

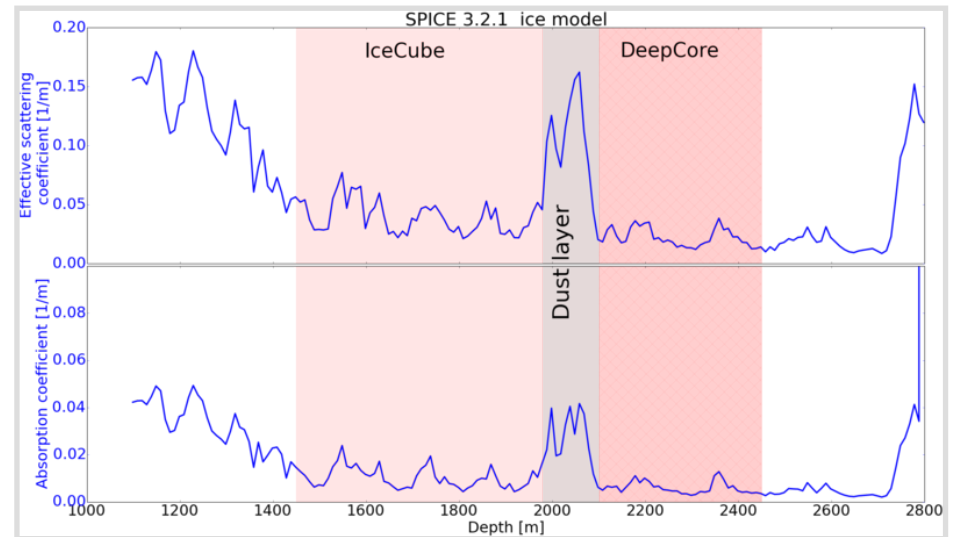
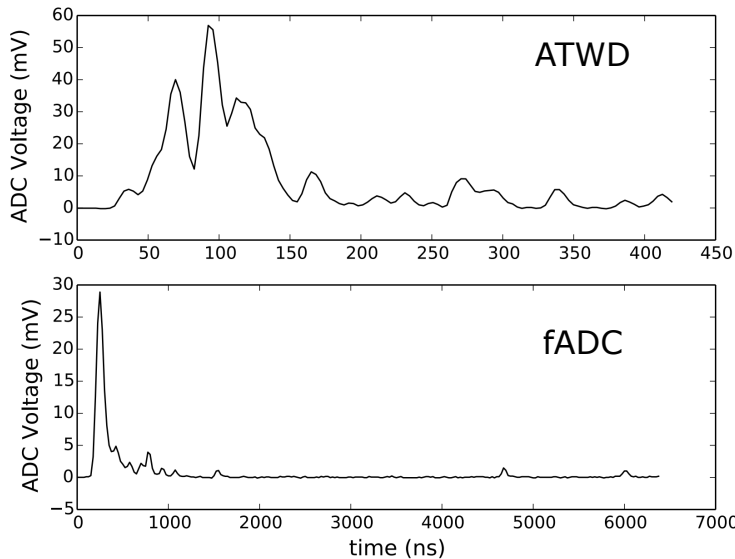
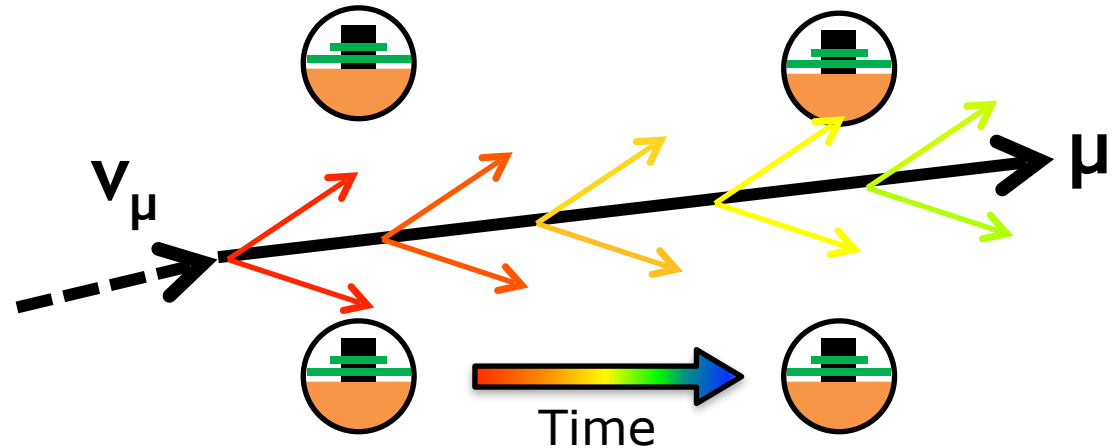
IceCube

Calibration

Summer Blot (DESY)

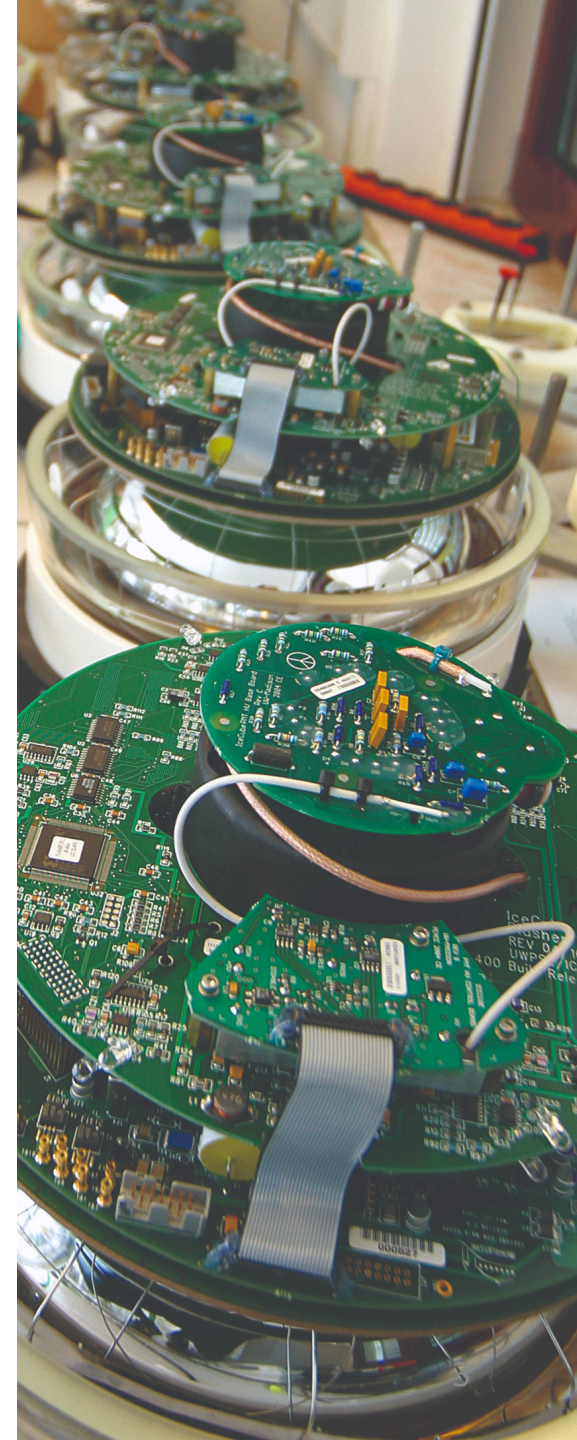
Calibration deliverables

- Geometry
- DOM response
- Ice properties



Calibration systems

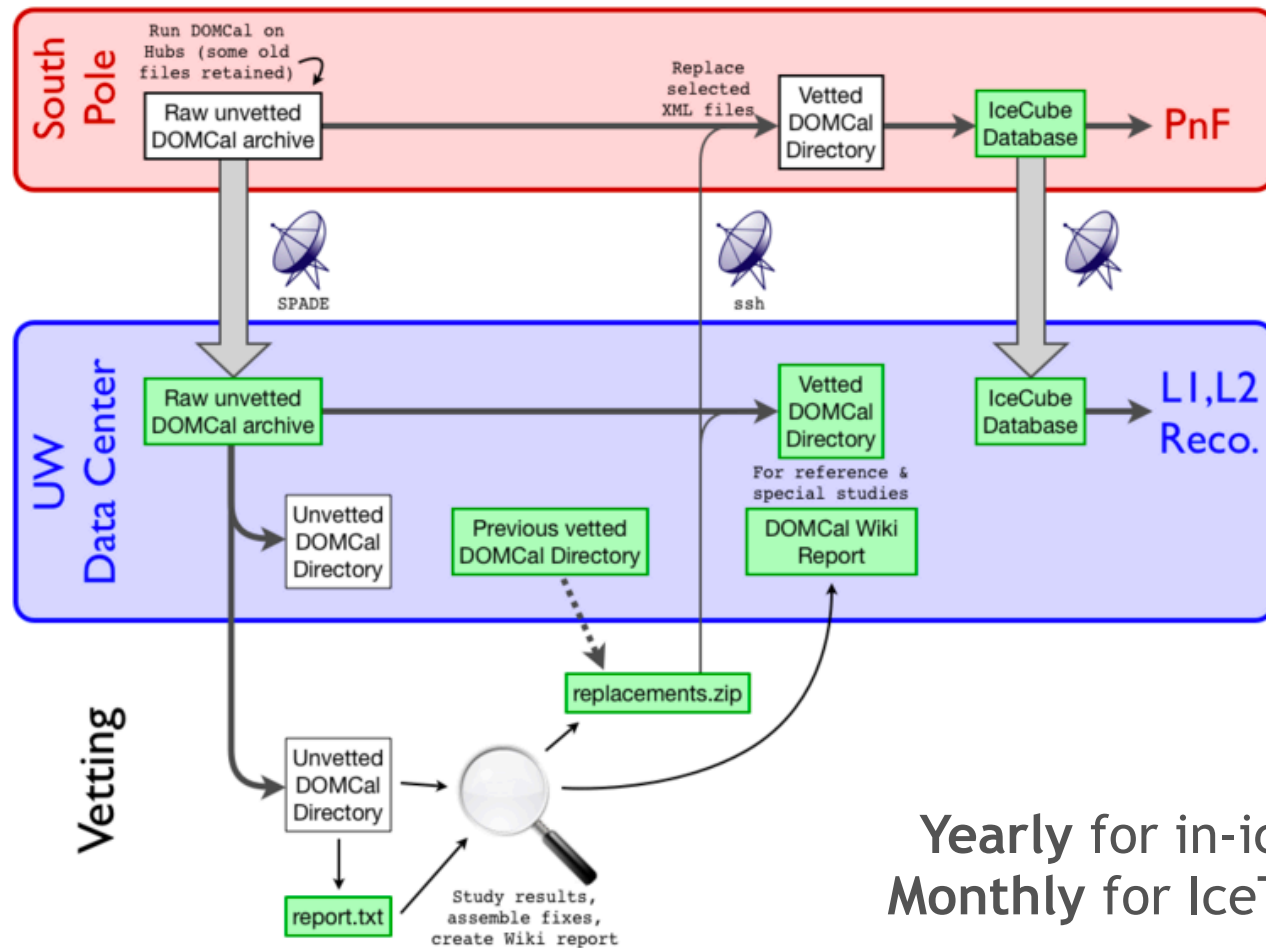
- DOM on-board self-calibration system (DOMCal)
- Reciprocal Active Pulsing Calibration (RAPCal)
- Pressure sensors
- 12 LED flashers / DOM
- N₂ pulsed laser (337 nm) "Standard Candle"
- 2 rotating video cameras "Sweden cameras"
- 8 dust logs (404 nm laser line)
- Inclinometers on 47 DOMs
- Atmospheric 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

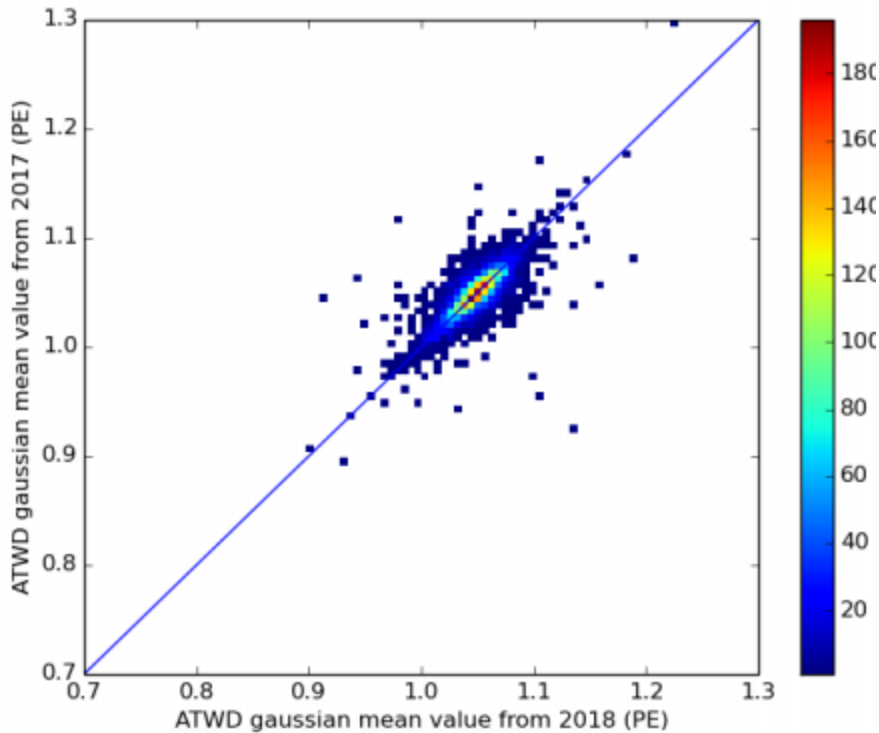
Calibration devices: DOMCal



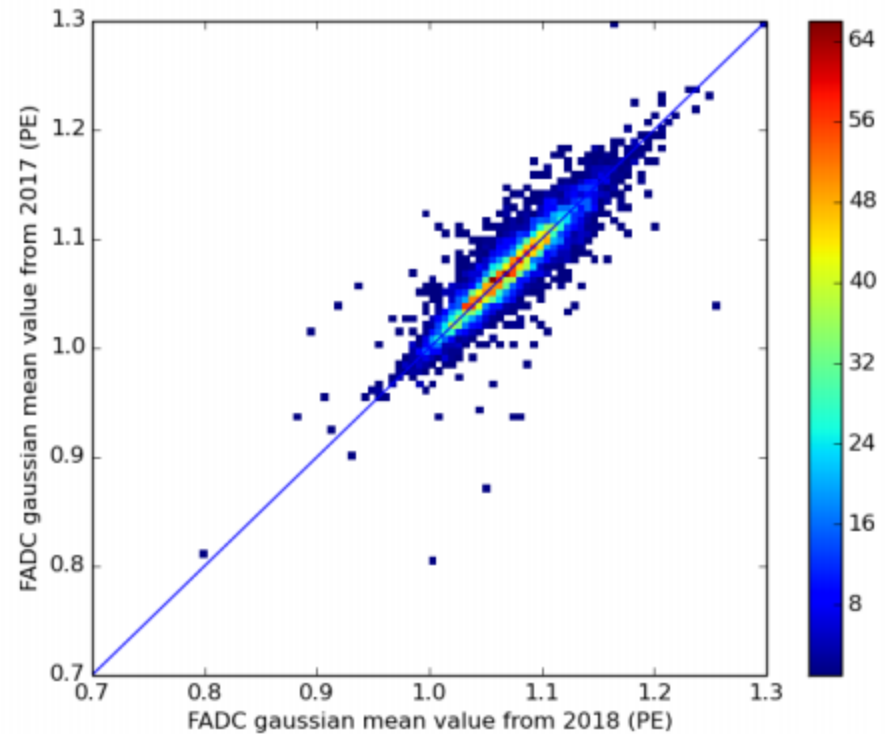
Yearly for in-ice DOMs
Monthly for IceTop DOMs

In-ice OM stability

ATWD

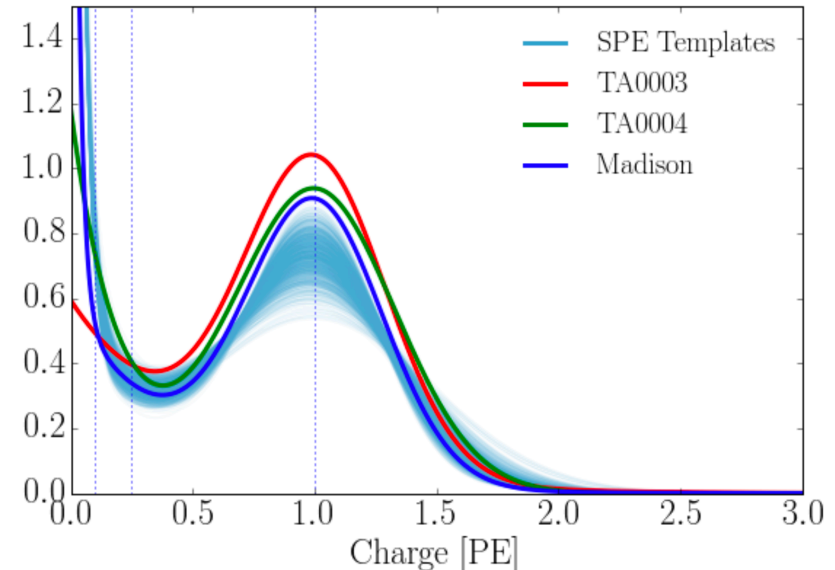
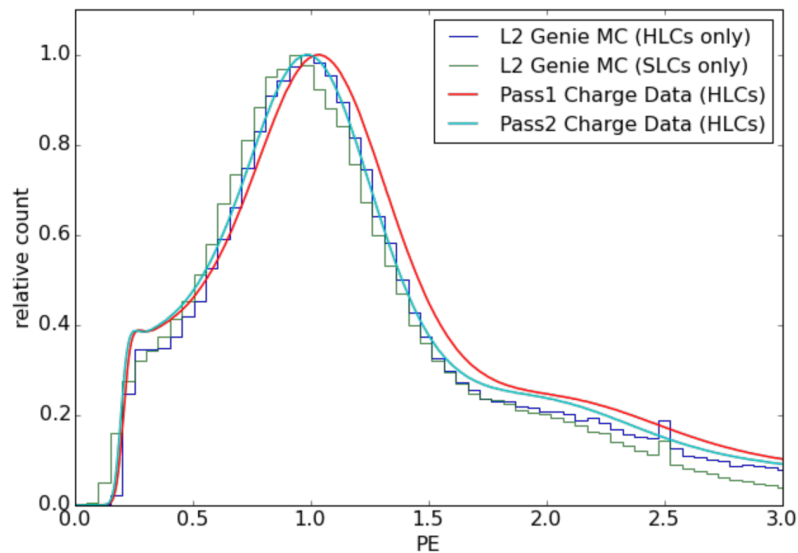


fADC



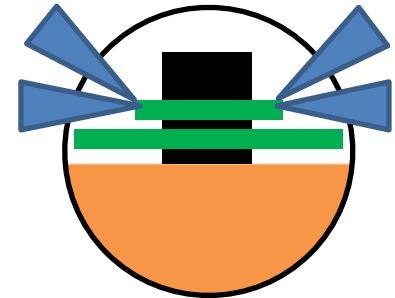
SPE recalibration

- 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
- Use to measure bulk ice and local OM properties
 - e.g. layered scattering and absorption ice model

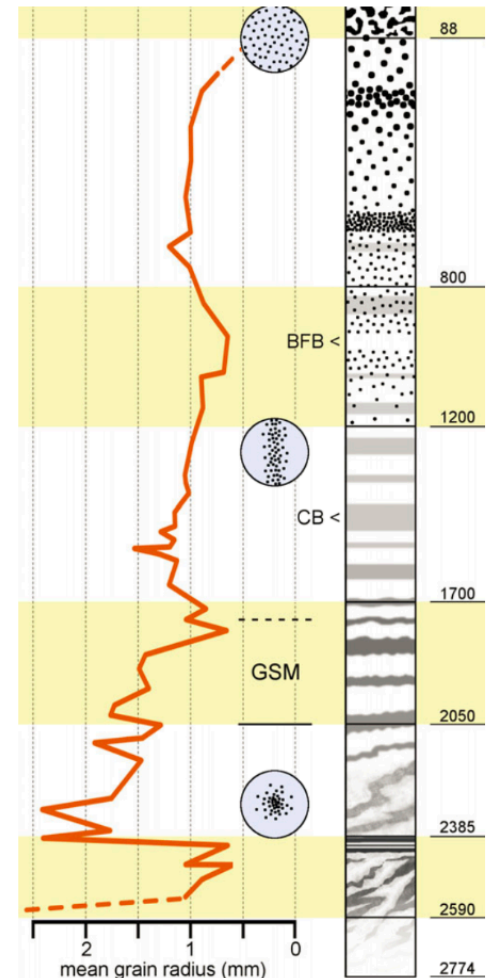
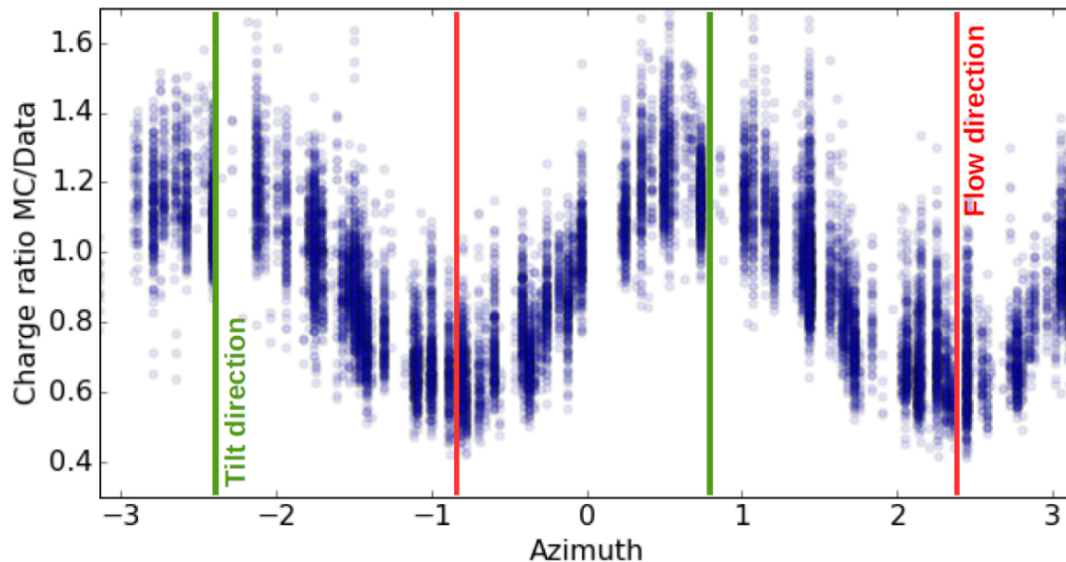


Ice models	SPICE Mie	SPICE Lea	SPICE 3	SPICE 3.1	SPICE 3.2
Strings fit	1	1	7	85	85
Anizotropy	0	8%	9%	10.8%	10.6%
Model error	29%	20%	10.7%	9.8%	9.8%

2013  2018 

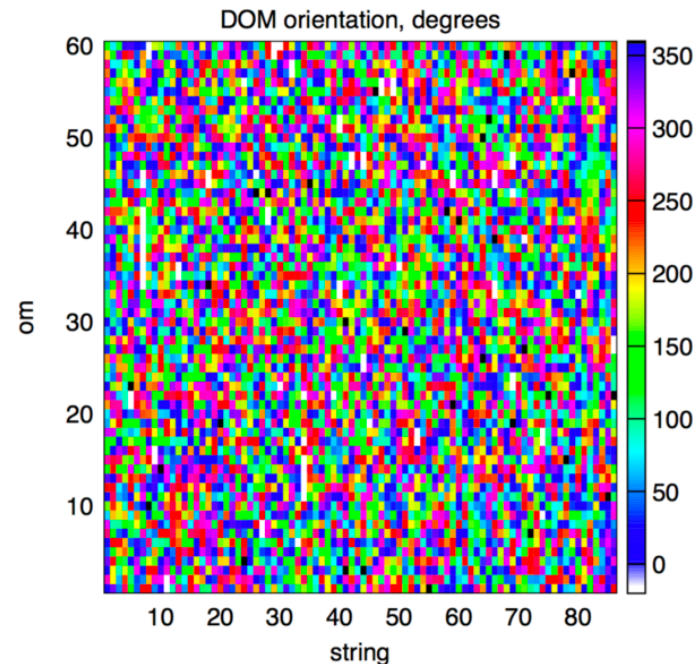
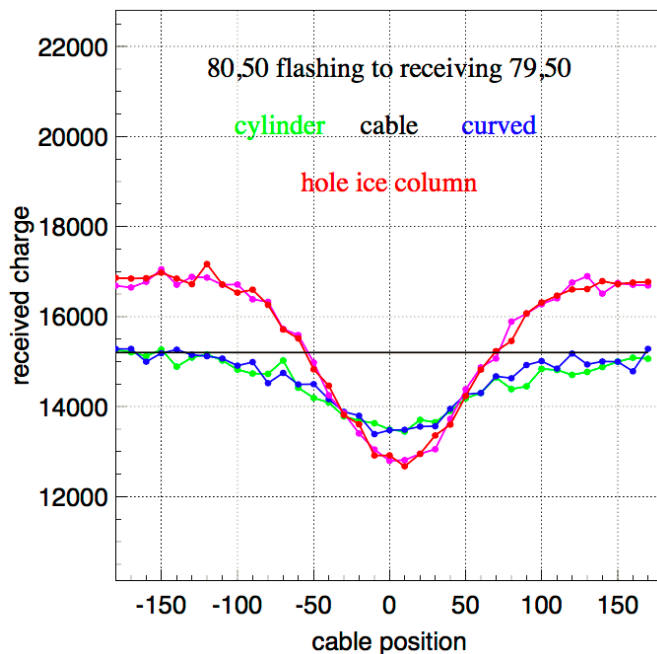
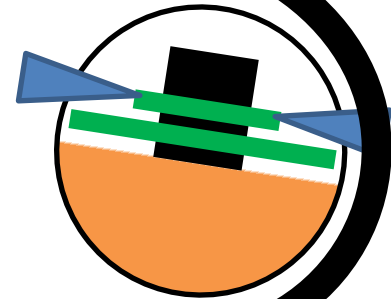
Anisotropy of light propagation

- Factor 2 more light received along ice flow axis compared to orthogonal direction
- Proper characterisation critical for many physics analysis (e.g. high-energy ν_{τ} reconstruction)
- Continue to investigate/model underlying cause
 - Strong ties to glaciology



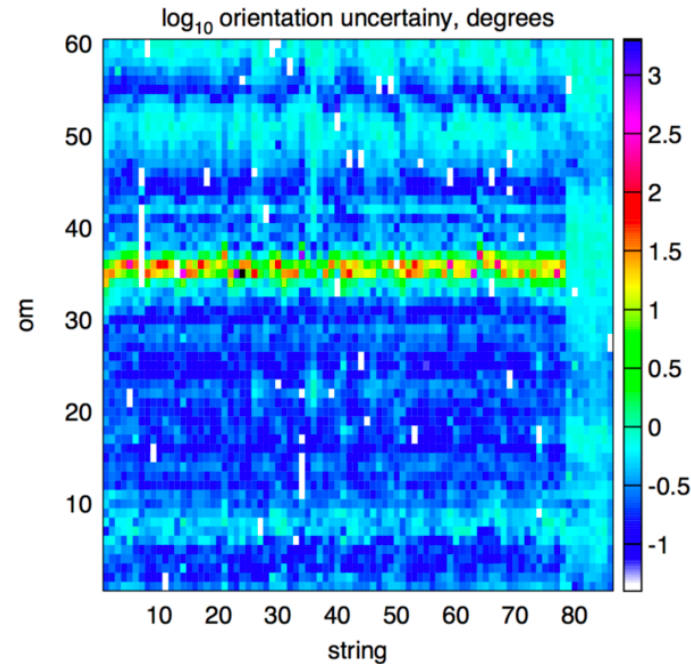
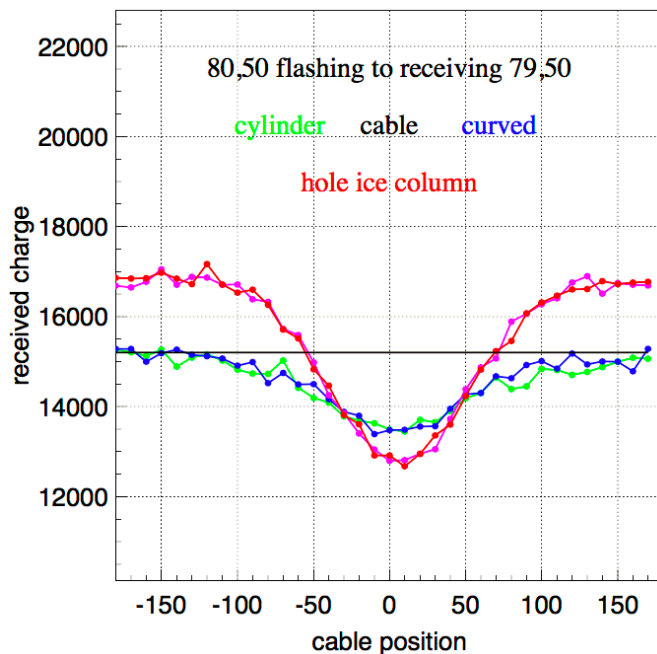
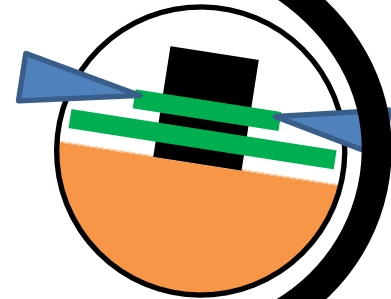
Towards Hi-def calibration

- In 2017-18 collected X TB of single LED data
- Investigating DOM-wise systematics: e.g. tilt, cable shadow
- Azimuthal position of main cable known better than 1% for most OM's



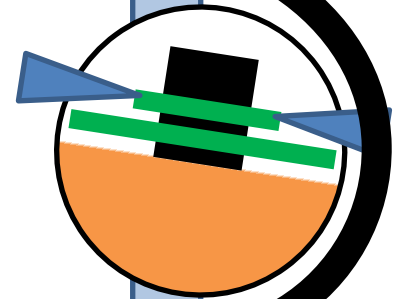
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Towards Hi-def calibration

- 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



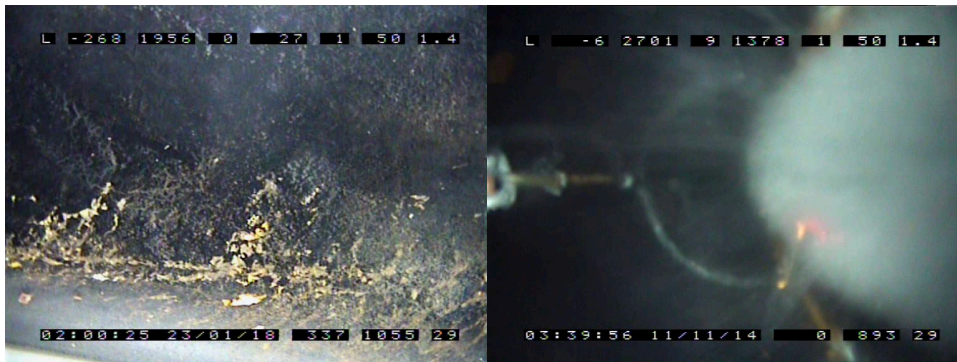
Plot showing new flasher derived hole ice models

Direct sim picture

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



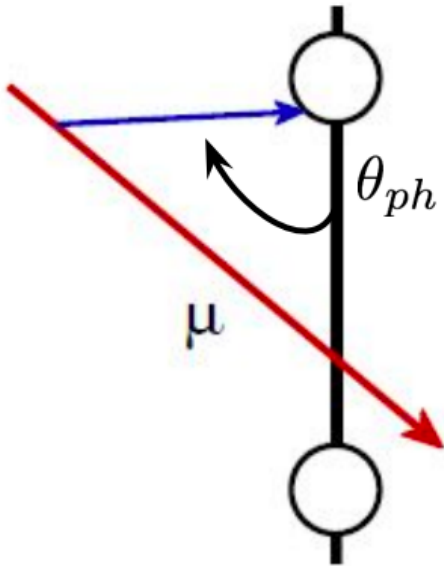
Standard Candle



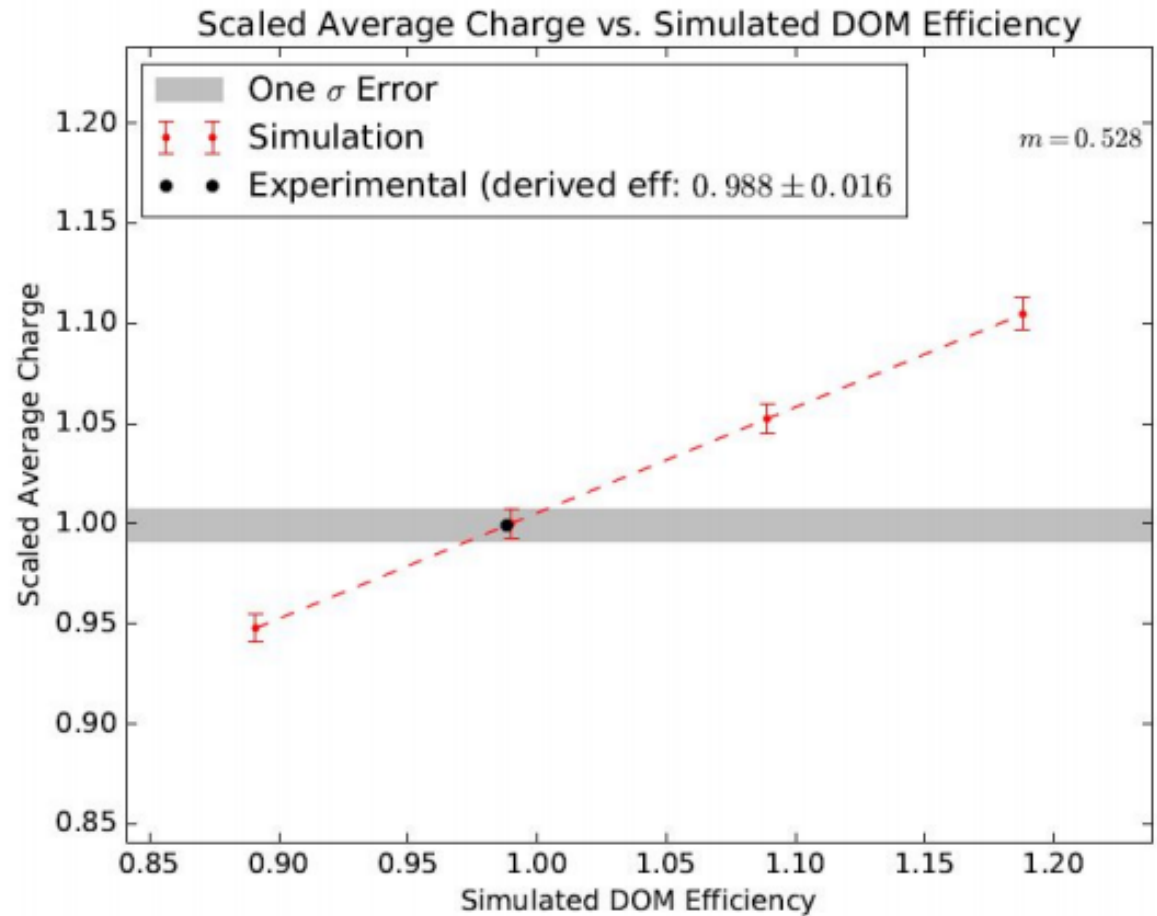
Atmospheric muons

- High statistics, natural calibration source
- Verify many calibration constants
 - DOM efficiency
 - Anisotropy of ice properties
 - Absolute pointing (moon shadow)

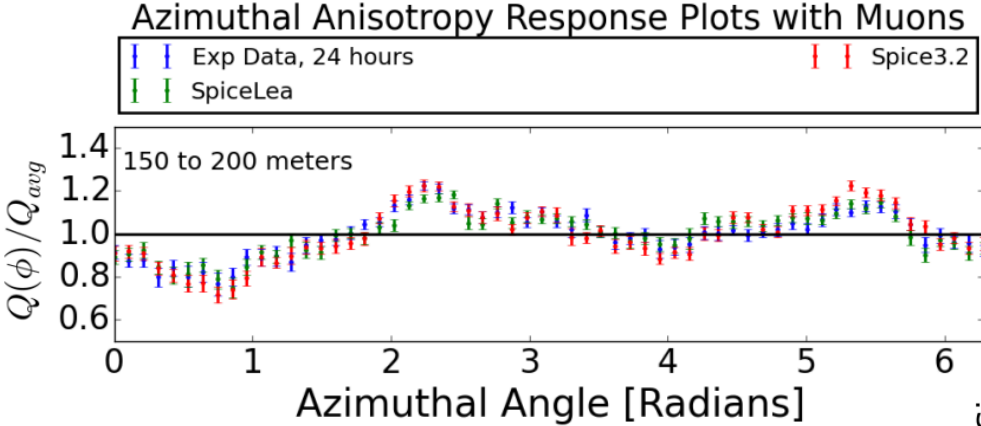
Atmospheric muons



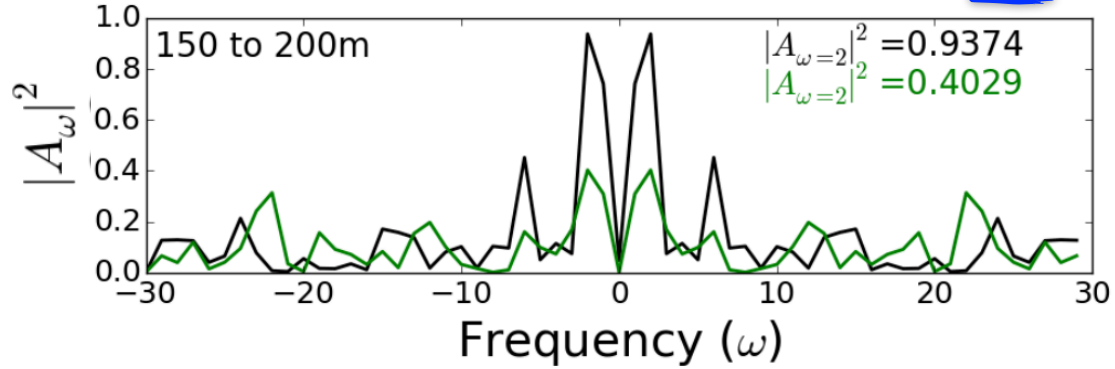
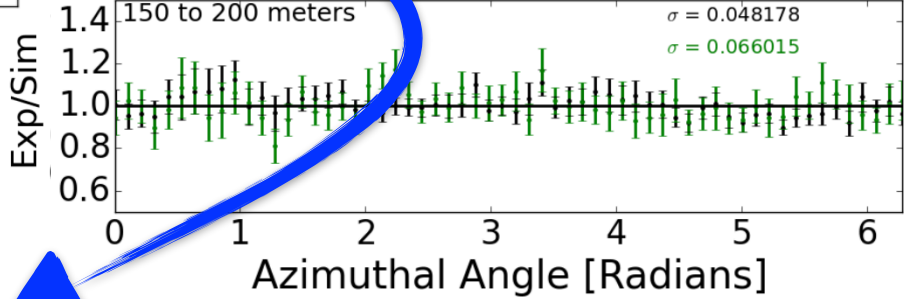
*Select inclined,
stopping muons*



Atmospheric muons



Take ratio of data / simulation



Fourier transform ratio

Want minimal $w=2$ mode

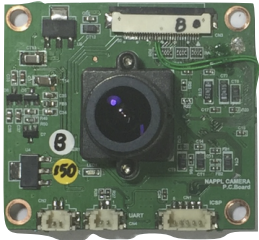
Lab measurements

- Picture of C. Wendt's setup at madison
- Snolab noise measurements

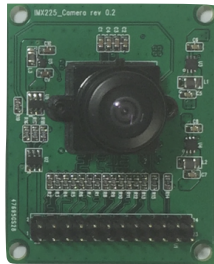
The future of IceCube calibration

- 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 while simultaneously testing many of these new technologies

CCD



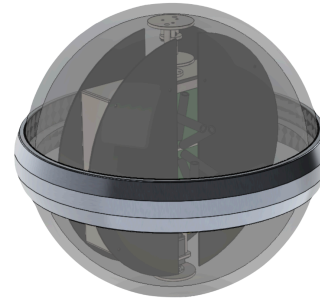
CMOS



Piezo-module



Pencil beam



POCAM



Outlook

- TDB

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