Measuring the optical properties of the IceCube drill holes

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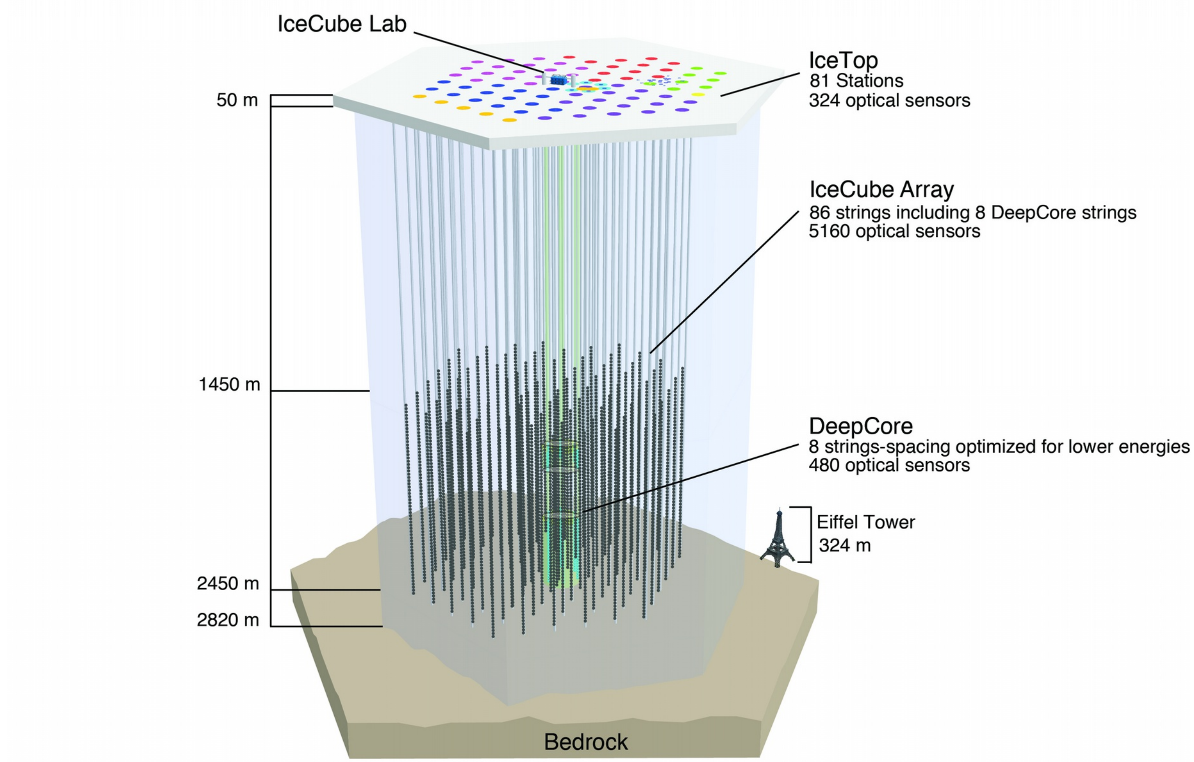
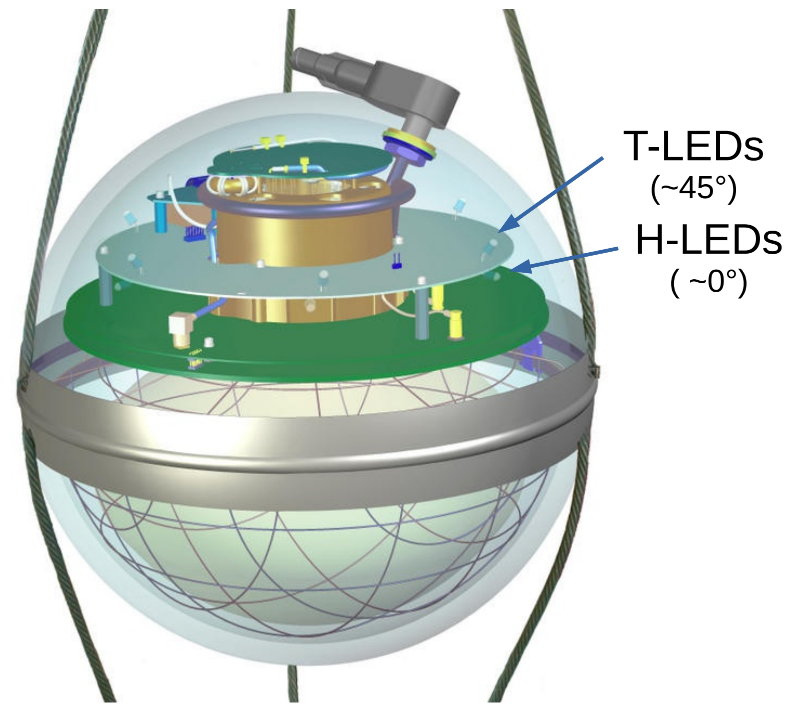
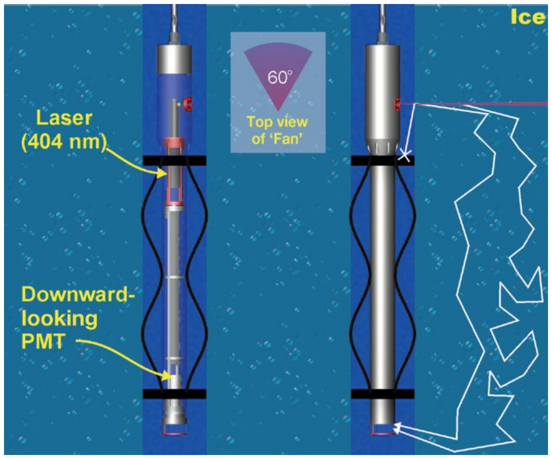
IceCube

- In-ice Cherenkov telescope at the geographic South Pole instrumented with 5160 DOMs containing a 10” PMT each
- DOMs are able to operate independently with full waveform digitization
- 6 pairs of on-board LED flashers for calibration purposes





The bulk ice from dust logger data



- deployed in 8 drill holes
- determined density of scattering centers
- vertical resolution ~2mm

Geophysical Research Letter
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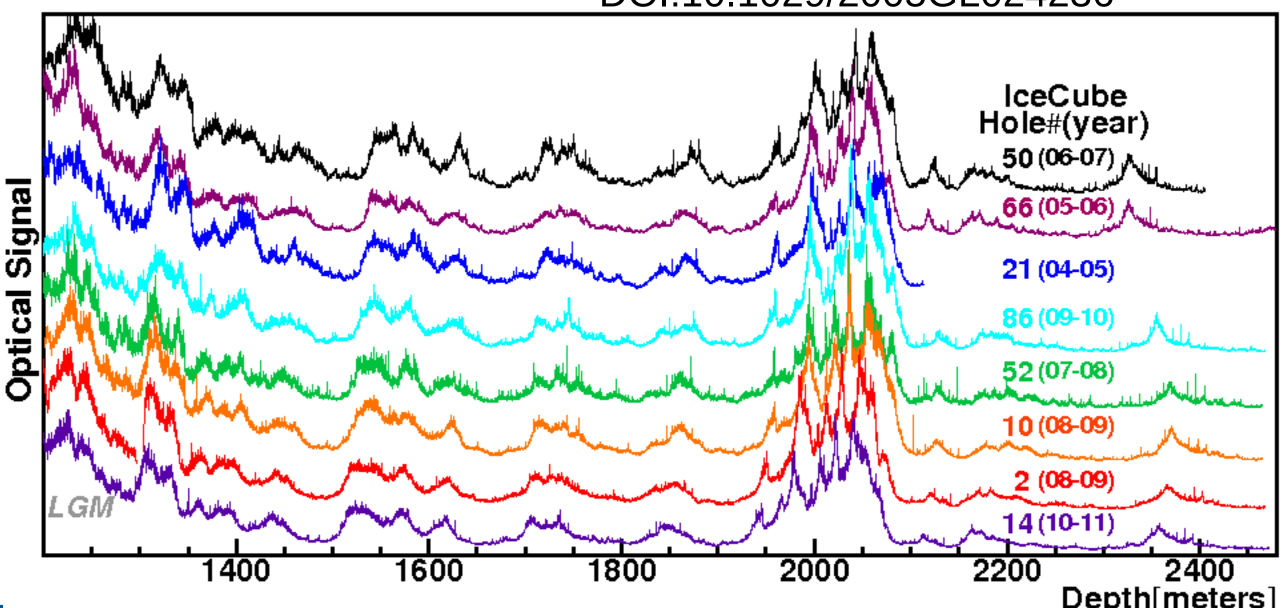
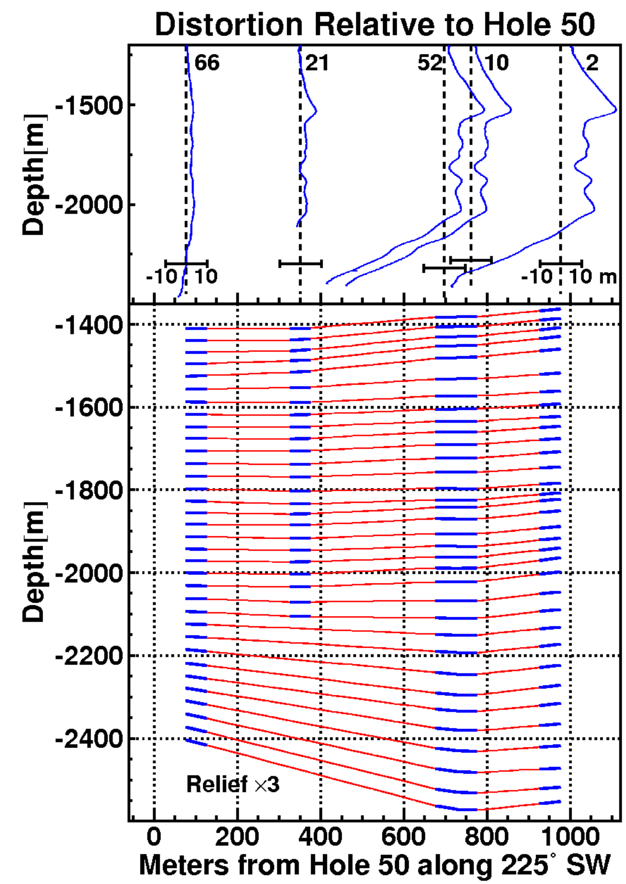
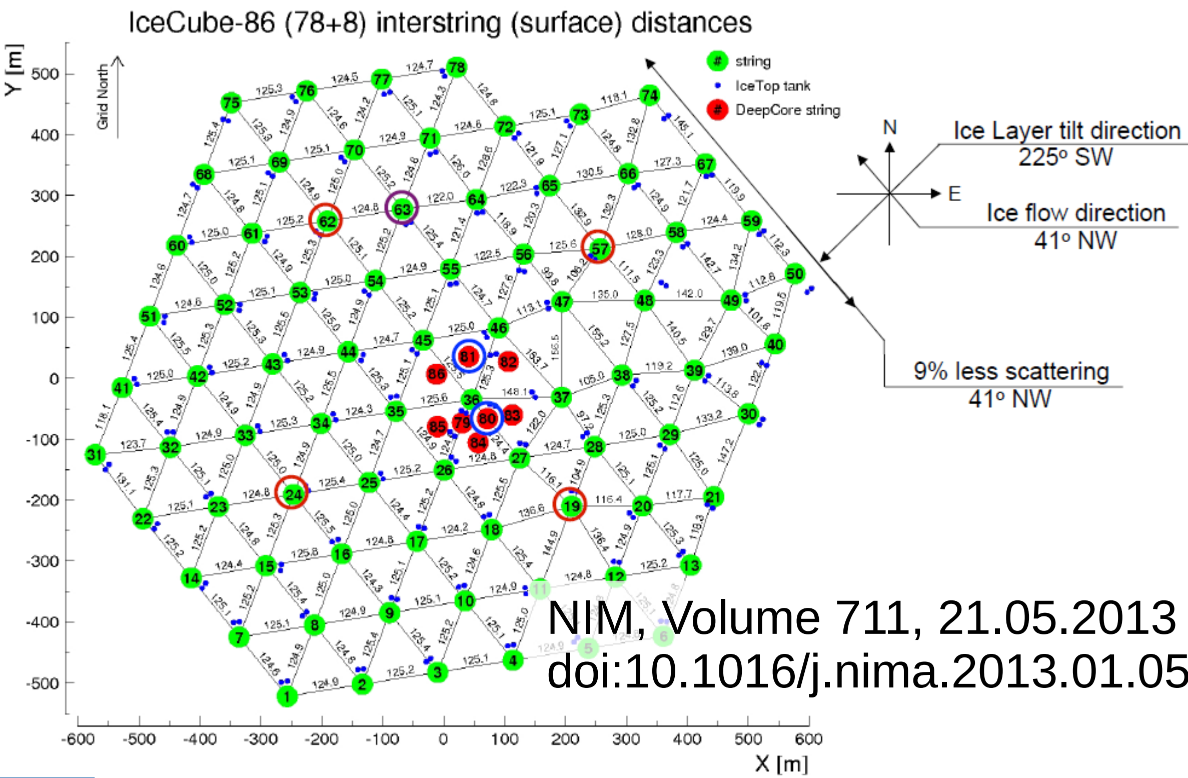


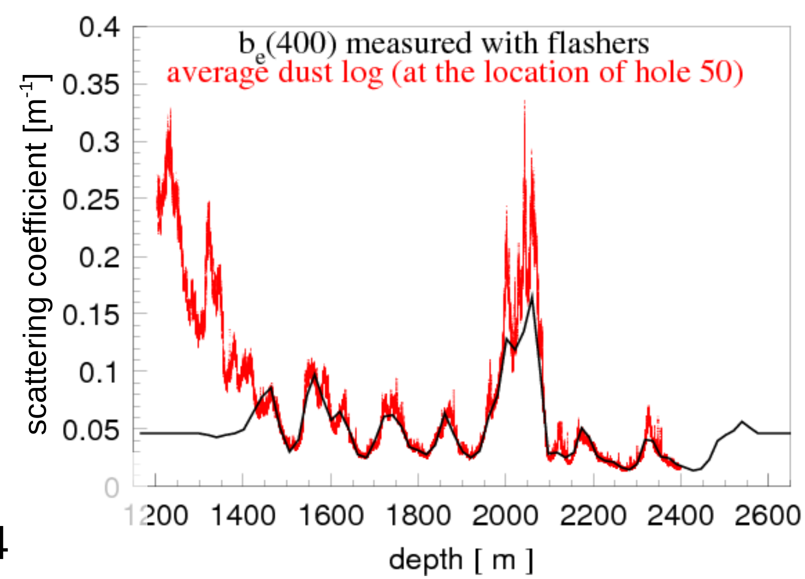


The bulk ice from Flasher data

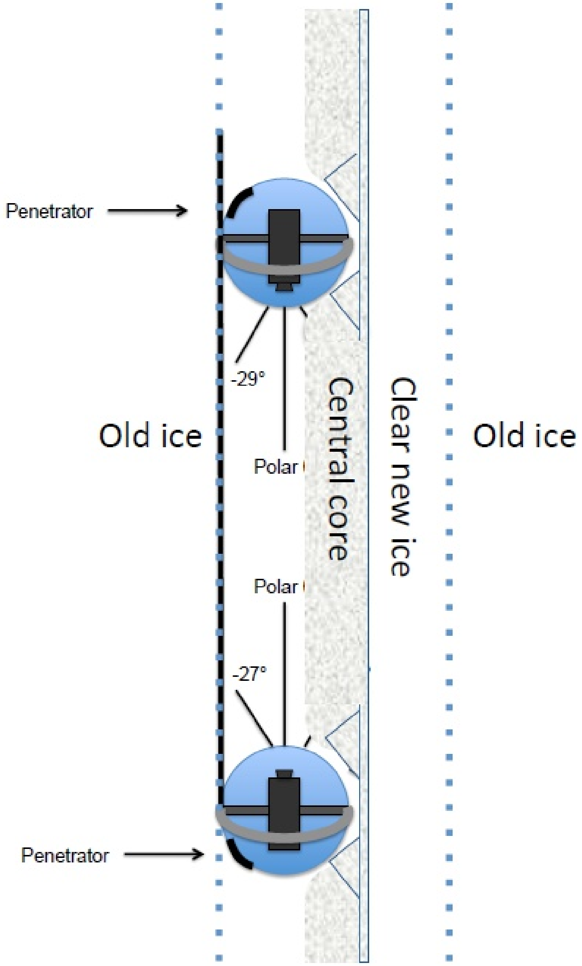
- Fit to inter-string measurements with flasher light from 7 strings combined with dust logger data yields 6-parameter 3D-ice model
- 5-50 m scattering length, 50-200 m absorption length
- ~10% model uncertainty



NIM, Volume 711, 21.05.2013
doi:10.1016/j.nima.2013.01.054



The hole ice

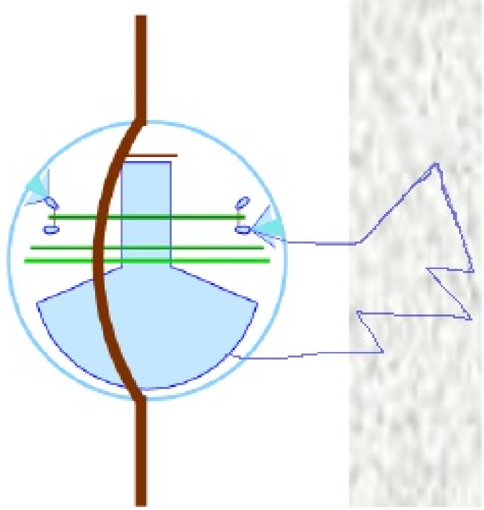


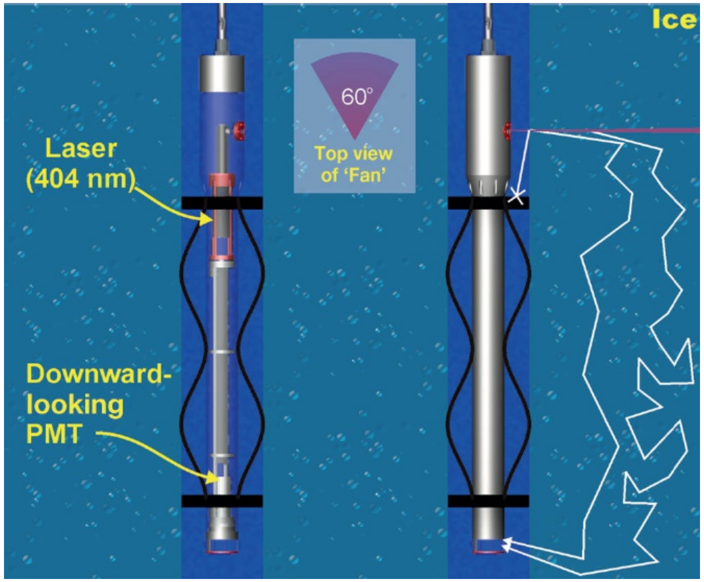
Swedish camera; https://www.youtube.com/watch?v=YWdn3InbsY0

The clear hole ice contains a central bubble column, which is a tightly confined region of small scattering length.

Observing the bubble column directly

- Inter-string flasher data and muon data has proven unsuitable to detect the bubble column
- **Try to operate DOMs like the dust logger:**
  - Turn on the flasher board LEDs in sequence.
  - The LED which results in the strongest signal (light being scattered back from the column) points in the direction of the column.



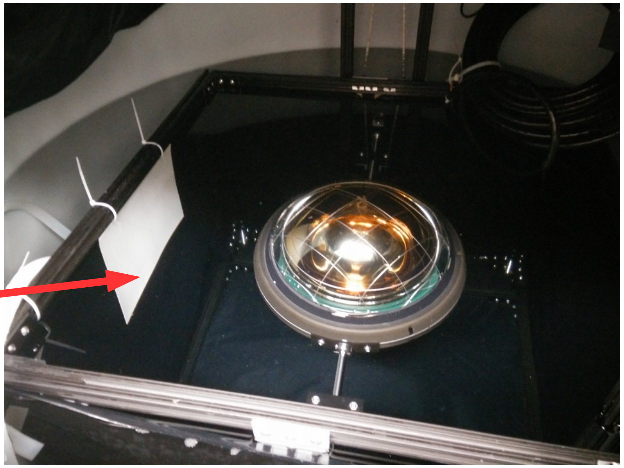


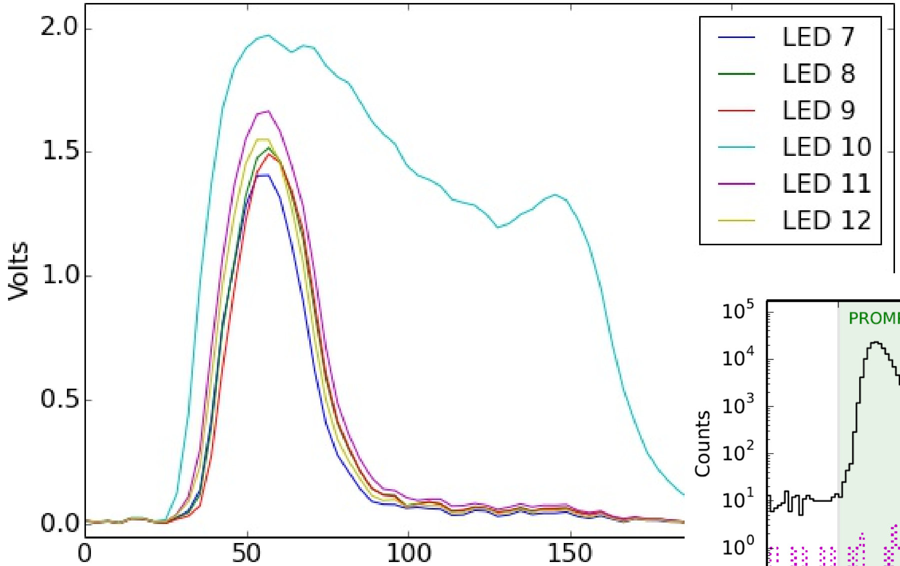
Lab tests

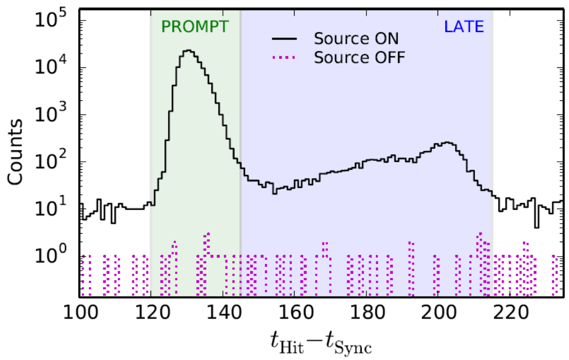
- DOM in dark water tank,
  reflective plastic surface on one side

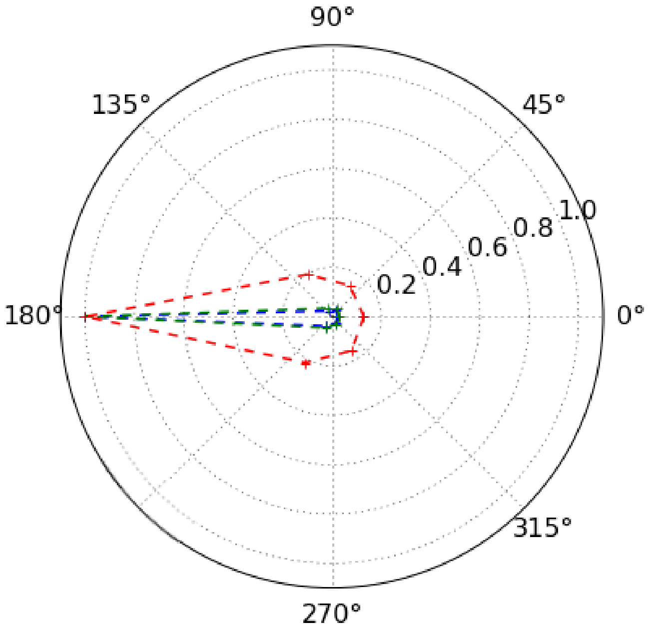
- Try to identify position of reflective surface

LAB BUBBLE COLUMN









DARD

Data Acquisition for a flasheR Dom

Challenges and solutions:

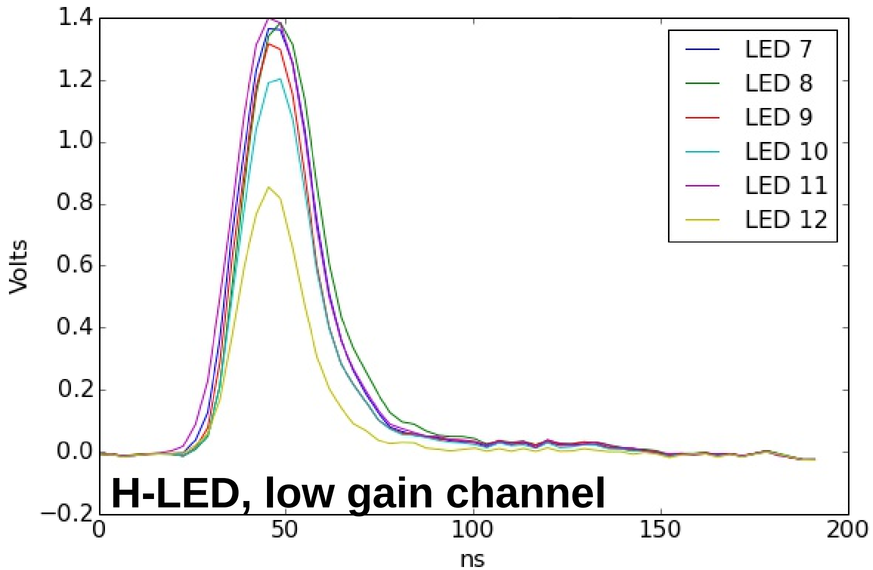
- Standard DAQ does not allow flasher operation with the PMT HV enabled → operate considered strings in debug-firmware

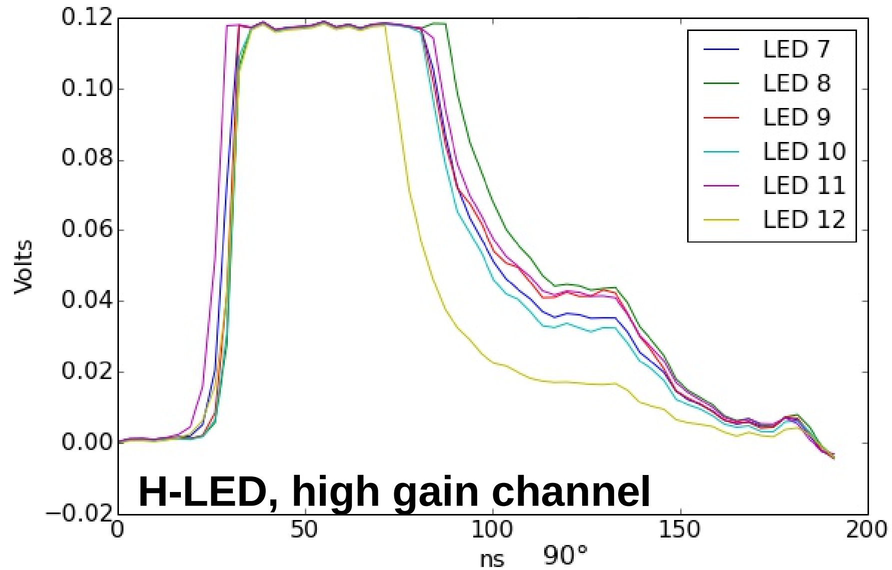
- At stable minimum pulse settings LEDs emit ~10^8 photons, which saturates PMT → lower gain from 10^7 to 10^5 → larger dynamic range

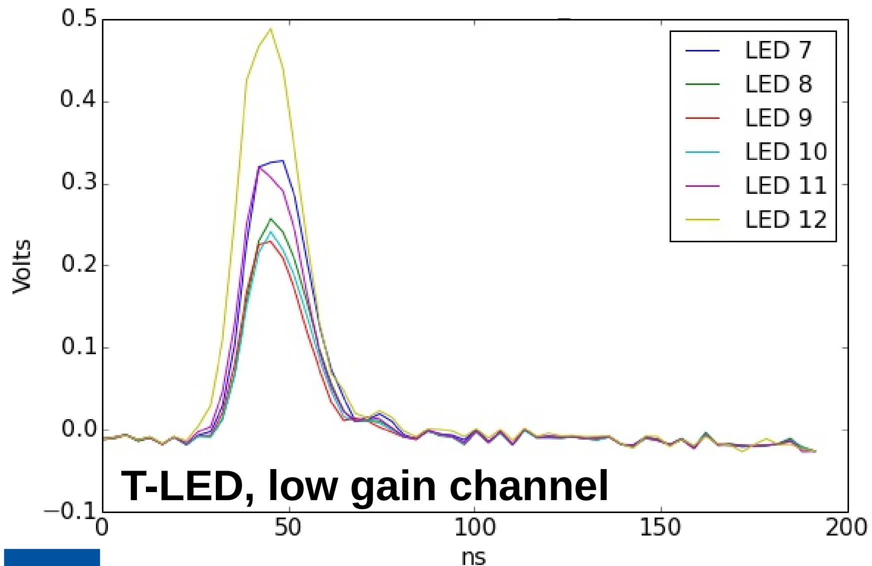
SPS (IceCube) operation:

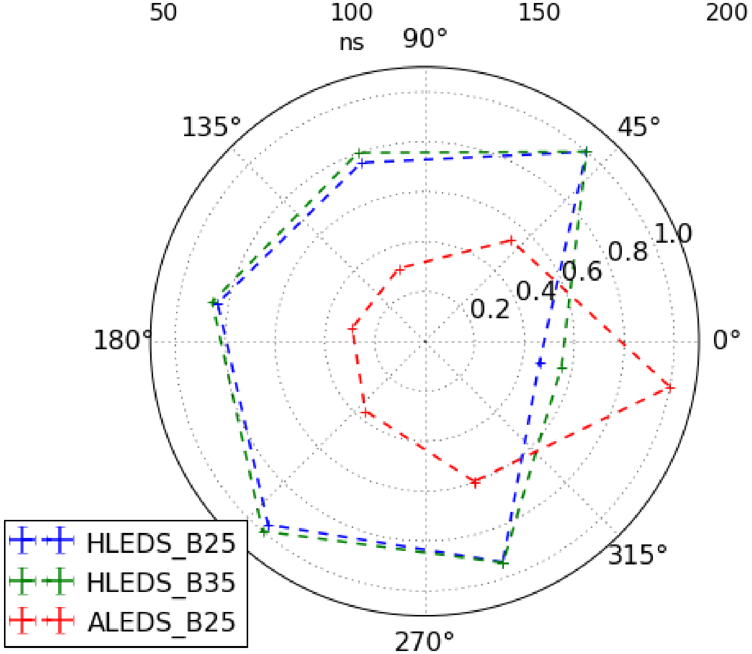
- 5 DOMs above the Swedish camera, 3 in shallow ice
- 3 brightness settings for H-LEDs, 1 for A-LEDs
  → 30 min run

Typical in-situ data









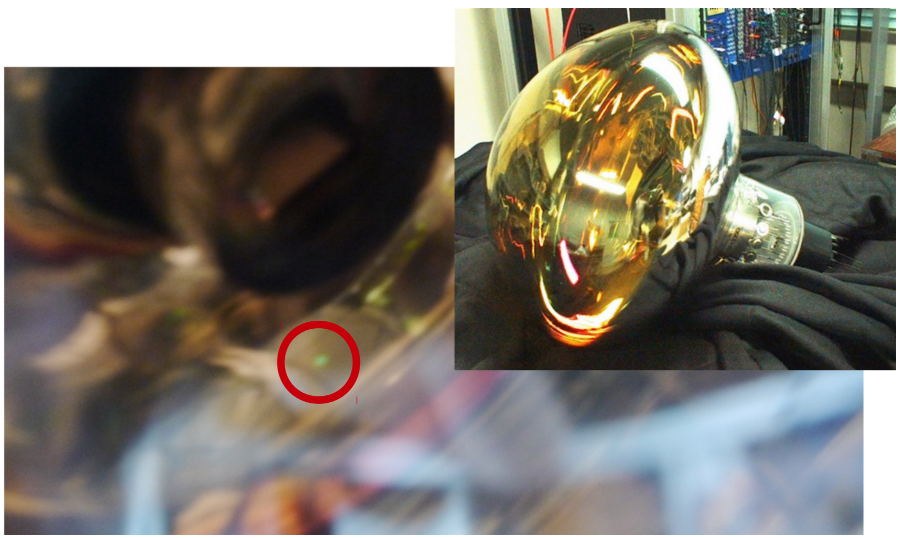
Challenges in data processing

- Why do horizontal and tilted LEDs show discrepancies
  - In absolute photon numbers?
    More photons from H-LED then T-LEDs.
  - In the angular pattern?

- How can we extract reliable photon numbers from high brightness waveforms, in order to be able to compare to simulation?

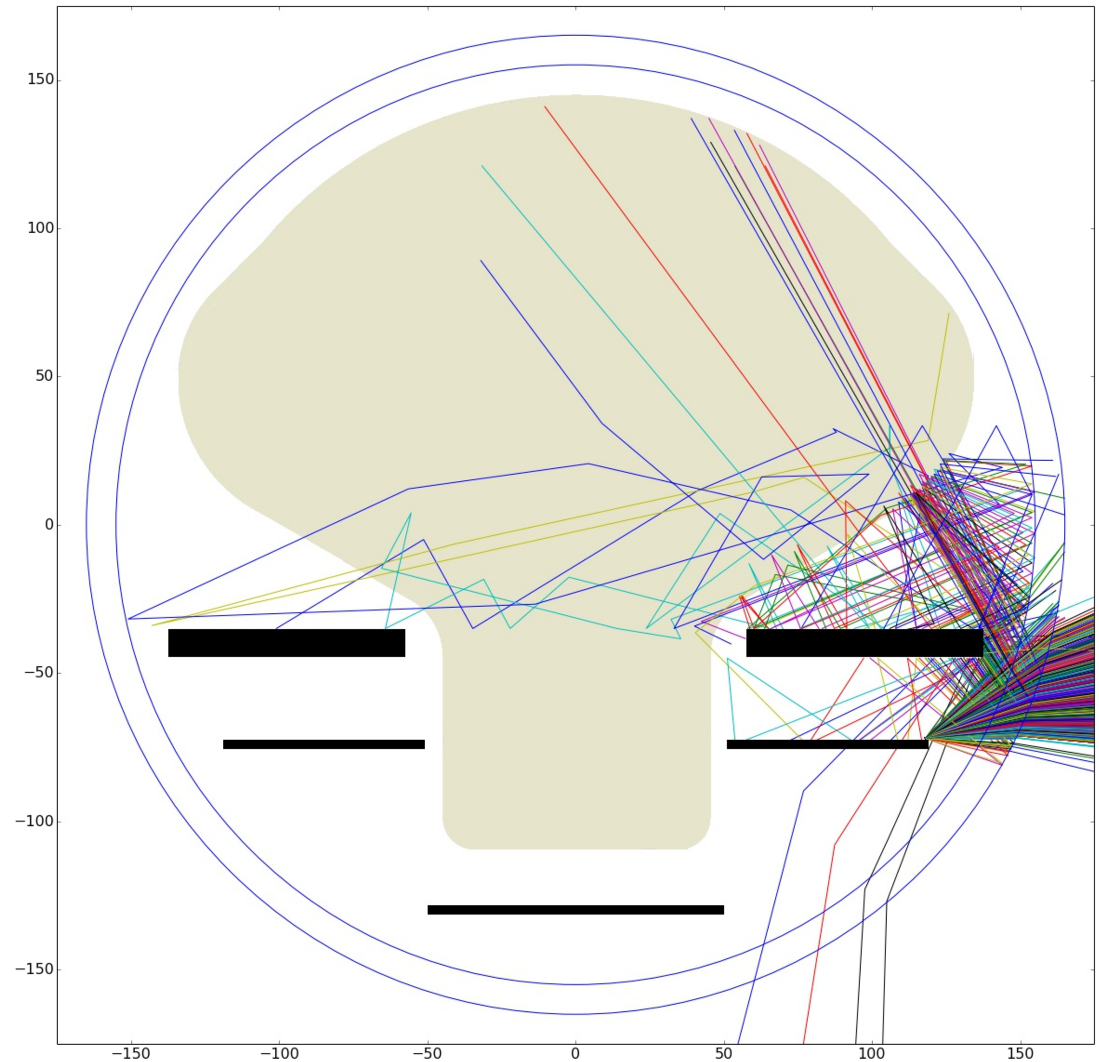
Geant4 simulation (H-LEDs)

Some photons reach the back of the PMT.



Hamamatsu does not control / measure aluminium deposition.

At 5% transmittance (rough estimate) ~0.23‰ of all photons reach the photocathode.

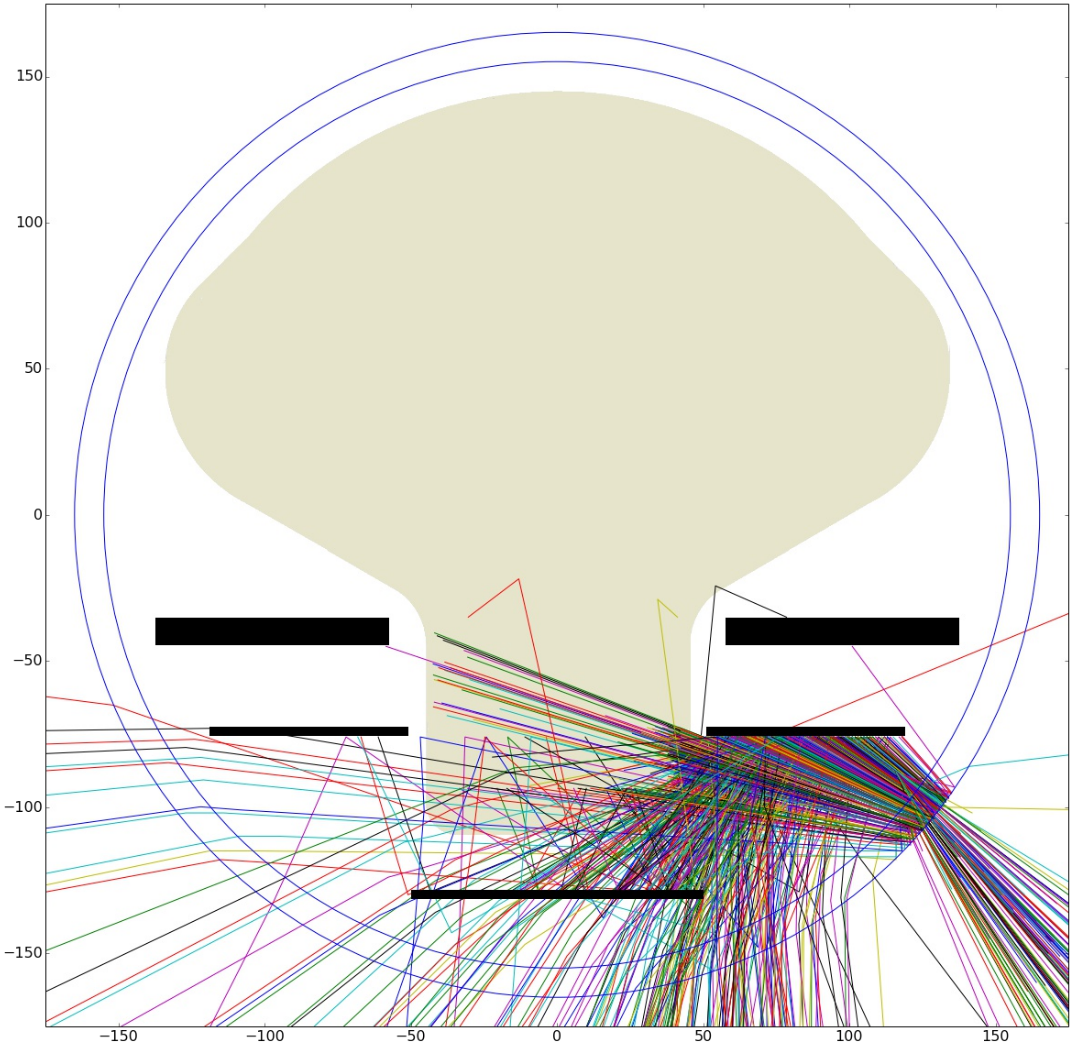


Geant4 simulation (T-LEDs)

No photons from the tilted LEDs reach the photocathode

→ explains discrepancy between horizontal and tilted LEDs

→ **tilted LEDs represent ice properties**



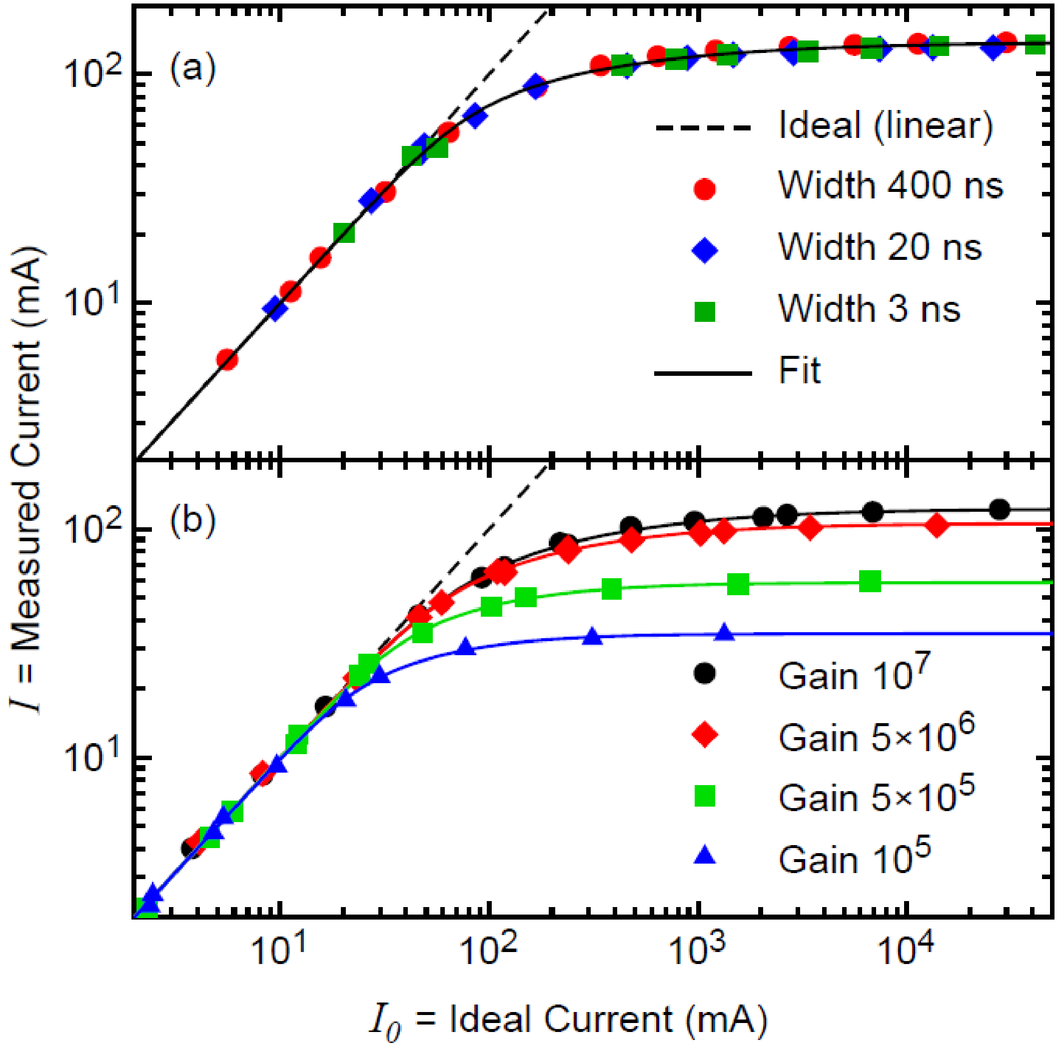
Photon counting

- PMT saturates at same current (~30mA) independent of the gain
  → dynamic range scales with gain

- Saturation curve has been reproduced for specific setup

- No T-LED waveform exceeds 20mA current spike
  → non-linearity from simple waveform integral <10%

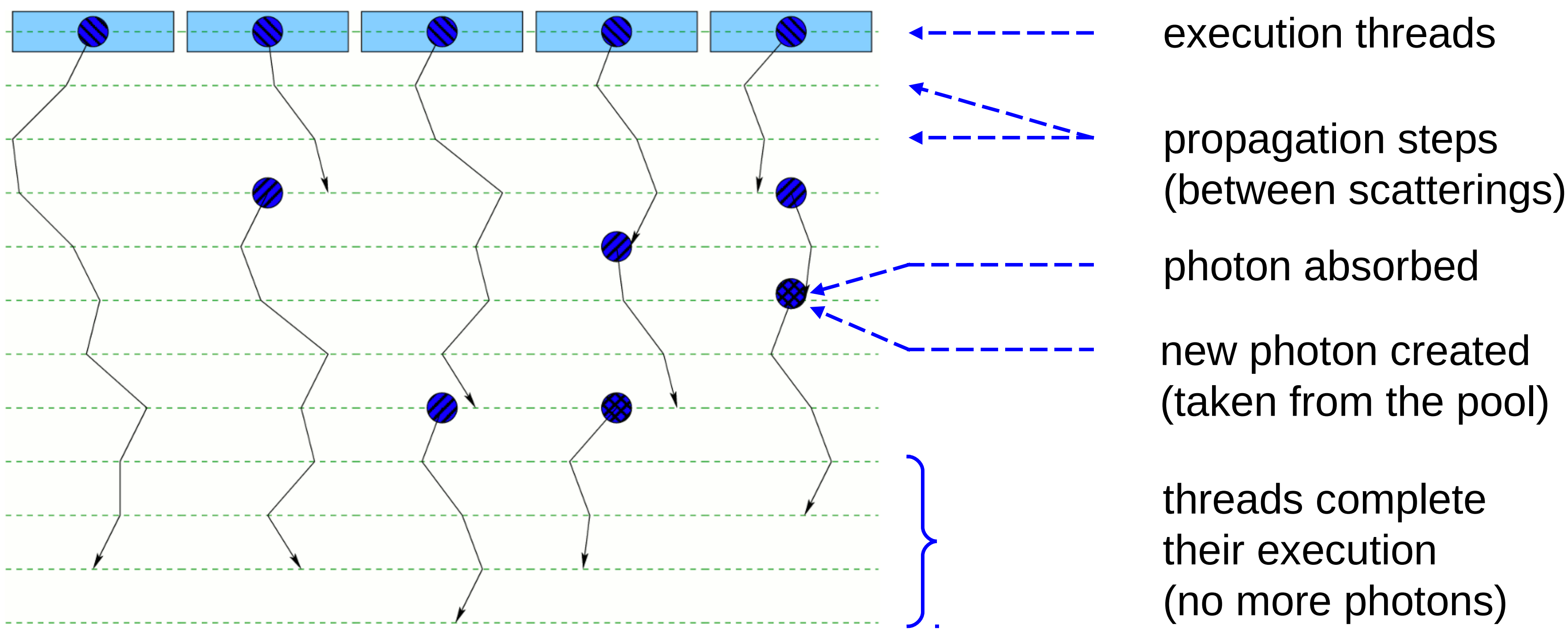
$$\mathrm{PE} = \frac{1}{\mathrm{Z}(\Omega)} \cdot \frac{1}{\mathrm{e}} \cdot \frac{1}{\mathrm{freq(Hz)}} \cdot \sum_{\mathrm{i}} \mathrm{V_i}$$



DOI: 10.1016/j.nima.2010.03.102

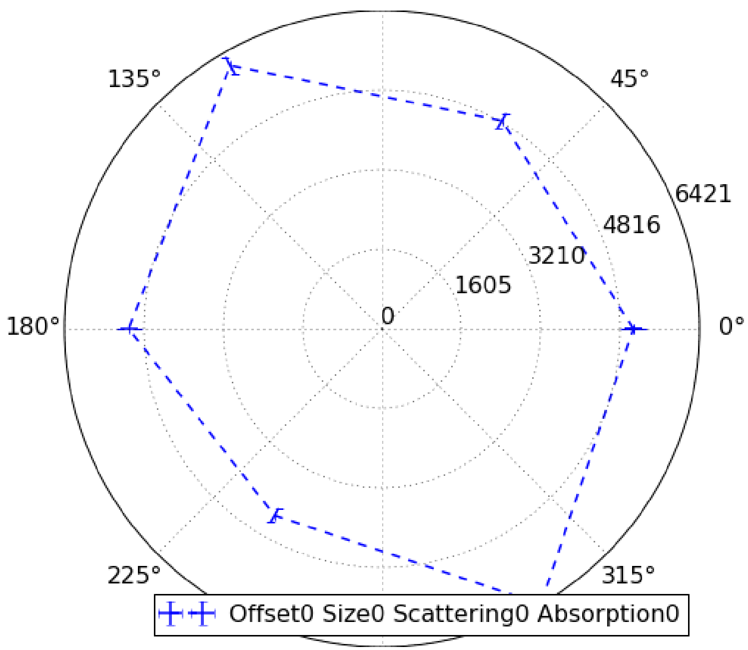
Photon Propagation Code (PPC)

- Direct photon propagation on GPUs incorporates bulk ice model
  - Photons from muons / flashers to all DOMs
- Enables arbitrary hole ice settings (size, position, optical properties)



PPC expectations

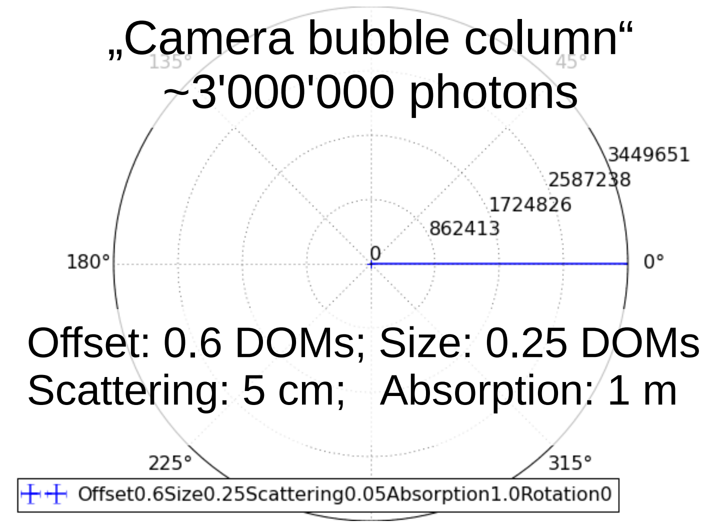
Bulk ice



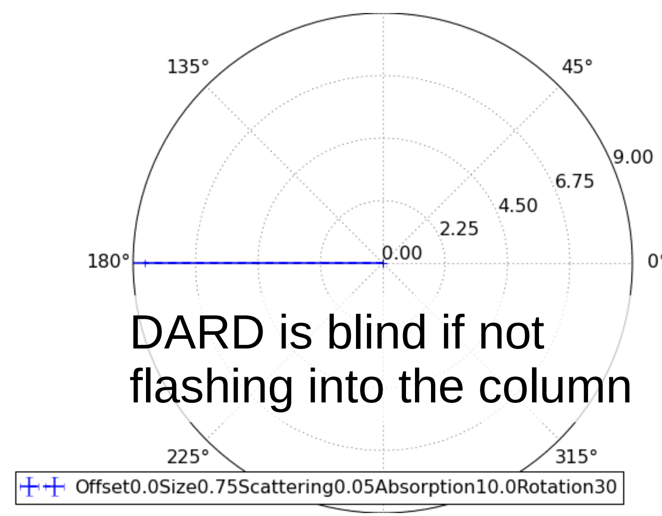
- 3000 – 5000 photons for T-LED flashes (~250'000'000 photons)
- Small asymmetries due to tilt and ice anisotropy

Bubble columns

„Camera bubble column“
~3'000'000 photons

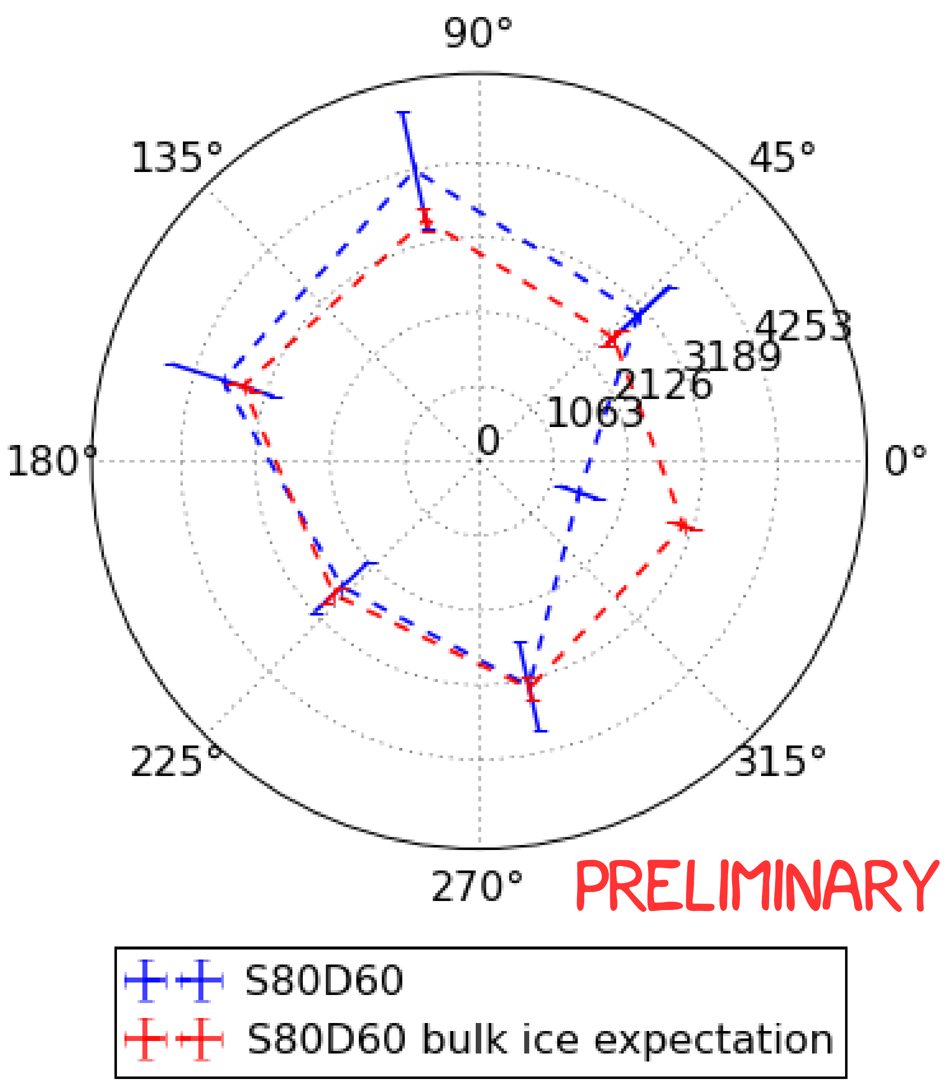


Offset: 0.6 DOMs; Size: 0.25 DOMs
Scattering: 5 cm; Absorption: 1 m



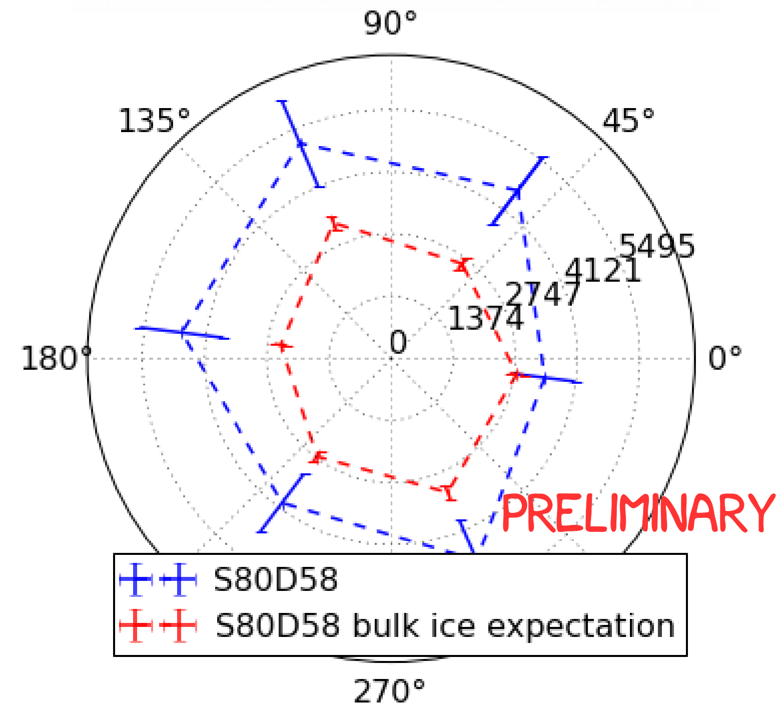
DARD is blind if not flashing into the column

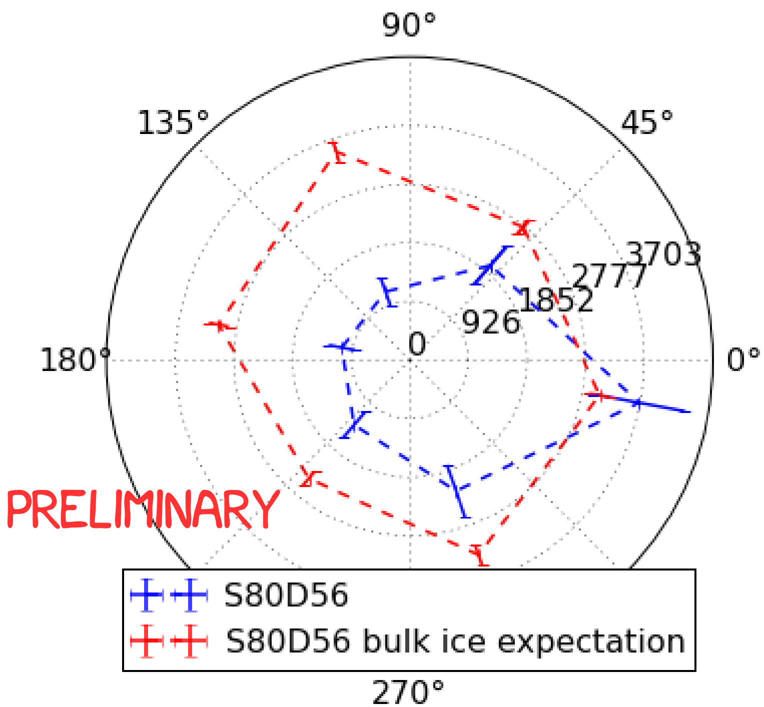
PPC – DARD comparison



- Half the DOMs show good agreement with the bulk ice only hypothesis
- Individual outliers explained by 20% LED variations and unquantified effects such as dust deposits

2 DOMs yield more photons then expected from bulk ice, but the effect is orders of magnitude smaller then expected from PPC simulation using parameters estimated from the Swedish camera





2 DOMs yield less photons then expected from bulk ice, this might be due to an slightly absorptive bubble column to one side

→ dedicated simulation for numerous bubble column parameters to follow

Summary

- New DAQ available for bubble column studies
- Horizontal LEDs illuminate the PMT directly
- Tilted LEDs represent ice properties

- Absolute photon numbers agree well with bulk ice expectation, for investigated DOMs the hole ice seems a much smaller effect than expected for the ice at the position of the Swedish camera

Future improvements

- Combined bulk and hole ice simulation
- Waveform simulation from simulated arrival time

- Measurement on DOMs in accidental drill caverns

Thank you for your attention!
Questions are welcome

Backup

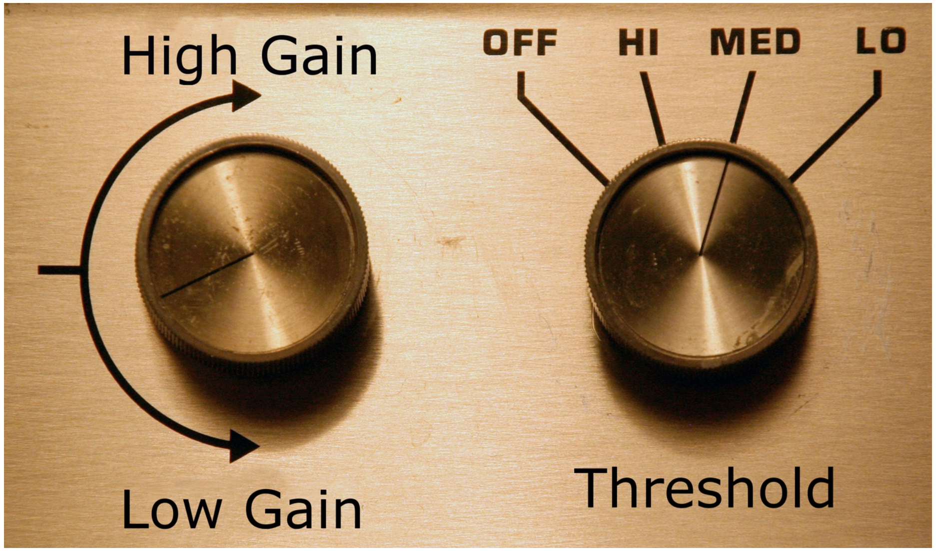
Why haven't we done this before?

Even at the low pulse setting each LED emits ~10^8 photons.

At nominal DOM settings this saturates the PMT of the flashing DOM and causes massive trigger rates.

But we can lower the gain (HV) so that each PE creates less charge.

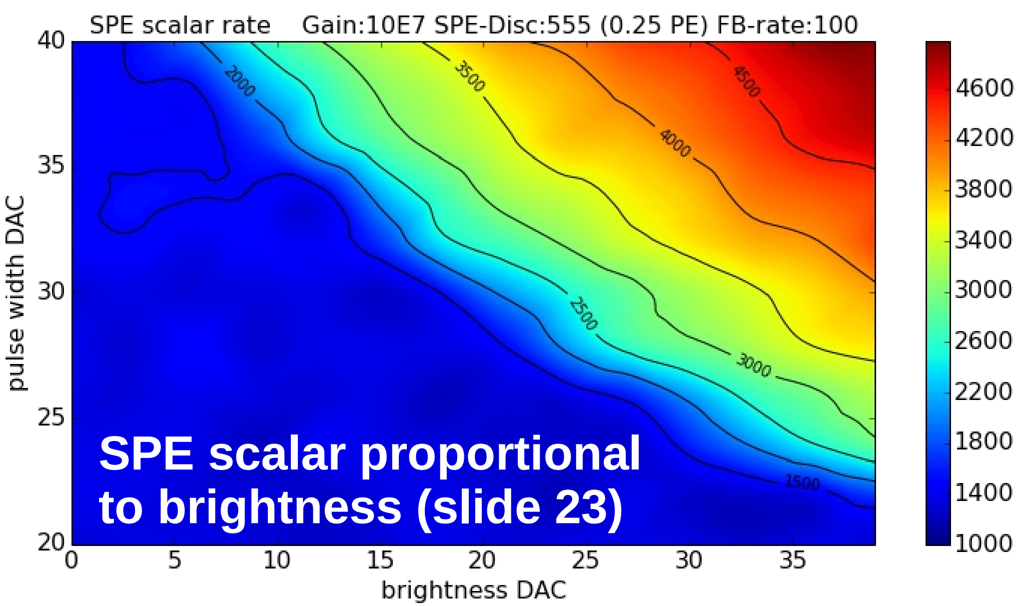
And we can play with the discriminators to control digitization rates.

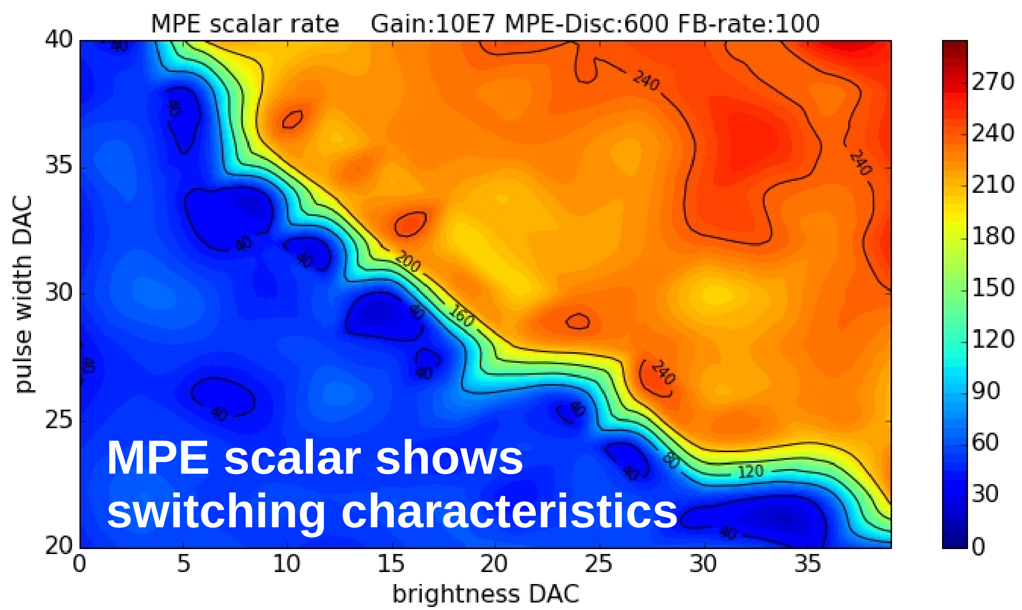


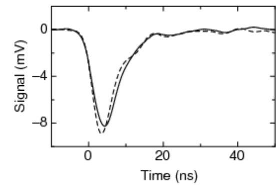
DAQ – Part I. (Goal: Scalars and FB control)

DOM in water tank sitting in IceBoot → flasher board, HV controlled with PyDOM (domterm wrapper)

LED1 (interpolated from 154 1sec points), compare to: https://wiki.icecube.wisc.edu/index.php/LED_light_output





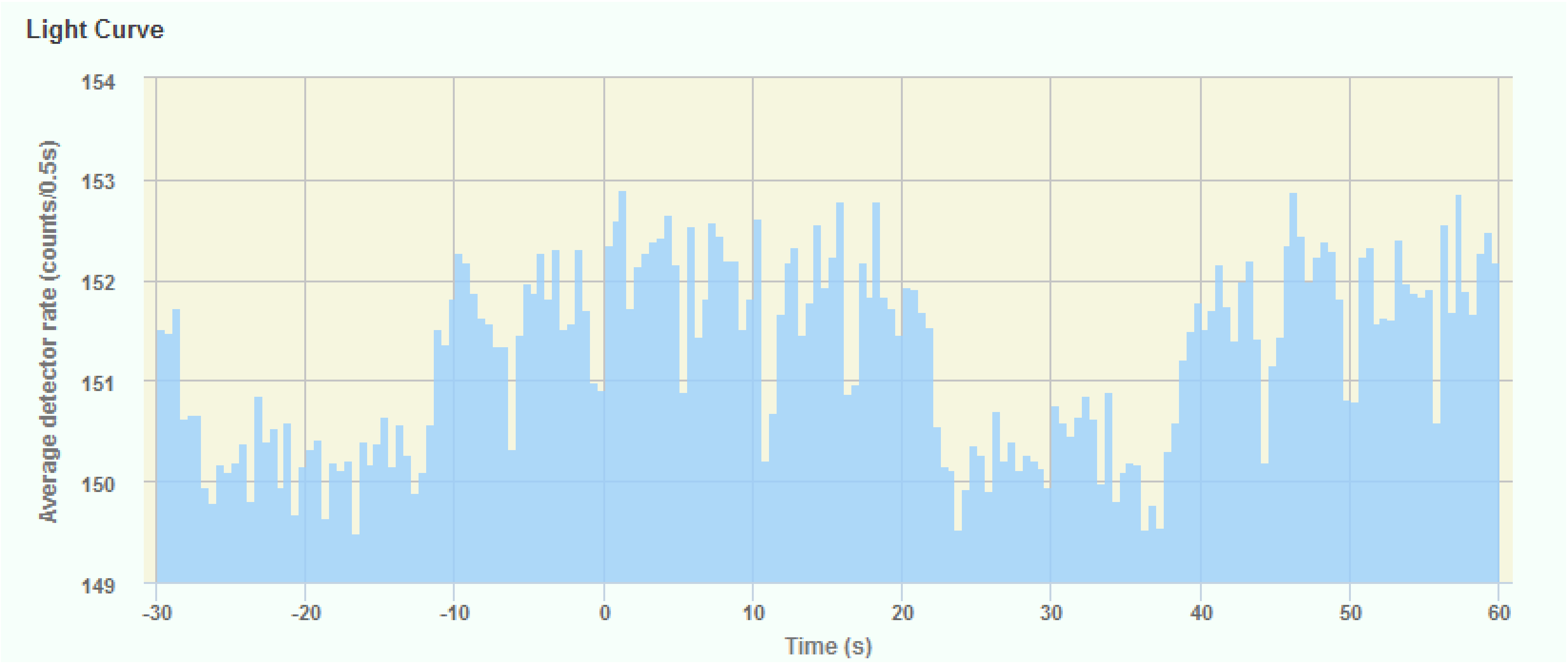


DAQ – Part II. (Goal: One waveform pre flash, no noise)

- Tried to modify pdaq and DOMapp to enable flasher operation through Omicron with HV forced on: did not work (wonky HV readback)
  - → We probably do not want to change pdaq and DOMapp at pole anyway
- Get waveforms manually through PyDOM and modify IceBoot to be able to trigger on FB: did not work (registers incomplete)
  - → We probably do not want to change IceBoot at pole anyway
- Trigger on SPE disc + digitize LED current on ATWD Ch3, discard events without LED waveform: did not work (LED not in digitization window (DL))
- Trigger on high SPE disc at low gain, demand FADC (lowest dynamic range) to be saturated: WORKS (see next slides for details)
  - → A little wasteful but only uses standard software

SN-DAQ

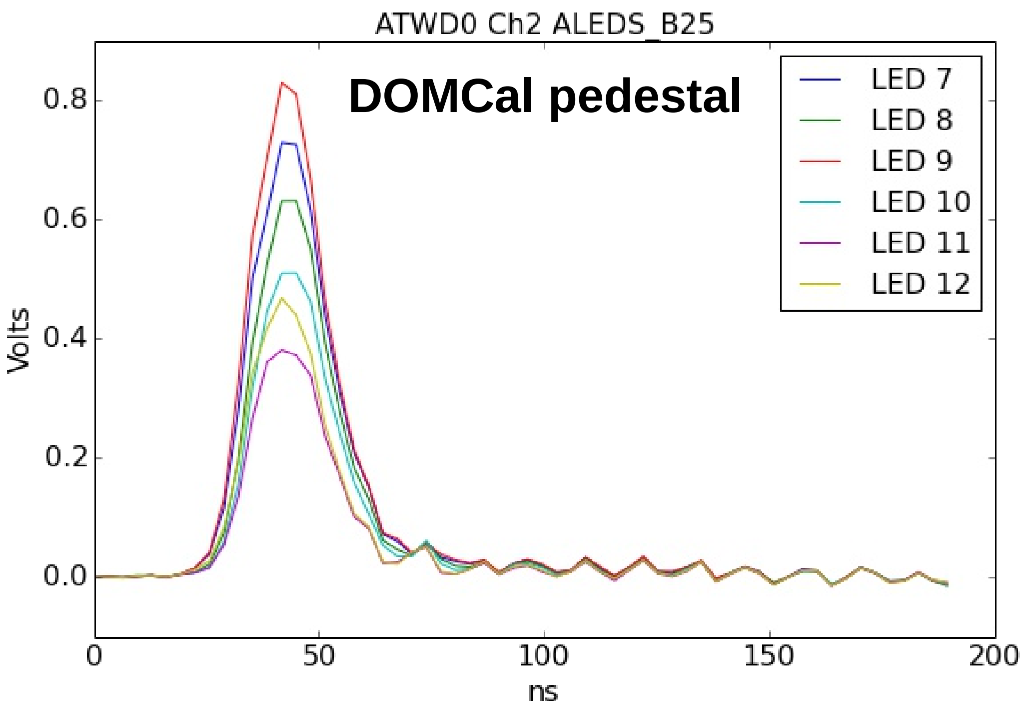
- Several high signficicance SN-alerts (up to 8.6) were triggered
- DOM operational pattern clearly visible in average detector rate

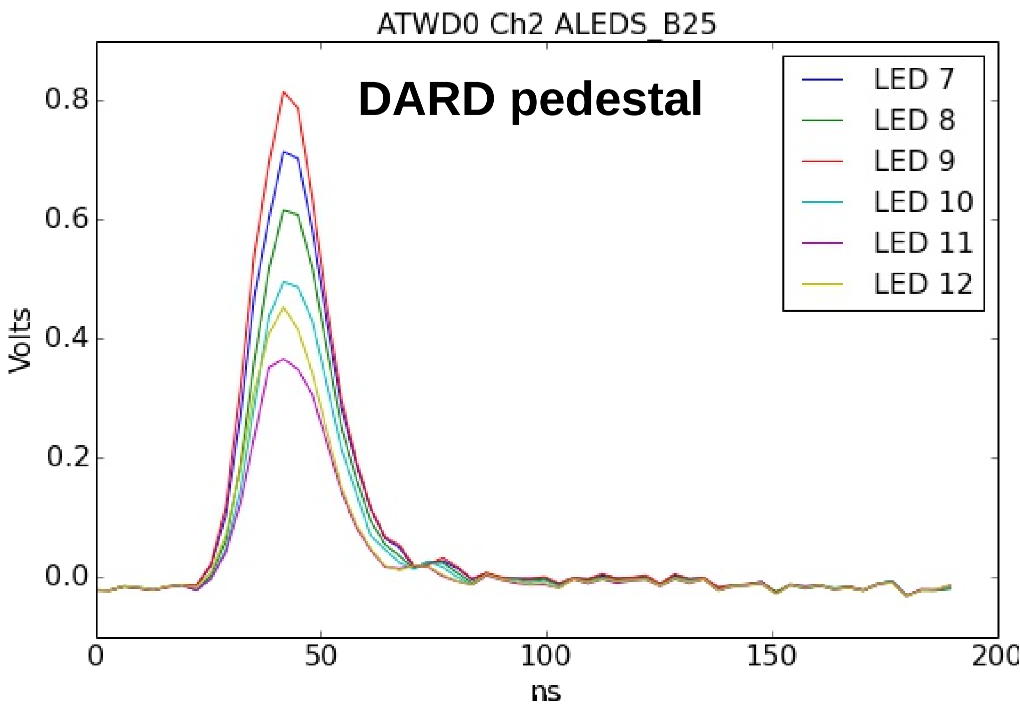


Pedestal subtraction (during voltage calibration)

The problem: Using the DOMCal pedestal values waveforms show jitter (which messes up integral calculations)

Solution: Use pedestals measured by DARD (CPU trigger) for pedestal
Use DOMCal calibration for voltage conversion



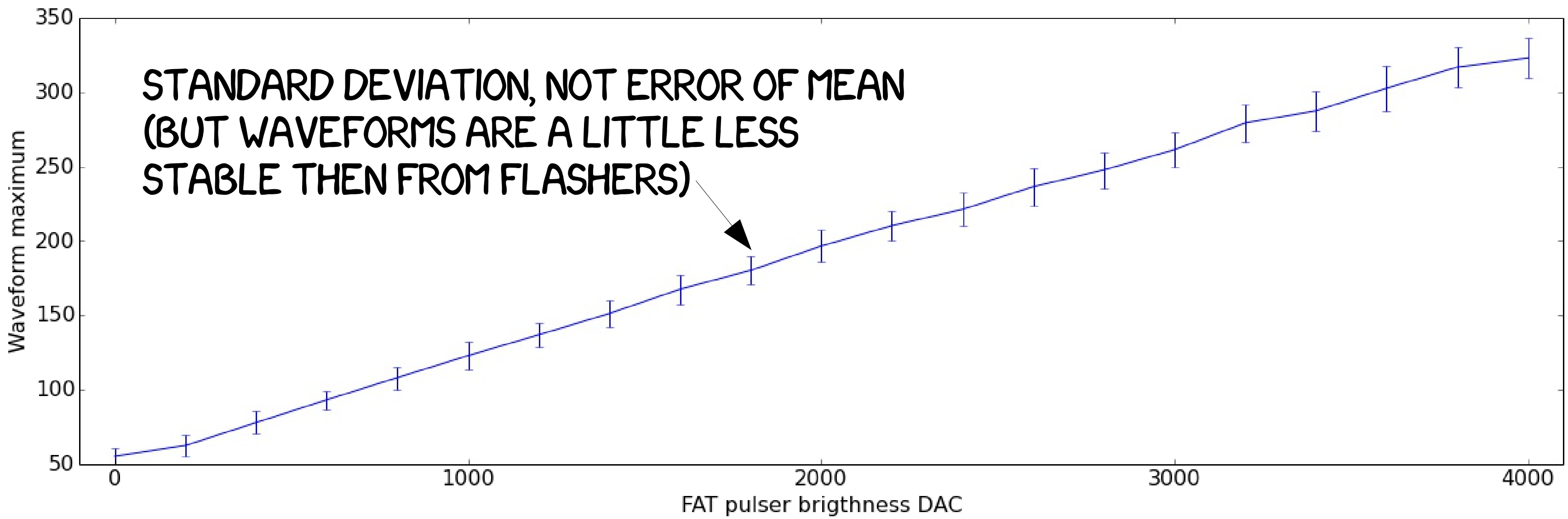


Photon counting

Reminer: Integral and late pulse peak used as brightness proxies

Goal: Quantify linearity of brightness proxies and characterize late pulse

Methode :
- Use FAT LED pulser (similar to flashers) in Chamberlin setup
- Measure brightness linearity vs. LED DAC using 2.55% filter
- Remove filter and measure proxies at high brightness



IceCube
South Pole Neutrino Observatory

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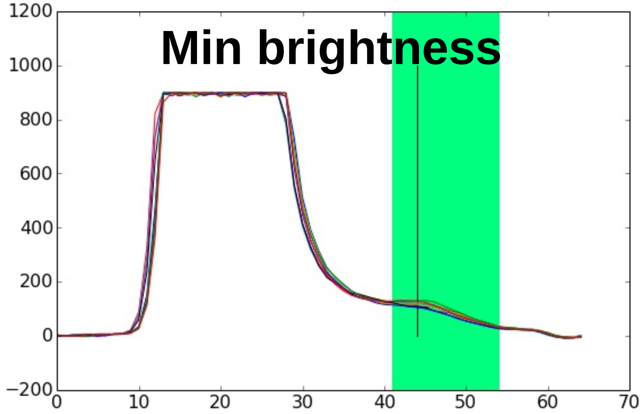

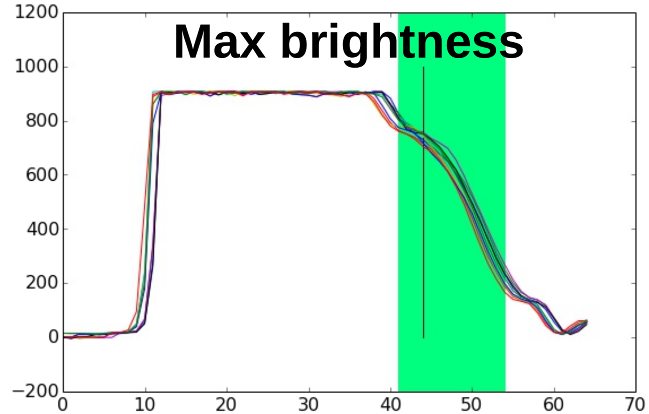

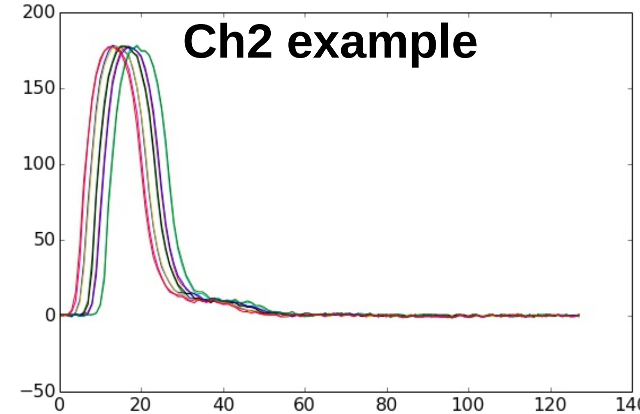

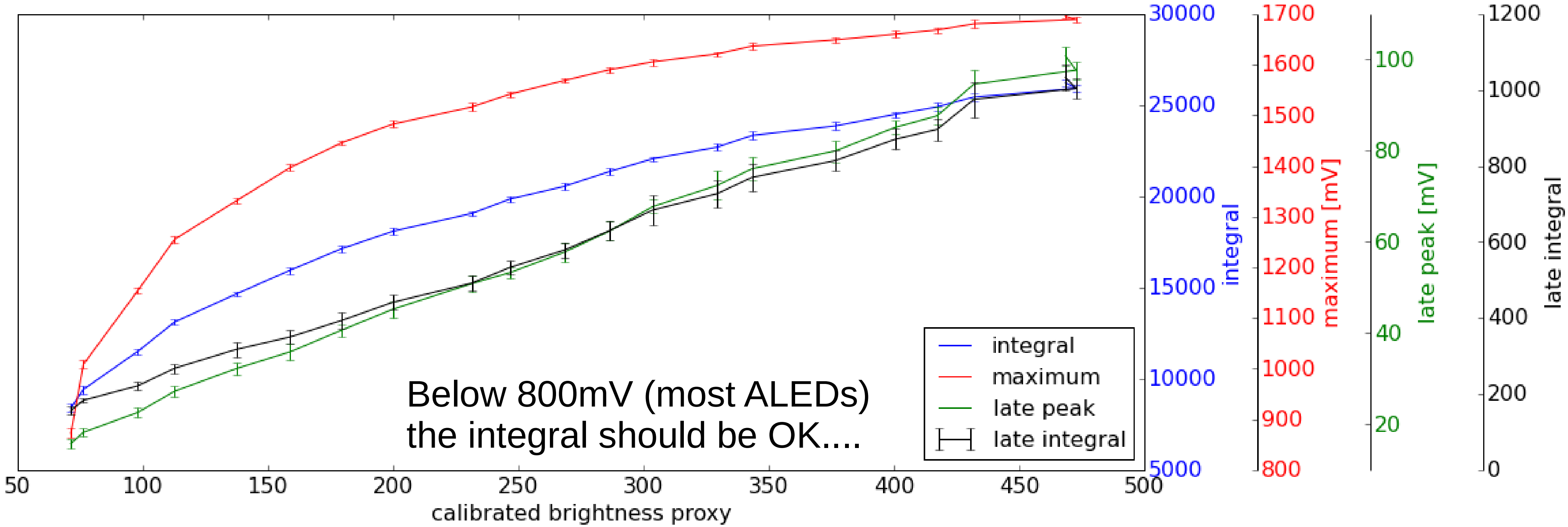

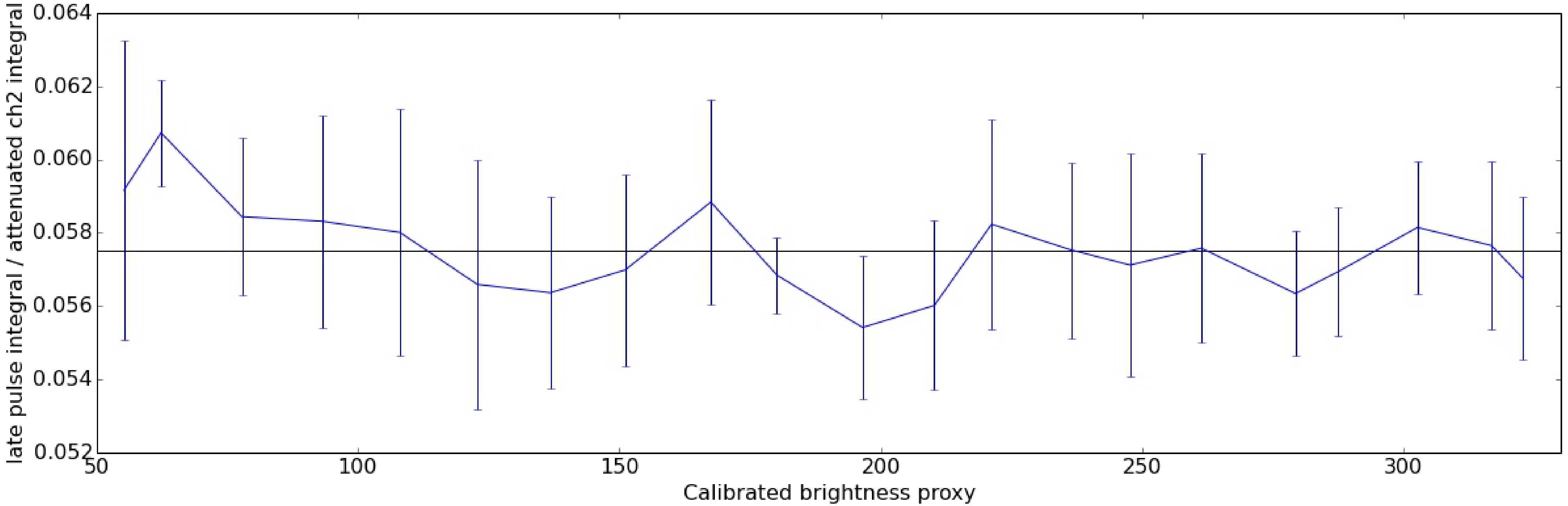

→ the late pulse integral contains a constant fraction of the arriving photons independent on the level of PMT saturation

The fraction is different for different LED pulse shapes. From low brightness ALED pulses in lab the fraction was established to be 2.4%