ICRR Inter-University Research Program 2020

Neutrino and Astroparticle Research Division

TRIUMF

New Photogrammetry Calibration (and Machine Learning Event Reconstruction) for Super-Kamiokande and Hyper-Kamiokande

Patrick de Perio

Feb. 9, 2021

Funding Summary

Approved amounts:

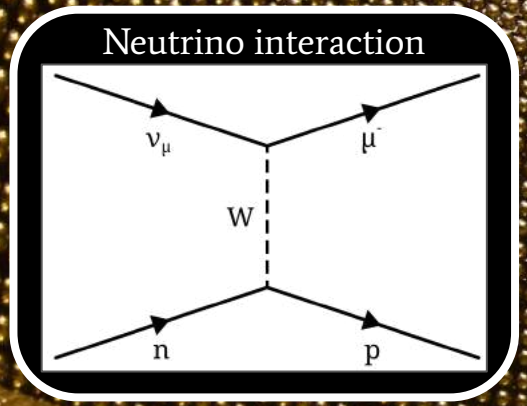
Year	Goods	Travel	Top-up	Total
2019	700,000	300,000	500,000	1,500,000
2020	200,000	300,000		500,000

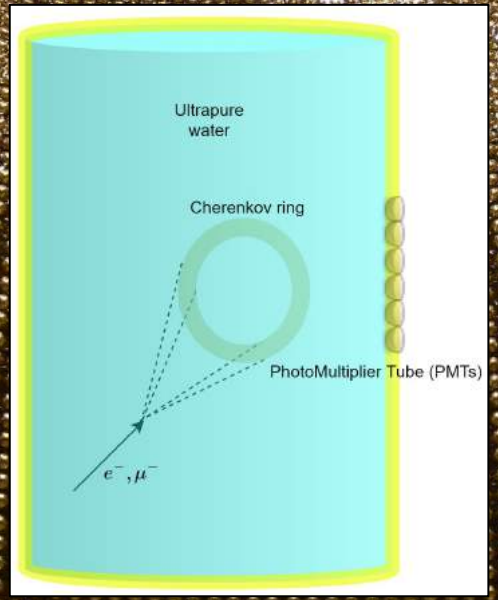
Actual spending:

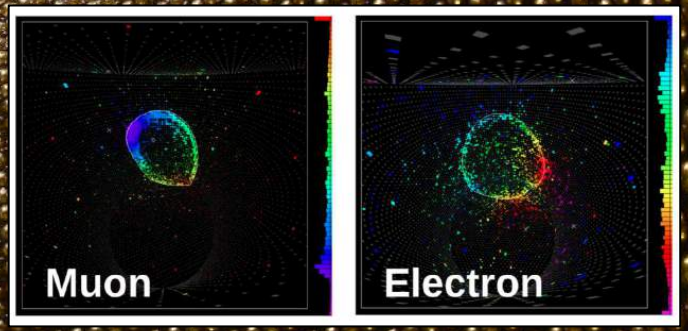
Year	Goods	Travel		Total	Remainder
2019	832,236	653,170		1,485,406	14,594
2020	78,782	127,339		206,121	293,879*

*Applied for carry-over due to Covid-19 pandemic

Super-Kamiokande

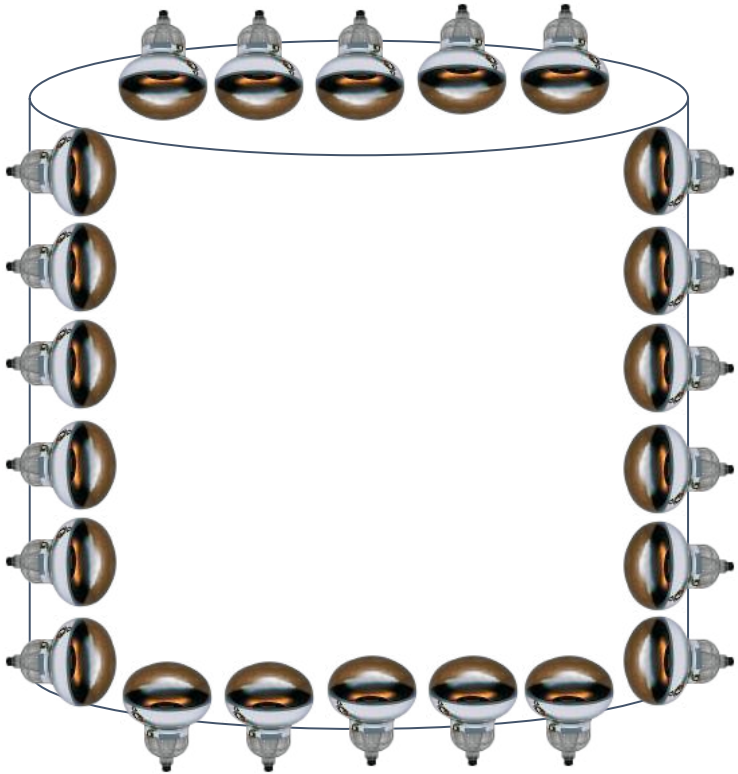






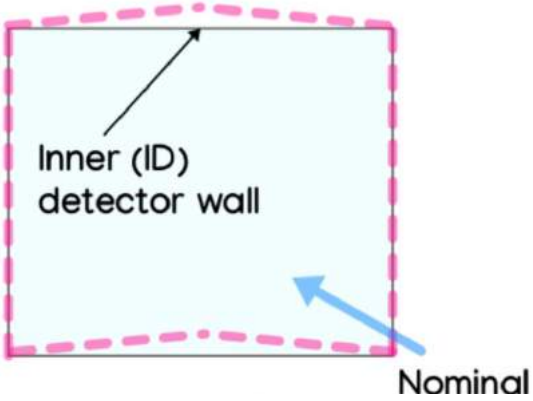
Systematic Error: Geometry

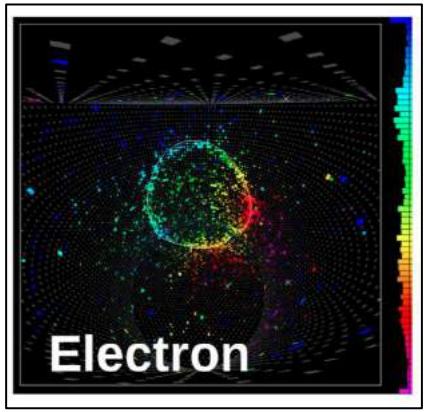
PMTs assembled in air



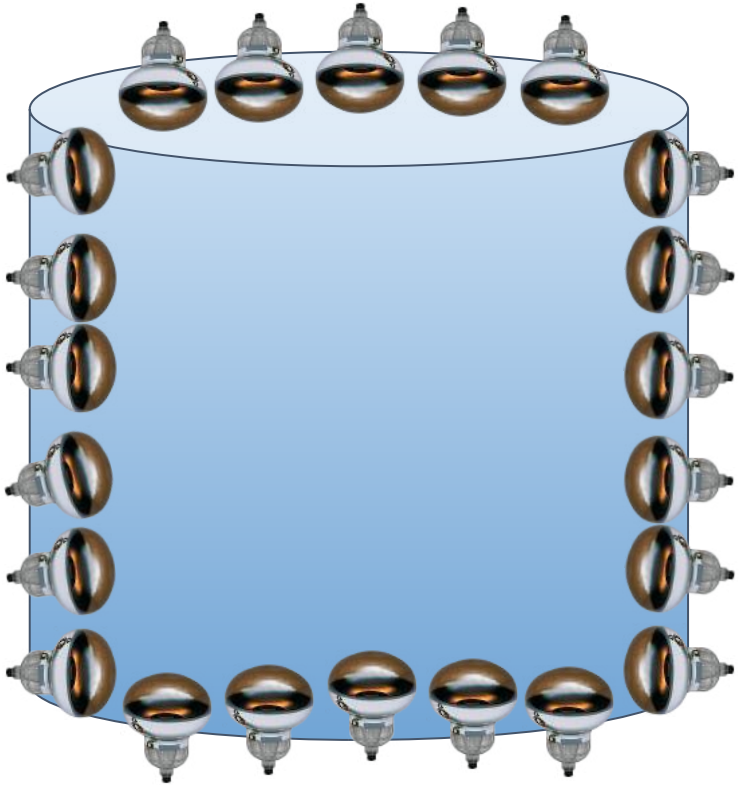
Systematic Error: Geometry

- Example systematic deviation of ID PMT geometry
- Nominal assumption in analysis can produce incorrect results
  - Critical for precision measurements



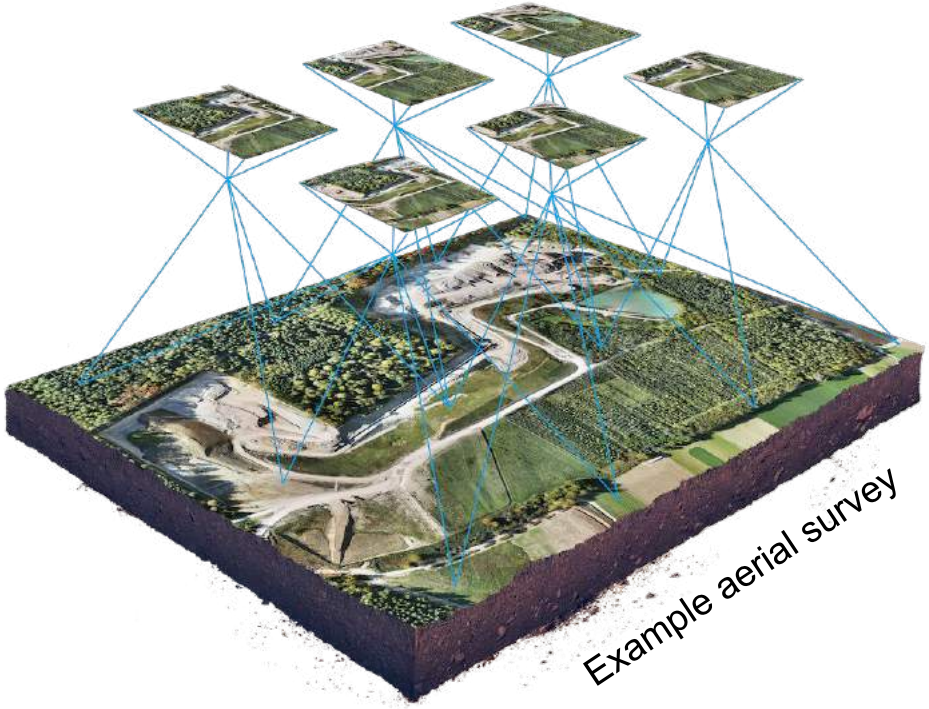


Potential PMT shifting due to buoyancy after water filling

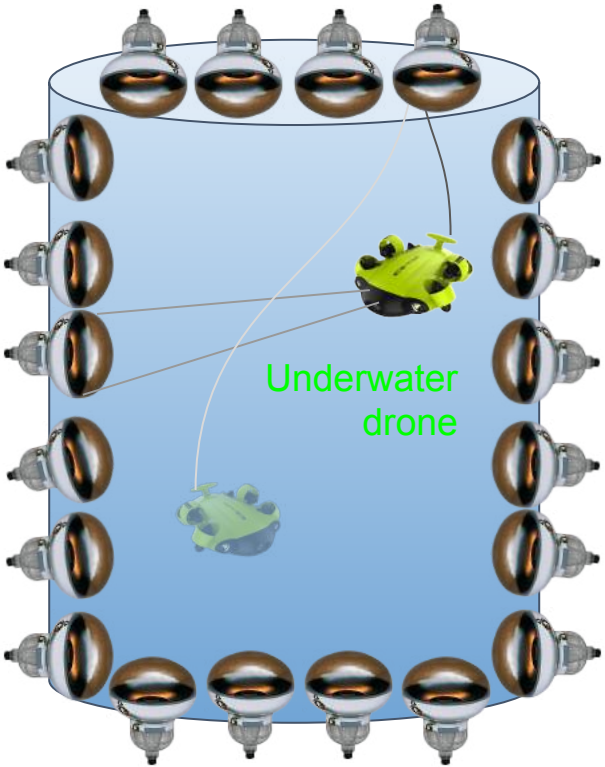


Photogrammetry

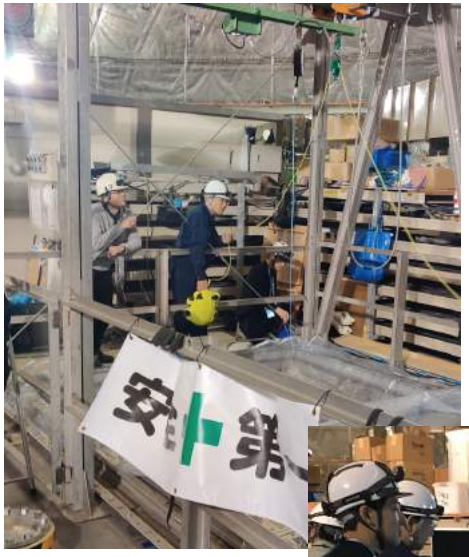
Reconstruct the 3D structure from multiple 2D photographs to mitigate systematic error



Example aerial survey



Underwater Drone

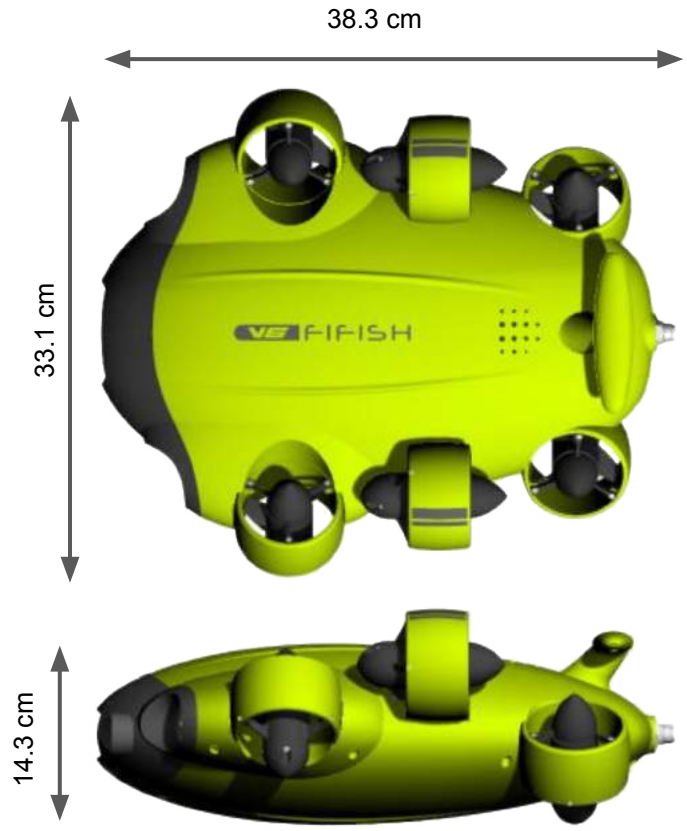


Deploying
From top of
Super-K
detector

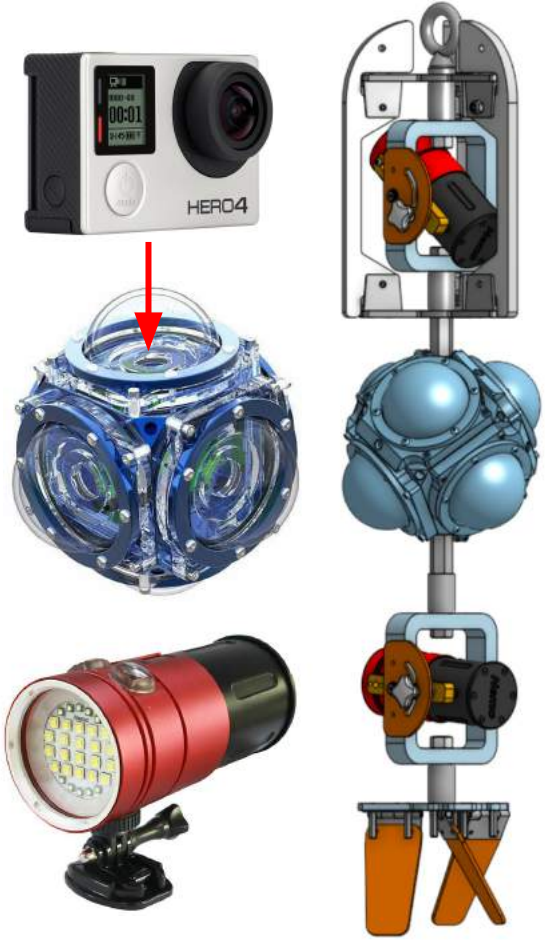
Feb. 2020

Inside SK outer detector

Remote piloting

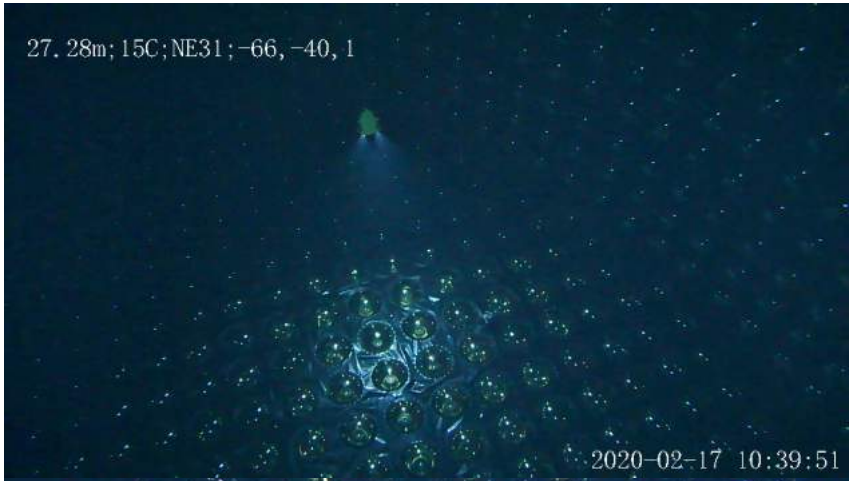


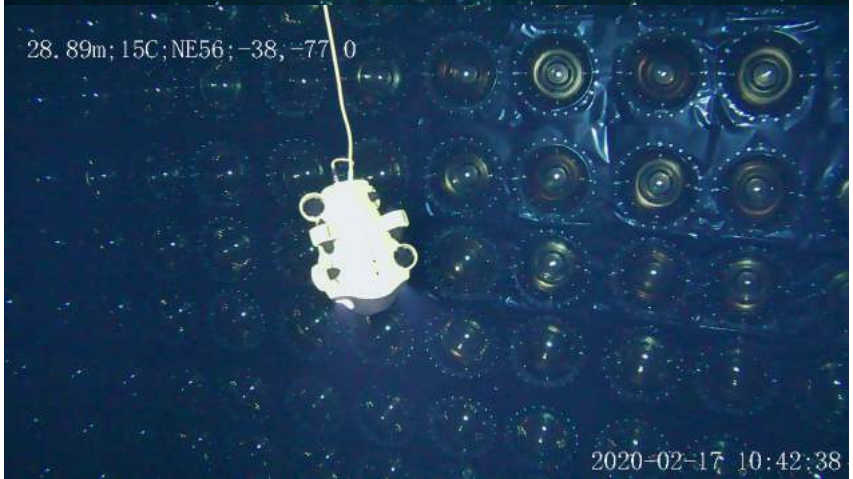
Backup Underwater Cameras, Lamps, and Deployment Hardware

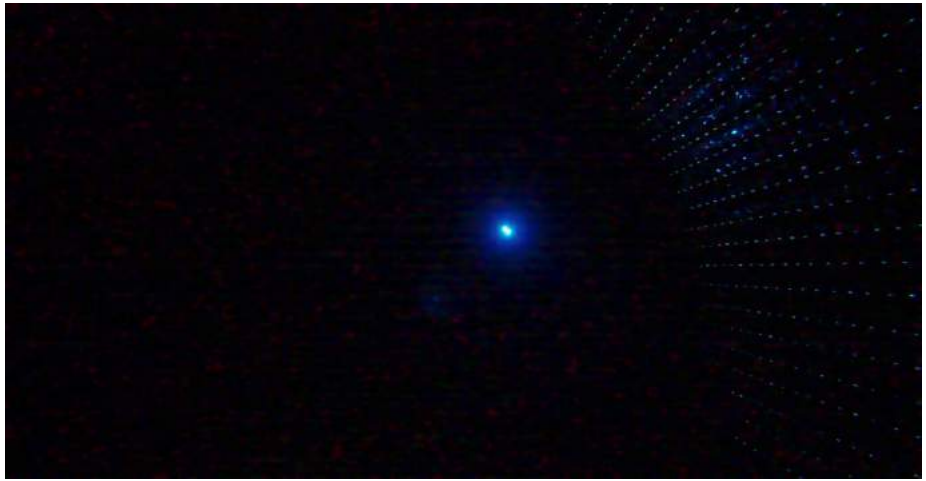


Top of Super-K detector

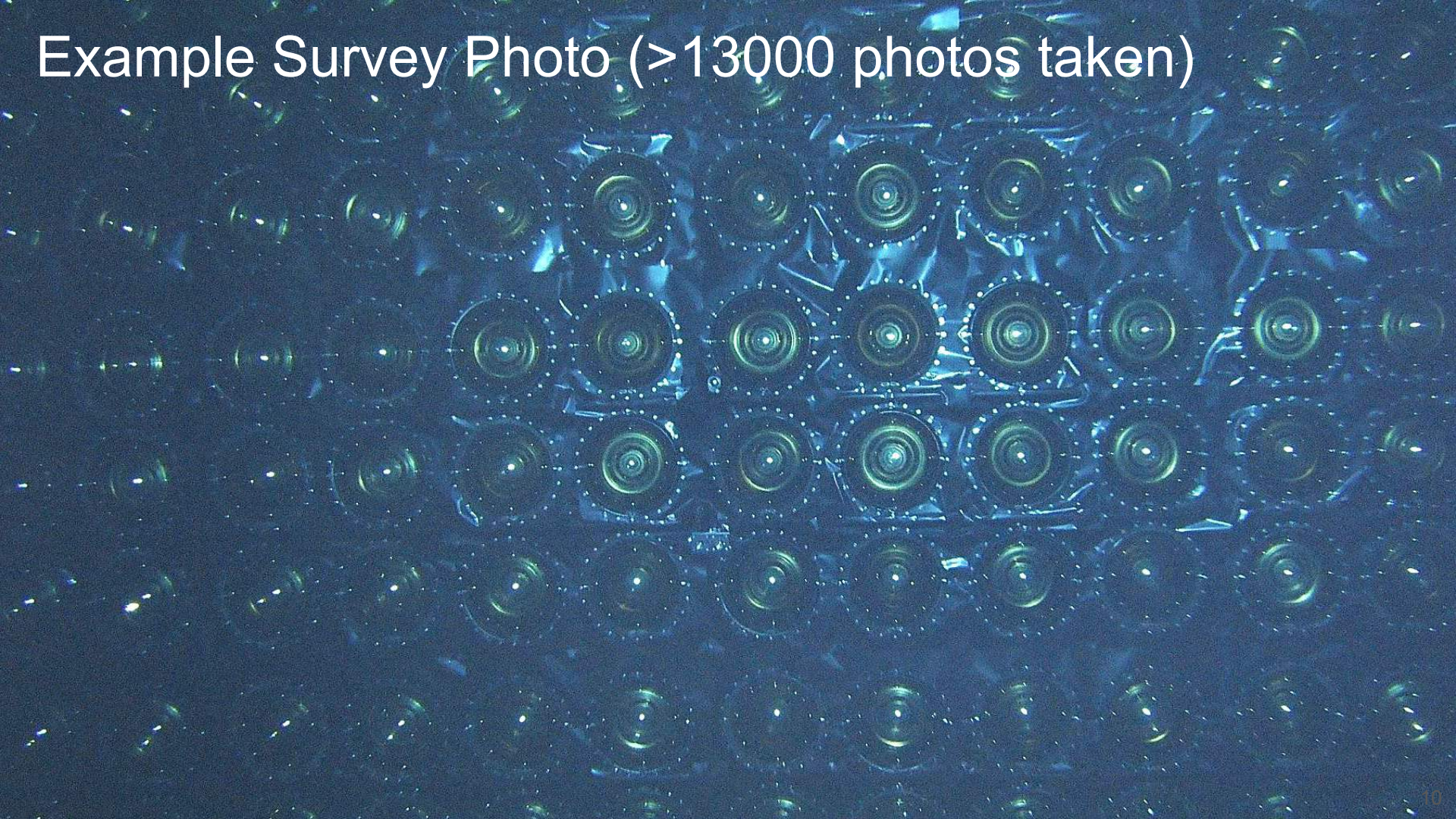
Photogrammetry Survey Highlights





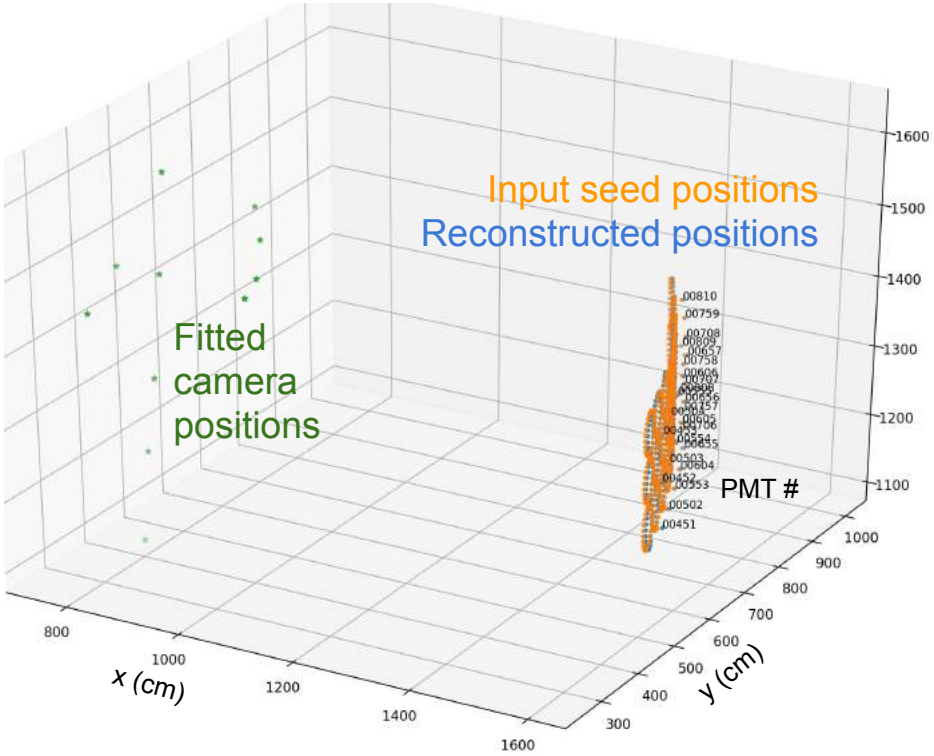


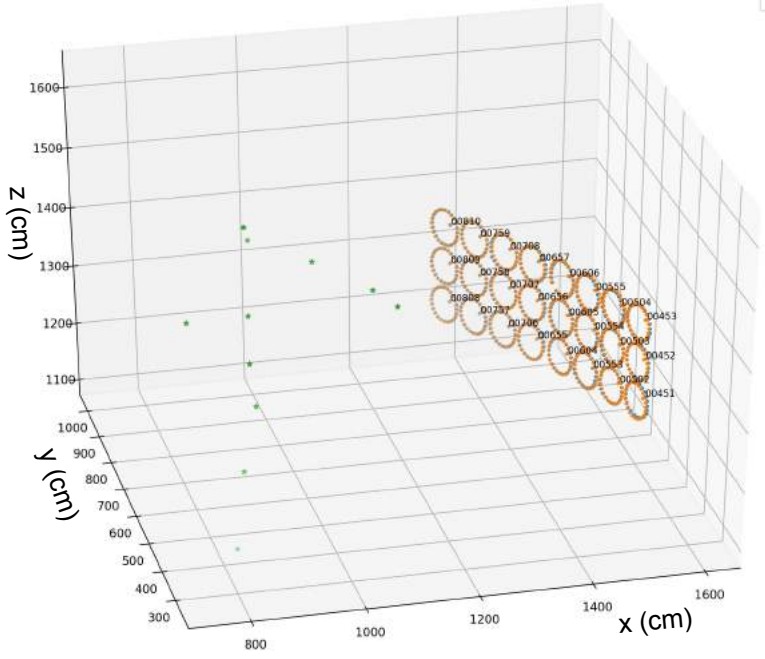
Example Survey Photo (>13000 photos taken)

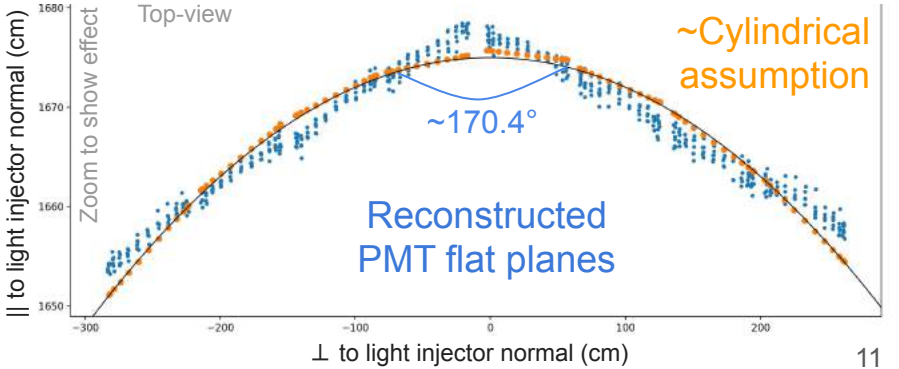


Photogrammetry Reconstruction

Work in progress

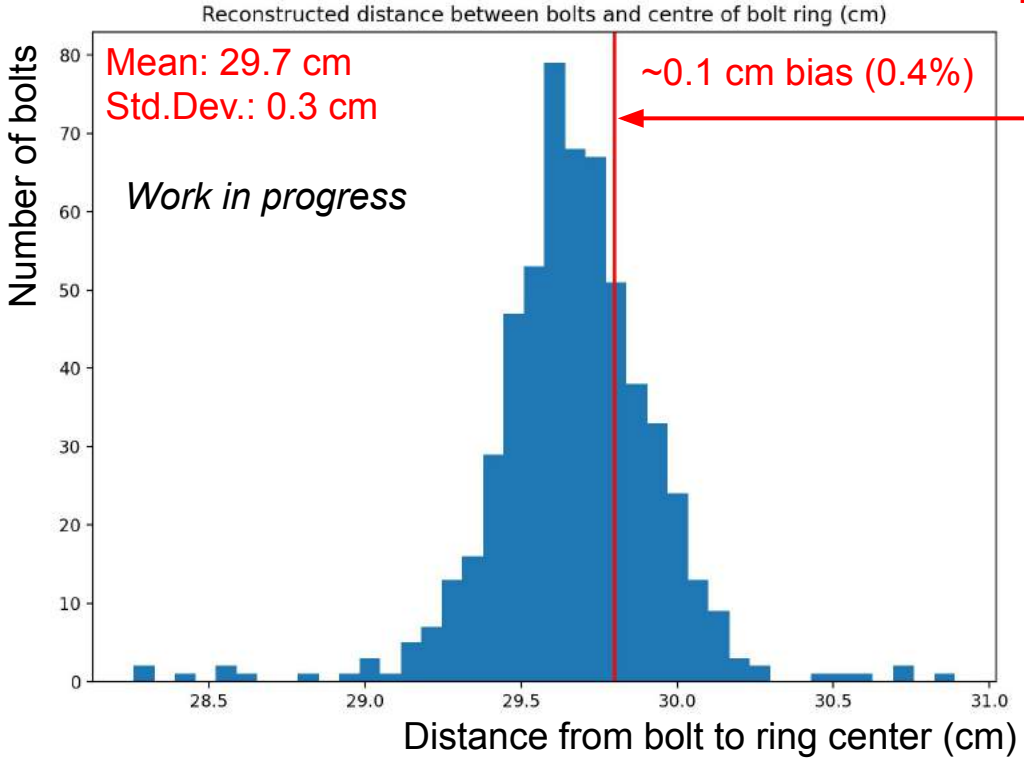


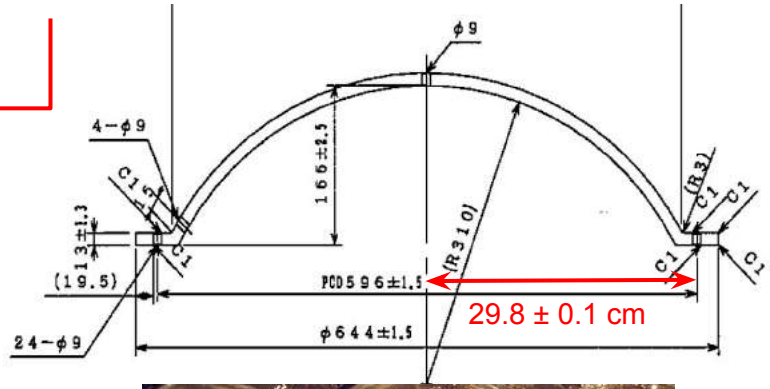




PMT Cover Bolt Ring Measurement

Nominal radius of bolts: 29.8 ± 0.1 cm

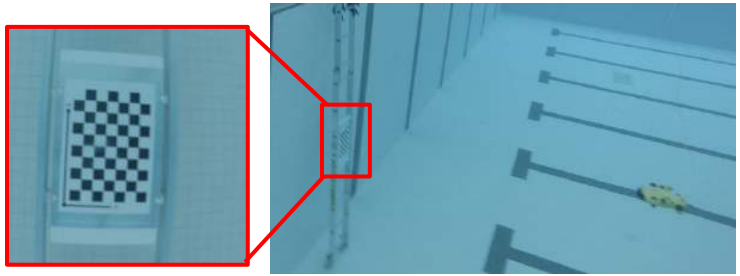




Funding Summary

- 2019 Goods: Drone, cameras and lamps, deployment hardware
- 2019 Travel: Detector survey and presenting work at collaboration meetings

- 2020 Goods: Cameras and lamps for PMT structure mockup test in Kamioka
- 2020 Travel: Temporarily shipped equipment to Canada to continue evaluations and calibration



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*Applied for carry-over due to Covid-19 pandemic

Future Work

- Evaluation of different underwater cameras and lamps with PMT mockup structure in Kamioka (and Canada)

- Evaluation, design, and testing of different drones
  - Development of global positioning systems and automatic piloting

- Design fixed camera/lamp mounting systems (on PMT support structures)

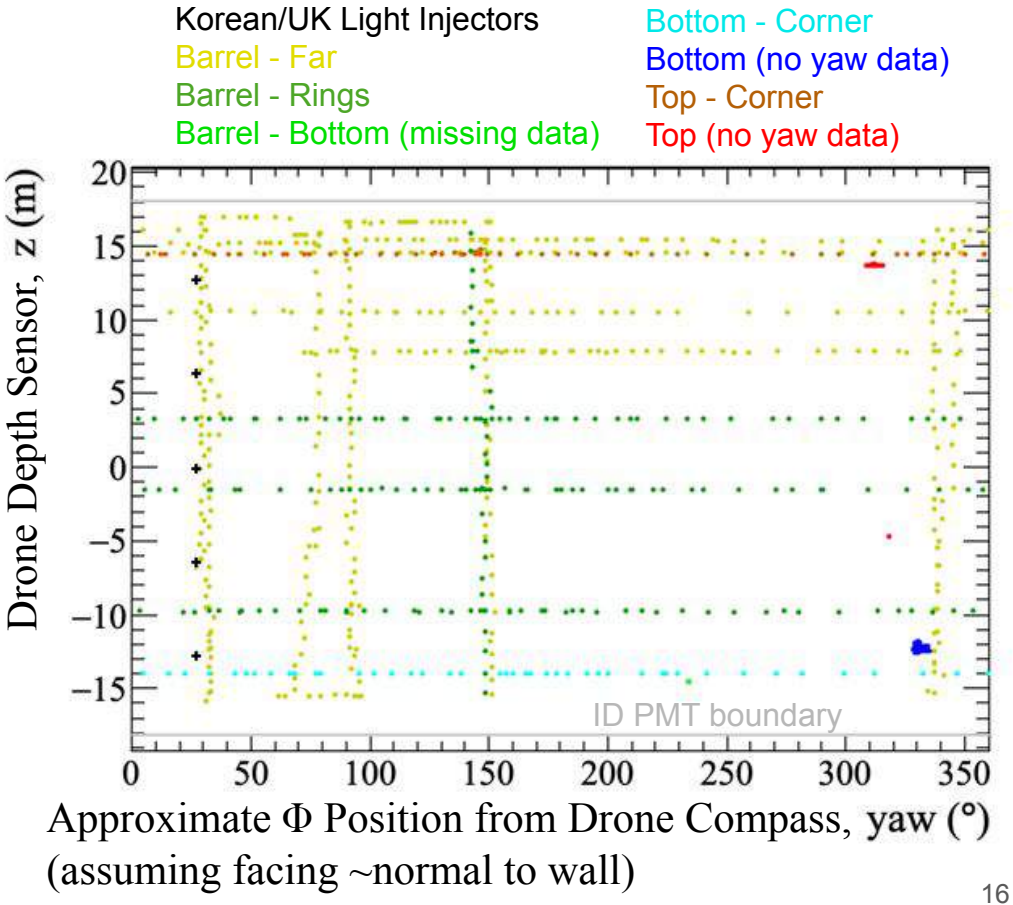
- Deliver complete photogrammetry systems for Hyper-Kamiokande and new Intermediate Water Cherenkov Detector (IWCD)
  - Also for Super-K in case of another future tank opening
  - Critical for precision measurements and discovery potentials

- *Many thanks to ICRR-IURP for your support in making this possible!!*

Appendix

Geometry Survey for Photogrammetry

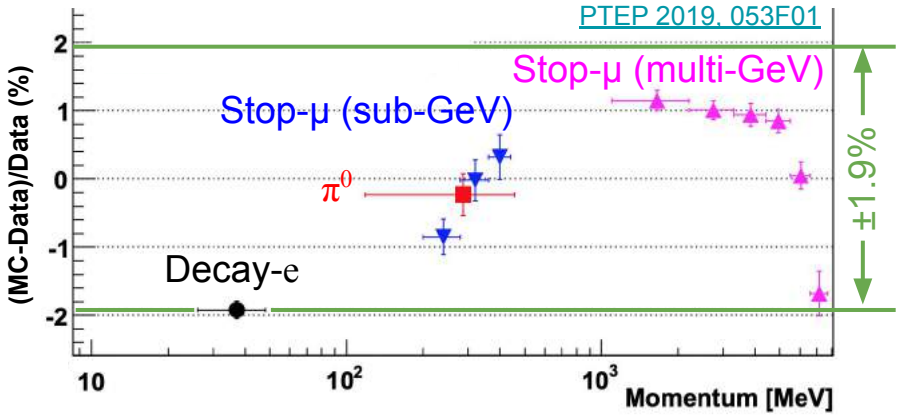
- Fairly good coverage of whole detector
  - Including top and bottom caps
  - ~1800 positions, ~13000 photos
- Potentially undersampled regions
  - Limited time: 5.5 hours total
  - Difficult to track during piloting
    - Sensor plots were not available during TOW
- Analysis will tell if this current photo set is sufficient



Motivation: Systematic Errors

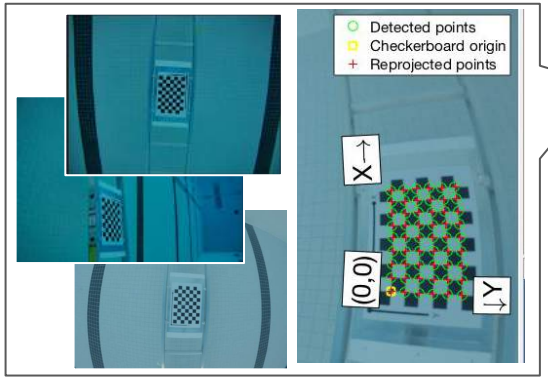
- Aim to achieve 1% level detector systematic error for e.g. δ_{CP} measurement

- Example here of current Super-K energy scale “error”
  - Derived from residual (unexplained) data/MC discrepancies
  - Therefore, not strictly propagated from the uncertainties in underlying physical parameters
    - i.e. Each point is a measurement with statistical error, but what is the systematic error in each point?



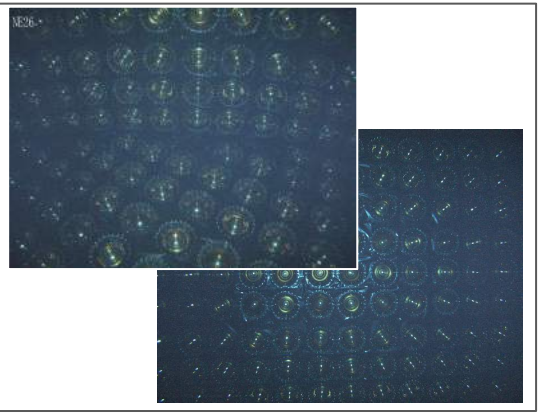
- Attempt to dig even deeper into physical parameters of the detector to try to resolve data/MC discrepancies and estimate systematic errors

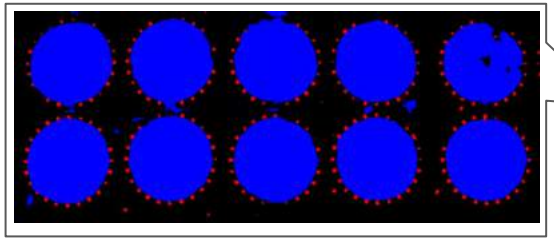
Overview of photogrammetry analysis



Calibration photos → Optics calibration

Photos of detector → Undistorted images

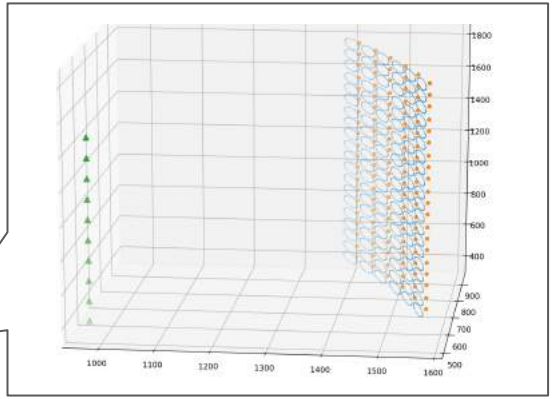


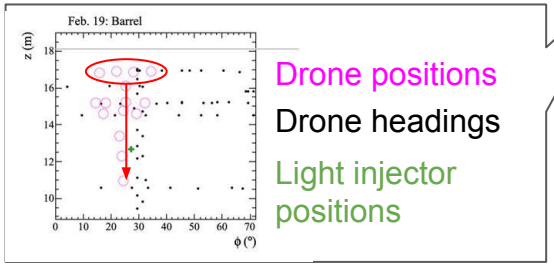


Feature detection

Feature labeling

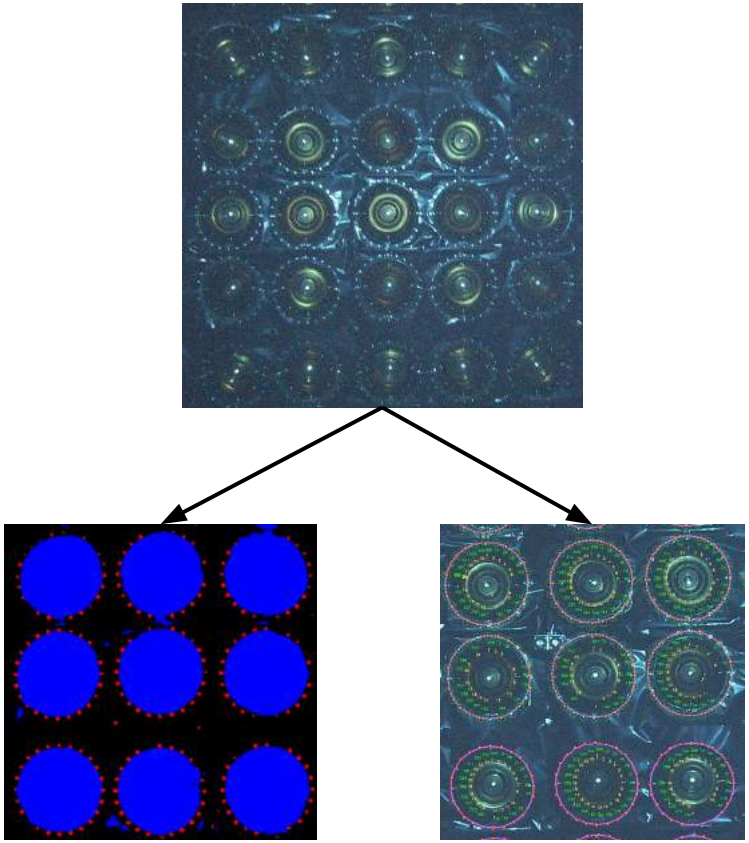
3D stereoscopic reconstruction





Feature Detection

- Developing algorithms to automatically detect features of interest and return their 2D pixel coordinates
- Traditional image processing: edge filtering, blob detection, Hough transforms, noise reduction, etc.
- Machine learning: training with many labeled masks



Machine Learning Semantic Segmentation (*Dan Martin*, Imperial College London)

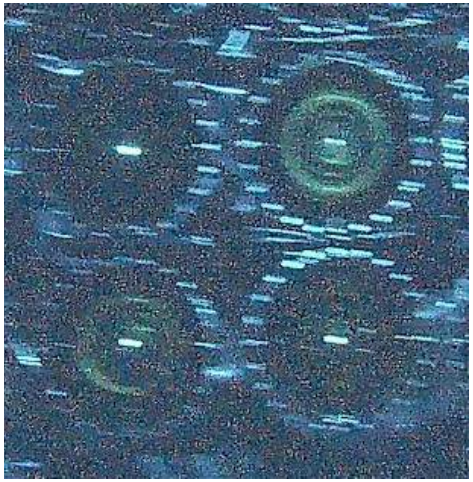
Traditional Image Processing (*Tapendra B C*, University of Winnipeg)

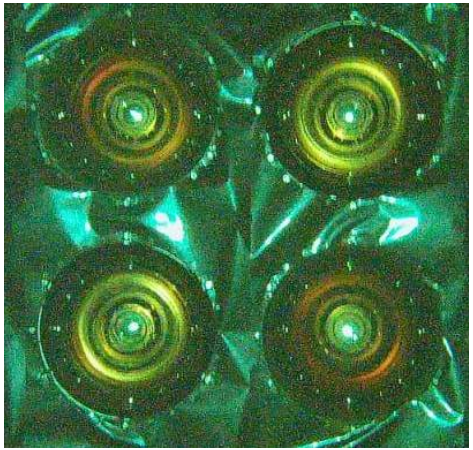
Feature Detection Difficulties

- Low light level (far distance) → Noisy images
  - Future: Multiple drones for optimally placed light sources

- Drone instabilities → Blurry images
  - 1800 positions to cover most of SK, but constrained to 5.5 hours
    - Sometimes insufficient time for drone to stabilize before photo
  - Future: work with companies to improve drone stability; budget more time for data taking, e.g. >24 hours for a single scan of HK
    - Develop automated piloting system together with a positioning system to minimize pilot error

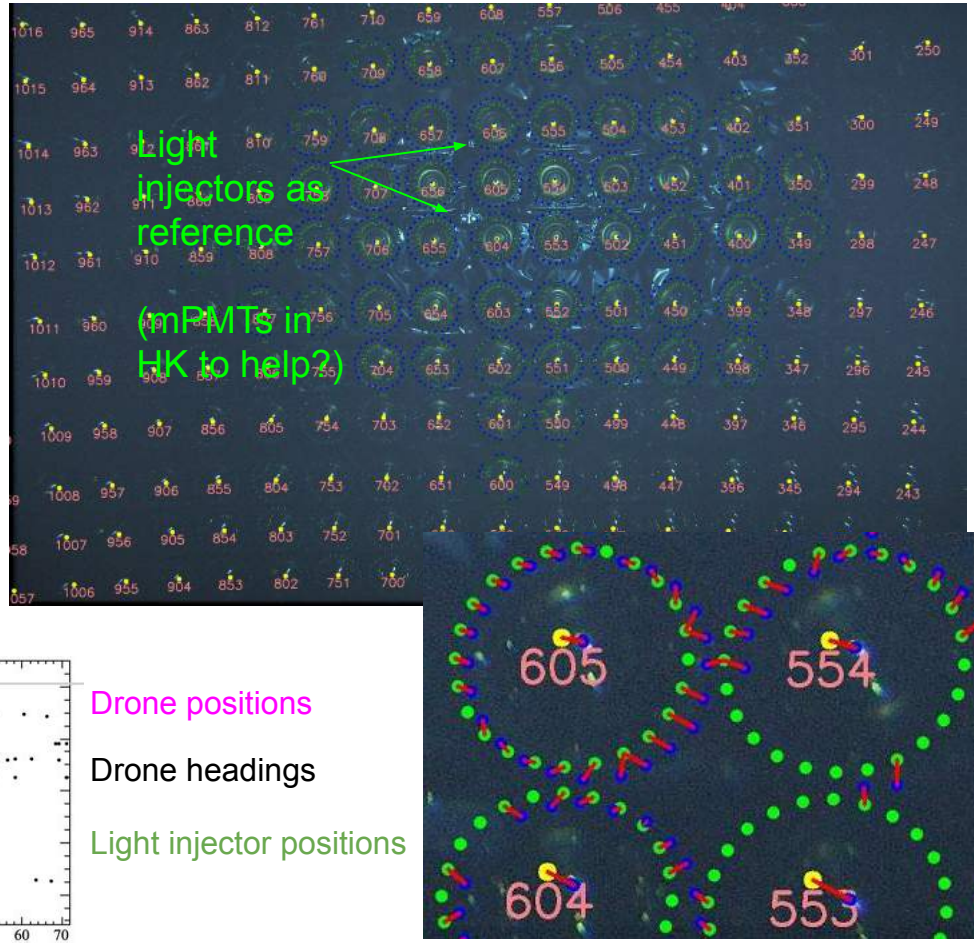
- PMT illumination risk → dark rate excitation
  - Tried yellow filter to suppress wavelength in high QE region
  - Severely affected quality of photos for feature detection
  - After survey, observed no significant increase in PMT dark rates; suggesting short periods of illumination with white light is OK
    - Similar experience on SNO+



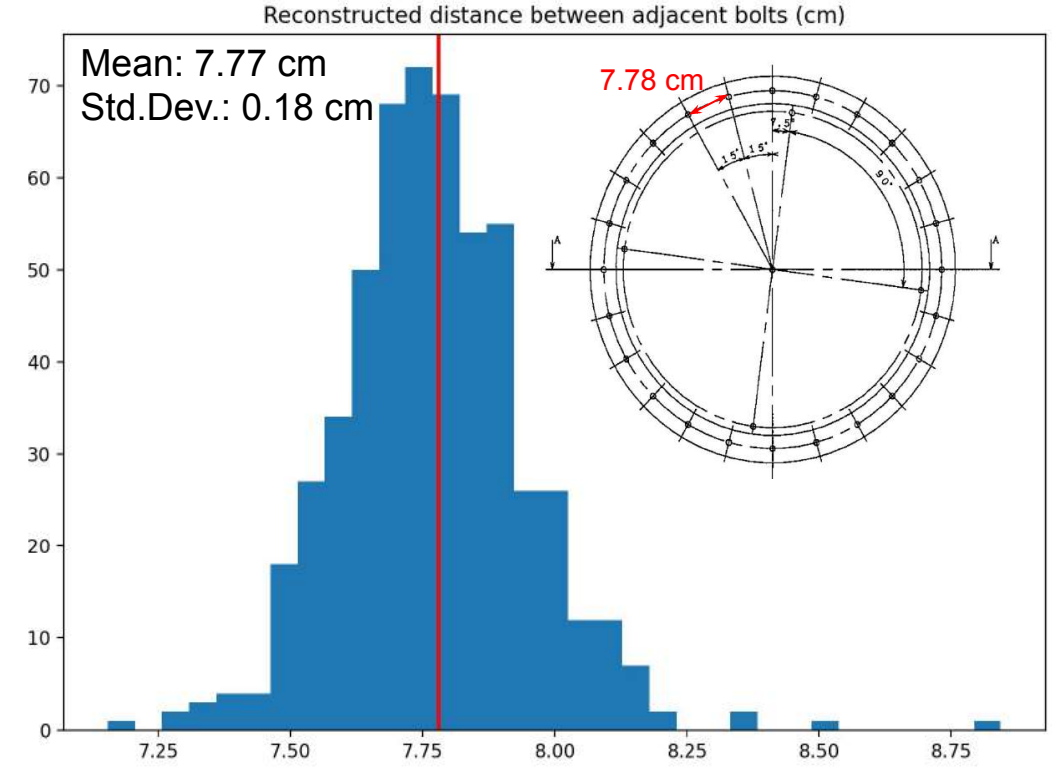


Feature Labeling

- Initial manual labeling demonstration of subset of SK photos estimates ~2000 hours for entire set
- Developing procedure to automatically label PMT (and bolt) IDs
  - Using some input reference, known PMT ID geometry, and potentially drone sensor info
    - Future: sonar/ ultrasonic positioning



Measuring distance between adjacent bolts



True distance between bolts should be ~7.78±0.02 cm

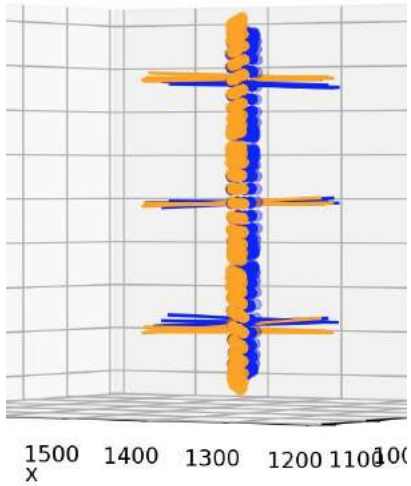
- Absolute scale is not determined by photogrammetry
- Look at spread of distances to estimate reconstruction errors
- (assume bolt distance is very precise in SK)

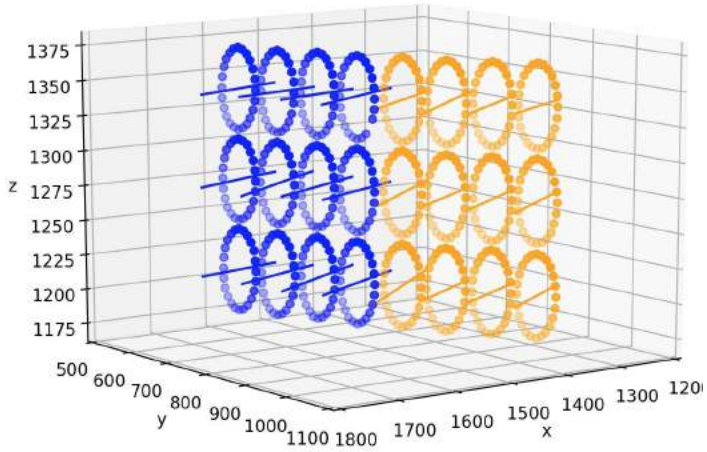
Spread suggests reconstructed distance errors of ~ 0.2 cm

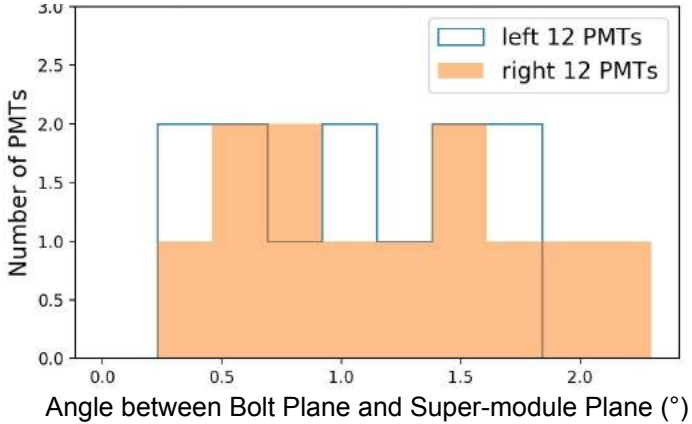
But larger errors might exist over longer distance measurements

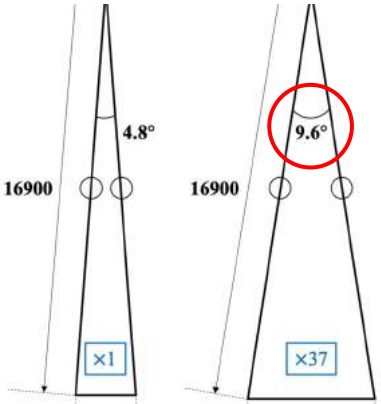
Planarity

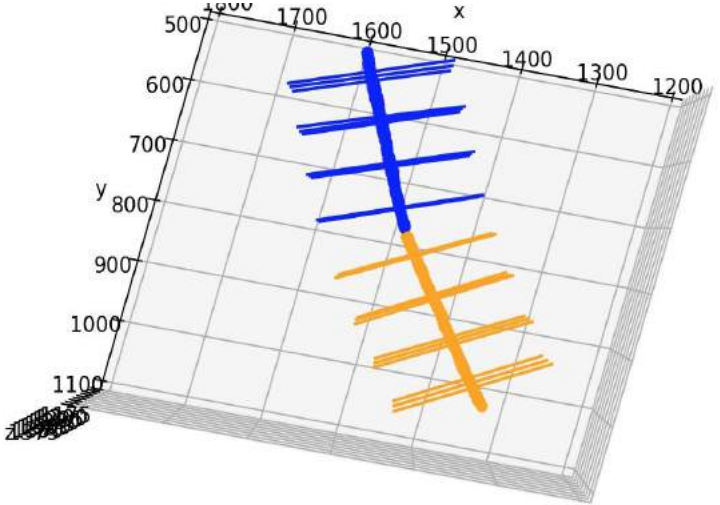
- Fit a plane to each bolt set
  - Get normal vector for each
- Angle between normal of fitted plane of each super-module = 9.42°





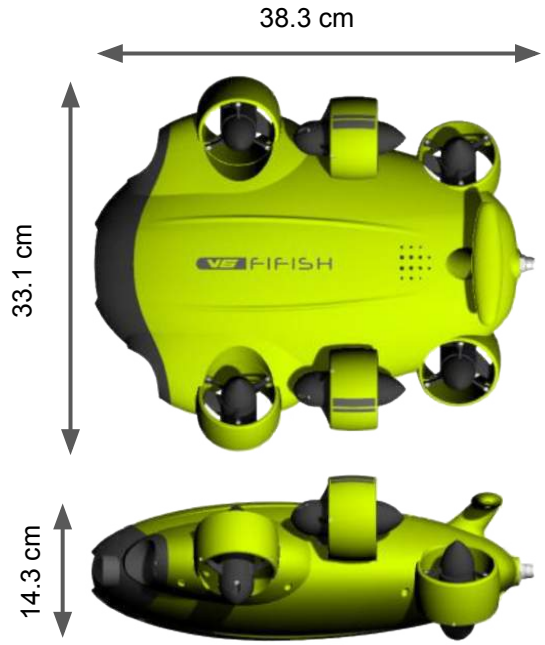






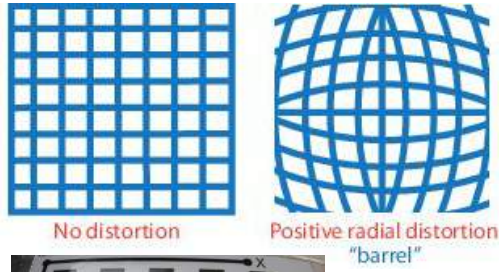
QYSEA FIFISH V6 Drone

- Relatively cheap (350000¥) consumer underwater drone
  - 100m depth rating
  - Small enough to fit through largest calibration port (~40 cm)
  - 6 DOF movement control (forward/backward, right/left, up/down)
    - Full orientation control (360° pitch, roll, yaw)
      - Can directly face end-caps; highly maneuverable
    - Depth and orientation sensors built in
  - Good low-light 12 MP camera sensor
    - Though flat lens port window not ideal for distortion
  - Sufficient (variable intensity) lighting: 4000 lumen total
  - Tethered for remote control and safety
    - Live stream to mobile device
  - 4 hour battery life (1 hour charge time)
- Two drones purchased
  - For backup in case of failure or recharging
- Company highly responsive and supportive
  - Quickly pushed firmware upgrades and troubleshooting

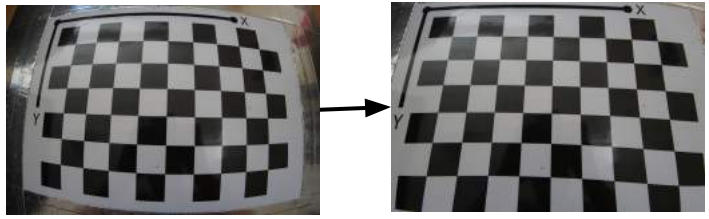


Camera Calibration

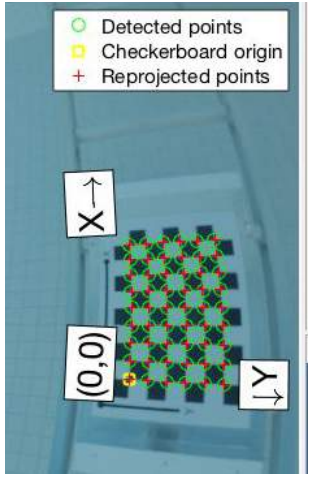
- Assume some distortion parameterization (e.g. fisheye) with free (intrinsic) parameters

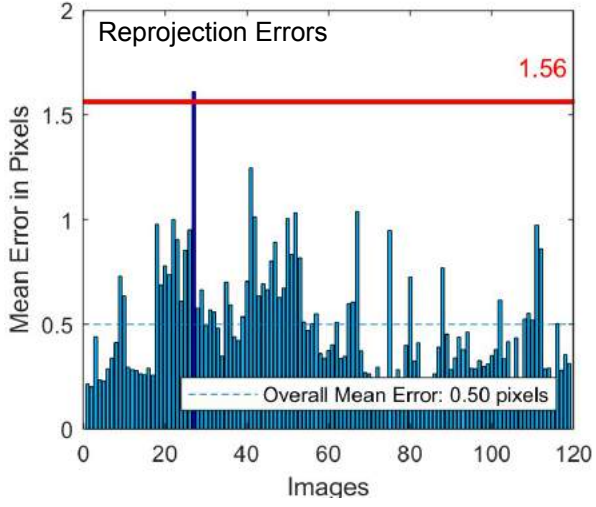


- Now assume calibration pattern points are perfectly known, fitting only camera pose (extrinsic) and intrinsic parameters



- Best mean reprojection error achieved = 0.35 pixels

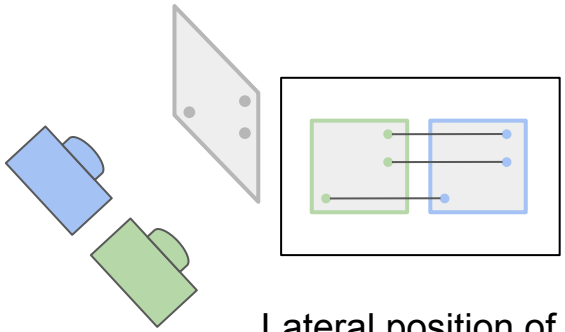




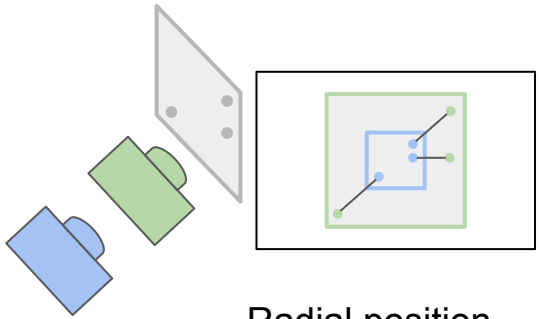
3D reconstruction: Determining (Seed) Camera Poses

Use seed 3D positions from expected geometry

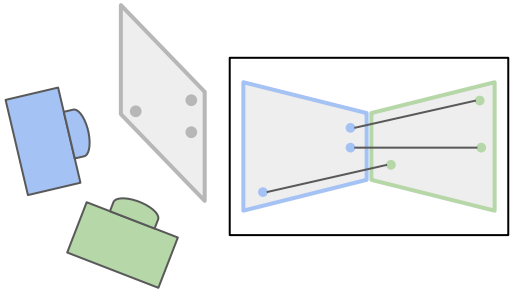
1. Load pixel coordinates of identified features in images
2. Determine camera poses from assumed ‘expected’ 3D feature positions
    - Camera poses: relative position and orientation in 3D space



Lateral position of camera



Radial position (distance) of camera

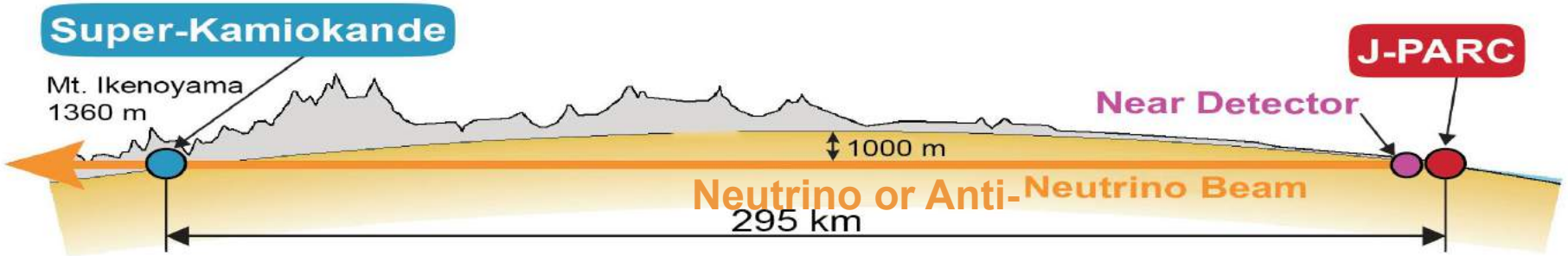


Orientation of camera

https://en.wikipedia.org/wiki/Perspective-n-Point

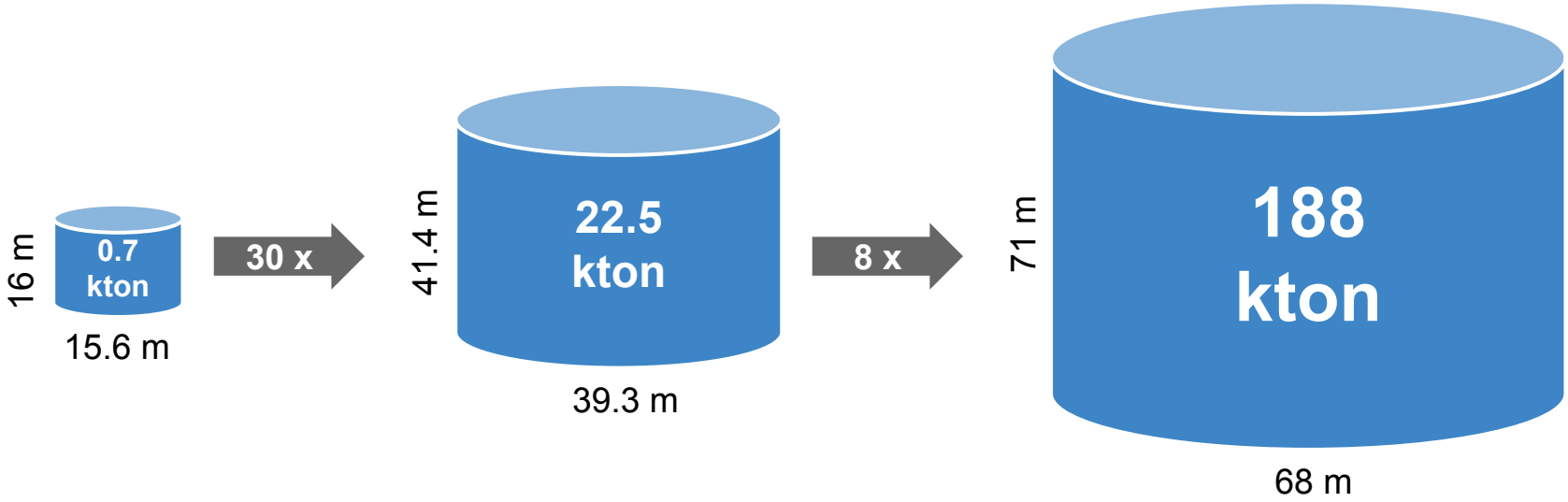
Machine Learning

The T2K



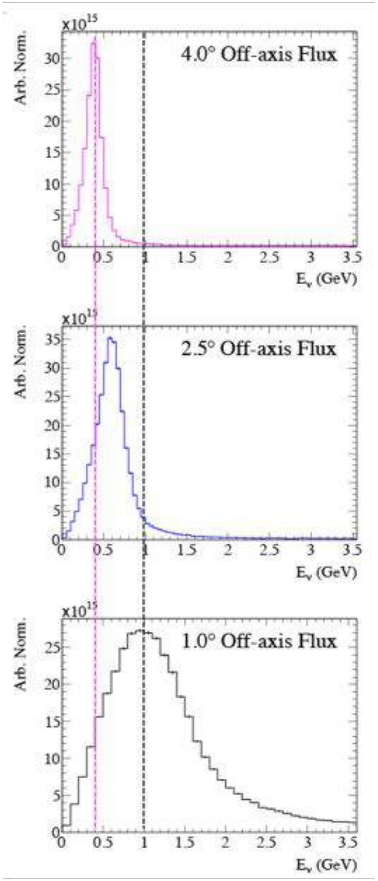
https://prezi.com/frzewoqflgsc/lbnl-rpm-oct-2019

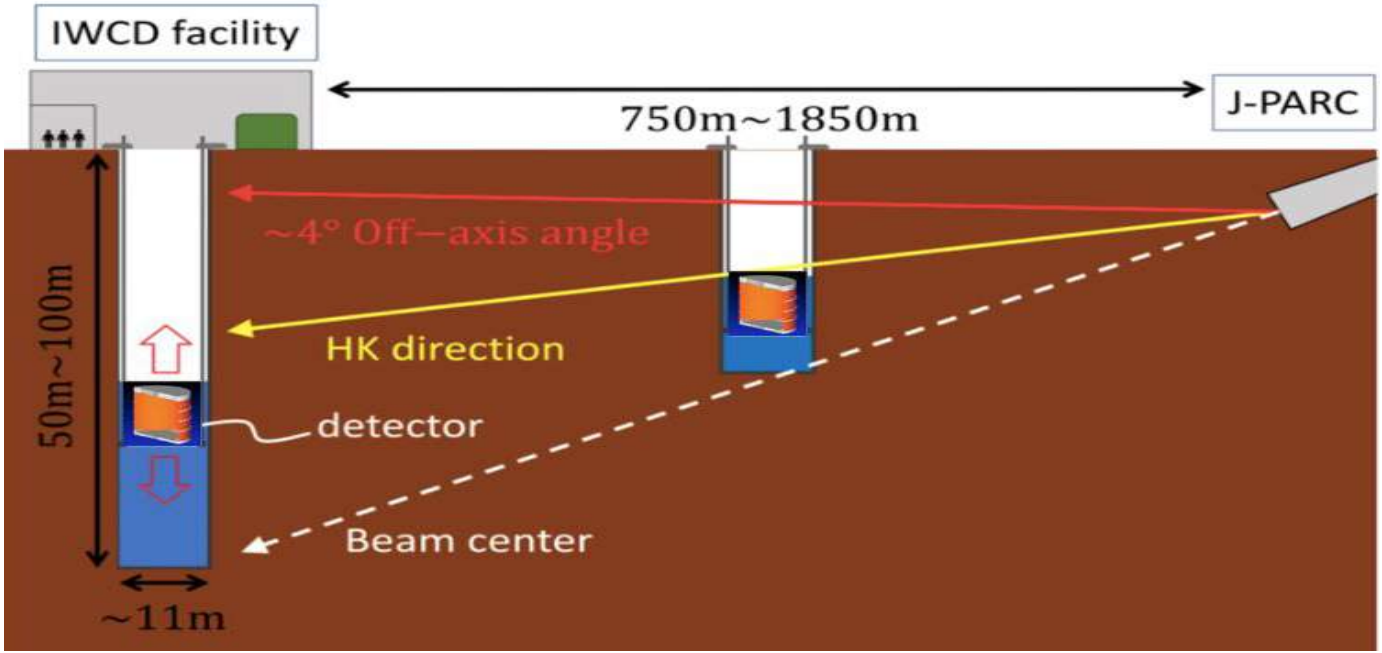
Kamiokande Super-Kamiokande Hyper-Kamiokande



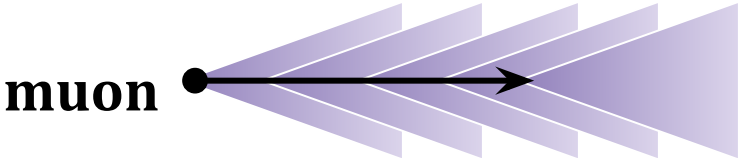
1983 - 1996	1996 - today (and beyond)	2027 - (and beyond)
Supernova 1987A  *2002 Physics*	Atm. Neutrino Oscillation  *2015 Physics*	δ_{cp}, proton decay, indirect DM search, more SNs, ...

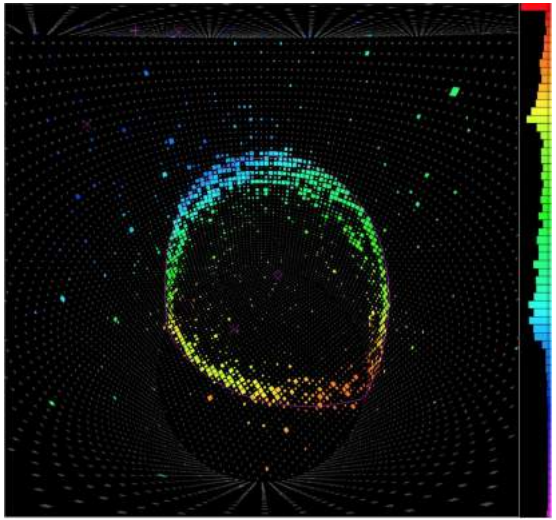
Intermediate Water Cherenkov Detector (NuPRISM)

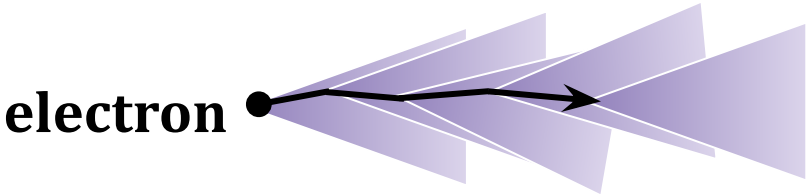


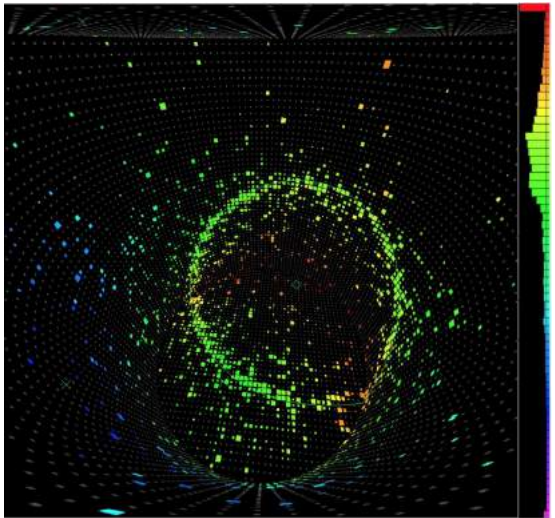


Particle Identification



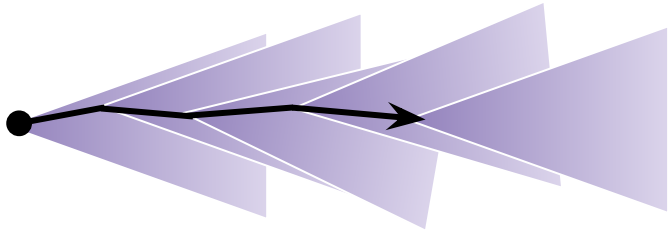




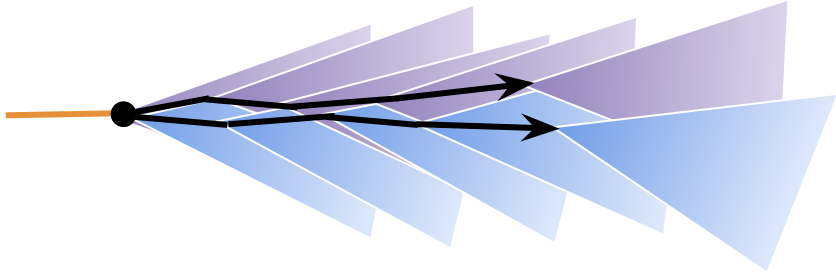


Gamma Background Discrimination

electron
(1 track)



gamma
(2 tracks)

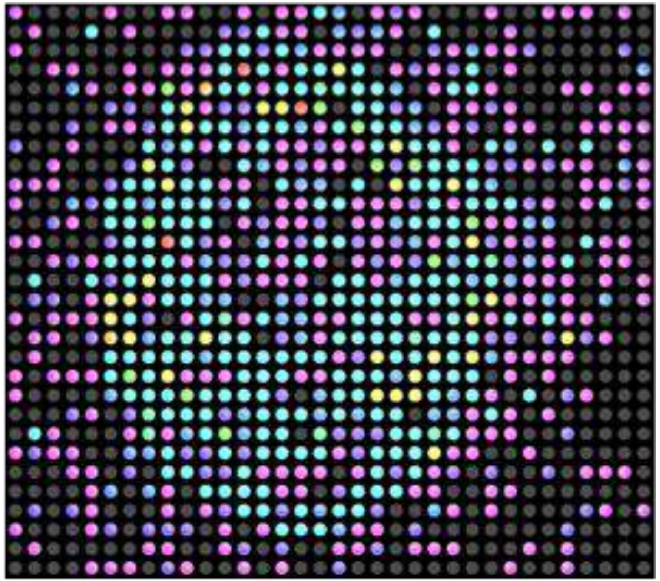


multi-PMT (mPMT)

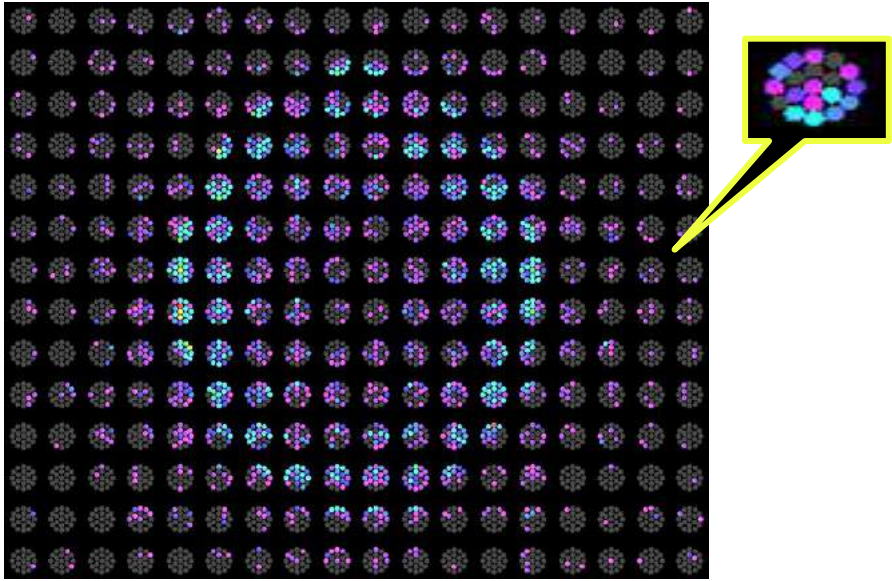
19 x 3" diameter PMTs in a single module

multi-PMT

Higher Granularity and Timing Resolution



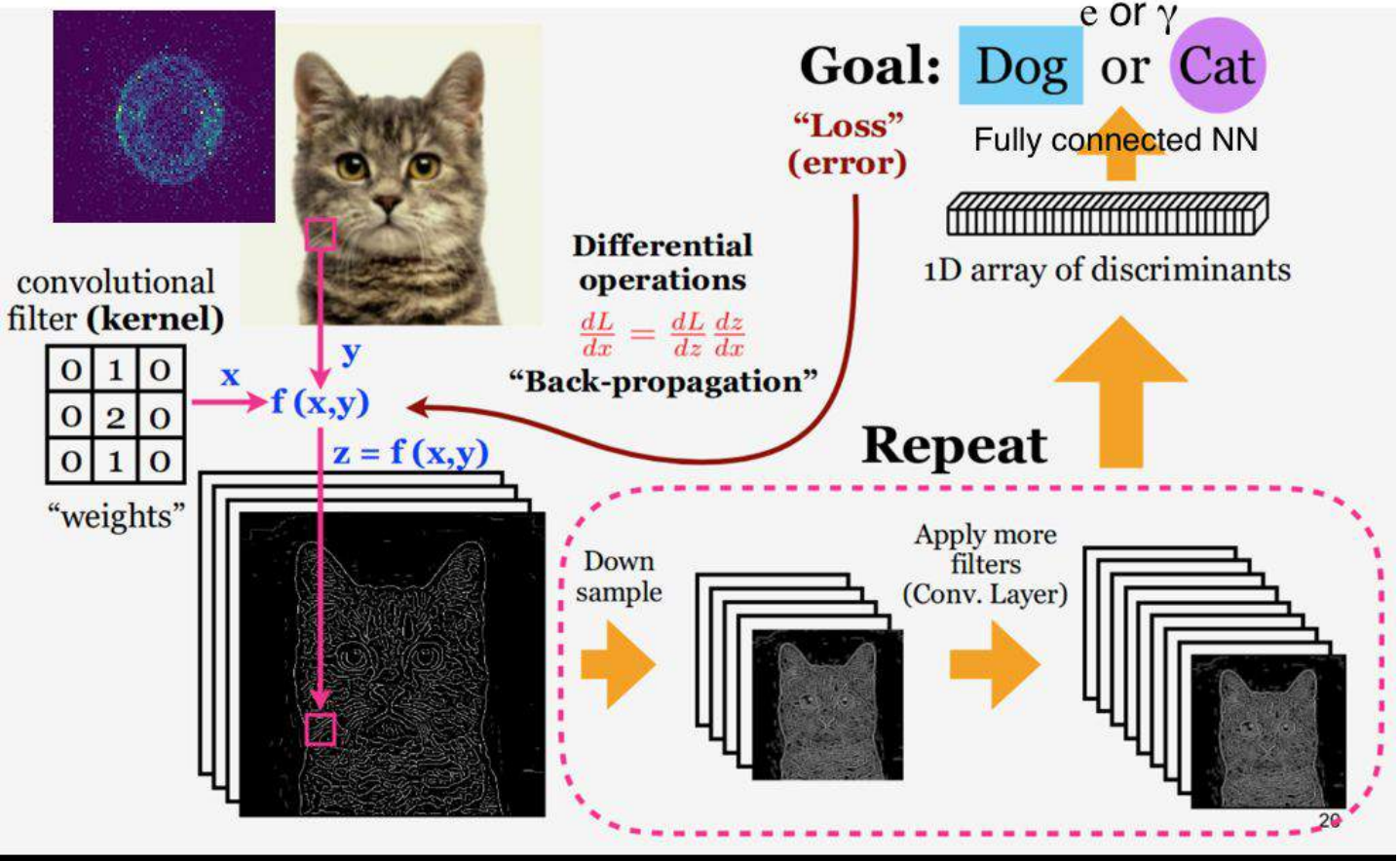
8” PMT



mPMT (3”)

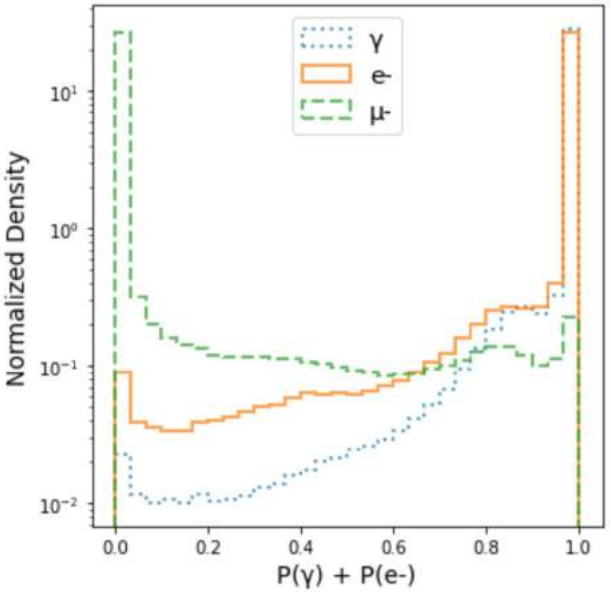
One Slide Crash Course on CNNs

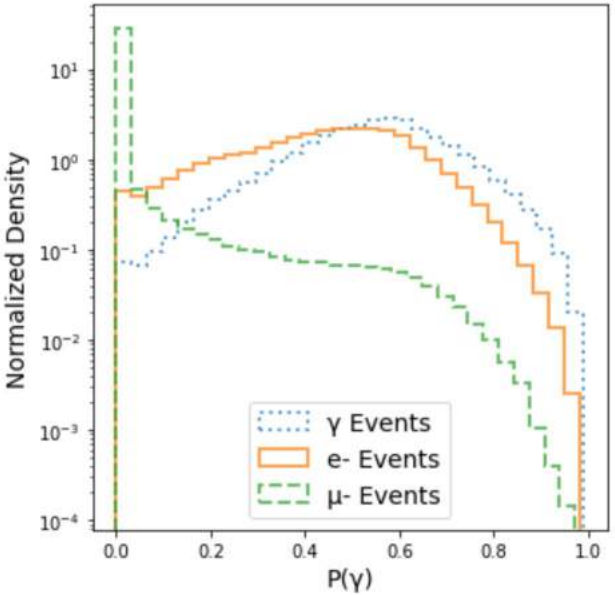
Kazu Terao (SLAC)



Event Reconstruction with Deep Learning

IWCD
Kinetic Energy < 1.5 GeV
Uniform position and direction



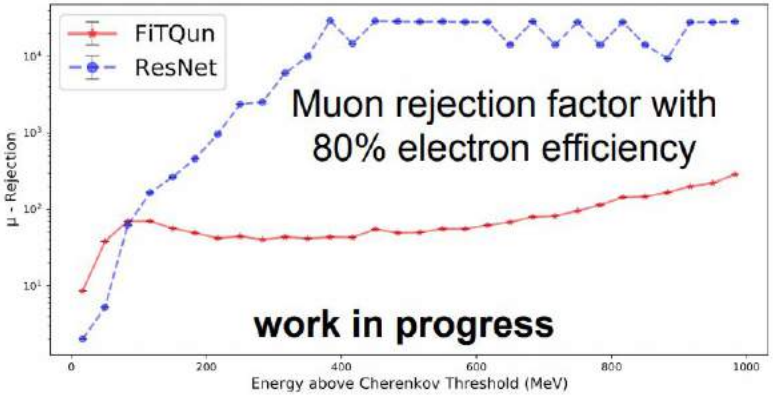


Machine learning reconstruction

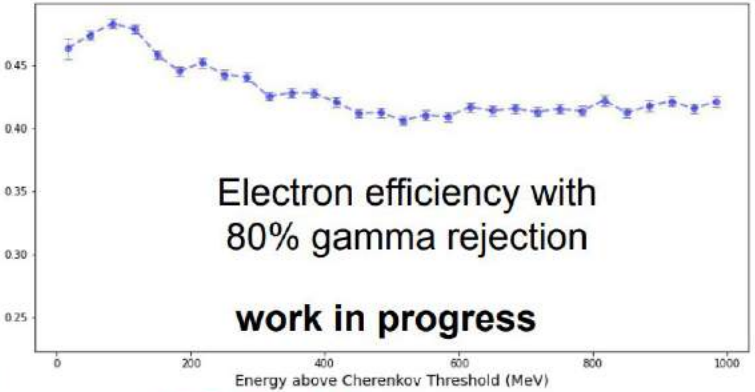
Initial studies of particle type classification in IWCD with ResNet CNN

ResNet-18 CNN architecture

- Cylinder unwrapped onto 40x40 pixel image
  - 1 mPMT per pixel
  - 38 channels: time, charge of the 19 PMTs per mPMT
- 3M of each of muons, electrons, gammas
  - Uniform positions throughout tank
  - Isotropic directions
  - Energies from 0 to 1 GeV above Cherenkov threshold



Significant improvement seen in muon vs electron discrimination



Neutral current gamma production is significant systematic uncertainty in oscillation analysis

While no electron/gamma separation with fiTQun has been successfully used, ML looks promising

Machine learning reconstruction

Many other possibilities under investigation

- Reconstruction of physical quantities
- PointNet (point cloud NN) & Graph NNs for flexibility of detector geometries
- New methods for mapping cylinder to CNN images
- Generative networks to calculate fiTQun likelihoods
- Generative networks for improving simulation and detector systematics