Super-Kamiokande and Hyper-Kamiokande

K-Neutrino symposium, CAU

2025.6.25

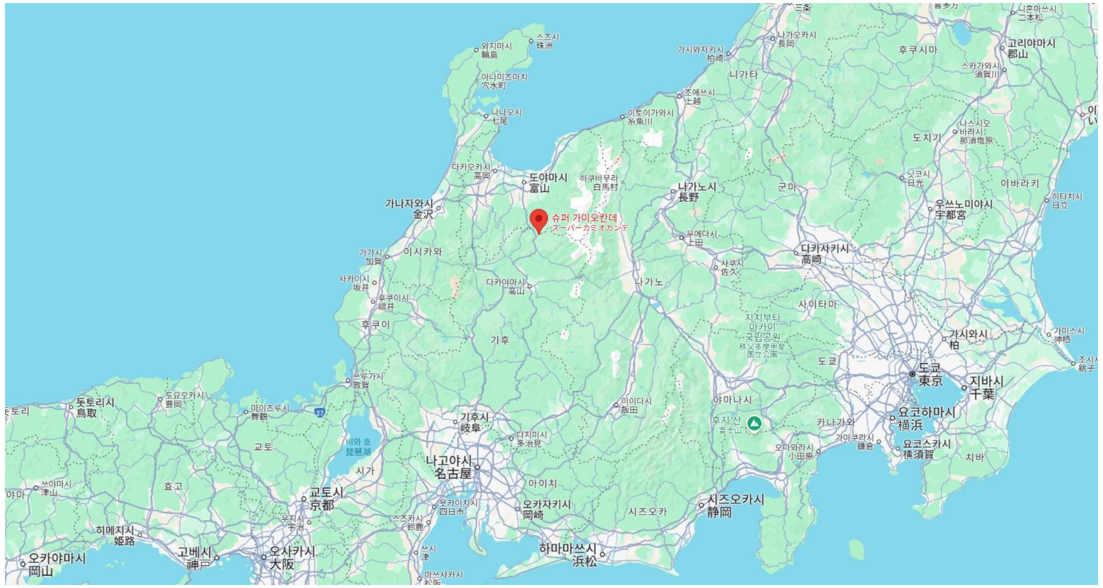
Seo Ji-Woong

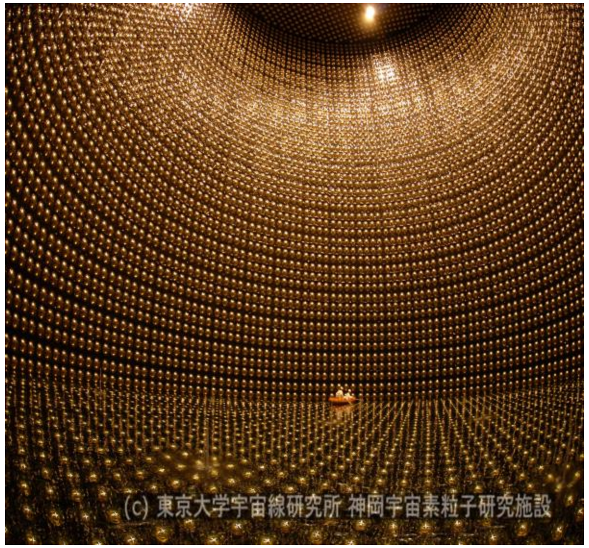
Super-Kamiokande

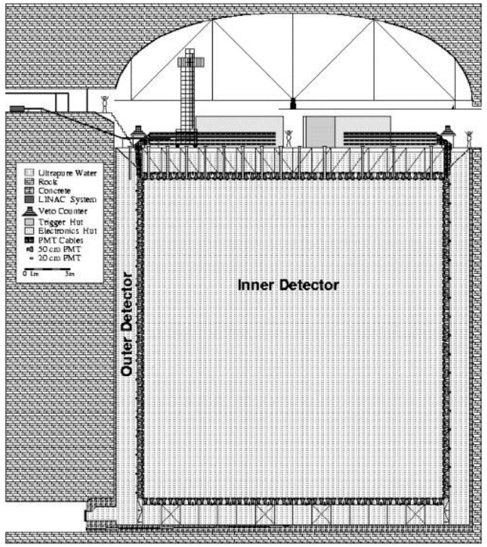
- World largest water Cherenkov detector
    - Located 1,000 m underground in the Gifu prefecture, Japan

- Upright cylindrical shape
    - Diameter ~39 m
    - Height ~42 m
    - Inner detector : ~11k PMTs, 20”
      (Photo coverage 40%)
    - Outer detector : ~2k PMTs, 8”

    - Filled with 50 kton of pure water
        - from 2020, Gd was added to water

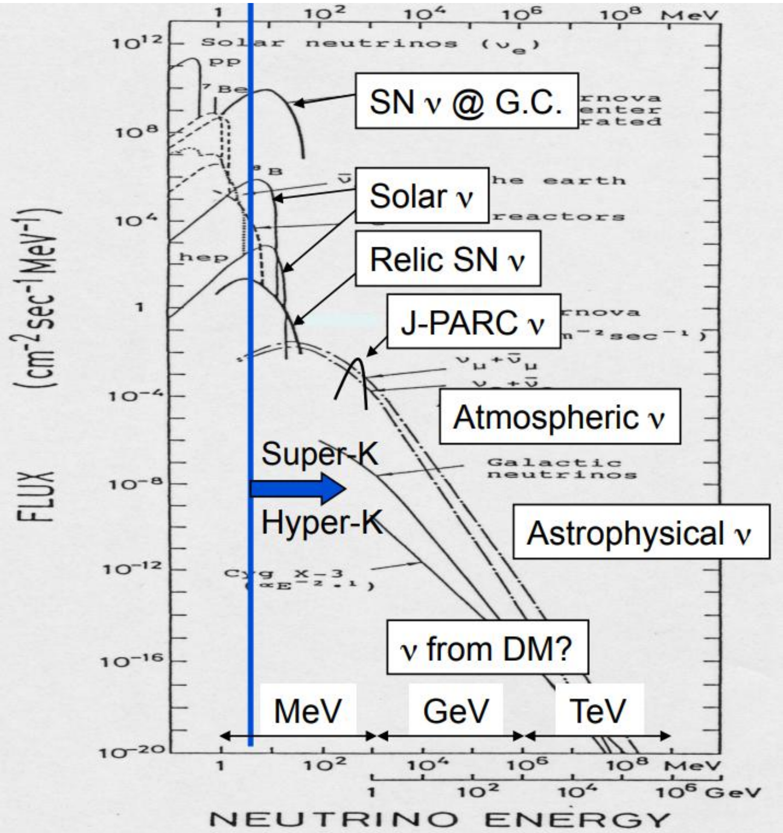

슈퍼 가미오칸데
スーパーカミオカンデ
도야마시
富山
가나자와시
金沢
나가노시
長野
다카야마시
高山
기후시
岐阜
나고야시
名古屋
교토시
京都
오사카시
大阪
고베시
神戸
시즈오카시
静岡
요코하마시
横浜
도쿄
東京

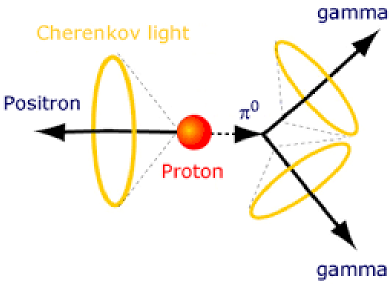

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

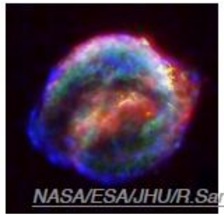

Ultrapure Water
Rock
Concrete
LINAC System
Veto Counter
Trigger Hut
Electronics Hut
PMT Cables
50 cm PMT
20 cm PMT
0 1m 5m
Inner Detector
Outer Detector

Physics target of Super-Kamiokande

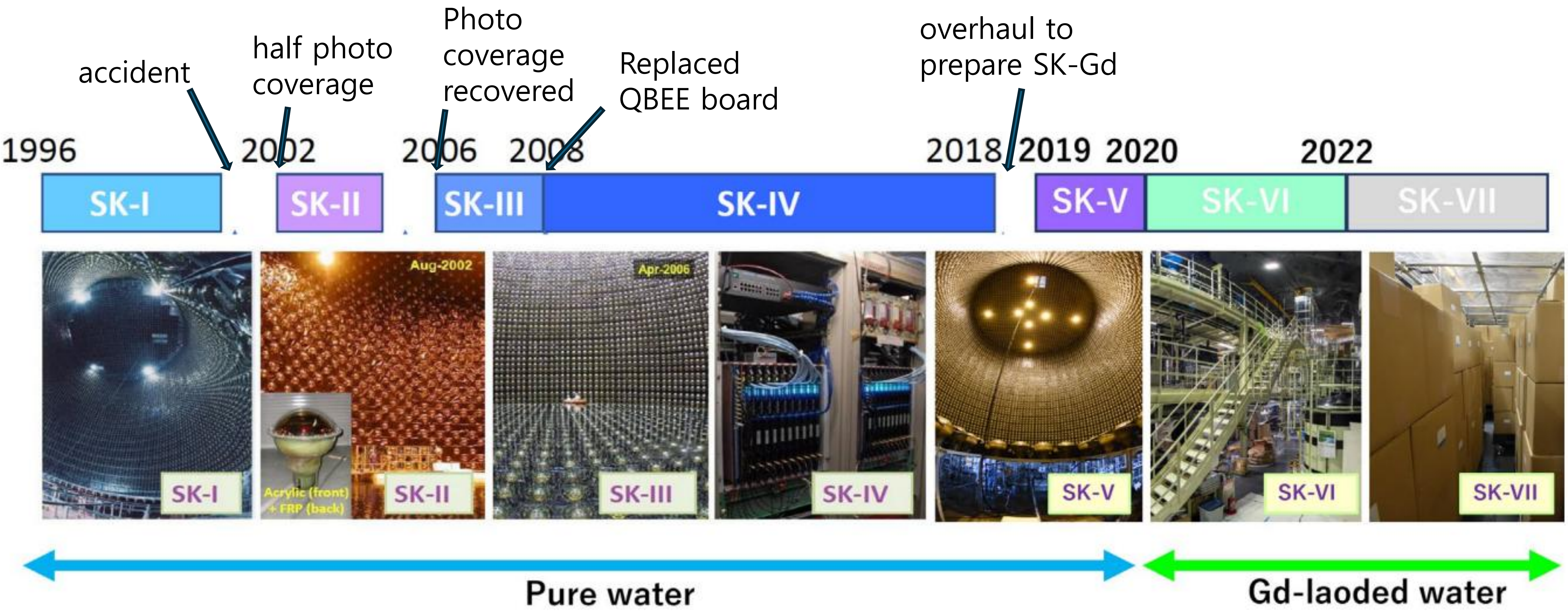
- Neutrino physics
  - Accelerator and atmospheric neutrinos : neutrino oscillation (CP violation, Mass ordering)
  - Solar neutrinos : Non-standard oscillations and interactions
- Neutrino astrophysics
  - Supernova, Solar, Astronomical objects
- Beyond standard model
  - Nucleon decay
  - Dark matter
  - Sterile neutrino, etc.




Cherenkov light
Positron
Proton
π^0
gamma
gamma


NASA/ESA/JHU/R.Sankrit & W.Blair

History of Super-Kamiokande



accident

half photo coverage

Photo coverage recovered

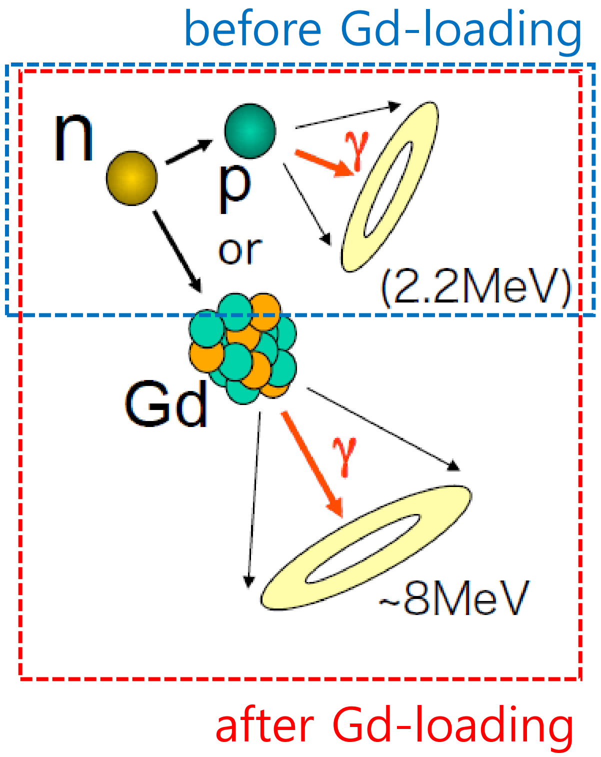
Replaced QBEE board

overhaul to prepare SK-Gd

1996
2002
2006
2008
2018
2019
2020
2022
SK-I
SK-II
SK-III
SK-IV
SK-V
SK-VI
SK-VII
Aug-2002
Acrylic (front) + FRP (back)
Apr-2006
SK-I
SK-II
SK-III
SK-IV
SK-V
SK-VI
SK-VII
Pure water
Gd-laoded water

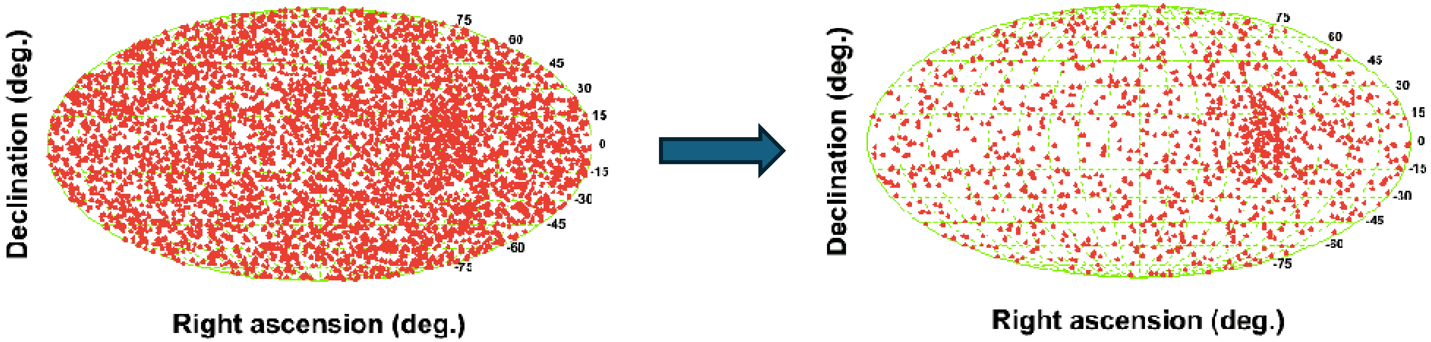
Super-Kamiokande with Gadolinium

- SK-Gd phase
  - Increase neutron tagging efficiency : 20~30% → ~50% (SK-VI 0.01%) → ~80% (SK-VII~ 0.03%)


before Gd-loading
n
p
γ
or
(2.2MeV)
Gd
γ
~8MeV
after Gd-loading

- Expectation of Gd-loading
  - Supernova neutrinos : DSNB, SRN, etc.
    - Increased sensitivity, directional resolution, reject IBD backgrounds

Reconstructed neutrino direction



Before neutron tagging

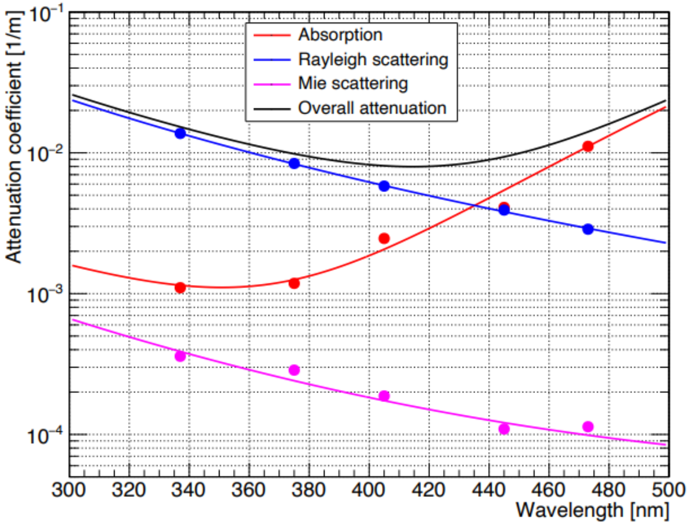
After neutron tagging

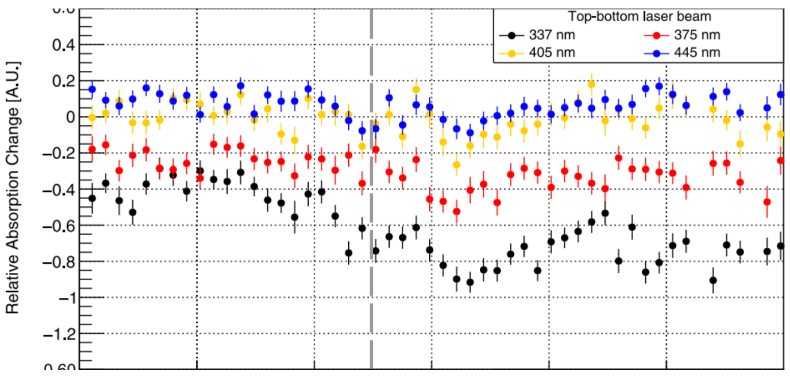
  - Background rejection is improved in atmospheric neutrino, solar neutrino and proton decay analyses

Korean contribution for Super-K

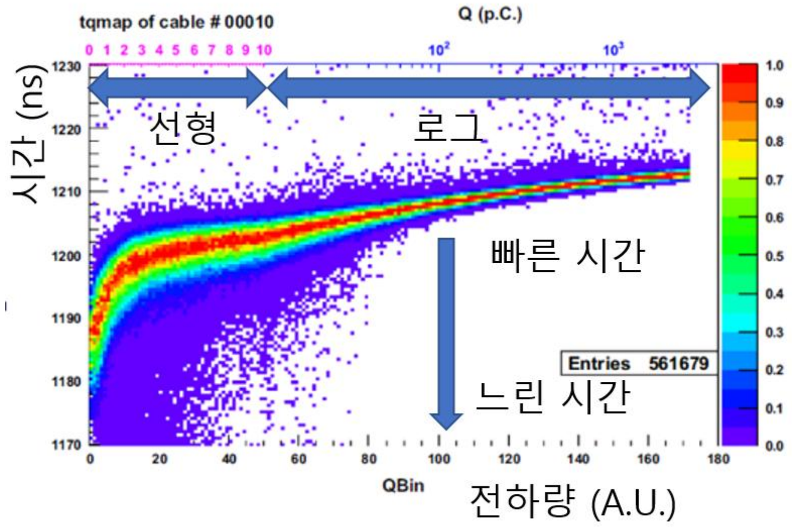
- 5 institutions, 13 researchers
  - According to the Super-Kamiokande collaboration author list, May 2025

- Calibration
  - Water parameter measurement
  - Monitoring attenuation length of Gd-loaded water
  - PMT timing-charge calibration





TQ map



Korean contribution for Super-K

- Solar neutrino analysis
  - Periodic time variations of the solar neutrino flux : Yang Jeongyeol(IBS)
    - Published 14 June 2024. Phys. Rev. Lett. 132, 241803

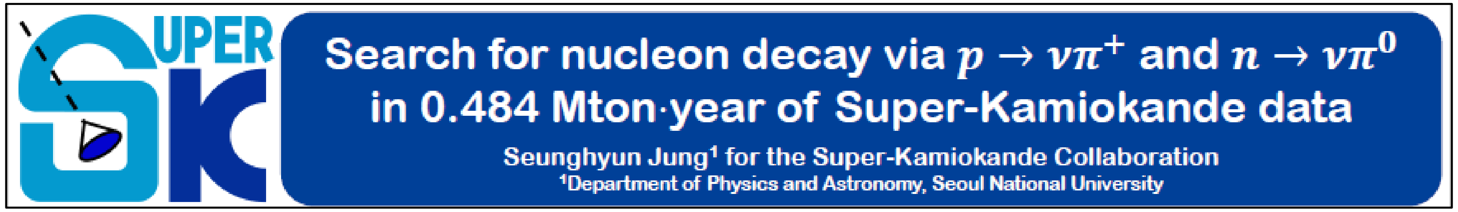
- Proton decay analysis
  - $p \rightarrow e^+\pi^0\pi^0$, $p \rightarrow \mu^+\pi^0\pi^0$: Seo Ji-Woong, Kwon Eunhyang (SKKU)
    - The publication is being prepared
  - $p \rightarrow \nu\pi^+, n \rightarrow \nu\pi^0$: Jung Seunghyun (SNU)
    - The publication is being prepared

  - $pp \rightarrow e^+\tau^+$(Jung Seunghyun), $p \rightarrow e^+\gamma$(Kwon Eunhyang), $p \rightarrow e^+K^0$ (Lee Minwoo)

- Atmospheric neutrino analysis
  - Search for sterile neutrinos using atmospheric neutrino (Seo Ji-Woong)

Introduction of poster presentation

- Nucleon decay
  - Jung Seunghyun (SNU)



Search for nucleon decay via $p \rightarrow \nu\pi^+$ and $n \rightarrow \nu\pi^0$ in 0.484 Mton·year of Super-Kamiokande data

Seunghyun Jung[1] for the Super-Kamiokande Collaboration

[1] Department of Physics and Astronomy, Seoul National University

  - Analyzed all Super-K pure water period data (SK-I to SK-V)
  - An improved pion interaction model is used compared to the previous analysis

  - Signal spectrum fitting was performed with updated systematics and enlarged fiducial volume
  - The 90% C.L. lower limits on partial lifetimes are set at 3.5×10^{32} and 1.4×10^{33} years for the $p \rightarrow \nu\pi^+$ and $n \rightarrow \nu\pi^0$ modes, respectively

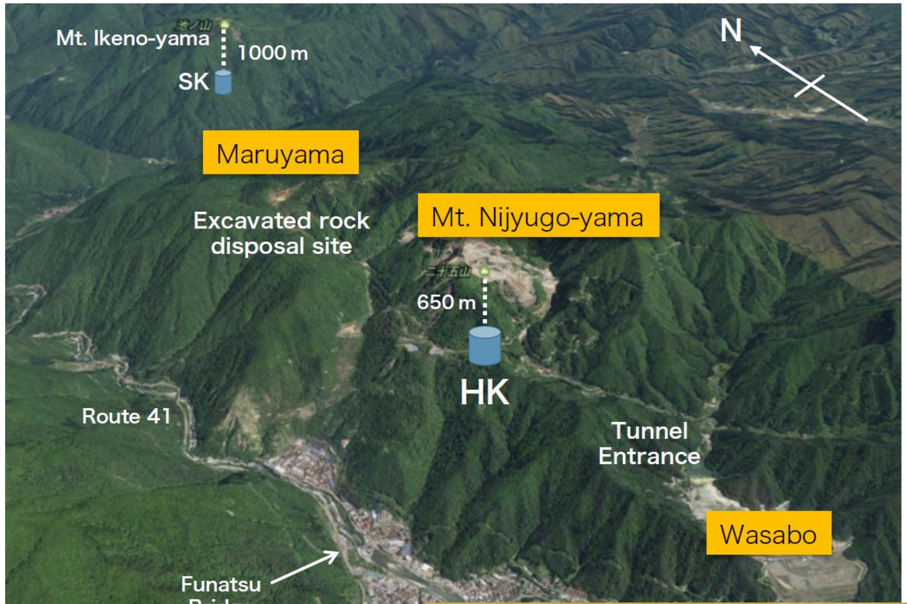
- For more details, please visit the poster and talk to the presenter!

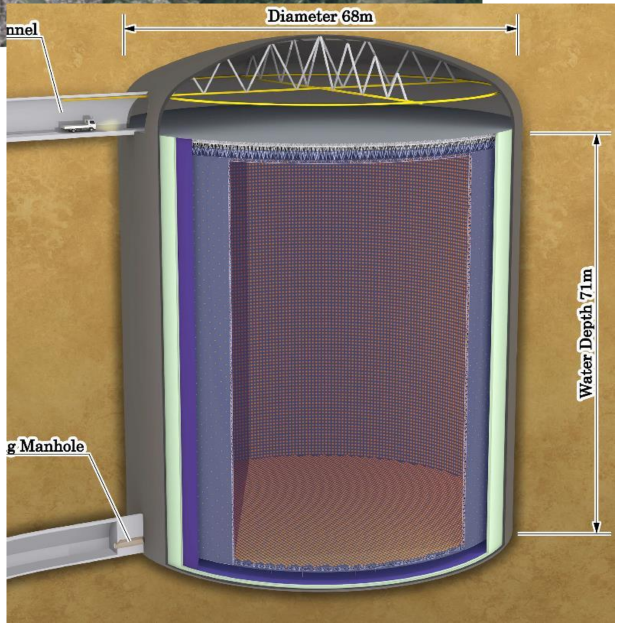
Hyper-Kamiokande

- Next generation water Cherenkov detector
    - Located 650 m underground in the Gifu prefecture, Japan

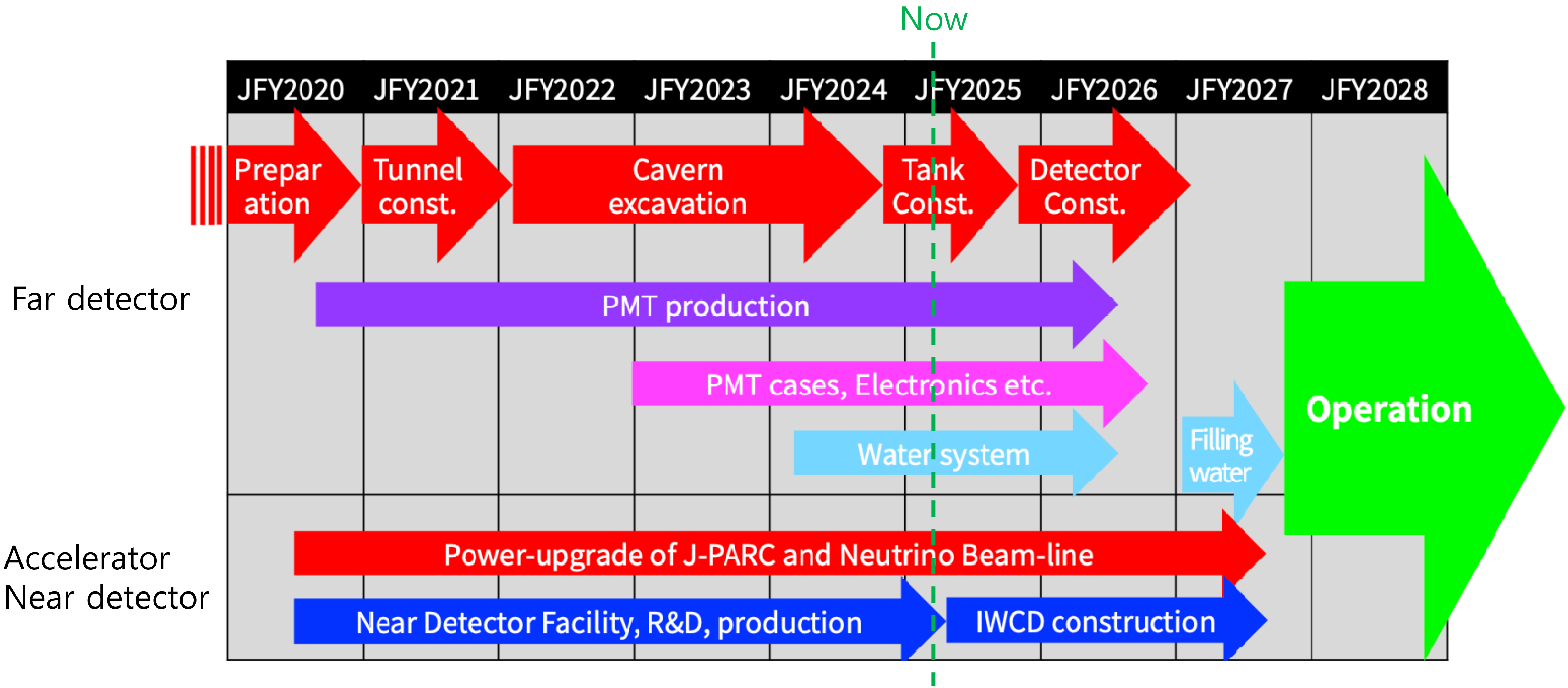
- Upright cylindrical shape
    - Diameter ~70 m
    - Height ~70 m
    - ~20k PMTs will be installed at inner detector
        - Photo coverage (20%)
    - Filled with 260 kton of pure water
    - 5 times larger than Super-K

- As of October 2024, about 600 researchers from 22 countries have participated in the experiment


Mt. Ikeno-yama
1000 m
SK
N
Maruyama
Excavated rock disposal site
Mt. Nijyugo-yama
650 m
HK
Route 41
Tunnel Entrance
Wasabo
Funatsu Bridge

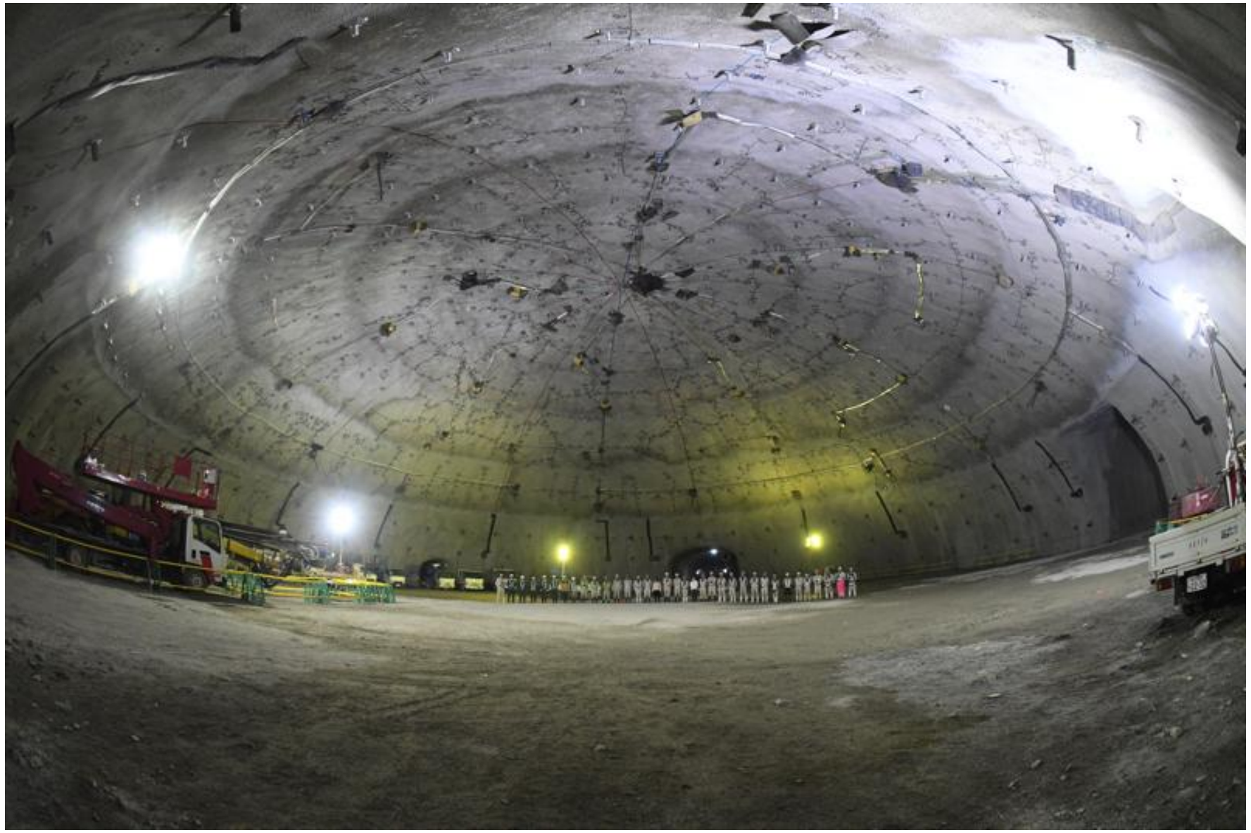

nnel
Diameter 68m
Water Depth 71m
g Manhole

Timeline of Hyper-Kamiokande

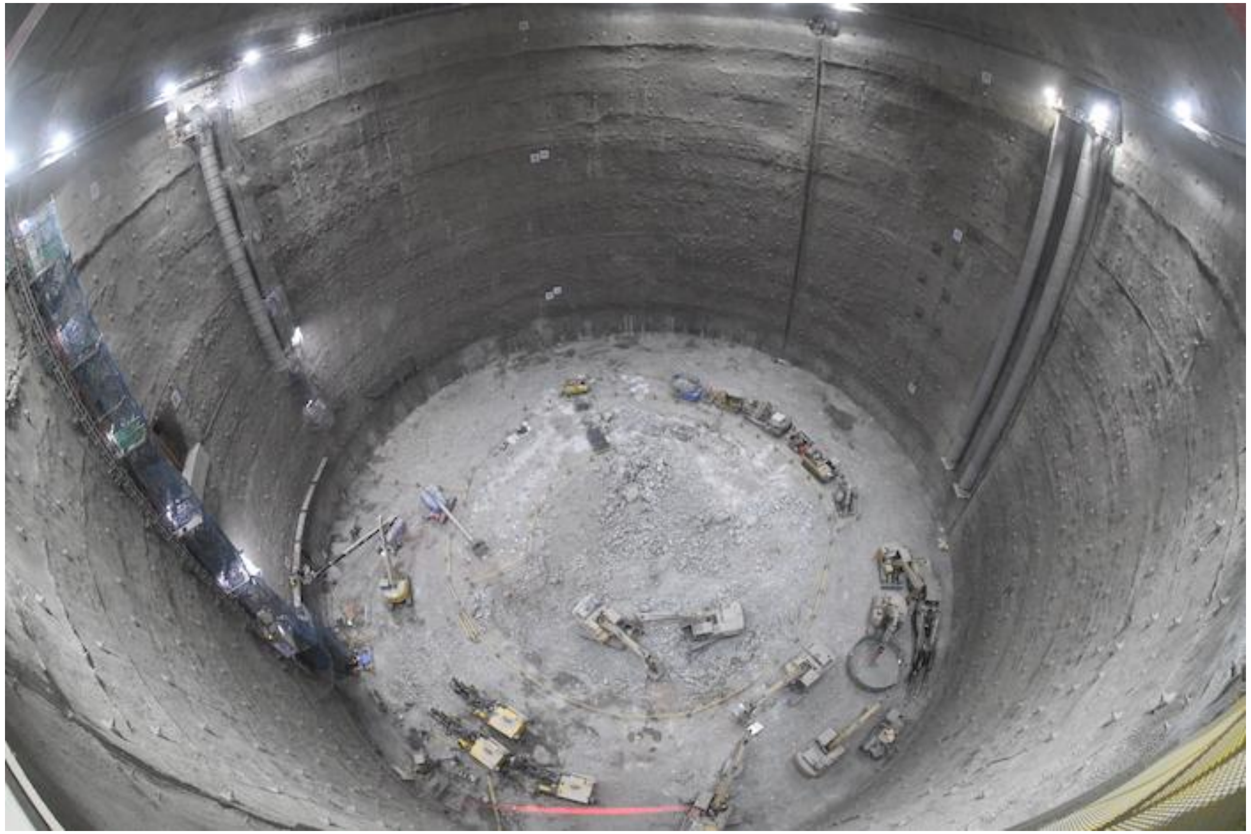

Now
JFY2020
JFY2021
JFY2022
JFY2023
JFY2024
JFY2025
JFY2026
JFY2027
JFY2028
Far detector
Preparation
Tunnel const.
Cavern excavation
Tank Const.
Detector Const.
PMT production
PMT cases, Electronics etc.
Water system
Filling water
Operation
Accelerator
Near detector
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
IWCD construction

Note: JFY=Japanese Fiscal Year starts on April 1st

Construction of Hyper-Kamiokande



Completion of the main cavern dome
Oct. 3, 2023



The main cavern being excavated to a depth of 45 m in the barrel section
Sep. 20, 2024

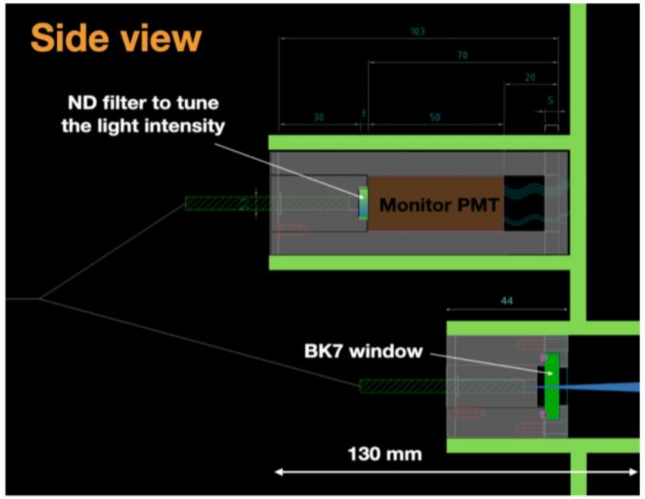
Construction of Hyper-Kamiokande

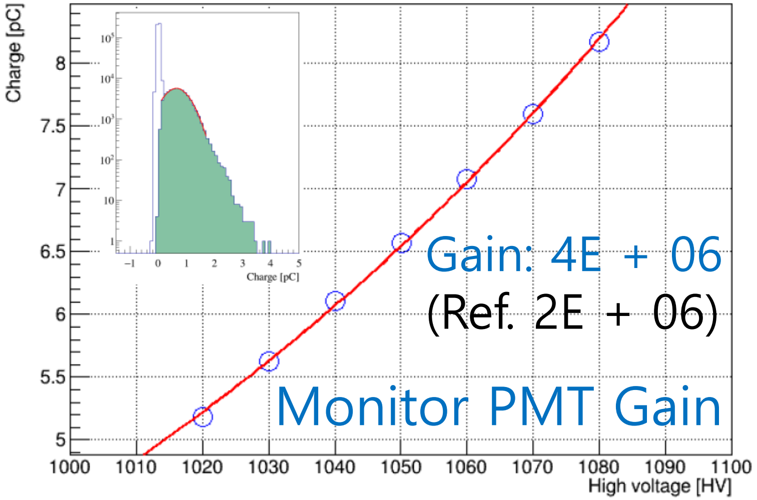
A test called the “100-sensor measurement” involves placing 100 photosensors in a darkroom, powering them on, and checking their electrical signal output.

Prototype 8cm photosensors for OD under consideration were tested in a darkroom to evaluate their performance.

Korean contribution for Hyper-K

- 7 institution, 19 researchers
  - According to the Hyper-Kamiokande collaboration author list on webpage, June 2025
- Calibration
  - Water parameter measurement same as Super-K
  - Laser injector design
  - Testing monitor PMT (NNVT and Hamamatsu) and fiber coupler
  - Laser simulation

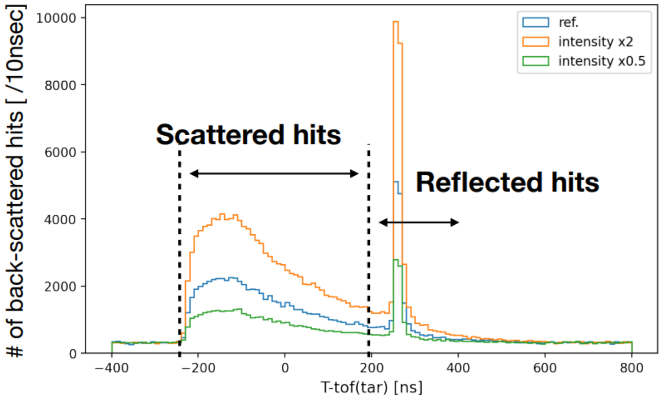

Side view
ND filter to tune the light intensity
Monitor PMT
BK7 window
130 mm
103
70
20
30
3
50
5
44



Gain: 4E + 06
(Ref. 2E + 06)

Monitor PMT Gain

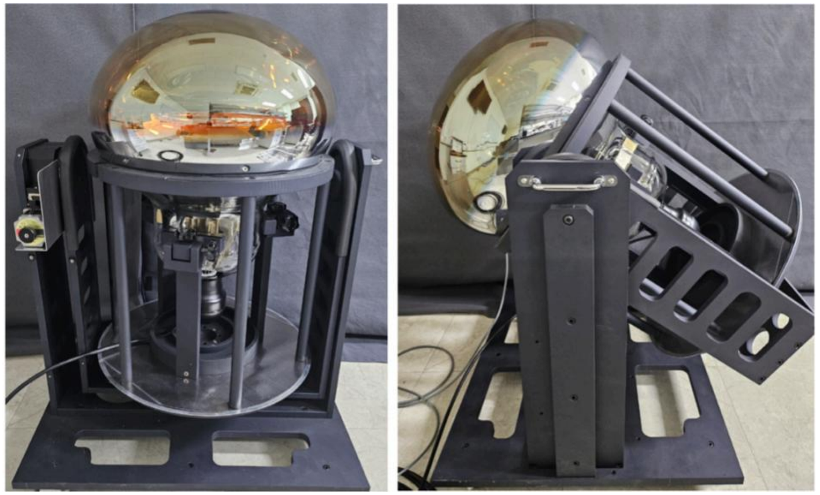
T-tof histogram
for injector region (back scattered region)



Korean contribution for Hyper-K

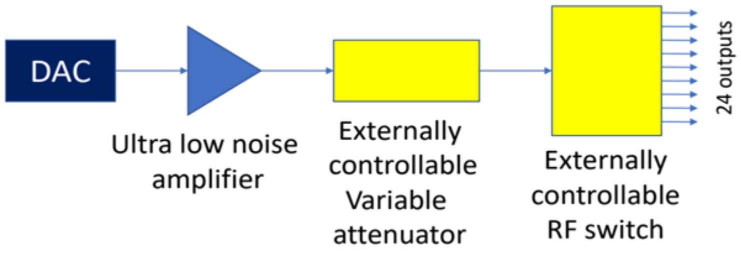
- PMT pre-calibration
  - PMT test before installation
    - Measure position dependence of QE×CE, gain, timing, charge, SPE response
    - Study QE dependence on angle, polarization, wavelength

  - Collaboration among Japan, Korea, and Australia
    - Calibration devices developed by Korean and Australian groups
    - Tested in CNU and the device being installed in Jikkento
    - Pre-calibration conducts in Japan

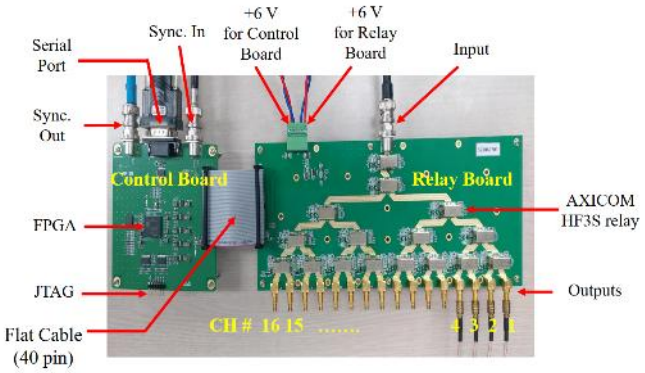


Korean contribution for Hyper-K

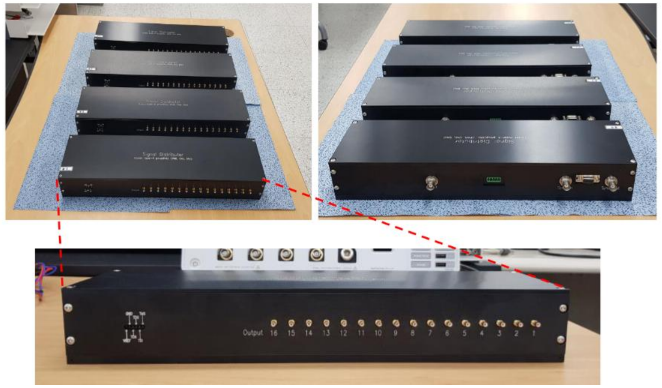
- Electronics
  - KNU has completed the development of a signal switcher for calibration.


DAC
Ultra low noise amplifier
Externally controllable Variable attenuator
Externally controllable RF switch
24 outputs

16-ch Signal Switcher


Serial Port
Sync. In
+6 V for Control Board
+6 V for Relay Board
Input
Sync. Out
Control Board
Relay Board
AXICOM HF3S relay
FPGA
JTAG
Outputs
Flat Cable (40 pin)
CH # 16 15 ....
4 3 2 1

Four Sets of 16-ch Signal Switcher Boxes



- Outer Detector (OD)
  - 3-inch NNVT test is done
  - Participate OD DAQ
  - CNU SRC plan to purchase 1 million USD over the next three years

- No Hyper-K poster is presented this time, but feel free to contact us for more information.

Summary

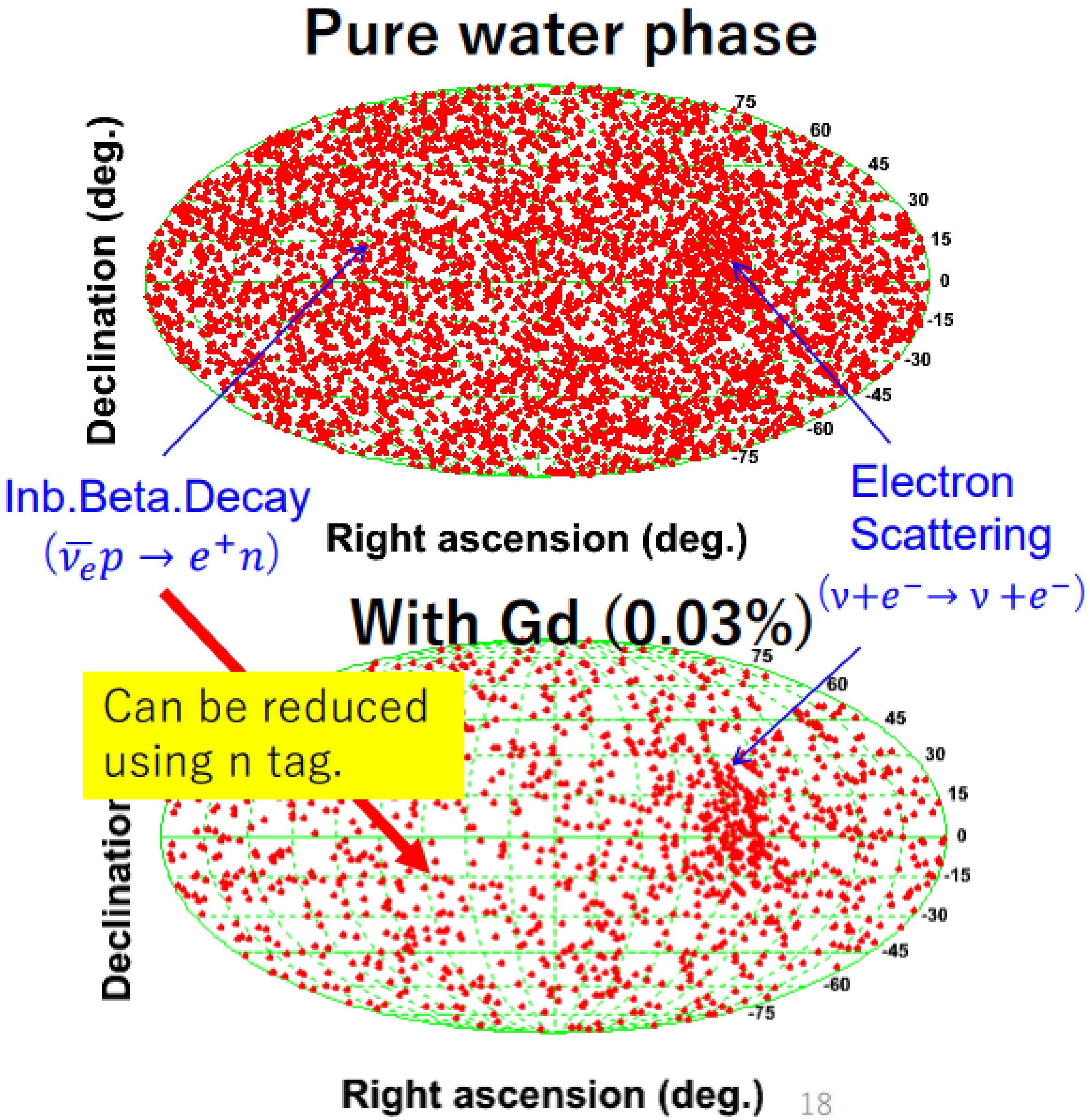
- Super-Kamiokande
  - Ultra pure water + Gd : Gd concentration is 0.01% (2020~2021) and 0.03% (2022~)
  - Gd-loaded water allows for improved neutron tagging efficiency
  - One poster presentation : proton decay analysis (Jung Seunghyun. SNU)
  - Korean contribution
    - Water parameter measurement, PMT T-Q calibration, water quality monitoring, physics analysis

- Hyper-Kamiokande
  - Next generation water Cherenkov detector
    - Volume increased about 5 times than Super-Kamiokande
    - Data taking will be started 2027
  - Construction and testing are on-going
  - Korean contribution
    - PMT pre-calibration, water parameter measurement, electronics design and produce, outer detector construction, laser injector design and test

backup

Galactic supernova burst detection

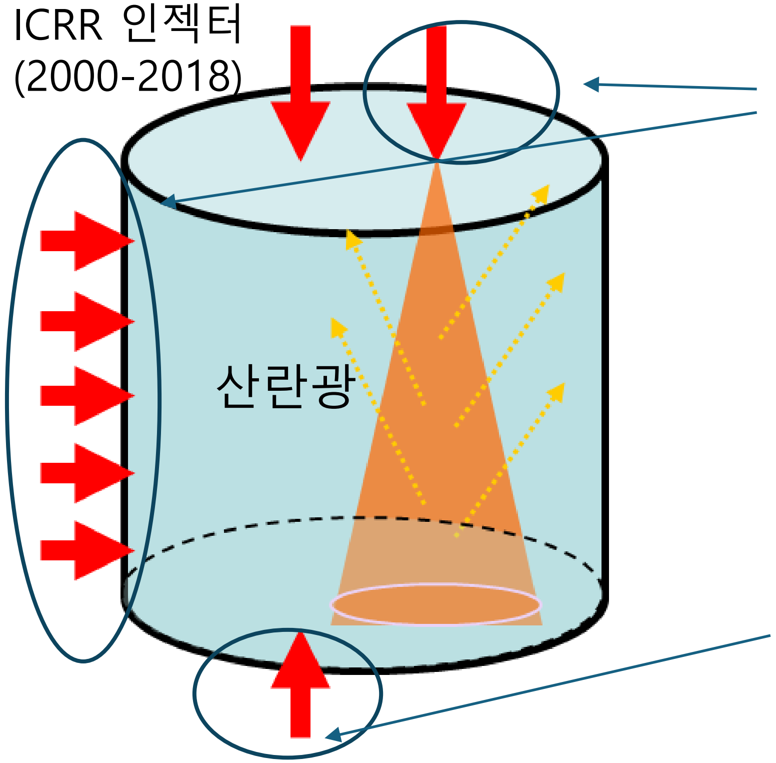
- Neutrinos can escape from a supernova earlier than photons.
  - Neutrinos arrive few min ~ hours before photons
  - Observation of the neutrino burst can inform telescopes.
    - SK can detect the direction of SN by itself
- Improvements in SK-Gd
  - Significance of SN is enhanced if we observe many IBD events.
    - Automatic alert
  - the pointing accuracy has been improved.



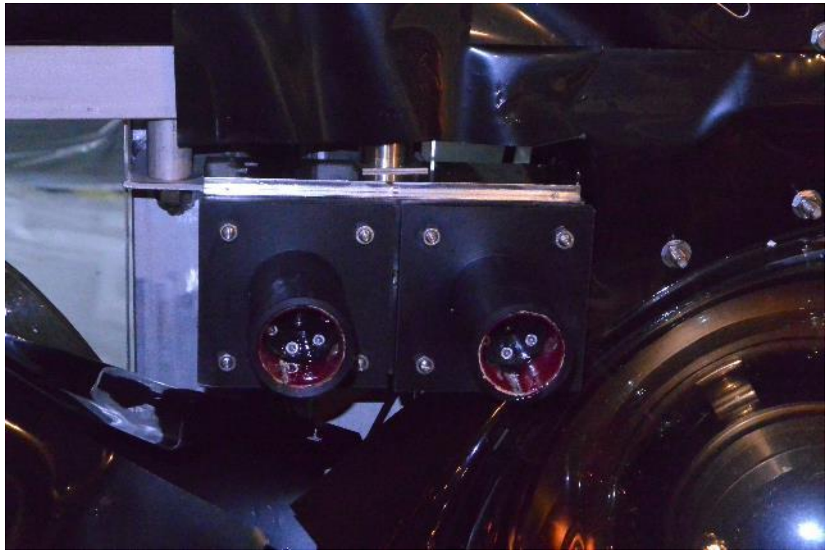
Can be reduced using n tag.

한국 그룹의 기여: 캘리브레이션

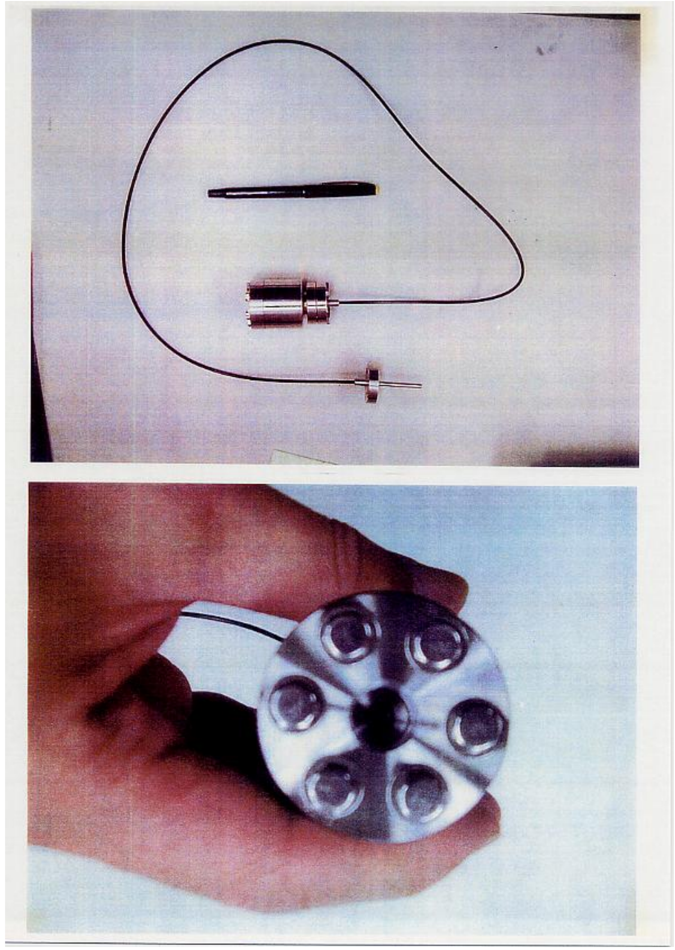
- SK-I 부터 20여년간 검출기 안쪽 벽에 설치된 빛 인젝터를 사용하여 빛의 SK 물에서의 산란률과 흡수율 측정과 그 변화 감시
- 산란률과 흡수율: 검출기 시뮬레이션, 에너지 캘리브레이션, 이밴트 재구성, 계통 오차 등에 중요한 변수



한국 그룹 인젝터와 지지대

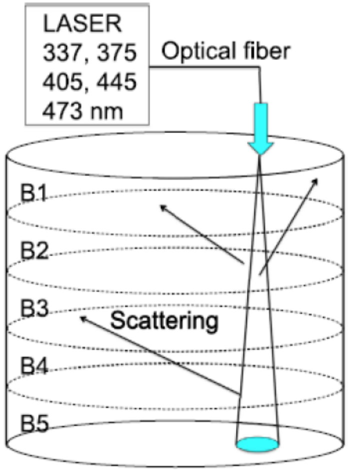


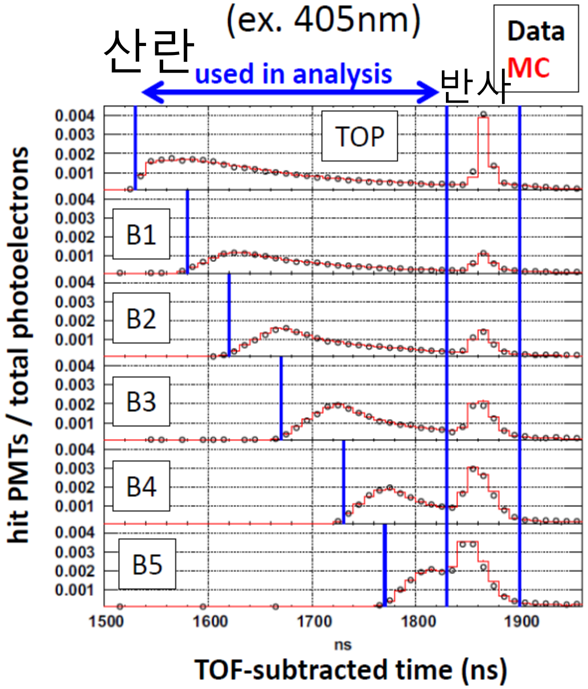
한국 그룹 인젝터
‘2002년 -

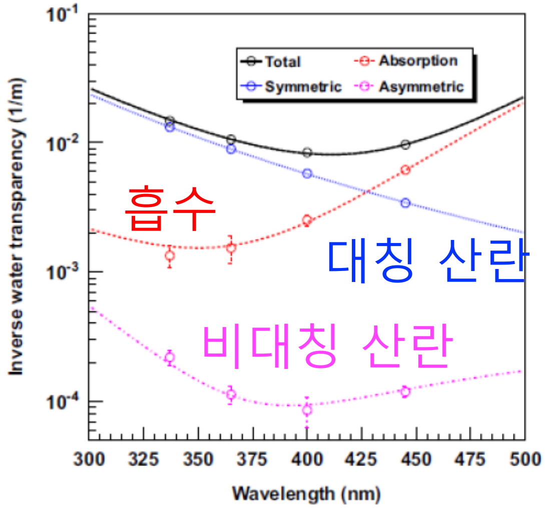


한국 그룹의 기여: 캘리브레이션

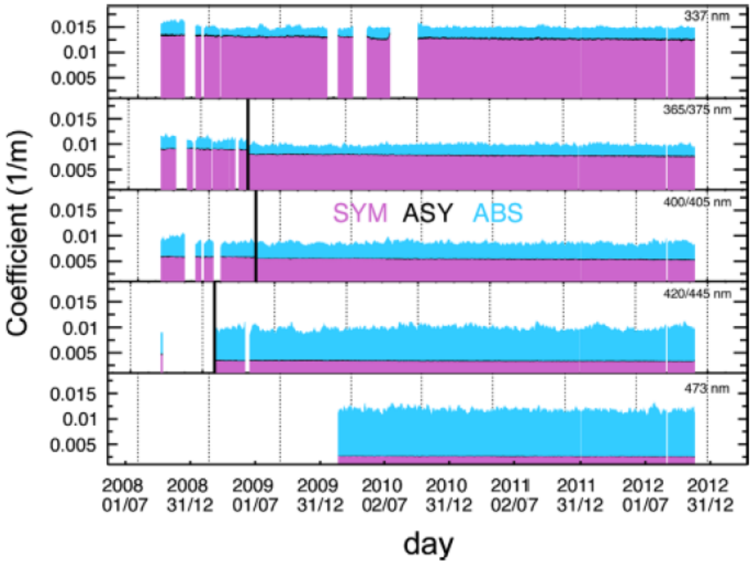
- 검출기 윗 면에 설치된 인젝터로 입사한 빛이 산란되어 PMT에 도달한 시간을 사용하여 다섯 파장에 대한 산란률과 흡수율을 측정.
- 이를 사용하여 SK 시뮬레이션에 파장에 따른 산란률과 흡수율의 모형을 결정.
- 산란률과 흡수율의 시간에 따른 변화를 감시
- Gd 두 번째 용해 후 SK-VII에서 빛의 산란/흡수 계수 측정 완료


LASER
337, 375
405, 445
473 nm
Optical fiber
B1
B2
B3
Scattering
B4
B5





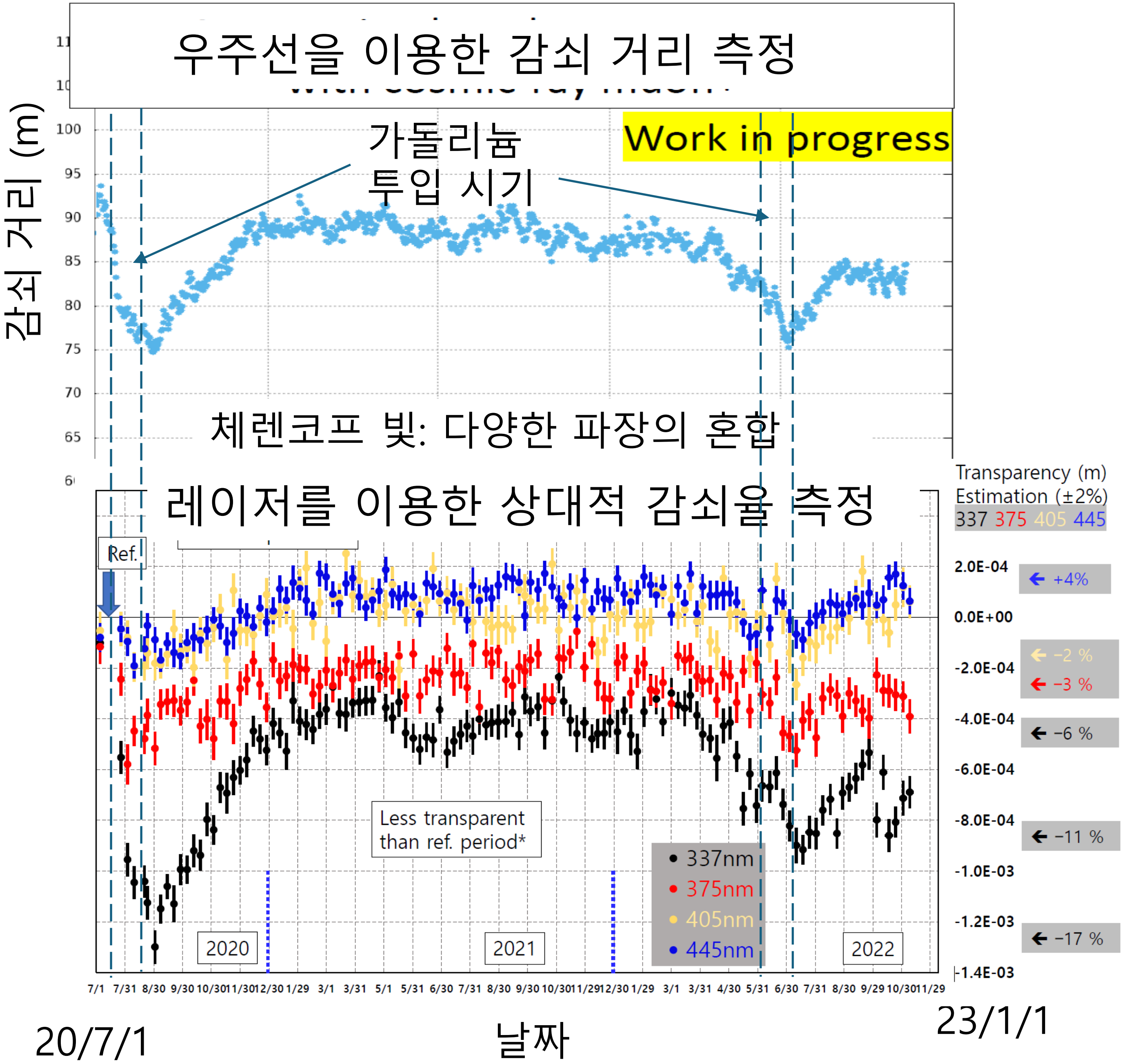
Data points (April 2009) fitted with empirical functions used in SKDETSIM



RMS/mean (Aug. 2008 – Nov. 2012):
~3% for symmetric scattering
20-40% for absorption

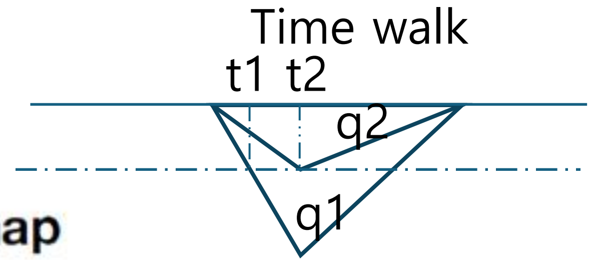
한국 그룹의 기여: 캘리브레이션
SK-Gd 물 투명도 변화 측정

- 광원 : 우주선(뮤온)에 의한 체렌코프 빛, 레이저, 제논 램프 등
- 가돌리늄 투입 동안 투명도 감소. 회복에 약 5개월.
- 짧은 파장에 큰 영향

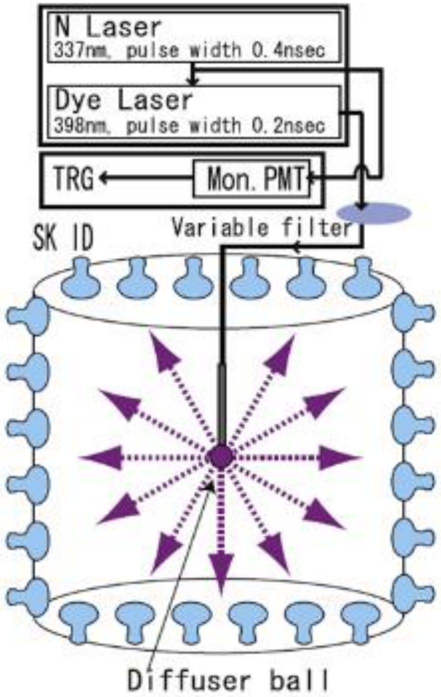


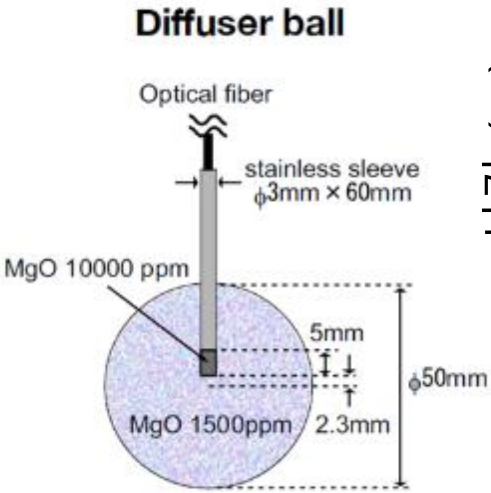
한국 그룹의 기여: 캘리브레이션

- 검출기 중심에서 퍼지는 레이저 빛을 사용하여, 전하량에 따른 PMT의 빛 검출시간 (PMT 신호의 discriminator 문턱 전압 넘는 시간)을 보정
- 2021년 12월부터 한국 그룹에서 담당

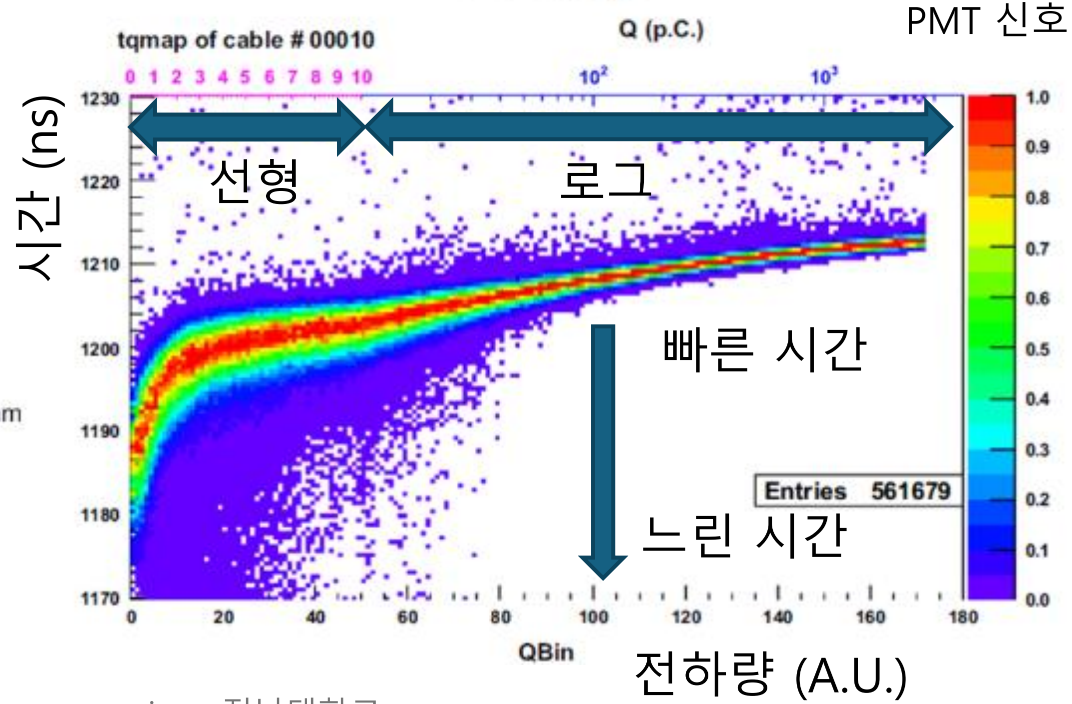

Time walk
t1 t2
q2
q1

PMT 신호 파형


N Laser
337nm, pulse width 0.4nsec
Dye Laser
398nm, pulse width 0.2nsec
TRG
Mon. PMT
SK ID
Variable filter
Diffuser ball

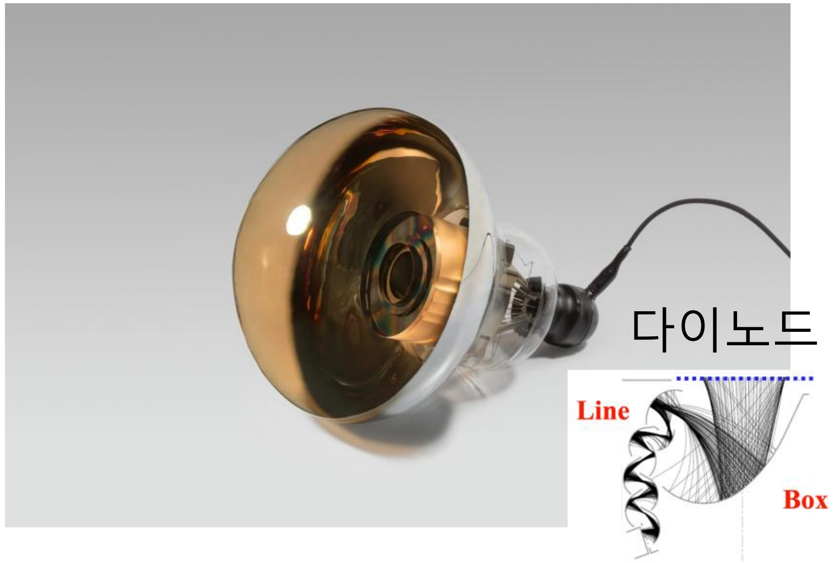

Diffuser ball
Optical fiber
stainless sleeve
ϕ3mm × 60mm
MgO 10000 ppm
5mm
ϕ50mm
MgO 1500ppm
2.3mm

TQ map



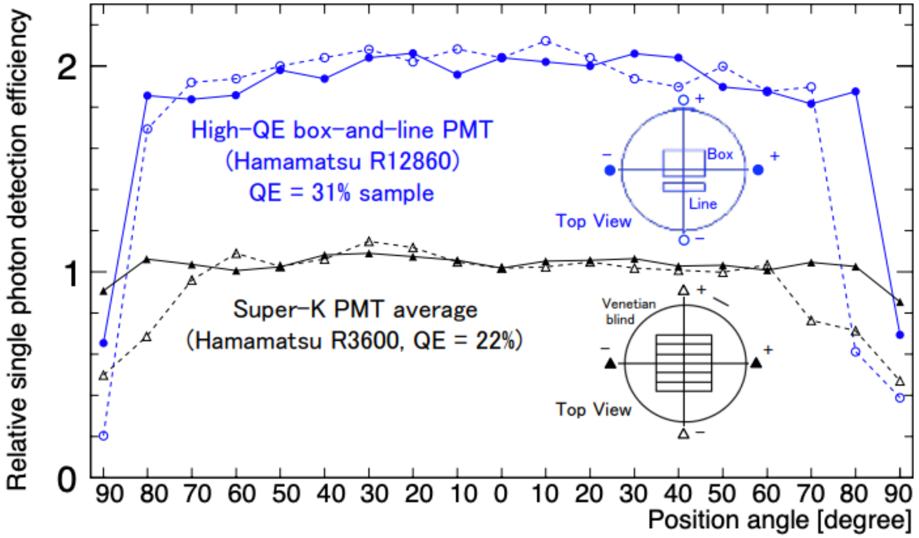
PMT

- Hamamatsu 사의 50 cm Box&Line PMT "R12860“
- SK PMT 와 같은 크기. 성능 대폭 향상
  - 빛 검출 효율 두 배 향상
  - 시간/전하 분해능 두 배 향상
- 20000 PMT 로 검출기 표면 20% 덮음.
- 생산과 검사 진행 중



다이노드 개선

각도에 따른 광자 검출 효율



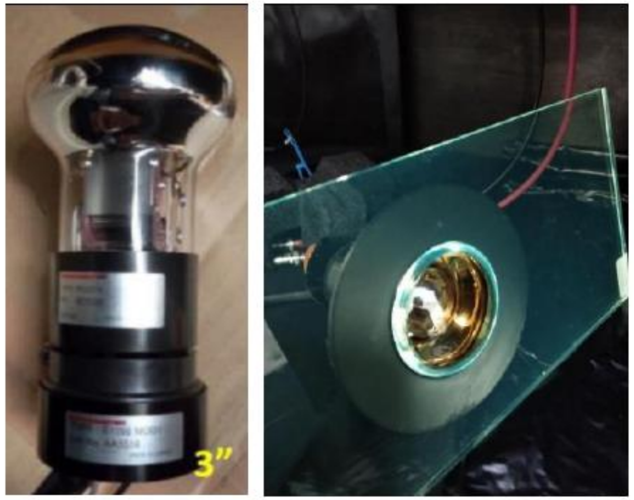
PMT 검사

- 제조된 PMT 카미오카에 운송. 1만개 이상
- 근처 폐교를 창고 겸 PMT 검사시설로 사용
- 기존 SK 시설도 사용.

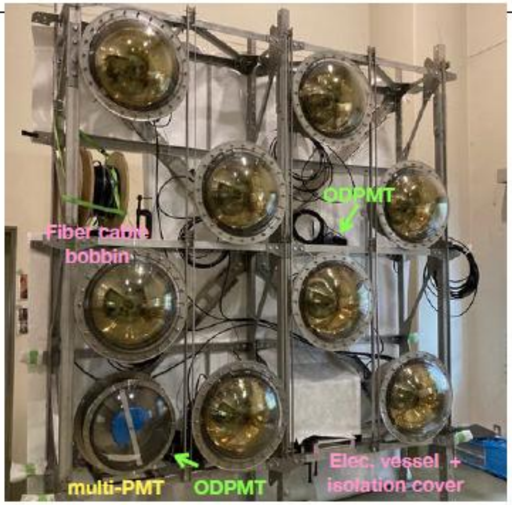
광센서와 수중 전단 보드 현황

(Wavlength shifting)

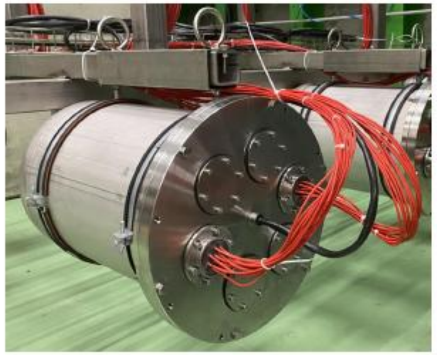
Outer detector: PMT+WLS plate

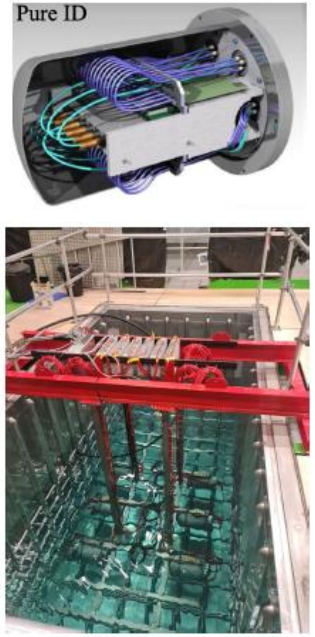


Photosensors/elec. mockup

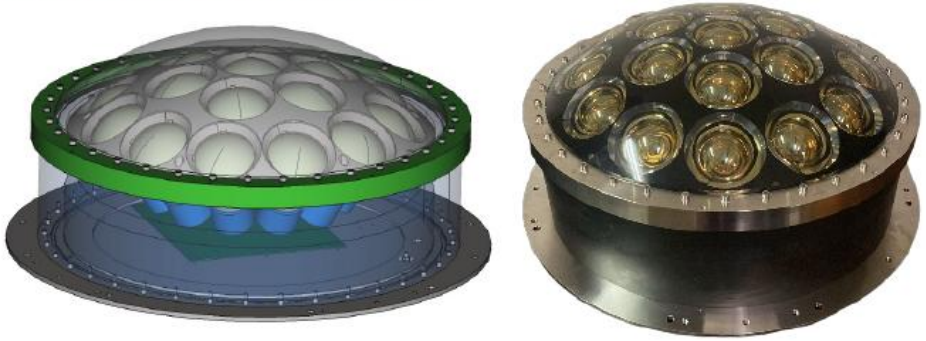

Fiber cable bobbin
ODPMT
multi-PMT
ODPMT
Elec. vessel + isolation cover

Underwater electronics: Case design and feedthrough

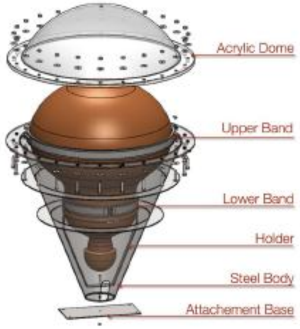


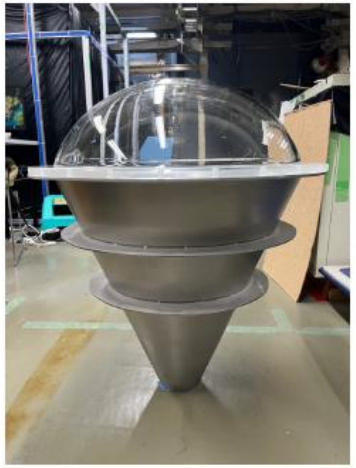


Multi-PMT module:

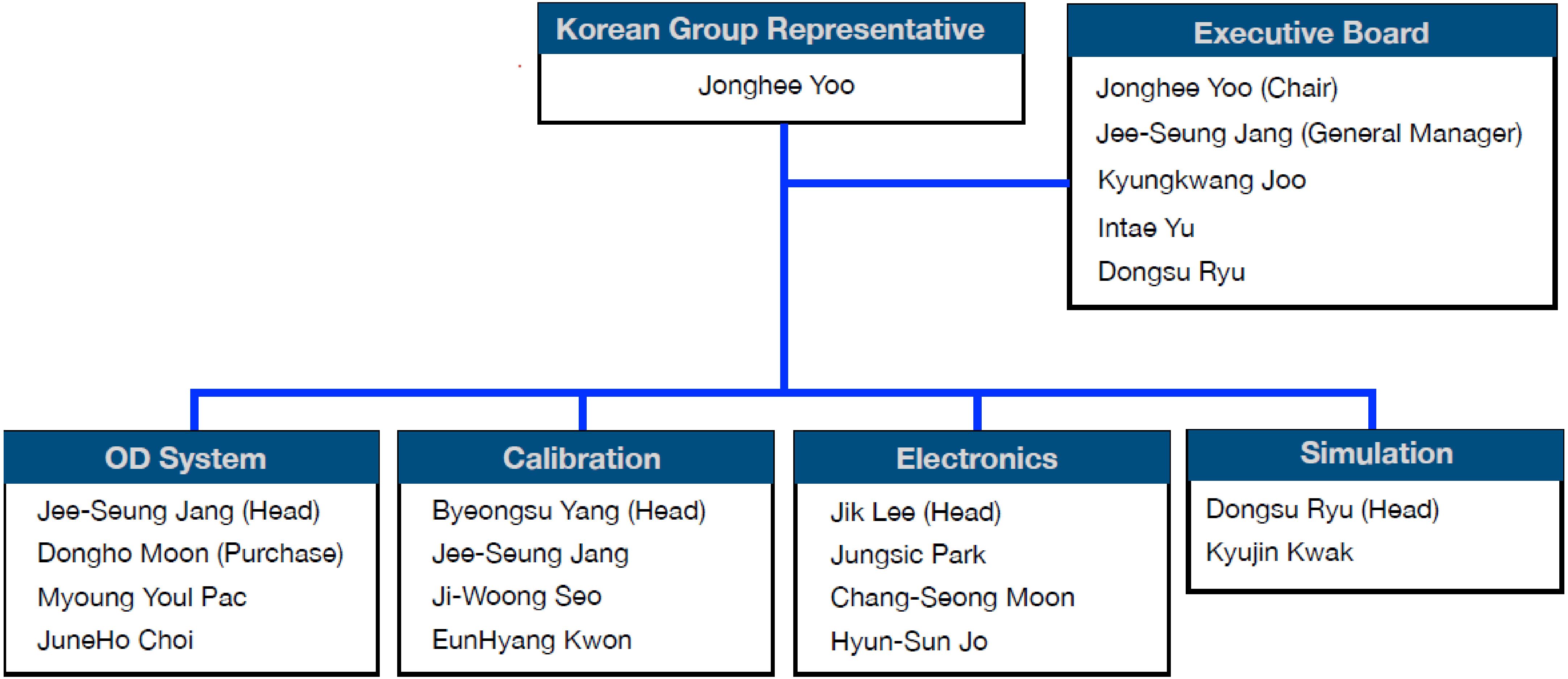


PMT cover


Acrylic Dome
Upper Band
Lower Band
Holder
Steel Body
Attachement Base



한국 그룹 조직도



Korean Group Representative

Jonghee Yoo

Executive Board

Jonghee Yoo (Chair)
Jee-Seung Jang (General Manager)
Kyungkwang Joo
Intae Yu
Dongsu Ryu

OD System

Jee-Seung Jang (Head)
Dongho Moon (Purchase)
Myoung Youl Pac
JuneHo Choi

Calibration

Byeongsu Yang (Head)
Jee-Seung Jang
Ji-Woong Seo
EunHyang Kwon

Electronics

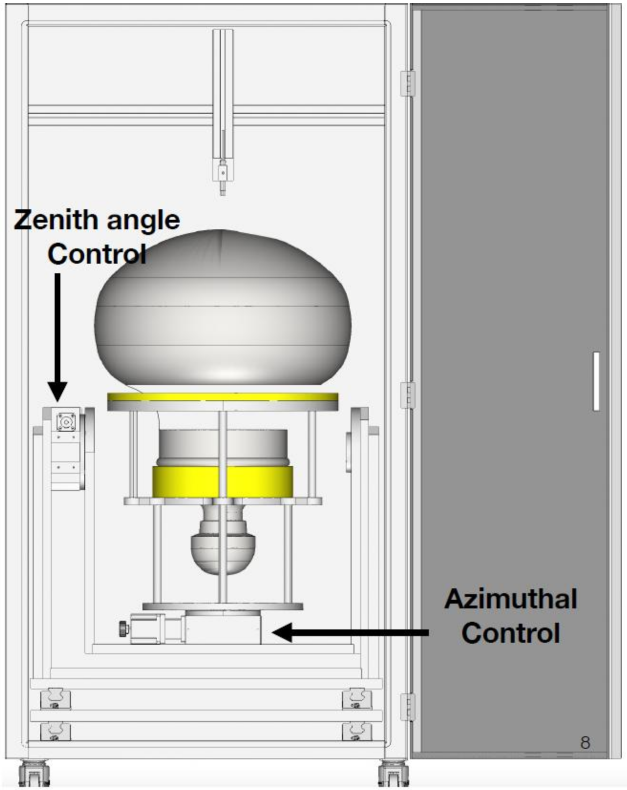
Jik Lee (Head)
Jungsic Park
Chang-Seong Moon
Hyun-Sun Jo

Simulation

Dongsu Ryu (Head)
Kyujin Kwak

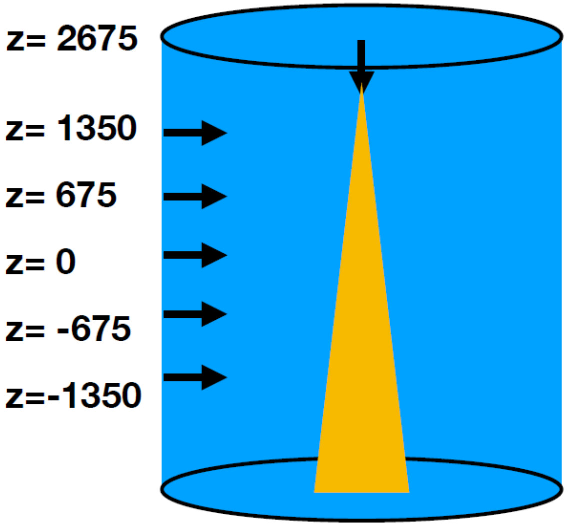
한국 그룹의 기여: PMT pre-calibration

- 약 2% (약 400개)의 PMT를 검출기에 설치 전 기본 성능 측정
  - QE X CE, Gain, 시간, 전하, 단일 전하 응답 등의 위치 의존성
  - QE의 각도, 편광, 파장 의존성
- 일본, 한국, 호주 그룹 협력
  - 한국과 호주 그룹이 캘리브레이션 장치 개발.
  - 일본 현지에서 pre-calibration 진행.
    수중 시험 진행
- 이번 여름부터 광주 과기원에서 개발한 장비로 일본에서 측정 예정

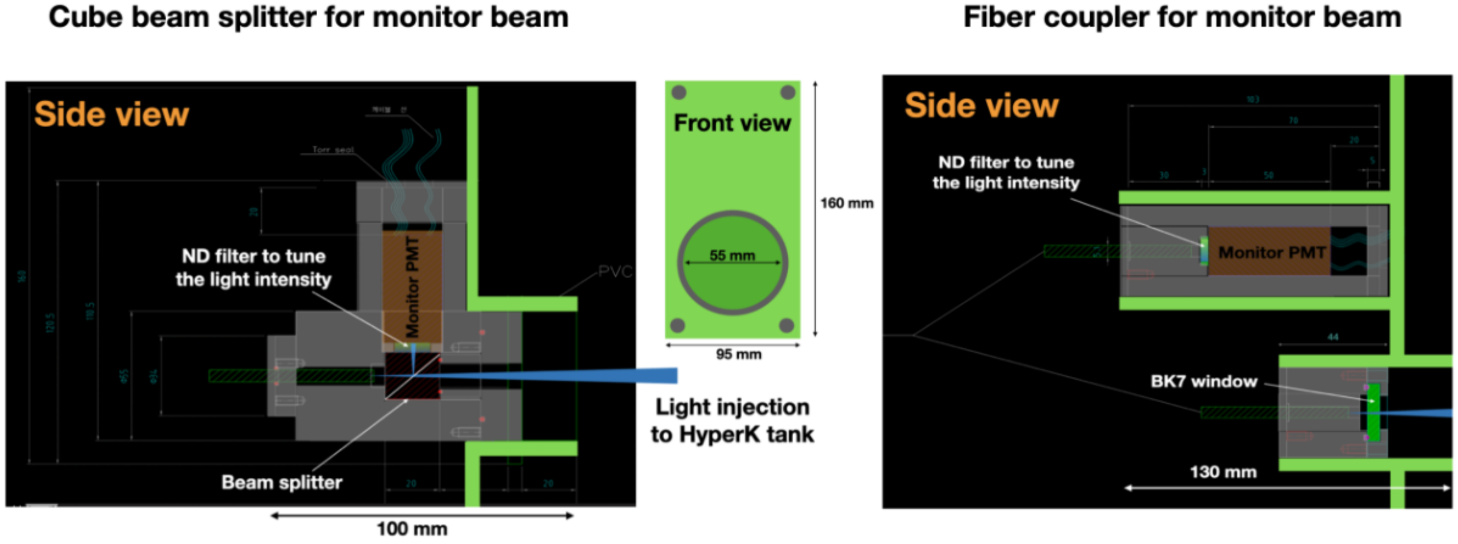

Zenith angle Control
Azimuthal Control
8

한국 그룹의 기여: 캘리브레이션

- SK에서와 같이 물에서의 산란률과 흡수율 측정과 그 변화 측정.
- 현재 빛 인젝터 설계 중. 시뮬레이션으로 성능 점검 (울산과기원 성광언 학생/SK 한국 연구원 협력)


z= 2675
z= 1350
z= 675
z= 0
z= -675
z=-1350

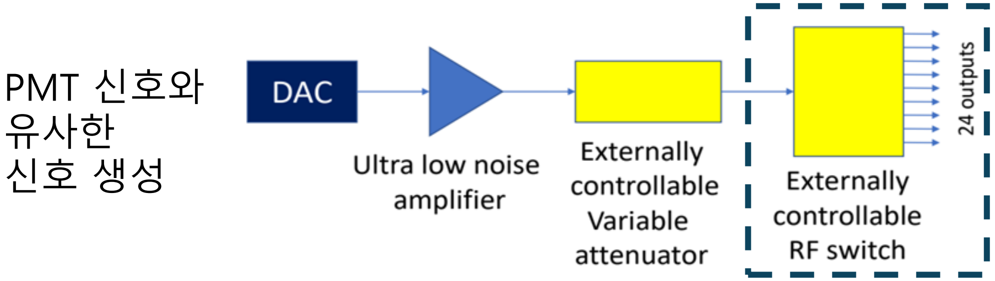
2 candidates for Korean injector


Cube beam splitter for monitor beam
Side view
ND filter to tune the light intensity
Monitor PMT
PVC
Beam splitter
100 mm
Front view
55 mm
160 mm
95 mm
Light injection to HyperK tank
Fiber coupler for monitor beam
Side view
ND filter to tune the light intensity
Monitor PMT
BK7 window
130 mm

We'd like to measure the injection light by monitor sensor

한국 그룹의 기여: 전자 장치

- 캘리브레이션 용 신호 분배기 경북대에서 개발 완료



PMT 신호와
유사한
신호 생성

DAC

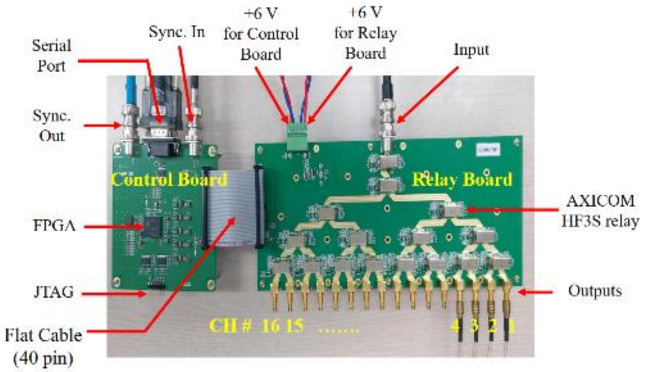
Ultra low noise amplifier

Externally controllable Variable attenuator

Externally controllable RF switch

24 outputs

16-ch Signal Switcher

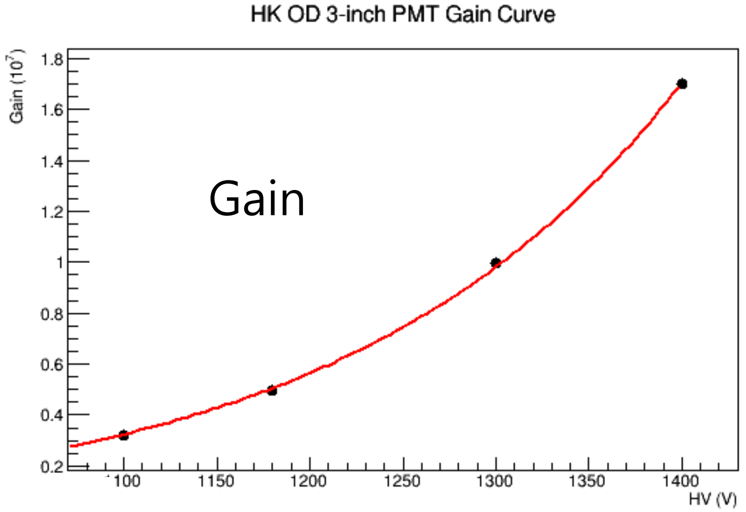

Serial Port
Sync. In
+6 V for Control Board
+6 V for Relay Board
Input
Sync. Out
Control Board
Relay Board
AXICOM HF3S relay
FPGA
JTAG
Outputs
Flat Cable (40 pin)
CH # 16 15 ……. 4 3 2 1

Four Sets of 16-ch Signal Switcher Boxes

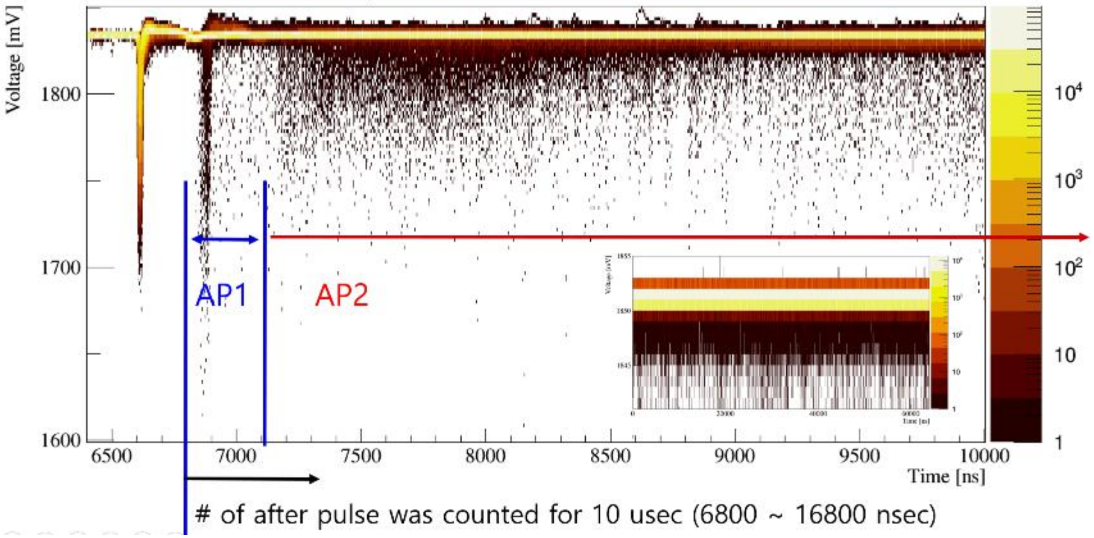
Output 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

한국 그룹의 기여: OD (바깥 검출기)

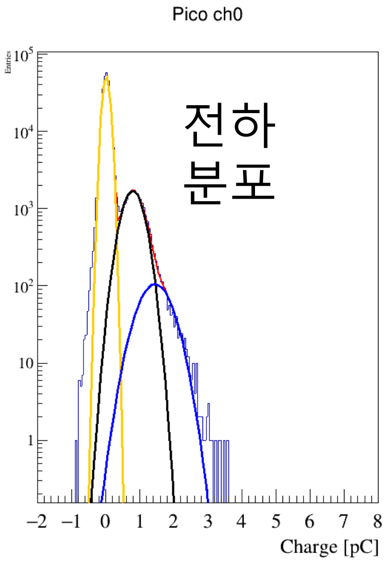
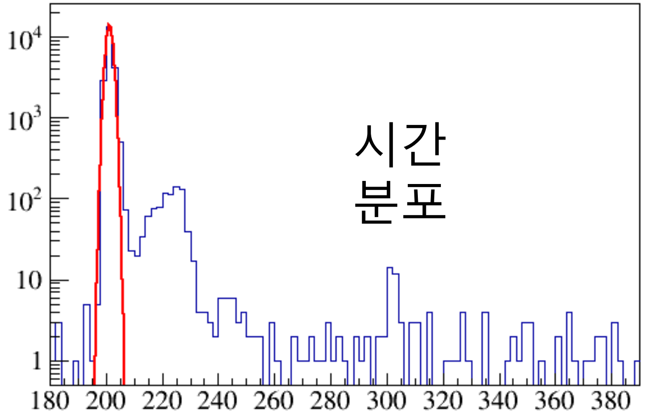
- OD PMT (3 inch NNVT) 시험 완료
- OD DAQ 참여.
- 3 년동안 1백만 USD 집행 예정: 전남대 SRC 집행 방법, 구매 장비 협의 중


HK OD 3-inch PMT Gain Curve

A measurement for afterpulse



# of after pulse was counted for 10 usec (6800 ~ 16800 nsec)


Pico ch0