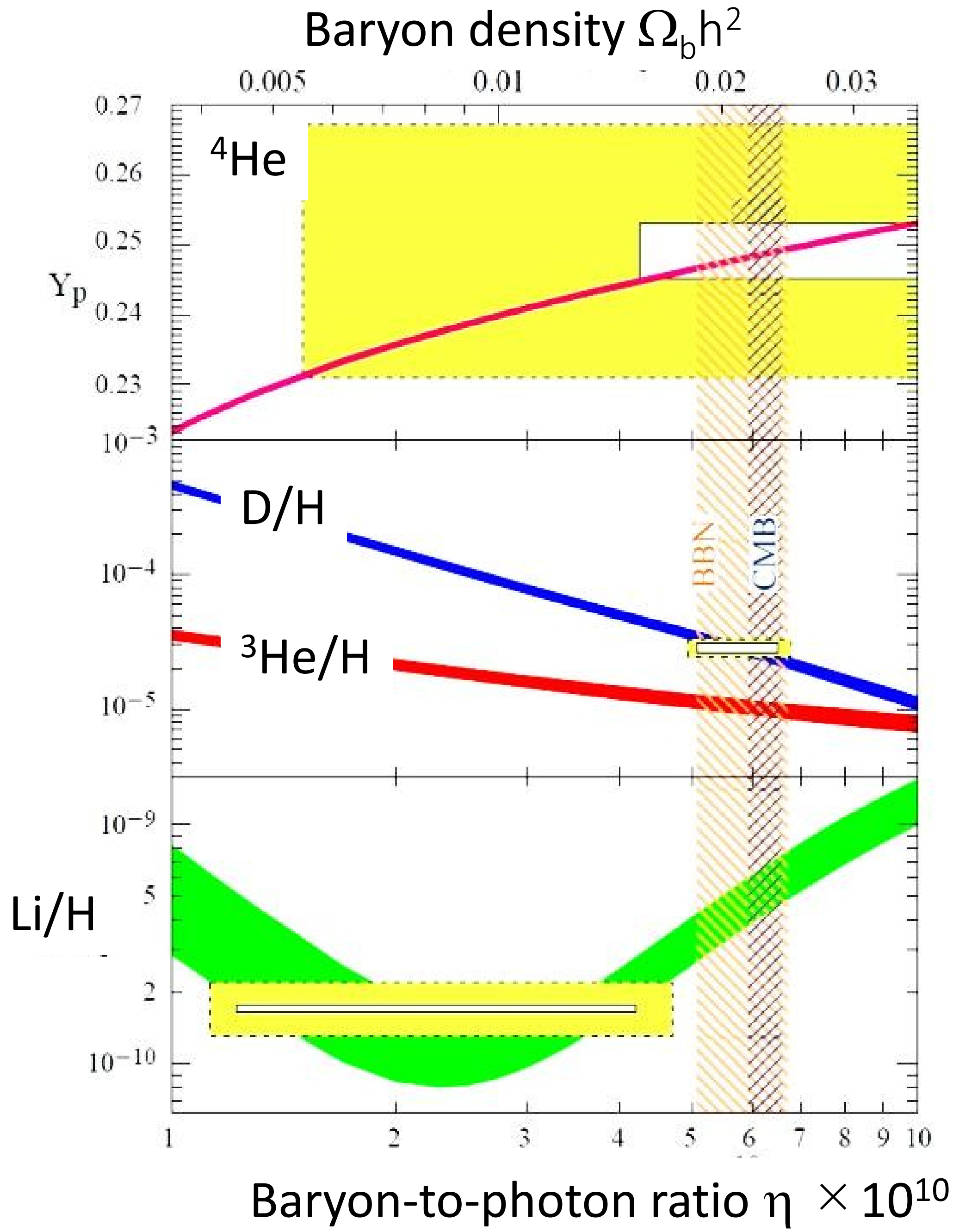
May 16th, 2019, RCNP

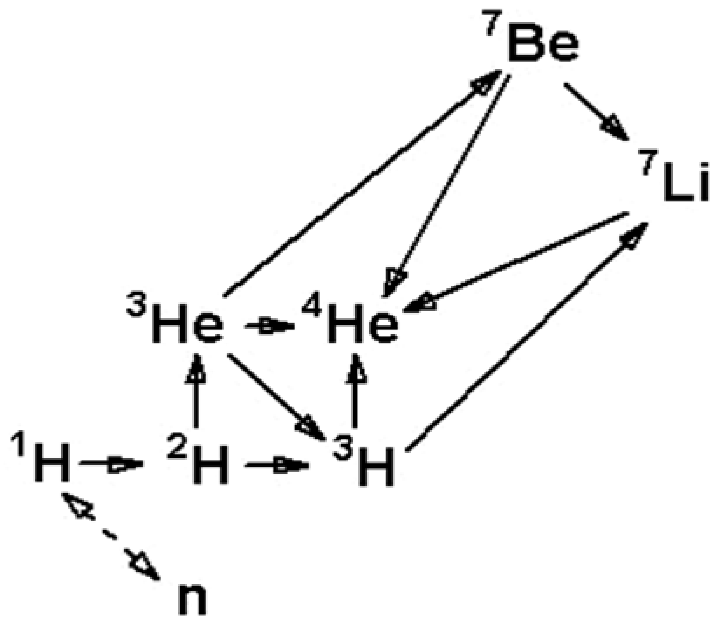
Neutron lifetime anomaly and symmetries

Tatsushi Shima

Research Center for Nuclear Physics, Osaka University, Japan

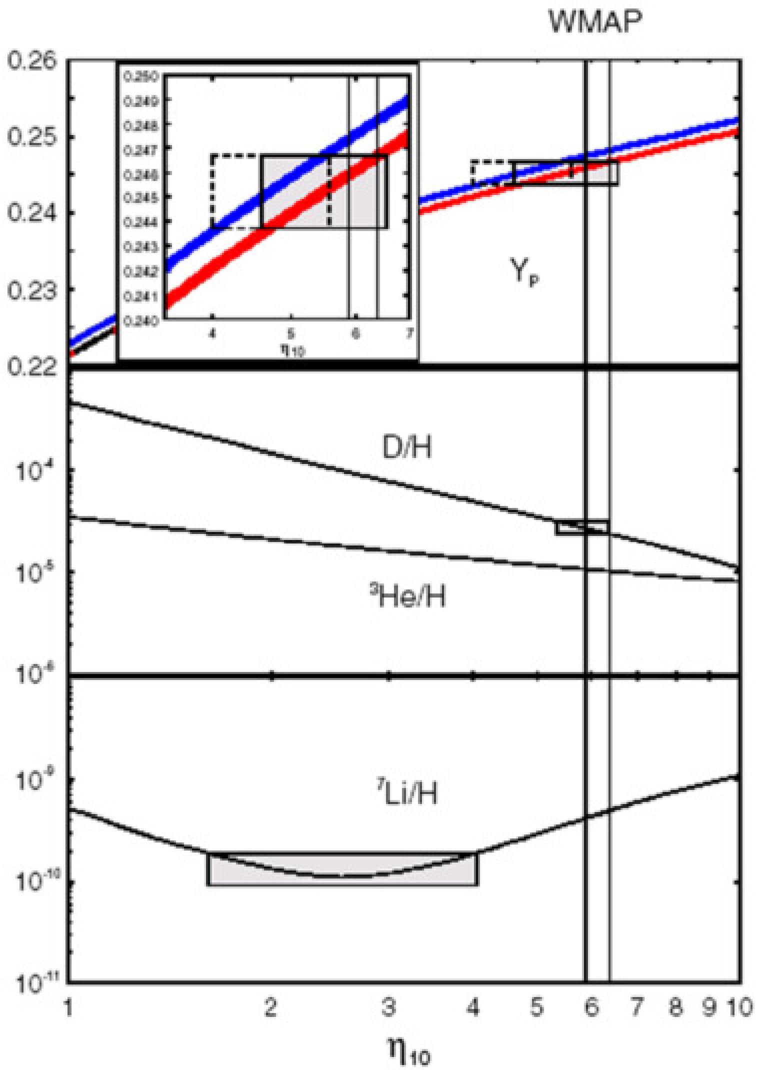
1. Neutron lifetime & Big-bang nucleosynthesis





R.H. Cyburt et al.,
JCAP 0811, 012 (2008)

SBBN vs. Abundance data vs. WMAP



$\tau_n = 885.7 \pm 0.8$ s (PDG2004)

$\tau_n = 878.5 \pm 0.7 \pm 0.3$ s (PNPI-ILL)

$\tau_n \downarrow \rightarrow g_A \uparrow \rightarrow n/p \downarrow \rightarrow {}^4He/{}^1H \downarrow$

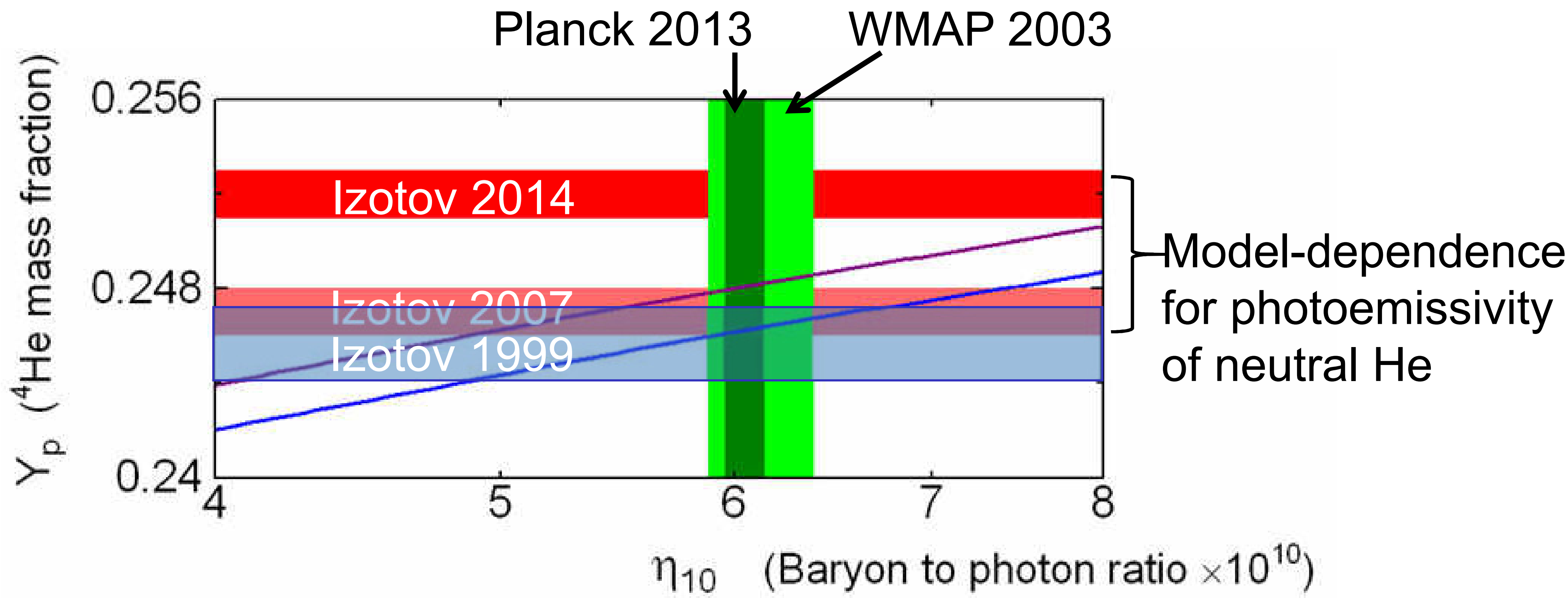
$\Delta[{}^4He/H]({}^3He(d,p){}^4He{:}4\%)=0.0022$

$\Delta[{}^4He/H](obs.)=0.003$

$\Delta[{}^4He/H](\tau_n{:}0.8\%)=0.0017$

G.J. Mathews, T. Kajino, T. S.
PRD71 (2005) 021302

^{4}He Mass Fraction and Neutron Lifetime

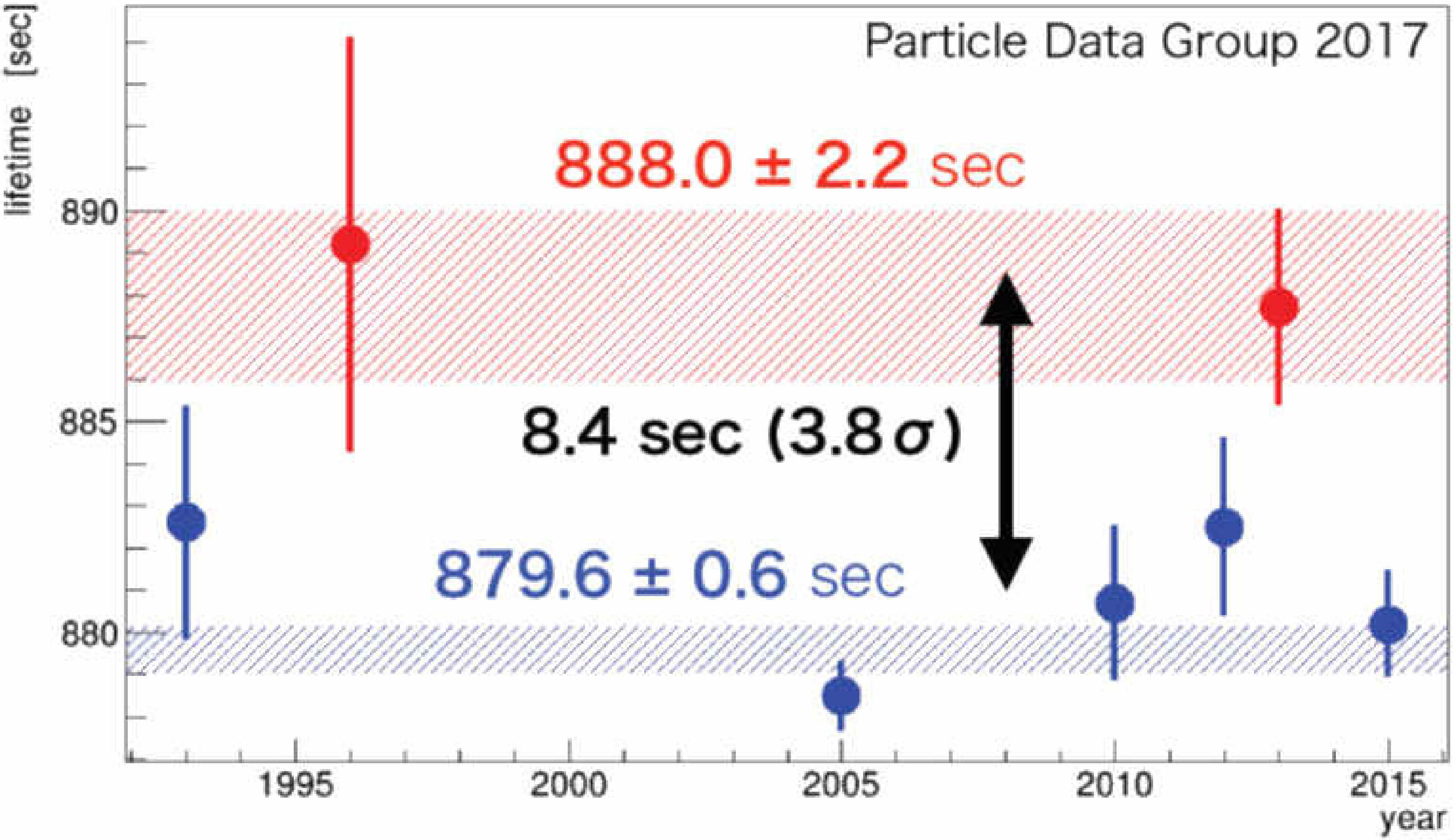


τ_n = 887.7 ± 1.2(stat) ± 1.9(sys) s (NIST, 2013)

τ_n = 878.5 ± 0.7(stat) ± 0.3(sys) s (PNPI, 2008)

Precise data of τ_n is indispensable for stringent test of BBN models !!

Current status of experimental data of neutron lifetime τ_n



Decay rate in flight

Survival rate in storage

Unitarity test of CKM matrix

$|V_{us}| = 0.2255(19)$ (decays of K, Y, tau)

$|V_{ub}| \sim 10^{-5}$

$V_{ud} = 0.97418(27)$ $(0^+ \rightarrow 0^+)$

$0.9746(22)$ (τ_n , PDG2008)

$0.9786(22)$ (τ_n , Serebrov 2005)

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(14)$ $(0^+ \rightarrow 0^+)$

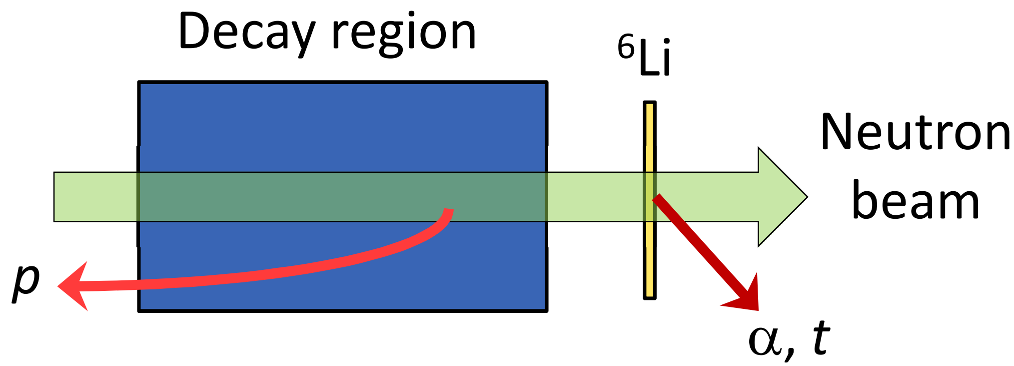
$1.0007(44)$ (τ_n , PDG2008)

$1.0085(44)$ (τ_n , Serebrov 2005)

Experimental method

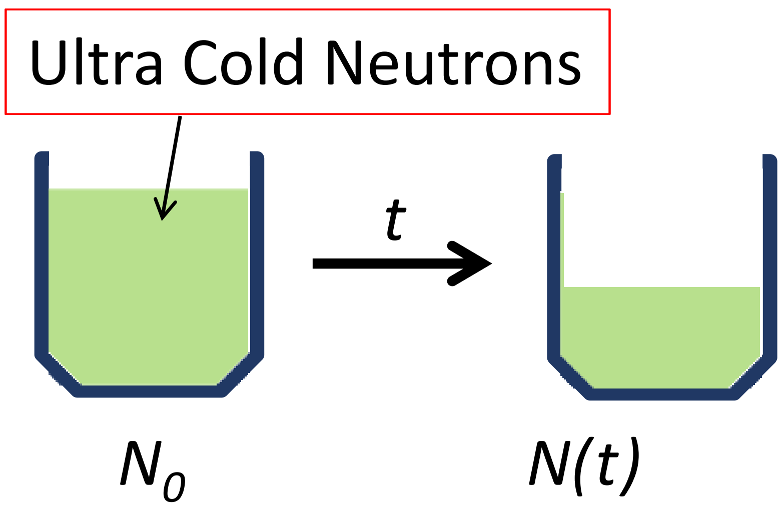
(A) Decay-rate measurement (Sussex-ILL-NIST)

$$R = \frac{dN}{dt} = \frac{N}{\tau_n}$$

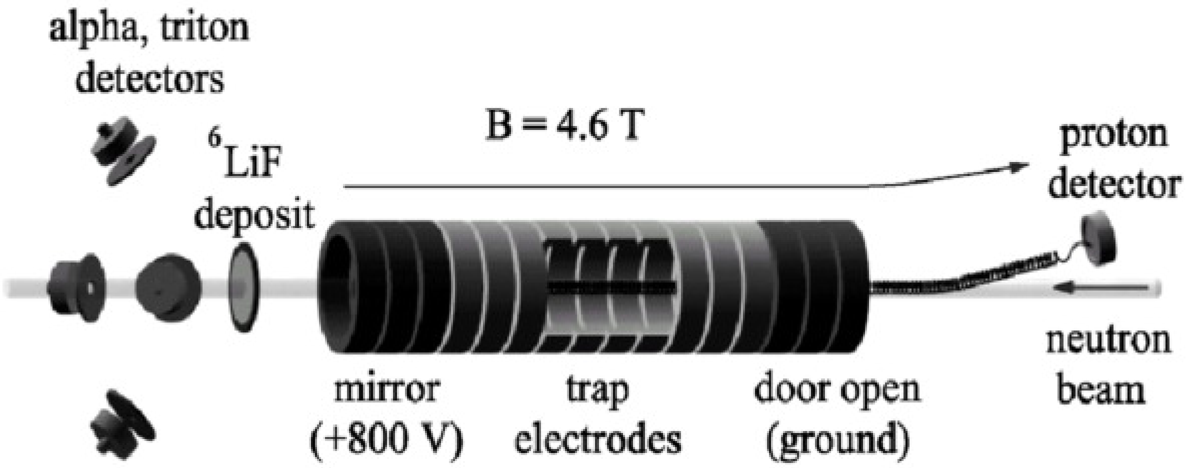


(B) Survival-prob. measurement (PNPI-ILL-JINR)

$$N(t) = N_0 \exp\left(-t/\tau_n\right)$$



NIST experiment J.S.Nico et al., PRC71, 055502 (2005)



$$N_n = L\int_A \frac{\Phi_n(v)}{v}\,da$$

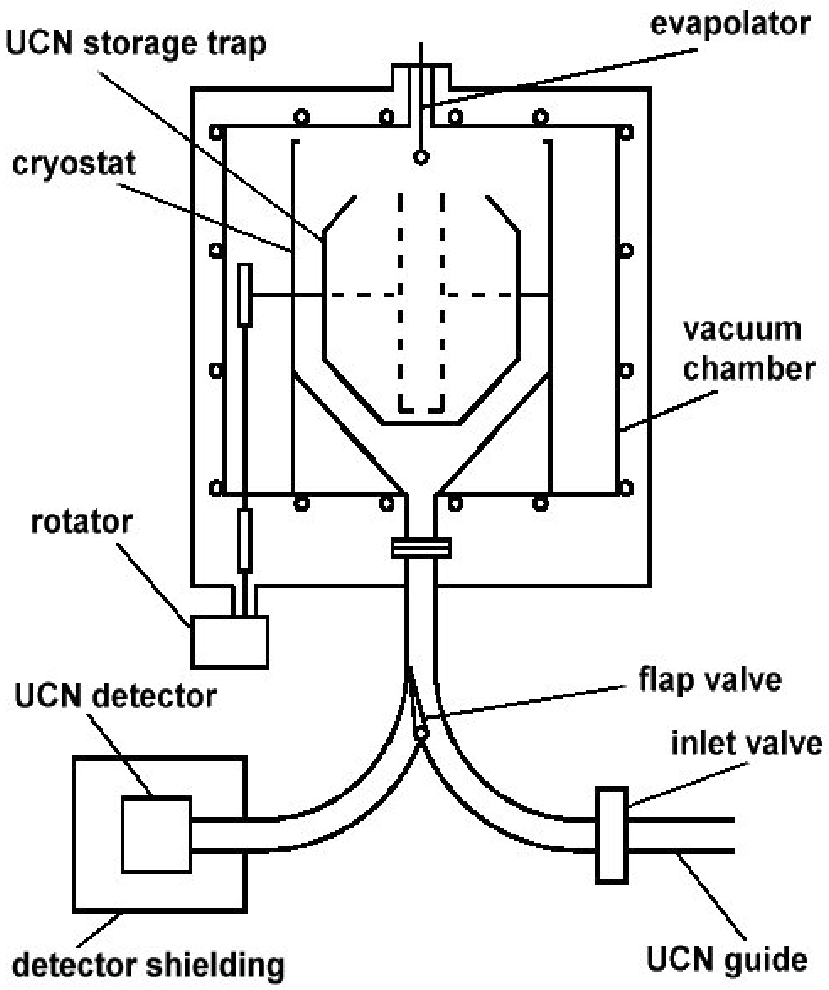
$$R_p = \dot{N}_p = \frac{\varepsilon_p L}{\tau_n}\int_A \frac{\Phi_n(v)}{v}\,da$$

$$R_\alpha = \dot{N}_\alpha = \varepsilon_{th} v_{th}\left[\sigma_{th}(n,\alpha)\right] N_{6Li}\int_A \frac{\Phi_n(v)}{v}\,da$$

$$\Rightarrow \frac{R_p}{R_\alpha} = \tau_n^{-1}\left(\frac{\varepsilon_p \sigma_{th} N_{6Li}}{\varepsilon_{th} v_{th}}\right) L$$

PNPI-ILL experiment

A.P.Serebrov et al., PRC78, 035505 (2008)

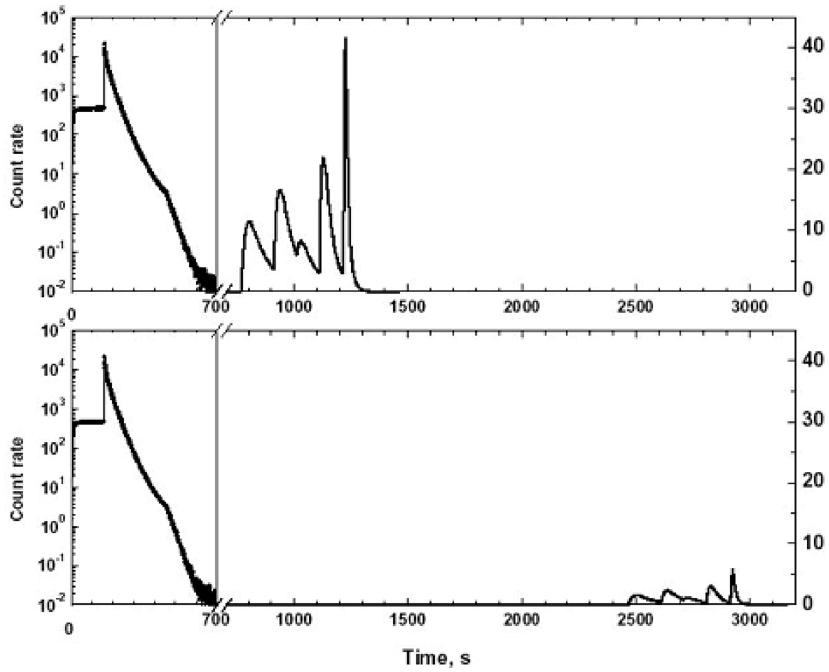


- Fomblin (no-H oil) coating

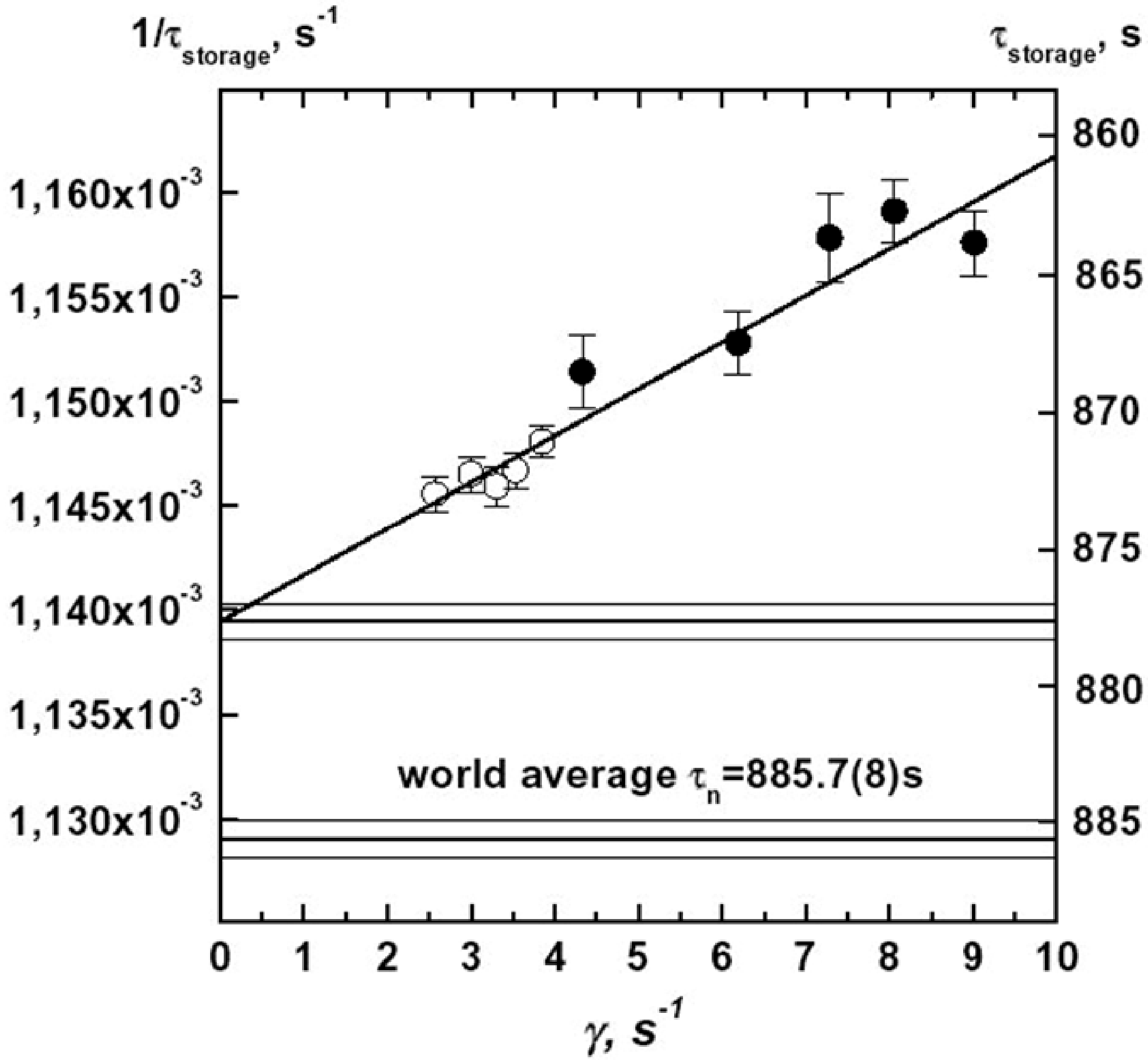
→ UCN loss; 2×10^{-6} /collision

- rotatable bottle

→ gravitational spectrometer

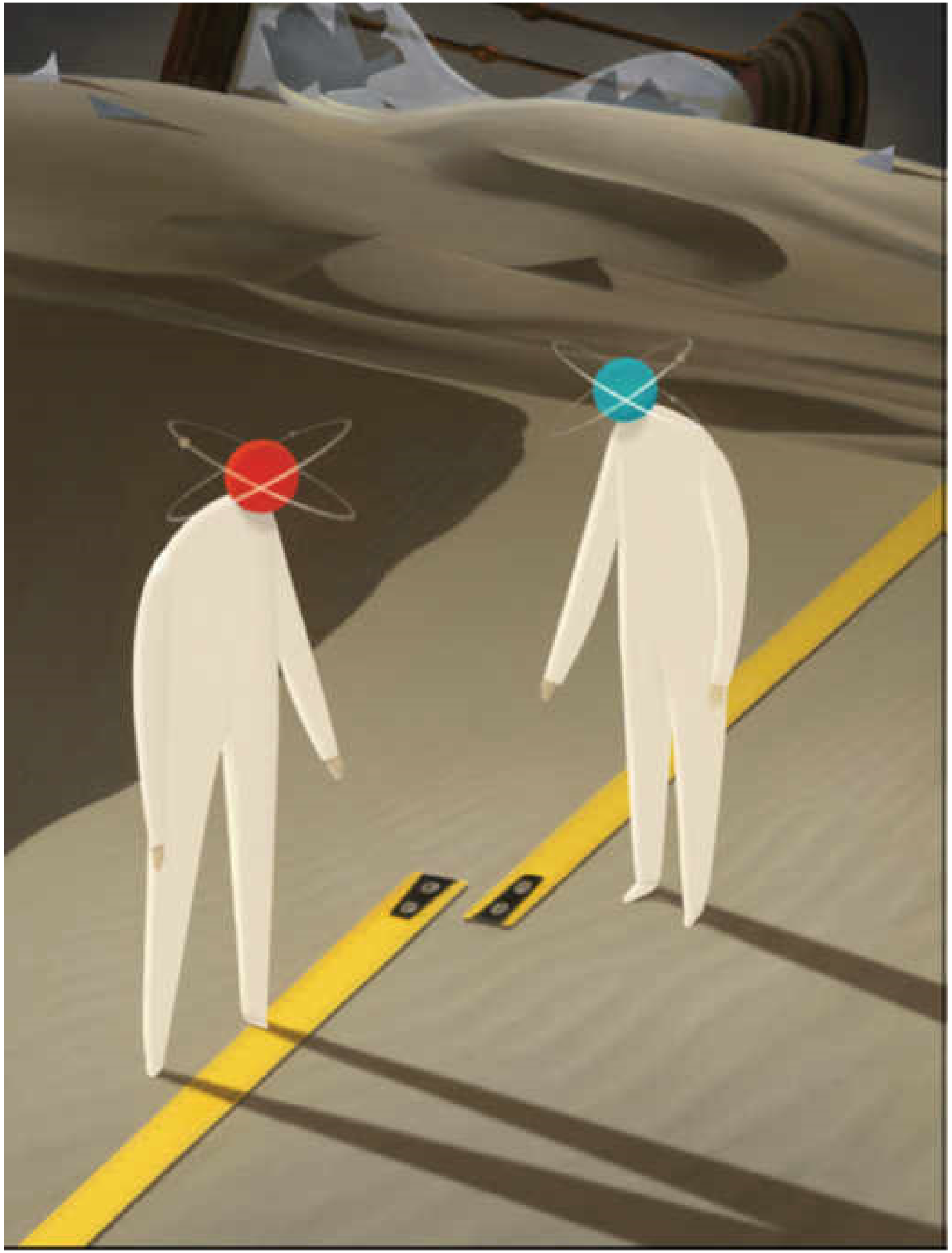


Result



τ_n = **878.5 ± 0.7** [stat] **± 0.3** [sys] **(sec)**

G.L. Greene & P. Geltenbort, Scientific American, April 2016



PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort

IN BRIEF

The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

- - - Is it an evidence of a new physics?

Neutron decay to dark sector with branching ratio of 1%

$n \rightarrow$ Dark Matter + γ

$n \rightarrow$ Dark Matter + Dark Matter’

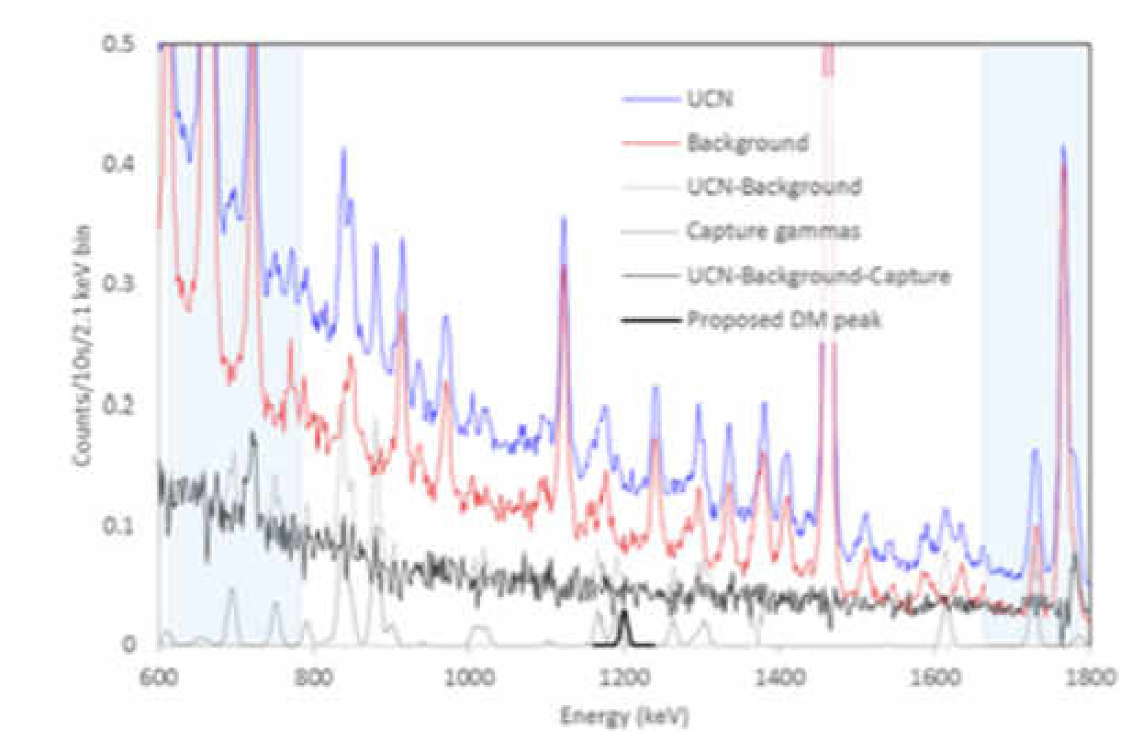
$n \rightarrow$ Dark Matter + e^+e^-

B. Fornal and B. Grinstein, PRL120, 191801 (2018)

n → Dark Matter + γ

Constraints from Q-values of n and ^{9}Be
→ 0.782 MeV < E_γ < 1.664 MeV

Z. Tang et al., PRL121, 022505 (2018)



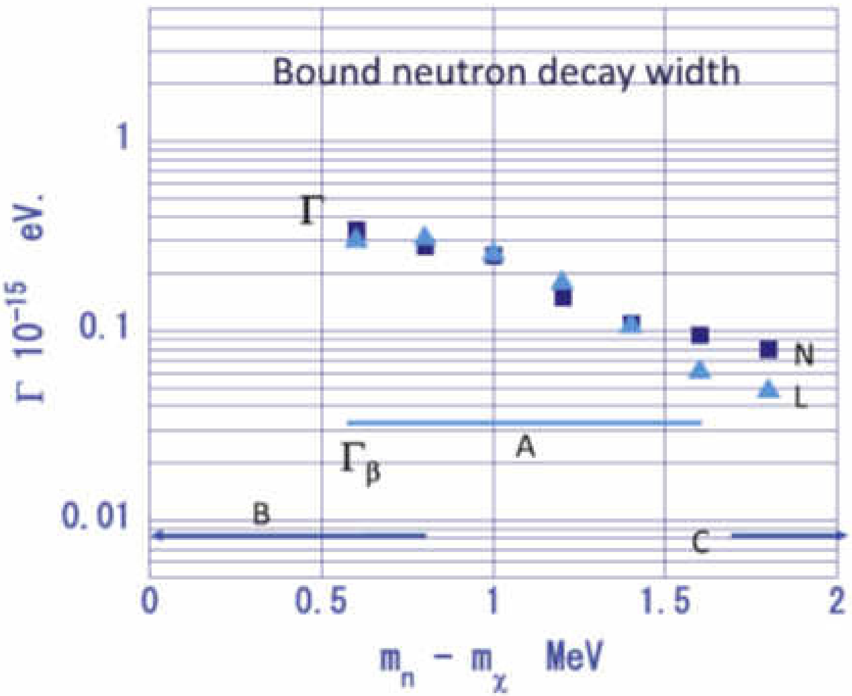
No signal

IOP Publishing   Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 46 (2019) 025104 (15pp)   https://doi.org/10.1088/1361-6471/aaf55b

Neutron disappearance inside the nucleus

H Ejiri[1] and J D Vergados[2]

[1] RCNP, Osaka University, Osaka, 567-0047, Japan
[2] University of Ioannina, Ioannina, Gr 451 10, Greece

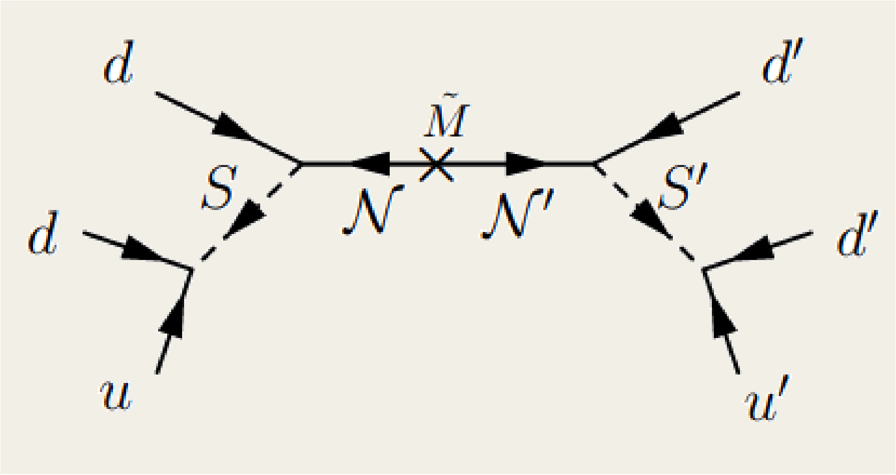


Constraint from ^{11}Be decay width

Neutron-Mirror Neutron Oscillation

Anti-neutron $\bar{n}$ $\psi_{\bar{n}} = CP\psi_n$

Mirror-neutron n' $\psi_{n'} = P\psi_n$



$$\left(SU(3)\times SU(2)\times U(1)\right)\times\left(SU(3)'\times SU(2)'\times U(1)'\right)$$

$$H_{nn'} = \begin{pmatrix} \Delta m - \mu_n B & 0 & 2\varepsilon & 0 \\ 0 & \Delta m + \mu_n B & 0 & 2\varepsilon \\ 2\varepsilon & 0 & -\Delta m & 0 \\ 0 & 2\varepsilon & 0 & -\Delta m \end{pmatrix}$$

* Mirror **B** is omitted.

$$P_{n\to n'}(t) = \frac{1}{2}\sin^2 2\theta_B^{\pm} \quad \text{, where} \quad \tan 2\theta_B^{\pm} = \frac{2\varepsilon}{\Delta m \mp \mu_n B}$$

$$\Rightarrow \quad P_{n\to n'} \to 1 \text{, if } \mu_n B \approx \pm\Delta m$$

Cf. MSW effect

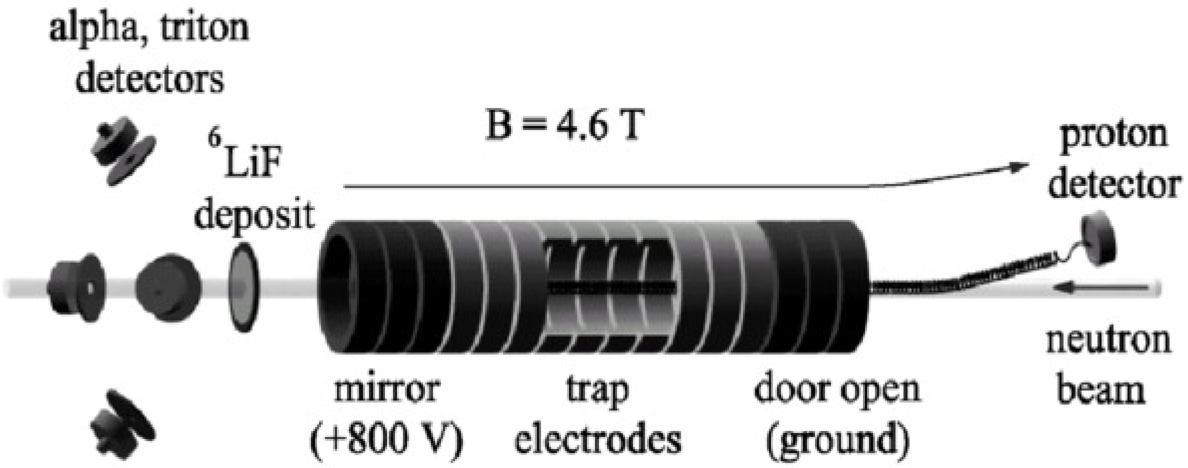
In case of NIST experiment,

$$B = 4.6\ [\mathrm{T}] \ \rightarrow\ \mu_n B = 2.77\times 10^{-7}\ [\mathrm{eV}]$$

$$P_{nn'} = \frac{\Delta\tau_n}{\tau_n} \simeq 0.01 \ \rightarrow\ \sin^2 2\theta_B^{\pm} \simeq 0.02 \ \rightarrow\ \tan 2\theta_B^{\pm} \simeq 0.144$$

$$\rightarrow\ \Delta m \sim \varepsilon \sim 3.6\times 10^{-6}\ [\mathrm{eV}] = 3.6\ [\mu\mathrm{eV}]$$

NIST experiment J.S.Nico et al., PRC71, 055502 (2005)



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$$R_p = \dot{N}_p = \frac{\varepsilon_p L}{\tau_n} \int_A \frac{\Phi_n(v)}{v} da$$

$$R_\alpha = \dot{N}_\alpha = \varepsilon_{th} v_{th} \left[\sigma_{th}(n,\alpha)\right] N_{6Li} \int_A \frac{\Phi_n(v)}{v} da$$

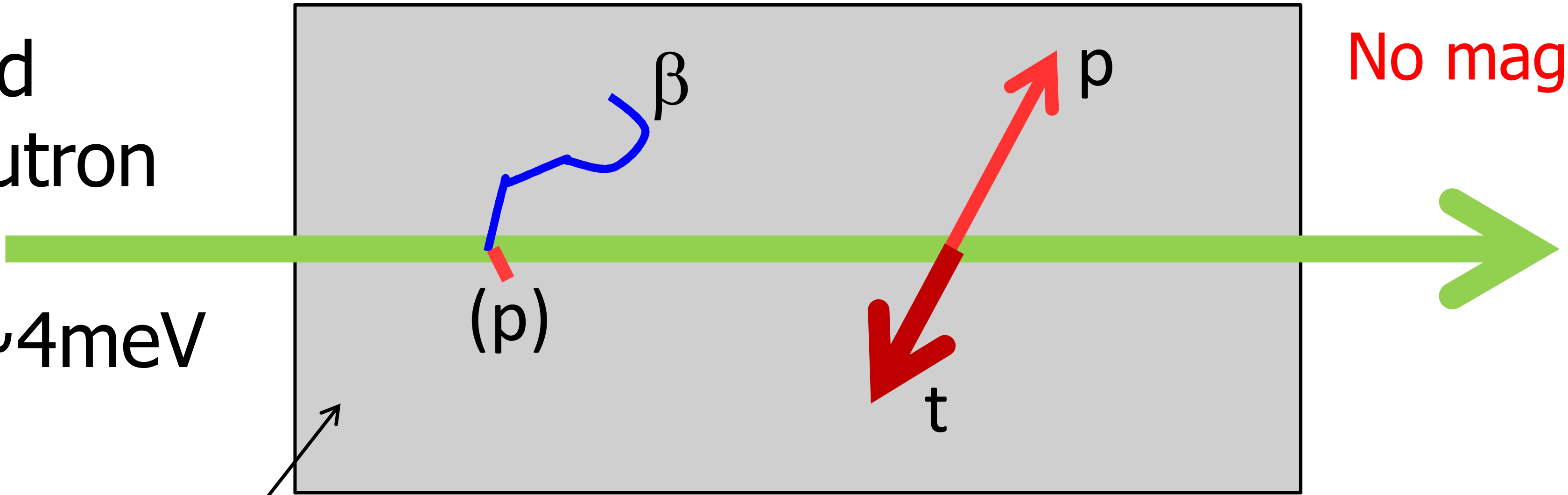
$$\Rightarrow \frac{R_p}{R_\alpha} = \tau_n^{-1} \left(\frac{\varepsilon_p \sigma_{th} N_{6Li}}{\varepsilon_{th} v_{th}} \right) L$$

Our method

--- simultaneous measurement of
neutron beta-decay and $^{3}He(n,p)^{3}H$ with
the same detector (**T**ime-**P**rojection **C**hamber)

Cold
Neutron

E_n~4meV



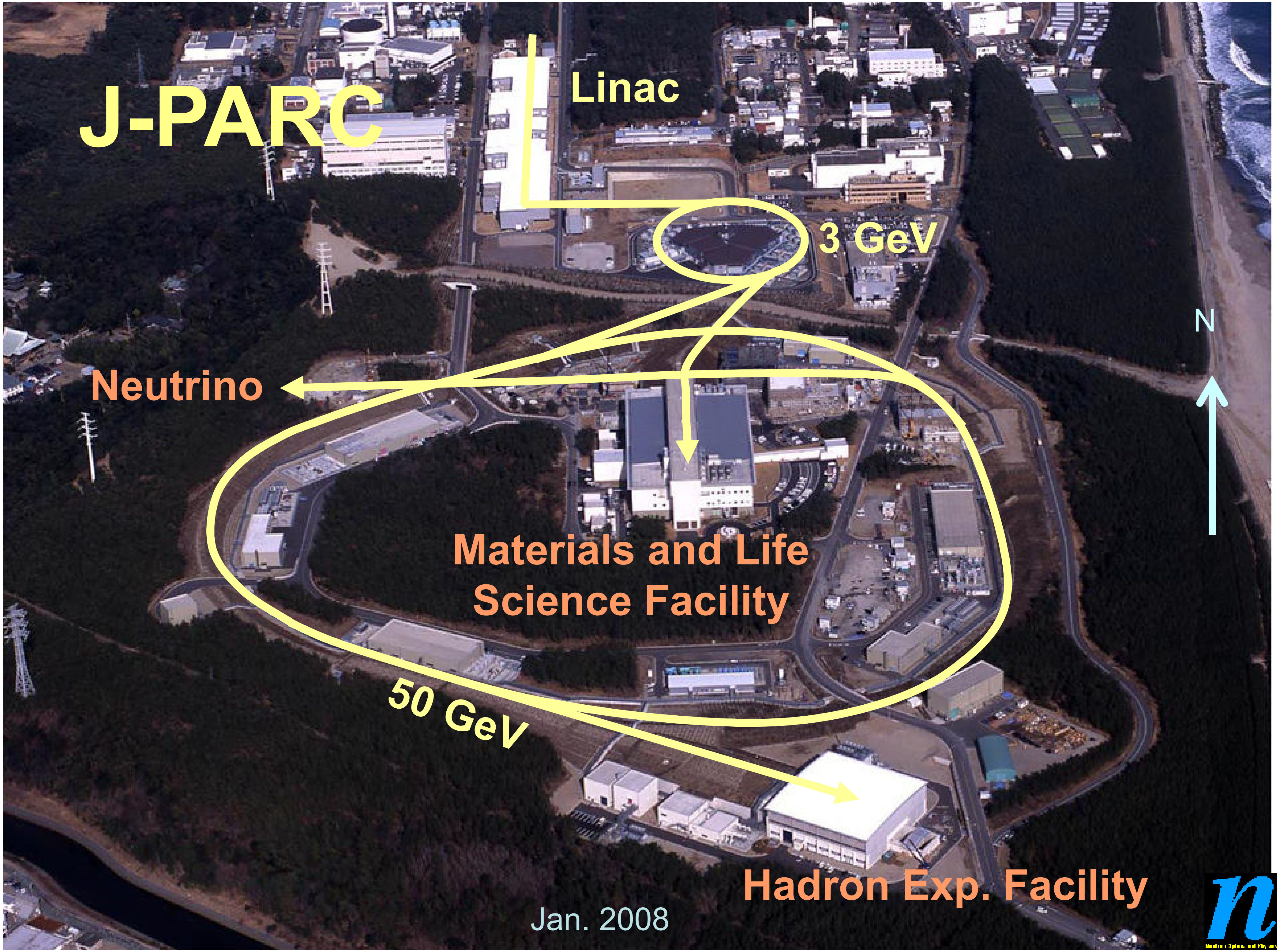
No mag. field !

β-decay

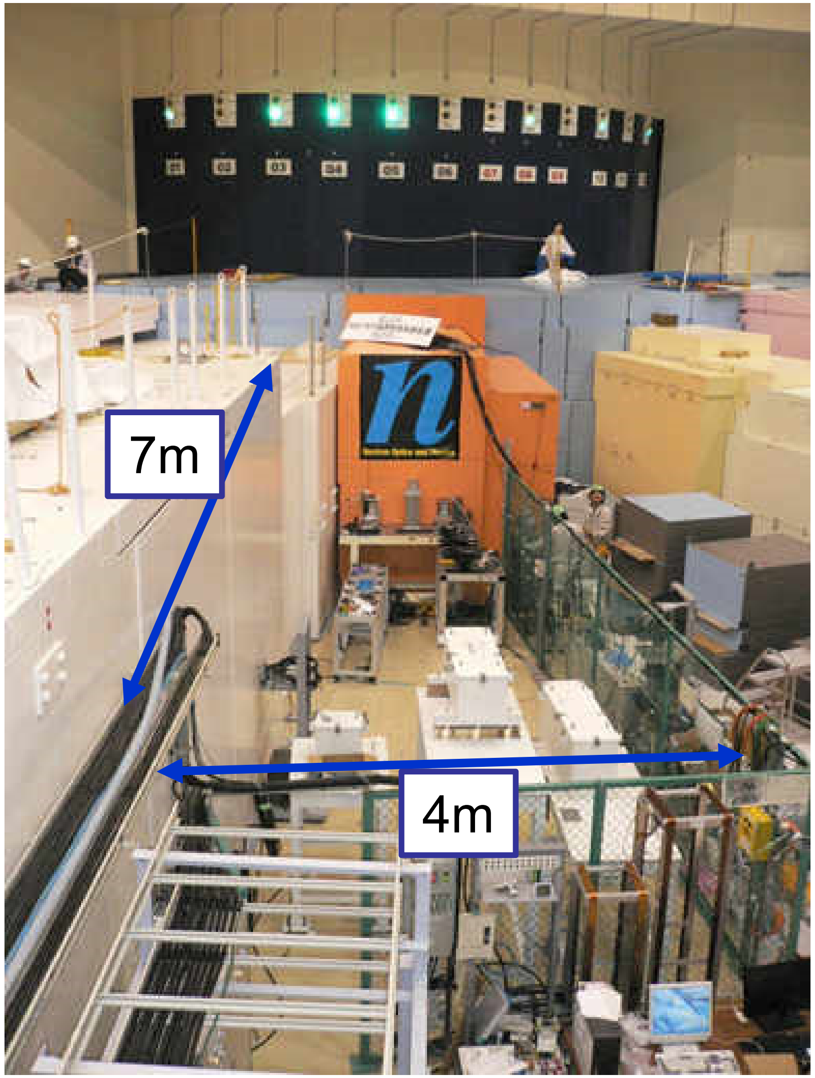
$^{3}He(n,p)^{3}H$
(Flux monitor)

Gas; $^{nat}He + {}^{3}He + CO_2$

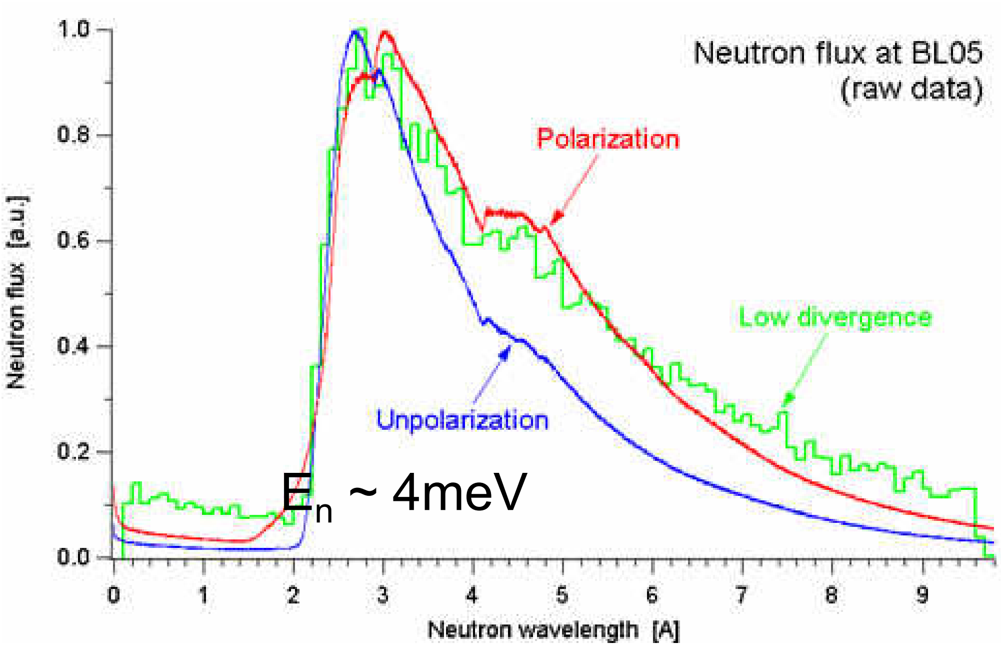
$$\tau_n = \frac{1}{\sigma_{3He}(v)\,v\rho}\,\frac{\left(N_{3He}/\varepsilon_{3He}\right)}{\left(N_{\beta}/\varepsilon_{\beta}\right)}$$


J-PARC
Linac
3 GeV
Neutrino
N
Materials and Life
Science Facility
50 GeV
Hadron Exp. Facility
Jan. 2008

BL05 - the NOP beamline at J-PARC/MLF



Performance of BL05 Beam line



Beam flux at 1MW

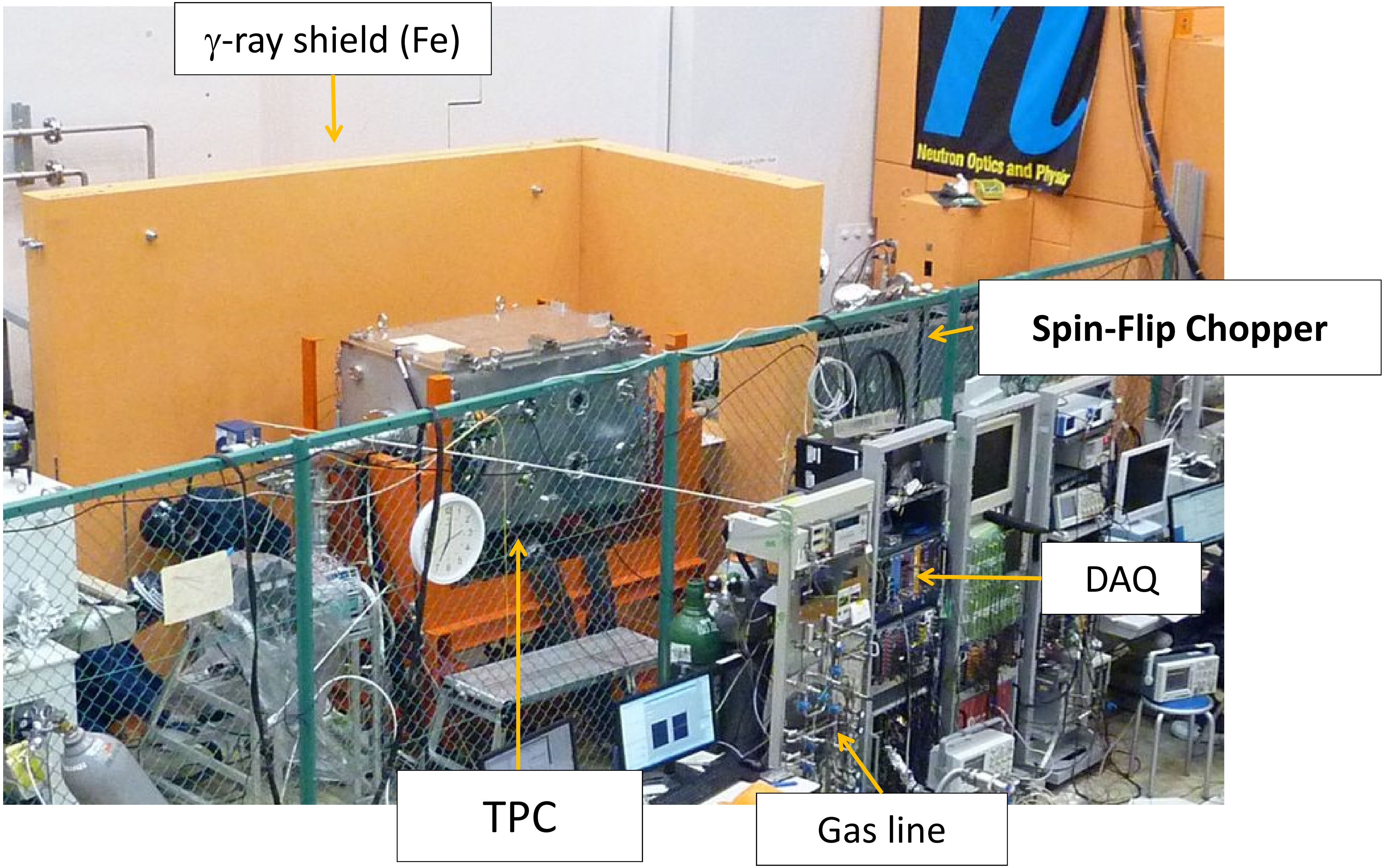
3.9×10^7 n/cm^2/s (23mrad x 9mrad)

9.4×10^7 n/cm^2/s (11mrad x 9mrad)

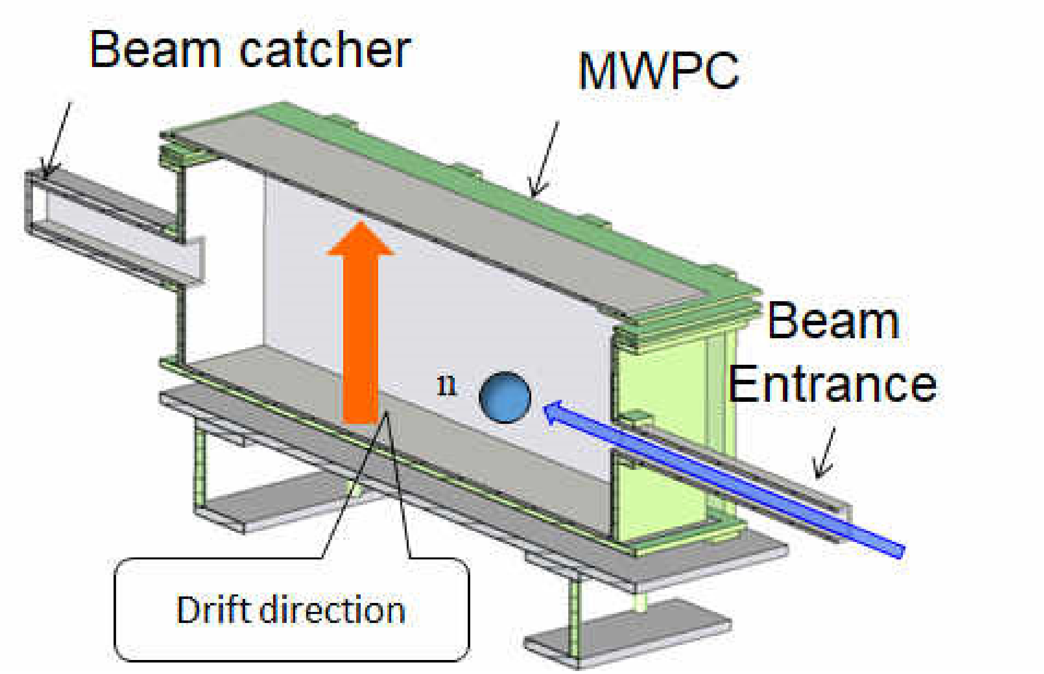
4.3×10^5 n/μstr/cm^2/s

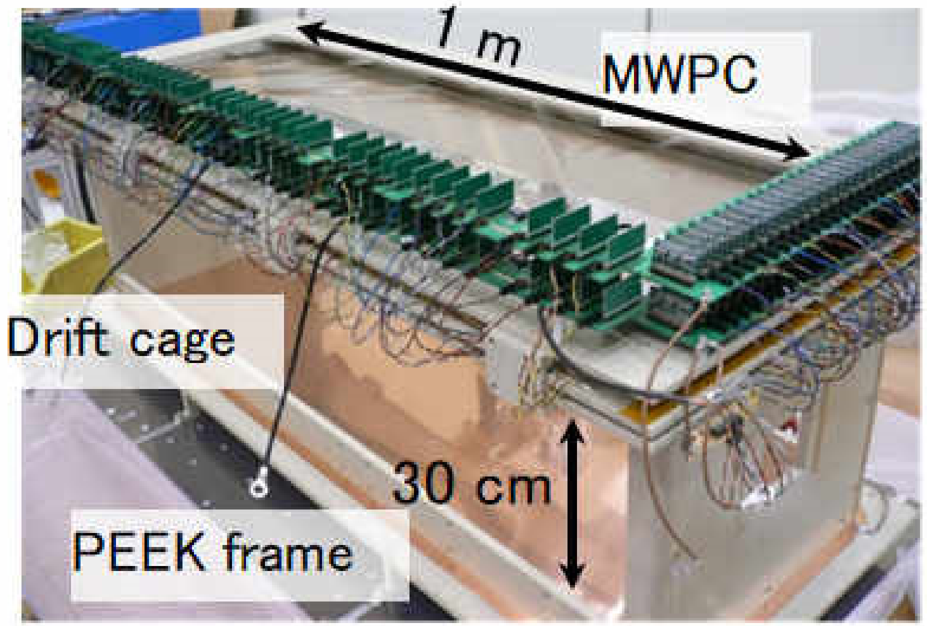
J-PARC/MLF/BL05

Y. Arimoto et al.,
Prog. Theor. Exp. Phys. 02B007 (2012)



Detector; Time Projection Chamber





Anode wire	29 of W-Au wires(+1750V)
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

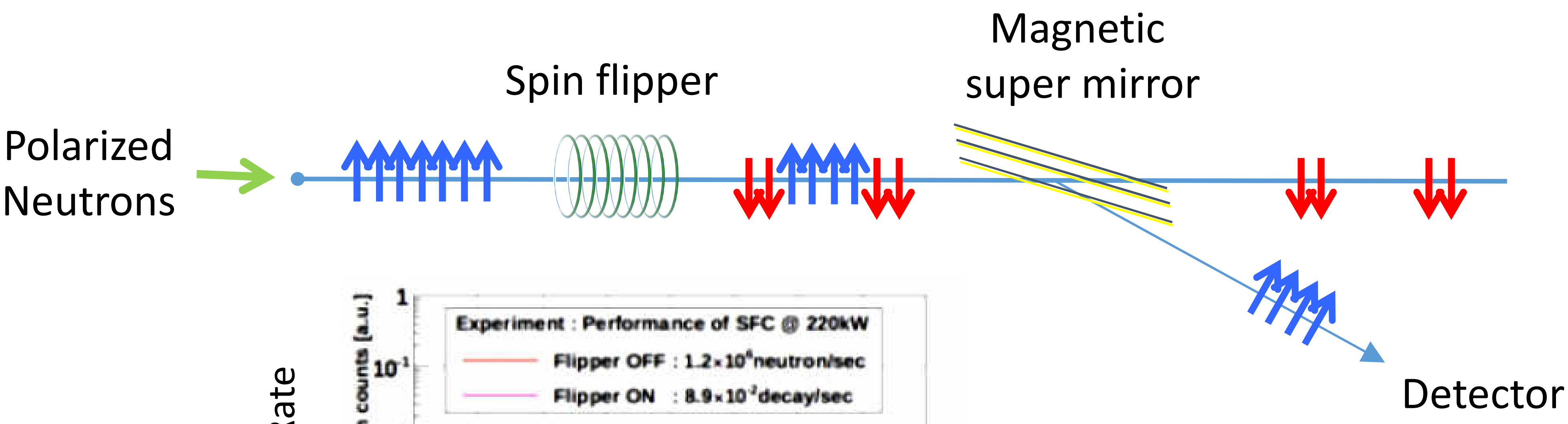
High efficiency detection for
both of β-decay and ^{3}He reaction

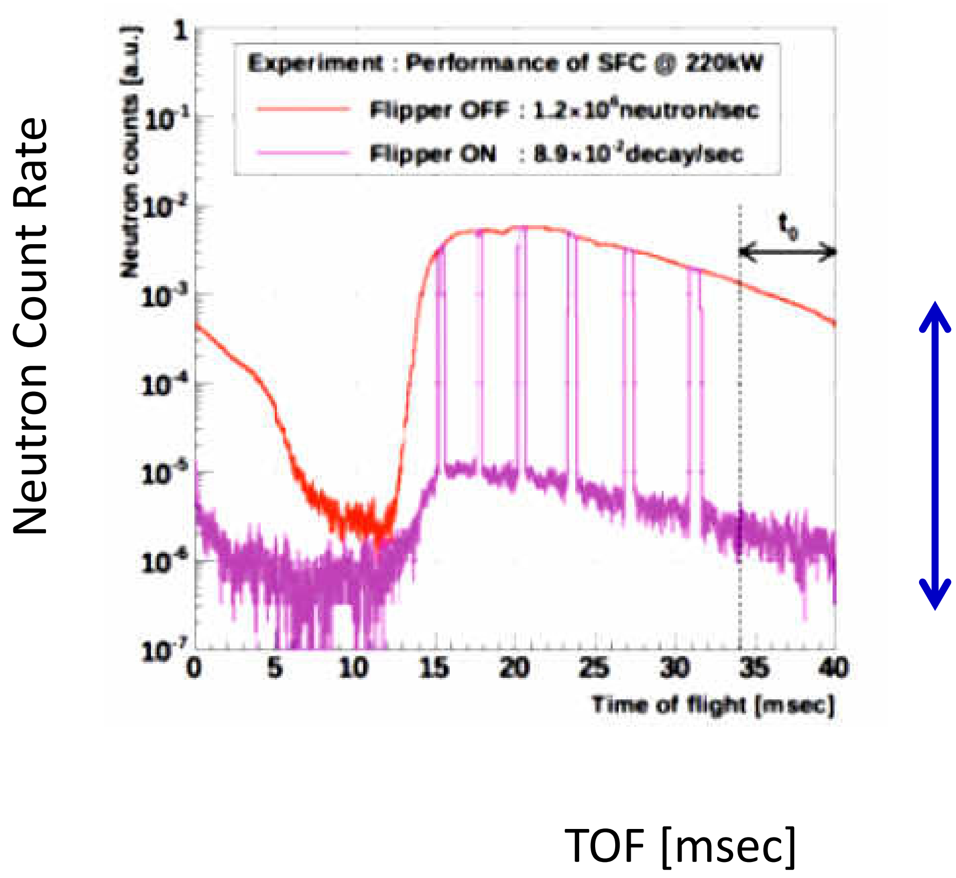
PEEK frame & inner ^{6}Li wall suppress BG.

S/N ~ 1:1

Spin-Flip Chopper

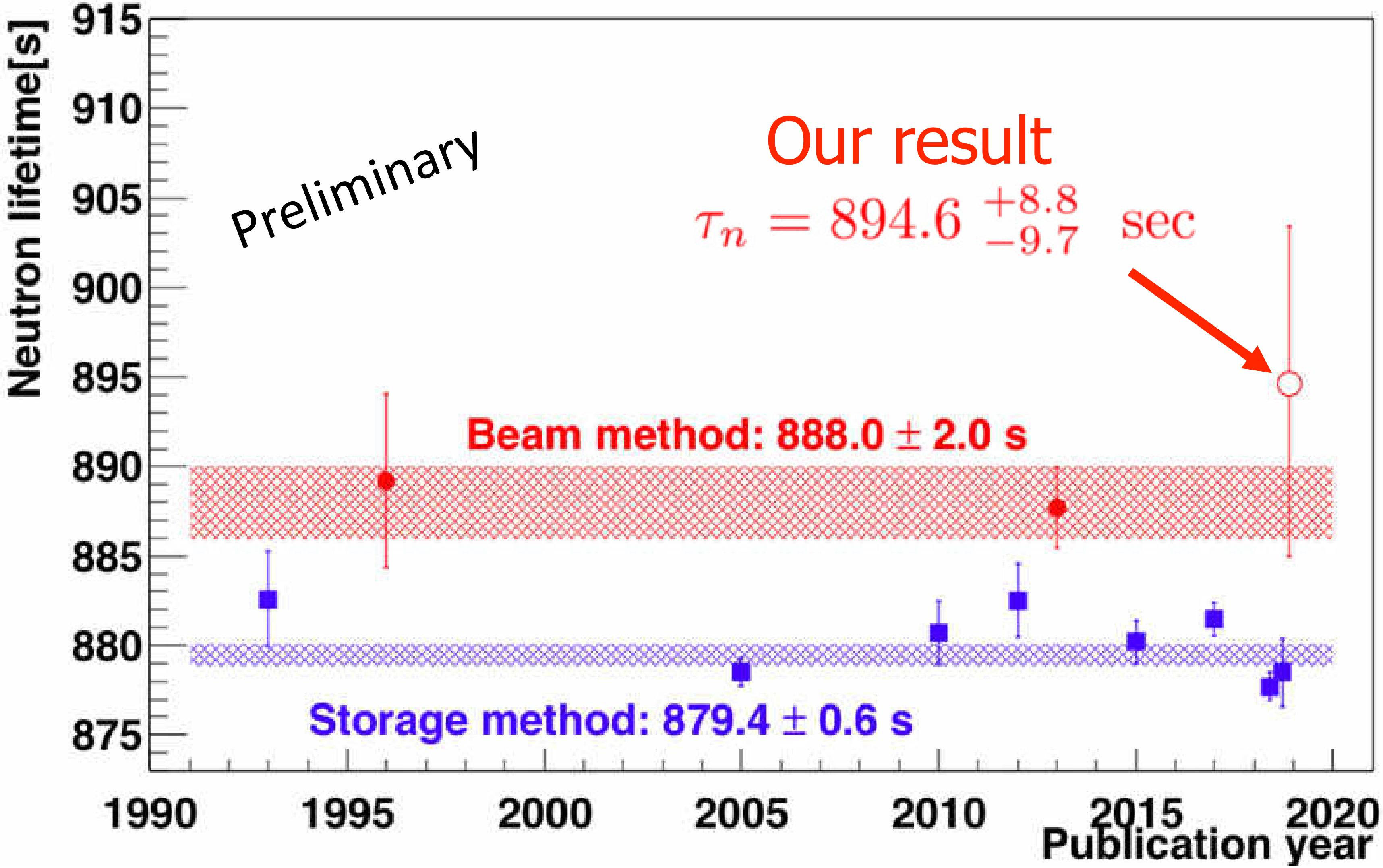
K. Taketani et al.,
NIM A634, S134-S137





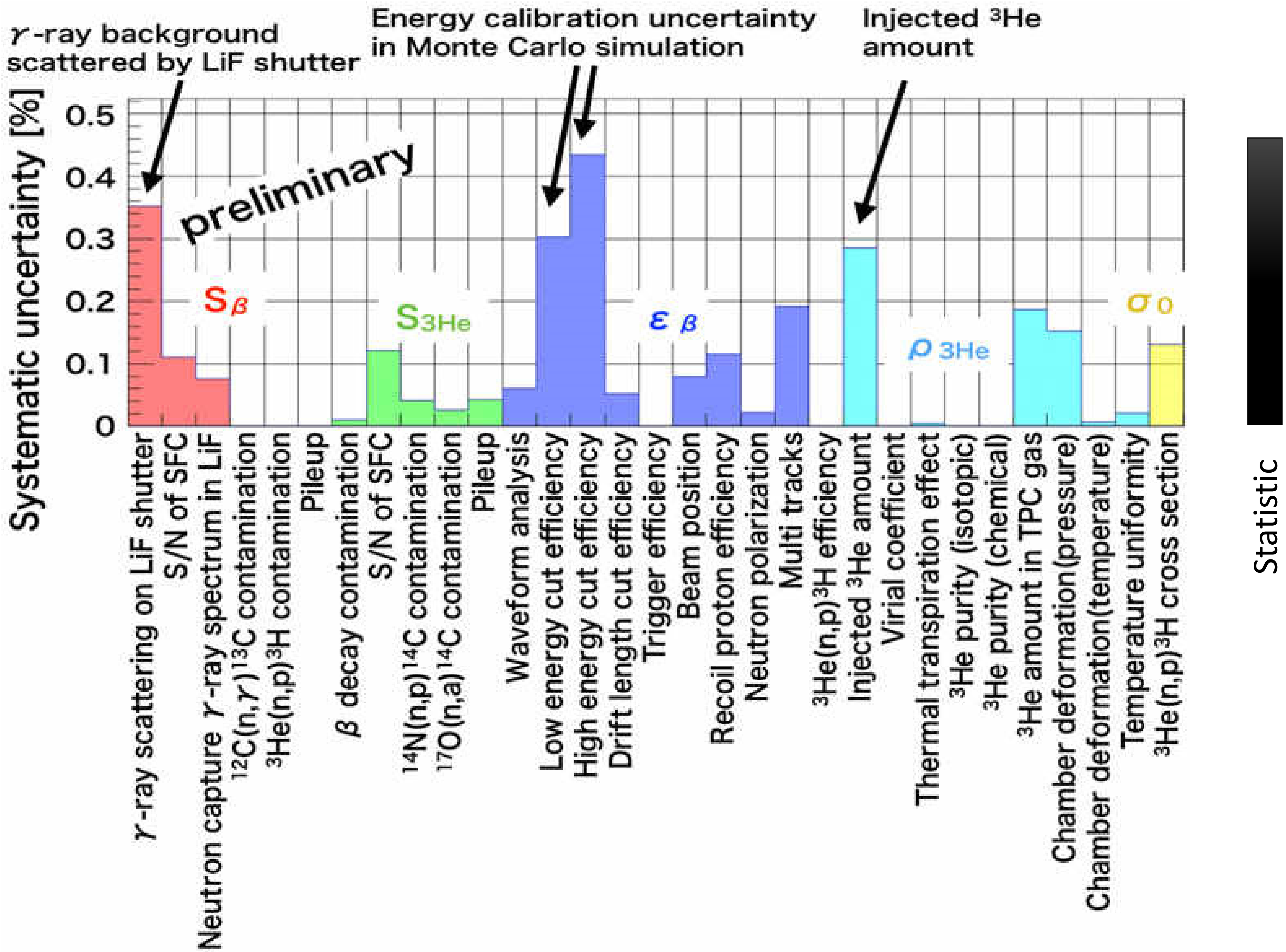
Beam ON : Beam OFF
~400 : 1

Result



- **1.6σ with Storage method**
- upgrade projects are ongoing to achieve our goal precision of 1 sec

Systematic uncertainties



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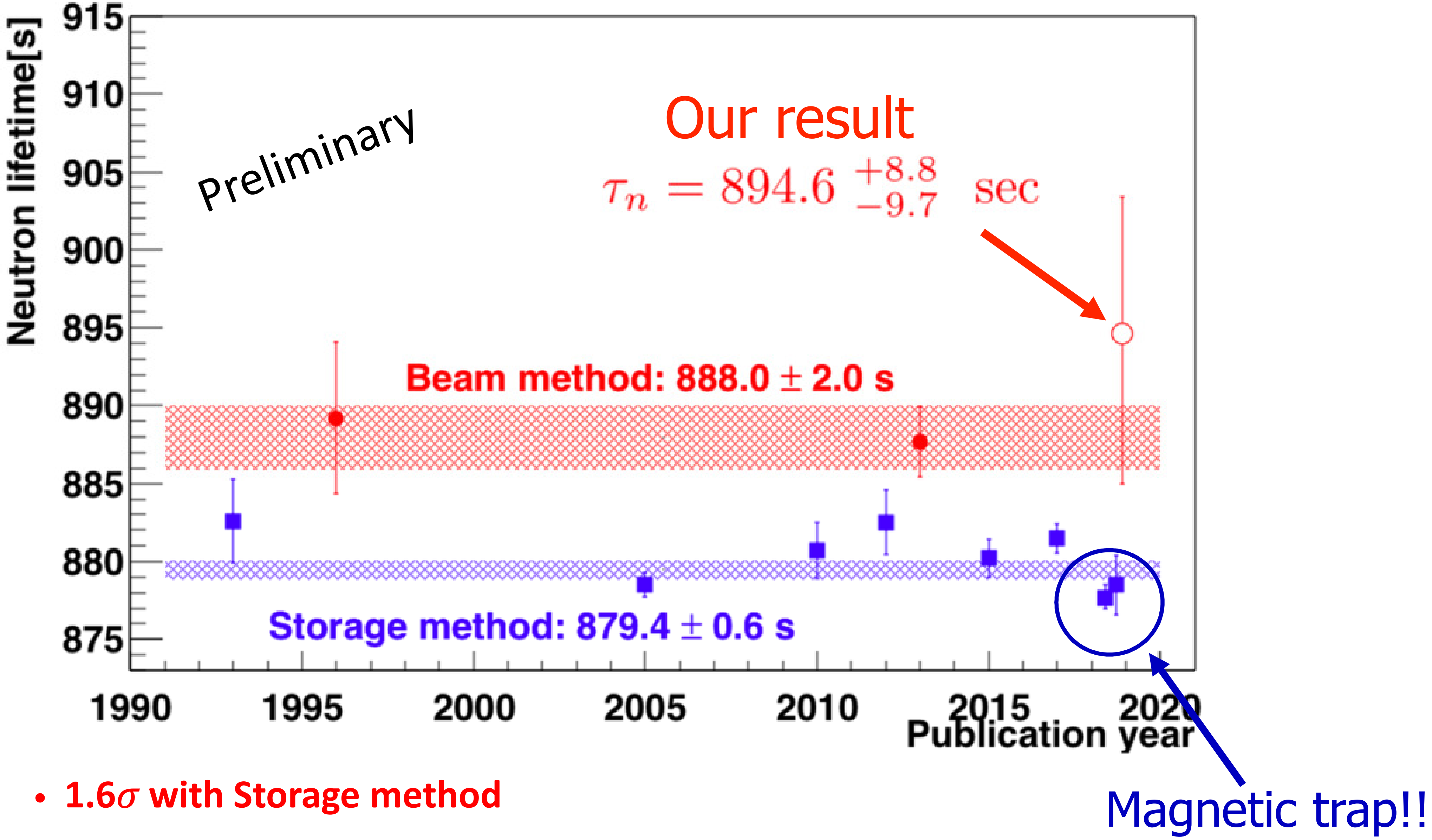

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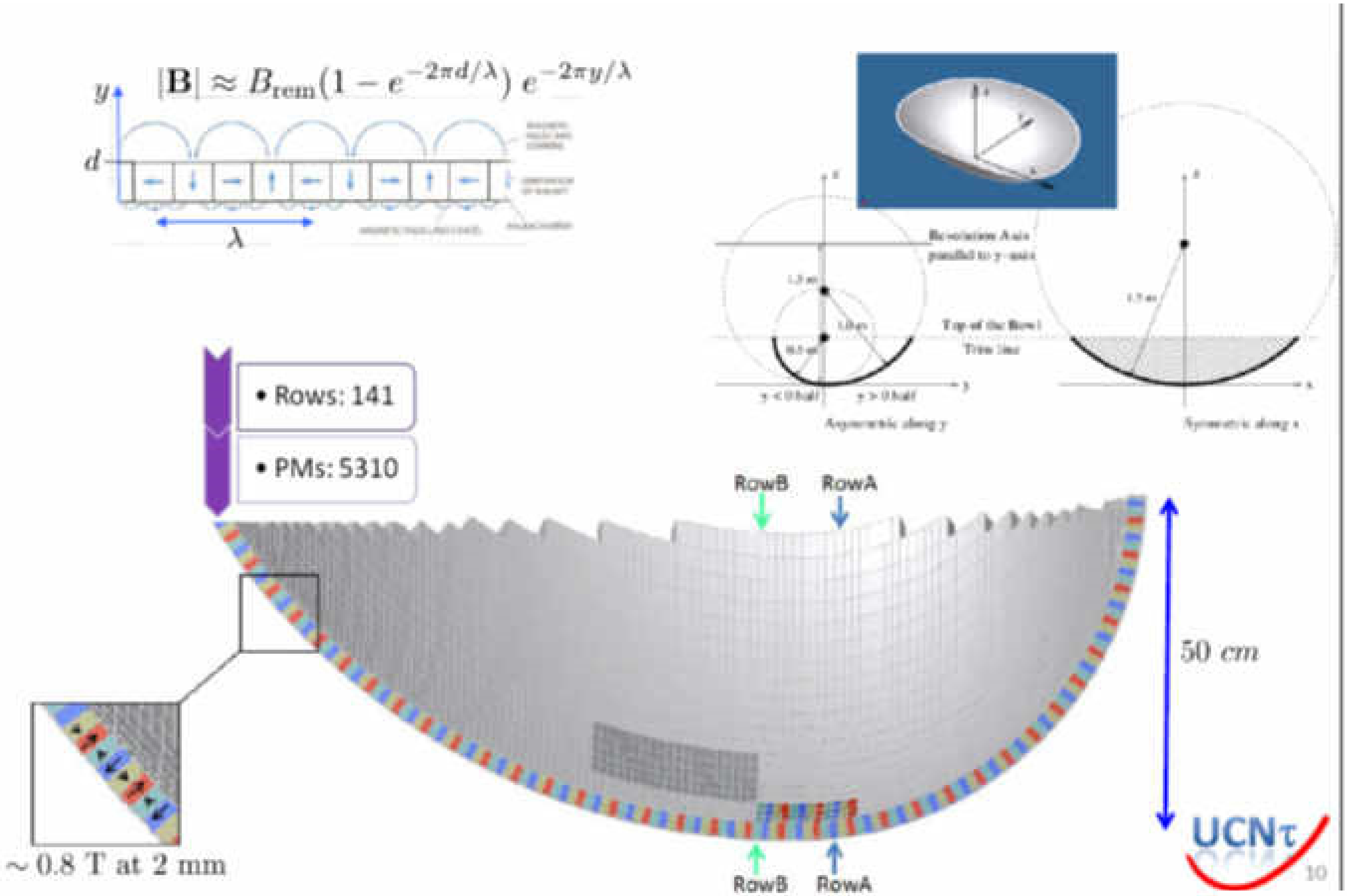
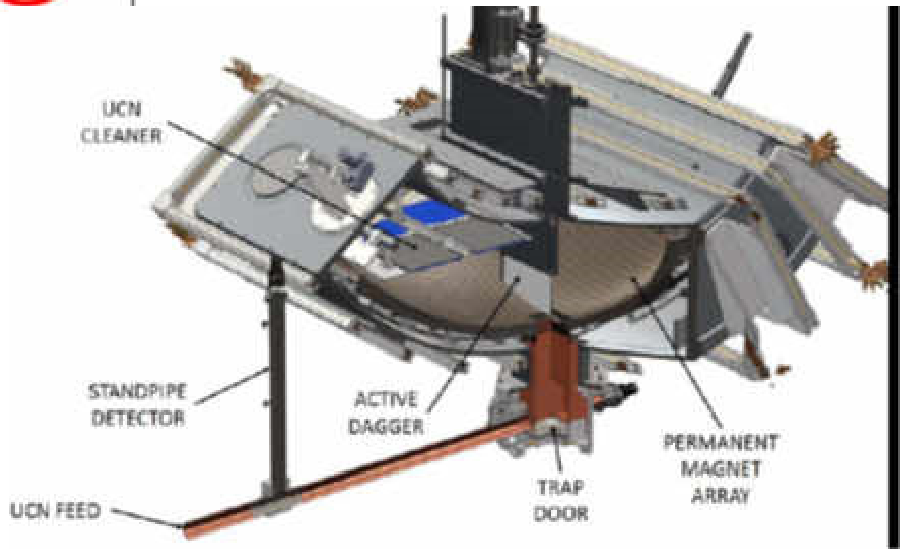
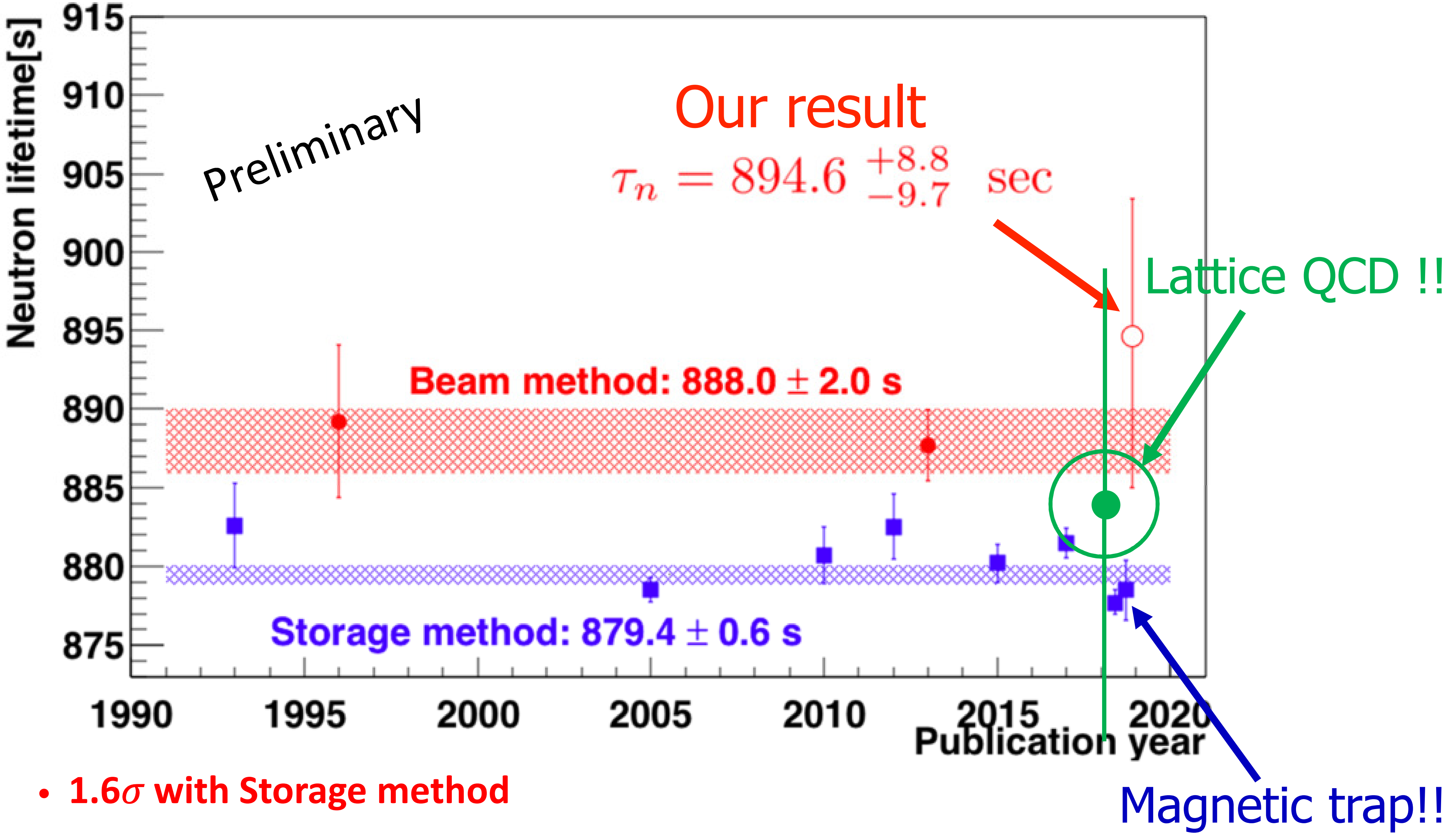




Pattie et al., Science 360, 627–632 (2018)

Result



- 1.6σ with Storage method
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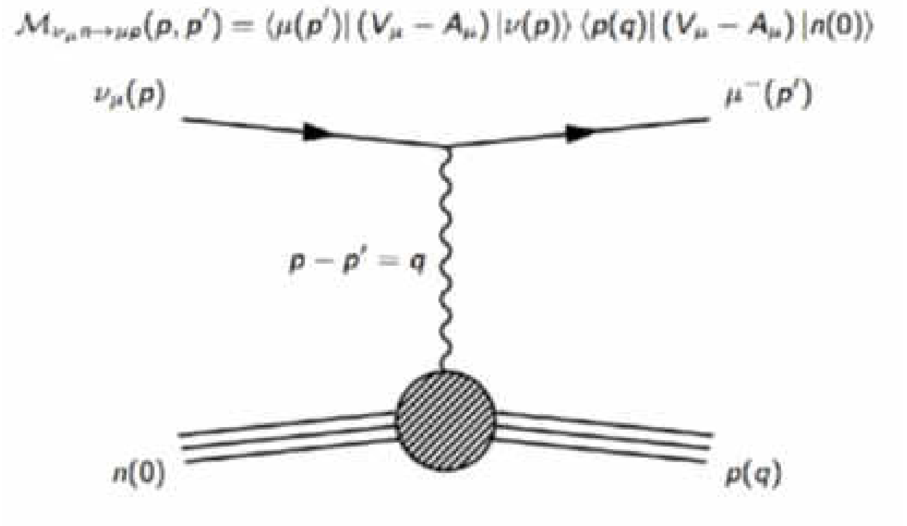
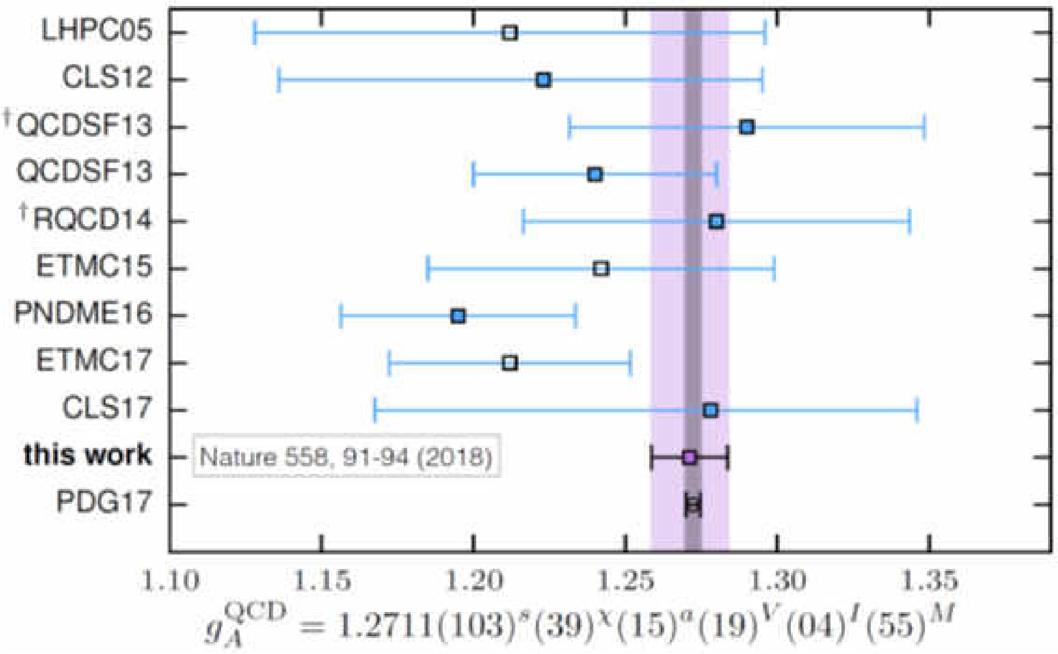
C.C. Chang et al., Nature 558, 91-94 (2018)





$$\tau_n = \frac{4908.6(1.9)}{|V_{ud}|^2\left(1+3g_A^2\right)} = 884(15)\ [\mathrm{s}]$$

Summary

Slow neutrons provide unique opportunities for studies of fundamental physics which is related to the evolution of the universe as well as the origin of elements.

Example;

- τ_n should be determined with ~0.1% accuracy for BBN.
- Study of T-violation and n-nbar oscillation are important for understanding the origin of baryon number in the universe.

and more…