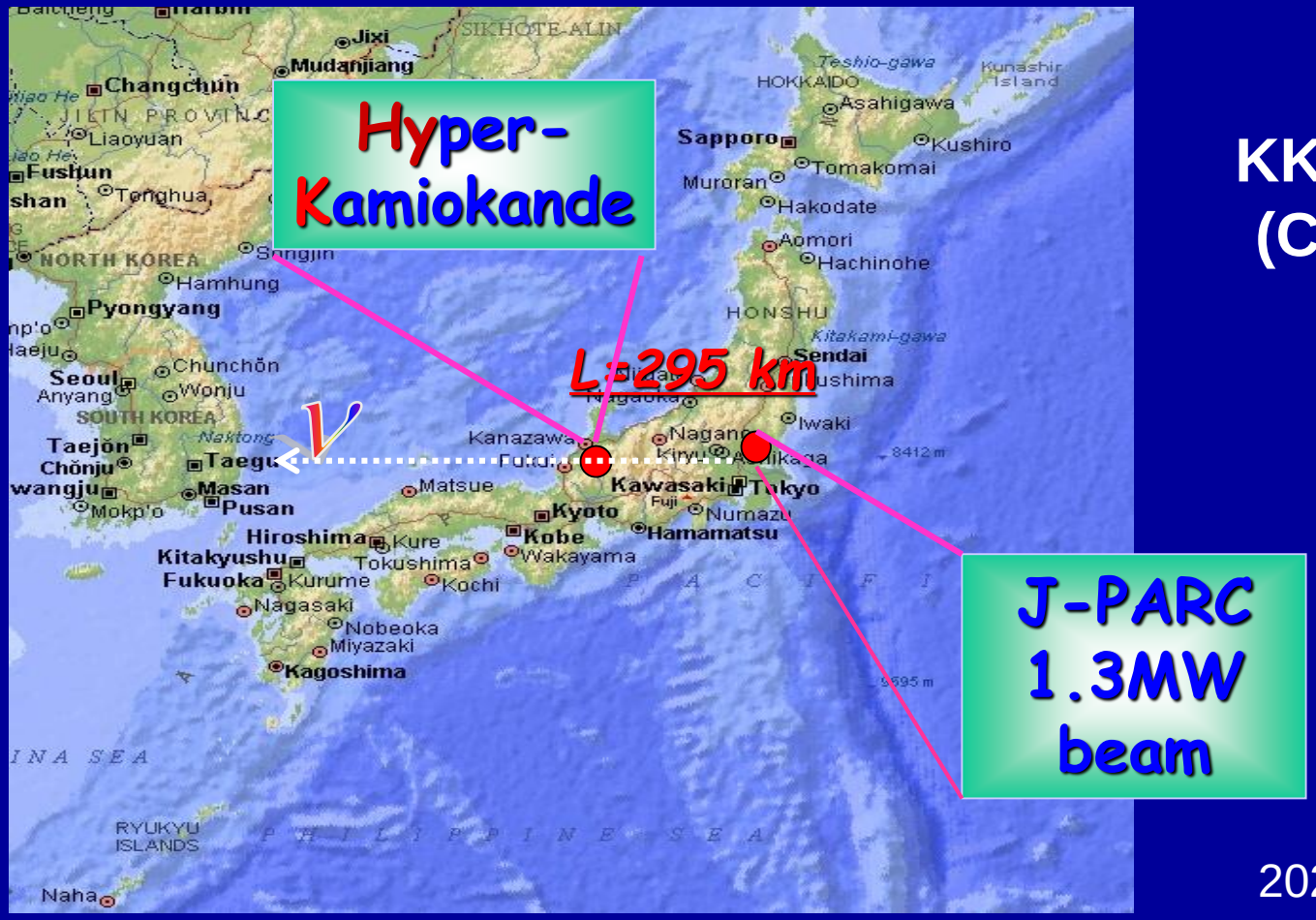
“Hyper-Kamiokande (HK)”



KK Joo
(CNU)

2020/12/04

2020 Meeting of the Division of Particles and Fields of the Korean Physical Society @Zoom

(Neutrino Frontier & Theory Frontier – Phenomenology)

Above all, I must say …

- Many of slides today are borrowed from

  - Masato Shiozawa (first Japanese Co-Spokesperson, ICRR, Tokyo Univ.)
  - Francesca Di Lodovico (first International Co-Spokesperson, King's College London, UK)
  - Both of them, elected recently (Dec.2, 2020)

- Prof. Carsten Rott (SKKU, HK Korean representative) and Dr. Sunny Seo provide many of them

I can't cover all items for 20 mins, so overall brief status update/K-HK group status will be reported

Neutrino Physics / Fundamental Questions on Neutrino

- 가속기 기반 CERN LHC (강입자 연구)는 입자물리학 선도적 역할을 해왔고 힉스 입자 발견 (2012)으로 표준모형의 검증 및 완성에 기여

- 하지만, 직간접적인 관측 사실에 비추어 보았을 때 표준모형은 여러 가지 문제점을 가짐

- **Absolute neutrino masses? (Why so small?)**
- **Neutrino mass ordering? (Normal or inverted?)**
- **Dirac or Majorana? (Neutrinoless double beta decay?)**
- **Leptonic CP violating phase?** (쿼크 sector는 비교적 잘 알려져 있음)
- **3 ν paradigm enough? (Sterile neutrino?)**
- **Why so large neutrino mixing angles?**
- **Neutrino burst from a SN in our galaxy, solar neutrinos, atmospheric neutrinos, geo-neutrinos, etc**

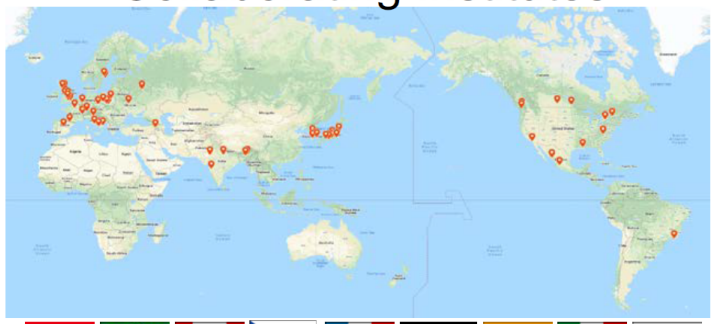
– 우주의 구성 원리와 진화 과정의 핵심을 관통하는 거대 주제들 중의 하나임

- 중성미자 물리학은 BSM을 살펴보기 위한 가장 큰 창문이며 좋은 역할을 담당해 옴

HK (Hyper-Kamiokande) Collaboration

19 countries, 93 institutes, ~430 people as of October 2020, still growing

Collaborating Institutes

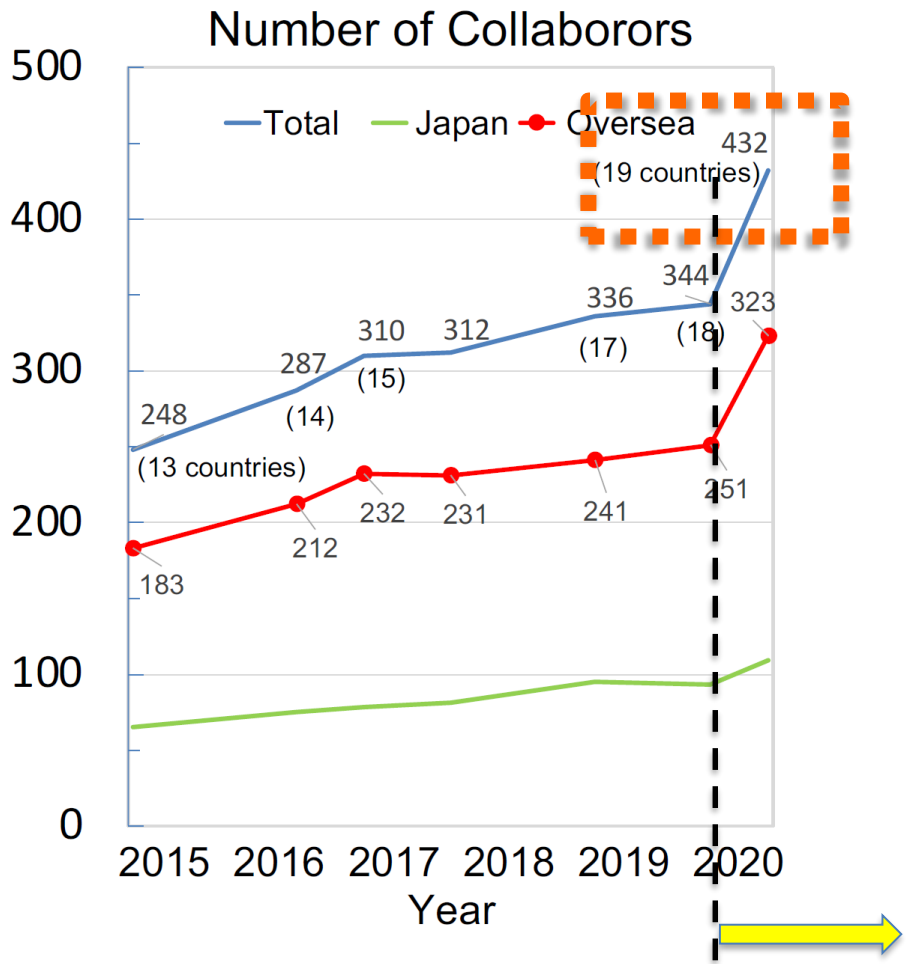


China (JUNO) ×

Europe	242 members
Armenia	3
Czech	3
France	23
Germany	1
Italy	53
Poland	37
Russia	21
Spain	26
Sweden	5
Switzerland	5

Asia	139 members
India	12
Korea	18
Japan	109

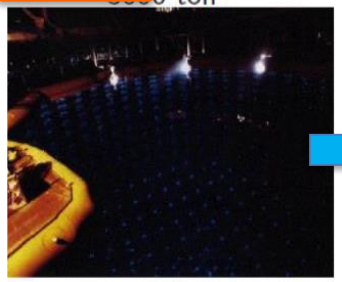
Americas	46 members
Brazil	3
Canada	29
Mexico	8
USA	9



- After mid of 2020, collaboration grows fast
- International community corresponds to ~75% of total collaborators

HK (Hyper-Kamiokande)

Kamiokande (1983-1996)



- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

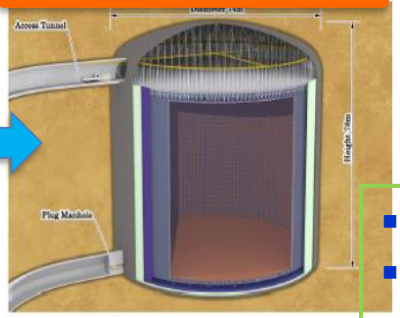
Super-Kamiokande (1996-)

50,000 ton

- Atmospheric neutrino oscillation.
- Solar neutrino oscillation with SNO.
- Far detector for KEK-PS (K2K) and J-PARC beam (T2K): electron neutrino appearance.
- World leading limit on

Hyper-Kamiokande (~2027)

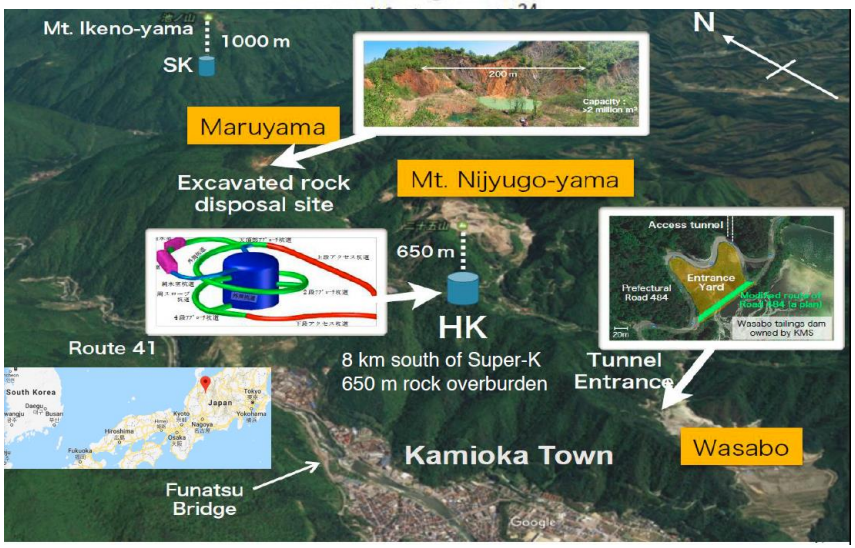
260,000 ton



Physics programme:

- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant,...
- Nucleon decay: $p \to e^+\pi^0$, $p \to K^+\bar{\nu}$,...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

명실상부한 일본/세계 중성미자 연구의 핵심장소 중의 하나



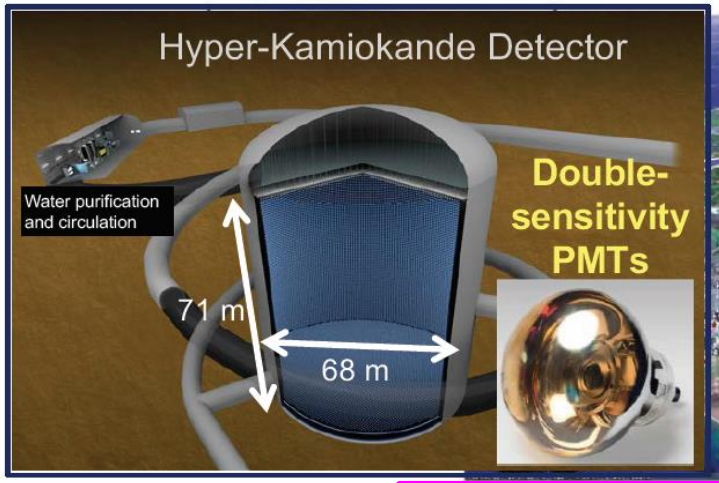
~30 yrs have passed since exps in Kamioka started

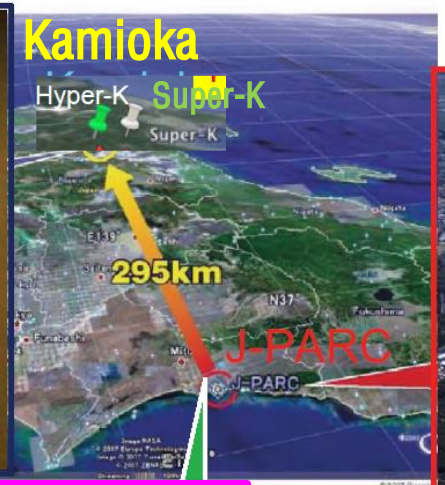
HK Status

- HK proto-collaboration was formed
- U of Tokyo commitment ensures that the HK construction will begin in April, 2020
- Two host institutions:
  - U of Tokyo (ICRR)
  - KEK (IPNS)
- Japanese funding agency (MEXT) provided a seed funding for HK in 2019. → standard process in Japan for large projects to begin with a year of seed funding
- MEXT has made an official budget request in August according to Yomiuri newspaper (2019. 8. 21).

→ Operation (목표): 2027 ~

HK Project in a Nutshell





J-PARC

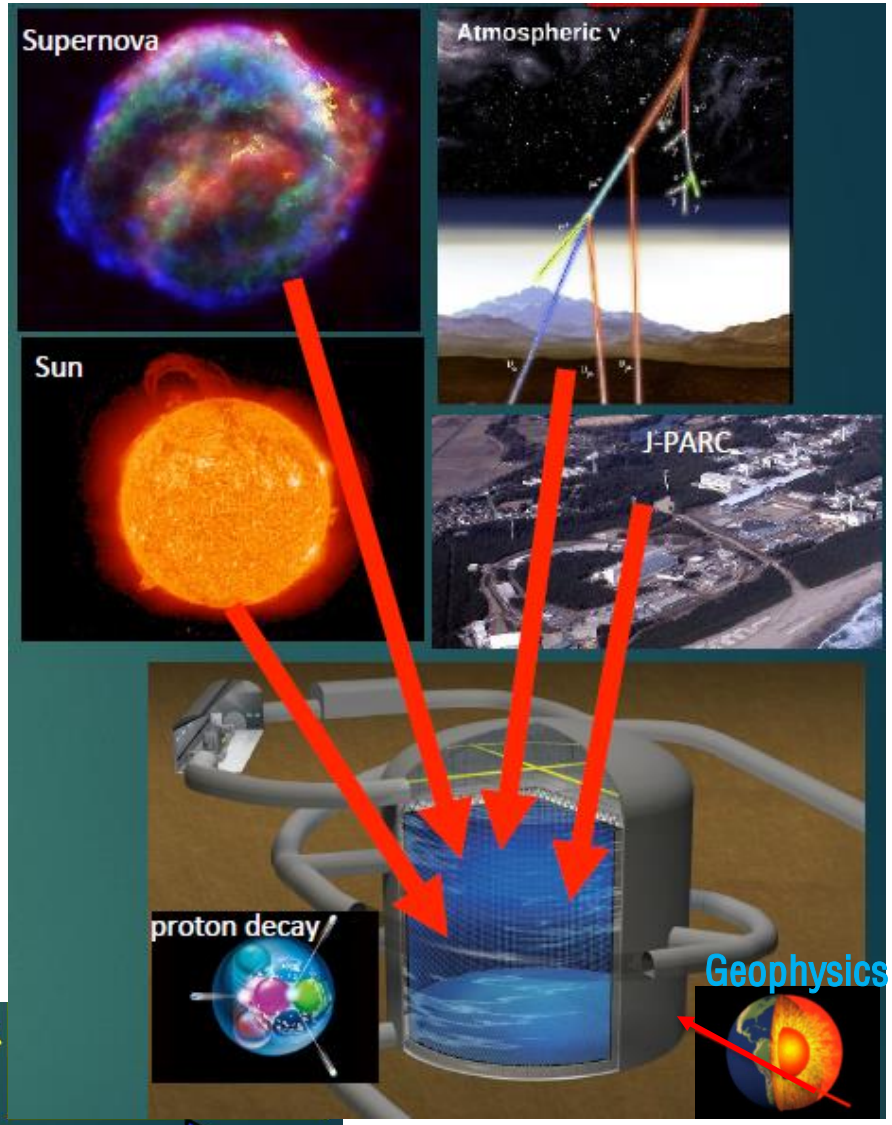
[Size]
Φ68m x H71m cylinder

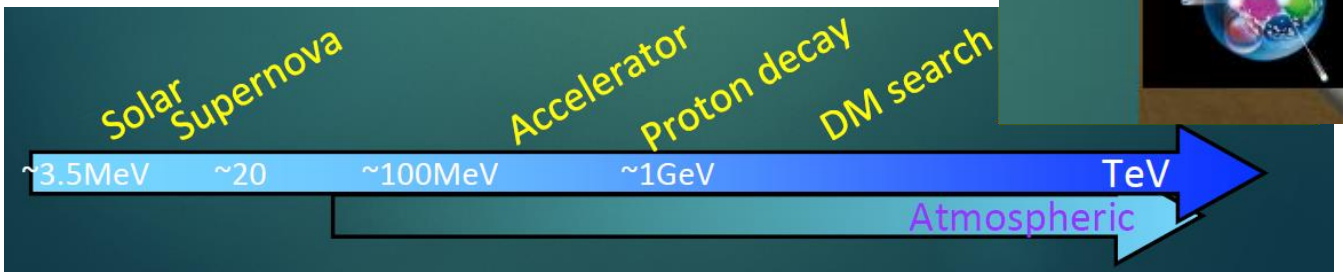
Near Detector (ND)

- HK detector
  - Total volume 260 kton (~5 x Super-K, 50 kton)
  - Fiducial mass 190 kton (~8.4 times larger than Super-K, 22.5 kton)
  - Photo sensors: 40,000 (~2 times x Super-K, better QE ~2 x SK)
- J-PARC neutrino beam
  - Upgraded 0.5 to 1.3 Mega Watt
- Upgrade near detector

HK Science Programs

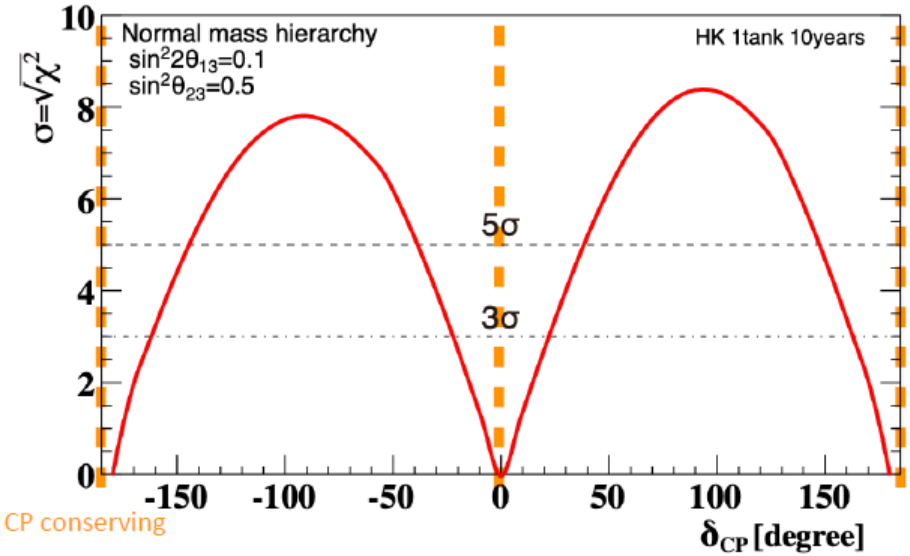
- Provide broad science programs
- Neutrino oscillation:
  Comprehensive study with beam and atmospheric neutrinos
- Search for proton decay:
  x10 better sensitivity than SK
- Neutrino astrophysics:
  Solar neutrino, SN (burst, relic) neutrino, etc
- Geophysics: neutrino oscillography of interior (chemical composition) of the Earth
- Maybe more

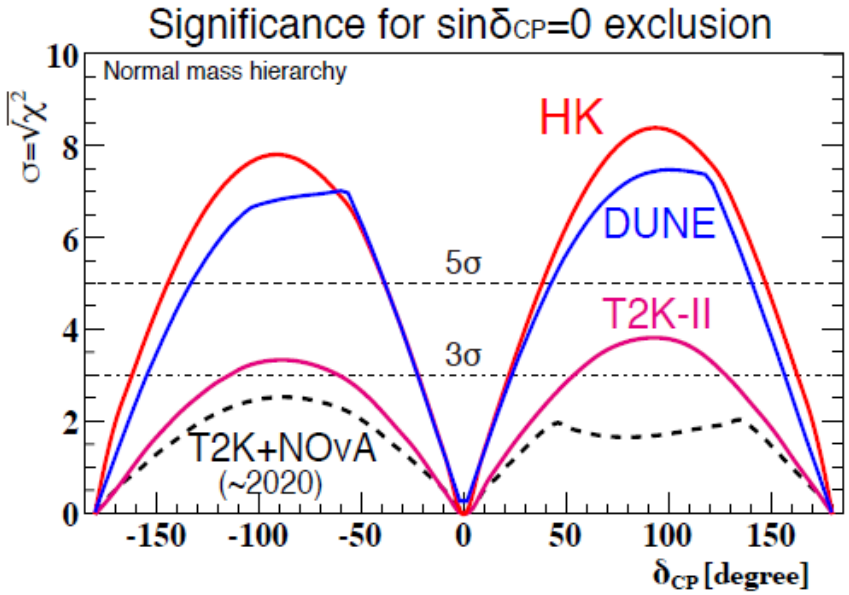




MeV to TeV
with a single detector

Physics Discovery Potential at HK: δ_{CP}





- Exclusion of $\sin\delta_{CP}=0$
  - ~8σ(6σ) for $\delta=\pm90°(\pm45°)$
  - >3σ(>5σ) significance for ~76%(57%) of δ_{CP} space
- δ_{CP} resolution:
  - 23° for $\delta_{CP}=\pm90°$
  - 7° for $\delta_{CP}=0°$or 180°

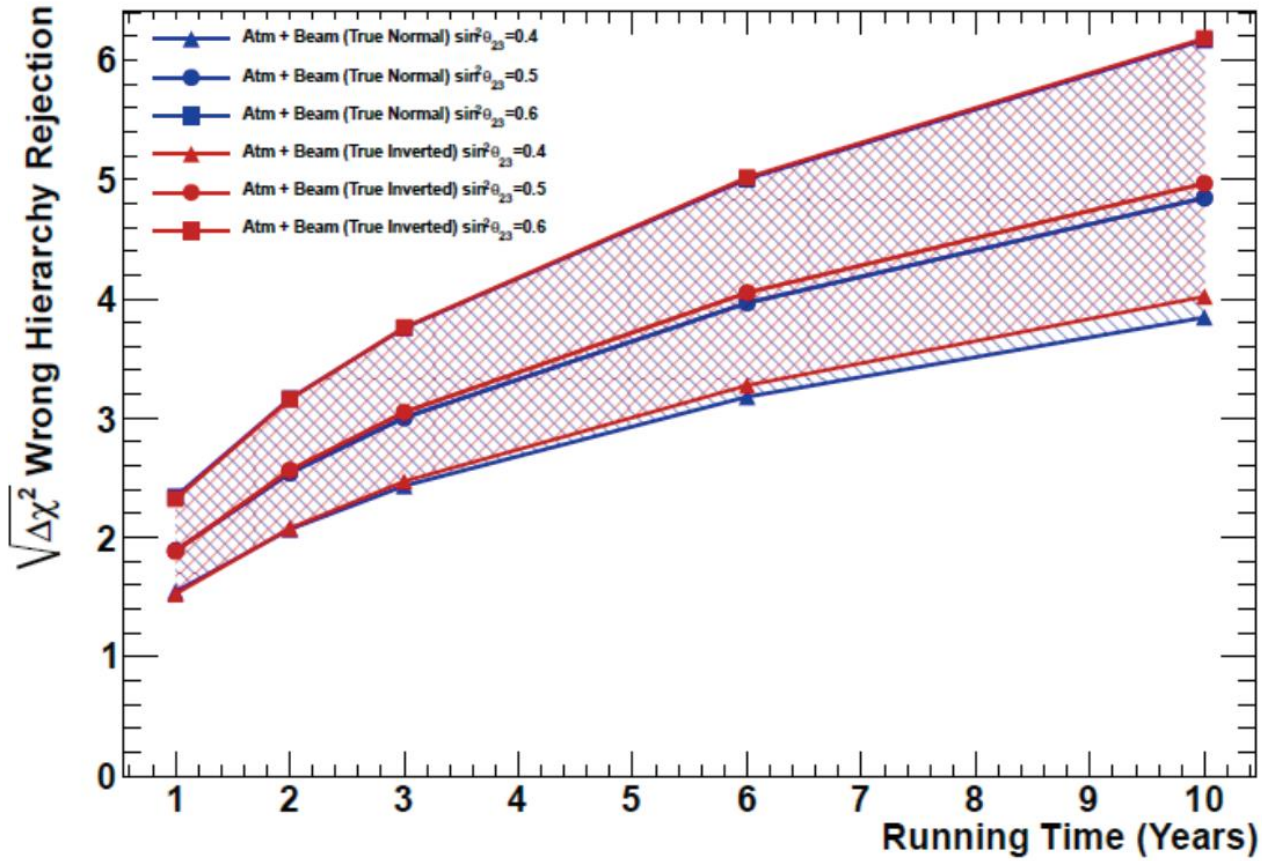
- T2K-NovA can reach ~4.5σ for $\delta=-90^o$ by 2026
- Will be enhanced further by combination with atmospheric neutrino
- Or, 2nd detector in Korea (possibly KNO) will help

➡ 입자물리 관점 (personal view): leptonic CP violation 측정 핵심적인 목적 중의 하나

Physics Potential at HK
(Mass Ordering Sensitivities)

- [Note] important input to CPV measurement & flavor model

Sensitivity to mass hierarchy

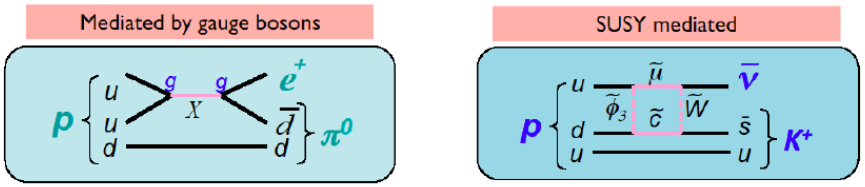


- ~3 sigma in 10yrs by combination of beam + atmospheric neutrino, while atmospheric neutrino only 2~4 sigma

Proton Decay Search

World leading searches from SK to HK

- Two major modes predicted by many models

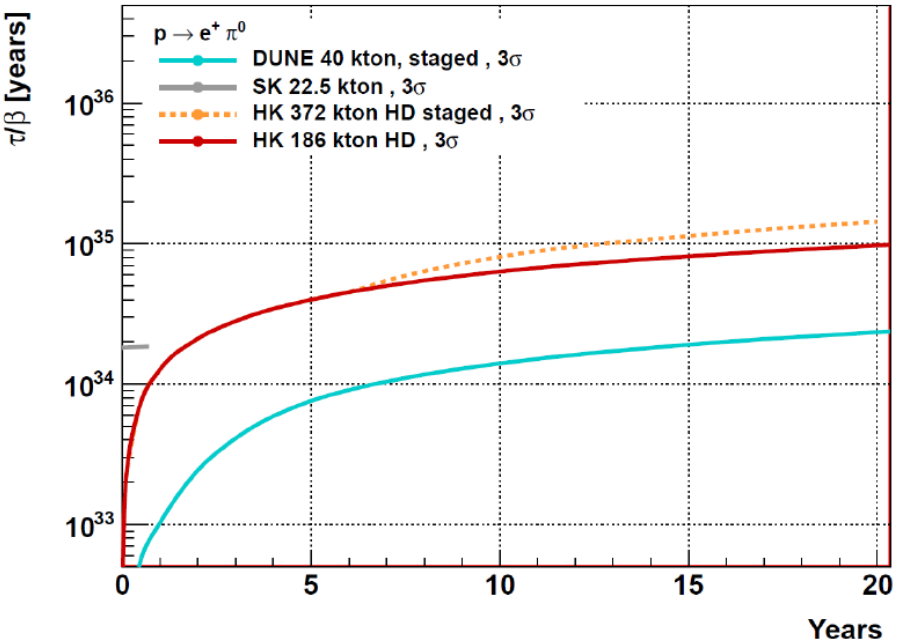


$p \to e^+\pi^0$

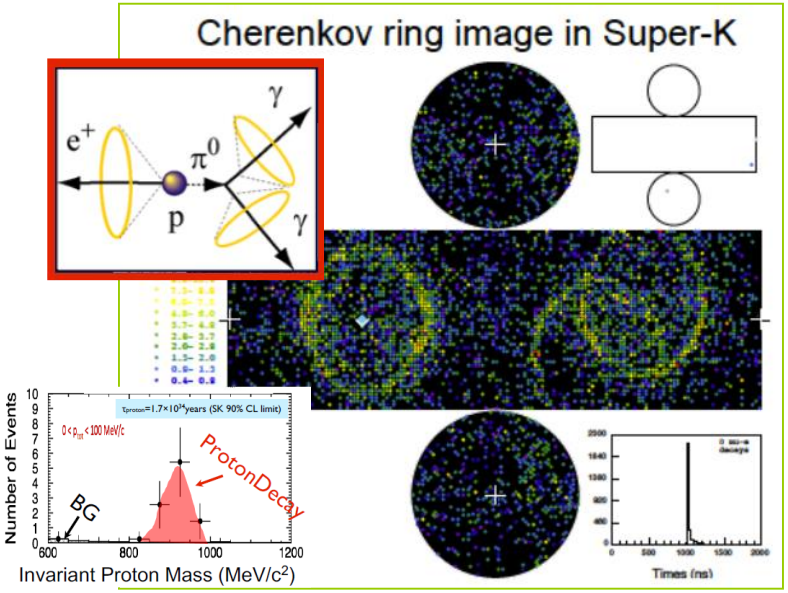
$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

$p \to \nu K^+$

$$\Gamma(p \to \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$



- Need broad searches including other possible modes



For the case of
$\tau_{proton} = 1.4 \times 10^{34}$ years
(Super-K limit)

- Neutron tagging is a key to further reduce the atmospheric neutrino backgrounds
- Clear signal expected just beyond present limit
- 3σ discovery potential will reach ~10^{35} yrs

Other Potentials

- HK has better sensitivity to non-standard neutrino interactions

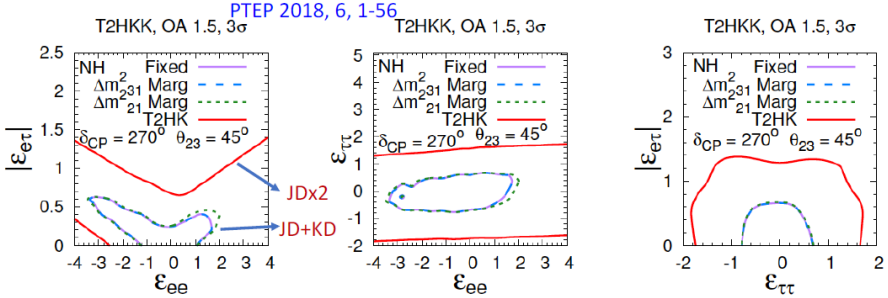
Non-standard ν Interaction Sensitivity

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \delta m^2_{21} & 0\\ 0 & 0 & \delta m^2_{31}\end{pmatrix}U^\dagger + V\right]$$

$$V = A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}}\\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}}\\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau}\end{pmatrix}$$

$$A \equiv 2\sqrt{2}G_F N_e E,$$

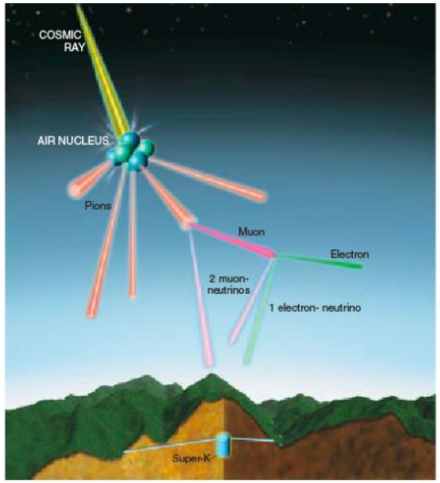
arXiv:1611.06118
PTEP 2018, 6, 1-56

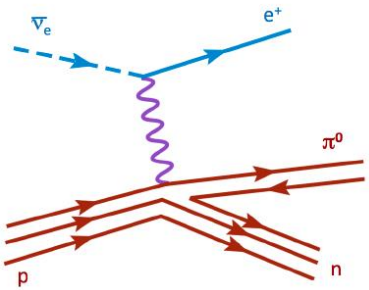


D. Marfatia@ICHEP2018: arXiv:1612.01443

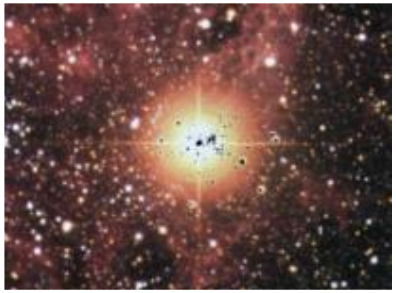
"T2HKK has the best sensitivity to CP phase (even) in the presence of NSI."

Background: Atmospheric Neutrinos

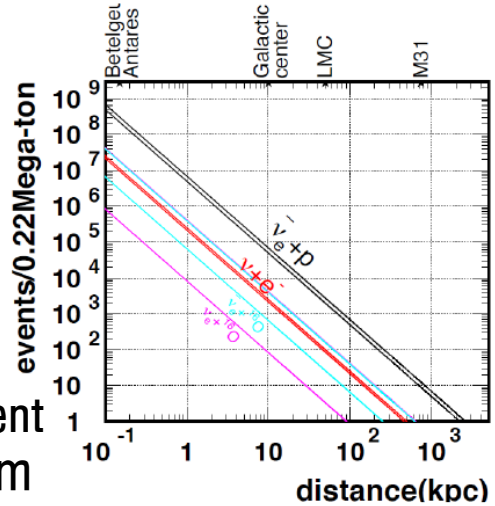




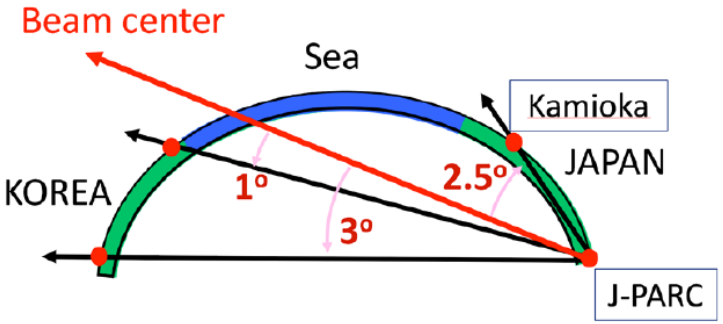
Astroparticle



1st multi-messenger event (Neutrino & light from SN1987A)



If possible, with KNO

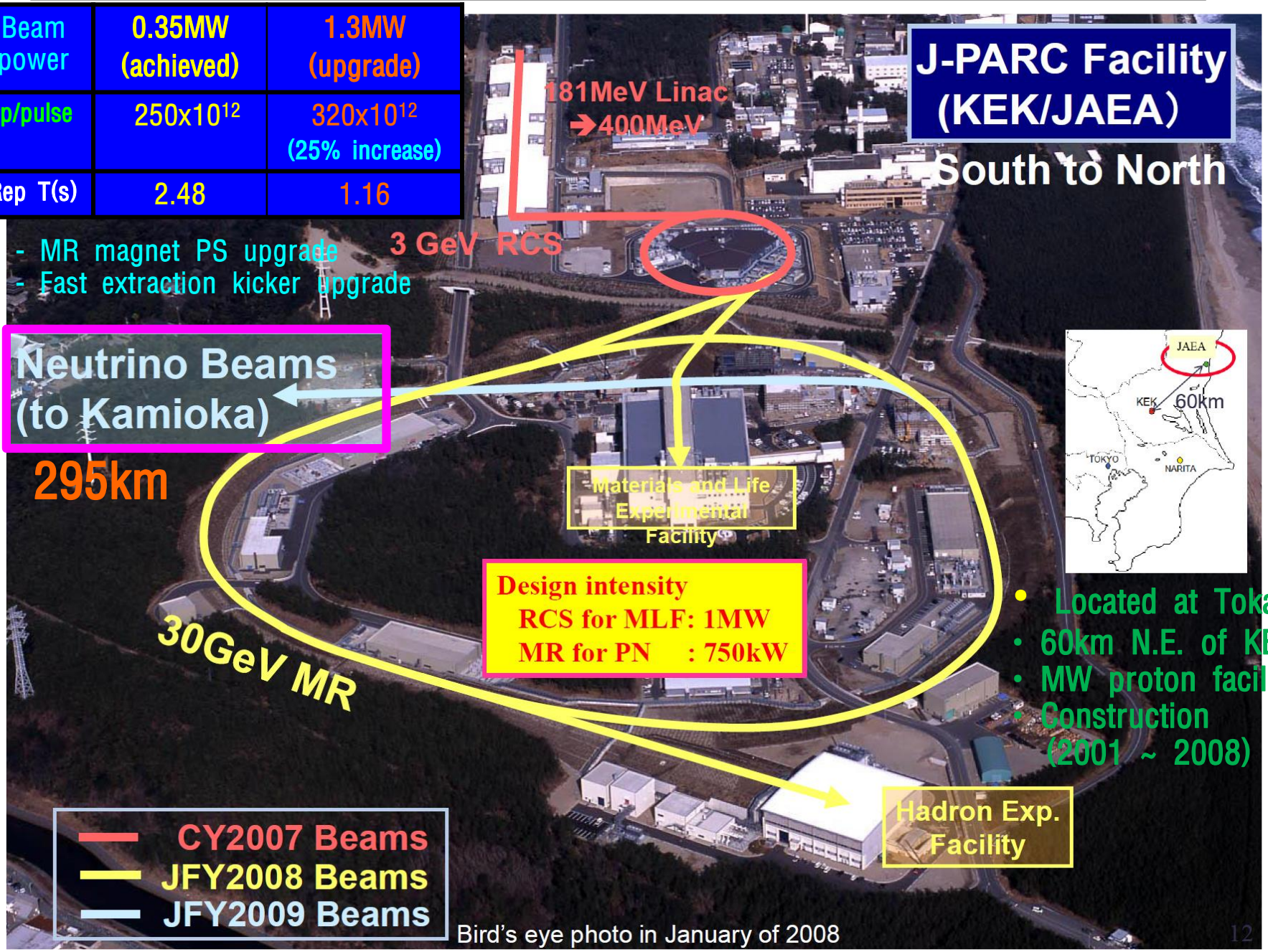


HK & KNO can serve as a neutrino telescope for >30 yrs

J-PARC (Japan Proton Accelerator Research Complex)

Beam power	0.35MW (achieved)	1.3MW (upgrade)
#p/pulse	250×10^{12}	320×10^{12} (25% increase)
Rep T(s)	2.48	1.16

- MR magnet PS upgrade
- Fast extraction kicker upgrade



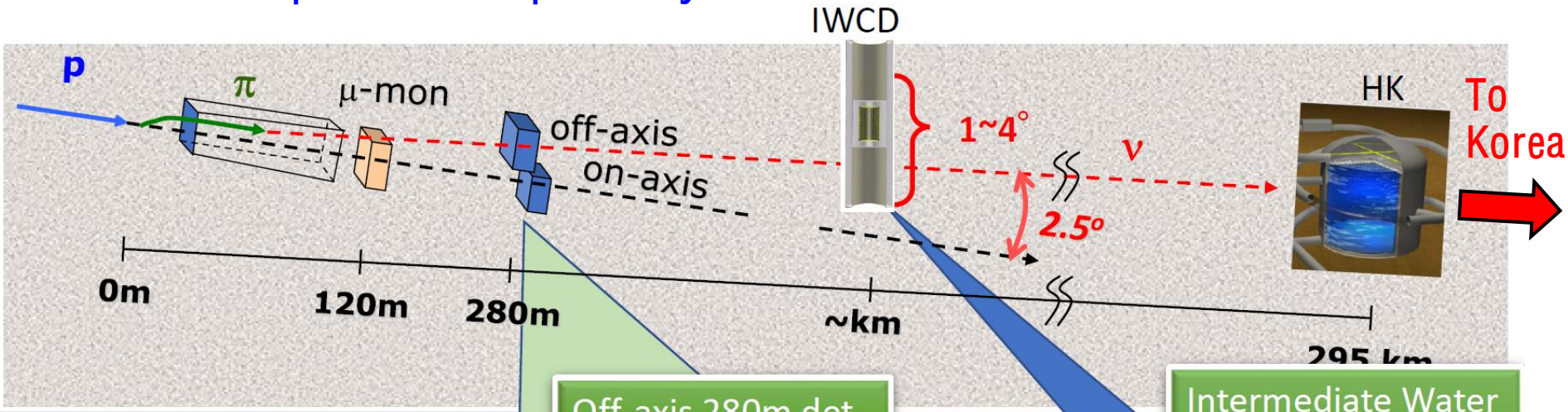
- Located at Tokai
- 60km N.E. of KEK
- MW proton facility
- Construction (2001 ~ 2008)

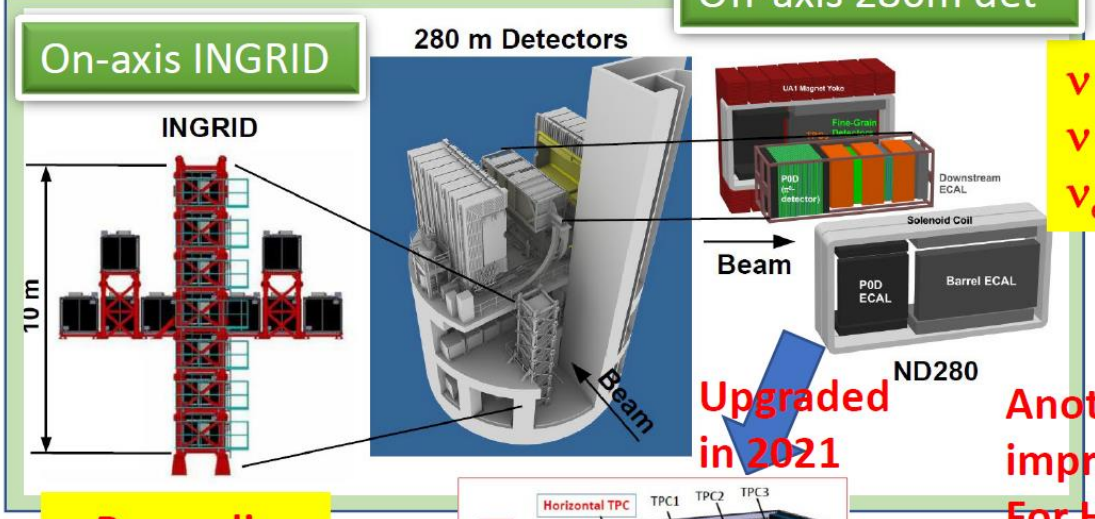
Bird's eye photo in January of 2008

J-PARC (bird's eye) View

Near/Intermediate Detectors

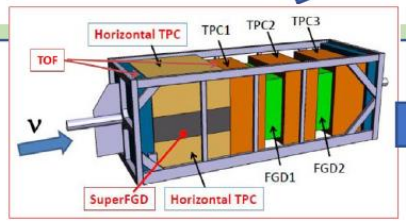
- Critical components to precisely understand J-PARC beam & ν interaction



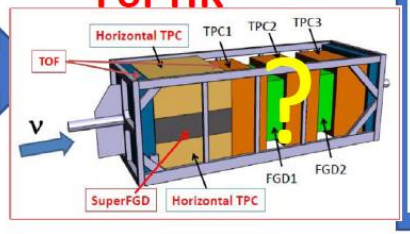


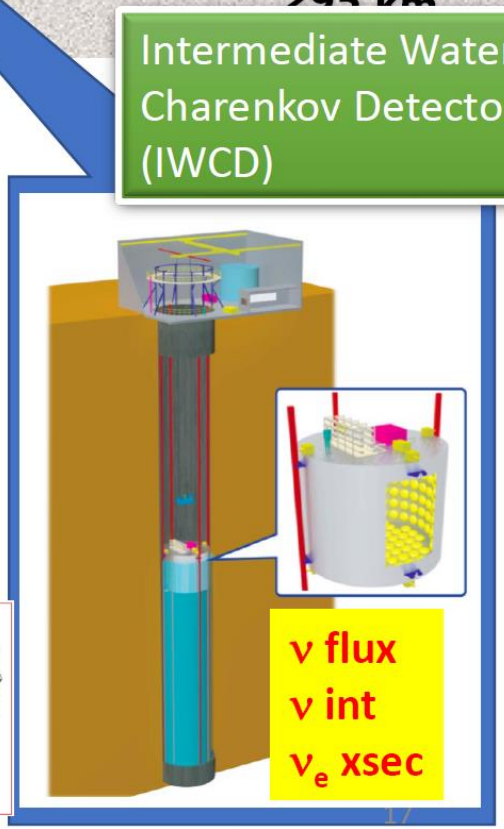
Need at least refurbishment (elec…)

Upgraded in 2021

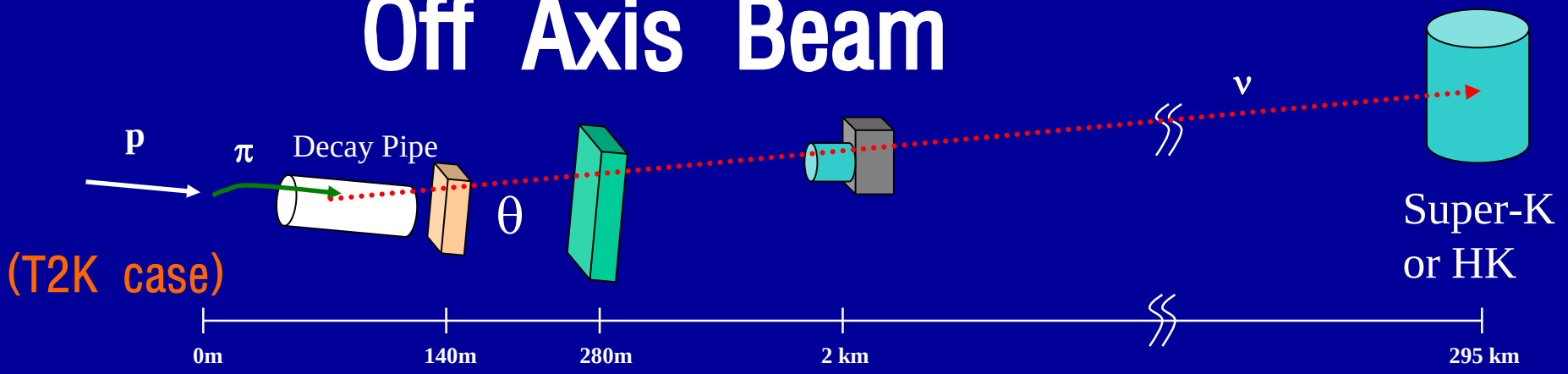


Another improvement For HK

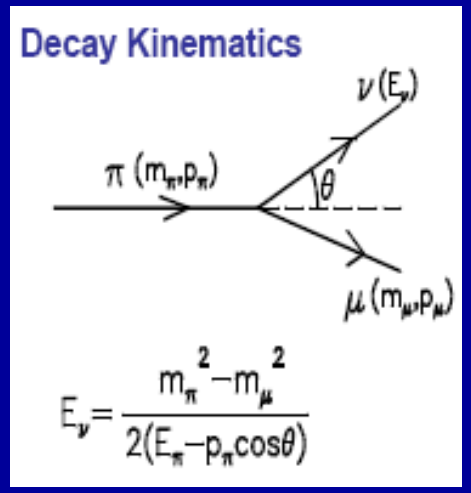


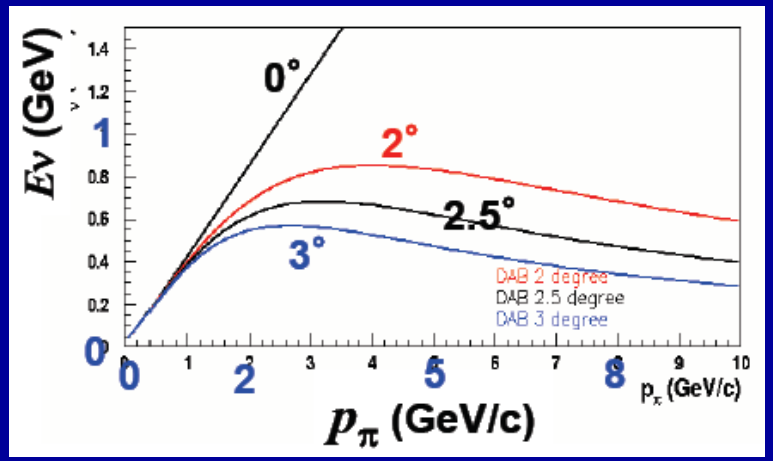


Off Axis Beam



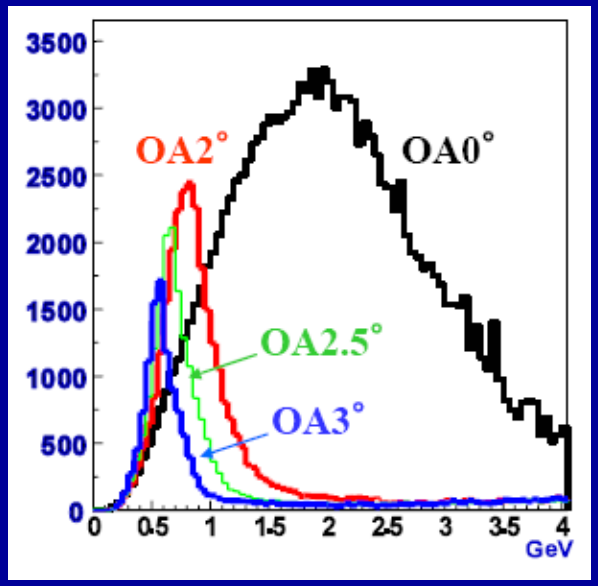
- Muon monitors @ ~140m
- First front detector @280m
- Second front detector @ ~2km
- Far detector @ 295km
  - Super-Kamiokande / HK



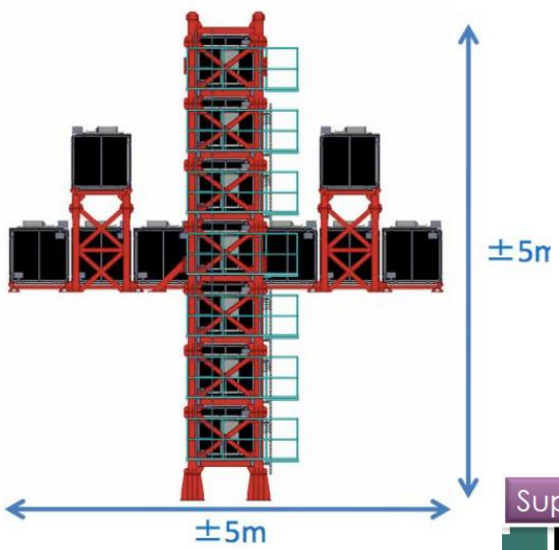


Quasi monochromatic beam

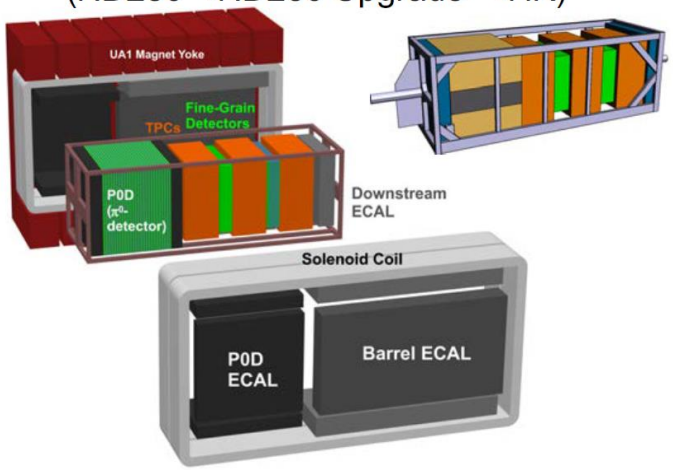
Tunable at oscillation maximum

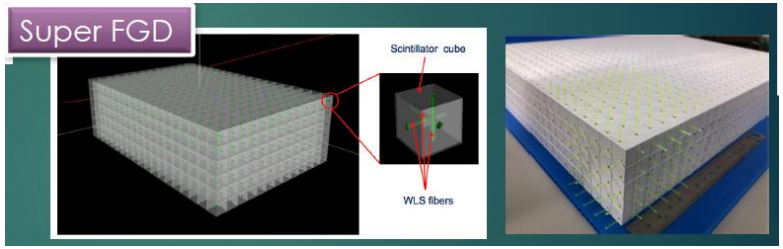


On-axis Detector
(INGRID)

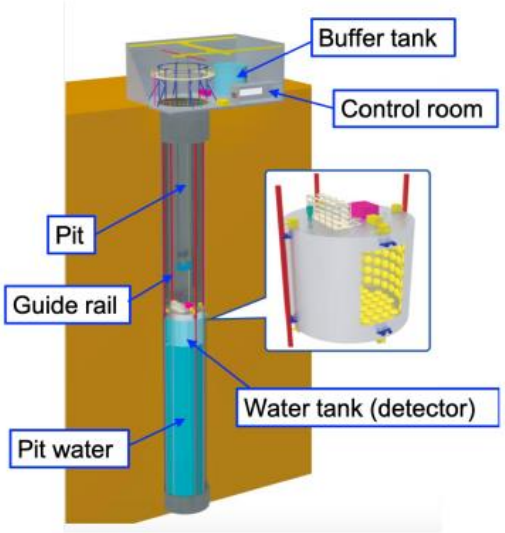


Off-axis Magnetized Tracker
(ND280→ND280 Upgrade →HK)



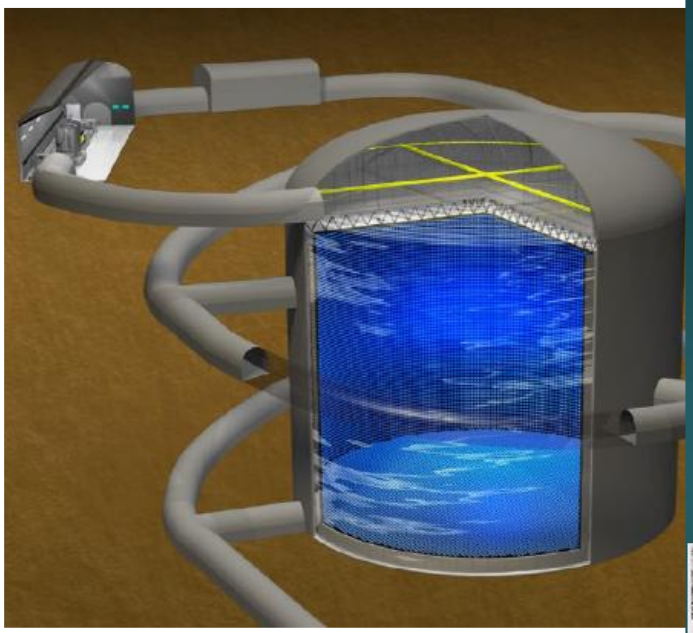


Off-axis spanning Intermediate water Cherenkov detector

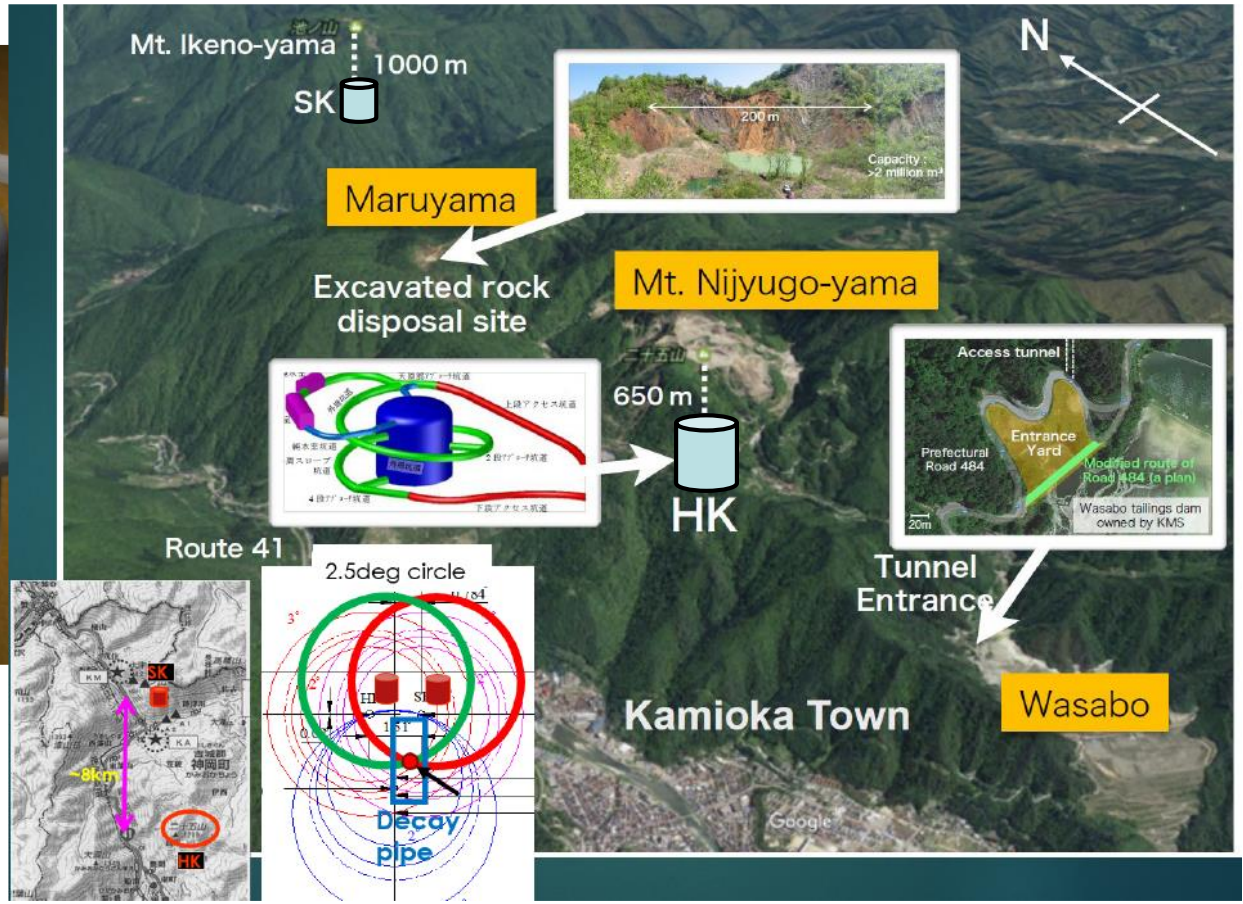


- On-axis detector: Measure beam (profile) direction and event rate
- Off-axis magnetized tracker: Measure primary (anti)neutrino interaction rates, spectrum and properties.
- Intermediate water Cherenkov detector: 1kt H_2O(Gd option) target with different off-axis angle(1, 2.5, 4°) to resolve neutrino-nucleus scattering kinematics

HK Detector/Site



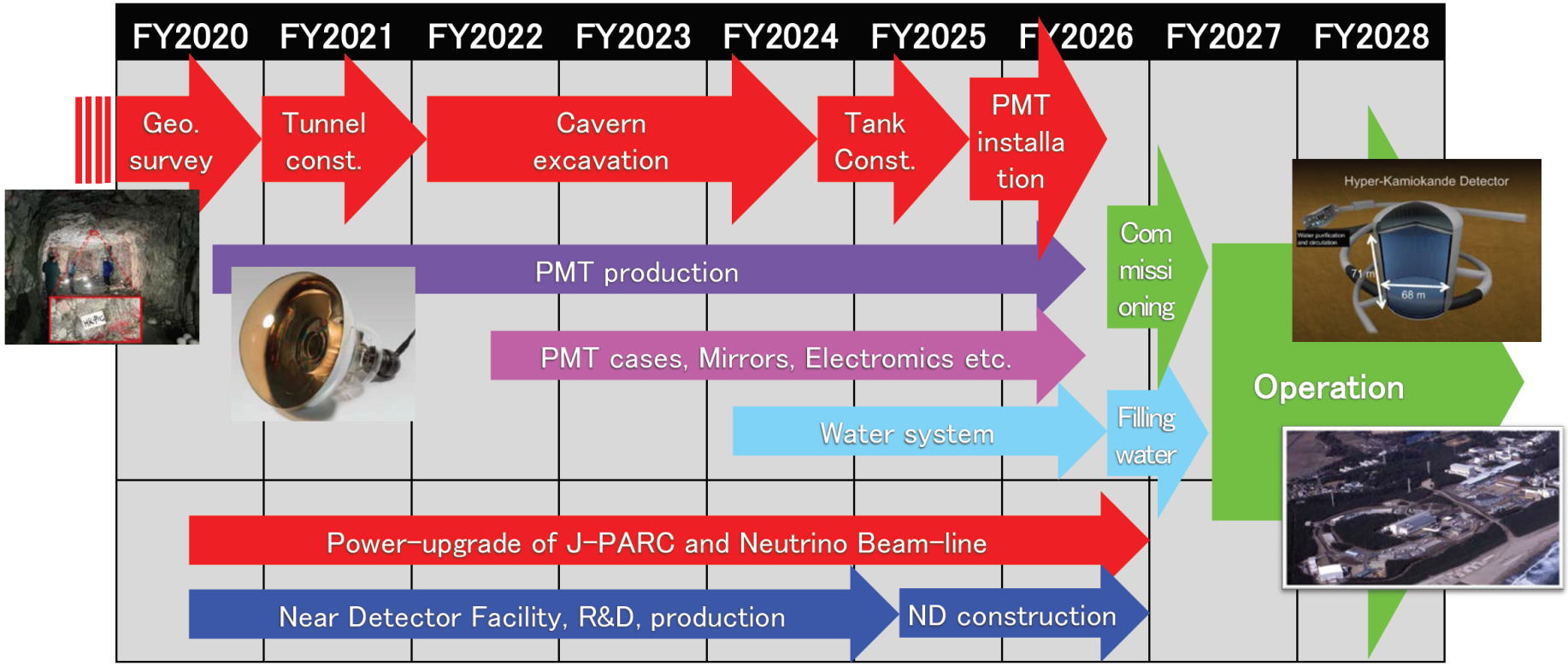
260kt (190kt fid.mass)



- ~40,000 50cm PMTs for inner detector
  + 40% coverage with new sensor
- ~6,700 20cm PMTs for outer detector
- Detector location (candidate) ~8km south of SK
- 650m overburden (1755m W.E.)

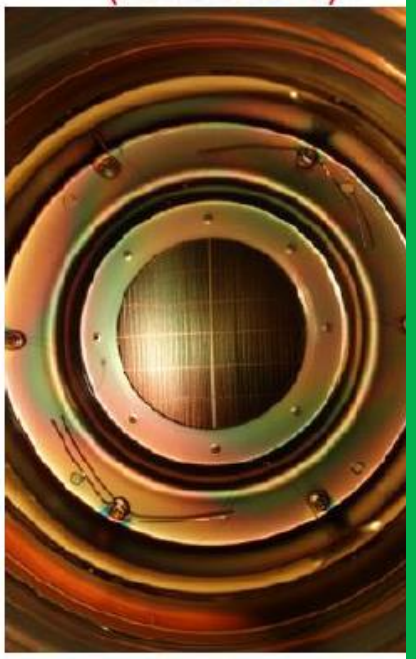
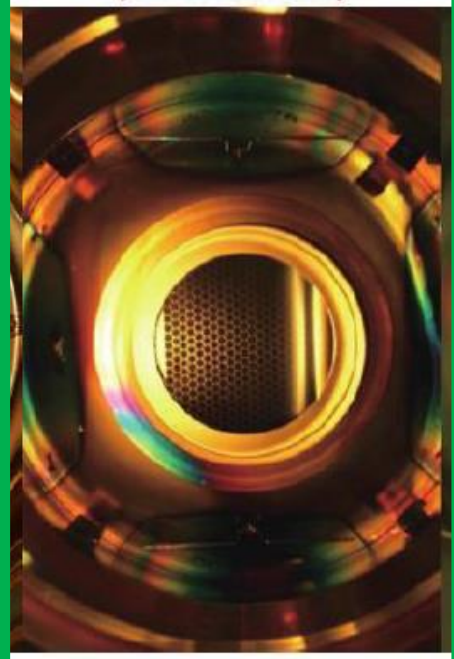
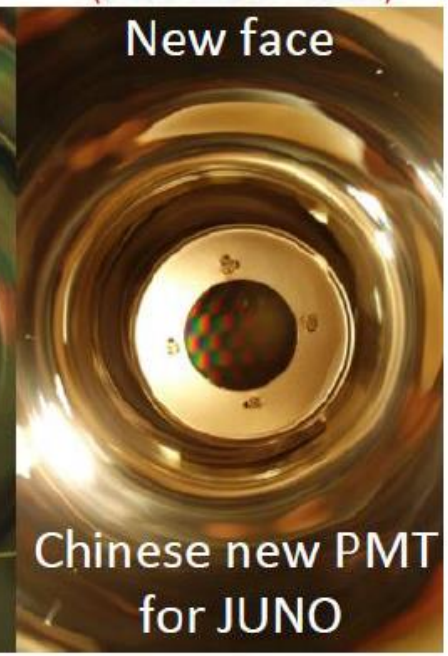
- Part of
  + PMT(Japan, 50% cover)
  + Water, electronics, tunnel, etc
- Rest of FD needs to be filled by foreign collaborators

HK Schedule



- 7 years construction from year 2020; 5 years excavation + subsequent 2 yrs detector construction. Data taking from 2027(summer)
- HK will start water filling and detector commissioning in Dec.-2026
- The participating countries need to be ready to start installation of their components by Dec.-2025 (We have ~5 years for preparation)

50 cm Photodetectors in world

(+Kamiokande PMT) Super-K PMT (HPK R3600)	Box&Line PMT (HPK R12860)	HPD (HPK R12850)	MCP PMT (NNVT GDB-6201)
			
CANNOT withstand 60m water height	*Candidate HK PD*	*R&D in progress*	*NOT alternative candidate now!*
→ Bye	→ Lower background	→ Take R&D over abroad	→ Need evaluation
11k in SK	34 in ICRR +140 this FY	11 in ICRR + Need R&D budget	4 in ICRR + a few w/ improved

'19/1/30 HK ID 50-cm Photodetectors (Nishimura)

[Note] PMT is one of important issues for KNO people
(please see KNO's talk for PMT domestic development - KNU,UoS)

HK PMT (Φ50 cm for Inner Detector)

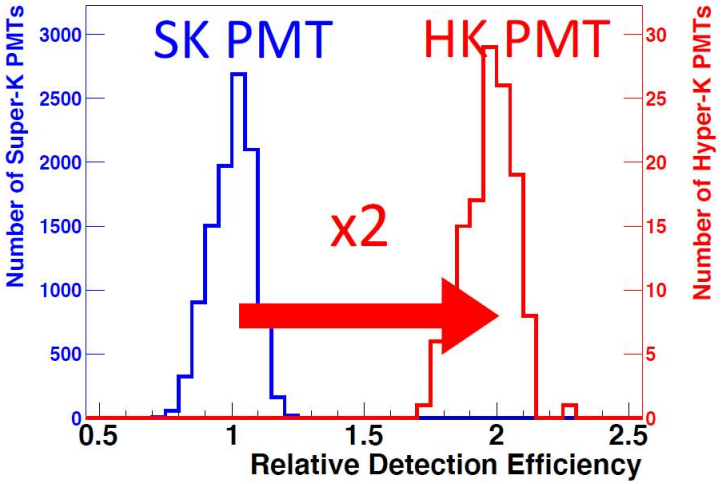
- The Box&Line PMT (R12860) fully satisfies HK requirements and is ready for mass production
- Contracted with Hamamatsu in October
- ~ 6 years production time: 300 PMTs within this JFY 2020 (by March 2021). HK aims at 20,000 in total by Oct. 2026.

Hamamatsu Box&Line (B&L) PMT (R12860)

φ50cm

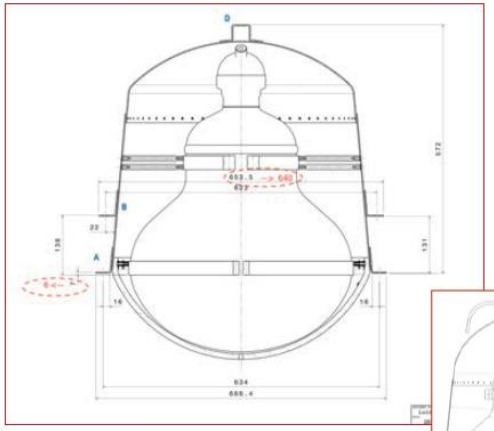
- Sensitivity: 2 x SK
- Noise rate: 1 x SK
- Time Resol.: 1/2 x SK

Single photon efficiency

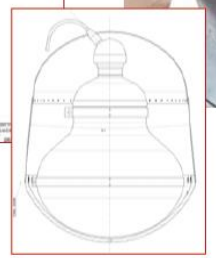


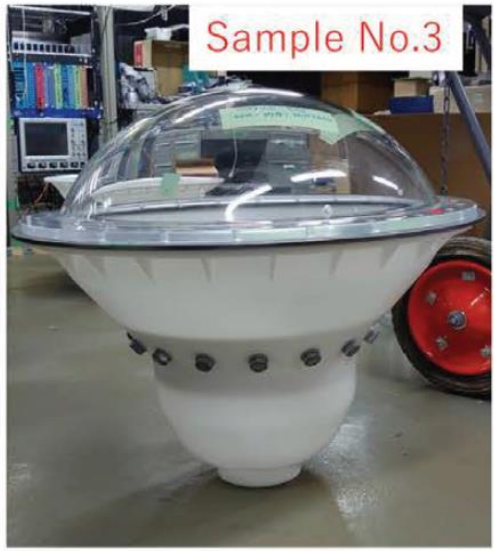
PMT Cover Test

works on attachment Cover-to-Structure (I)



Notice that even though the key dimensions will not vary, the shape in the back will be slightly different :

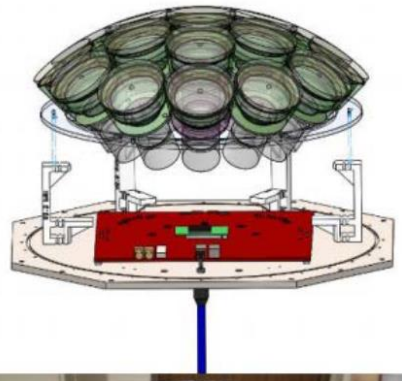




- Cover is to prevent chain reaction of PMT implosion in the high water pressure (which the SK experienced in 2001)
- 3 cover proposal being developed. Further R&D on material test, fabrication method, installation method, full validation under water pressure etc.
- Full validation test in early 2021, Production starts in 2022

m(ulti)-PMT for Inner Detector

19 7.5-cm PMTs / module



Prototype at TRIUMF

HK FD mPMT Electronics at INFN

- Collection of small size (3inch) PMTs in a single enclosure (adapted from KM3NET's original mPMT)

- Need critical contributions by international countries
- Brand new technology for the large-scale water Cherenkov detectors (pro and con)
- HK aims to realize >5000 mPMT with best effort
- Cost reduction, finding more countries to contribute
- Also studying different module configurations
- Schedule
  - mPMT review of physics & design by ~ Sep. 2022
  - mPMT contract negotiation in 2022
  - assembly between 2023 and 2026

Expression of Interest (EoI) Korea Groups

- Historically many successful past/present collaborative neutrino physics efforts between Japan and Korea (SK/K2K/T2K/JSNS2→HK)

- Expanding scientific scope of HK: Construction of a second large volume neutrino detector in Korea to significantly enhance the science program HK program (T2HKK or KNO?)

- Participation (7 institutions, ~20 peoples)
  - Chonnam National Univ.
  - Dongshin Univ.
  - GIST
  - KAIST
  - Kyungpook National Univ.
  - Sungkyunkwan Univ.
  - UNIST

- 2nd detector in Korea (active ~50 participants. Please see KNO talk)

▪ Intended contribution to HK

- Laser calibration systems & water transparency measurement (currently in charge of SK, lots of experiences)

- Outer detector electronics (good domestic company)

- Contributions to computing (with KISTI source)

▪ Funding landscape and long term funding prospects

- Key & essential issue (especially common funds for the time being)
- Contribution($) to HK detector construction is mandatory, not optional
- Apply SRC, BRL, individual funding etc & try every possible ways
- Desperate, needs some breakthrough…

Summary

HK is the next generation multi-purpose project
(260kt HK detector, 1.3MW J-PARC)

Broad science with unprecedented sensitivities CP violation in neutrino, proton decay, astro-particle/geo physics, etc.

Many interesting challenges ahead toward big goal
Your challenges are welcome!

Last, for coming next 30, HK exp will continue to be exciting

International innovative contributions are needed to realize the world-leading project. Financial supports are indispensable

Mass production of detector components will start in a few years

Data taking / operation will start ~summer 2027

Not covered: Tunnel, cavern, water tank, purification, electronics/DAQ, calibration, computing, etc