# A new result of neutron lifetime measurement with cold neutron beam at J-PARC

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On behalf of J-PARC neutron lifetime collaboration

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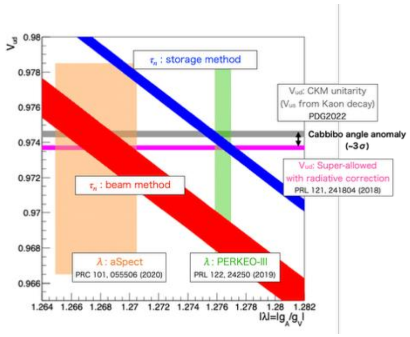
# Neutron lifetime

➢ Test of standard model

- $V_{ud}$ of the Cabibbo-Kobayashi-Maskawa (CKM) matrax can be calculated with:
  - Neutron lifetime ($\tau_n$)
  - Axis/vector coupling constant $\lambda \equiv G_A/G_V$

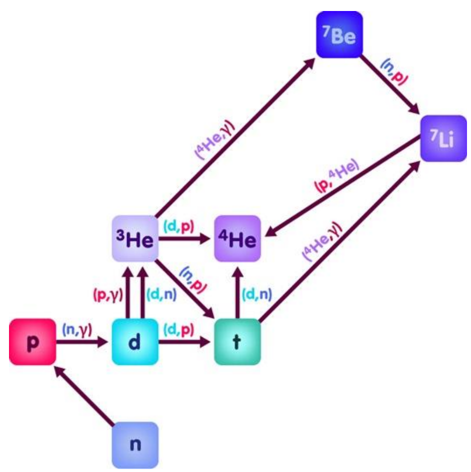
$$|V_{ud}|^2 = \frac{(4905.7 \pm 1.7)\ \text{sec}}{\tau_n(1+3\lambda^2)}$$

→ Verification of the unitarity of the CKM matrix

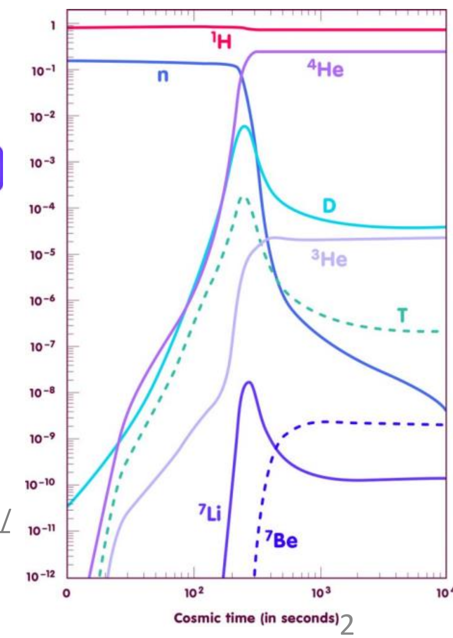



➢ An input parameters for the Big Bang Nucleosynthesis (BBN)

- Abundance of light elements in early universe can be calculated with:
  - Baryon-to-photon ratio
  - Nuclear cross sections
  - Neutron lifetime

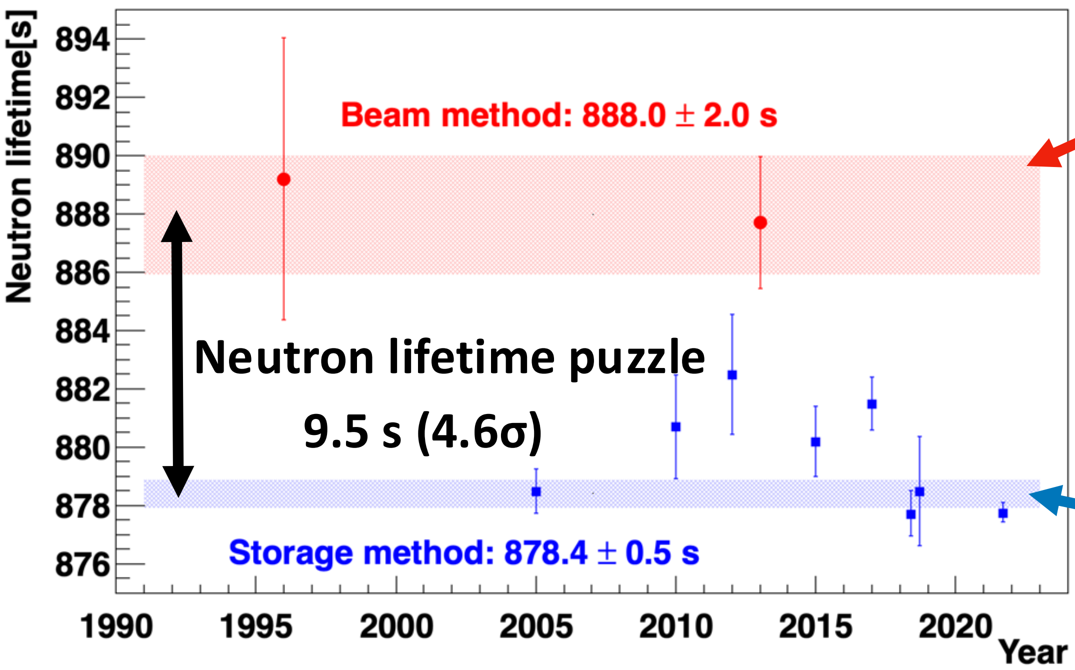



https://www.einstein-online.info/en/spotlight/bbn_phys/

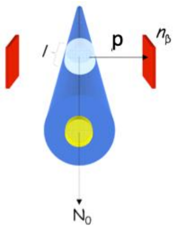



- The neutron lifetime is an important parameter for physics

# Neutron Lifetime Puzzle




Beam method: Count the decay



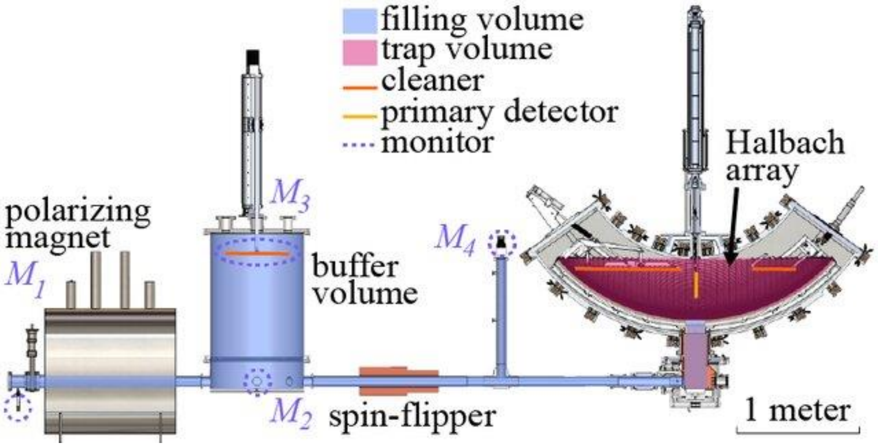

$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}$$

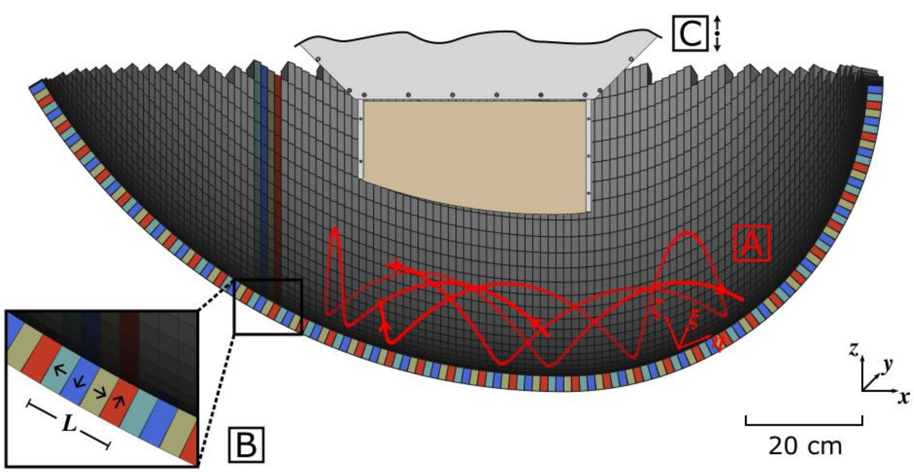
Storage method : Count the missing


$$\frac{N_1}{N_2} = \mathrm{e}^{-(t_1 - t_2)/\tau}$$

- **Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6*σ*)**
  - Experimental uncertainties that were not taken into account? (Phys. Rev. D **103**, 074010)
  - New physics?
    - \- Dark decay? (Mod. Phys. Lett. A **35**, 2030019 (2020))
    - \- Soft scattering with dark matter? (Phys. Rev. D **103**, 035014)
    - \- Mirror neutron oscillation? (EPJ C **79:** 484 (2019))

# UCNτ experiment




- The most accurate experiment have done in Los Alamos in 2021.

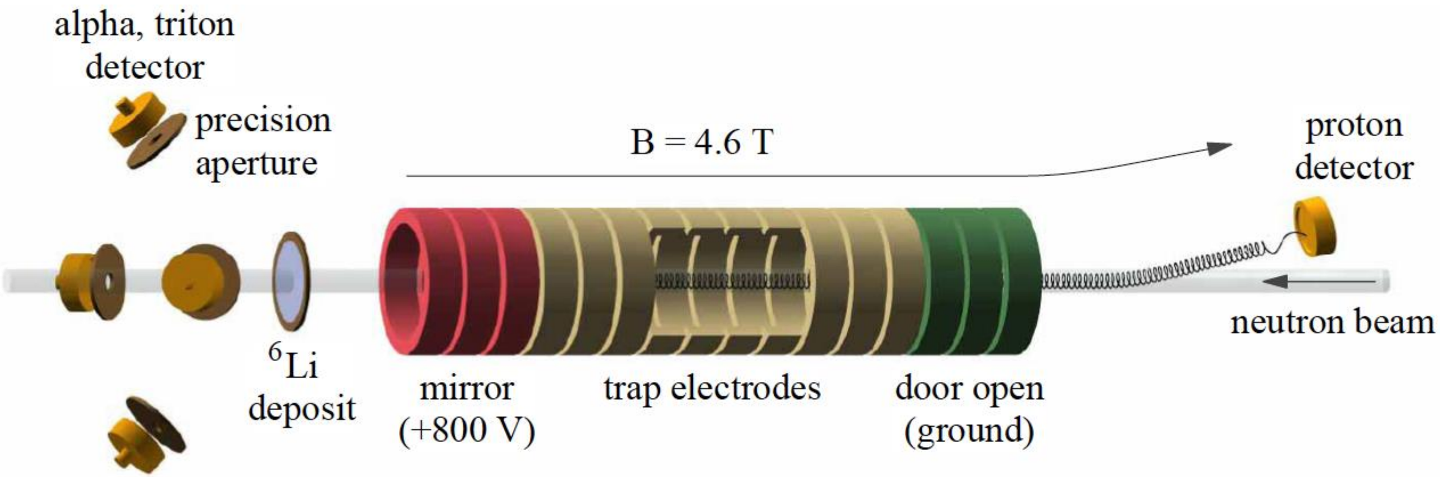
F. M. Gonzalez *et al* ( UCN τ Collaboration), Phys. Rev. Lett. 127, 162501 (2021)

$$\tau_n = 877.7 \pm 0.28_{stat}{}^{+0.22}_{-1.06}{}_{syst}\ s$$

- Storing UCNs in magnetic bottle, and detecting with scintillation detector.

N. Callahan *et al.* Phys. Rev. C **100**, 015501

# Beam method
# NIST experiment by proton counting

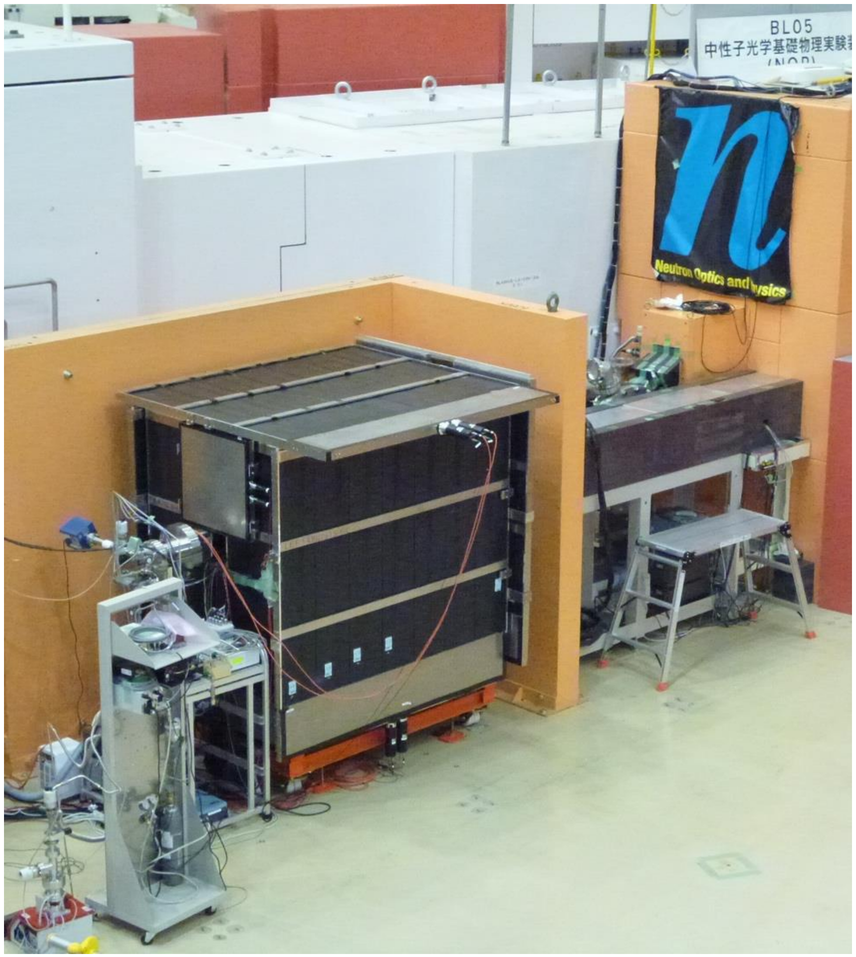



1. Monochromatic beam is transported to the magnetic trap. Neutron flux is monitored by a well calibrated $^6$Li/SSD detector.
2. Protons from the neutron decays captured in the magnetic trap with electrodes. Stored protons are released and detected by a SSD with thin surface layer.

$$\tau_n = 887.7 \pm 1.2\,[stat.] \pm 1.9\,[syst.]\,s = 887.7 \pm 2.3\,[combined]\,s$$


A. T. Yue et al., "Improved determination of the neutron lifetime." Physical review letters 111.22 (2013): 222501.
J. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam." Physical Review C 71.5 (2005): 055502.

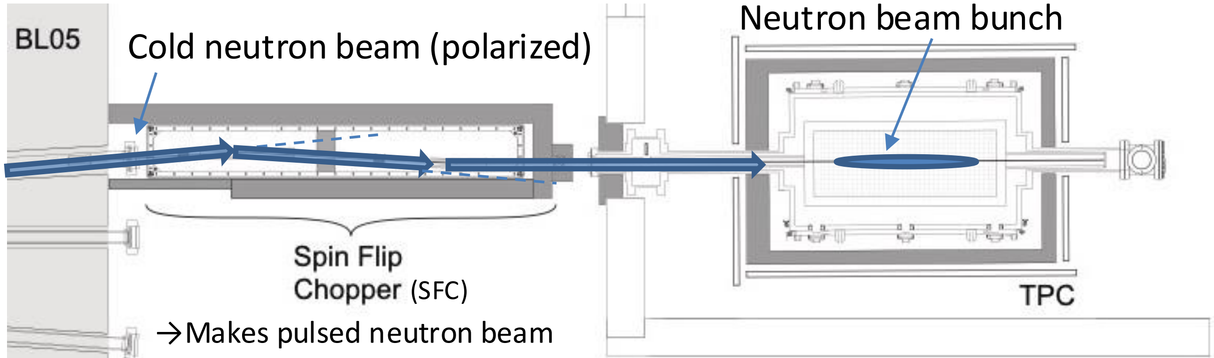
# Neutron Lifetime experiment using pulsed neutron at J-PARC




K. Mishima[1], Y. Fuwa[2], T. Hasegawa[1], T. Hoshino[4], R. Hosokawa[4], G. Ichikawa[3], S. Ieki[5], T. Ino[3], Y. Iwashita[6], M. Kitaguchi[1], S. Makise[4], S. Matsuzaki[4], T. Mogi[7], K. Morikawa[1], N. Nagakura[7], H. Okabe[1], H. Otono[4], Y. Seki[5], D. Sekiba[8], T. Shima[9], H. E. Shimizu[10], H. M. Shimizu[1], N. Sumi[3], H. Sumino[6], M. Tanida[4], T. Tomita[4], H. Uehara[4], T. Yamada[6], S. Yamashita[11], K. Yano[4], T. Yoshioka[4]

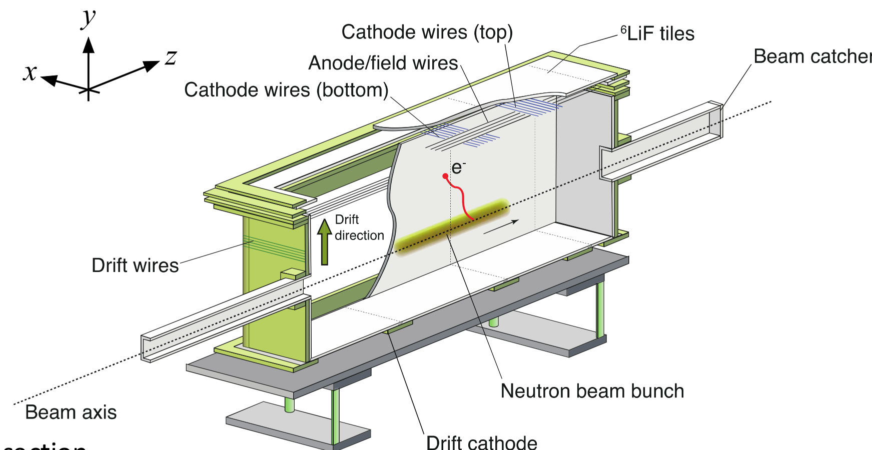
Nagoya Univ.[1], JAEA[2], KEK[3], Kyushu Univ.[4], Tohoku Univ.[5], Kyoto Univ.[6], The Univ. of Tokyo[7], Univ. of Tsukuba[8], Osaka Univ.[9], Sokendai[10], Iwate Pref. Univ.[11]

# Lifetime measurement at J-PARC/BL05 (Beam Line 05)




→Makes pulsed neutron beam into bunches by magnetic mirrors and spin flippers

- Detector: Time Projection Chamber (TPC)
  - Gas: $^4$He, $CO_2$, $^3$He
    (~85%, ~15%, 0.5 - 2 ppm, respectively)
    Total pressure: 100 kPa or 50 kPa
  - Signals are detected with a Multi Wire Proportional Chamber (MWPC)

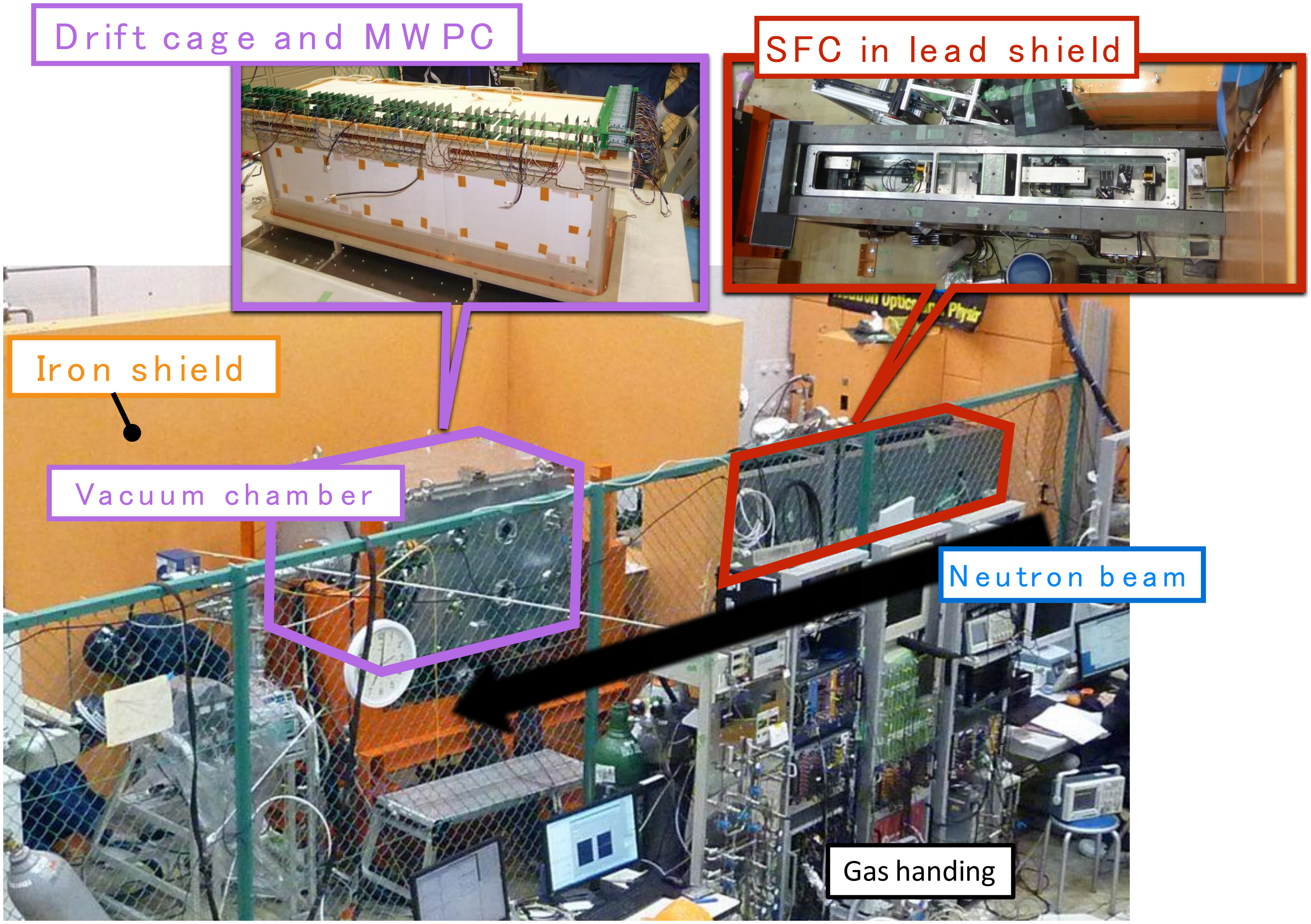



$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\frac{(S_{\mathrm{He}}/\varepsilon_{\mathrm{He}})}{(S_\beta/\varepsilon_\beta)}$$

$\rho$ : $^3$He dencity
$\sigma_0$ : $^3$He neutron absorption cross section
$v_0$ : Velocity of neutron
$S_{\mathrm{He}}$ : Number of $^3$He neutron absorption event
$S_\beta$ : Number of neutron $\beta$ decay
$\varepsilon_{\mathrm{He}}, \varepsilon_\beta$ : Efficiency

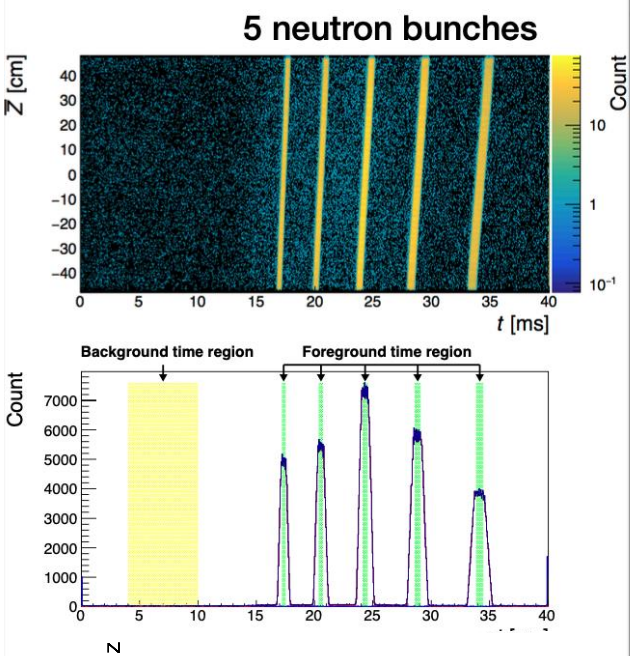
- We aim to provide the most precise experimental neutron lifetime value for beam method as an important piece to solve the neutron lifetime puzzle
  - **Goal: measurement with ~1 s accuracy**

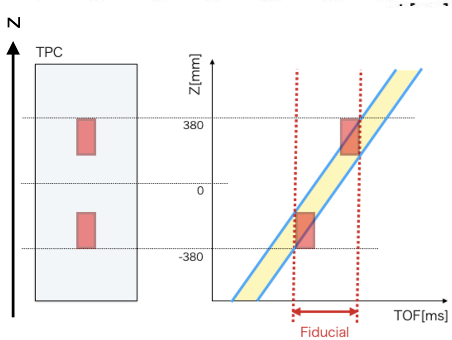
# Experimental Setup



# Analysis

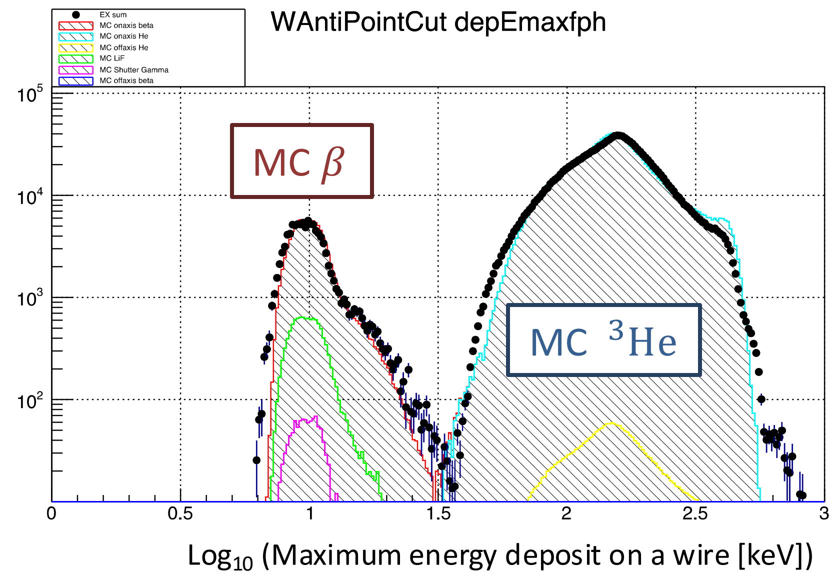
Selection by TOF




TOF cut applied when the neutron bunches are completely in the TPC.

Selection by maximum energy deposit



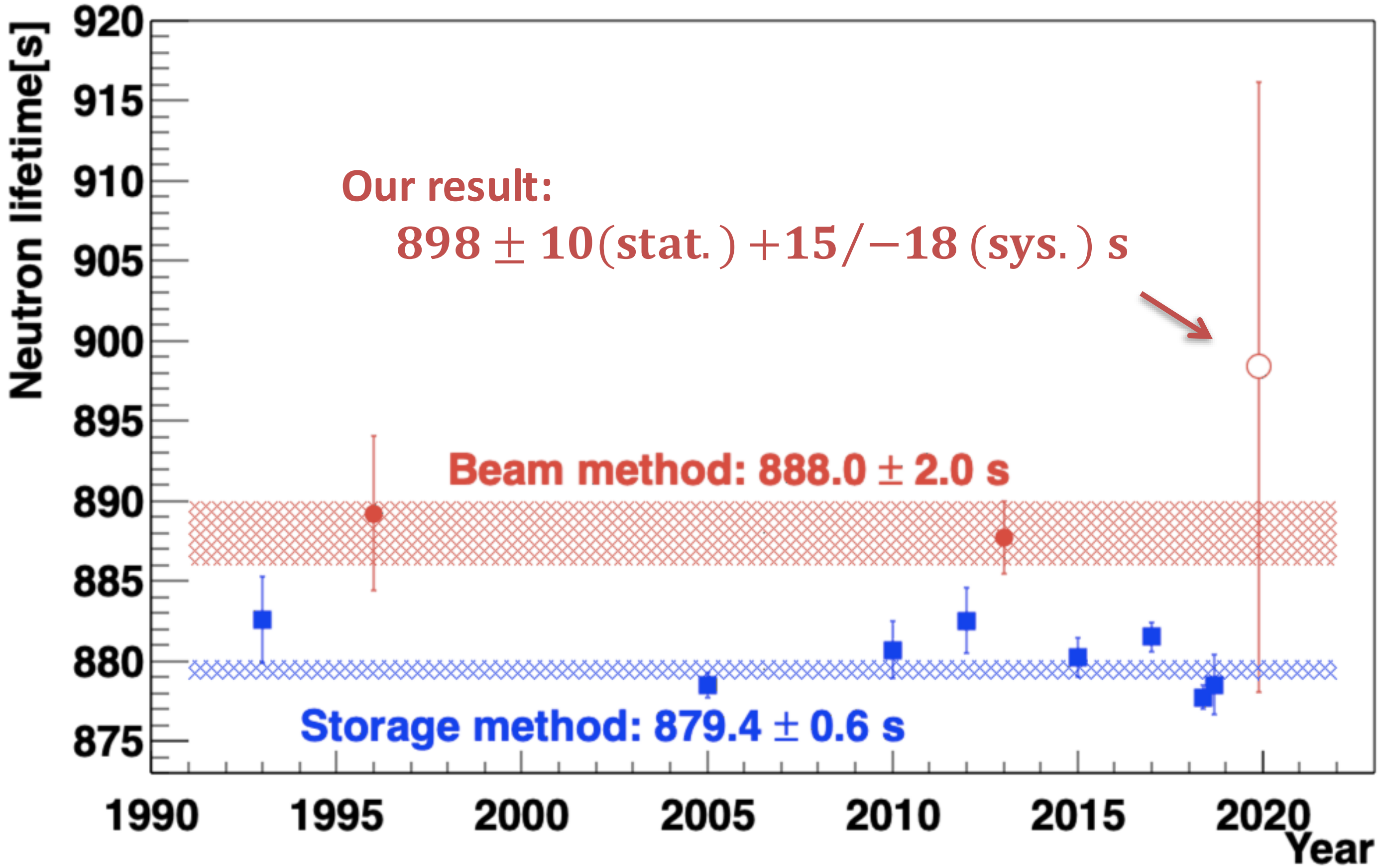

This cut can clearly distinguish $\beta$ and $^3He(n,p)^3H$ events

# The first result of J-PARC experiment

Our first result was

$$\tau_n = 898 \pm 10_{\mathrm{stat}}\,{}^{+15}_{-18}{}_{\mathrm{sys}}\ \mathrm{s}$$

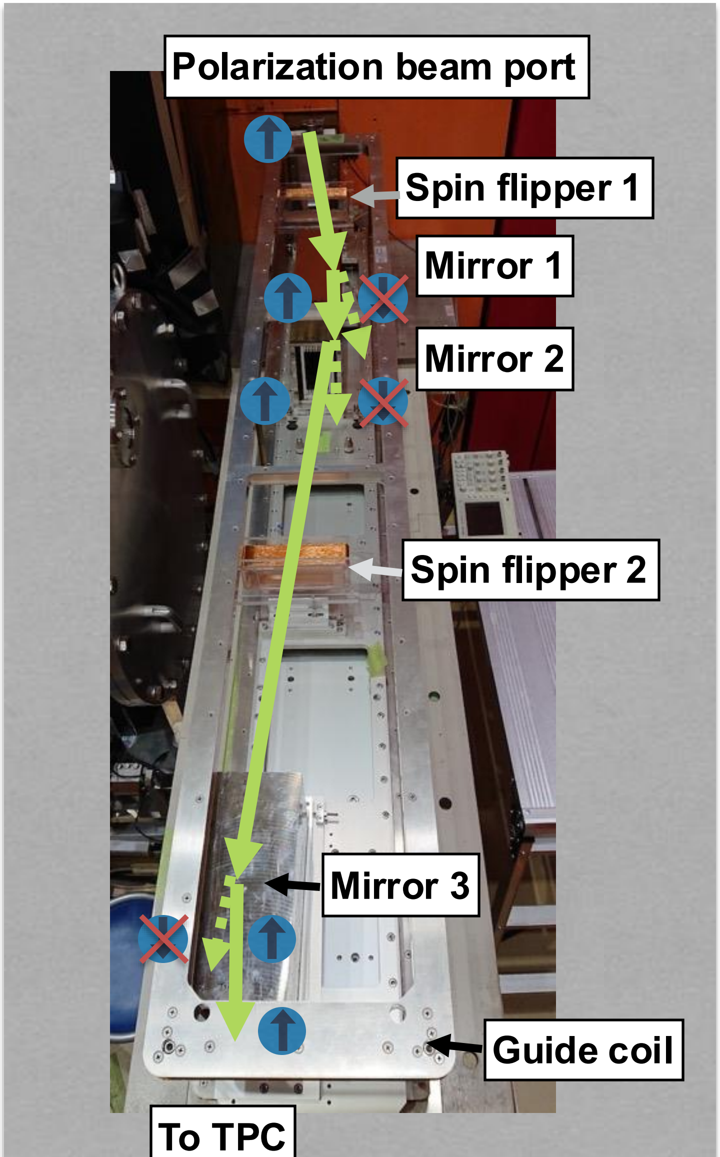
consistent with Beam and Storage methods




K. Hirota *et al.*, *Prog. Theor. Exp. Phys.* (2020) 123C02, https://doi.org/10.1093/ptep/ptaa169

# Updates

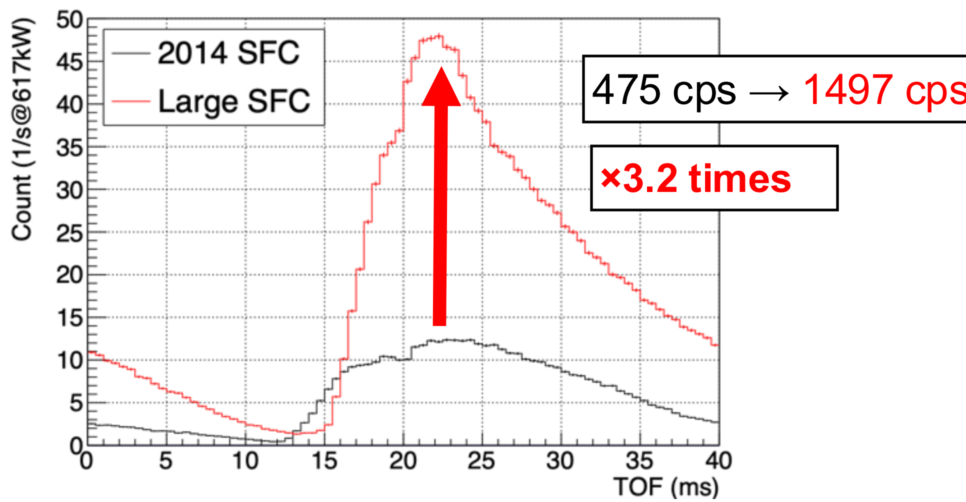
# Upgrade of the Spin Flip Chopper




**Spin Flip Chopper (SFC)**

- The neutron intensity is limited by the size of the mirrors.
- Larger mirrors were installed in 2020.

Magnetic mirror
25 mm×140 mm×15→100 mm×200 mm×26




Neutron event rate at the exit of SFC

- Larger magnetic mirror increases intensity by 3.2 times
- Statistical accuracy of 1 s can be reached in 3 months of measurement
- Neutron polarization $P \sim 99\%$

# Data obtained

Physics measurements taken on 49 gas sets in 2014 - 2023

- With 100 kPa

| Acquisition year | Num. of Gas Set | MLF Power [kW] | DAQ time [h] |
|---|---|---|---|
| 2014 | 1 | 300 | 59 |
| 2015 | 1 | 500 | 31 |
| 2016 | 4 | 200 | 424 |
| 2017 | 14 | 150, 300, 400 | 1303 (A) |
| 2018 | 6 | 400, 500 | 614 |
| 2019 | 3 | 500 | 348 |
| 2021 | 1 | 700 | 38 |
| 2022 | 3 | 700, 800 | 253 (B) |
| 2023 | 1 | 800 | 126 |

First result (stat. 10 s)

Statistic ~2.2 s

After SFC Upgrade

- With 50 kPa

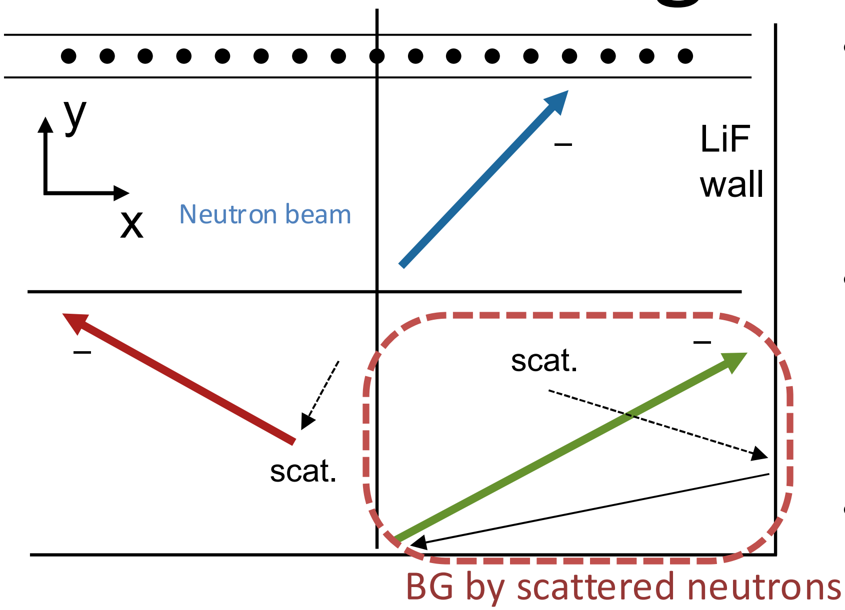
| Acquisition year | Num. of Gas Set | MLF Power [kW] | DAQ time [h] |
|---|---|---|---|
| 2017 | 3 | 150,300 | 253 |
| 2018 | 3 | 400, 500 | 357 (C) |
| 2021 | 1 | 700 | 86 |
| 2022 | 7 | 700, 800 | 839 (D) |
| 2023 | 1 | 800 | 155 |

Statistic ~1.8 s

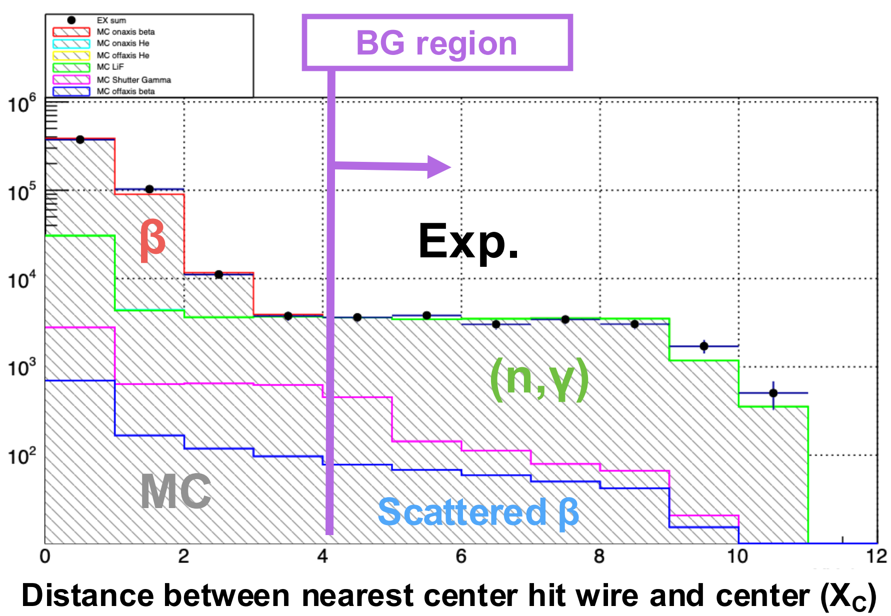
After SFC Upgrade

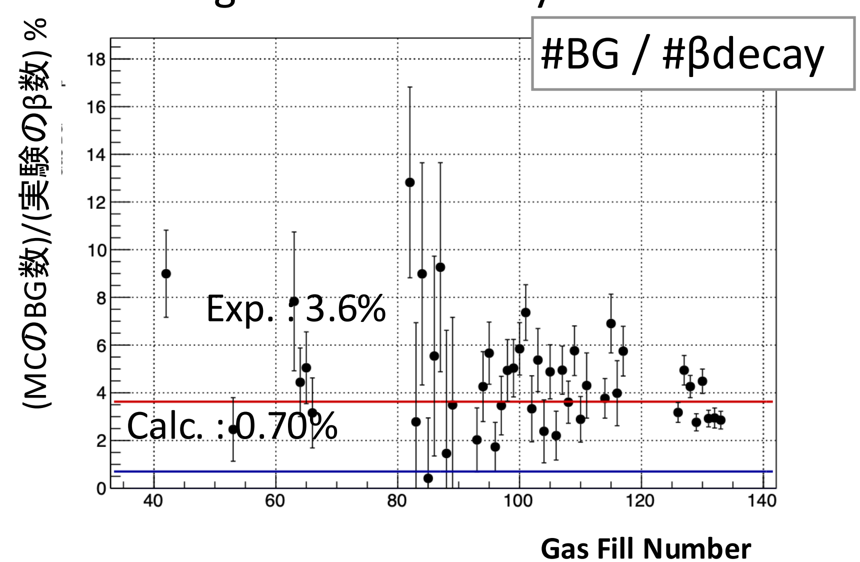
**The combined Statistic is 1.4 s**

# Excess of background




- Neutrons scattered by the TPC operating gas are absorbed by the LiF inner wall, some of which emit γ-rays, creating (n,γ) background (BG) events.
- Although the events are created in the BG region close to the wall, the amount of the events was about five times larger than expected.
- The indeterminacy in the distribution of the (n,γ)BGs and the large uncertainty in the rate at which the BGs leak into the signal region were the largest sources of systematic error.



# Low gas pressure operation

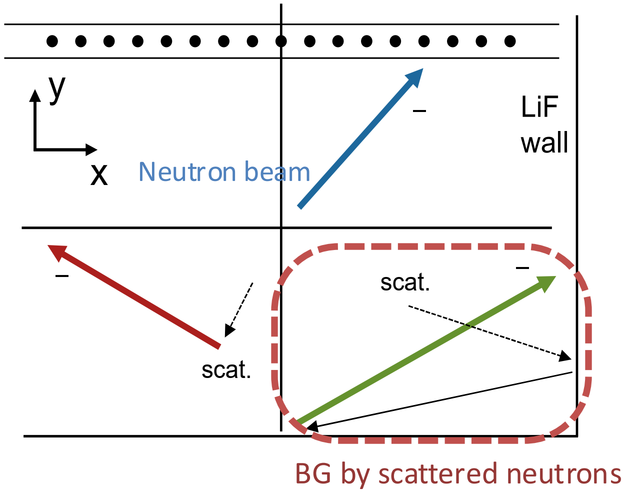
- First result (2014-2016): TPC gas pressure 100 kPa

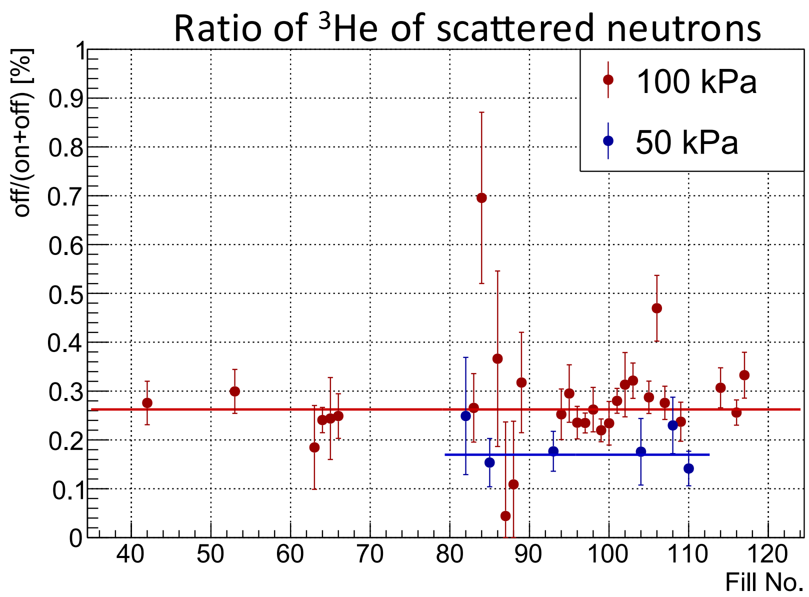
( $^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 85$ kPa: 15 kPa: 50 – 200 mPa )

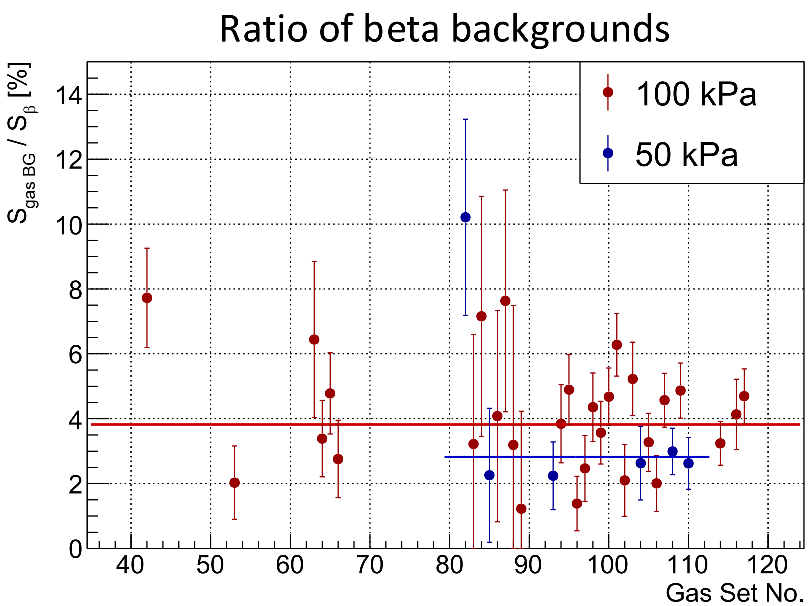
- Number of background events due to gas scattering ∝ Number of scattered neutrons

- Operation with gas pressure with **50 kPa** can reduce background

( $^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 42.5$ kPa: 7.5 kPa: 50 – 200 mPa )

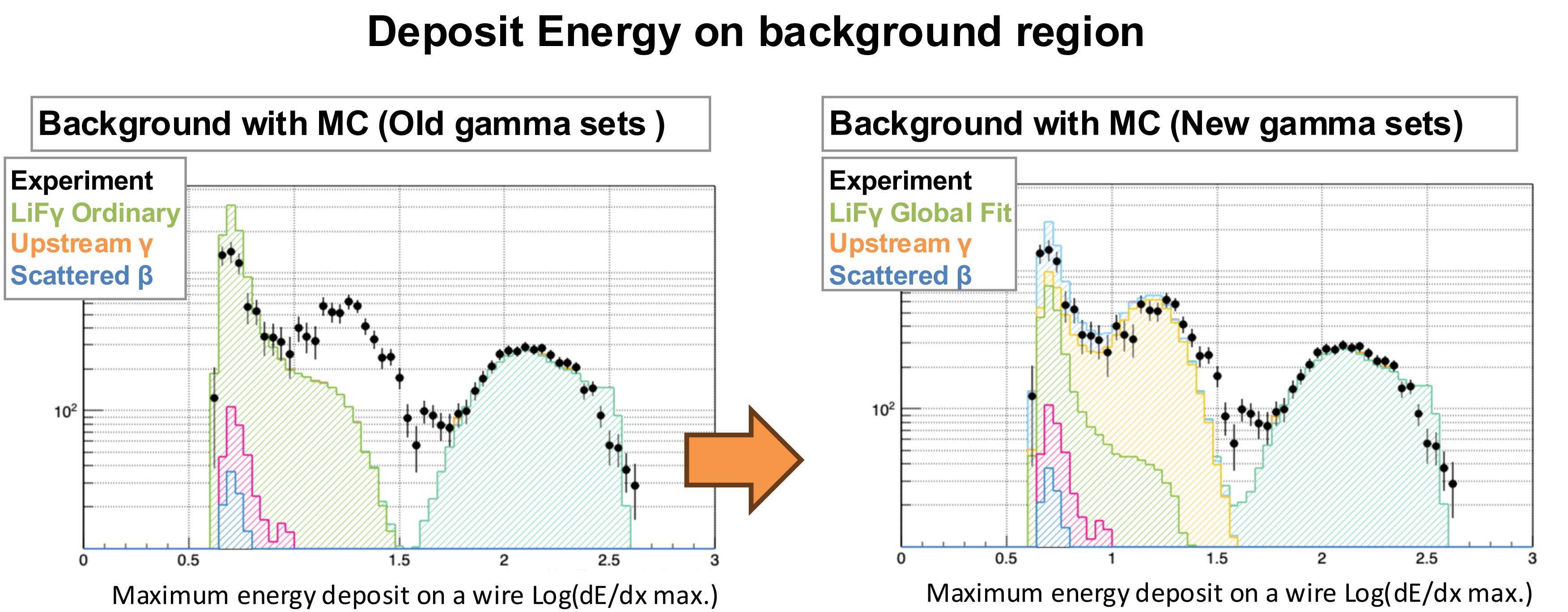



Measurement at 50 kPa reduces the number of background events due to gas scattering to 60% of that at 100 kPa.

# Background and its simulation



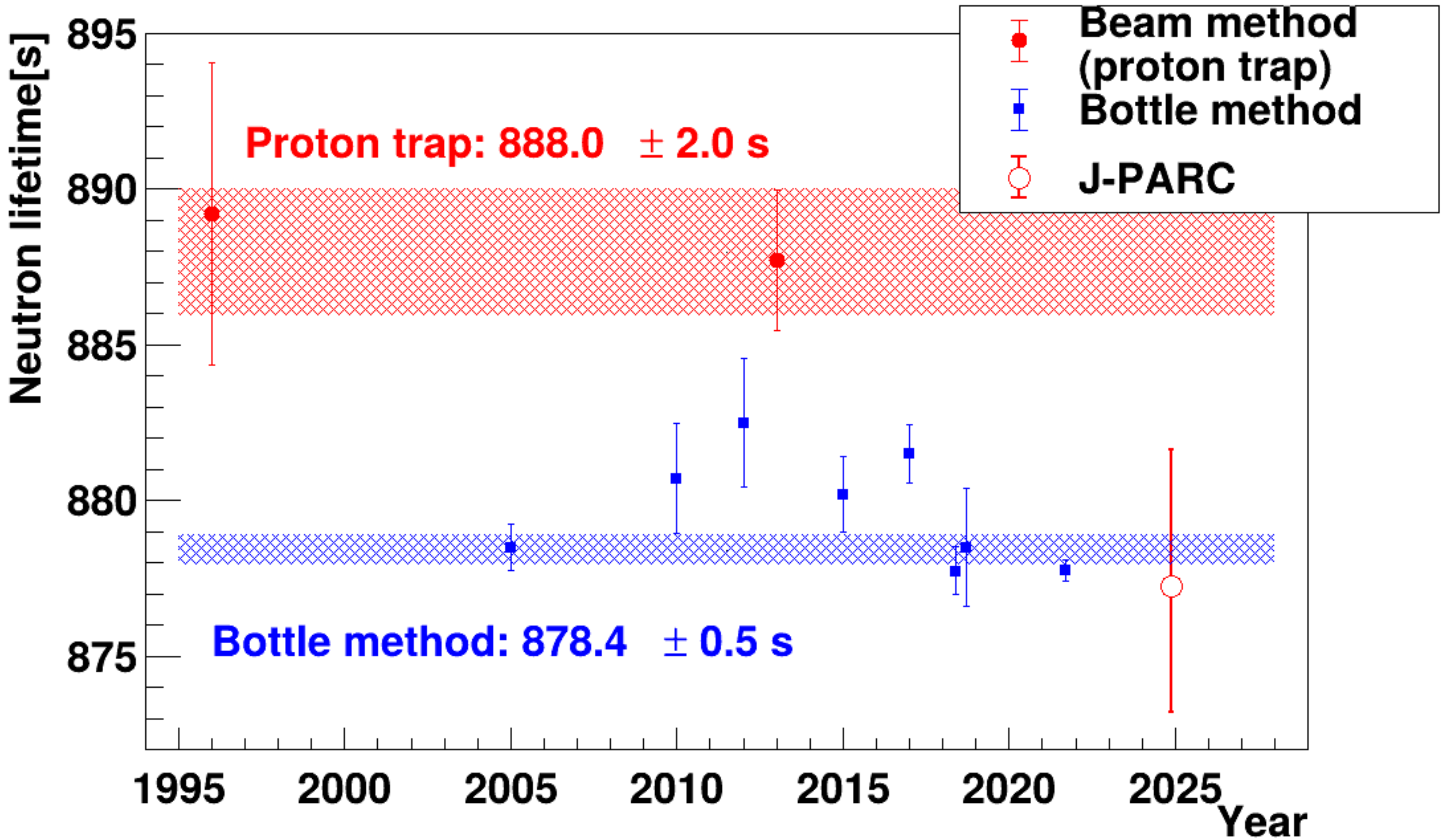

- In previous analyses, a single gamma ray was used to find the energy condition that best reproduced the background.
- A single gamma ray could not reproduce it. Therefore, we attempted to reproduce it using multiple gamma rays.
- Gamma rays of 200 keV (92%) and 5000 keV (8%) can reproduces background. (Chi2/ndf=209/202).

# A new result from J-PARC

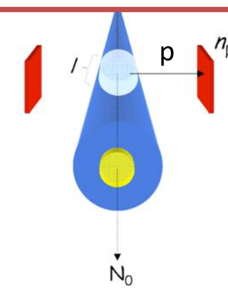
The improved results using data from 2014 to 2023 are as follows:

$$\tau_n = 877.2 \pm 1.7(stat.)^{+4.0}_{-3.6}\,(sys.) = 877.2^{+4.4}_{-4.0}\ \mathrm{s}$$

[Y. Fuwa et al., arXiv:2412.19519v1]




Beam method
(proton trap)
Count the dead

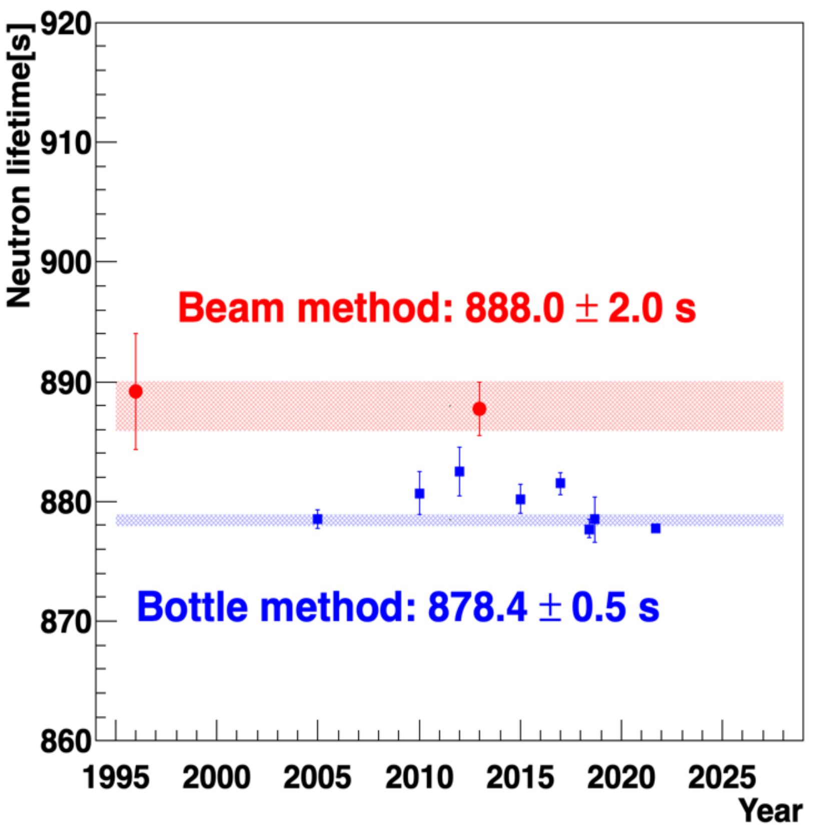


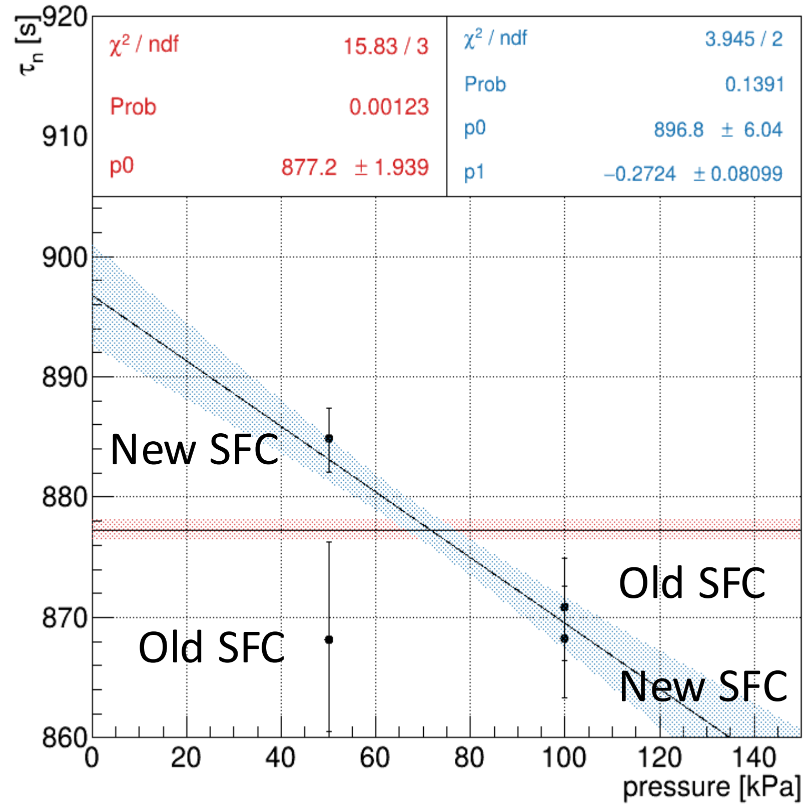

Bottle method
Count the living


This value gives a 2.3$\sigma$ tension with the average value obtained from the proton trap.

# Discussion

- The $\chi^2$/NDF of our fitting is large.
- If there is a pressure dependence, the fitting is going to be better, and then consistent with beam method.



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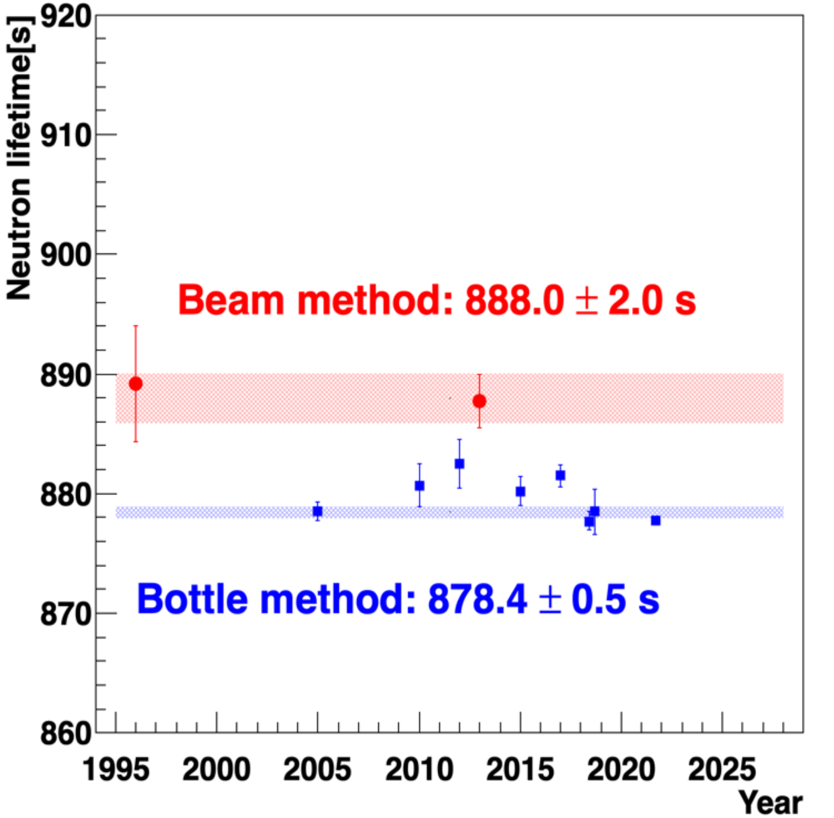
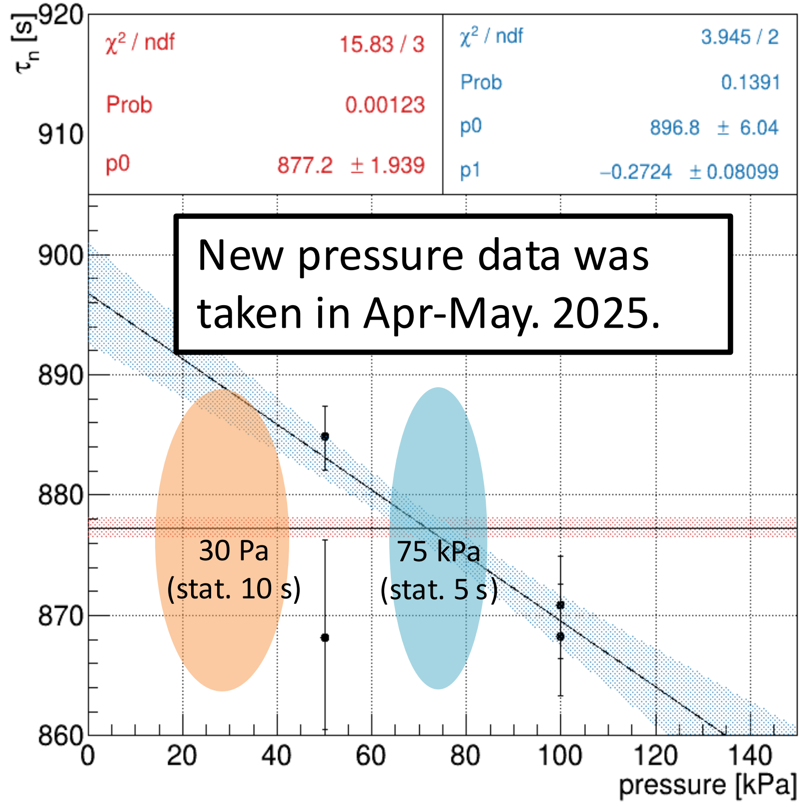
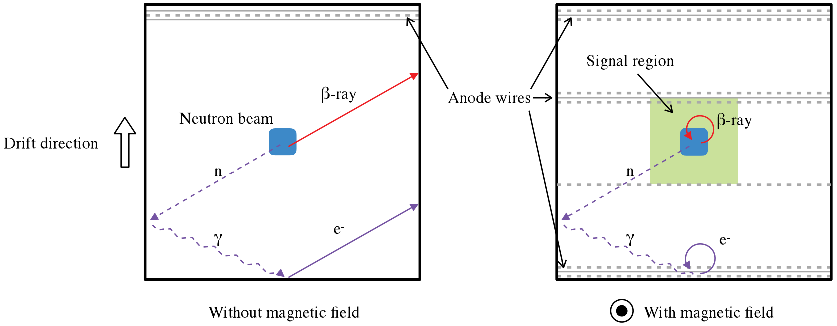
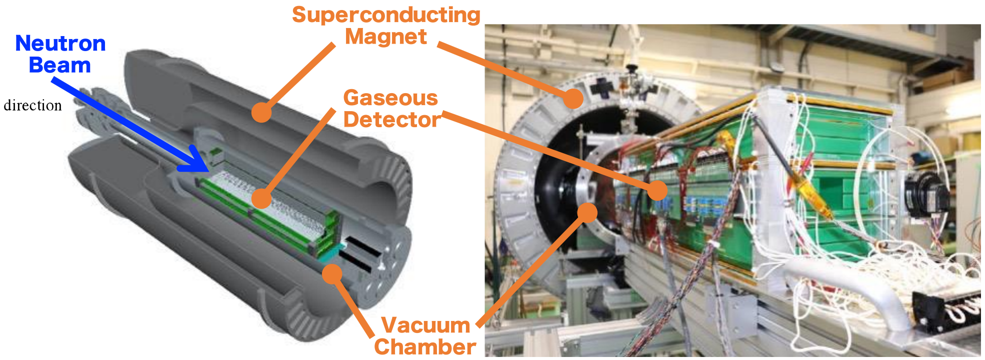


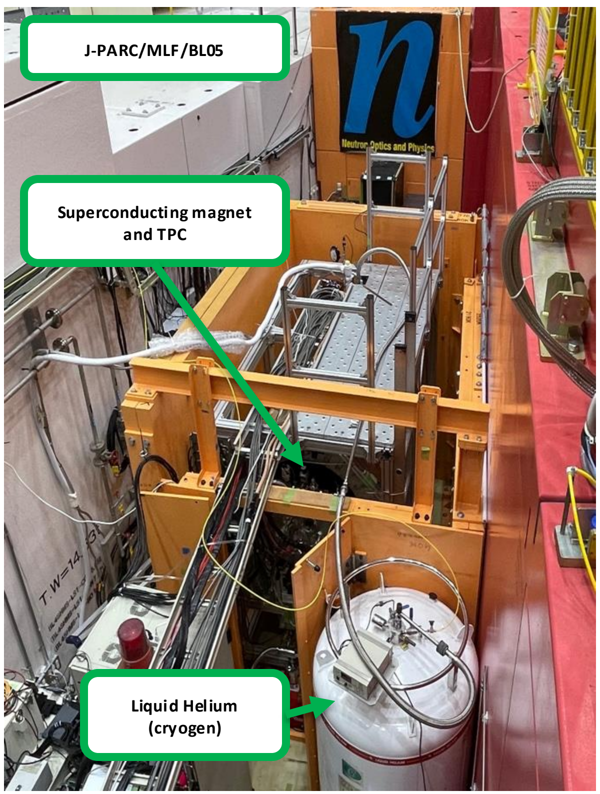



# Background suppression with solenoidal magnetic field

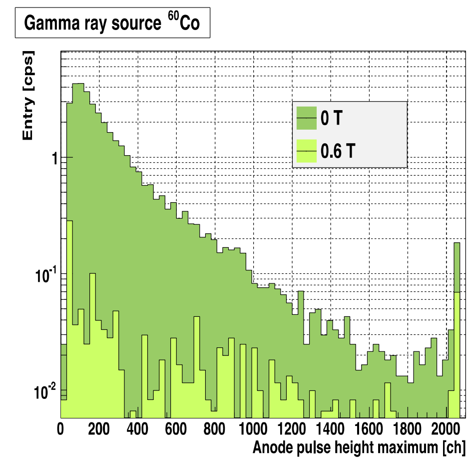



N. Sumi *et al.*, *Nucl. Inst. Meth. Phys. Res A* 1045 (2023) 167586.




To achieve 1 s, we are preparing for background suppression by using multi-layered TPC in a solenoid magnetic field. The magnetic field can suppress the gamma ray background to 1/50.




Gamma ray suppression with magnetic field

The first data was obtained on this apparatus in Feb. 2024. 2 days of physics run, corresponds to ~90 s. The next run will come in next June.

Approved for the new JSPS budget (KibanA).

# Summary

- Neutron lifetime is an important parameter for particle, nuclear, and astro-physics.
- However, the value have 9.5 s (4.6σ) discrepancy with two method of measurements
  - **$\tau_n$ = 888.0 ± 2.0 （Beam method）**
  - **$\tau_n$ = 878.4 ± 0.5 （Storage method）**
- A new "beam" experiment is ongoing at J-PARC
  - We obtained physics data (statistic 1.7 s).
  - Analysis has been fixed and opened blind in Nov. 2024.
  - The result is now on arXiv:

    Y. Fuwa et al., arXiv:2412.19519v1

$$\tau_n = 877.2 \pm 1.7\ (stat.)^{+4.0}_{-3.7}(sys.)\ [\mathrm{s}]$$

  - This result is consistent with bottle method measurements but exhibits a 2.3σ tension with the average value obtained from the proton-detection-based beam method.

- There is a still room for discussion in our results.
- Additional data will be taken with less background conditions.
- A new apparatus with a solenoid magnet is getting ready for physics measurements.