Status and future prospect of long baseline experiments with J-PARC neutrino beam and near detectors

2019-Apr-25 INR, Moscow

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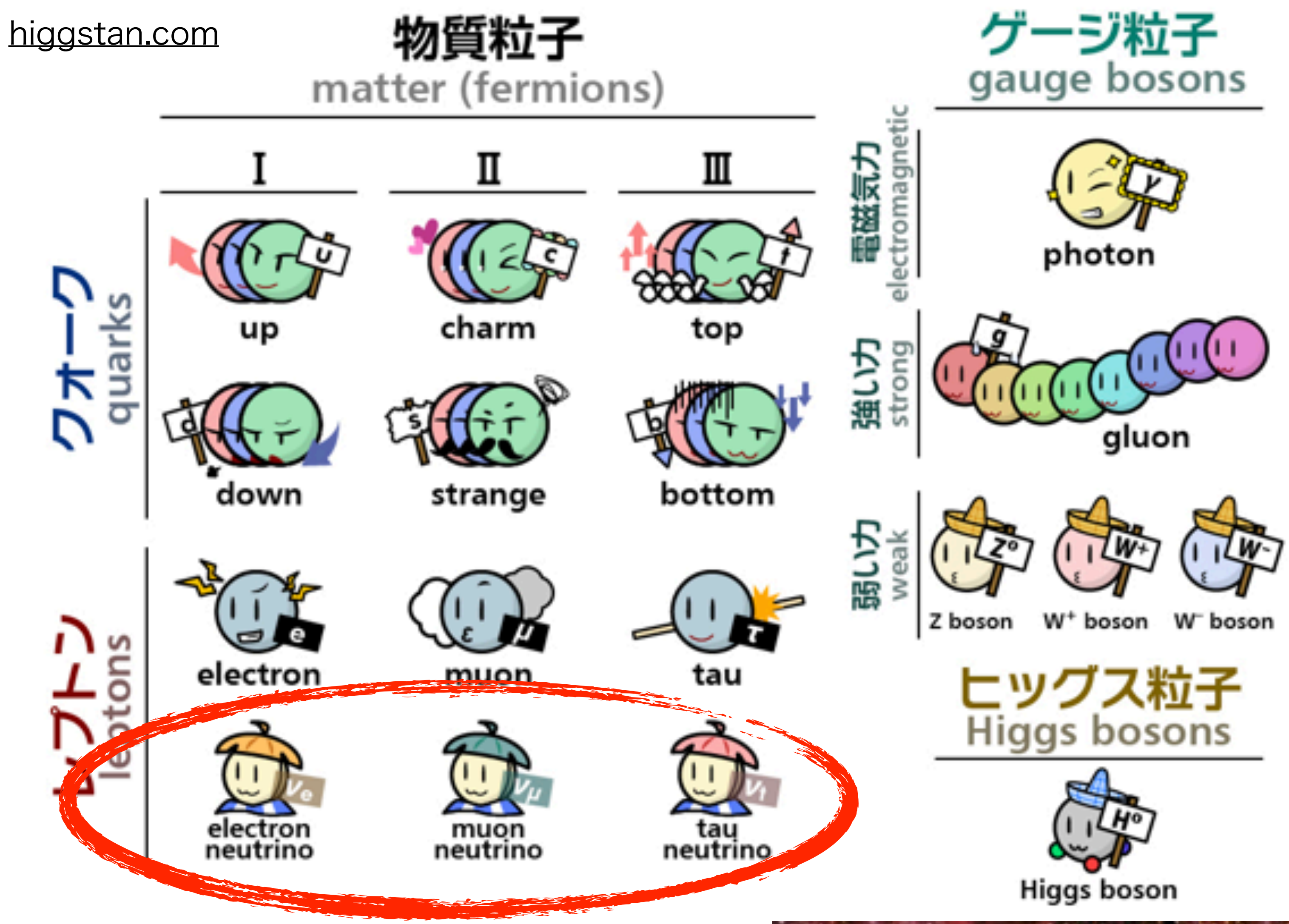
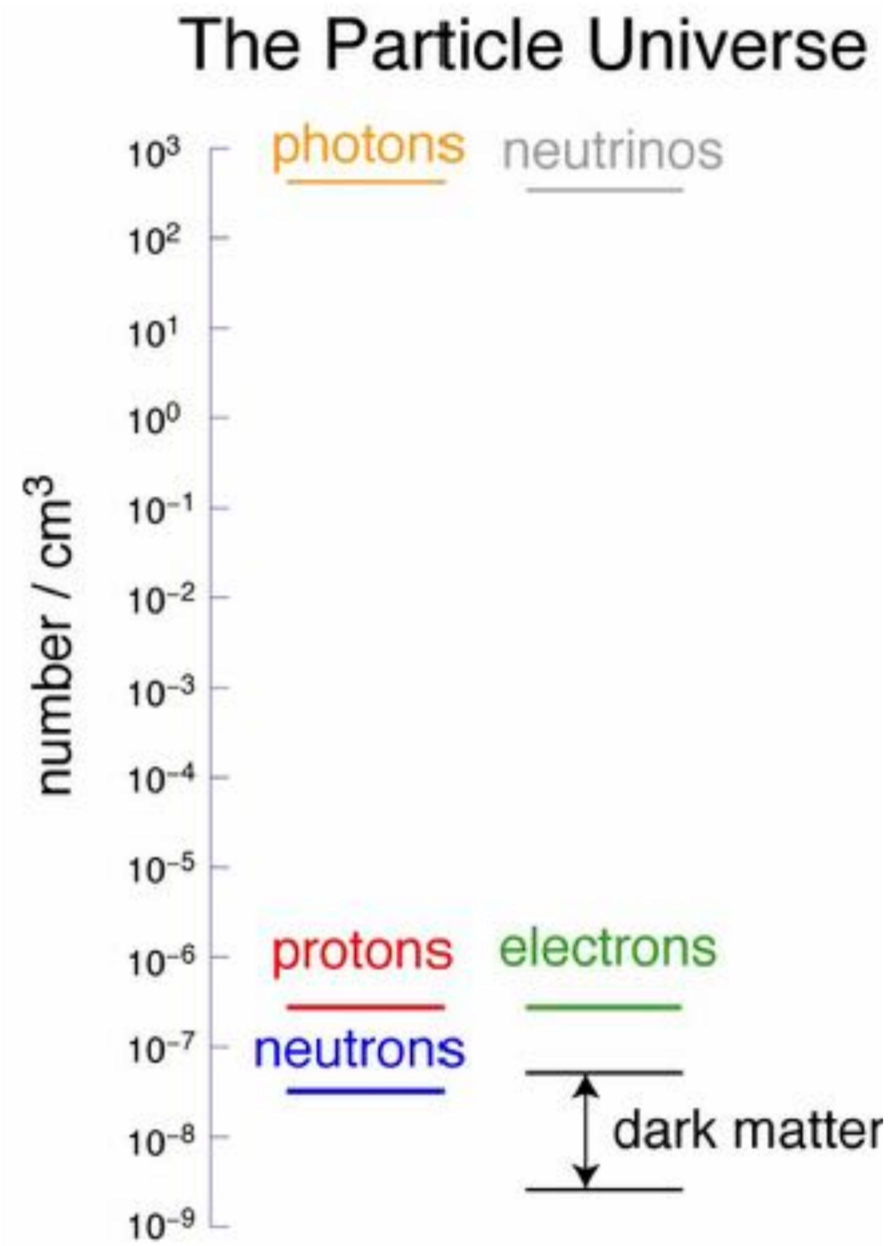
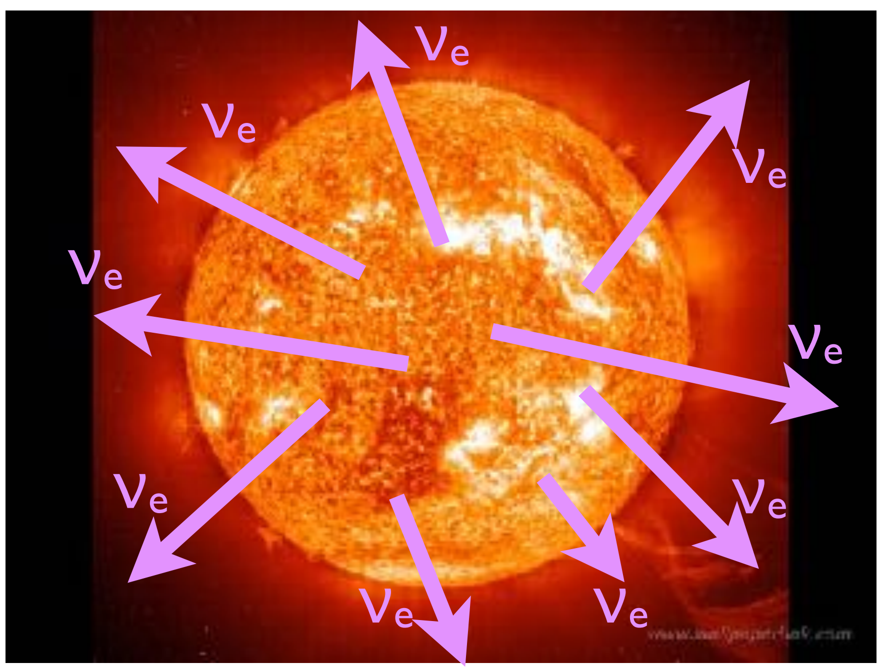
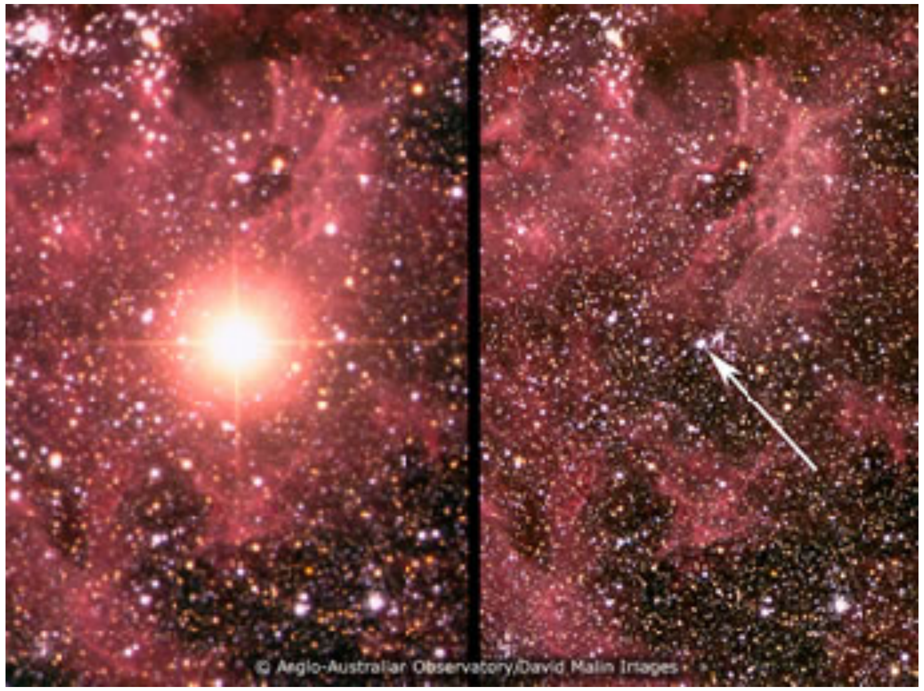
M.Yokoyama (U. Tokyo)

Neutrinos


higgstan.com
物質粒子
matter (fermions)
I
II
III
クォーク
quarks
up
charm
top
down
strange
bottom
レプトン
leptons
electron
muon
tau
electron neutrino
muon neutrino
tau neutrino
ゲージ粒子
gauge bosons
電磁気力
electromagnetic
photon
強い力
strong
gluon
弱い力
weak
Z boson
W⁺ boson
W⁻ boson
ヒッグス粒子
Higgs bosons
Higgs boson


The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter


νe


© Anglo-Australian Observatory/David Malin Images

It's special, mysterious particle..

higgstan.com

Tiny but non-0 mass

Mass other than Higgs mechanism?

Electrically neutral

Particle=antiparticle?

Large mixing

Suggestion for Grand Unification?

Abundant in Universe

Evolution of Universe

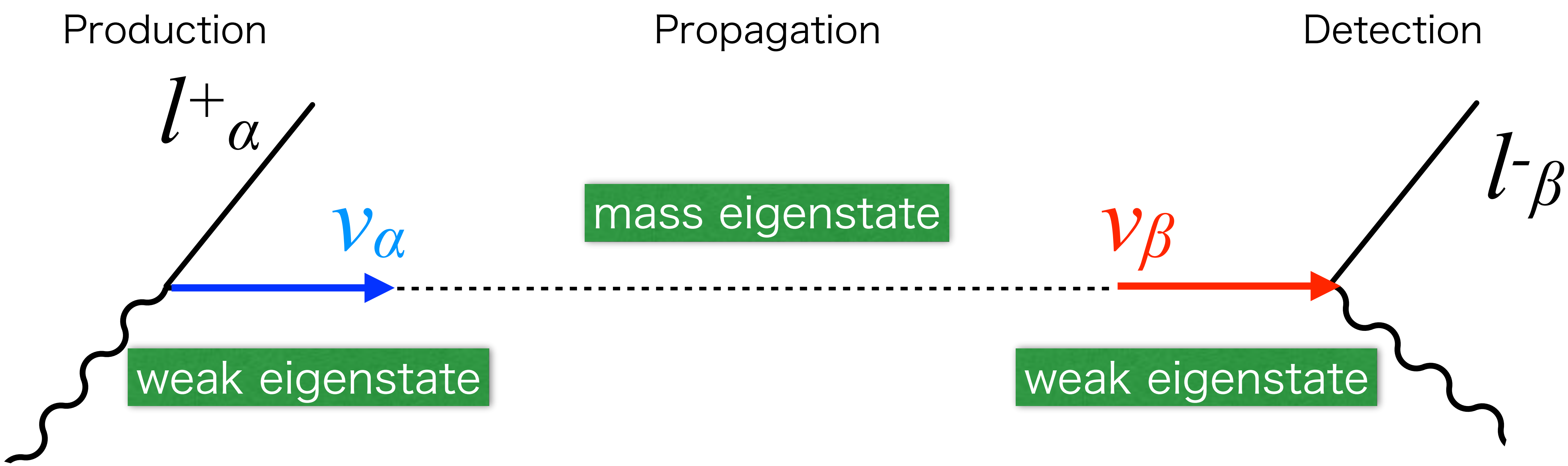
Particle-antiparticle asymmetry?

Origin of matter?

Its properties are of great importance in particle- and astro-physics

Neutrino oscillation

Flavor (weak eigenstate) of neutrino can be changed during the propagation



$$|\nu_\alpha\rangle = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left[\frac{1.27\Delta m^2 L}{E_\nu}\right]$$ (2 flavor case)

$\Delta m^2 = m_1^2 - m_2^2$ [eV^2]

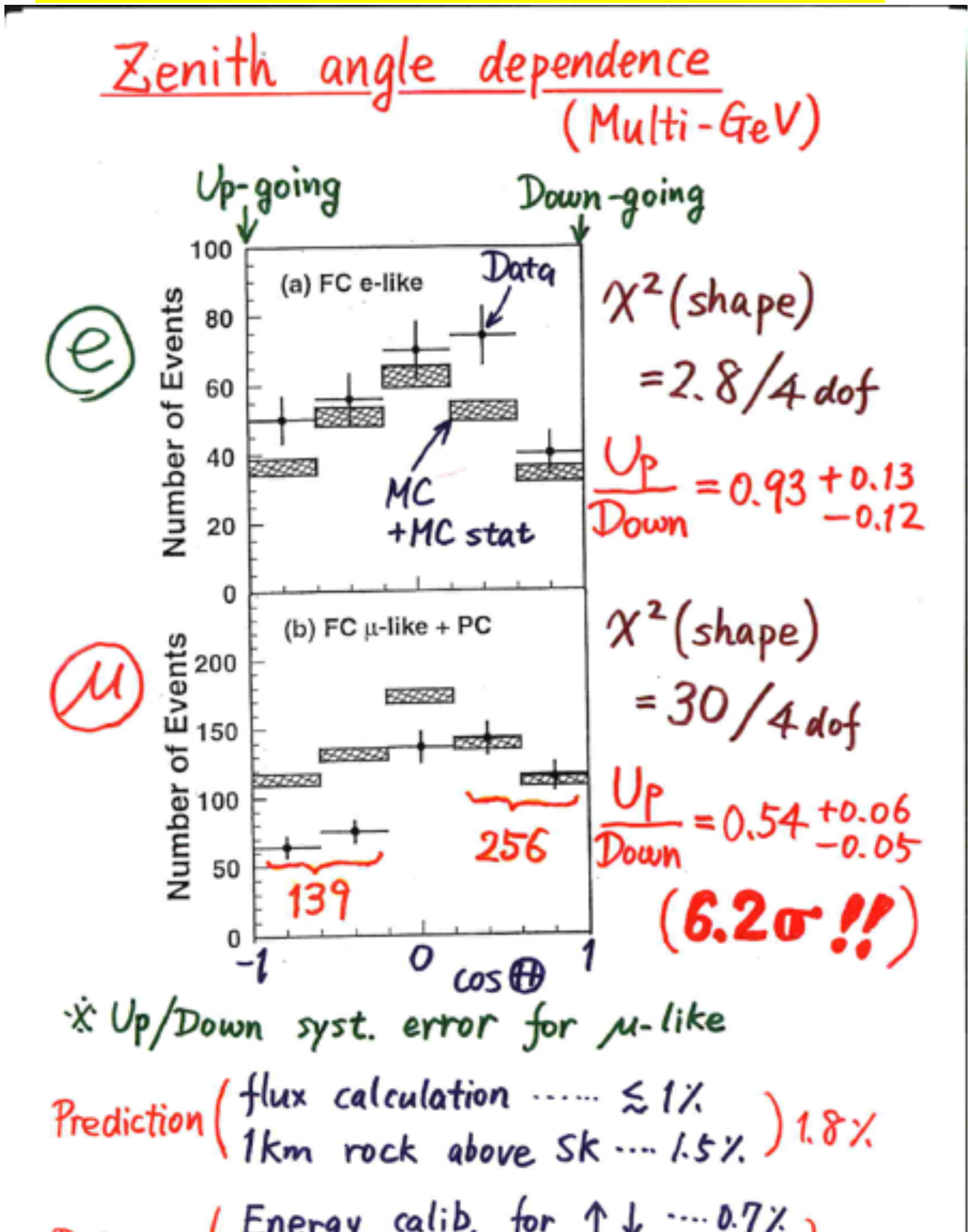
θ: mixing angle

L [km], E_ν [GeV]

Happens only if the neutrino has a finite mass ($\Delta m^2 \neq 0$)

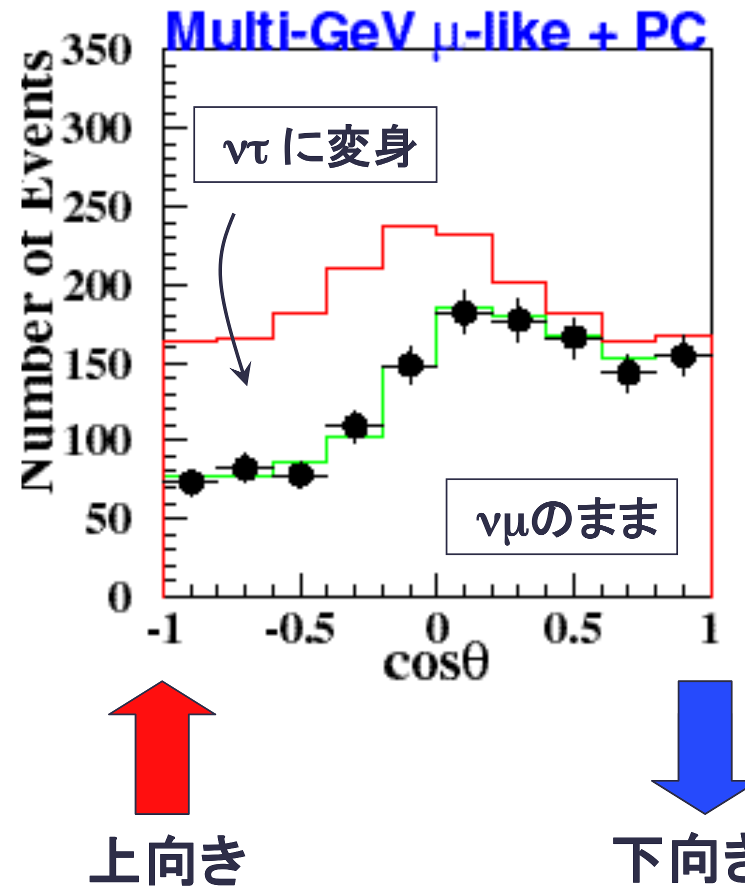
Nobel Prize in 2015

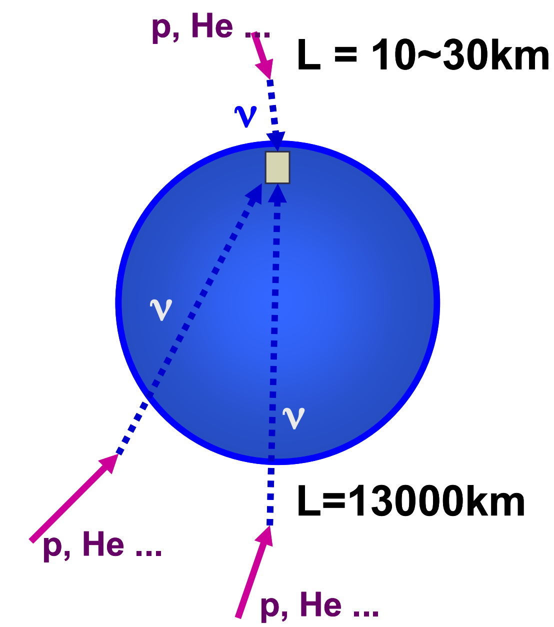
First firm evidence for neutrino oscillation



Amazing progress in ~20 years

- 1998, neutrino oscillation discovered by **Super-K** atmospheric neutrino observation

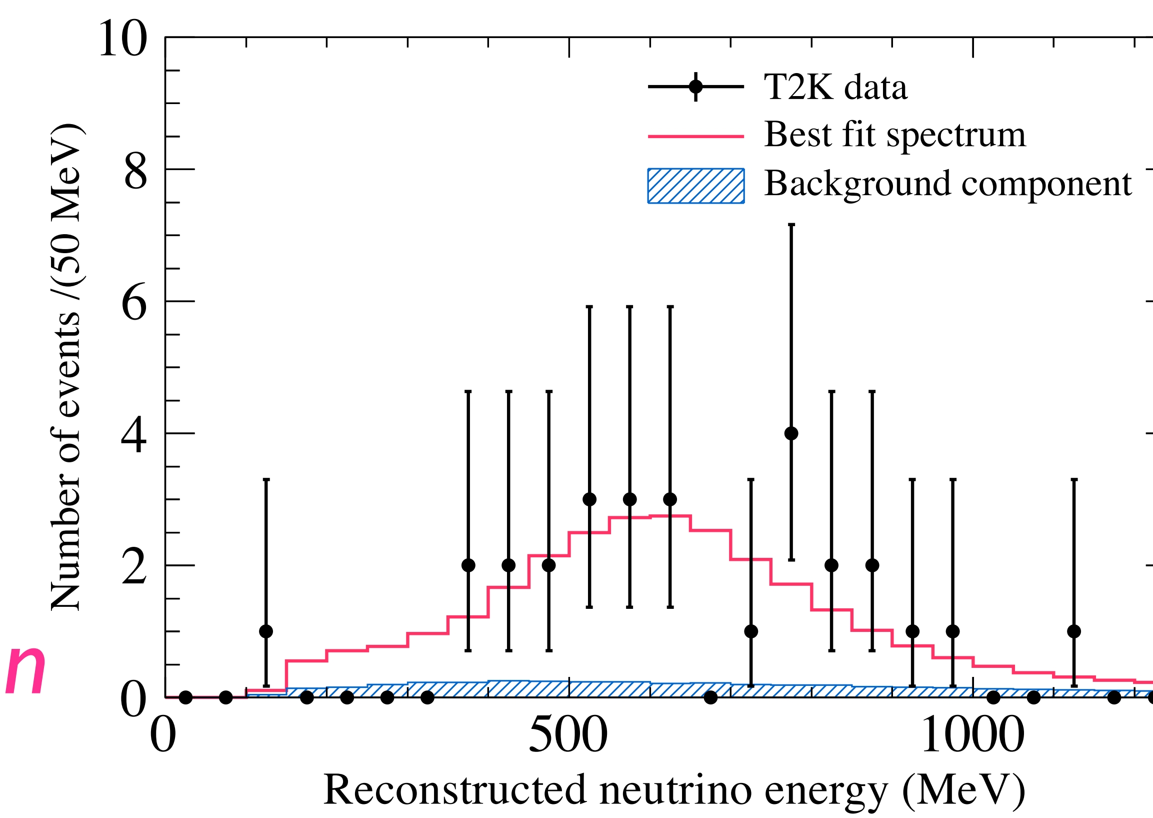




- Solar neutrino oscillation confirmed by SNO(2001) and **KamLAND** (2002)

- Accelerator-based neutrino oscillation experiments: **K2K**, MINOS, OPERA

- **T2K** experiment discovered $\nu_\mu \rightarrow \nu_e$ in 2011, Daya-bay discovered non-zero θ_{13} (established 3-flavor oscillation)



Experiments in Japan lead the world on neutrino oscillation physics

Present understanding of ν oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i\rangle$$

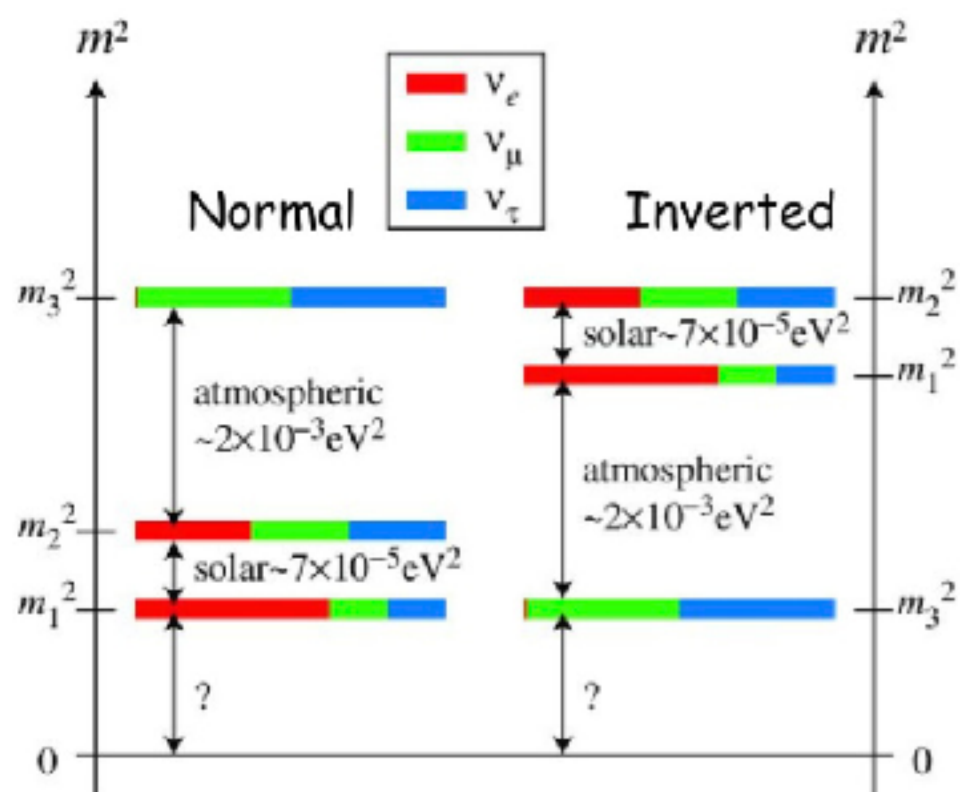
$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

All of the three mixing angle and two mass square differences are measured

Next physics targets are :

CP violation parameter : δ CP



Mass ordering

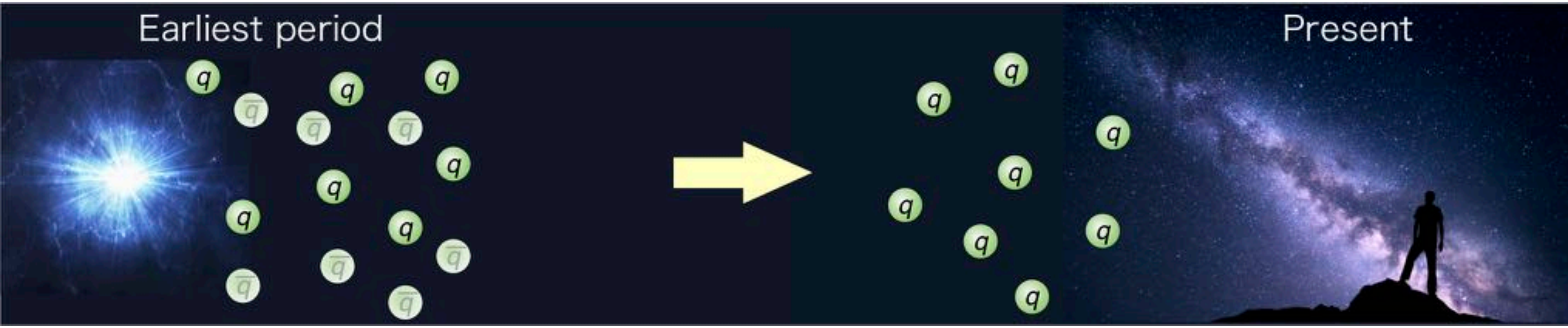
$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

large difference to quark mixing matrix

$$|V_{CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

Any flavor symmetry ?

CP violation



- CP violation(CPV) is one of the 3 Sakharov's conditions to create the matter dominant universe

- The size of CPV (J_{CP}) in neutrino oscillation can be three order of magnitudes larger than one of the quark

$J_{CP} \cong 0.0327 \sin\delta$ ⟷ J_{CP}~$3\text{x}10^{-5}$ (quark)

CPV through δ may be sufficient source for the matter dominant universe

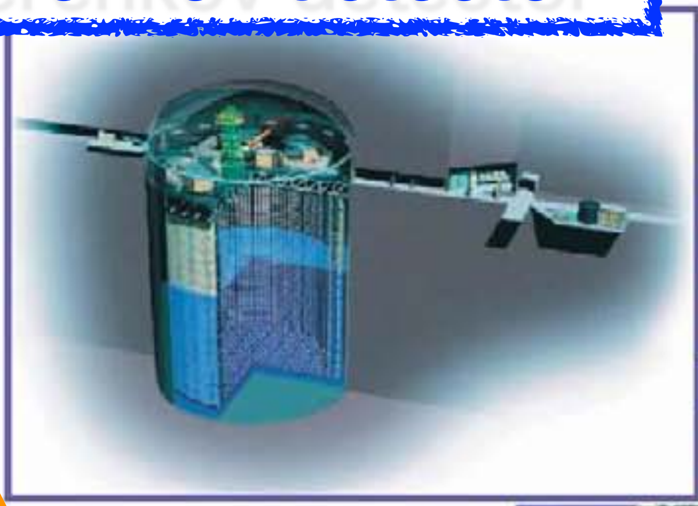
[Nucl. Phys. B774 (2007) 1 etc.]

Long baseline experiments with J-PARC

same?

Large size Water Cherenkov detector

$$Prob.(\nu_\mu \rightarrow \nu_e) \Leftrightarrow Prob.(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



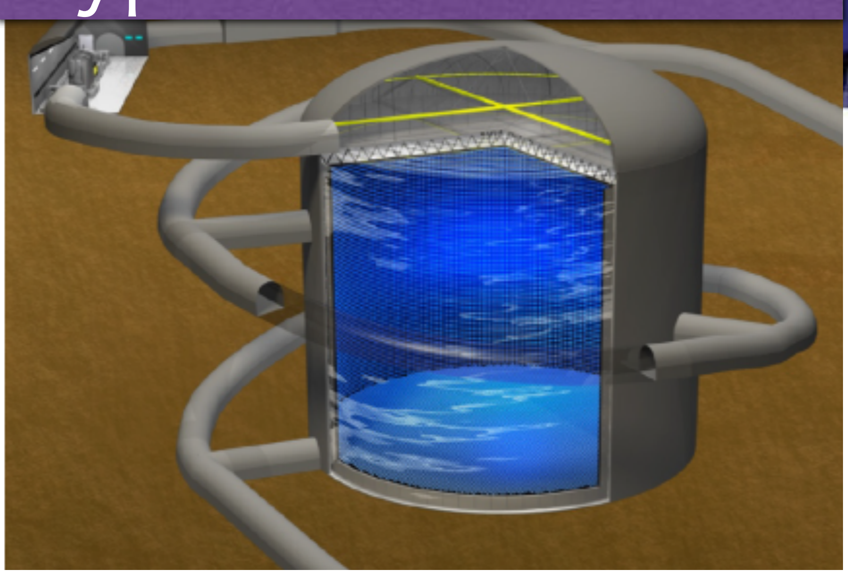
Super-Kamiokande
(ICRR, Univ. Tokyo)

High intensity ν beam

J-PARC Main Ring
(KEK-JAEA, Tokai)

Intermediate detector

Hyper-Kamiokande



T2K → T2K-II → Hyper-Kamiokande
(2010~) (2027~)

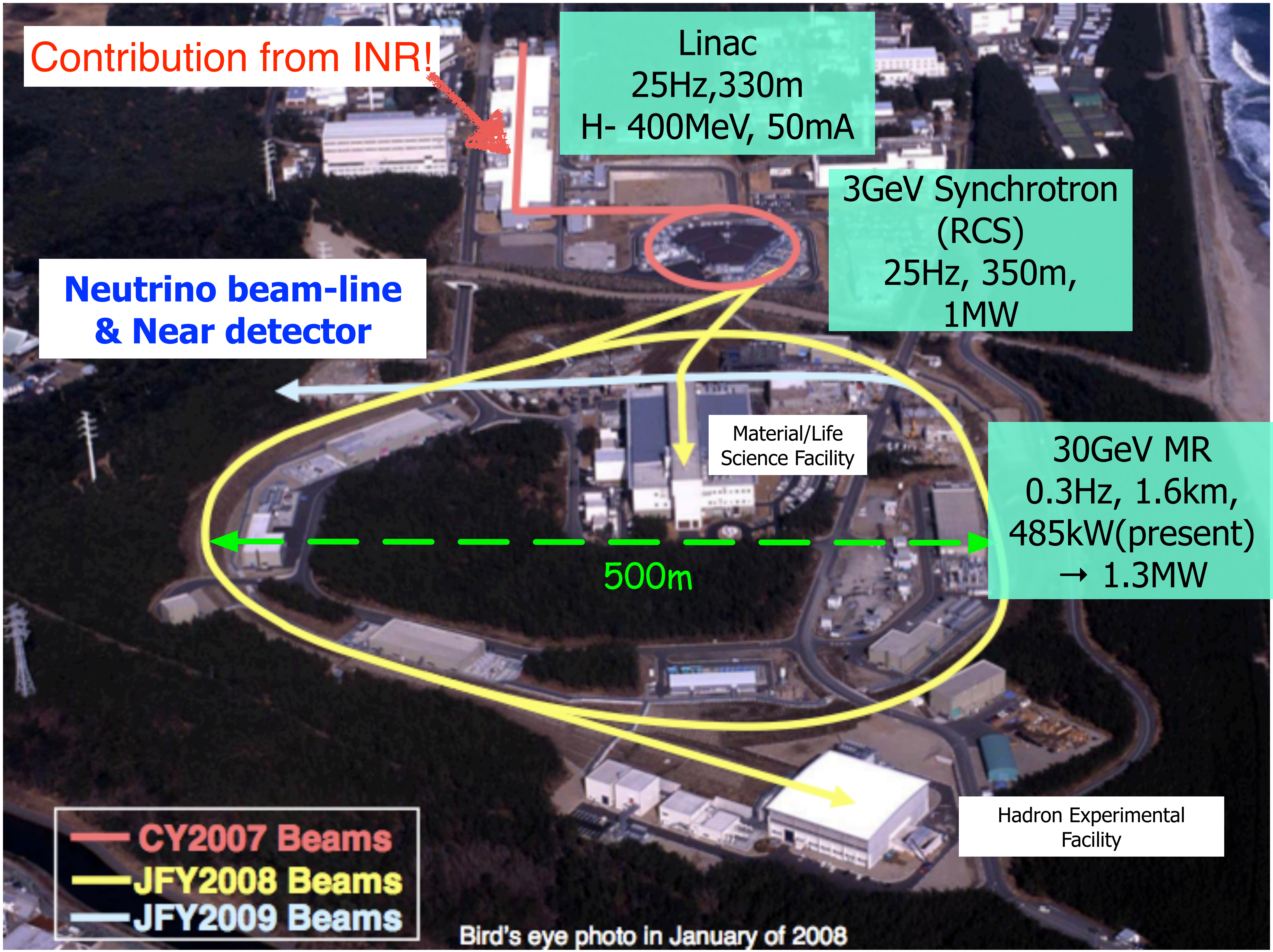
T2K collaboration

International collaboration

(as of 2019 Jan. : ~500 members, 68 institutes, 12 countries)

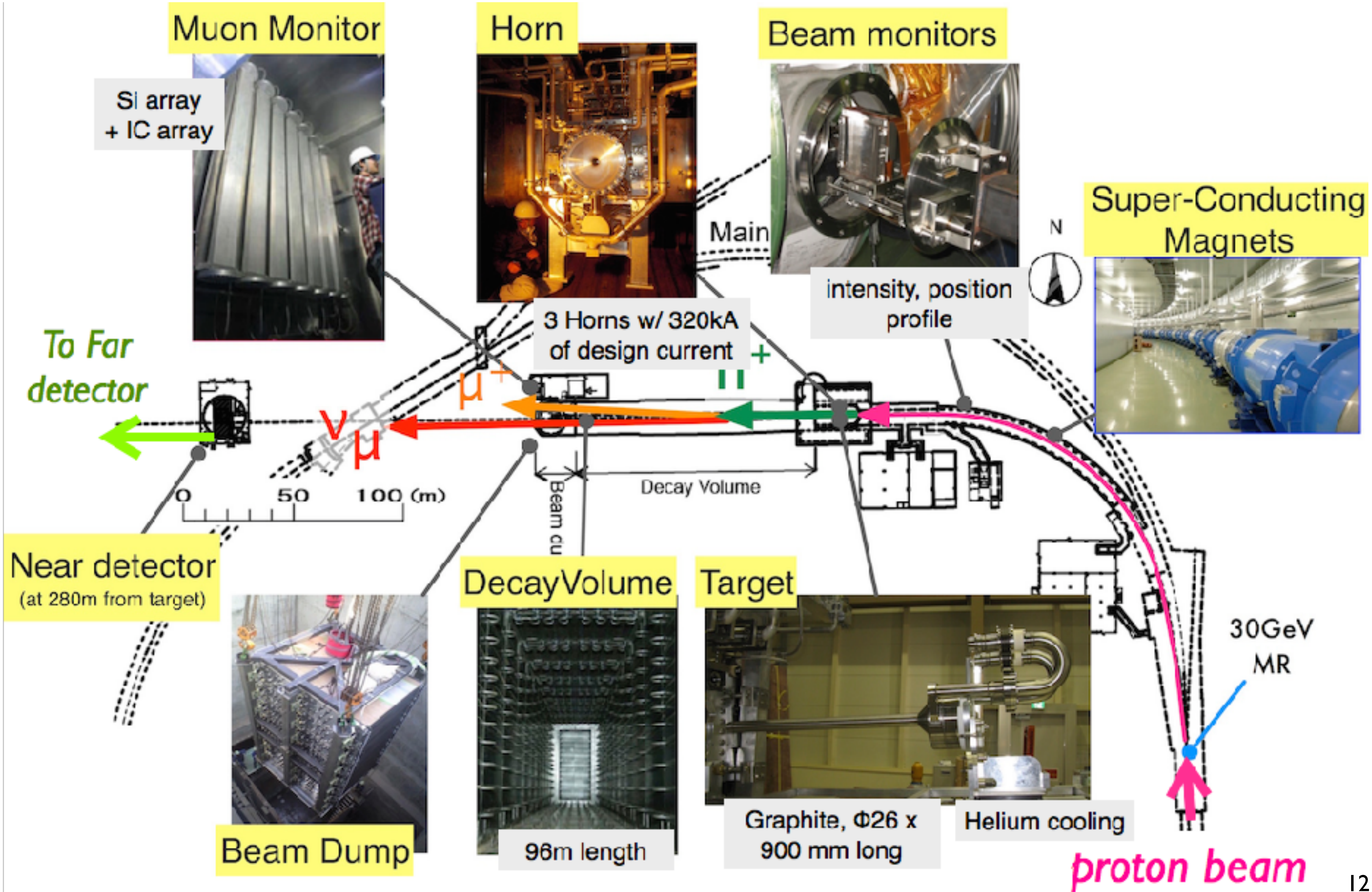
Recently, CERN neutrino group has joined !

J-PARC & Neutrino beam-line



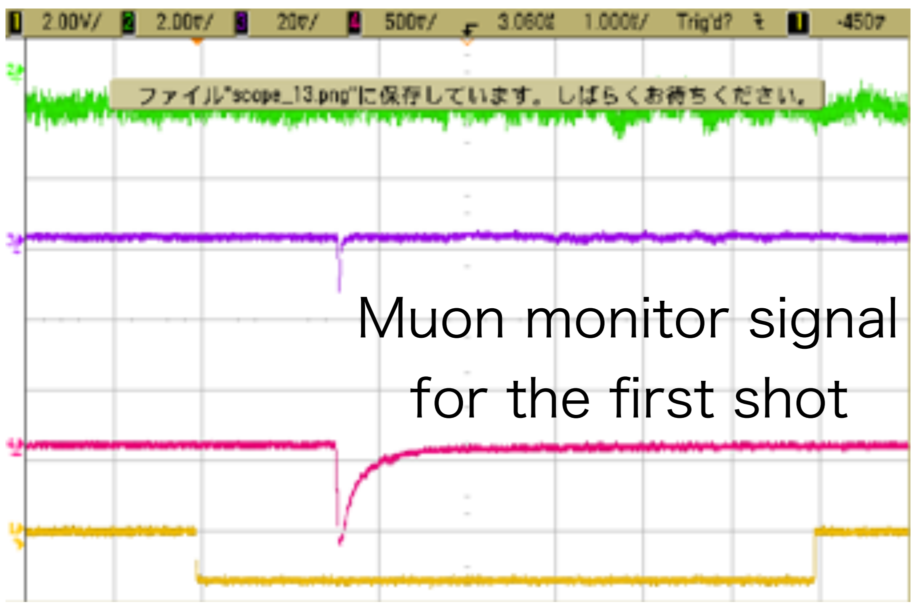
J-PARC neutrino facility

Producing a high intensity neutrino beam



10 year anniversary this week!

- First beam to J-PARC beamline was delivered on April 23, 2009



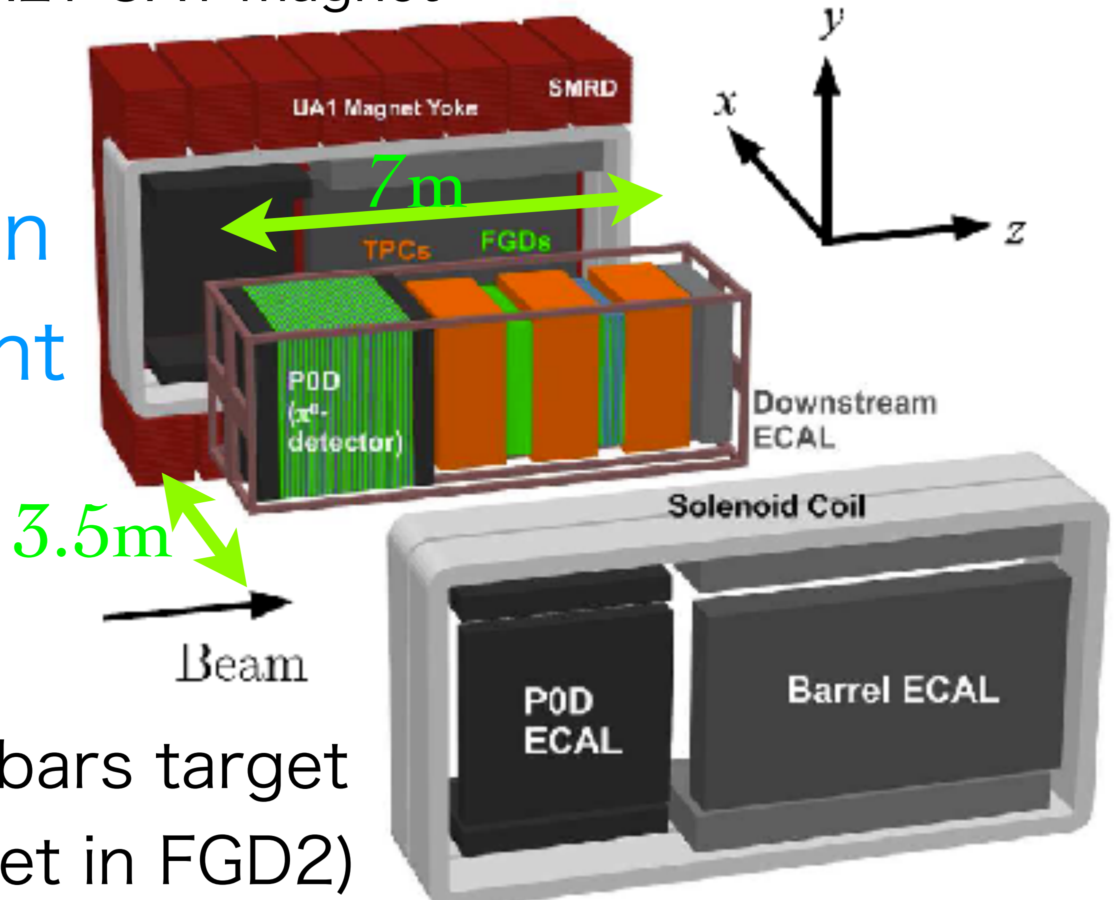
Near Detectors

ND280 @ Off-axis

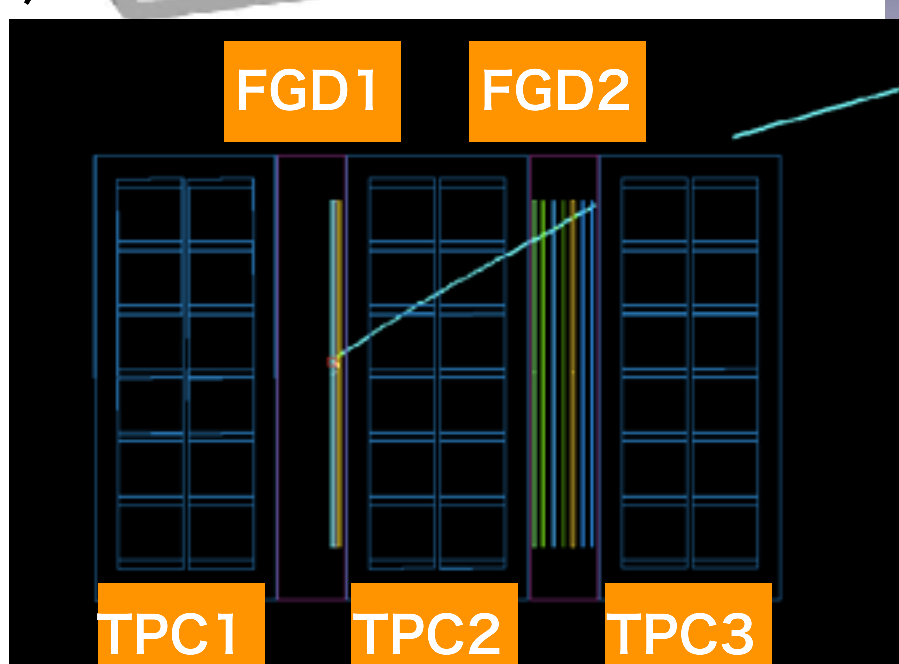
0.2T UA1 magnet

ν flux,

ν interaction measurement

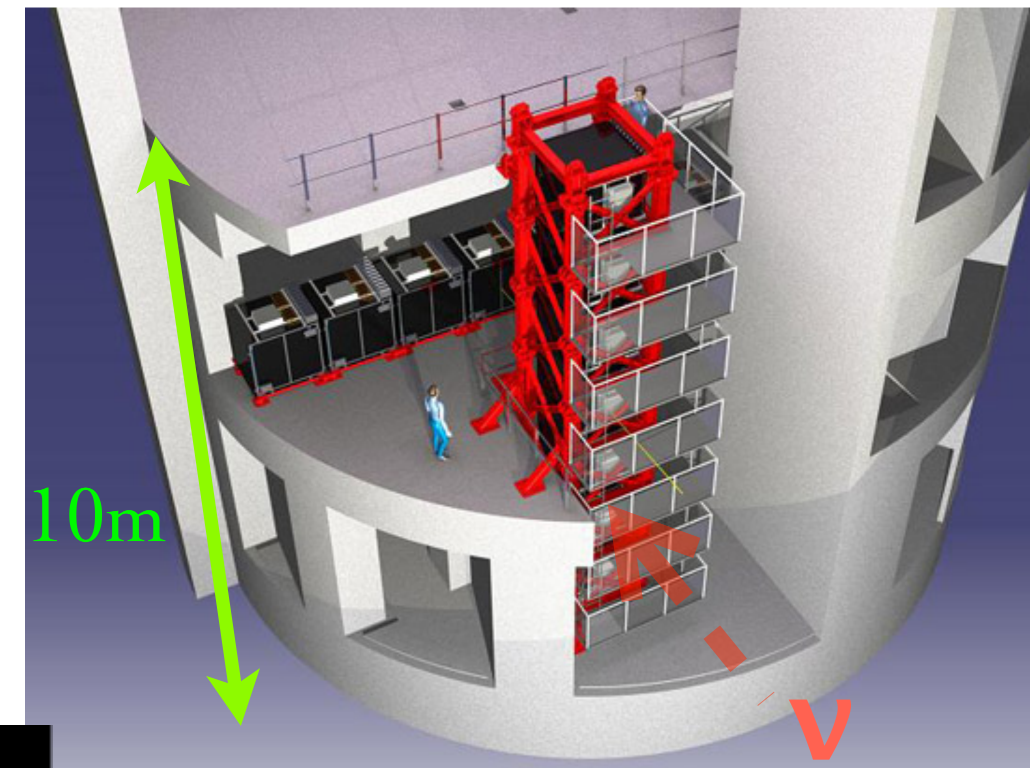


- FGD
  - scintillator bars target (water target in FGD2)
- TPC
  - momentum, dE/dx measurement



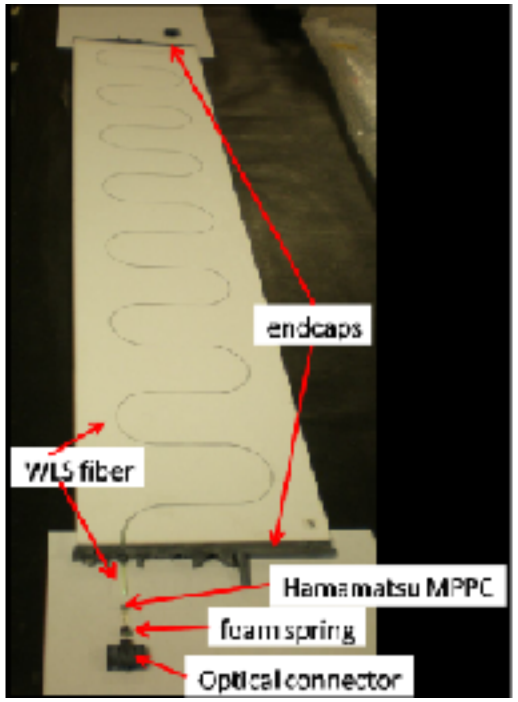
INGRID @ On-axis

ν beam direction, intensity measurement



Cooperation with Russia/INR

SMRD detector for ND280

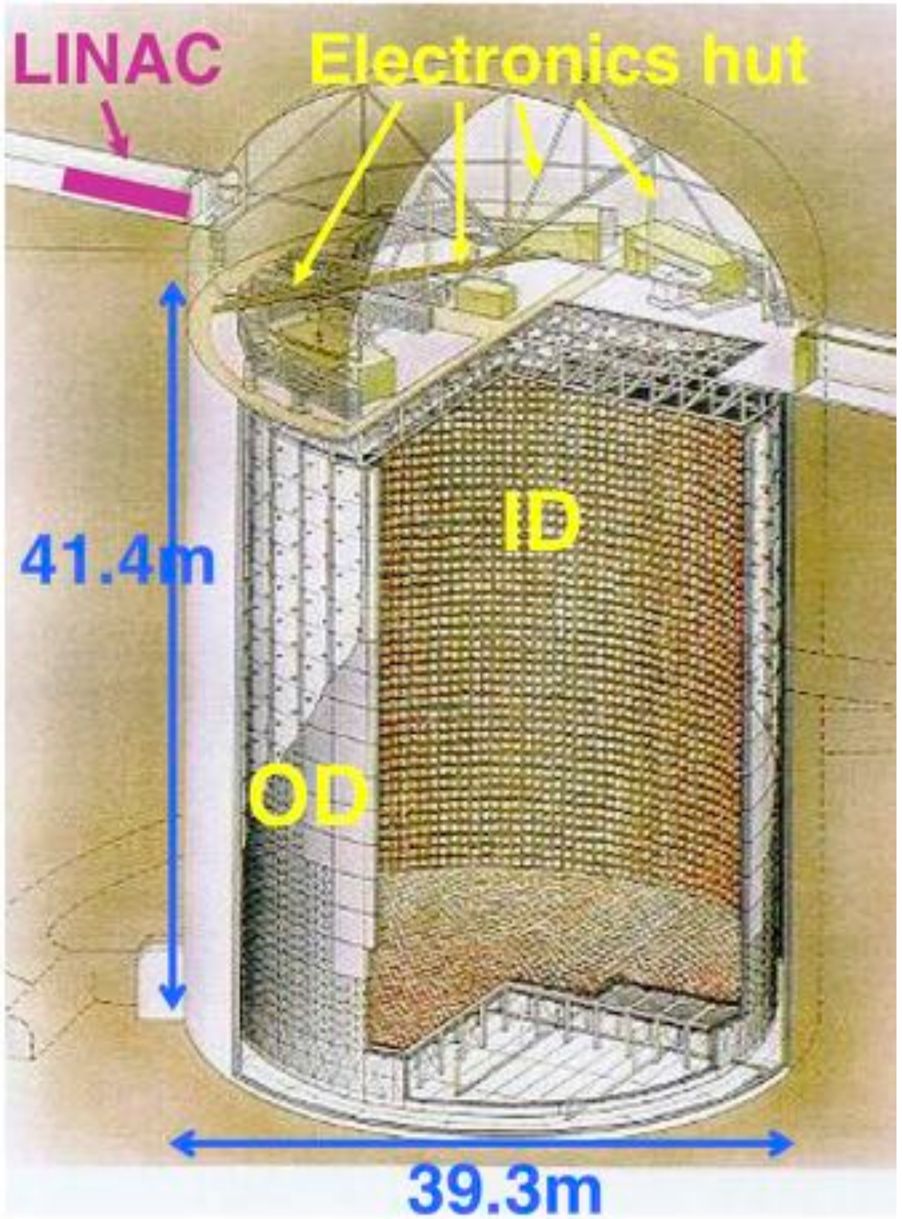


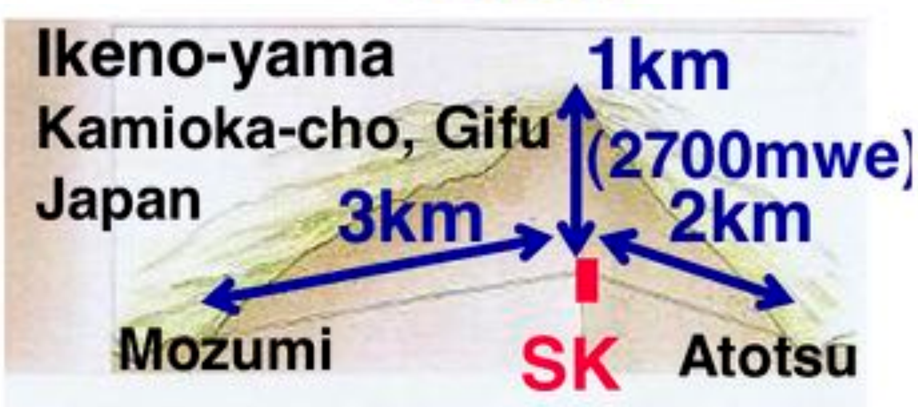
Baby-MIND/
WAGASCI
detectors

First 192x192 cube sheet

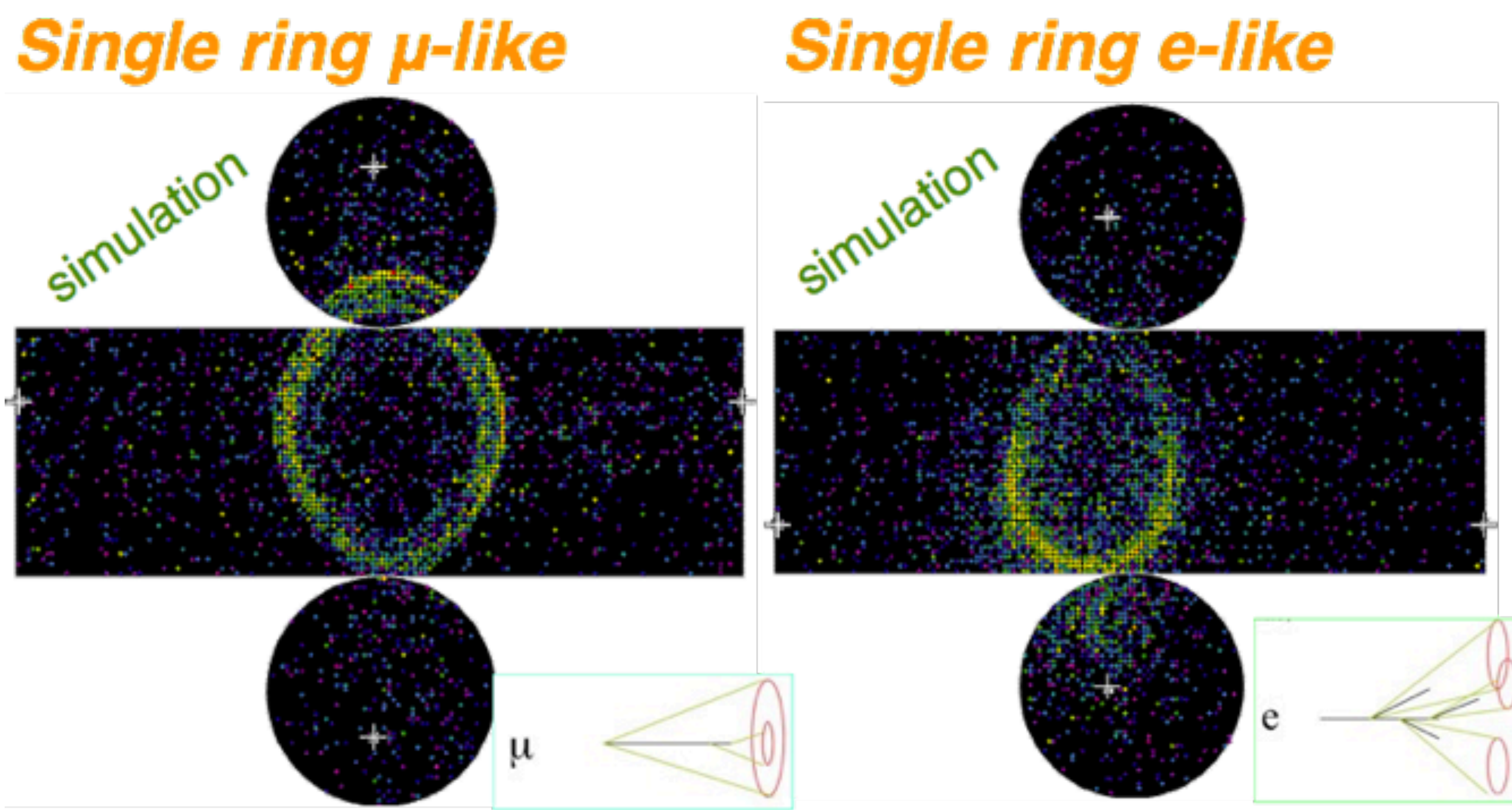
SuperFGD for
ND280 upgrade

Far detector (Super-K)

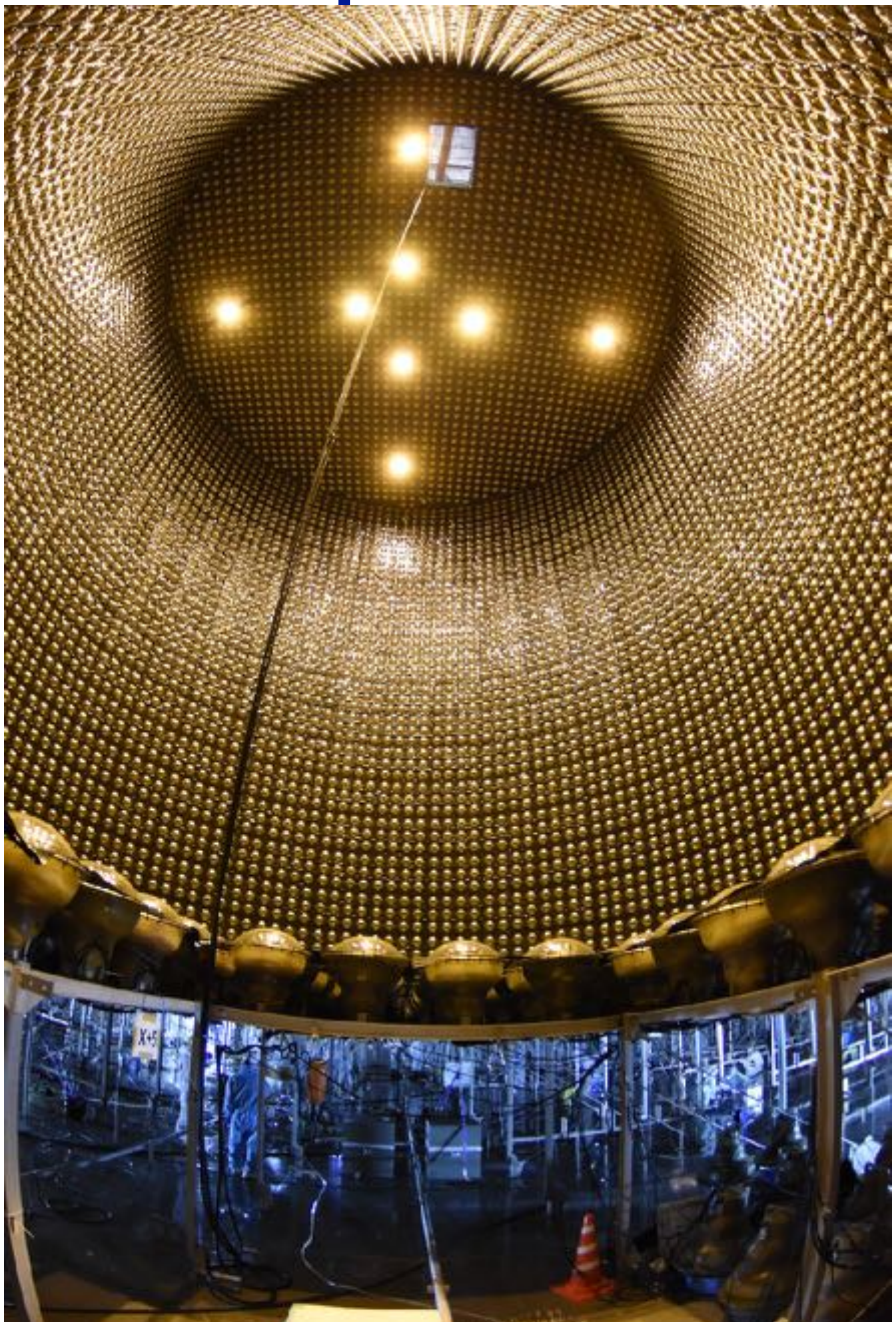




- 50kton water Cherenkov detector
- ID: ~11,000 x20inch PMTs
- Good e-like/μ-like separation
- 4π acceptance
- Refurbishment in summer 2018 for Gd loading (planned in 2019-2020)



Super-K refurbishment in 2018

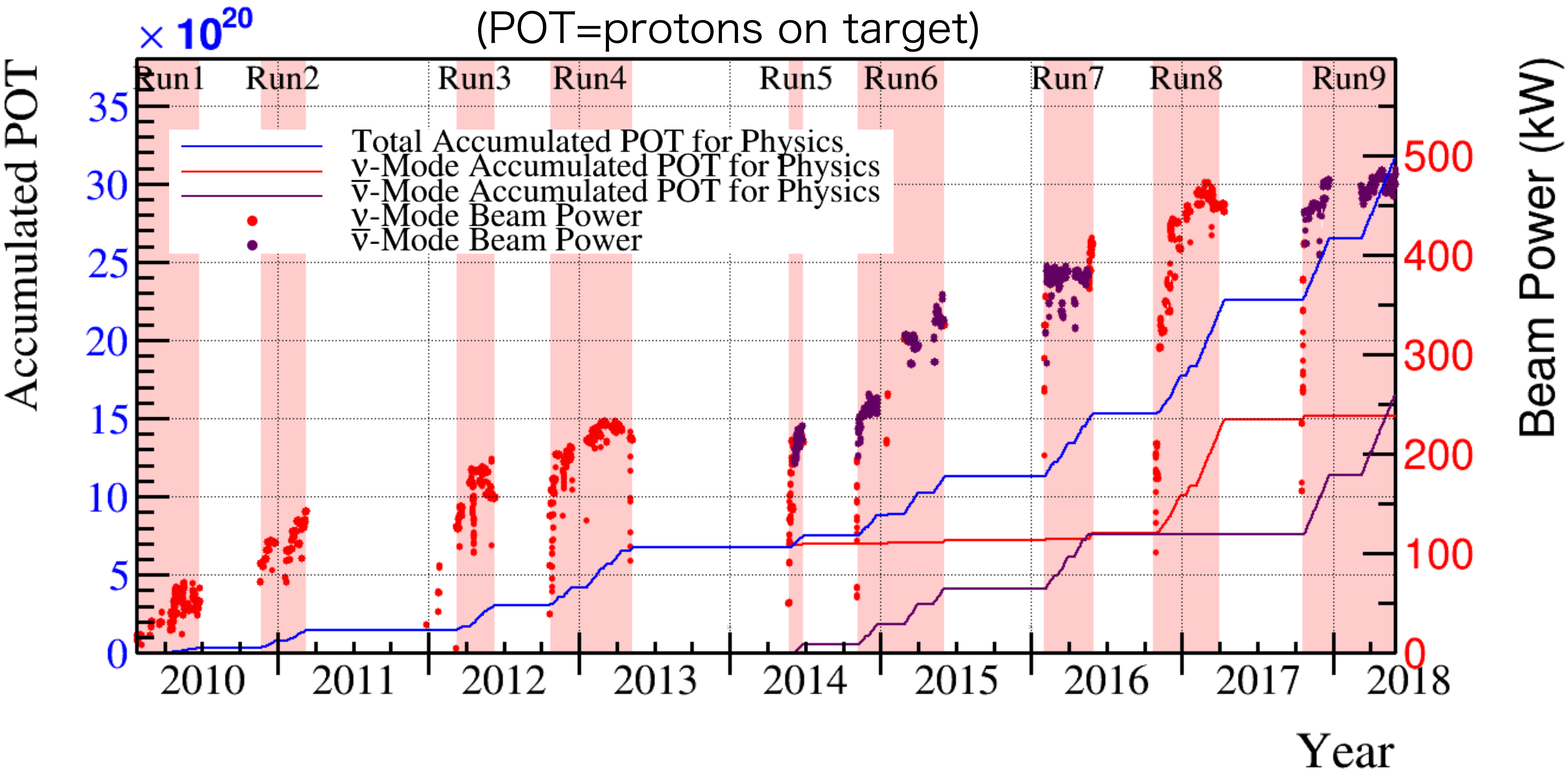


Operation resumed in Jan. 2019 (SK-V)
No water leakage observed
after refurbishment

Gd loading scheduled
in the beginning of 2020

Accumulated POT and beam power

(POT=protons on target)



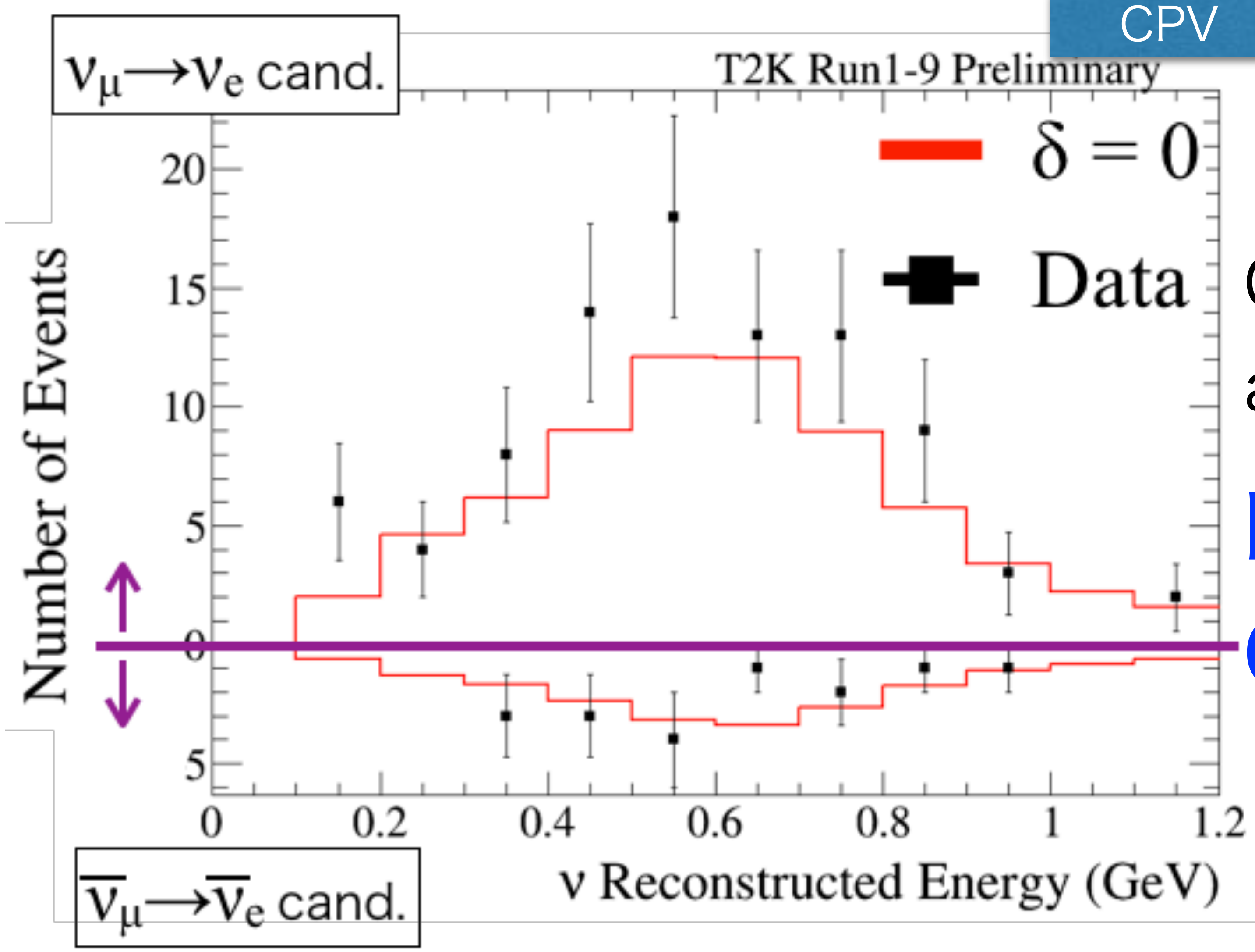
Accumulated 15.1×10^{20} POT for neutrino mode and 16.5×10^{20} POT for anti-neutrino mode

(total POT corresponds to 40% of the T2K approved POT)

Latest results

- **Results with all the data collected in the 2010~2018 period (9years)**

	Obs.	Expectation $\delta=-\pi/2$	Expectation $\delta=\pi$	Expectation $\delta=\pi/2$	Expectation $\delta=0$
$\nu_\mu \rightarrow \nu_e$ candidates	**90**	81.4	68.6	55.5	68.3
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ candidates	**15**	17.1	19.3	21.7	19.4
		CPV	CPC	CPV	CPC



CP conserving values (δ=0, π) are excluded with 2σ level

Indication of neutrino CP violation ?

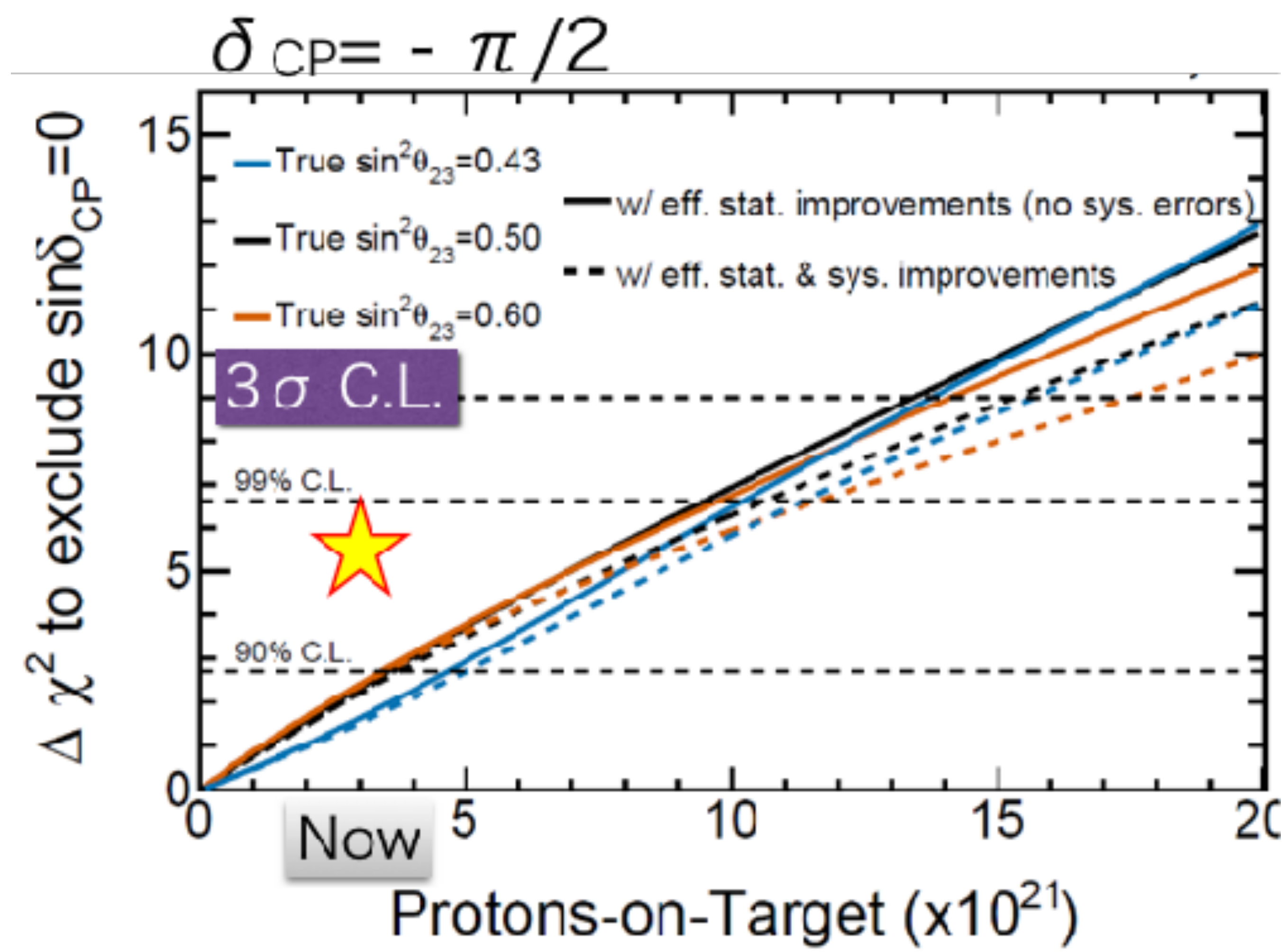
→ **Need more data for confirmation**

T2K-II

Toward discovery of CPV, we plan to accumulate more data up to 2×10^{22} POT by 2027 (J-PARC E65 [T2K-II])

J-PARC PAC stage-1 status

- Beam power upgrade to 1.3MW
- Near detector upgrade to reduce the total systematic error down from 6% to ~4%

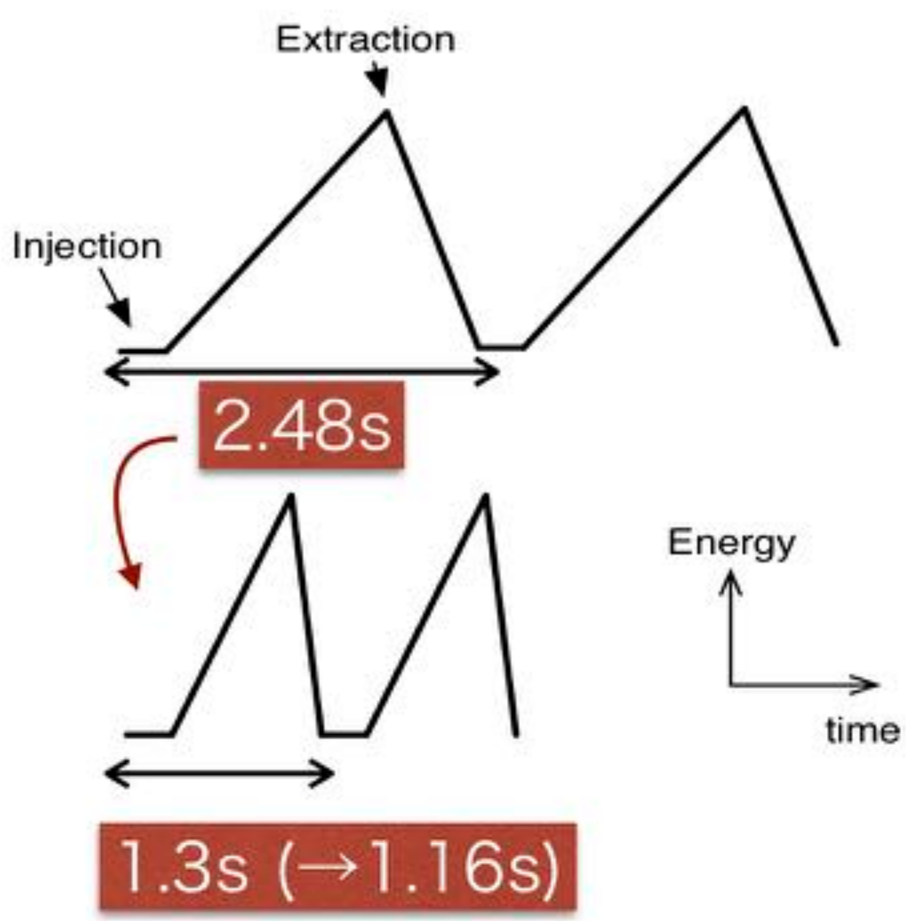


>3σ CPV sensitivity

Beam power upgrade to 1.3MW

Power ∝ 30GeV x # of protons x 1/$T_{rep.}$

Shorten rep. rate + higher protons/pulse
by upgrading
- Main Power Supply [Funding started]
- RF
- Beam dump etc.



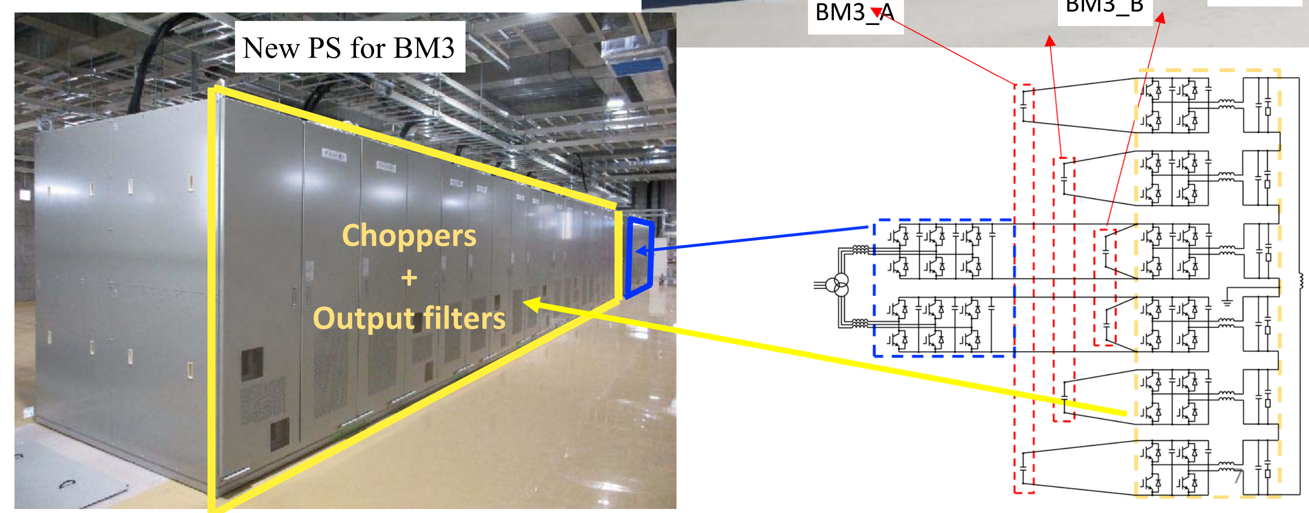
	Achieved	Target
Beam power [MW]	0.5	1.3
# of protons per pulse	2.6 x 10^{14}	3.2 x 10^{14}
Rep. Time [sec]	2.48	1.16

Main Ring status

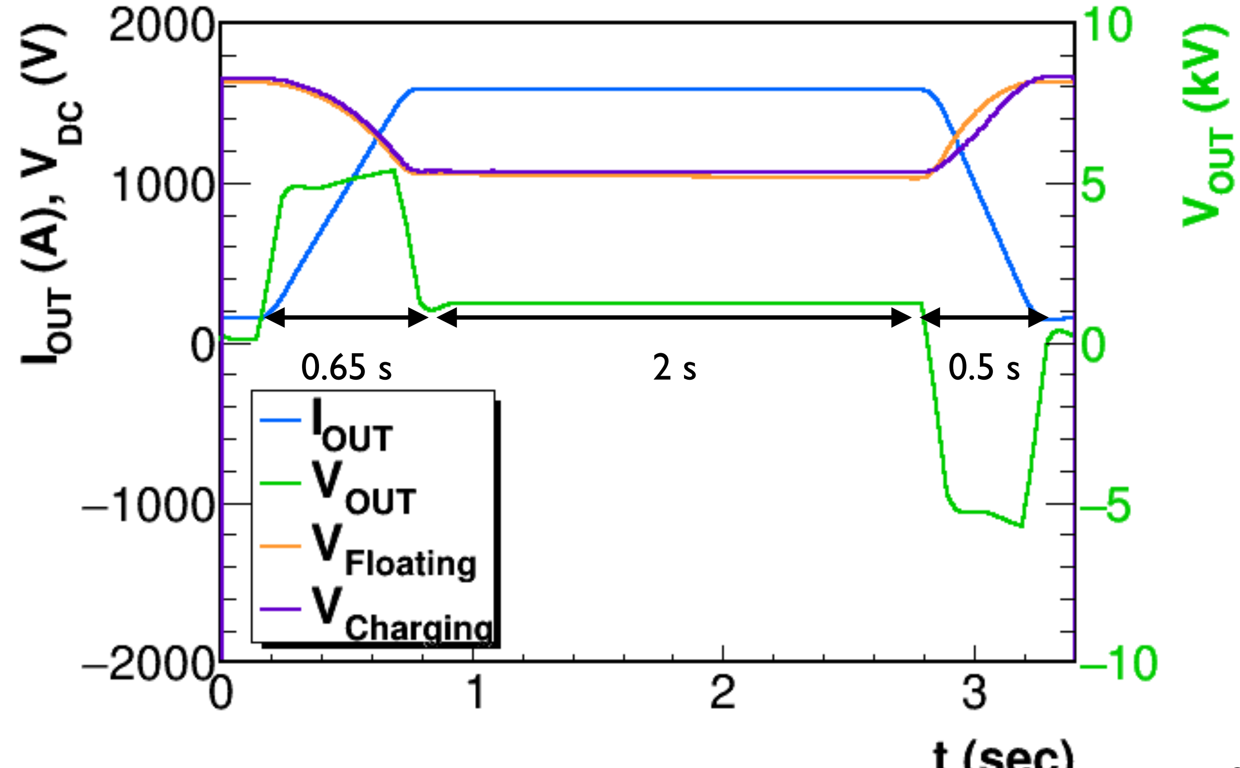
- New power supply
  - Commissioning w/ an actual BM3 magnet was successfully performed →1.29 sec cycle was confirmed
- RF upgrade
  - New 2nd harmonic RF system for 1.32s operation was assembled

- A new power supply was designed with capacitor banks for the cycle of 1.3 s.
- The power supply for the BM3 family was constructed and installed at D4.
- It has been tested with the BM3 family.

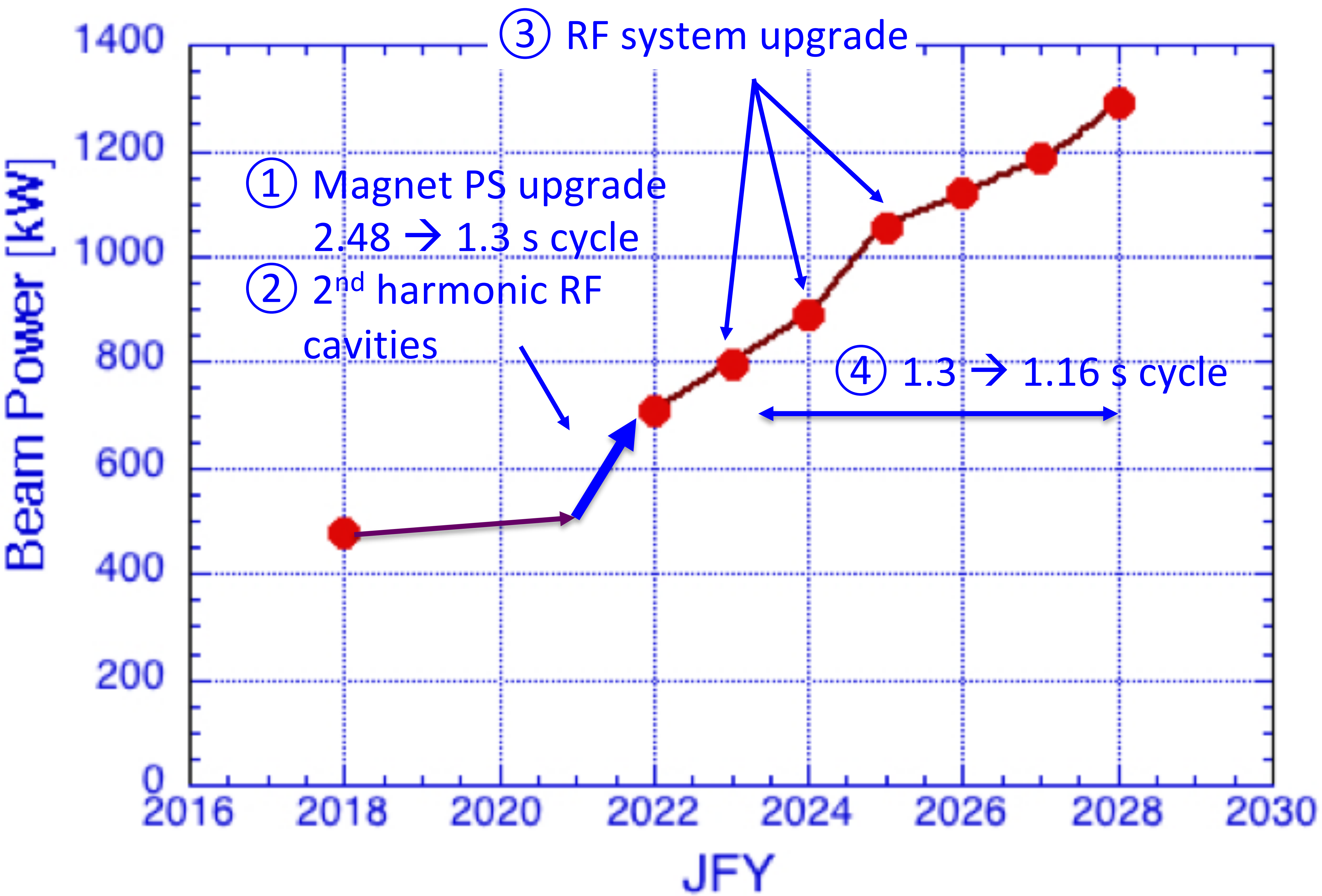
Capacitor Banks for BM3



- New 2nd harmonic cavity with 4 accelerating gaps

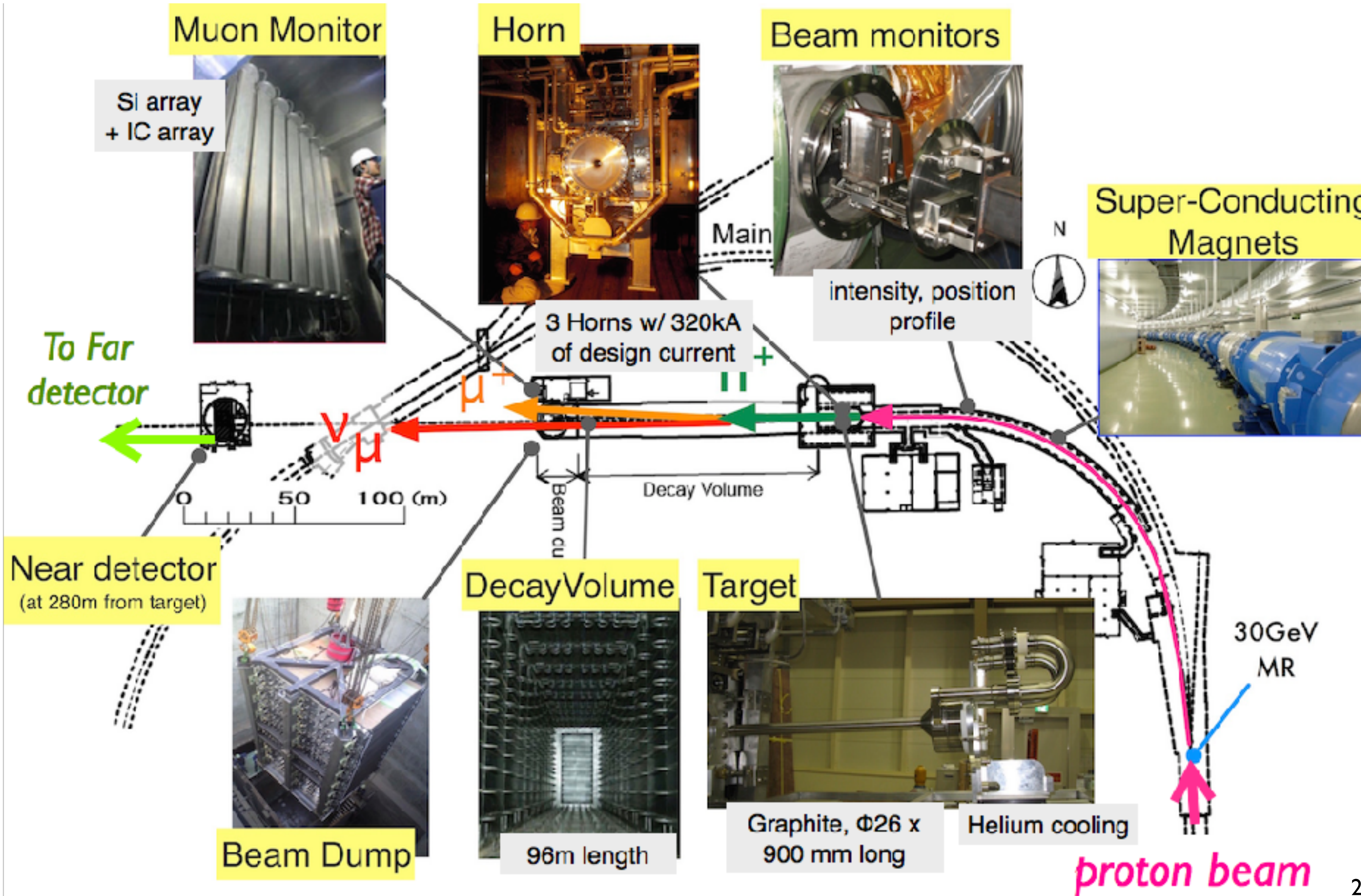


Upgrade plan of MR



J-PARC neutrino facility

Producing a high intensity neutrino beam



Neutrino beamline upgrade toward 1.3MW

Inaccessible part (decay volume, beam dump, etc) were designed and built for multi-MW

- Increasing cooling capability for the heat generated by beam (higher beam power)

  : *Horn, Target, He vessel etc.*

- Accepting high repetition rate (~1Hz) beam

  : *Horn, DAQ*

- Increasing capability of radio-active waste

  : *Radio-active water disposal capacity*

- Realizing safe and stable operation

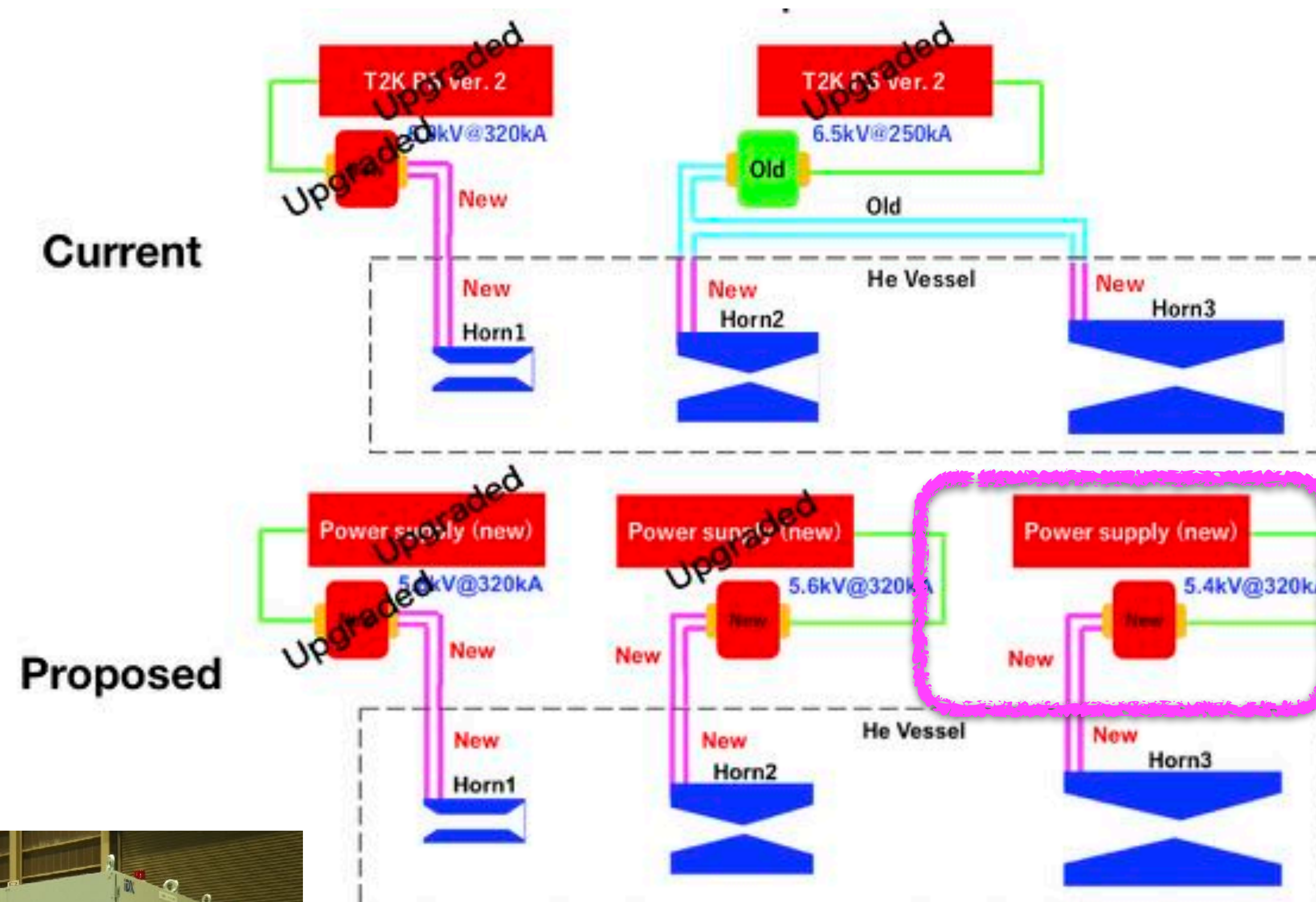
  : *Interlock, beam monitor,*

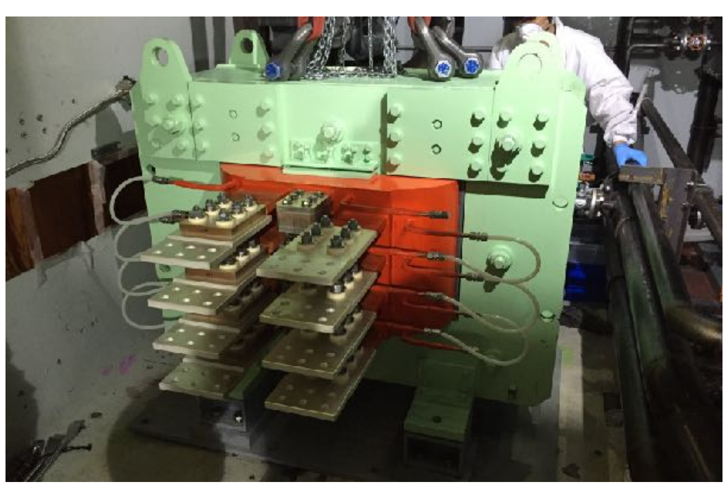
  primary beamline etc.

Horn upgrade

- Plan to upgrade the horn electric system to realize 1.16s repetition and higher current (present 250kA → 320kA)

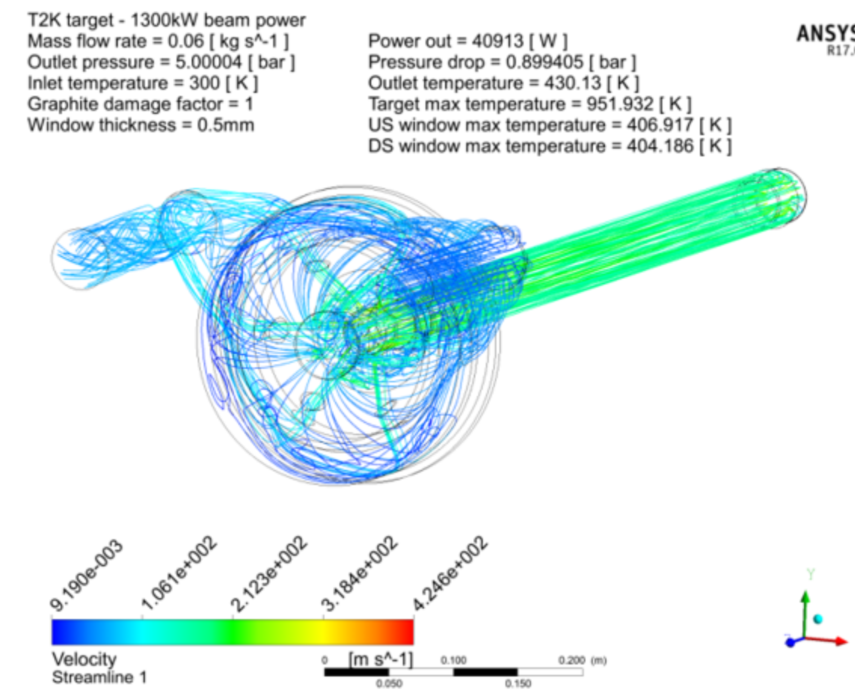
- 320kA is also beneficial to reduce wrong sign flux
- One horn - one power supply - one pulse-transformer configuration





- Design and production of new target and horns with reinforcing cooling capability
- Fast DAQ for 1Hz operation w/ newly developed network-based ADC modules
- Upgrade of beam monitors

Reinforcing cooling capability (target, horn etc.)

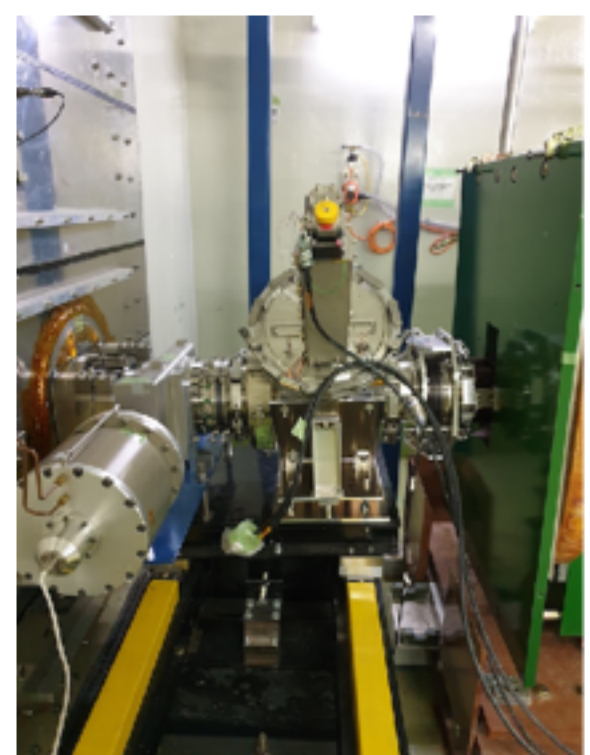


We are proceeding necessary R&D on high beam power facility with international and domestic cooperation

Upgrade for 1Hz rep.

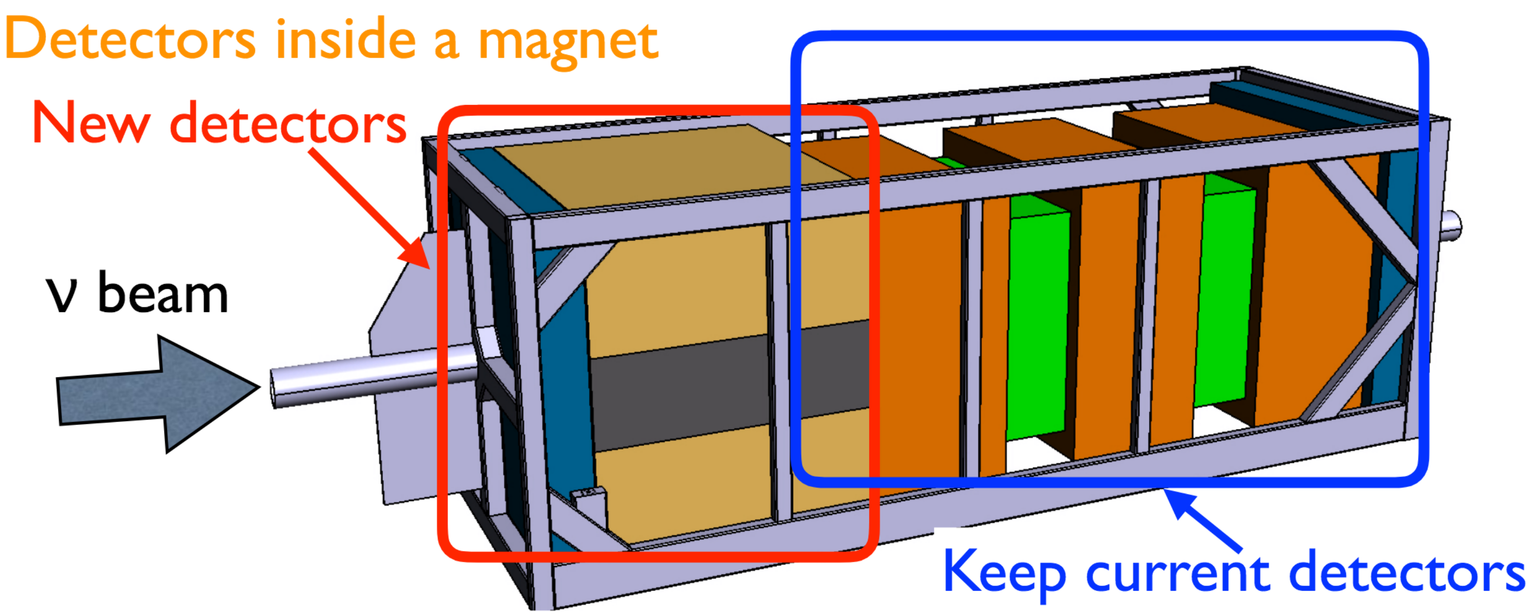
Improvement of maintenance scheme and New beam profile monitor R&D

New Ti Wire SEM:



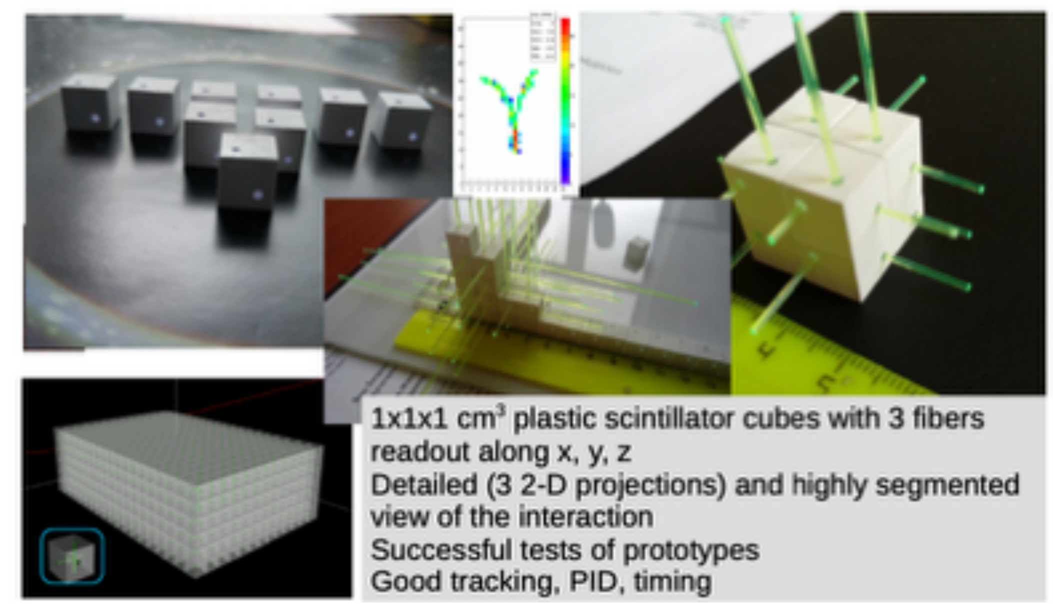
Near Detector upgrade

Replacing part of ND280 with new detectors to enhance capability



Super-FGD

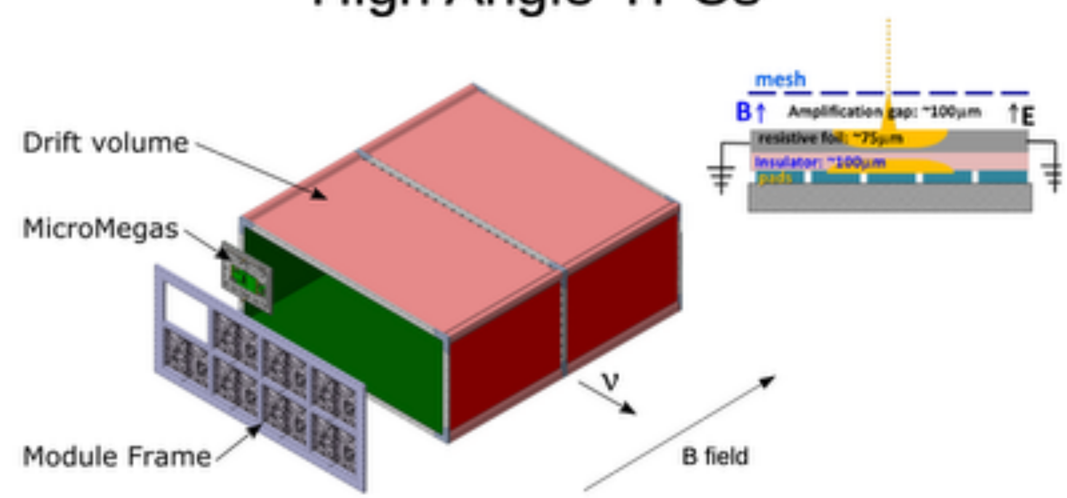
arXiv:1707.01785



- *TDR submitted to PAC and reviewed (J-PARC & CERN)*
- *Strong collaboration of experts from Europe (incl. CERN), Japan and USA*
- *will be approved as CERN NP07*

Aiming installation in 2021

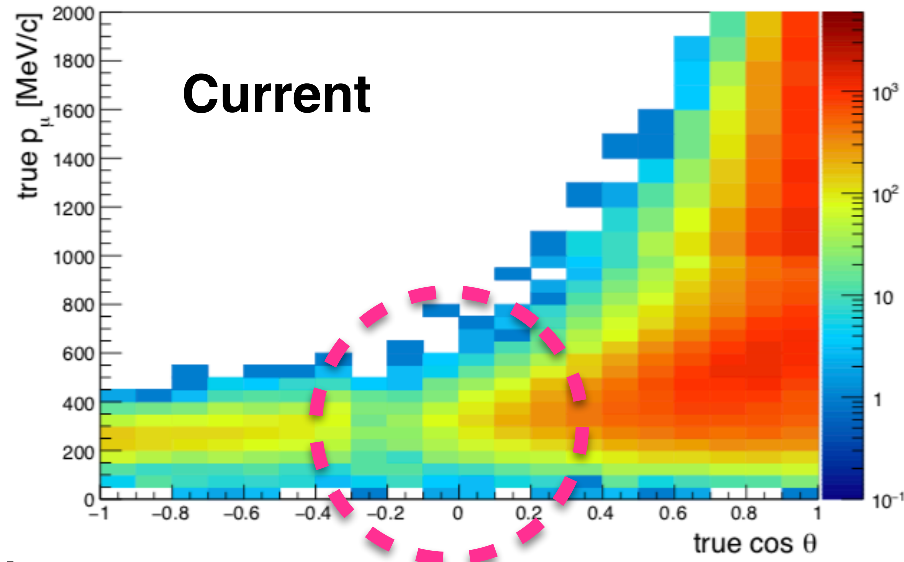
High Angle-TPCs

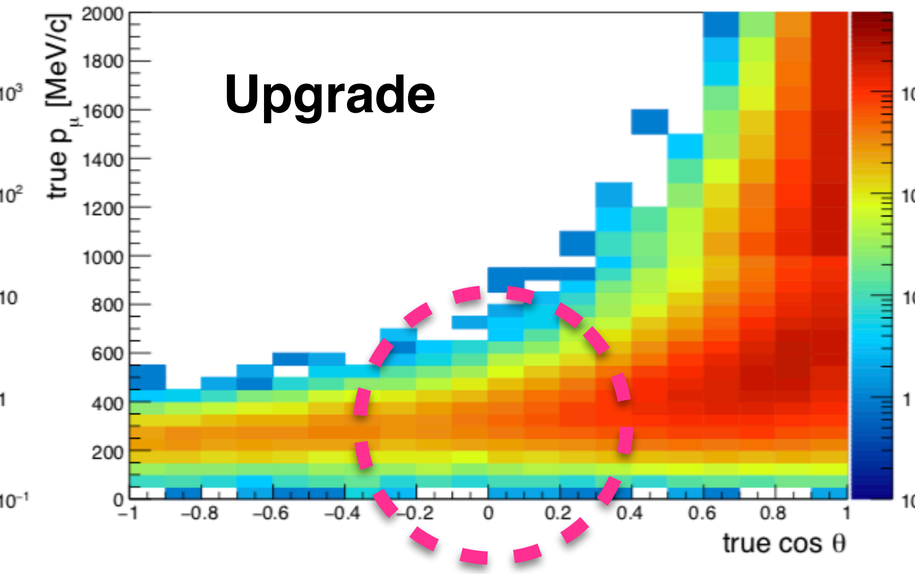


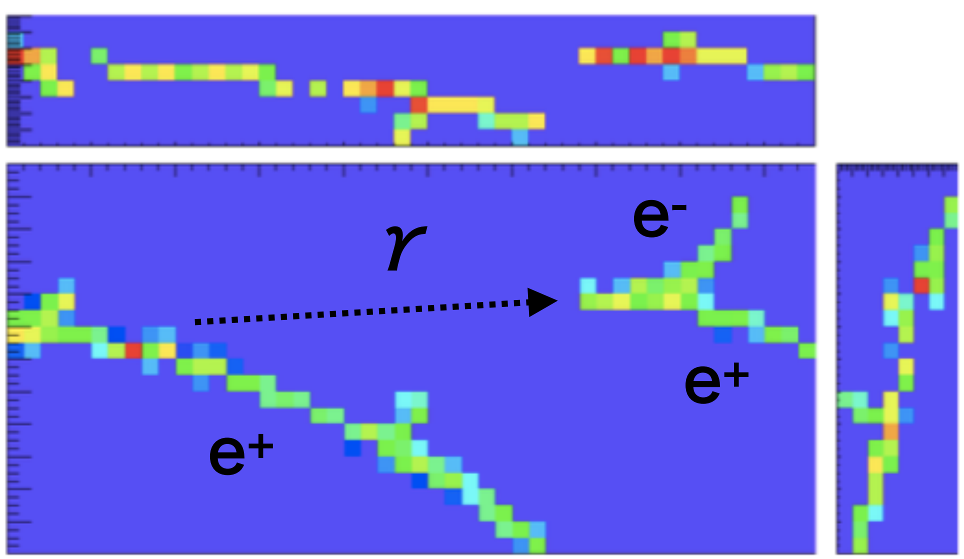
- Atmospheric pressure TPC using the same gas mixture as the present TPC
- Main difference with the existing TPC: thin field cage, resistive Micromegas
- Large overlap with the TPC group
- Benefiting from ILC TPC developments and RD51

Near Detector upgrade

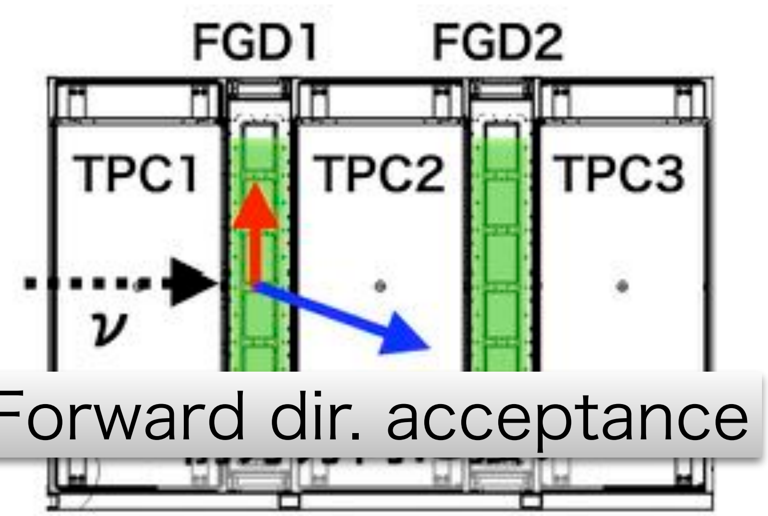
- Large angle acceptance will be improved
- High granularity can improve vertex reconstruction efficiency

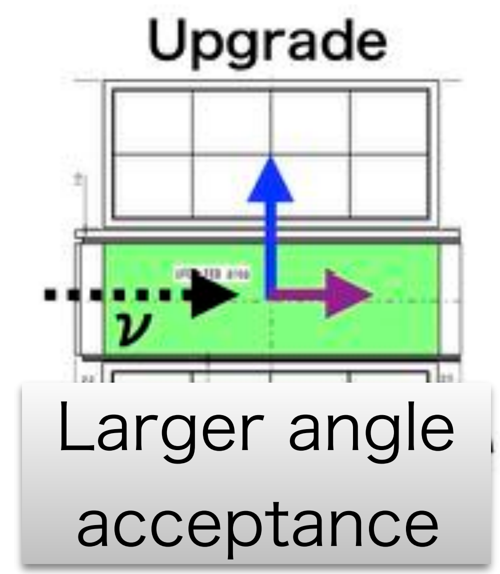




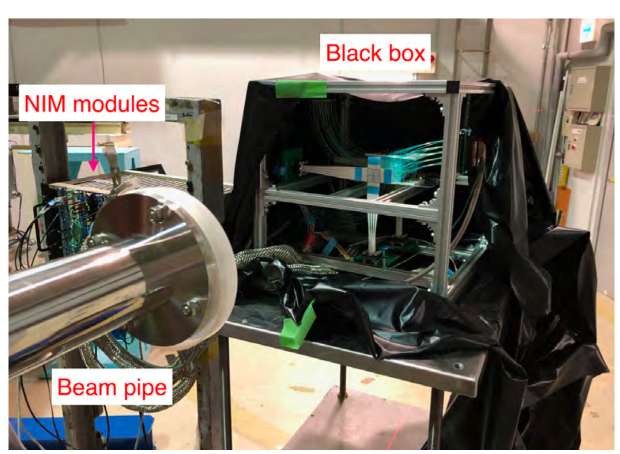


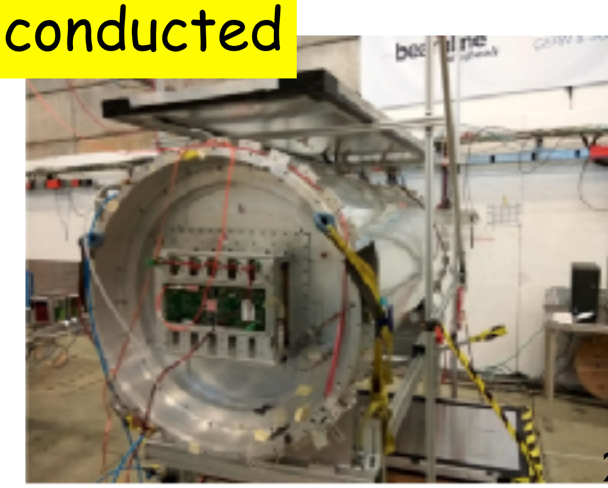
Positron, 1 GeV, B = 0.2T





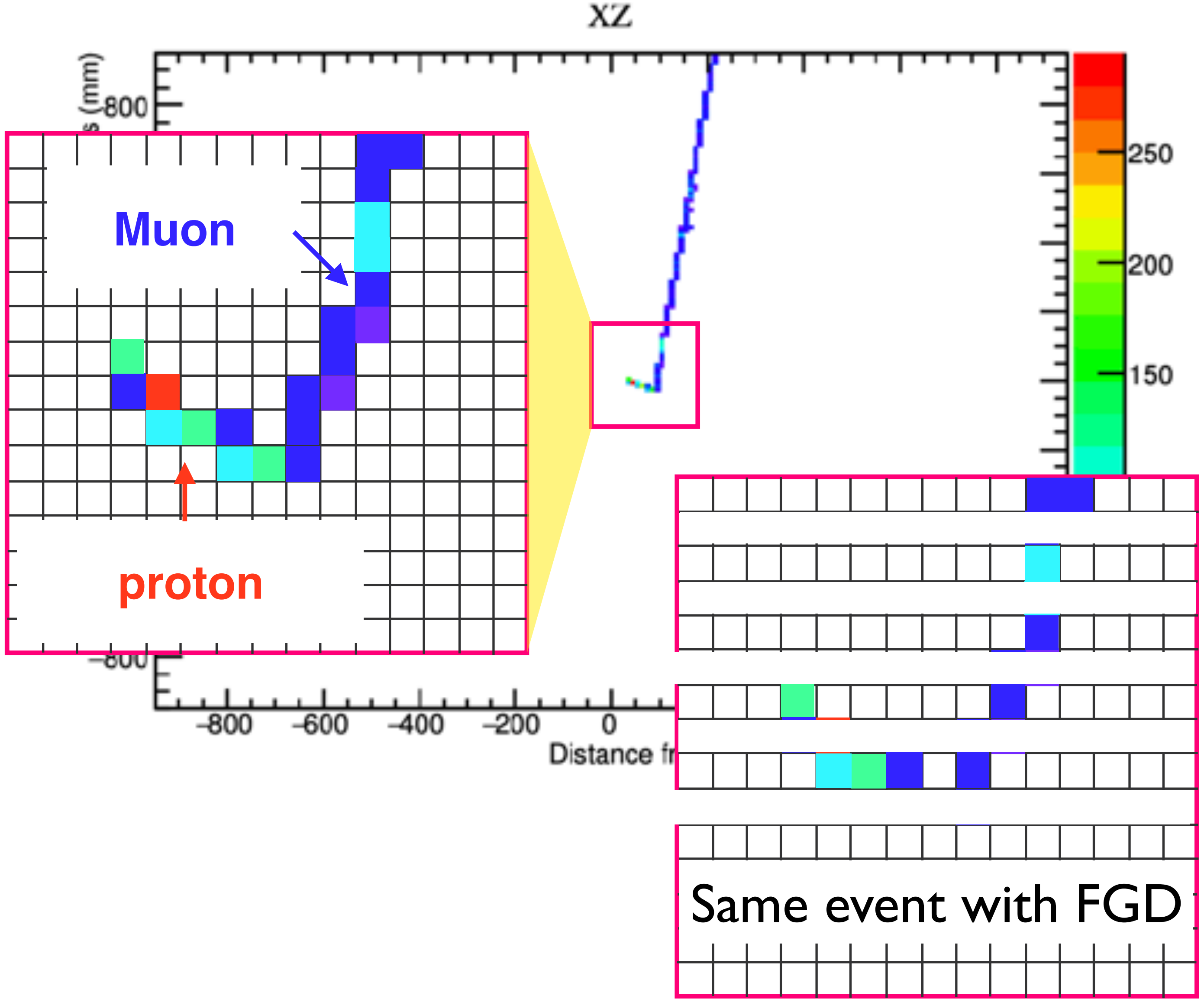
Test beams for prototypes of SuperFGD, TPC, TOF are conducted

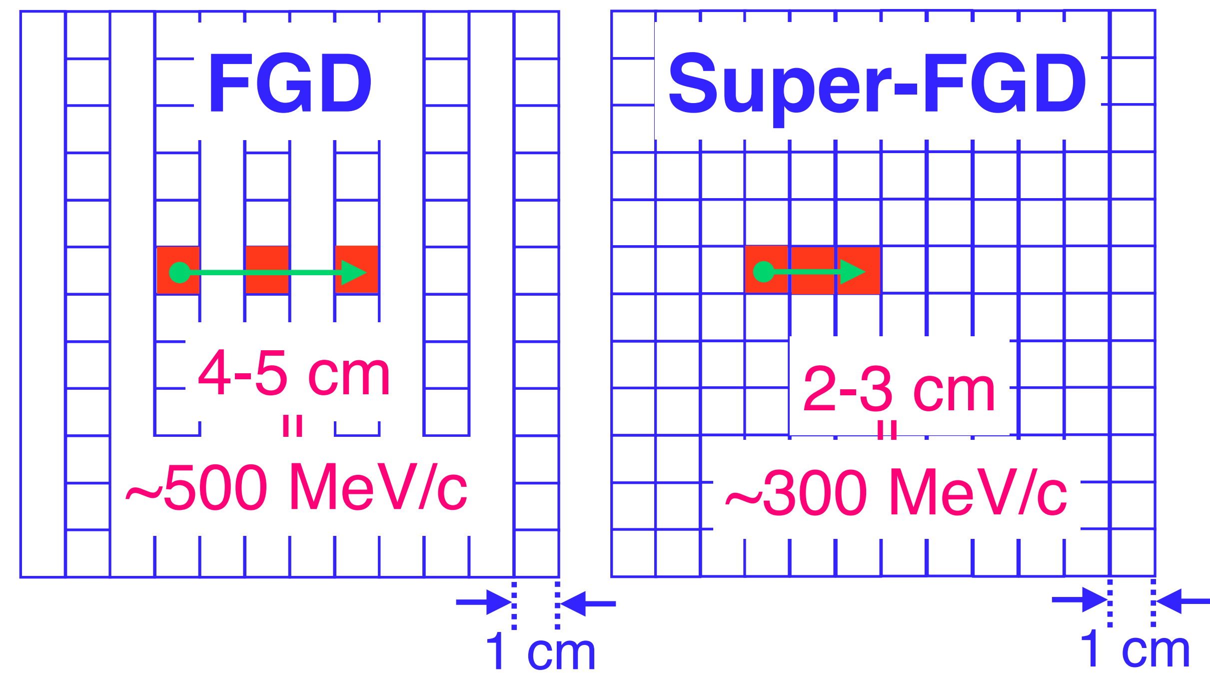




SuperFGD

Conveners: M. Yokoyama and Y. Kudenko



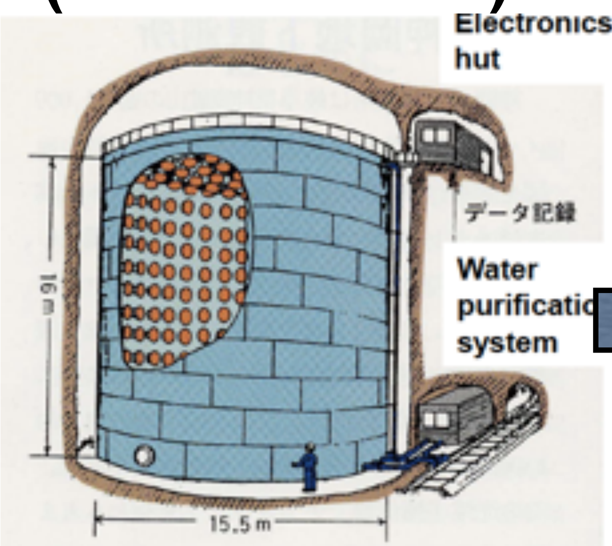


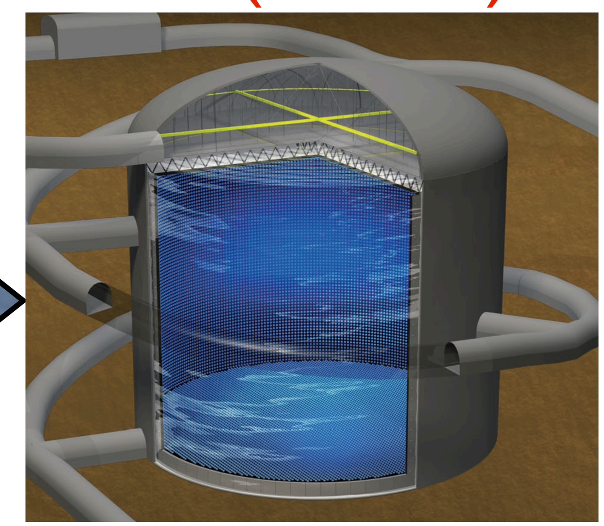
First 192x192 cube sheet @INR

- Full image of 2D projection × 3 directions
- Low threshold without weak direction

Beyond SK/T2K:
The Next Generation

Kamiokande (1983-1996)	Super-Kamiokande (1996-)	Hyper-Kamiokande (2027-)



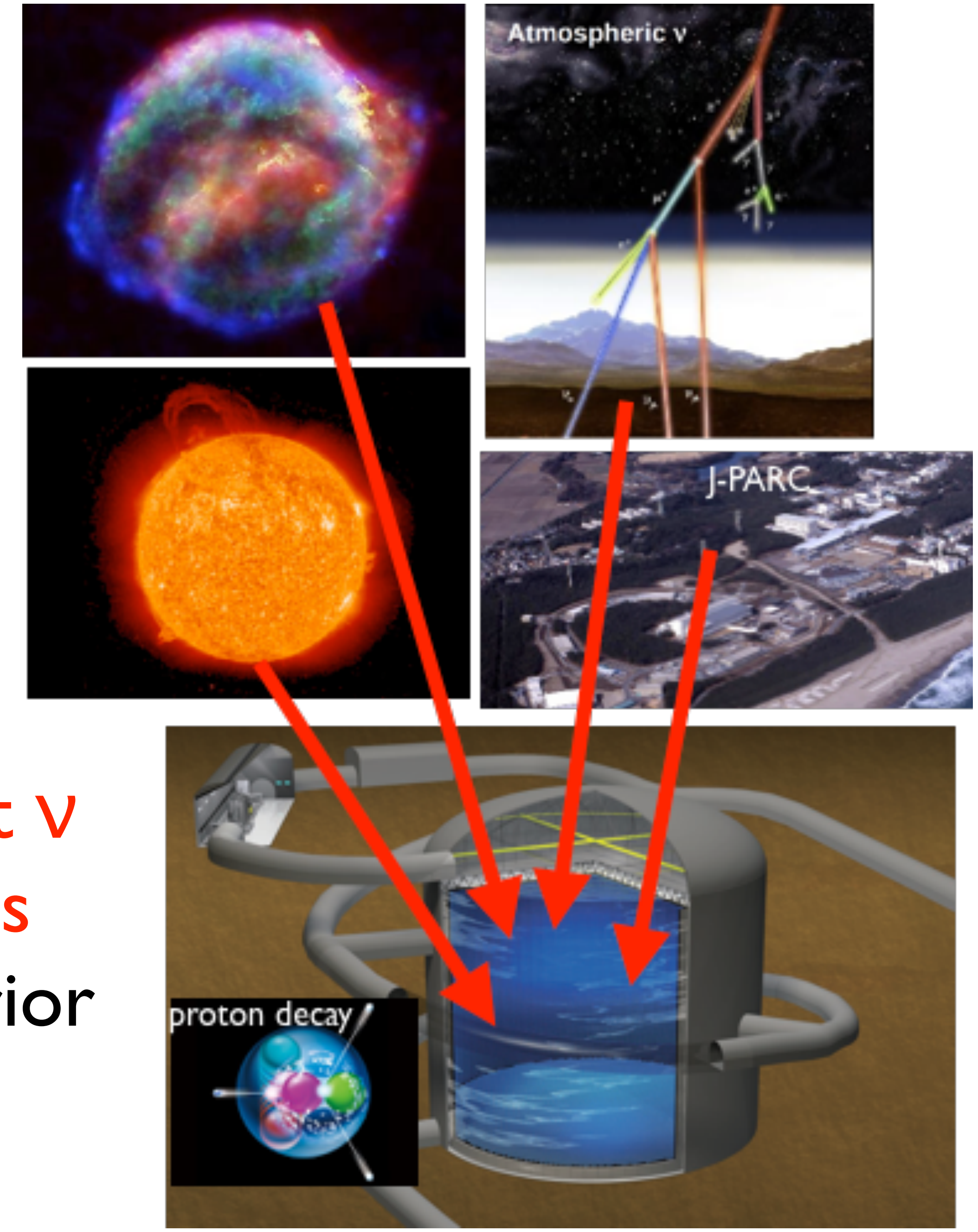


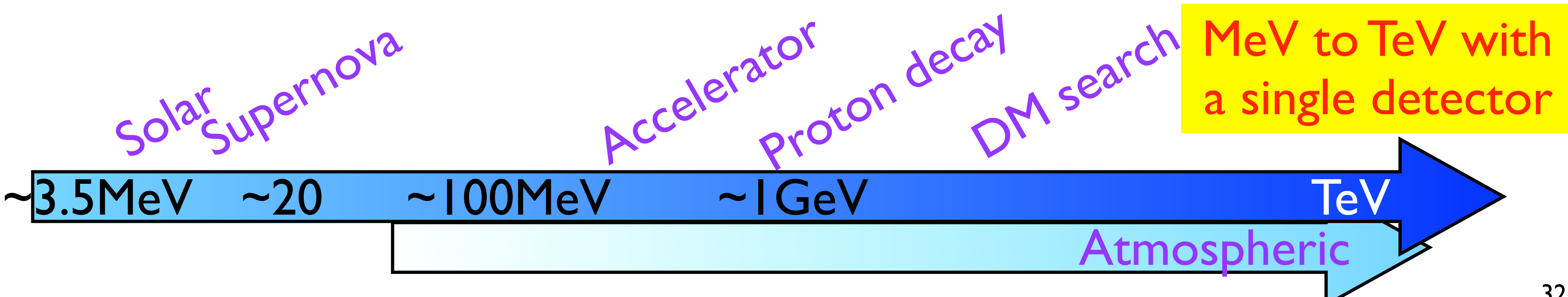
3kton	50kton	260kton
20% coverage with 50cm PMT	40% coverage with 50cm PMT	40% coverage with high-QE 50cm PMT

Nucleon Decay Experiment
Neutrino Detection Experiment

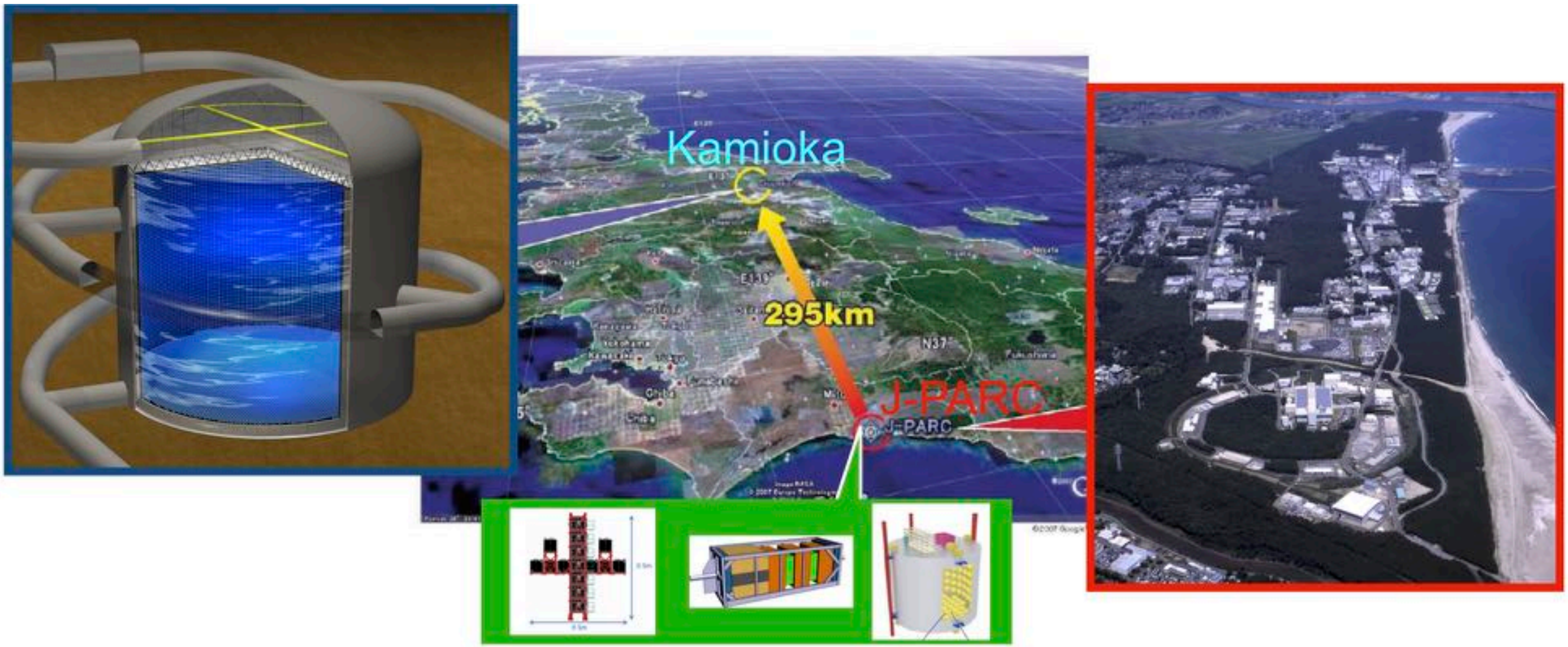
Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrino oscillography of interior of the Earth)
- Maybe more (unexpected)





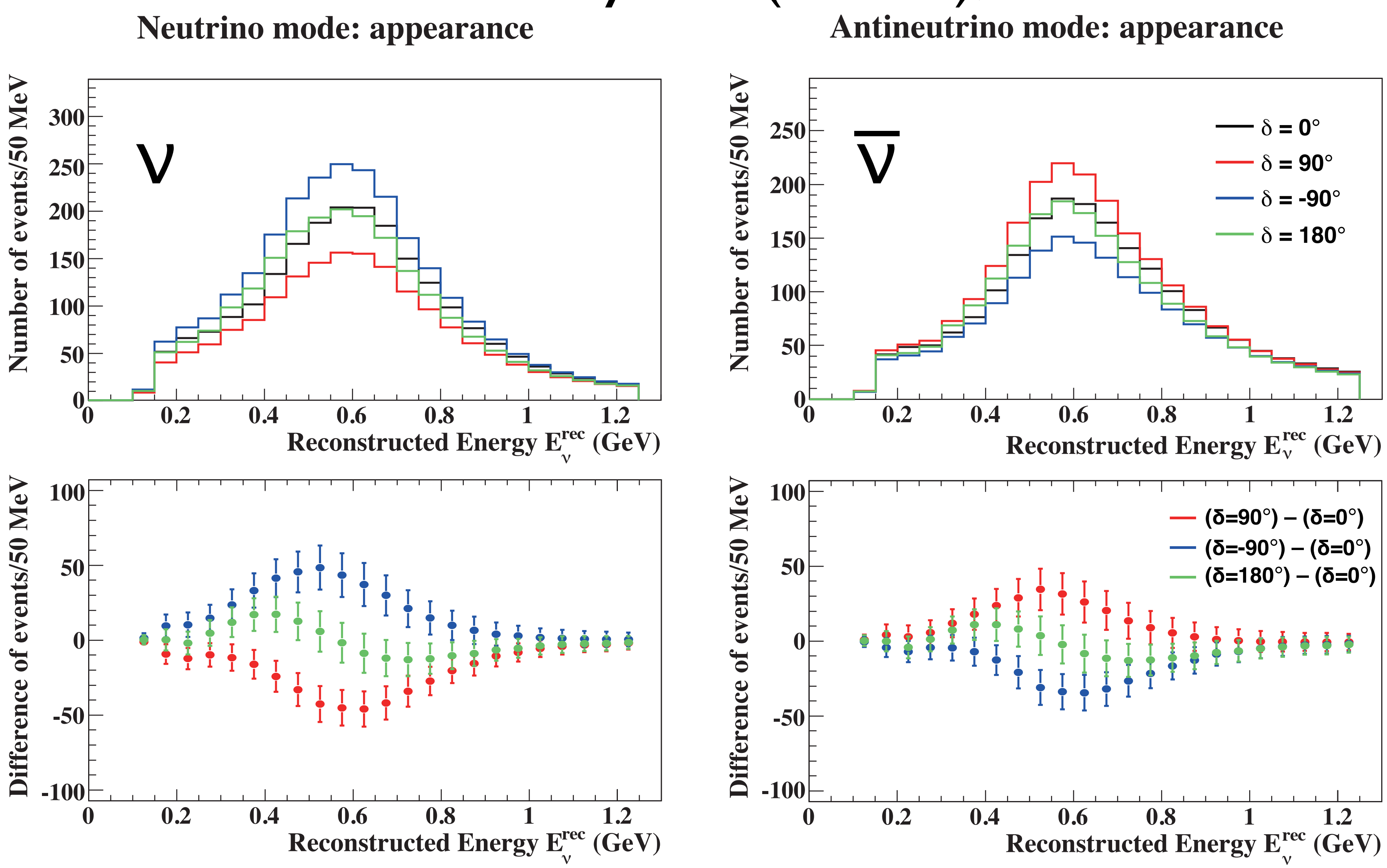
Long baseline exp. with HK



- J-PARC beam (1.3MW), near and intermediate detectors, and Hyper-Kamiokande
  - Same beamline and far detector technique
  - Expertise with T2K will be directly applicable

Expected events at HK

For 1.3MW×10years (10^8sec), ν:ν=1.3

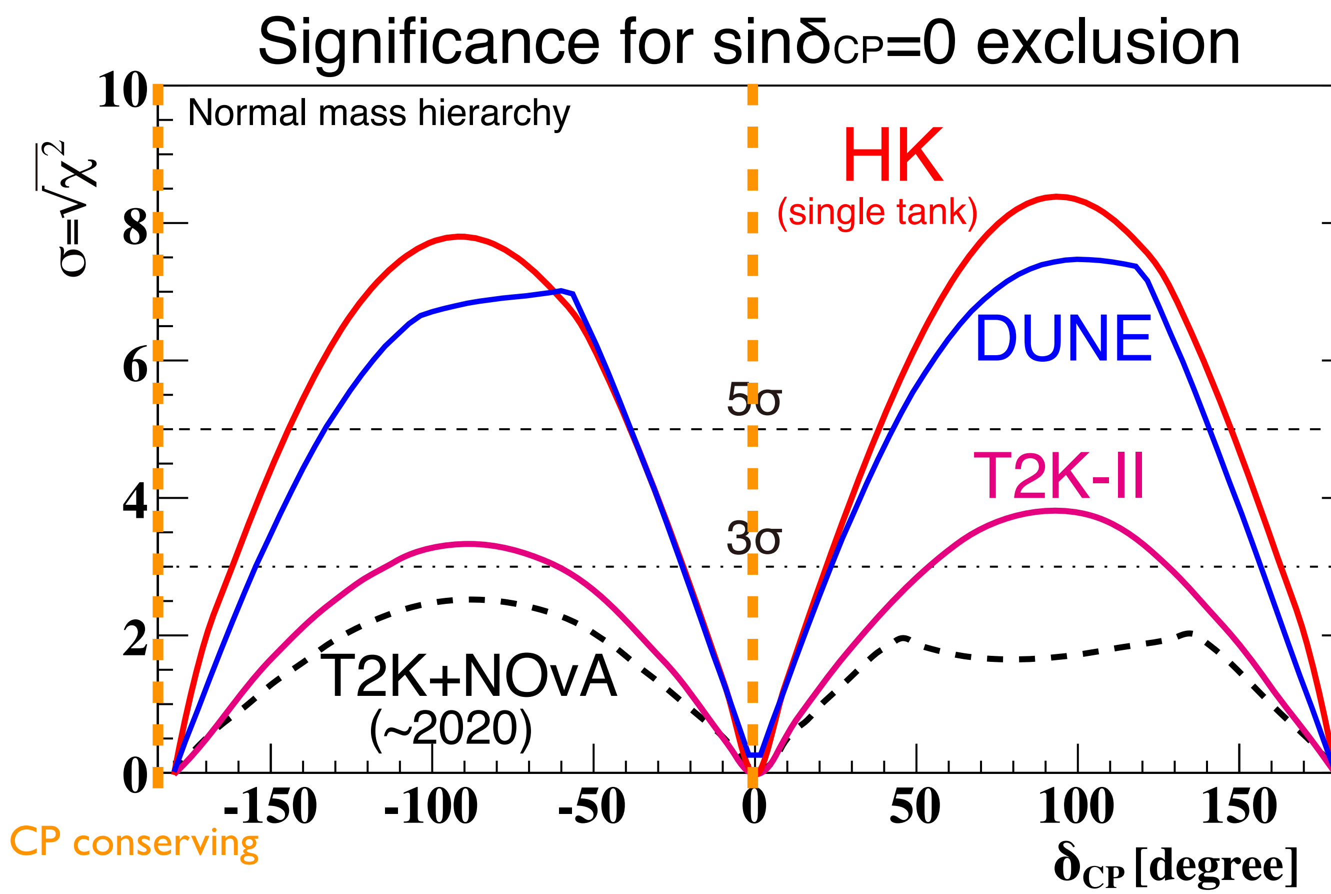


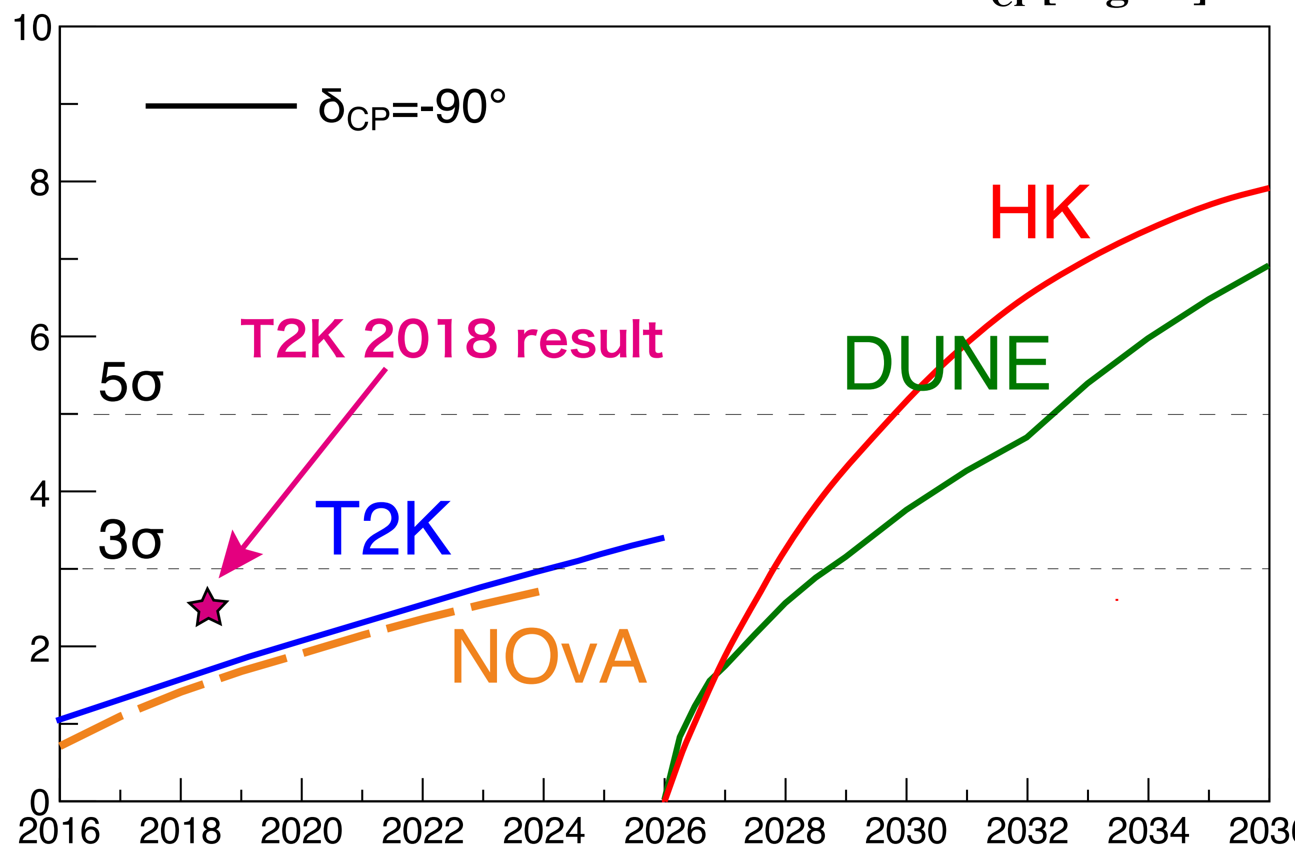
for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\bar{\nu}$ beam	1,183	206	4	317	196

Expected sensitivity: CP violation

- Exclusion of $\sin\delta_{CP}=0$
  - ~8σ(6σ) for δ=±90°(±45°)
  - >3σ(>5σ) significance for ~76%(57%) of δ_{CP} space
- δ_{CP} resolution:
  - 23° for δ_{CP}=±90°
  - 7° for δ_{CP}=0°or 180°

Further enhanced by combination with atmospheric ν





Seamless program of Japan-based experiments for study of CP-violation

T2K→T2K-II→HK

Summary & Outlook

- With data collected so far, T2K reported an indication of large CPV in neutrino oscillation
  - J-PARC and neutrino beamline stably operated with ~500kW
- We plan to upgrade accelerator, beamline and near detectors aiming to detect neutrino CPV with 3σ sensitivity
- With Hyper-K, we will study CPV in more detail
- Your participation are highly welcome !!