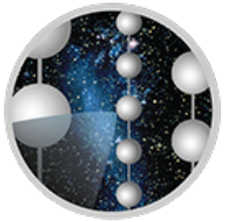
2021 TEV Particle Astrophysics Conference

IceCube Upgrade & the Performance of the D-Egg Optical Modules

C. Hill, M. Meier, R. Nagai, N. Shimizu, A. Ishihara, & S. Yoshida
for the IceCube Collaboration

CHIBA UNIVERSITY



IceCube
South Pole Neutrino Observatory

ICEHAP
International Center for Hadron Astrophysics

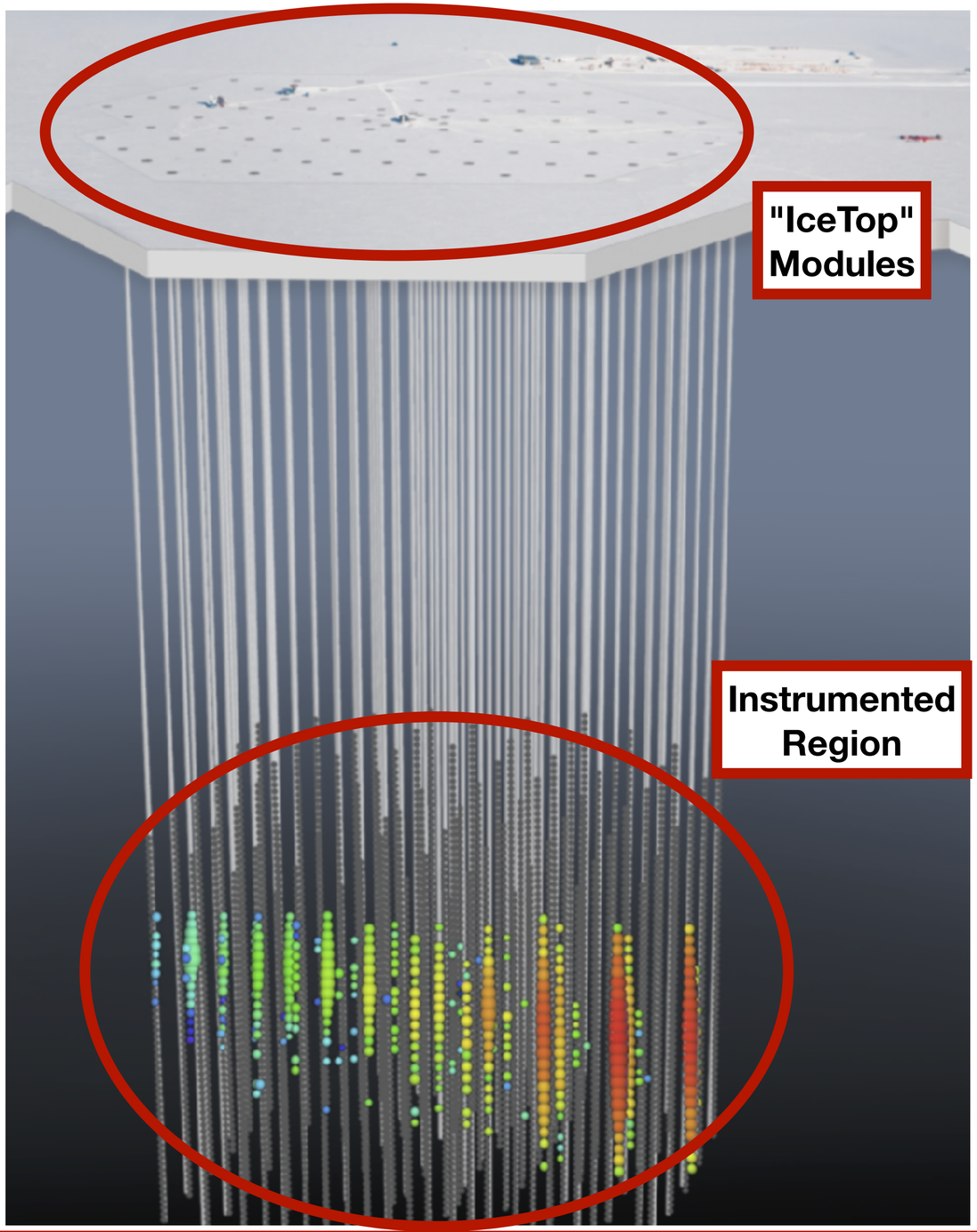
Outline

- IceCube & IceCube Upgrade
- Next Generation Module: D-Egg
- D-Egg Acceptance Testing
- Summary

https://higgstan.com/

The IceCube Detector

- IceCube is located at the geographic South Pole and has been collecting data for 10 years now.
- IceCube's deep-ice optical modules detect Cherenkov light from charged particles traversing the ice.
- 5160 optical moduels are installed in the ice between 1450 m - 2450 m, with instrumented volume ~1 km^3.



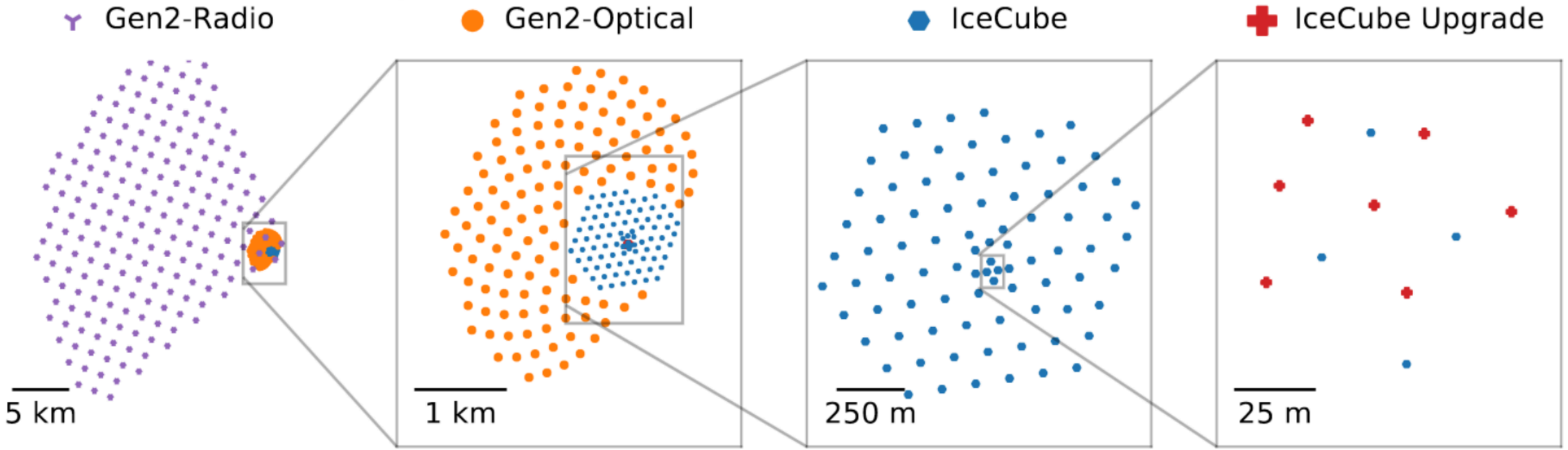
IceCube Upgrade & "Gen2"

Current Generation IceCube Sensors

IceCube Upgrade Novel Optical Sensors

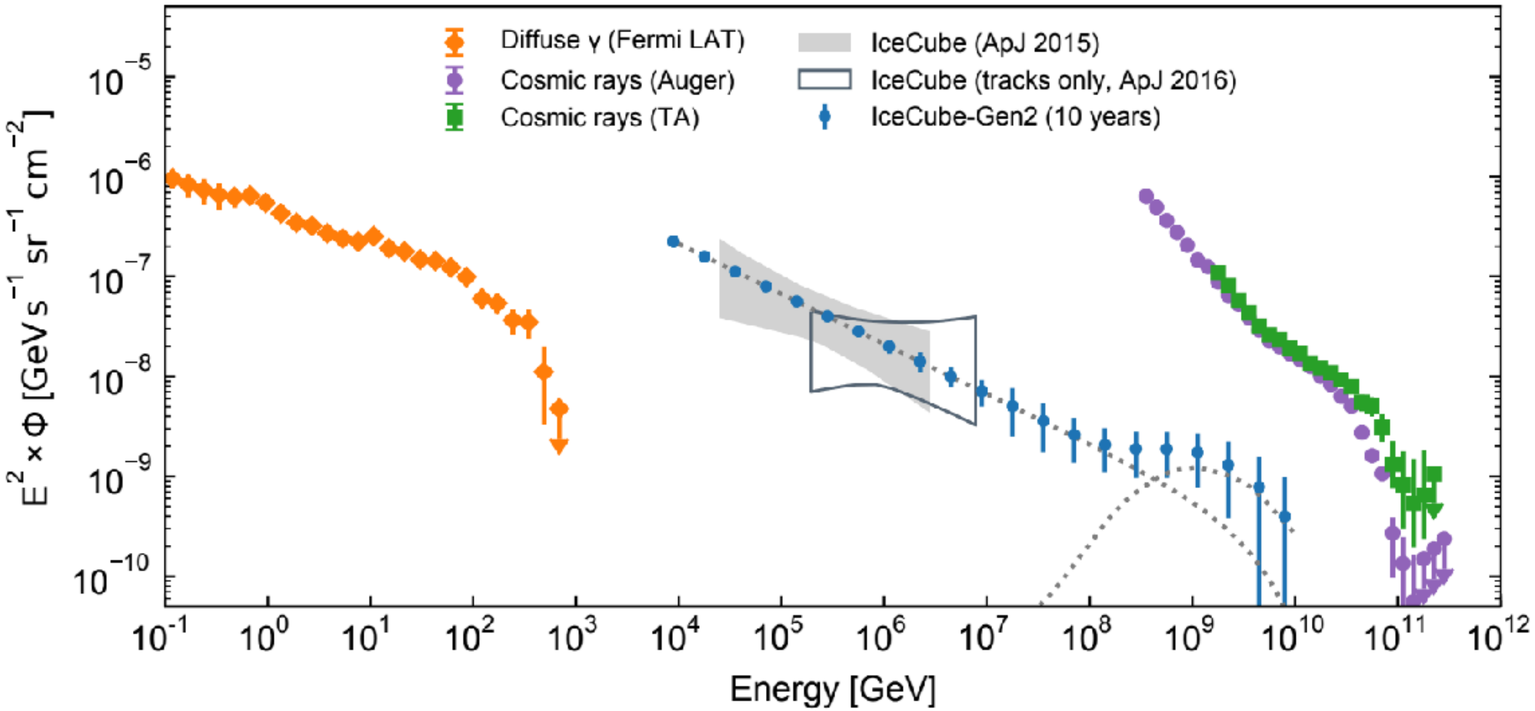
- IceCube Upgrade involves development & deployment of novel optical modules - called "D-Egg" and "mDOM".
- The Upgrade also provides a practical test-bed for the planned larger scale deployment of optical modules for IceCube Gen2.
- Expanding to IceCube Gen2 will provide a considerable boost in sensitivity at higher energies.

IceCube Upgrade & "Gen2"



- IceCube Upgrade involves development & deployment of novel optical modules - called "D-Egg" and "mDOM".
- The Upgrade also provides a practical test-bed for the planned larger scale deployment of optical modules for IceCube Gen2.
- Expanding to IceCube Gen2 will provide a considerable boost in sensitivity at higher energies.

IceCube Upgrade & "Gen2"



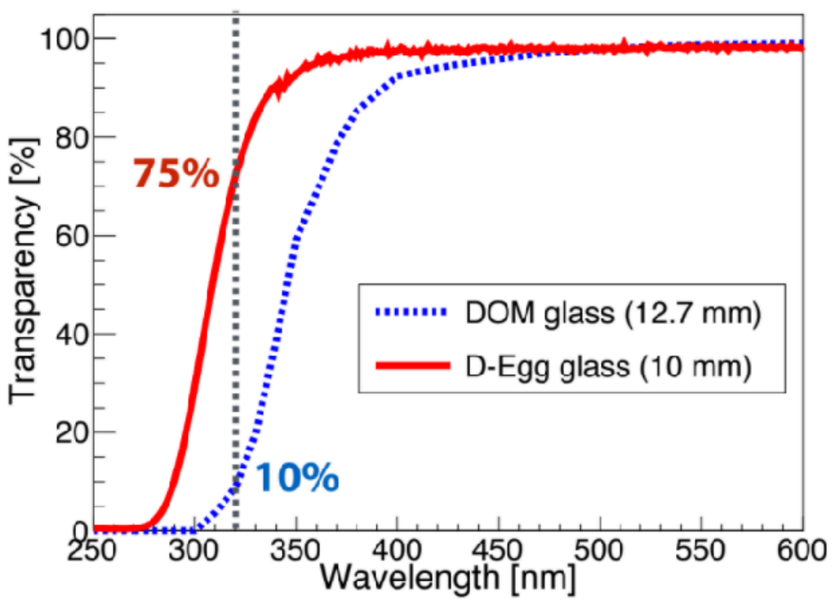
- IceCube Upgrade involves development & deployment of novel optical modules - called "D-Egg" and "mDOM".
- The Upgrade also provides a practical test-bed for the planned larger scale deployment of optical modules for IceCube Gen2.
- Expanding to IceCube Gen2 will provide a considerable boost in sensitivity at higher energies.

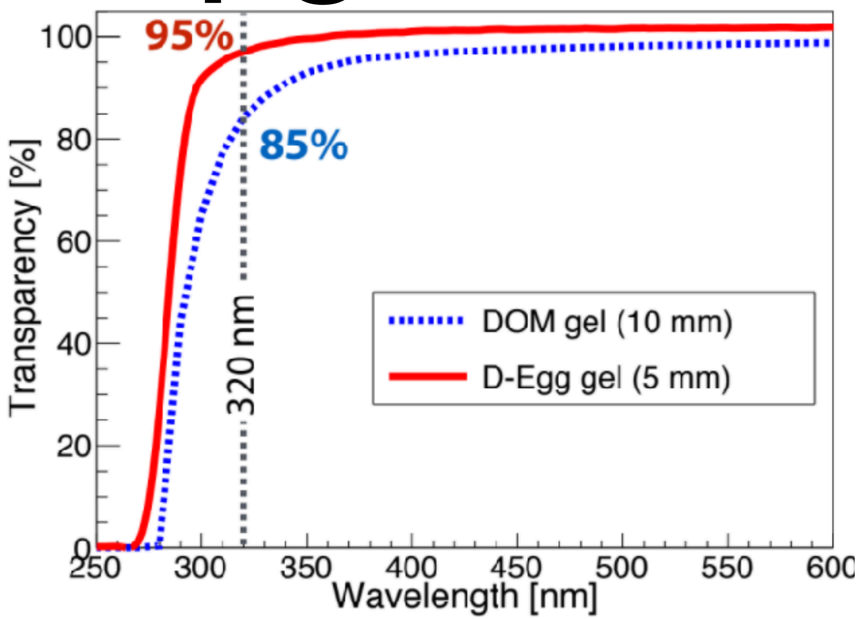
IceCube Upgrade: D-Eggs

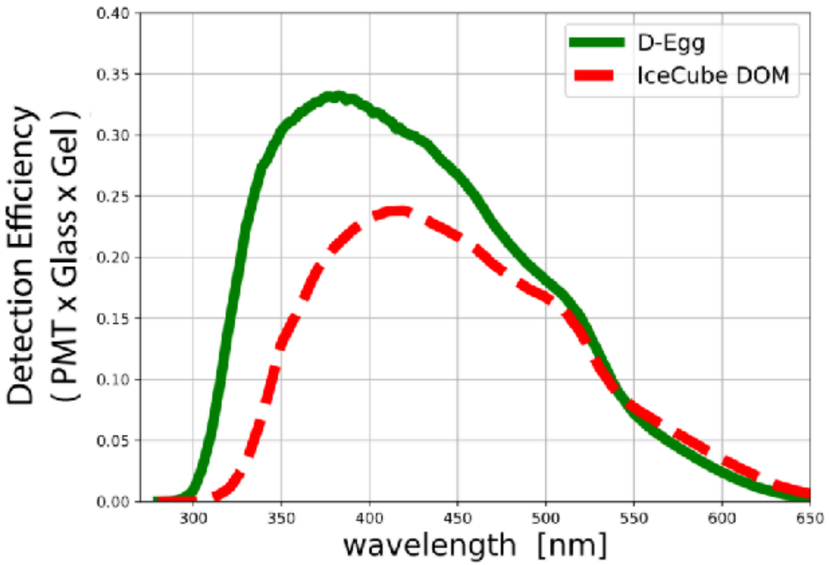
- D-Eggs are next-generation optical modules to be deployed as part of the IceCube Upgrade (start 2022/2023).
- The dual-PMT design improves photo-detection efficiency and provides additional directional information.
- A reduced diameter compared to the current optical modules decreasing drilling costs during deployment and low power consumption makes D-Eggs a cost efficient choice.
- Additional calibration devices are installed in the D-Eggs to provide to measure specific IceCube systematic uncertainties related to ice formation and deployment.
- The D-Egg project has already completed production, with over 300 modules assembled in total.

D-Egg prepared for testing

IceCube Upgrade: D-Eggs



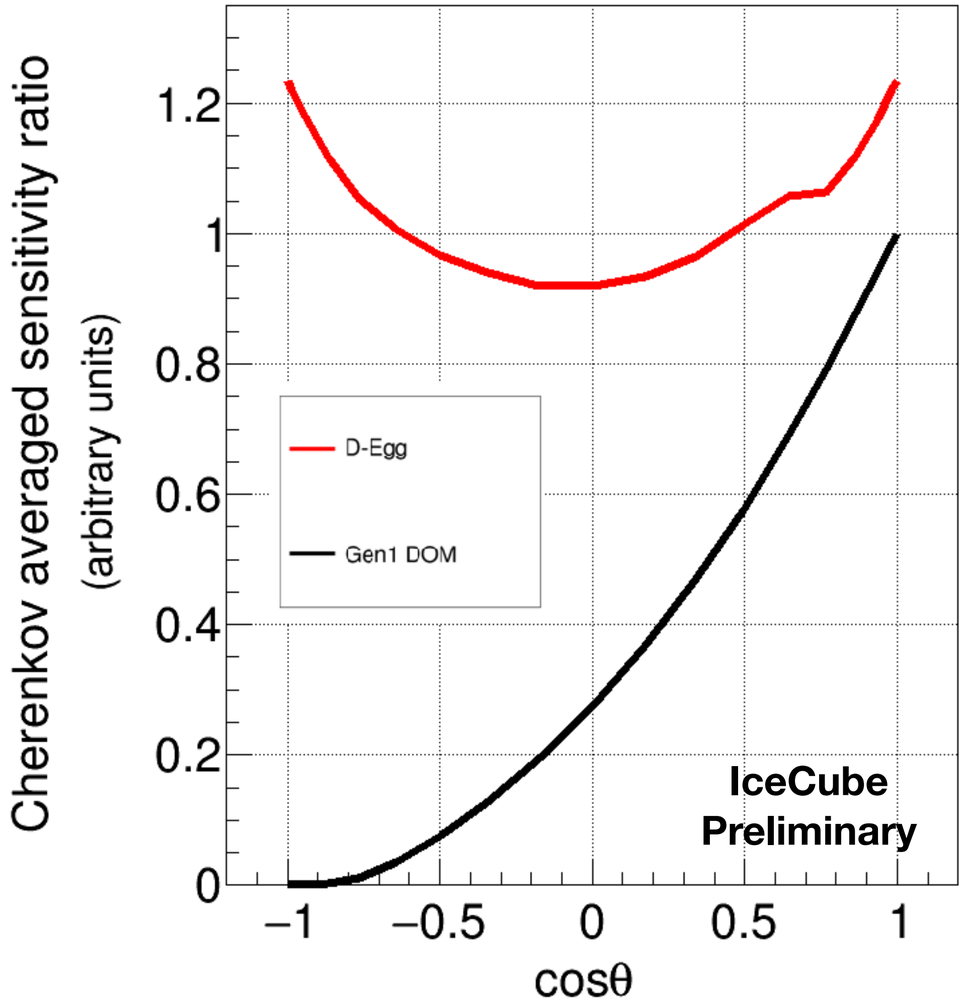




- In addition to higher quantum efficiency PMTs, the optical properties of the D-Eggs themselves have also been improved.
- Thickness & chemical composition of the glass shell improved to increase transparency at low wavelengths and optical coupling gel thickness decreased.
- This results in a boost in detection efficiency, even when only considering a single D-Egg pmt.

IceCube Upgrade: D-Eggs

- Combining all improvements of the D-Eggs relative to the current IceCube optical modules, considerable improvements across the full cos(θ) space are expected!



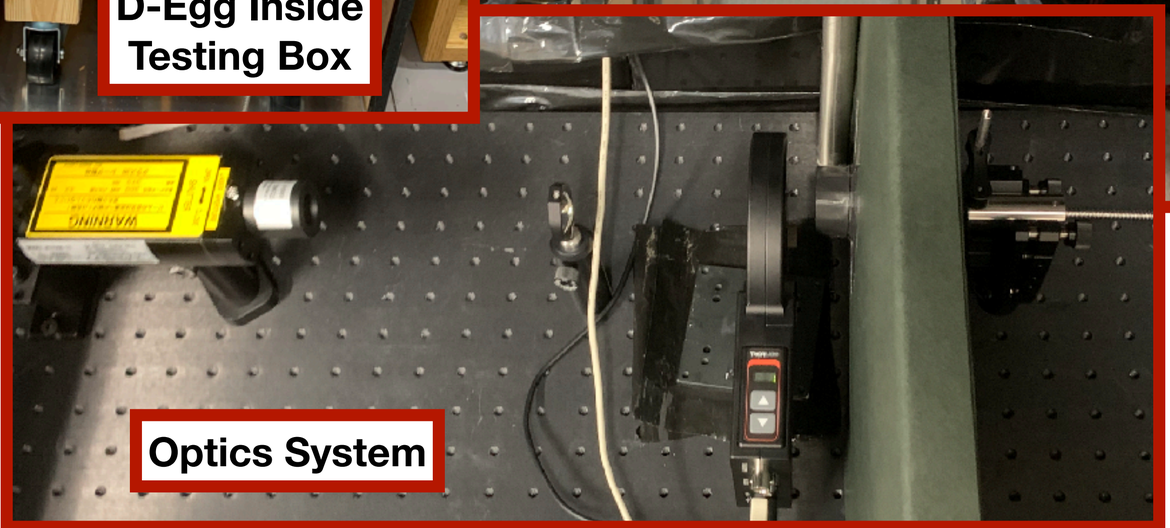
D-Egg Acceptance Testing

- ~300 D-Eggs need to undergo testing before modules are sent to the South Pole.
- Acceptance testing ensures reliability of modules shipped to and deployed at the South Pole - modules cannot realistically be retrieved for maintenance!
- Testing occurs mainly at cold temperatures (-20°C & -40°C) for several weeks.
- Tests examine the D-Egg's reliability, functionality & performance.

D-Egg in a "deployed" configuration

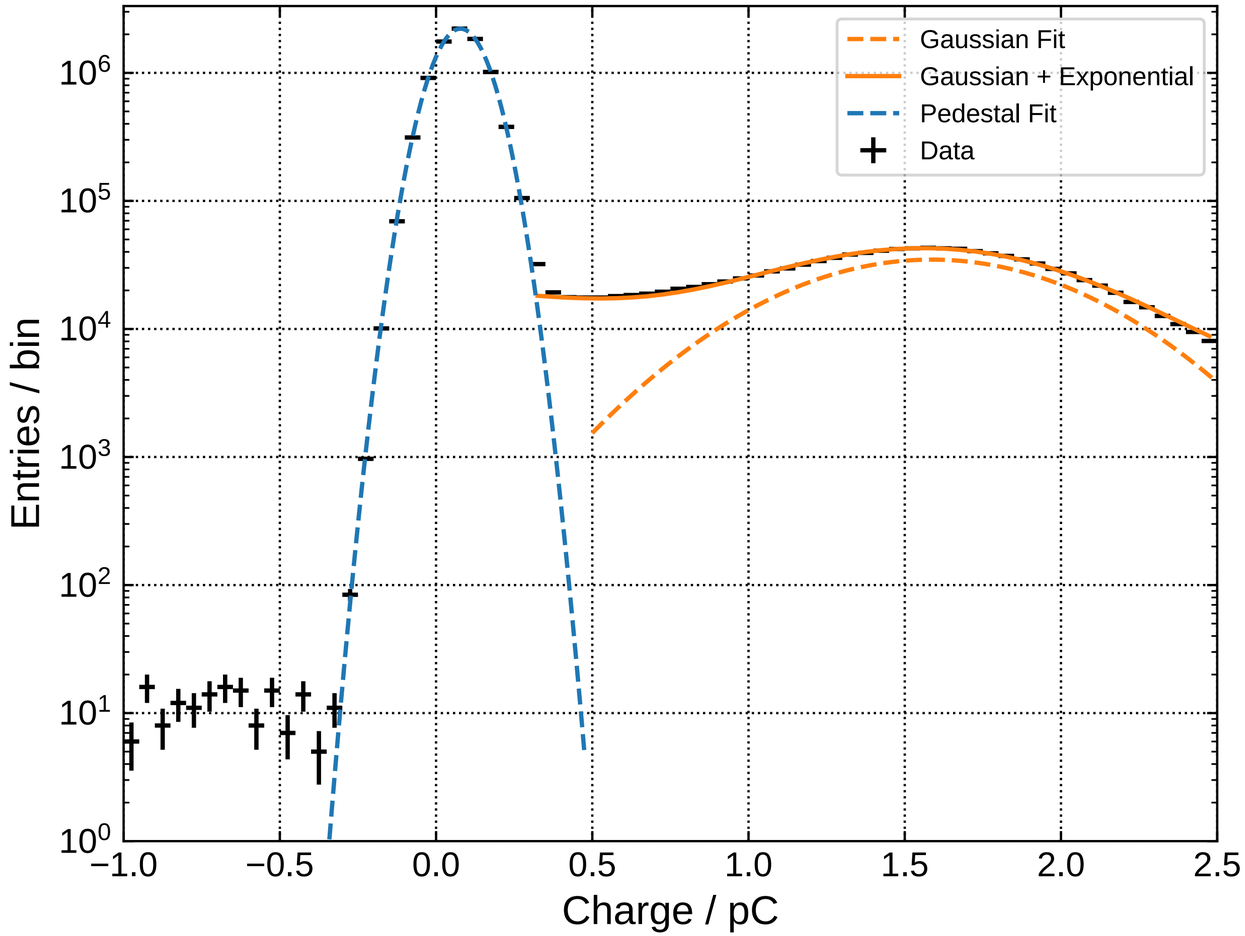
Acceptance Testing Site

- Acceptance testing involves installing D-Eggs into a dark & cold environment: testing "boxes" inside industrial sized freezer.
- Dark environment useful for performing gain calibrations & measuring PMT dark rates.
- The optics system delivers UV-wavelength laser light into each box to test the PMT response.
- Capabilities to test 16 D-Eggs simultaneously.

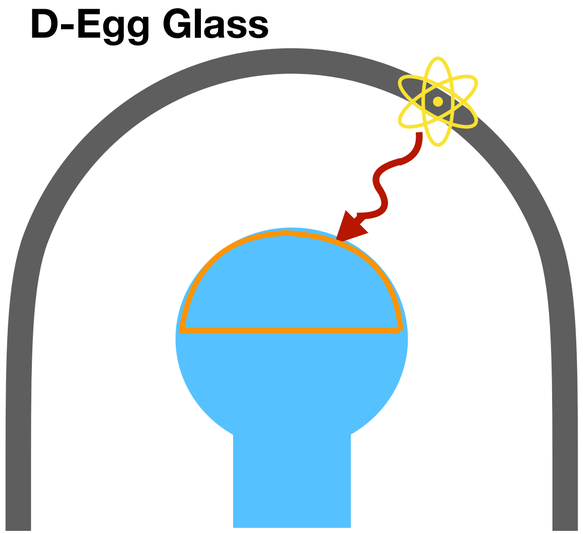


Single Photo-electrons (SPE)

- SPE waveform shape and charge distribution especially important for event reconstruction & PMT calibration.
- Low-charge interactions (noise) contribute to the pedestal region, which are subtracted using a baseline prior.
- Interactions above the pedestal contribute to a Gaussian term used to extract the PMTs gain.
- Intermediate regions are better described when the fit includes an additional exponential term (solid orange).



PMT Dark Noise

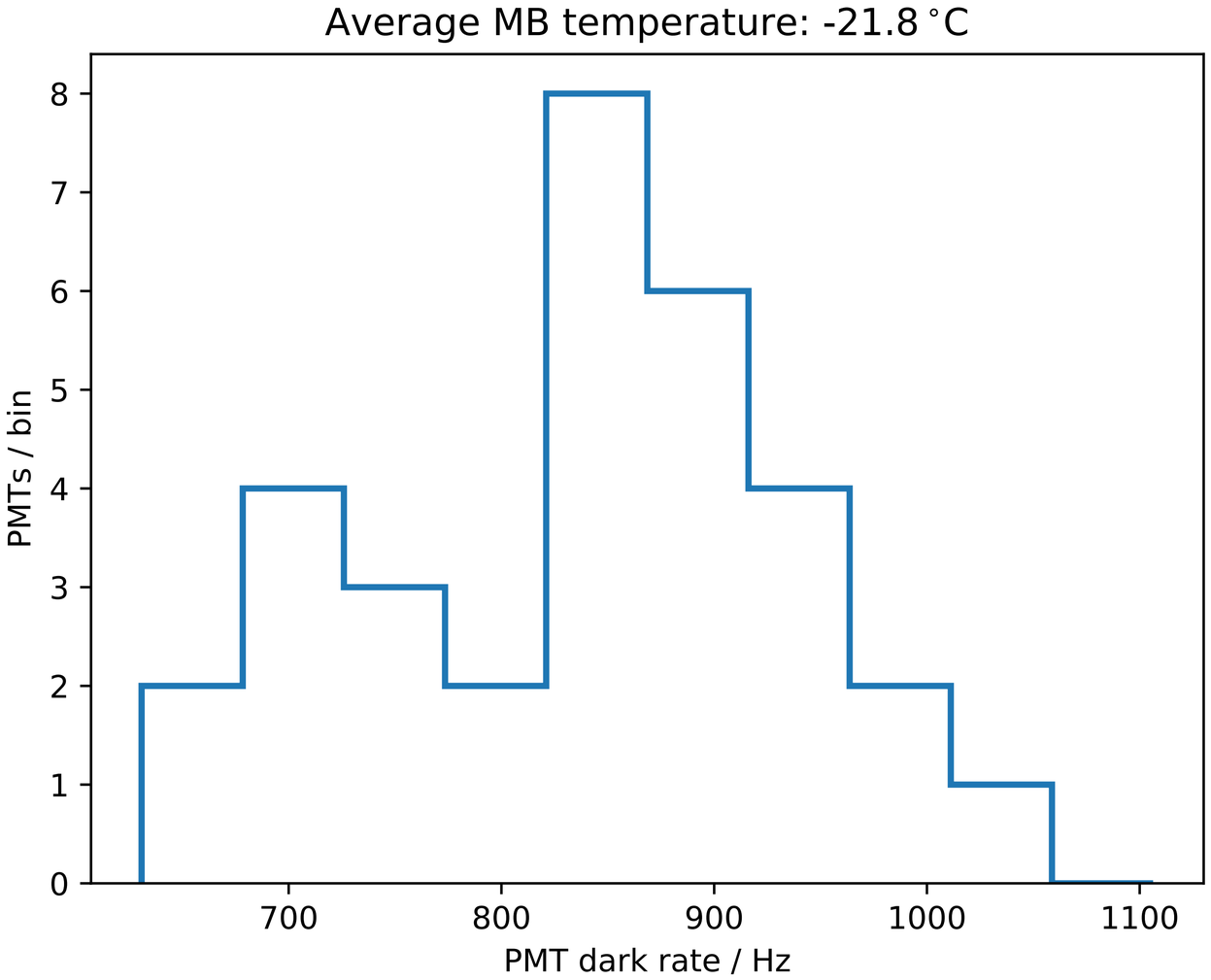


Integrated PMT dark rate impacted by glass refractive index boundary

- Dark noise are backgrounds which do not originate from photons hitting the PMT photo-cathode.
- Typically: thermionic cathode emission, PMT afterpulses, and radioactive processes.
- For example: decays of isotopes in the UV-transparent D-Egg glass are detected by the PMT.
- In the South Pole ice, the refractive index between the glass and ice are closely matched, but not in air.
- To compare measurements in the lab to future measurements in-ice, calibration measurements where the refractive index was matched to expected in-ice values extracted a factor ~2.5 decrease.

PMT Dark Noise

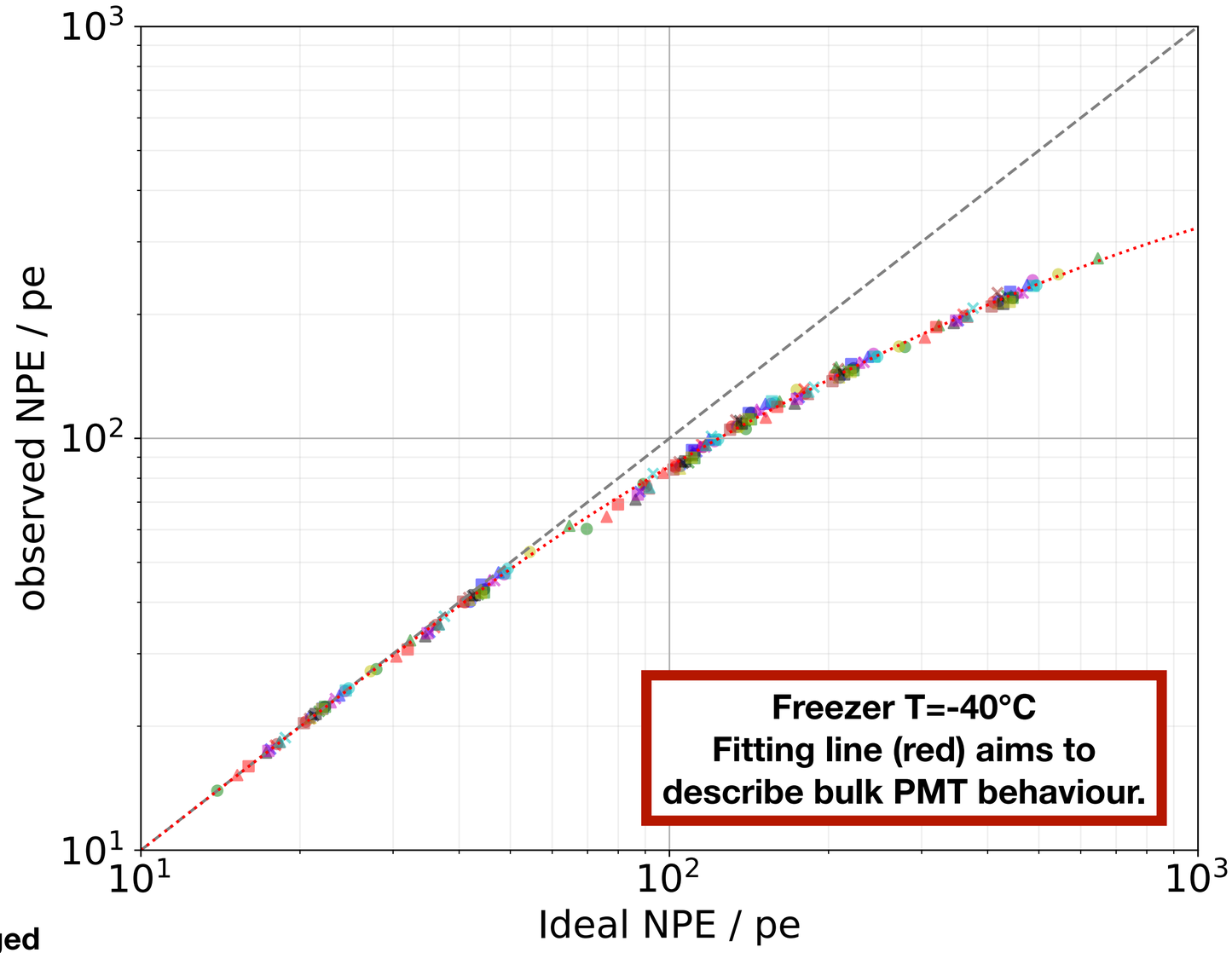
- Dark noise rates were measured for 16 D-Eggs at cold temperature (32 PMTs).
- To replicate in-ice conditions the PMTs are operated at 10^7 gain and a fixed threshold of 0.25 x $\langle A_{SPE} \rangle$ with artificial 100 ns deadtime.
- The refractive index calibration factor was applied uniformly, giving a median dark rate of 853 Hz per PMT.
- Acceptance testing requirements aim for individual PMT dark rates at or below ~1000 Hz.



PMT Linearity

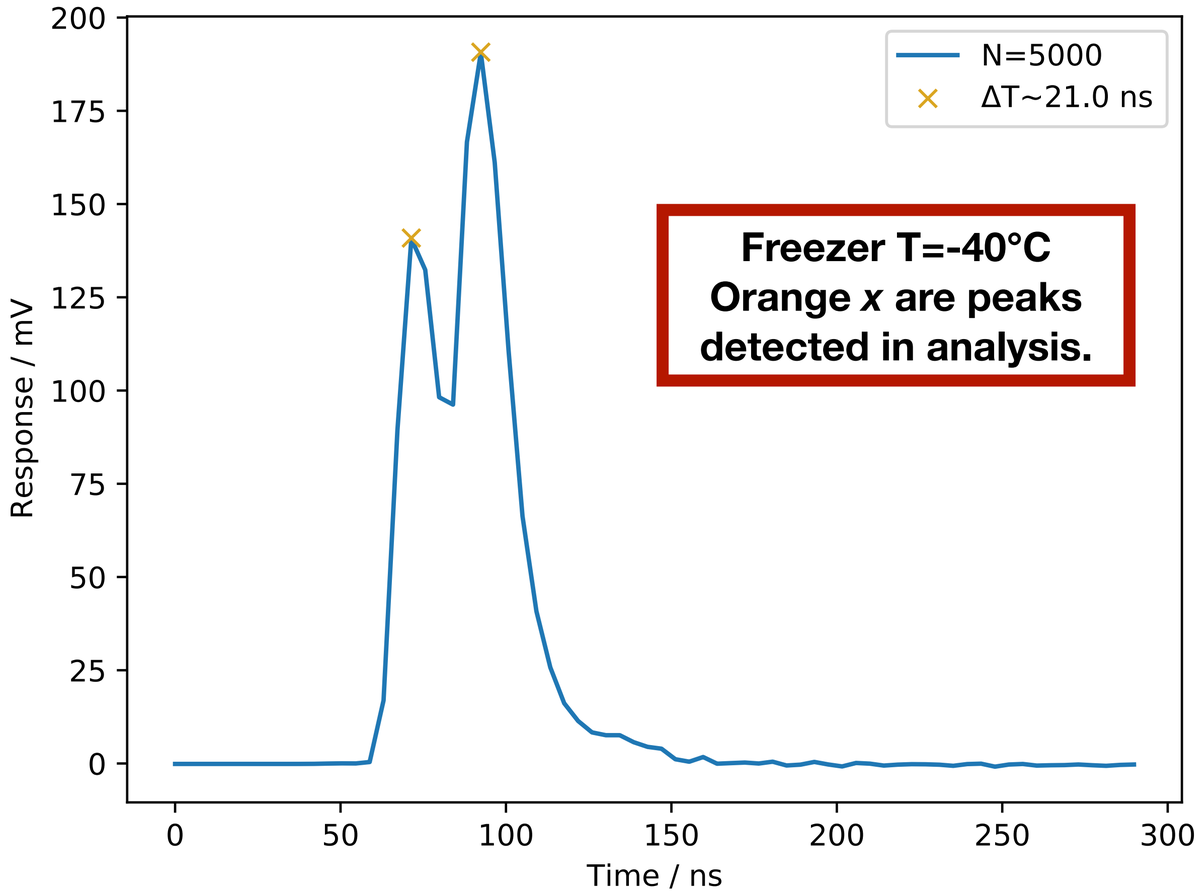
- PMT linearity critical for energy reconstruction in-ice.
- Pulsed laser light with 6 neutral-density filters allow probing PMTs in both linear & non-linear regions.
- 31* PMT linearities simultaneously measured - variance in ideal PE results from setup geometry.
- The strongest attenuating ND filter (5%) is assumed to be linear, and ideal PE is scaled by the filter strengths.
- Starting from around 60 PE (ideal), the integrated D-Egg PMTs begin diverging from linear.

***1 fibre channel was damaged**

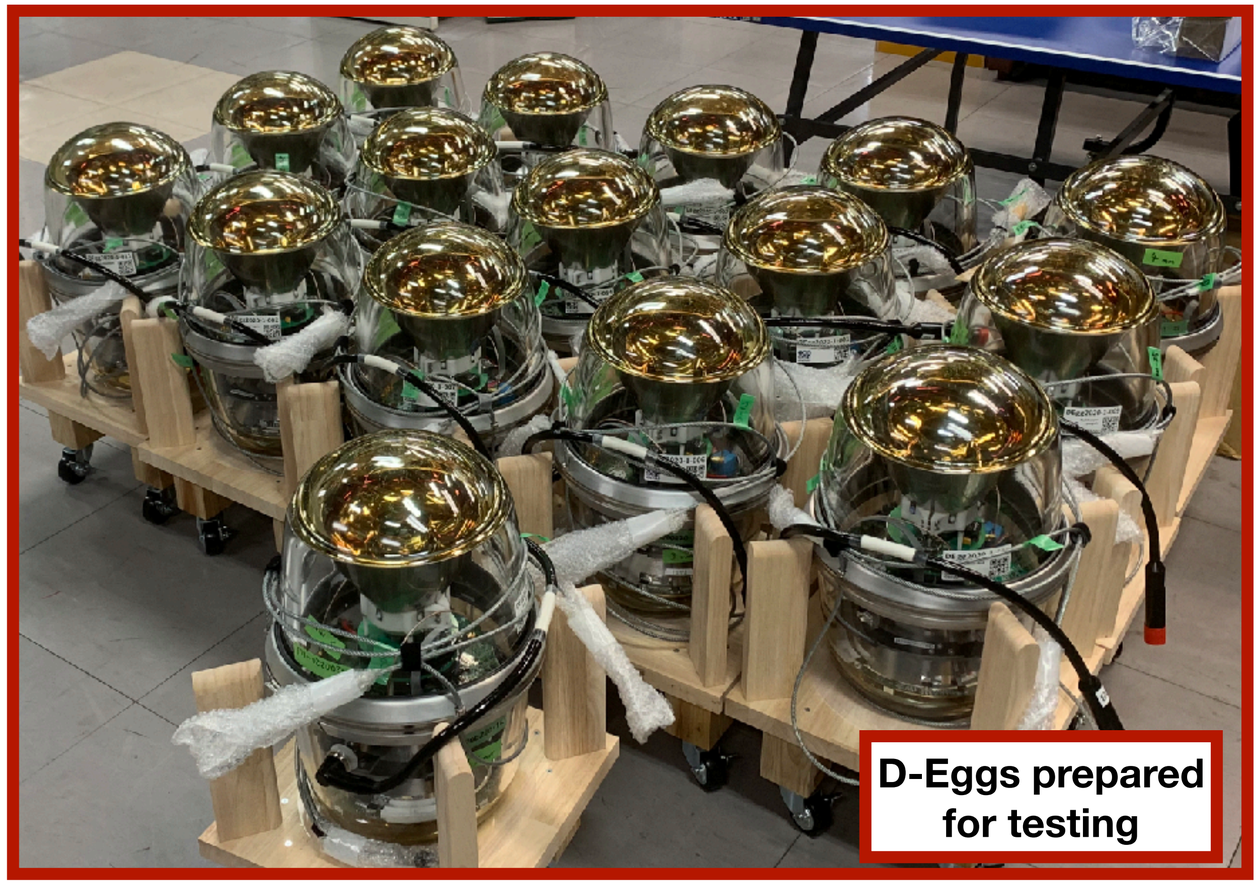


Double-Pulse Testing

- Identification of two pulses separated by a few nanoseconds is a possible indicator of high energy ν_τ CC interactions.
- For acceptance testing, a baseline double-pulse signal is produced by the laser and sent to the PMTs.
- All 32 PMTs could process the double pulse signal and extract the 2 peaks.
- Timing separation consistent with expected pulse separation to within the mainboard clock bin width (4.2 ns).



Summary



D-Eggs prepared for testing

- Over 300 D-Eggs have been produced and now need to undergo acceptance testing before deployment.
- Large-scale hardware verification at cold temperatures and PMT performance testing has begun.
- Measurements of the D-Egg PMT properties are consistent with expectations and requirements.
- Initial acceptance testing results indicate that D-Eggs are ready to go to the South Pole!

Thank You!