TRIUMF

Photogrammetry position calibration for water Cherenkov detectors

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TIPP 2021

The Super-K & Hyper-K Experiments

Current generation **Super-K** and next generation **Hyper-K** are world-leading neutrino experiments

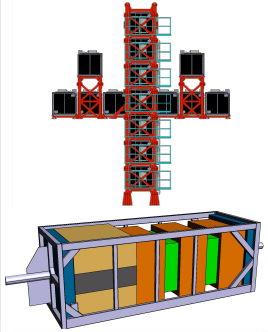
Broad & ambitious physics programmes covering many neutrino sources and proton decay measurements

Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities

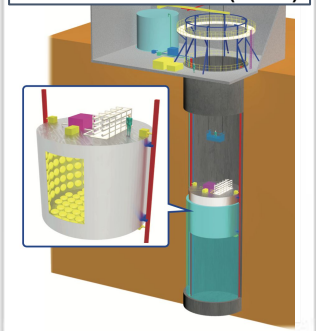
Also see talks by M. Hartz (IWCD), M. Pavin (WCTE) and T. Lux (ND280)

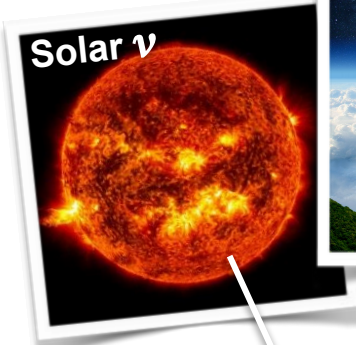
Water Cherenkov Test Experiment (WCTE) at CERN

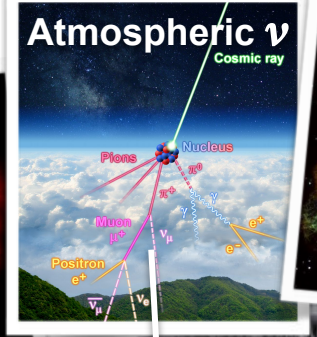
Near detectors

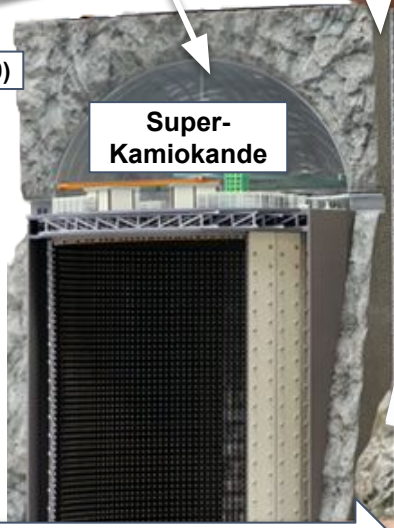


Intermediate Water Cherenkov Detector (IWCD)

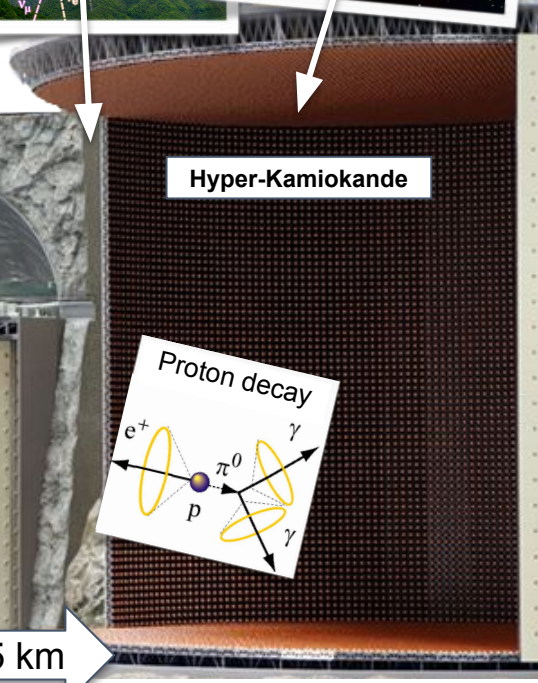








Super-Kamiokande

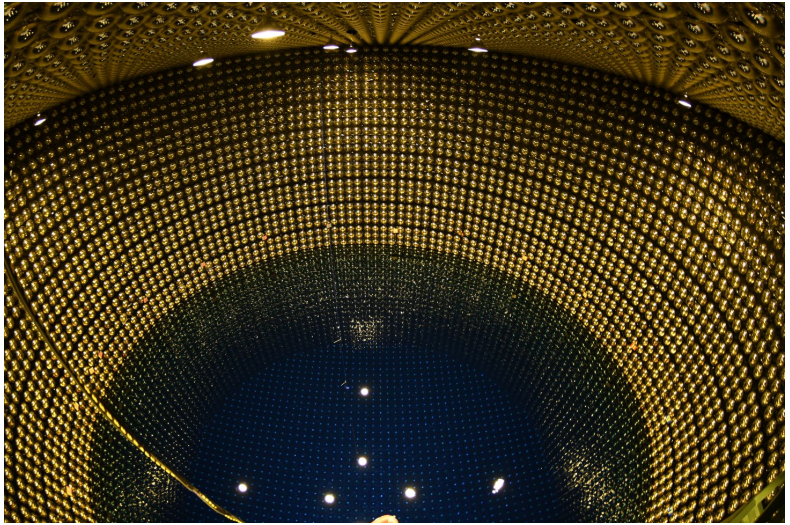


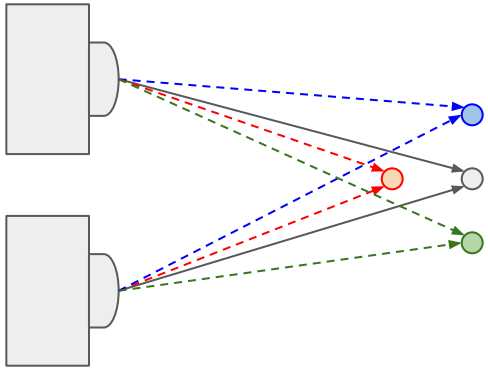
Hyper-Kamiokande

280 m → ~ 1 km → ~ 295 km

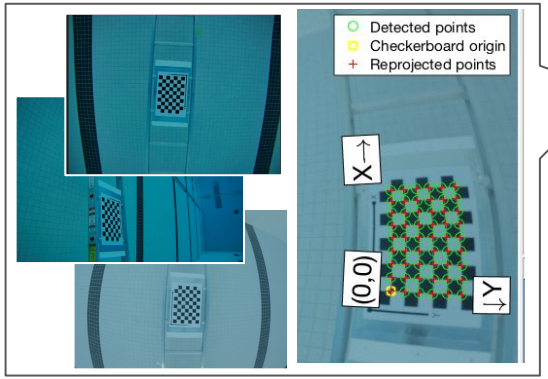
Photogrammetry motivation

- As measurements become more precise, accurate calibration of all detector aspects becomes more critical
- Over time and during water filling, buoyancy forces on large vacuum-filled PMTs could cause small systematic shifts in their positions
- Confirmation of the PMT positions could reduce systematic effects on particle reconstruction
  - e.g. require < 1% error on fiducial volume
- In-situ measurement of PMT positions can directly quantify this effect independently of other effects
- **Photogrammetry** uses stereoscopic reconstruction: photographs from multiple locations to measure the 3D geometry



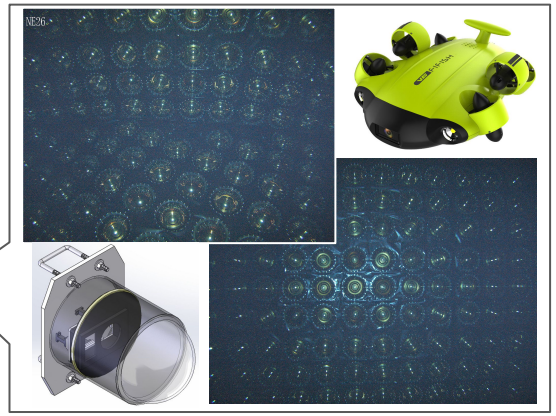


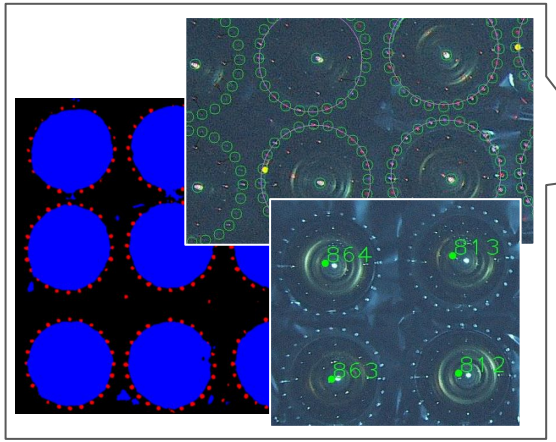
Photogrammetry procedure overview



Calibration photos → Optics calibration

Photos of detector → Undistorted images

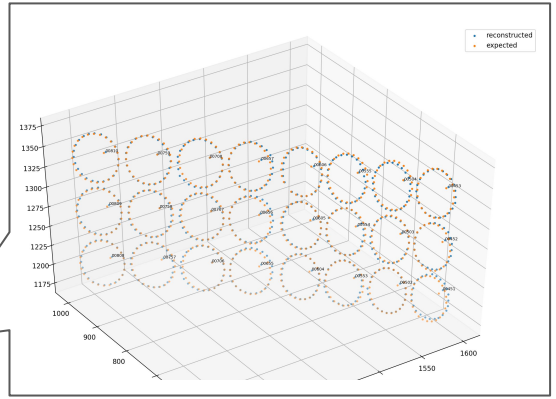




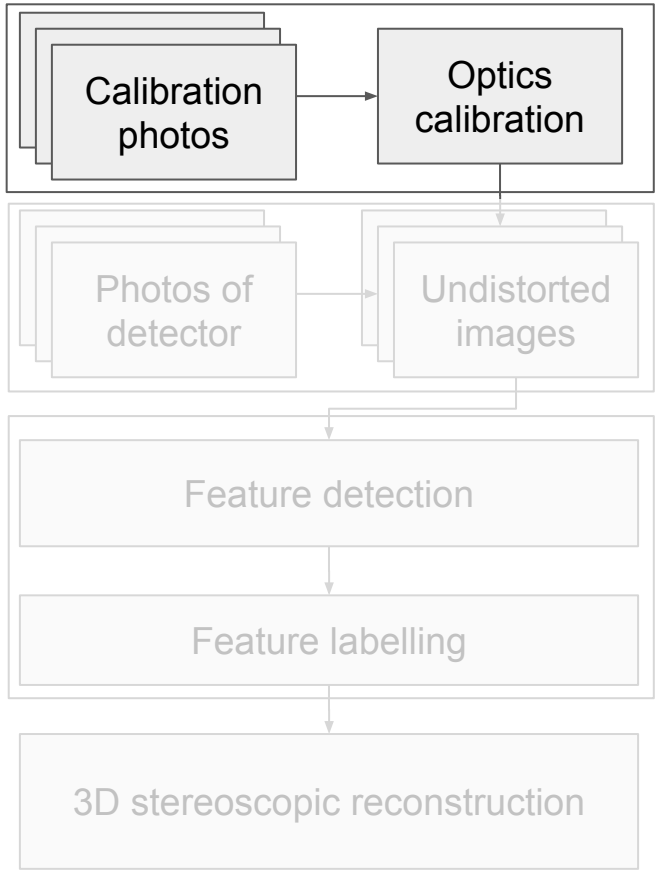
Feature detection

Feature labelling

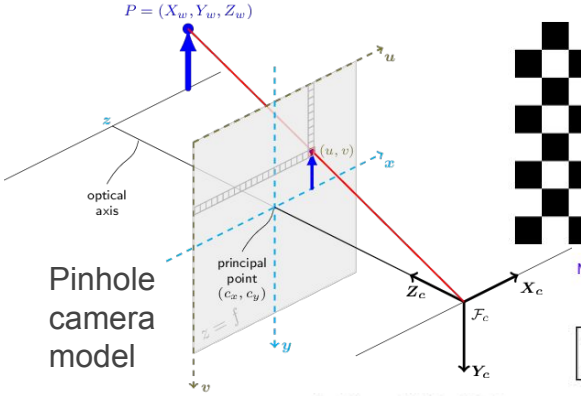
3D stereoscopic reconstruction



Camera calibration

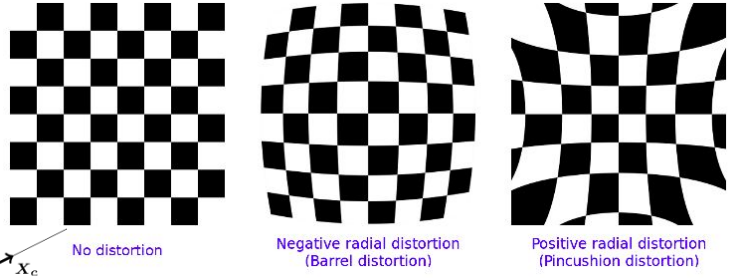


- Camera model transforms 3D locations to 2D image pixels



Pinhole camera model

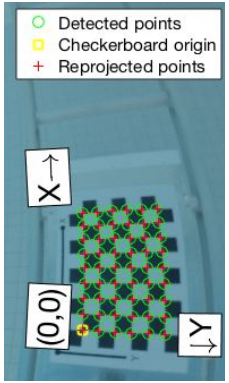
$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} f_x x'' + c_x \\ f_y y'' + c_y \end{bmatrix} \qquad \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} X_c/Z_c \\ Y_c/Z_c \end{bmatrix}$$



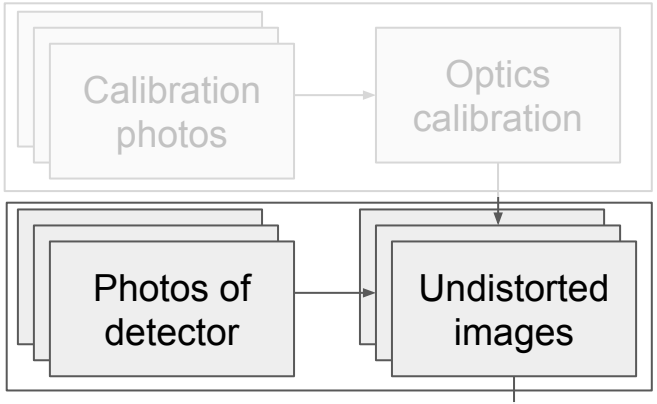
$$\begin{bmatrix} x'' \\ y'' \end{bmatrix} = \begin{bmatrix} x' \frac{1+k_1r^2+k_2r^4+k_3r^6}{1+k_4r^2+k_5r^4+k_6r^6} + 2p_1x'y' + p_2(r^2+2x'^2) + s_1r^2 + s_2r^4 \\ y' \frac{1+k_1r^2+k_2r^4+k_3r^6}{1+k_4r^2+k_5r^4+k_6r^6} + p_1(r^2+2y'^2) + 2p_2x'y' + s_3r^2 + s_4r^4 \end{bmatrix}$$

Lens distortion model

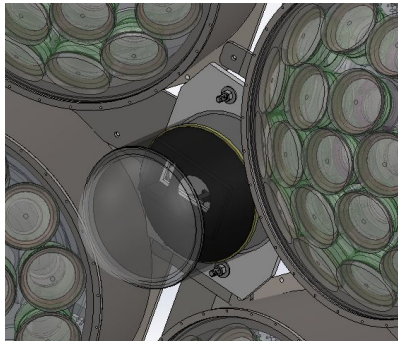
- Underwater photos taken in pool with checkerboard calibration pattern
- Camera model params determined using MATLAB camera calibration toolbox



Photogrammetry data taking

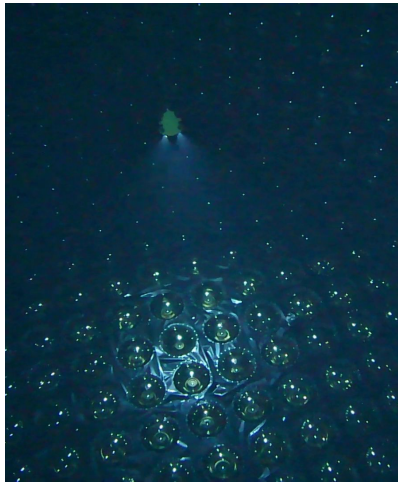


- Photographs taken using fixed or movable cameras inside detector
  - Fixed camera designs under development for future detectors WCTE, IWCD and Hyper-K
  - Remotely operated submersible used in Super-K for 5.5 hours during detector upgrade work in Feb. 2020

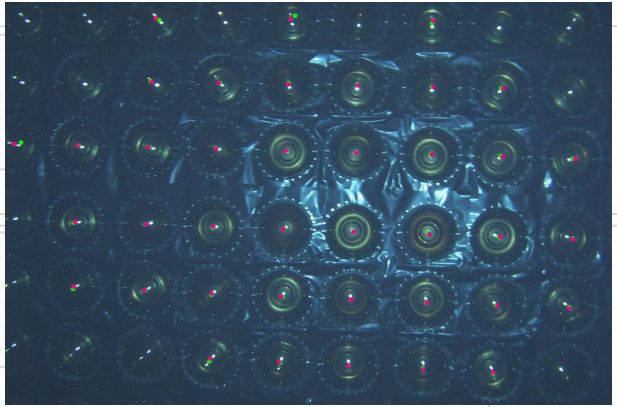


QYSEA FIFISH V6

- 100 m depth rating
- Small enough to fit through largest calibration port (~40 cm)
- Highly maneuverable (360° pitch, roll, yaw)
- Depth and orientation sensors
- 12 MP camera sensor
- 4000 lumen total, variable intensity lighting
- Tethered for remote control and safety
  - Live stream to mobile device
- 4 hour battery life (1 hour charge time)



Feature Identification

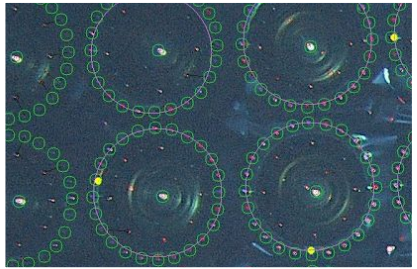


Feature detection

Feature labelling

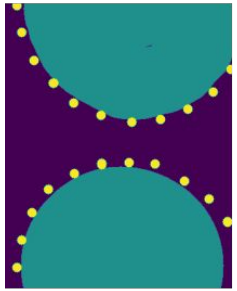
3D stereoscopic reconstruction

- Identifying and matching PMTs in repeating pattern is very challenging
- Image processing methods used for identifying the features to be reconstructed: Bolts and PMT centres
  - Traditional blob detection and Hough transforms
    - Using OpenCV software
  - Machine-learning convolutional neural networks
    - UNet with Image Segmentation Keras package
- Current precision of ~ 2 - 4 pixels
  - Hope to improve on this with further development

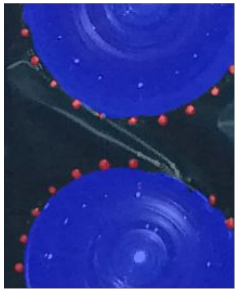


Blob detection & Hough transform ellipse finding

Original image

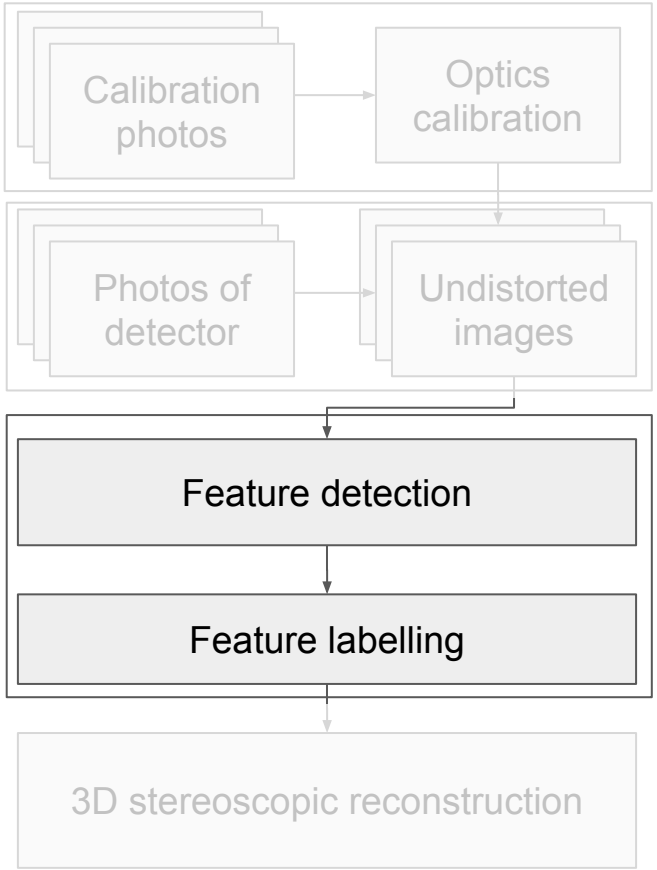


Segmented by eye for training

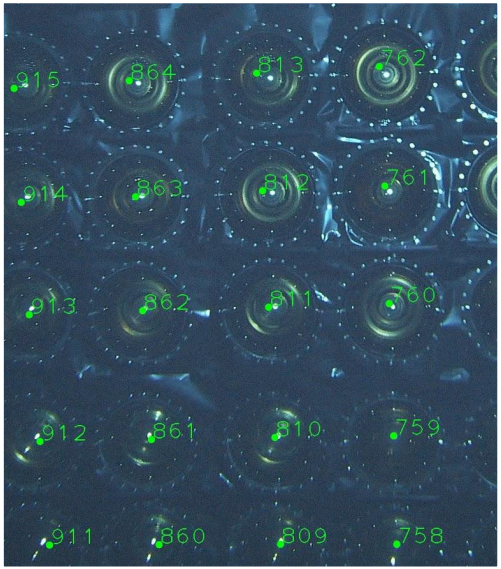


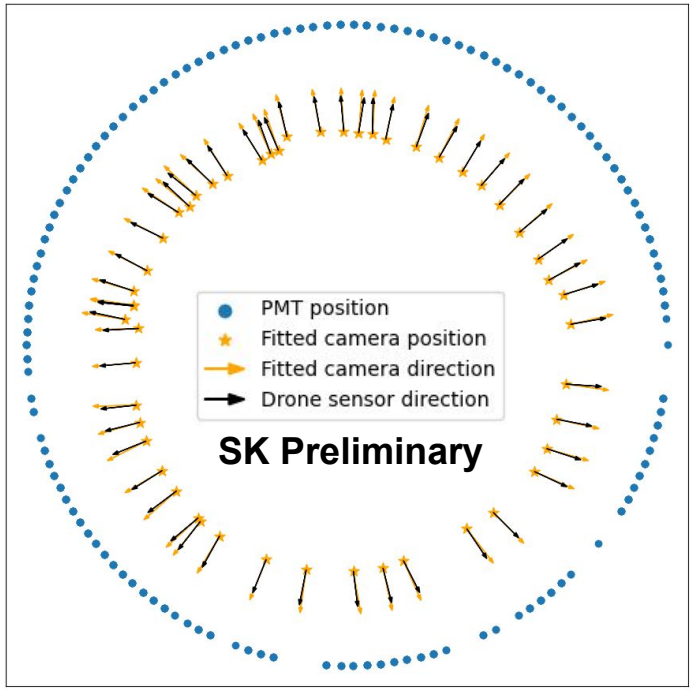
Segmented by CNN

Feature Labelling



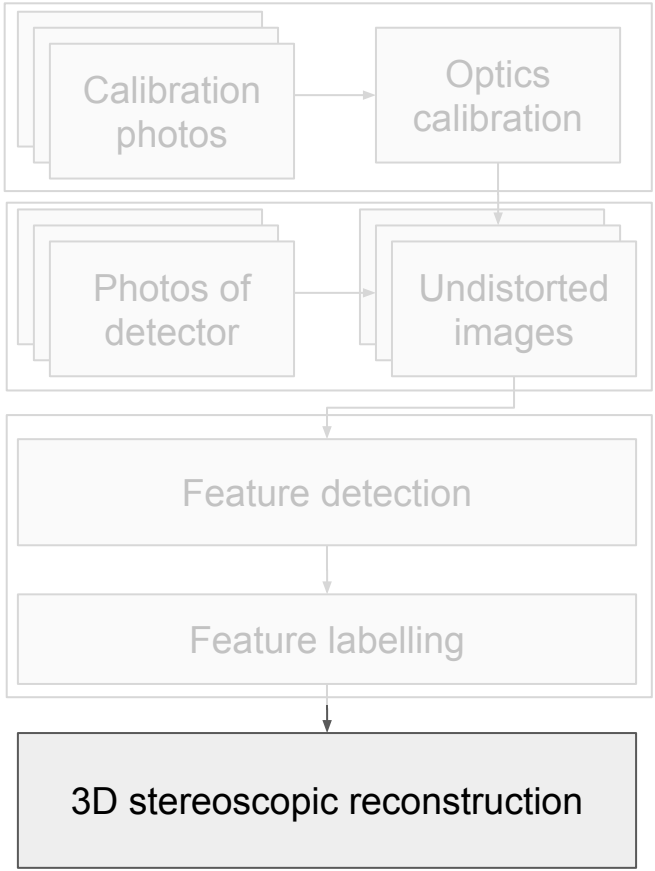
- Identifying and matching PMTs in repeating pattern is very challenging
- Camera position or submarine sensors used to match features between images





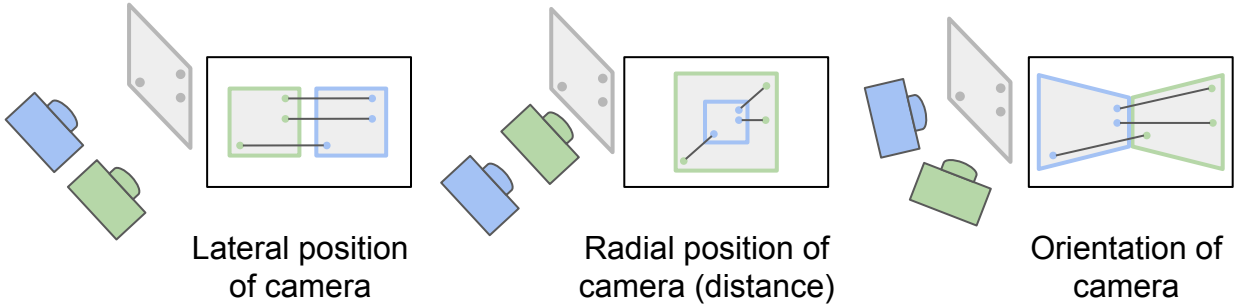
Note: gaps due to lack of overlapping photographs at some locations

Stereoscopic reconstruction

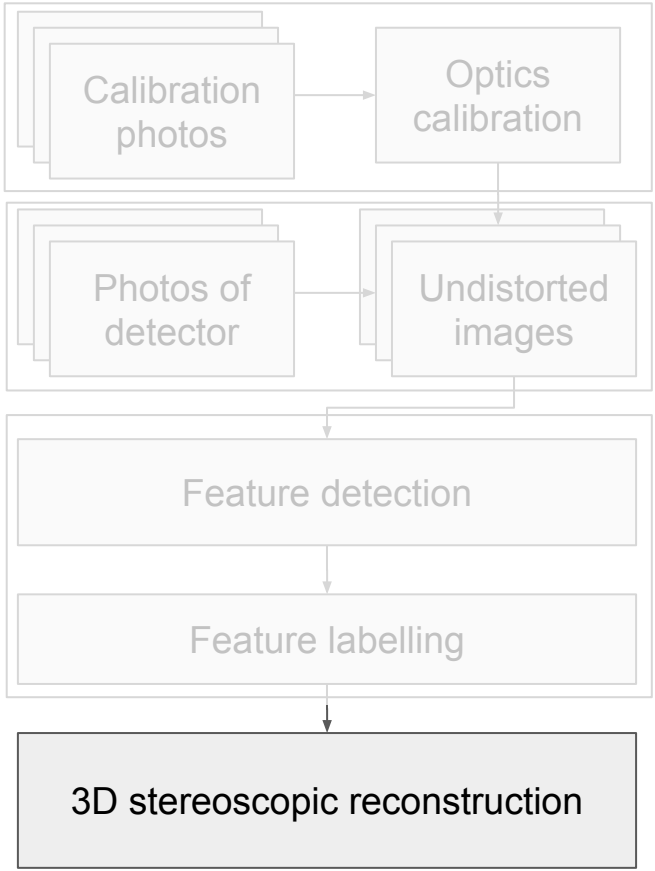


Use OpenCV to perform photogrammetric reconstruction on of identified feature locations

1. Determine camera poses from assumed ‘expected’ 3D feature positions
   - Camera poses: relative position and orientation in 3D space

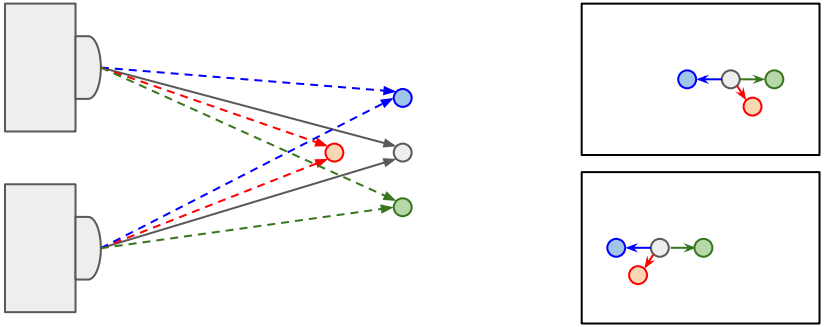


Stereoscopic reconstruction

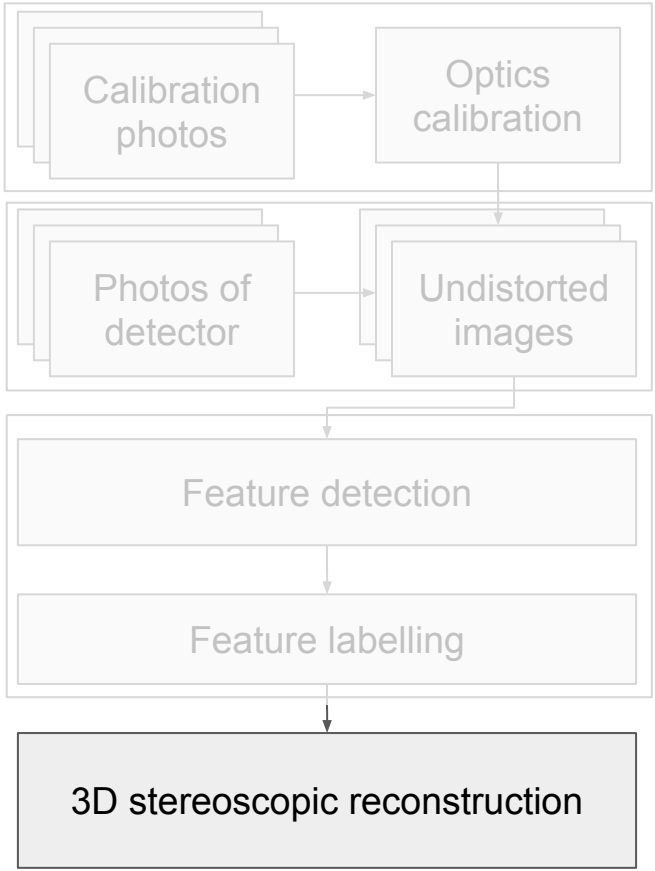


Use OpenCV to perform photogrammetric reconstruction on of identified feature locations

1. Determine camera poses from assumed ‘expected’ 3D feature positions
   - Camera poses: relative position and orientation in 3D space
2. Fit 3D positions of features ‘bundle adjustment’
   - Vary camera poses and 3D feature positions simultaneously

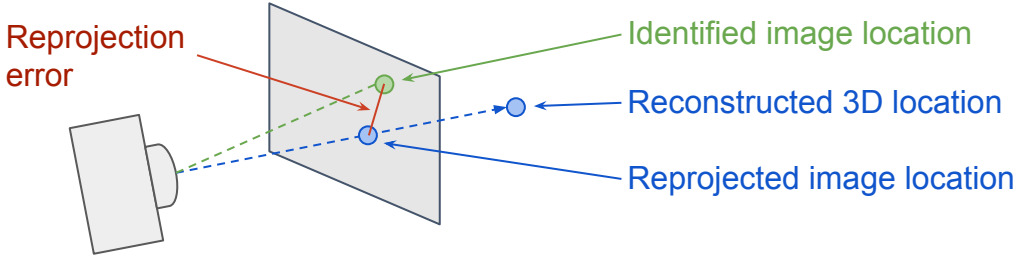


Stereoscopic reconstruction



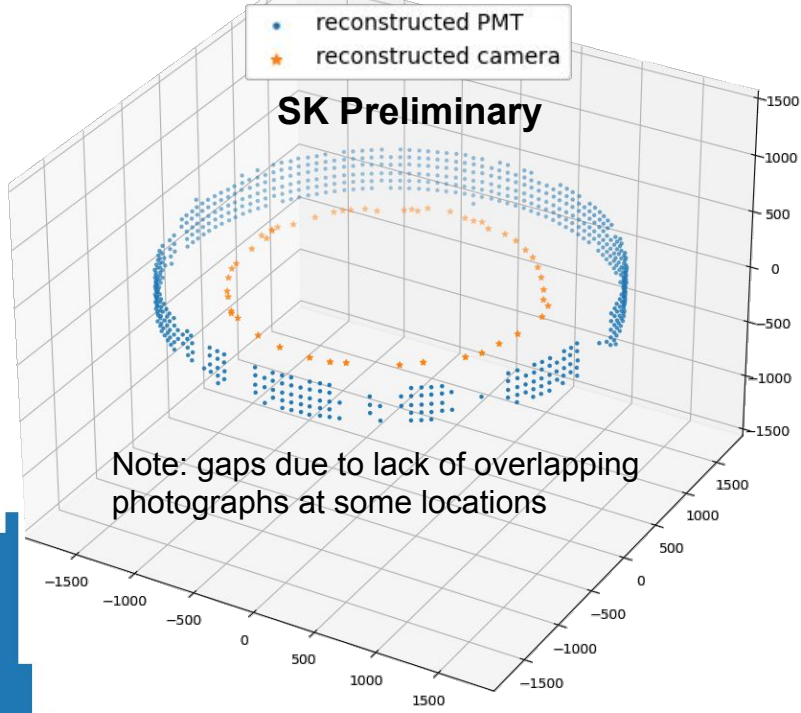
Use OpenCV to perform photogrammetric reconstruction on of identified feature locations

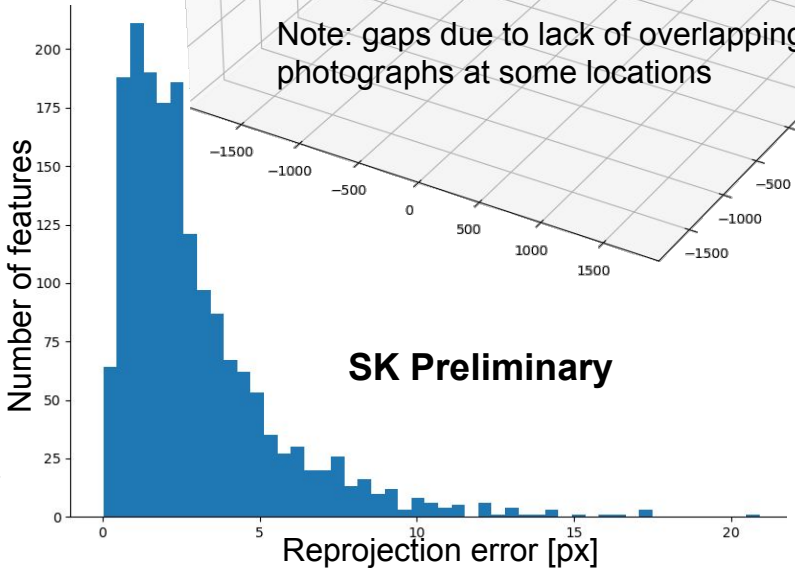
1. Determine camera poses from assumed ‘expected’ 3D feature positions
   - Camera poses: relative position and orientation in 3D space
2. Fit 3D positions of features ‘bundle adjustment’
   - Vary camera poses and 3D feature positions simultaneously
   - Minimise reprojection errors



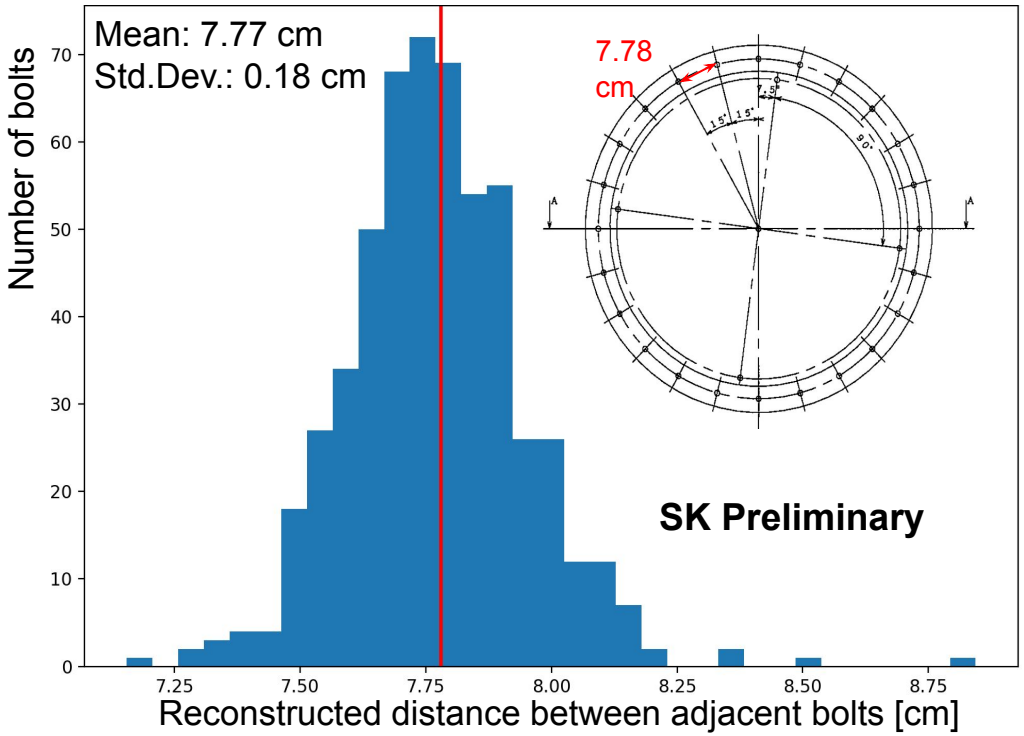
Results at Super-K

- 3D reconstruction achieved from one ring of images around Super-K
- Analysis of results is currently underway
- Reprojection errors provide measure of fit quality
  - Mean error: 3 pixels
  - 1px error ~ 1 cm position error
- Full tank reconstruction & analysis planned for better understanding Super-K geometry





Results at Super-K



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 Super-K)

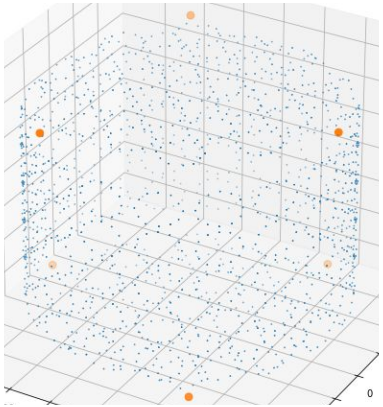
Spread suggests reconstructed distance errors of ~ 0.2 cm

But larger errors might exist over longer distance measurements

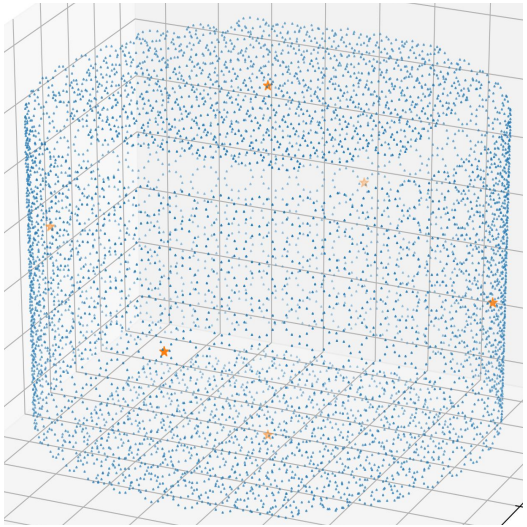
Simulations for future detectors

Simulation framework to test photogrammetry configurations

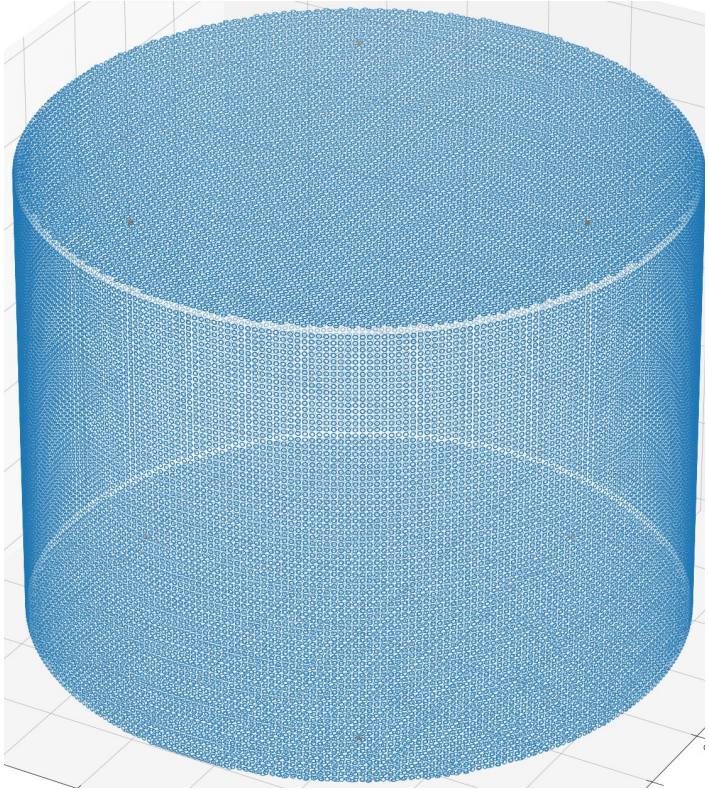
- Simulate images for different detector geometries & camera configurations
- Calculate expected 3D reconstruction precision



WCTE

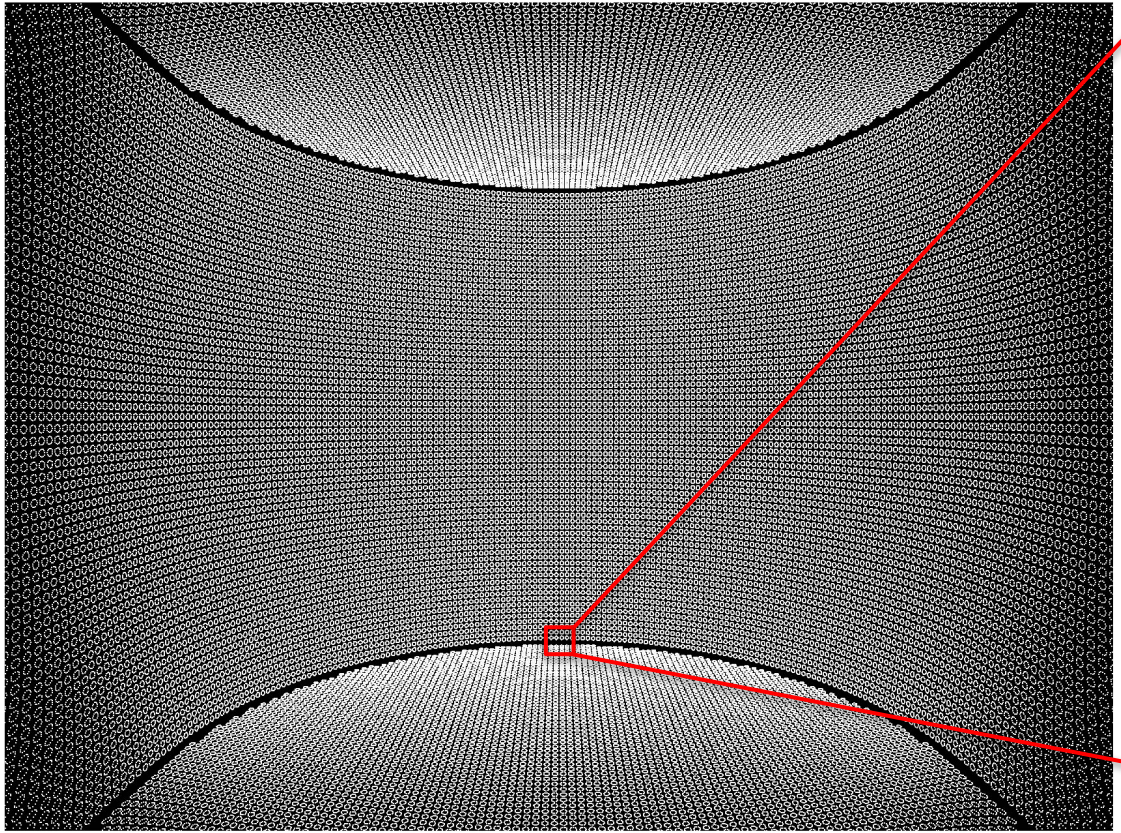


IWCD

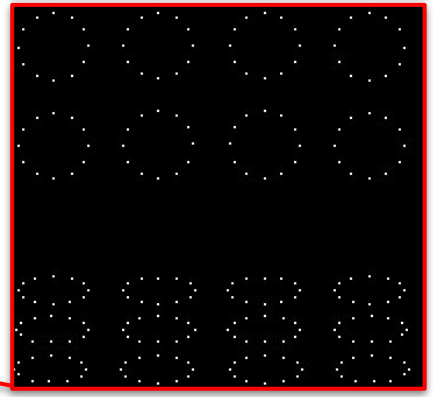


Hyper-K

Simulations for future detectors



Sony A6000 resolution

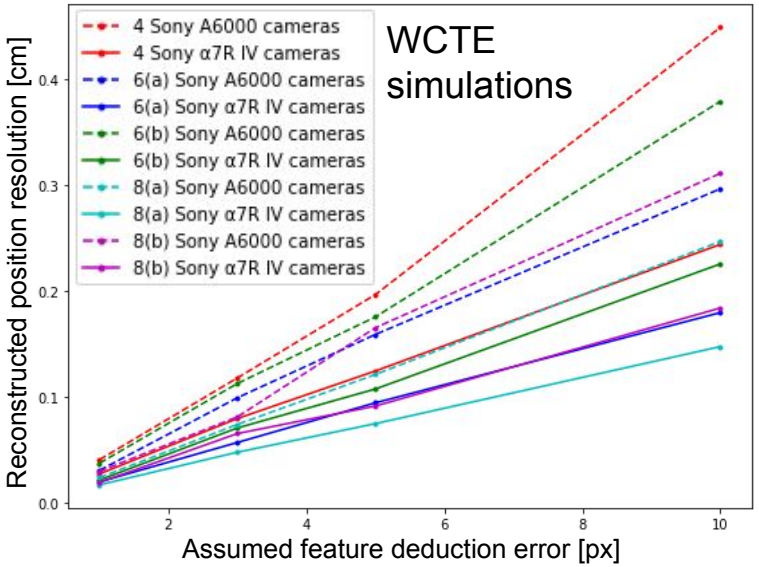


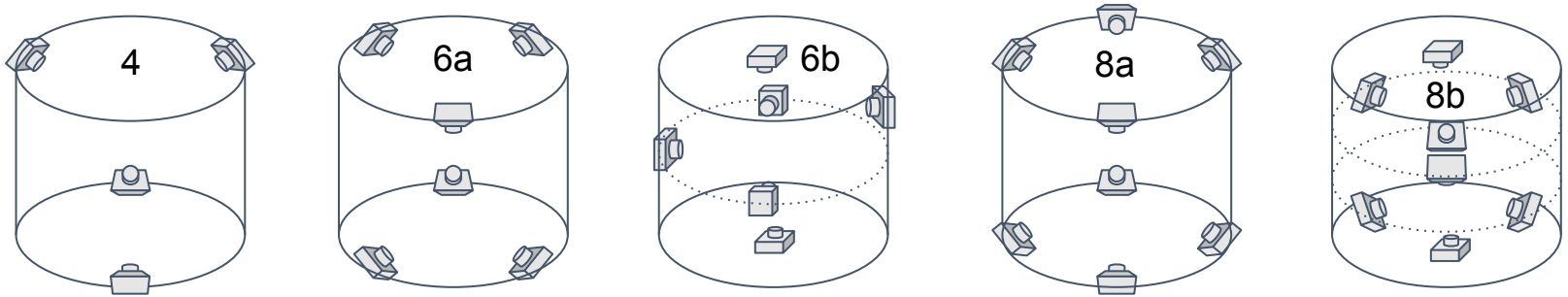
Sony a7R resolution

Simulations for future detectors

Simulation framework to test photogrammetry configurations

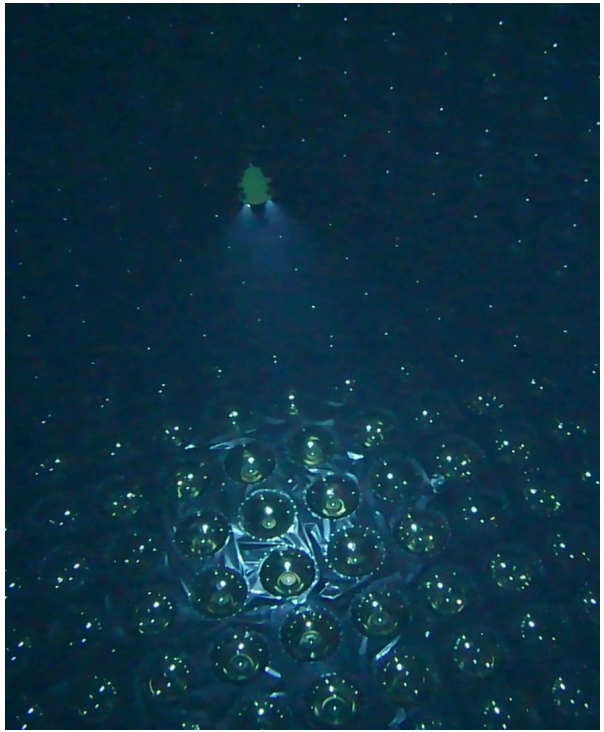
- Simulate images for different detector geometries & camera configurations
- Apply smearing for feature identification error
- Calculate expected 3D reconstruction precision
- Optimise camera configuration for each experiment





Summary

- As neutrino measurements become more precise, accurate calibration of all detector aspects becomes more critical
- Photogrammetry can provide precise in-situ measurement of detector geometry
- With Super-K we have demonstrated the full photogrammetry chain
  - Calibration of cameras, and data taking in the detector
  - Identification and labelling of features to reconstruct in images
  - Stereoscopic reconstruction of 3D geometry
  - Analysis work is ongoing with plan to extend to full detector
- Simulations and R&D for future detectors to optimise hardware configurations and understand physics impact



Thank you for your attention