TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Water Cherenkov for Long baseline neutrino oscillation

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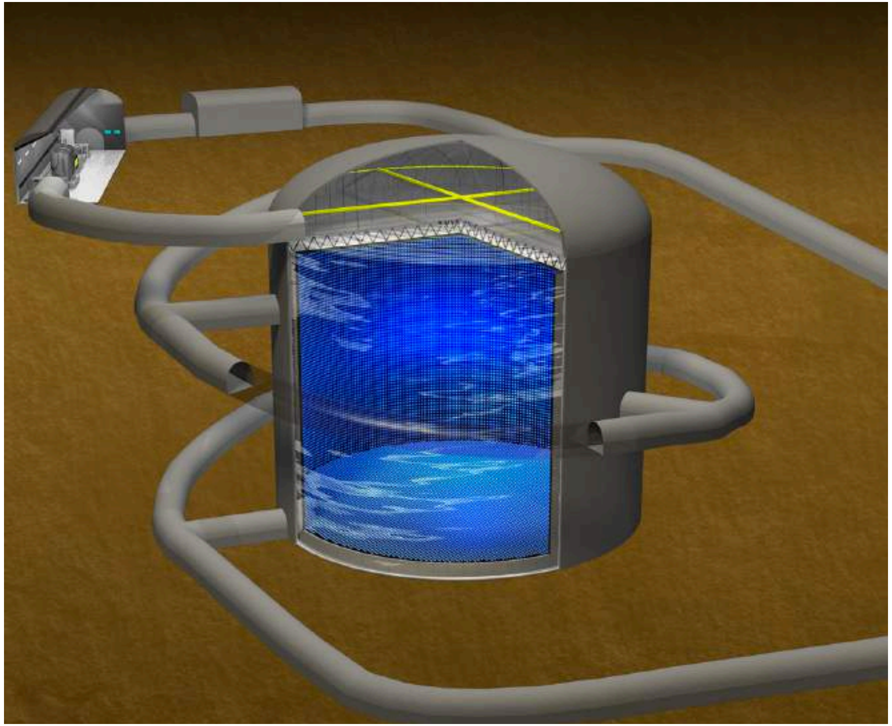
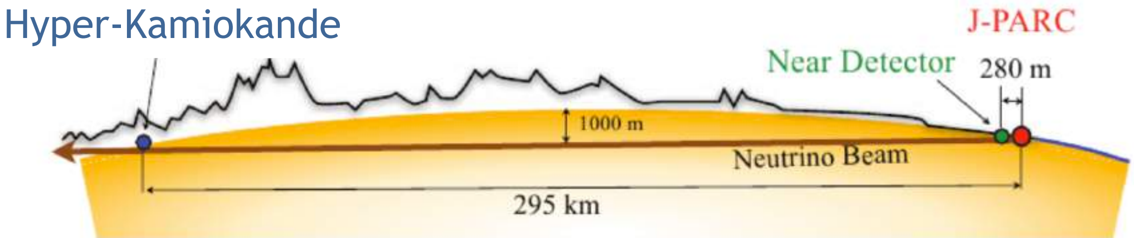
JUne 7, 2019

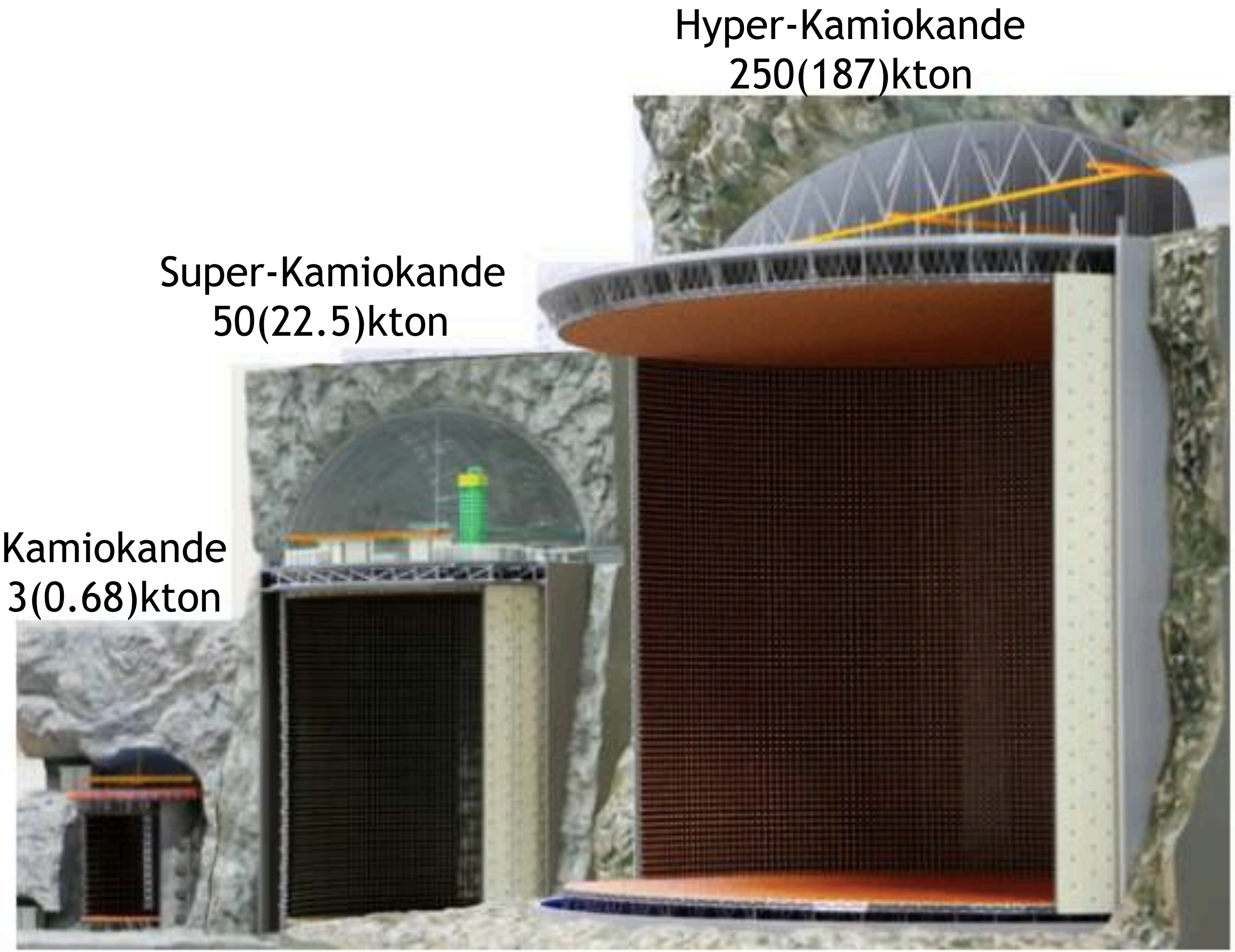
Hyper-Kamiokande





- 187kton (fid.) water Cherenkov
  - 8 times larger than SuperK
- Physics goal
  - precision ν oscillation
    - long baseline neutrinos
    - atmospheric neutrinos
  - neutrino astronomy
    - supernova & solar neutrino
  - new physics
    - nucleon decays
    - dark matter
    - non-standard ν interaction (NSI)
- Construction to start in 2020

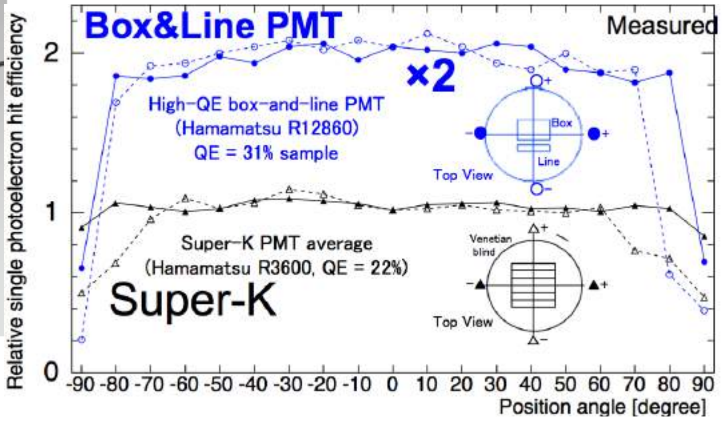
Water Cherenkov detectors in Kamioka

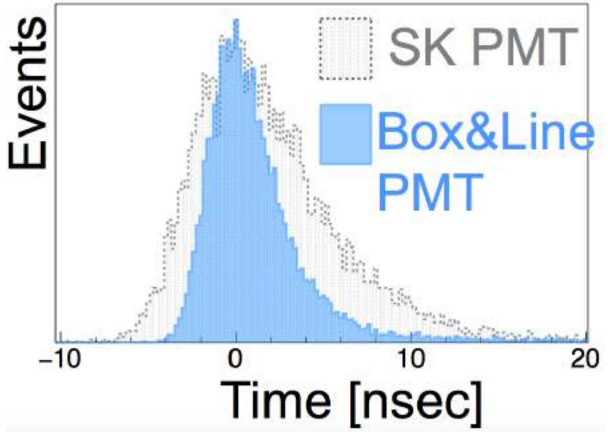


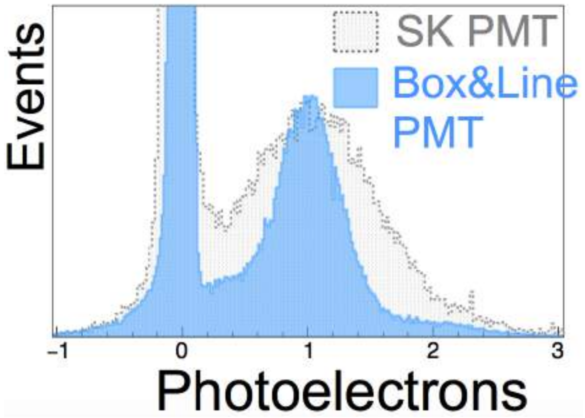
- Precise neutrino oscillation studies
  - larger detector
  - more precise information
    - better efficiency
    - better timing
    - less noise
    - more granularity
  - better calibrations
    - control of systematics

Hyper-K 20” photosensor development

Bq/kg	U	TH	K-40
20” HK	5.4	1.8	1.6
20” SK	5.5	1.8	18.2



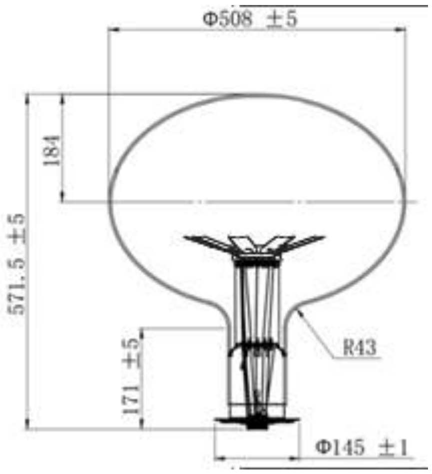




- New Hamamatsu 20” Box&Line PMT
  - x2 better photon detection efficiency:
    - QE=30%, CE=95%
  - x2 better transit time spread:
    - TTS=2.7nsec FWHM
  - x2 better single photoelectron resolution
    - 53%→35%
  - x2 better pressure resistance:
    - 60m water depth
  - x2 higher dark rate:
    - 8kHz: effort to reduce it
    - radioactivity in the glass
  - Hamamatsu mass production started for JUNO project

MCP PMT for JUNO

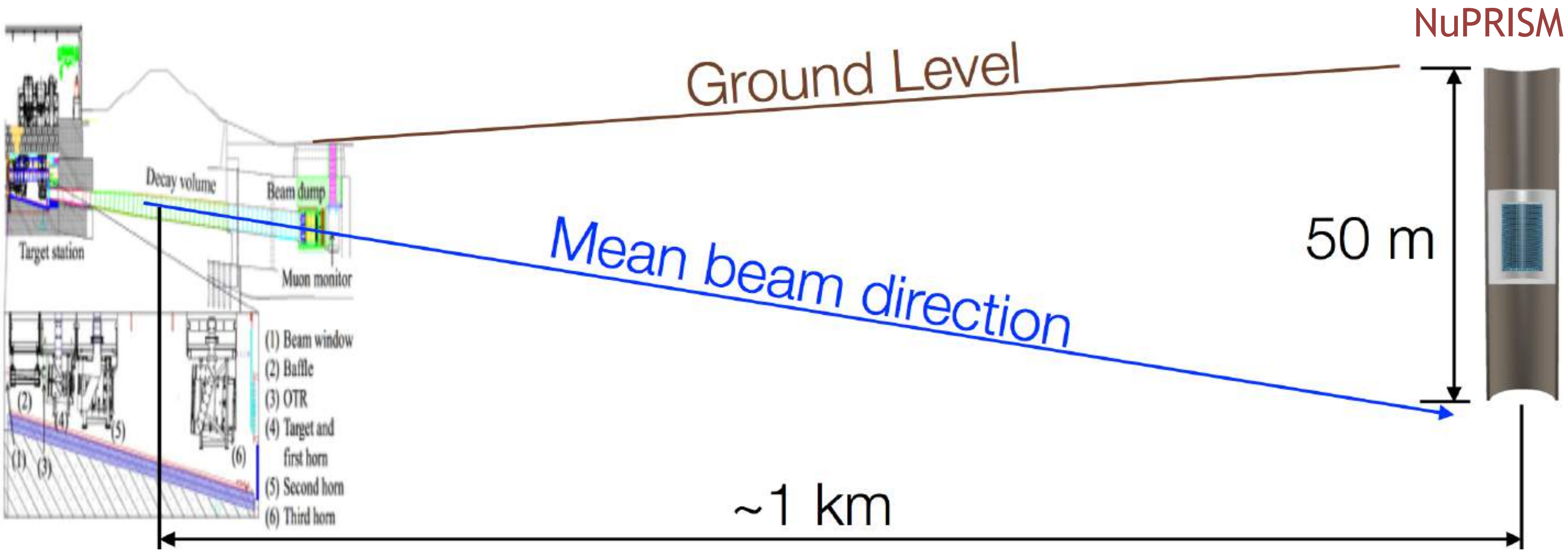
Type	8″			20″					
	GDB-6081			GDB-6201			GDB-6203		
	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.
Photocathode characteristics									
Spectral Range(nm)		300-650			300-650			300-650	
Maximum sensitivity at (nm)		380			380			380	
Sensitivity									
Luminous(μA/lm)		70			80			80	
QE at 405 nm(%)		26			30			30	
Supply Voltage(V)	1500	1900	2400	1500	1750	2000	1650	1900	2000
Gain		1×10^7			1×10^7			1×10^7	
Anode Dark Current(nA)		100	700		150	1000		100	1000
Background Noise@22℃(cps)		5 k	20 k		30 k	100 k		25 k	100 k
Single Electron Spectrum									
Energy Resolution(%)		60			35			40	
Peak to Valley Ratio		2.5		3	7	10	2.5	4.5	6
Anode Pulse									
Rise Time(ns)		1.4			1.4			1.4	
TTS (FWHM) (ns)		3			15			5.5	



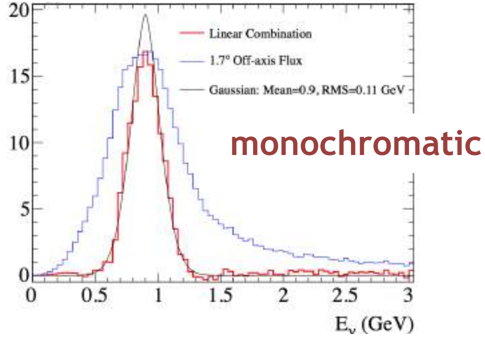
Photocathode coverage

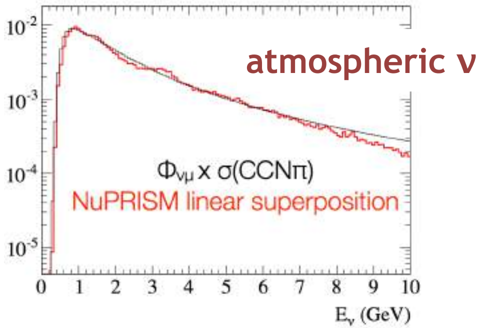
- SuperK:
  - 40% coverage with 20” R3600 PMT’s
    - 10 pe/MeV: 1000 photoelectrons for 100MeV electrons
  - atmospheric neutrino reconstruction and efficinecy were similar at SK-III with 20% photocathode coverage:
    - 1/2 in light yield and 1/2 in granularity was OK for atm. ν
- HyperK:
  - 20% coverage with x2 better detection efficiency 20” PMT
    - light yield is the same
    - granularity near the wall is similar to SK-III
  - Significant improvements expected by adding multi-PMT’s
    - intermediate water Cherenkov detector (IWCD/NuPRISM)
    - improved reconstructions on events near the wall and multi-ring events
    - neutron tagging (anti-neutrino tagging)

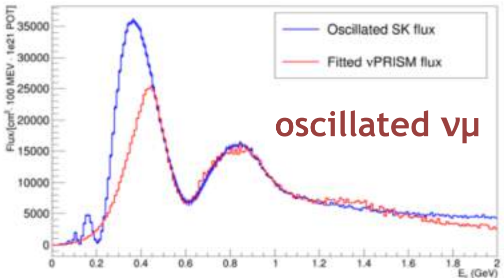
Intermediate water Cherenkov IWCD/NuPRISM

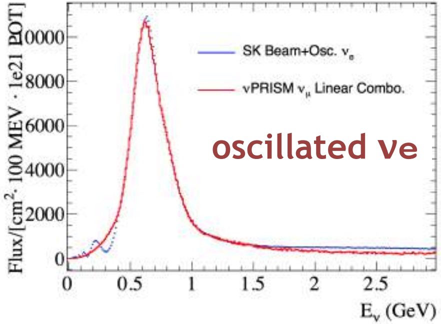


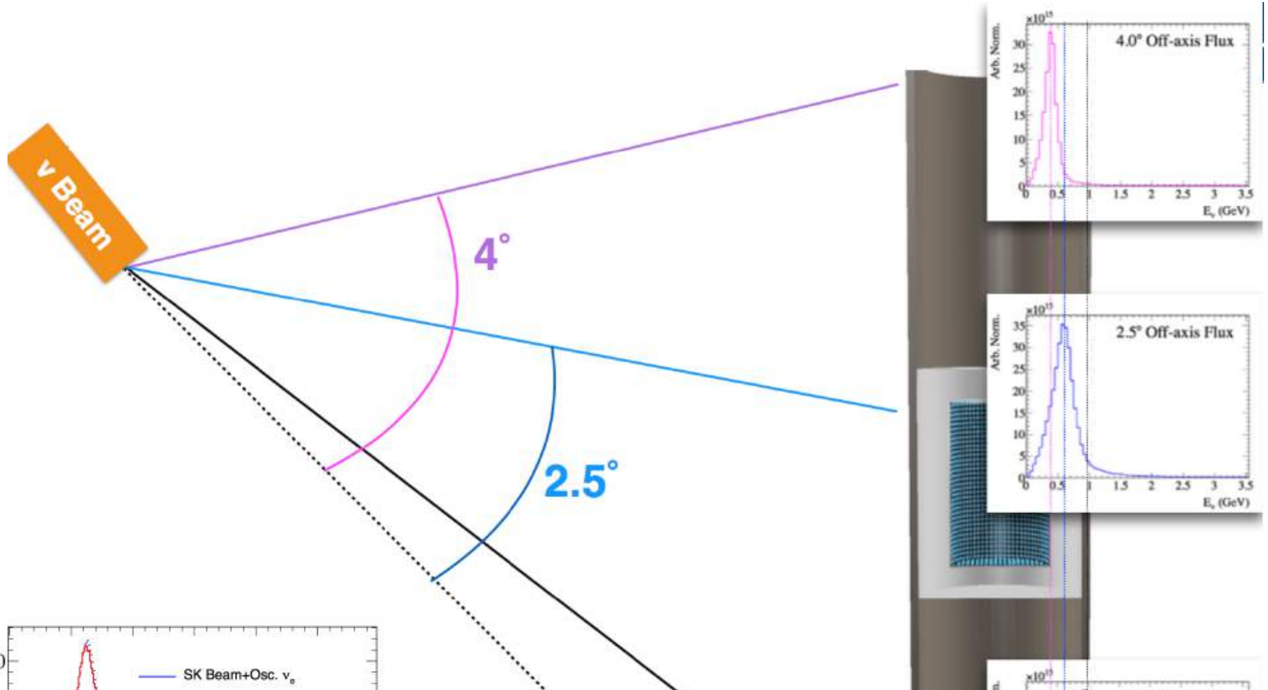
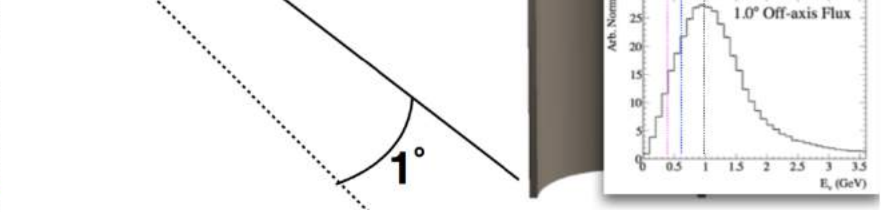
NuPRISM linear combination





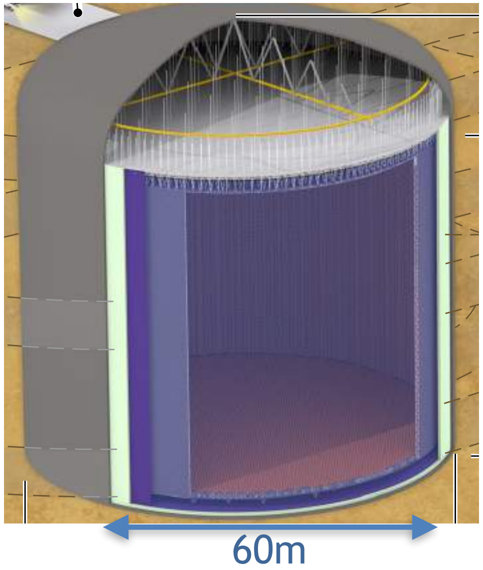


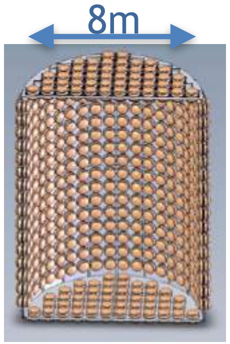


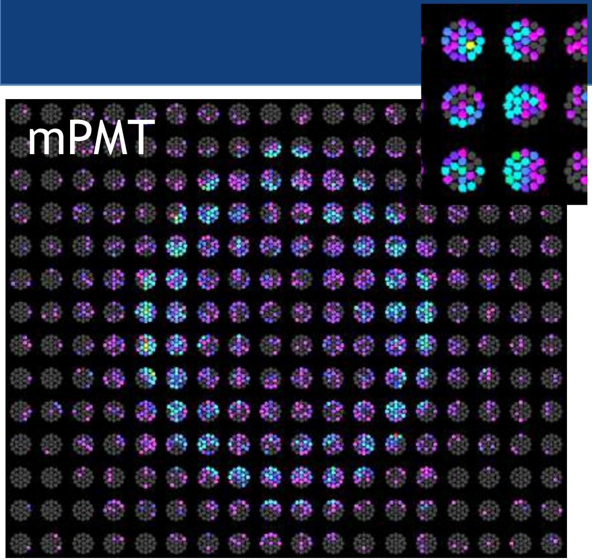



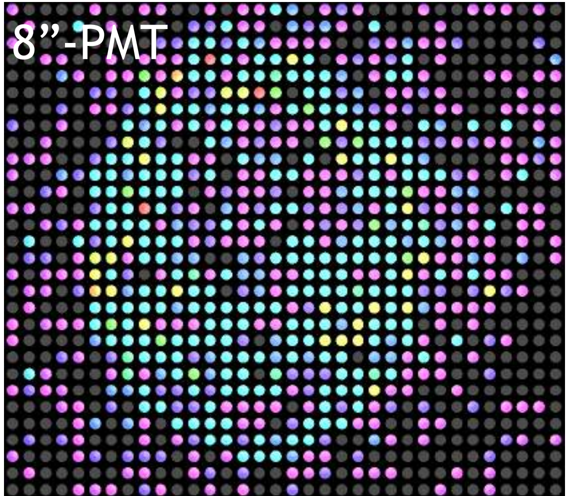
IWCD/NuPRISM detector requirement

- Lesson from the K2K 1kton near water Cherenkov
  - 20” PMT was too coarse in event reconstruciton
  - limited by the detector calibration
- Fiducial volume (vertex) systematics
  - 1% uncertainty: 2ΔR/R=1% → ΔR=0.5%R
    - HK:15cm, IWCD:2cm
  - Finer granularity and better timing are required:
    - SK: 50cm(PMT)/30m=1.7%, TTS(σ)=2.5nsec ~ 50cm
    - HK: 50cm(PMT)/60m=0.8%, TTS(σ)=1.1nsec ~ 20cm
    - IWCD: 7.6cm(PMT)/8m=0.9%, TTS(σ)=0.6nsec ~ 12cm
- Precise calibration
  - Precise (~1cm) position information: Photogrammetry
  - Secondary interactions and other potential problems
    - IWCD test beam experiment

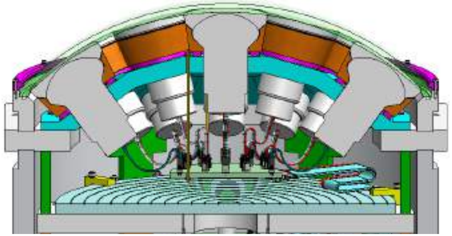


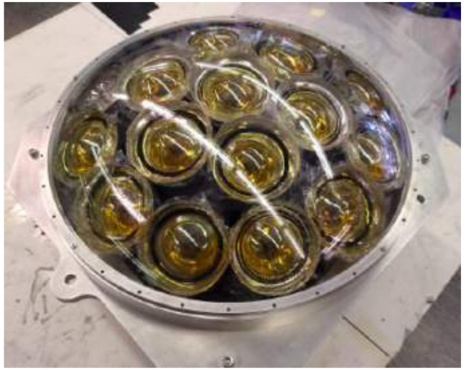


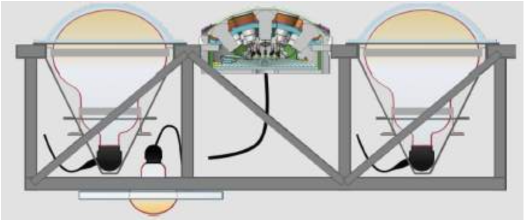




- multi-PMT (mPMT)
  - Concept developed by KM3NeT
  - 19 of 3" PMT's in 20" vessel
    - economical 3" PMT's
- mPMT for IWCD (NuPRISM)
  - finer granularity and better timing resolution for a smaller detector
- mPMT for HyperK
  - improved event reconstruction
  - finer granularity
    - multi-ring reconstruction
  - x2 better timing and lower dark rate
    - neutron tagging





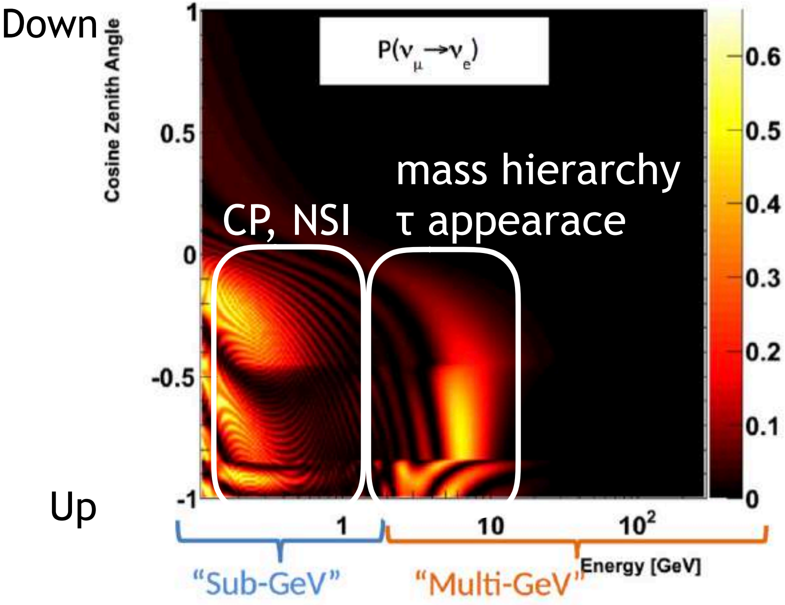


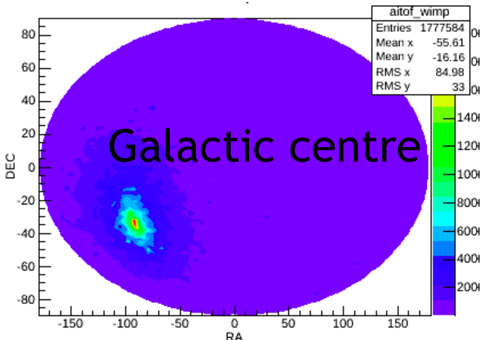
3” PMT (R14374, XP82B)

- Benefit of 3” PMT’s for multi-PMT
  - Finer granularity: 3/20=15% in size, $3^2/20^2$=2.25% in area
  - TTS (FWHM): 1.4nsec (Hamamatsu R14374), 3.7nsec (HZC XP82B20)
    - TTS = 5.5nsec (SK 20” R3600), 2.7nsec (HK 20” R12860)
  - Dark rate (10^{o}C): 60Hz (R14374), 120Hz (XP82B20)
    - Dark rate 8kHz for HK PMT: 8kHz x $3^2/20^2$=180Hz
  - Stability:
    - 3” is less sensitive to magnetic field and mechanical shocks
- Economical option is developed for PET detector (and KM3NeT)
  - 20” PMT: \$10/inch^2 (\$4000/PMT)
  - 3” PMT: \$20/inch^2 (\$200/PMT)
    - light concentrator to enhance sensitivity for mPMT

Multi-ring event reconstructions

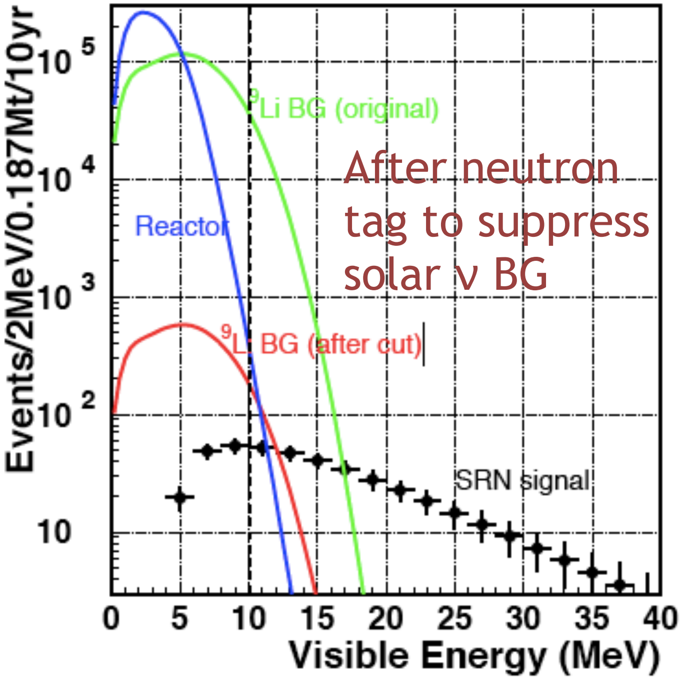
- CC1π measurement
  - Additional events in the CP violation studies
  - identify anti-neutrino (CC1π-) and neutrino (CC1π+) in atmospheric ν
    - mass hierarchy (several GeV)
    - CP (1-2GeV)
- Proton decay reconstruction
- Astronomical neutrinos, indirect dark matter
  - neutrino direction pointing

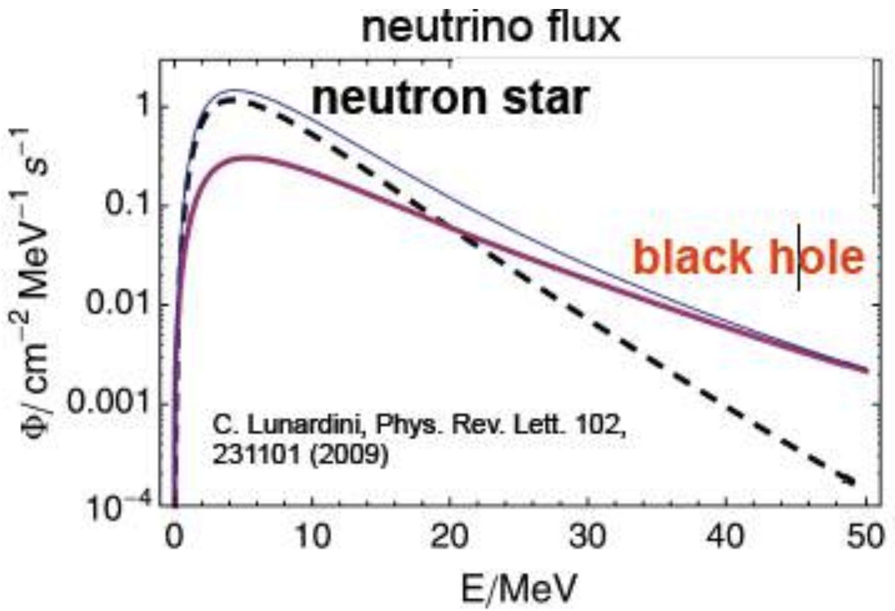




- Scientific benefit of the neutron tagging = $\bar{\nu}$ tagging
  - study wrong sign component in CP measurement
    - neutrino contamination in anti-neutrino cancels CP
  - sub-GeV atmospheric neutrino oscillogram
    - anti-neutrino has forward cross section: neutrino direction
  - supernova neutrino detection
    - reject solar ν backgrounds in relic supernova ν: energy spectrum
    - enhance ν_e elastic in supernova burst: supernova direction
- Requirements for neutron tagging: $np \rightarrow d\gamma(2.2\text{MeV})$
  - limited by accidental dark hit backgrounds:
    - low dark rate and better timing of the new 3” PMT’s has an impact

Neutrinos from the past supernova explosions:
History of black hole formation can be investigated

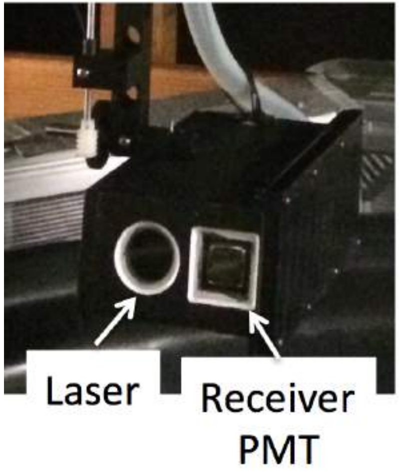


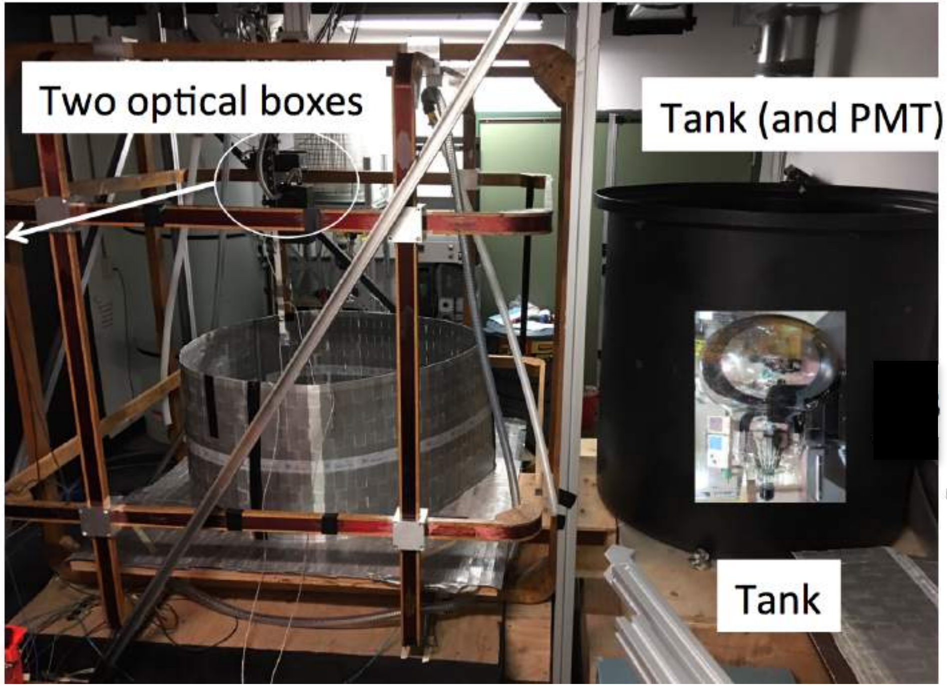


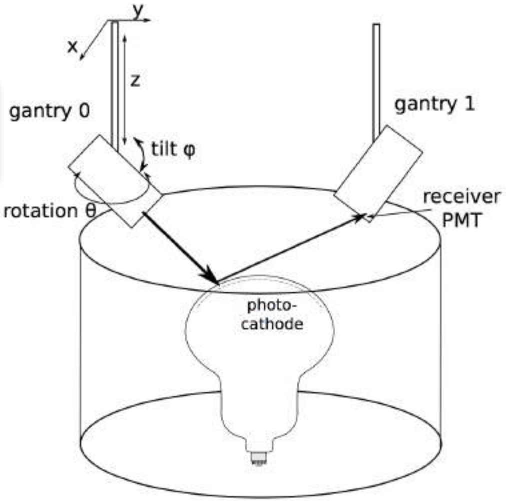
Water Cherenkov detector and calibration

- 1% level calibration is required for future water Chrenkov
  - Detailed understanding of all the elements required
    - rely on physics control samples as check of systematics
- Calibration of each components
  - water transmission and reflection: laser light source
  - position calibration (source, PMT): photogrammetry similar to SNO+
  - in-situ PMT response measurement:
    - photon detection efficiency, timing calibration, magnetic field measurement
    - measure environmental parameters: temperature, magnetic field
  - ex-situ PMT response measurement: photosensor test facility
    - characterize basic responses of the PMT
- Measurement of physics process in water Cherenkov: beam test
  - Hadron interactions inside the water
  - Cherenkov photon distribution measurement, e.g. impact of delta-ray production

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer
- Magnetic shielding
  - compensation coil, Giron shield

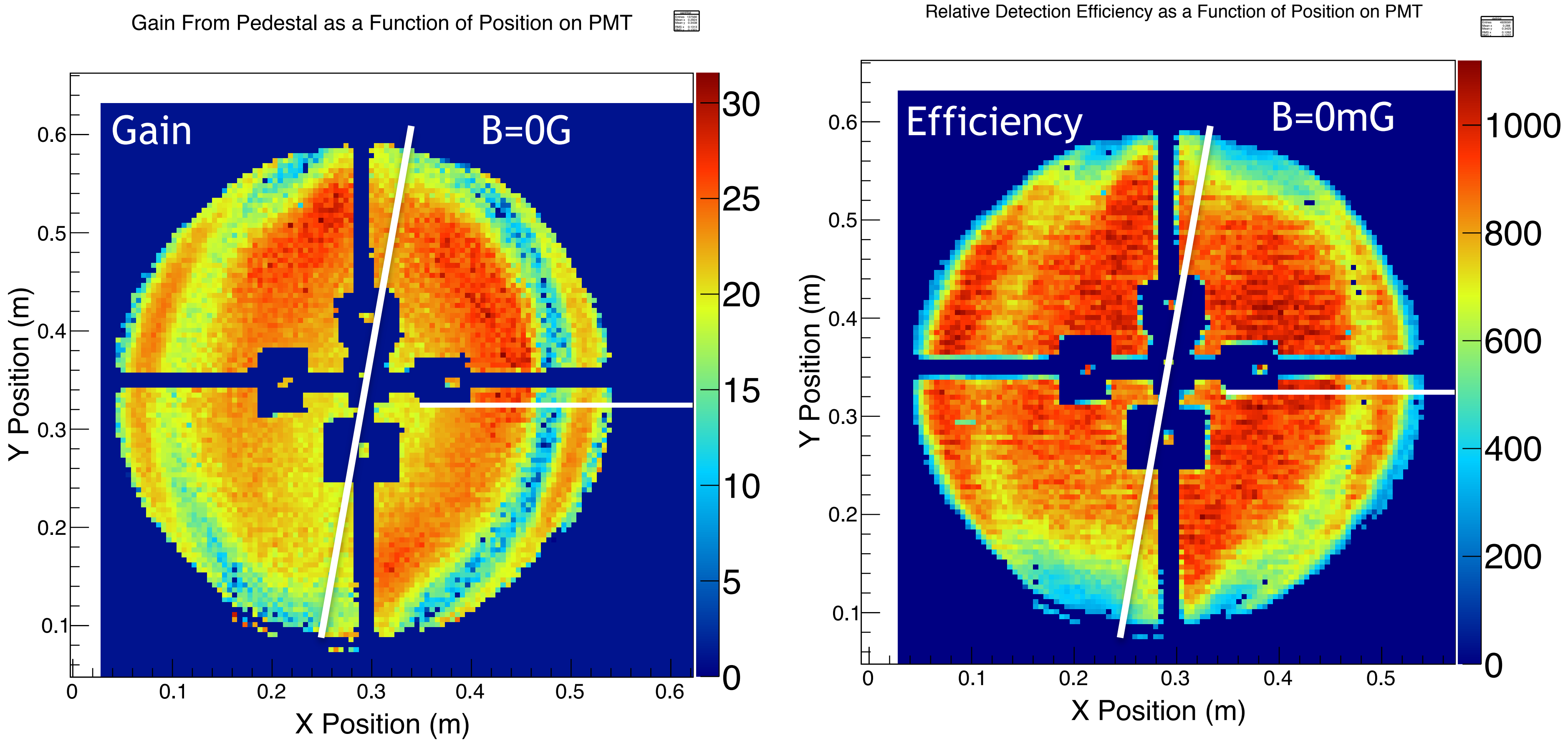






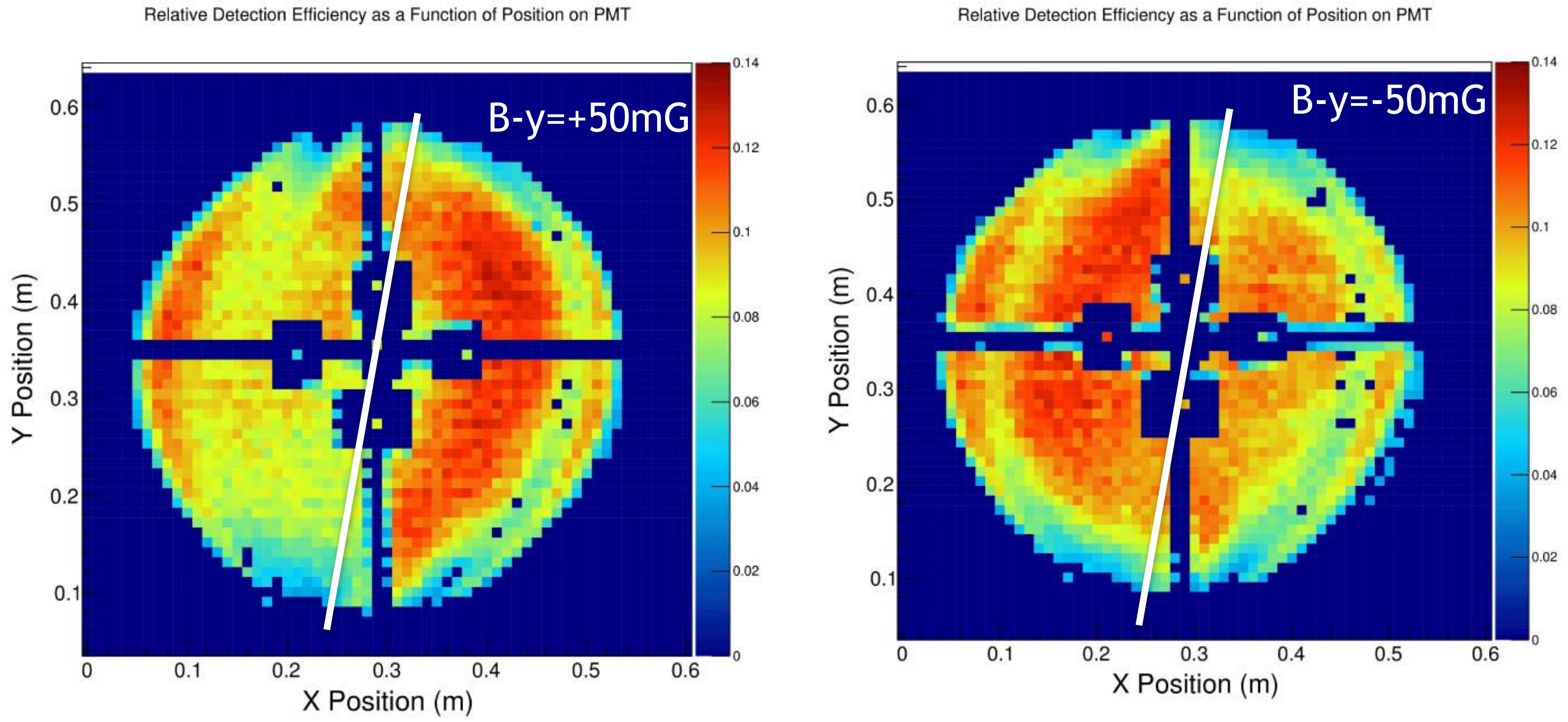
Gain and relative detection efficiency after B compensation

Pattern (big valley!) in Gain and Efficiency reflecting the dynode structure



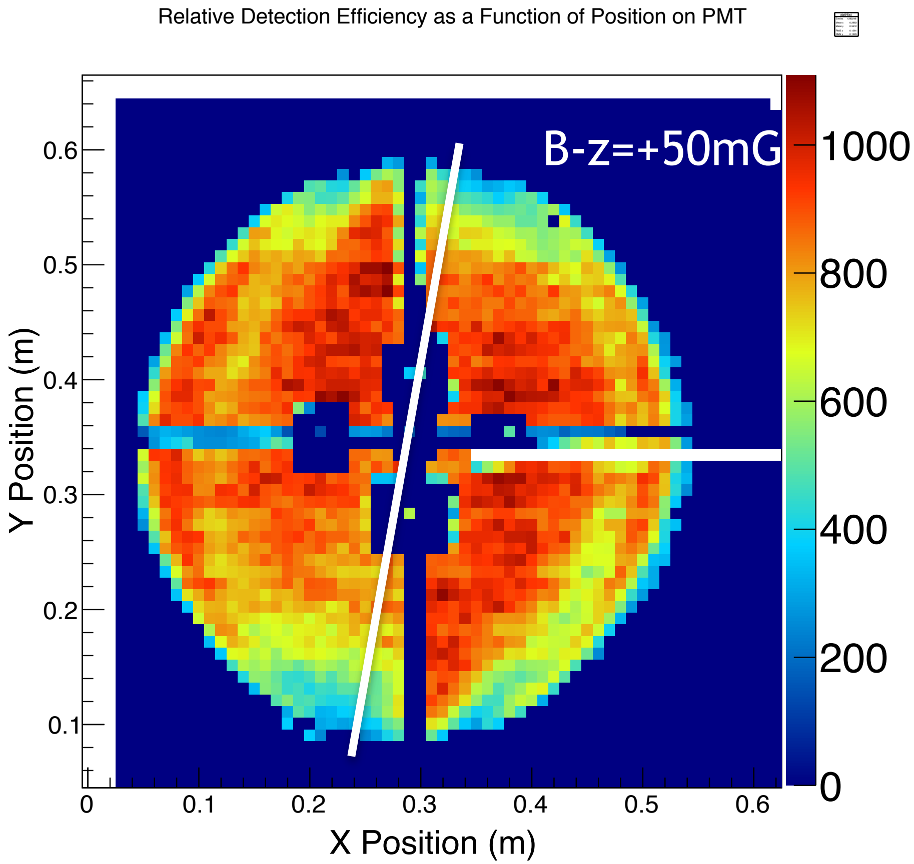
Detection efficiency with B-y (+-50mG)

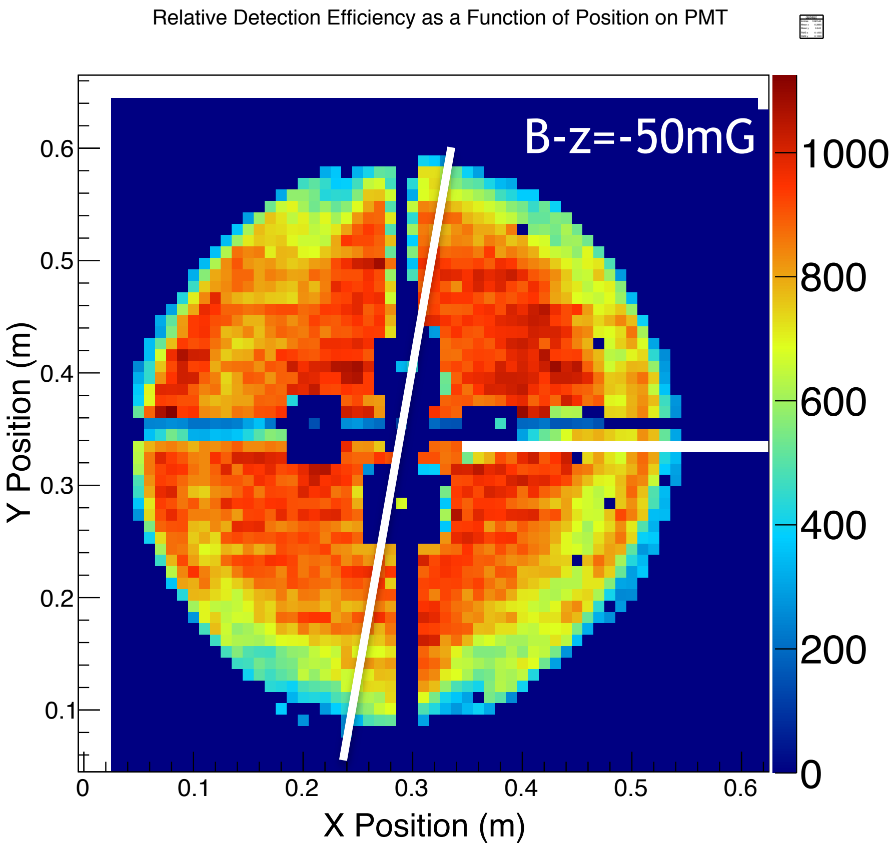
By has a large effect



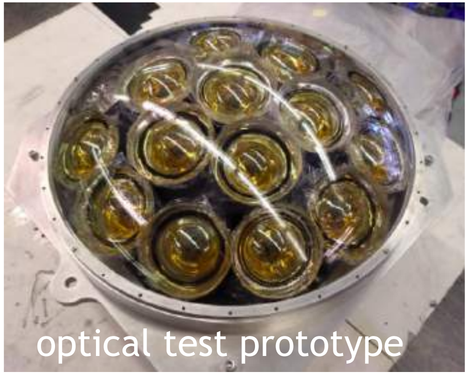
Detection efficiency B-z (+-50mG)

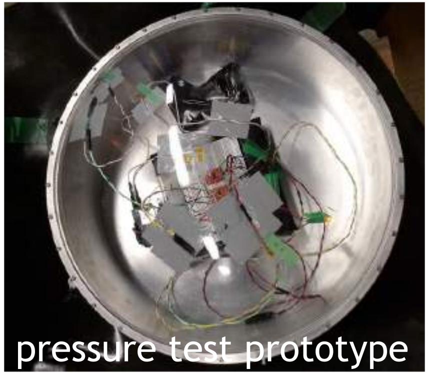
Bz has little effect



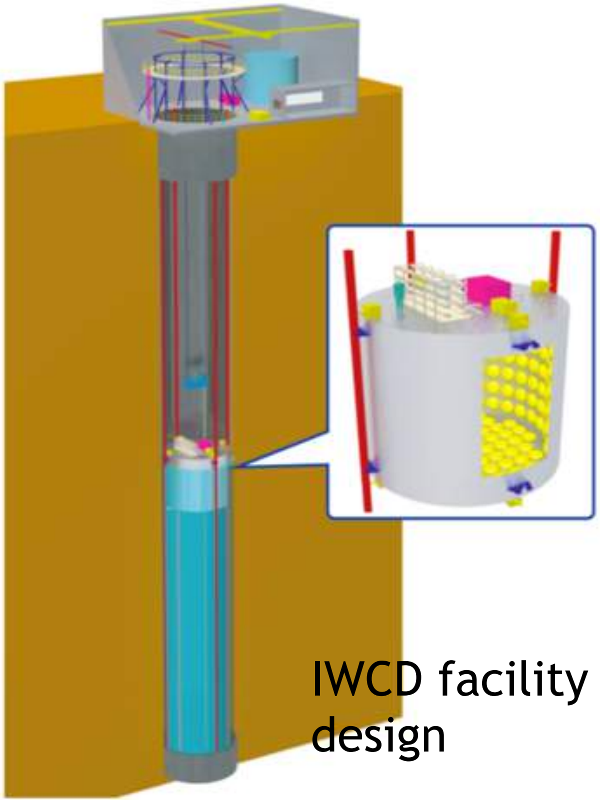


FY2018 RTI: prototype

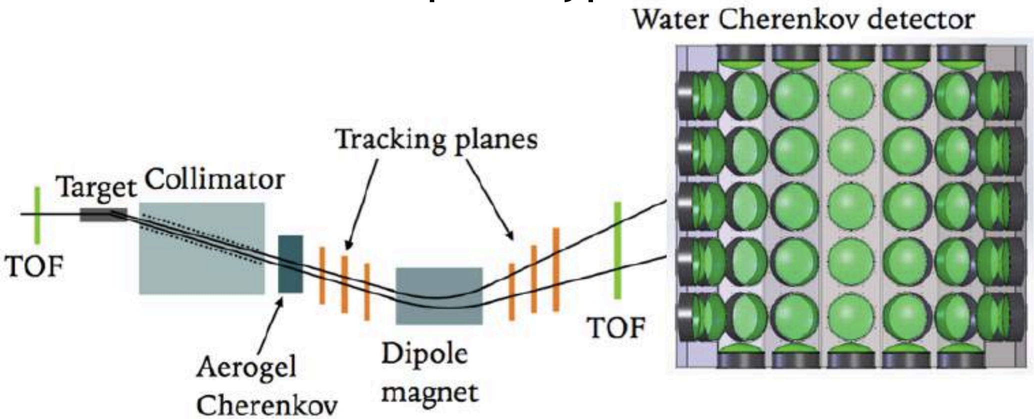




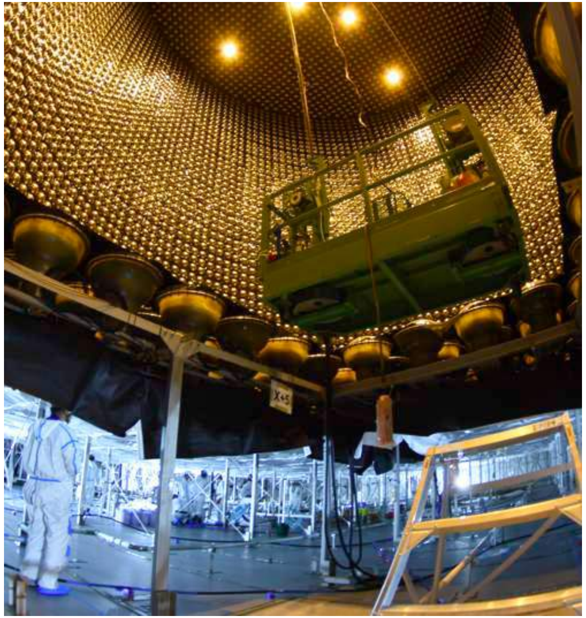
CFI-IF proposal (2019) IWCD/NuPRISM

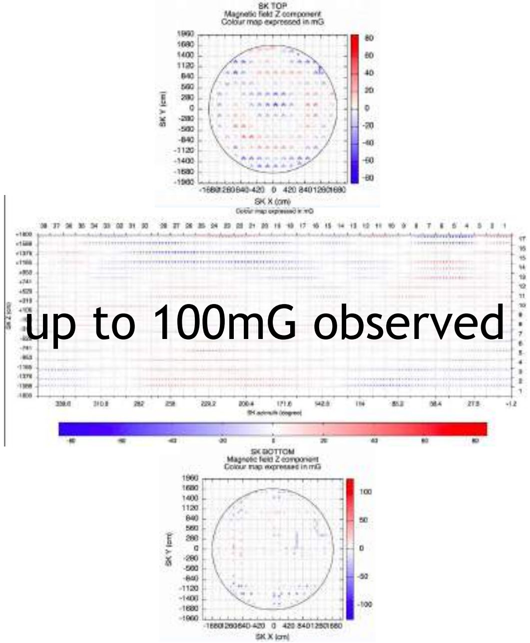


FY2019 RTI: beam test prototype



SuperK refurbishment and water Cherenkov calibration





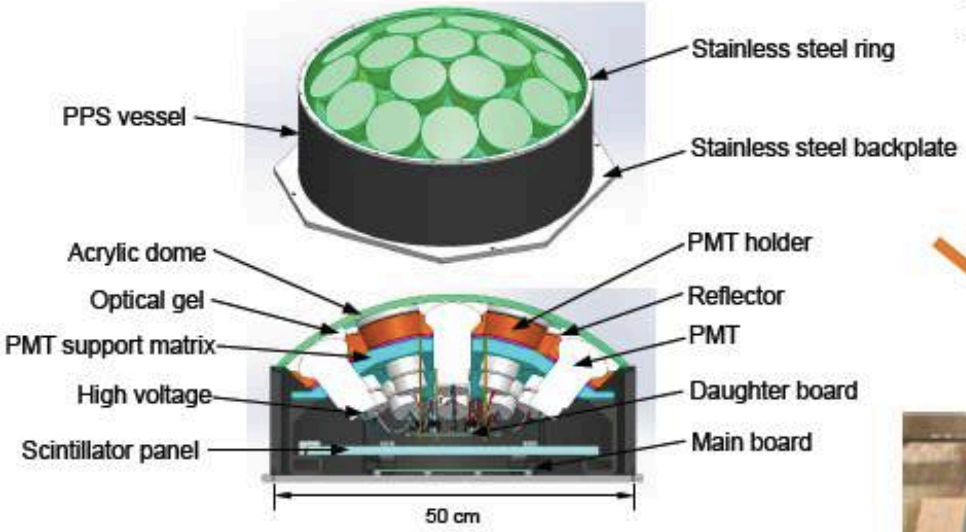
360 degree underwater camera for photogrammetry

soak test with pure water in Kamioka

- SuperK water leak stopped after refurbishment, ready for Gd phase
  - residual magnetic field and PMT orientation measurements were performed
- Canadian group is involved in the calibration campaign
  - Canadian group is also preparing test photogrammetry in SuperK

- Stringent requirements for the future water Cherenkov
  - goal of the systematic uncertainty is ~1%
    - need to be smaller than the statistical uncertainty of 3% at HK
    - even more challenging for smaller detector like IWCD/NuPRISM

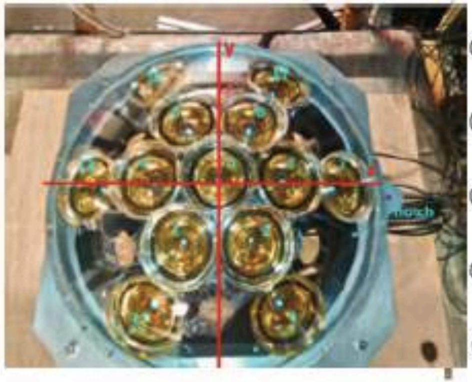
- Improvement in hardware and calibration
  - new 20” PMT with better timing, efficiency, and resoution
  - multi-PMT with superior segmentation and timing resolution
  - improved calibration method being developed
    - photosensor test facility, photogrammetry

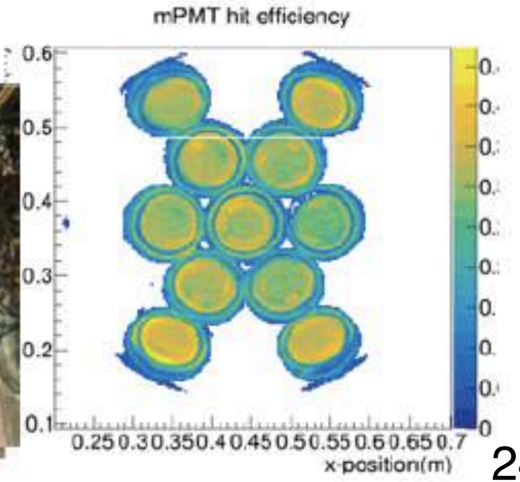


Prototypes

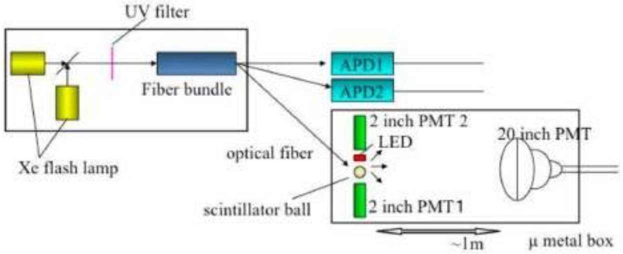
pressure

optical

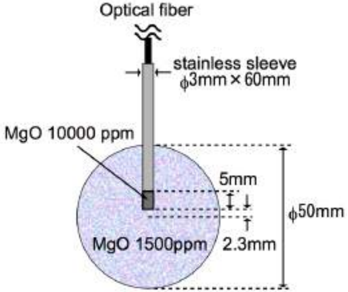




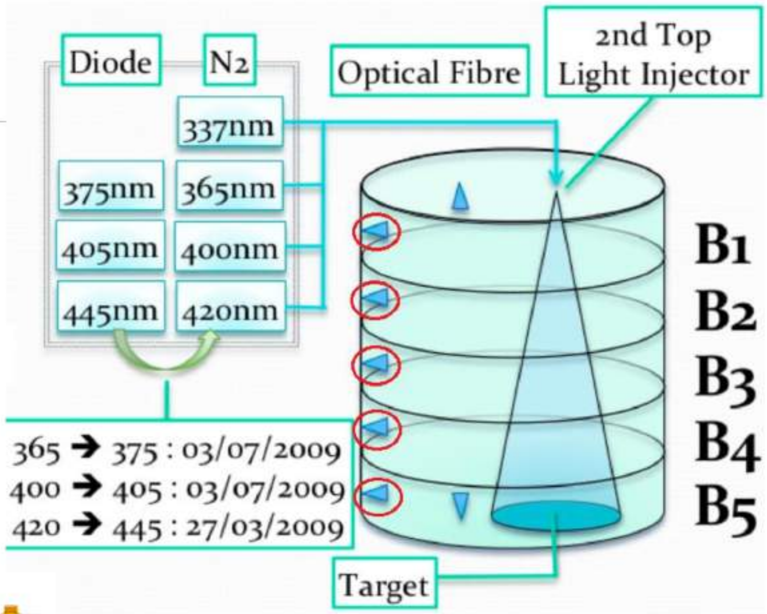
Xe ball

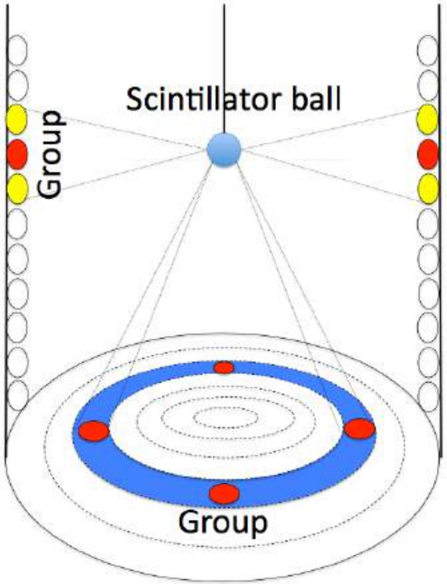


Laser ball



Auto-laser system



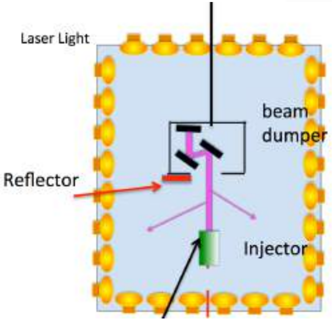


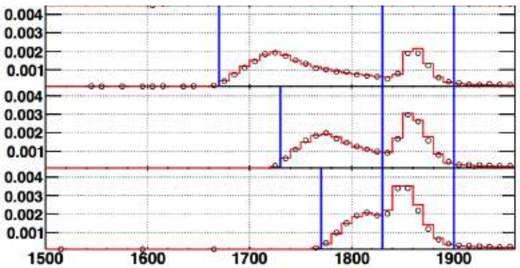
Ni(^{252}Cf) ball

$$^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$$

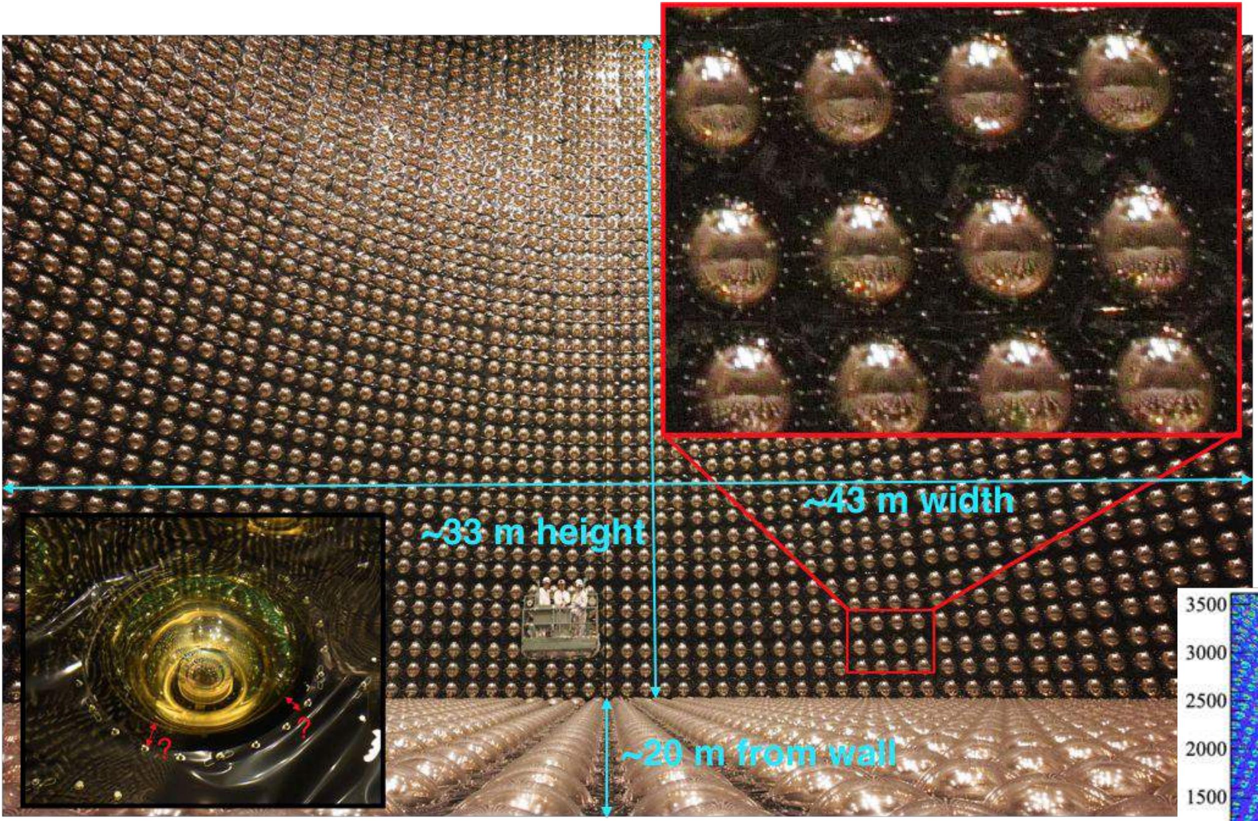
[9MeV]

Rayleigh

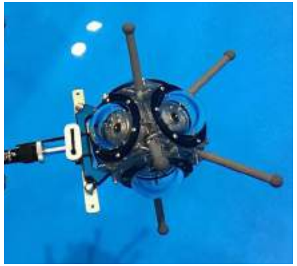


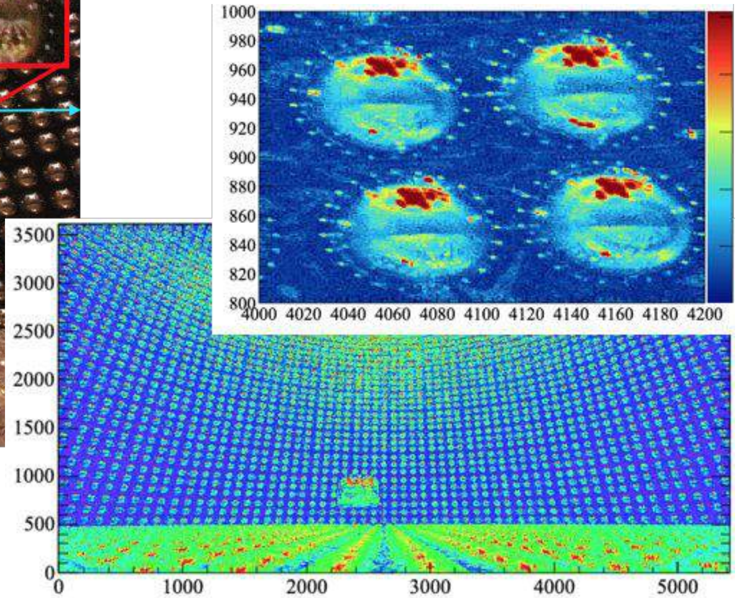


Photogrammetry possibility at SK



360Abyss underwater camera





Photogrammetry test






- Precise response of water Cherenkov requires studies
  - backward light mismatch (~10%) in SK: impact on vertex
    - difference observed in delta ray simulation models
  - hadron interactions in water
  - Demostration of the calibration procedure with known beam
- Prototype IWCD detector test at CERN (Fermilab)