Sokaku Seminar 3

Big-Bang Nucleosynthesis and Neutron Lifetime Measurement

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Introduction -What is nucleosynthesis?-

- There are three types of nucleosynthesis,
  - **Big-Bang Nucleosynthesis (BBN)**
    - The formation of elements (nucleosynthesis) that occurred after the big-bang
    - Important to understand the evolution of the early universe
  - Stelar Nucleosynthesis
    - Nucleosynthesis takes place in the center of the stars
    - Explains the formation of elements from He up to Fe
  - Supernova Nucleosynthesis
    - During a supernova explosion, heavier elements than Fe are produced

- BBN provides the formation of light elements, but the precession of neutron lifetime limits the uncertainty of the prediction

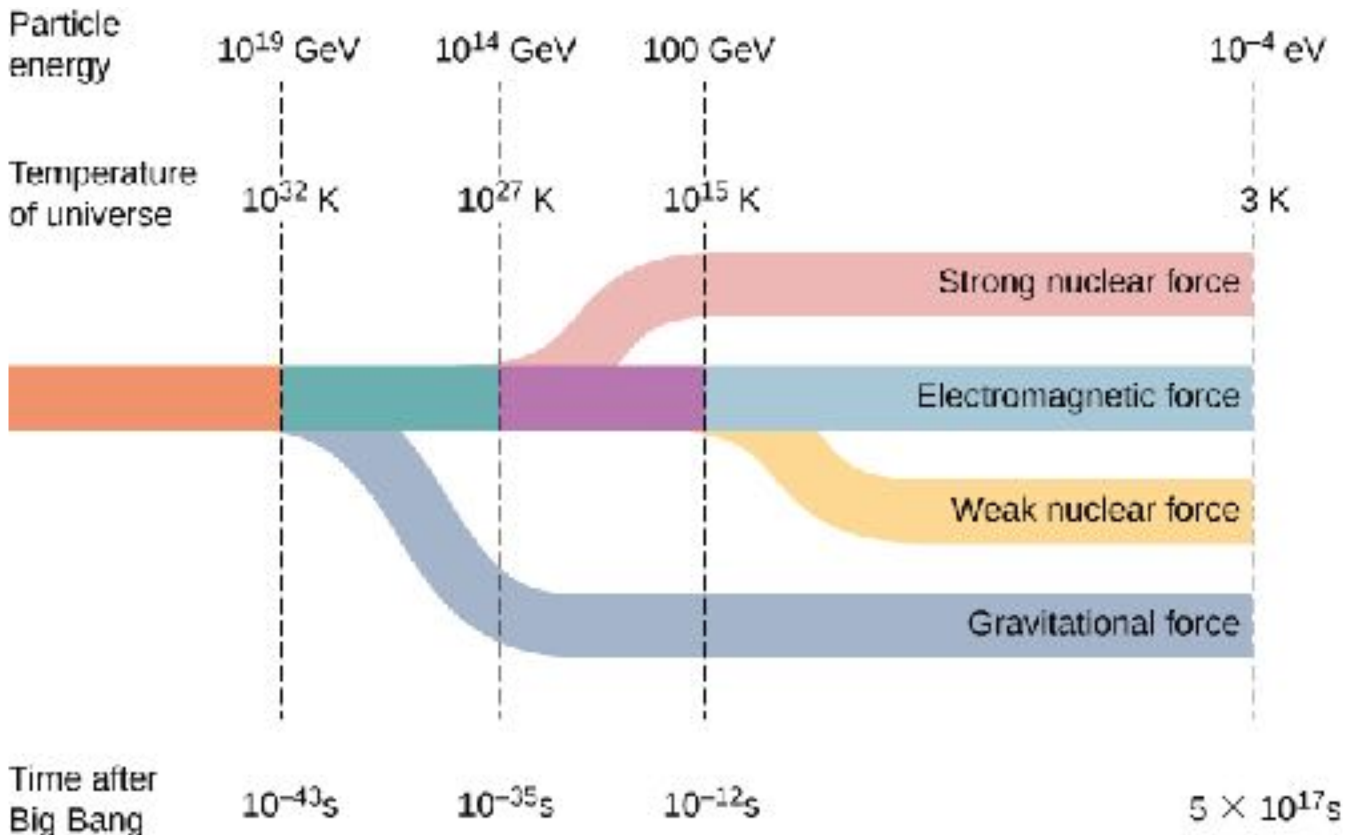
Contents

Early Universe

Evolution of the Early Universe

- According to the Big-Bang theory, the universe started from a hot and dense state
- While cooling to the present state, which now we observe, separation of the 4 fundamental interaction occurred

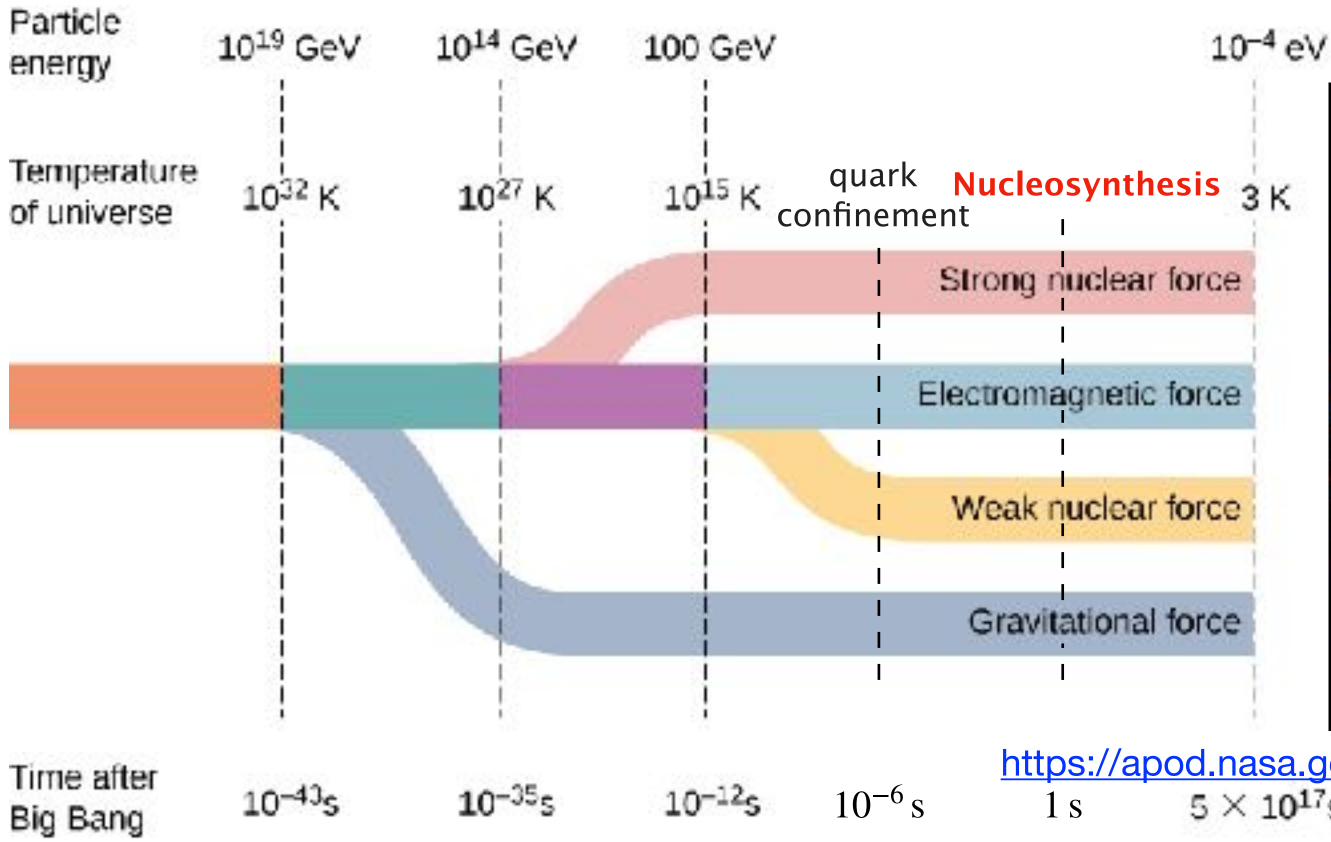
- First, gravity froze out and became distinct (10^{-43} sec after the Big-Bang)
- Next, strong interaction froze out and induced inflation, which is an exponential expansion
- Then, electromagnetic and weak interactions froze out 10^{-12} sec after the Big-Bang

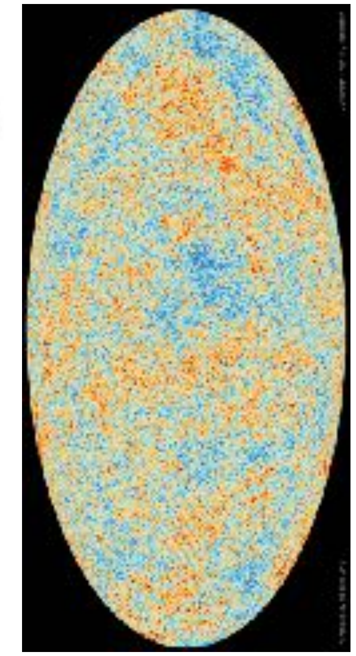


https://openstax.org/books/university-physics-volume-3/pages/11-7-evolution-of-the-early-universe

- The history of the universe is the history of phase transition

Evolution of the Early Universe





https://apod.nasa.gov/apod/image/1807/CMB2018_Planck_4672.jpg

- Quarks and gluons cannot be isolated below the Hagedorn temperature ($T_{\mathrm{H}} \sim 150\,\mathrm{MeV}$)
- Protons and Neutrons were born here, but electrons still moved freely $10^{-12}\,\mathrm{sec}$ after the Big-Bang.

- Nucleosynthesis starts when the temperature cools down to $10^9\,\mathrm{K}$
- It is around $1\,\mathrm{sec}$ after the Big-Bang.

- When the universe is cooled down to 3000 K, electrons become bound to the nucleus
  → Photons can to travel straight ahead (clear up of the Universe)

Big-Bang Nucleosynthesis (BBN)

Before BBN ($t < 1$ sec)

- Before the BBN, neutrons and protons were at thermodynamic equilibrium

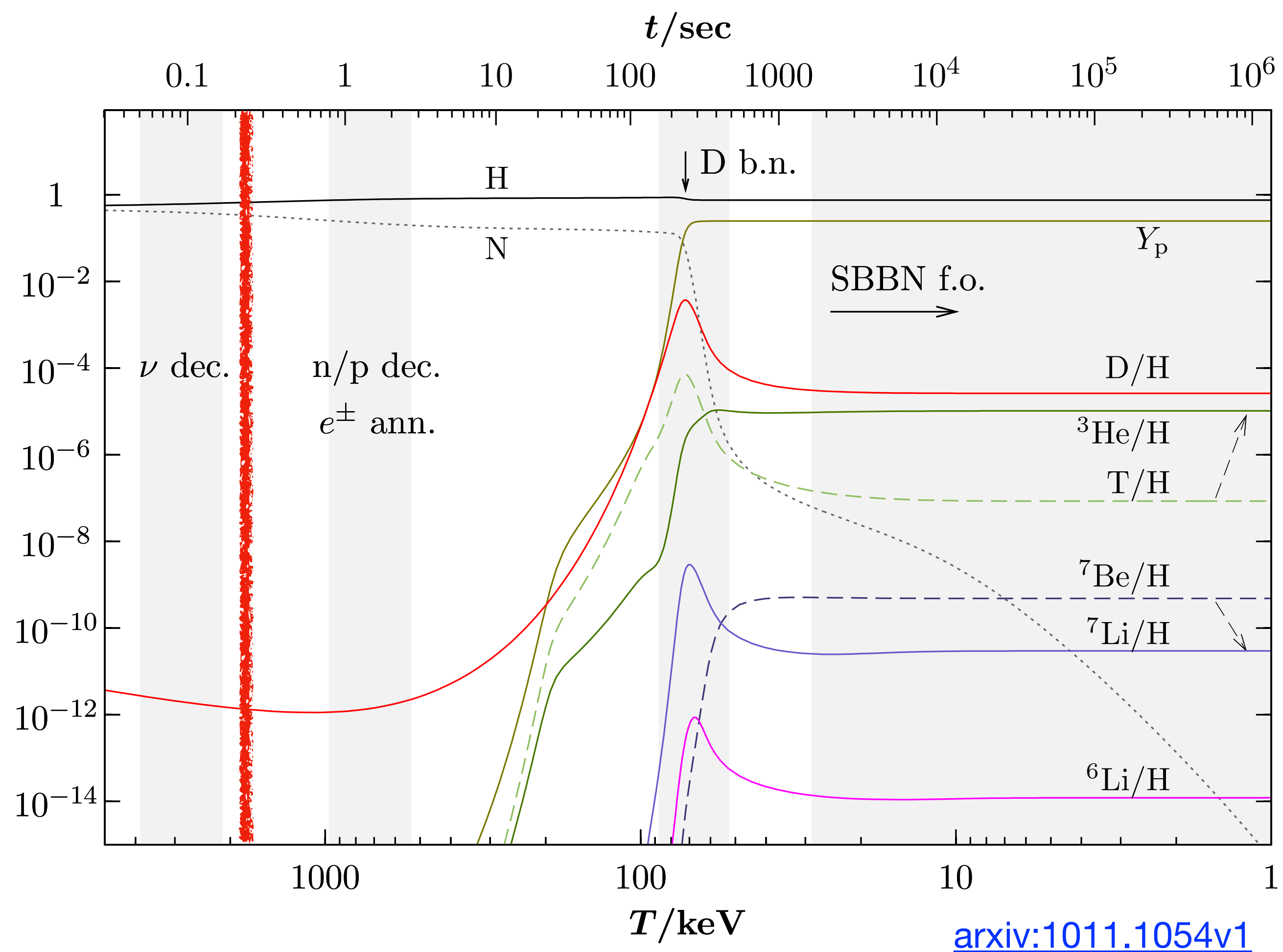
$$p + e^- \longleftrightarrow n + \nu_e$$

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

$$n \longleftrightarrow p + e^- + \nu_e$$

- Here, the n/p ratio (the ratio of number density) is given by Boltzmann distribution
- Because of the very high temperature ($kT \gg \Delta mc^2$),

$$\frac{n}{p} \simeq \exp\left(-\frac{\Delta mc^2}{kT}\right) \sim \exp 0 = 1$$



arxiv:1011.1054v1

Freeze-Out ($t \sim 1$ sec)

- The temperature of the universe decreases as it expands
- Eventually, the rate of the reactions

$$\mathrm{p} + \mathrm{e}^- \longleftrightarrow \mathrm{n} + \nu_\mathrm{e}$$
$$\mathrm{n} + \mathrm{e}^+ \longleftrightarrow \mathrm{p} + \bar{\nu}_\mathrm{e}$$

  become smaller than the expansion rate of the universe (neutrino decoupling)

- At this moment, ratio n/p is fixed at a constant value,

$$\frac{n}{p} \simeq \exp\left(-\frac{\Delta mc^2}{kT_\mathrm{f}}\right) \simeq \frac{1}{6}$$

- Freeze-out temperature T_f is about a few MeV
- Interestingly this ratio depends on all the 4 fundamental interactions

- The neutrinos are cooled as the universe expands, and are now expected to be moving at $1.9\,\mathrm{K}$
- These are called Cosmic Neutrino Background (CNB) which have been searched for, but such a low energy particles are difficult to detect

Decay of Neutron ($t > 1$ sec)

- Fixed ratio n/p only decreases by neutron beta decay

$$\mathrm{n} \longrightarrow \mathrm{p} + \mathrm{e}^- + \nu_\mathrm{e}$$

- On the other hand, production of deuteron preserves the number of neutrons, because neutrons are stable inside nuclei

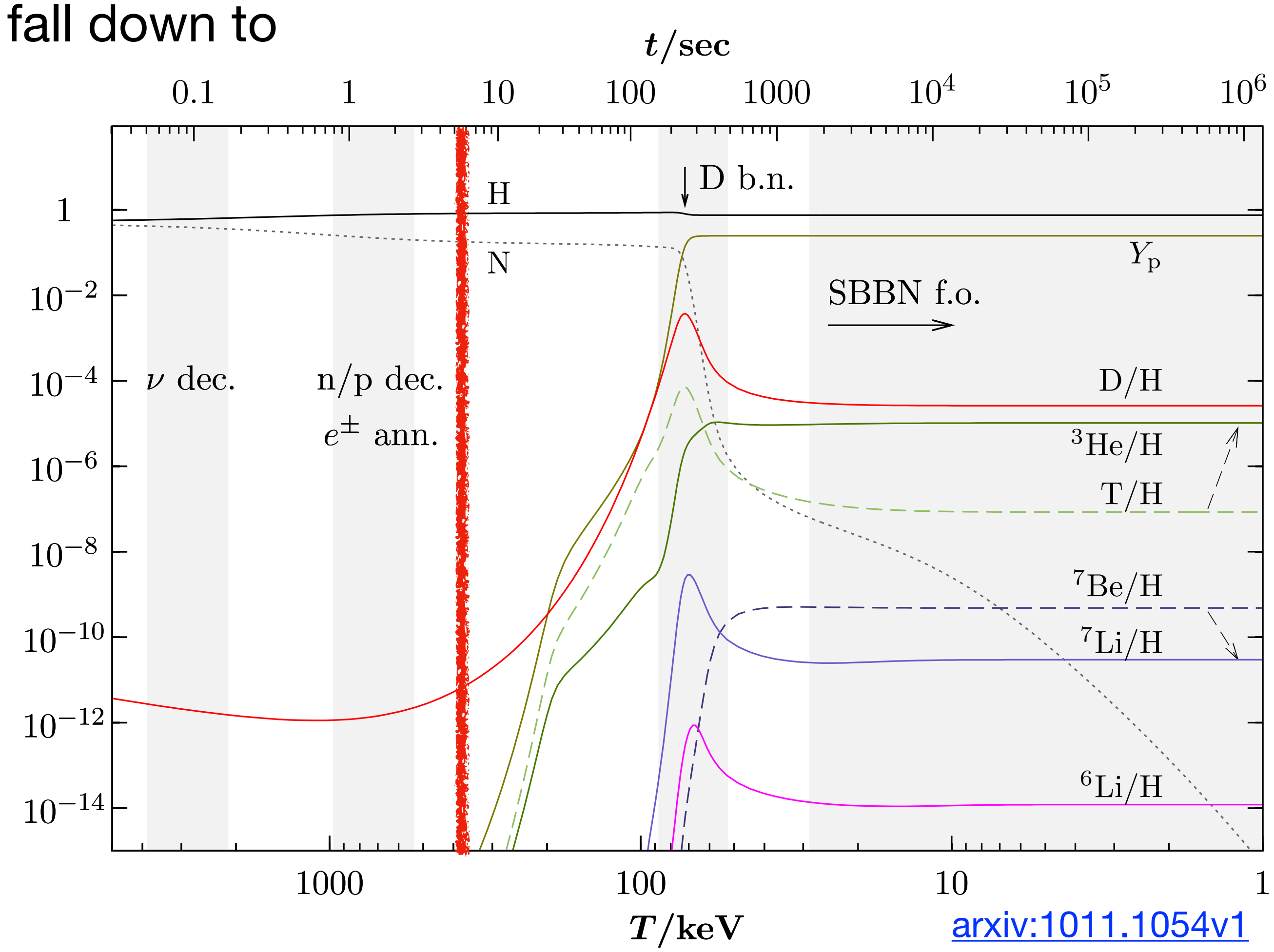
$$\mathrm{p} + \mathrm{n} \longrightarrow \mathrm{D} + \gamma$$

- Before the production of deuteron begin, ratio fall down to

$$\frac{n}{p} \simeq \frac{1}{7}$$

- All the neutrons we have in our universe were preserved at this time.

- The creation of D causes the formation of He



arxiv:1011.1054v1

Nucleosynthesis

- Once D formation has occurred, further reactions proceed to make He
- He and photon are produced by the reaction between deuteron and nucleon

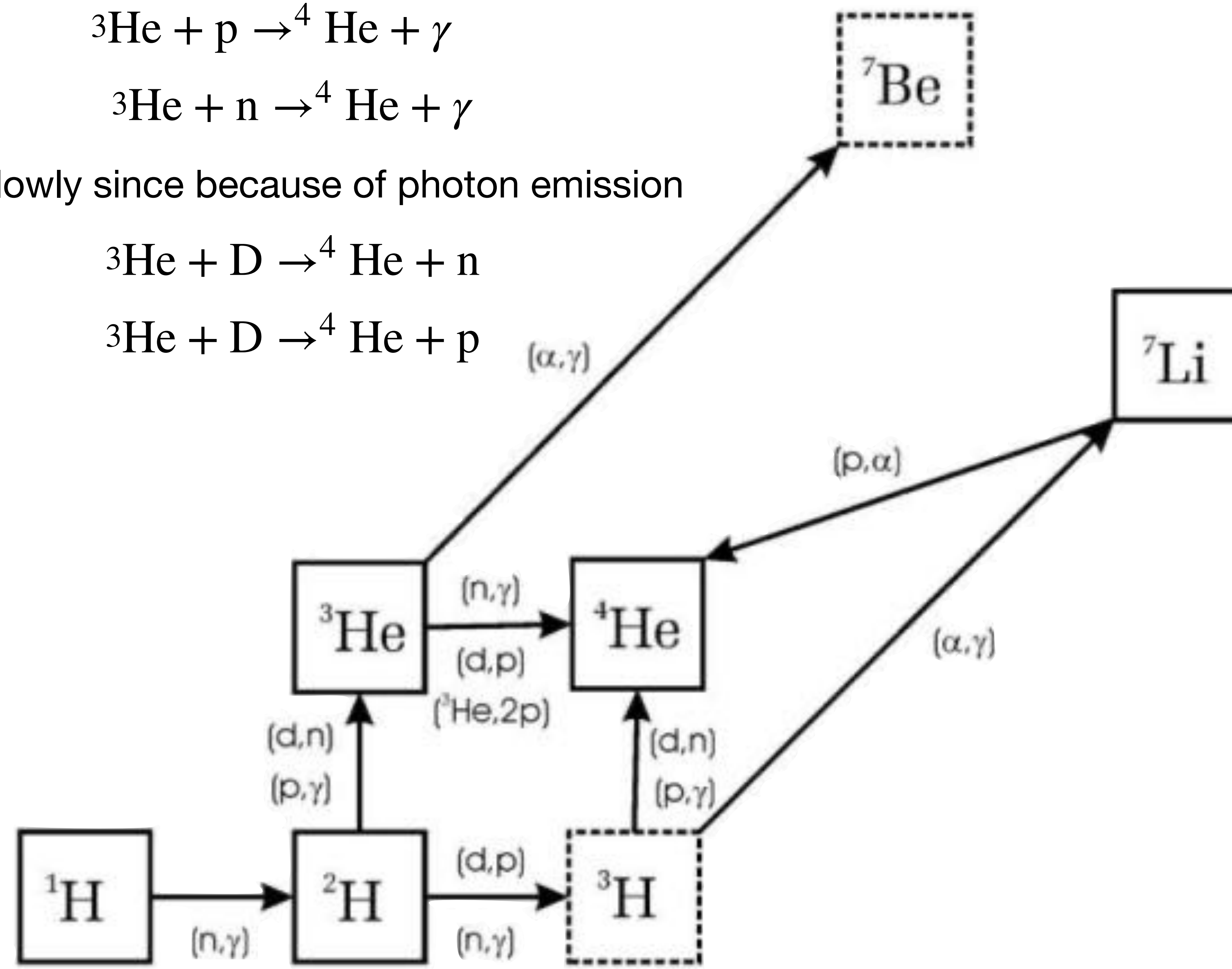
$$\mathrm{D} + \mathrm{n} \to {}^{3}\mathrm{H} + \gamma, \qquad {}^{3}\mathrm{He} + \mathrm{p} \to {}^{4}\mathrm{He} + \gamma$$

$$\mathrm{D} + \mathrm{p} \to {}^{3}\mathrm{He} + \gamma, \qquad {}^{3}\mathrm{He} + \mathrm{n} \to {}^{4}\mathrm{He} + \gamma$$

- These reactions proceeds slowly since because of photon emission

$$\mathrm{D} + \mathrm{D} \to {}^{3}\mathrm{H} + \mathrm{p}, \qquad {}^{3}\mathrm{He} + \mathrm{D} \to {}^{4}\mathrm{He} + \mathrm{n}$$

$$\mathrm{D} + \mathrm{D} \to {}^{3}\mathrm{H} + \mathrm{n}, \qquad {}^{3}\mathrm{He} + \mathrm{D} \to {}^{4}\mathrm{He} + \mathrm{p}$$



https://ned.ipac.caltech.edu/level5/Sept16/Rauscher/Rauscher3.html

Calculation of Abundance of Light Nuclei

- From a simple calculation, $^4\mathrm{He}$ mass fraction Y_p can be calculated using n/p as,

$$Y_\mathrm{p} = \frac{2 \times n/p}{n/p + 1} \simeq \frac{2 \times \frac{1}{7}}{\frac{1}{7} + 1} = 0.25$$

- In practice, in BBN theory, the differential equations are solved numerically using a nuclear reaction network that takes into account a 12 reactions,

$$\mathrm{n} \longrightarrow \mathrm{p} + \mathrm{e}^- + \nu_\mathrm{e}$$

$$\mathrm{D} + \mathrm{n} \rightarrow {}^3\mathrm{H} + \gamma, \qquad {}^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + \gamma$$

$$\mathrm{D} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma, \qquad {}^3\mathrm{He} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \gamma$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{H} + \mathrm{p}, \qquad {}^3\mathrm{He} + \mathrm{D} \rightarrow {}^4\mathrm{He} + \mathrm{n}$$

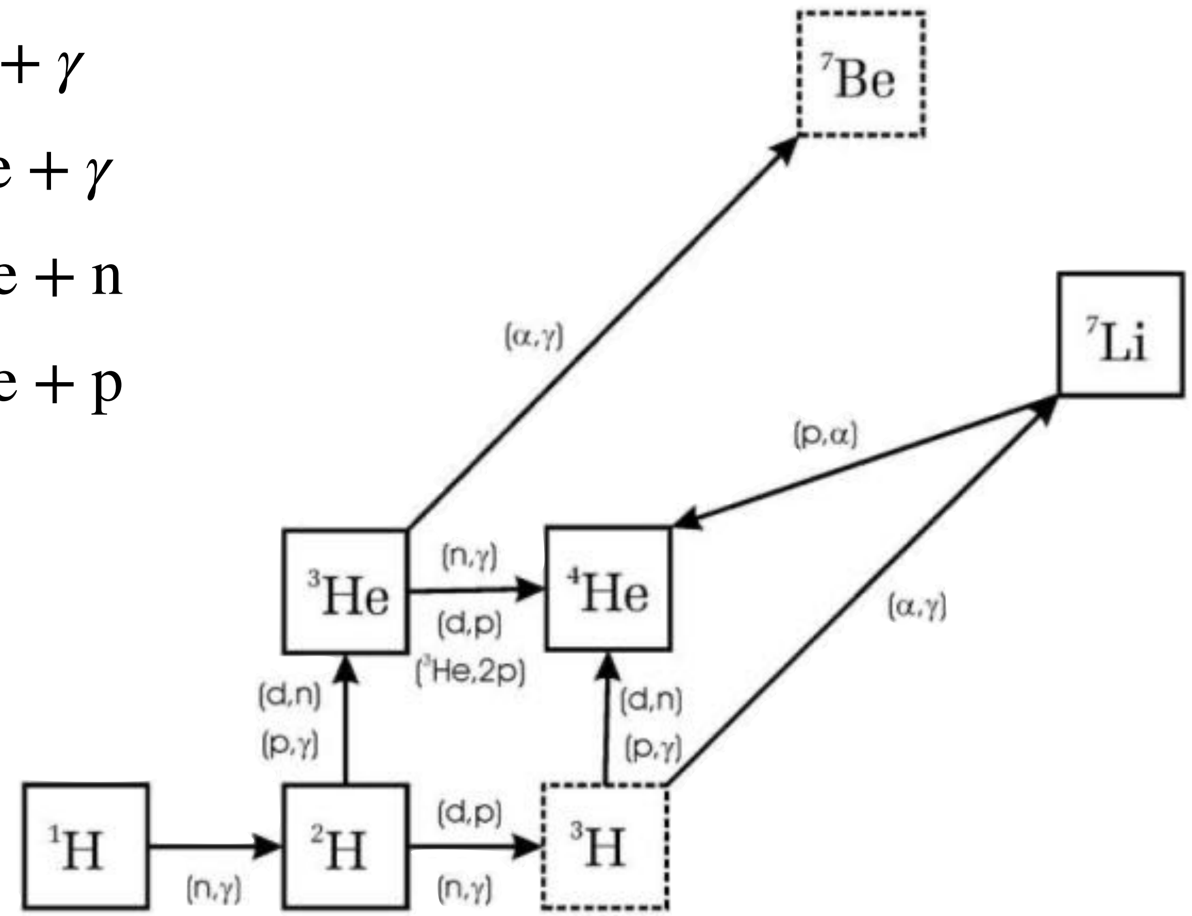
$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{H} + \mathrm{n}, \qquad {}^3\mathrm{He} + \mathrm{D} \rightarrow {}^4\mathrm{He} + \mathrm{p}$$

and also,

$$^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$$

$$^7\mathrm{Be} + \mathrm{n} \longrightarrow {}^7\mathrm{Li} + \mathrm{p}$$

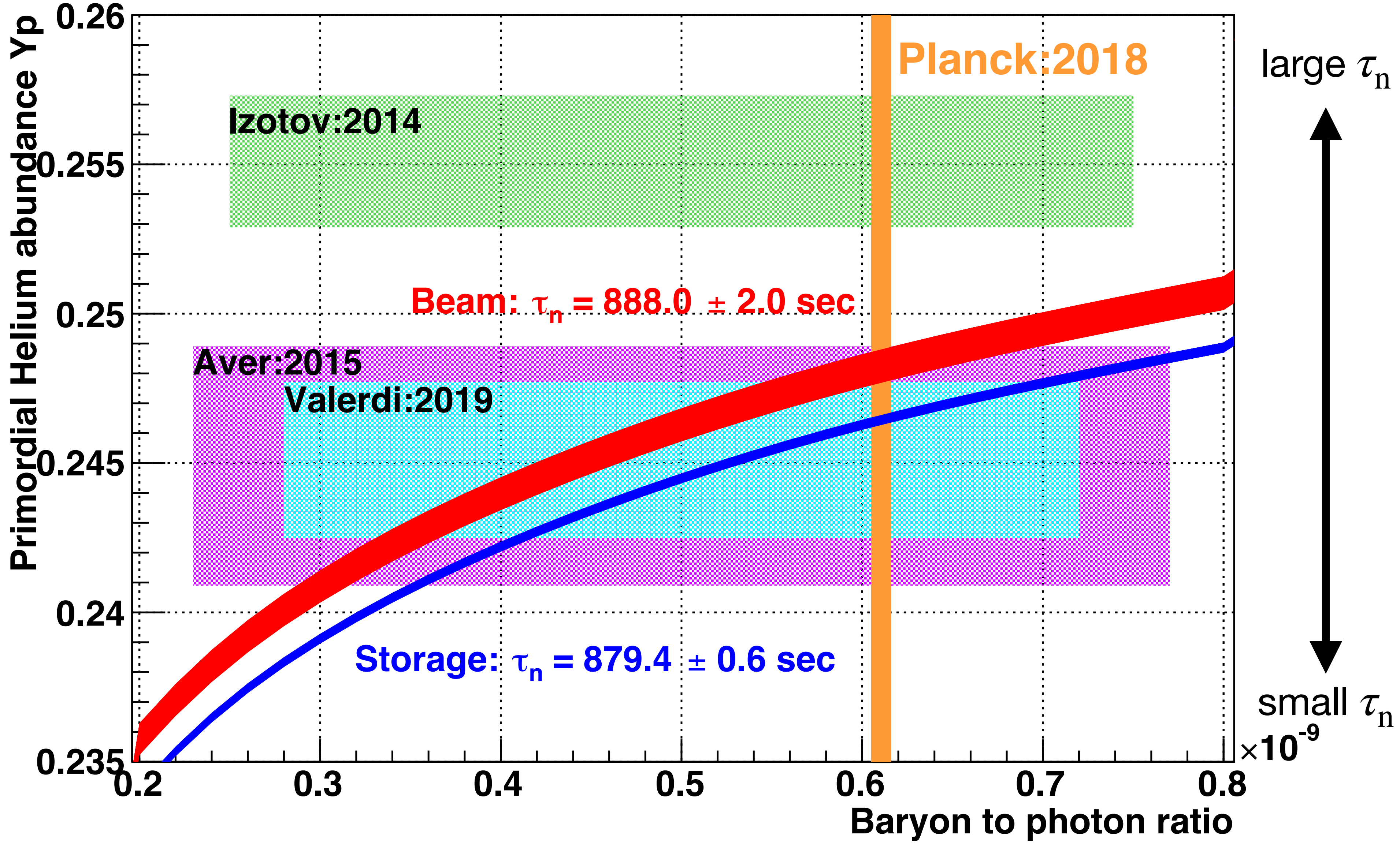
$$^7\mathrm{Li} + \mathrm{p} \longrightarrow 2\,{}^4\mathrm{He}$$



https://ned.ipac.caltech.edu/level5/Sept16/Rauscher/Rauscher3.html

Era of Accurate Cosmology

- Thanks to the remarkable development of observational techniques, cosmology is now entering an era in which it can be tested accurately
- Neutron lifetime is one of the input parameter and it limits the precession of the $^4\mathrm{He}$ mass fraction, Y_p
- Red and blue lines show the resent measurements of the neutron lifetime



Neutron Lifetime Measurement

Physics Motivation of Neutron Lifetime Measurement

- As we have seen, measurement of neutron lifetime is important for the verification of cosmology

- V_{ud}, one of the element of the CKM matrix,

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cd}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{td}} \end{pmatrix}$$

  can be also determined from the neutron lifetime

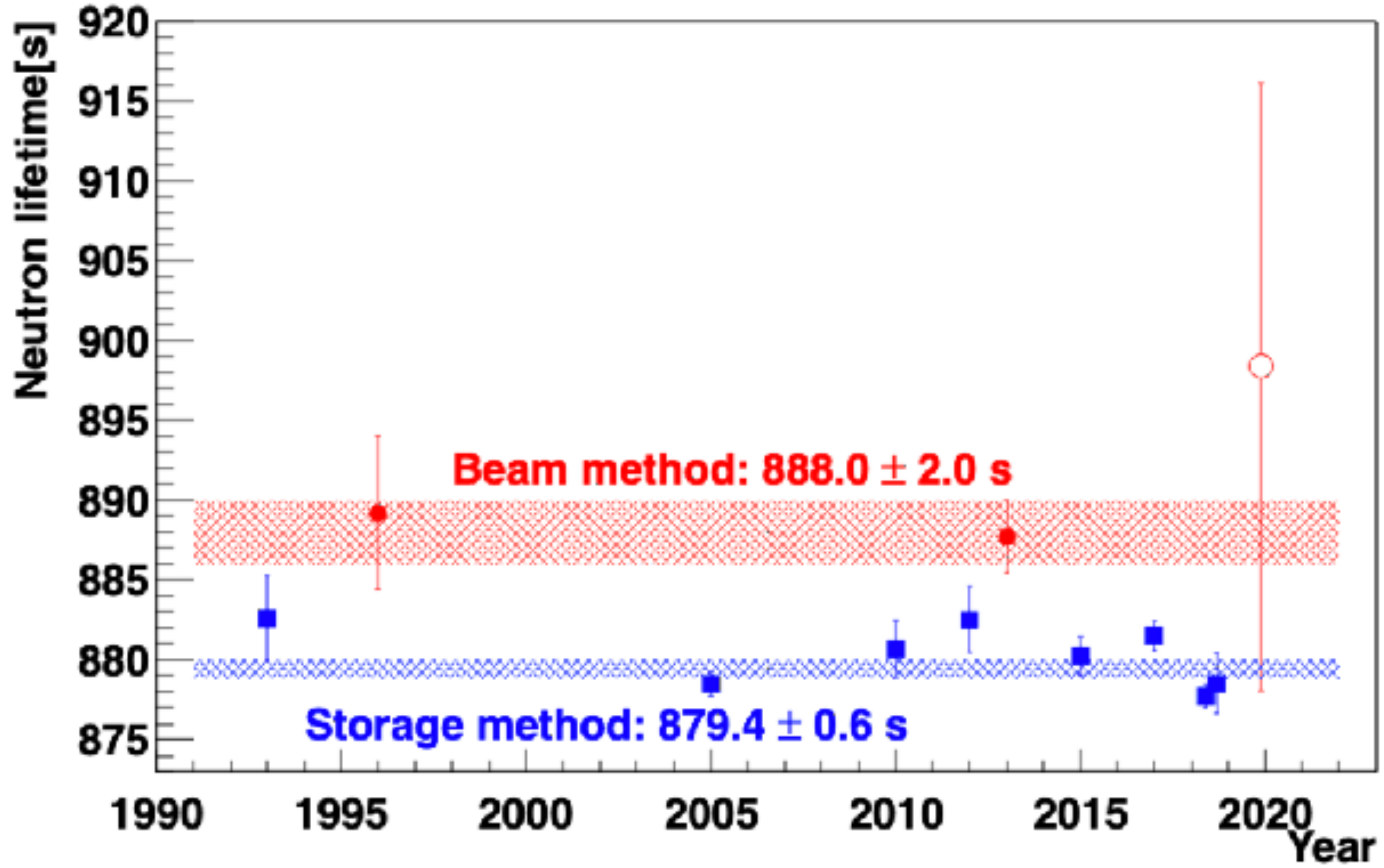
$$\left| V_{\mathrm{ud}} \right|^2 = \frac{(4908.7 \pm 1.9)\,\mathrm{sec}}{\tau_{\mathrm{n}} \left(1 + 3\lambda^2\right)}$$

- Neutron beta decay is the most simple beta decay snd also no theoretical uncertainty included

- Again, neutron lifetime is an important parameter in the weak interaction of the Standard Model, cosmology, and astrophysics

Neutron Lifetime Puzzle

- Two methods have been carried out to measure neutron lifetime, but the discrepancy between them is about $8\ \mathrm{sec}\ (4\sigma)$
- This problem is called "Neutron Lifetime Puzzle"



- Systematic errors that have been missed in the two methods have been studied, but the puzzle has not been resolved

Neutron's Dark Decay

- To explain the neutron lifetime puzzle, a decay of neutrons into the dark matter has been proposed
- A neutron could decay into a dark matter χ with the following three decay modes,

$$\mathrm{n} \longrightarrow \chi + \gamma$$

$$\mathrm{n} \longrightarrow \chi + \mathrm{e}^+ + \mathrm{e}^-$$

$$\mathrm{n} \longrightarrow \chi + \phi$$

(ϕ: another DM particle)

- The first process was searched but no signal was detected
- The second process distorts the energy spectrum of normal beta decay, but no $\mathrm{e}^{\pm}$ pair emission was found in the energy of $37.5\,\mathrm{keV} < E_{\mathrm{e^+e^-}} < 664\,\mathrm{keV}$ with 5σ
- The third reaction is not observable, but gives a constraint on neutron stars
- The theory requires $M_{\mathrm{NS}} < 0.7 M_{\odot}$, though heavier NS is already discovered

Storage Method (Gravitational Trap)

- There are two methods for measuring neutron lifetime, "storage method" and "beam method"

- UCNs are trapped in a bottle coated by fluorine-containing polymer
- Number of the survived neutrons N_1 and N_2 are counted after distinct storing times t_1 and t_2
- Neutron lifetime $\tau_{\rm n}$ is calculated from,

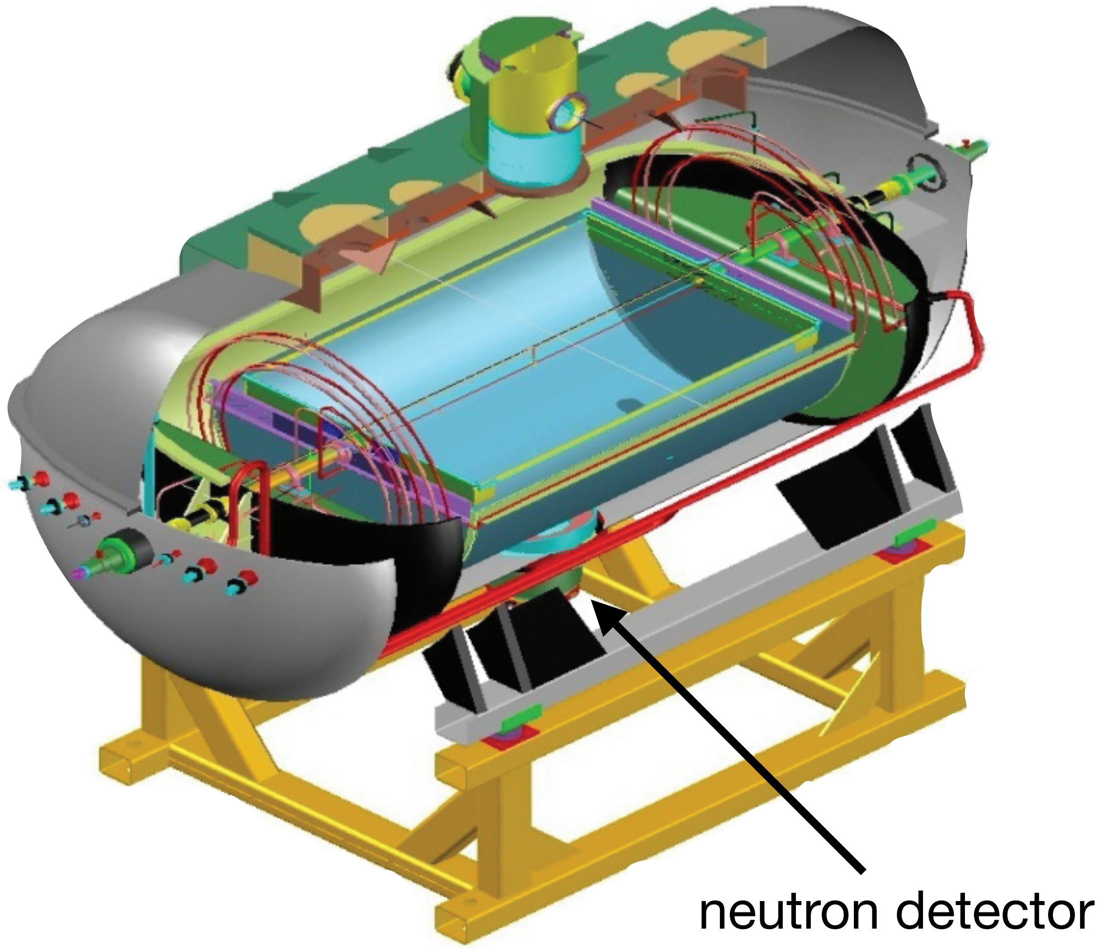
$$\frac{\ln(N_1/N_2)}{t_2 - t_1} = \frac{1}{\tau_{\rm n}} + \frac{1}{\tau_{\rm wall}}$$

- $\tau_{\rm wall}$ is for the correction of leakage of the UCNs

- By varying both the size of the bottle and the energy, loss effect was estimated

- The final result from this experiment was

$$\tau_{\rm n} = 881.5 \pm 0.7_{\rm stat} \pm 0.6_{\rm syst}\ \mathrm{sec}$$

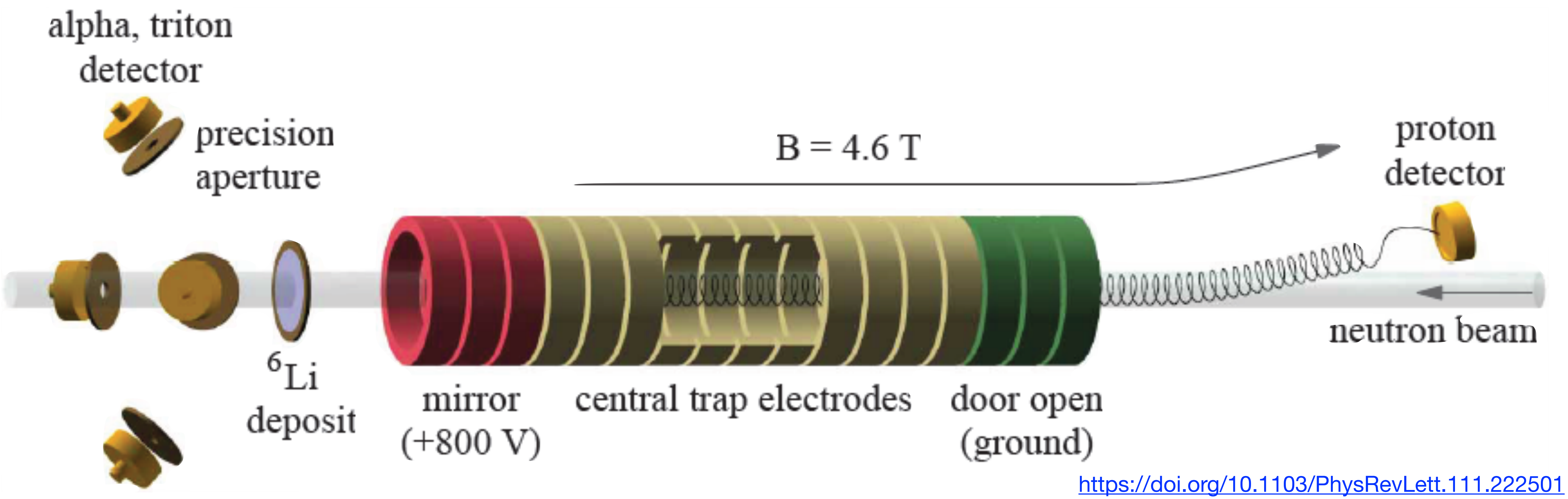


https://doi.org/10.18502/ken.v3i1.1733

Beam Method (Proton Counting)

- Protons from neutron beta decay were trapped by the penning trap technique
- The flux of neutron was monitored by using $^{6}\mathrm{Li}$ plate which converts neutrons to charged particles
  - $\mathrm{n} + {}^{6}\mathrm{Li} \longrightarrow \alpha + {}^{3}\mathrm{H}$
- Alpha particle and triton were detected by surrounding Si detectors
- This experiment published the result of

$$\tau_{\mathrm{n}} = 887.7 \pm 1.2_{\mathrm{stat}} \pm 1.9_{\mathrm{syst}}\ \mathrm{sec}$$



https://doi.org/10.1103/PhysRevLett.111.222501

Neutron Lifetime Measurement at J-PARC

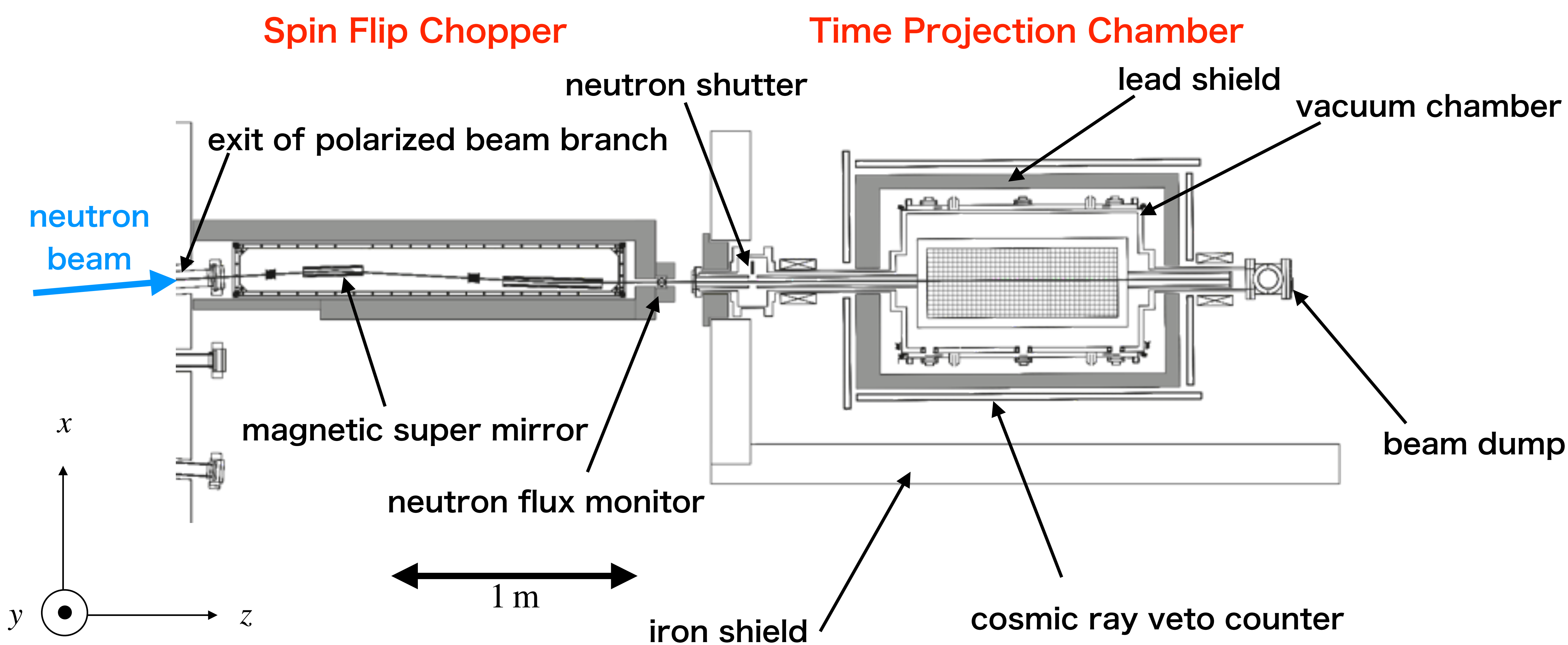
- There still remains a discrepancy between beam and storage methods
- Eliminate the possibility of unknown systematic errors
  → Run a completely different experiment that does not introduce similar systematic errors

- We are now carrying on a precise measurement of neutron lifetime at J-PARC MLF
- We are using thermal neutrons produced by colliding a $3\ \mathrm{GeV}$ proton beam to a mercury target

https://etd.canon/en/casestudy/jparc.html

Neutron Lifetime Measurement at J-PARC MLF

- By using a device called “Spin Flip Chopper (SFC)” neutron beam is formed into bunches
- Each bunch enters the Time Projection Chamber (TPC) one at a time
- Beta decay ray and proton from $^3\mathrm{He(n,p)}^3\mathrm{H}$ reaction are counted simultaneously
- Neutron flux is measured from the count rate of $^3\mathrm{He(n,p)}^3\mathrm{H}$ reaction



Neutron Lifetime Measurement at J-PARC

- The number of beta decay events is

$$S_\beta = N\left[1 - \exp\left(-\frac{t}{\tau_n}\right)\right] \sim N\frac{t}{\tau_n}$$

- The number of ${}^3\mathrm{He(n,p)}{}^3\mathrm{H}$ reaction is

$$S_{^3\mathrm{He}} = N(1 - \exp(-\rho\sigma v t)) \sim N\rho\sigma v t$$

- From above two equations, the neutron lifetime is obtained

$$\tau_n = \frac{1}{\rho\sigma v}\frac{S_{^3\mathrm{He}}/\varepsilon_{^3\mathrm{He}}}{S_\beta/\varepsilon_\beta}$$

- We reported our first measurement !

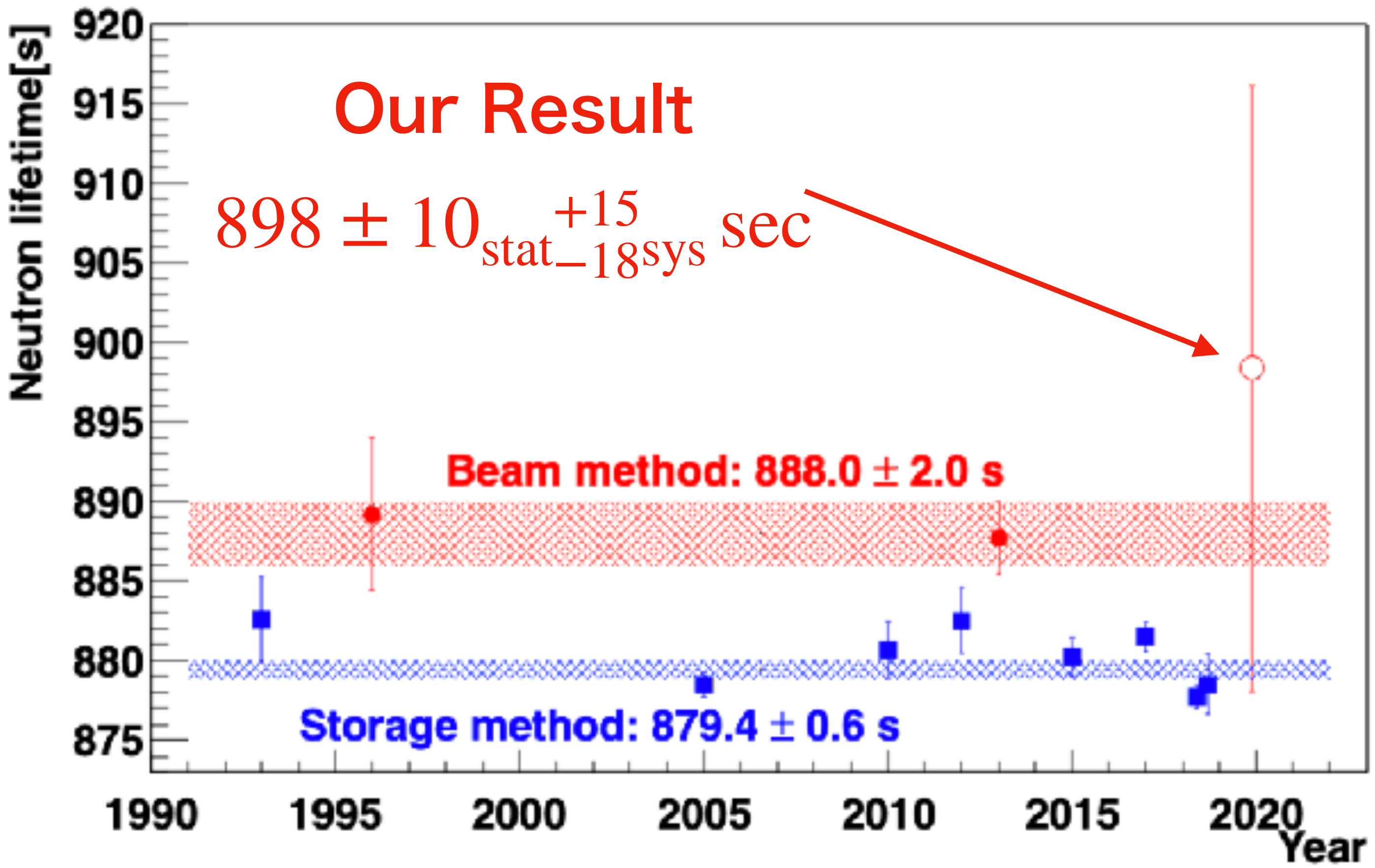
N···number of neutrons entering TPC

ρ···number density of ${}^3\mathrm{He}$

σ···cross section of ${}^3\mathrm{He(n,p)}{}^3\mathrm{H}$

v···neutron velocity

t···time during neutron exist in the TPC



Upgrades

- We demonstrated the feasibility of our electron counting method at J-PARC
- I am going to J-PARC next week to install the new Spin Flip Chopper
- It has larger mirrors so more neutrons can guided to TPC
- Also improving our analysis to reduce systematic errors
- Our goal is to determine the neutron lifetime with an accuracy of 1 second

Summary

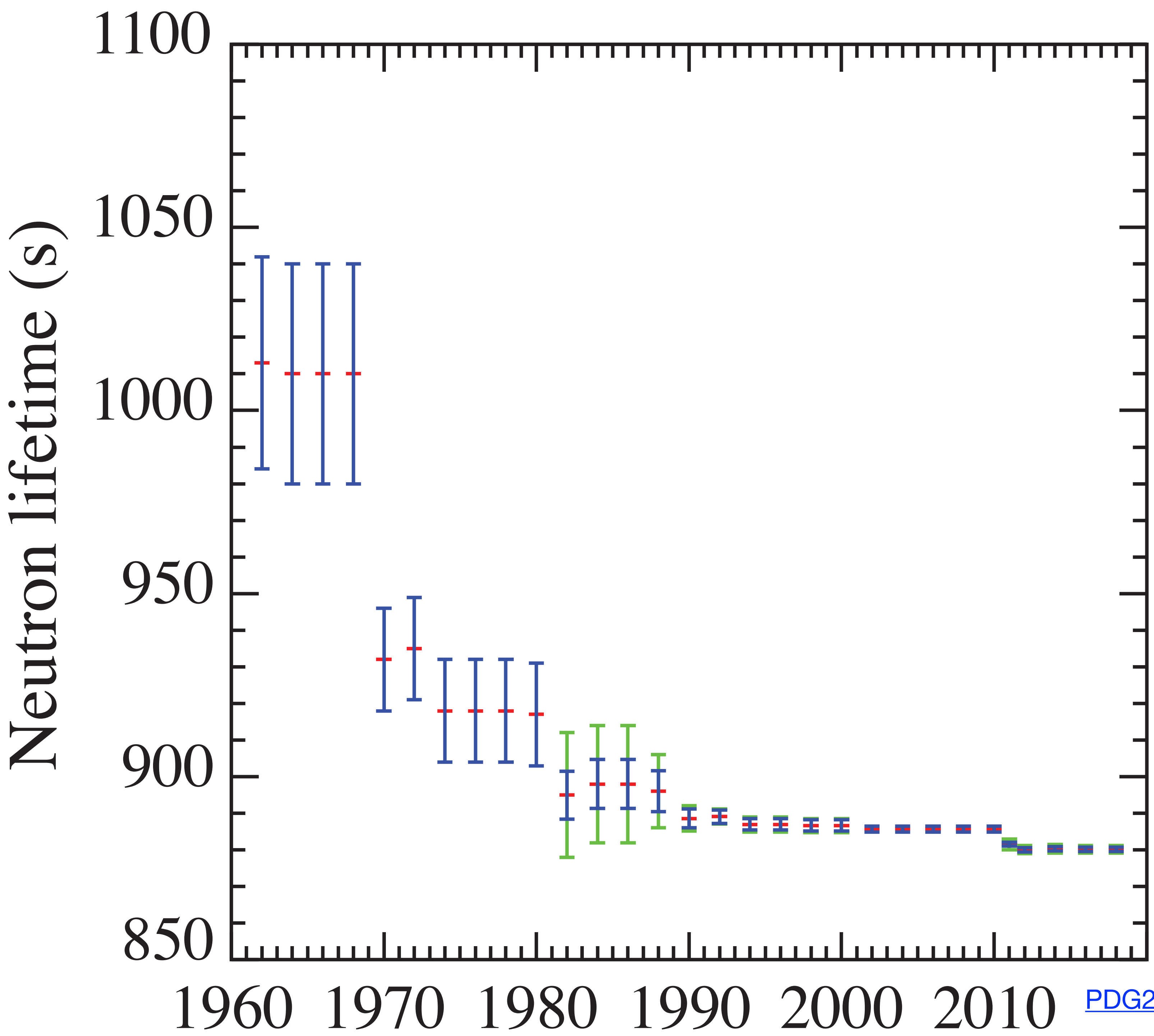
- Measurement of Neutron lifetime τ_n is an important parameter for Big-Bang Nucleosynthesis
- Precise measurement of τ_n leads to accurate calculation of abundances of light elements
- There's still a possibility of neutron dark decay

- Neutron lifetime can be a key to BSM physics

- We are in the middle of an experiment right now, and look forward to the new results !

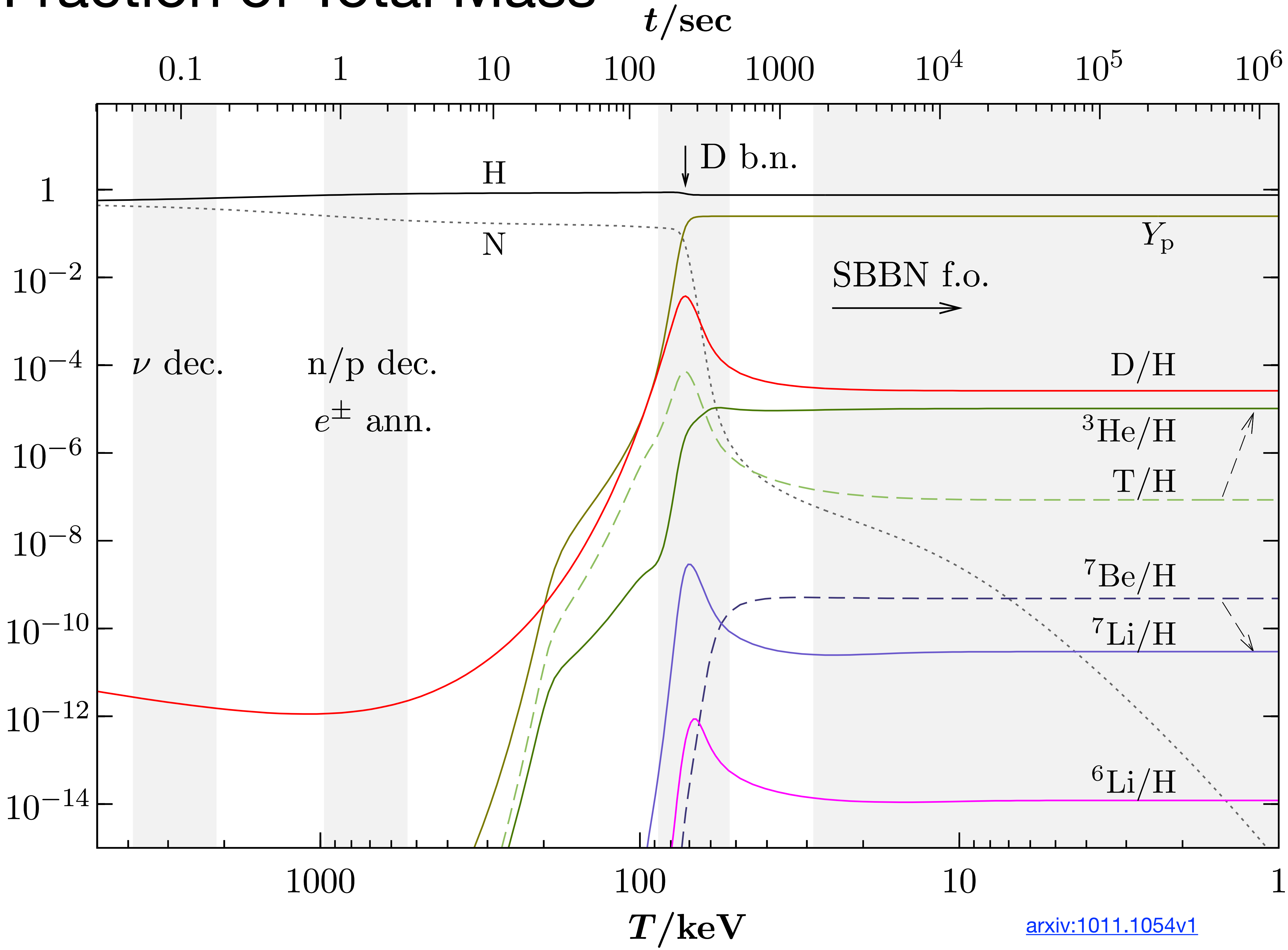
back up

History of Neutron Lifetime Measurement



PDG2020

Fraction of Total Mass



arxiv:1011.1054v1

From Precision Cosmology to Accurate Cosmology

- Peebles "From Precision Cosmology to Accurate Cosmology" (2002)
- Precision Cosmology
  - This is the dawning of the age of precision cosmology, when all the important parameters will be established to one significant figure or better, within the cosmological model.
- Accurate Cosmology
  - In the age of accurate cosmology the model, which nowadays includes general relativity theory and the CDM model for structure formation, will be checked tightly enough to be established as a convincing approximation to reality.

https://www.princeton.edu/news/2019/10/08/princetons-james-peebles-receives-nobel-prize-physics

Baryon to Photon Ratio

- Baryon to photon ratio η is derived from compression of the results of BBN and observation of $\mathrm{D/H}$

$$5.8 \times 10^{-10} < \eta < 6.5 \times 10^{-10}$$

- η is related to the baryon density Ω_{b}

$$\Omega_{\mathrm{b}} = 3.66 \times 10^{7} \eta h^{-2}$$

- The *Planck* result for

$$\Omega_{\mathrm{b}} h^{2} = 0.0224 \pm 0.0002$$

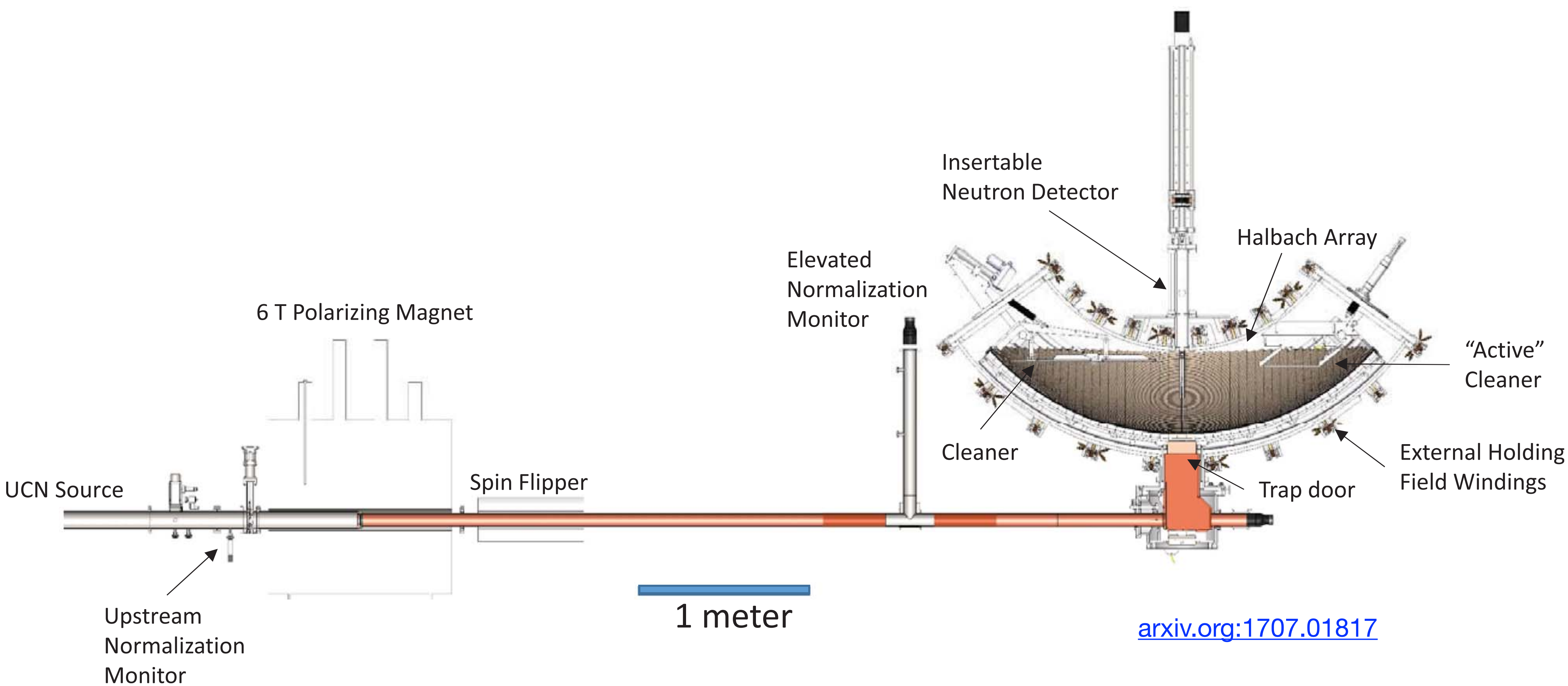
- can be translated into

$$\eta = 6.12 \pm 0.04$$

Storage Method (Magnetic Trap)

- Similar experiment was held using magnetic trap instead of gravitational trap
- It prevents the interaction between the neutron and wall material
- This experiment published the result of

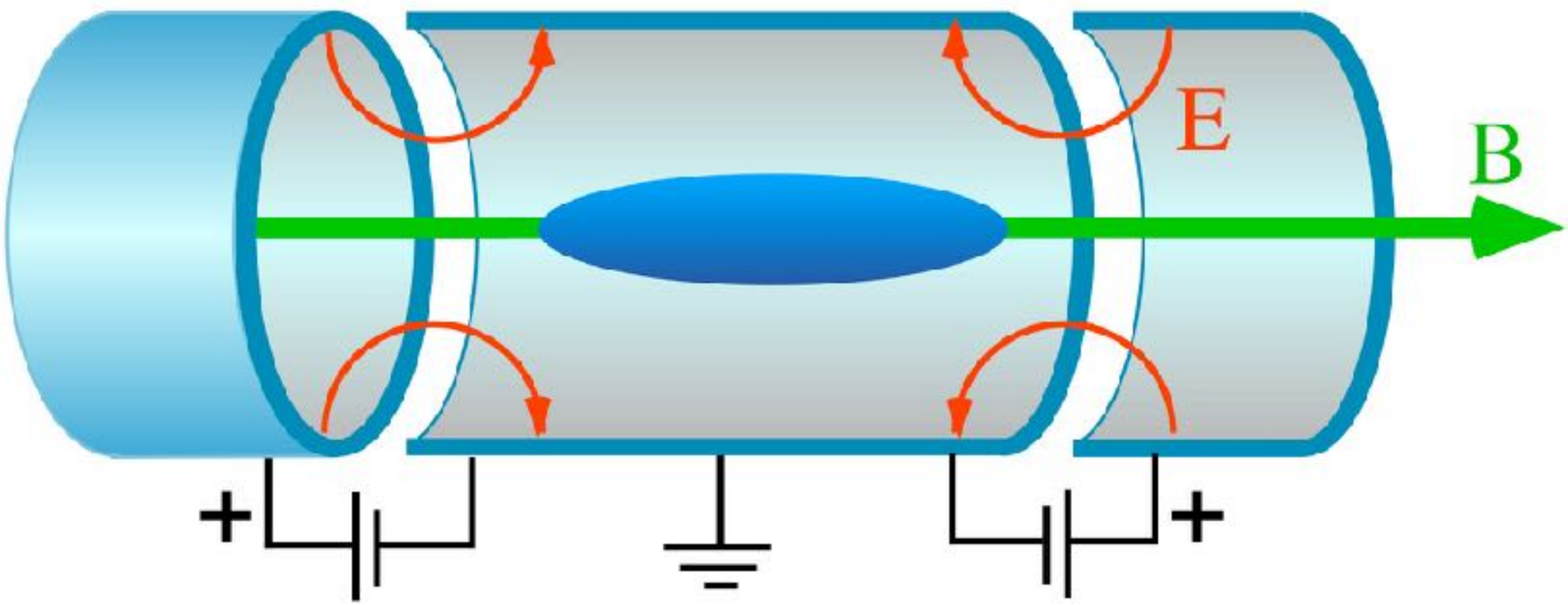
$$\tau_n = 877.7 \pm 0.7_{\mathrm{stat}}{}^{+0.4}_{-0.2\,\mathrm{syst}}\ \mathrm{s}$$



arxiv.org:1707.01817

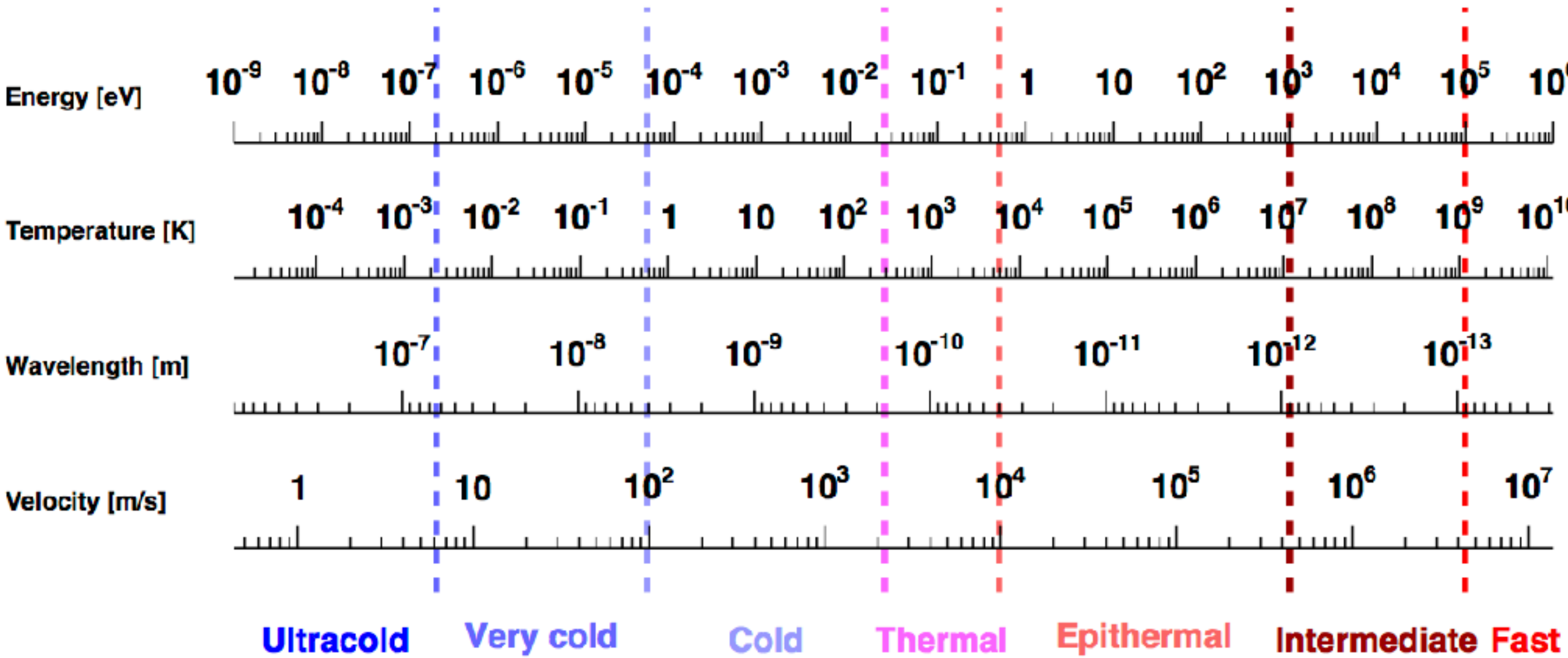
Penning Trap

- Penning trap stores charged particles by using both electric and magnetic fields
- It is particularly used for mass spectroscopy



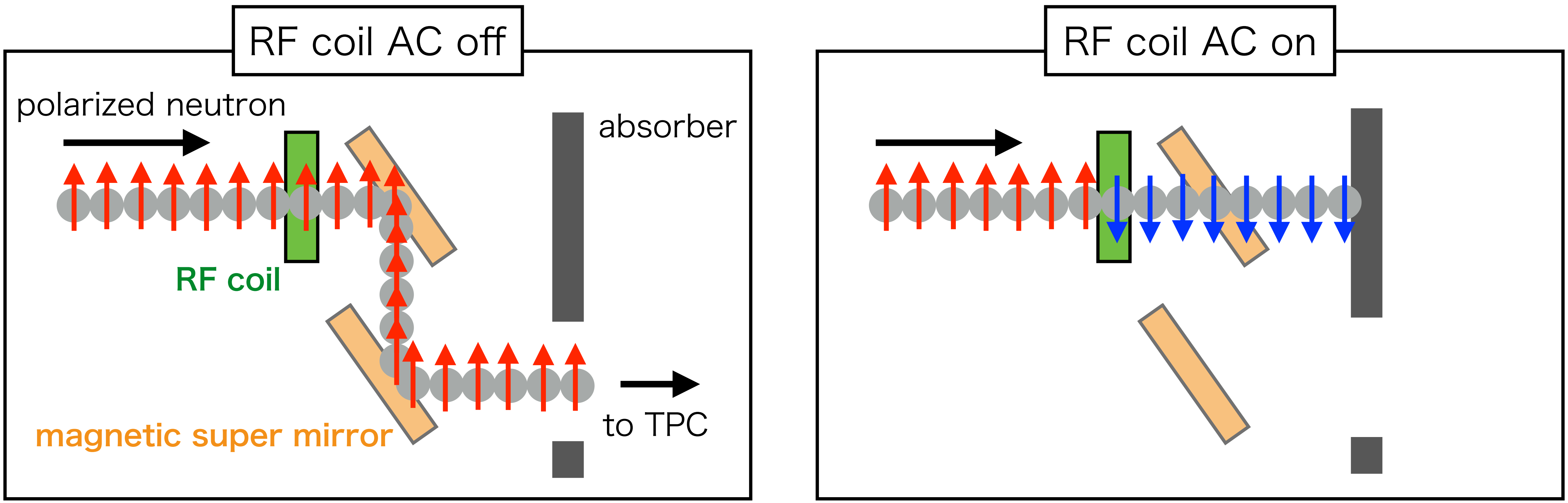
https://en.wikipedia.org/wiki/Penning_trap#/media/File:Penning_Trap.jpg

Neutron Classification

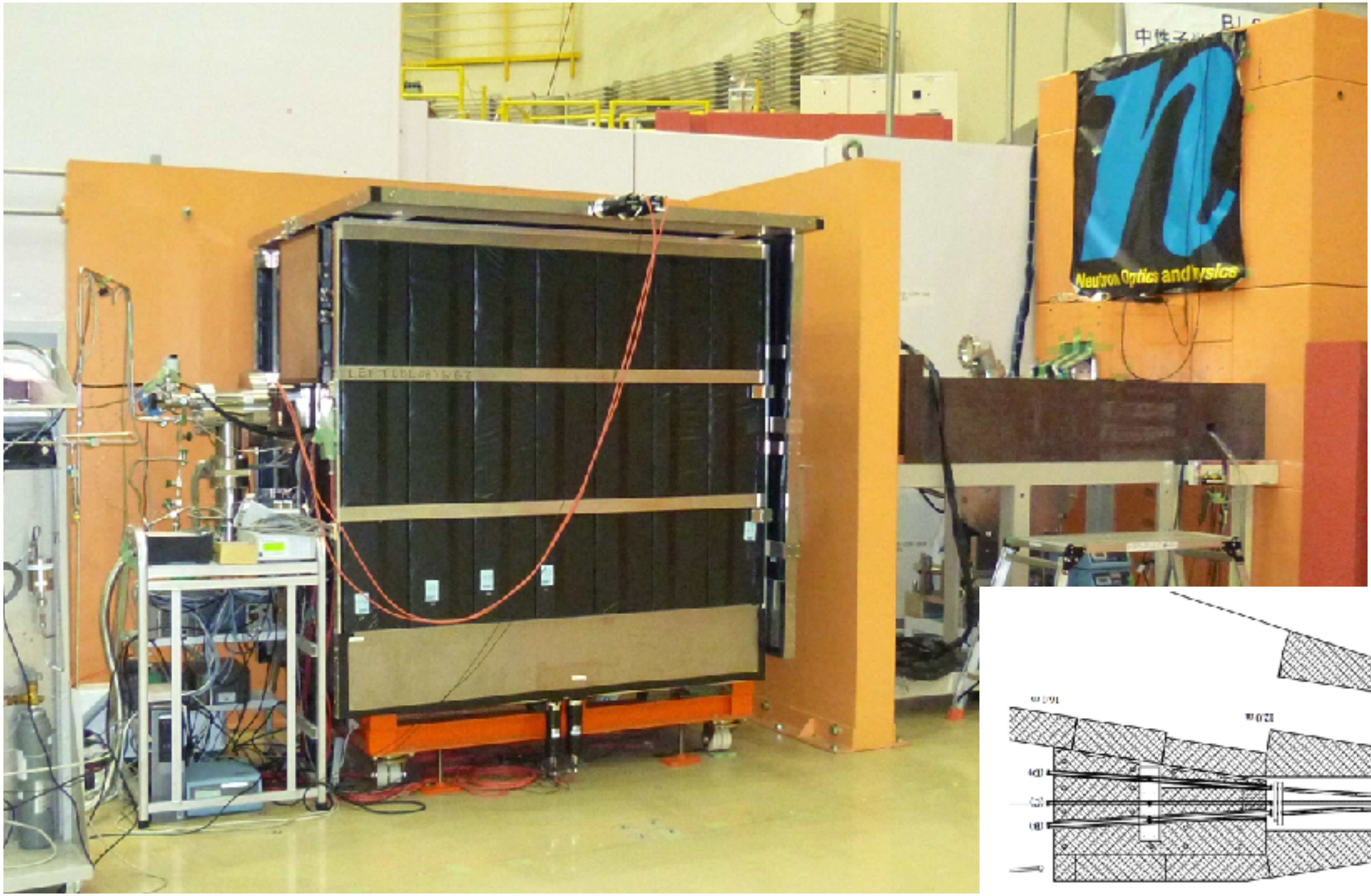


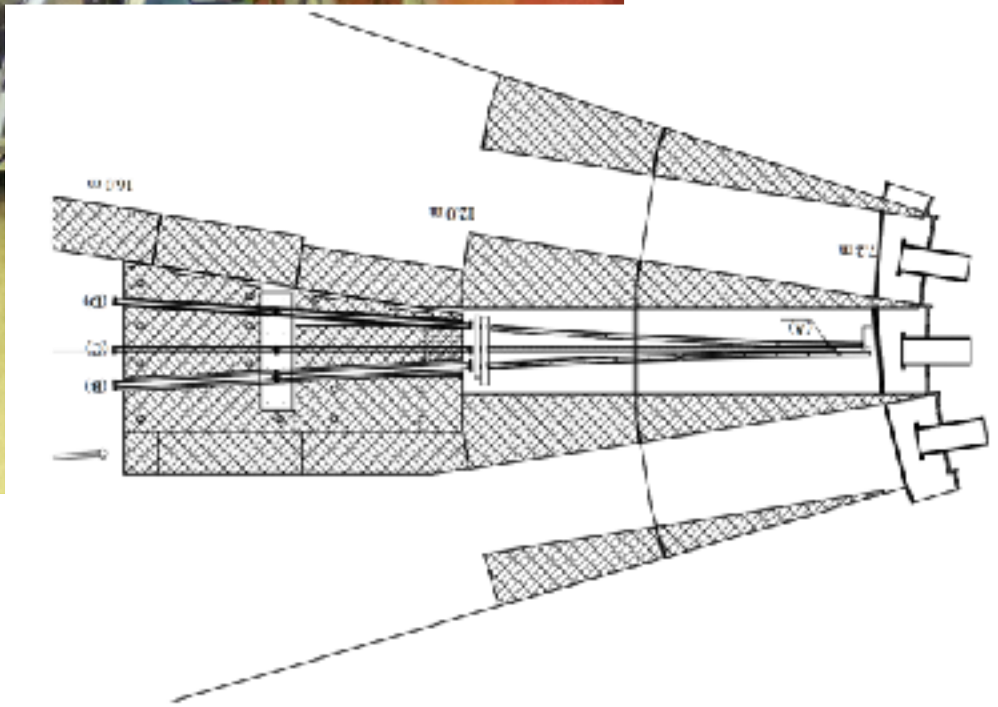
Spin Flip Chopper

- The SFC consists of two radio frequency (RF) coils and three magnetic super-mirrors
- To maintain the polarization of the neutrons, the magnetic field of $B_y = 1\,\mathrm{mT}$ is applied in the vertical direction
- Spin direction is flipped by passing the magnetic field in the RF coil
- Flipped neutrons can pass the super-mirror

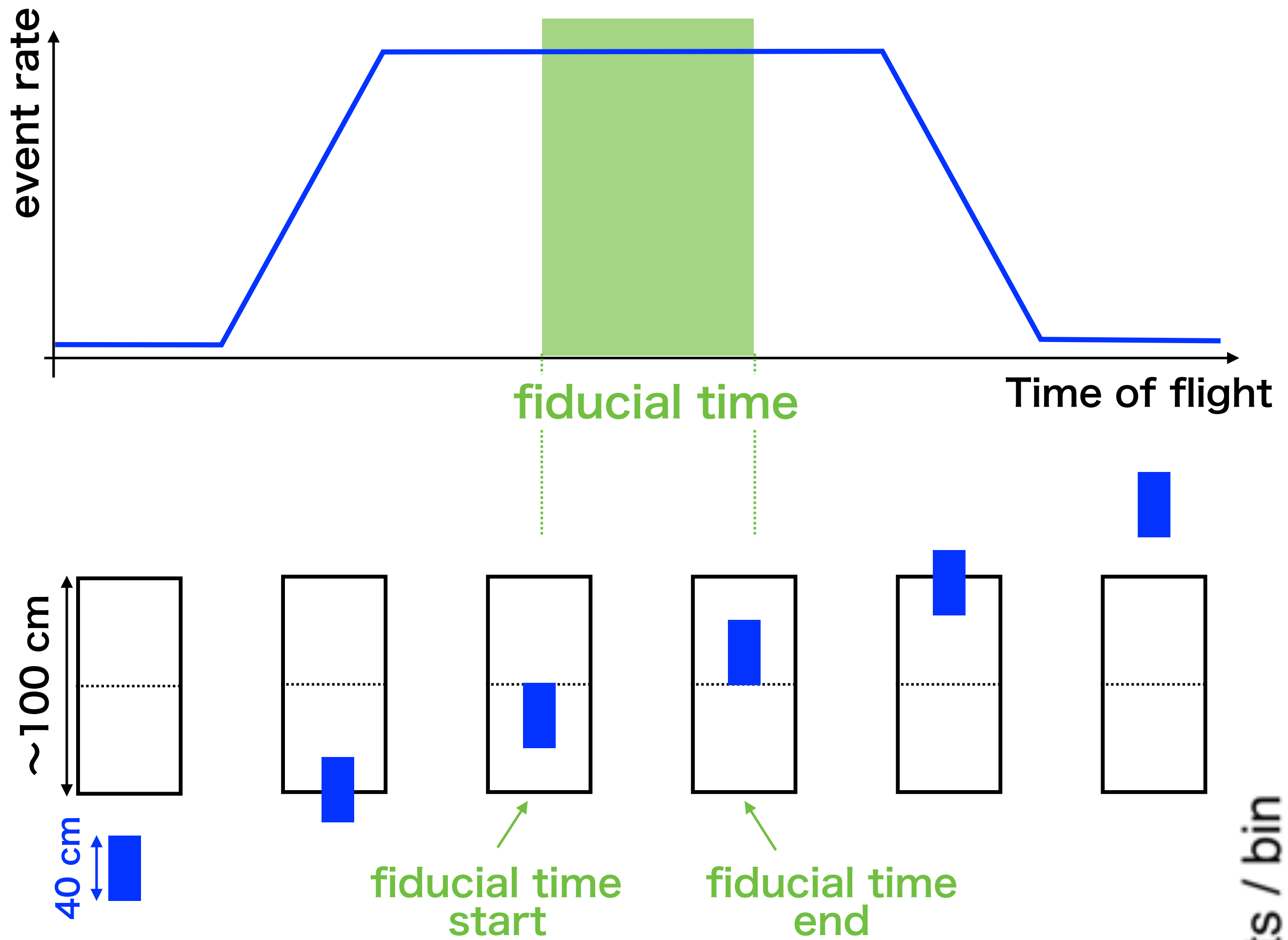


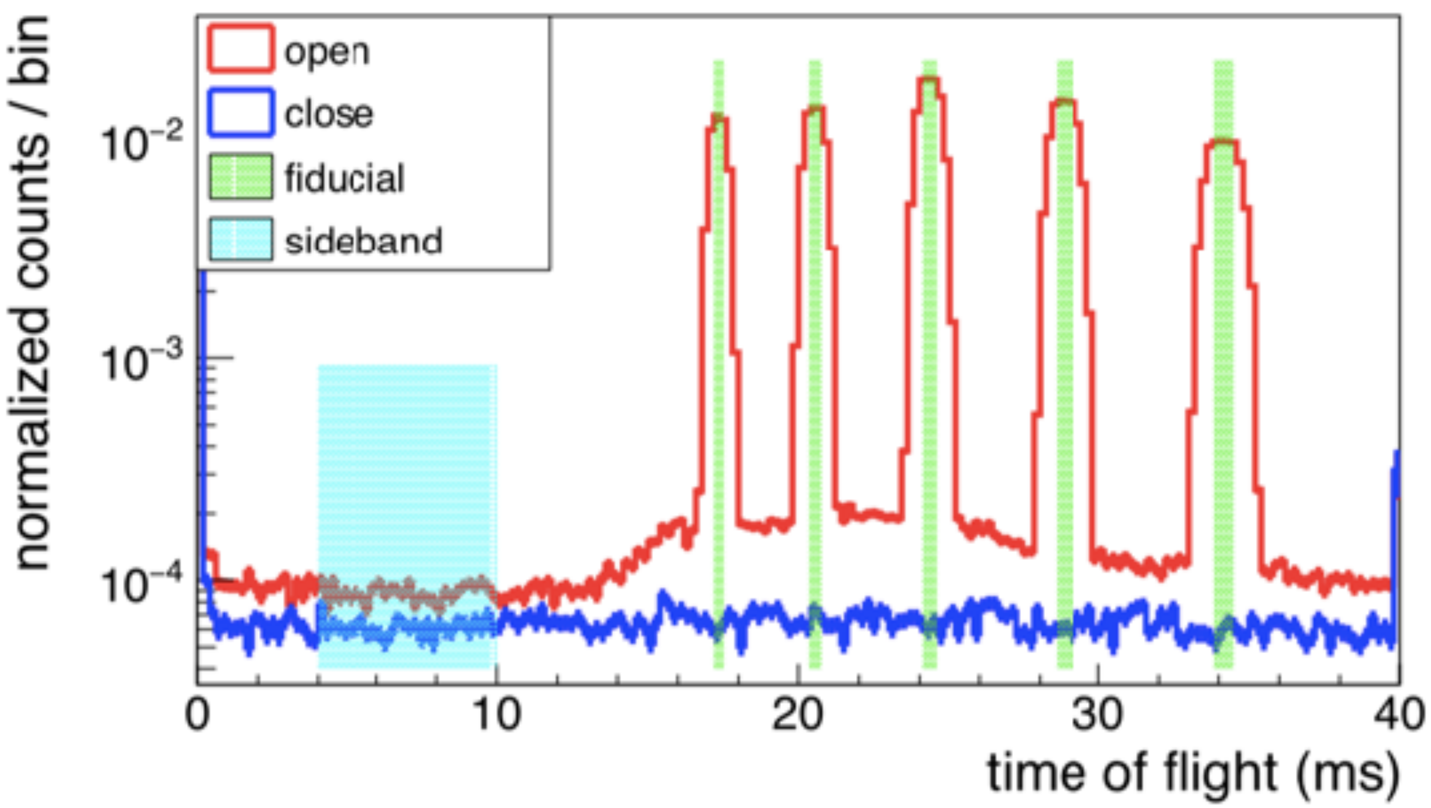
J-PARC MLF BL05 “NOP”





neutron time of flight distribution





Reference

(1) P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

(2) N. Nagakura PhD thesis, (2018)

(3) N. Sumi PhD thesis, (2020)

(4) arXiv:1011.1054v1

(5) Geoffrey L. Greene and Peter Geltenbort, The Neutron Enigma, Scientific America

(6) G. J. Mathews, T. Kajino, and T. Shima Phys. Rev. D 71, 021302(R)

(7) Lecture notes about nuclear physics by K. Muto