Performance of the D-Egg optical sensor for the IceCube-Upgrade

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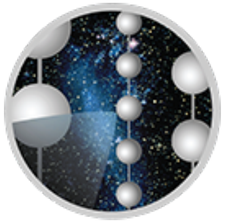


IceCube
South Pole Neutrino Observatory

ICEHAP
International Center for Hadron Astrophysics

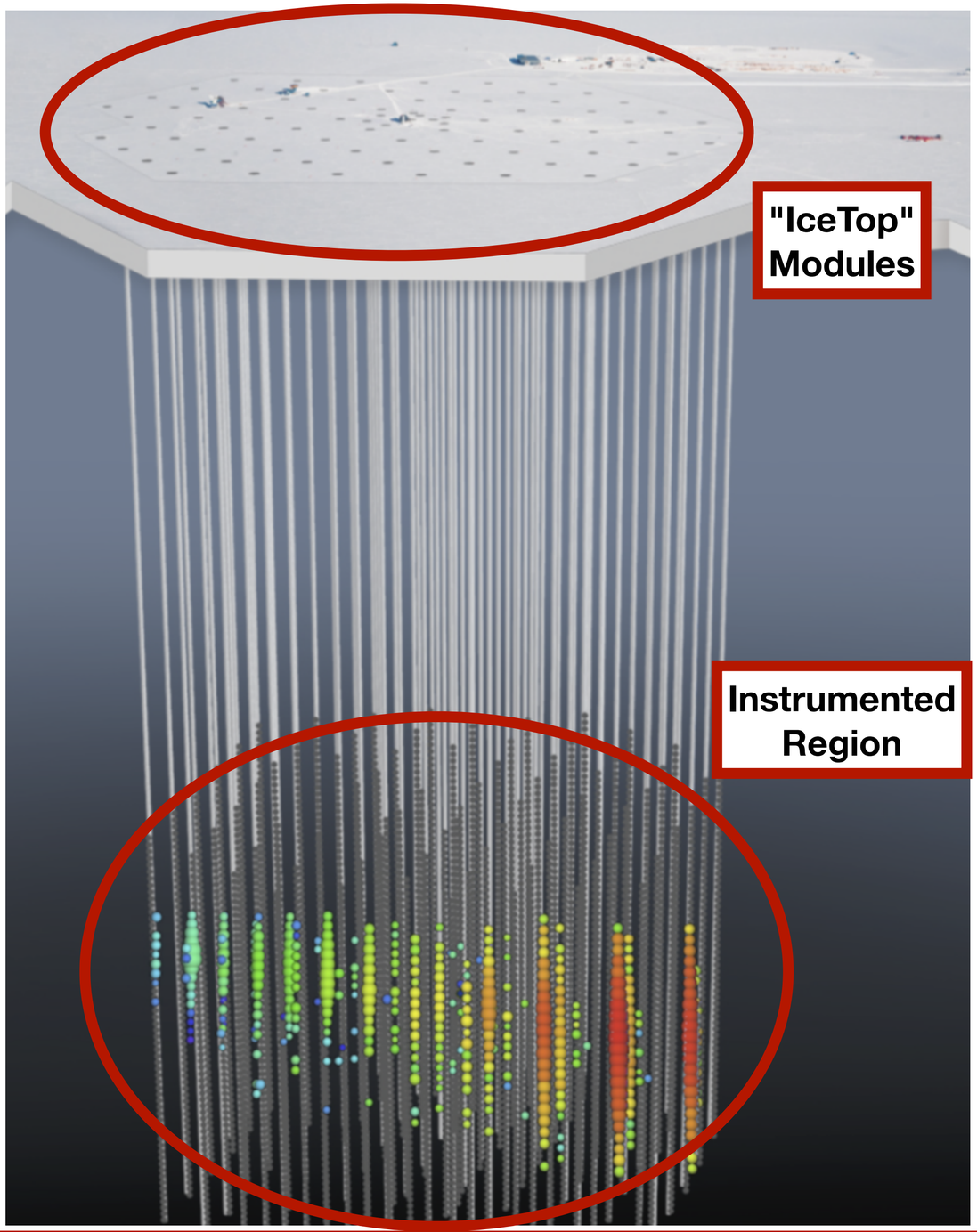
Outline

- IceCube & IceCube Upgrade
- Dual optical sensor in an Ellipsoid Glass for Gen2 (D-Egg)
- Acceptance Testing Procedure
- Testing Results
- Summary

https://higgstan.com/

IceCube Upgrade

- 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.



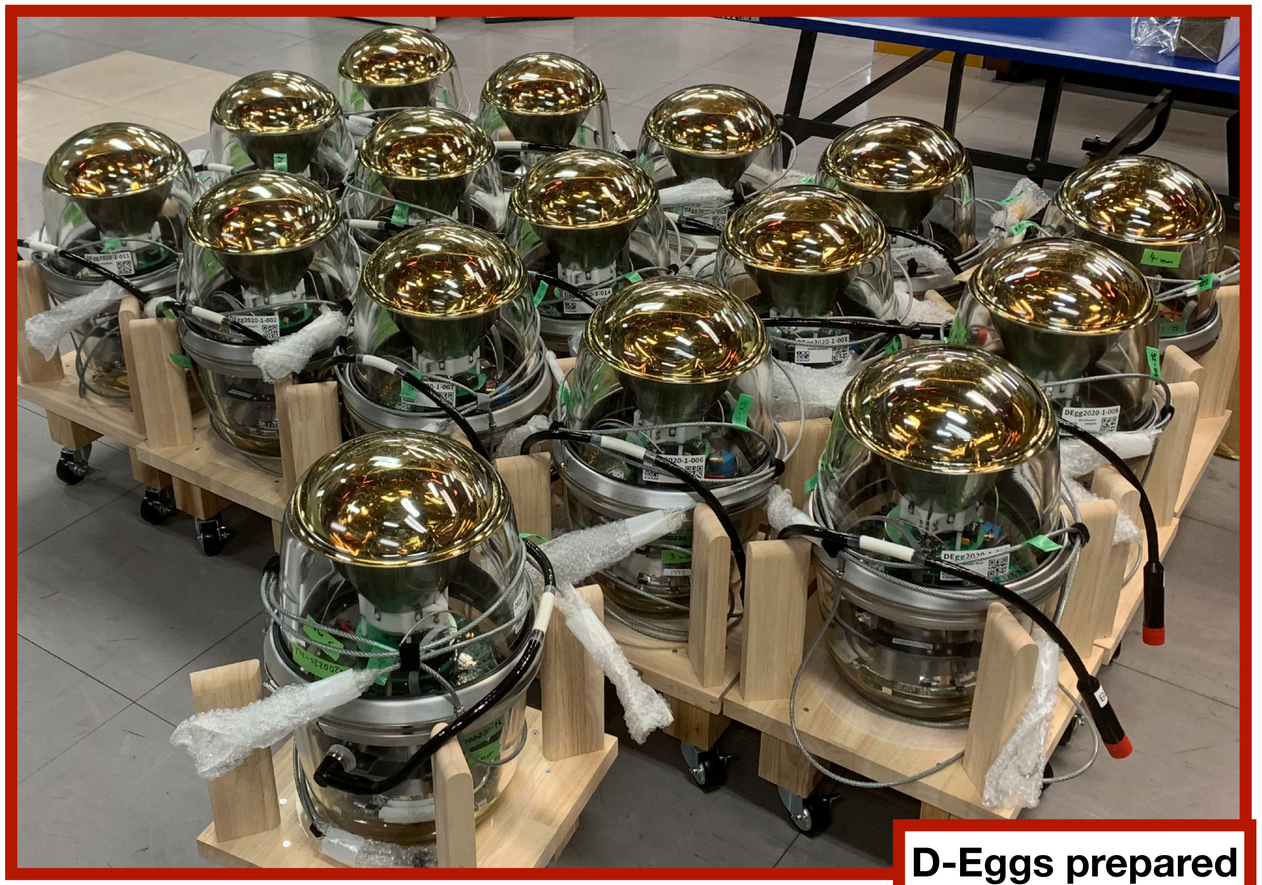
IceCube Upgrade: D-Eggs

- D-Eggs are next-generation optical modules to be deployed as part of the IceCube Upgrade (start 2022/2023).
- D-Eggs offer improved photo-detection efficiency over the traditional IceCube DOMs and a reduced diameter, decreasing drilling costs during deployment.
- Calibration devices installed in the D-Eggs provide the opportunity to measure and reduce current leading IceCube systematic uncertainties.
- The D-Egg project has reached the stage of mass production, with over 300 modules to be finished this year.

D-Egg prepared for testing

D-Egg Acceptance Testing

- Acceptance testing ensures reliability of modules shipped to and deployed at the South Pole.
- All modules undergo acceptance testing: ~300 D-Eggs.
- Testing occurs mainly at cold temperatures (-20°C & -40°C) for several weeks.
- Tests examine the D-Egg's reliability, functionality & performance.



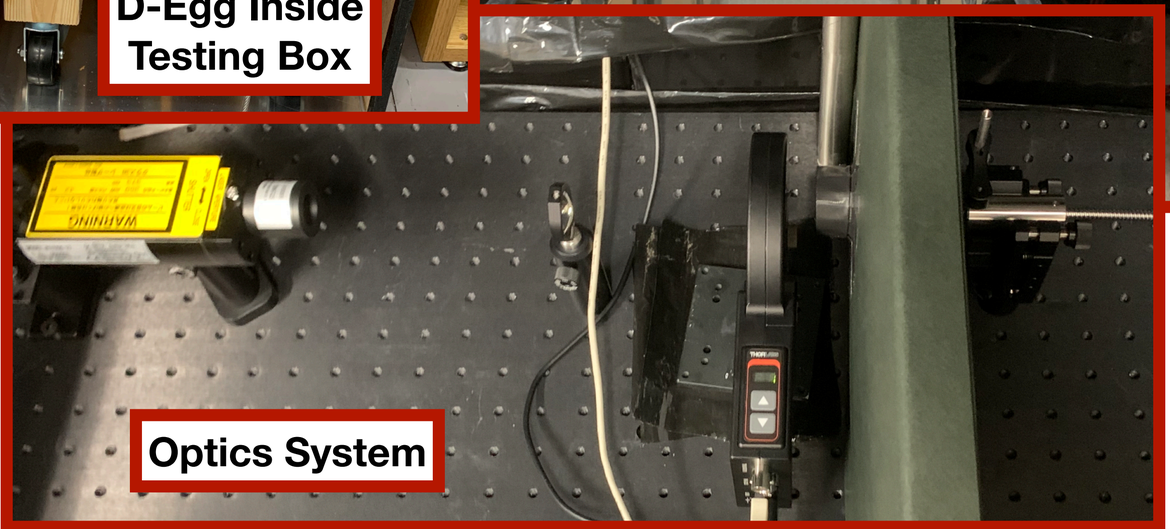
D-Eggs prepared for testing

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.

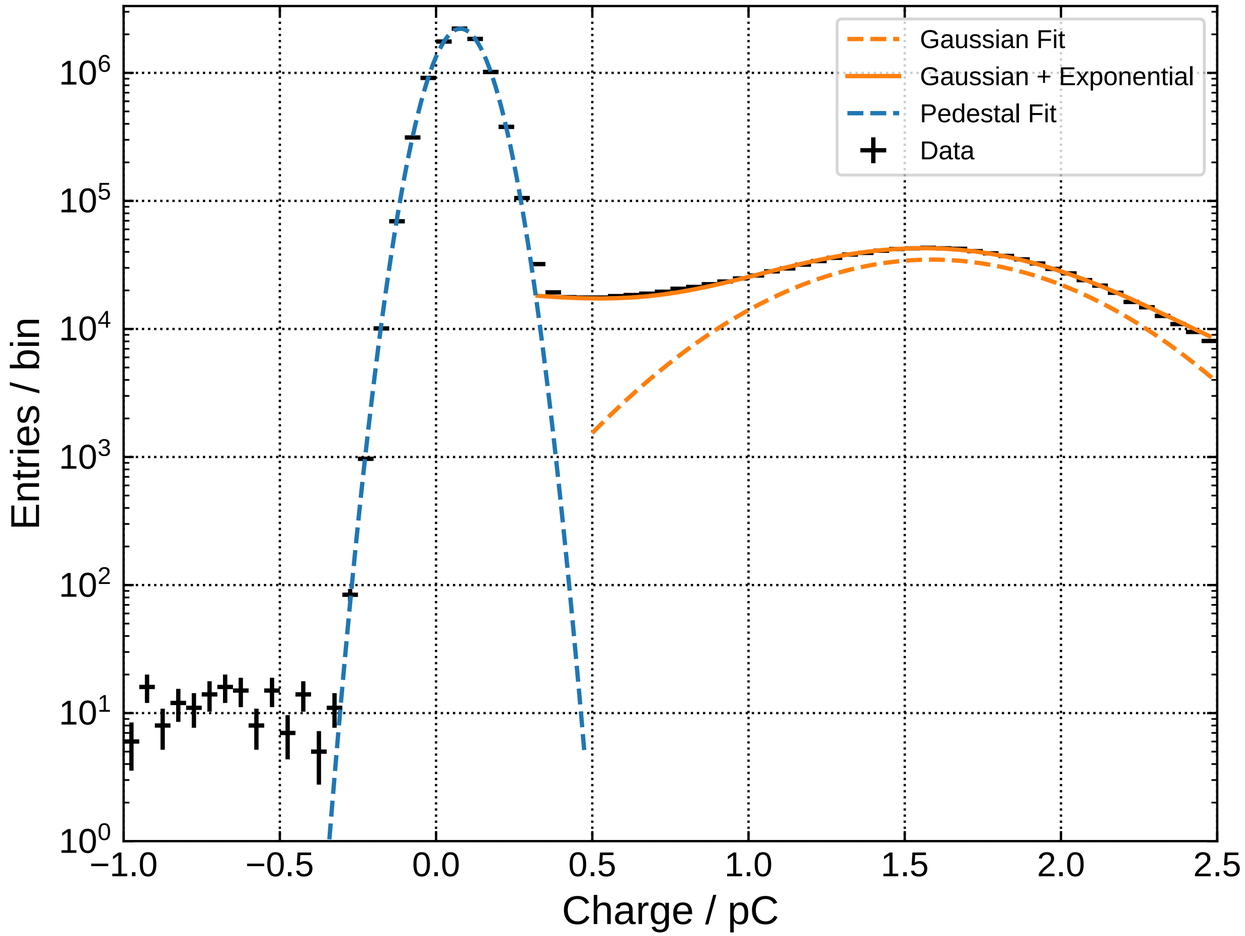

D-Egg Inside Testing Box


Freezer at -40°C, 16 D-Eggs

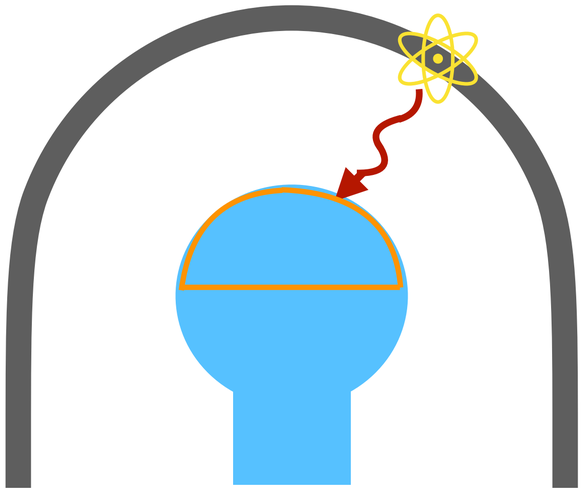

Optics System

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

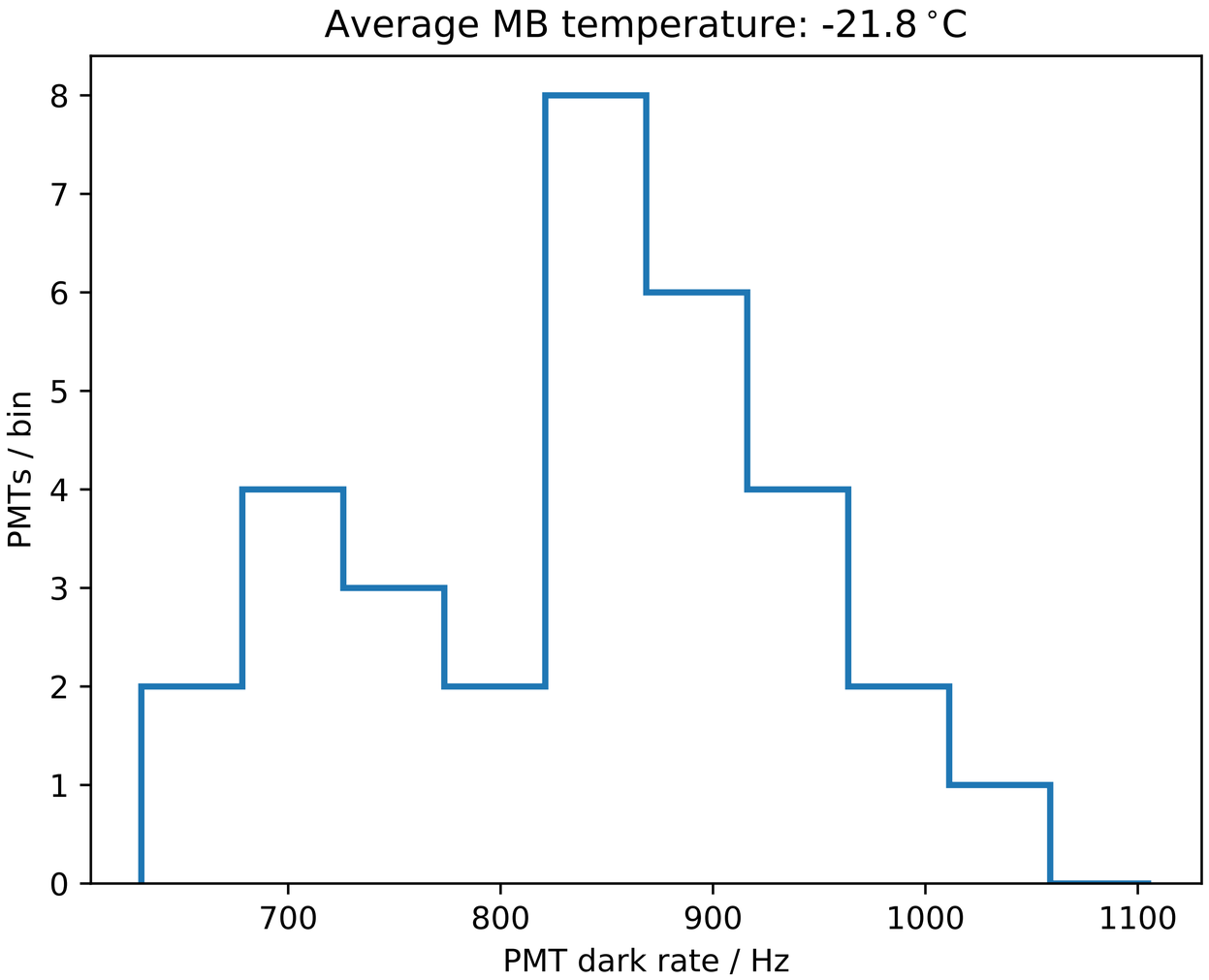


PMT dark rate impacted by glass refractive index boundary

- 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

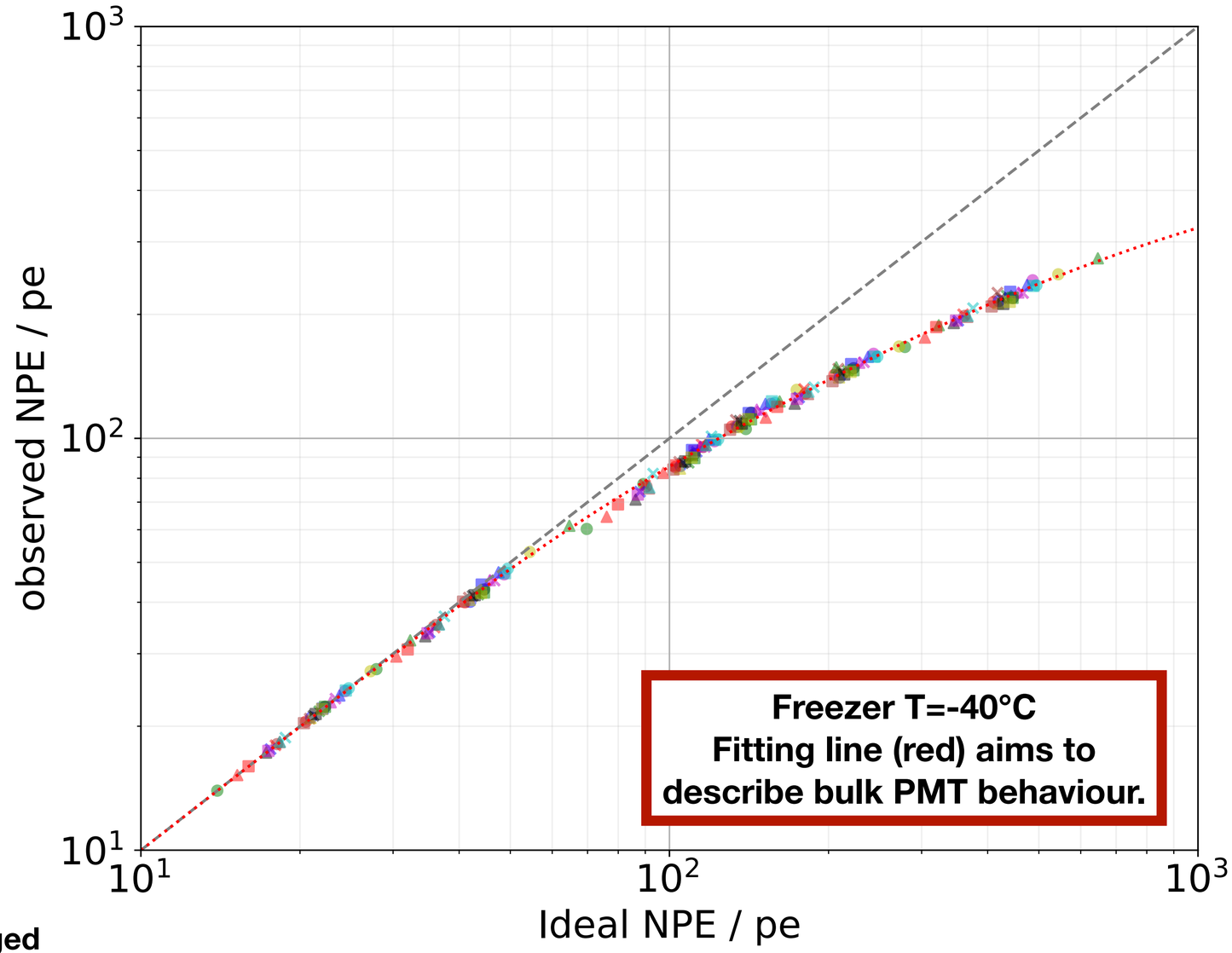
- Dark noise rates were measured for 16 D-Eggs at cold temperature (32 PMTs).
- To replicate in-ice conditions the PMTs are operated at 10^7 gain and a fixed threshold of 0.25 x $\langle A_{SPE} \rangle$ with artificial 100 ns deadtime.
- The refractive index calibration factor was applied uniformly, 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

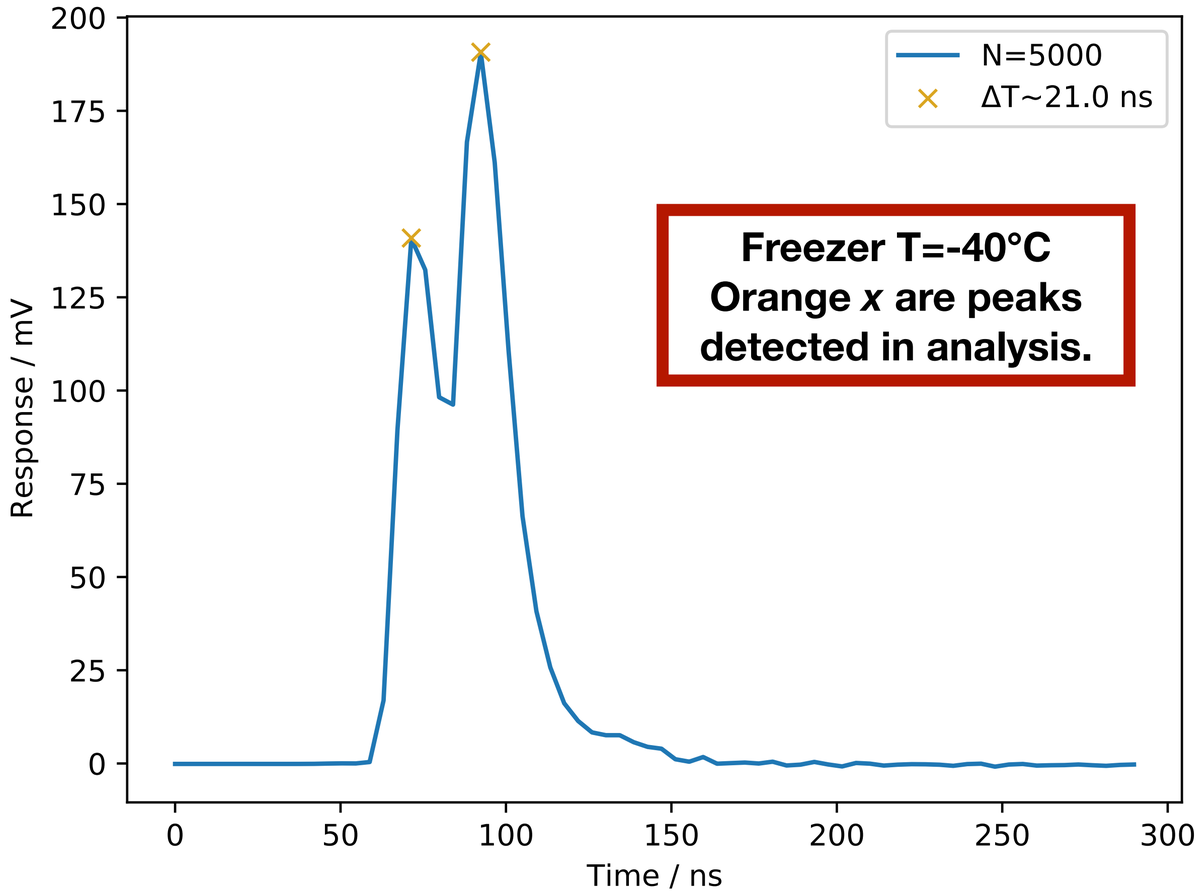
- PMT linearity critical for energy reconstruction in-ice.
- Pulsed laser light with 6 neutral-density filters allow probing PMTs in both linear & non-linear regions.
- 31* PMT linearities simultaneously measured - variance in ideal PE results from setup geometry.
- The strongest attenuating ND filter (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

- Over 300 D-Eggs will be produced by the end of the year, and all will 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!