

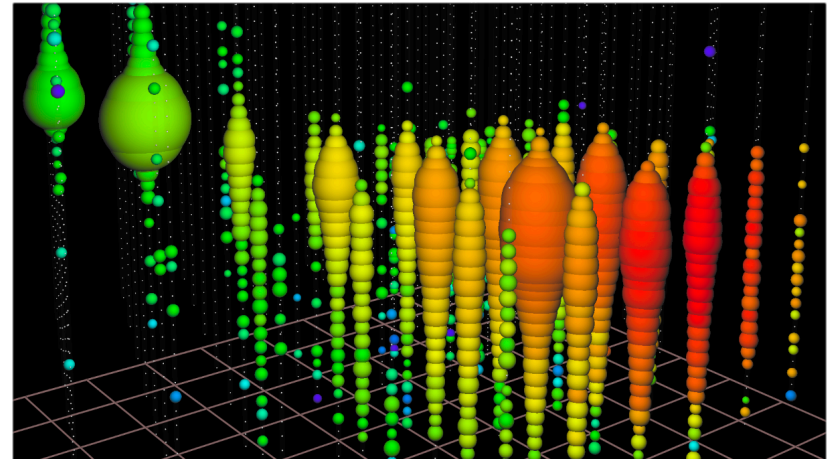
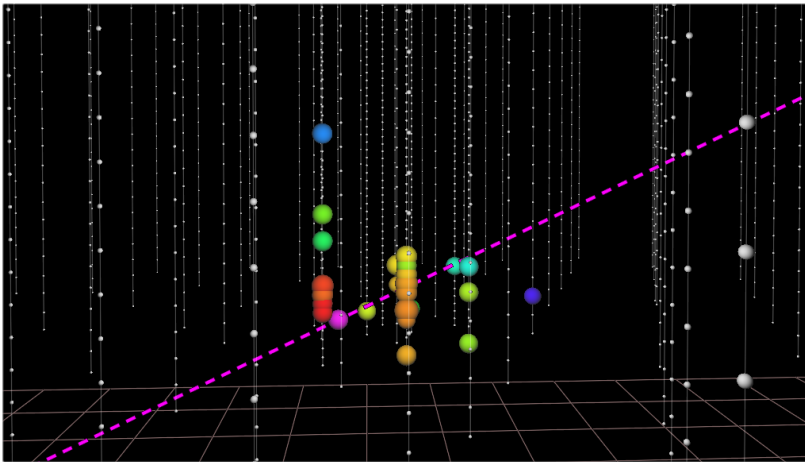
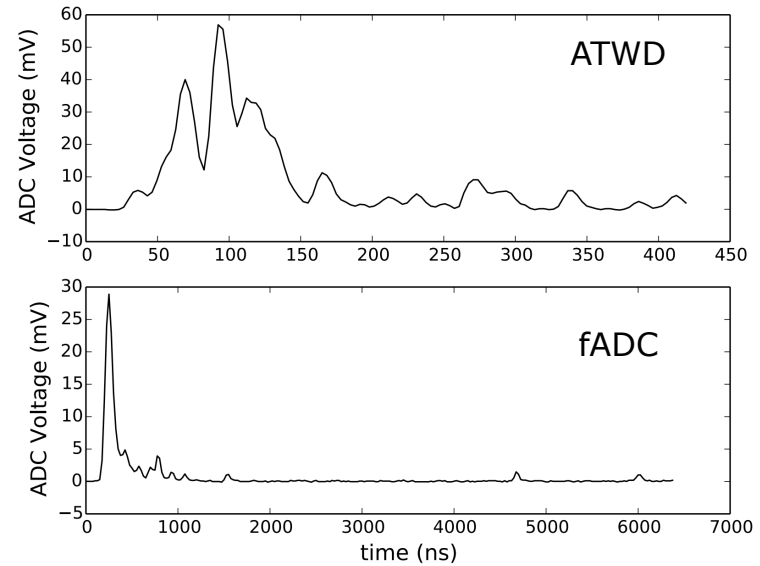
IceCube

Calibration

Summer Blot
(DESY)

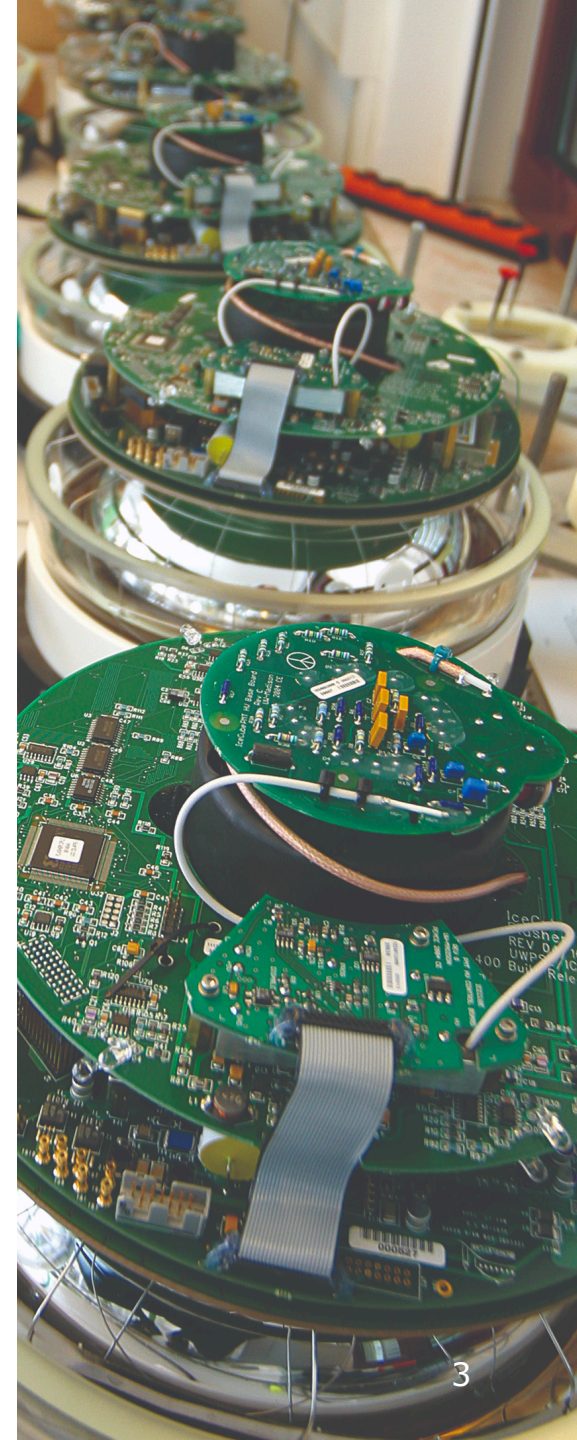
Calibration deliverables

- 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
- N₂ 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



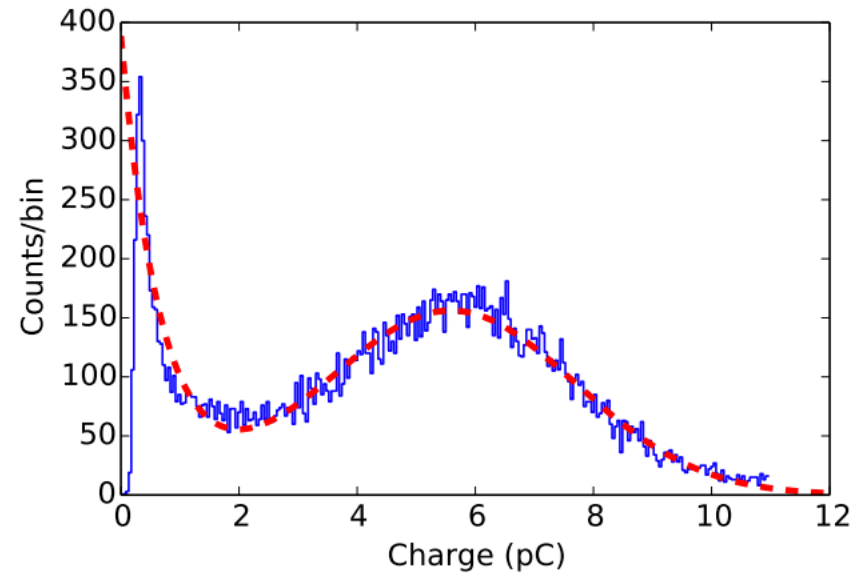
Calibration activities

- 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

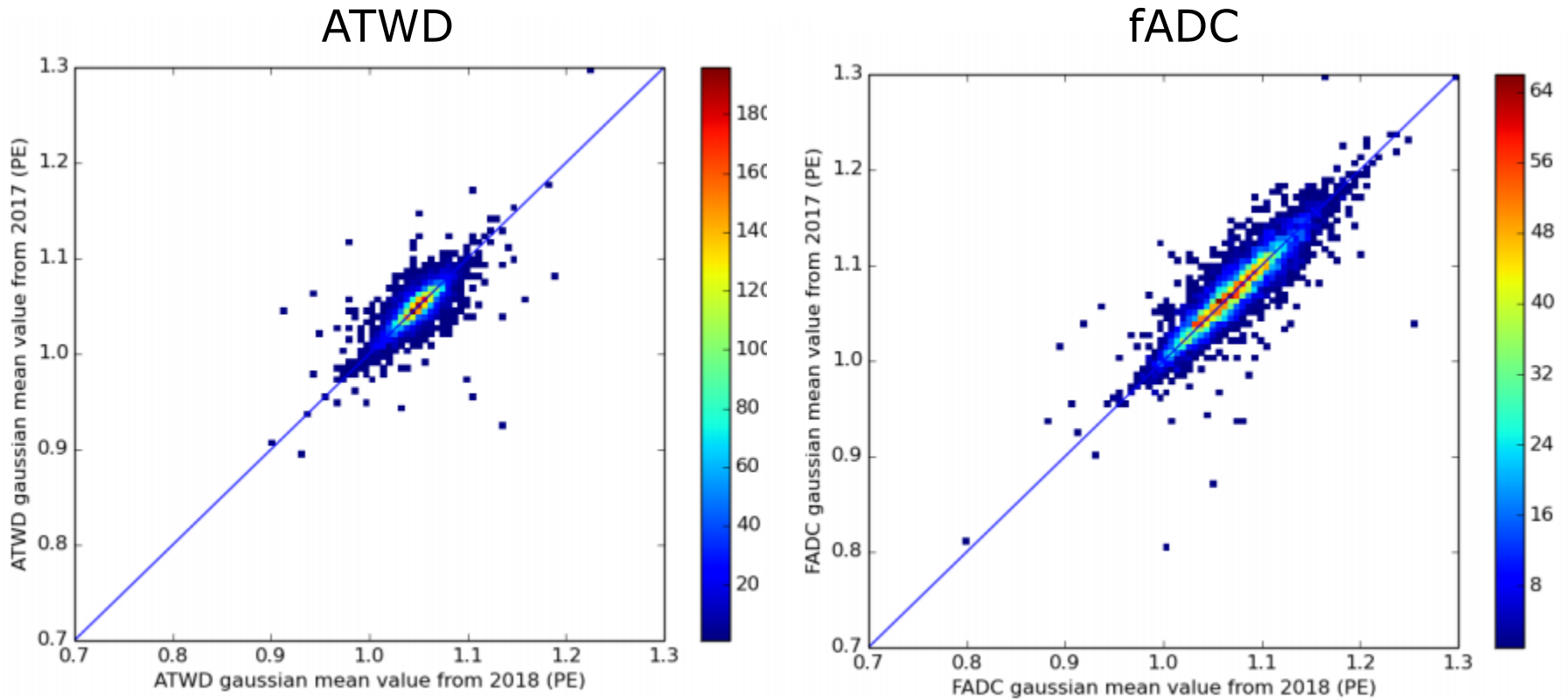
(DOM on-board self-calibration system)

- 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

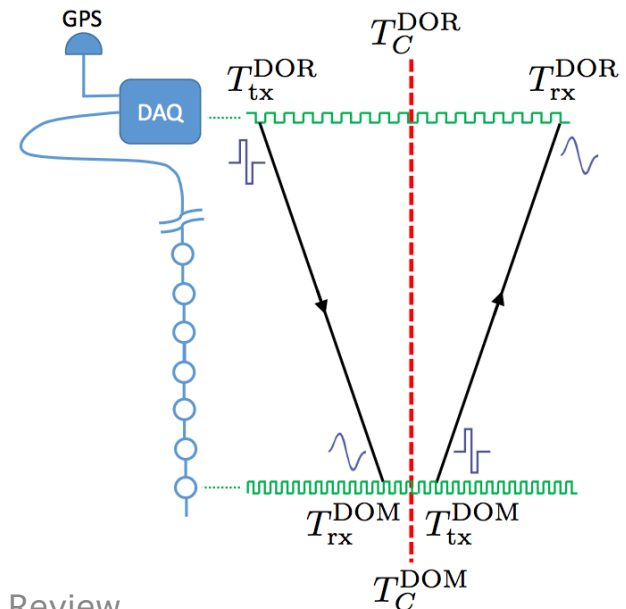
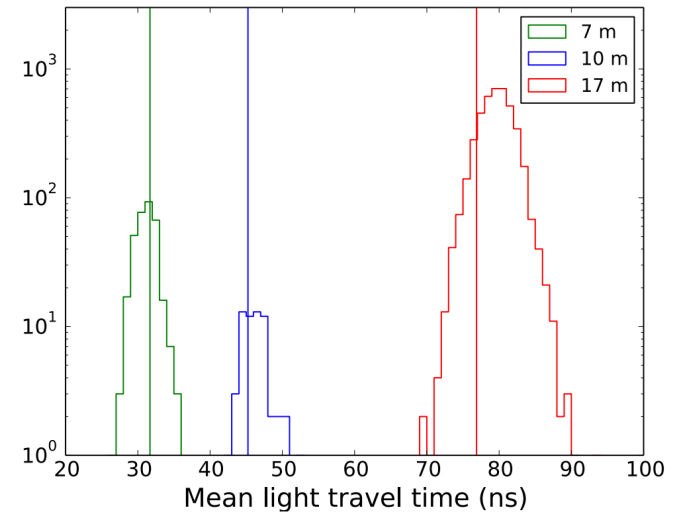
In-ice OM stability



Comparison of calibrations from 2017 to 2018

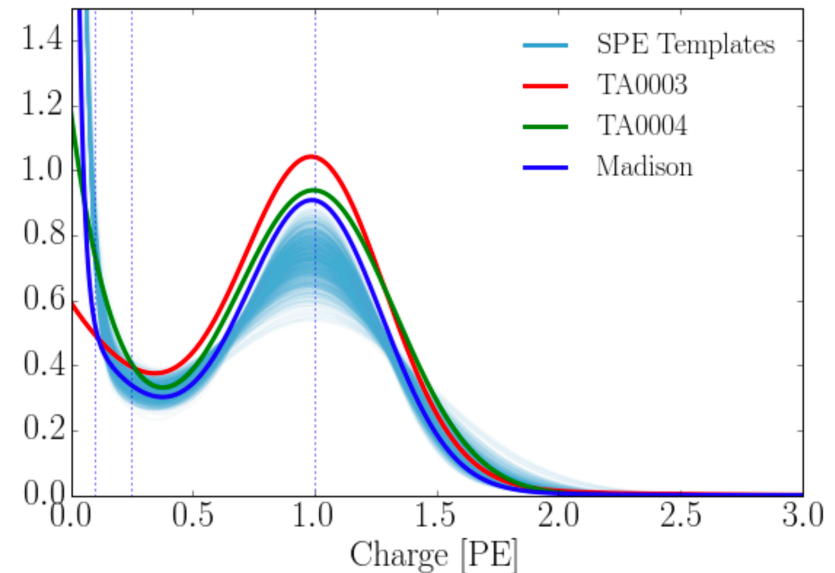
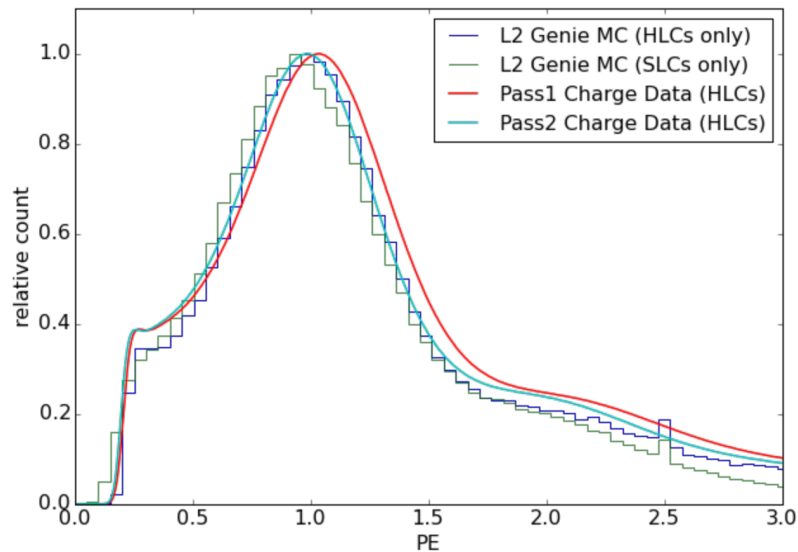
Timing calibration

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



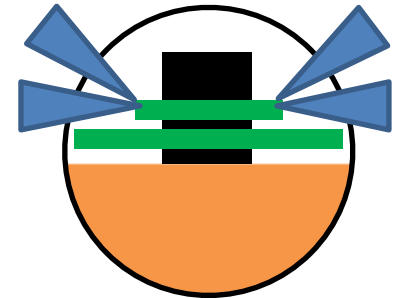
SPE recalibration

- Offline analysis of SPE distributions revealed Gaussian peak not centred at 1 PE, but rather $\sim 4\%$ 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

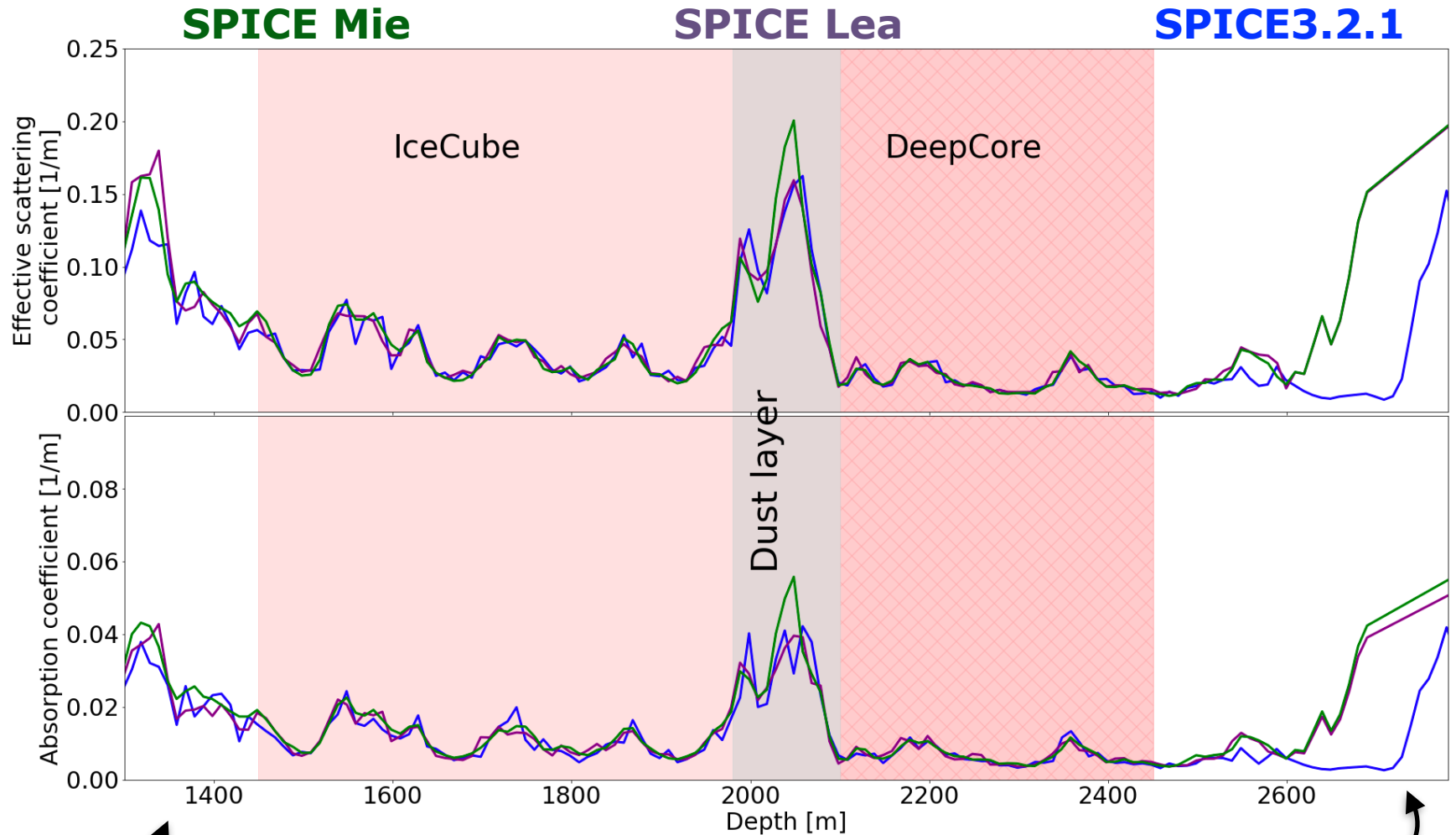
- 12 LEDs / DOM @ 400 nm
- 16 cDOMs with 340, 370, 450 and 505 nm
- Documentation via wiki pages
- Used for timing calibration and measurement of bulk ice and local OM properties
 - e.g. layered scattering and absorption ice model



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 

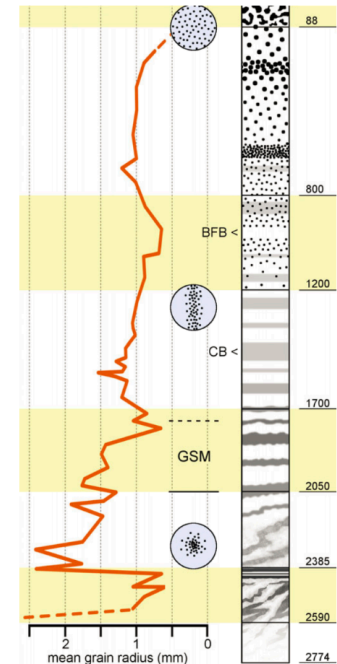
Ice models over time



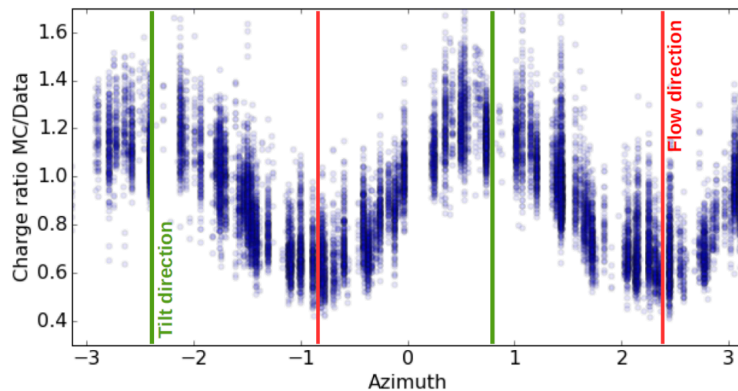
Large variations where data is extrapolated
IceCube Upgrade will be key in these regions!

Anisotropy of light propagation

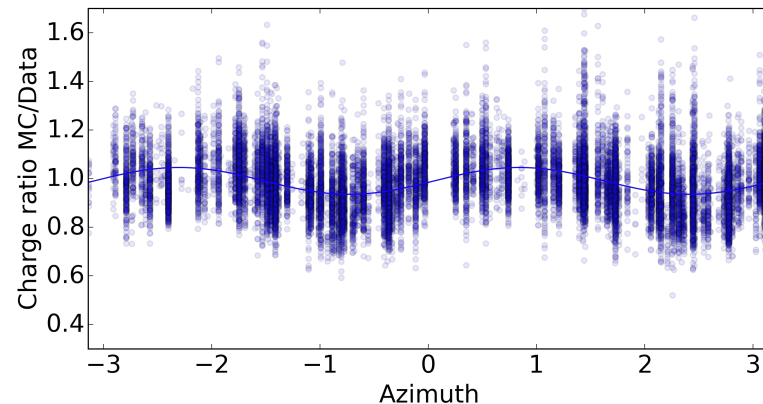
- More light received along ice flow axis compared to orthogonal
- Proper characterisation critical for many physics analysis (e.g. high-energy ν_T reconstruction)
- Continue to investigate underlying cause
 - Strong ties to glaciology & SPICEcore



No anisotropy in simulation

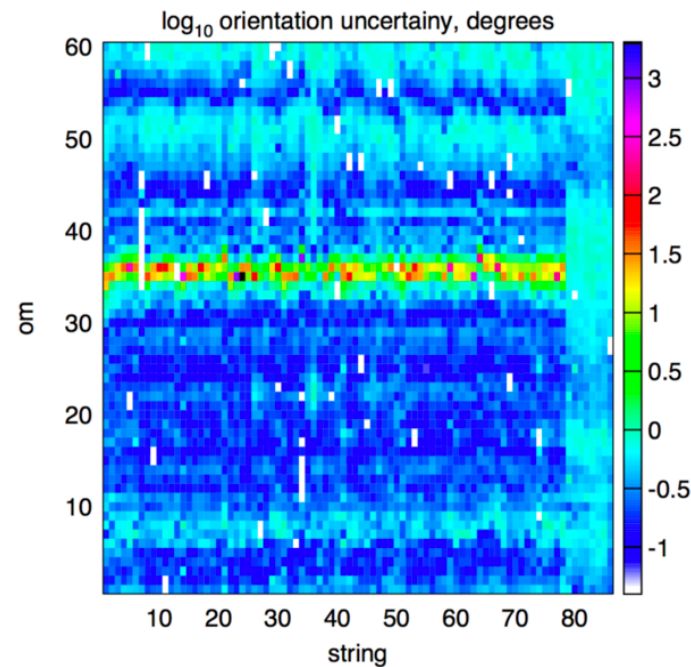
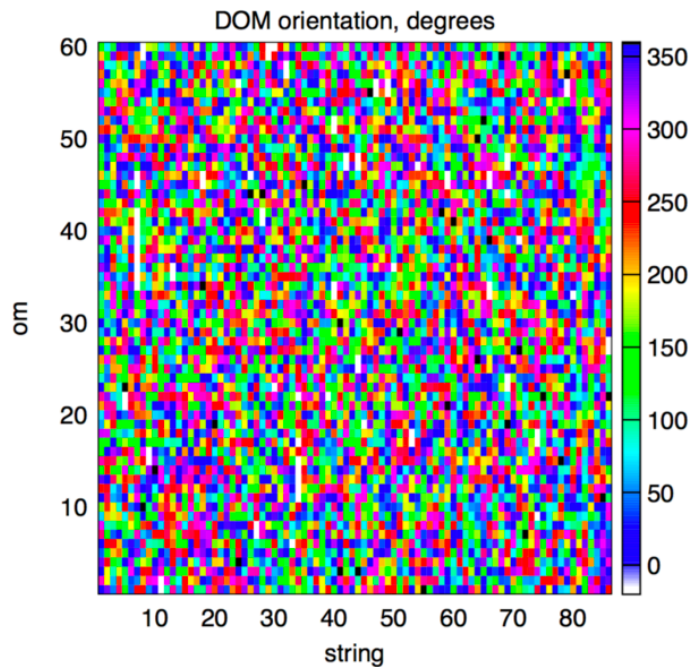
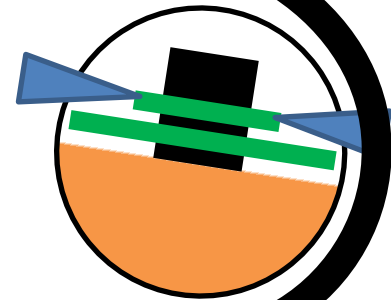


With anisotropy in simulation



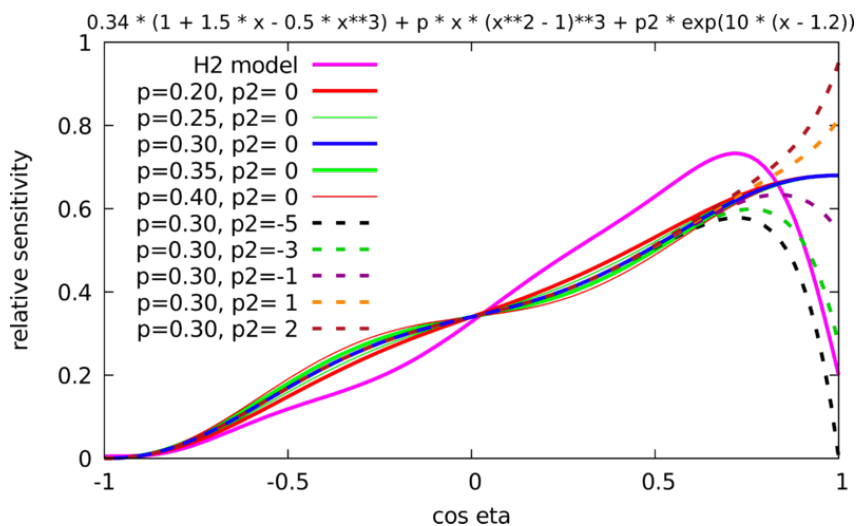
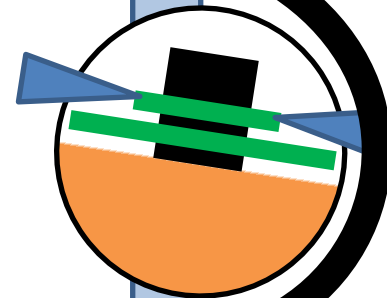
Towards more precise calibration

- 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

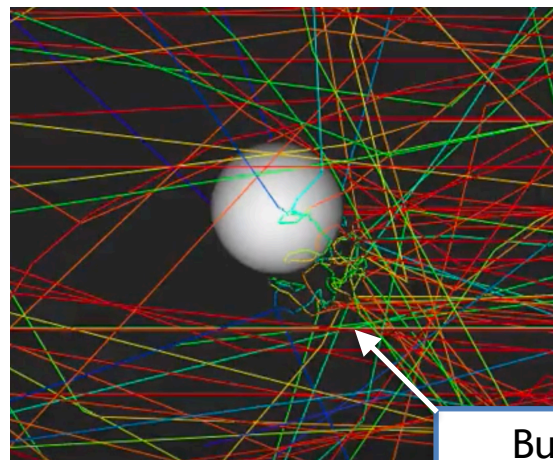


Towards more precise calibration

- 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

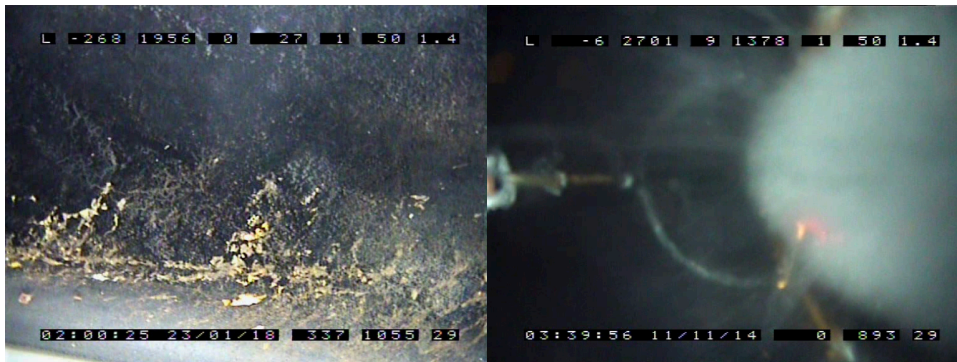


Bubble
column here

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 N₂ lasers with Cherenkov cone emission pattern
 - Energy scale, linearity, vertex resolution

Sweden Camera

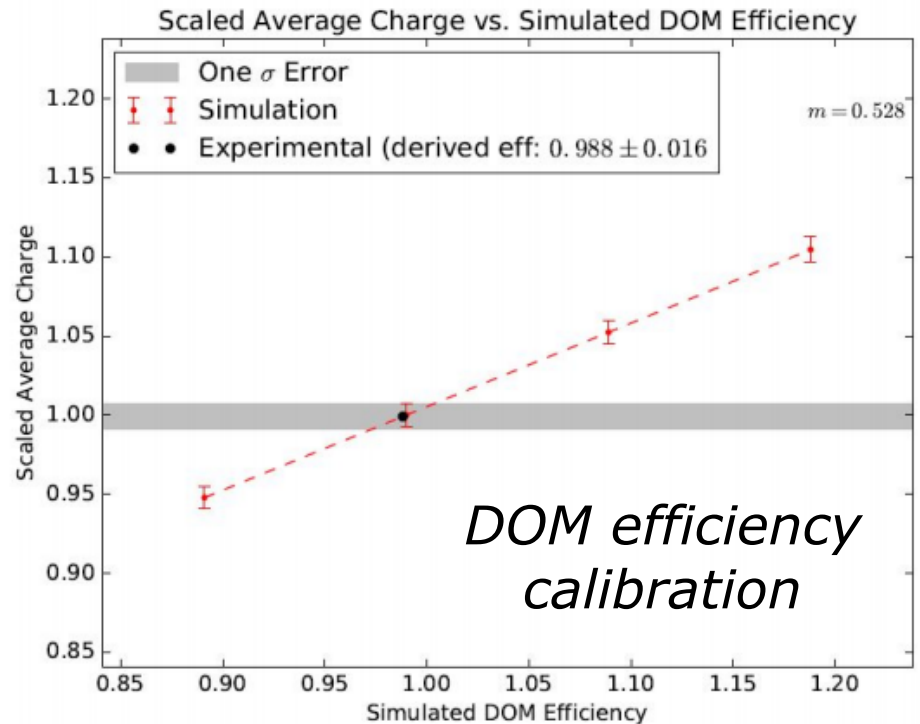
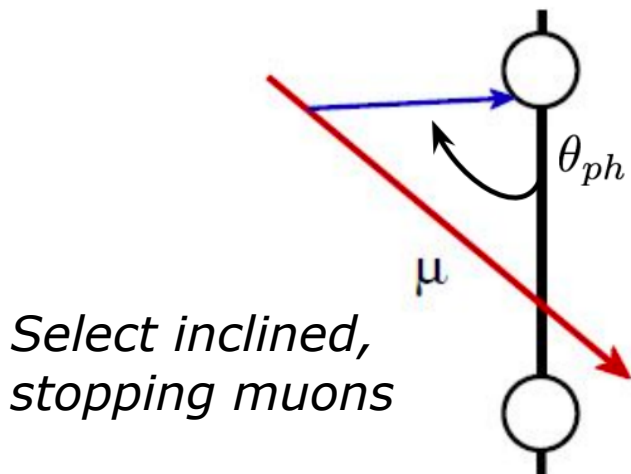


Standard Candle

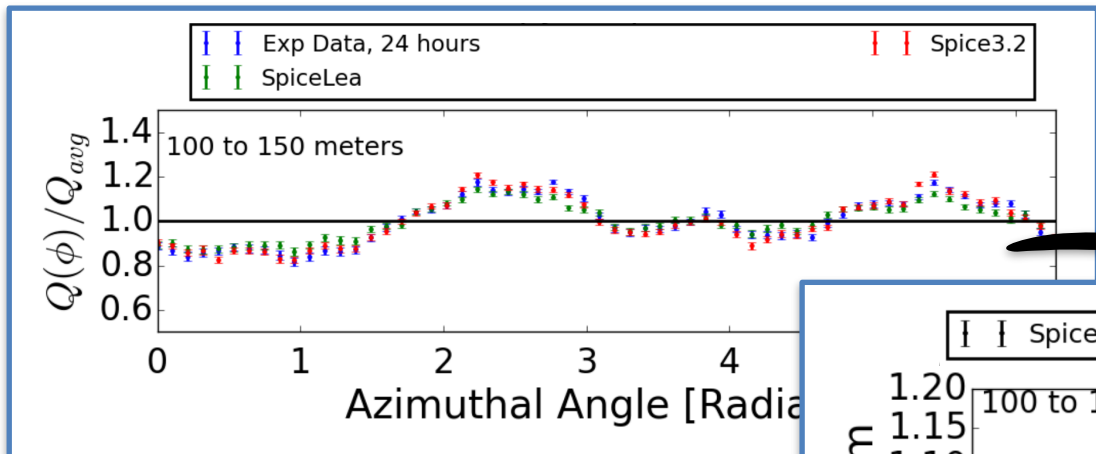


Atmospheric muons

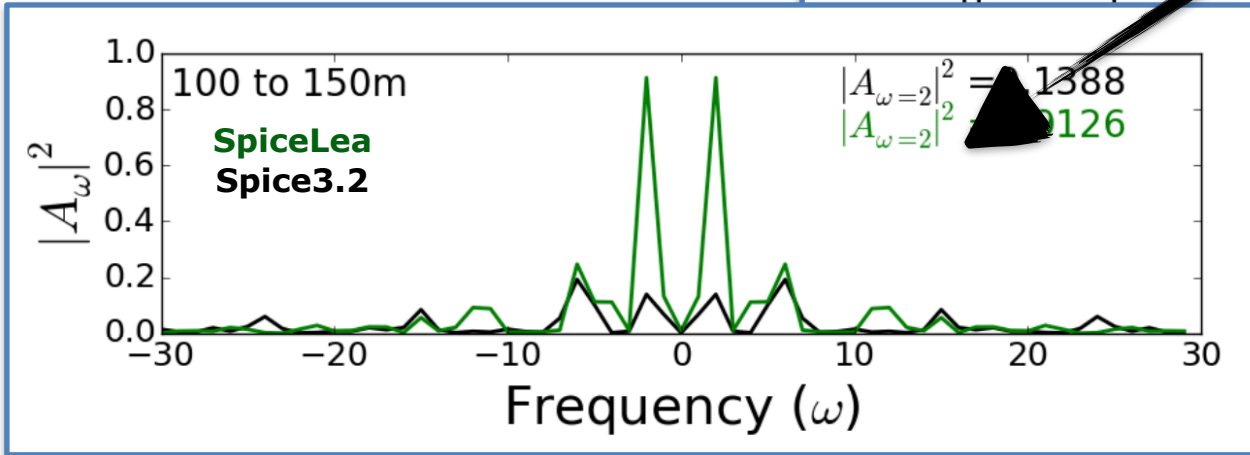
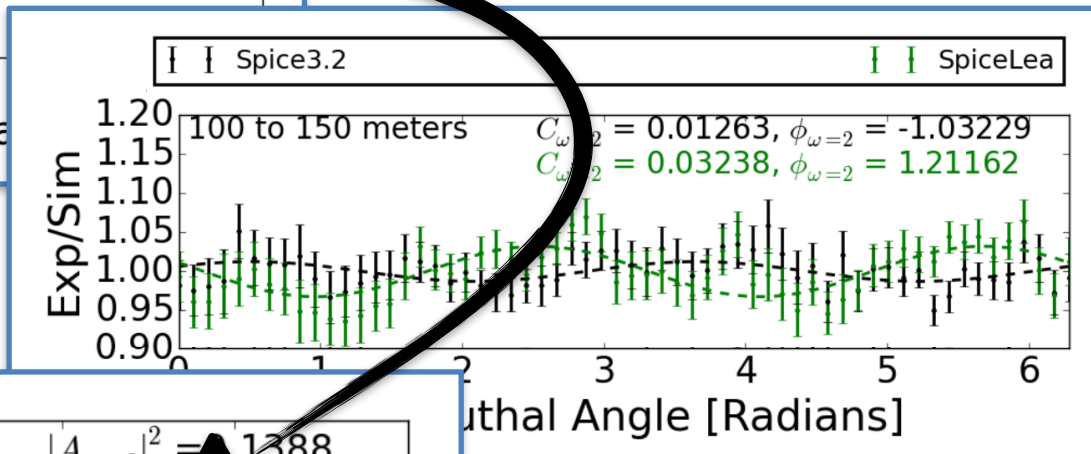
- High statistics, natural calibration source
- Verify many calibration constants
 - DOM efficiency
 - Ice anisotropy
 - Absolute pointing (moon shadow)



Anisotropy check with muons



Take charge ratio data /simulation

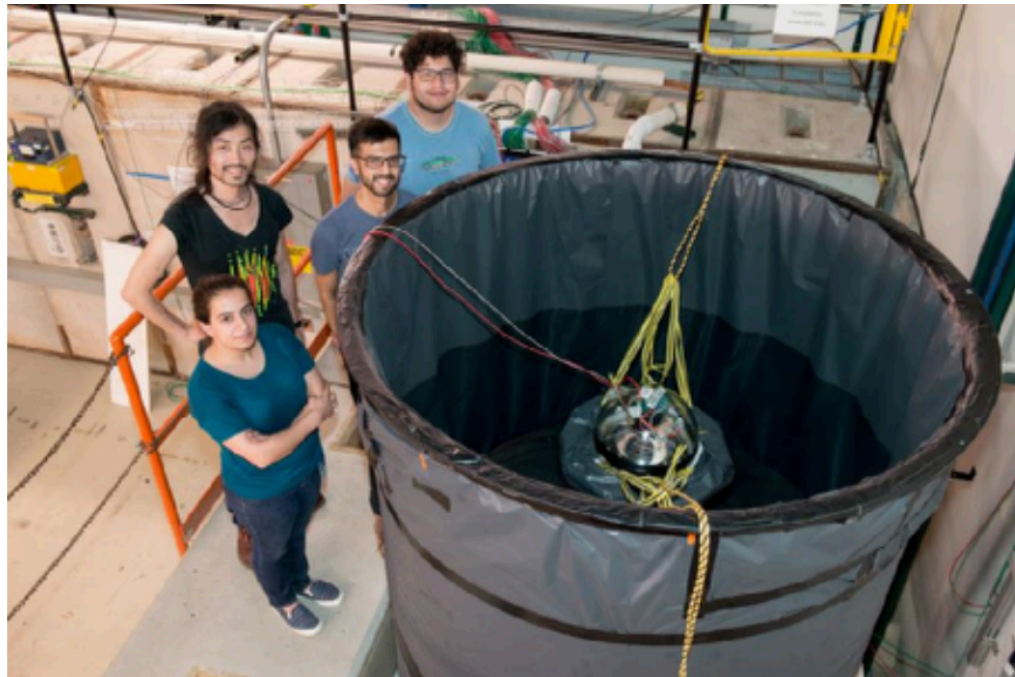


Fourier transform ratio

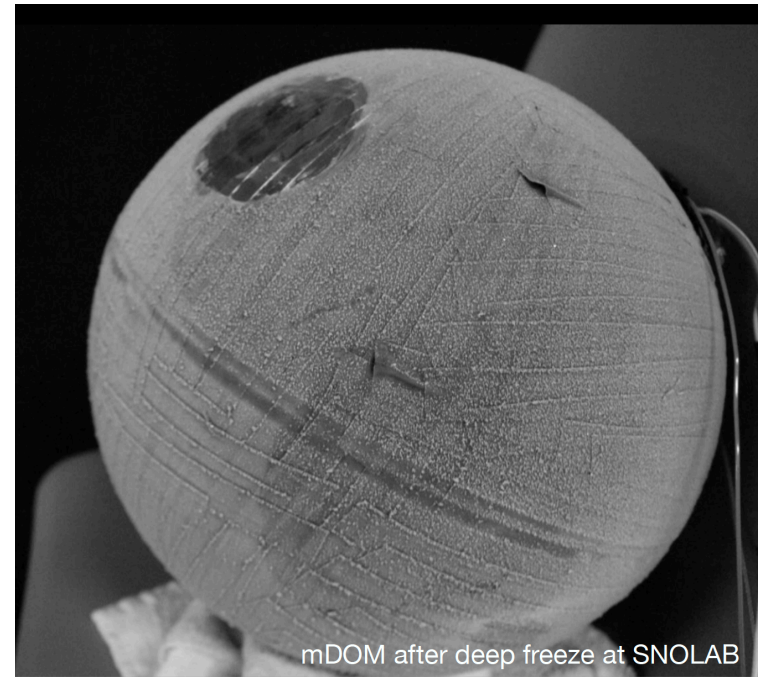
*Want minimal
w=2 mode*

Lab measurements

Beam test at Fermilab

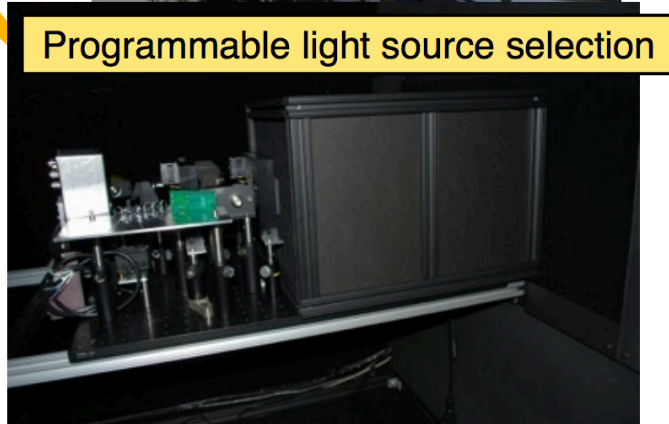
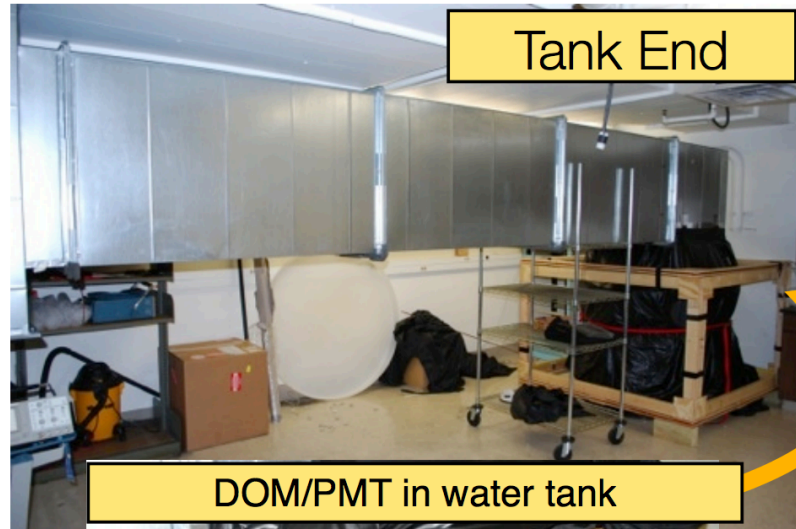
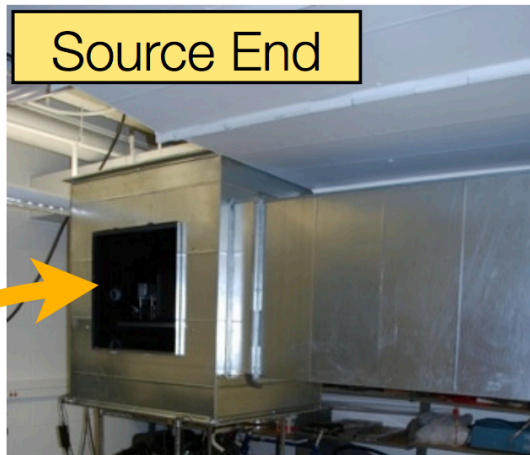


Noise measurements of
DOMs at SNOLAB



Lab measurements

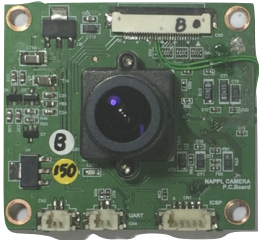
In-water DOM calibration project at UWMadison



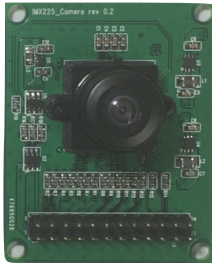
The future of IceCube calibration

- 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



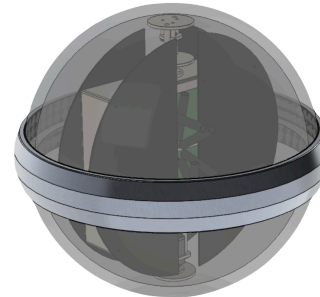
CMOS



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 FWHM 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 ($^\circ$)	σ_θ ($^\circ$)	σ_ϕ ($^\circ$)
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