Highlights from J-PARC

This file is also at

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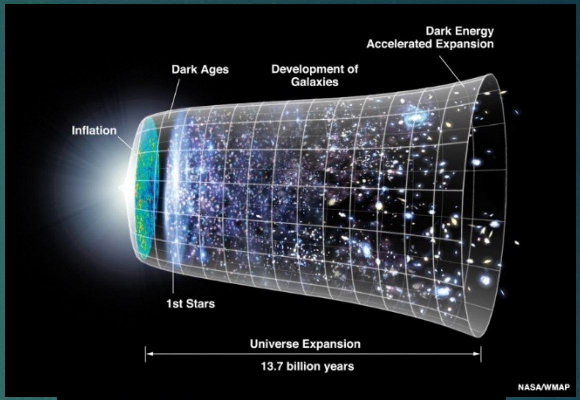
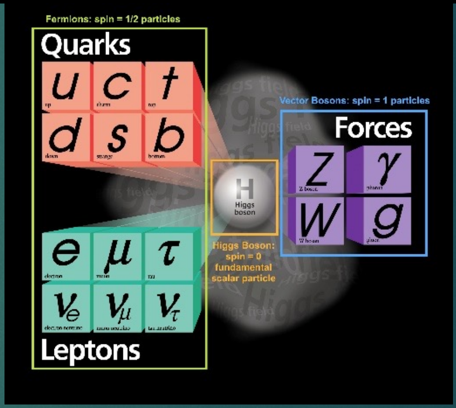
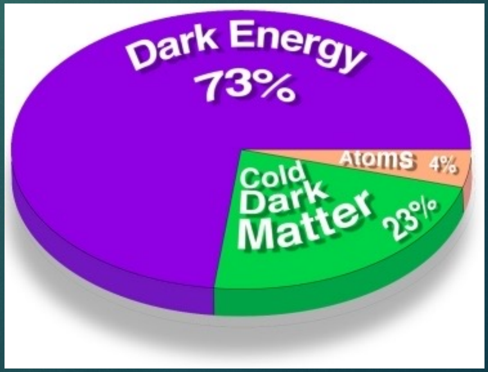
Fundamental questions in our universe

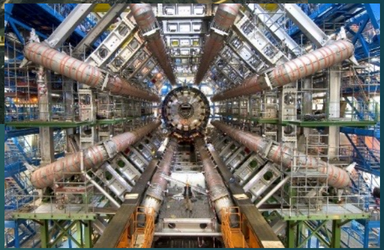


- Origin/fate of our universe
- Origin of matter
  - Where necessary CP violation comes from?
  - B-L non-conservation
- Origin of mass:
  - Higgs is really what we ordered?
- What is beyond standard model?
- Dark matter
- Dark energy



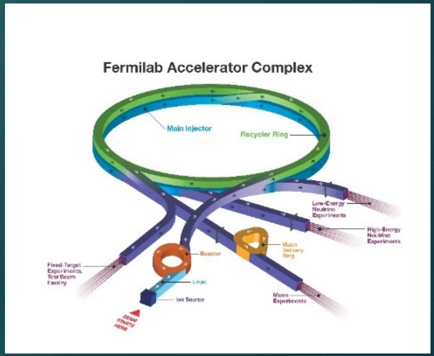


Approaches

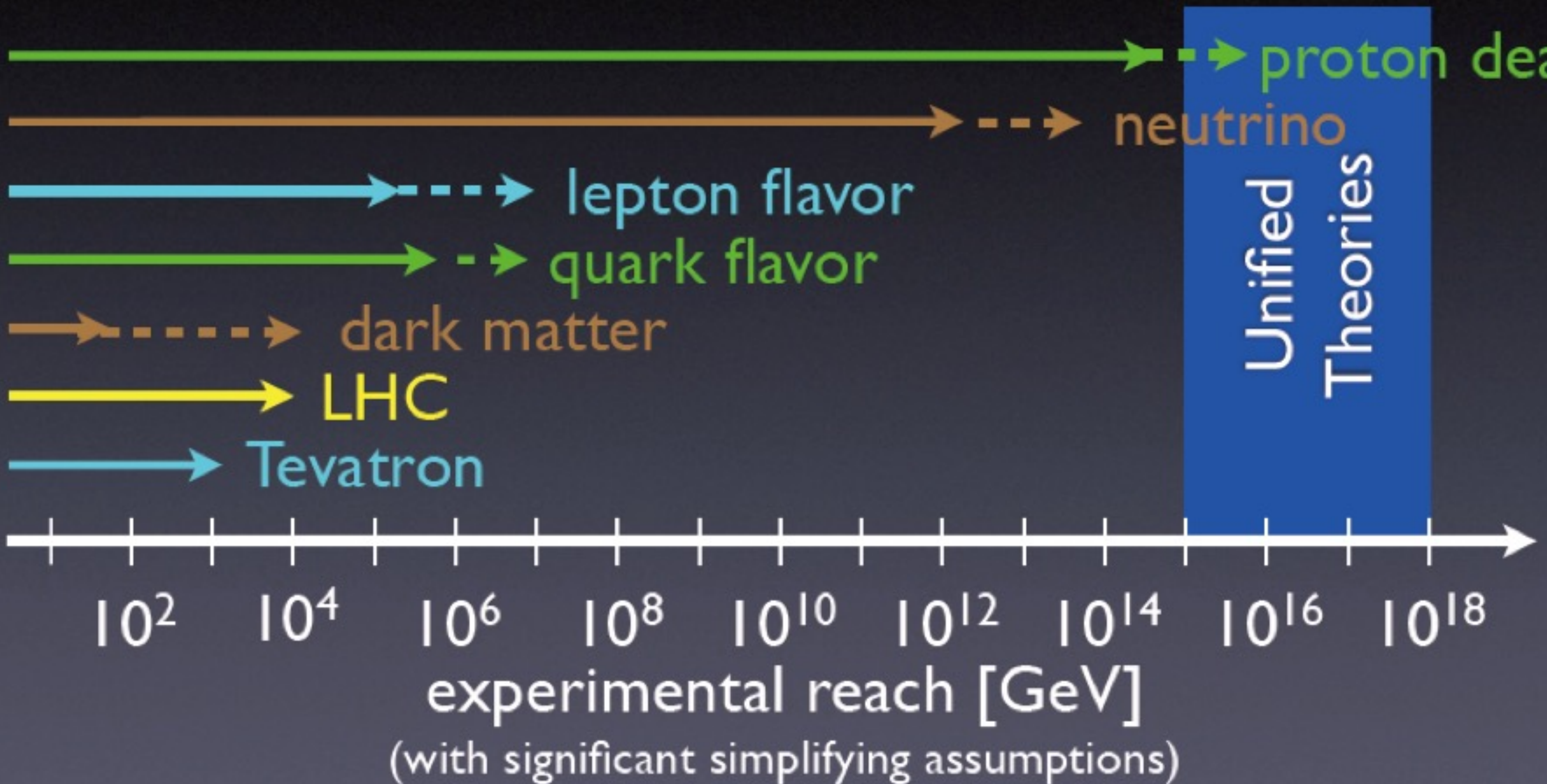


- High energy
  - Direct search
  - Tevatron (1.9TeV)→ LHC(14TeV) → ILC → ??
- **High intensity**
  - **Indirect search through loop diagram**
  - **Can probe higher mass scale than beam energy**
  - **e+e-: KEKB,PEP-II → SuperKEKB**
  - **Proton: J-PARC, FNAL-MI, LNBF,**

Fermilab



Power of Expedition



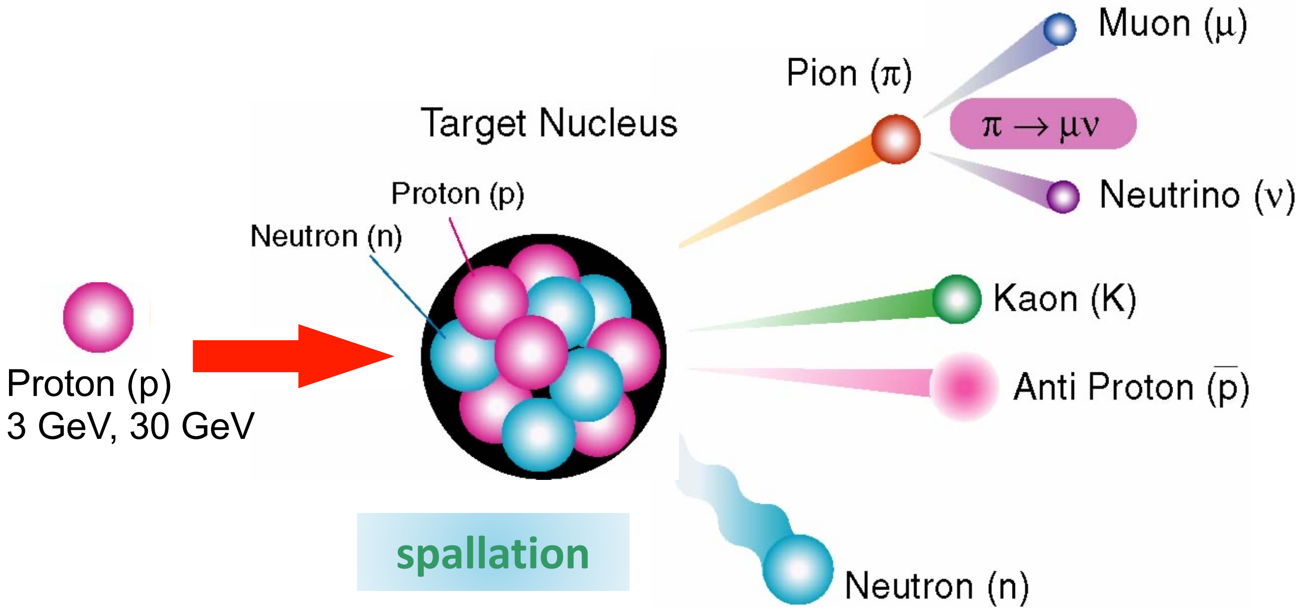
courtesy Zoltan Ligeti

a slide by Hitoshi Murayama

J-PARC

Japan Proton Accelerator Research Complex

Intensity-Frontier accelerators and multi-purpose user facilities

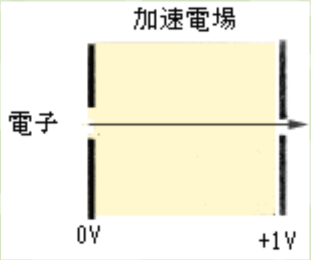


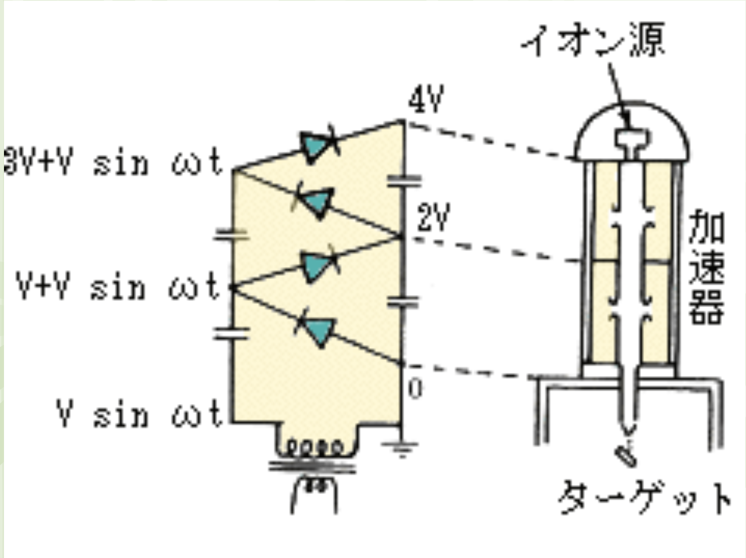
Variety of secondary particles generated with high-energy and high-intensity protons

Acceleration

Principle of acceleration

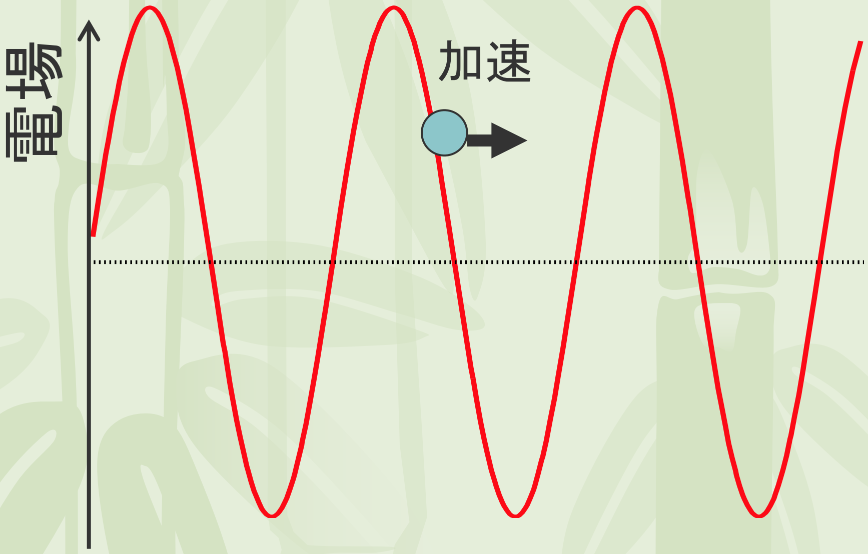
DC acceleration





Cockcroft-Walton (CW) type high-voltage DC generator

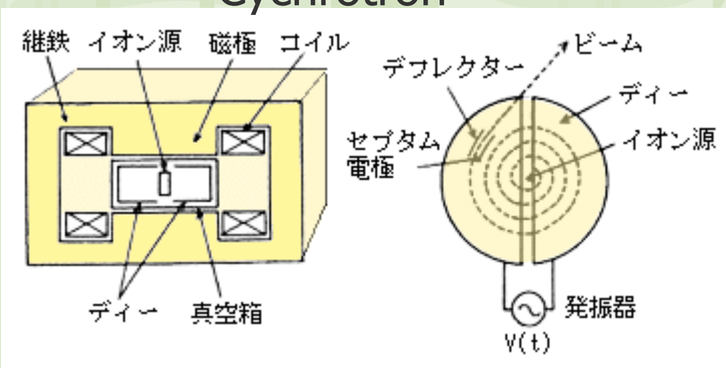
RF acceleration



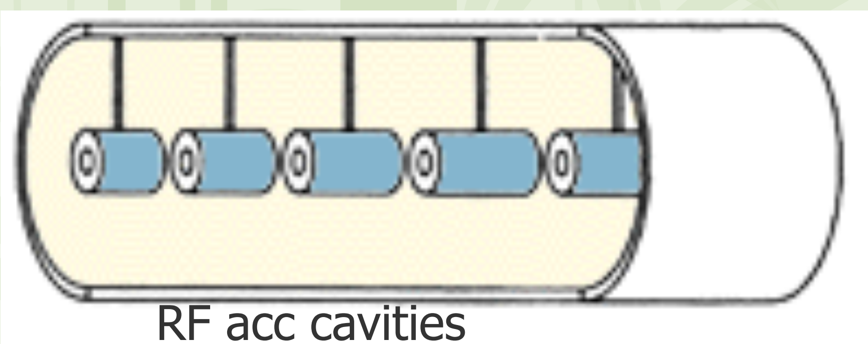
強力な電磁波を特殊な金属チューブ（RF空洞、RF cavity）内に発生させる

Types of accelerators

Cychrotron



Linear accelerator



Synchrotron

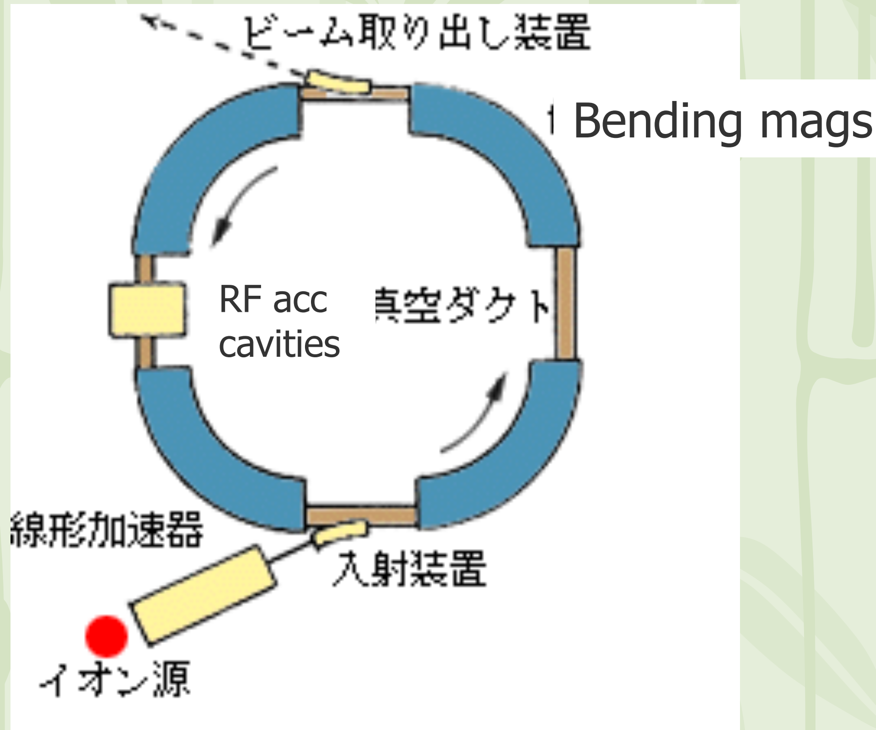


図1.シンクロトロンの構成

Gradually accelerate by circulating beam by ~10^5 times with RF acceleration at one place (~10^5eV) @J-PARC

Beam power

- Precision/sensitivities of experiments ∝ # of produced and used particles
  - Neutrino, pion, Kaon, neutron, etc,..
- # of produced particles

  ∝ [proton energy] x [# of protons/s] x [experiment time(s)]

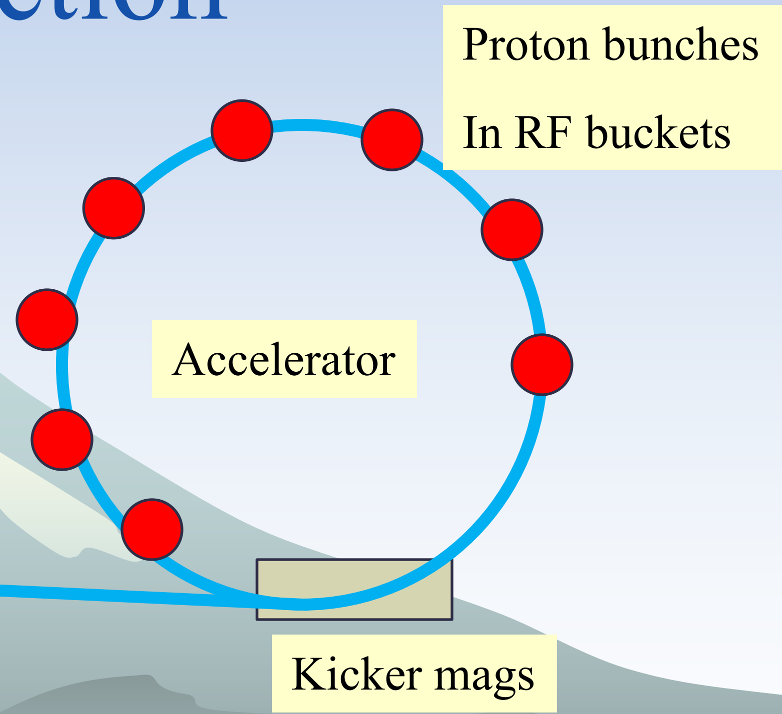
  eV (or Joule) x 1/s x s

  = Watt x s = Joule
- We use Watt to represent beam intensity

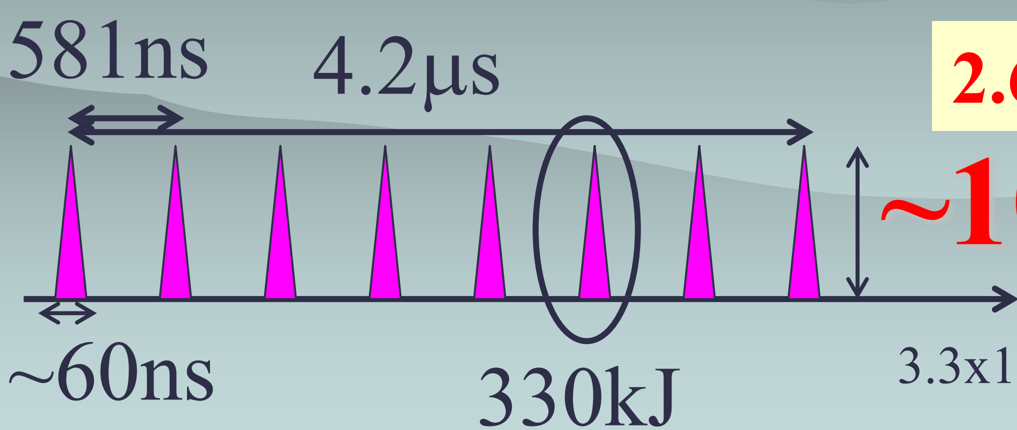
Beam extraction from acc. ring

1. Fast extraction

- Immediately after reaching top energy, turn on very fast extraction kicker magnets (rising time of ~100ns) and extract all the circulating proton beams in single turn
- Very short pulse proton beam (μs)
- Bunched by acc RF
- Suited for long baseline neutrino experiments
  - Identify ν event in far detector by timing information
  - Good for ν production (pion focusing device "Horn" need pulsed operation)



T2K case

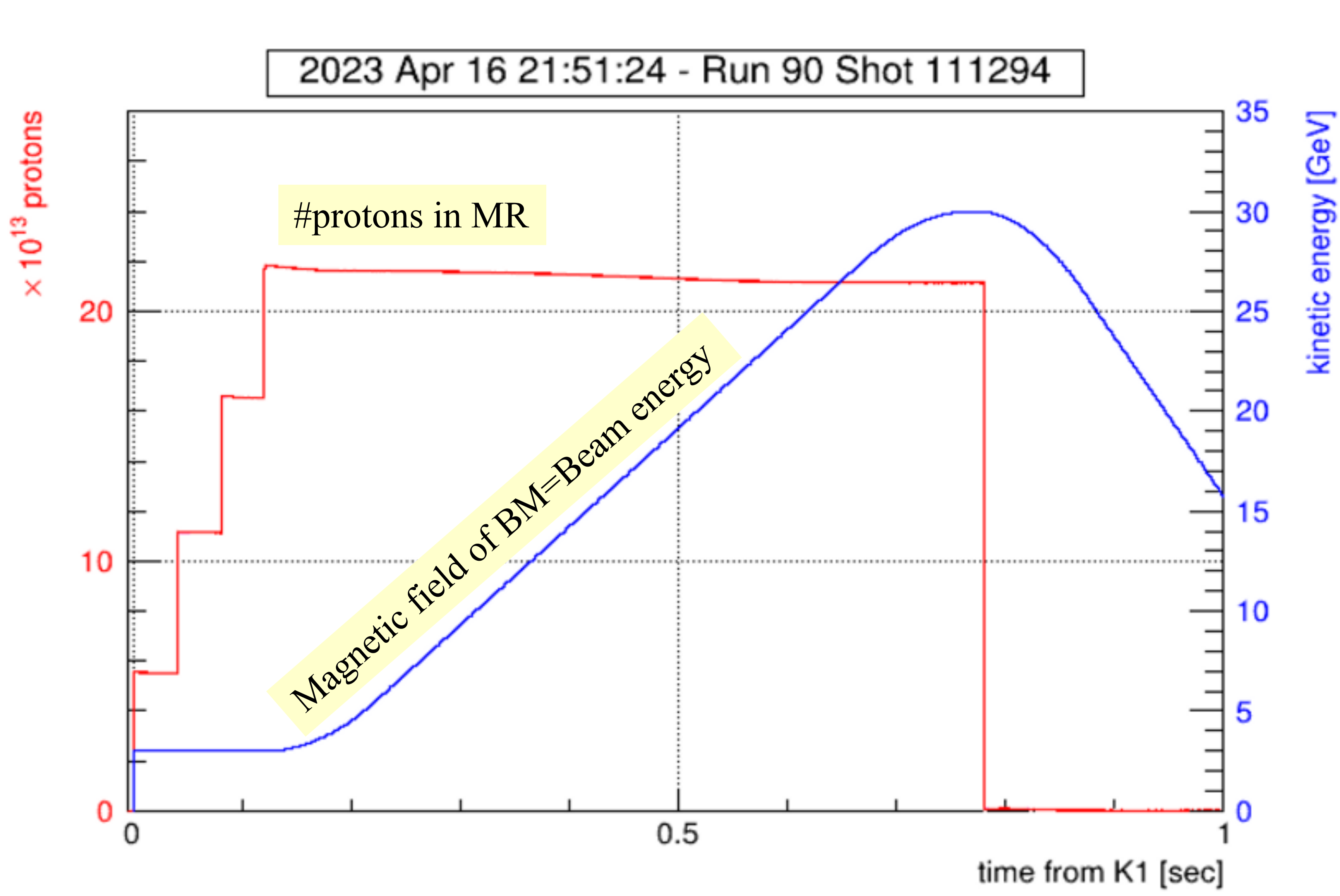


2.6MJ in ~4us!

~10TW!

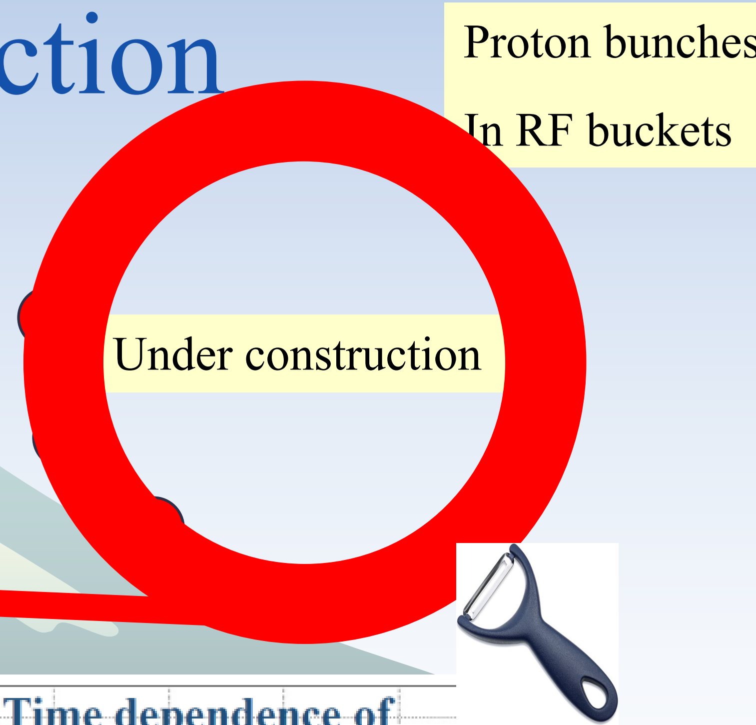
3.3×10^{14} protons in 8 bunches in ~4μs

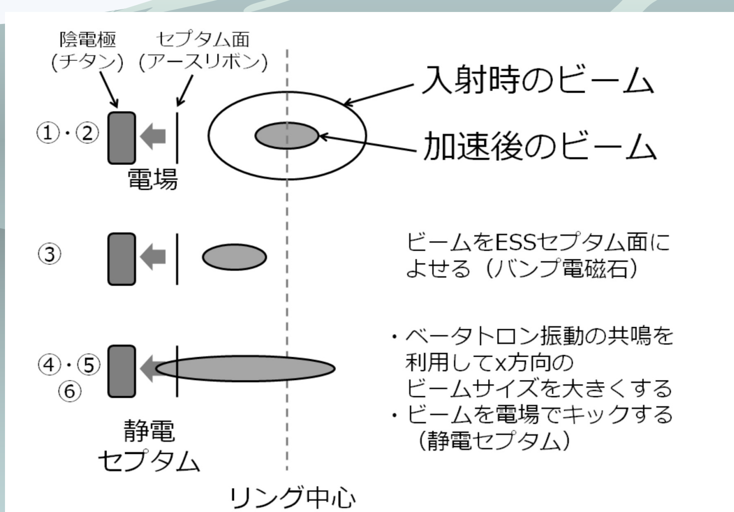
Typical acc pattern (J-PARC) of fast extraction

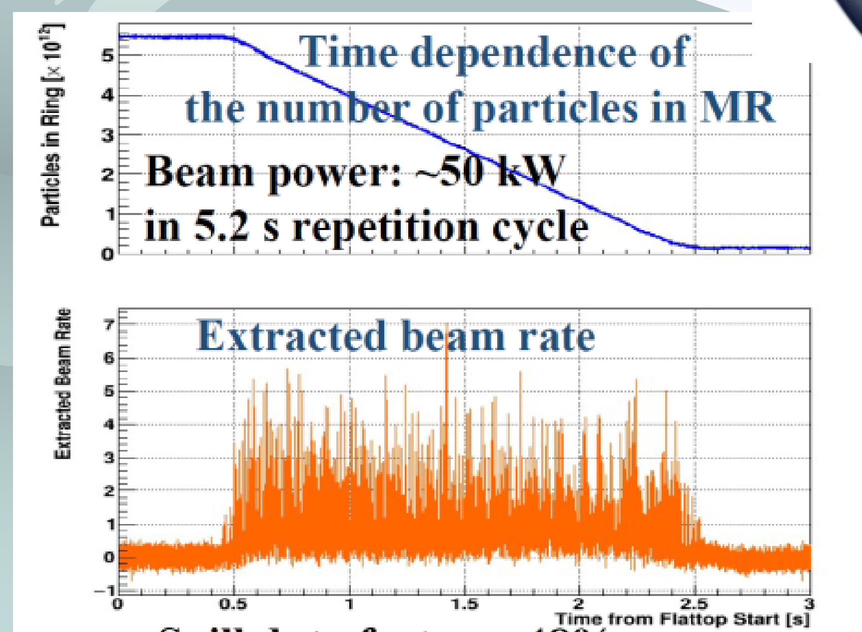


Beam extraction from acc. ring
2. Slow extraction

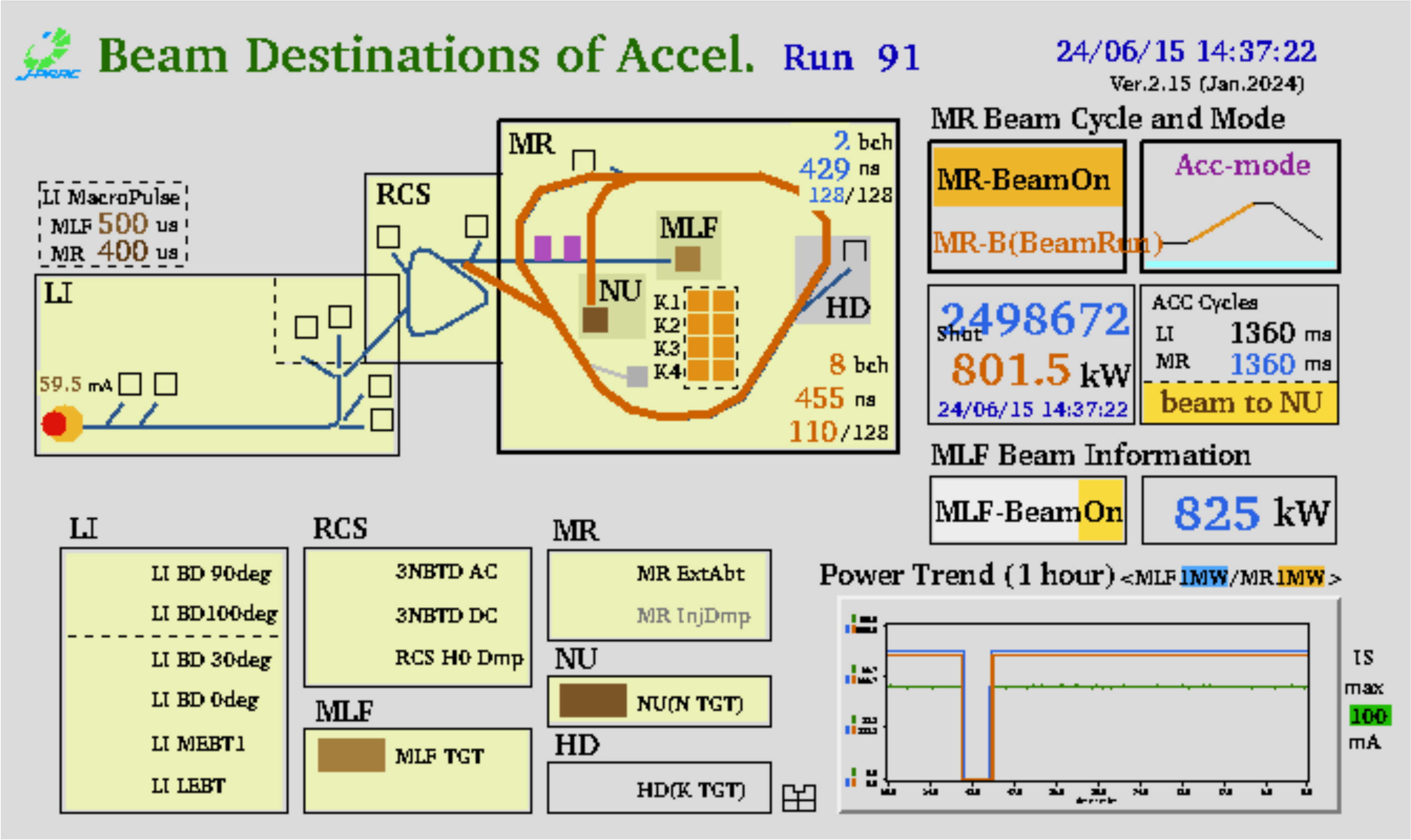
- Semi-DC beam of ~seconds
- After reaching top energy
- Turn off RF acc voltage
- wait ~ O(s) → Bunch structure disappear
- Move beam closer to “peeler”= electrostatic septum
- Gradually “scrape” proton beam and extract







MR 800kW FX operation achieved



Main ring upgrade plan

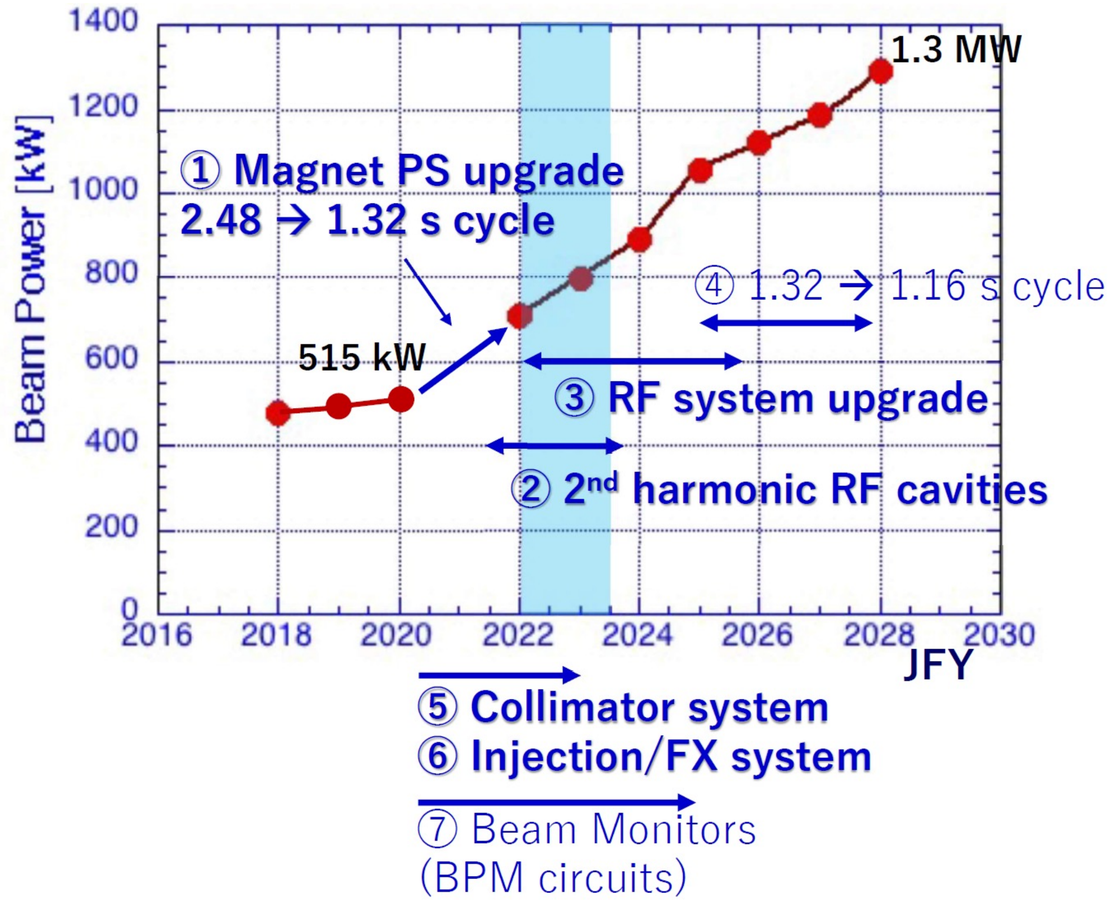
More Rapid Cycle:

2.48 s → 1.32 s → 1.16 s

- Main Power Supply to be renewed
- High gradient RF Cavity
- Improve Collimator
- Rapid cycle pulse magnet for injection/extraction

More Protons / Pulse：

- Improve RF Power
- More RF Systems
- Stabilize the beam with feedback



In April 2023
Successful demonstration of
MR-FX 30 GeV acceleration
766 kW eq. (2.17e14 ppp) in 1.36 s cycle

Bird's eye photo in January of 2008

Science at MLF w/ n/mu

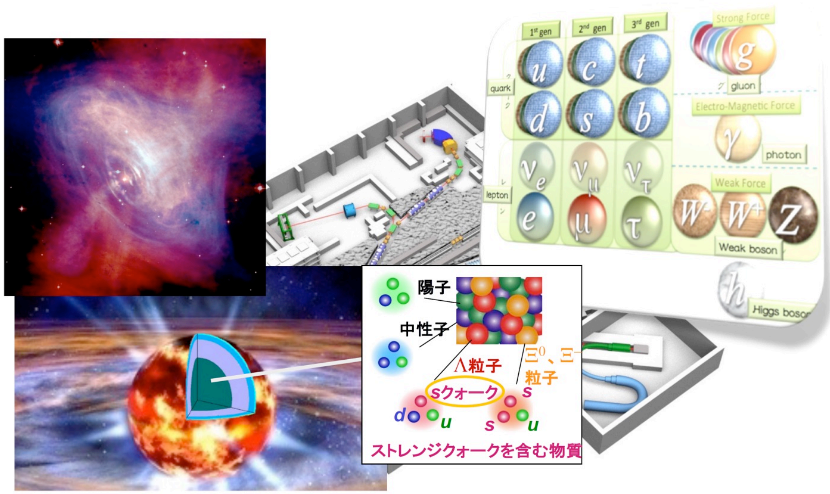
物質や Materials and life sciences 起源を探る

Neutrino experiment

Explore origin of matter in the universe

Hadron experiments

Explore origin of matter formation

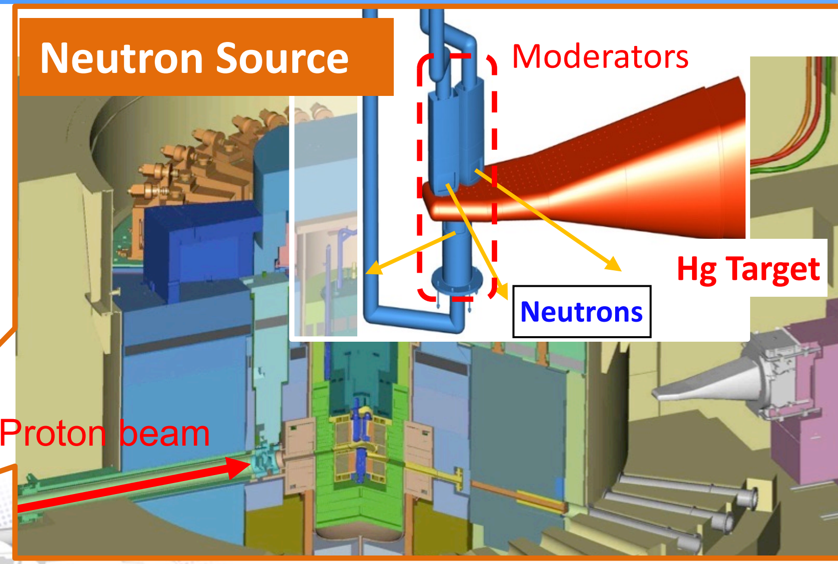


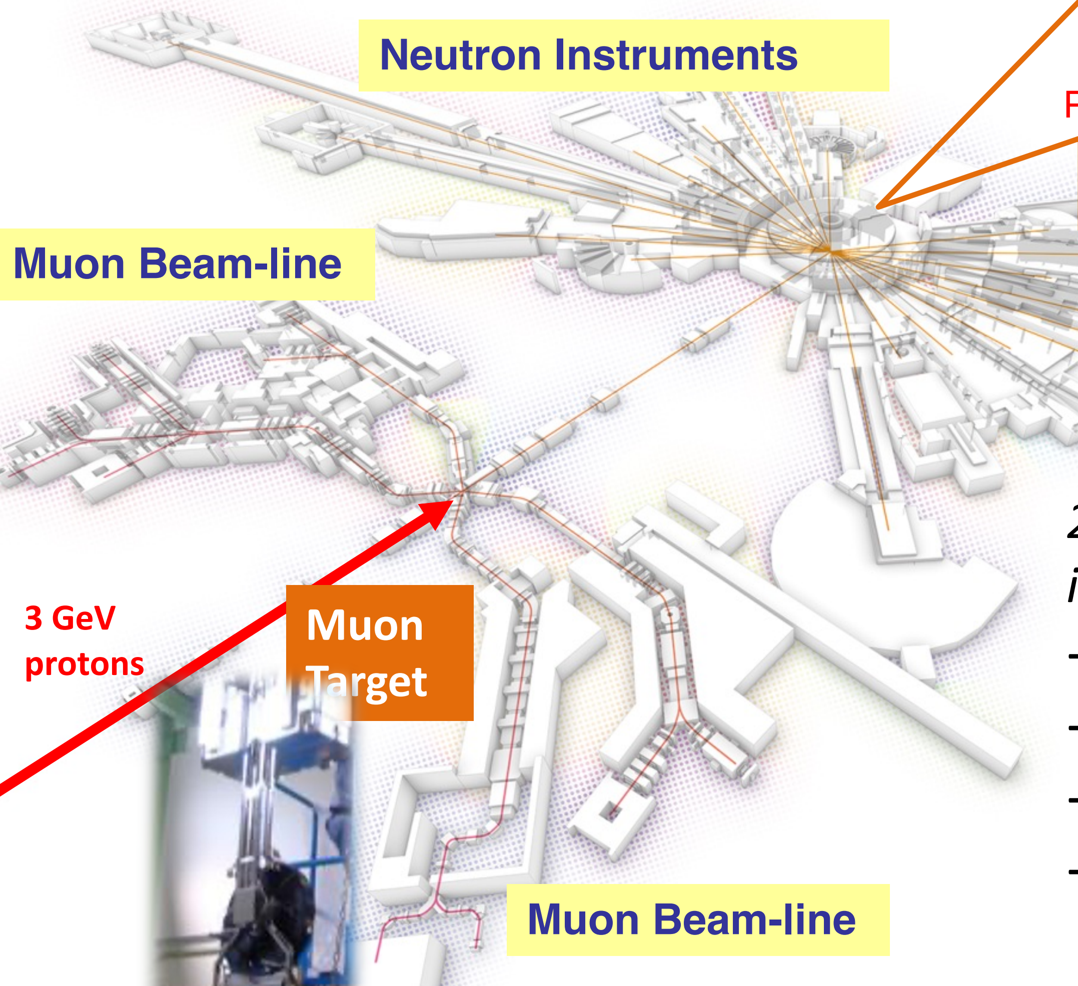
Development Accelerator Driven nuclear transmutation System: ADS

Experiments at MLF

Materials and Life Science Experimental Facility (MLF)

- **Neutron** and **muon** beams
  - materials science, life science, industrial applications
- **most powerful** neutron and muon sources





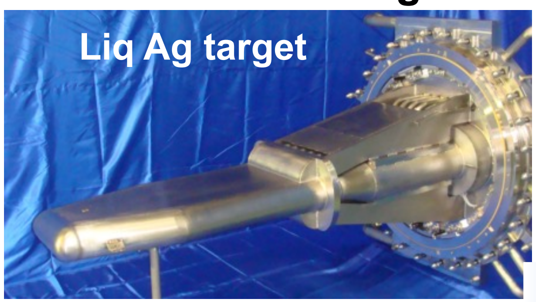
21 neutron and 4 muon beam lines are in operation, carrying out studies of

- *high-temperature superconductors*
- *protein, soft matter*
- *fuel cell, catalyst, new materials*
- *innovative products and drugs*

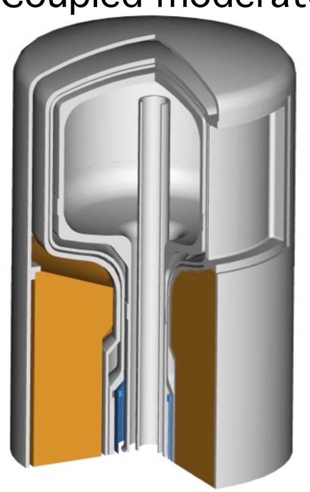
etc.

World leading neutron intensity

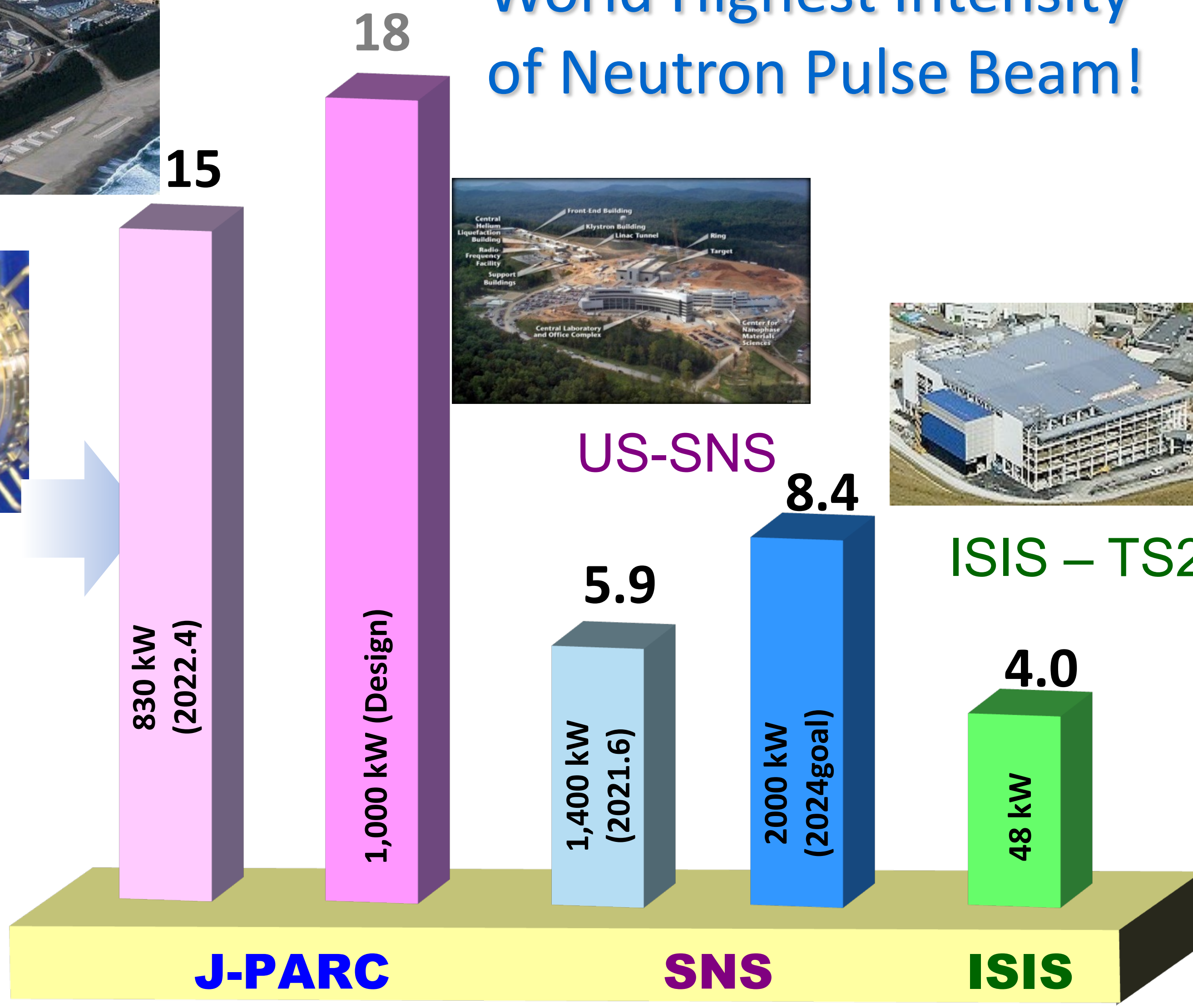
JAEA's technologies



Coupled moderator



World Highest Intensity of Neutron Pulse Beam!



Unit: 10^{12} n/(sr・pulse)

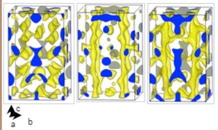
Only a few of recent outcome from MLF

Neutron Science — Designing materials for All-Solid-State Li Batteries

Tokyo Tech.、IMSS KEK、Univ. of Tokyo 、J-PARC Center

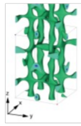
Science 2023 IF : 63.832
11,663 download

$Li_{10}GeP_2S_{12}$
Nature Materials 2011



High ionic conductivity is observed when Li ions diffuse in 3D direction. However, high -T is required.

$Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$
Nature Energy 2016



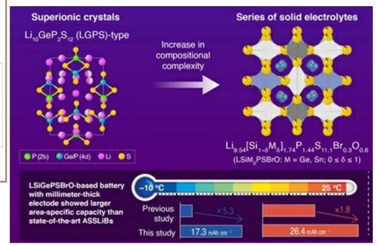
Discovered a material in which Li ions diffuse in a 3D direction even at room-T.

Tokyo Tech, IMSS KEK, TOYOTA, Ibaraki Pref., Ibaraki Univ.,J-PARC Center

Citations over 3,000 (Sum), TOP 0.01%

$Li_{9.54}[Si_{0.6}Ge_{0.4}]_{1.74}P_{1.44}S_{11.1}Br_{0.3}O_{0.6}$

Thick-film cathode with 1.8 times the current capacity per electrode area is fabricated. Combined with Li metal anode, all solid-state battery exhibiting high-capacity and high-current characteristics is realized.



Analysis of the crystal structure containing Li by neutron diffraction leads to an understanding of the Li ion diffusion mechanism, contributing to the development of all solid-state batteries

Elucidates that the super ionic conductivity of the new material originates from a crystal structure with a complex and highly disordered atomic distribution (High-entropy material).

Neutron Science — Development of high-strength magnesium alloy

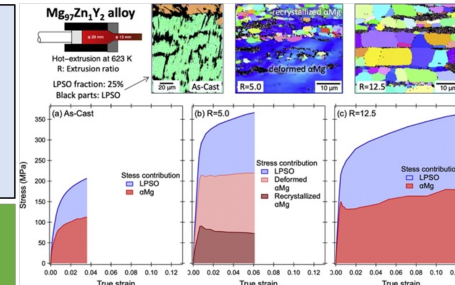
[15 Aug. 2023 Press Release] Why Are High-Strength Magnesium Alloys Developed in Japan So Strong？
In-situ Neutron Diffraction Experiments Elucidate the Behavior of Each Constituent Phase during Deformation

JAEA, Kumamoto Univ., J-PARC Center

IF:9.209
Acta Materialia (2023) Citation : 7

- Because of their **lightweight and high strength per density,** Mg-alloys (LPSO-Mg alloys) developed at Kumamoto Univ. are expected to have various applications.
- The strength of LPSO-Mg alloys is greatly enhanced by high-T extrusion processing, but **the mechanism has not yet been clarified**.

In-situ neutron diffraction experiments revealed that **the extrusion conditions affected the overall strength and ductility of the alloy** due to different micro-structural development.



(upper) Mg alloys used in this study and EBSD images after high-T extrusion process. (lower) Contribution of each of the LPSO-Mg alloy constituent phases to strength during tensile deformation.

- **Provides guidelines for the development of lightweight, high-strength Mg alloy materials with ductility, rigidity suitable for specific purposes.**
- **Contribution to energy saving and safety of aircraft and** automobiles through practical use of lightweight and high-strength materials.

Water visualization in a fuel cell used in FCEV

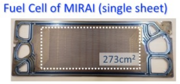
Supported by NEDO FC-Platform Program

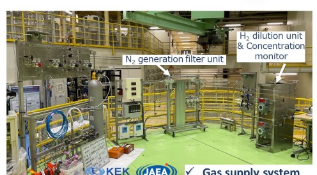
FC•Platform
NEDO

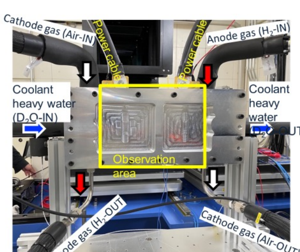
Visualization of water distribution inside an operating fuel cell of the 2nd generation TOYOTA MIRAI

FCEV TOYOTA MIRAI

Fuel Cell of MIRAI (single sheet)

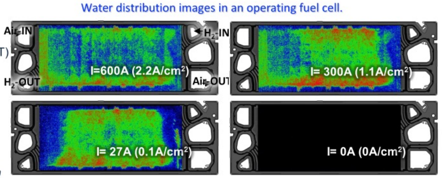






Fuel cell was assembled with thick Al end plates.

Water distribution images in an operating fuel cell.



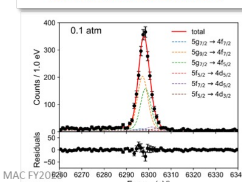
14

D line: High-resolution X-ray spectroscopy of muon atoms

Physics under ultra-high electric field opened up by Muon Atoms

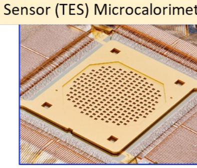
The energy of muonic X-rays was determined **with extremely high accuracy using a TES detector** with an energy resolution **10 times higher** than that of conventional semiconductor detectors

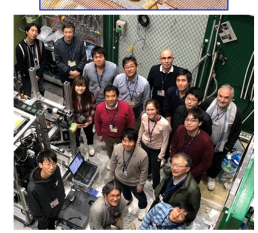
Quantum Electrodynamics Verified with Muonic Atoms



MAC FY2023
2024/2/22

Superconducting Transition-Edge Sensor (TES) Microcalorimeter





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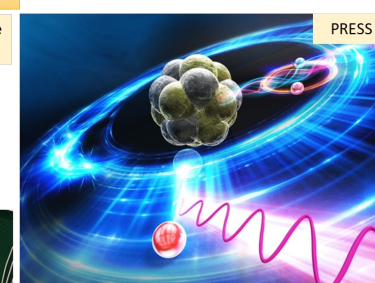
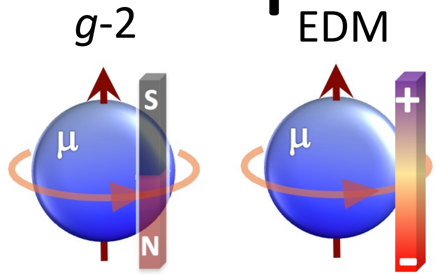


Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

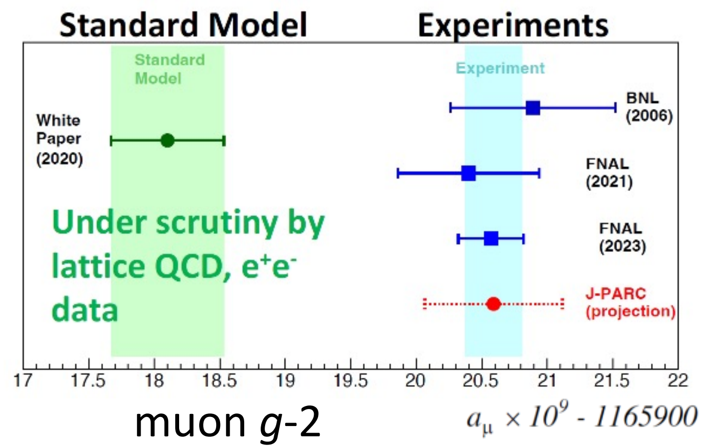
T. Okumura *et al.*, Phys. Rev. Lett. 130, 173001 (2023)

~500 experiments/year

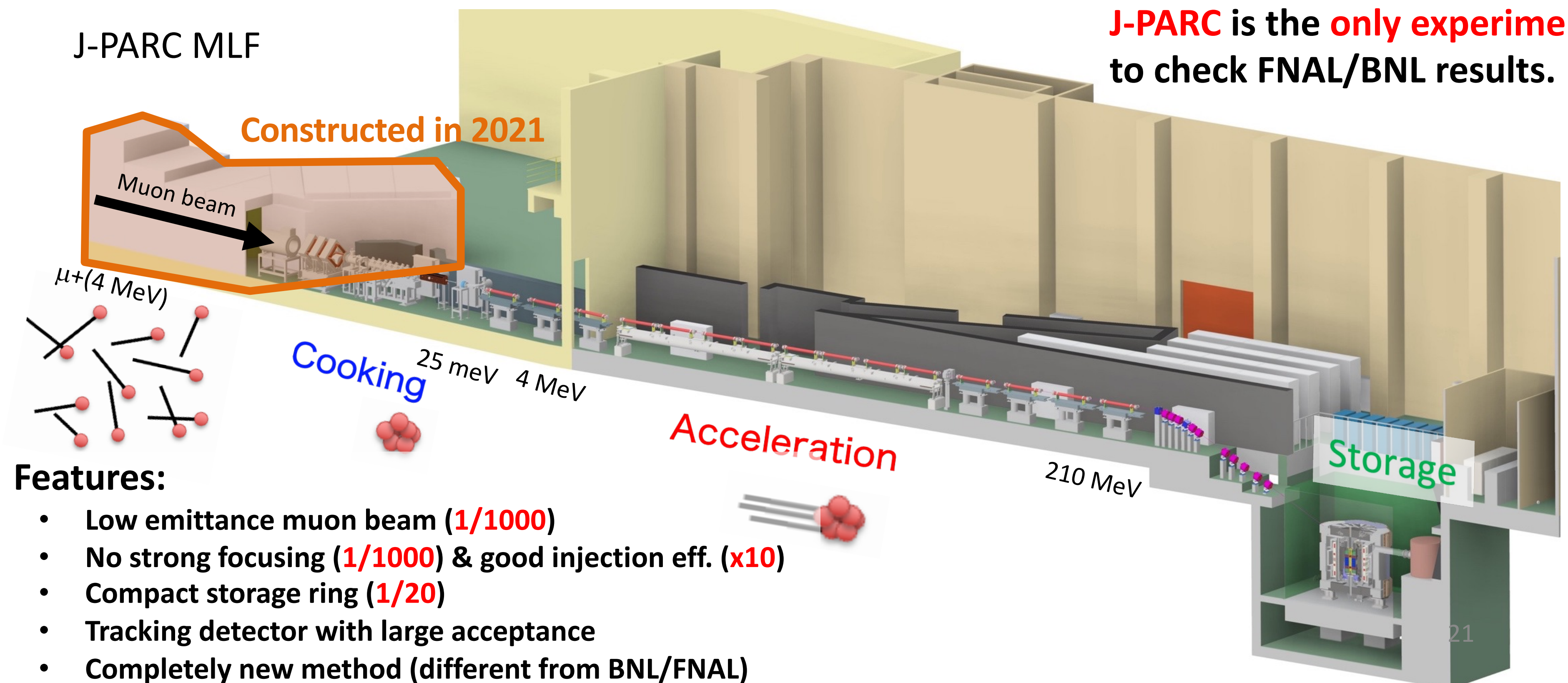
J-PARC muon g-2/EDM experiment



- Aim to reach
  - μ g-2: 450ppb
  - μEDM: 1.5e-19
- Aiming for data taking from 2028



J-PARC is the only experiment to check FNAL/BNL results.

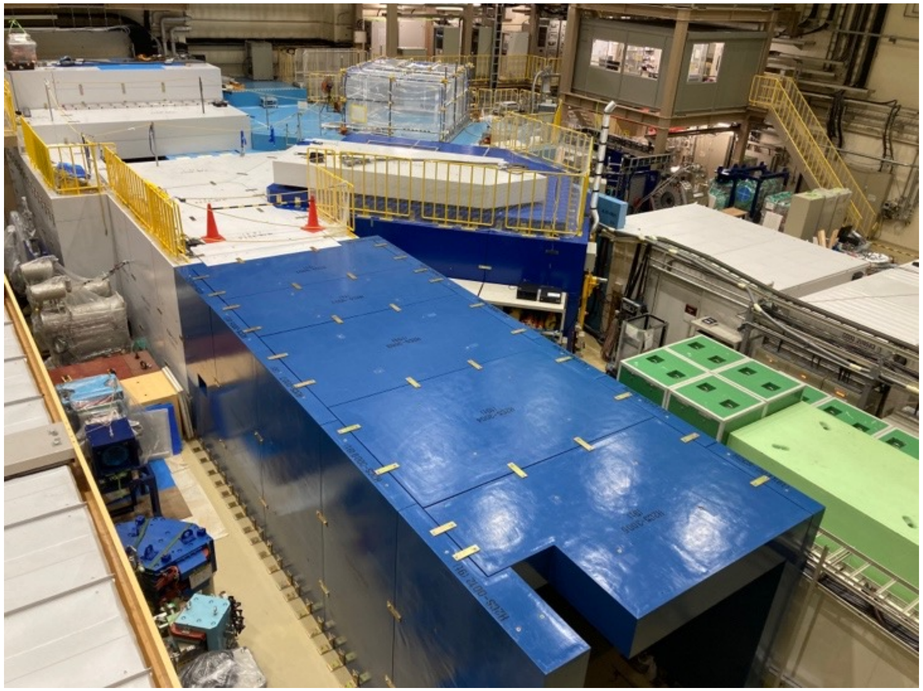


Features:

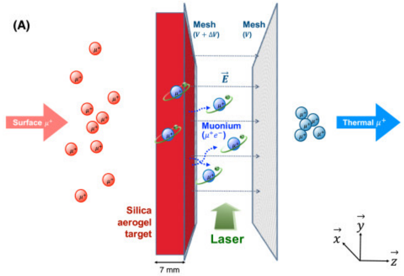
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely new method (different from BNL/FNAL)**

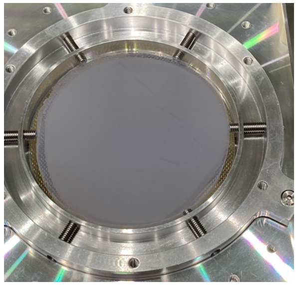
J-PARC muon *g*-2/EDM experiment

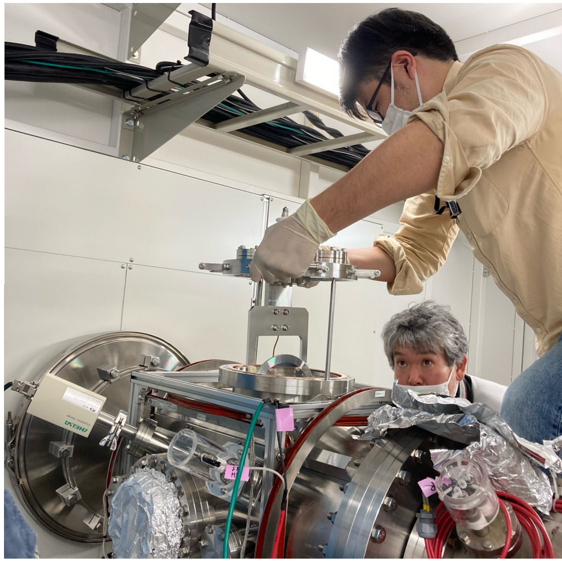
New radiation shields for beamline extension (2022)



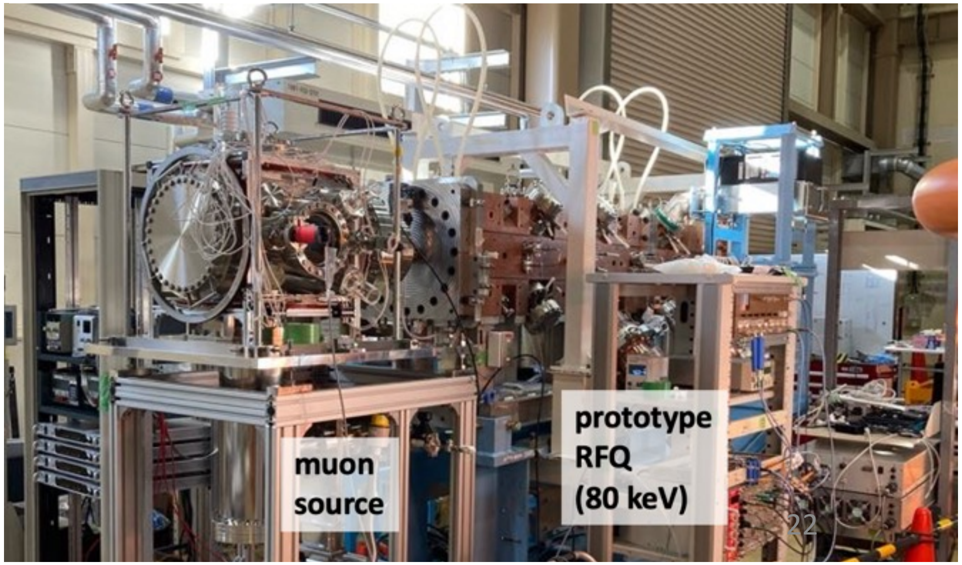
Muon cooling test (2022~)



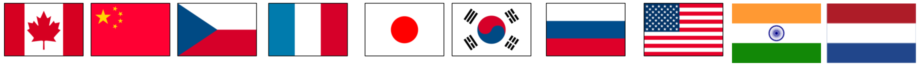




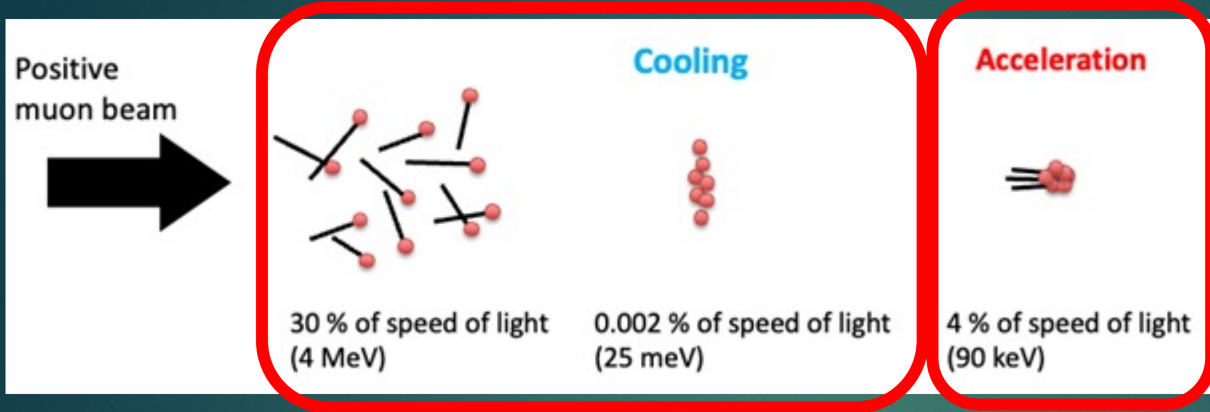
Muon cooling + acceleration test (2024~)

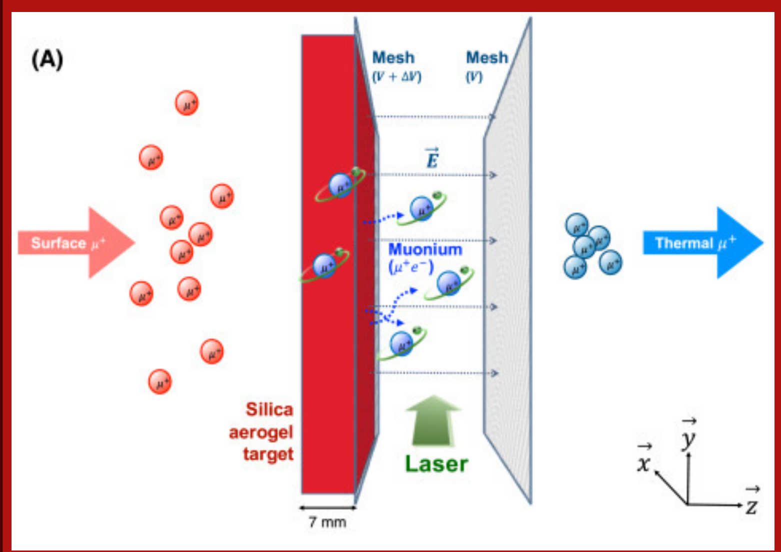


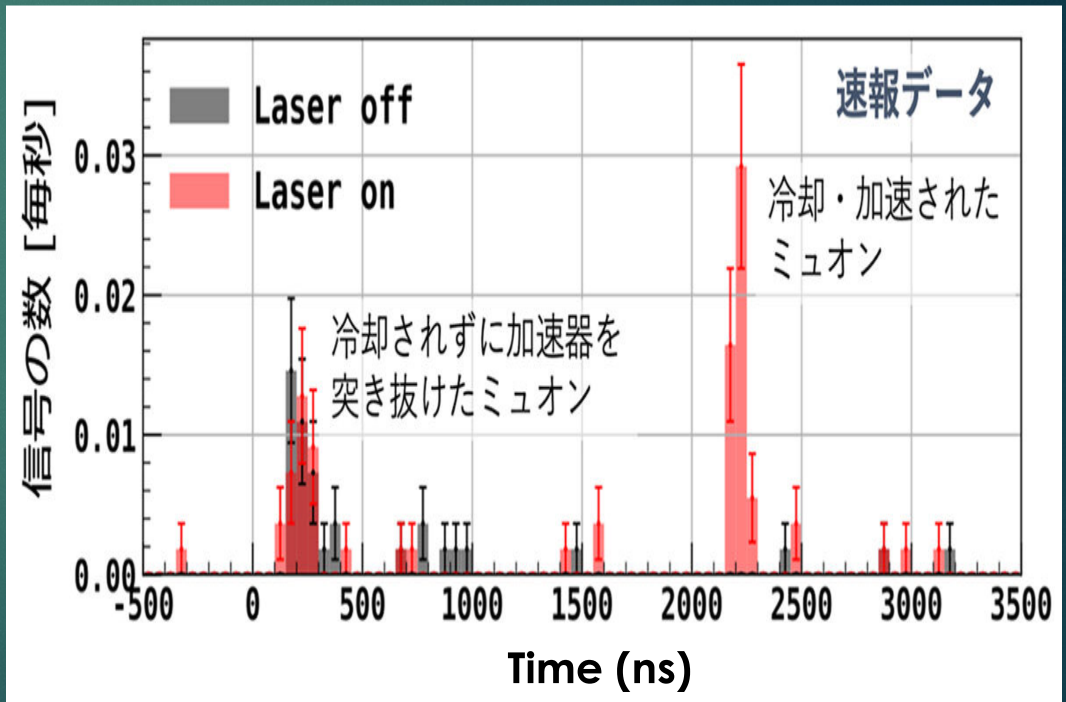
The collaboration (114 members fro 10 countries)



World first acceleration of muons (May 2024)







https://j-parc.jp/c/en/press-release/2024/05/23001341.html

7th Plenary Workshop of the Muon g−2 Theory Initiative

September 9-13, 2024 @ KEK, Tsukuba, Japan

https://conference-indico.kek.jp/event/257

International Advisory Committee

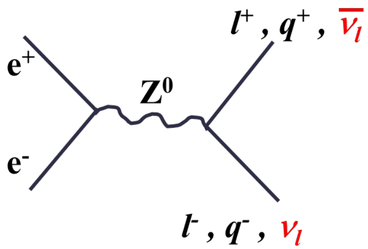
- Gilberto Colangelo (University of Bern)
- Michel Davier (University of Paris-Saclay and CNRS, Orsay), co-chair
- Aida X. El-Khadra (University of Illinois), chair
- Martin Hoferichter (University of Bern)
- Christoph Lehner (University of Regensburg), co-chair
- Laurent Lellouch (Marseille)
- Tsutomu Mibe (KEK)
- Lee Roberts (Boston University)
- Thomas Teubner (University of Liverpool)
- Hartmut Wittig (University of Mainz)

$(g\text{-}2)_7$

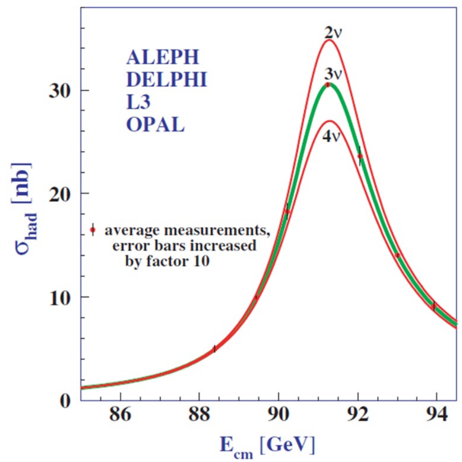
Local Organizing C1ommittee

- Kohtaroh Miura (KEK)
- Shoji Hashimoto (KEK)
- Toru Iijima (Nagoya)
- Tsutomu Mibe (KEK)

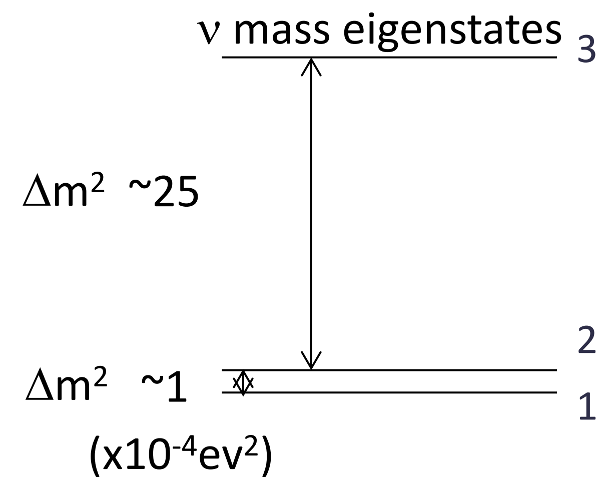
4^{th} (sterile) neutrino?

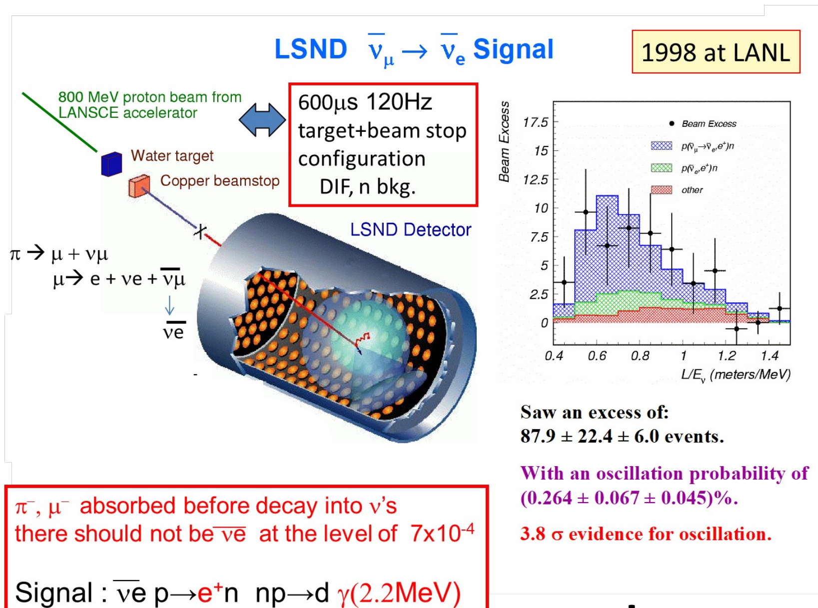


Nν=2.994+-0.012

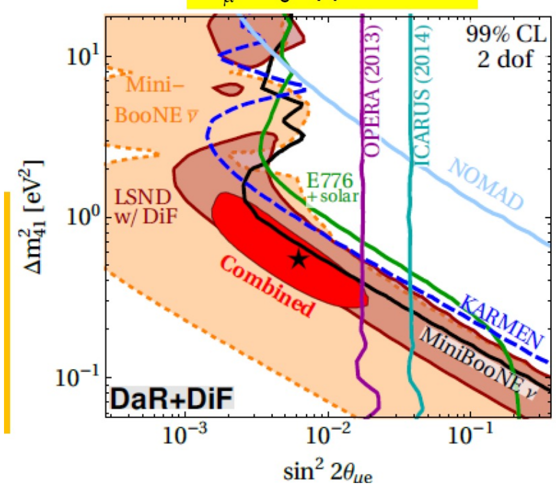


From solar&reactor&atm ν&acc ν





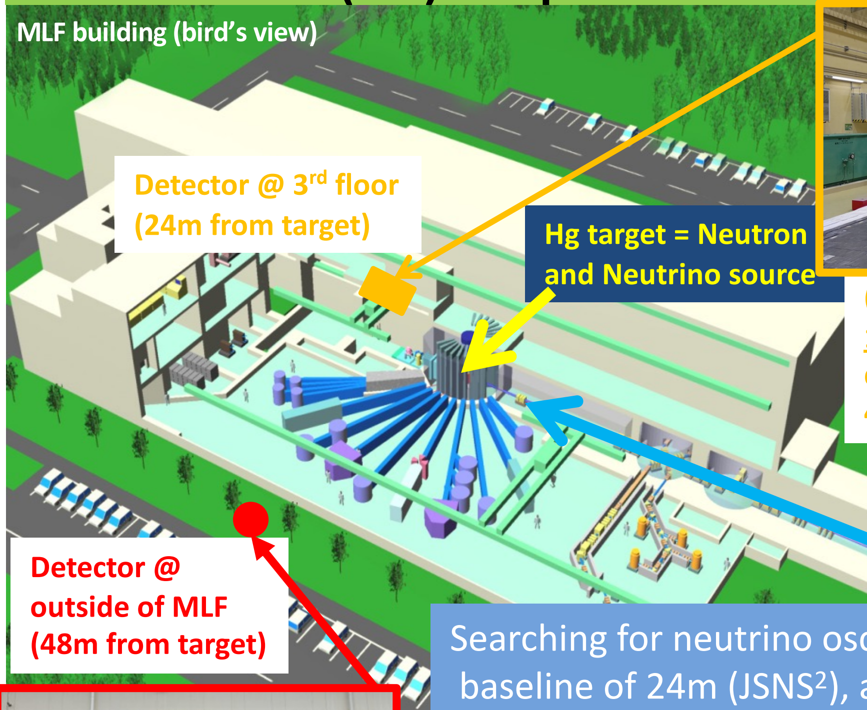
$\nu_\mu \rightarrow \nu_e$ appearance



Δm^2 ~1eV^2
~10000 $x10^{-4}ev^2$
New mass diff?

Long standing unresolved question

JSNS^2(-II) experiment : Search for sterile neutrinos



MLF building (bird's view)

Detector @ 3rd floor
(24m from target)

Hg target = Neutron
and Neutrino source

Detector @
outside of MLF
(48m from target)

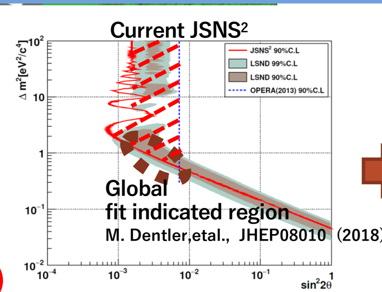
3GeV
pulsed
proton
beam

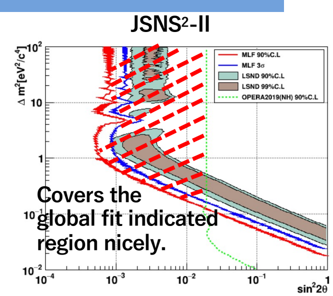
(JSNS^2)
17t GdLS fiducial (target)
detector (4.6m dia. x
4.0m height, 120 10" PMTs)

Searching for neutrino oscillation … th
baseline of 24m (JSNS^2), and 48…

(JSNS^2-II:
New detector)
32t GdLS
fiducial

(6.2m dia. x
6.2m (h)
~230 10" PMTs)





(JSNS^2) : 1MW x 3 years

- The long physics runs (2021-2024)
  - In total, ~19 months.
  - 0.88 MW beam now.
  - 4.093 x 10^{22} POT so far
  - Sterile ν analyses are on-going
  - Will continue data taking !!

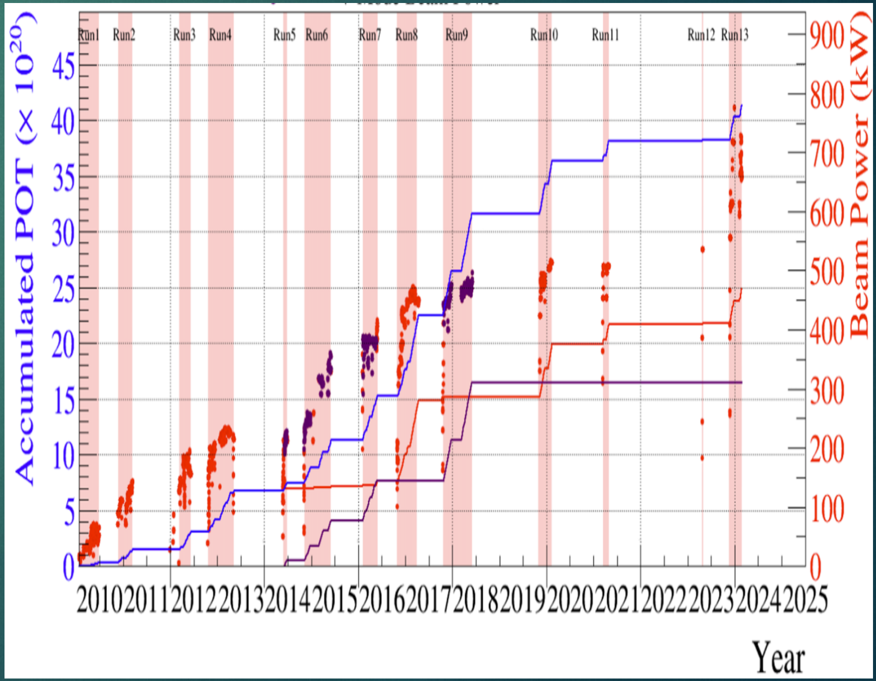
(JSNS^2-II): 1MW x 5 years

- 2nd phase of the experiment
  - new far detector : 32 tons fiducial in 48m baseline.
  - Improved the sensitivity, especially in low Δm^2 region.
  - Stage-2 approval was granted.
  - **Will take data soon !**

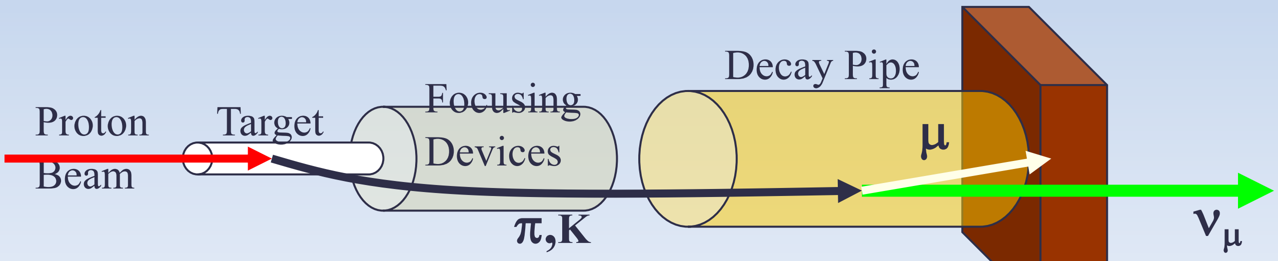
Neutrino experiments

T2K (Tokai to Kamioka) experiment

- Evidence → Observation of $\nu_\mu \rightarrow \nu_e$ (2011-2013)
- Updated goals
  - **Measure CPV phase, contribution to mass hier. determ.**
- Operation status
  - 800kW operation achieved (2024)
  - Delivered POT: ~4e21

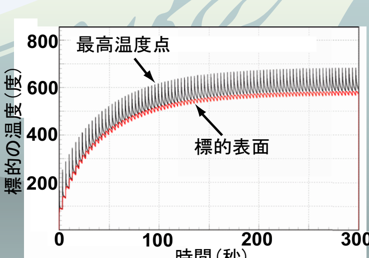


Neutrio beam production



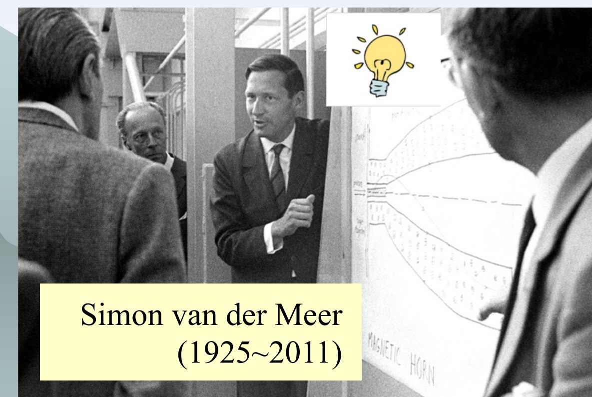
- Pure ν_μ beam (≳99%)

Graphite target for T2K

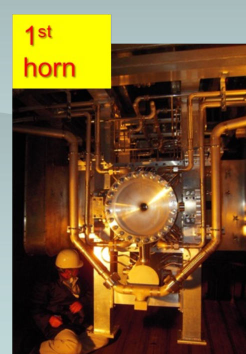


Electromagnetic horn

- 320kA/1ms pulse, 1.3sc rep.



Simon van der Meer (1925~2011)



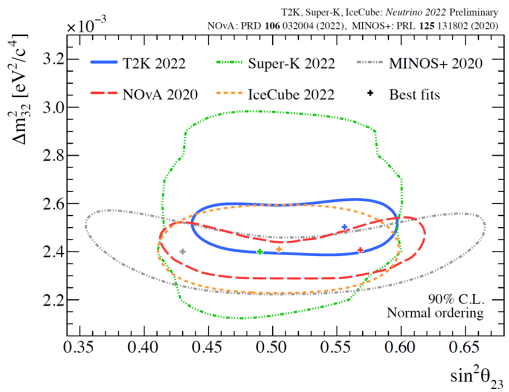
T2K results (2022)

- 3.6×10^{21} POT (2010~2022) analyzed
- Large area of δCP excluded at 3σ
- CP converving excluded at 90%
- Weak preference of normal ordering

New analysis will be presented in Nu2024 (Mon, June 17, 2024, tomorrow!)

Δm^2_{32} vs. θ_{23}

Atmospheric mixing parameters



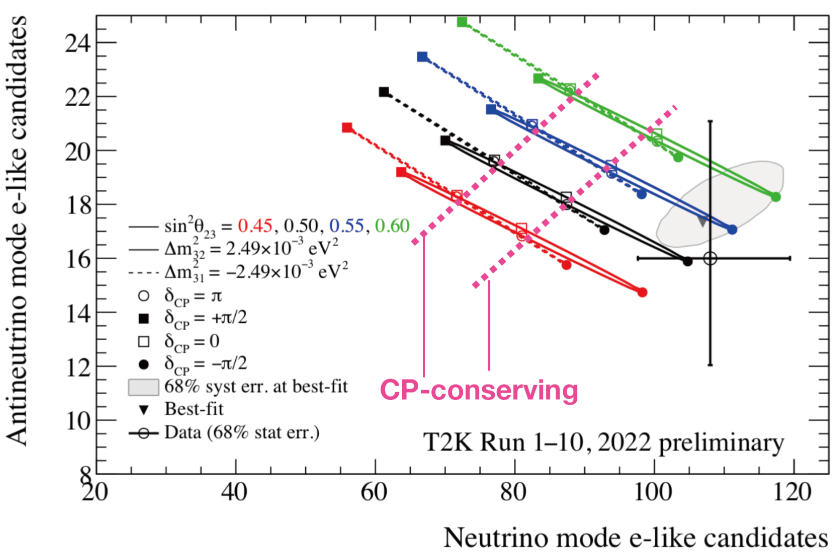
World-leading measurement of atmospheric params, still compatible with both θ_{23} octants

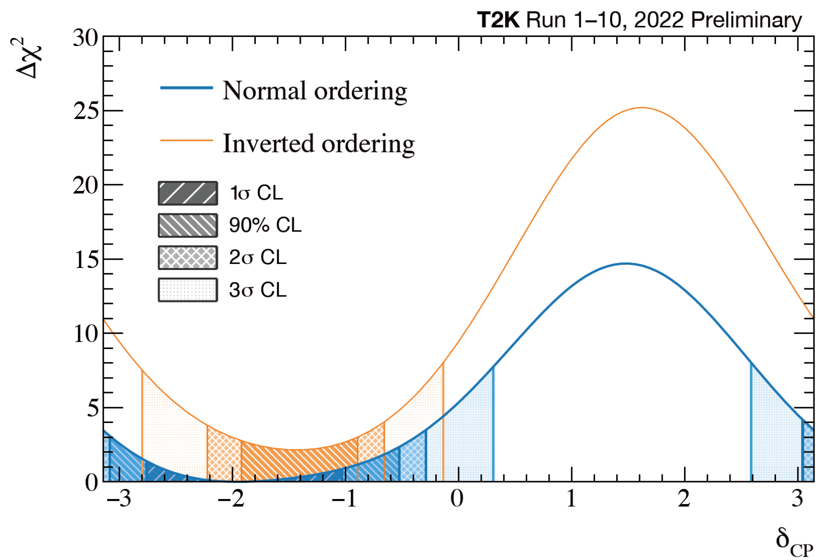
New interaction model and ND samples cause largest change compared to 2020

Multi-ring ν_μCC1π sample only gives small contribution due to being above oscillation maximum

δ_{CP}

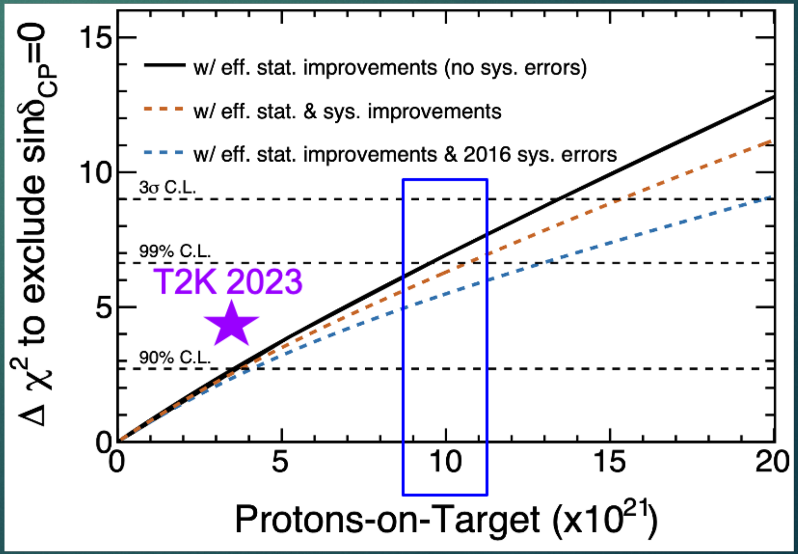
Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$





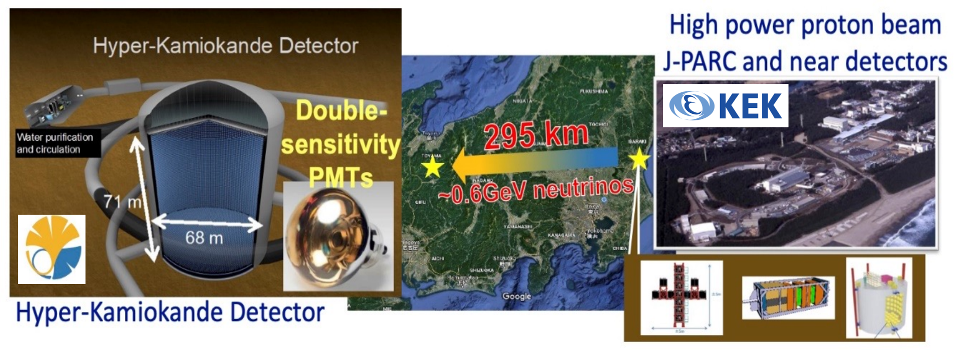
T2K upgrade & prospect

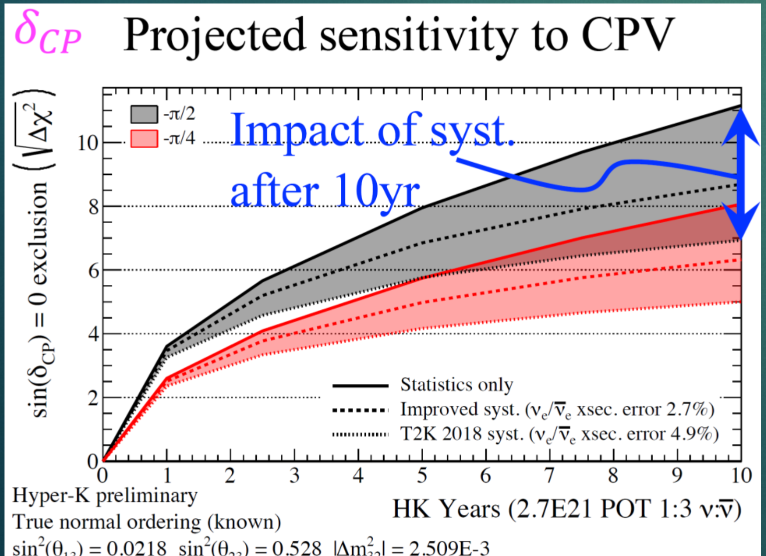
- To improve further sensitivity
  - Upgrade ND280 for systematics
  - Beamline upgrade for higher beam power upto 1.3MW
- Aim to reach 99%CL (if maximal CPV) with 10 x 10^{21} POT

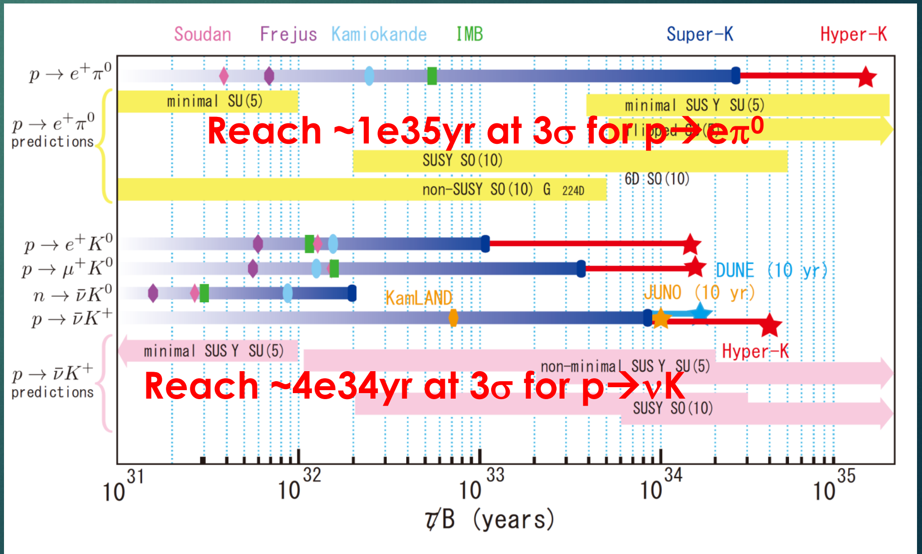


Hyper-Kamiokande project

- Project consists
  - New 190kt Hyper-Kamiokande det
  - Beam power upgrade to 1.3MW
  - Near detector upgrade
- Physics goals
  - CPV in neutrino sector
  - Search for proton decay
  - Atm-nu, solar-nu and supernova nu
- Construction started in 2020
- **Aiming to start operation in 2027.**

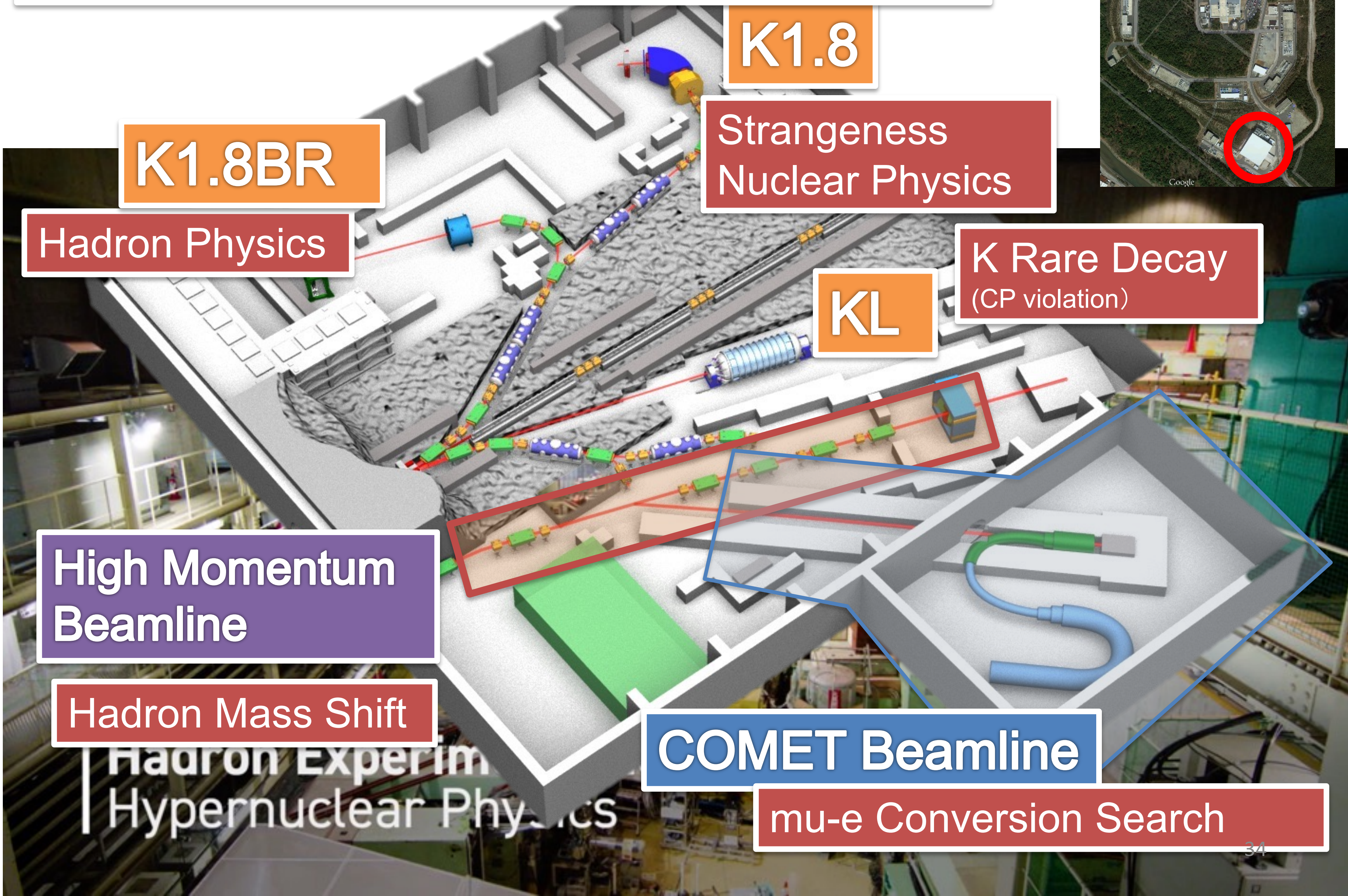






Experiments at Hadron Experimental Facility w/ SX beam

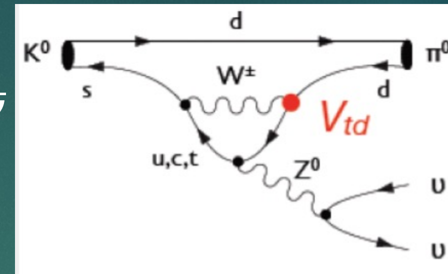
Hadron Experiment Facility

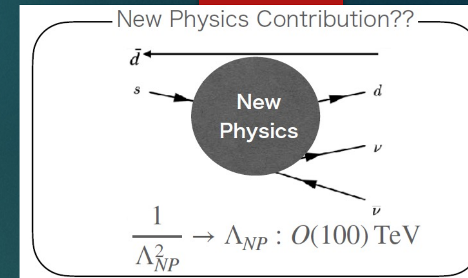


KOTO experiment

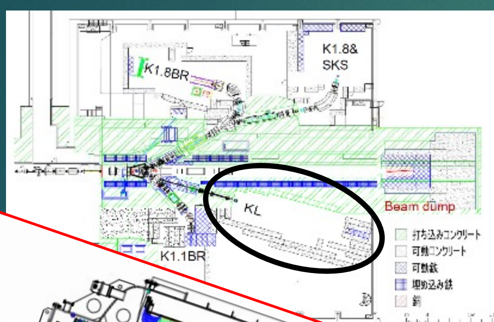
- Search for CP violating decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$

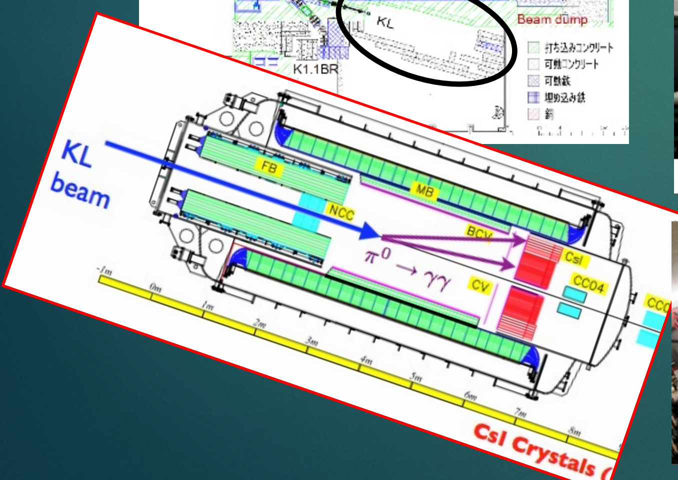
CP- CP+
$$K_L \rightarrow \pi^0 \nu \bar{\nu}$$

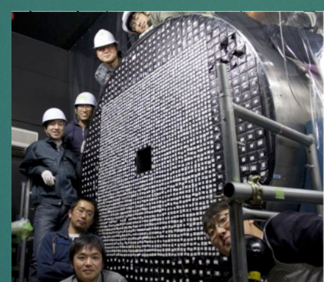


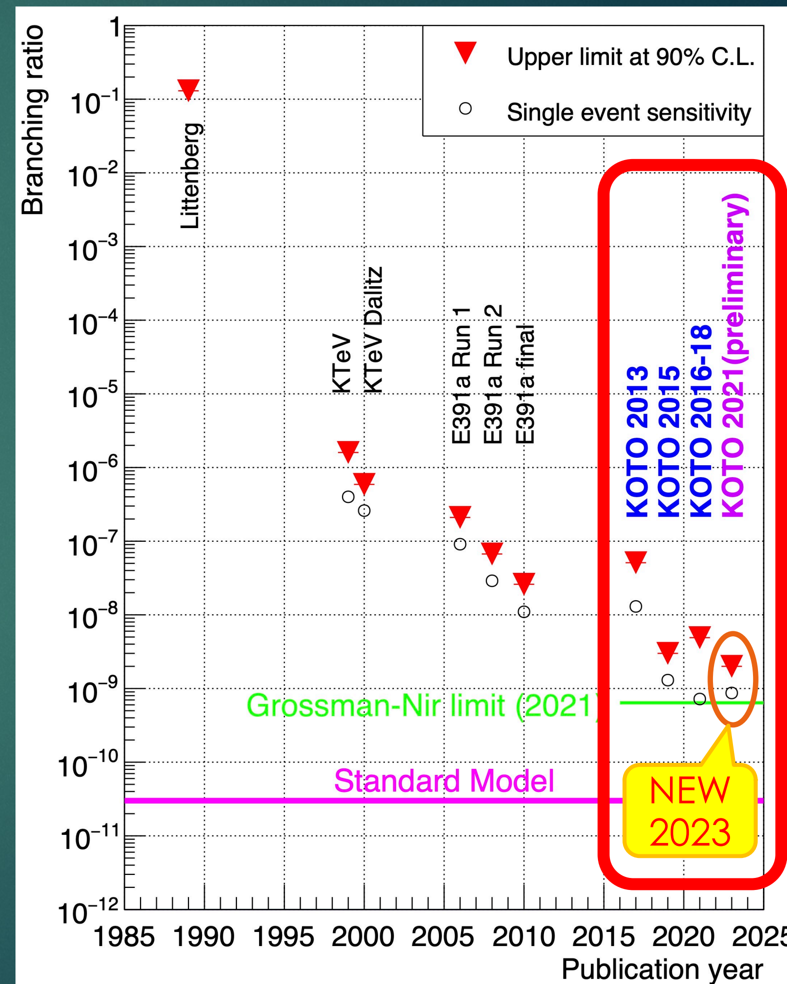


- SM pred. is very small ~3e-11
  → **Sensitive to New Physics**
- Latest result (Sept.2023)
  - **BR<2.0x10-9 @90% C.L.**
- Aim sensitivity better than 1×10^{-10}



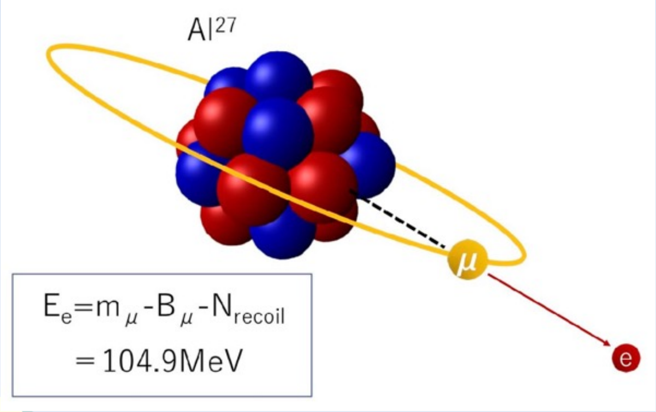


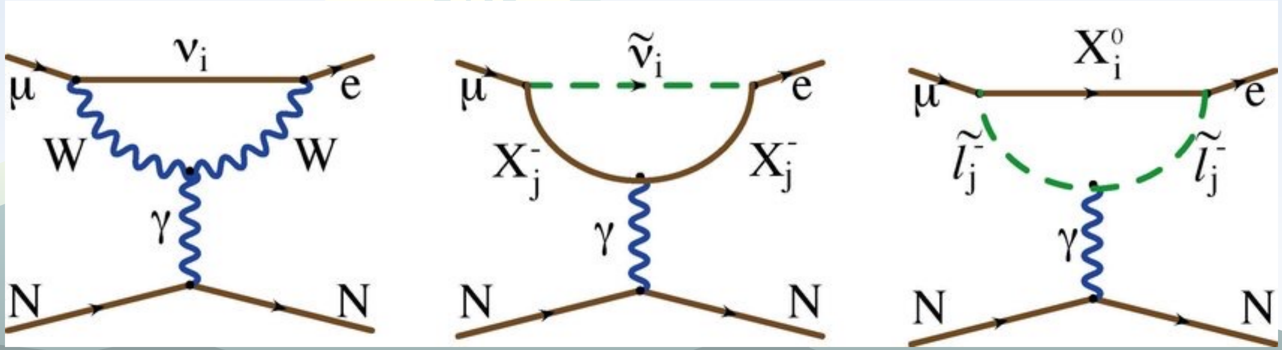

CsI calorimeter

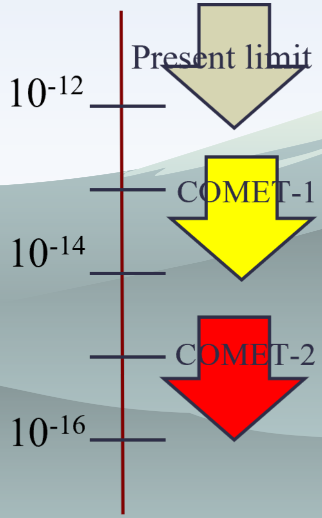


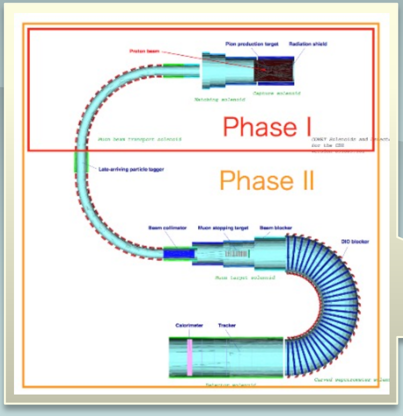
COMET experiment

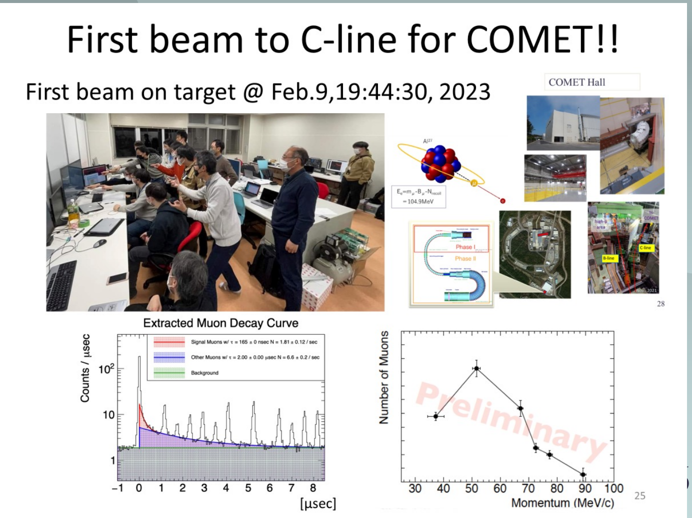
- μ→e conversion search
  $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - Very small $O(10^{-54})$ in SM
  - **Discovery = New Physics!**
- First commissioning in FY2022









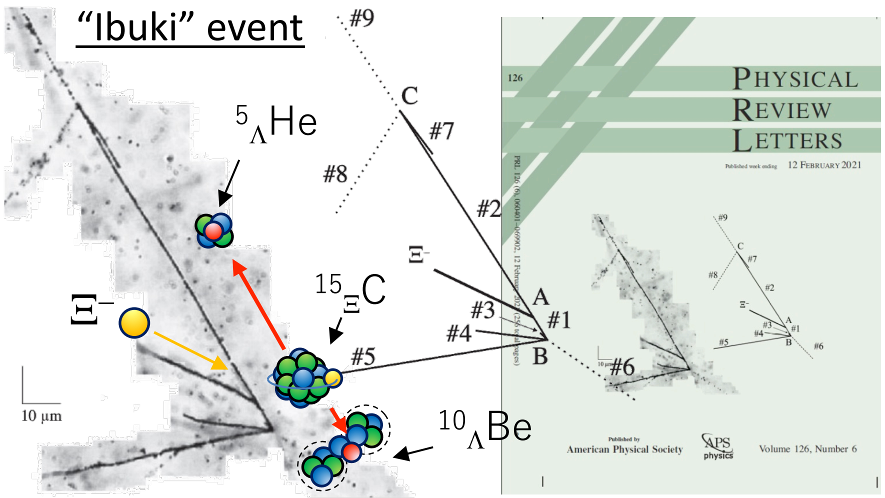


【Nuclear physics at Hadron Experimental Facility】

大強度陽子加速器施設 J-PARC

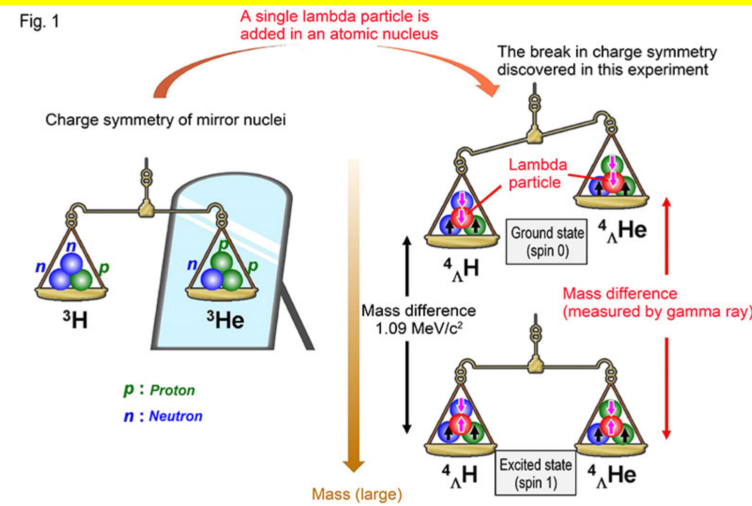
Elucidation of the property and origin of “generalized nuclear force” including strangeness

Mass measurement of Xi hypernuclei



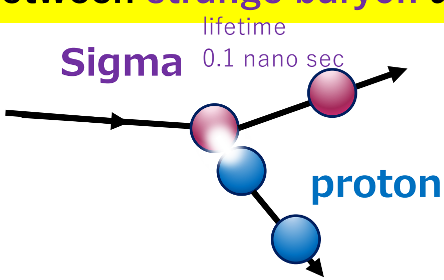
→ confirm the force between Xi (Ξ) and nucleon is attractive

Discovery of charge symmetry breaking in the force between Lambda (Λ) and nucleon

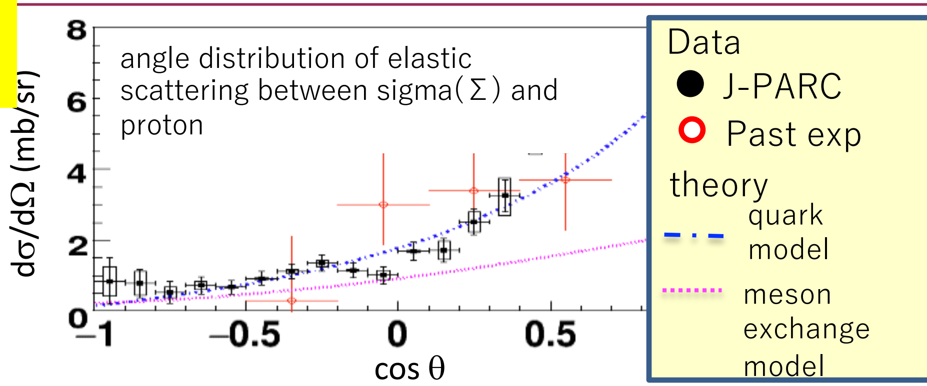


3H and 3He are the same on mass and structure in mirror images.
If a single lambda particle is added, it is found that a large difference appears in mas of ground state and excited state.

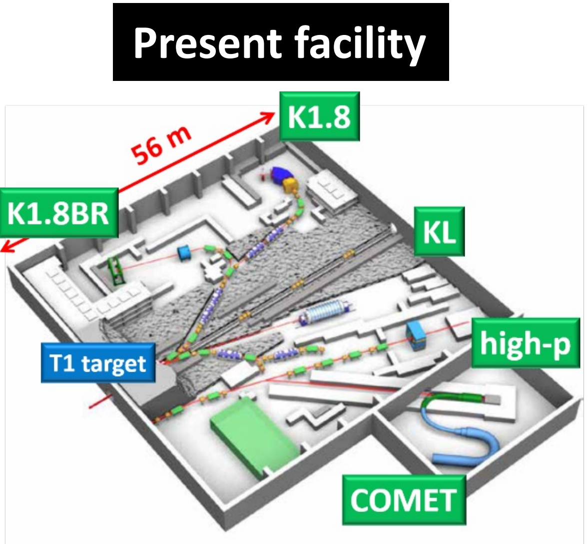
Establishment of scattering experiments between strange baryon and proton



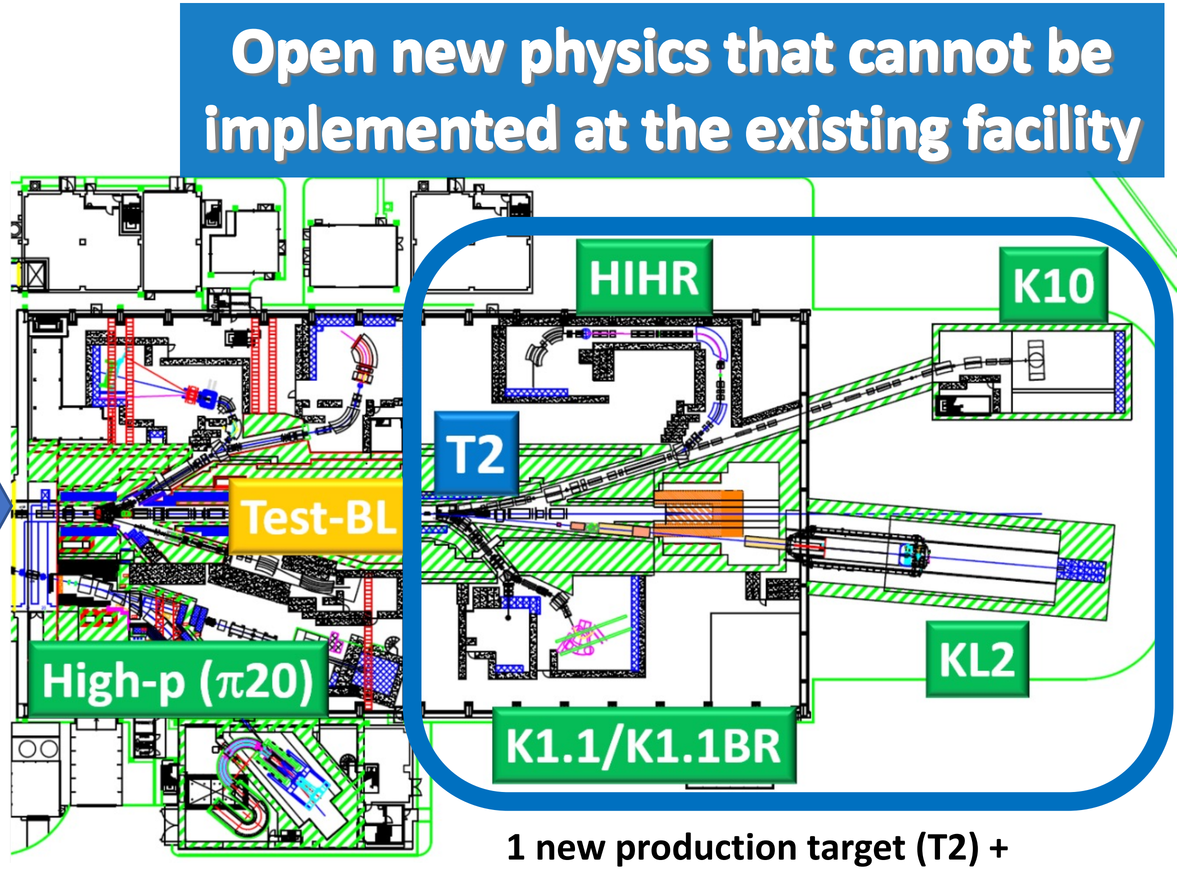
→ improve the precision of scattering angle distribution by x10 for the first time in 50 years



Hadron Experimental Facility EXtension (HEF-ex) project



1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



1 new production target (T2) +
4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +
2 modified beamlines (High-p (π20), Test-BL)

KEK-PIP 2022 Priory Number 1

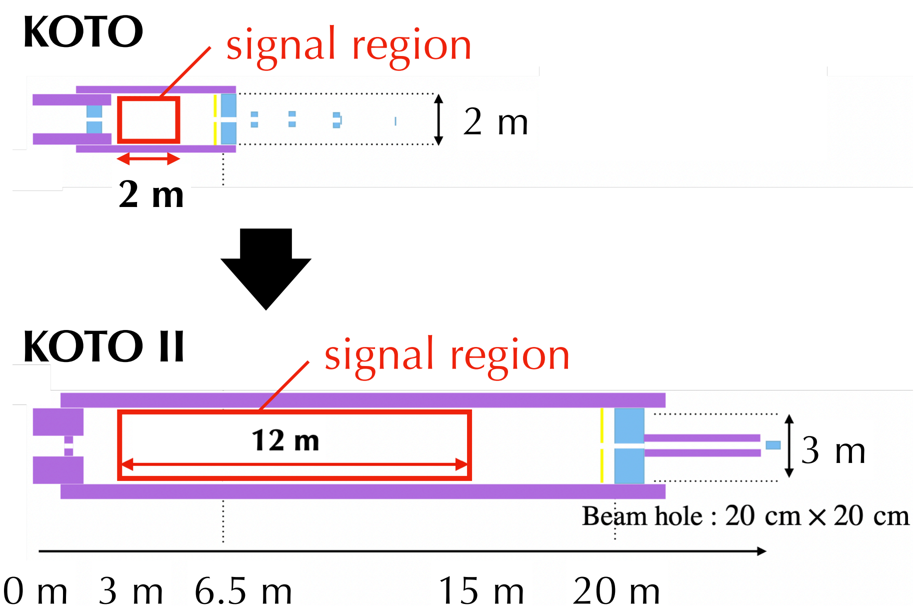
KOTO II @ HEF-ex

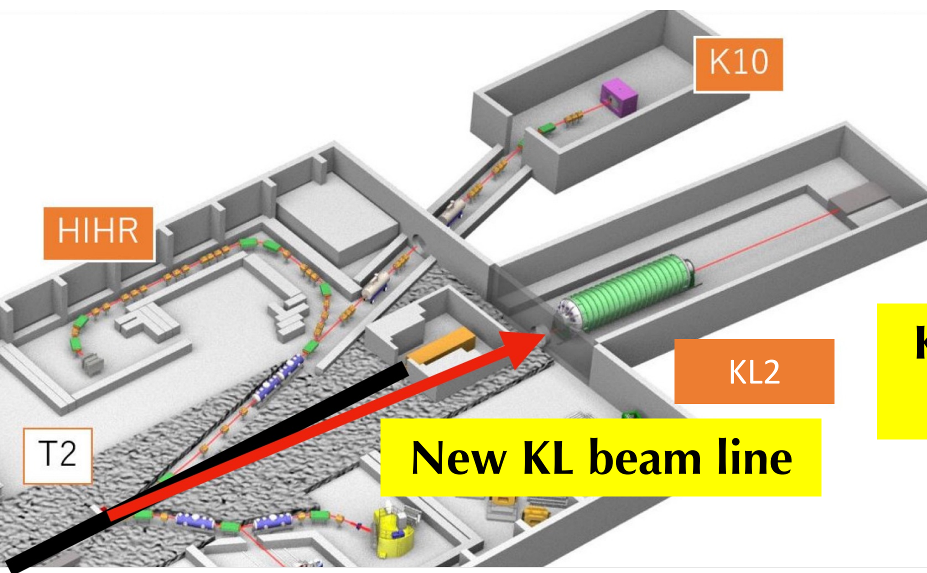
Search for new source of CP violation beyond Standard Model (SM)

New Phase of the $K_L \to \pi^0 \nu \bar{\nu}$ study

- From "Search" to "Measurement of the branching ratio" -

- More K_L
  - Smaller extraction angle
    (16° for KOTO → 5° for KOTO II)
- Larger detector
- More signal acceptance





KOTO II detector behind dump at the end of extended hall

KOTO II @ HEF-ex

Search for new source of CP violation beyond Standard Model (SM)

New Phase of the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ study

Expect 35 SM signal / 40 background events

assuming 100kW beam, and 3×10^7 s running

(corresponding to 6.3×10^{20} P.O.T.)

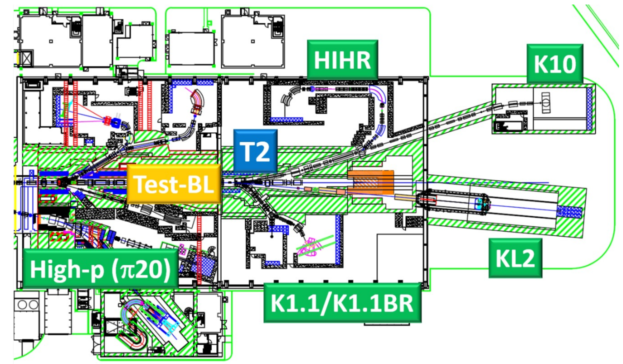
- Single Event Sensitivity (SES) = 8.5×10^{-13}
- 5.6σ observation of $K_L \rightarrow \pi^0 \nu\bar{\nu}$ (SM)
- 25% precision for the branching ratio
- If 44% deviation from SM prediction is observed

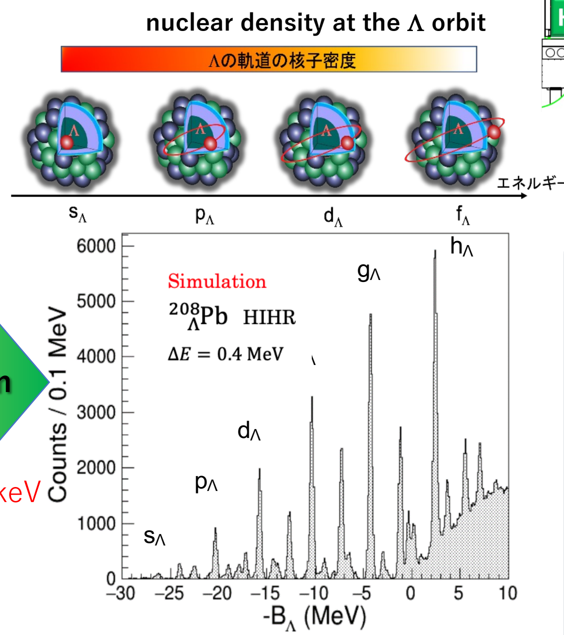
  → Indication of New Physics at 90% confidence level

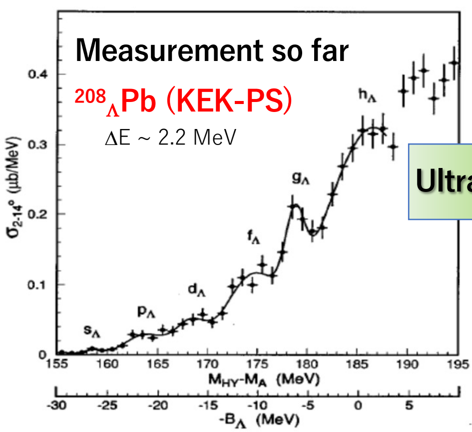
KOTO II detector behind dump at the end of extended hall

A Highlight of future nuclear physics at extended HD hall

Elucidation of YN interaction in nuclear matter
First high-resolution spectroscopy of the heaviest Λ hypernucleus at HIHR



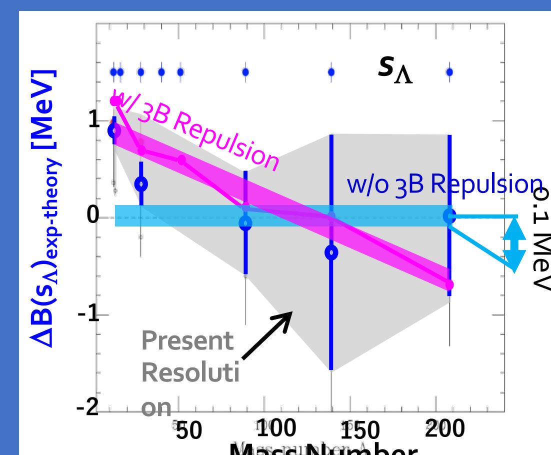




Ultra high-resolution

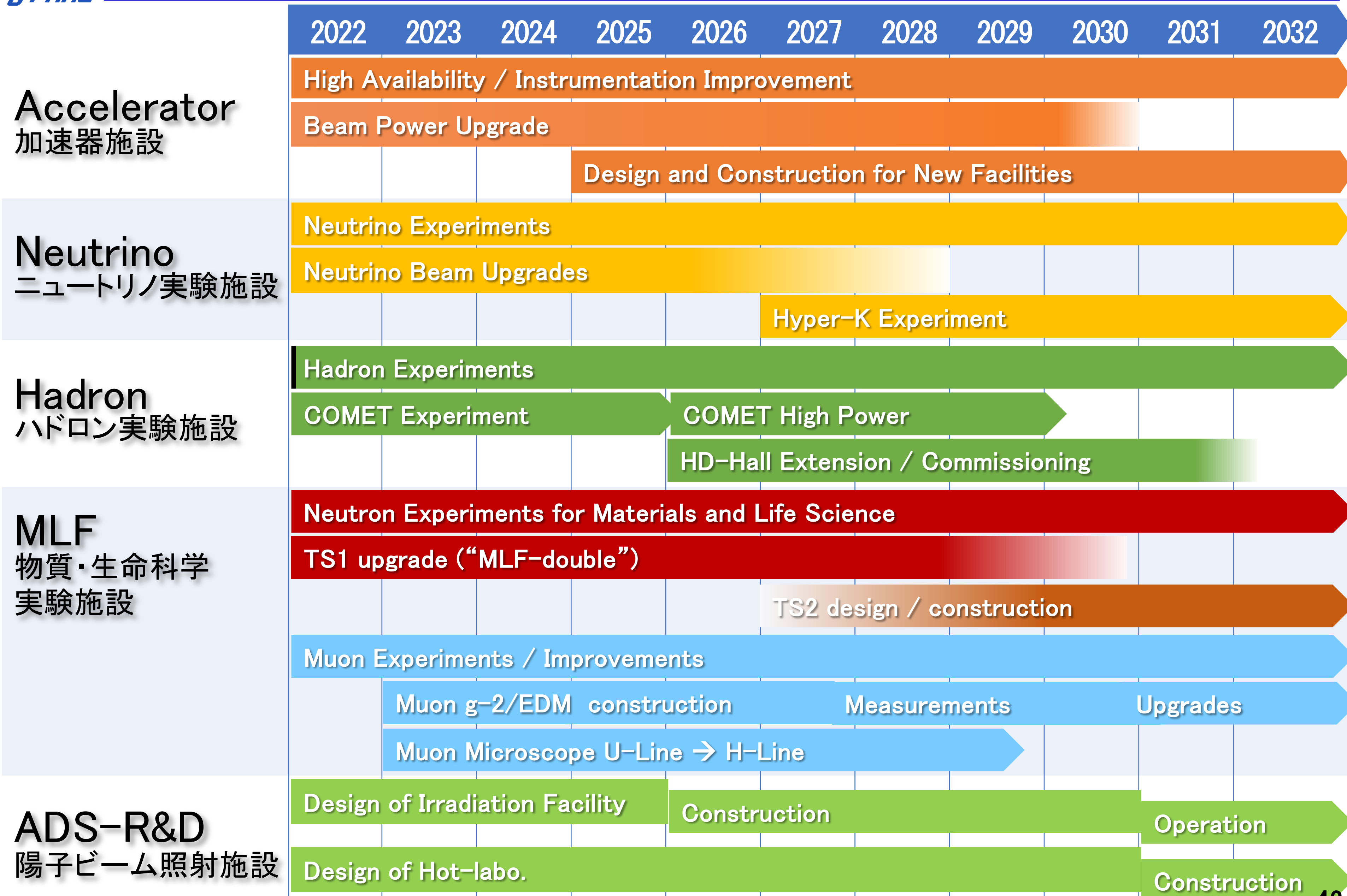
Resolution 400 keV
(5 times better than KEK-PS)

Effect of multi-body force to the Λ single-particle energies



Clarify **density-dependent Λ interaction** and **multi-body force** via the systematic measurements for the **understanding high-density matter and neutron stars**.

J-PARC future plan



J-PARC Symposium 2024

- Discuss
  - Scientific output/achievements in the last 15 years
  - Future projects for coming 30 years
- Oct 14-17, 2024 @ Mito (new city culture center)
- Registration will start soon!
- Come & enjoy science discussions and Mito/Japan

https://j-parc.jp/symposium/j-parc2024/

Summary

- J-PARC is the world leading intensity frontier proton accelerator research complex
  - 3GeV RCS/MLF: reached at 840kW stable operation
  - 30GeV MR: 800kW stable operation achieved
- J-PARC is unique facility covering wide range of research fields
  - Particle, nuclear physics, material and life sciences and industrial applications, Archeology, planetary science
- Many exciting projects are being conducted/prepared

Discoveries would come tomorrow

Your participations for the discoveries are highly welcome!