21st Rencontres du Vietnam, Neutrino Physics
2025.7.22

Overview and Future of J-PARC

Takashi Kobayashi

J-PARC, JAEA/KEK

2004@Hanoi

VietNam 2004
5th Rencontres du Vietnam
Particle Physics and Astrophysics
Hanoi
August 5 to August 11, 2004

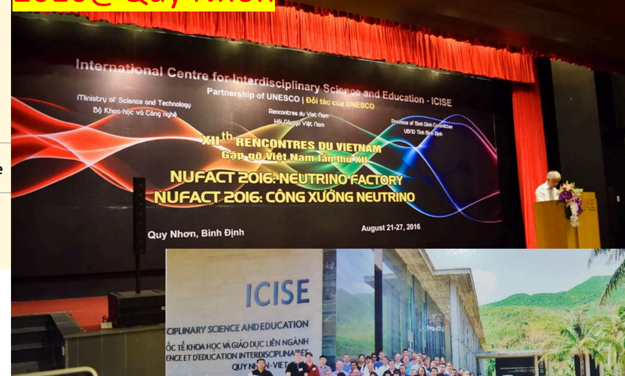
Sous le haut patronage de Monsieur Jacques Chirac, Président de la République Française

New Views in Particle Physics

Aug. 9, 2004
@Hanoi

(Present long baseline neutrino experiments and)
Future Projects to measure θ_{13} and the CP violation phase

2016@Quy Nhon



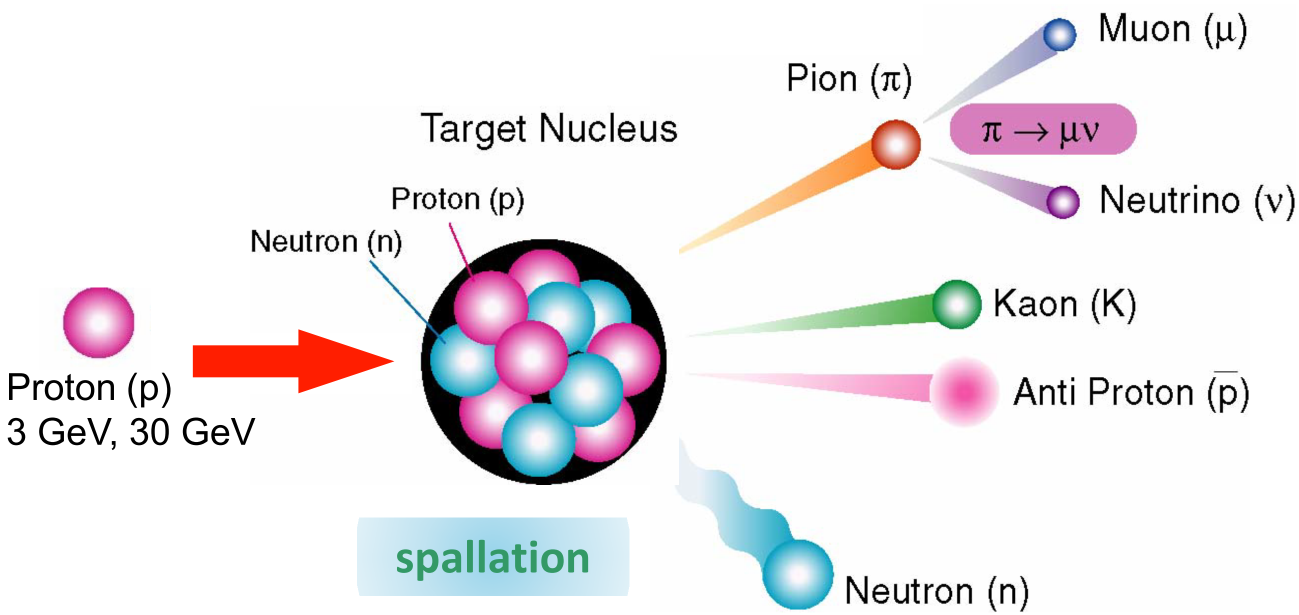
2018@Hanoi

Present and future accelerator-based neutrino experiments in Japan

J-PARC

Japan Proton Accelerator Research Complex

Intensity-Frontier accelerators and multi-purpose user facilities



World-leading high precision/sensitivity experiments with world-leading high intensity beams on wide variety of fields


Japan Proton Accelerator
Research Complex：J-PARC
J-PARC Facility
(KEK/JAEA)
South to North
400MeV LINAC
3 GeV RCS
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
Design intensity
RCS for MLF: 1MW
MR for PN : 750kW
30GeV MR
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
JAEA
KEK
60km
TOKYO
NARITA
Bird's eye photo in January of 2008

Mysteries of matter and universe explored at J-PARC

Origin of matter

Neutrino/Kaon

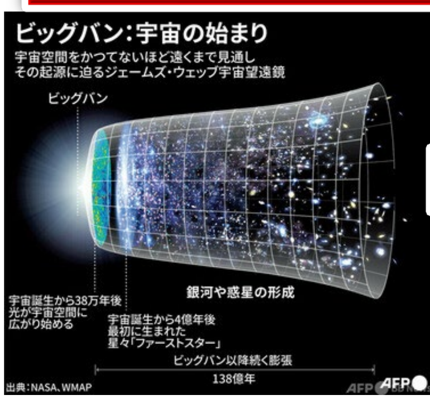
J-PARC：大強度陽子加速器施設

n/muon

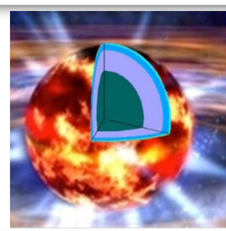
Li/Solar batteries, Tires, Memories

Fuel sell

How universe started?

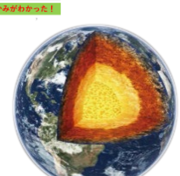


Neutron star?



Kaon, Pion, etc

Solar system?

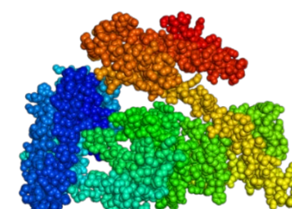


Deep interior of earth

Space, auto drive, etc

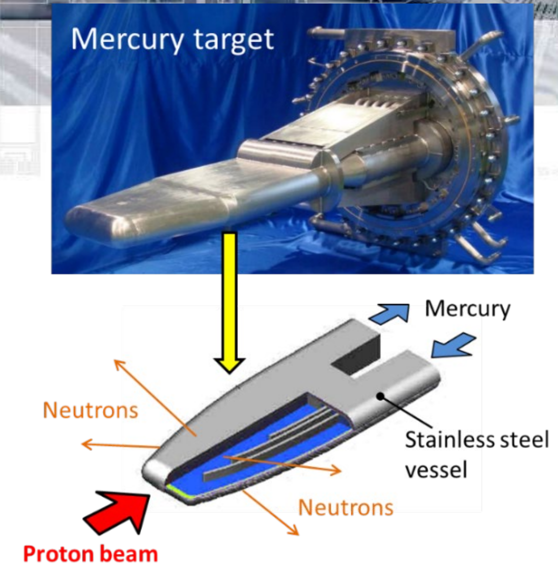
Soft error

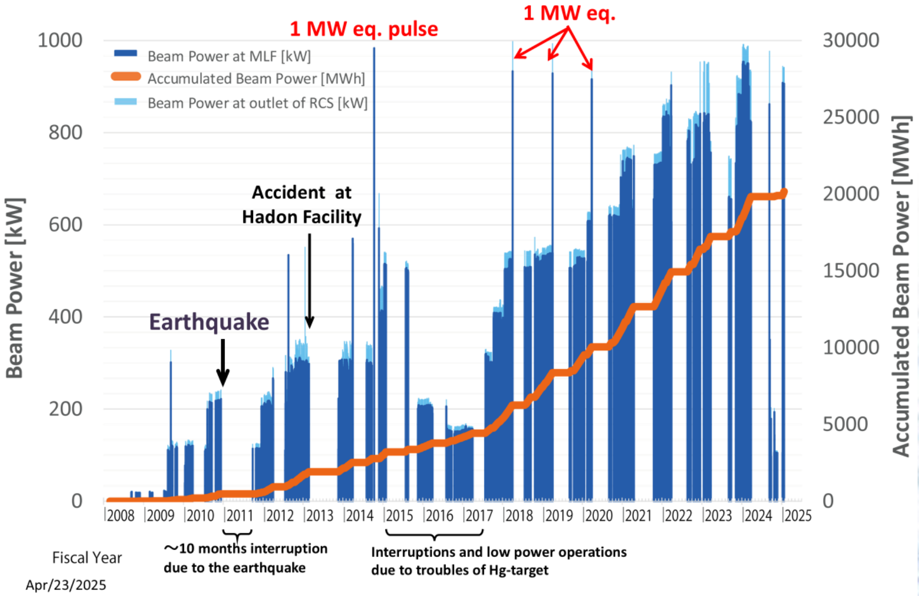
Life science

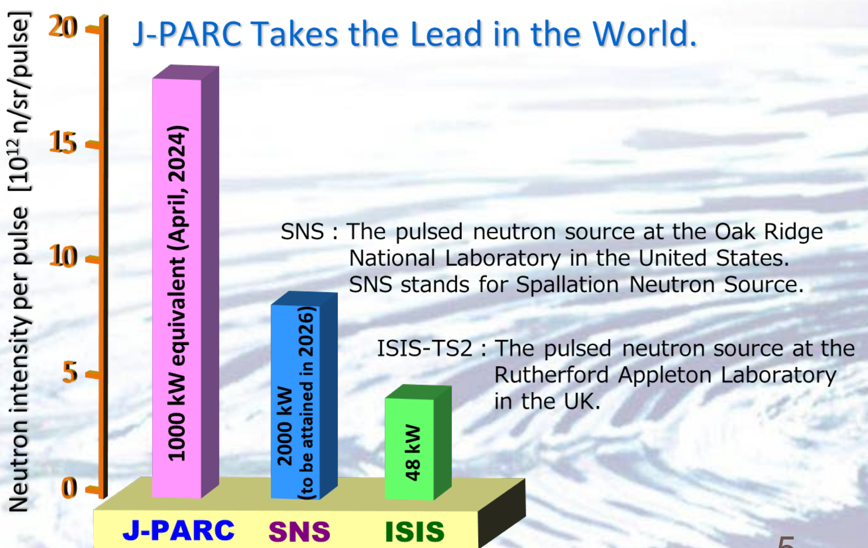


RCS/MLF: 1 MW stable operation achieved

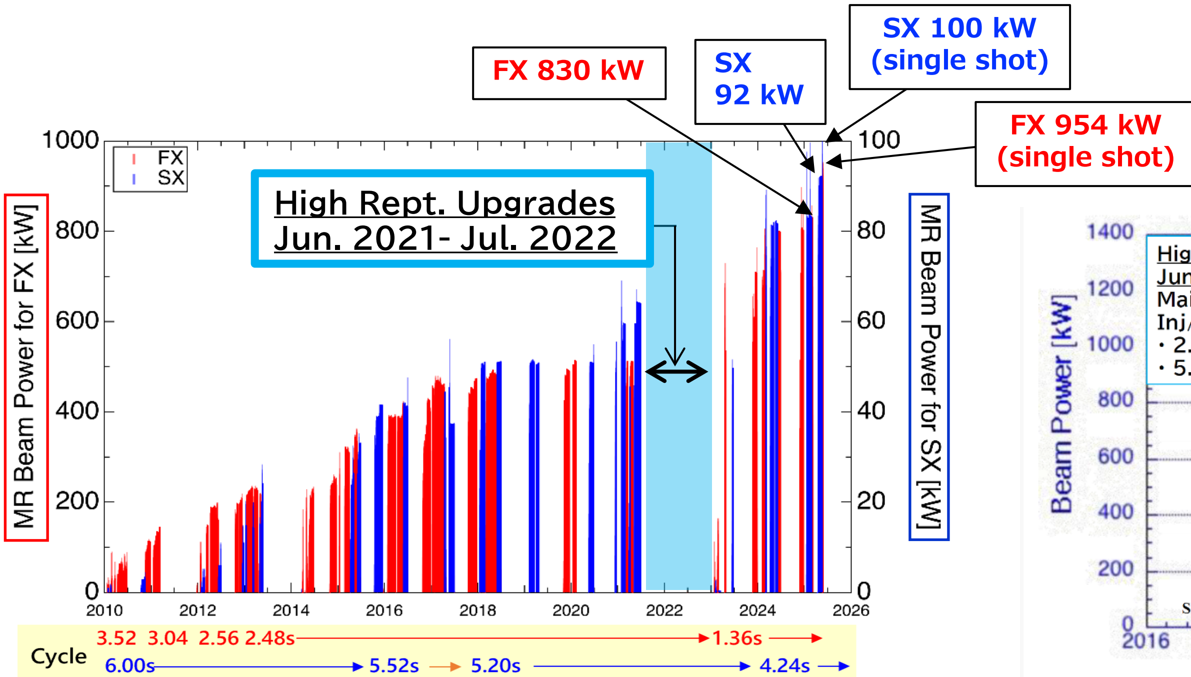
- **The World's Most Powerful Pulsed Neutron Source at J-PARC MLF Achieved Target Performance (press released on May 31,2024)**
  - "continuous operation with a proton beam power equivalent to 1000 kW" starting from April 8, 2024

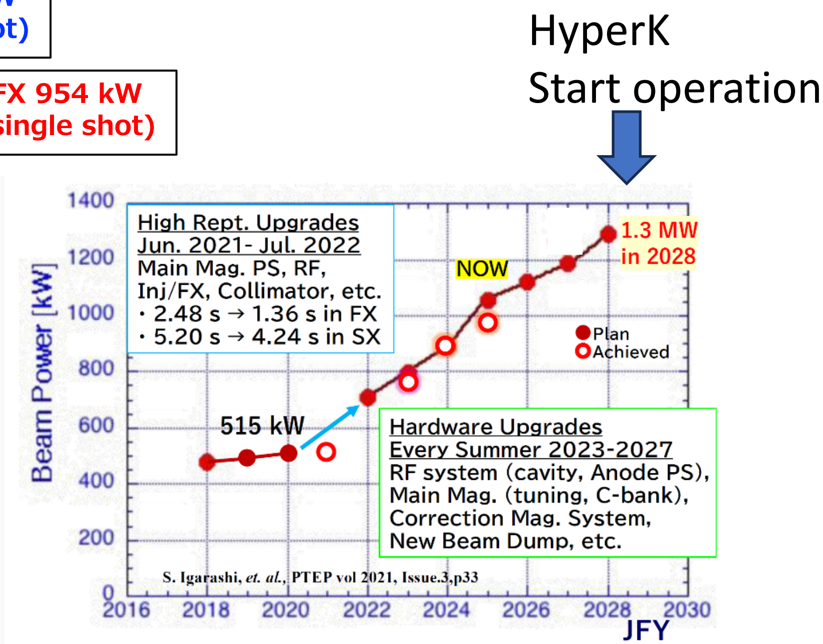






MR beam power history / plan





FX for Neutrino

- 830 kW stable operation
- 954 kWequiv single shot acceleration

SX for HD

- 90 kW stable operation
  - **SX >8x10^{13}ppp World record!**
- 100 kWequiv extraction succeeded

Materials and Life Science Experiments

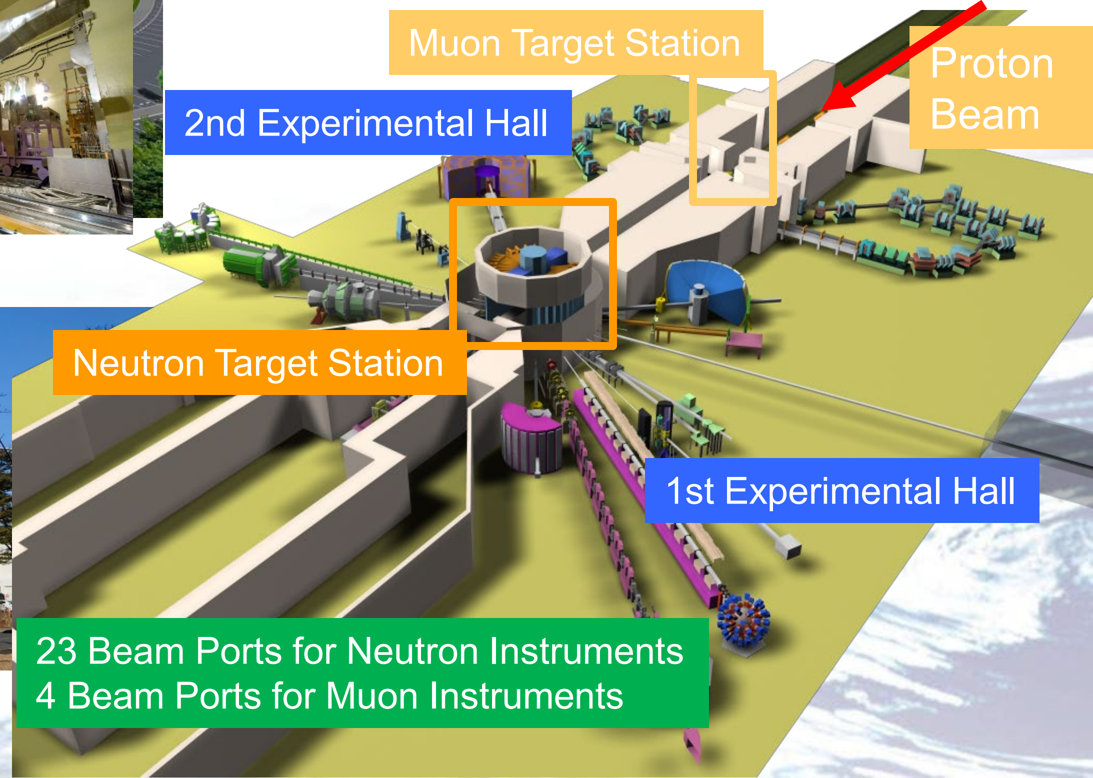
Materials & Life Science Experimental Facility

■ Neutron & Muon Beam Facility for Materials & Life S

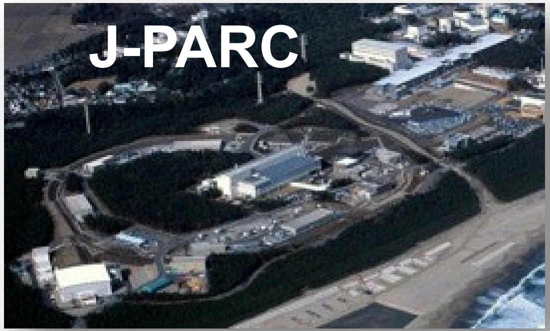
The World Highest-Class Neutron & Muon Sources.

Neutron Source:

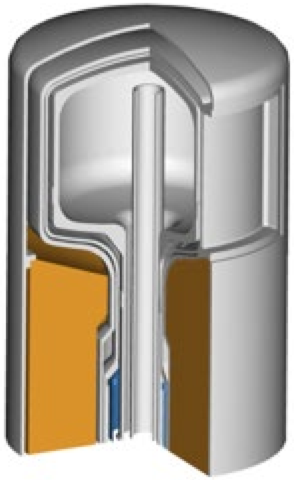
- 1MW
- Liq. Mercury Target
- Liq. H_2 Moderators



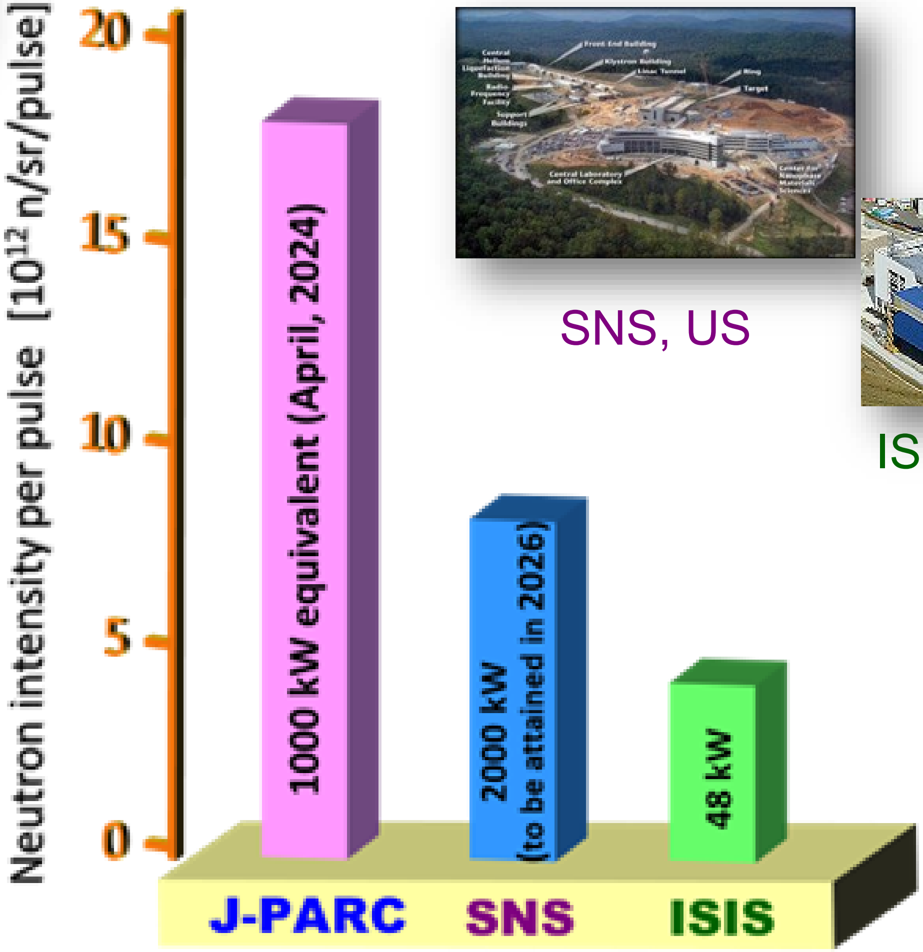
Neutron Intensity at MLF



Hi-performance Moderator



World Highest Intensity of Neutron Pulse Beam!

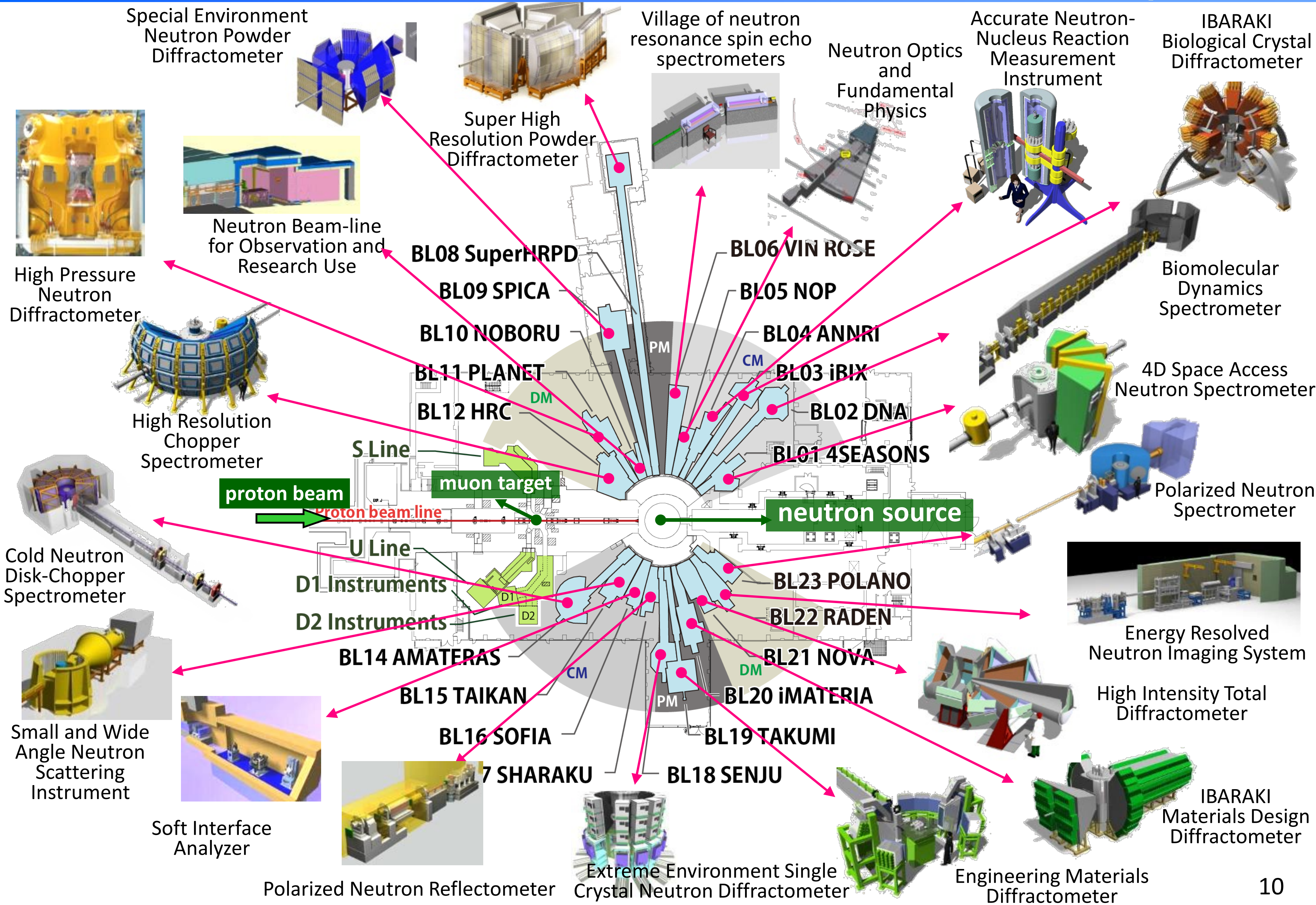


SNS, US

ISIS – TS2, UK

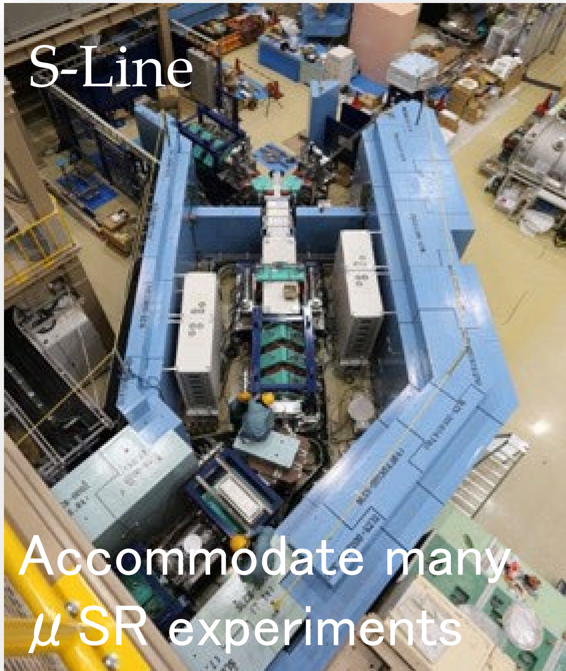
Neutron Instruments in MLF

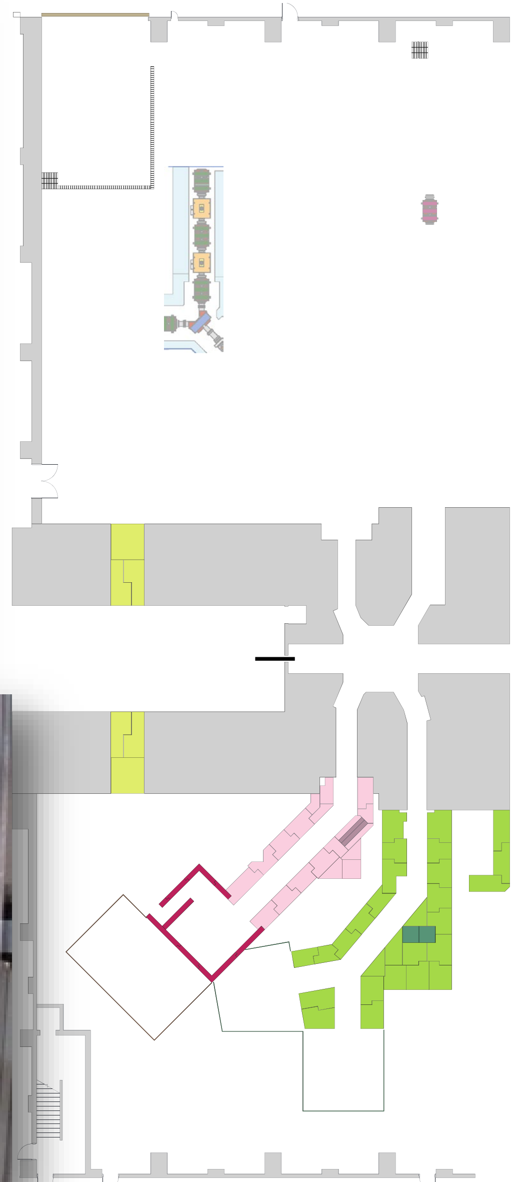
23 beam ports
21 in operation

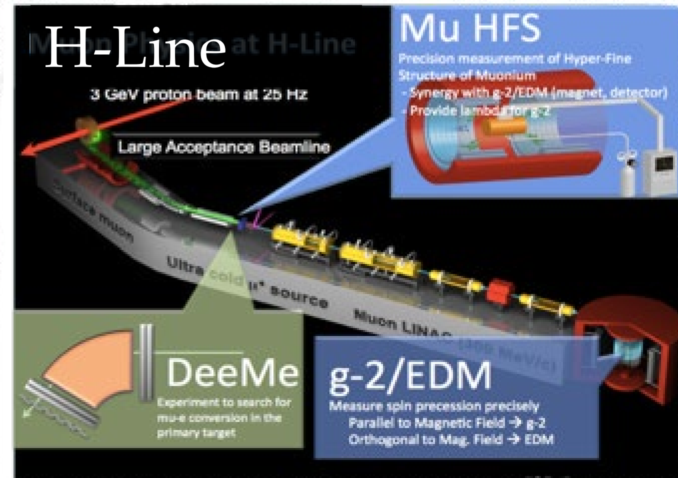


Neutron Instruments at MLF

Muon Facility MUSE @ MLF







Fundamental Science with a large scale international coll.

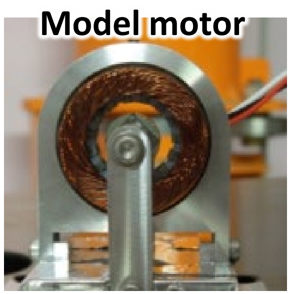
Some highlights of researches at MLF

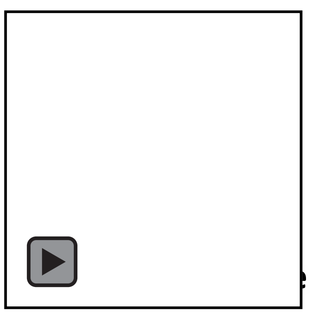
Improve efficiency of motors by visualizing magnetic field distribution during motor operation

Consume 57% of domestic electricity

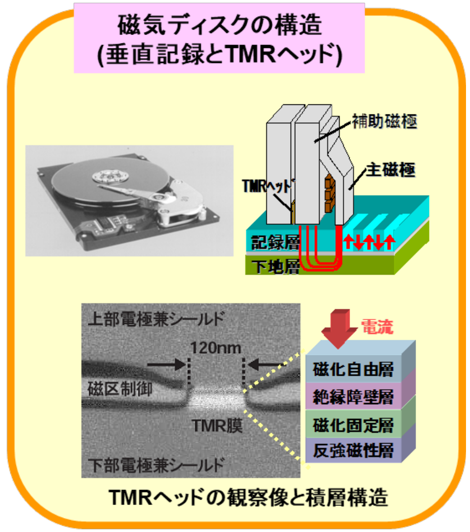
Energy loss: 563 TWh/year

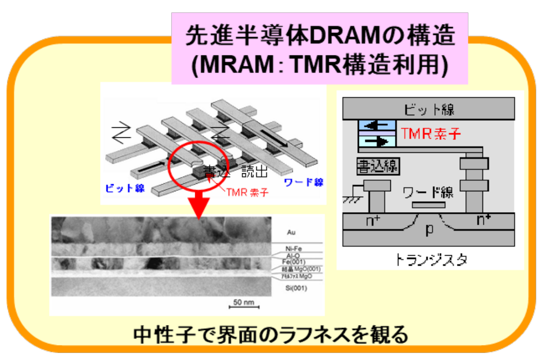
1% efficiency improvement
⇒ Reduction of 2.1 million tons/year of CO_2 emissions



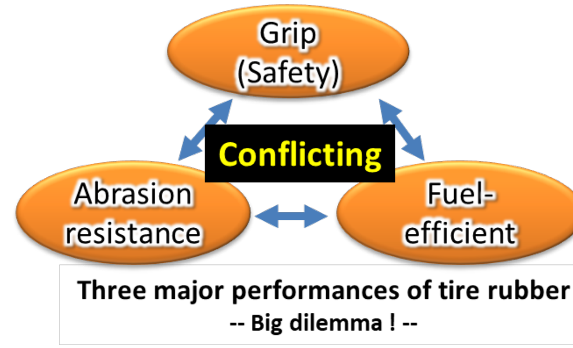


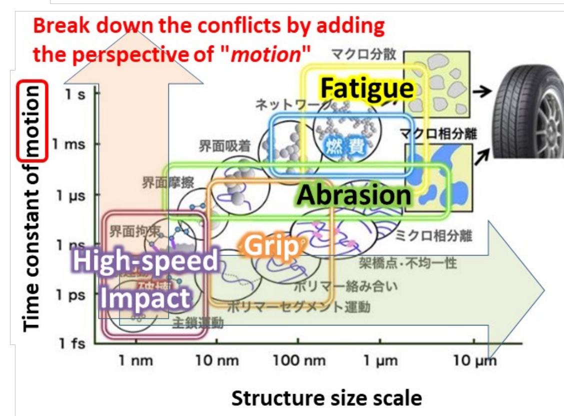
Magnetic device development





Improve performance of tires





Water visualization in a fuel cell used in FCEV

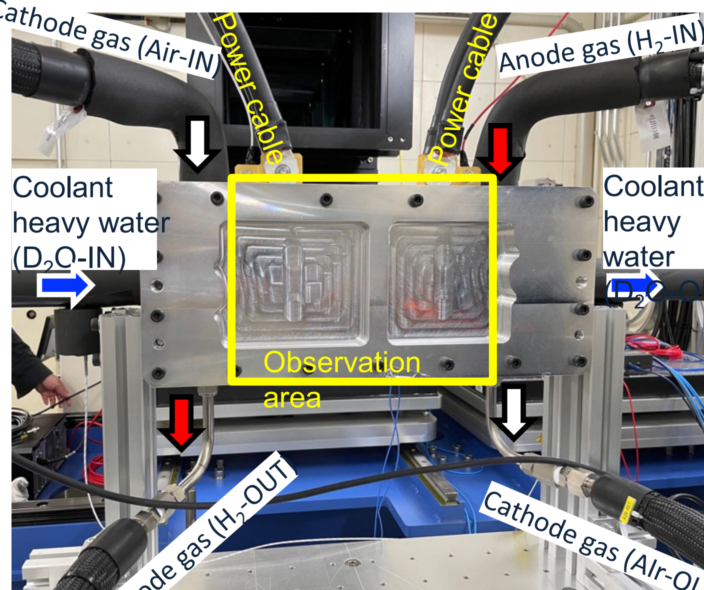
FC•Platform
NEDO

Supported by NEDO FC-Platform Program

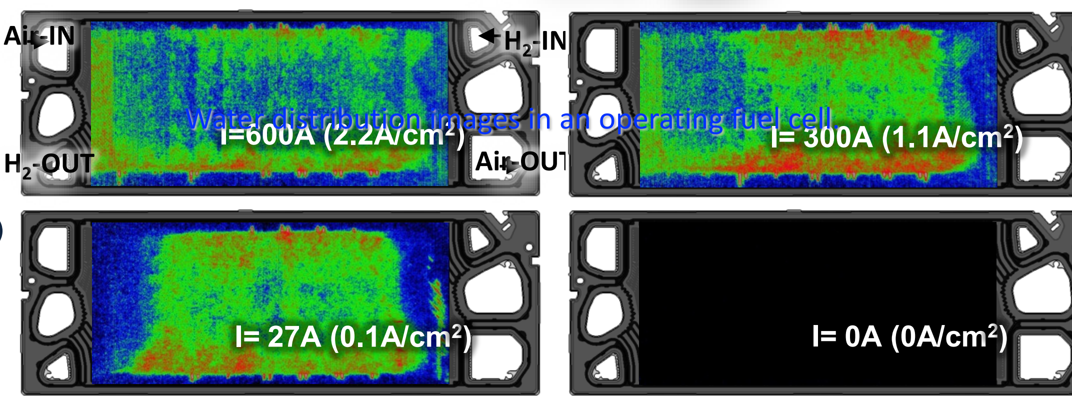
Visualization of water distribution inside an operating fuel cell of the 2nd generation TOYOTA MIRAI

FCEV TOYOTA MIRAI

Fuel Cell of MIRAI (single sheet)



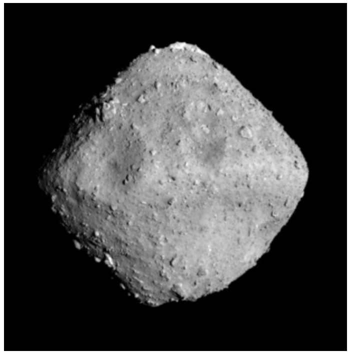
Fuel cell was assembled with thick Al end plates.

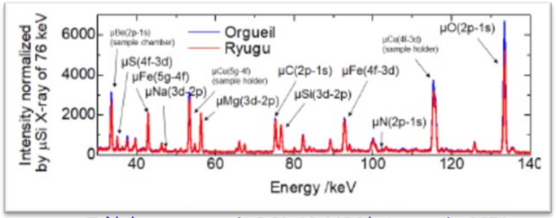


Water distribution images in an operating fuel cell

Some highlights of researches w/ Muon

Asteroid samples returned by the Hayabusa2 mission measured with X-ray from Muon facility





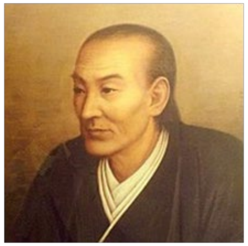
T. Nakamura *et al.*, DOI: 10.1126/science.abn8671

Non-destructive elemental analysis of a medicine bottle that cannot be opened

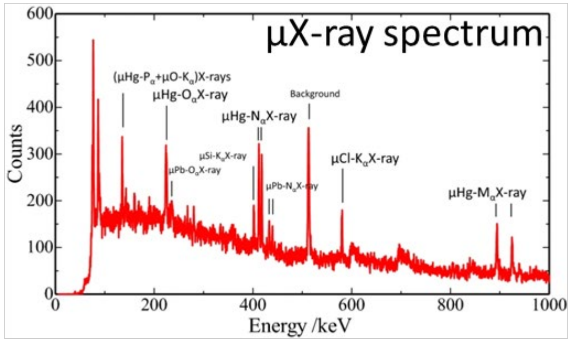
- ✓ The lid is stuck and impossible to open.
- ✓ Possibility of chemically unstable in the atmosphere

Muonic X-ray elemental analysis non-destructively revealed that the material inside the bottle is Hg_2Cl_2.

The medicine bottle

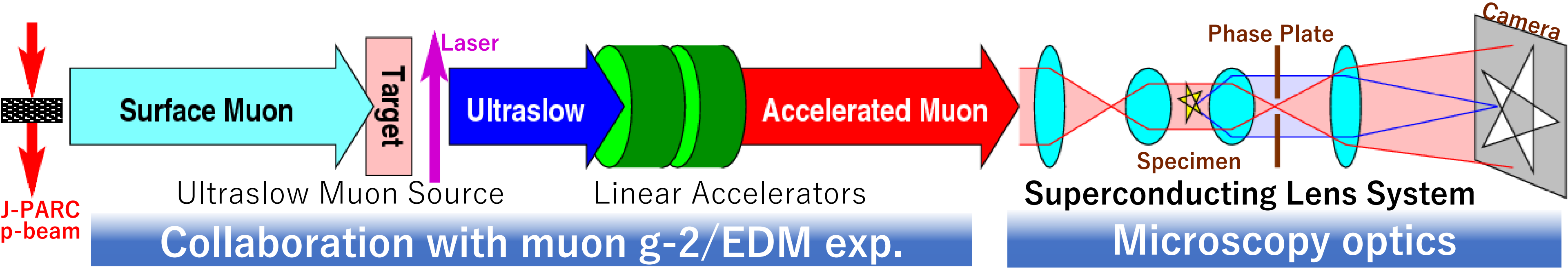


OGATA Kōan (緒方 洪庵)
1810~1863 (Edo period)
Doctor, *Rangaku* scholar



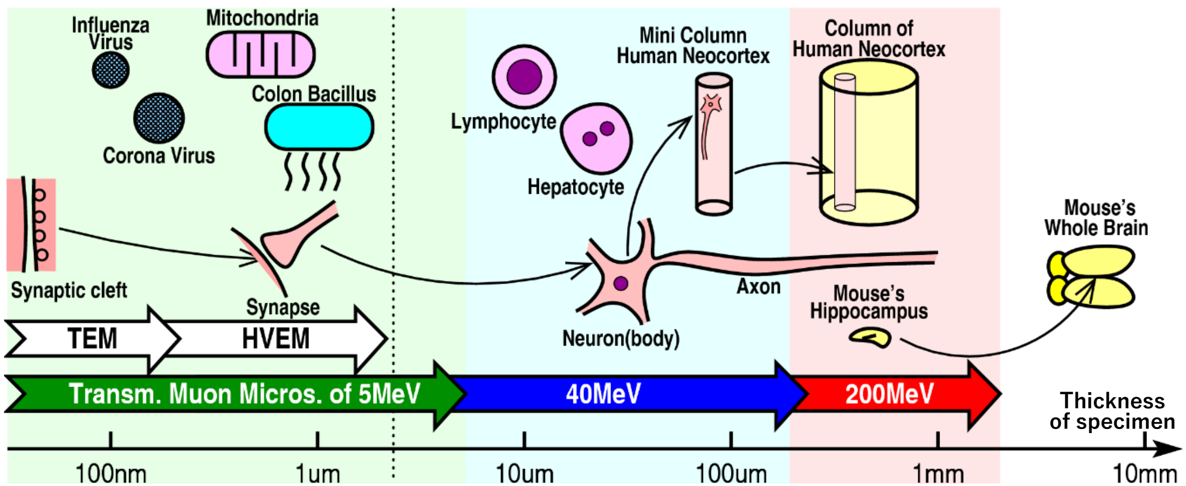
A future plan: Transmission Muon Microscope

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

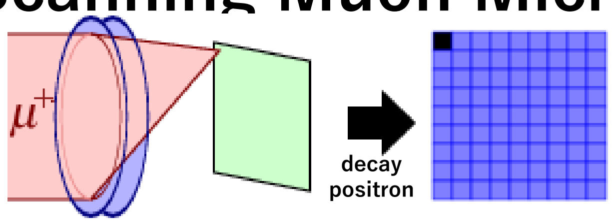


Nano scale visualization of electromagnetic fields in macroscopic objects

- 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.



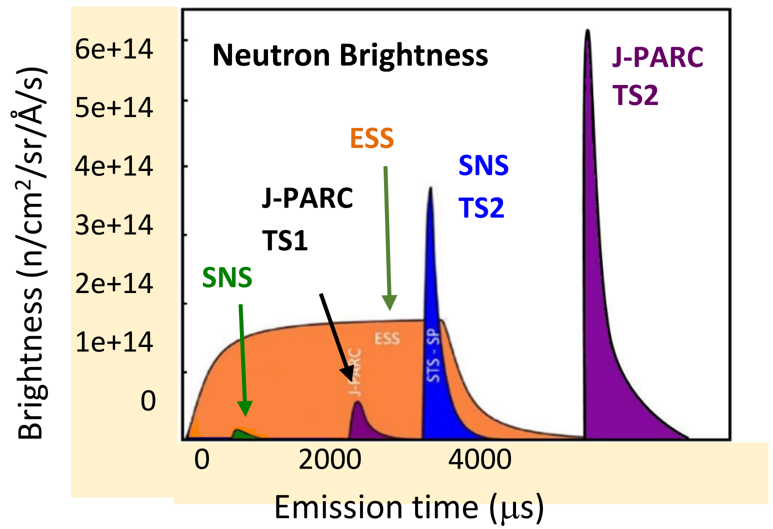
Scanning Muon Microscope

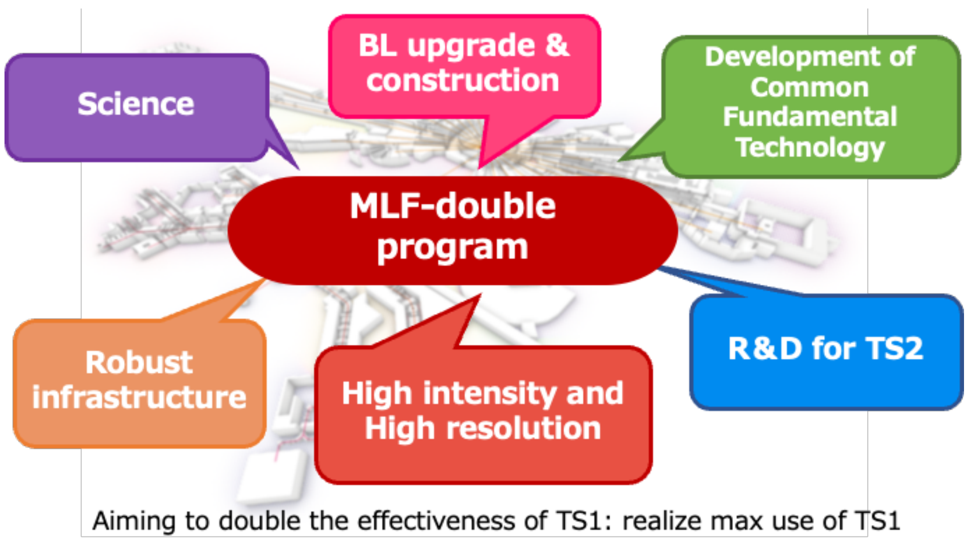


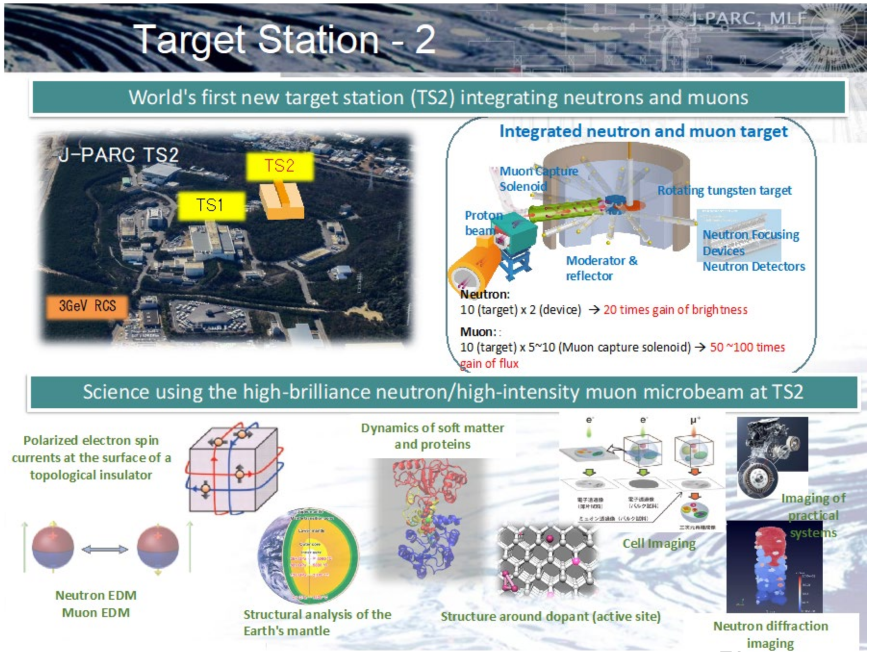
3-dim mapping of magnetic field and its fluctuation, density of Fermi surface, state of hydrogen, and etc. in nano resolutions. → **Scanning μSR microscope**

MLF roadmap

- "MLF-double"
  - Double effective output
- 2nd target station (~2030's)
  - n : x20, mu: x50~100

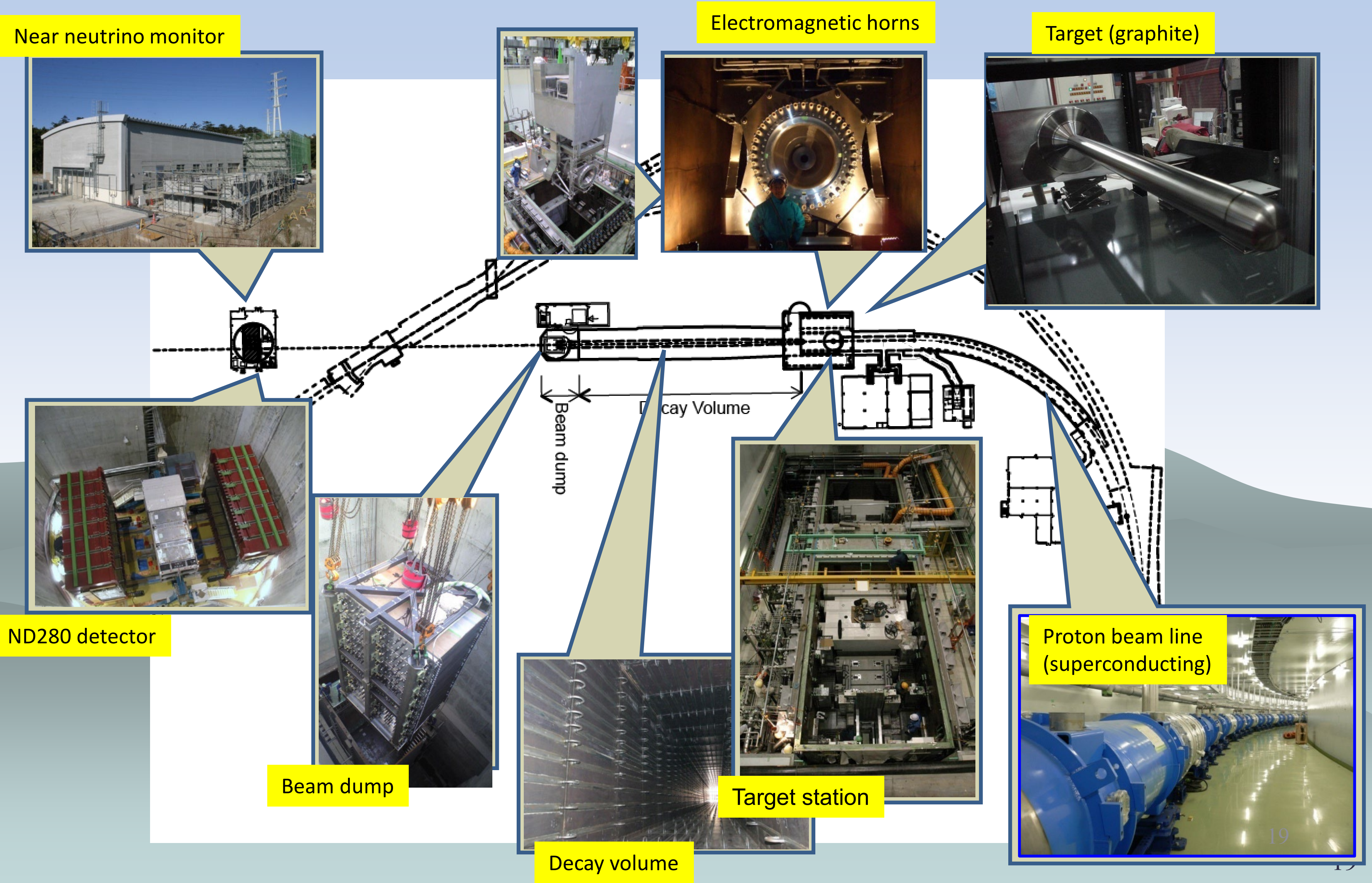




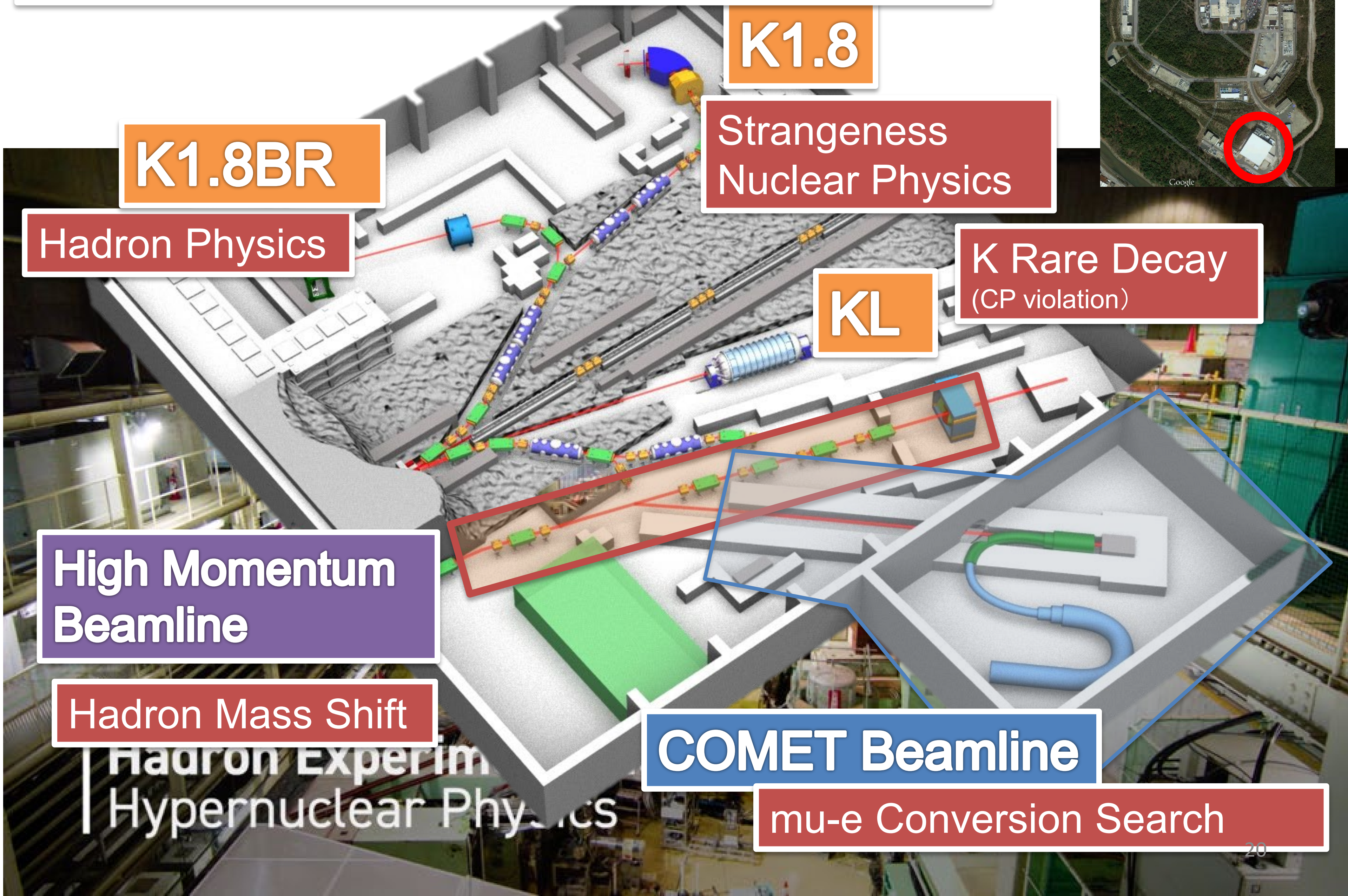


Particle and Nuclear physics experiments

Neutrino experimental facility



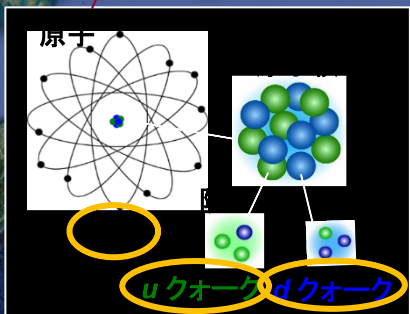
Hadron Experiment Facility



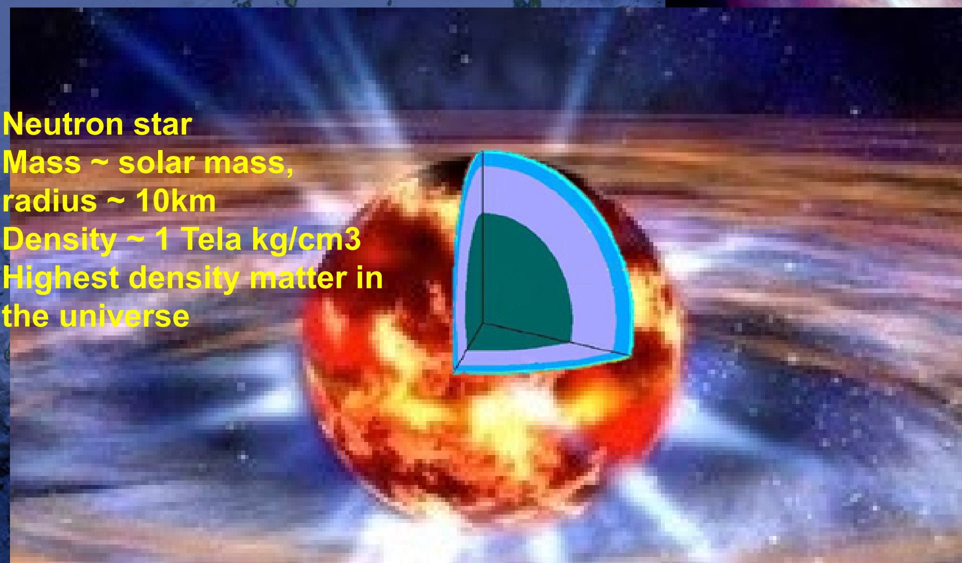
Particle and nuclear physics at J-PARC

Flagship nuclear physics science at Hadron hall

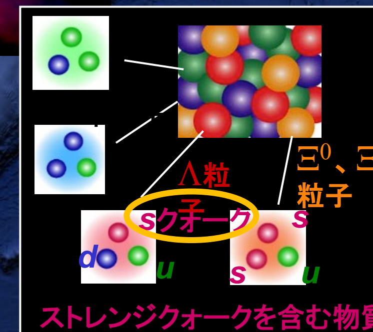
Understanding matter state of neutron star interior → Building new matter picture



u,dクォークと電子
からなる物質

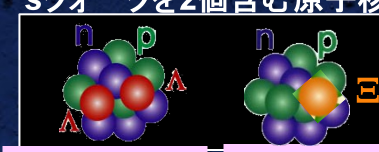


ストレンジ核物質？



Not understood yet

sクォークを2個含む原子核



ΛΛハイパー
核

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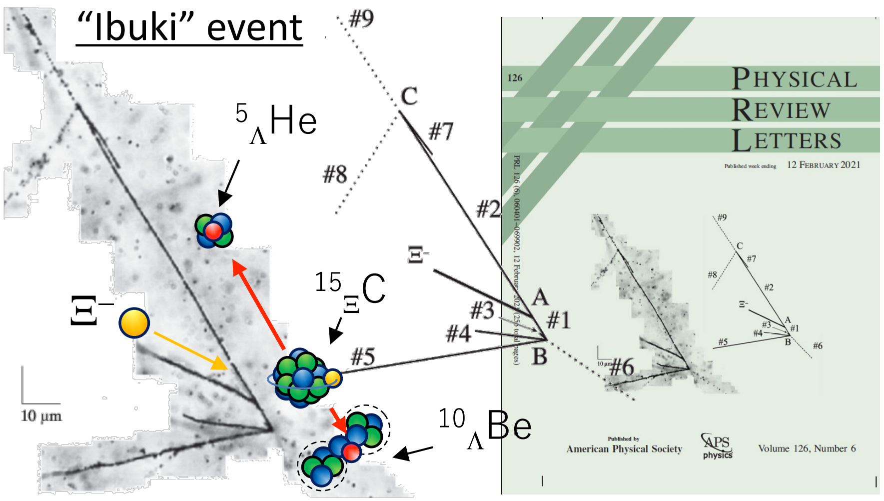
Create “neutron star” in laboratory

【Nuclear physics at Hadron Experimental Facility】

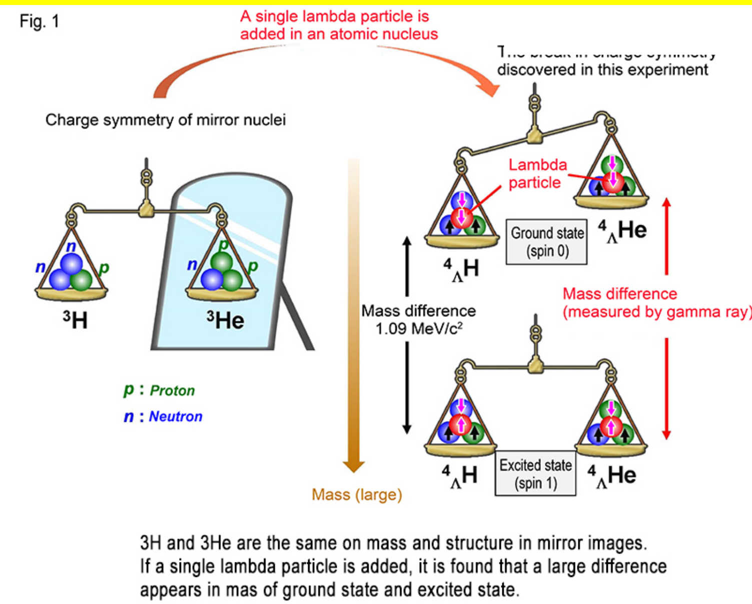
Elucidation of the property and origin of "generalized nuclear force" including strangeness

Mass measurement of Xi hypernuclei

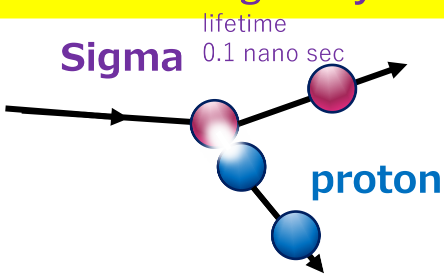


→ confirm the force between Xi (Ξ) and nucleon is attractive

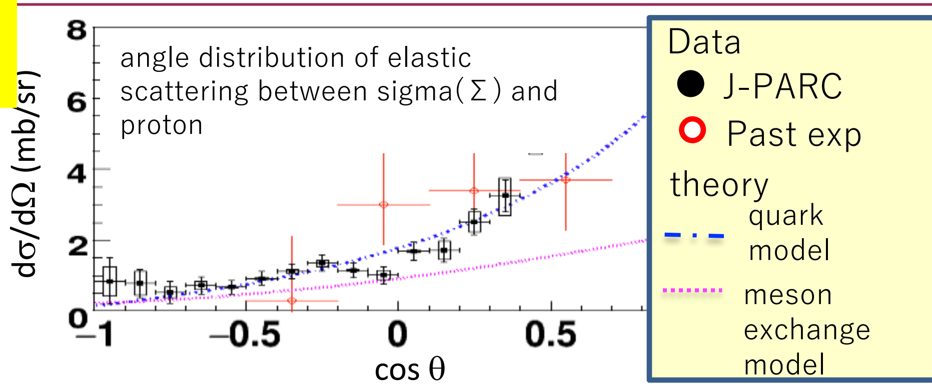
Discovery of charge symmetry breaking in the force between Lambda(Λ) and nucleon



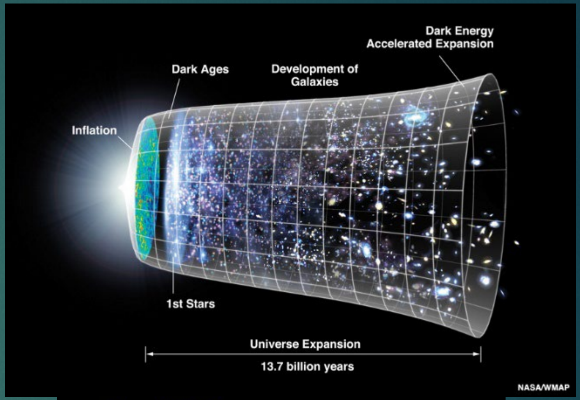
Establishment of scattering experiments between strange baryon and proton



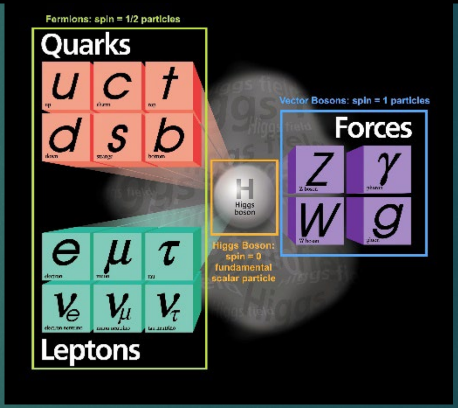
→ improve the precision of scattering angle distribution by x10 for the first time in 50 years

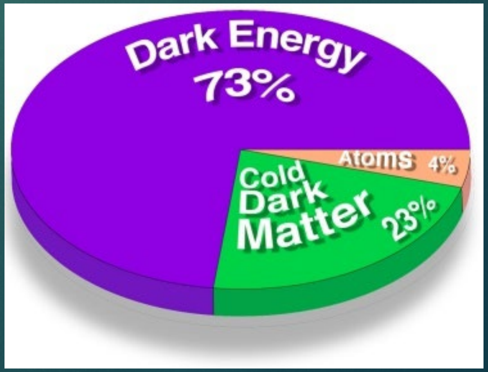


Fundamental questions in our universe

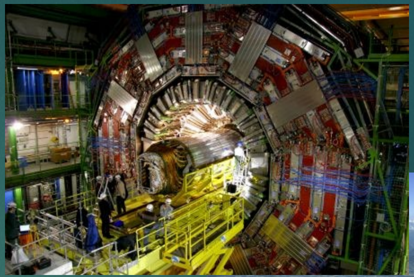


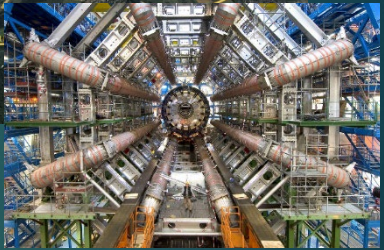
- Origin/fate of our universe
- Origin of matter
  - Where necessary CP violation comes from?
  - B-L non-conservation
- Origin of mass:
  - Higgs is really what we ordered?
- What is beyond standard model?
- Dark matter
- Dark energy





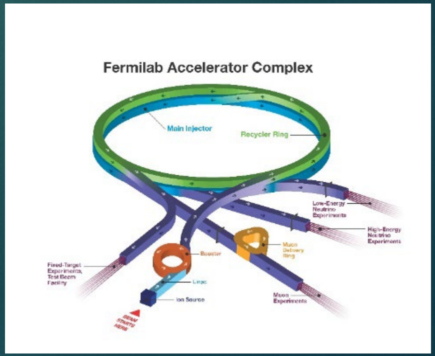
Approaches

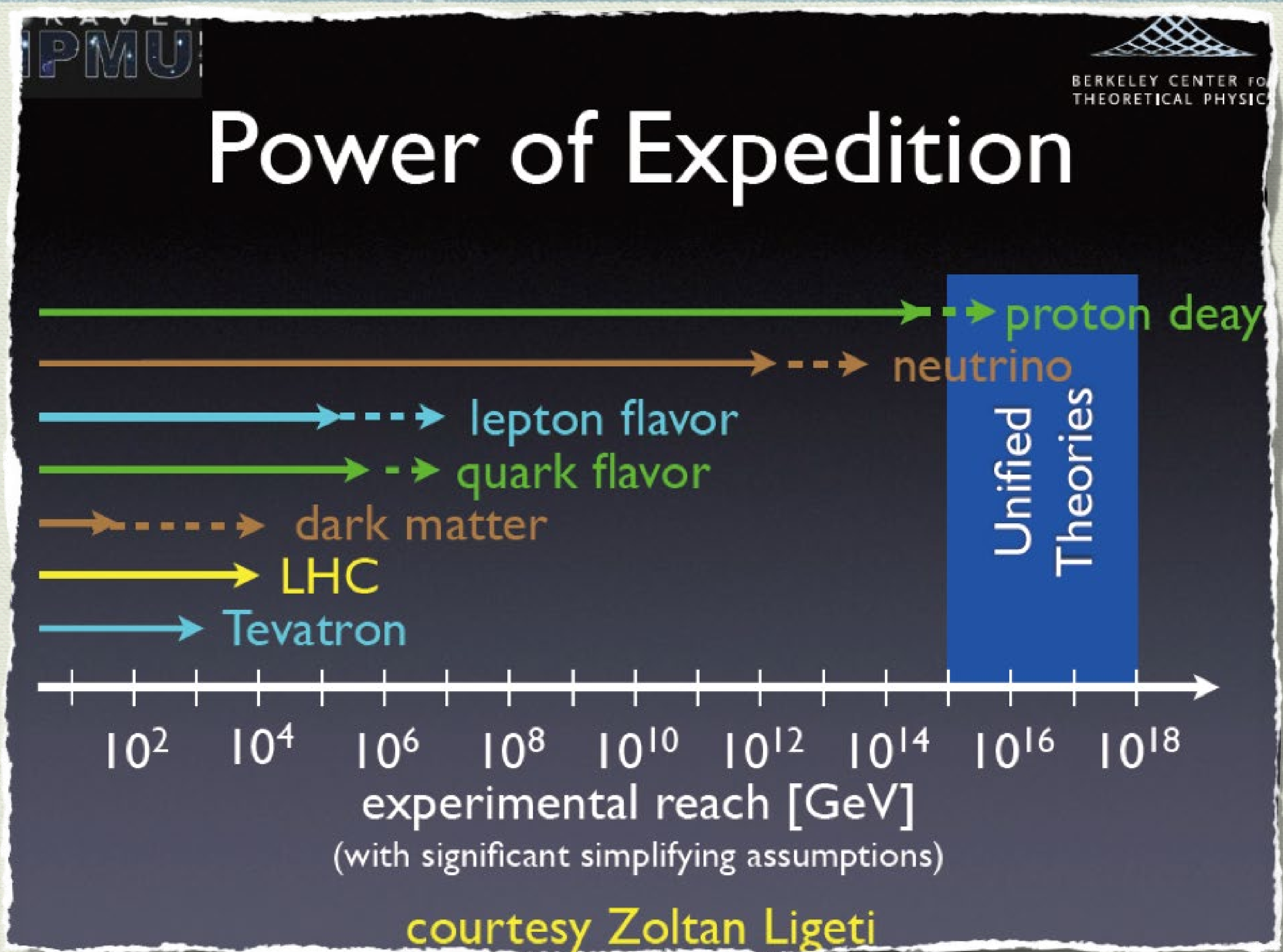




- High energy
  - Direct search
  - Tevatron (1.9TeV)→ LHC(14TeV) → ILC → ??
- High intensity
  - Indirect search through loop diagram
  - Can probe higher mass scale than beam energy
  - KEKB,PEP-II → SuperKEKB
  - J-PARC, FNAL-MI, LNBF,

Fermilab



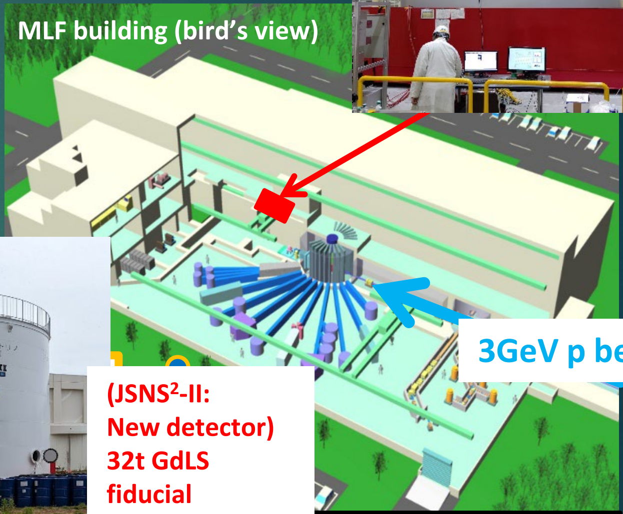


a slide by Hitoshi Murayama

Mysterious 4^{th} (Sterile) neutrino exist? JSNS^2(-II) Experiment

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

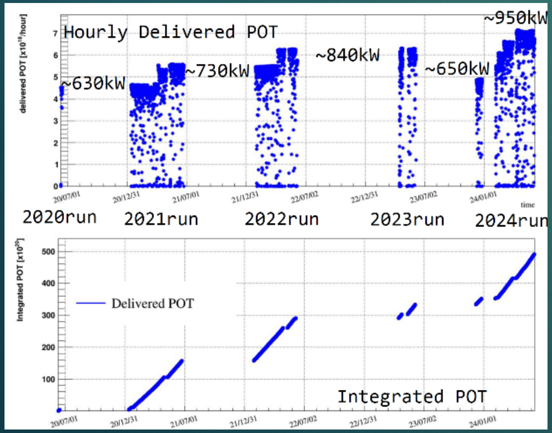
Searching for neutrino oscillation : $\nu_\mu \rightarrow \nu_e$ with baselines of 24m (JSNS^2), and 48m (JSNS^2-II)



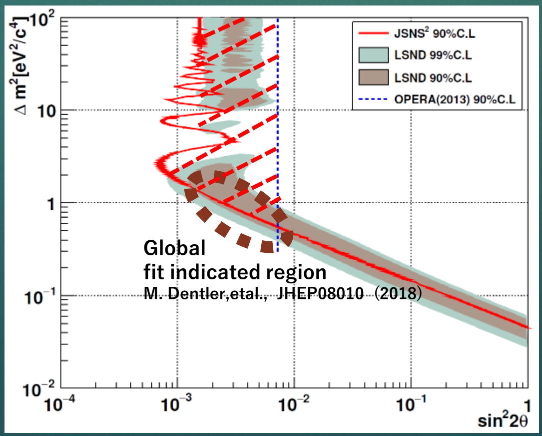
(JSNS^2-II: New detector) 32t GdLS fiducial

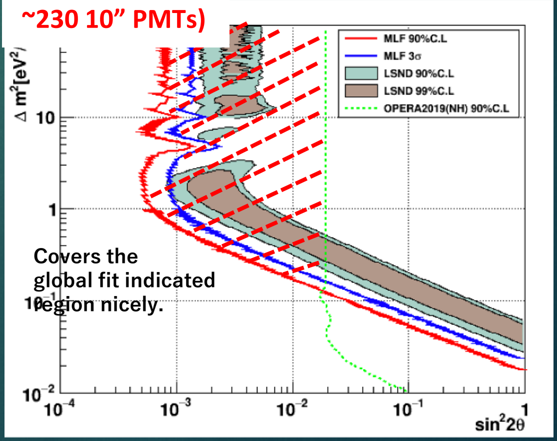
(6.2m dia. x 6.2m (h) ~230 10" PMTs)

- Long standing mystery (>25yrs) of possible existence of non-interacting 4^{th} neutrinos
- (JSNS2) : 17t GdLS x 1MW x 3 years
  - The long physics runs (2021-2024) In total, ~20 months.
  - Maximum 0.95 MW beam.
  - 4.85 x 10^{22} POT so far
  - Sterile ν analyses are on-going
  - Signal region without PSD (in 2022 data) was opened.
- (JSNS2-II): 32t GdLS@48m x 1MW x 5 years
  - 2nd phase of the experiment
  - new far detector : 32 tons fiducial in 48m baseline.
  - Improved the sensitivity, especially in low Dm2 region.
  - Commissioning run with beam



Current JSNS^2



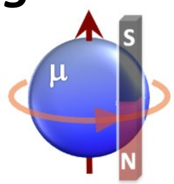


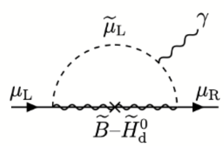
J-PARC muon *g*-2/EDM experiment

Studies on physics beyond the standard model in quantum loops

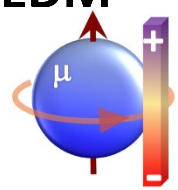
g-2 C, P, T conserved

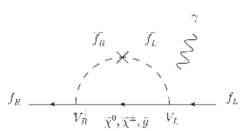
Examples: Super Symmetric particles



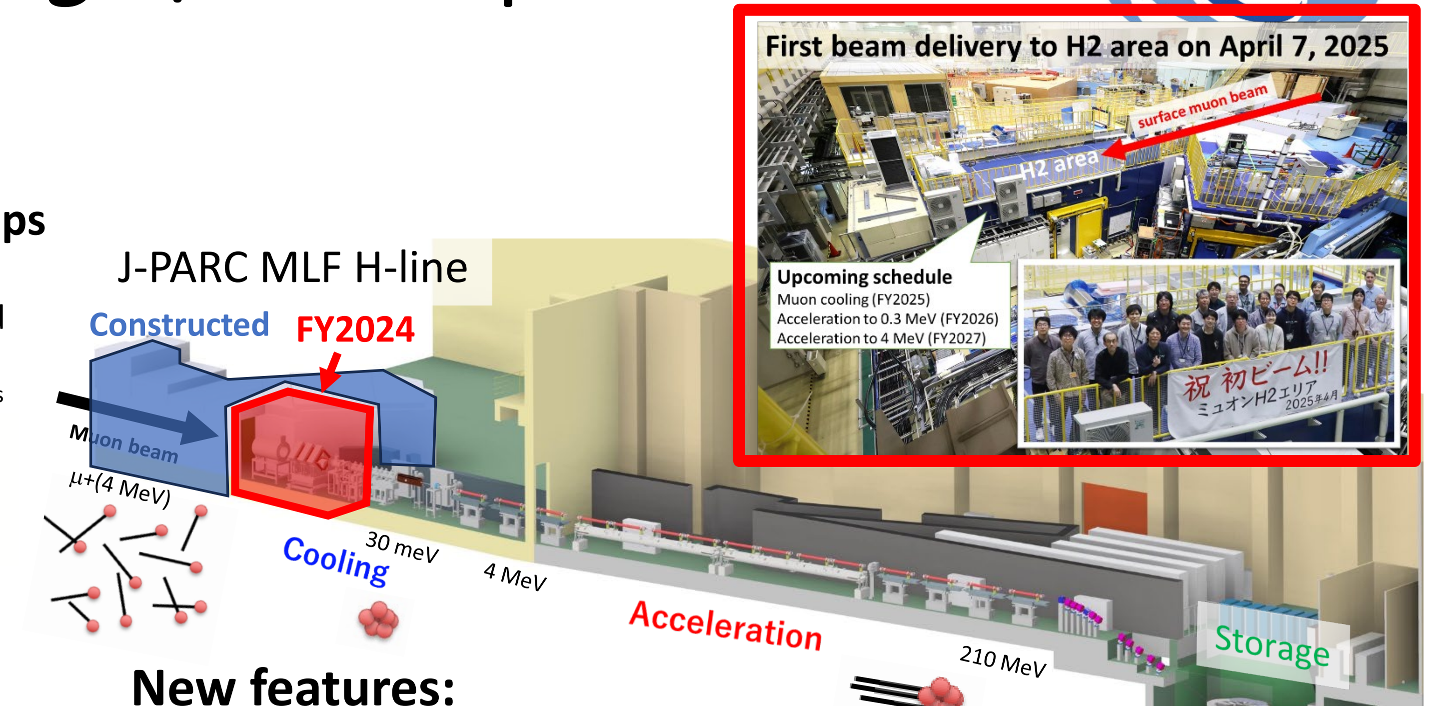


EDM P & T-violating





Prog. Theor. Exp. Phys. 2019, 053C02 (2019)



New features:

- Low emittance muon beam (1/1000)
- No strong focusing (1/1000) & good injection eff. (x10)
- Compact storage ring (1/20)

The only experiment to test FNAL/BNL *g*-2 results.

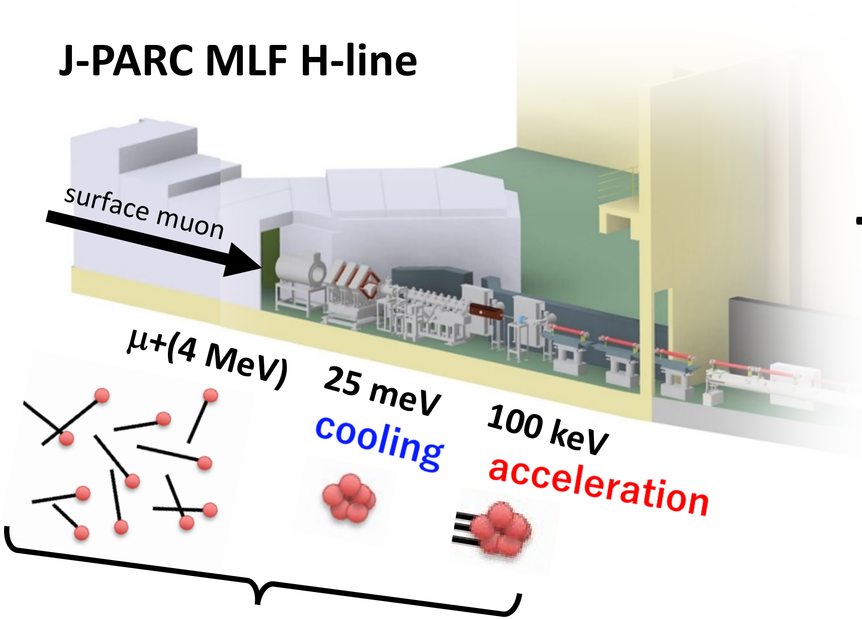
***g*-2 : 450 ppb**

EDM : 1.5 E-21 ecm

Aim to start data taking from 2030

Acceleration of positive muon

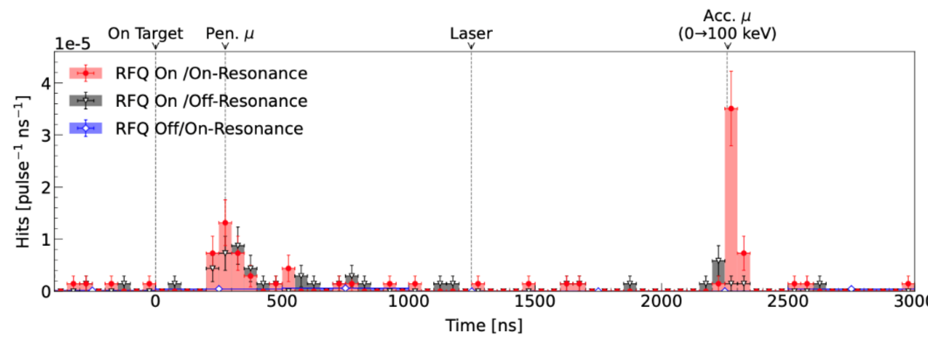
Phys. Rev. Lett. 134, 245001 (editor's choice!)



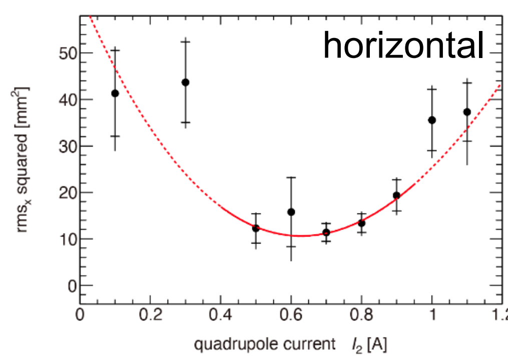
This part was demonstrated at MLF S2 area in April 2024.

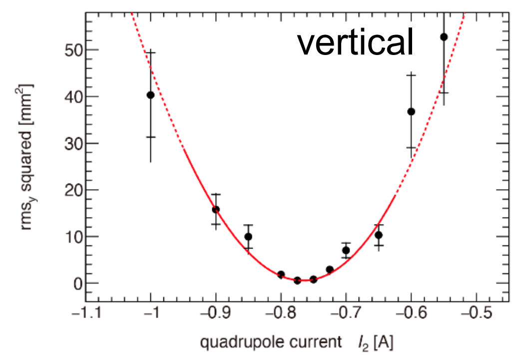
Muon cooling and acceleration to 100 keV was demonstrated.

Time of flight



Transverse emittance





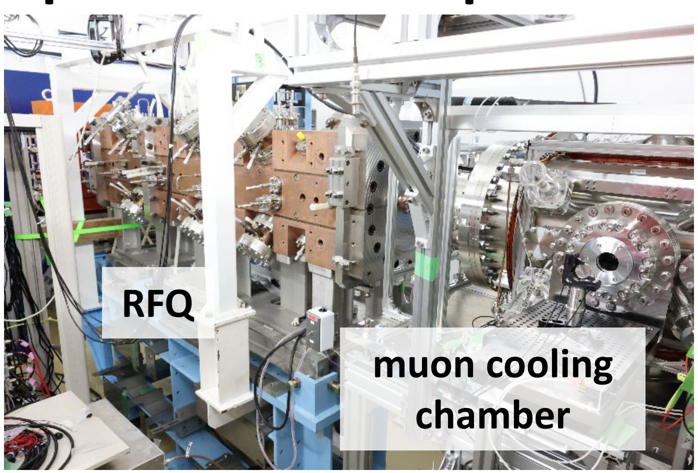
$\varepsilon_x = 0.85 \pm 0.25^{+0.22}_{-0.13}$ π mm mrad

Reduction by 1/200

$\varepsilon_y = 0.23 \pm 0.03^{+0.05}_{-0.02}$ π mm mrad

Reduction by 1/400

Experimental setup



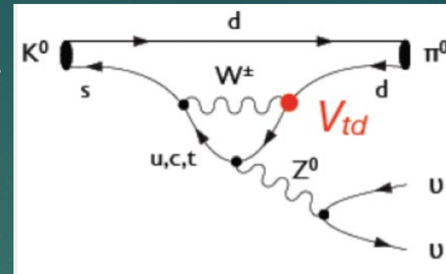
KOTO experiment

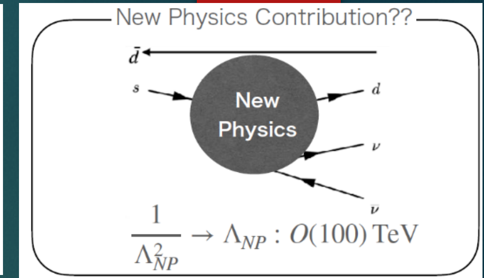
- Search for CP violating decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$

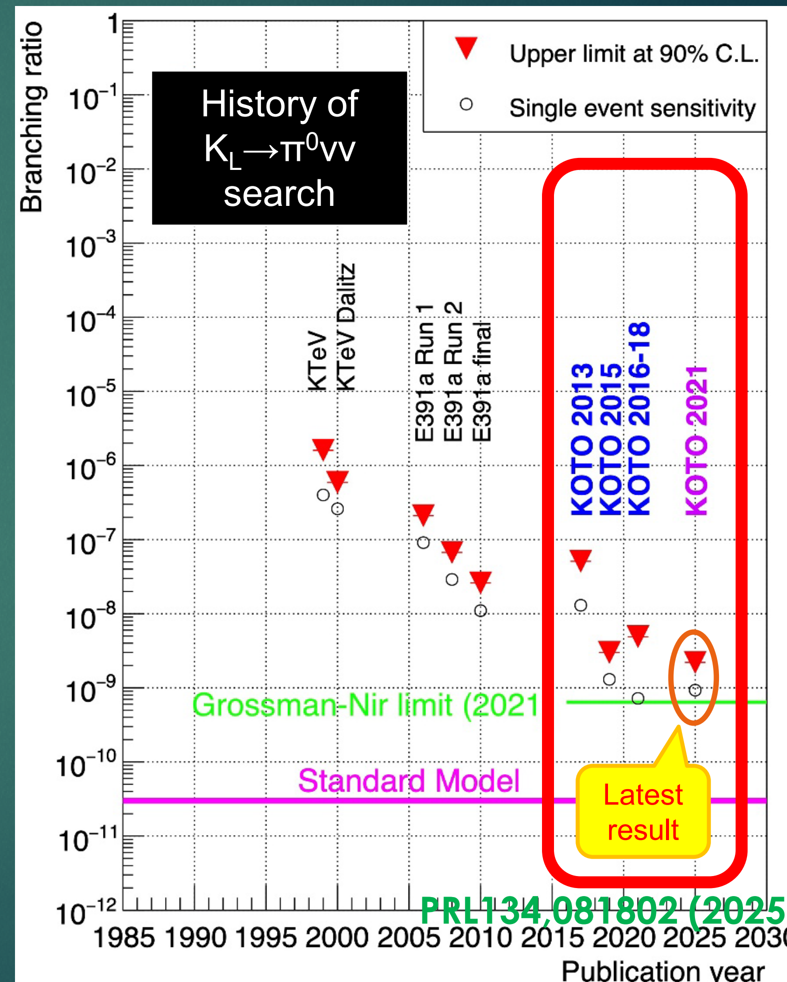
CP- CP+

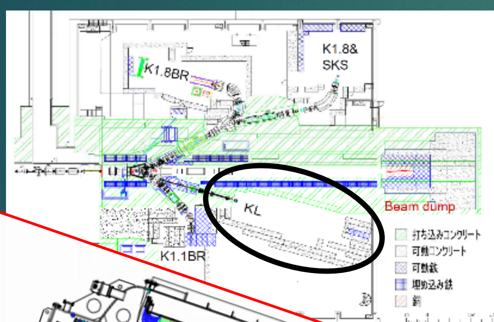
$$K_L \rightarrow \pi^0 \nu \bar{\nu}$$

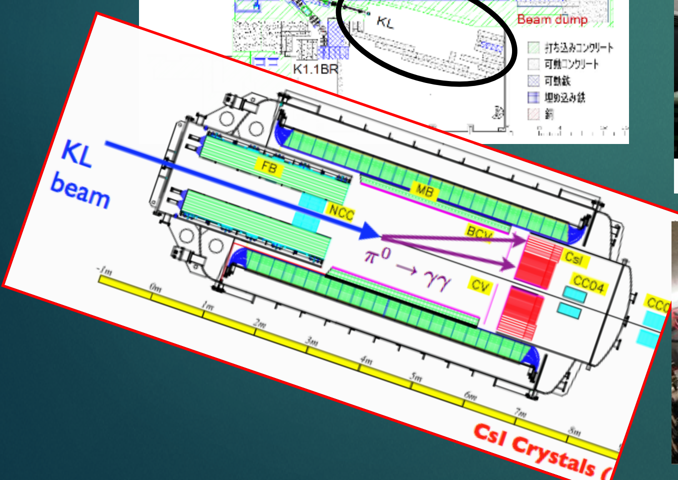
- SM pred. is very small ~3×10^{-11}
  → **Sensitive to New Physics**
- Latest result (data in 2021)
  - **BR<2.2×10^{-9} @90% C.L.**
- Aim sensitivity better than 1×10^{-10}

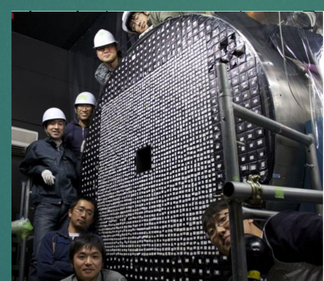








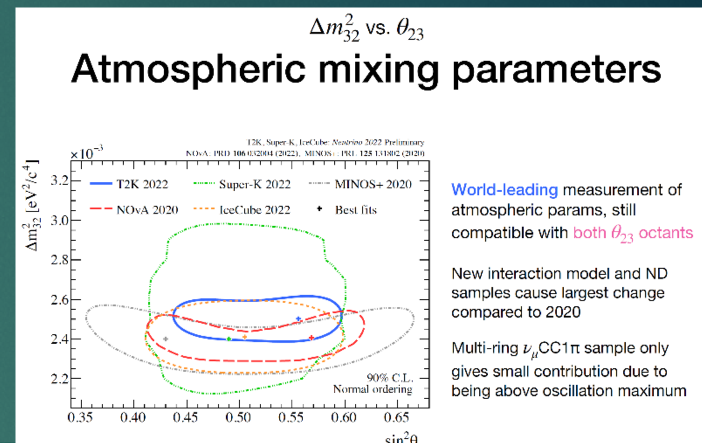


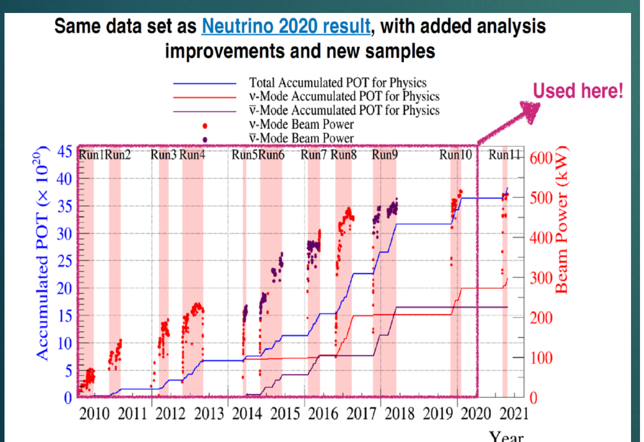

CsI calorimeter

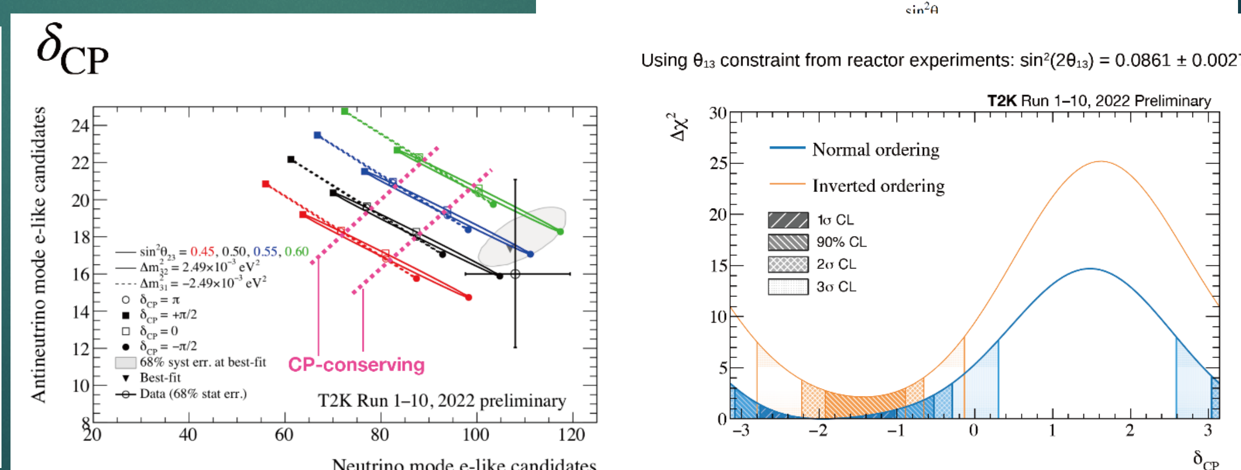
T2K experiment

- Status
  - **760kW operation achieved (2023)**
  - Delivered POT: 4.1e21 (nu:2.5/anu:1.7)
- Latest results
  - 3.6×10^{21} POT (2010~2022) analyzed
  - World leading measurement of atm param
  - Large area of δCP excluded at 3σ
  - CP converving excluded at 90%
  - Weak preference of normal ordering

~570 members, 78 Institutes, 14 countries (incl. CERN)

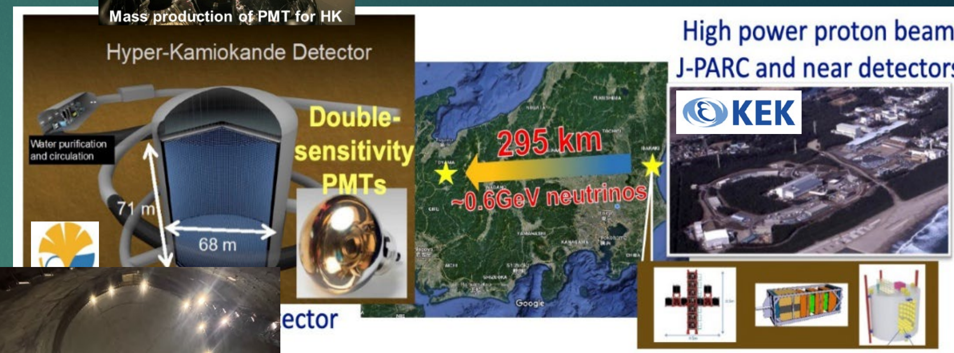


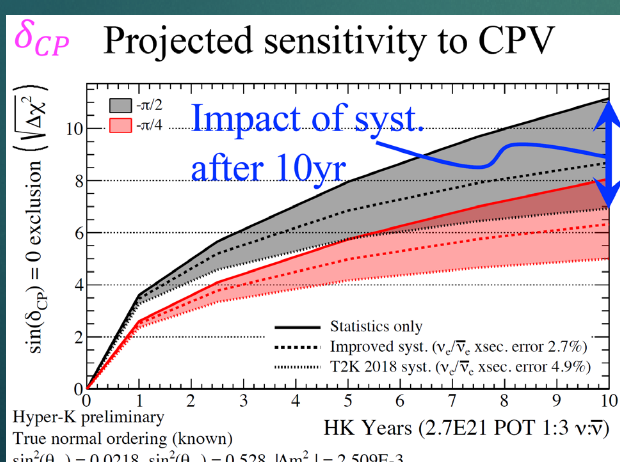


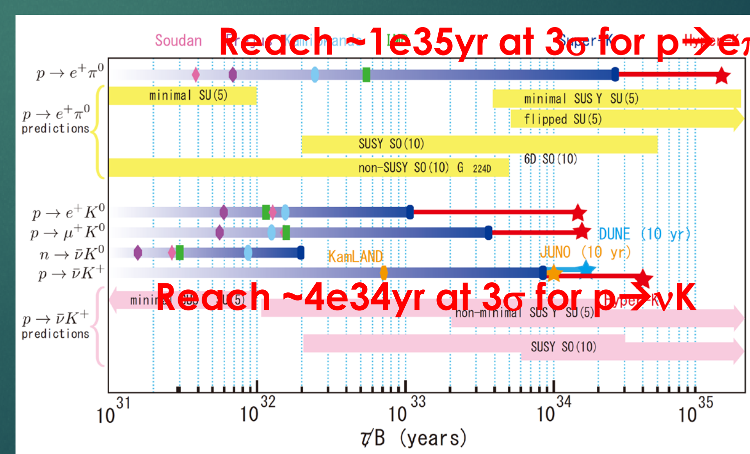


Hyper-Kamiokande project

- Project consists
  - 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
  - Cavern excavation completing
- **Aiming to start operation in 2028**





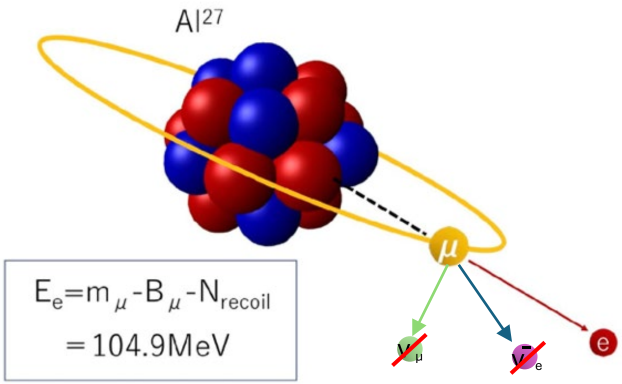


COMET experiment at J-PARC

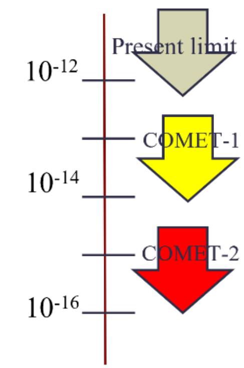
US-Japan

search for mu-e conversion down to the level of 10^{-16}

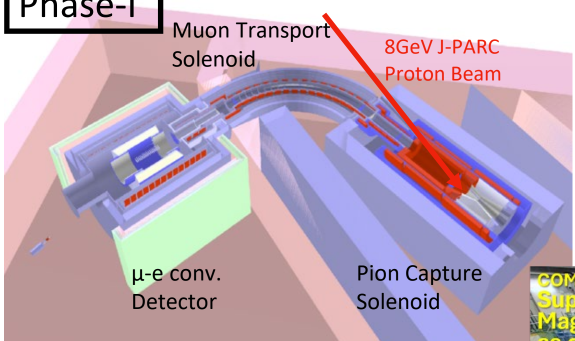
- Search for muon "decay" to one electron without emitting neutrinos
  - Aiming at **100 times better** sensitivity ($<10^{-14}$) than past experiments (U.L. 7×10^{-13} @ 90% C.L.) in **Phase I**
  - Eventually in **future 2nd phase** (in 2030's), **10,000 times better sensitivity ($< 10^{-16}$) is envisioned**
    - Facility upgrade toward Phase II is discussed in the framework in the international collaboration

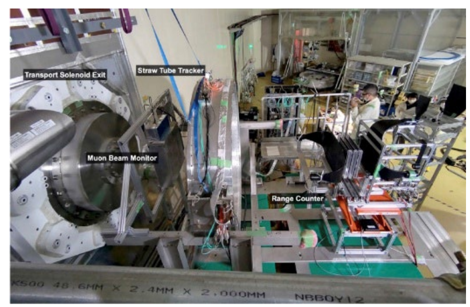


$$E_e = m_\mu - B_\mu - N_{recoil} = 104.9\,\text{MeV}$$

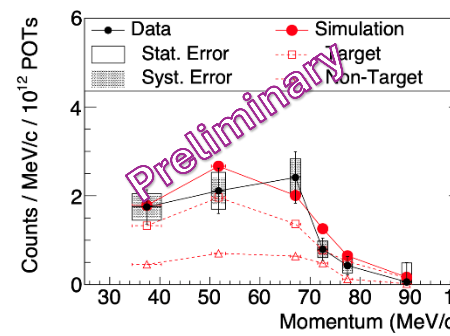


Phase-I





Engineering Run in 2023



8GeV Backward pi/mu production confirmed

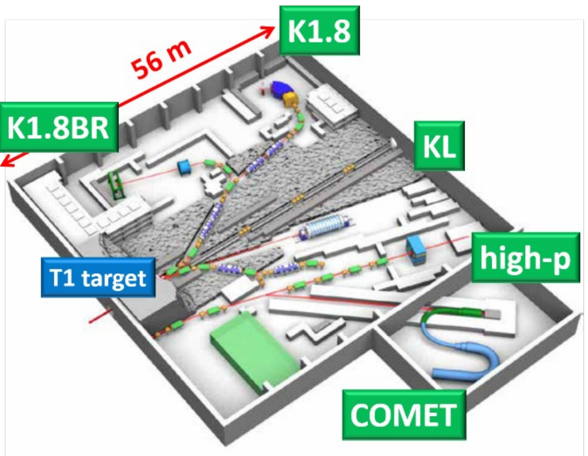
	2022	2023	2024	2025	2026	2027	2028
Eng. run		★					
Facility	Magnet construction (2022–2024)		Installation & test (2024–2026)			Beam PW upgrade (2027–2028)	
Detectors	Construction Stand-alone test (2022–2025)		Installation (2024–2025)		CR test (2026)		
Phys. run						Phase-I Physics (2027–2028)	

COMET Phase-I Timeline

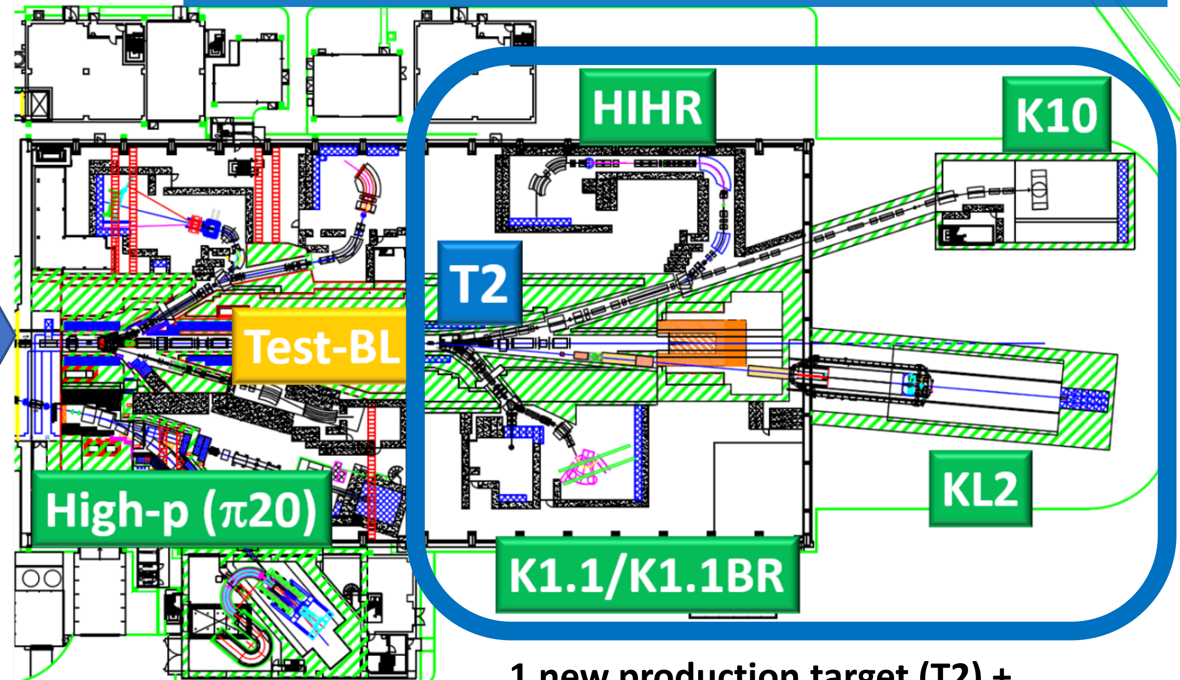
Hadron Experimental Facility Extension (HEF-ex) project

Open new physics that cannot be implemented at the existing facility

Present 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)

KEK-PIP 2022 Priory Number 1

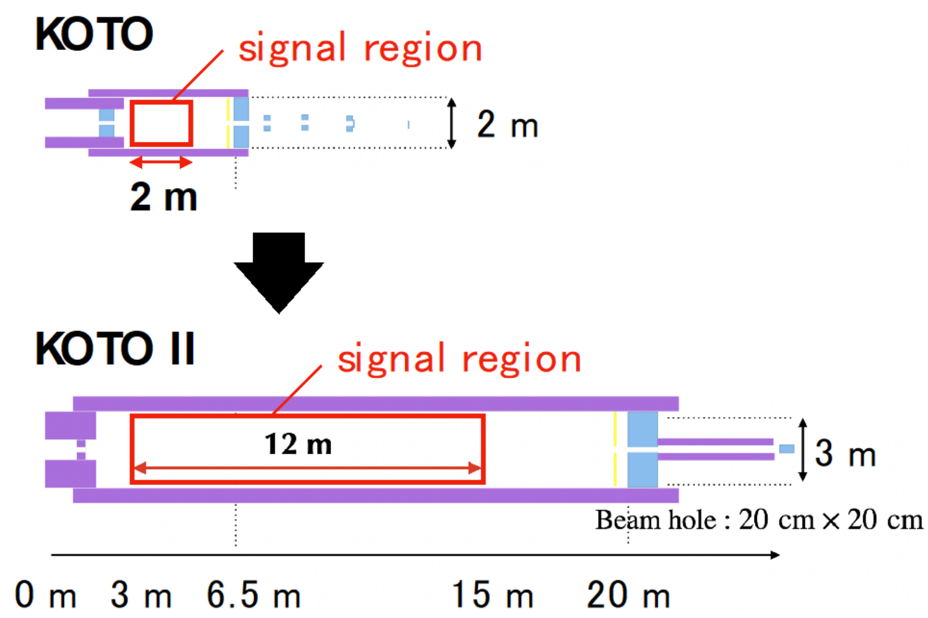
KOTO II @ HEF-ex

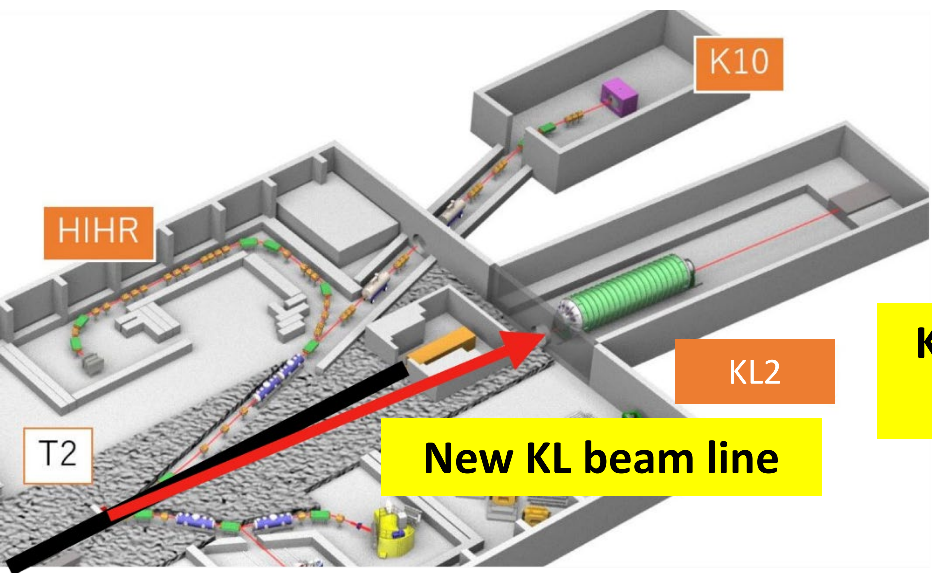
Search for new source of CP violation beyond Standard Model (SM)

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

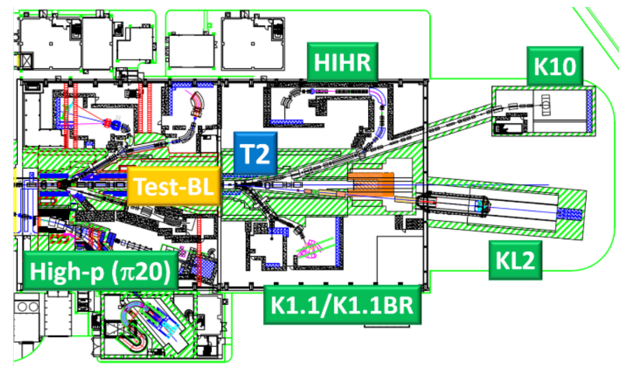
assuming 100kW beam, and 3×10^7 s running

(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

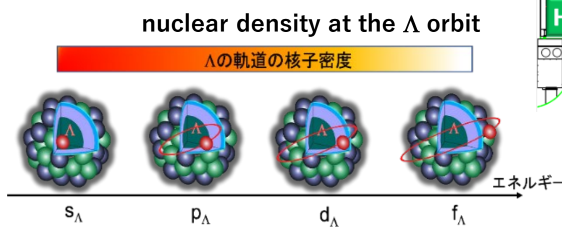
KOTO II detector behind dump at the end of extended hall

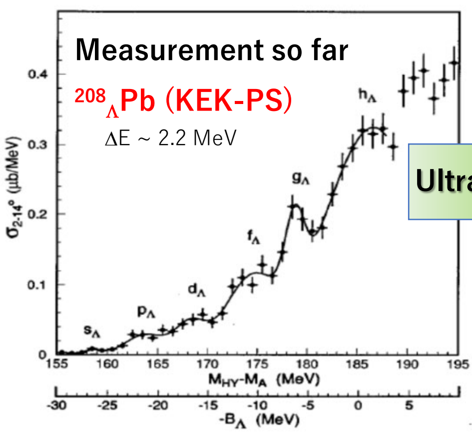
A Highlight of future nuclear physics at extended HD hall



Elucidation of YN interaction in nuclear matter

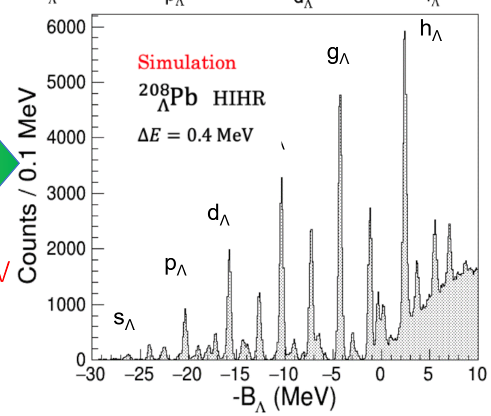
First high-resolution spectroscopy of the heaviest Λ hypernucleus at HIHR



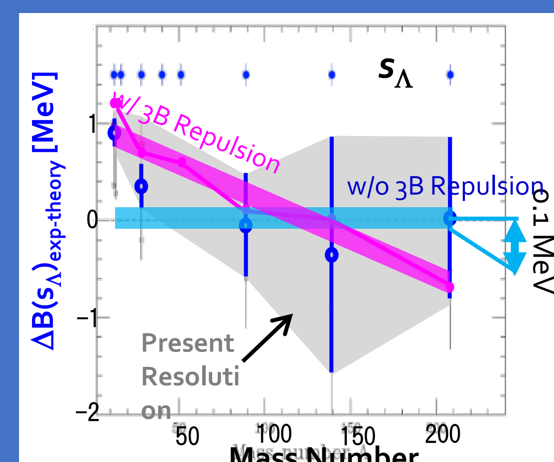


Ultra high-resolution →

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



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

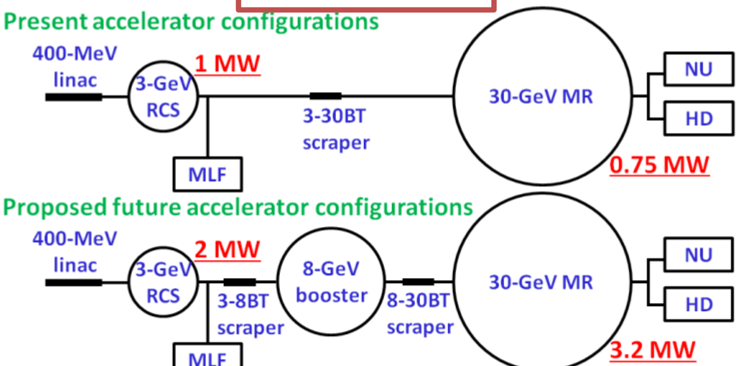


Clarify **density-dependent Λ interaction** and **multi-body force** via the systematic measurements for the **understanding high-density matter and neutron stars**.

Ideas for Multi-MW for long term future

- 3.2 MW with a new 8-GeV Booster in J-PARC
- 9 MW with a 9-GeV proton driver in the KEKB Tunnel after the B-factory project.

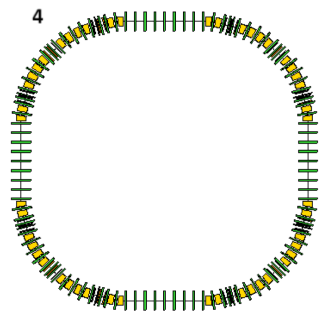
J-PARC Tokai site



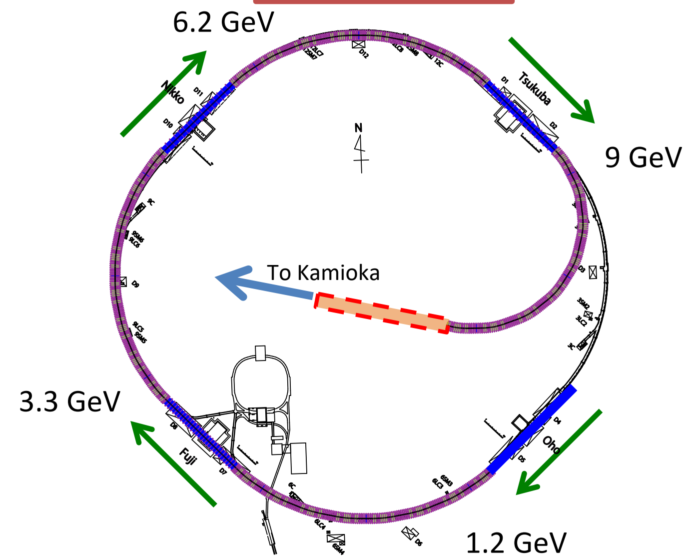
	RCS	8-GeV booster	MR
Physical aperture (mm mrad):	486π	189π	81π
Collimator aperture (mm mrad):	324π	126π	54-60π
Collimator capability (kW):	4	4	4

	3-8BT	8-30BT
Scraper aperture (mm mrad):	126π	54-60π
Scraper capability (kW):	2	2

Conceptional Design of 8 GeV Ring
Circumference 696.666 m
Super-periodicity 4
Transition gamma ~15 GeV



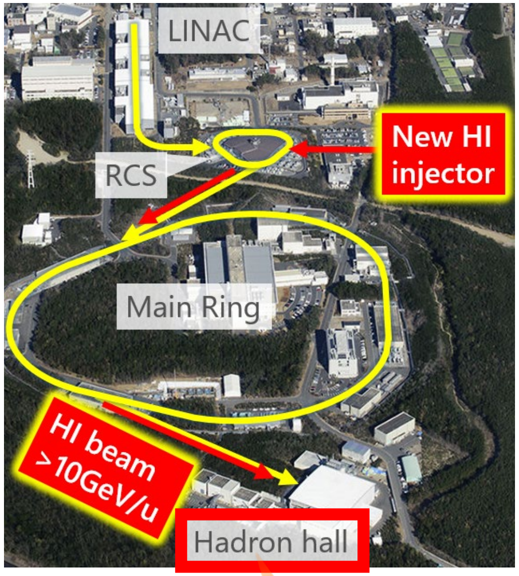
KEK Tsukuba site



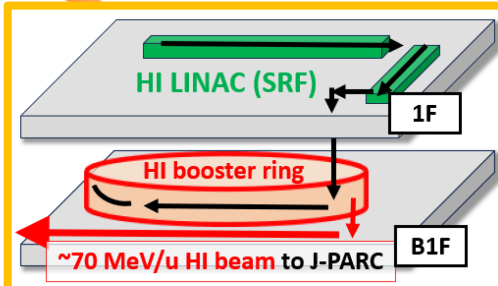
For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.
- Peak current : 100 mA (pulse)
- Beam duty : 1 %
- Beam power : 9 GeV x 0.1 A x 1 % = **9 MW**

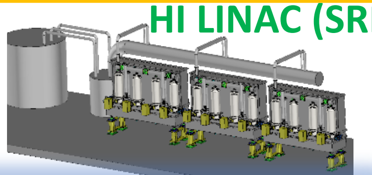
R&Ds : High duty horn, higher gradient SC cavity, high power target...

J-PARC HI : J-PARC Heavy-Ion Program



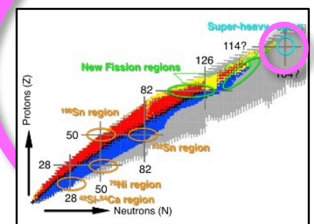
- Construction of **new HI injector** nearside J-PARC
- Use of **existing High-intensity** accelerators (**RCS, MR**)
- **Heavy-ion beams** with **the world highest luminosity**
- **Realize various new experiments (0.5MeV/u – 11GeV/u)**



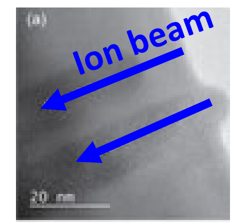


Goals for low energy HI beams

Superheavy element



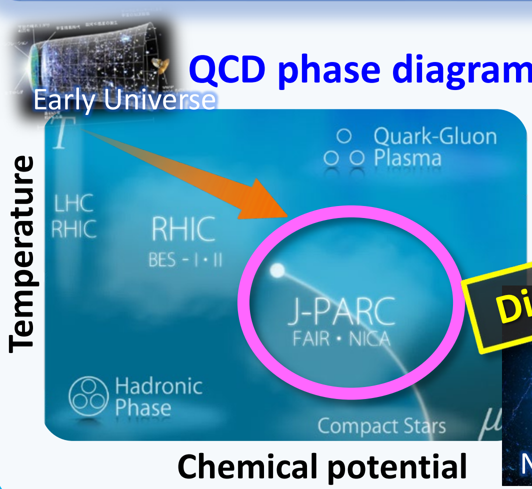
Material irradiation



Nuclear chemistry

Space irradiation tech.

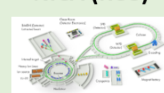
Physics Goals for high energy HI beams



Exploring extremely dense matter
- ✓ QCD phase transitions & critical point
- ✓ Equation of state for neutron stars
- ✓ Color superconducting phases

Search for hadronic/hypernuclear
- ✓ Hadron interaction /structure
- ✓ New Hypernuclei and strangelet

International "Hot" Situation

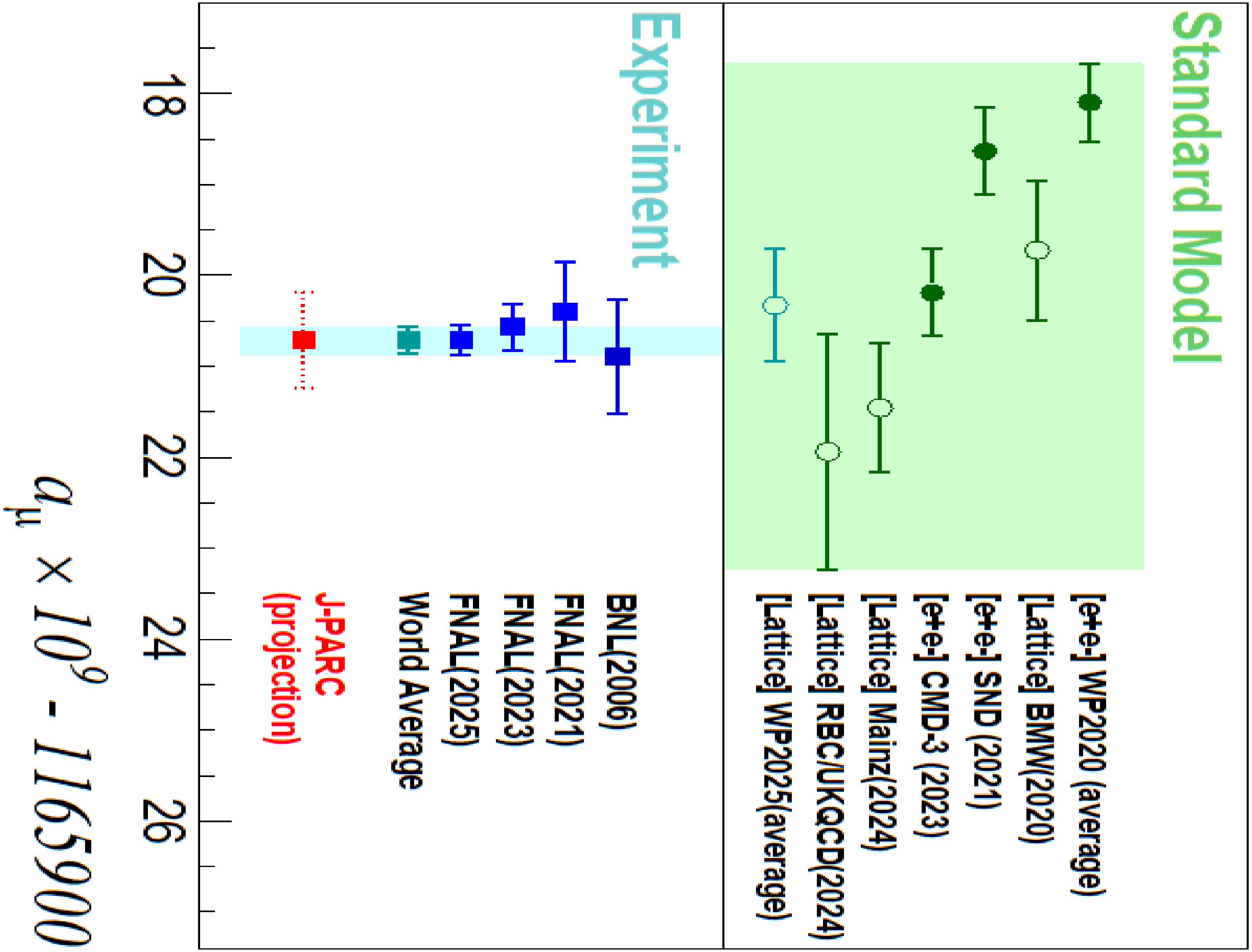
Status	On-going	Construction	Construction	Construction	Plan
Project	RHIC-BESII (USA) 	NICA (RUS) 	HIAF (CHN) 	FAIR (EU/GER) 	J-PARC-HI 
Interaction Rate	10^3 Hz	10^3～10^5 Hz	10^5～10^6 Hz	10^6～10^7 Hz	> 10^8 Hz

Summary

- J-PARC is the world leading intensity frontier proton accelerator research complex
  - 3GeV RCS/MLF: achived 1MW operation
  - 30GeV MR
    - **830kW stable operation for NU**
    - **90kW stable operation for HD**
- 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 fprojects are being conducted/prepared
  - COMET
  - Mu g-2
  - Hadron hall extension : KEK's highest priority in KEK-PIP 2022
  - T2K → Hyper-Kamiokande
  - And more

We welcome your more participation for exciting physics at J-PARC!

ミューオンg-2の現状



Experiment
Standard Model
18
20
22
24
26
$a_\mu \times 10^9 - 1165900$
J-PARC (projection)
World Average
FNAL(2025)
FNAL(2023)
FNAL(2021)
BNL(2006)
[Lattice] WP2025(average)
[Lattice] RBC/UKQCD(2024)
[Lattice] Mainz(2024)
[e+e-] CMD-3 (2023)
[e+e-] SND (2021)
[Lattice] BMW(2020)
[e+e-] WP2020 (average)