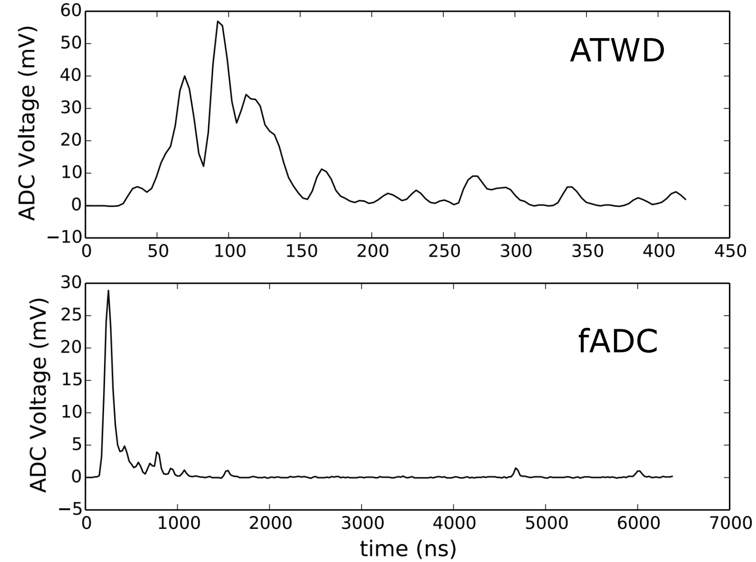
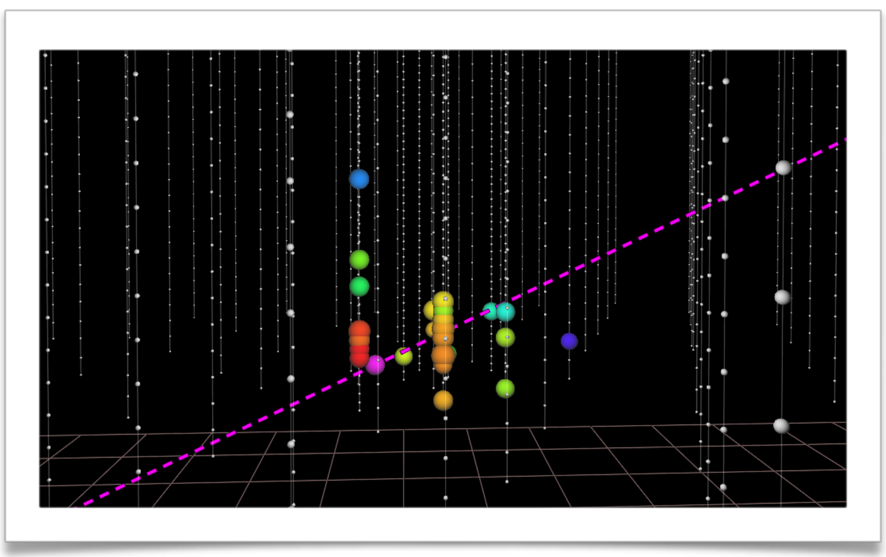
Calibration

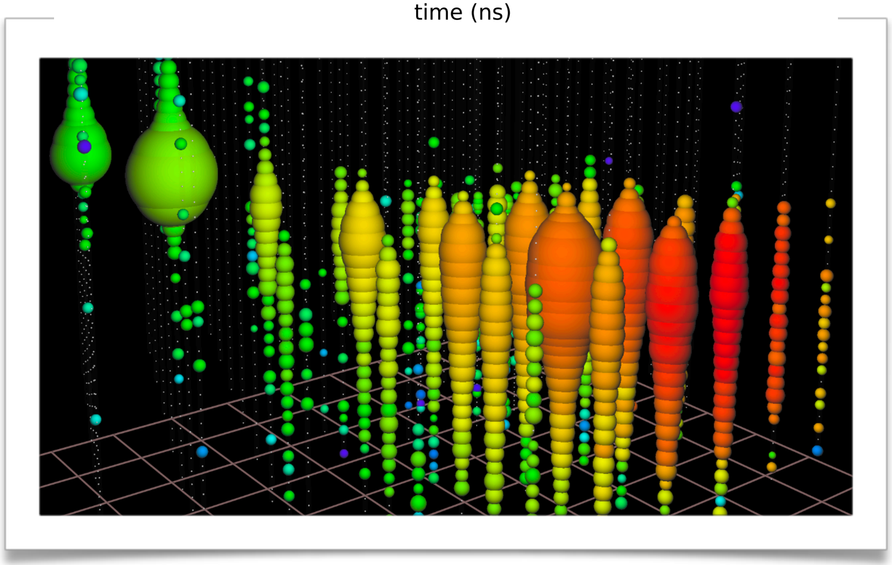
Summer Blot
(DESY)

Calibration deliverables

- Geometry
- DOM response
- Ice properties

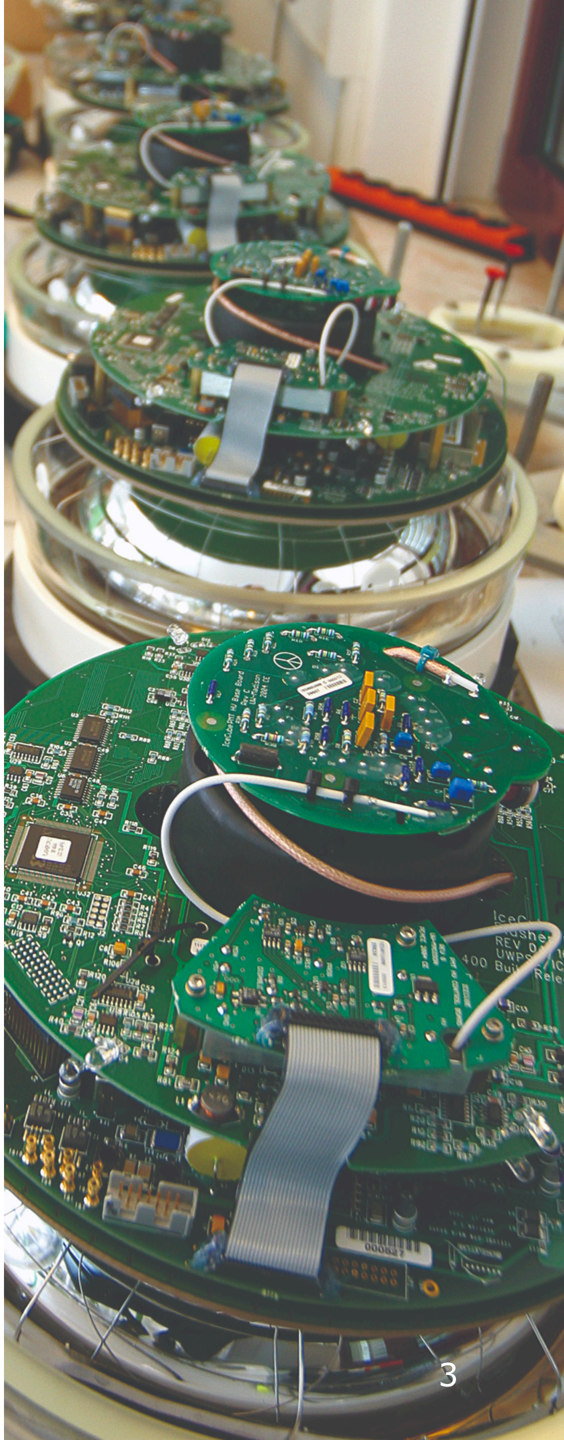






Calibration systems

- DOM on-board self-calibration system (DOMCal)
- Reciprocal Active Pulsing Calibration (RAPCal)
- Pressure sensors
- 12 LED flashers / DOM
- N_2 pulsed laser (337 nm) “Standard Candle”
- 2 rotating video cameras “Sweden cameras”
- 8 dust logs (404 nm laser line)
- Inclinometers on 47 DOMs
- Atmospheric muons



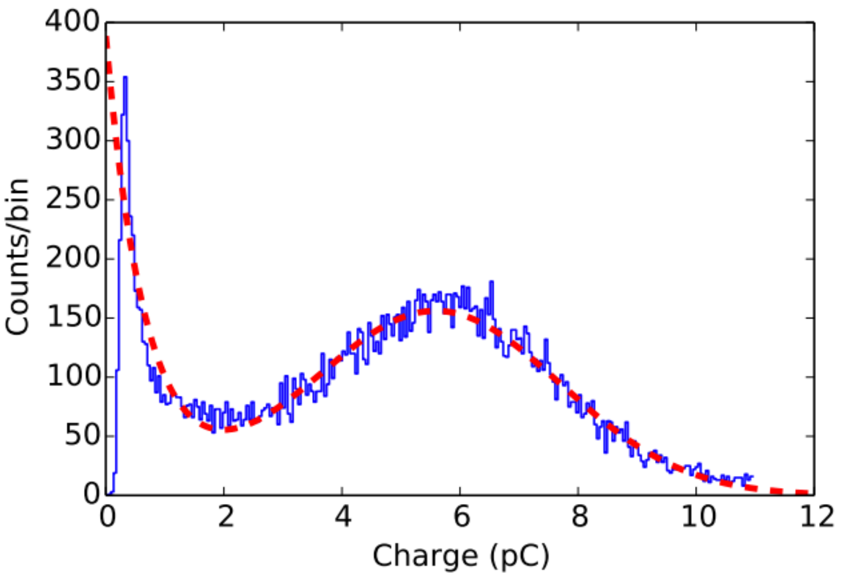
Calibration activities

- DOM response is stable since gain re-calibration
- Physics analyses constantly pushing the limits of reconstruction and require more precise modelling of ice and DOM-wise properties
  - Astrophysical tau identification, hadronic cascade identification from early muons and delayed neutron capture, inelasticity, low energy physics…
- Constantly improving understanding of the ice & DOMs
  - Taking new data, e.g. single LED runs
  - Making best use of existing data (e.g. improved algorithms, machine learning)
- Better calibrations are a key driver of the IceCube Upgrade

DOMCal

(DOM on-board self-calibration system)

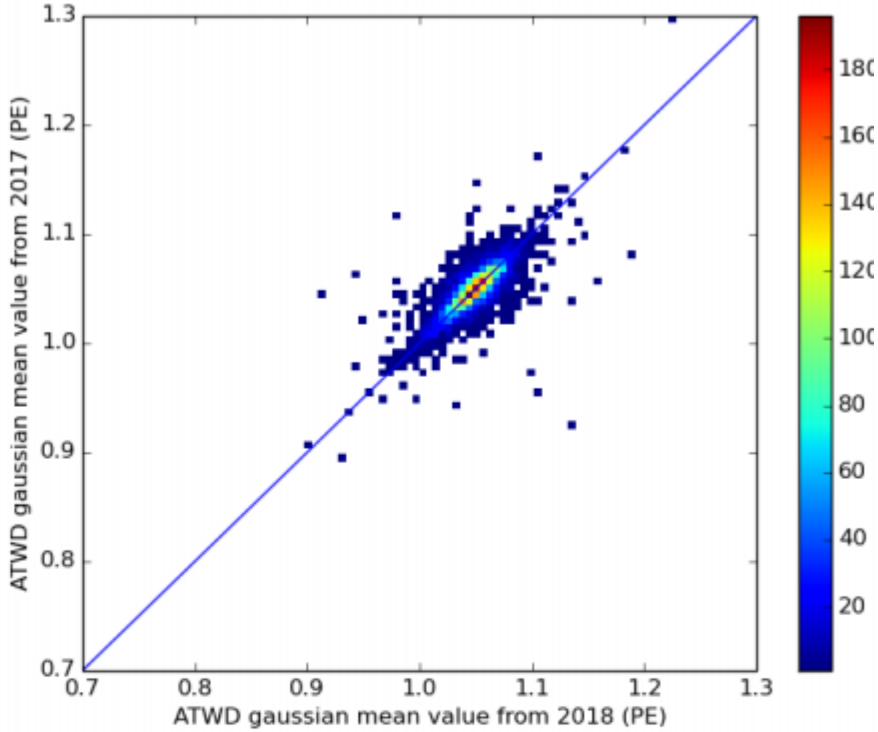
- Illuminate DOM via dedicated LED on main board
- Calibrate ATWD and FADC waveforms for charge response
- Transit time
- Results are sent North for verification, required adjustments/patches are implemented & stored in database



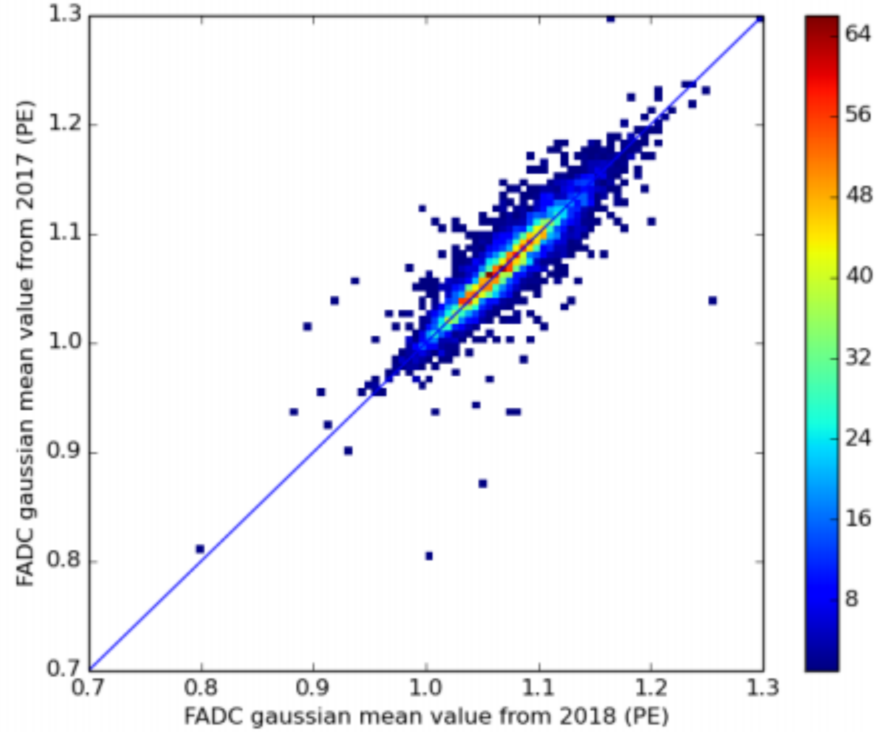
Yearly for in-ice DOMs
Monthly for IceTop DOMs

In-ice OM stability

ATWD



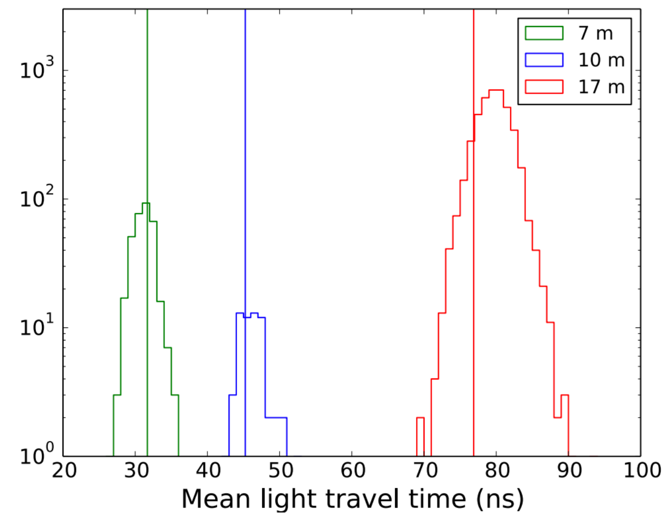
fADC

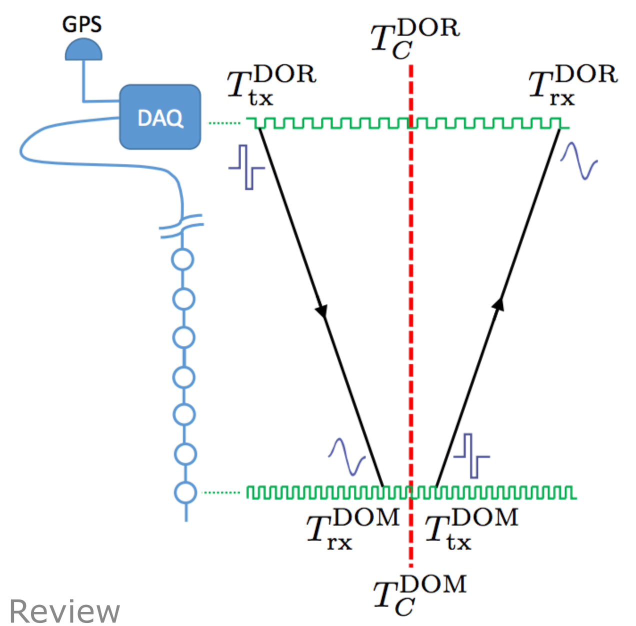


Comparison of calibrations from 2017 to 2018

Timing calibration

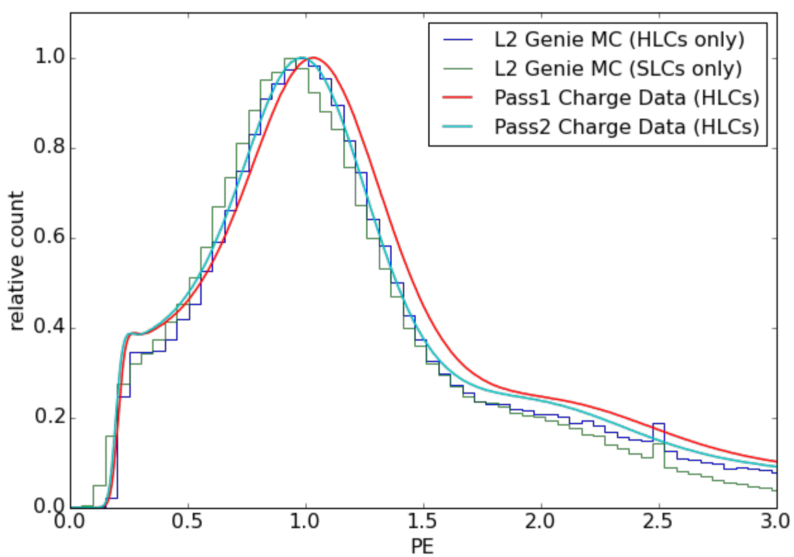
- Timing resolution verified using LED flashers on neighbouring DOMs
  - ~2.8ns (FWHM)
- Time synchronisation between OMs performed in RAPCal system
  - Continuously running
  - Agnostic to cable length and transmission properties
  - Very stable delays with typical spread ~0.6σ

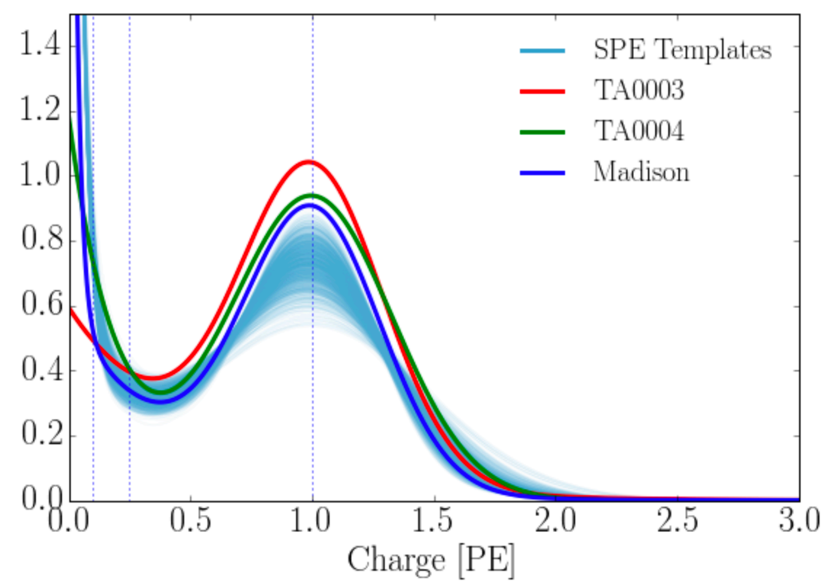




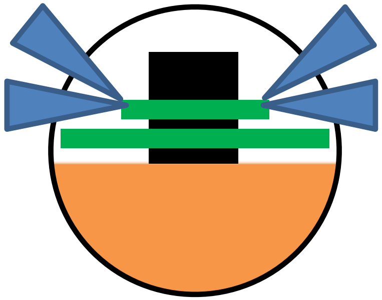
SPE recalibration

- Offline analysis of SPE distributions revealed Gaussian peak not centred at 1 PE, but rather ~4% too high
- Decision made to re-calibrate charge for each DOM for all data from 2010-2016, a.k.a. “pass 2”
- Further efforts ongoing to improve modelling of charge response
    - Personalised SPE templates for each DOM in Monte Carlo





Calibration devices: LED flashers

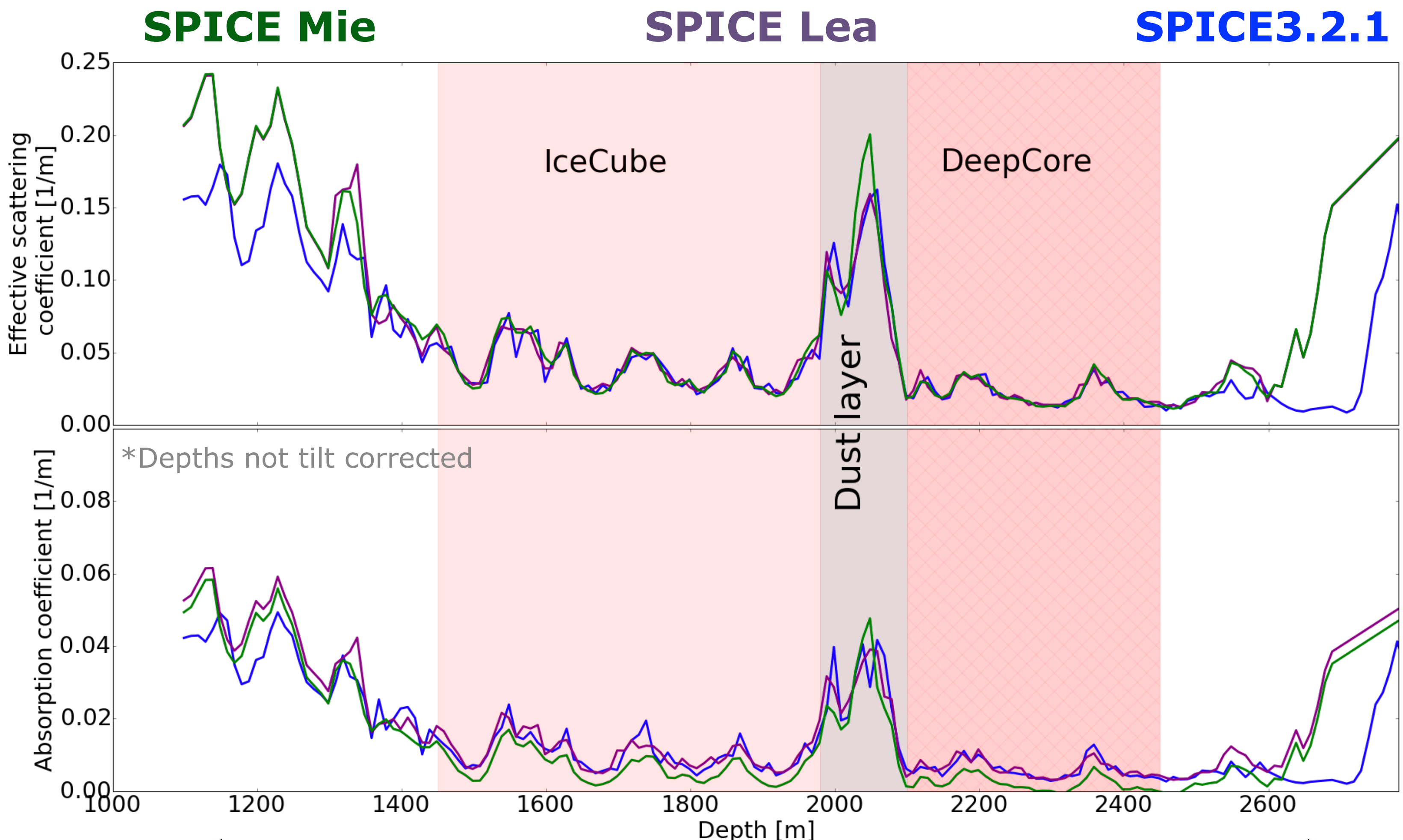


- 12 LEDs / DOM @ 400 nm
- 16 cDOMs with 340, 370, 450 and 505 nm
- Documentation via wiki pages
- Used for timing calibration and measurement of bulk ice and local OM properties
  - e.g. layered scattering and absorption ice model

Ice models	SPICE Mie	SPICE Lea	SPICE 3	SPICE 3.1	SPICE 3.2
Strings fit	1	1	7	85	85
Anizotropy	0	8%	9%	10.8%	10.6%
Model error	29%	20%	10.7%	9.8%	9.8%

2013 → 2018 →

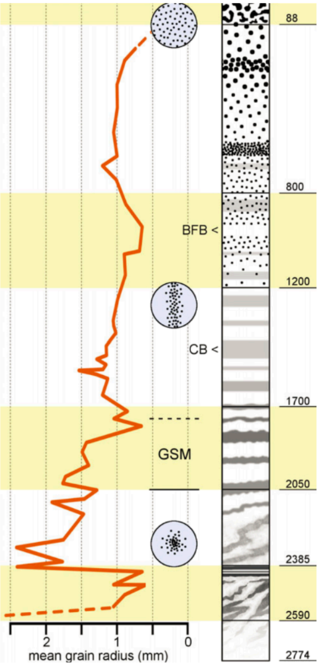
Ice models over time



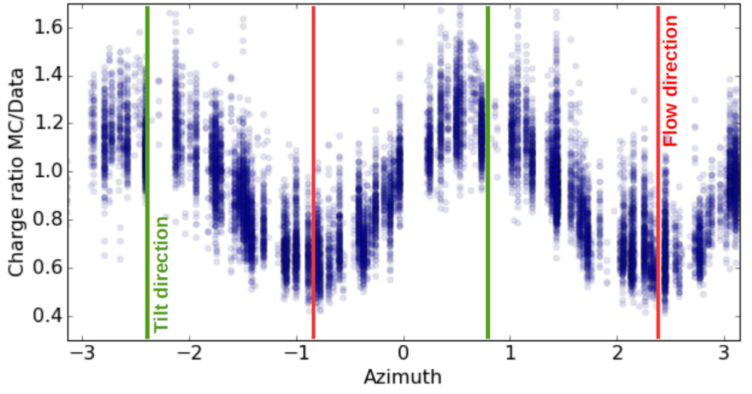
Large variations where data is extrapolated
IceCube Upgrade will be key in these regions!

Anisotropy of light propagation

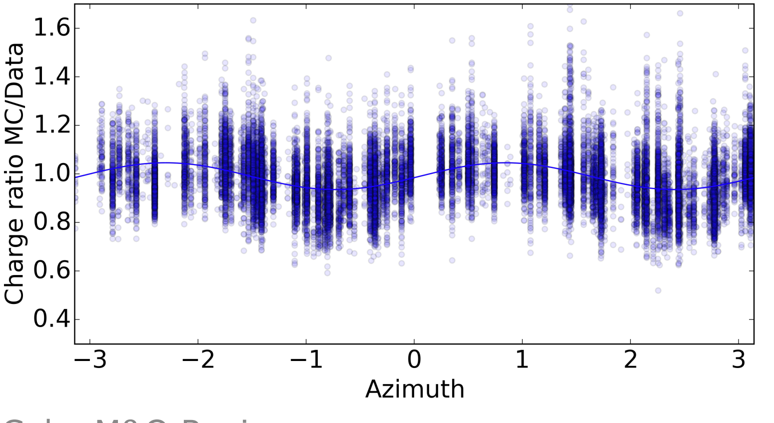
- More light received along ice flow axis compared to orthogonal
- Proper characterisation critical for many physics analysis (e.g. high-energy ν_τ reconstruction)
- Continue to investigate underlying cause
  - Strong ties to glaciology & SPICEcore



No anisotropy in simulation

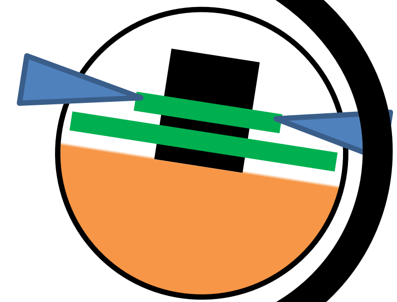


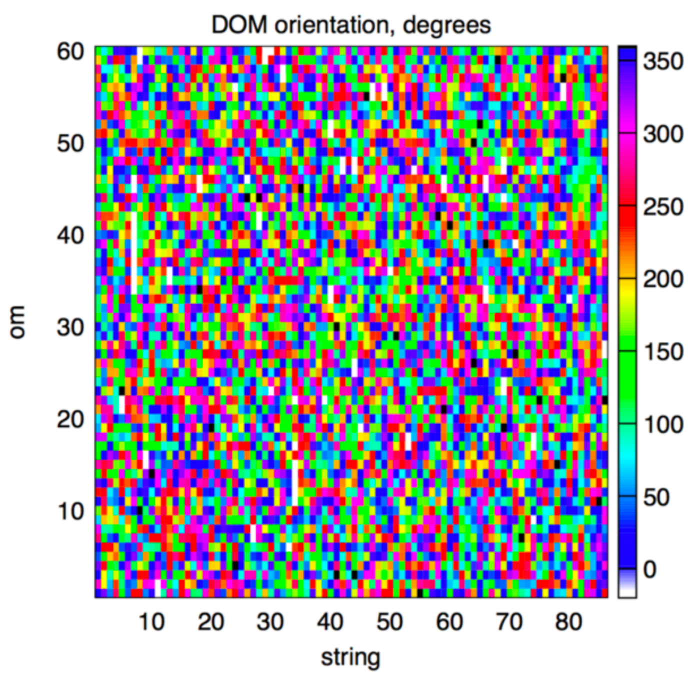
With anisotropy in simulation

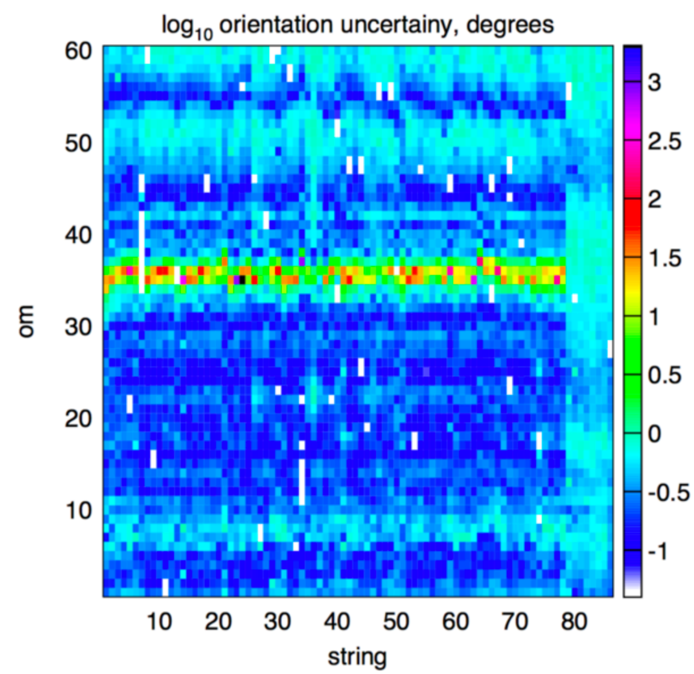


Towards more precise calibration

- In 2017-18 collected data from all LEDs individually (*>60,000*)
- Investigating DOM-wise systematics: e.g. tilt, cable shadow
- Azimuthal position of main cable known better than 1% for most OM's

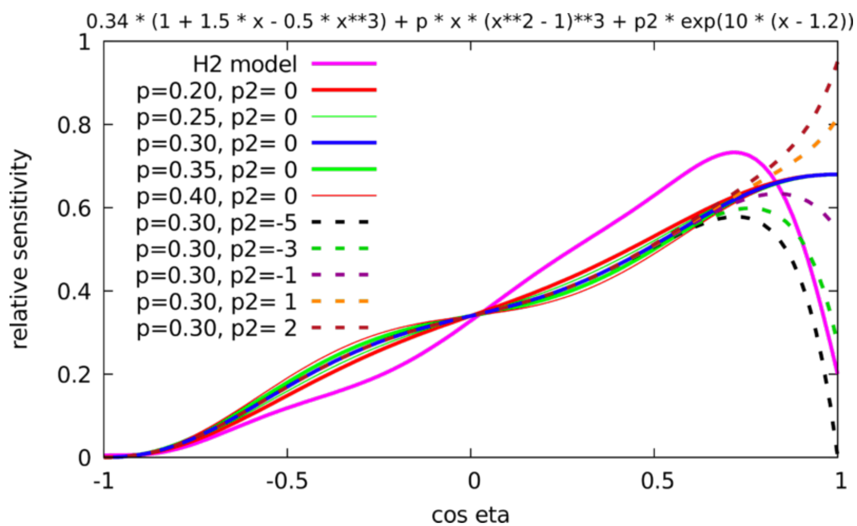




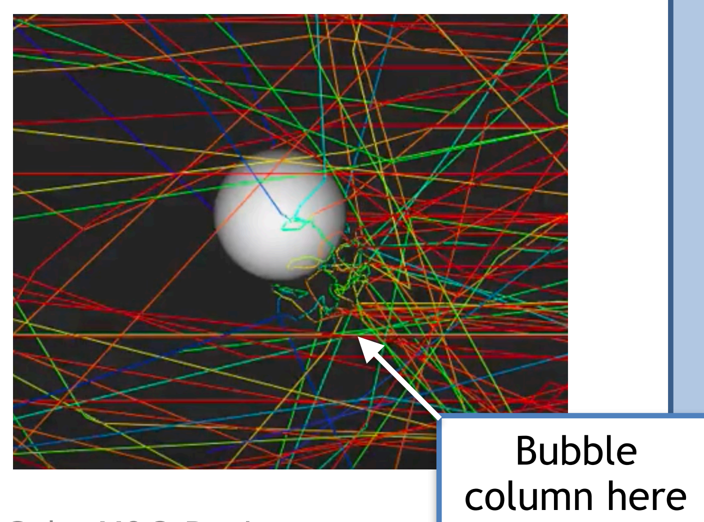


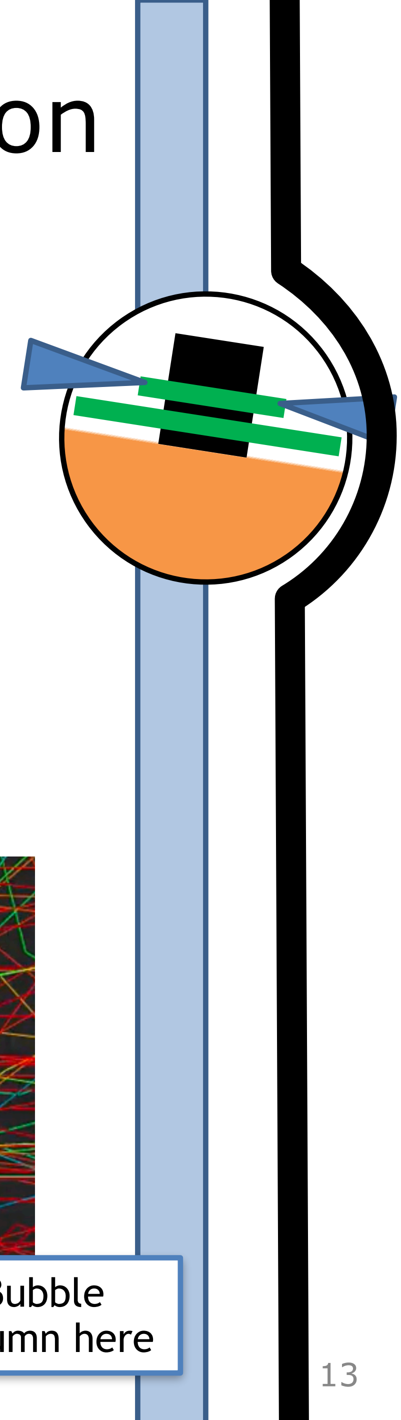
Towards more precise calibration

- Observation: angular acceptance different from lab measurement - reduced in forward region
- Hypothesis: trapped bubbles/impurities during re-freezing of hole
  - Theory supported by camera images
- Moving from "effective models" to direct simulation



Bird's eye view

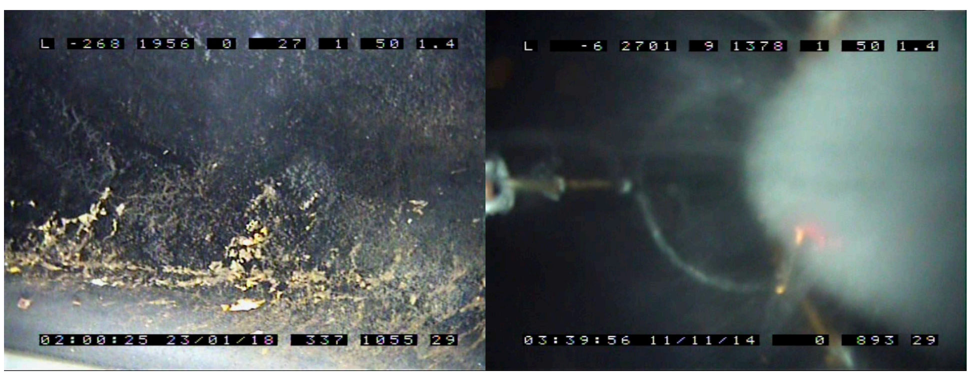




Additional in-ice calibration devices

- Sweden/bubble cameras
  - Monitor deployment, freeze-in process
  - Qualitative assessment of local ice properties: bubbly ice, drill water contamination
  - **New!** Simulation of camera optics to make quantitative measurements
- Standard candle
  - 337 nm pulsed N_2 lasers with Cherenkov cone emission pattern
  - Energy scale, linearity, vertex resolution

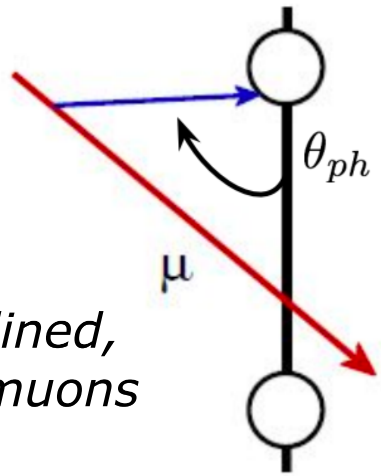
Sweden Camera



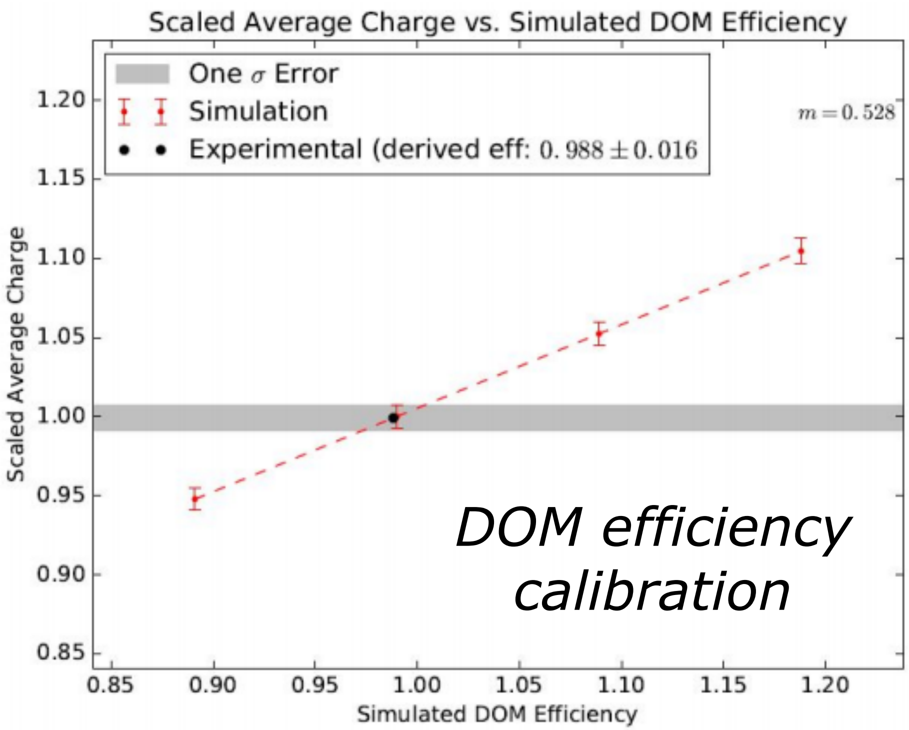
Standard Candle

Atmospheric muons

- High statistics, natural calibration source
- Verify many calibration constants
  - DOM efficiency
  - Ice anisotropy
  - Absolute pointing (moon shadow)

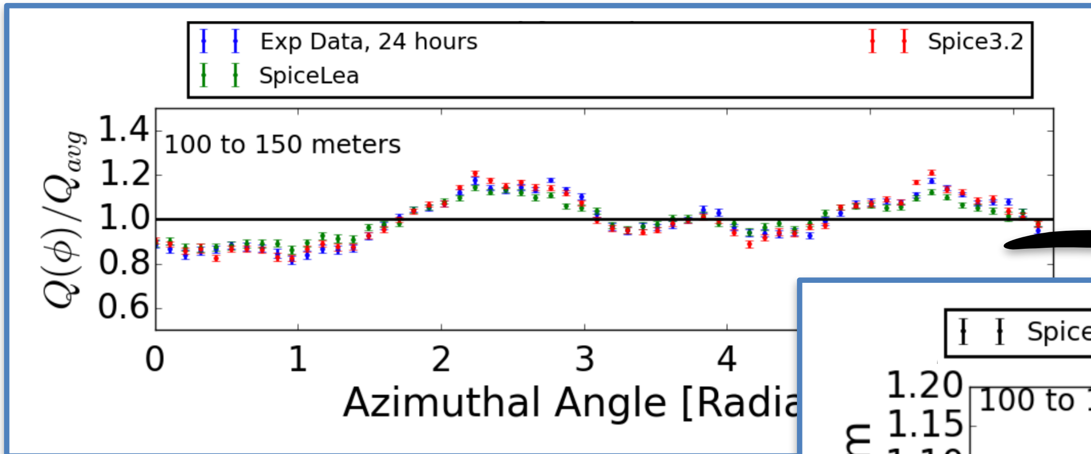


Select inclined, stopping muons

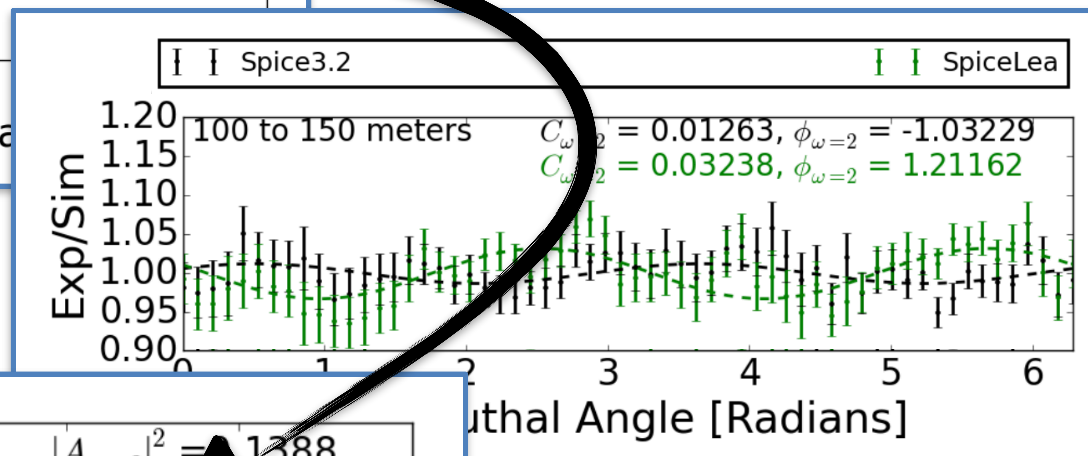


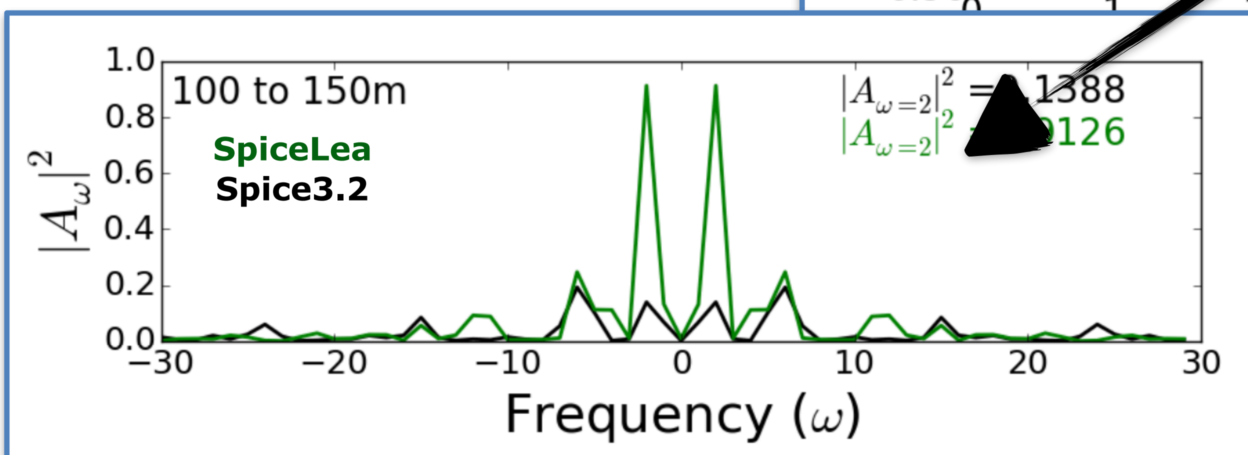
DOM efficiency calibration

Anisotropy check with muons



Take charge ratio data /simulation



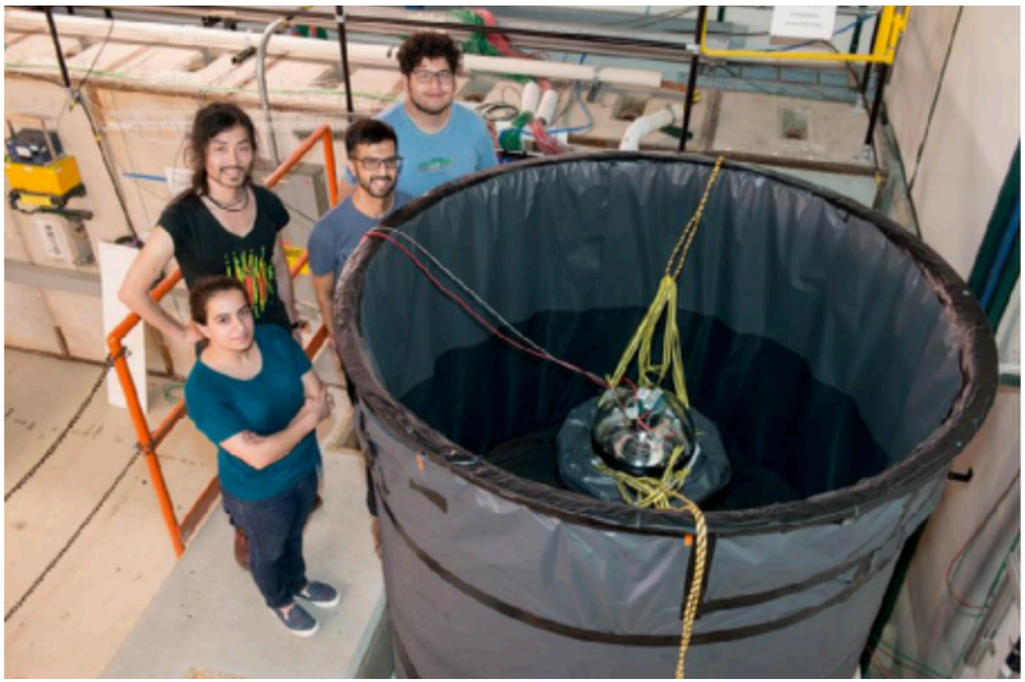


Fourier transform ratio

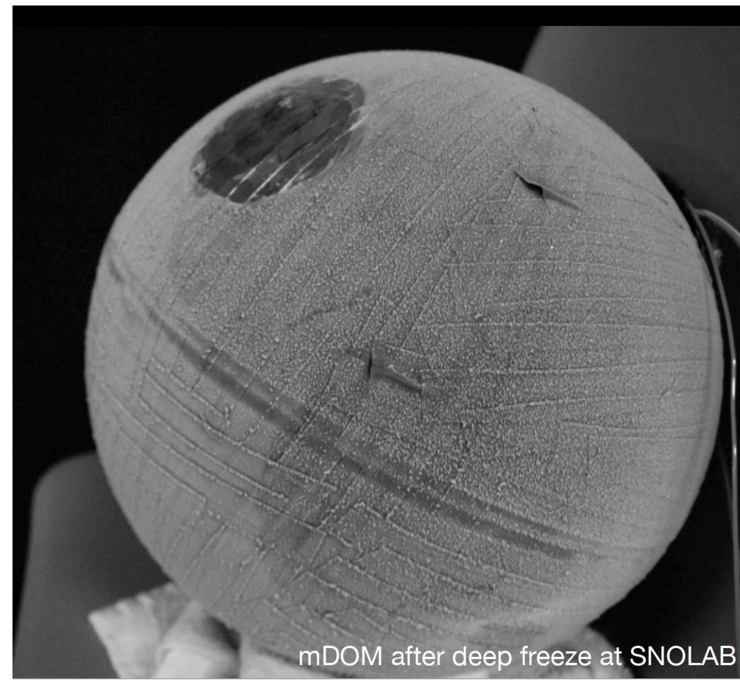
Want minimal w=2 mode

Lab measurements

Beam test at Fermilab

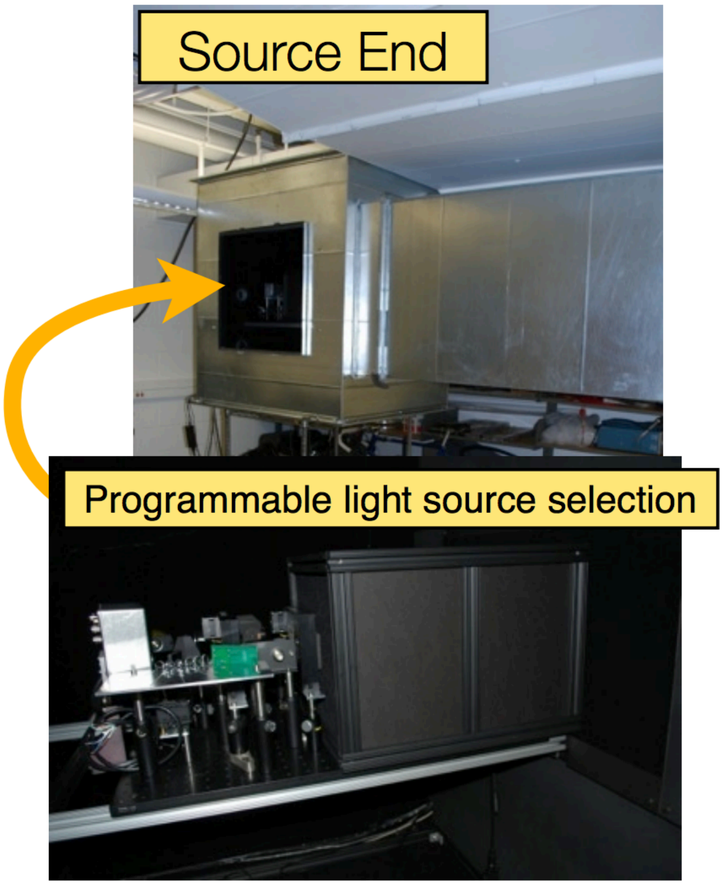


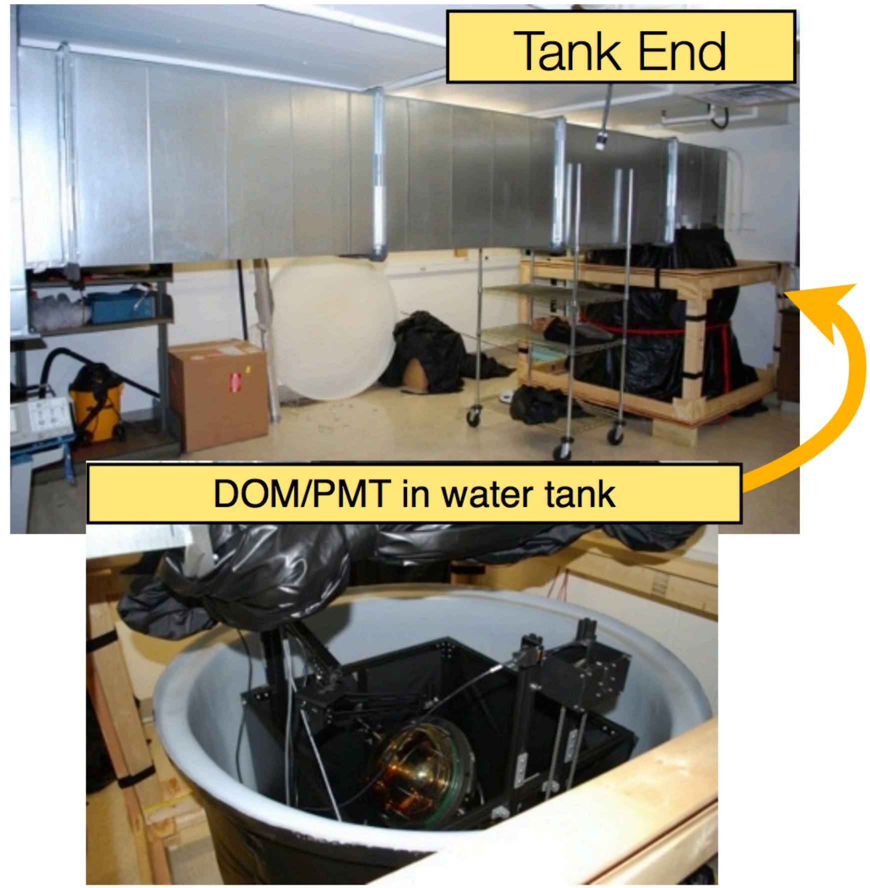
Noise measurements of DOMs at SNOLAB



Lab measurements

In-water DOM calibration project at UWMadison

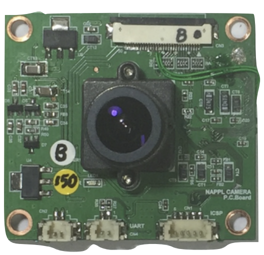




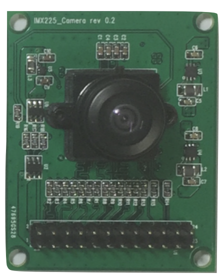
The future of IceCube calibration

- Several devices in R&D/prototype phase for IceCube Upgrade and Gen2
- Building on experience from IceCube to determine new device capabilities and requirements
- Using the SPIceCore at South Pole to cross-calibrate ice properties and simultaneously test many of these devices

CCD

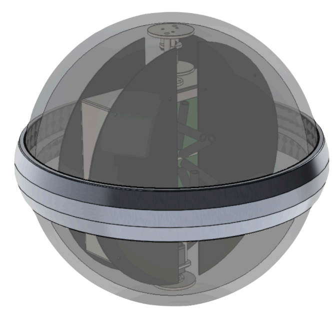


CMOS



Piezo-module

Pencil beam



POCAM

Summary

- "Bread and butter" calibrations are stable
- Physics program is driving the need for ever more precise calibrations of ice and optical modules
- Close collaboration with software and reco/systematics working groups necessary to make calibrations useful to whole collaboration
- Looking forward to the opportunities that new calibration devices at shorter baselines and new locations will bring with the IceCube Upgrade!

Backup

Calibration devices: LED flashers

Table 1: Properties of the standard IceCube flasher LED (tilted (t) and horizontal (h)) and the cDOM LEDs, including wavelength λ, emission FWHW σ in air, DOM polar angular emission FWHM in ice σ_θ, and DOM azimuthal angular emission FWHM in ice σ_ϕ.

LED	nominal λ (nm)	measured λ (nm)	σ air (°)	σ_θ (°)	σ_ϕ (°)
ETG-5UV405-30	405	399	30.0	9.7 (t) 9.2 (h)	9.8 (t) 10.1 (h)
UVTOP335-FW-TO39	340	338	51.0	36.1	42.9
NS370L_5RFS	370	371	55.2	39.1	42.9
LED450-01	450	447	6.8	4.8	5.3
B5-433-B505	505	494	6.4	4.5	4.9