Calibration of the IceCube Neutrino Observatory

Dr. Martin Rongen for the IceCube Collaboration

Workshop on the evaluation of advanced electronics and instrumentation for Water Cherenkov experiments
April 11th 2022

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SOUTH POLE NEUTRINO OBSERVATORY

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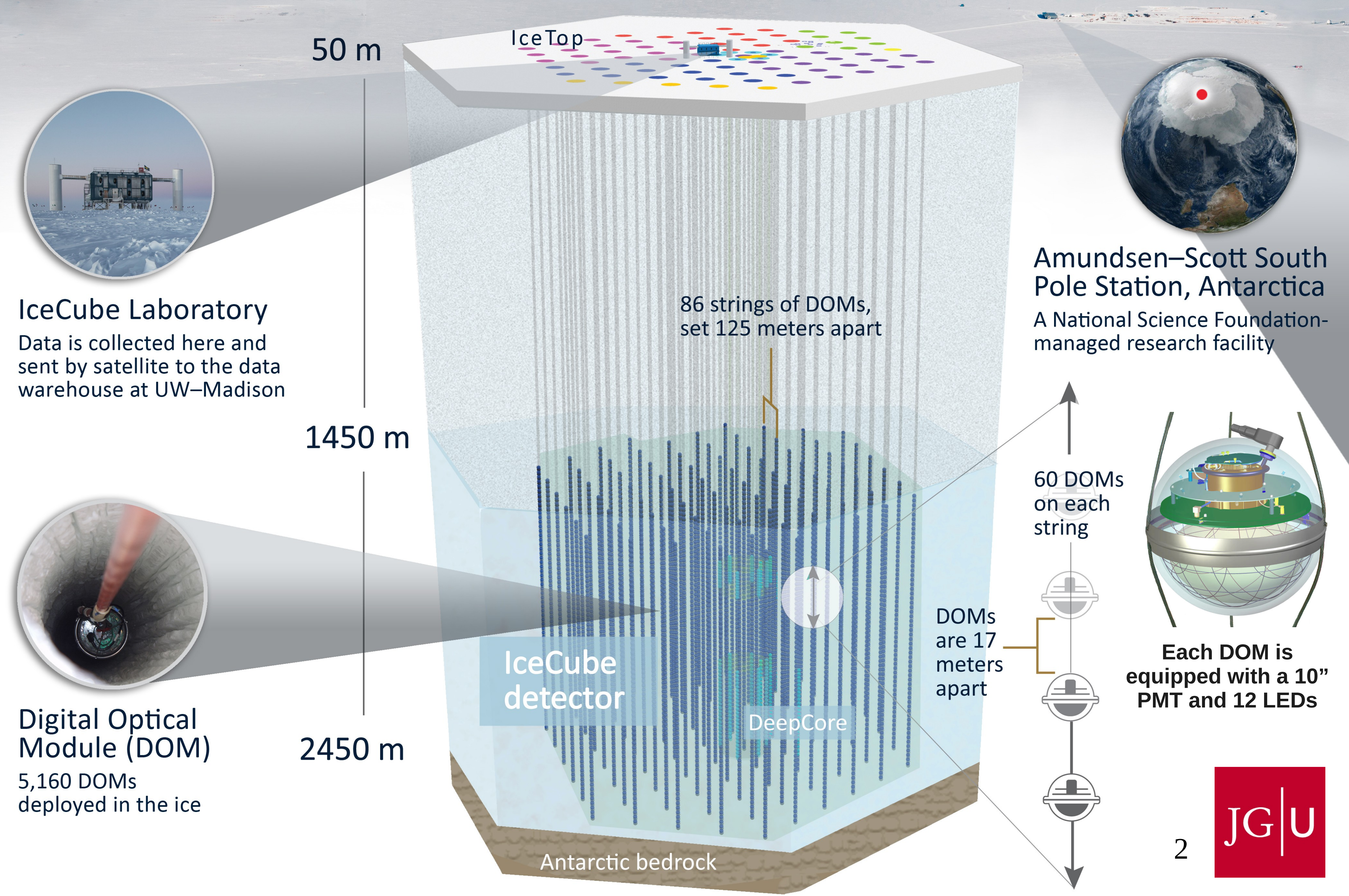
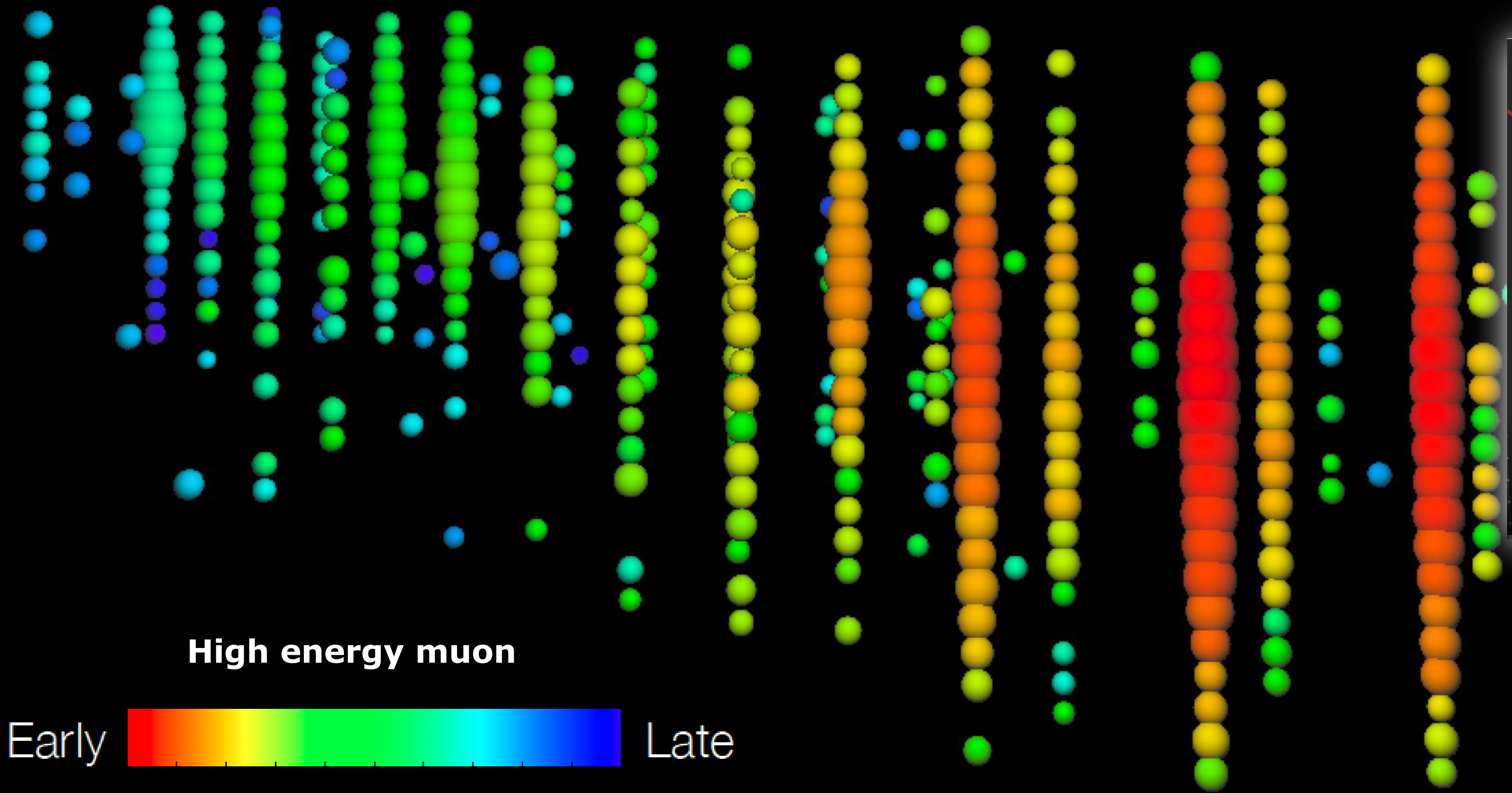
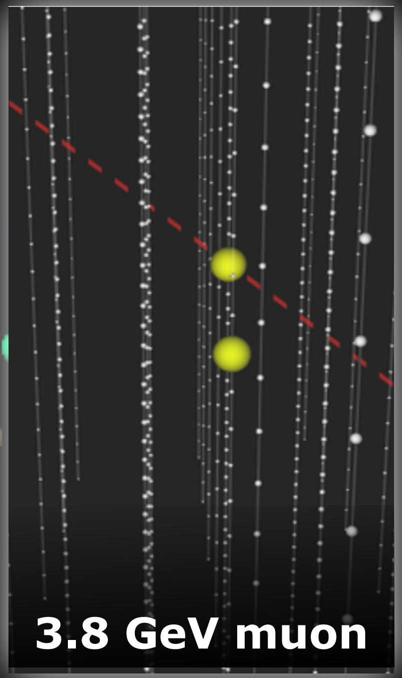
The IceCube Neutrino Observatory

Design and construction



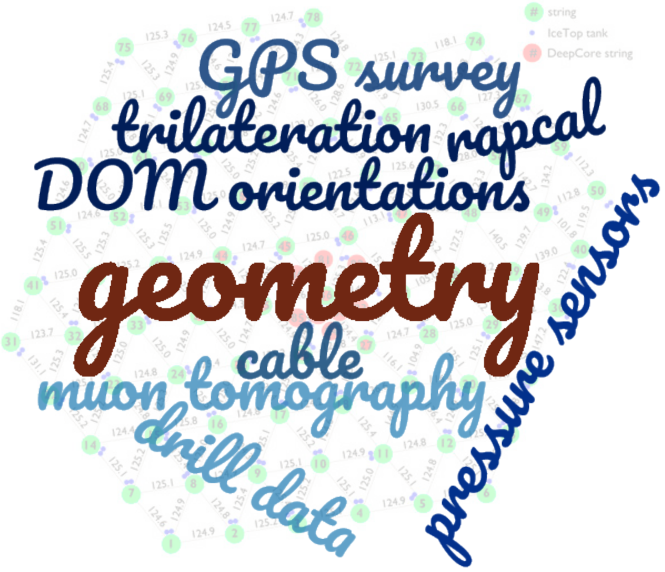
What does our data look like?

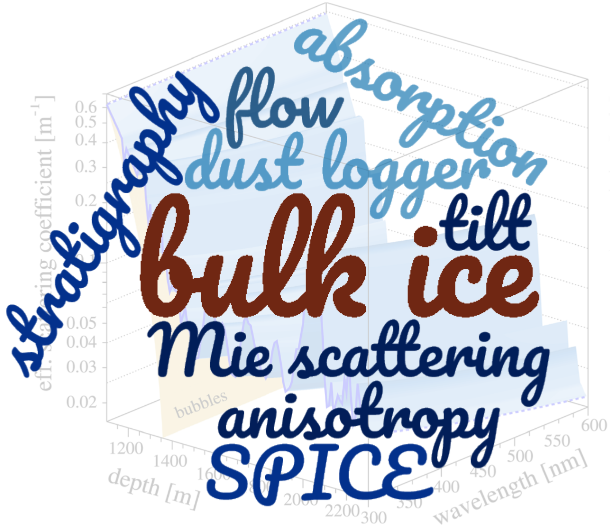


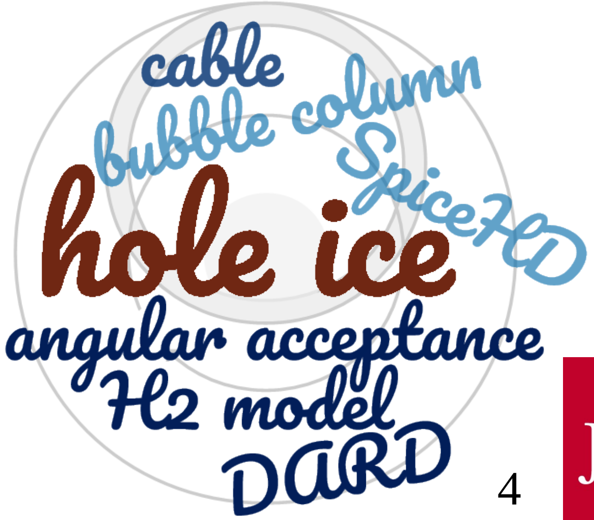


IceCube Calibration Aspects

- Detector is extremely homogeneous
- Data consists "only" of photon arrival times at module locations
  - Calibration of these quantities vital to reco physics quantities
- Here only focusing on recent highlights and topics of general interest







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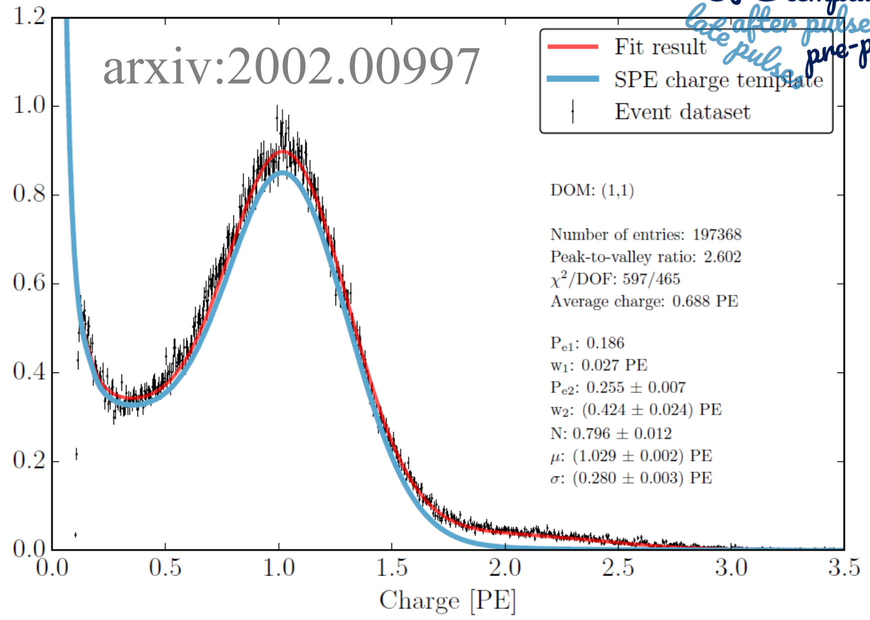
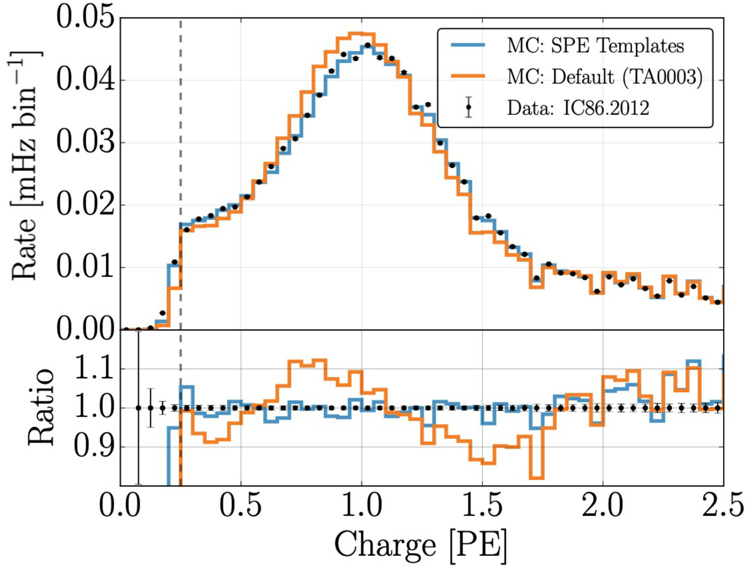
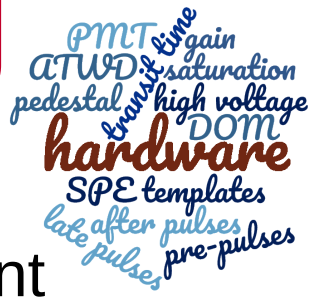
PMT single photon charge distributions

- Determination of received photon count requires precise calibration of PMT charge amplification
- Prior to ~2018 experimental single photon charge distributions were simply fitted with Gaussian + Exponential (as commonly done in the field)
- New calibration correctly models irreducible multi-PE contamination using a convolutional fitter
- Resulting „SPE Templates“ used in MC yield sizable data-MC improvement



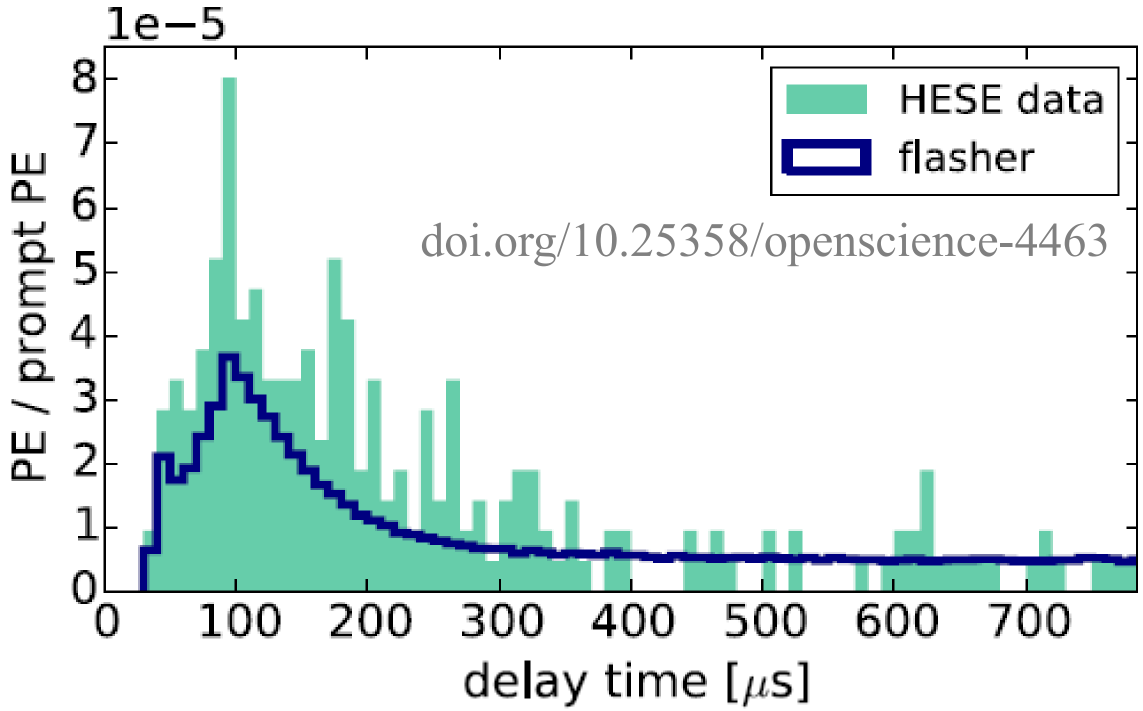


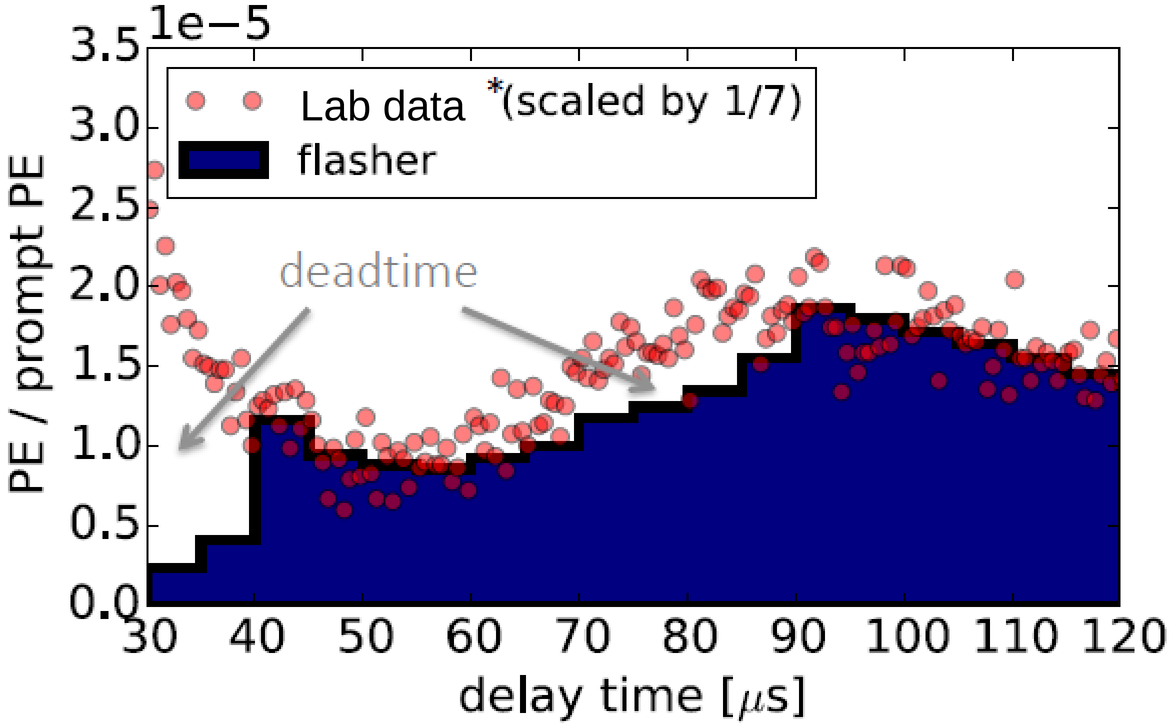
PMT very late afterpulses



- Usually PMT afterpulses are considered on the <10 us scale
- ~100 us after a cascade, neutron echo yields smoking gun for hadronic event

- First experimental search found expected timing signature,
  BUT for ALL events and also seen in LED flasher and laboratory PMT data
- Identified (and confirmed by Hamamatsu) as a not yet understood PMT effect
- DAQ software for in-situ per-PMT characterization currently in development



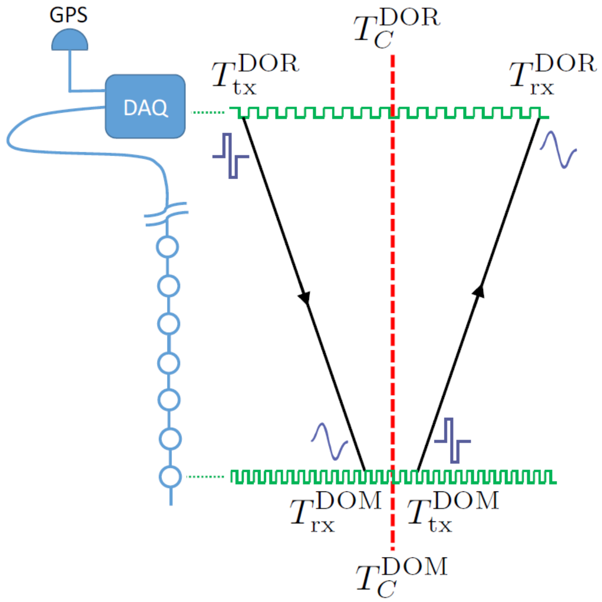


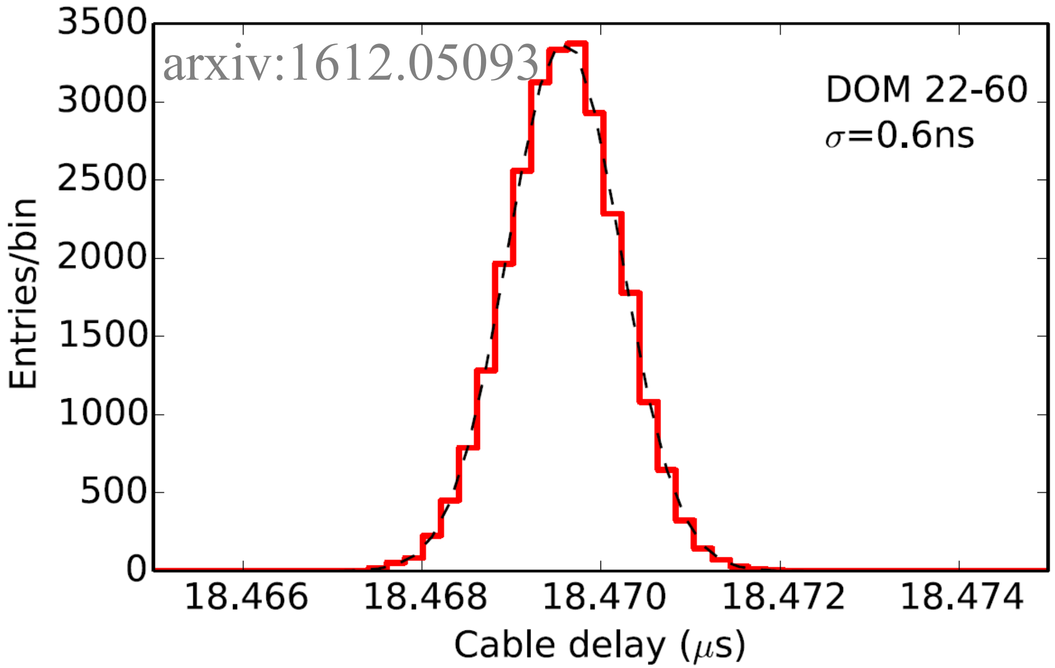
RapCal Timing System

- DOMs do not have a common global clock
  → 5160 free-floating clocks

- A bipolar pulse is transmitted from the surface to each DOM and vise versa every second, with each transmission and receipt being timestamped

  → absolute clock alignment to <1ns, cable delay and clock frequency & phase correction





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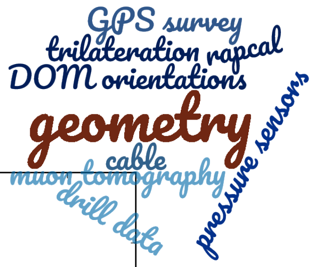
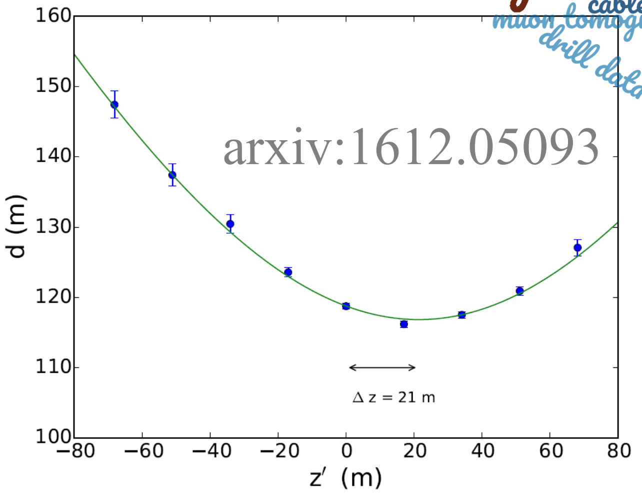
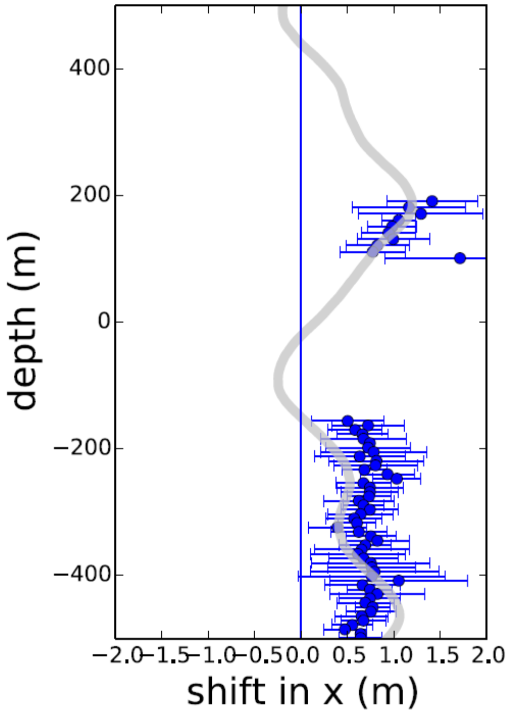
Geometry calibration



- Relative detector geometry is literally frozen in place, but hard to survey (contrary to water detectors)
- Currently using surface coordinates of holes for all DOMs below, with depths corrected by LED data
- Due to ~m drill deviations this is only an approximation, and with continuously improving reconstructions is starting to significantly contribute to the pointing uncertainty
- Trilateration of DOM positions using muon or LED data are being attempted but very challenging due to ice properties





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Hole ice and cable positions

- Refrozen water columns of drill holes feature clear outer region and central core of strongly scattering ice

- This “bubble column” shades part of the photocathode, is leading detector systematic to most neutrino oscillation studies and has proven hard to calibrate with confidence

- Recent updates to bulk ice (see later) and determination of DOM orientations (for cable shadow) enabled studies locating bubble column relative to every DOM

arxiv:2107.10435

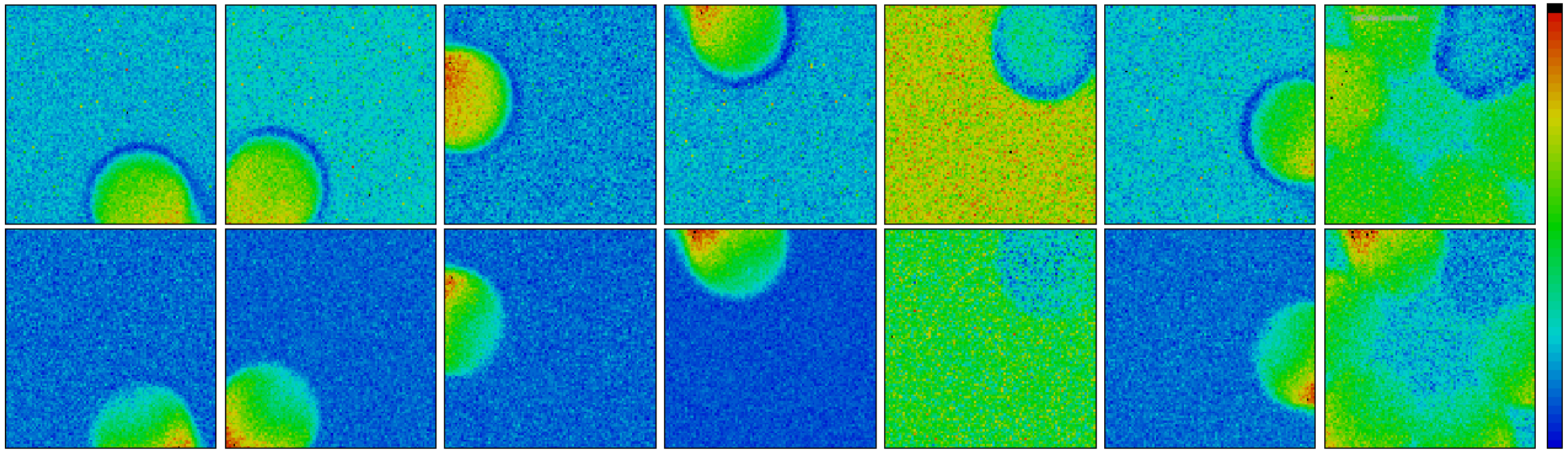

Figure 7: Fine-grid hole ice scan for DOM 34,5: tilted LEDs 1-6 (top) and horizontal LEDs 7-12 (bottom). From left to right: 6 individual LEDs followed by their sum. Color scale is from blue (best) to red (worst). x and y axes show relative coordinates from DOM center to hole ice column center.

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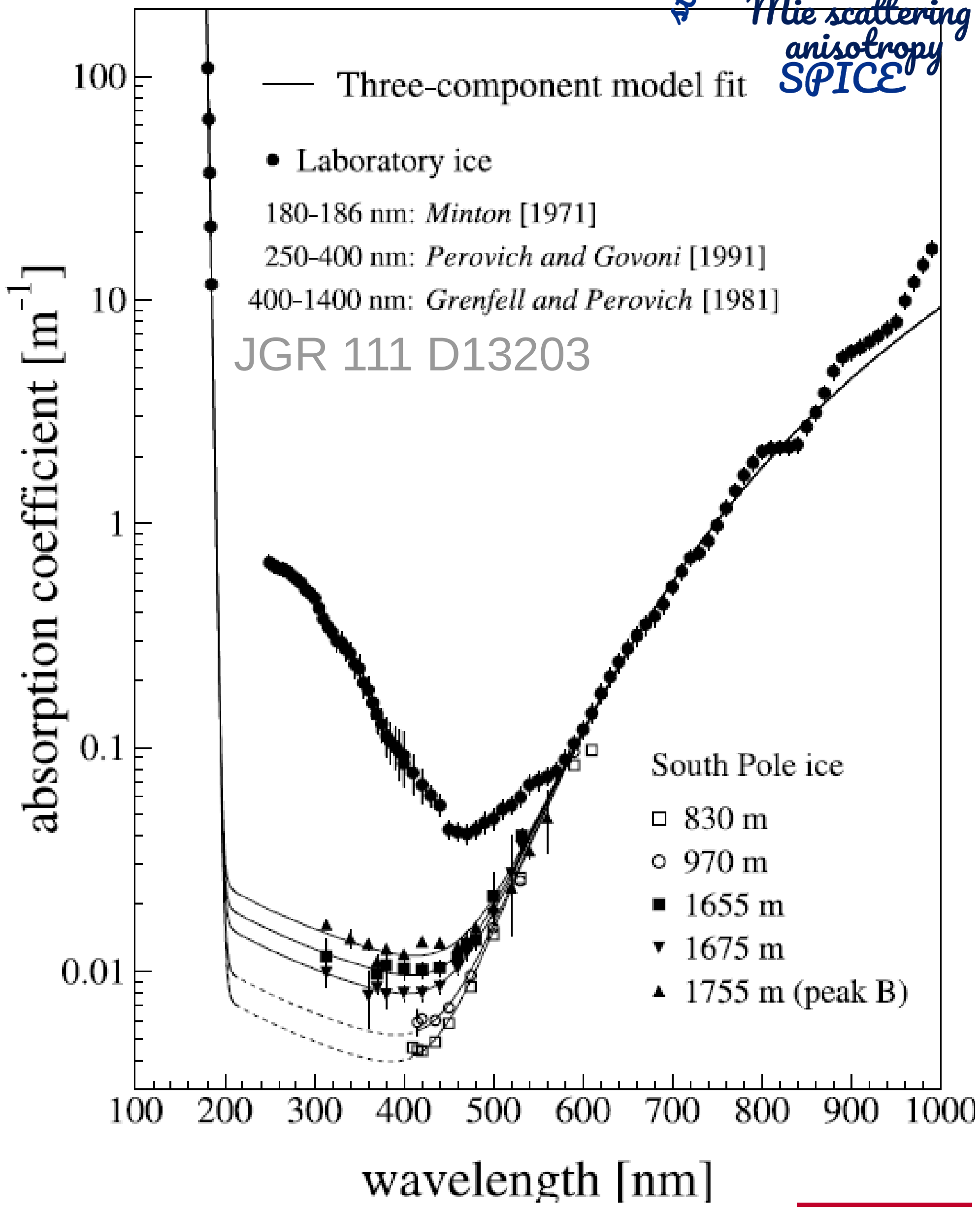
The Antarctic Glacier

- Compacted snow up to 100'000 years old
- Absorption length ~100m,
  one of the least absorbent known solids
- Above 1300m air bubbles dominate scattering
- Below 1300m air bubbles get incorporated into crystal structure forming transparent craigite
- Scattering (~20m eff.) dominated by impurities and correlated to absorption

  → we can‘t manipulate our detection medium and only study it in-situ



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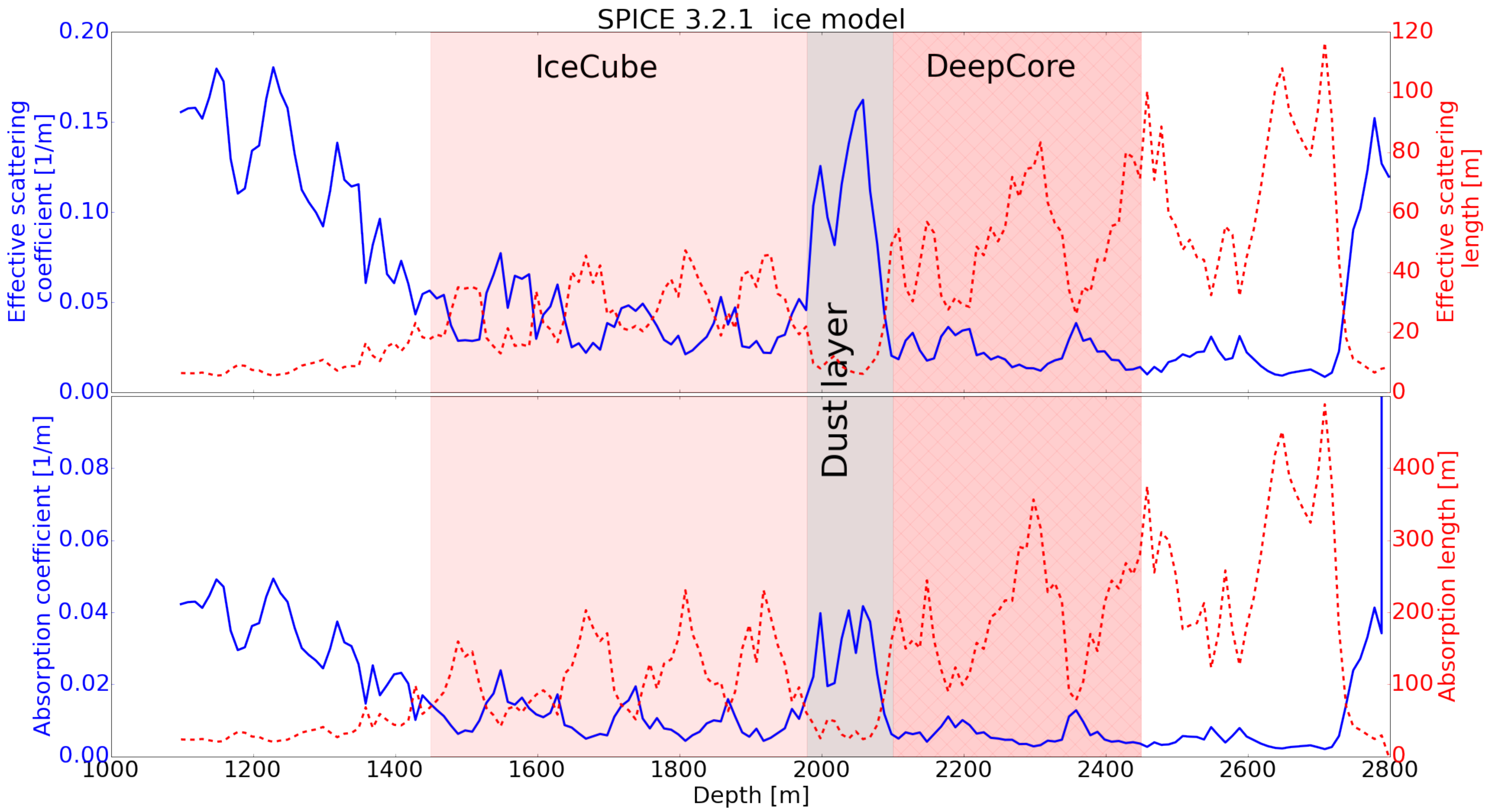
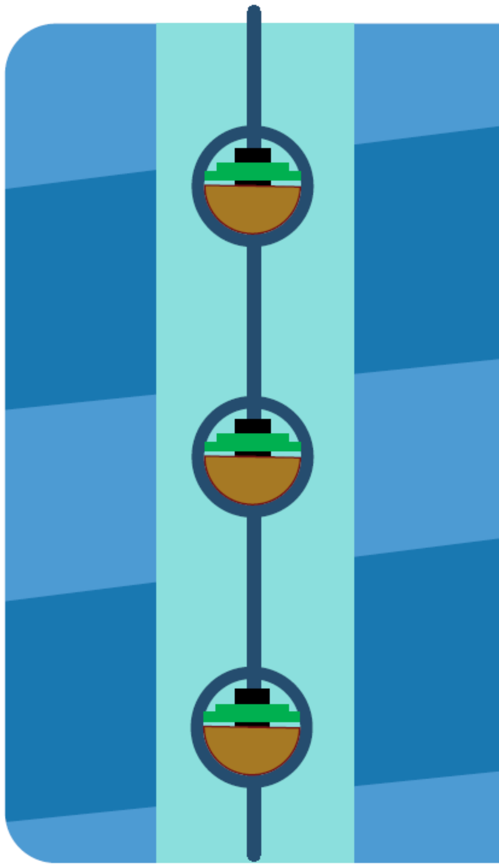
The layered ice model (SPICE)





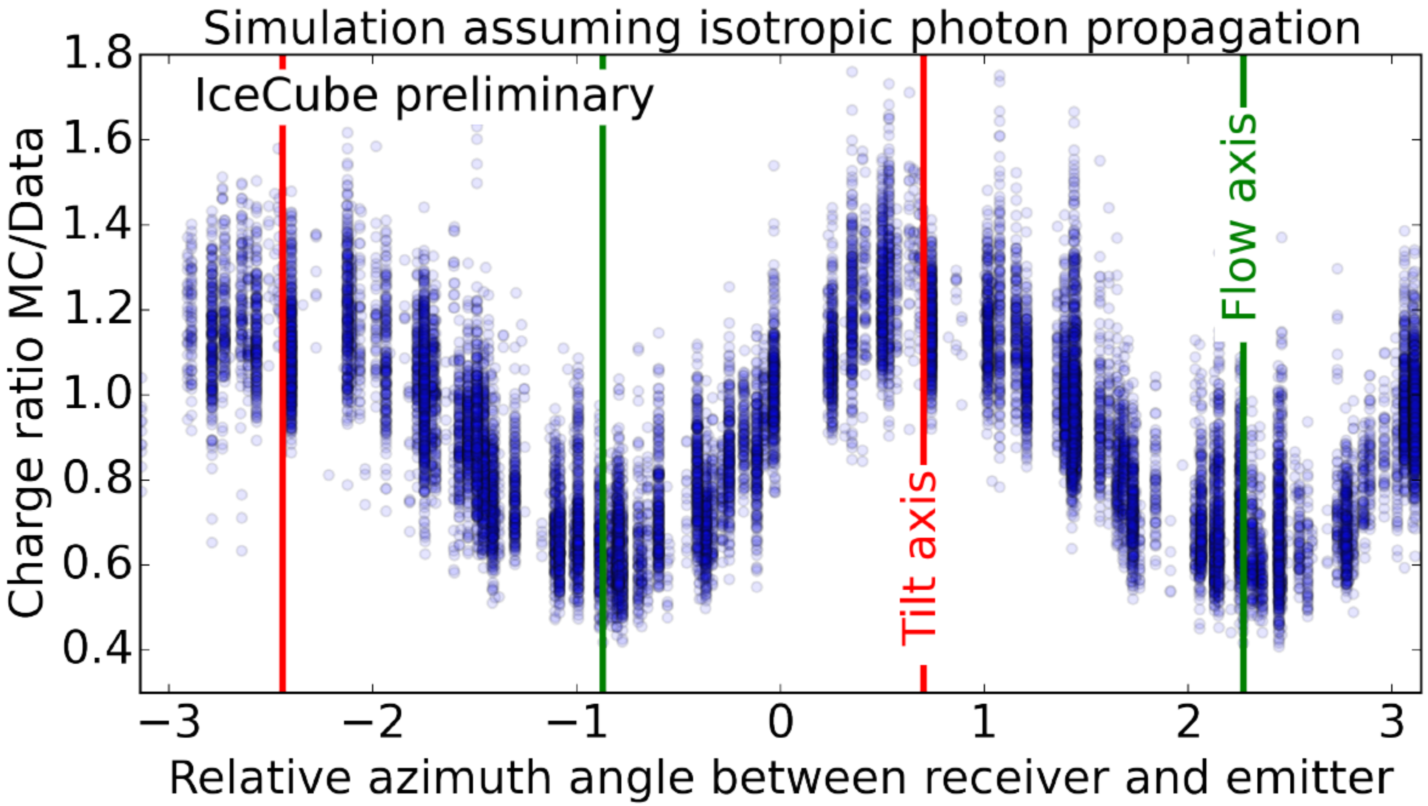
Ice Optical Anisotropy

- Observed charge from LED flashers depends on direction of receiver DOM with respect to emitter DOM

- Maximum intensity seen along the local ice flow direction

- In 2013 implemented as a modification to the Mie scattering function but never achieved good data agreement

arxiv:2107.08692



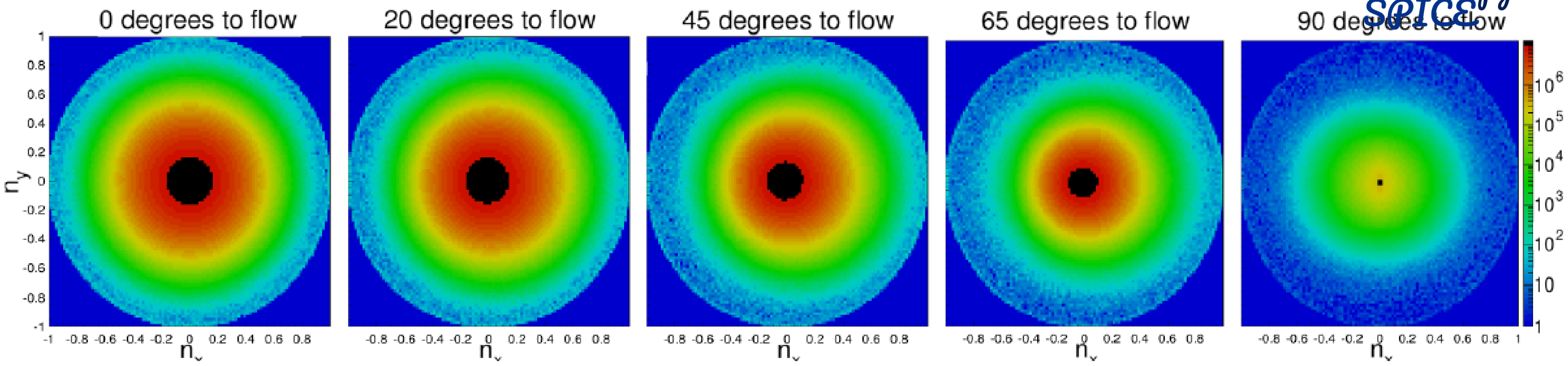
The birefringence explanation

doi:10.22323/1.358.0854 & arxiv:2107.08692

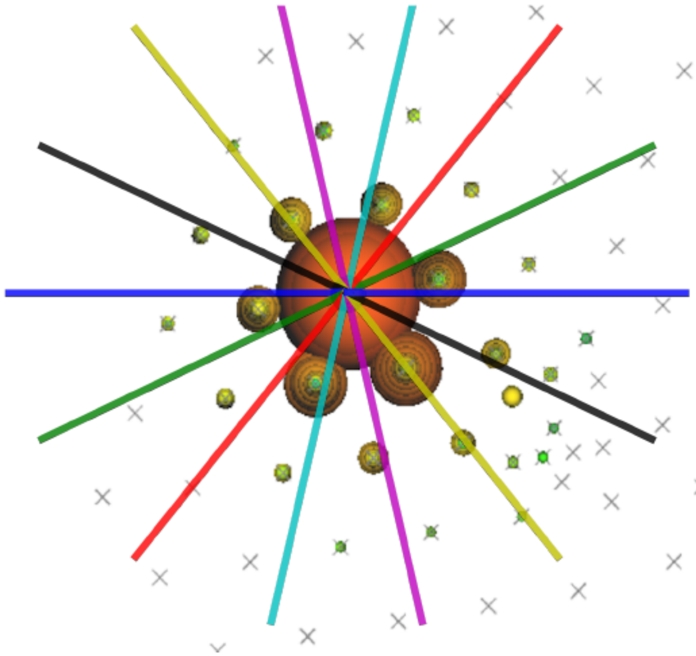
- Continued refraction and reflection on boundaries of birefringent crystals leads to:

  1. Diffusion which is largest along the flow
  2. A small deflection towards the flow axis

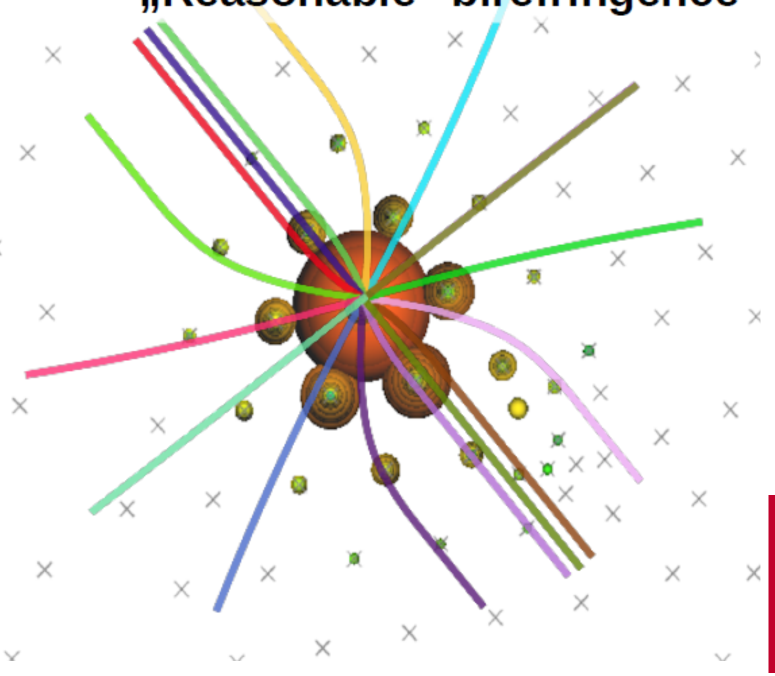
- Diffusion & deflection given by average crystal size & shape



No birefringence



„Reasonable“ birefringence



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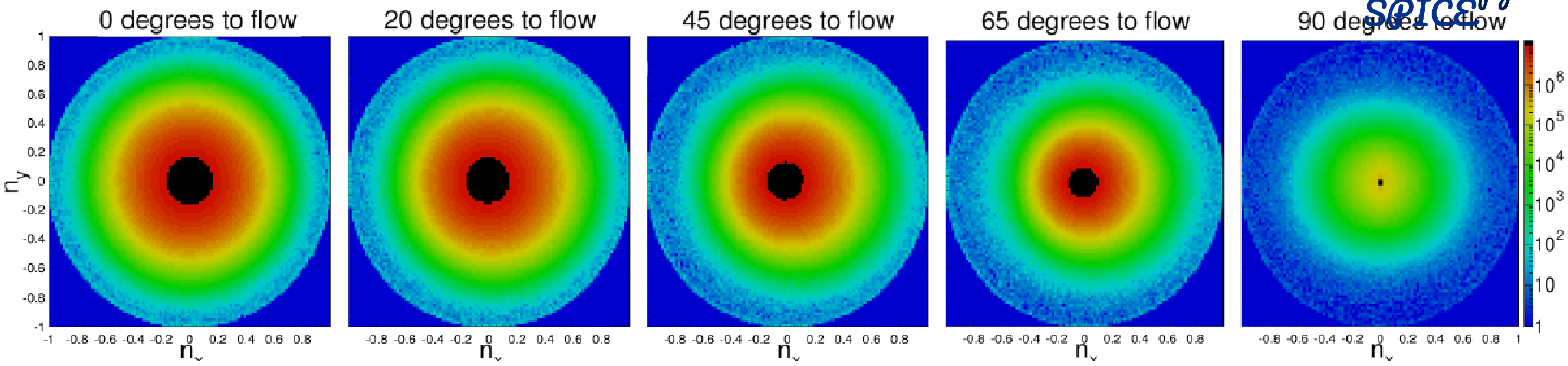

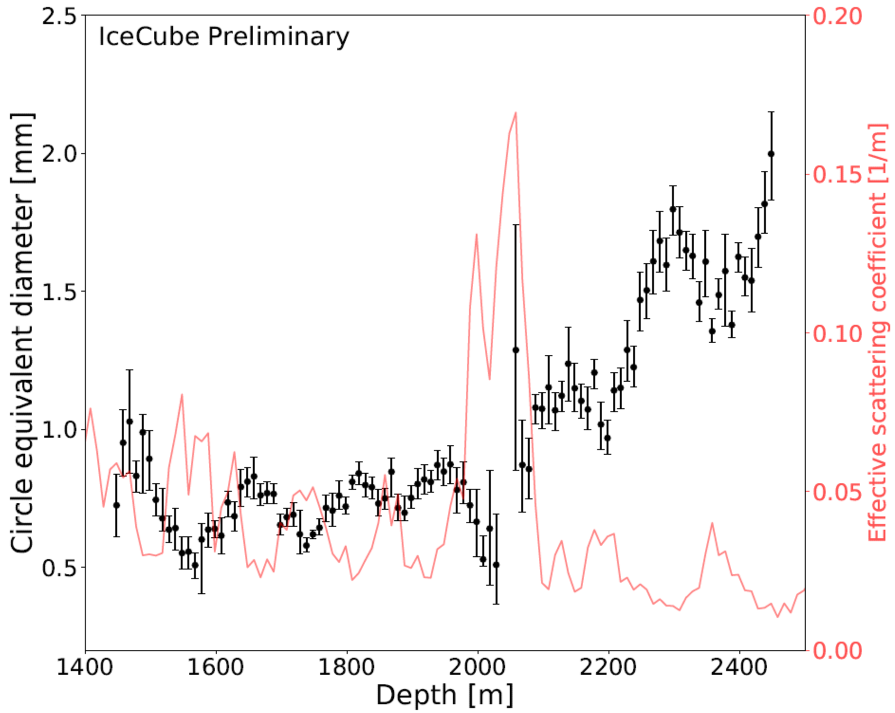

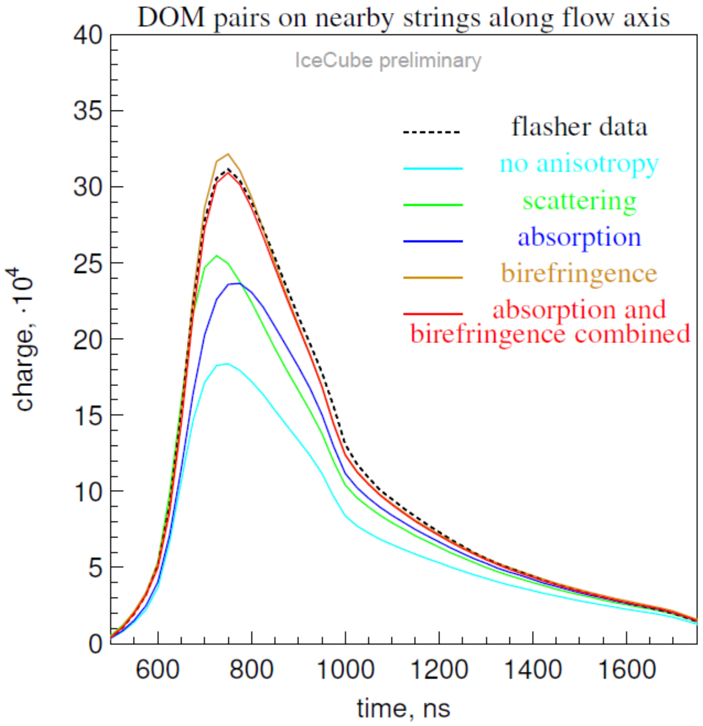

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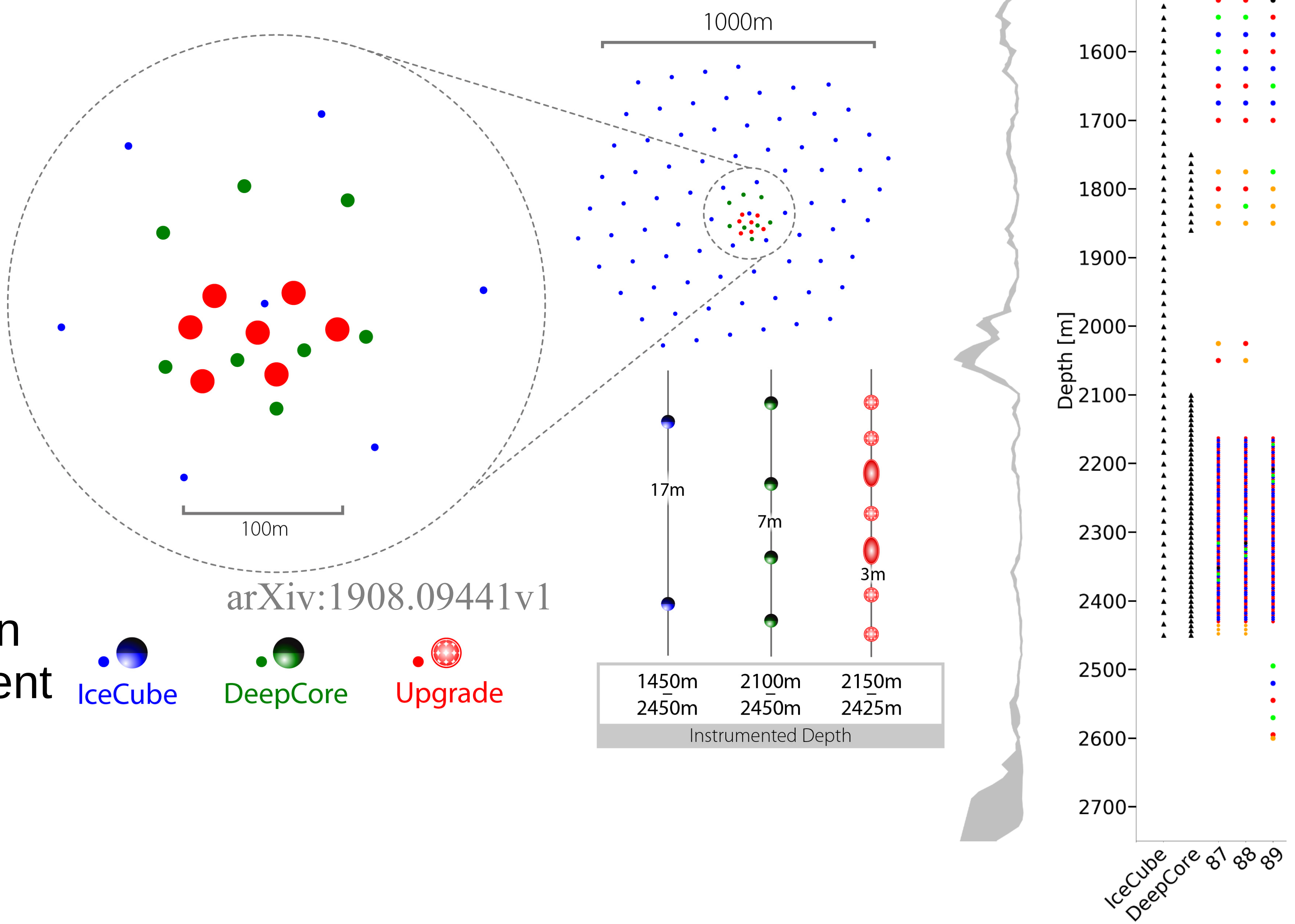
IceCube Upgrade

- 7 new strings with ~20 m spacing
- 3 m vertical spacing (in science region) between 90 optical sensors per string
- Located inside IceCube-DeepCore
- Sparse instrumentation above and below current IceCube depths



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The case for the IceCube Upgrade

I. Build a dense infill detector inside DeepCore

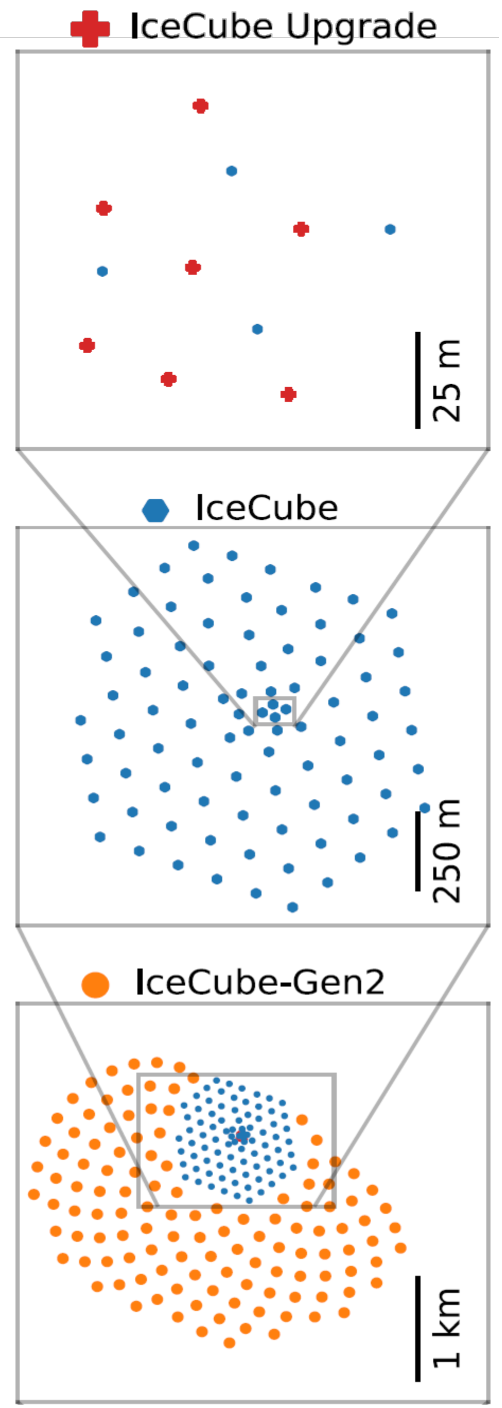
I. Tau Neutrino Appearance → Unitarity check on the PMNS matrix
II. Neutrino mass hierarchy

II. Improve IceCube (ice) calibration

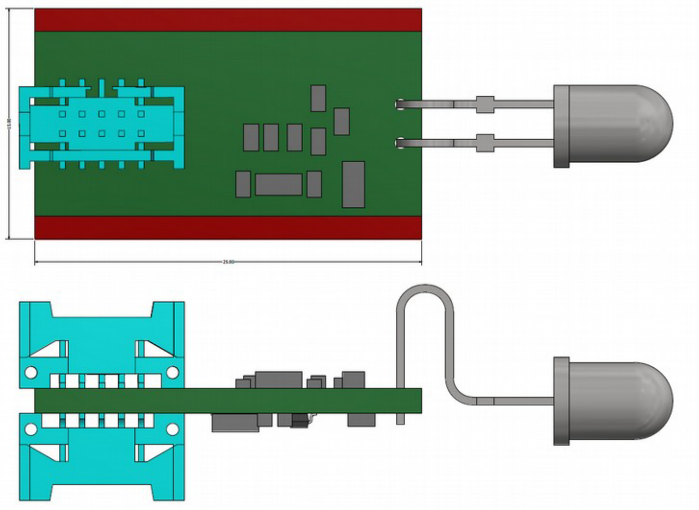
I. Reduce angular uncertainty → better point source sensitivity
II. Reduce known systematics
→ allow for more aggressive cuts in a variety of analyses

III. Testbed for crucial aspects of IceCube Gen2

I. Sensor (and drilling) technology
II. Ice quality & shear between 2500m and the bedrock (~2800m)

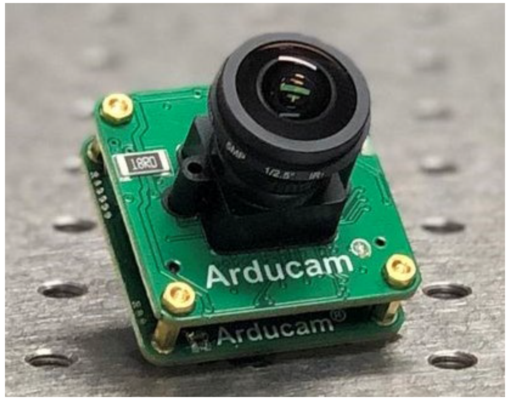


Integrated calibration devices



Nanosecond LED flashers
installed in every module type
→ new default system
for ice studies

arxiv:1908.10780



Upgrade Camera system:
Based on success of hole ice cameras,
low-cost cameras installed in every module
(complimented by updated standalone SweCams)

arxiv:1908.07734

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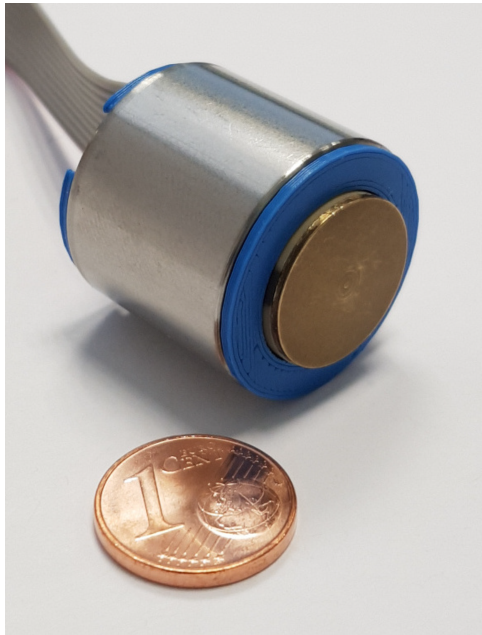
Standalone calibration devices

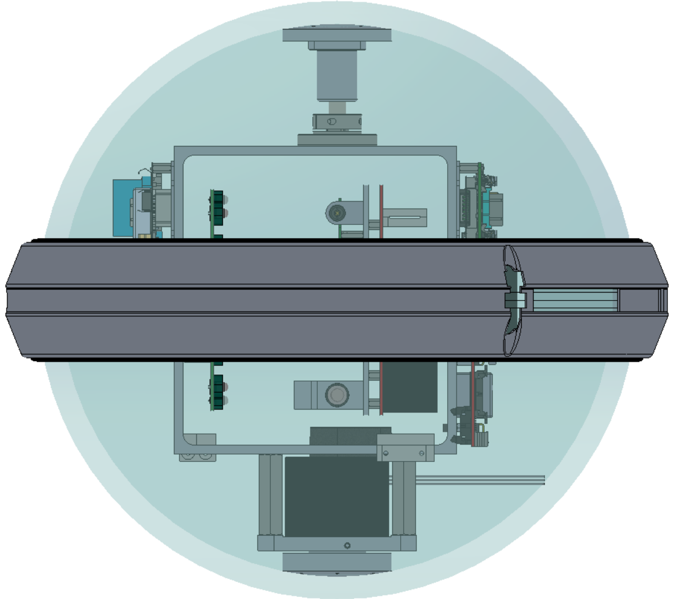


Acoustic
calibration system:
Acoustic emitters for
independent geometry
calibration

arxiv:2108.05631

POCAM:
4π isotropic light source
for relative DOM
efficiency, hole ice and
general bulk ice studies

arxiv:2108.05298



Pencil Beam:
Freely steerable, collimated, nanosecond
LED light sources → can emit in any direction,
for example sweeping target DOMs

arxiv:2108.03291

Summary

- Reconstruction of event topologies in IceCube relies on precise knowledge of
  - the amount, timing and location of the received light *(hardware)*
  - the attenuation and delay the light has experienced during propagation *(ice)*

- IceCube has diverse and unique but well established calibration
- Calibration continues to be improved, with substantial discoveries along the way (i.e. curved photon trajectories in microstructure of glacial ice)

- But, IceCube now moving from statistics to systematics limited regime
  - Previously subdominant effects (detector geometry, ice details) becoming limiting

- IceCube Upgrade will provide innovative data to tackle yet unresolved systematics

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An international effort

THE ICECUBE COLLABORATION

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University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
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University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

LED flasher light curve sensitivity

- Observation of photon arrival time distributions from pulsed light sources, allows for measurement of absolute absorption & scattering lengths
- Normalization independent, but observations at different distances help
- Distributions badly modeled by analytic random walk
  → full simulation needed