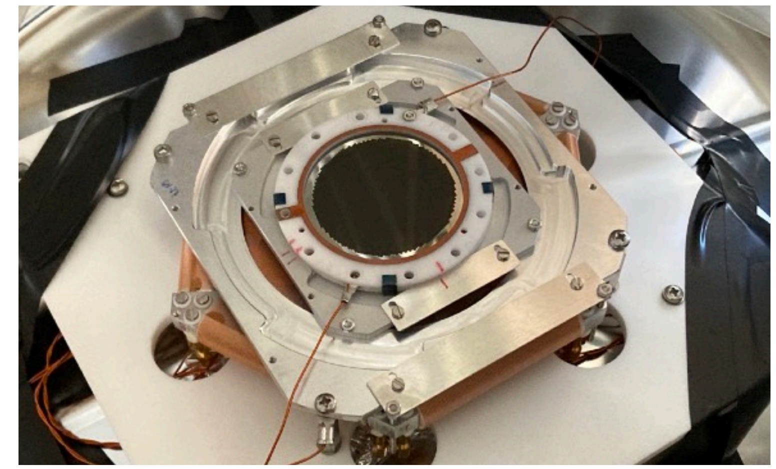

- A new measurement of the Weinberg angle using muonic atoms.
- Parity-violating mixing between 2S-2P states results in anisotropic single-photon emission (M1).
- Muonic X-rays are measured by a scintillator-based calorimeter.

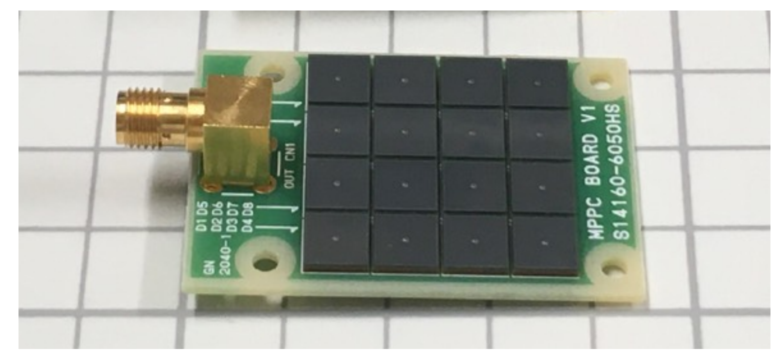
S. Kanda, EPJ Web Conf. 262, 01010 (2022).

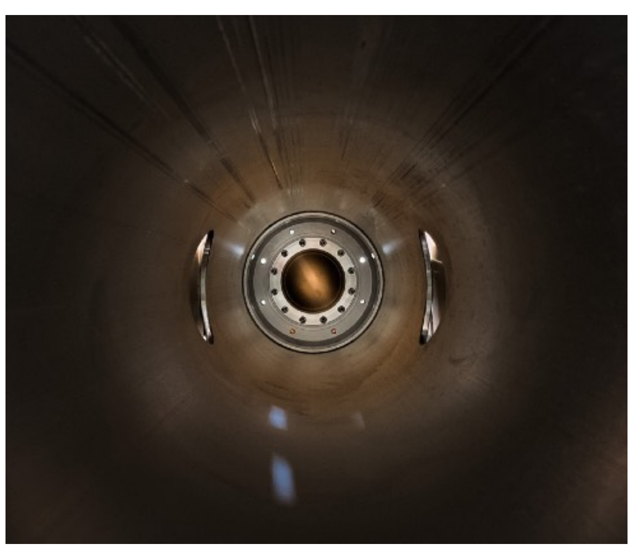
# Reboot the project at J-PARC

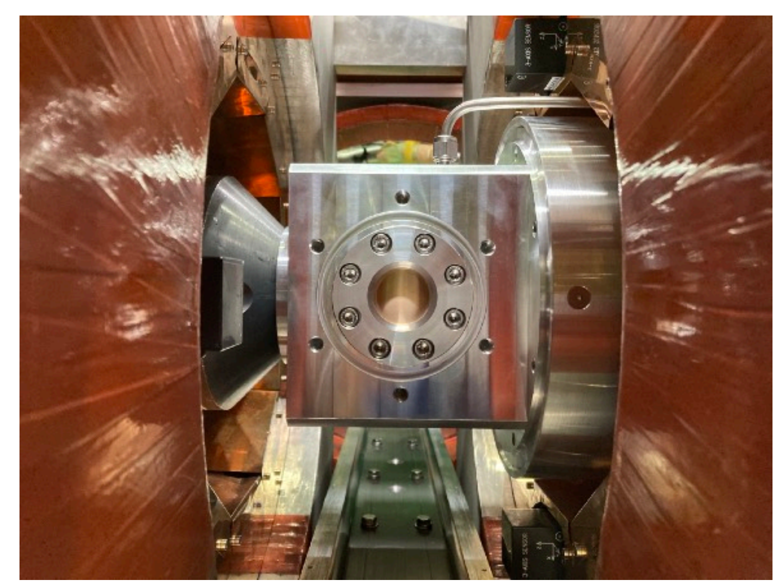
## towards realizing the first spectroscopy









# Summary

## and outlooks

- For a deeper understanding of the proton radius, a new measurement of the ground-state hyperfine splitting in muonic hydrogen is in preparation.
- In the experiment, the angular asymmetry of muon decay electrons is to be measured for detection of the state transition.
- We are working to complete the apparatus developments and realize the experiment.