Precise Neutron Lifetime Measurement Using Pulsed Neutron Beams at J-PARC

N. SUMI[1], K. HIROTA[2], G. ICHIKAWA[3], T. INO[3], Y. IWASHITA[4], S. KAJIWARA[5], Y. KATO[5], M. KITAGUCHI[6], K. MISHIMA[3], K. MORIKAWA[7], T. MOGI[5], H. OIDE[8], H. OKABE[7], H. OTONO[9], T. SHIMA[2], H. M. SHIMIZU[6],Y. SUGISAWA[10], T. TANABE[11], S. YAMASHITA[11], K. YANO[1] and T. YOSHIOKA[9]

[1]Department of Physics, Kyushu University
[2]Research Center for Nuclear Physics, Osaka University
[3]KEK, High Energy Accelerator Research Organization
[4]Institute for Chemical Research, Kyoto University
[5]Department of Physics, The University of Tokyo
[6]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University
[7]Department of Physics,Nagoya University
[8]Department of Physics, Tokyo Institute of Technology
[9]Research Center for Advanced Particle Physics, Kyushu University
[10]Institute of Applied Physics, University of Tsukuba
[11]International Center for the Elementary Particle Physics, The University of Tokyo

J-PARC Symposium 2019 @ Tsukuba
26/Sep./2019 PN/MLF-SY: Symmetry in particle and nuclear physics

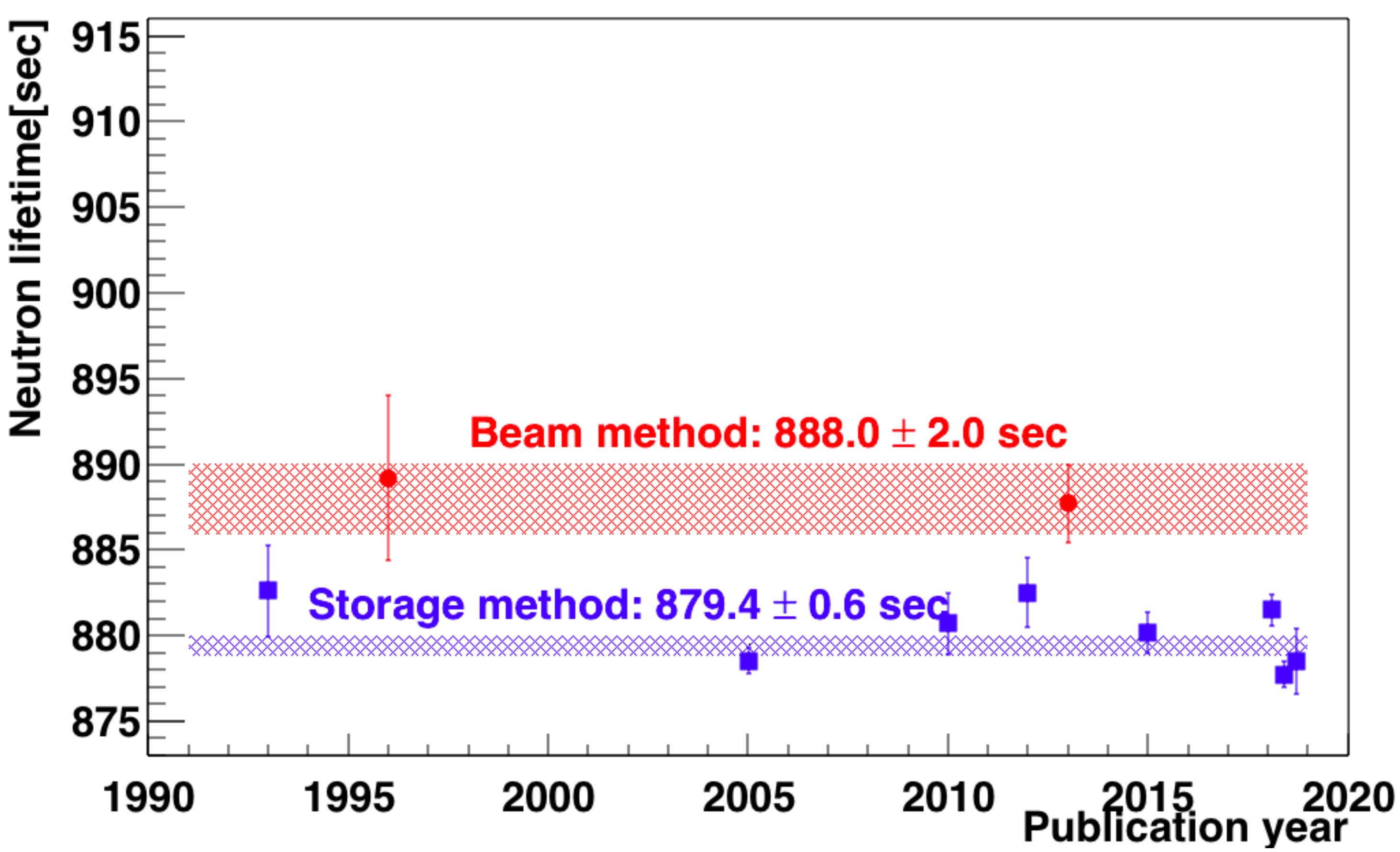
Neutron Optics and Physics

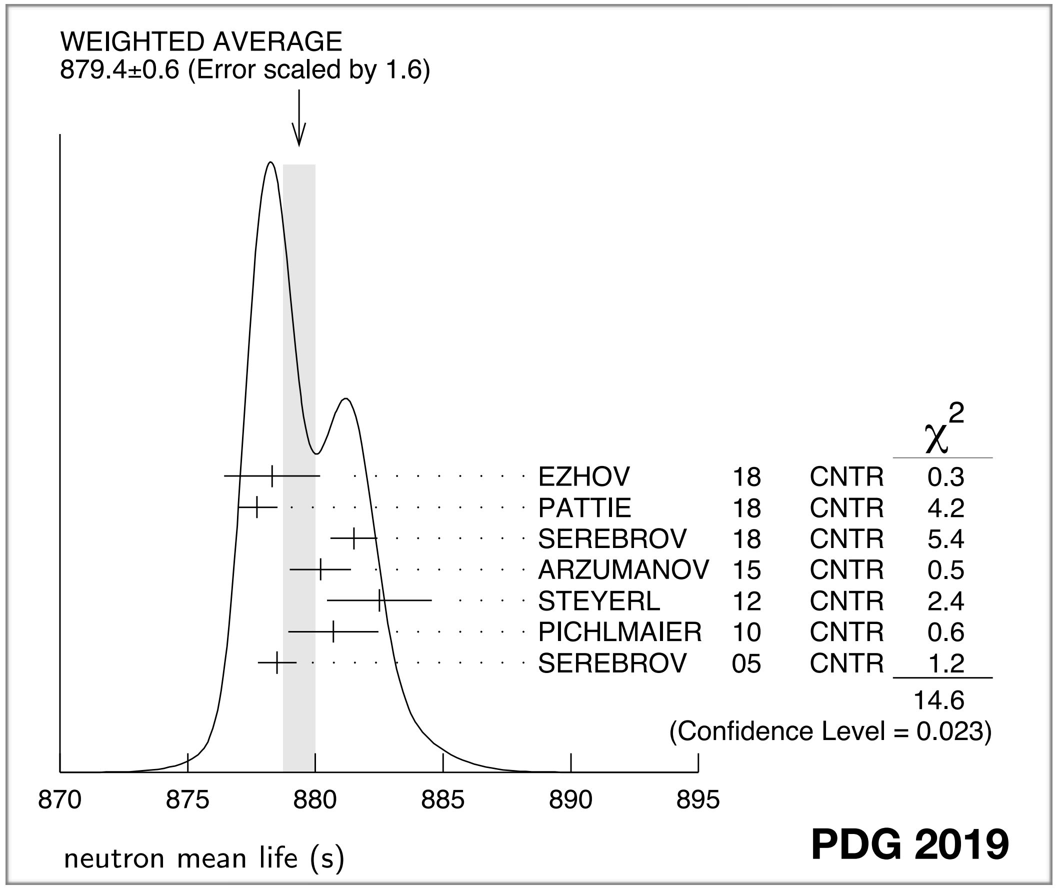
Neutron lifetime

- The neutron decay with a mean lifetime of 879.4 ± 0.6 sec.

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

- The lifetime has been measured by two types of method.
  - **Beam method count dead neutrons.**
  - **Storage method count living neutrons.**
- **The discrepancy (8.6 sec or 4.0σ) of these two methods is a long time problem.**



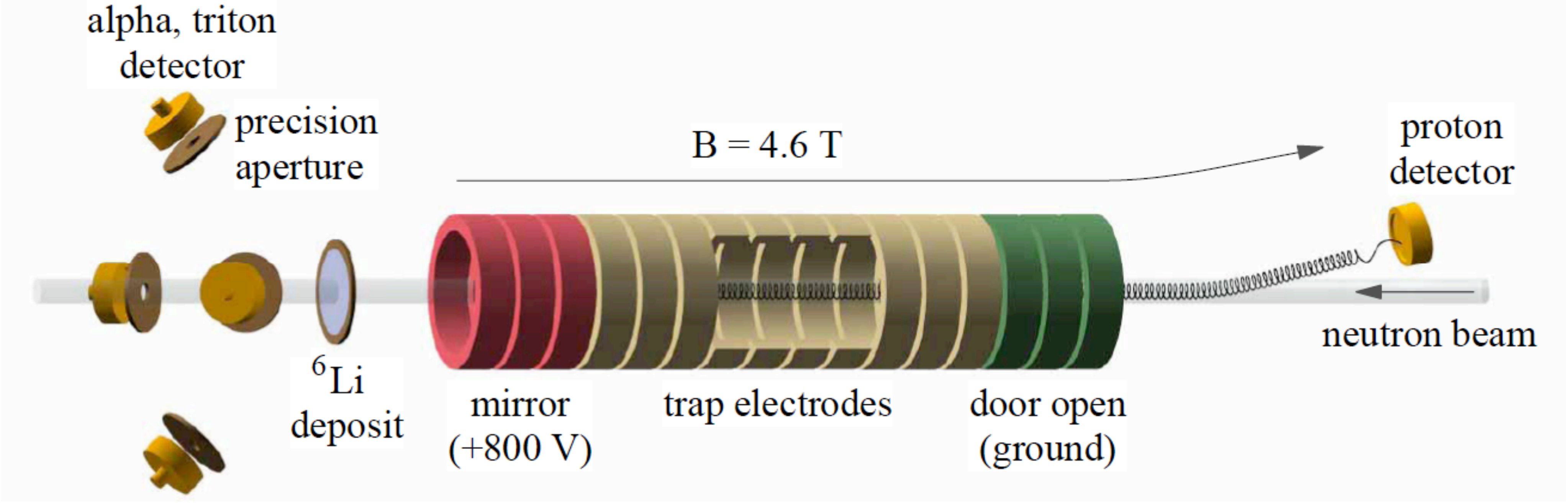


Beam method

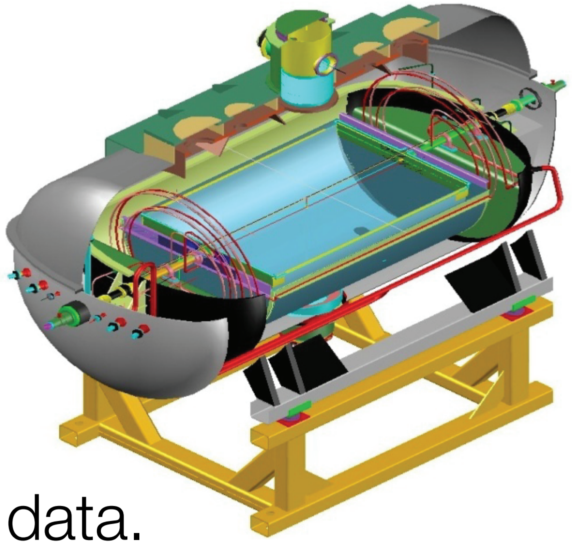
- Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam.
  J. Nico et al. Physical Review C 71.5 (2005): 055502.
  τ_n = 886.6 ± 1.2 (stat) ± 3.2 (syst) sec

- Improved determination of the neutron lifetime.
  A. T. Yue et al., Physical review letters 111.22 (2013): 222501.
  τ_n = 887.7 ± 1.2 (stat) ± 1.9 (syst) sec

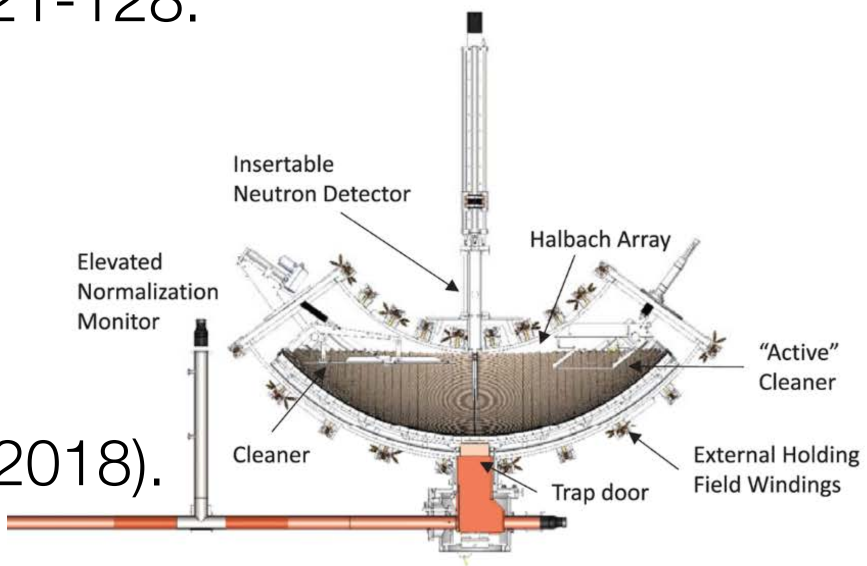
- Monochromatic neutron beam was transported to the magnetic trap.
  - Neutron flux was monitored by a ^{6}Li and detectors.
  - Protons from the neutron decays trapped in the magnetic and electric field.
  - Stored protons are released and detected by a proton detector.



Storage method

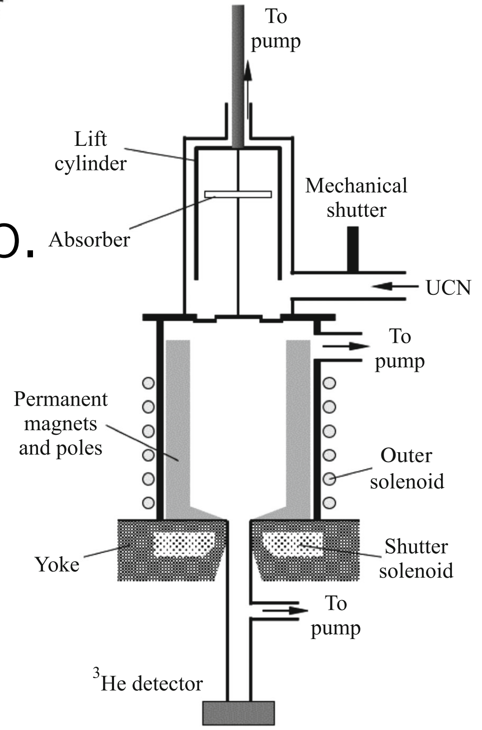


- PNPI/ILL Large storage bottle
  - New neutron lifetime measurements with the big gravitational trap and review of neutron lifetime data. Serebrov, A. P. et al., KnE Energy & Physics, 3(1) (2018) 121-128. **τ_n = 881.5 ± 0.7 (stat) ± 0.6 (syst) sec**



- LANL Magnetic Trap
  - Measurement of the neutron lifetime using an asymmetric magneto-gravitational trap and in situ detection. R. W. Pattie Jr. et al., Science 10.1126/science.aan8895 (2018). **τ_n = 877.7 ± 0.7 (stat) $^{+0.4}/_{-0.2}$ (syst) sec**

neter

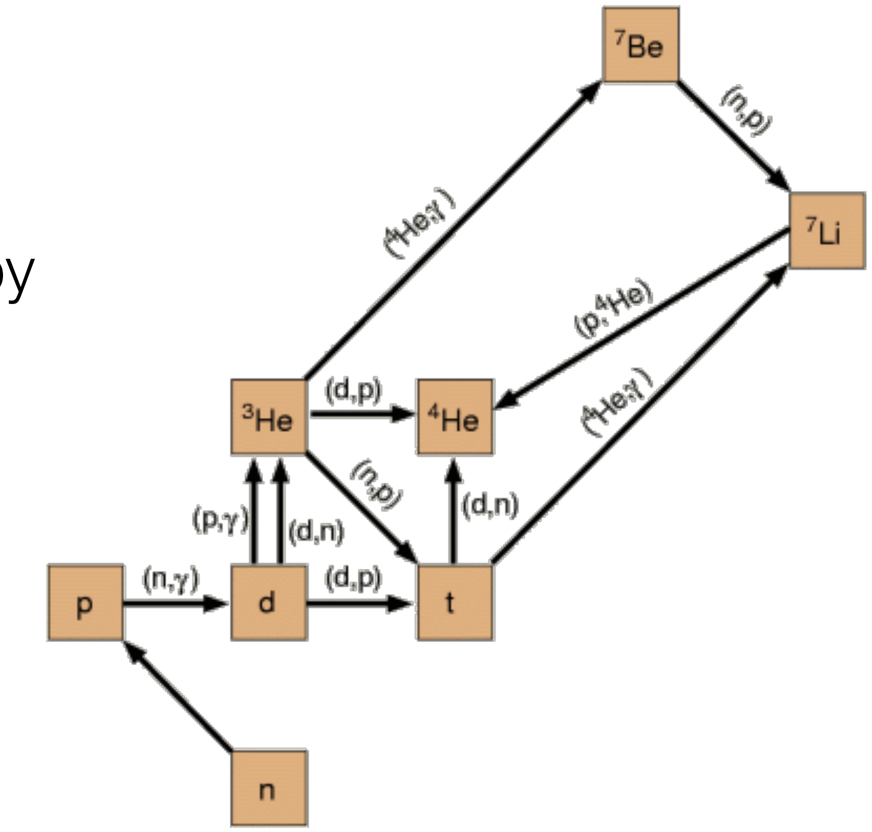


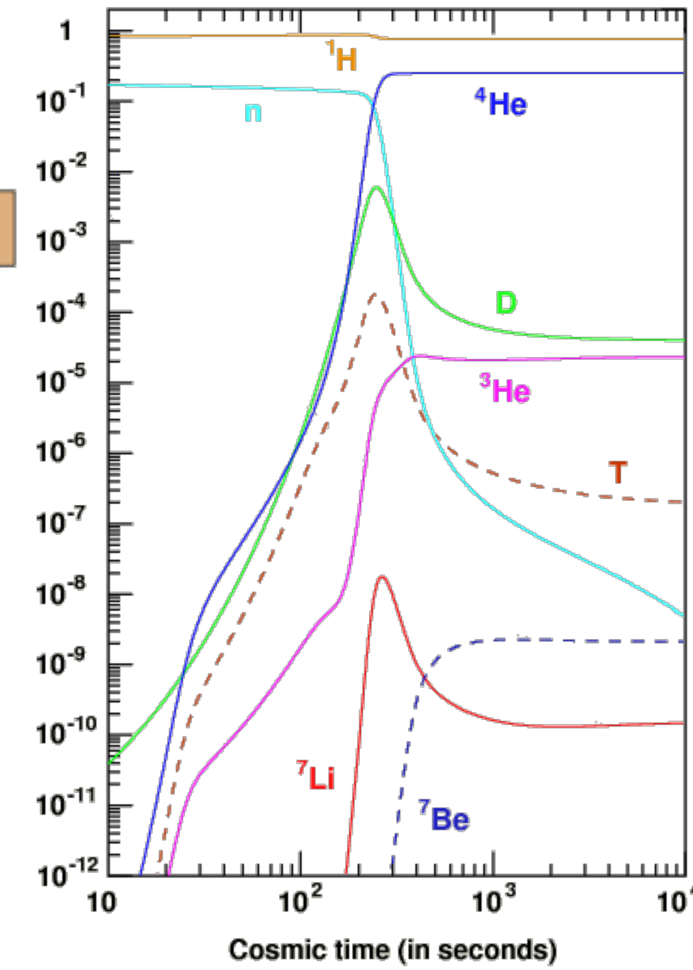
- PNPI/ILL Magnetic bottle
  - Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap. Ezhov, V. F. et al., JETP Letters (2018) 1-6. **τ_n = 878.3 ± 1.6 (stat) ± 1.0 (syst) sec**

Physics motivation

Big bang nucleosynthesis

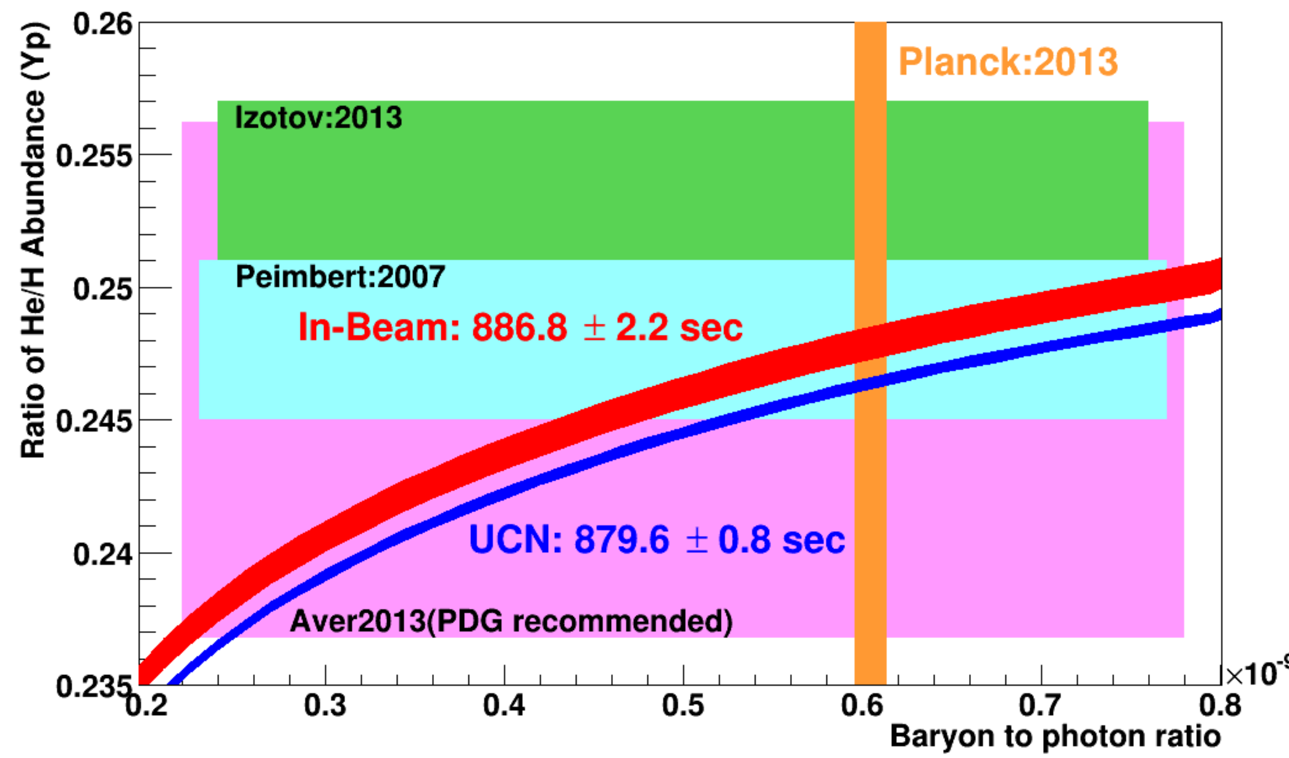
- Light elements (A≦7) were created in 10^3 seconds after the big bang.
- Abundance of them is calculated by
  - baryon-to-photon ratio
  - nuclear cross sections
  - **neutron lifetime**.





http://www.einstein-online.info/spotlights/BBN_phys

- A recent observation[1] has a small inconsistency with the standard cosmology. Effective neutrino generation $N_{eff} = 3.51 \pm 0.35$ is 1.5σ deviation from 3.
- CMB+BAO observation[2] independently result Neff = 3.26 ± 0.28 which has 1.0σ deviation from 3.



1. Izotov, Y. I., G. Stasińska, and N. G. Guseva. Astronomy & Astrophysics 558 (2013): A57.
2. Valentino E, et al., Physics Letters B 761 (2016) 242–246.

Unitarity of CKM matrix

- Neutron decay is one way to verify
  the unitarity of the CKM matrix (Cabibbo-Kobayashi-Maskawa).

- Calculation of V_{ud} from neutron decay is simpler than nuclear ones
  but parameters have larger uncertainty.
  - Neutron lifetime τ_n (0.07%)
  - Axis/vector coupling constants $\lambda \equiv G_A/G_V$ (0.18%)

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\ \mathrm{sec}}{\tau_n(1+3\lambda^2)}$$

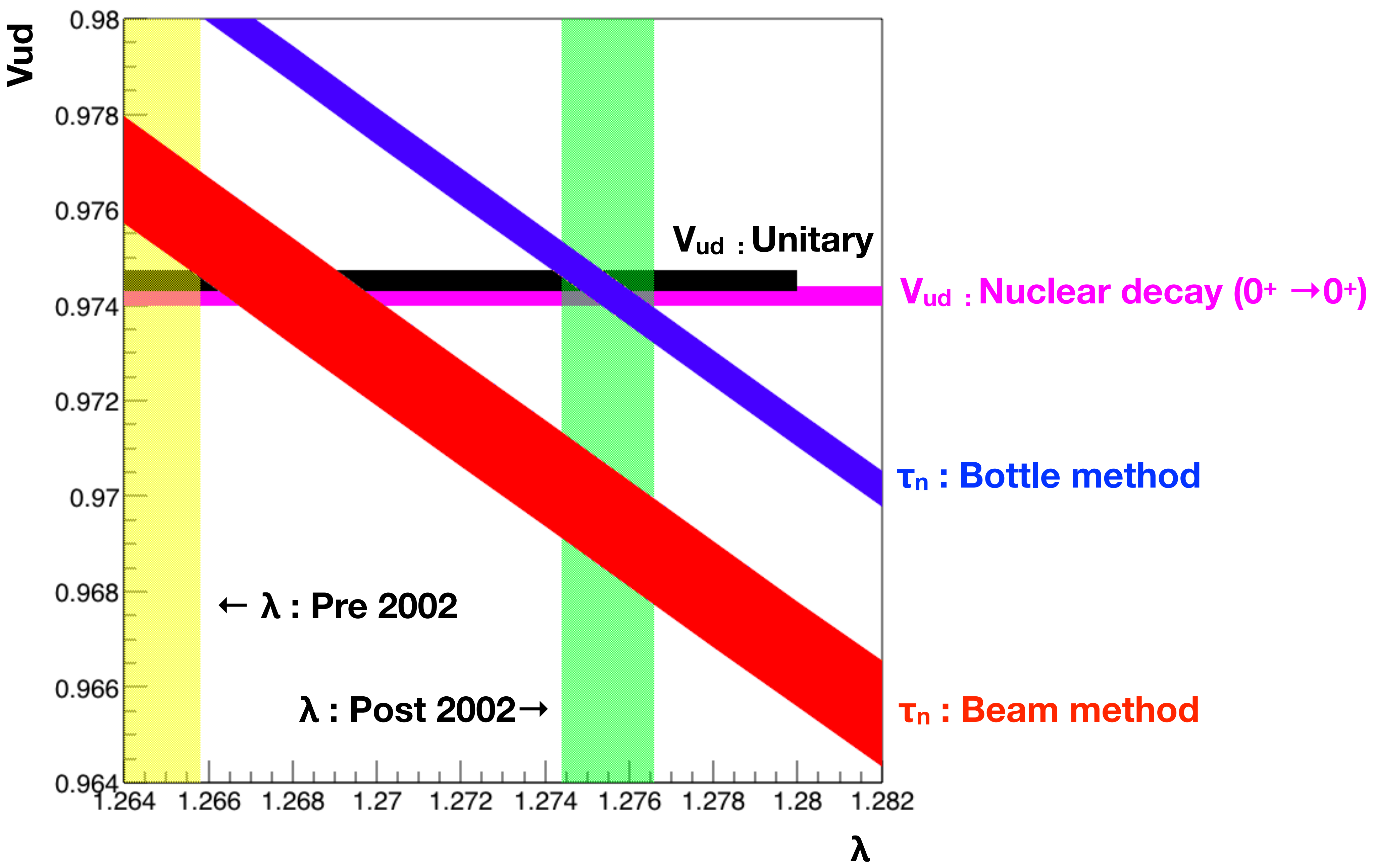
- The parameters summarized by PDG2019 is consistent with unitarity.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005$$

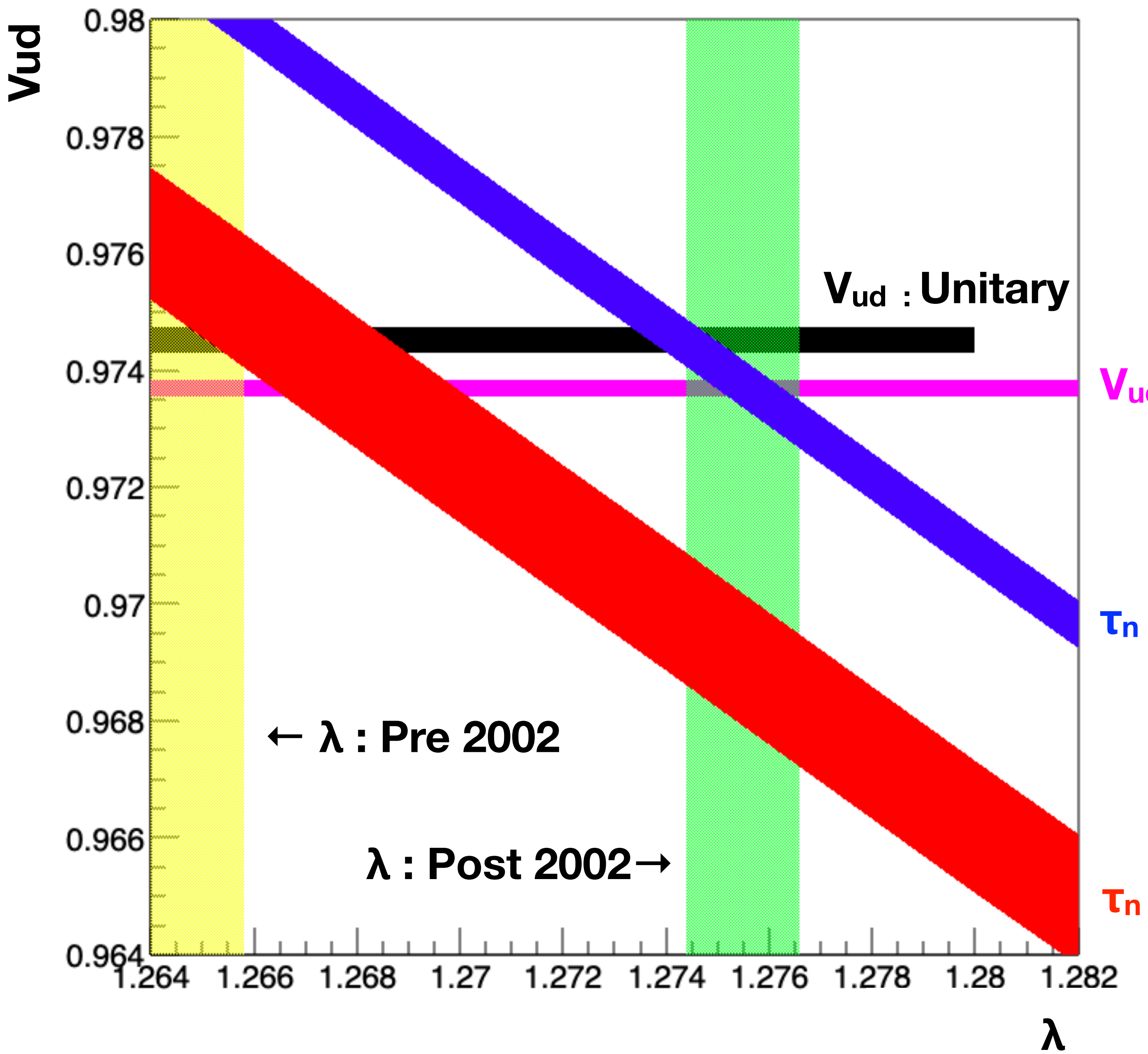
$$V_{CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359\ ^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896\ ^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

PDG 2019

Unitarity of CKM matrix : V_{ud} and λ



Unitarity of CKM matrix : V_{ud} and λ



with new radiative correction

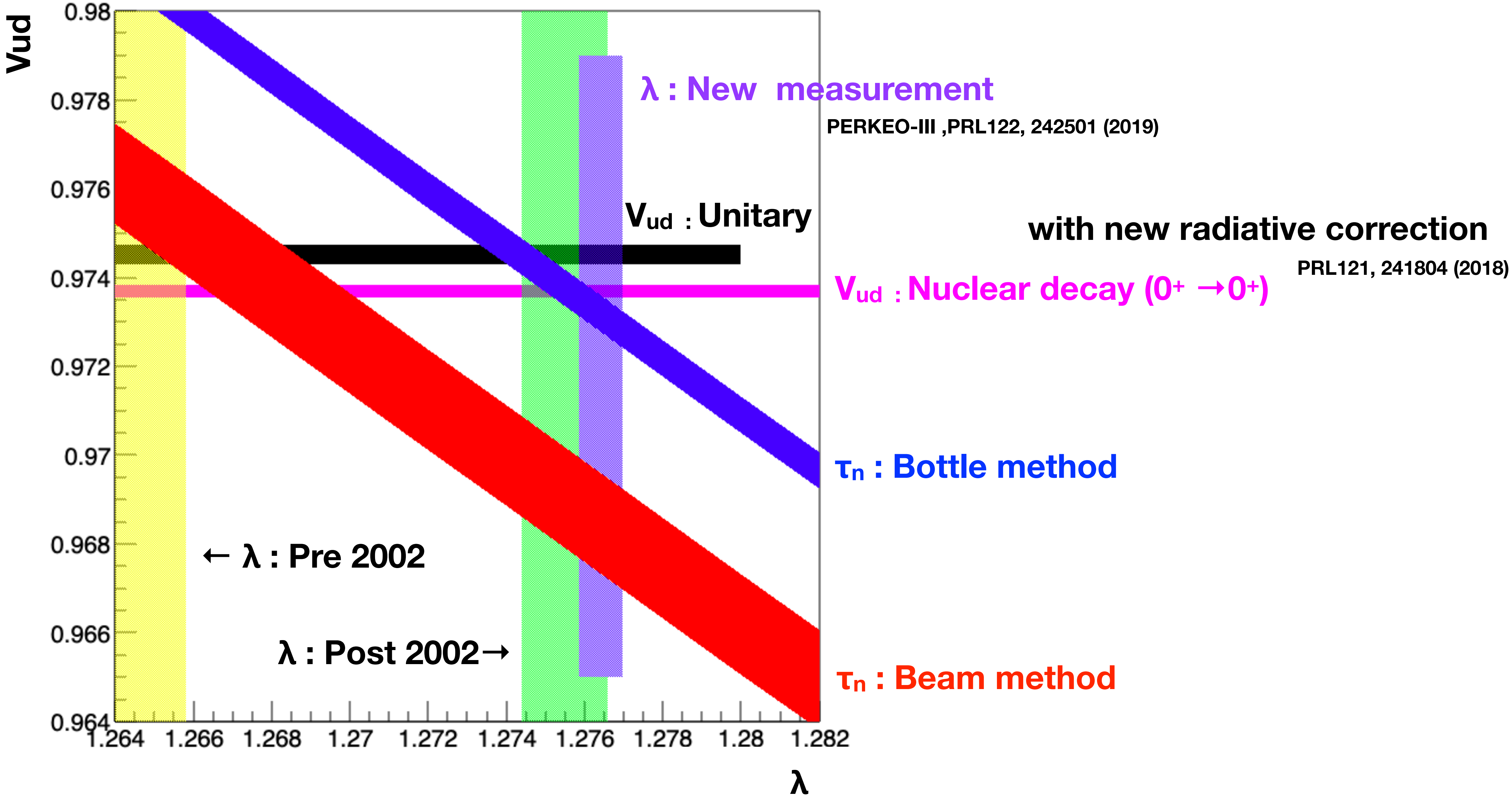
PRL121, 241804 (2018)

V_{ud} : Nuclear decay ($0^+ \rightarrow 0^+$)

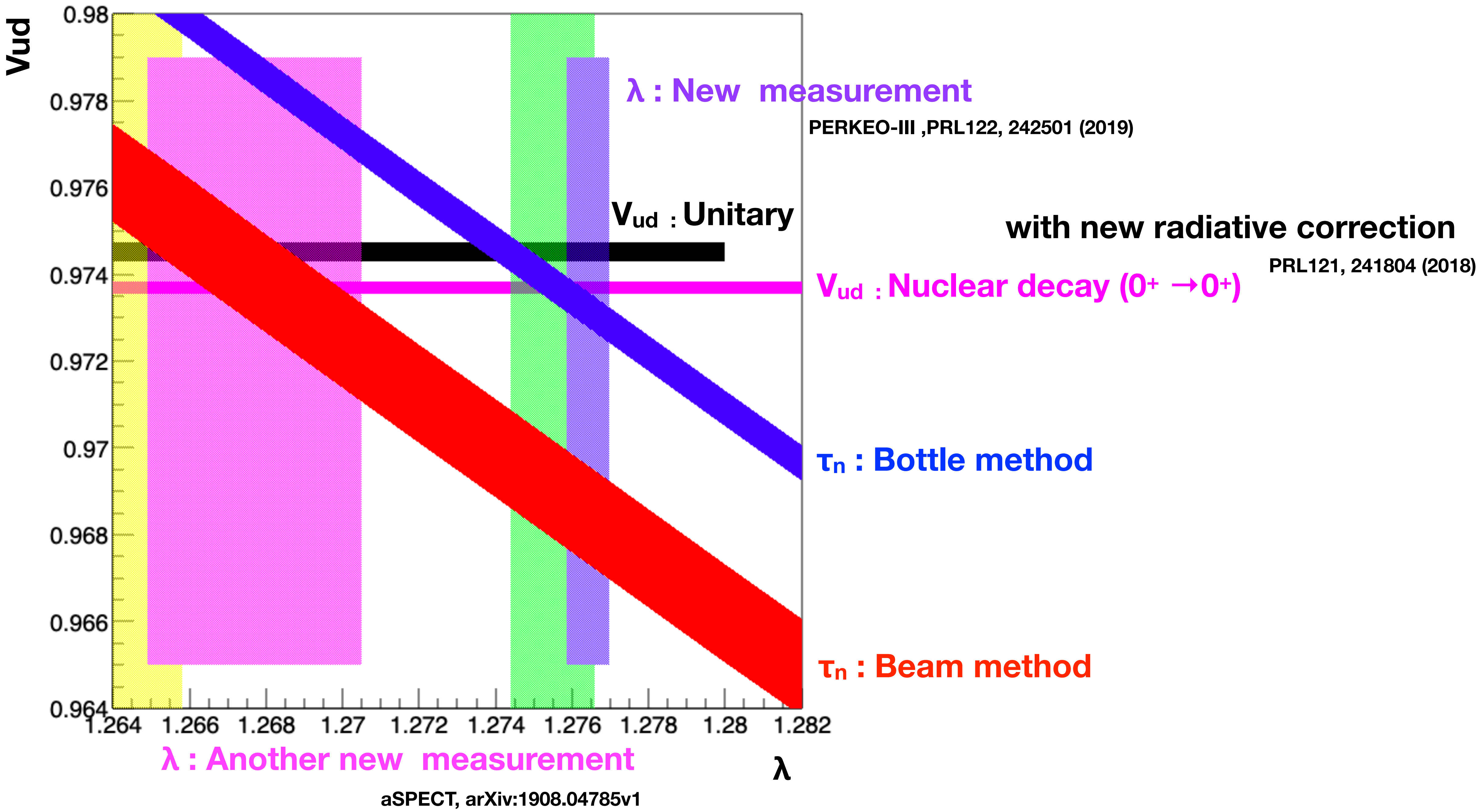
τ_n : Bottle method

τ_n : Beam method

Unitarity of CKM matrix : V_{ud} and λ



Unitarity of CKM matrix : V_{ud} and λ



Neutron dark decay

Neutron dark decay

PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion   Featured in Physics

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA

(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

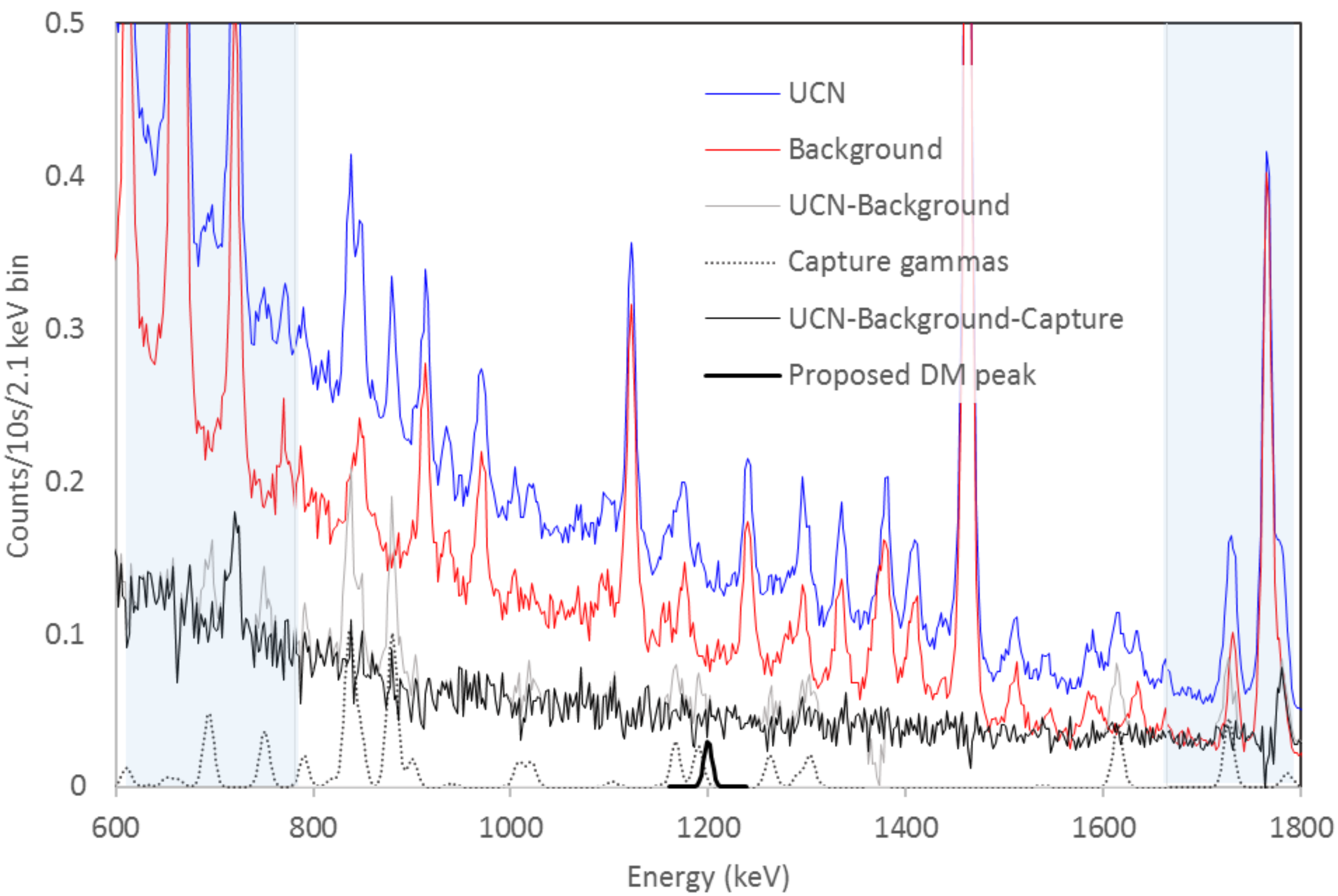
- This paper suggested that the discrepancy can be explained by previously unobserved dark matter decay modes with **1%** of usual beta decay.

- Three decay mode candidates, where χ and ϕ are dark matters
  - $n \to \chi\gamma$ $\quad (937.900 \text{ MeV} < m_\chi < 938.783 \text{ MeV})$
  - $n \to \chi e^+ e^-$ $\quad (937.900 \text{ MeV} < m_\chi < 938.543 \text{ MeV})$
  - $n \to \chi\phi$ $\quad (937.900 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV})$

- The arrowed mass ranges are very short.
  - These boundaries come from the stability of proton and ^{9}Be.

Decay mode : $n \to \chi\gamma$

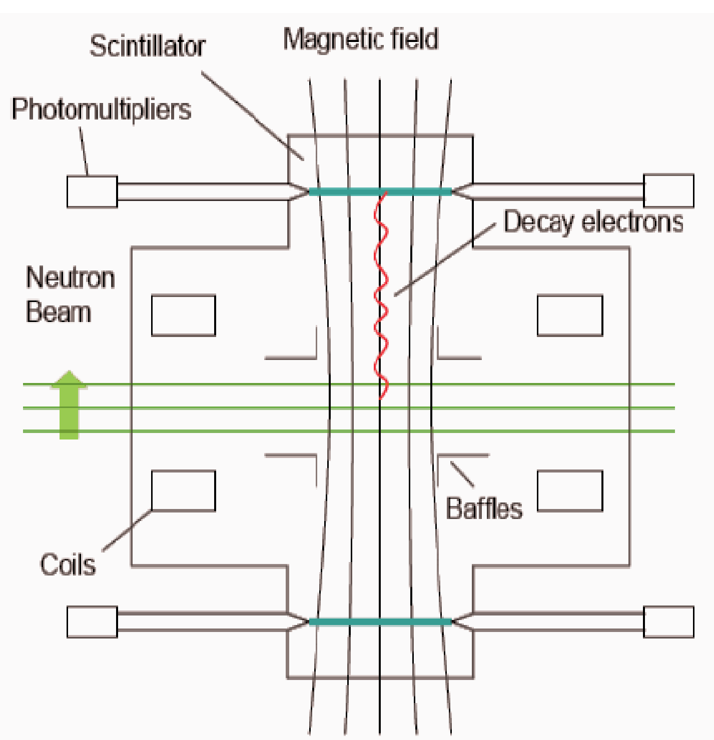
- The predicted energy range of gamma ray is $0.782\ \mathrm{MeV} < E_\gamma < 1.664\ \mathrm{MeV}$.
- The dark decay emits monochromatic gamma ray.
    - No gamma ray peak was observed with a germanium detector.

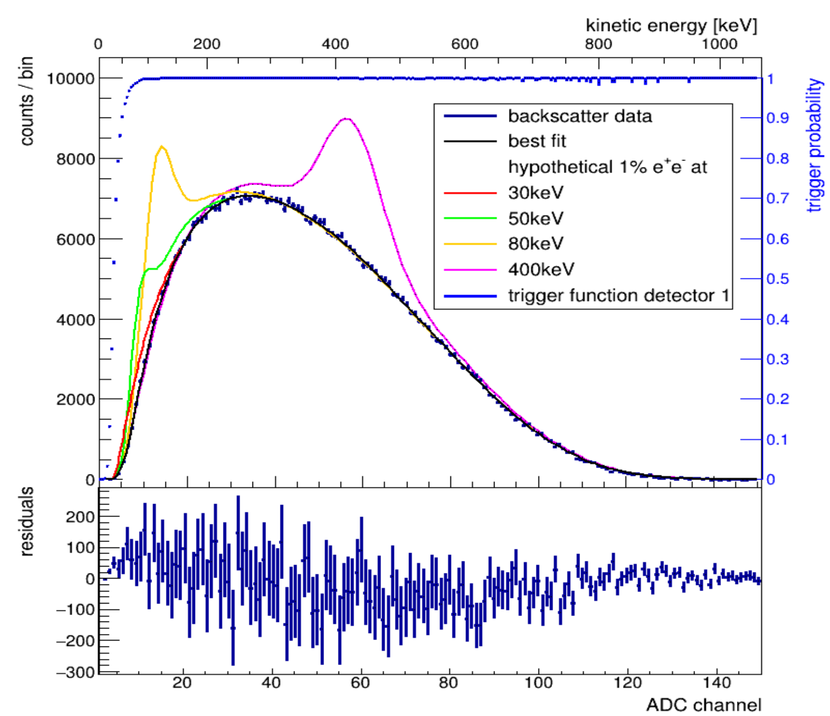


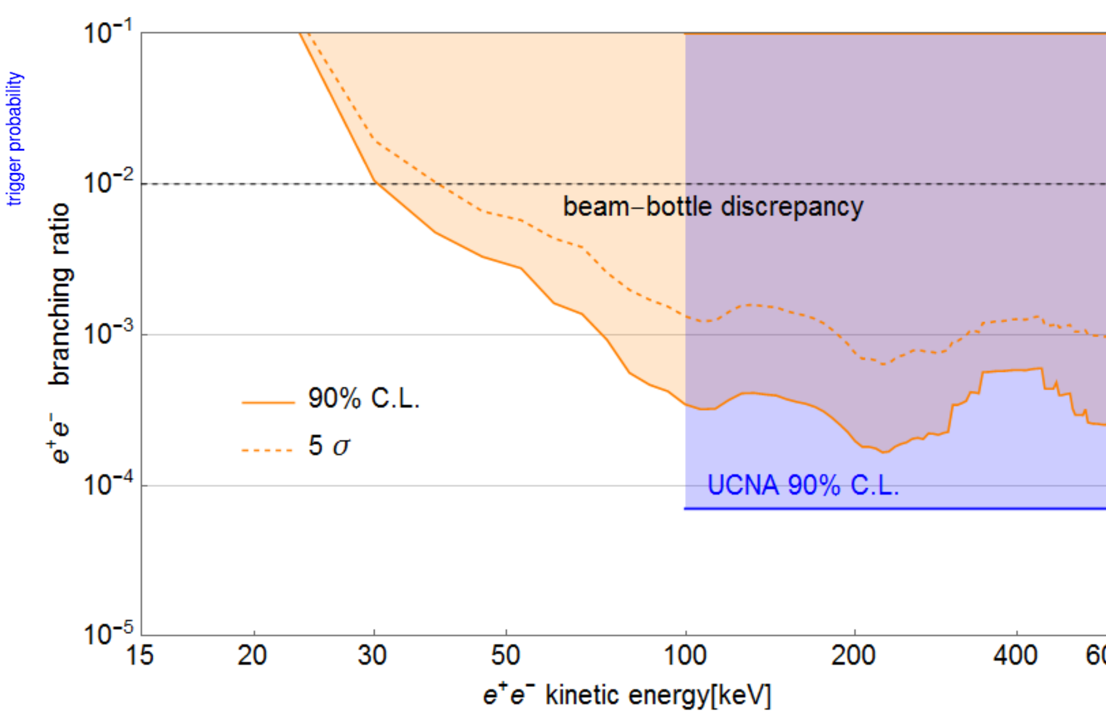
Phys. Rev. Lett. **121**, 022505

Decay mode : $n \to \chi e^+ e^-$

- They searched dark decay branch, $n \to \chi e^+ e^-$, in the electron spectrum data taken for λ measurement (PERKEO-II).
  - Constraints on the Dark Matter Interpretation $n \to \chi e^+ e^-$ of the Neutron Decay Anomaly with the PERKEO II experiment
  - This work constraints electrons energy for $37.5\ \mathrm{keV} < E_{e^+e^-} < 664\ \mathrm{keV}$ with 5σ.
  - $E_{e^+e^-} < 30\ \mathrm{keV}$ is still alive.





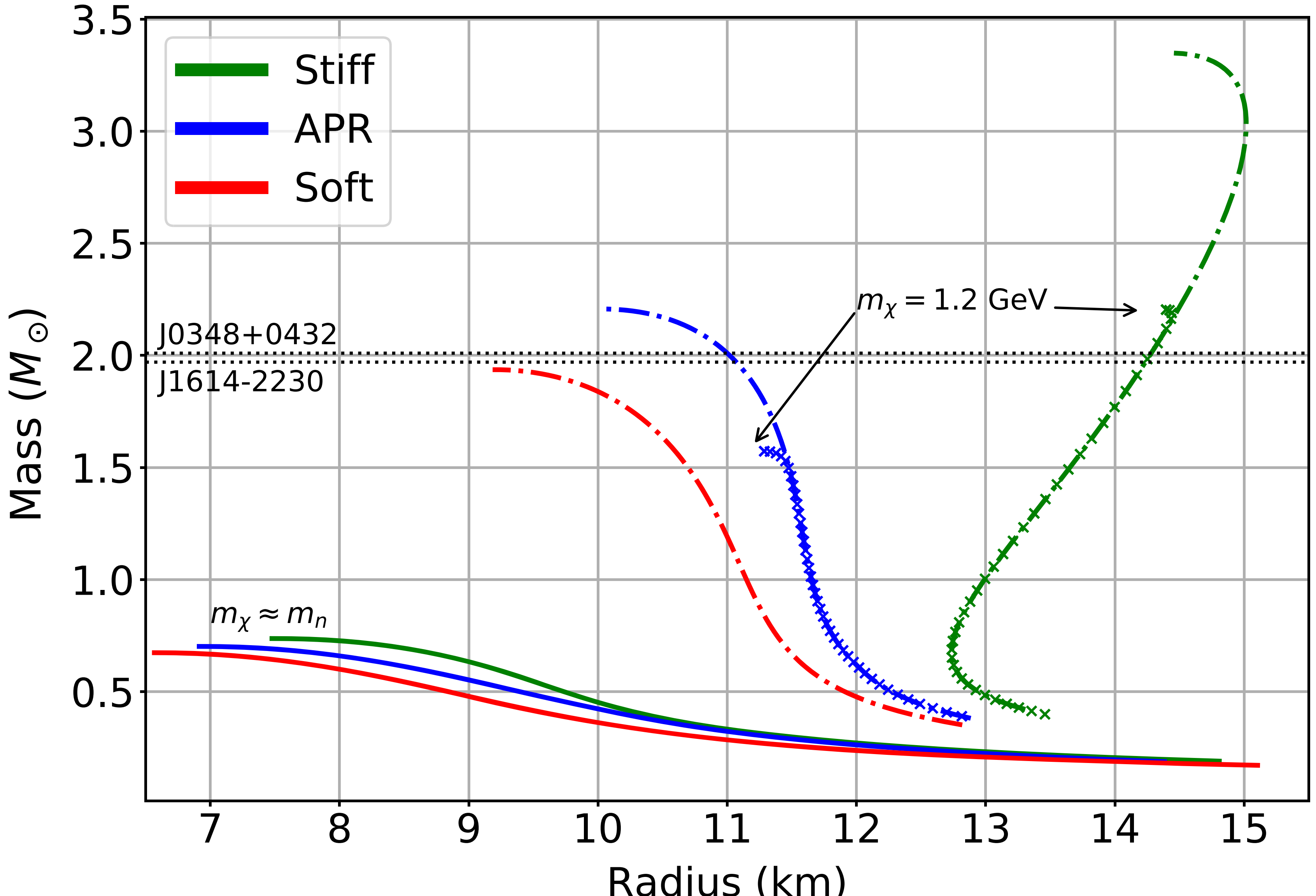


Phys. Rev. Lett. **122**, 222503

Decay mode : $n \to \chi\phi$

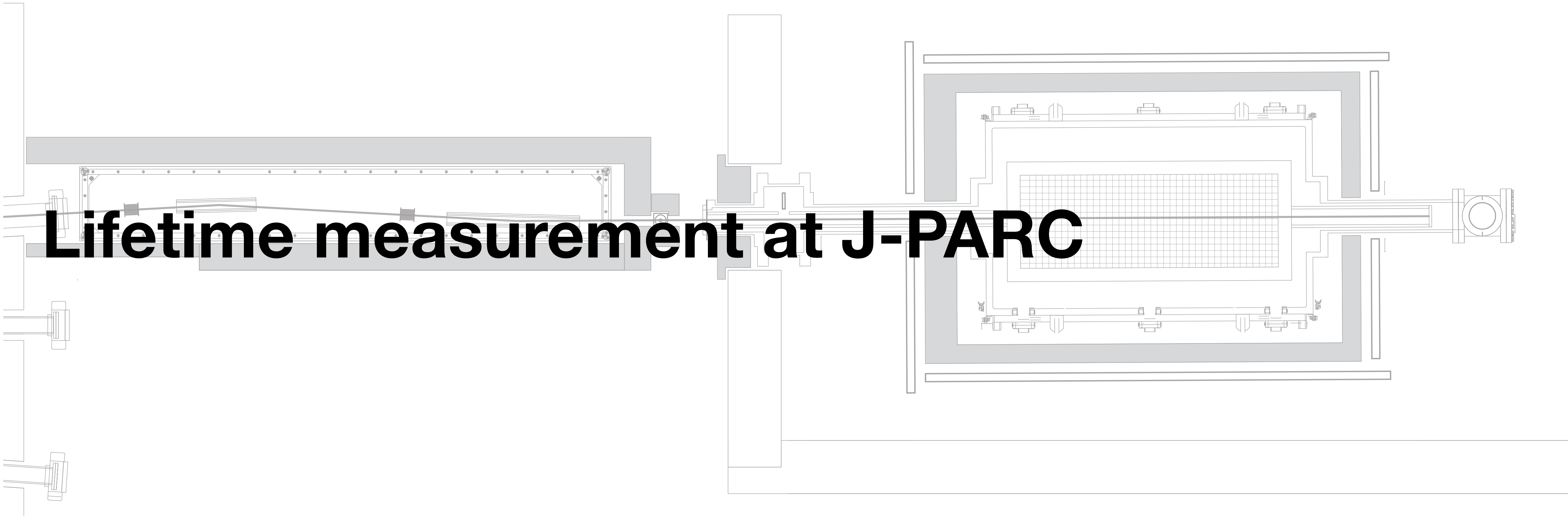
- Neutron star gives a constraint on characteristics of χ.
  - Suppose $m_\chi \sim m_n$, neutron star whose mass is over 0.7M⊙ cannot be exist.
  - Actually 2M⊙ neutron stars are observed and they require $m_\chi = 1.2$ GeV.
  - χ must have repulsive self-interactions.

APR : calculated by Akmal, Pandharipande, and Ravenhal
Stiff & Soft : uncertainties associated with the nuclear interactions



Phys. Rev. Lett. **121**, 061802

Lifetime measurement at J-PARC

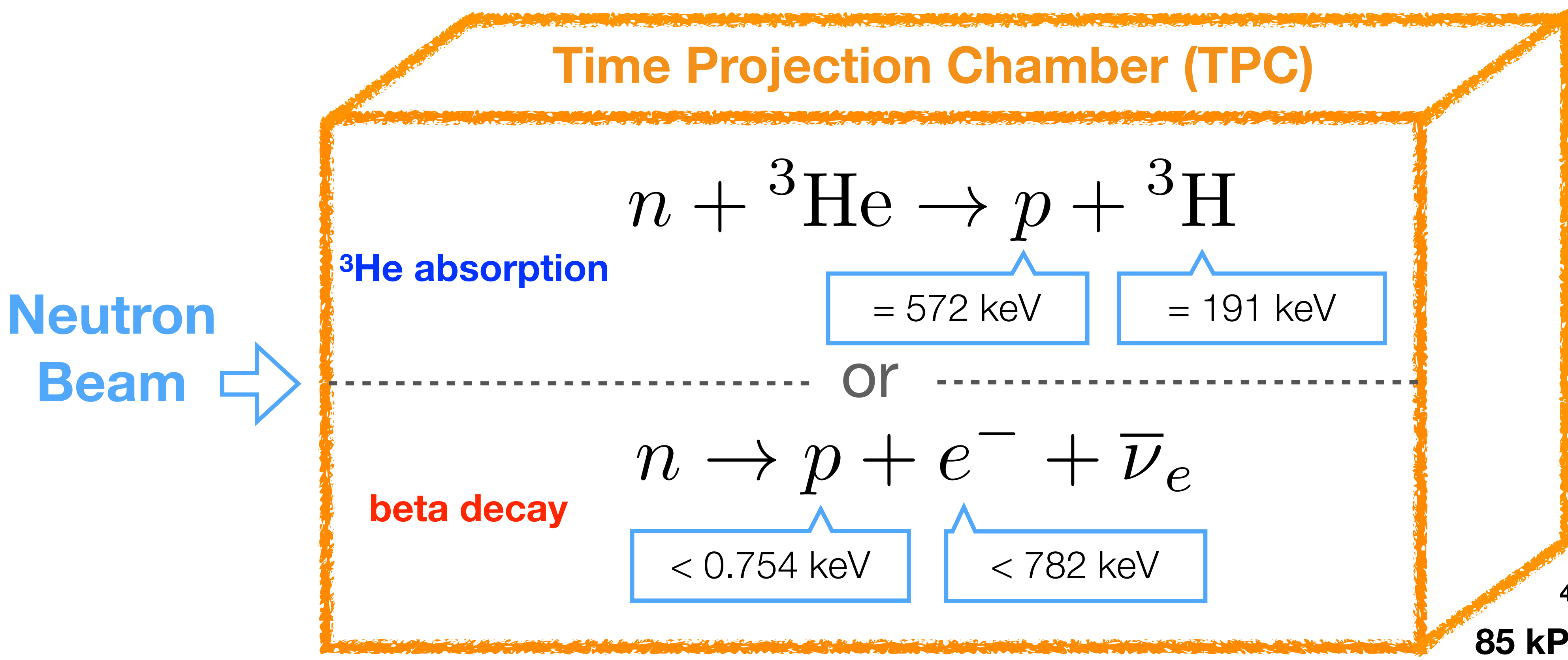


Measurement principle

- Neutron lifetime is calculated from the number of **beta decay** and **^{3}He absorption**.
  - This is an in situ detection system of the neutron decay and flux.

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

τ_n	Neutron Lifetime		
ρ	^{3}He density	S_β	Number of beta decay signal
σ	^{3}He neutron absorption cross section	S_{He}	Number of ^{3}He absorption signal
v	Neutron velocity	ε	Cut efficiency



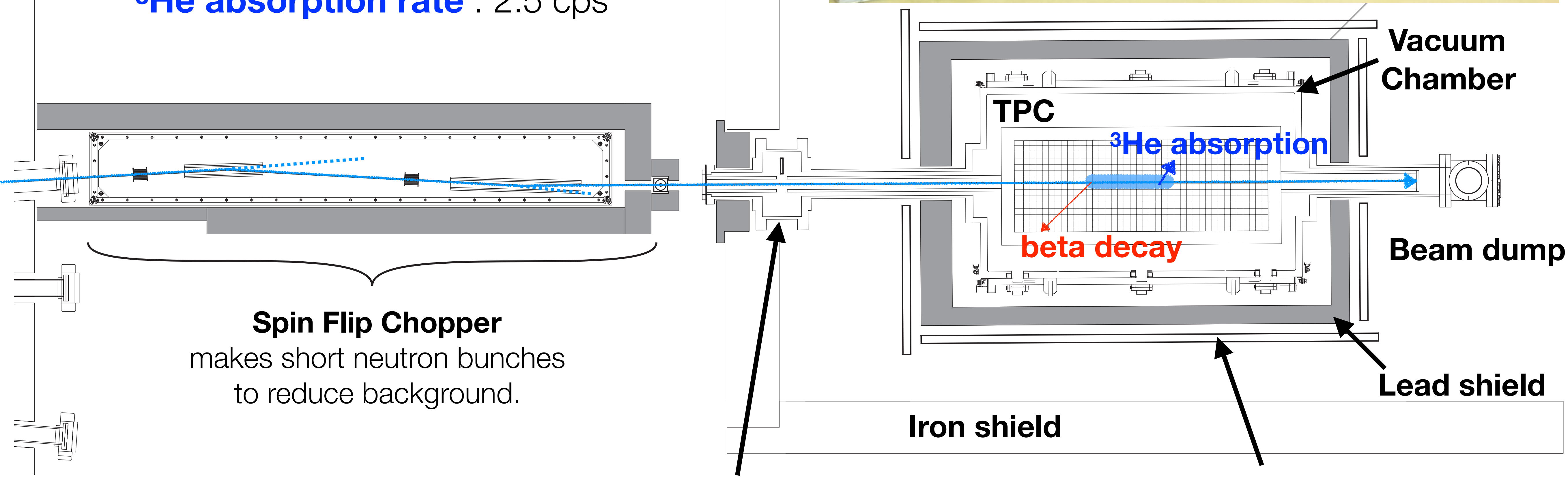
TPC Gas
^{4}He:CO_2:^{3}He =
85 kPa:15 kPa: 100 mPa

J-PARC MLF BL05

Neutron is produced
by injecting proton beam
to mercury target.

Beam line property

Neutron energy : ~10 meV
Neutron velocity : ~1000 m/s
beta decay rate : 0.1 cps
^{3}He absorption rate : 2.5 cps



^{6}LiF shutter
is a 5 mm thick ^{6}LiF plate
to control neutron beam.

Cosmic veto counters
is plastic scintillators
to identify cosmic ray.

Acquired data

- We acquired 6 measurement series.
  - One measurement is corresponding to one gas set (~ one week).
  - In this talk, the datasets (until 2016) were used for analysis.
  - Total beam time was 282 hours.

Gas	Date	MLF power [kW]	Beam time [hour]
I	May 2014	300	35.3
II	April 2015	500	15.8
III	April 2016	200	17.5
IV	April 2016	200	72.7
V	May 2016	200	69.4
VI	June 2016	200	71.1

Analysis

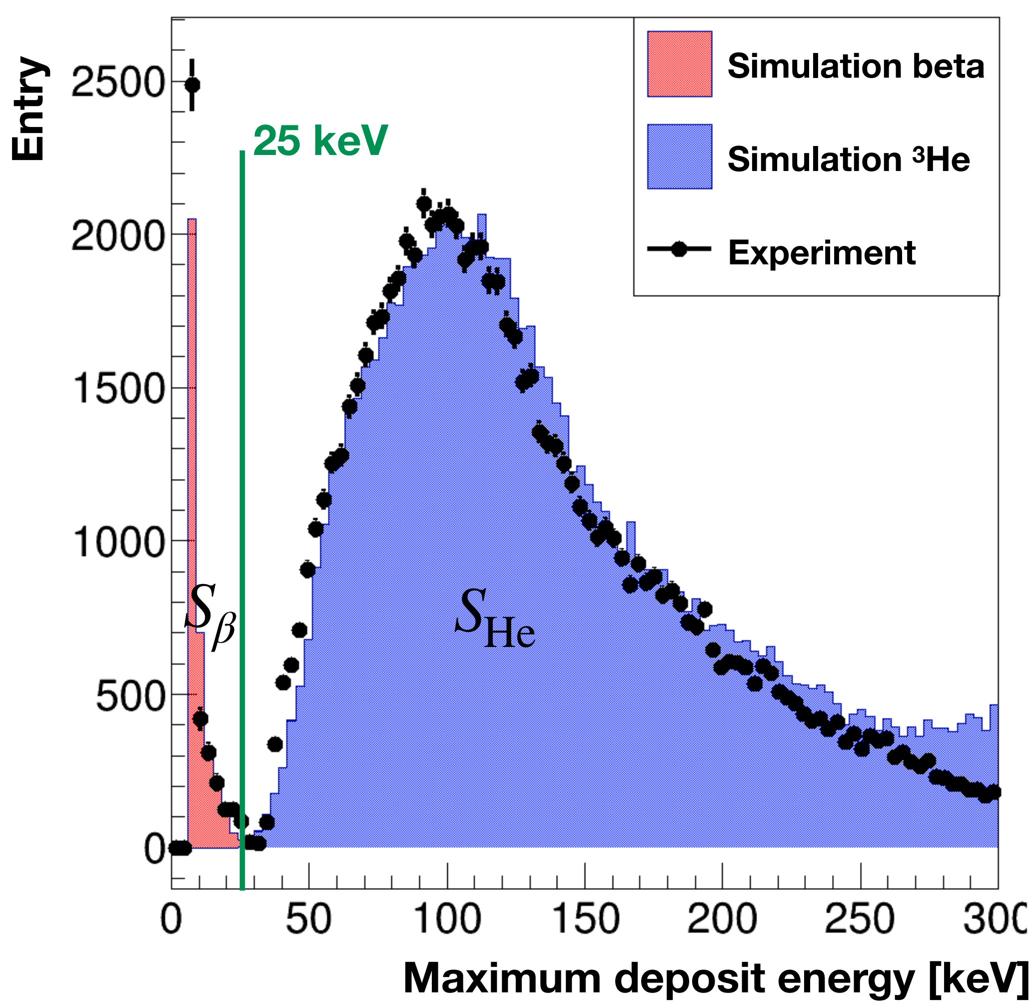
- We counted the number of S_β, S_{He} using
  - time of flight
  - energy deposit
  - track geometry.

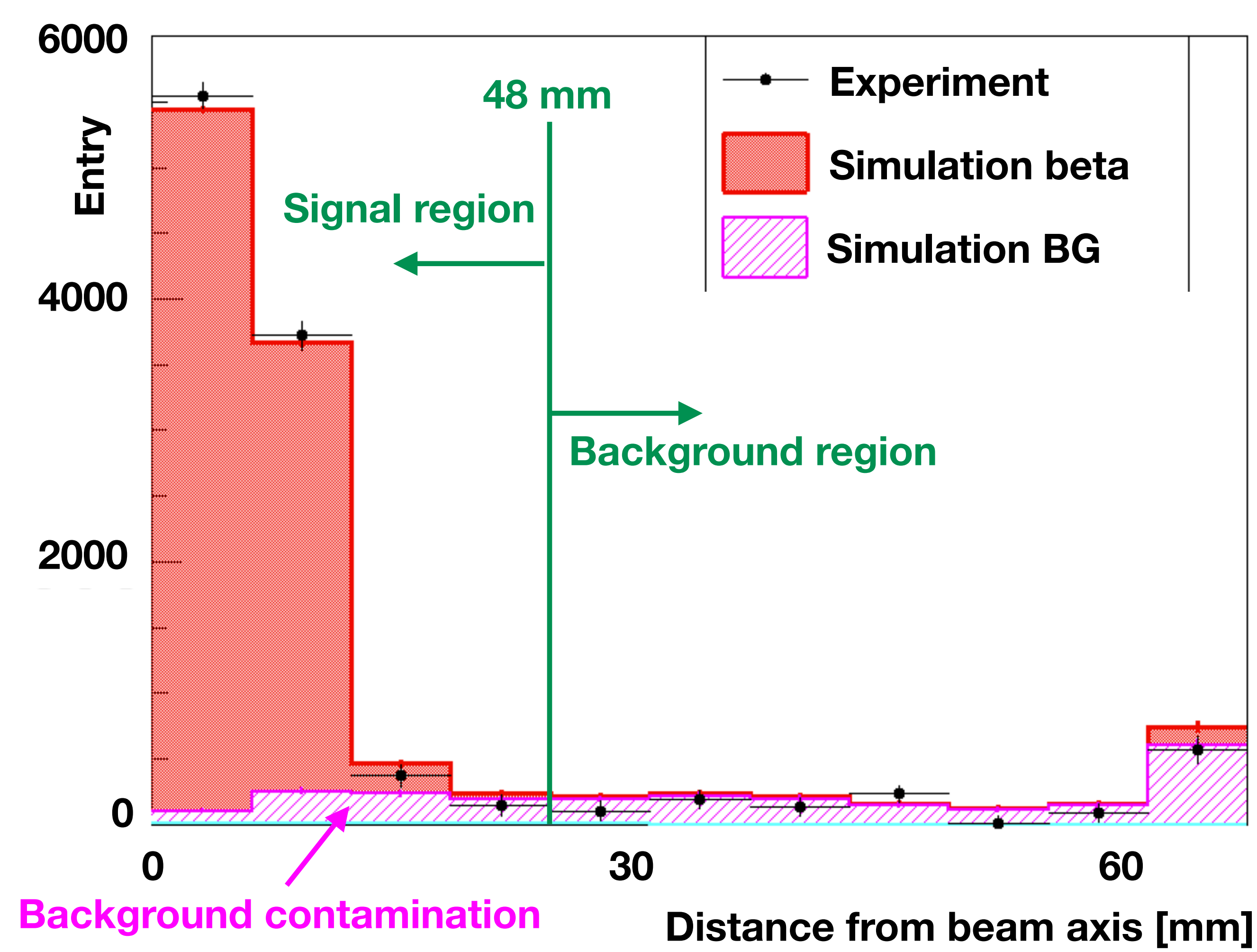
↓ Data analysis

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

Injected ^{3}He ↑ ↑Literature value 5333 ± 7 barn 2200 m/s ↑ Simulation analysis

- Cut efficiencies ε_β, $\varepsilon_{\mathrm{He}}$ were calculated by simulation.
- Background contamination for S_β was estimated by simulation.
  - The scattering neutrons produce this irremovable background.

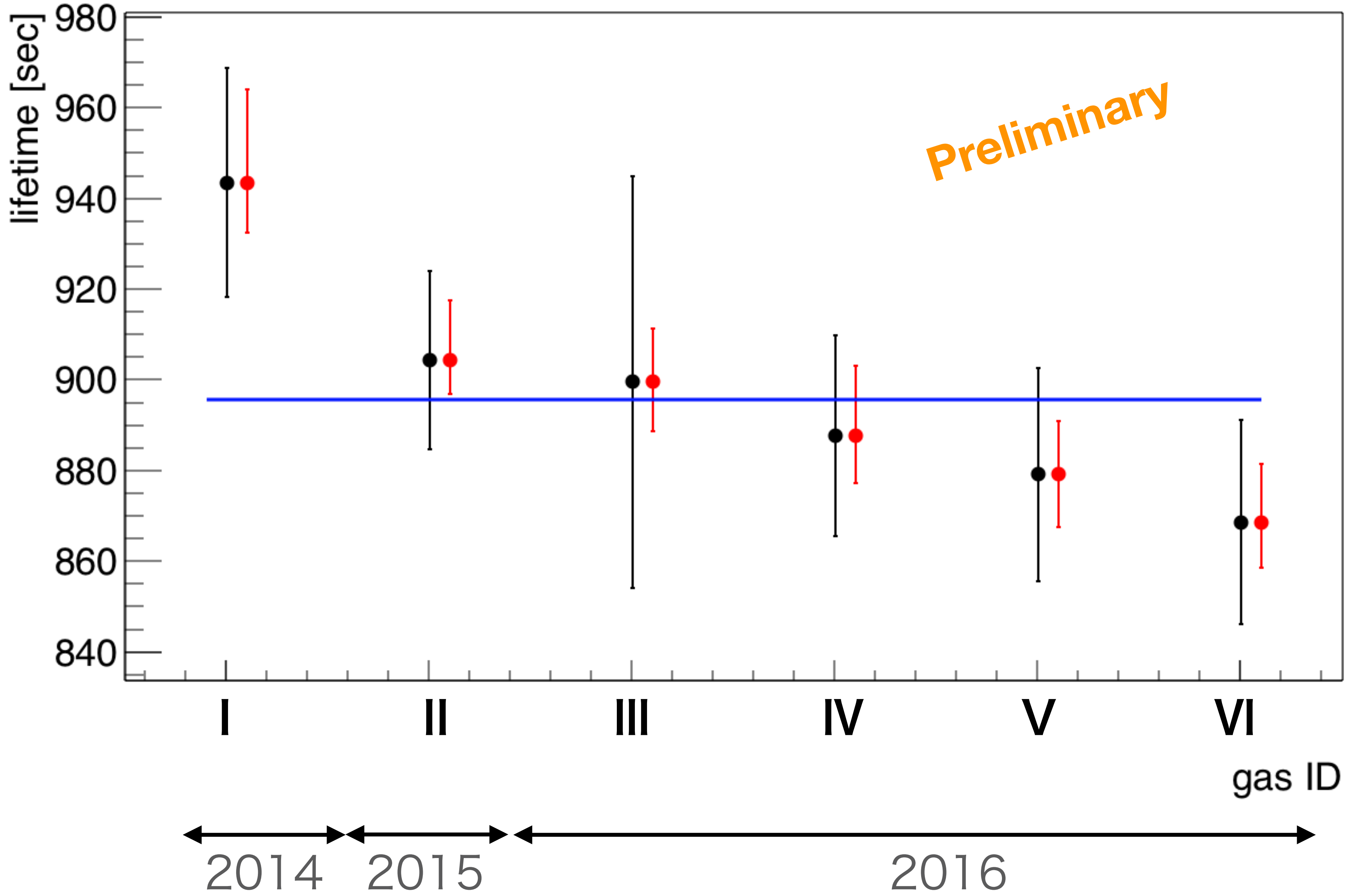




Results

- The neutron lifetime was calculated for each measurement.
- The combined results from 2014 to 2016 is

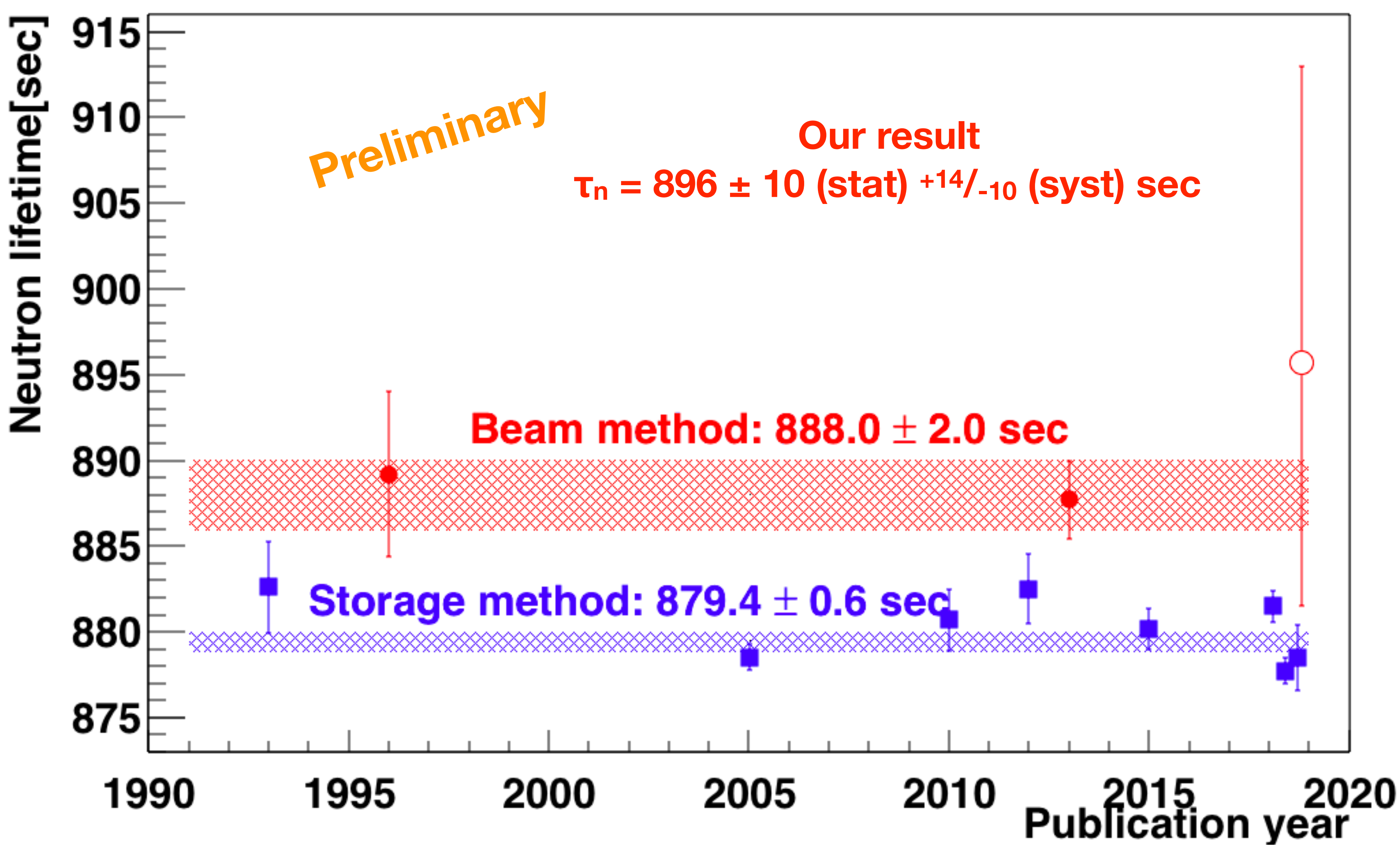
$$\tau_n = 896 \pm 10\ (\text{stat})\ {}^{+14}_{-10}\ (\text{syst})\ \text{sec}$$



Results

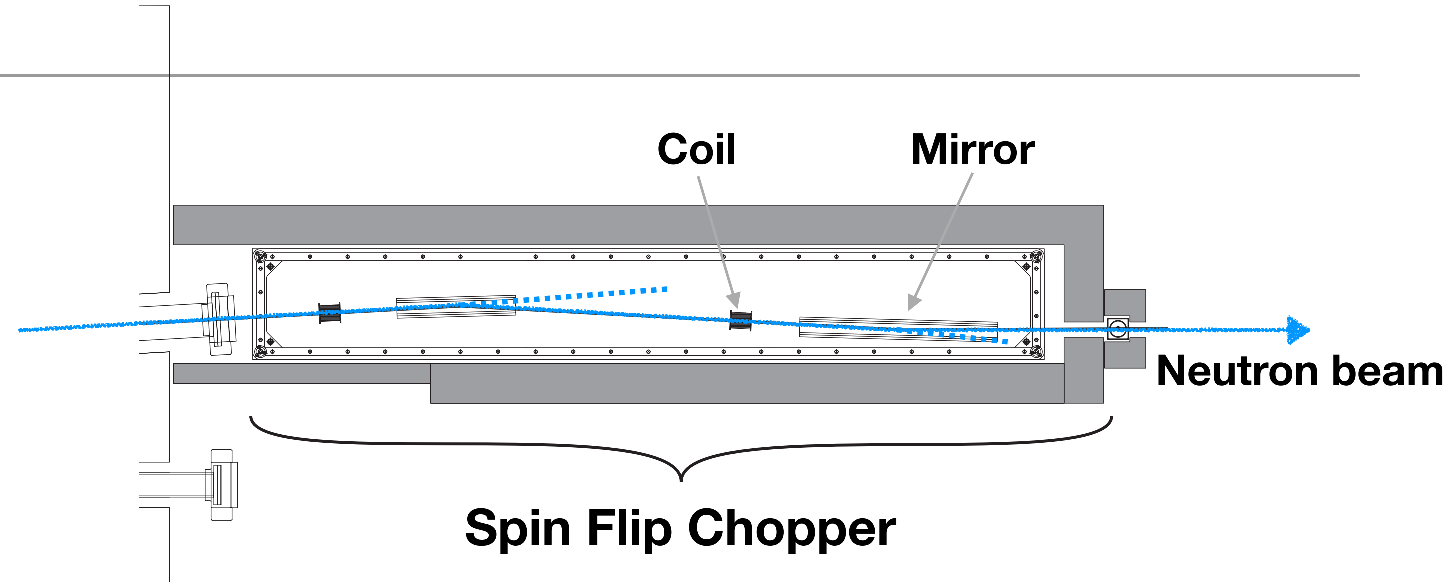
- Out result is plotted on the neutron lifetime history.
  - It is consistent with the other beam method and 1.0σ away from the storage method.

- Upgrade projects are ongoing to achieve our goal precision of 0.1% (1 sec).

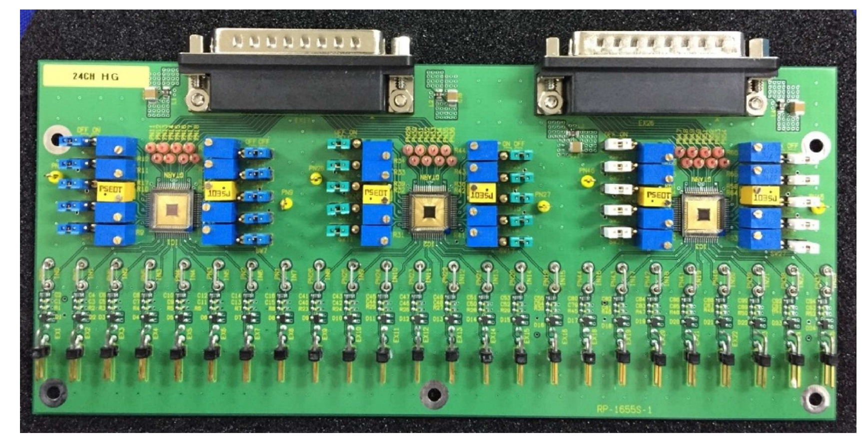


Upgrade plans

- Neutron beam upgrade
  - Neutron bunching machine (SFC) coil and mirror will be enlarged to transport more neutron beam.
  - Five times beam will be available. And **100 days** measurement achieves 0.1% (1 sec) accuracy.

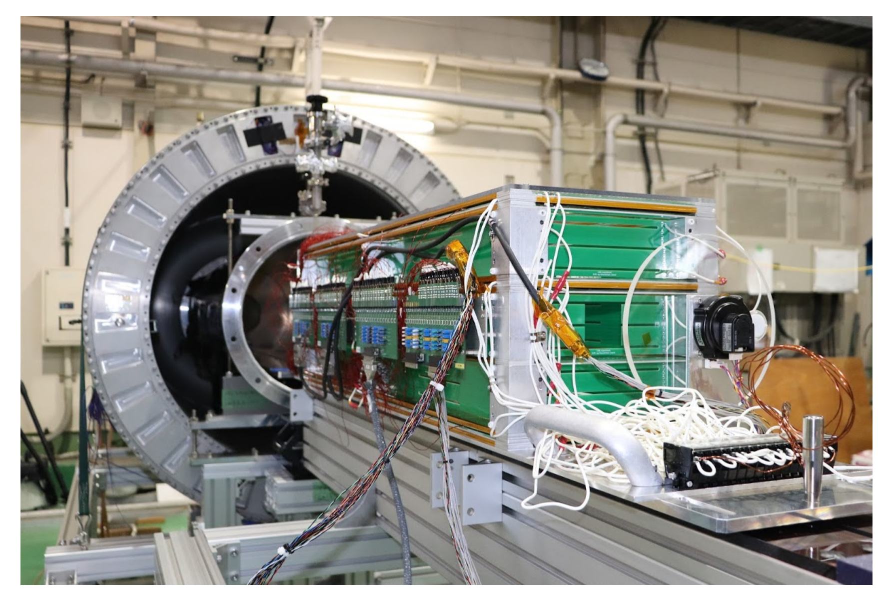


- Low gas pressure operation
  - Lower scattering neutron in the TPC gas leads lower backgrounds **(×1/2-1/10)**.
  - New ASIC amplifier was developed for lower power consumption **(×1/50)** and higher gain **(×1-10)** compared to current amp.



New ASIC amp

- Solenoidal magnet background suppression
  - Background electron coming from detector walls will be suppressed by magnetic field **(×1/20)**.
  - The detector commissioning was completed. We will have a beam test on the next month.



Magnet and detector

Summary

- Neutron lifetime is an important parameter for BBN and CKM matrix, however there is **8.6 s (4.0σ)** deviation between two methods of measurement.
- The discrepancy may be explained by unobserved neutron dark decay modes.
  - Some of them were already eliminated.
- We are measuring the neutron lifetime at J-PARC MLF BL05.
  - The acquired data (2014-2016) were analysed.
- Our result is

$$\tau_n = 896 \pm 10\ (\mathrm{stat})\ {}^{+14}_{-10}\ (\mathrm{syst})\ \mathrm{sec}$$

- Upgrade plans are ongoing
  - Beam optics upgrade makes beam intensity by 5 times
  - Low gas pressure operation suppress the background
  - Magnetic field suppress the background