# Measurement of neutron lifetime by using pulsed neutron beam

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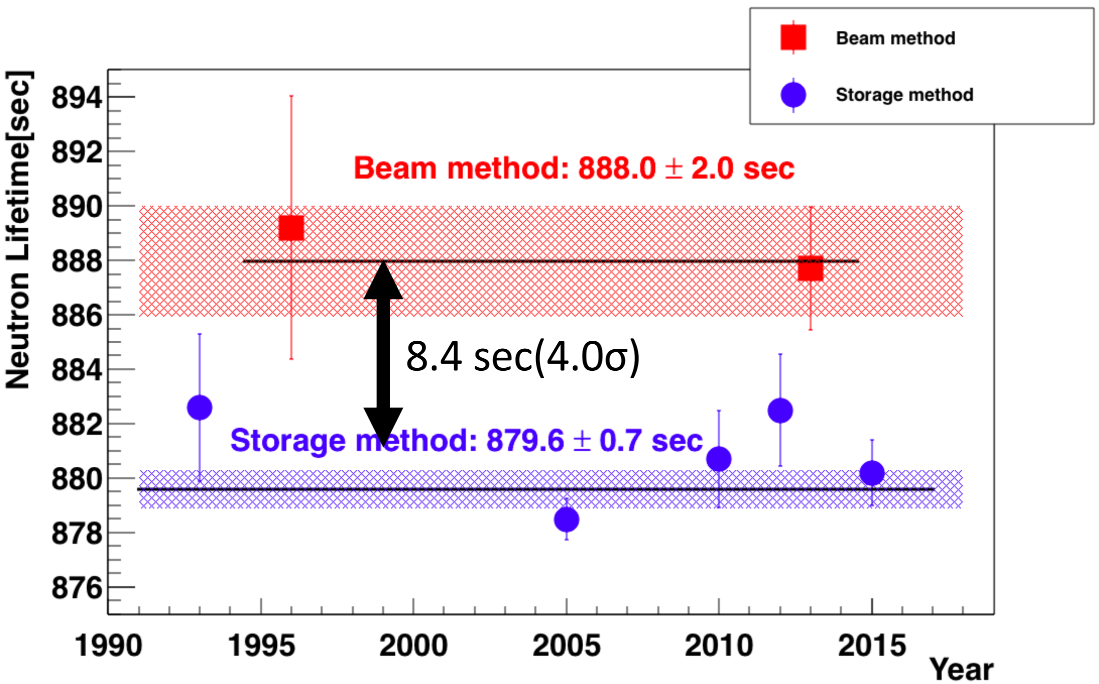
# Neutron Lifetime

Neutron lifetime is an important parameter for both of particle physics and cosmology.

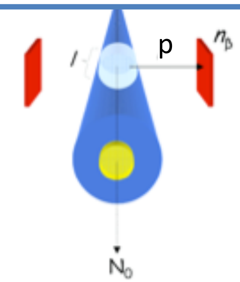
**880.2±1.0s (PDG2017)**

There is 8.4sec (4.0σ) deviation of the value of lifetime between two methods of measurement.

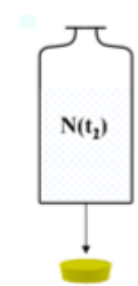



PGD2016

In-beam method
Count the dead




Storage method
Count the living



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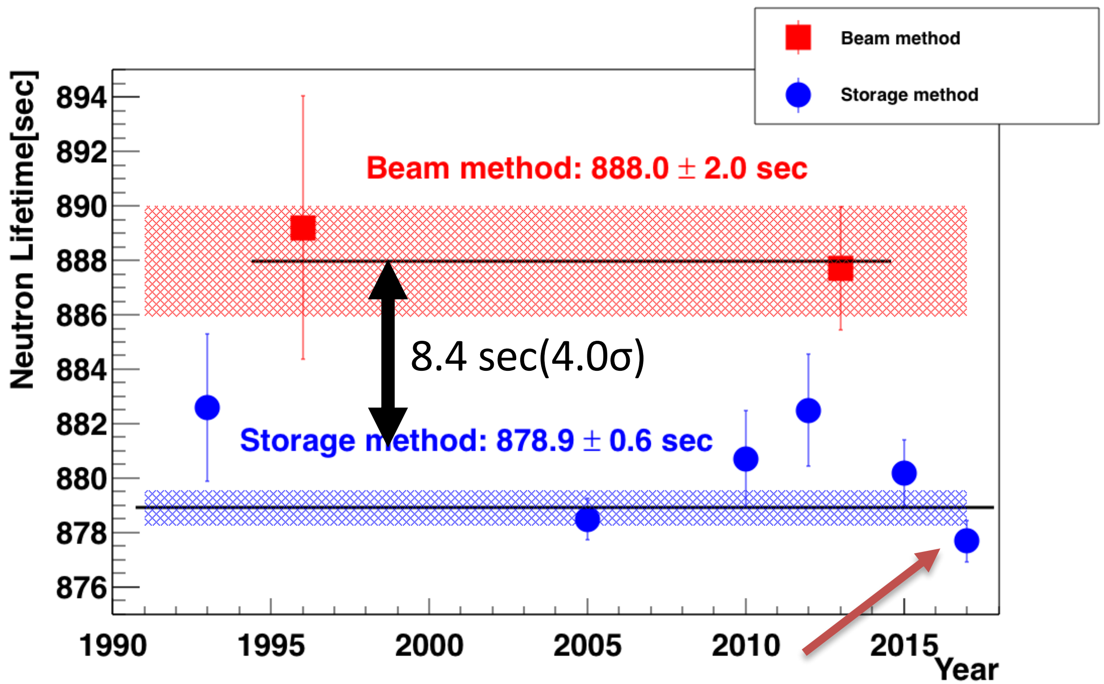
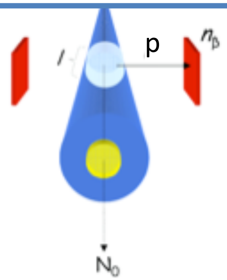



In-beam method
Count the dead




Storage method
Count the living

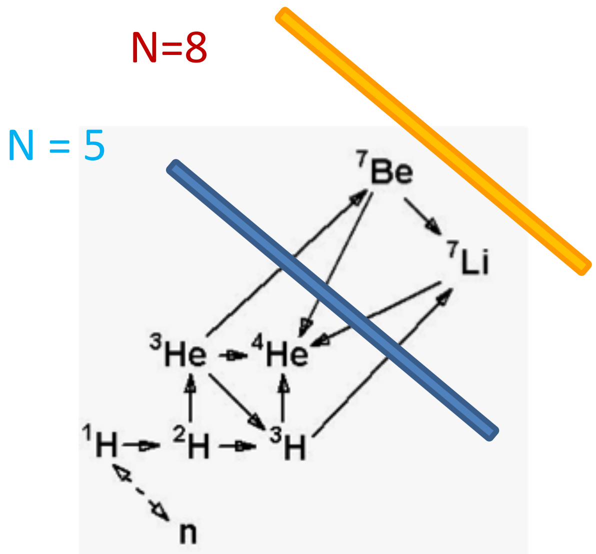
**Measurement of the neutron lifetime using an asymmetric magneto- gravitational trap and in situ detection**

https://arxiv.org/abs/1707.01817

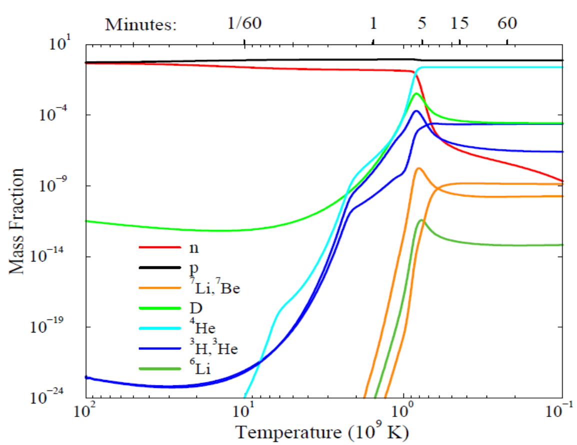
**877.7 ± 0.7(stat) +0.3/-0.1(sys) sec**

# Big bang nucleosynthesis

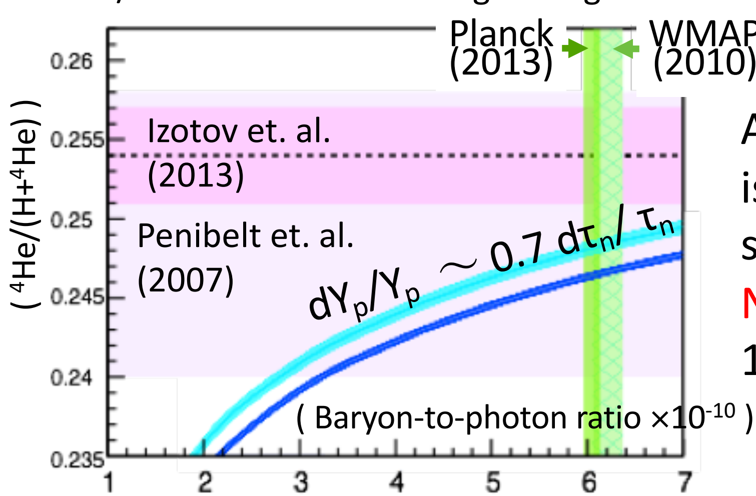
## CMB & He/H & Neutron Lifetime




Light elements up to N=7 were created in 3 minute after the big bang (Big Bang Nucleosynthesis). Abundance of them can be calculated by baryon-to-photon ratio, nuclear cross sections, and **the neutron lifetime**.




He/H observation of HII region in galaxies




A recent observation[1] is not consistent with standard cosmology. $N_{eff} = 3.51 \pm 0.35$, 1.5 $\sigma$ deviation from 3.

CMB+BAO observation[2] Independently result $N_{eff} = 3.26 \pm 0.28$, which has 1.0 $\sigma$ deviation from 3. We may missing something in the early universe.

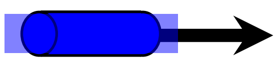
1. Izotov, Y. I., G. Stasińska, and N. G. Guseva. "Primordial 4He abundance: a determination based on the largest sample of H II regions with a methodology tested on model H II regions." *Astronomy & Astrophysics* 558 (2013): A57.
2. Valentino E, et al., “Reconciling Planck with the local value of H0 in extended parameter space”, Physics Letters B 761 (2016) 242–246.

# Principle of our experiment

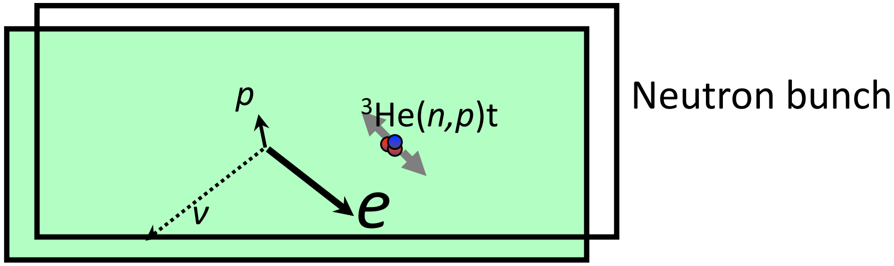
Cold neutrons are injected into a TPC.
The neutron β-decay and the $^3He(n,p)^3H$ reaction are measured simultaneously.

Principle (Kossakowski,1989)

Neutron bunch shorter than TPC



Count events during time of bunch in the TPC




$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $S_\beta = \epsilon_e N \frac{L}{\tau_n v}$

$^3He(n,p)^3H$ $S_n = \epsilon_n N \rho \sigma L$

$\tau_n$ : lifetime of neutron
v : velocity of neutron
$\varepsilon_e$ : detection efficiency of electron

$\varepsilon_n$ : detection efficiency of $^3He$ reaction
ρ : density of $^3He$
σ : cross section of $^3He$ reaction

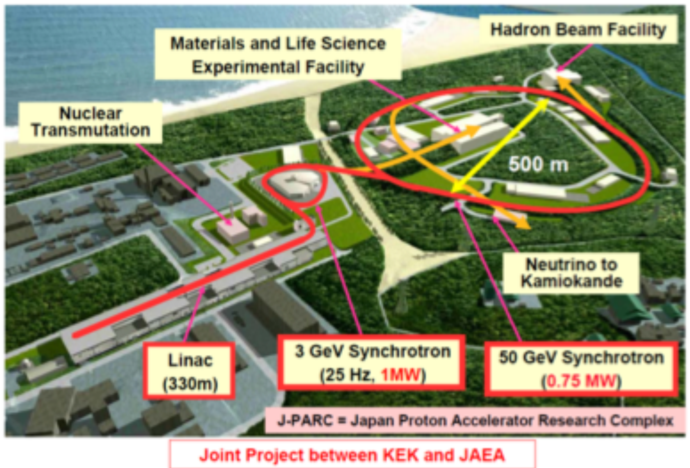
$$\sigma v = \sigma_0 v_0$$ $\sigma_0$=cross section@$v_0$, $v_0$=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

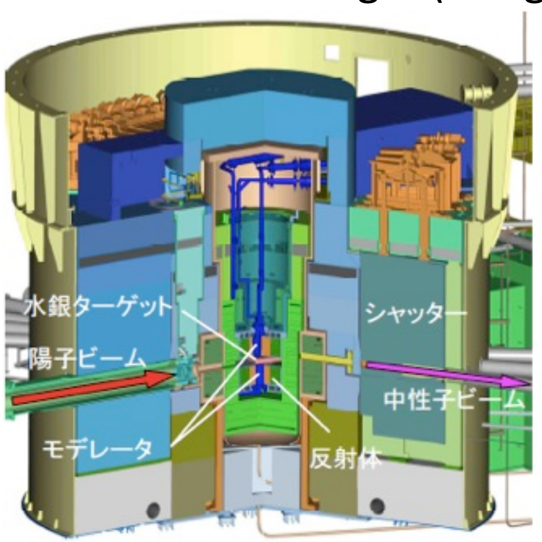
Our goal is measurement with 1 sec uncertainty.

# J-PARC / MLF / BL05

J-PARC
Materials and Life Science Experimental Facility(MLF)

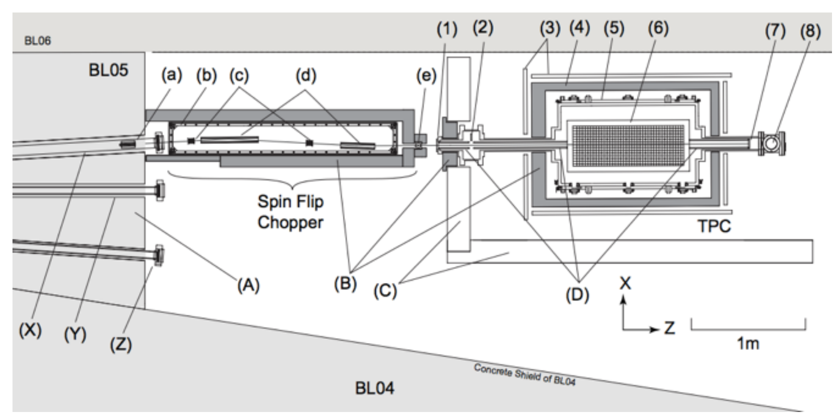



Spallation neutron target (designed for 1MW)



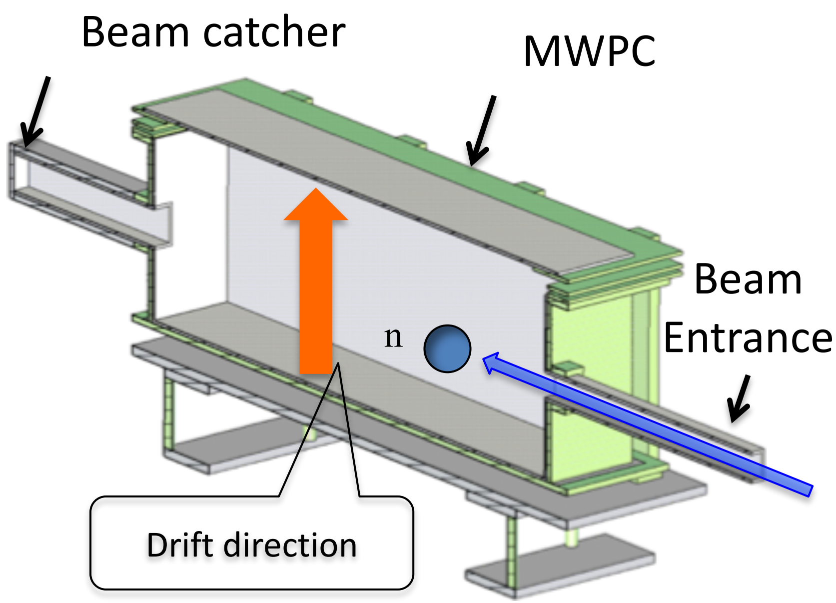

Pulsed neutron Beam line BL05
Neutron optics and physics(NOP)

Schematic view of experimental setup

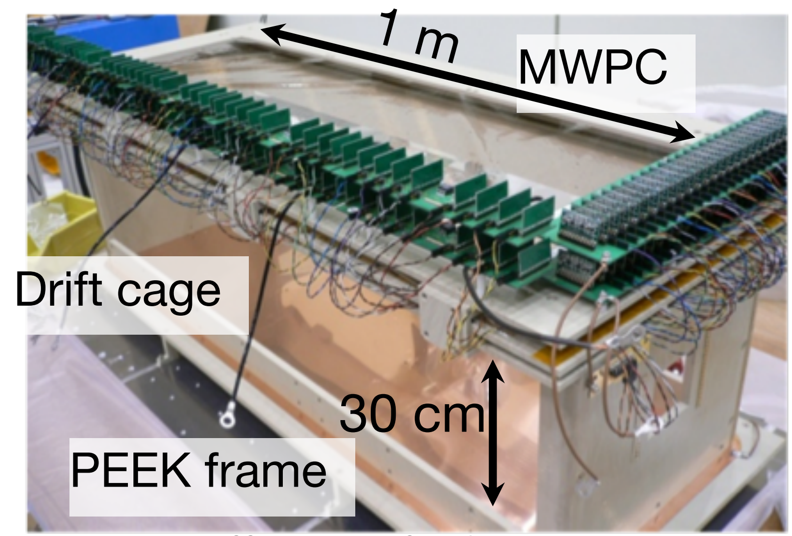


# Time Projection Chamber(TPC)

High efficiency and Low background TPC is used beta and $^3He(n,p)^3H$ detection.



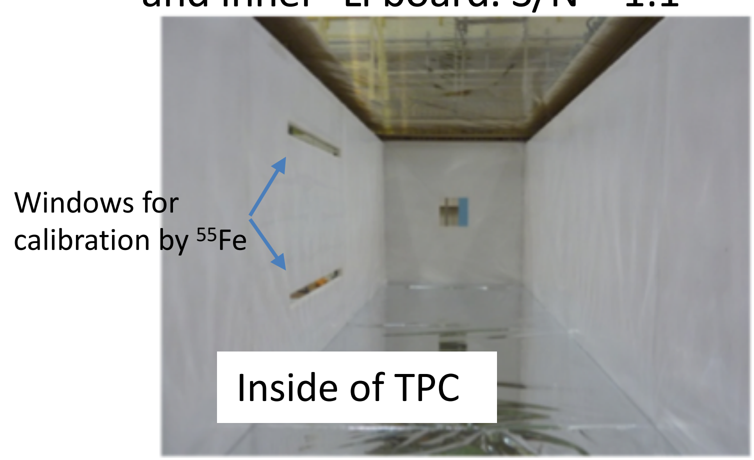

| | |
|---|---|
| Anode wire | 29 of W-Au wires(+1720V) |
| Field wire | 28 of Be-Cu (0V) |
| Cathode wire | 120 of Be-Cu (0V) |
| Drift length | 30 cm (-9000V) |
| Gas mixture | He:CO2=85kPa:15kPa |
| TPC size(mm) | 300,300,970 |




Trigger efficiency for beta >97%

for $^3He(n,p)^3H$ > 99.9%

Low background with PEEK frame and inner $^6Li$ board. S/N ~ 1:1



# Fiducial / Sideband of TOF and Shutter Open / Close

**Prompt γ ray from upstream**

Neutrons captured in the upstream of TPC produce γ ray backgrounds.

Backgrounds are reduced by using bunched neutron and TOF method.

**2 types of data Beam IN / Dump**

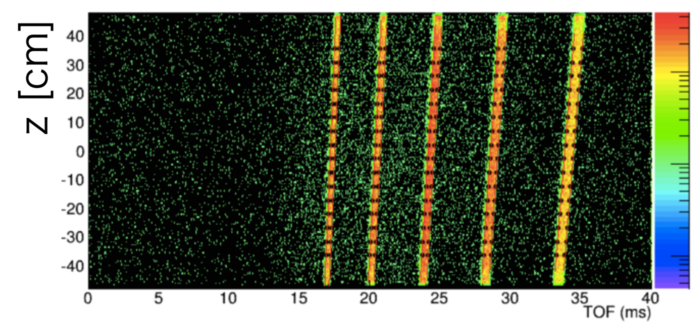
**Beam IN** : Neutron pass through the TPC. (RED)

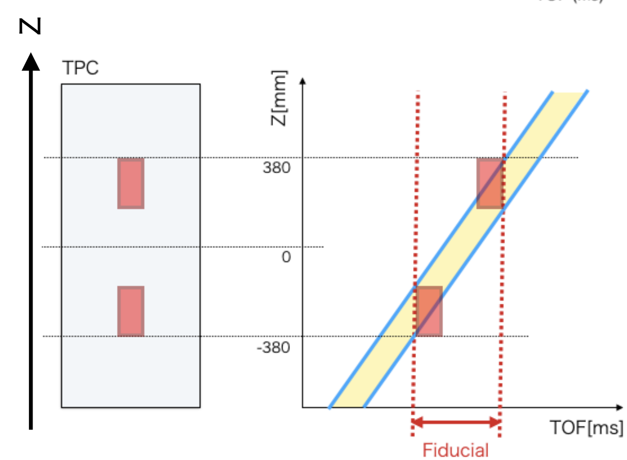
**Dump** : Neutron is dumped. (BLACK)

BLUE = RED - BLACK

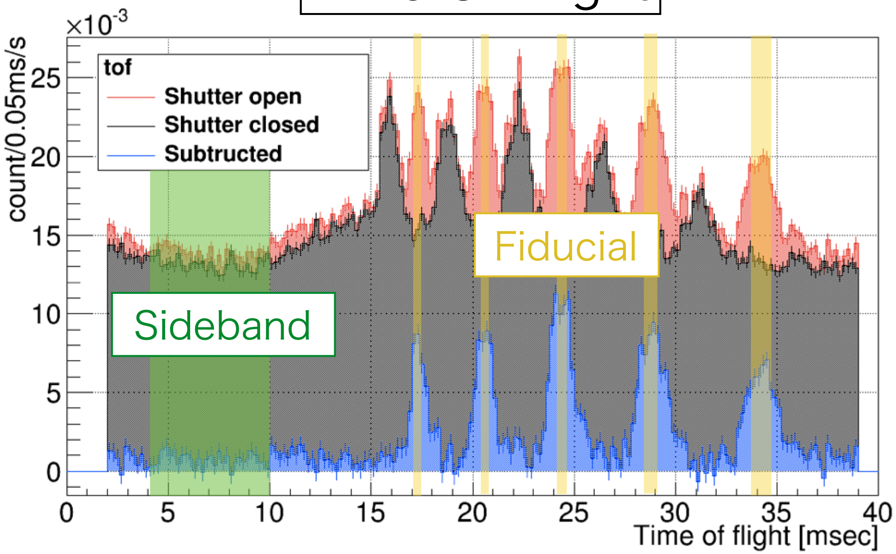
＊ 5 peaks indicate the number of bunches.

z position vs TOF




Time-Of-Flight



# How to obtain the neutron lifetime

Counts in signal cut region

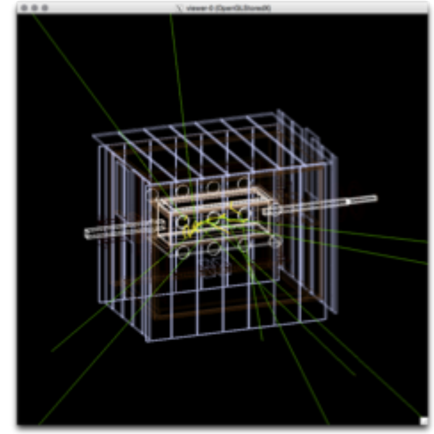
Monte Carlo with cut

$$\tau_n = \frac{1}{\rho\sigma_{He}(v_0)v_0}\frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

$^3$He dopant (gas expansion)
+ $^3$He in $^{nat}$He (mass spectroscopy)

Literature value
(5333±7 barn)

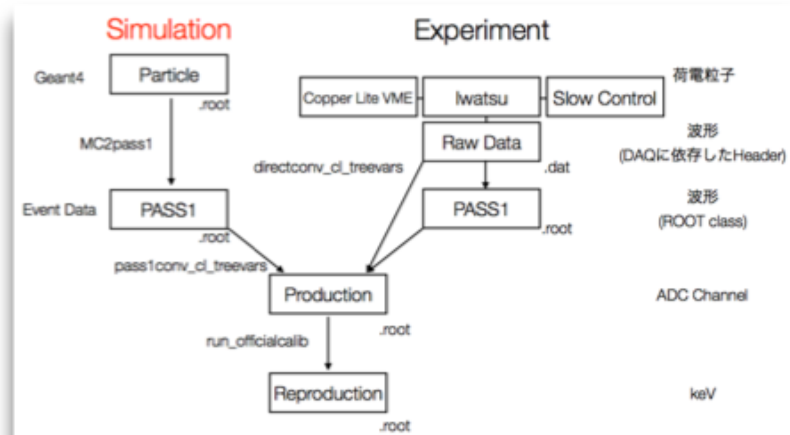
# Monte Carlo simulation



- To determine detection efficiency: ε
- Evaluation of signals and backgrounds

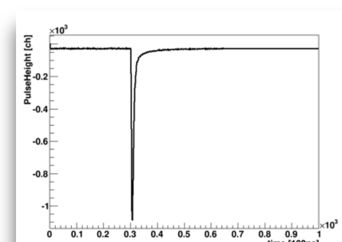
**Geant4.9.6.p04** was used.

1. Tracks by each event are made, and their energy deposit in the TPC are recorded.
2. Responses by their energy deposit of the detector were calculated:
   - Electron/ion pair creation
   - Recombination
   - Drift time and loss of electron drift
   - Saturation on wire due to space charge




3. Wave forms were created for each wire as the same format with experiment
4. MC data are analyzed as same as the experimental data

Waveform

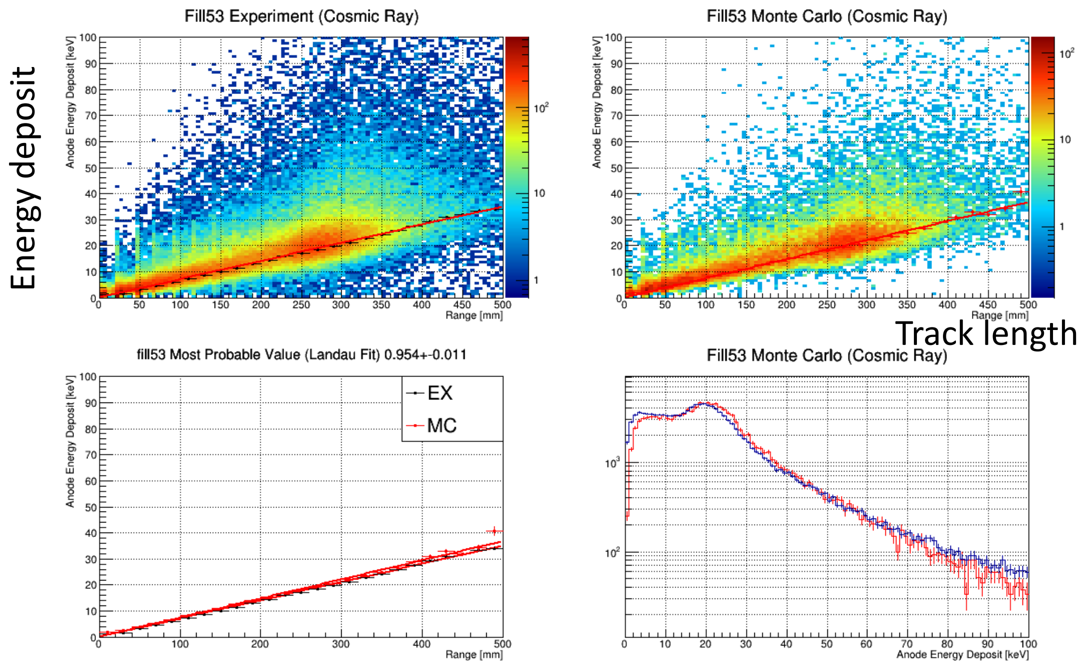


# Monte Carlo simulation

- Parameters of MC simulation were adjusted by spectrum of $^{55}$Fe X-ray(5.9 keV)

- MC events
  - Neutron β decay
  - $^{3}$He(n,p)$^{3}$H
  - γ-rays from SFC
  - γ-rays by scat. neutrons
  - X-rays from $^{55}$Fe source
  - Cosmic rays

Track length and energy deposit of cosmic rays




Energy deposit of cosmic rays experimental and MC simulation had 5-9% discrepancy.
The discrepancy was used to evaluate systematic uncertainty of the efficiencies

# How to obtain the neutron lifetime

$$\tau_n = \frac{1}{\rho\,\sigma_{He}(v_0)\,v_0}\,\frac{\left(S_{He}/\epsilon_{He}\right)}{\left(S_\beta/\epsilon_\beta\right)}$$

Counts in signal cut region ($S_{He}$, $S_\beta$)

Monte Carlo with cut ($\epsilon_{He}$, $\epsilon_\beta$)

$\rho$: $^3$He dopant (gas expansion)
+ $^3$He in $^{nat}$He (mass spectroscopy)

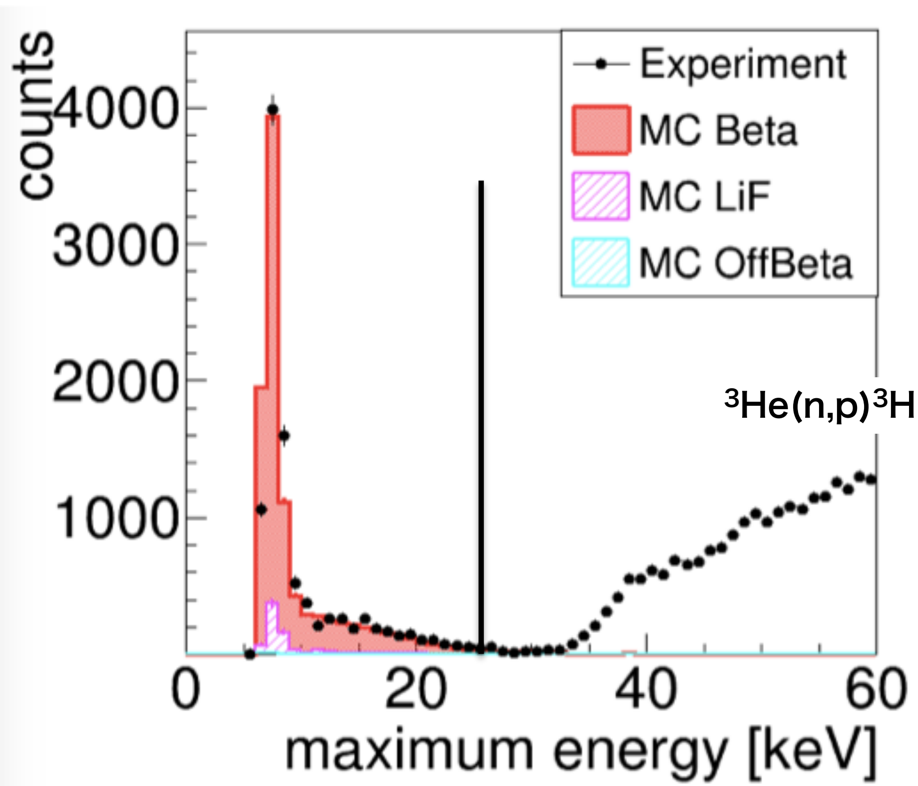
$\sigma_{He}(v_0)$: Literature value
(5333±7 barn)

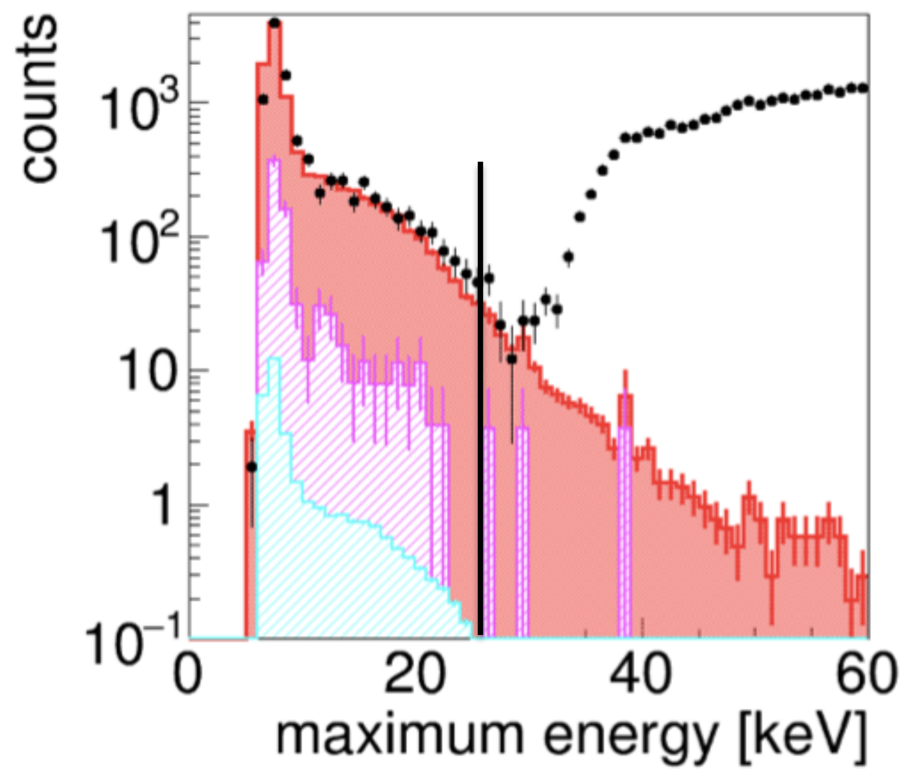
# Separation of signal events ($\beta$ decay and $^3$He)

Two kinds of signal events can be separated by maximum energy deposit among all wires

**$\beta$ decay** : **small** maximum energy deposit

**$^3He(n, p)^3H$** : **large** maximum energy deposit



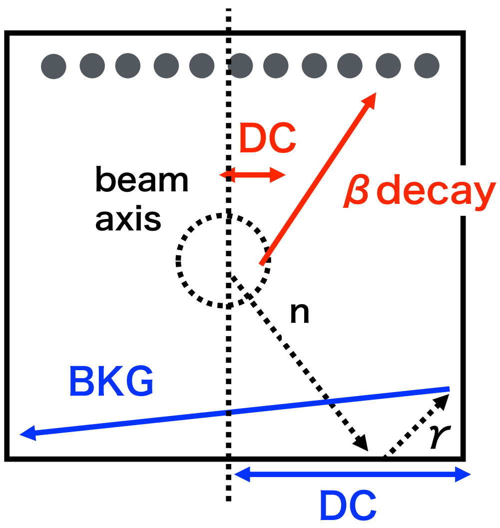
# Spectrum of beta decay and Beam-induced background

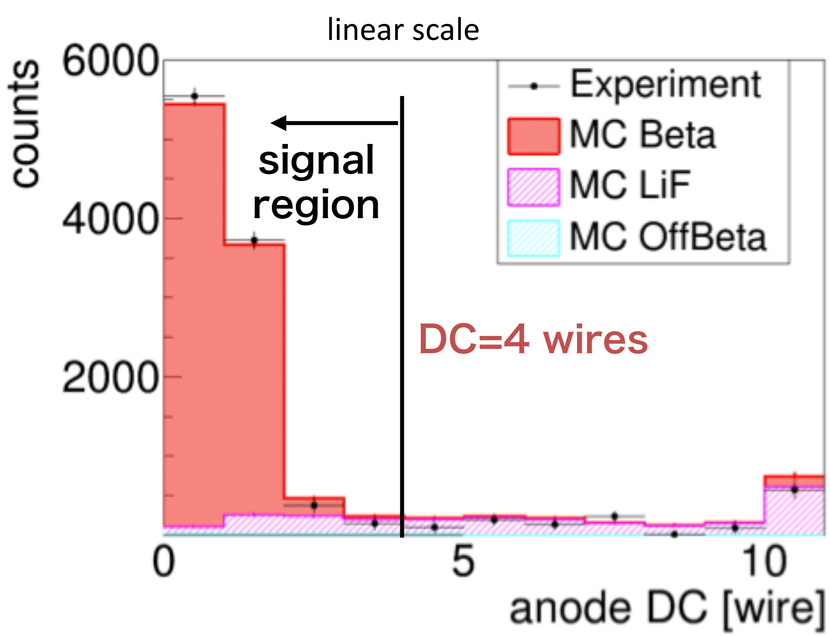
Neutrons scattered by TPC gas produce $\gamma$ rays, which caused background (few % of $\beta$ events). These can be identified track topology.

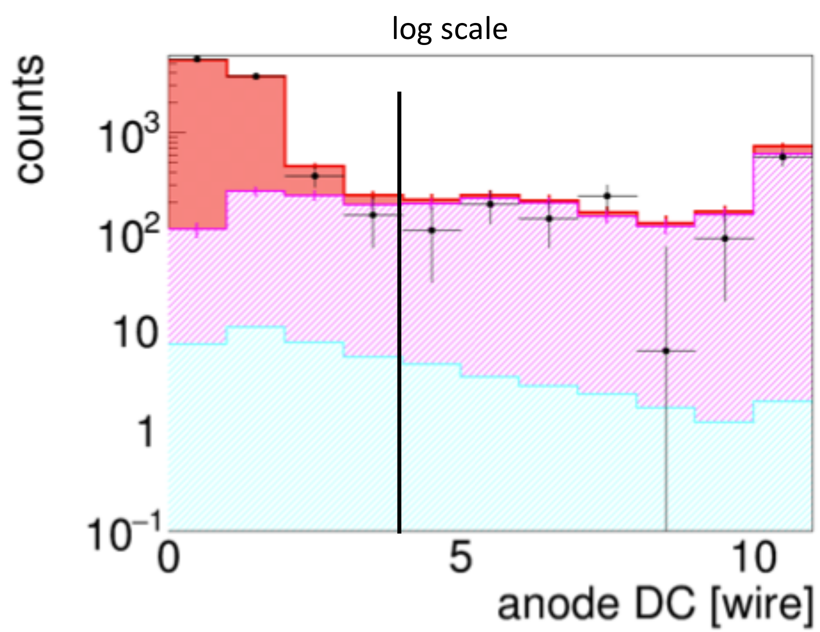
**"DC"**

Distance from beam Center

background has large DC value



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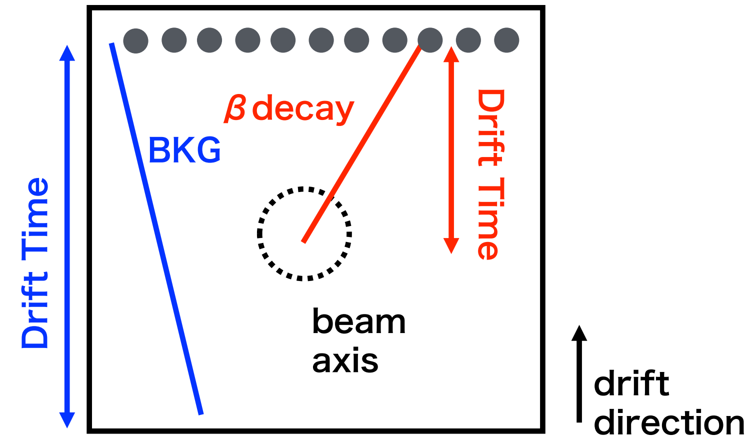
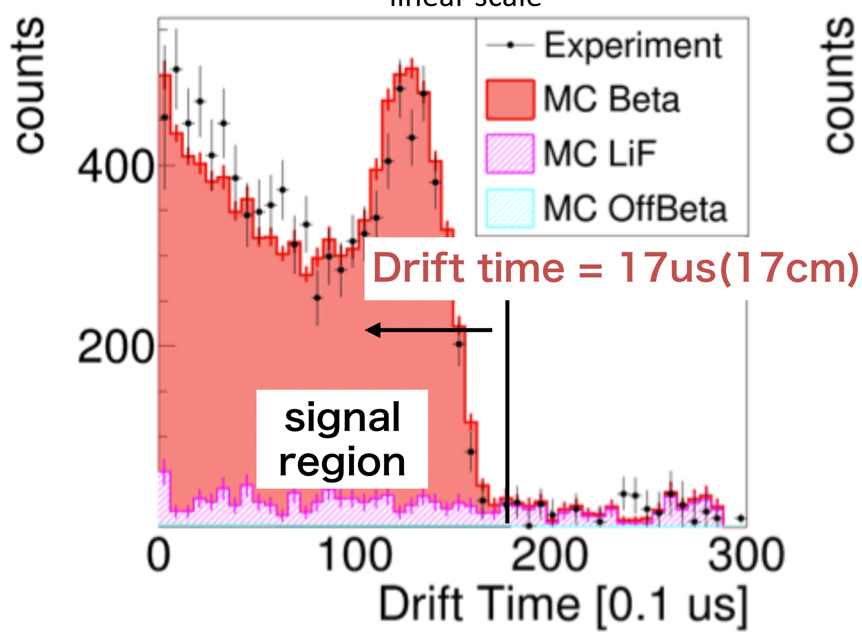
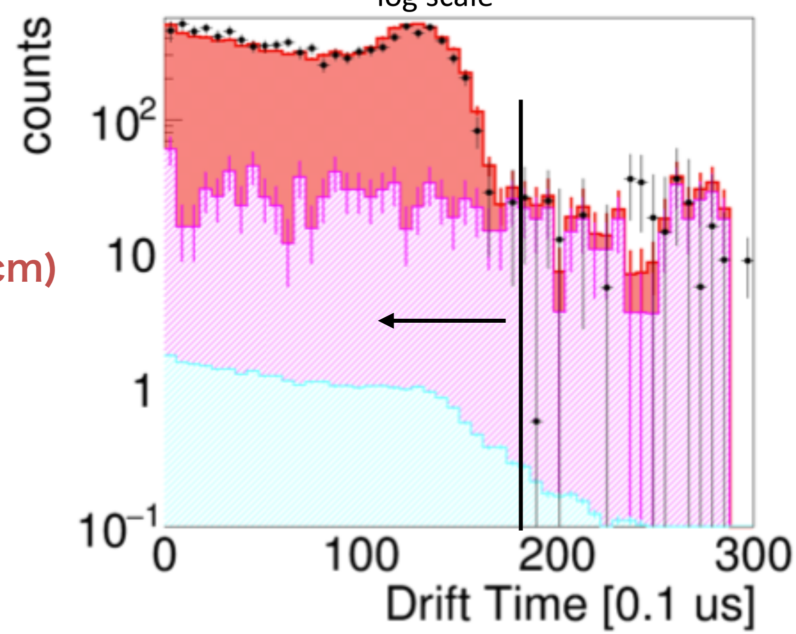



**“Drift time”**
arrival time difference of drifting electrons
background has long Drift time

linear scale




log scale



# How to obtain the neutron lifetime

$$\tau_n = \frac{1}{\rho \sigma_{He}(v_0) v_0} \frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

Counts in signal cut region

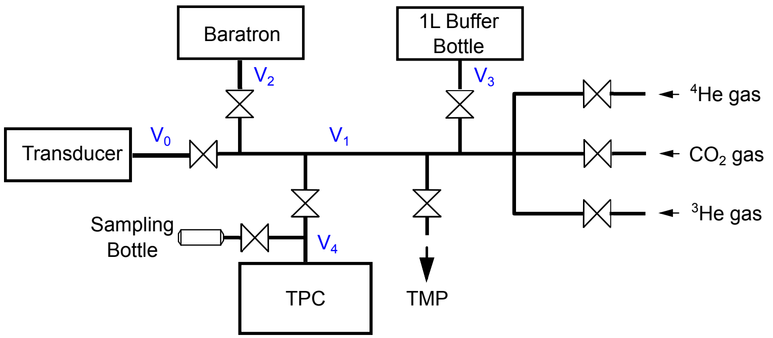
Monte Carlo with cut

$^3$He dopant (gas expansion)
+ $^3$He in $^{nat}$He (mass spectroscopy)

Literature value
(5333±7 barn)

# Determination of $^3$He number density ($\rho$)

1. A volume ratio of two vessel were measured by pressure change of gas.
   - $^3$He gas was injected (~90 mPa)
   - $^{nat}$He was injected (~85 kPa)
   - $CO_2$ was injected (~15 kPa)



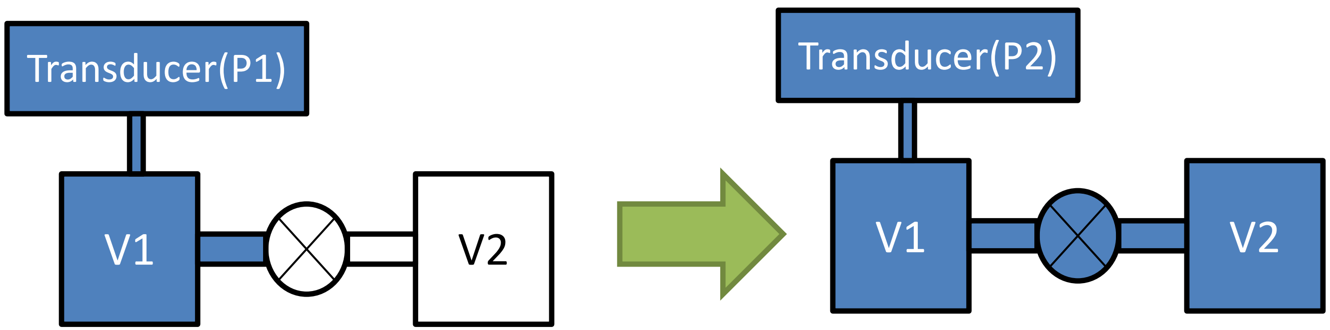

2. $^3$He/$^4$He ratio was measured by mass spectroscopy, and evaluate $^3$He amount in $^{nat}$He (~10 mPa)
3. Corrections during operation were applied (~0.3%)
   - Chamber deformation by pressure
   - Chamber deformation by temperature change
   - Temperature non-uniformity by heat from pre-amplifier
4. The operation gas was sampled and measured by mass spectroscopy, and cross-checked by the value determined 1-3.

# Gas expansion method

To inject $^{3}$He (~90 mPa) with accuracy of O(0.1%),

1. Volume ratio of a standard volume (40 $cm^3$) and a TPC vessel (600 liter) was measured precisely.
   - 2 buffer volumes were used between the standard volume to TPC vessel.
   - 3 pressure gauges with different full scales were used.
2. $^{3}$He was filled in a standard volume (~3 kPa)
3. $^{3}$He gas released into the TPC vessel.

$$V1/V2 = 6.681\,(13) \times 10^{-5}$$



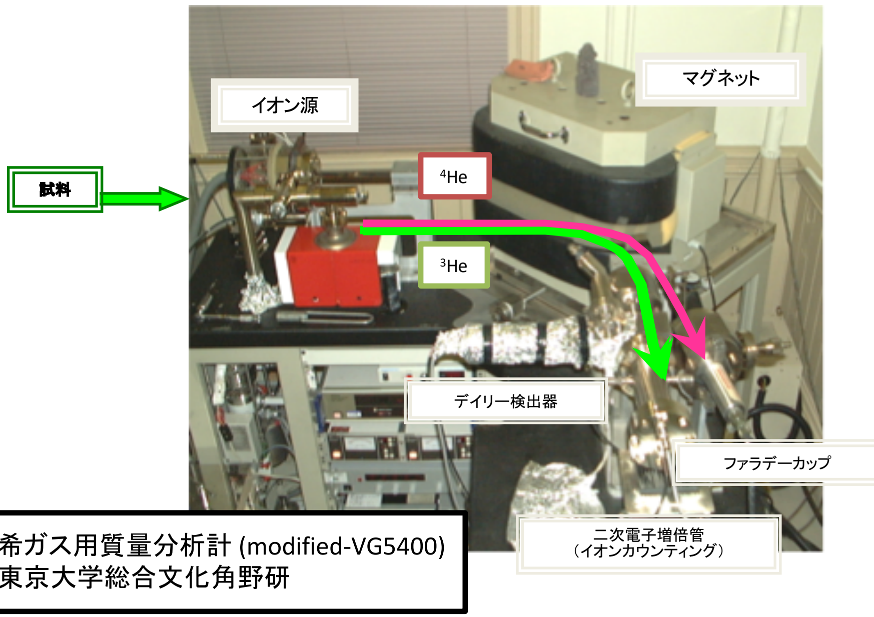

This method requires linearity for volume measurement and $^{3}$He injection

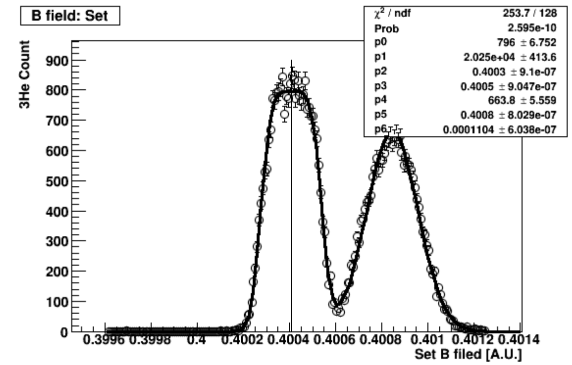
Pressure gauges for the gas handling system

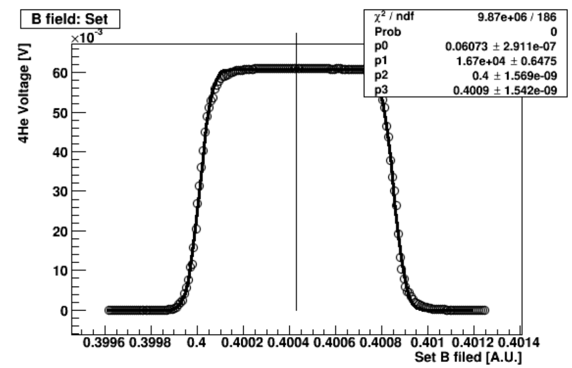
| 圧力計 | 機種 | Full scale | 不確かさ |
|---|---|---|---|
| Piezoresistive transducer | Mensor CPG2500 | 120 kPa | 0.01% of Full Scale |
| Piezoresistive transducer | Mensor CPG2500 | 35 kPa | 0.01% of Full scale |
| Baratron pressure gauge | MKS 69011TRA | 1333 Pa | 0.05% for reading |

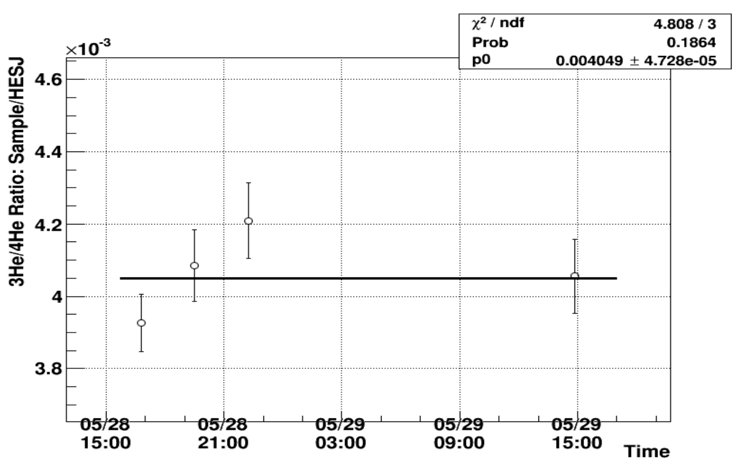

# Mass spectrometry of $^3He/^4He$

The amount of $^3He$ in $^{nat}He$ was evaluated by He pressure and $^3He/^4He$ ratio measured by mass spectrometry.



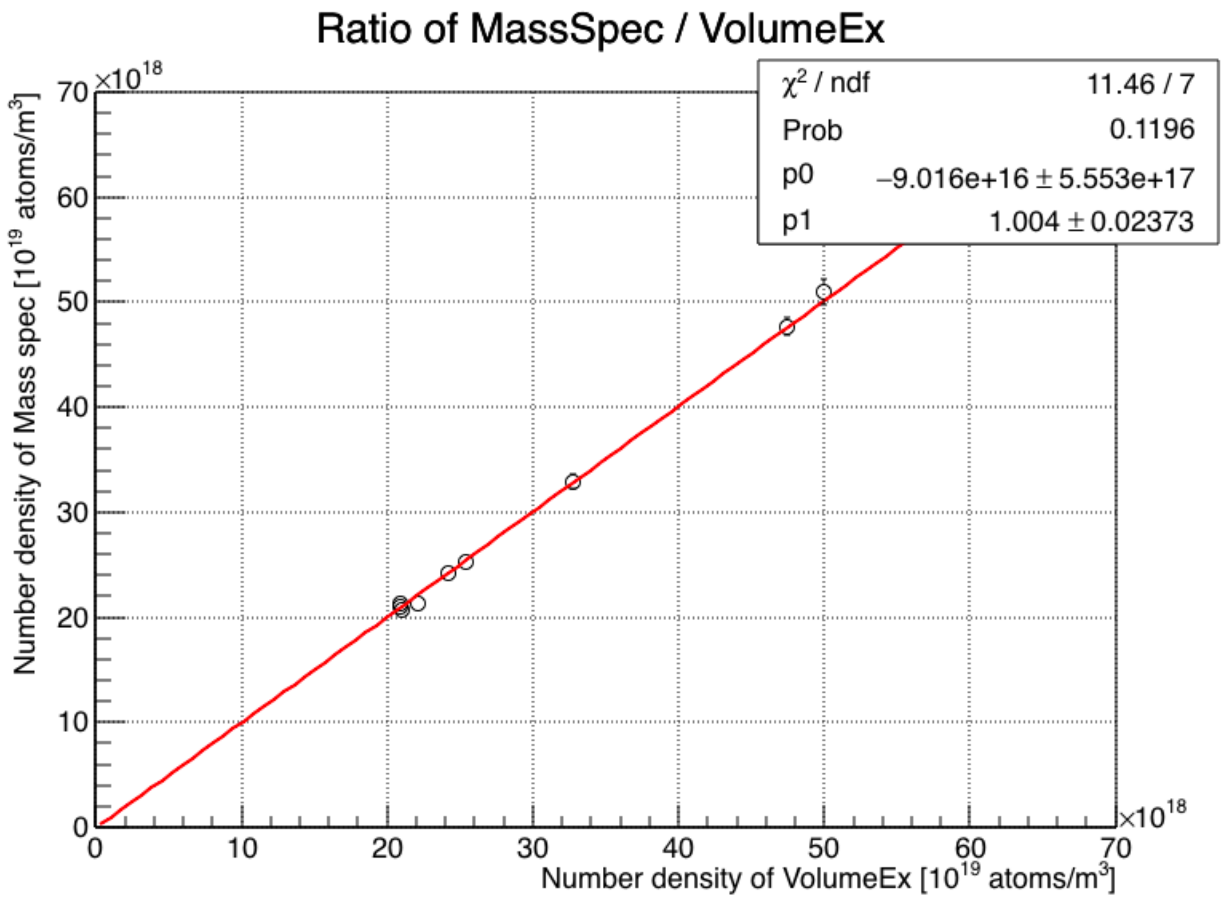




- $^3He/^4He$ ratio in $^{nat}He$ was
  **$^3He/^4He$ = 0.1107(14) ppm**
- $^3He$ in $^{nat}He$ was 9.4 mPa for $^{nat}He$ of 85kPa for operation gas of the TPC.

# Gas expansion v.s. Mass spectroscopy

After the experimental operations, the TPC gases were sampled and measured by mass spectrometer. The measured values are compared with gas expansion method.




The two methods gave consistent results.

# Uncertainty Budgets of a fill

$$\tau_n = \frac{1}{\rho\sigma_{He}(v_0)v_0}\frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

| $S_\beta$ | Correction (%) | Uncertainty (%) |
|---|---|---|
| Statistic | | 1.7 (stat.) |
| Beam induced background | -2.6 | 1.3 (stat.) |
| $CO_2$ recoil | | +0/-0.25 |
| Pile up | +0.62 | 0.19 |
| **$S_\beta$ sub total** | | **2.2(stat.) +0.20/-0.33(sys.)** |

| $S_{3He}$ | Correction (%) | Uncertainty (%) |
|---|---|---|
| Statistic | | 0.24 (stat.) |
| $^{14}N(n,p)^{14}C$ | -0.18 | 0.07 |
| $^{17}O(n,p)^{14}C$ | -0.56 | 0.03 |
| Pile up | -0.11 | 0.01 |
| **$S_{3He}$ sub total** | | **0.24(stat.) +0.07/-0.07(sys.)** |

| $\sigma_{3He}$ | Value [barn] | Uncertainty (%) |
|---|---|---|
| **$\sigma_{3He}$ sub total** | **5333±7** | **±0.13 (sys.)** |

| $v_0$ | 2200 [m/s] | Exact |
|---|---|---|

| $\epsilon_\beta$ | Efficiency (%) | Uncertainty (%) |
|---|---|---|
| Max pulse height(3He/$\beta$) | 98.7 | +0.30/-0.31 |
| Low Energy rejection | 99.9 | +0.04/-0.07 |
| Triton $\beta$ decay rejection | 98.7 | +0.05/-0.05 |
| Anode DC cut | 97.3 | +0.35/-0.48 |
| Drift length cut | 99.2 | +0.13/-0.18 |
| **$\epsilon_\beta$ sub total** | **94.3** | **+0.62/-0.72(sys.)** |

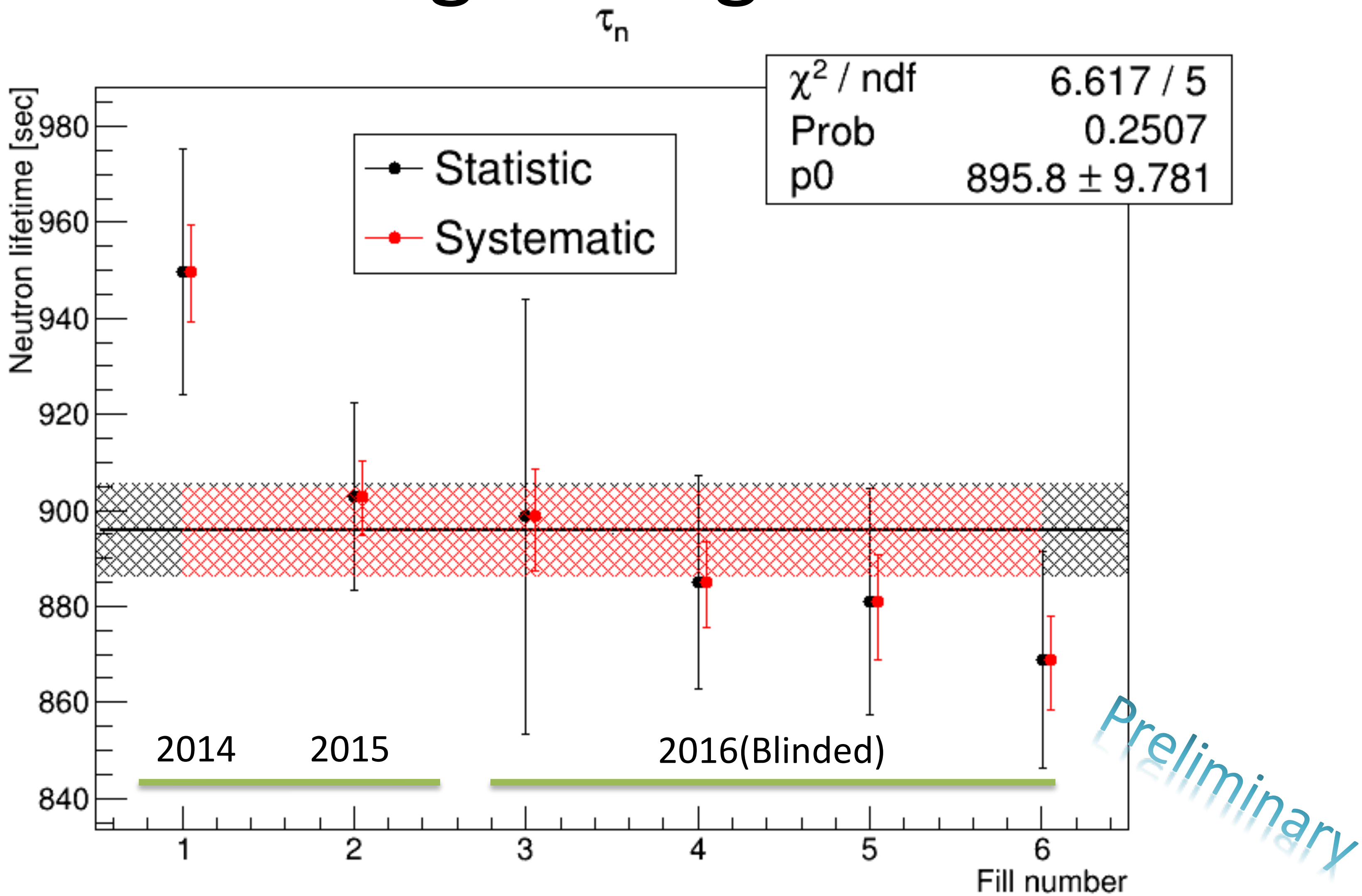
| $\epsilon_{3He}$ | Efficiency (%) | Uncertainty (%) |
|---|---|---|
| **$\epsilon_{3He}$ sub total** | **99.997** | **+0.003/-0.006 (sys.)** |

| $\rho_{3He}$ | Correction (%) | Uncertainty (%) |
|---|---|---|
| Injected $^3He$ | | +0.28/-0.29 |
| $^3He$ in TPC gas | | ±0.16 |
| Corrections in TPC | -0.16 | ±0.33 |
| **$\rho_{3He}$ sub total** | | **+0.45/-0.45 (sys.)** |

Preliminary

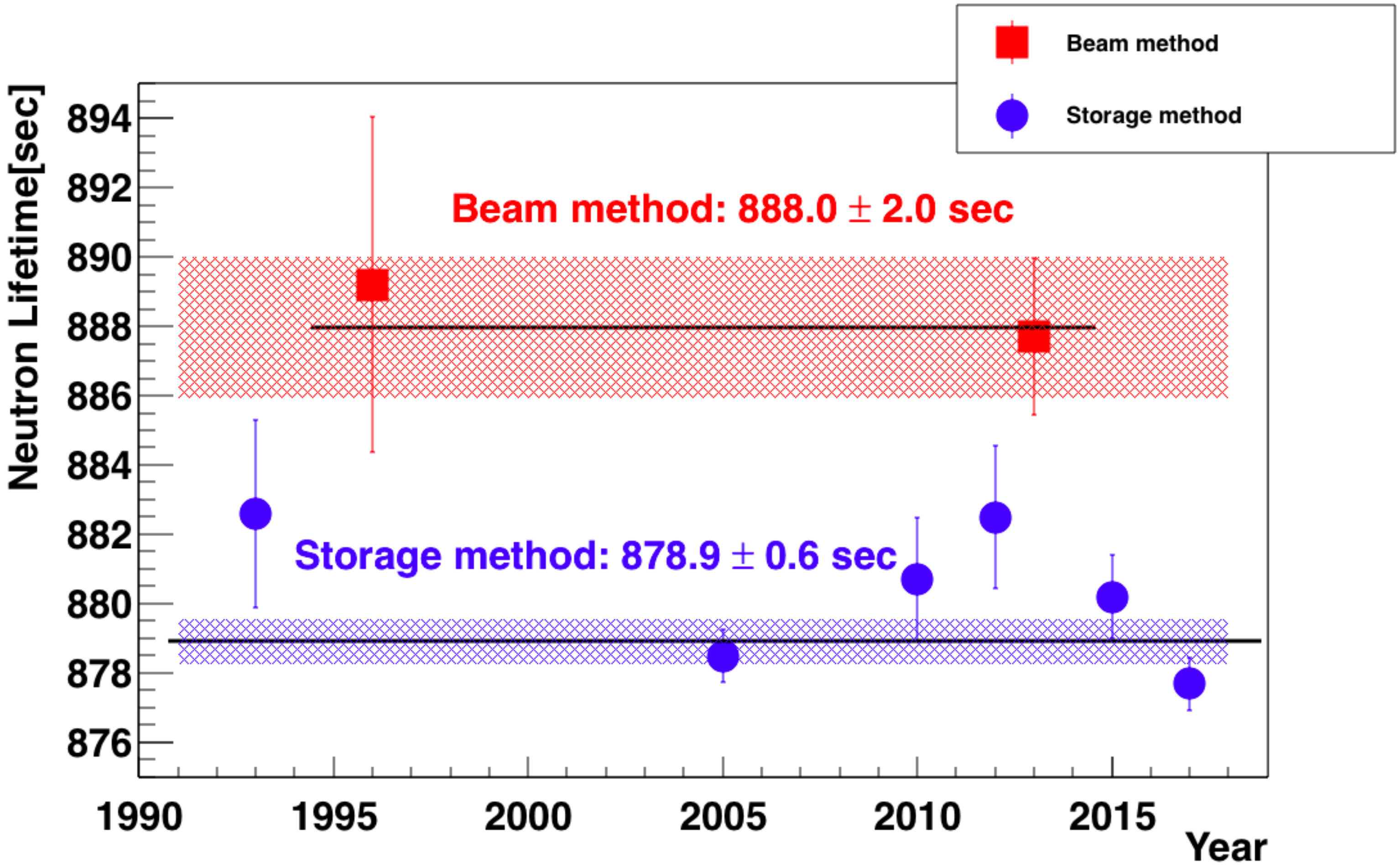
Total $\tau_n$ uncertainty of a fill (500kW 3 days ) is
**2.17(stat.) +0.85/0.88(sys.) %**

# Fitting of all gas fills

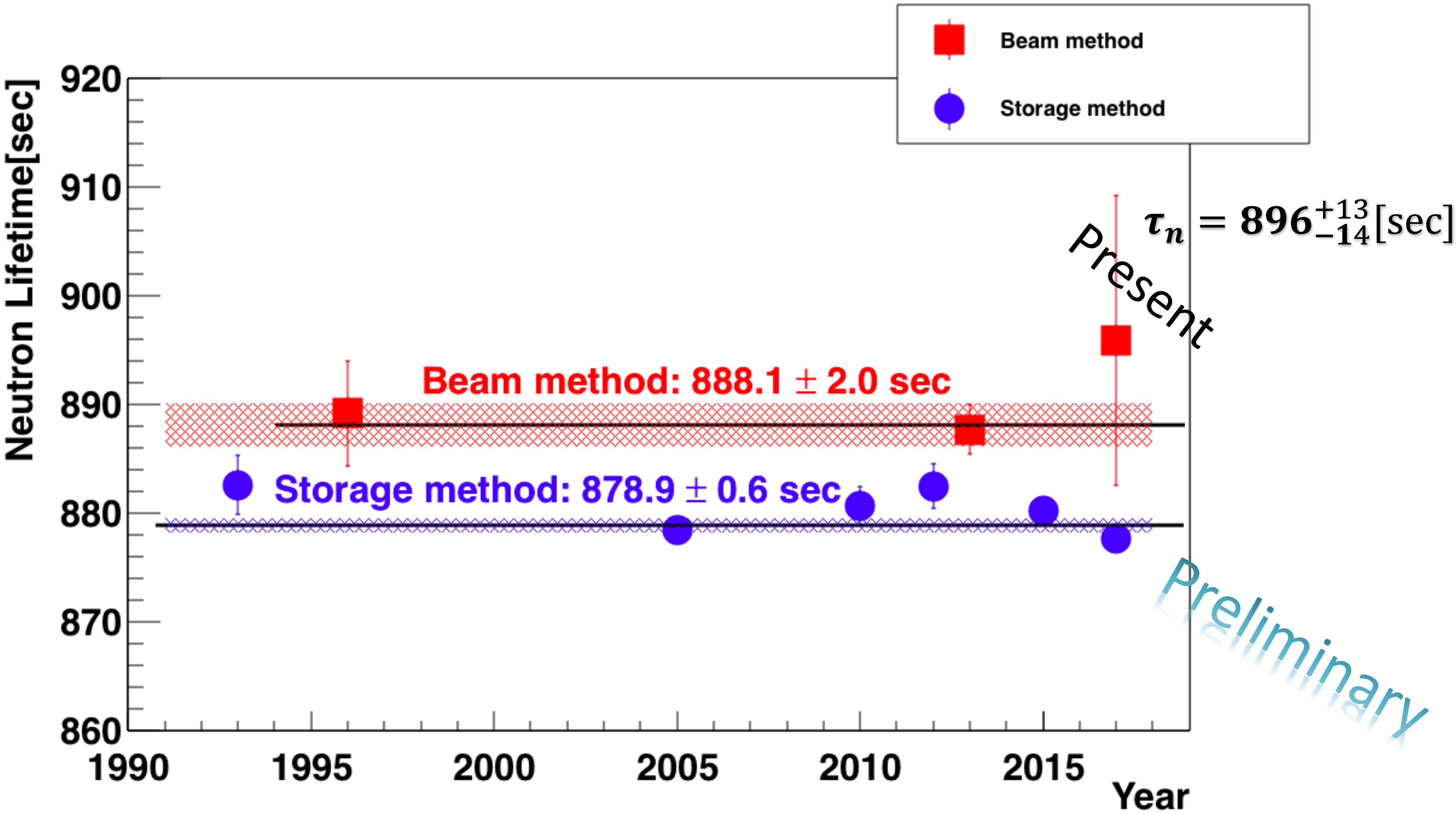



$\tau_n$ = **895.8 ± 9.8(stat.) +8.9/−9.9 (sys.) [sec]**

# Measurements of the neutron lifetime



# Measurements of the neutron lifetime

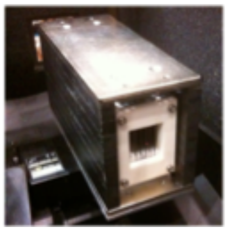



1.1$\sigma$ difference with $\tau_n$ (PDG2017) = 880.2±1.0 sec

# Update Plan

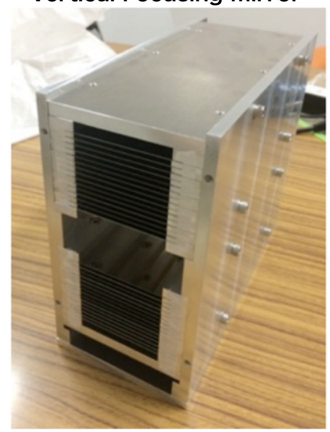
## Statistic

Enlarge beam size 2 × 2[cm] -> 3 × 10[cm]
and focusing

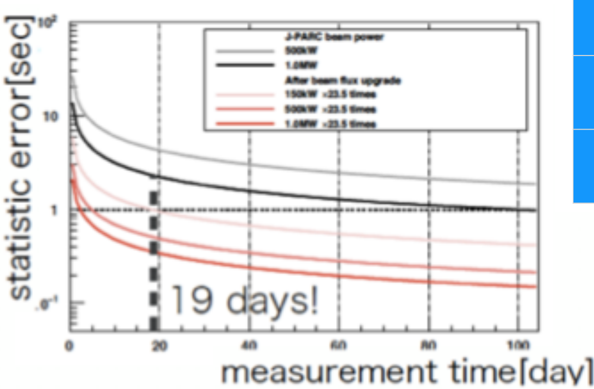


Enlarged Supper Mirror

Vertical Focusing Mirror



**Intensity will be 23 times.**
**150kW operation reaches 0.1% accuracy in 19days!**




| | flux[/n/sec/MW] | ratio to current flux |
|---|---|---|
| current mirror | 5.96±0.29 E+6 | 1.0 |
| enlarged mirror same beam size | 1.49±0.05 E+7 | 2.5 |
| enlarged mirror enlarged beam size | 1.40±0.02 E+8 | 23.5 |

## Temperature stability

New ASIC preamplifier


GTARN test board

openit

No. of ch. : 8ch/chip
power consum. : 8.9mW/ch
gain : 1.4V/pC
ENC : 5000

Power consumption will be 1/50.

**Updates will be implemented in 2017- 2018**

R. Kitahara et al., NOP2017, T.Tomita et al, RCNP workshop (Jul.2017)

# Summary

- Neutron lifetime is an important parameter, however there is 8.4sec (4.0σ) deviation of the value of lifetime between two methods of measurement.
- We are measuring the neutron lifetime at pulsed neutron beamline(BL05) at J-PARC.
  - Goal is 1 sec accuracy.
- Our first result is

Preliminary

$$\tau_n = 896 \pm 10(stat.)\,^{+9}_{-10}\,(sys.)[sec]$$

  - Systematic uncertainty will be smaller with more intelligent cuts.
  - More statistic will be collect in 2017-2018 (300-500 kW).
- Upgrades of low power amplifiers and large SFC are prepared.