Oct. 10, 2022
@ESS
**The Commissioning Workshop of ESS-J-PARC collaboration**

# Introduction to J-PARC

Takashi Kobayashi
J-PARC, JAEA/KEK

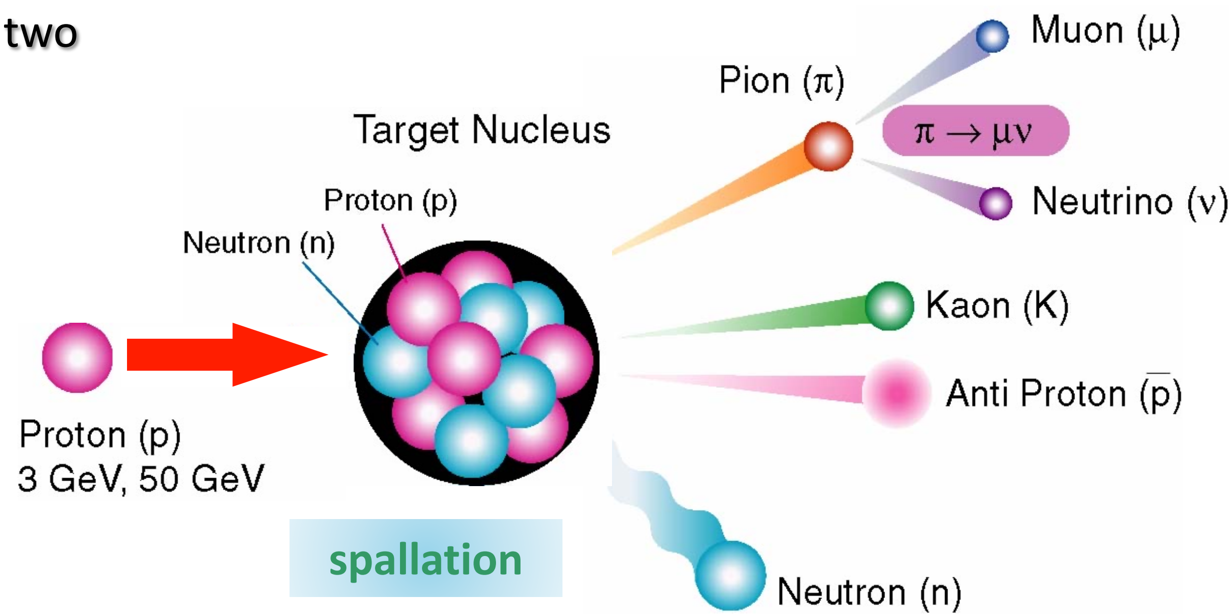
# Versatile Quantum Beams for Microscopic World

J-PARC

Japan Proton Accelerator Research Complex

**Power-frontier accelerators and multi-purpose user facilities**

Jointly operated by two organizations:
- KEK, and
- JAEA

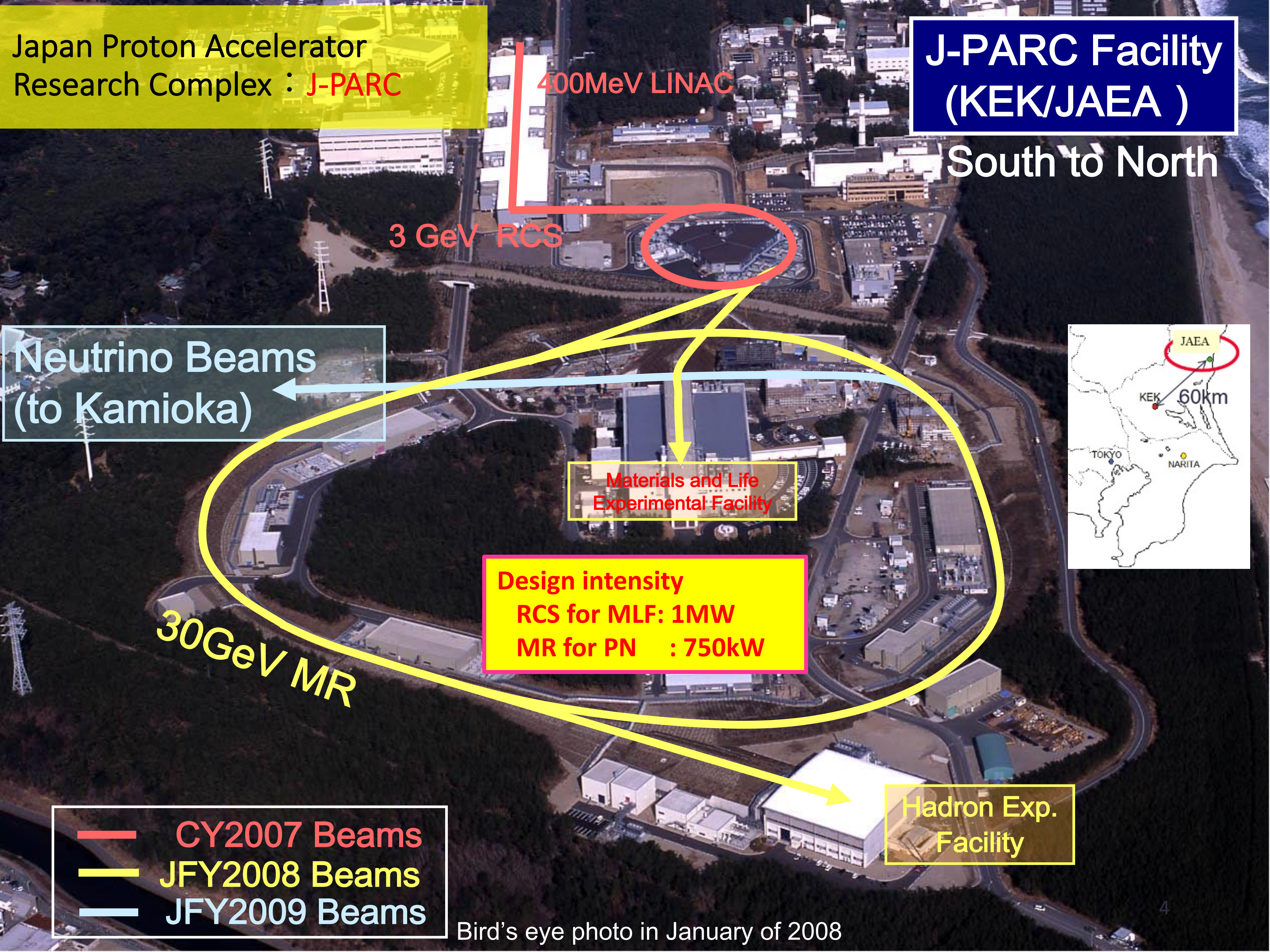



**Variety of secondary particles generated with high-energy and high-intensity protons**

# Versatile Quantum Beams for Microscopic World

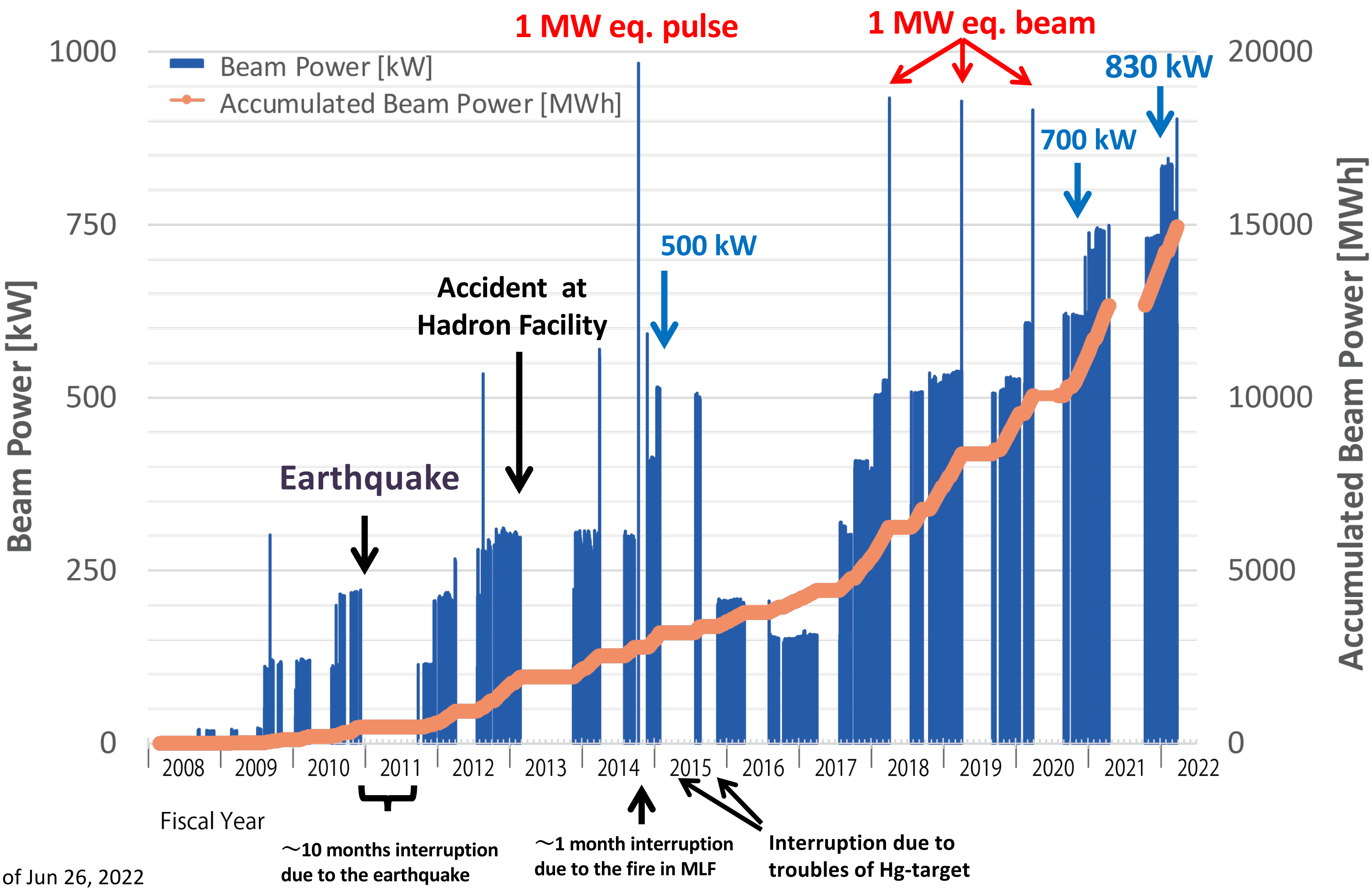
J-PARC

- Constructed jointly by High Energy Accelerator Research Organization (**KEK**) and Japan Atomic Energy Agency (**JAEA**)
  - construction from 2001 to 2007
  - beam commissioning from 2007 to 2009
  - construction cost: \152.4B
- Operated by J-PARC Center
  - J-PARC Center is joint organization of KEK and JAEA
  - ~600 staff from JAEA(~250) and KEK(~280) and CROSS(~70)
  - operations for user programmes from 2008
  - **~ 3,000-person·day** users / month *(before COVIT-19 pandemic)*



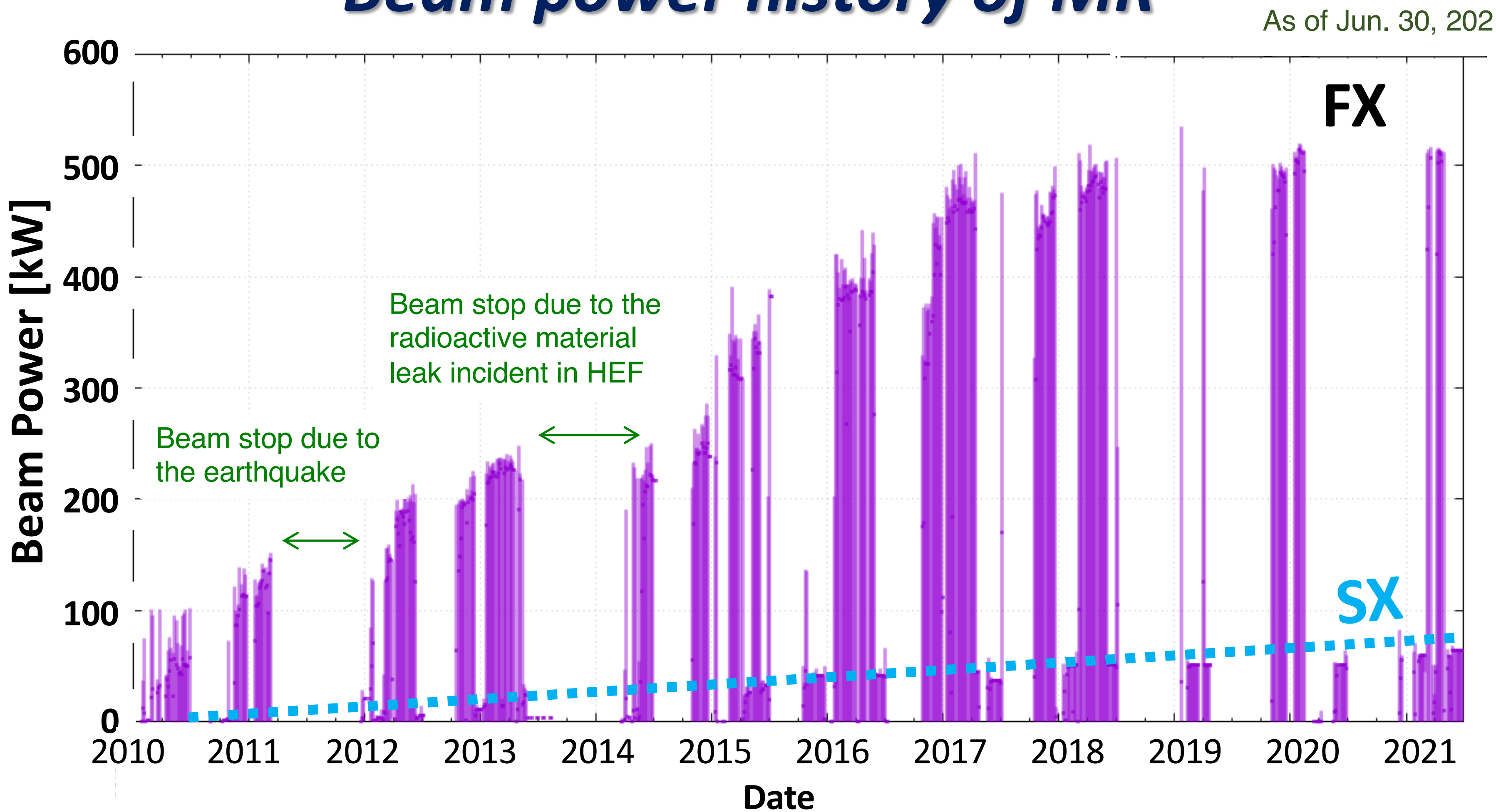
Bird's eye photo in January of 2008

# Beam Power History at MLF




as of Jun 26, 2022

# Beam power history of MR




**Max. beam power :**

- Fast extraction ~ 515 kW (2.66 x$10^{14}$ ppp), the world highest ppp in synchrotrons.
- Slow extraction ~ 64 kW (~ 7.0 x$10^{13}$ ppp) for users with the world highest extraction efficiency of 99.5 %

# MR power upgrade

- Original design power: 750kW
- Present beam power goal: 1.3MW
- Method
  - Increase repetition rate from 2.48→1.16s
    - Upgrade power supply
    - Upgrade RF
    - Upgrade injection/extraction magnets
  - Increase #p/bunch
    - Upgrade RF systems and feedback system
- Status
  - Upgrade plan started ~10years ago
  - Constution/installation of all new components are done
    - Summer 2021-Summer2022 long shut down for installation
  - Almost ready to operate at 1.3s rep cycle from this fall

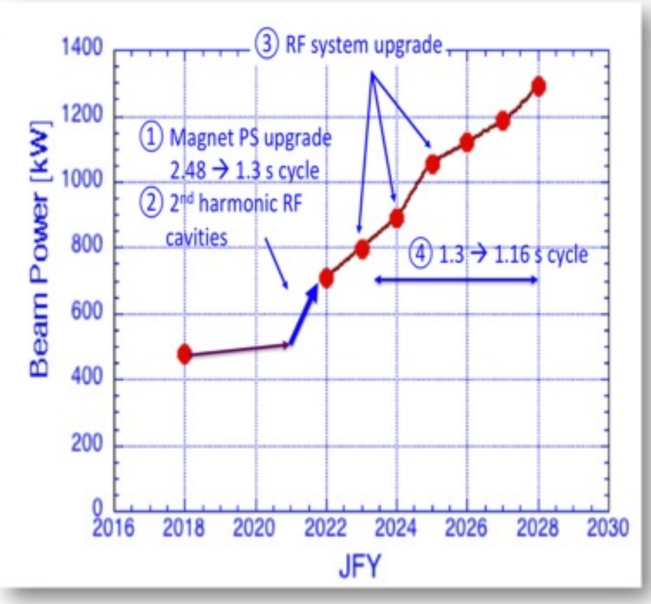
**More Rapid Cycle:**

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 :**

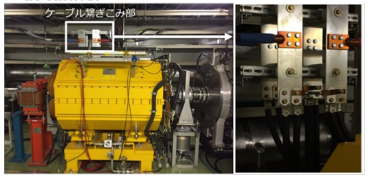
- Improve RF Power
- More RF Systems
- Stabilize the beam with feedback



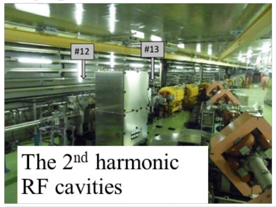

New power supply

QDN power supply into D2
(Chopper + Filter + Control Panels)

New PS is now connected to magnets at tunnel

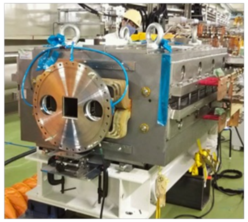


Upgrade of RF





New extraction septum



## Science at MLF w/ n/mu

物質や Materials and life sciences 起源を探る

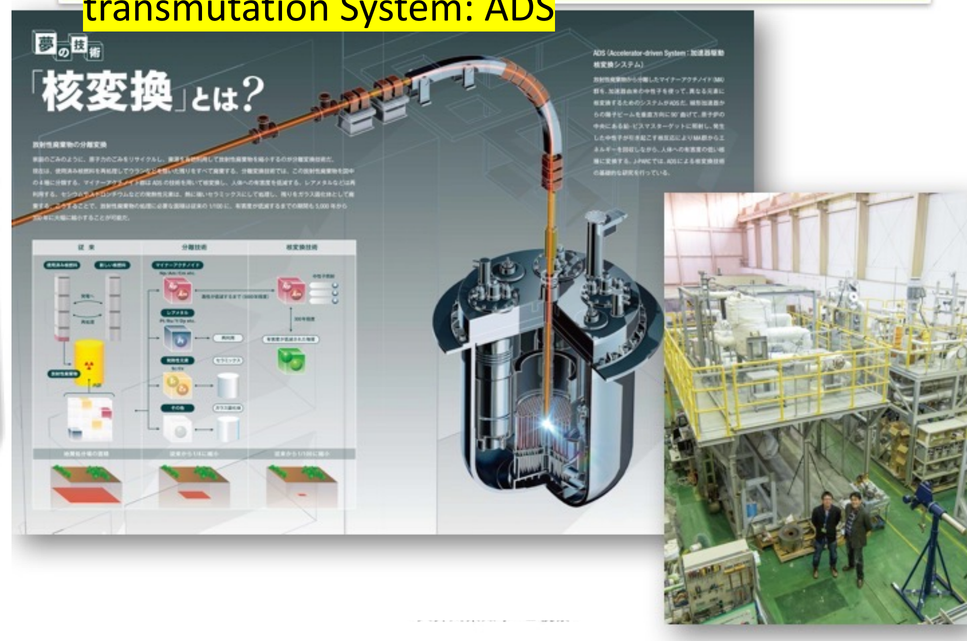

## Neutrino experiment

Explore origin of matter in the universe


## Hadron experiments

物質の形成過程における謎を探る！


## Development Accelerator Driven nuclear transmutation System: ADS



# Materials and Life Science Experimental Facility

# Materials & Life Science Experimental Facility

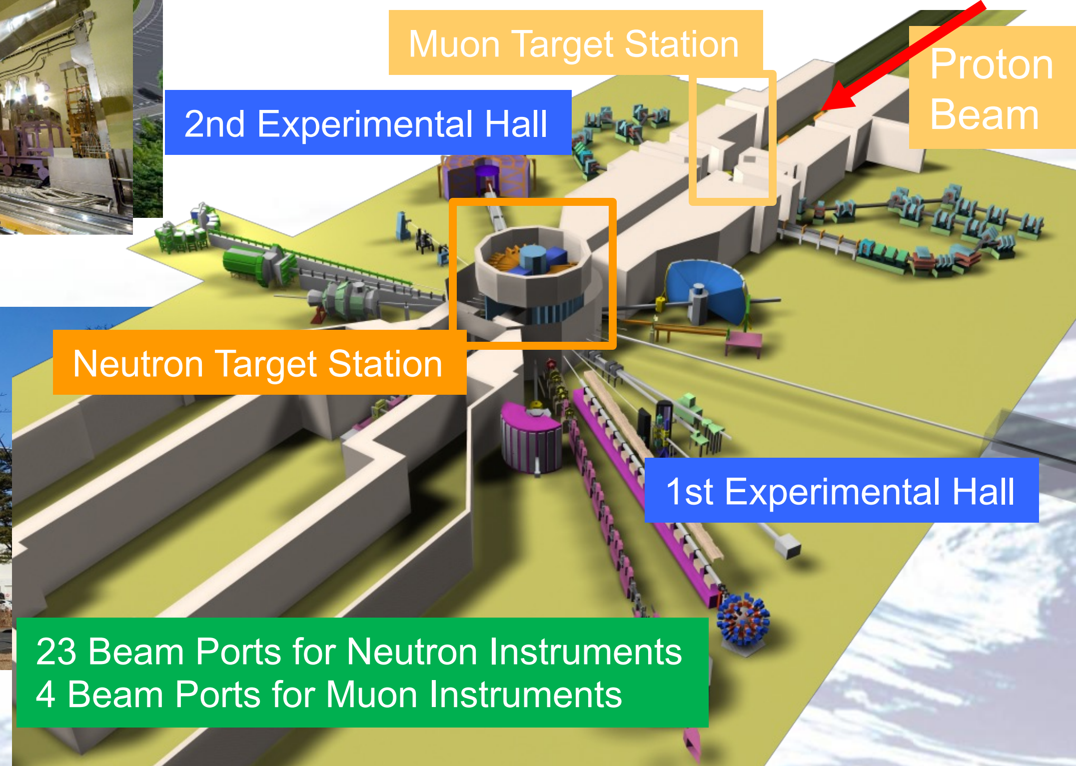
J-PARC, MLF

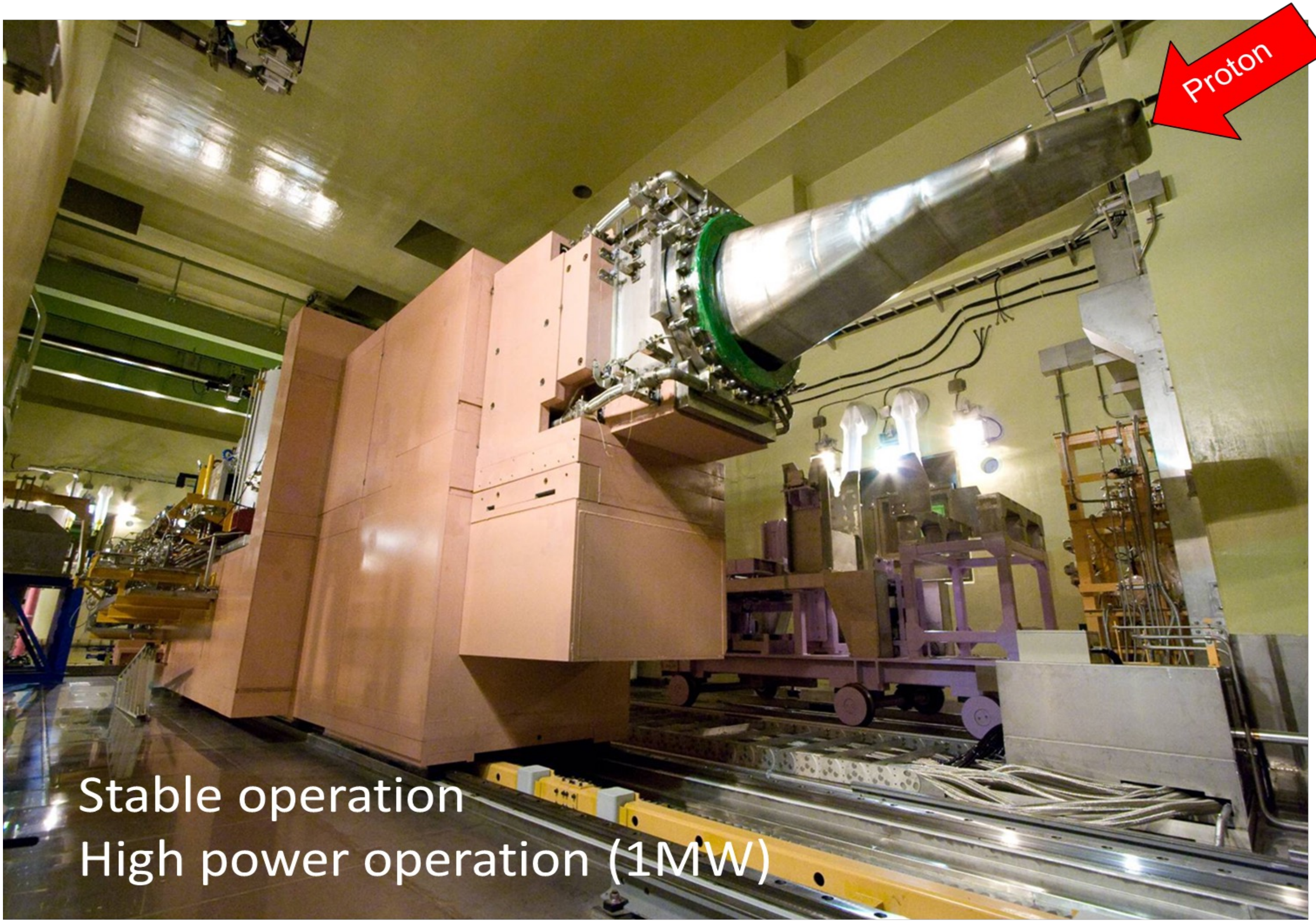
■ Neutron & Muon Beam Facility for Materials & Life S



The World Highest-Class
Neutron & Muon Sources.

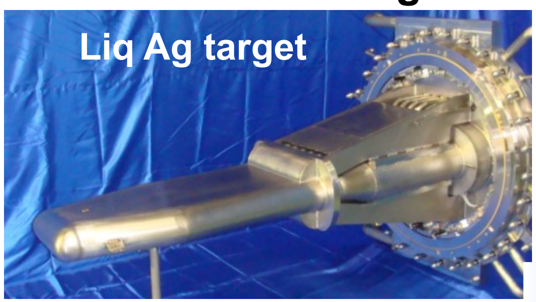
Neutron Source:
- 1MW
- Liq. Mercury Target
- Liq. $H_2$ Moderators



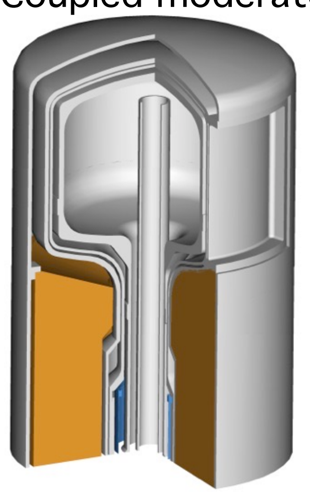

Proton
Stable operation
High power operation (1MW)

# Materials and Life Science Facility（MLF）

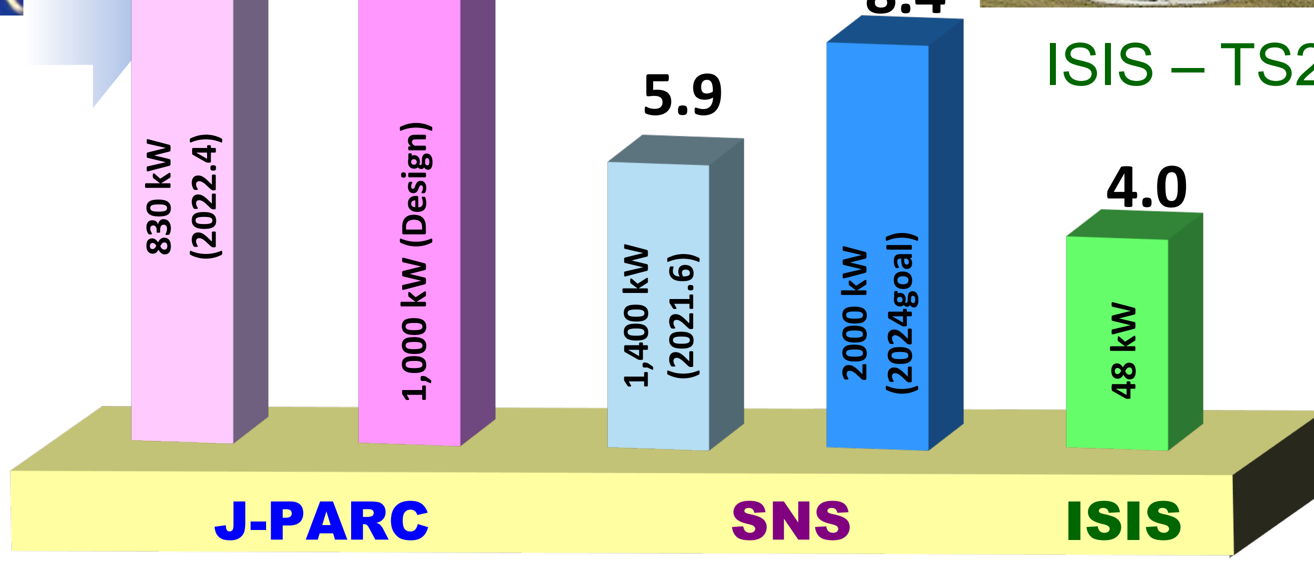

**JAEA's technologies**




Coupled moderator



## World Highest Intensity of Neutron Pulse Beam!



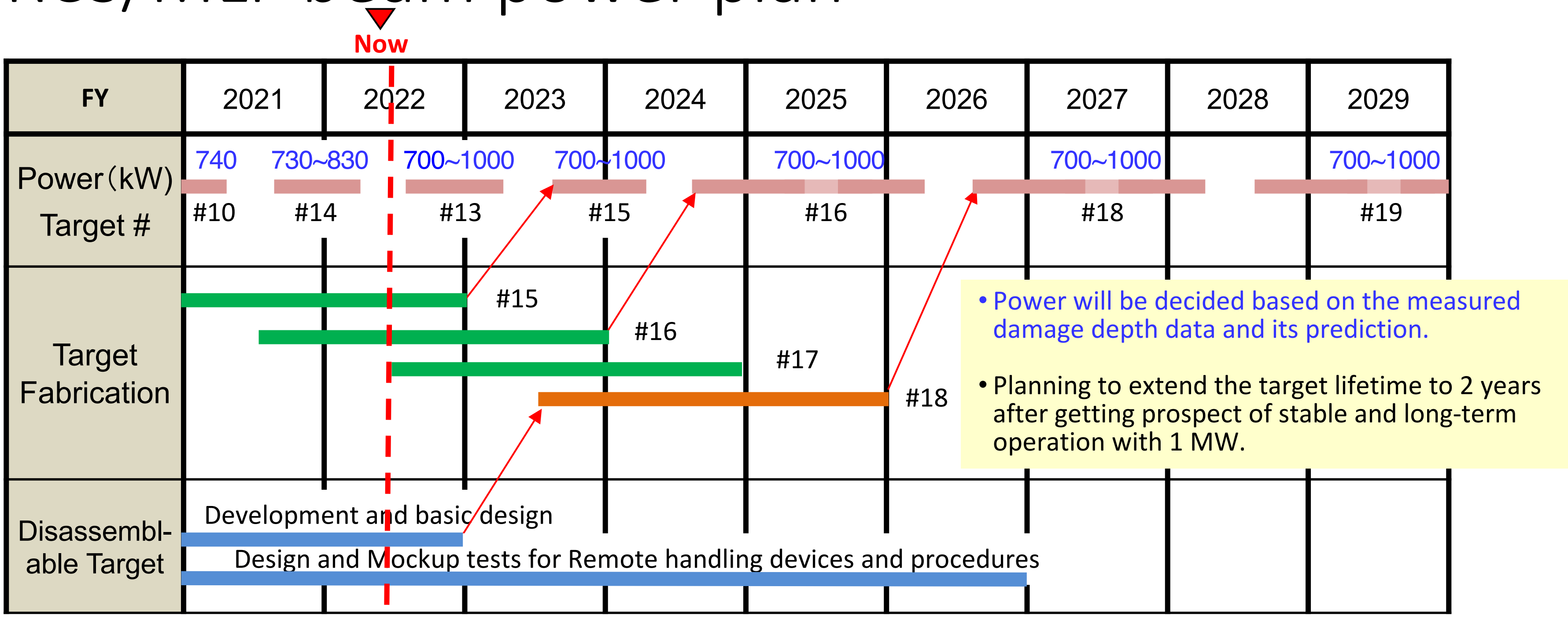


US-SNS

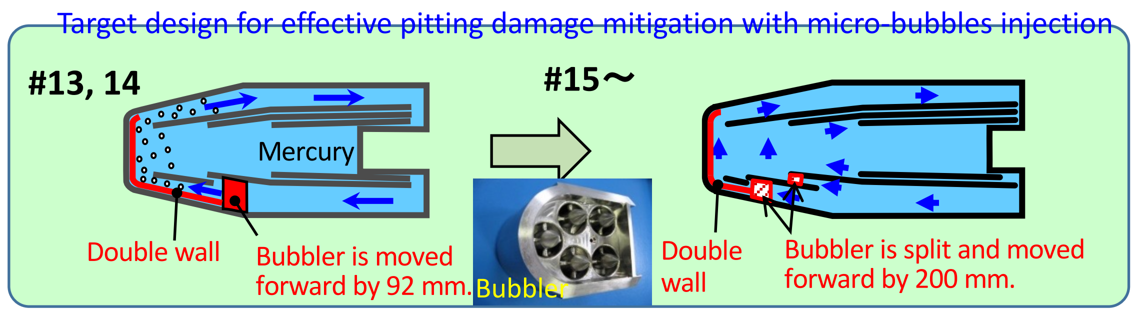
ISIS – TS2

Unit：$10^{12}$ n/(sr･pulse)

# RCS/MLF beam power plan

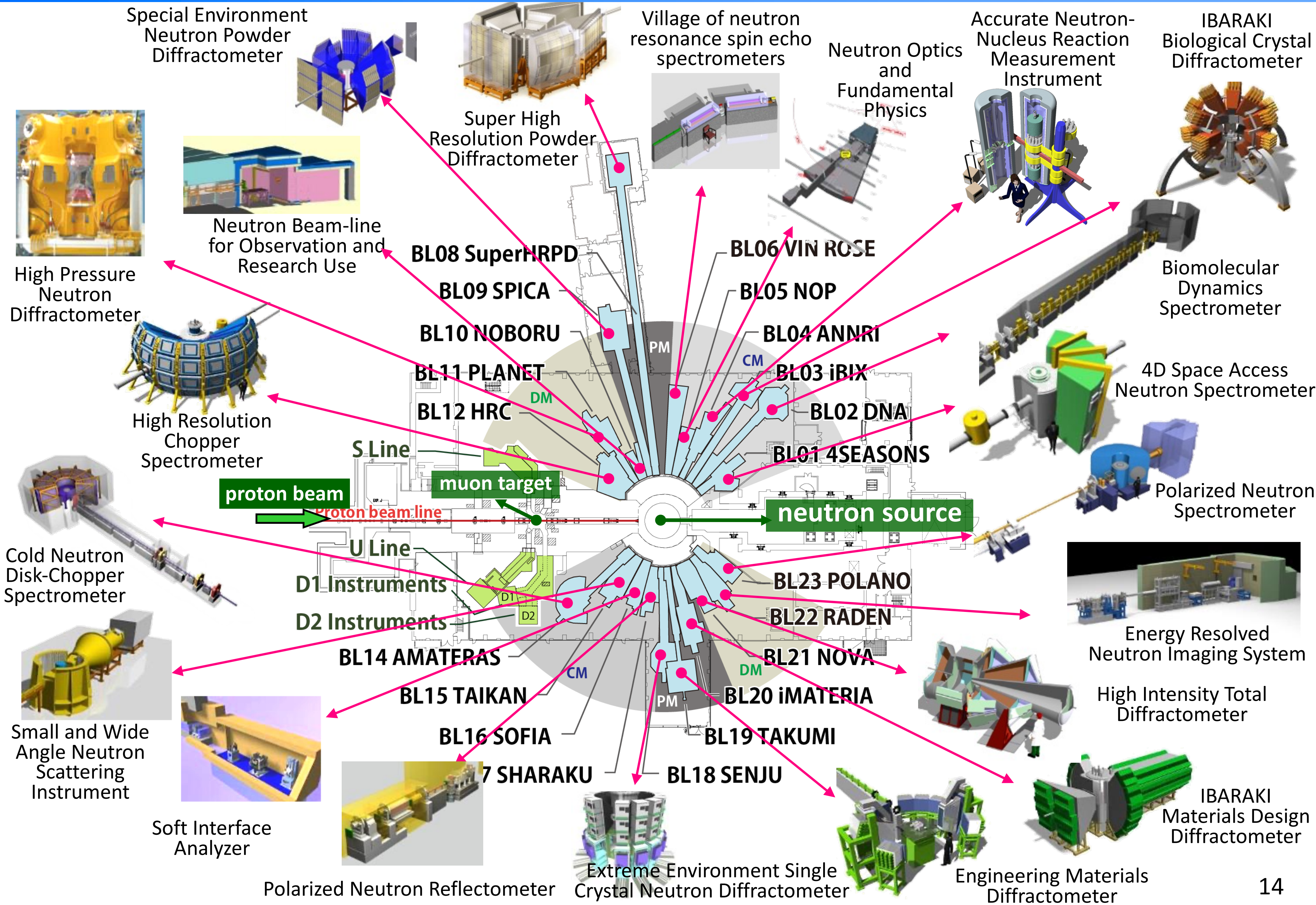



- FY2022: 830 kW operation from Apr. to Jun.
- +100 kW/yr
- Aim to reach 1MW design power within a few years
- Develop target for
  - 2-year operation
  - Disassemble type



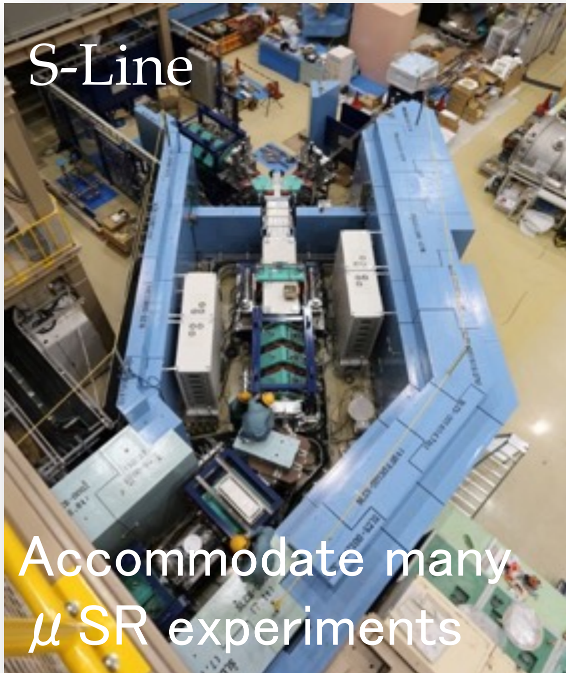

# Neutron Instruments in MLF

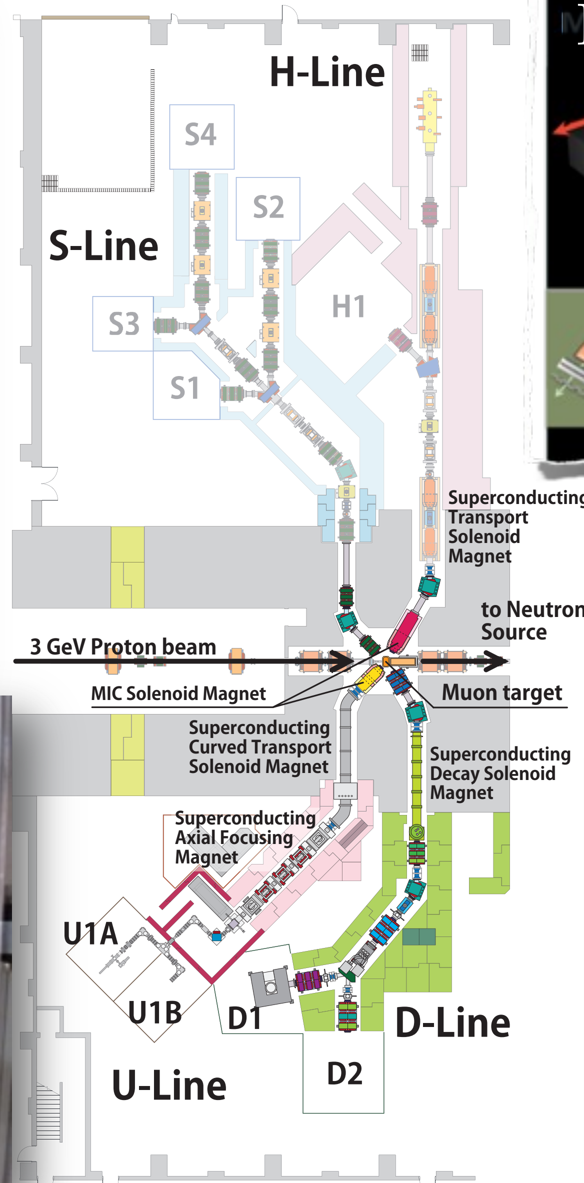
**23 beam ports**
**21 in operation**

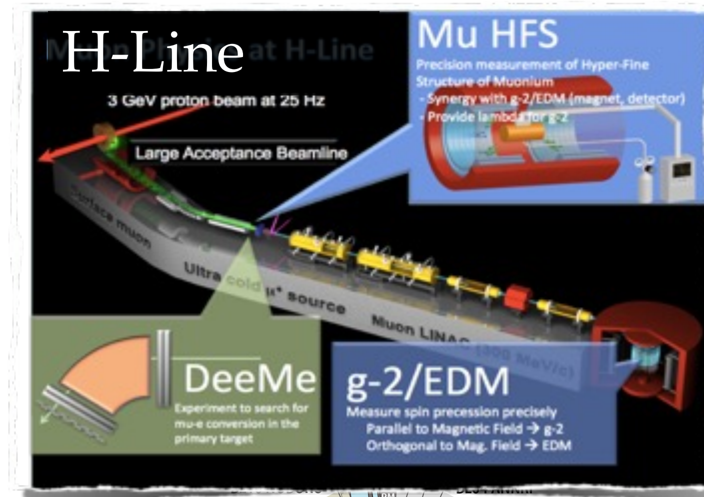


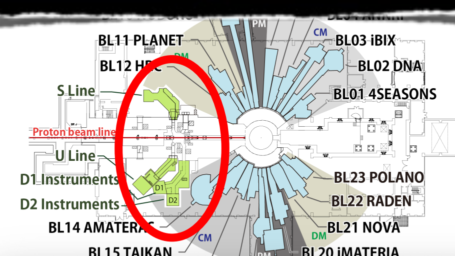
# Neutron Instruments at MLF

# Muon Facility MUSE @ MLF



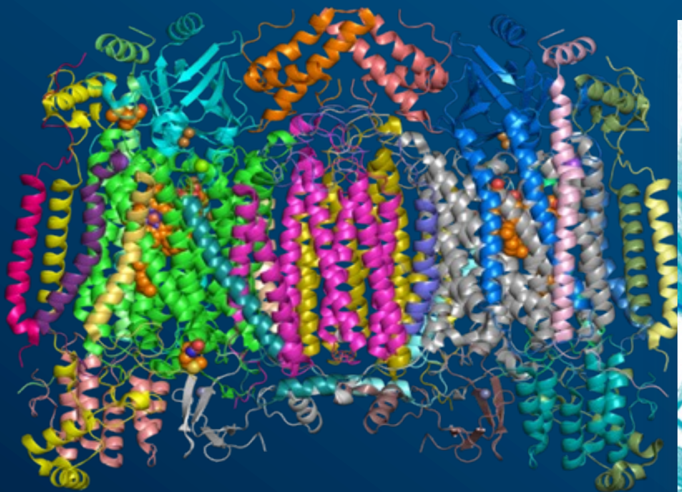



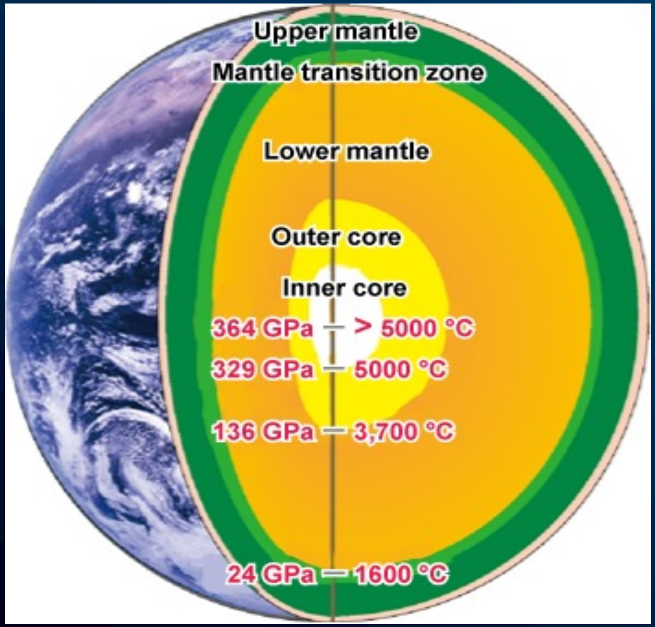





# Science at MLF




ADVANCED 4D NANO DESIGN




# BL01 Spin texture induced by non-magnetic doping and spin dynamics in 2D triangular lattice antiferromagnet $h$-Y(Mn,Al)$O_3$

# BL17 Emergence of spin-orbit coupled ferromagnetic surface state derived from Zak phase in a nonmagnetic insulator FeSi

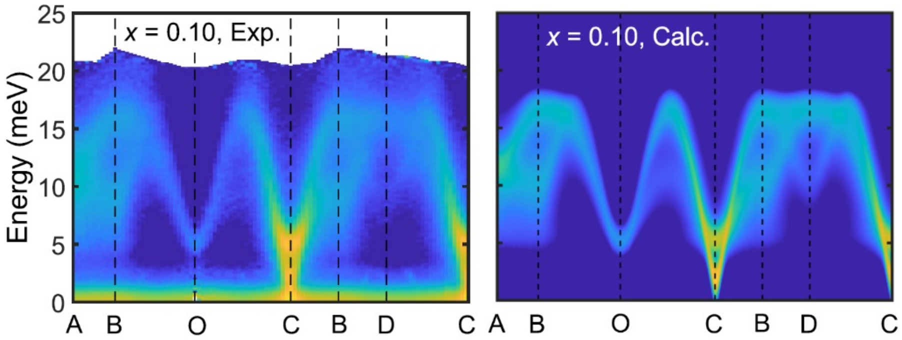
**Background**: Impurities are an inevitable problem in condensed matter physics and materials science. Magnetism is no exception, and understanding how impurities affect the materials' magnetic property is a long-standing question.

**Method** Impurity effect is investigated by measuring spin excitations in frustrated $h$–Y($Mn_{1-x}Al_x$)$O_3$ using TOF neutron spectroscopy, which are compared with theoretical model.

**Results** Spin excitation spectra are well explained by theoretical model considering impurities. It is found that there are non-trivial effects of impurities in a frustrated magnet.

**Significance** It presents a new possibility in applied physics by showing that one can easily generate a giant spin structure similar to a magnetic Skyrmion using impurities.

P. Park *et al*. Nat. Commun. 12, 2306 (2021).
DOI: 10.1038/s41467-021-22569-3




Impurity dependence of spin excitations in $h$–Y($Mn_{1-x}Al_x$)$O_3$.

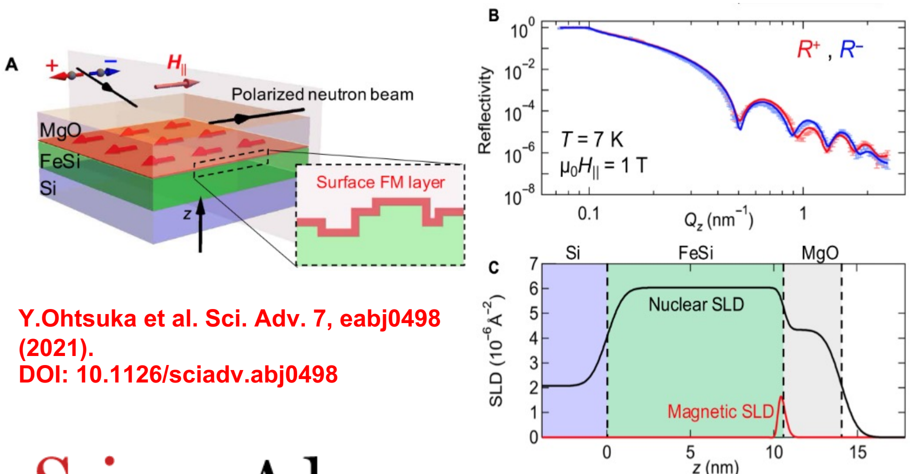
nature communications

**Background**: Topological insulators have attracted attention for the spintronic functionality. However, in existing materials, that state derives from the strong spin of heavy elements, and this has problems in terms of the rarity and toxicity of heavy elements.

**Method** FeSi thin films were prepared on Si substrate. The magnetic structure was examined by polarized neutron reflectometry.

**Results** The PNR measurement revealed the existence of the magnetic layer with the thickness of 0.35 nm at the surface of the FeSi film. The ab initio calculation showed that these surface properties are closely related to the Zak phase of the bulk band topology.

**Significance** These results provide hints for developing another route to explore noble metal–free materials for spin-orbit coupling-based spin manipulation.




Y.Ohtsuka et al. Sci. Adv. 7, eabj0498 (2021).
DOI: 10.1126/sciadv.abj0498

ScienceAdvances

# BL22 Success in Visualizing Water Inside Automotive Fuel Cells with Pulsed Neutron Beam

NEDO, J-PARC Center, Nissan Arc, FC-Cubic
Collaboration with：Totoya Central Lab, Honda R&D, TOYOTA corp.

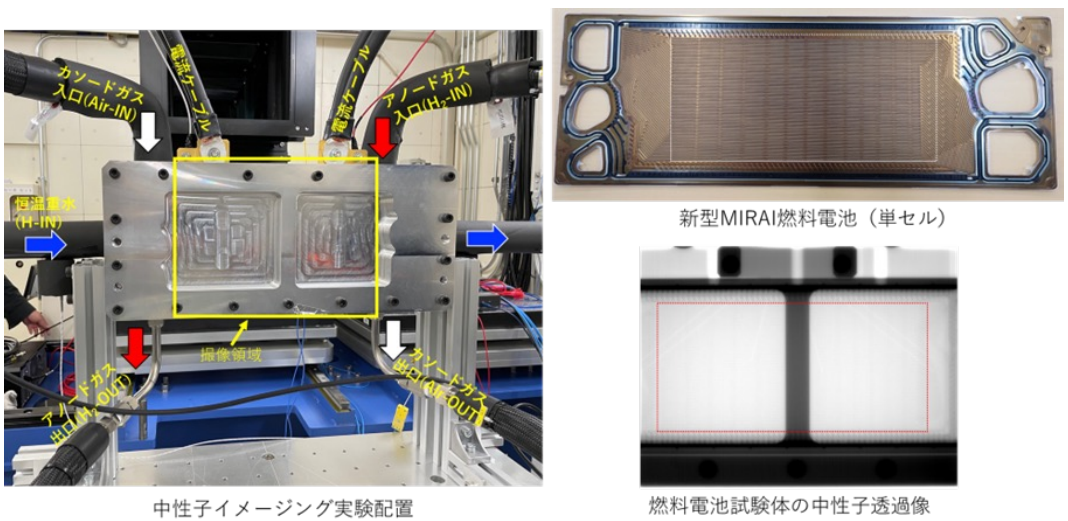


Fig. Fuel cell cell used in neutron imaging water visualization experiments

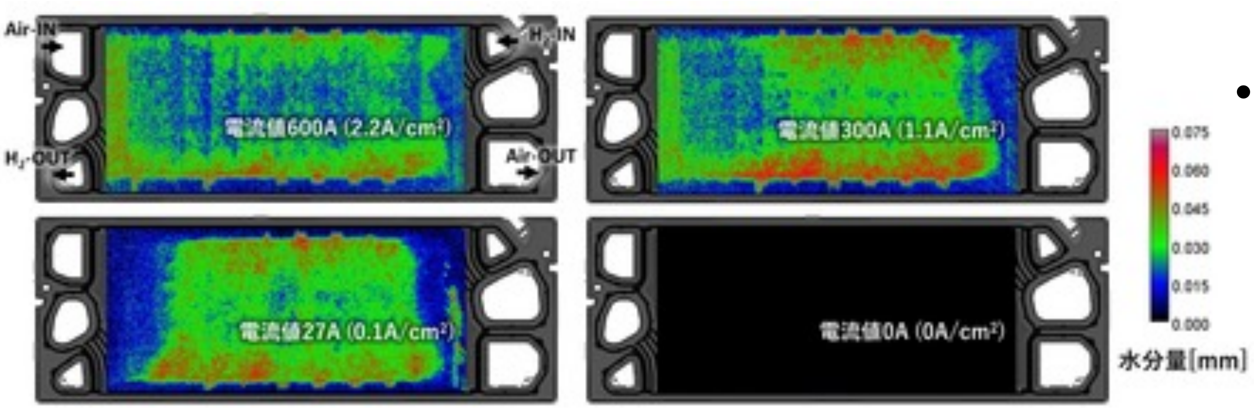
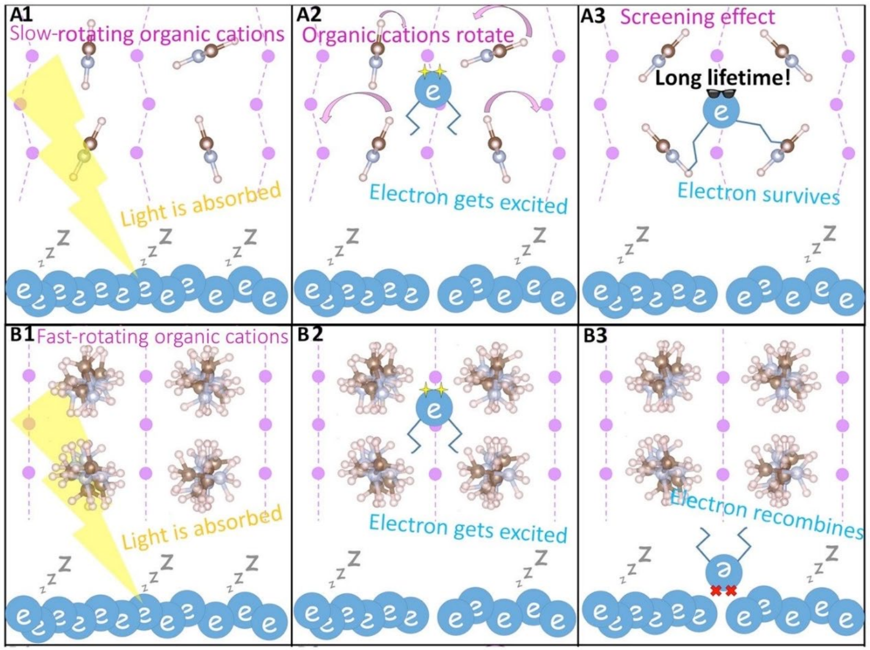


Fig. Visualized image of water behavior in a fuel cell of MIRAI (change in water distribution with current value)

- Success in Visualizing the Behavior of Water Generation and Discharge inside a Fuel Cell Cell (2nd Generation MIRAI) of Actual Size Installed in a Fuel Cell Vehicle (FCV)
- This is the first time in the world that a pulsed neutron beam has been used to clarify the behavior of water inside an actual size cell.

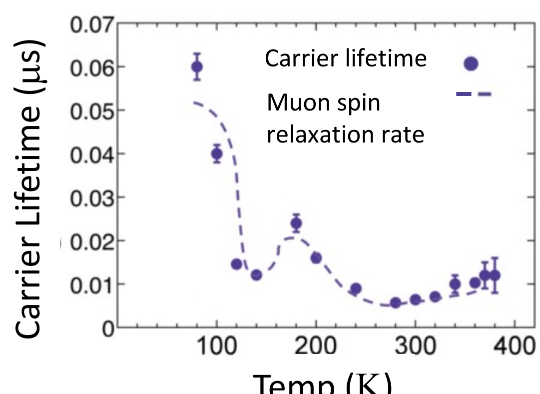
# S1 Elucidating the Mechanism of High Efficiency of Next-Generation Solar Cell Materials using Muon



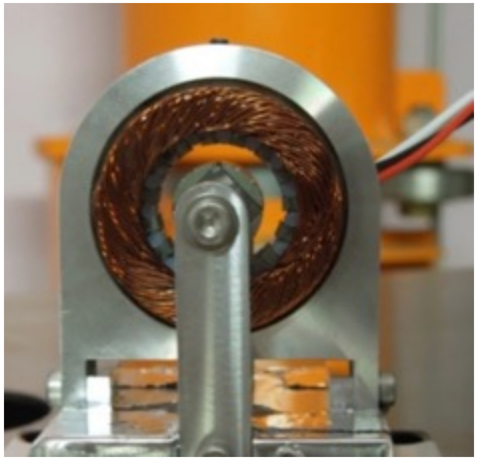

Moderate suppression of the speed of free rotational motion of organic molecules is important for long charge carrier lifetime

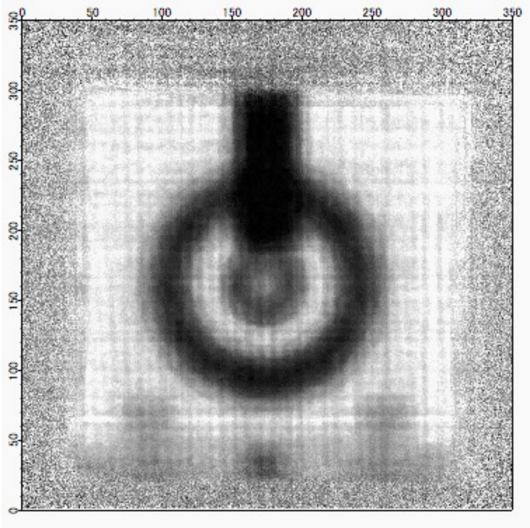
A. Koda, et al., *PNAS* 119 (4) e2115812119 (2022)

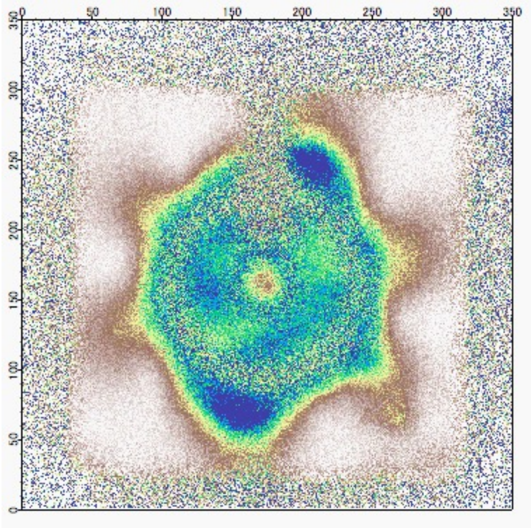
- Lead methylammonium iodide (CH3NH3PbI3), a typical organic-inorganic hybrid perovskite compound that is promising as a next-generation solar cell material
- Observation of the motion of organic molecules by general-purpose μSR experiments
- Clear correlation between high photoelectric conversion efficiency and the motion of organic molecules in the crystal



# Magnetic Imaging @ RADEN





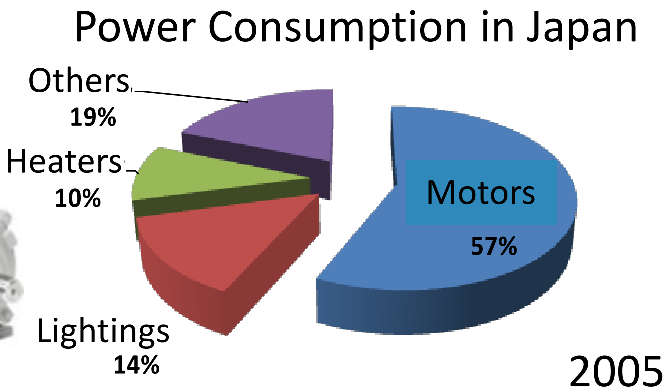


**The world's 1st demonstration of visualizing magnetic field of a working motor.**

**Collaboration with Hitachi Ltd.**

HITACHI
Inspire the Next

**RADEN results are used to improve simulation technology to design higher performance motors.**




Supported by Photon and Quantum Basic Research Coordinated Development Program by MEXT (2013-2018)

Motors consume more than 50% of total electric power in Japan

# D2 Instrument (Muon Spectrometer for Basic Sci. Exp.)

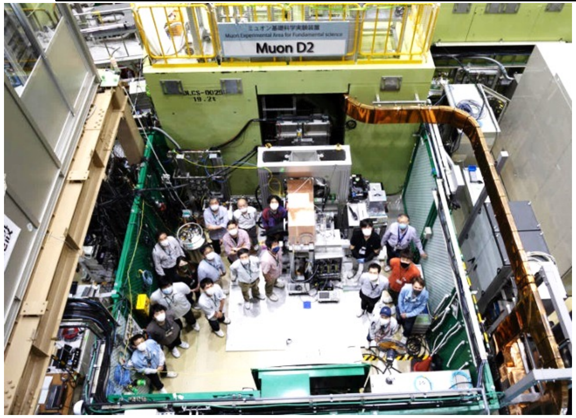

## Research & development highlights in 2021

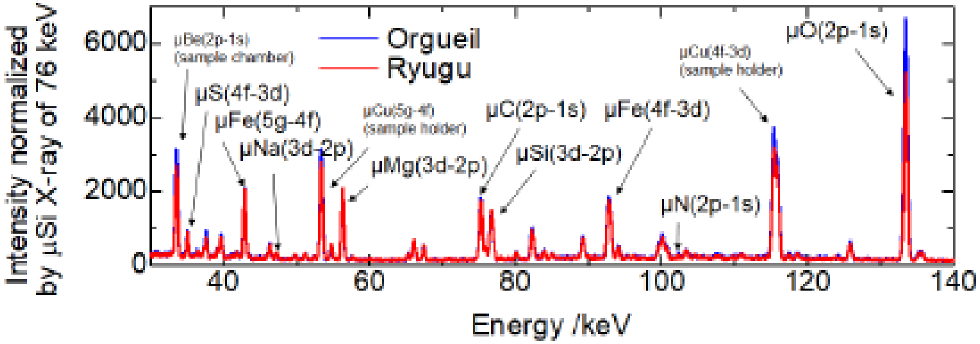
**2019MS01**

**Non-destructive elemental analysis of return samples from asteroid *Ryugu***

- ✓ Need to know the elemental composition of the entire stone, including light elements such as C.
- ✓ Possibility of chemically unstable in the atmosphere

*Muonic X-ray elemental analysis was employed as an initial analysis of Ryugu samples.*

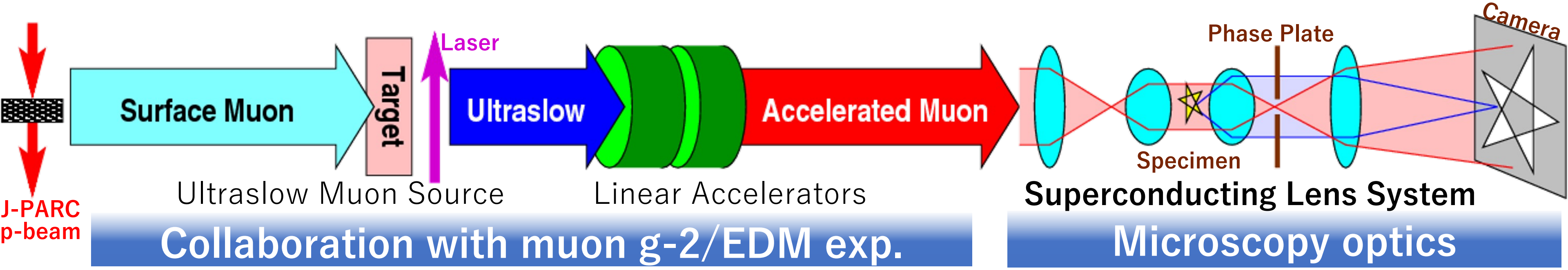




Ryugu stones could become a new standard representative of the Solar System.

T. Nakamura *et al.*, *Science* 10.1126/science.abn8671 (2022).

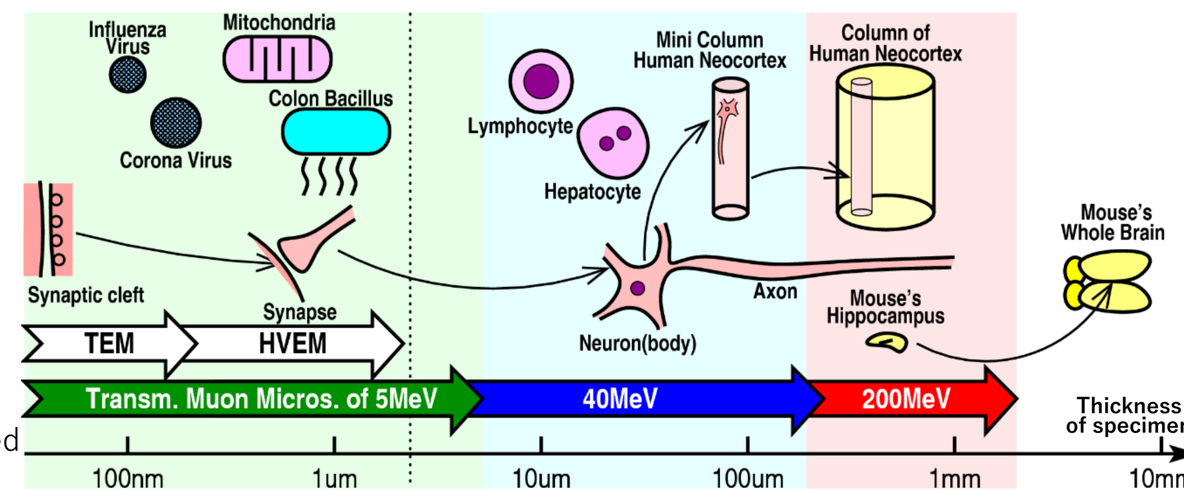
# Future project: Transmission Muon Microscope

= Accelerated Muon : Strong Penetration + Ultraslow Muon : High Luminance / Resolution

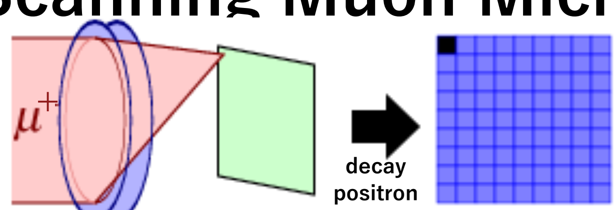



## Nano scale visualization of electromagnetic fields in macroscopic objects

- Any methods for TEMs are applicable, like Lorentz imaging or Zernike phase contrast.
- Functional imaging of living/cryo-tissues: Cross scale understanding of our brain from synapse, neuron, network to organ.
- Industrial use: It can see EM fields in packaged IC/LSI, Li ion battery, solar cell, piezo, etc.




## Scanning Muon Microscope

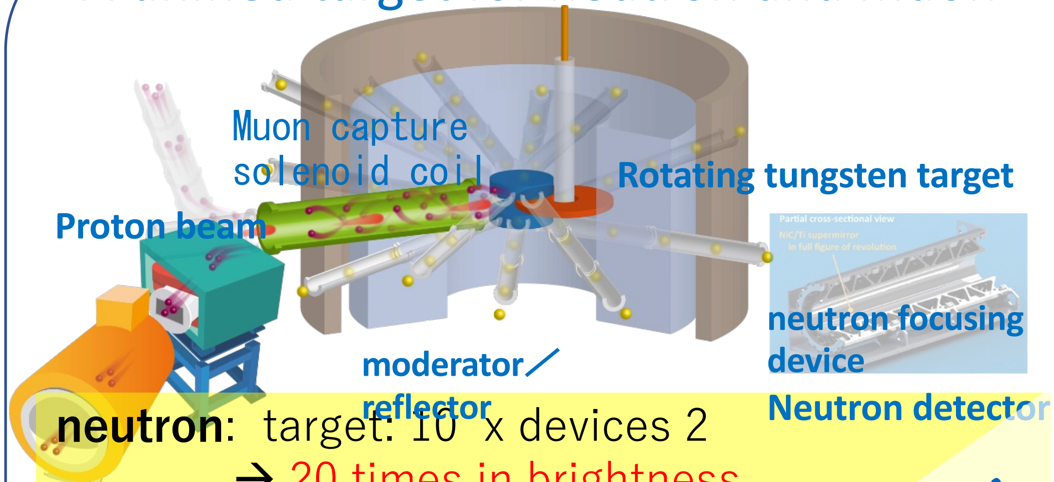



3-dim mapping of magnetic field and its fluctuation, density of Fermi surface, state of hydrogen, and etc. in nano resolutions. → **Scanning μSR microscope**

| Schedule | 2022 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 32 | 33 | 2034~ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| g-2/EDM exp. | Construction | | | | Eng. run ➡ Phys. run | | | | | | | |
| Transmission | Design | | Const. | | Phase 1 run | | | | | | | Phase 3 |
| Scanning | | | Design | | | Const. | | | Phase 2 run | | | |

# Future plan: New Neutron and Muon Target station (TS2)

## A unified target for neutron and muon

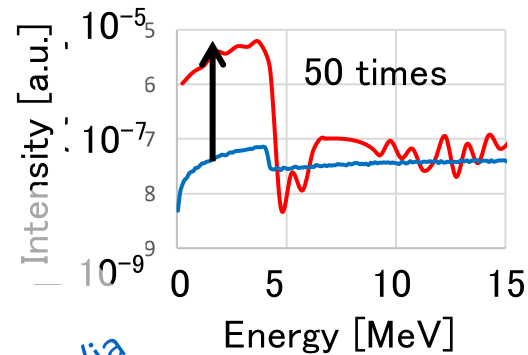


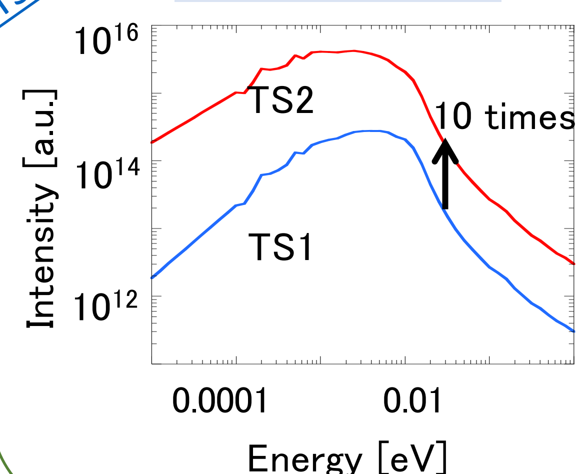

**neutron**: target: 10 x devices 2
→ 20 times in brightness

**Muon** :target：10 x capture solenoid 5～10
→ 50 ～ 100 times in intensity

**CDR:** http://j-parc.jp/researcher/MatLife/ja/publication/files/TS2CDR.pdf

## Calculation of Intensity




## Accelerator Upgrade

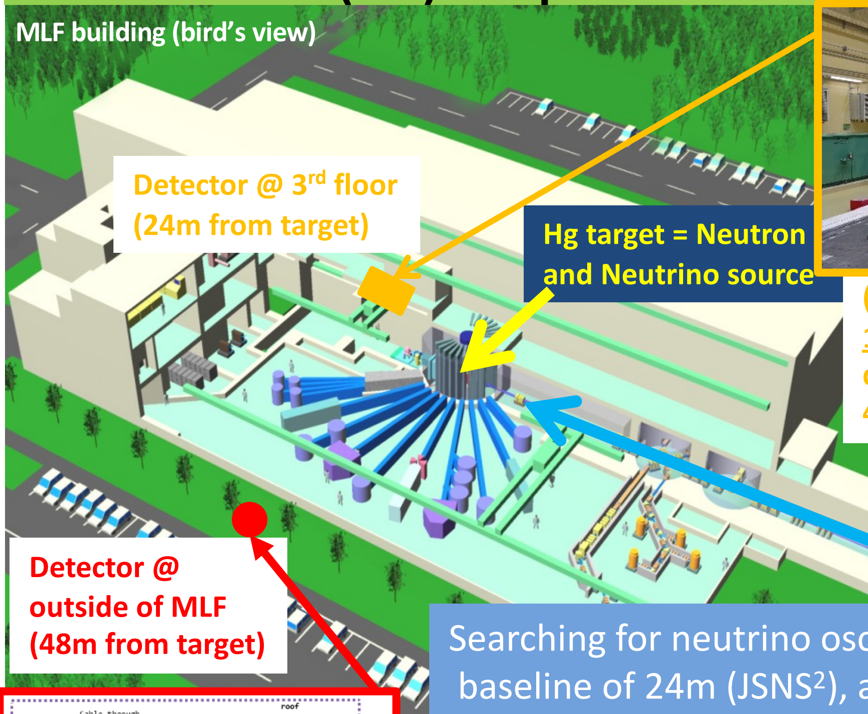
Power 1 MW → 1.5 MW (TS1:1MW, TS2: 0.5MW)

Repetition 25 Hz → 25 HZ (TS1:17Hz, **TS2: 8Hz**) **Long wavelength**

| | | 1 MW | 1.5 MW |
|---|---|---|---|
| Peak current | [mA] | 50 | 62.5 |
| Pulse width | [ms] | 500 | 600 |
| Repetition | [Hz] | 25 | 25 |
| Average current | [mA] | 333.3 | 500 |
| Max energy in lineac | [MeV] | 400 | 400 |
| Max energy in RCS | [GeV] | 3 | 3 |

# Particle and nuclear physics at J-PARC

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




Detector @ 3$^{rd}$ floor (24m from target)

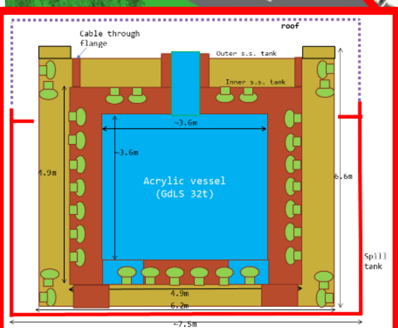
Hg target = Neutron and Neutrino source

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

3GeV pulsed proton beam

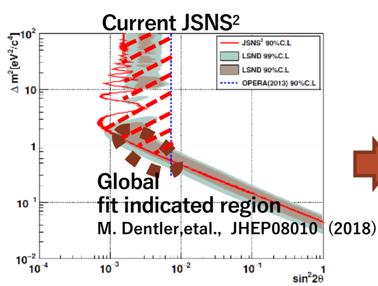
Detector @ outside of MLF (48m from target)

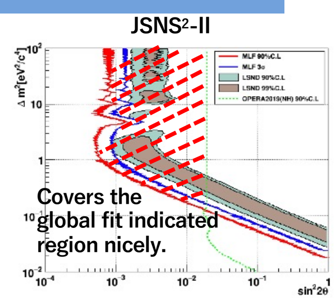
Searching for neutrino oscillatio[n] … th baseline of 24m (JSNS$^2$), and 48…




(JSNS$^2$-II: New detector) 35t GdLS fiducial

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



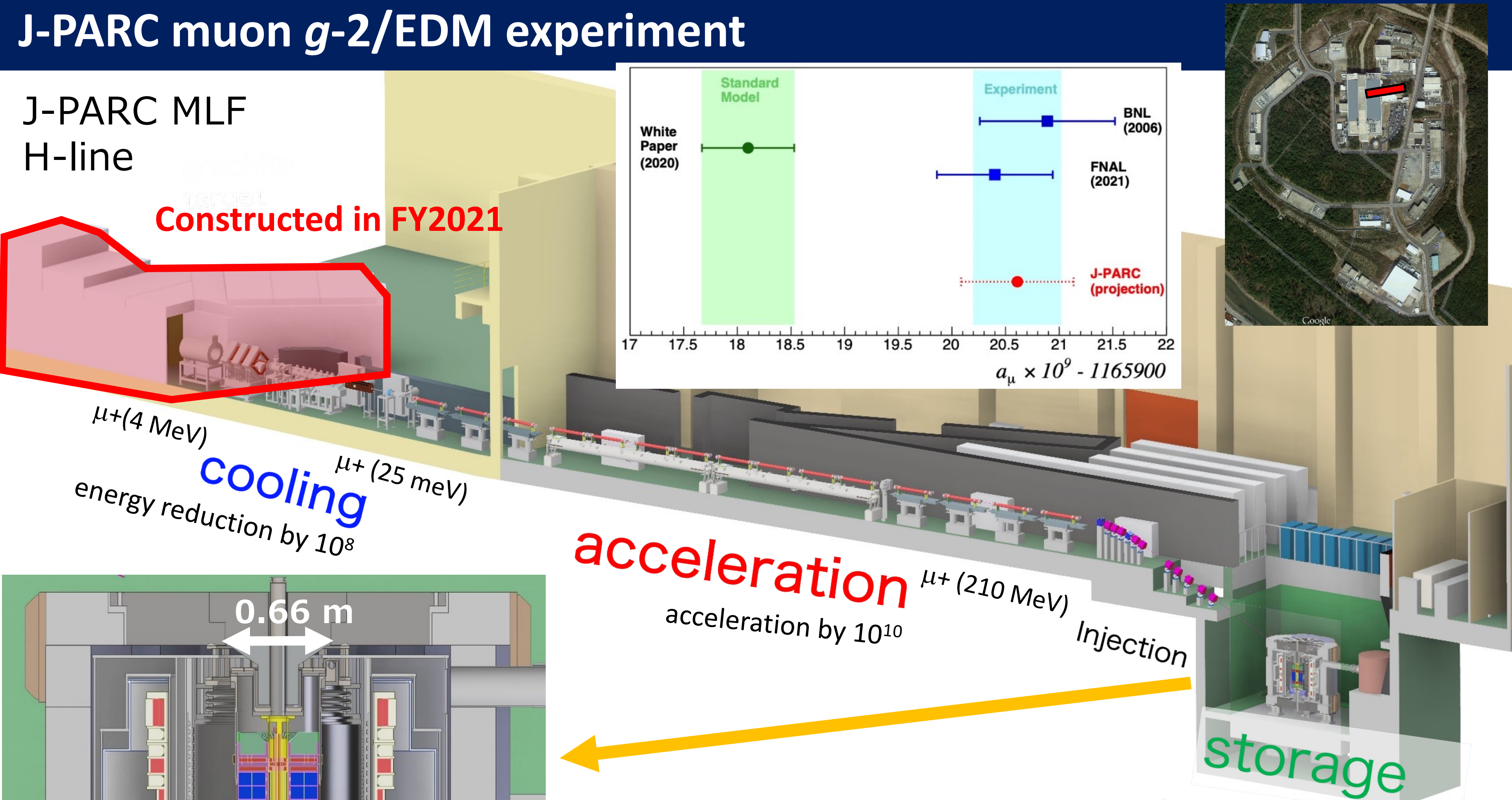

## (JSNS$^2$) : 1MW x 3 years

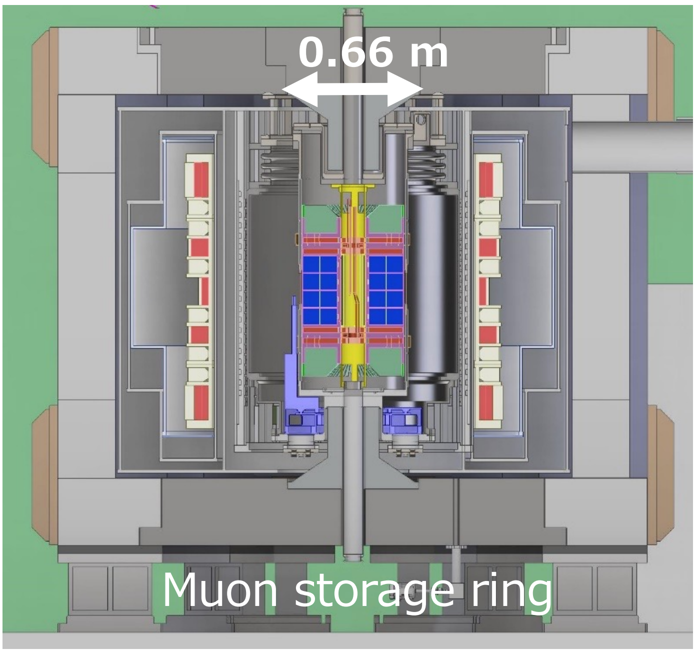
- The first long physics run in 2021.
  - More than 6 months.
  - Data analyses are on-going.
- **<u>The 2$^{nd}$ Physics run was started from 28-Jan (2022).</u>**

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

- 2$^{nd}$ phase of the experiment
  - new far detector : 32 tons fiducial in 48m baseline.
  - Improved the sensitivity, especially in low $\Delta m^2$ region.
  - Stage-1 status. Stage-2 approval is being discussed.
  - **Detector construction : on-going**

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

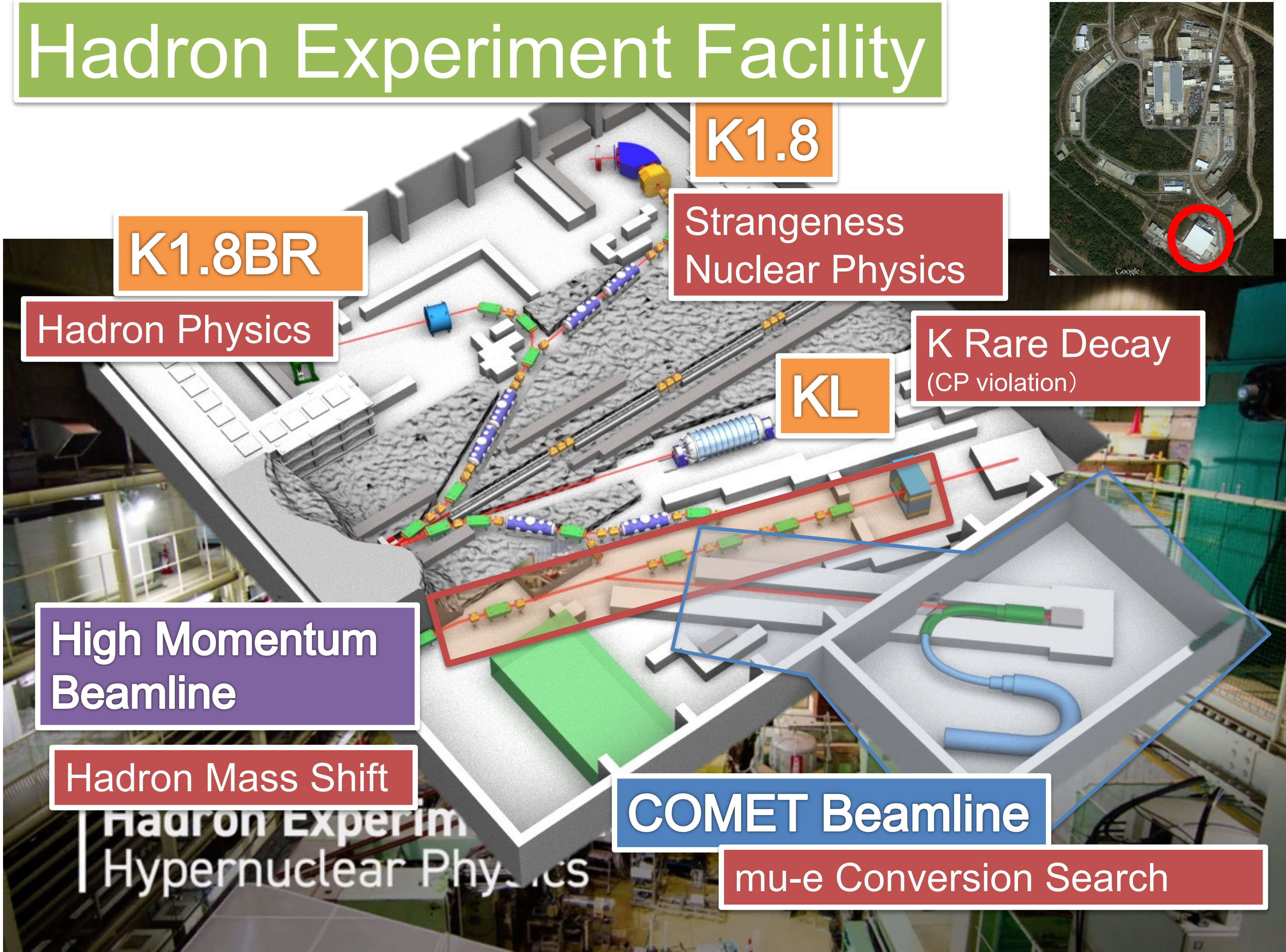



Measurement of g-2 and EDM with a compact storage ring (1/20 of FNAL/BNL g-2) with new muon beam by cooling and acceleration

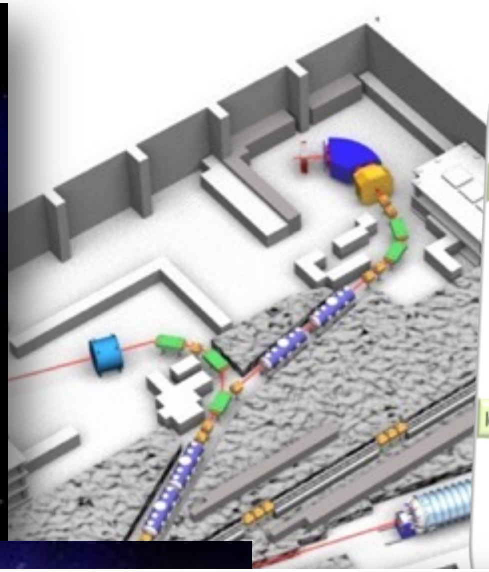
**Construction of main facility starts in 2022 aiming at operation in 2027**

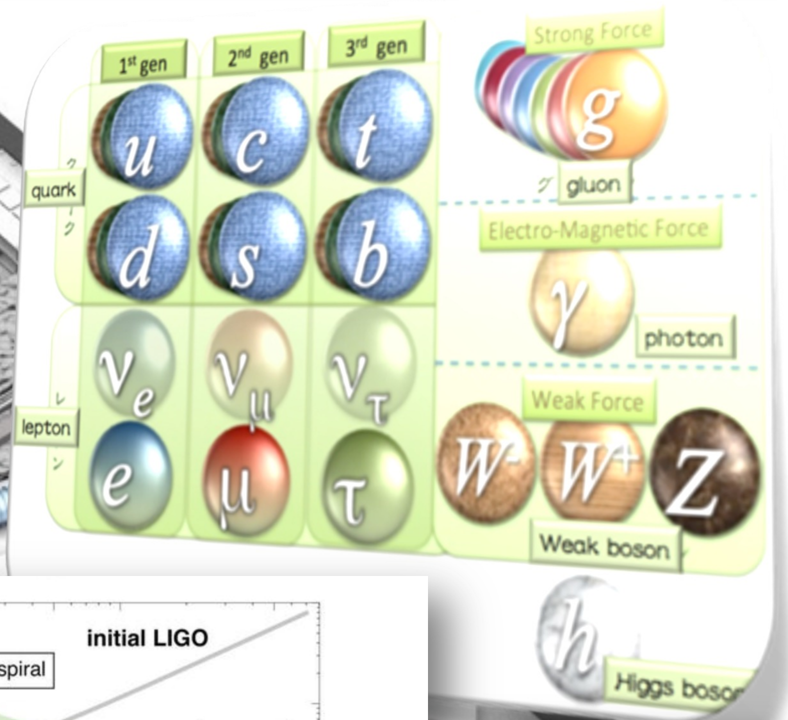
# Hadron Experiment Facility

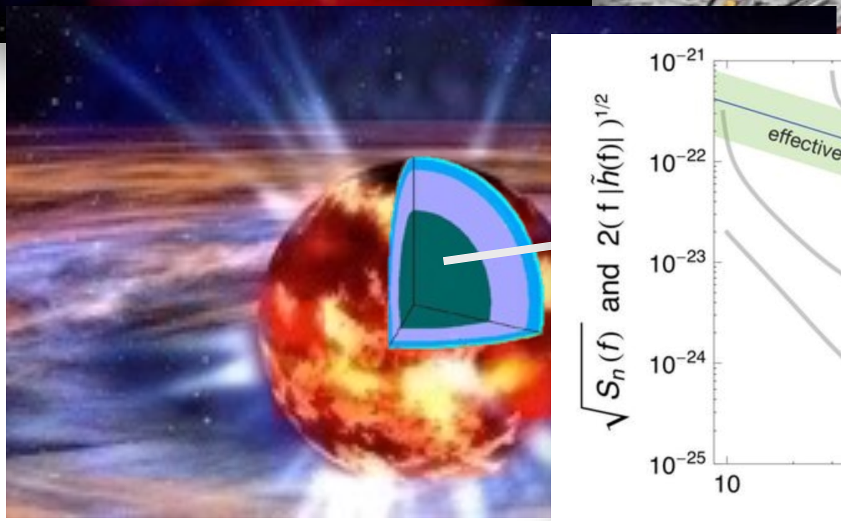


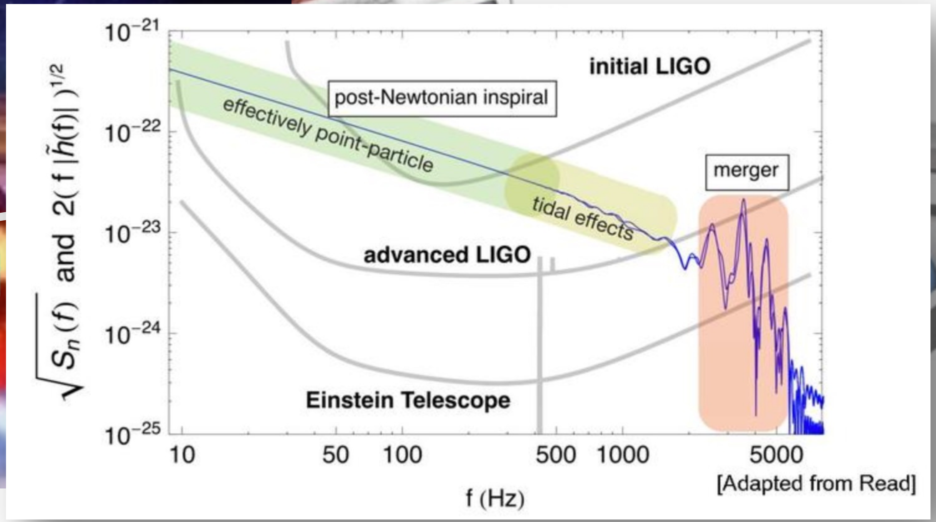
# Hadron beams for…

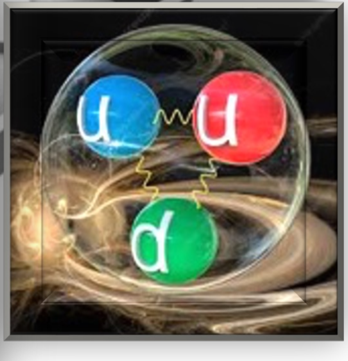
## Exploration of the mysteries in formation of matter!





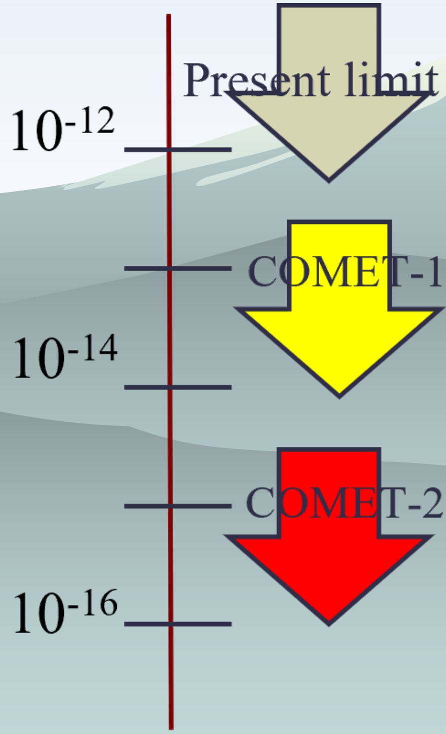



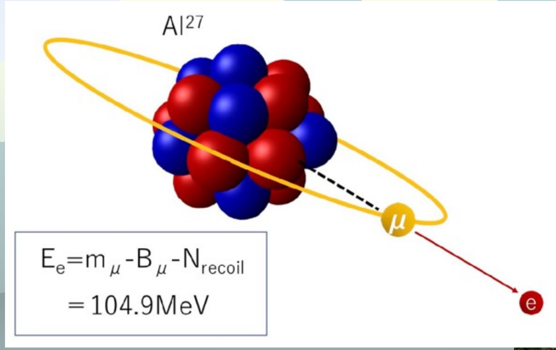


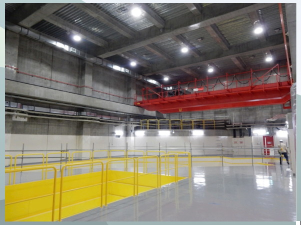
# COMET experiment

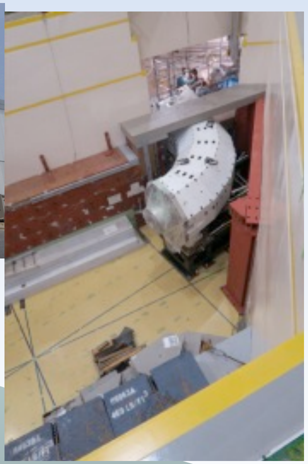
- μ→e conversion search $\mu^{-}+(A,Z)\rightarrow e^{-}+(A,Z)$
  - Very small $O(10^{-54})$ in SM
  - **Discovery = New Physics!**
- Proton beamline ready in 2022
- First commissioning in 2022
- Capture Solenoid installation in 2023, followed by the start of physics run of Phase-1

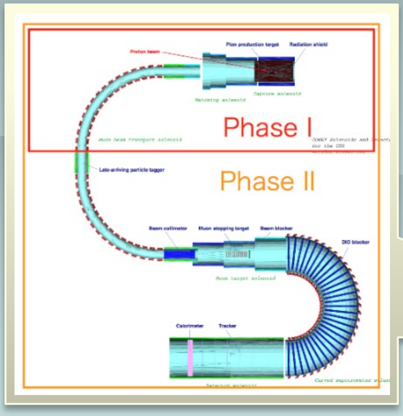


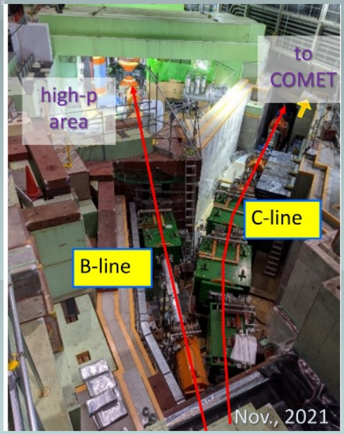

COMET Hall





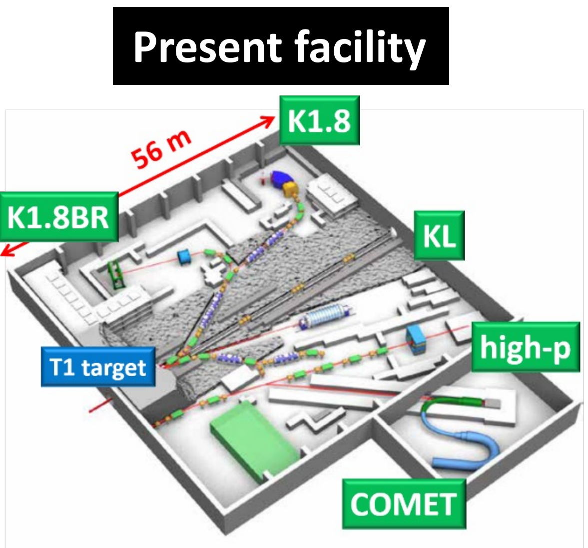




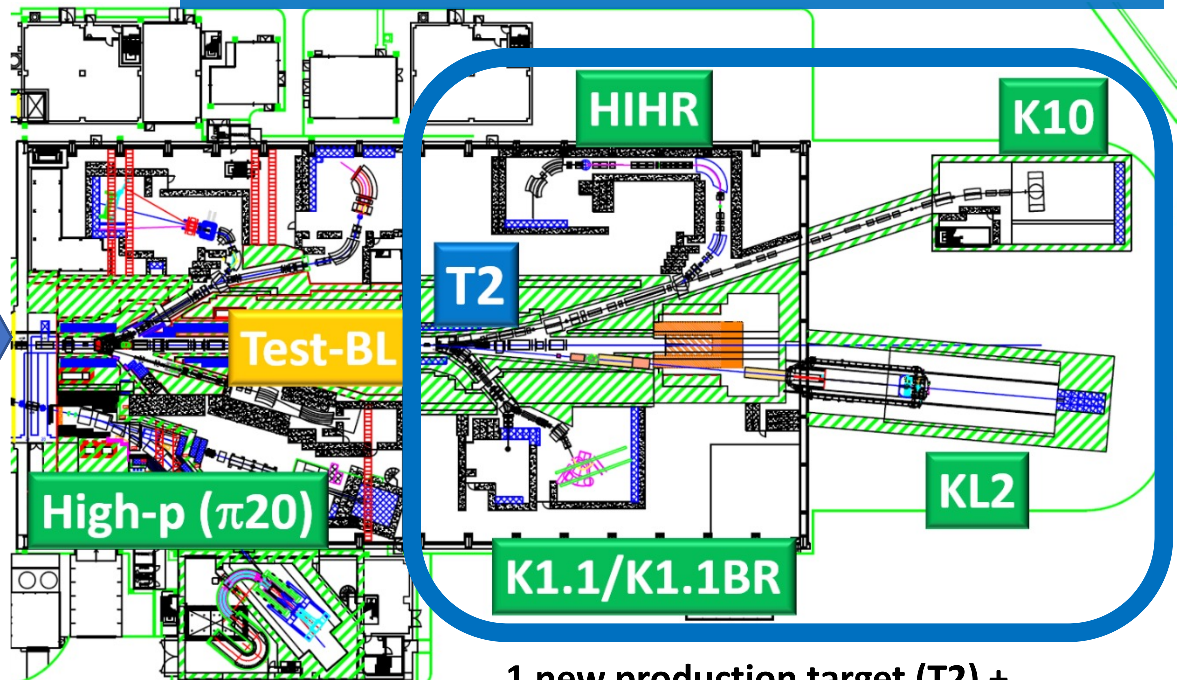


# Hadron Experimental Facility Extension (HEF-ex) project

**Open new physics that cannot be implemented at the existing facility**




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)

# Neutrino and Anti-neutrino for…

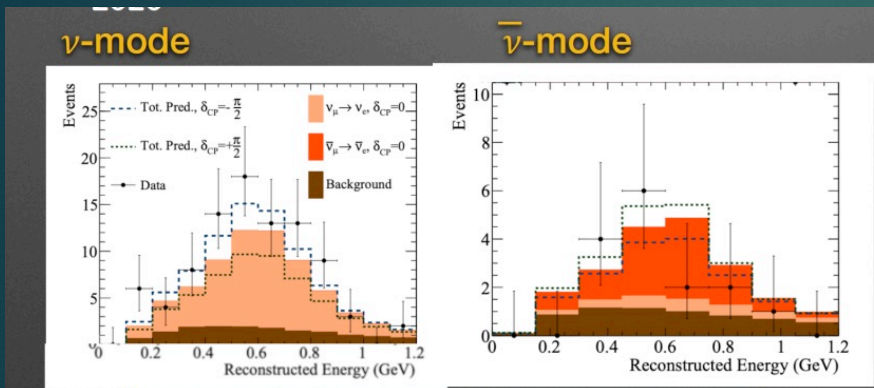
## Elucidation of the origin of universe and matter!



## Where did anti-matter go?

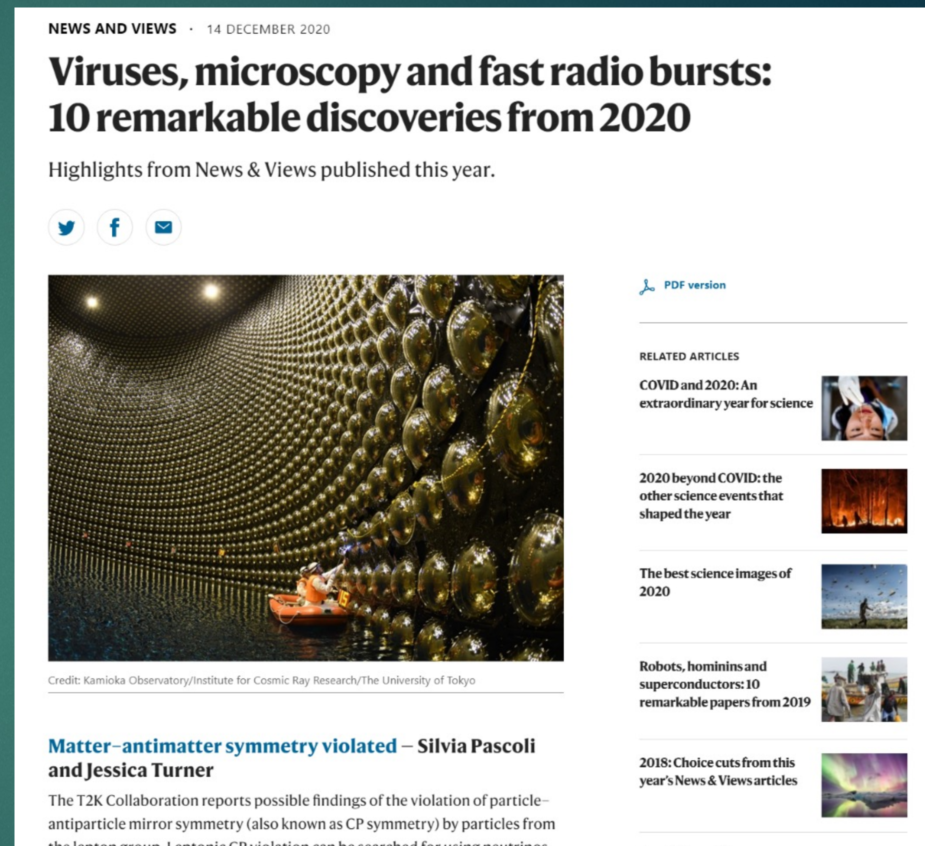
# T2K latest results (2020)






| | ν-mode | $\bar{\nu}$-mode |
|---|---|---|
| Observed | 90 | 15 |
| Exp ($\delta_{CP}=-\pi/2$) | 81.7 | 17.2 |
| Exp ($\delta_{CP}=0$) | 68.4 | 19.6 |

- $3.13\times10^{21}$ protons on target (2010~2020)
- CP phase measurement
  - Excluded CP conservation at ~ 95%CL
  - ~35% region of CP phase delta excluded > 3sigma


NEWS AND VIEWS · 14 DECEMBER 2020

Viruses, microscopy and fast radio bursts: 10 remarkable discoveries from 2020

Highlights from News & Views published this year.

Credit: Kamioka Observatory/Institute for Cosmic Ray Research/The University of Tokyo

Matter–antimatter symmetry violated – Silvia Pascoli and Jessica Turner

The T2K Collaboration reports possible findings of the violation of particle–antiparticle mirror symmetry (also known as CP symmetry) by particles from the lepton group. Leptonic CP violation can be searched for using neutrinos.

PDF version

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2020 beyond COVID: the other science events that shaped the year

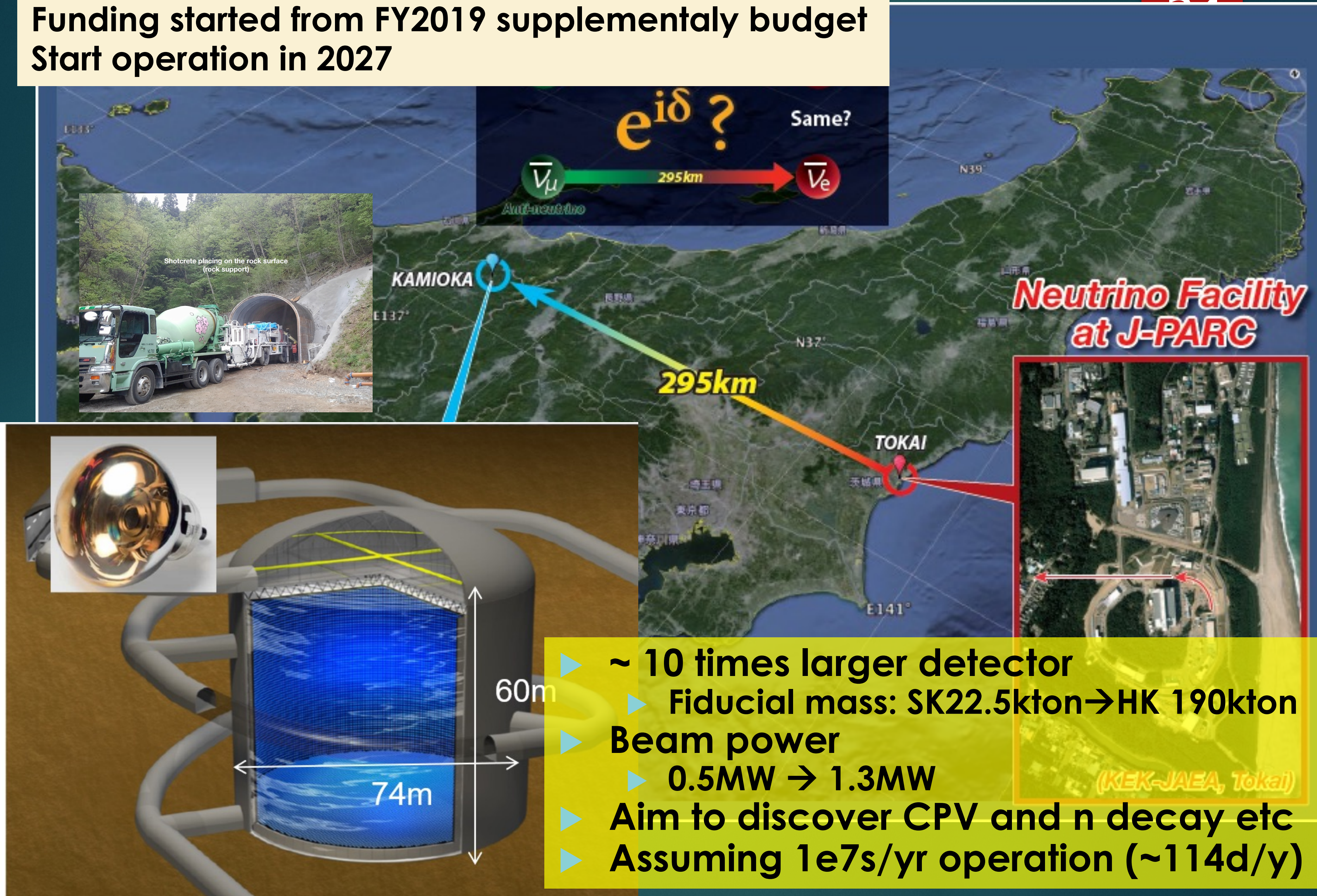
The best science images of 2020

Robots, hominins and superconductors: 10 remarkable papers from 2019

2018: Choice cuts from this year's News & Views articles

# Hyper-Kamiokande construction ongoing

**Funding started from FY2019 supplementaly budget**
**Start operation in 2027**

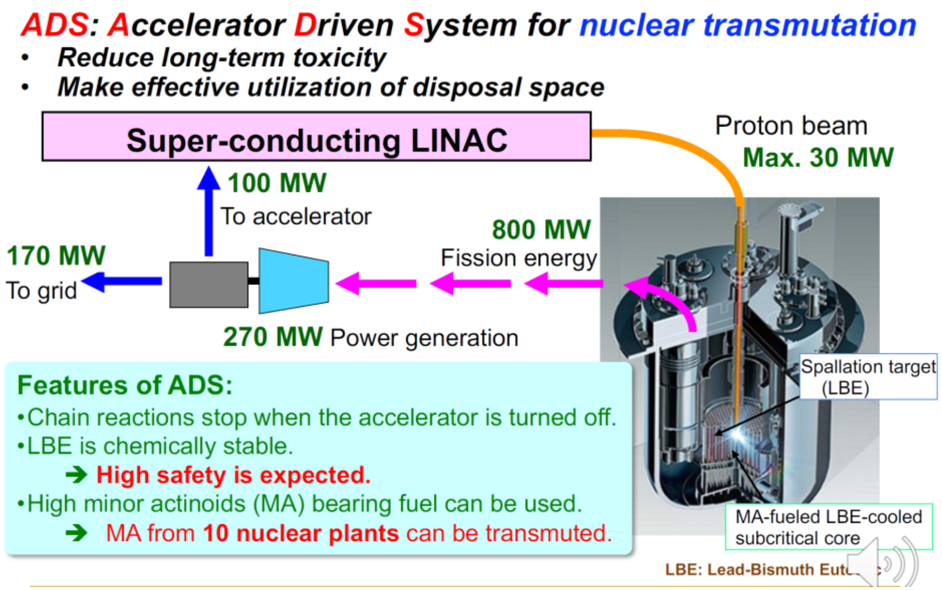



- ~ 10 times larger detector
  - Fiducial mass: SK22.5kton→HK 190kton
- Beam power
  - 0.5MW → 1.3MW
- Aim to discover CPV and n decay etc
- Assuming 1e7s/yr operation (~114d/y)

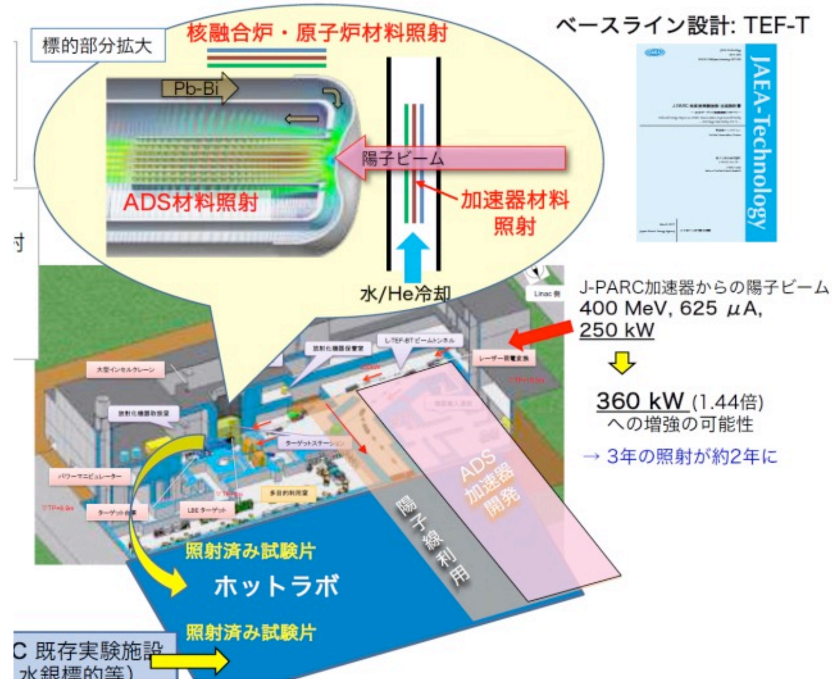
# J-PARC


## Transmutation Experimental Facility (Phase II)

# Accelerator Driven system for nuclear transmutation

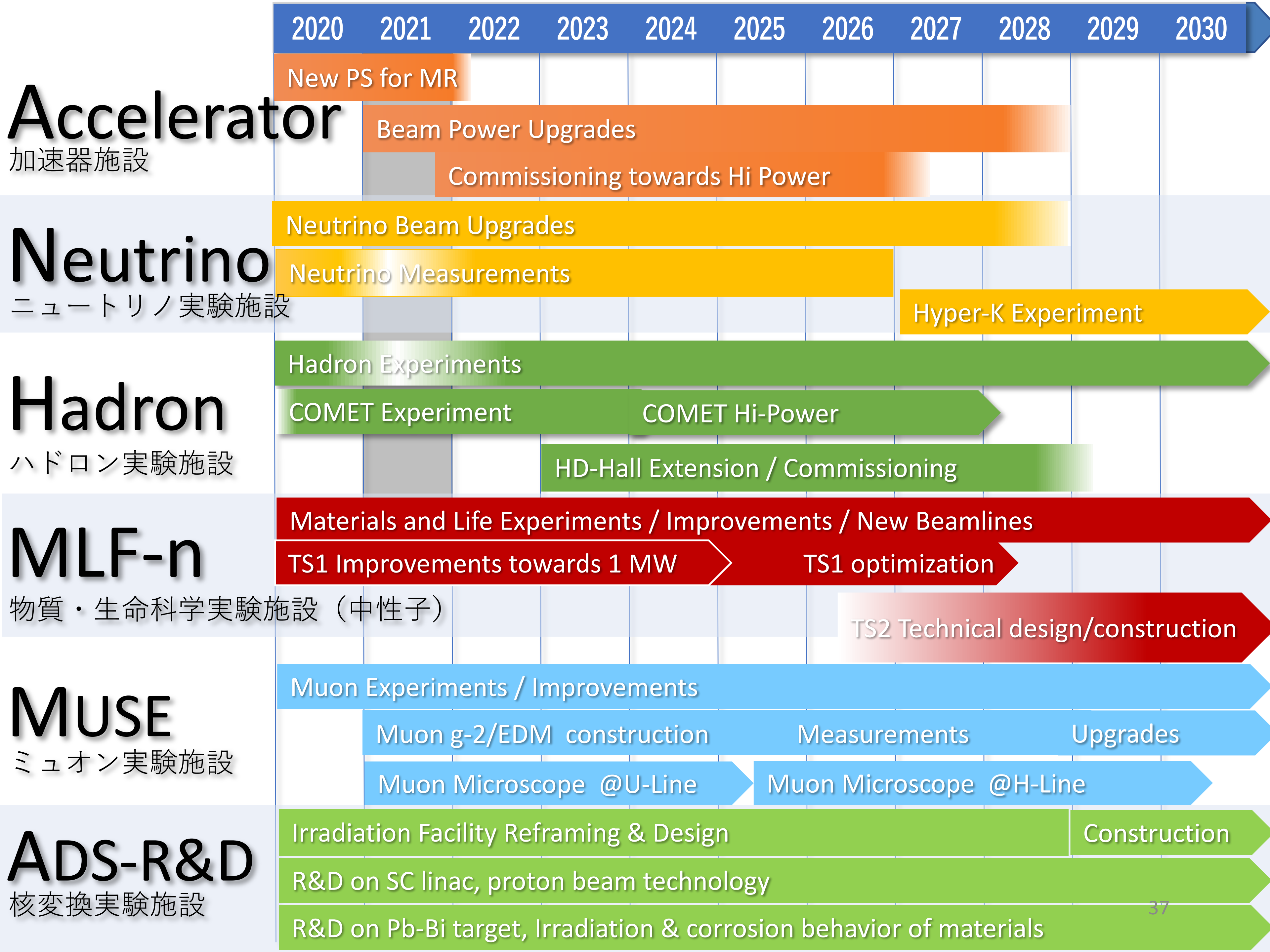



New concept of proton irradiation facility for R&D toward ADS realizaiton




Continue

- Aim to realize proton irradiation facility at J-PARC for R&D
  - Evoke various needs of proton/neutron beam for various application and form user community
- Element technology development such as circulation of Liquid Lead-bismuth eutectic (LBE), proton beam control technology



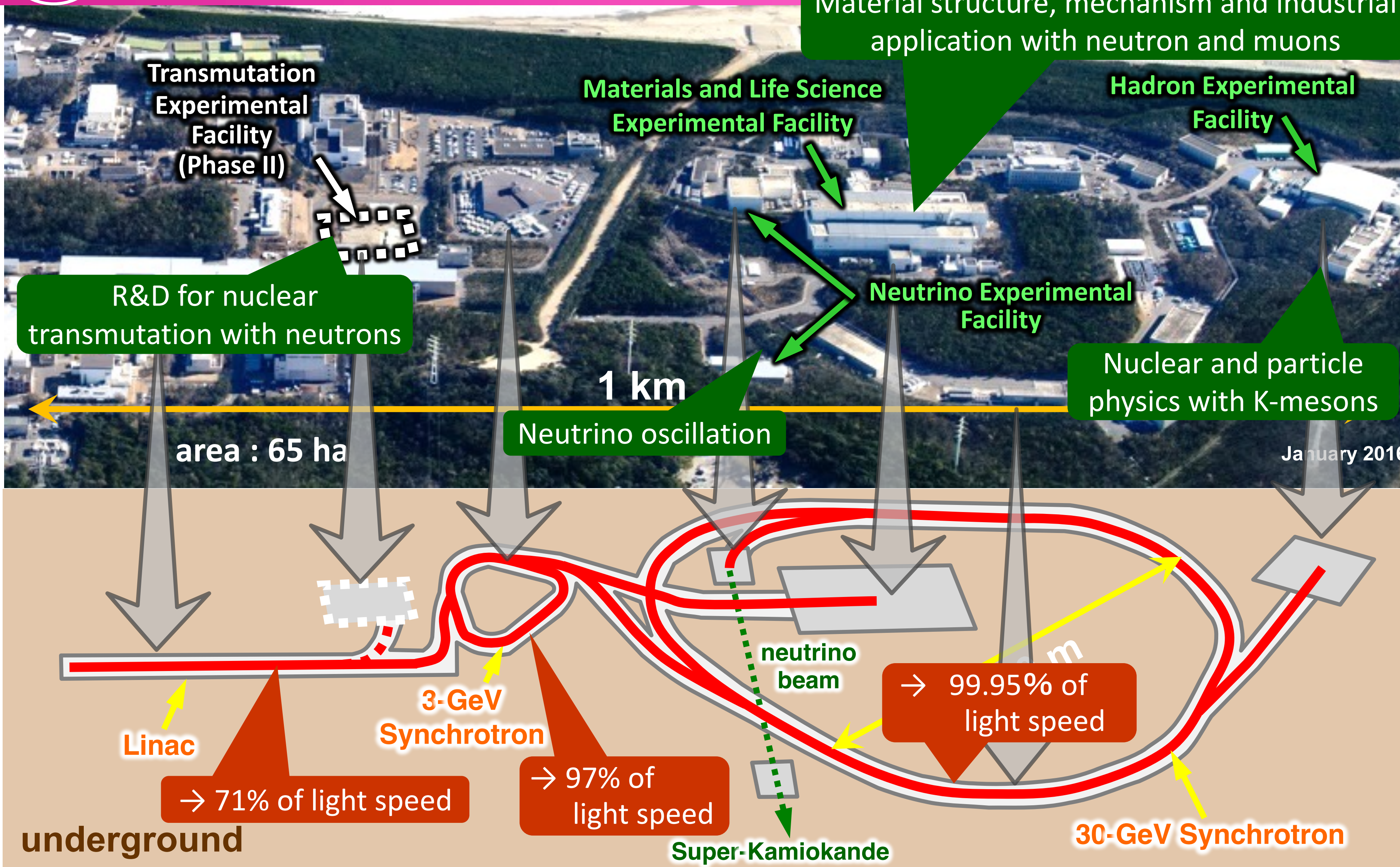
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Accelerator
加速器施設
New PS for MR
Beam Power Upgrades
Commissioning towards Hi Power
Neutrino
ニュートリノ実験施設
Neutrino Beam Upgrades
Neutrino Measurements
Hyper-K Experiment
Hadron
ハドロン実験施設
Hadron Experiments
COMET Experiment
COMET Hi-Power
HD-Hall Extension / Commissioning
MLF-n
物質・生命科学実験施設（中性子）
Materials and Life Experiments / Improvements / New Beamlines
TS1 Improvements towards 1 MW
TS1 optimization
TS2 Technical design/construction
MUSE
ミュオン実験施設
Muon Experiments / Improvements
Muon g-2/EDM construction
Measurements
Upgrades
Muon Microscope @U-Line
Muon Microscope @H-Line
ADS-R&D
核変換実験施設
Irradiation Facility Reframing & Design
Construction
R&D on SC linac, proton beam technology
R&D on Pb-Bi target, Irradiation & corrosion behavior of materials

# Summary



- J-PARC is the world leading intensity frontier proton accelerator research complex
  - 3GeV RCS/MLF: reached at 830kW stable operation
  - 30GeV MR
    - 515kW for neutrino
    - 64kW for hadron
- J-PARC is unique facility covering wide range of research fields
  - Particle, nuclear physics, material and life sciences and industrial applications, Archeology, planetary science
- J-PARC is open to world community for discovery and innovation
- Continue to achieve  world leading scientific outcome
- Will continue with variety of future programs

# Japan Proton Accelerator Research Complex




3 proton accelerators and 3 experimental facilities

# J-PARC Accelerators

## High-intensity proton accelerators

- **Linac**
  - length: 249 m
  - energy: 400 MeV, 71% of light speed
  - beam extracted to RCS and Transmutation Experimental Facility

- **Rapid-Cycling Synchrotron (RCS)**
  - circumference: 348 m
  - energy: 3 GeV, 97% of light speed
  - beam power: 1 MW (0.7 MW)
  - beam extracted to MR and Materials and Life Science Experimental Facility

- **Main Ring (MR)**
  - circumference: 1,568 m
  - energy: 30 GeV, 99.95% of light speed
  - beam power: 0.75 MW (0.51 MW)
  - beam extracted to Hadron Facility or Neutrino Facility

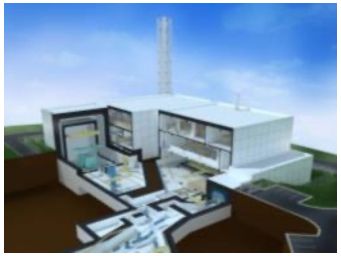


numbers in parentheses are current operation parameters

# J-PARC Experimental Facilities

Wide range of research fields

- **Materials & Life Science Experimental Facility**
  - neutron and muon beams
  - materials science, life science, industrial applications
- **Hadron Experimental Facility**
  - K mesons, π mesons, muons ····
  - nuclear physics and particle physics
- **Neutrino Experimental Facility**
  - muon neutrino beams
  - neutrino oscillation search with Super-Kamiokande
- **Transmutation Experimental Facility (Phase II)**
  - R&D for accelerator-driven nuclear transmutation with neutrons



PHYSICAL REVIEW LETTERS

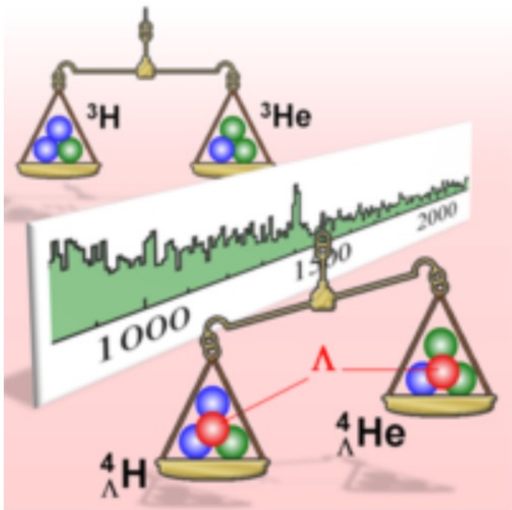


Editors' Suggestion

# Observation of Spin-Dependent Charge Symmetry Breaking in $\Lambda N$ Interaction: Gamma-Ray Spectroscopy of ${}^{4}_{\Lambda}\mathrm{He}$

T. O. Yamamoto *et al.* (J-PARC E13 Collaboration)

Phys. Rev. Lett. **115**, 222501 (2015) – Published 24 November 2015

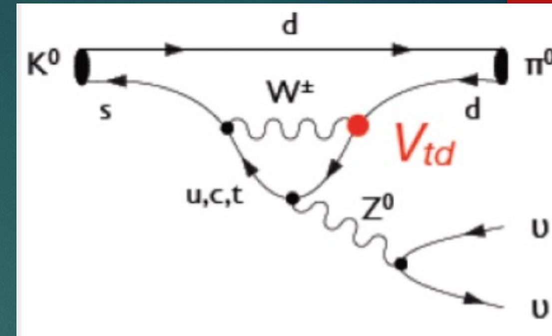



The energy spacing of the spin-doublet states in the ${}^{4}_{\Lambda}$He hypernucleus indicate a large spin dependent charge symmetry breaking in the $\Lambda N$ interaction.

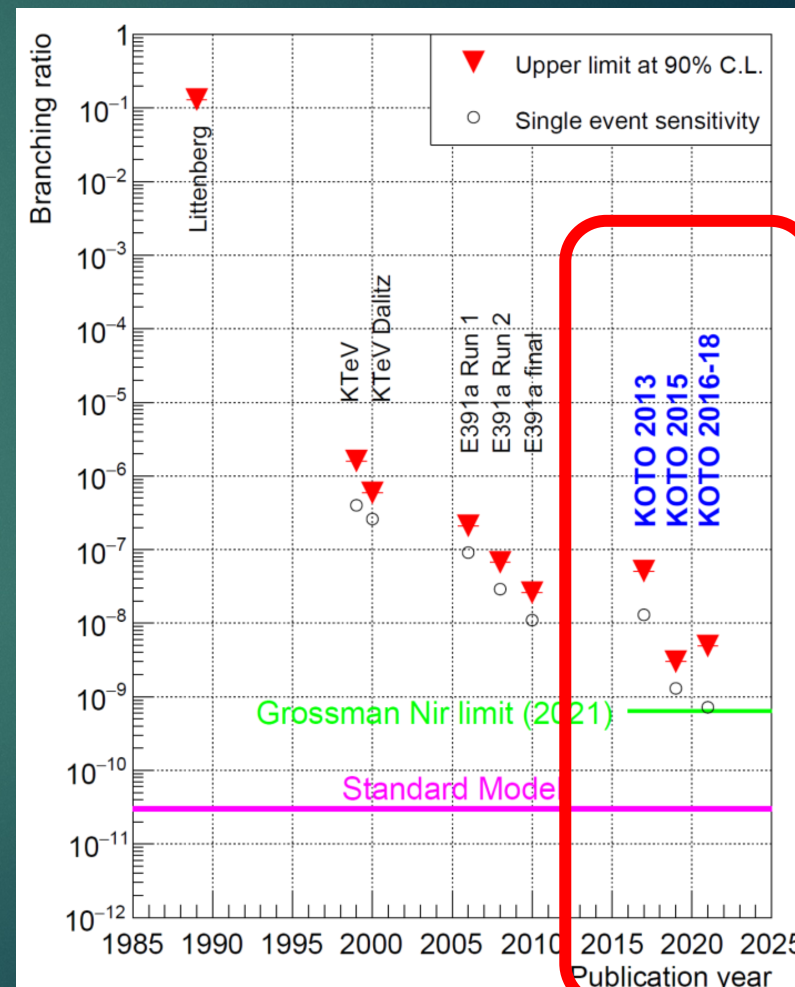
# KOTO experiment

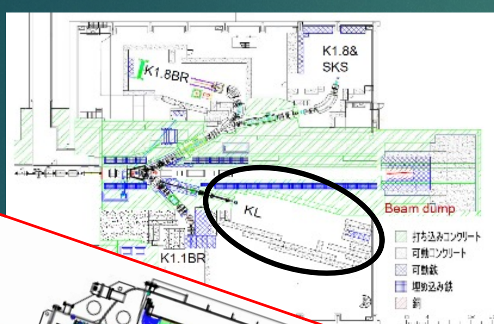
- Search for CP violating decay $K_L \rightarrow \pi^0 \nu\bar{\nu}$

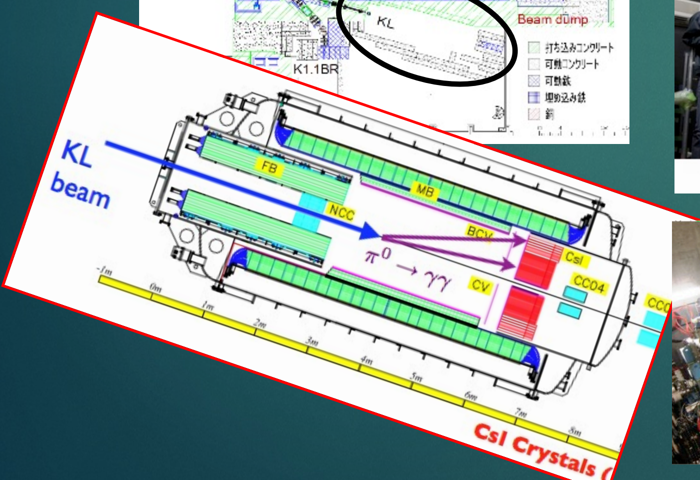
CP- CP+
$$K_L \rightarrow \pi^0 \nu\bar{\nu}$$

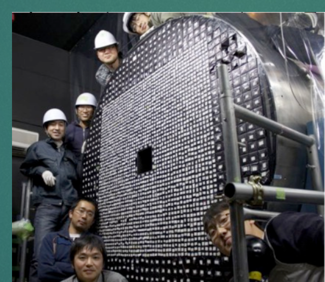



- SM pred. is very small ~2.4e-11
  → **Sensitive to New Physics**
- Upp bound: 4.9x10$^{-9}$ (90%CL) PRL 126, 121801 (2021) **Editors' Suggestion**
- further accumulate physics data toward the sensitivity better than 1x10$^{-10}$





CsI calorimeter