IceCube
South Pole Neutrino Observatory

The IceCube Neutrino Observatory as an Instrument for Glaciology

Martin Rongen, Dmitry Chirkin for the IceCube Collaboration

7th Workshop of the SCAR AAA 2023, September 2023, Svalbard

Erlangen Centre for Astroparticle Physics

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The optics of the IceCube Neutrino Observatory

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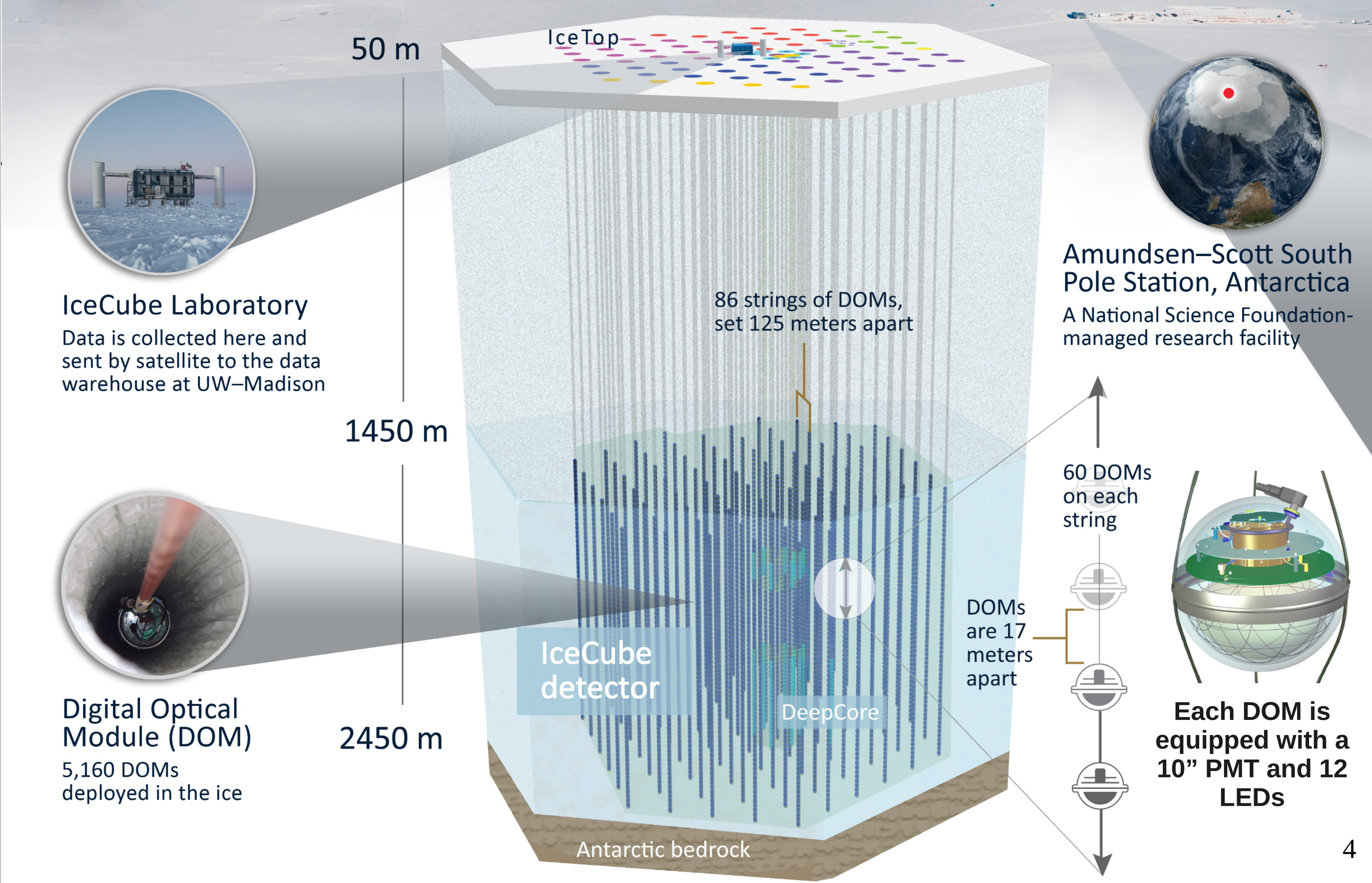
The IceCube Neutrino Observatory

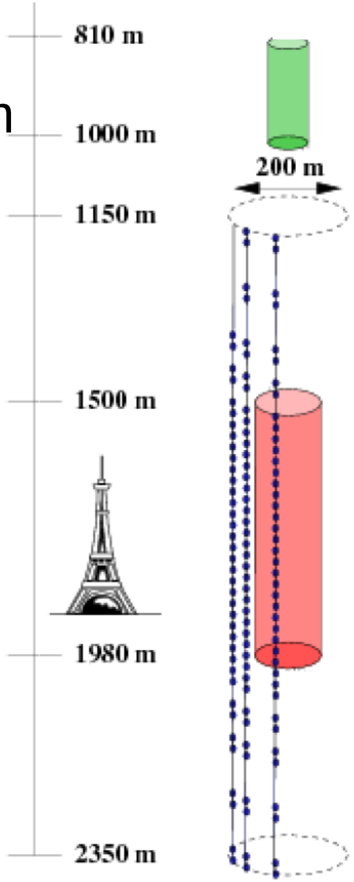
Design and construction



Glacial ice as detection medium

- In particle physics one usually carefully designs the detection medium
- Deploying into natural glacial ice we don‘t have that luxury (predecessor experiment (AMANDA-A) limited as scattering at 1 km depth was far worse than predicted at the time)
- The optical scattering & absorption properties directly impact physics performance
    - Trigger performance, angular reconstruction, energy reconstruction, particle identification, ...

→ we need to calibrate the detection medium in-situ



The Glacier @ IceCube

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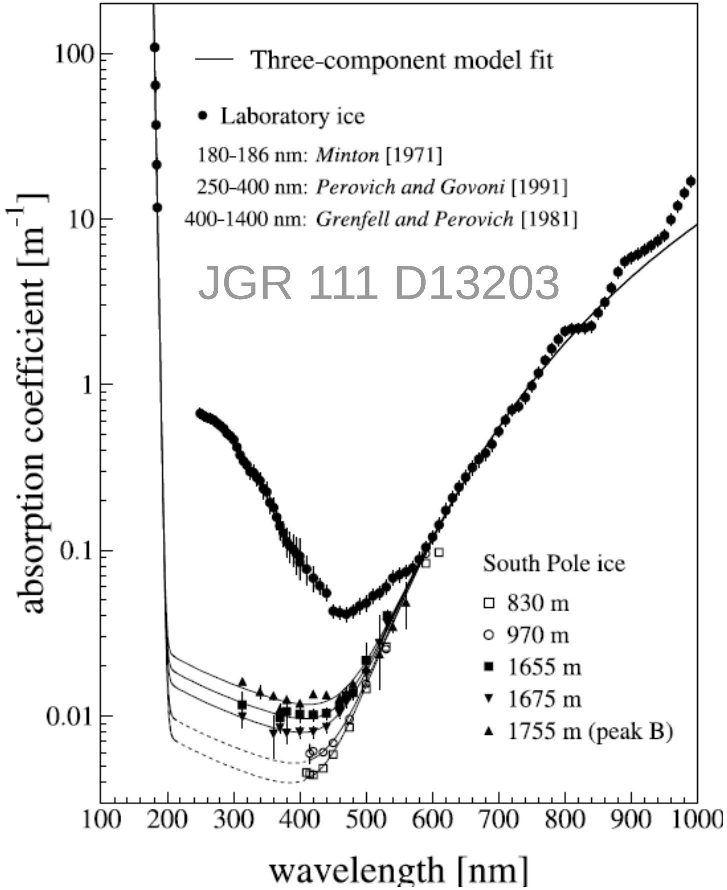
- Compacted snow up to 100'000 years old
- *Absorption* length ~100m,
  one of the least absorbent known solids
- Above 1300m air bubbles dominate *scattering*
- Below 1300m air bubbles get incorporated into crystal structure forming transparent craigite
- *Scattering* (~20m eff.) dominated by impurities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



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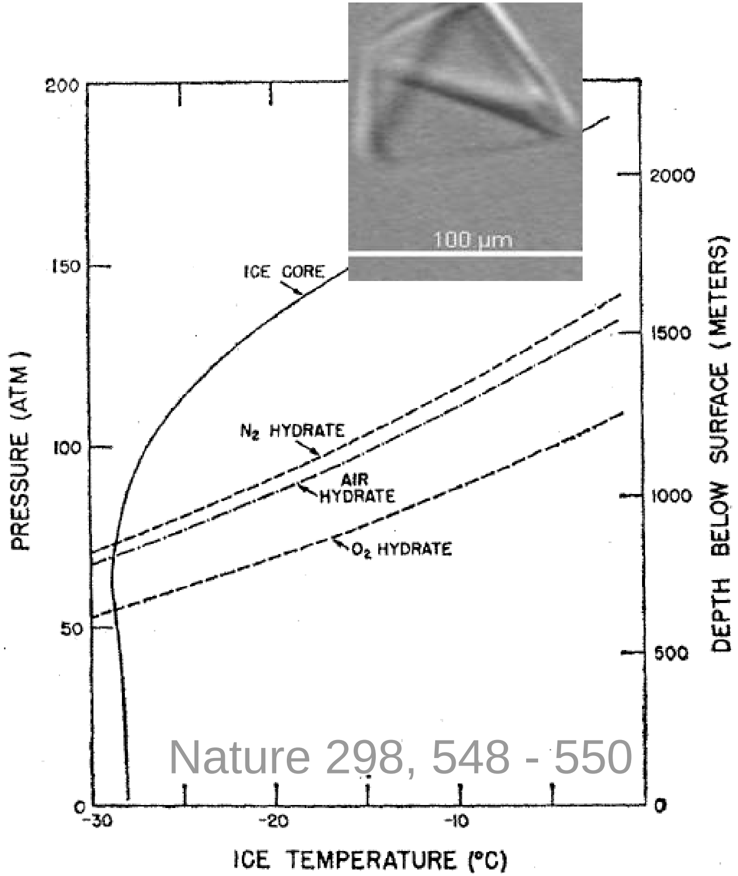

Nature 298, 548 - 550

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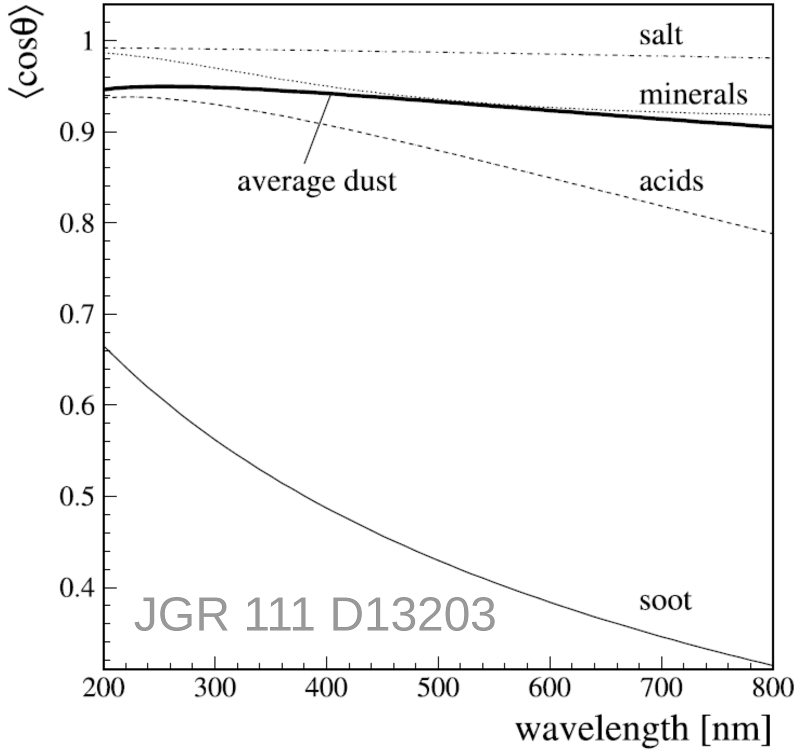


Analytic modeling

$$a(\lambda) = \sum_j N_j \int_{r_{min}}^{r_{max}} dr \left[A_j(r, \lambda, m_j) \frac{df_j}{dr} \right]$$

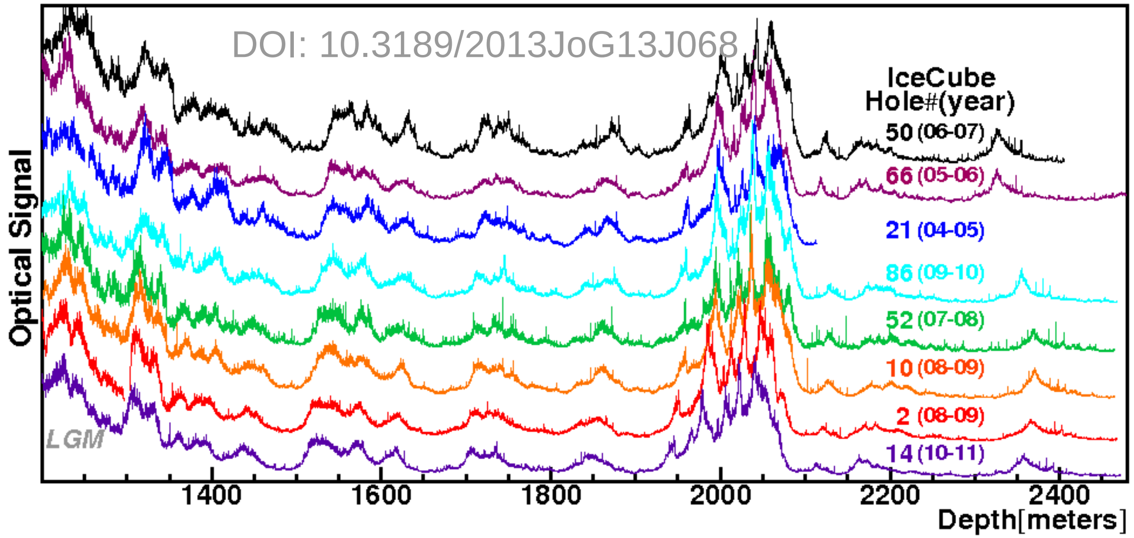
Absorption length to be obtained	Summing over impurity densities
Per component size distribution	Per component Mie cross sections

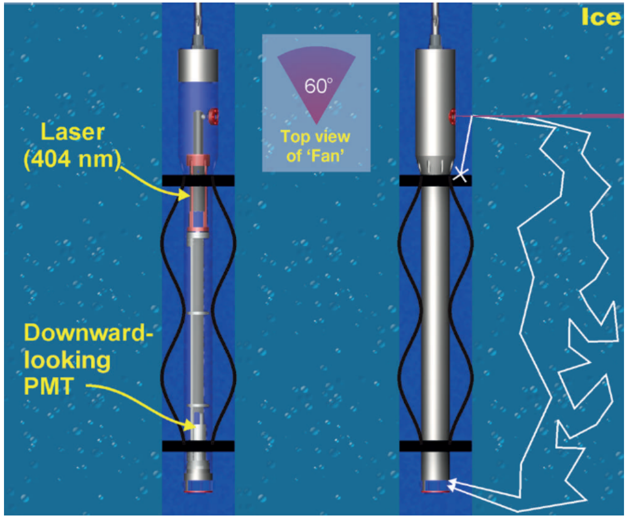
- Given the number densities, size distributions and complex refractive indices of all impurities the
  - absorption length, scattering length and angular deflection function
  - and their scaling with wavelength

  can be calculated from first principle Mie theory

The DustLogger

- Horizontal fan of light emitted into ice
- Scattering centers can deflect light into PMT
  → Signal proportional to density of scattering centers
- Yields high resolution stratigraphy but not absolute absorption & scattering lengths





Milankovitch Cycles

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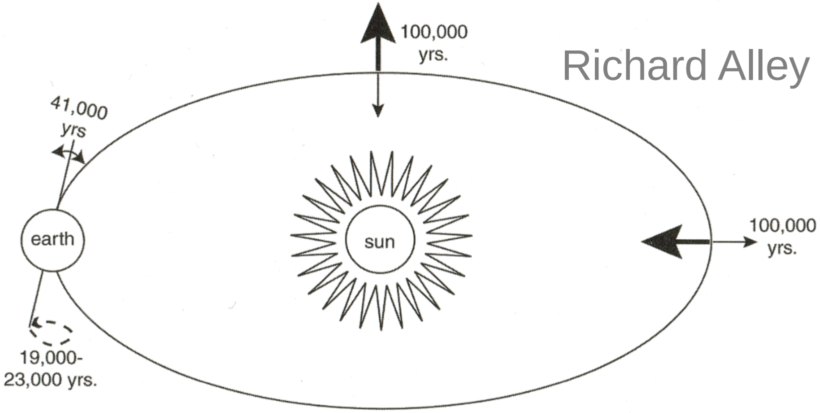
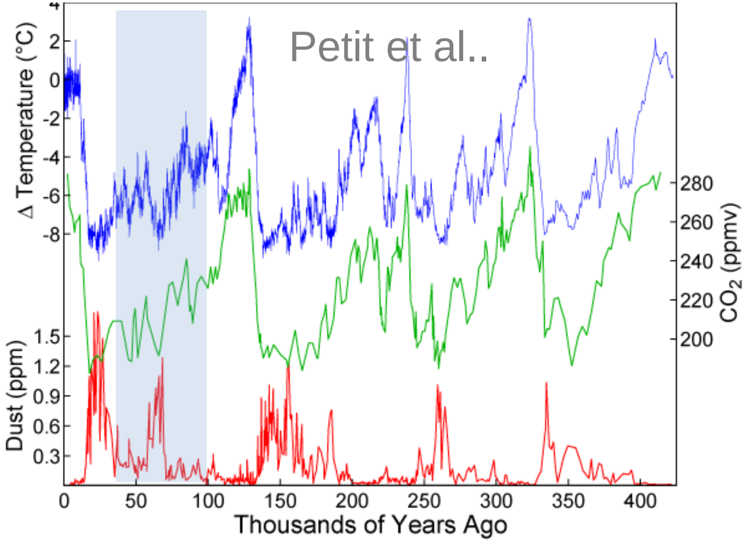
- Stratigraphy can be understood when considering the Earth’s climate history
- Climate is governed by periodic changes in Earth‘s orbit (Milankovitch Cycles)
- The overall incident sun intensity hardly changes, but the distributions on the hemispheres changes (most landmasses on the Northern Hemisphere)
- Cold, dry climate periods (stadials) feature high impurity concentrations



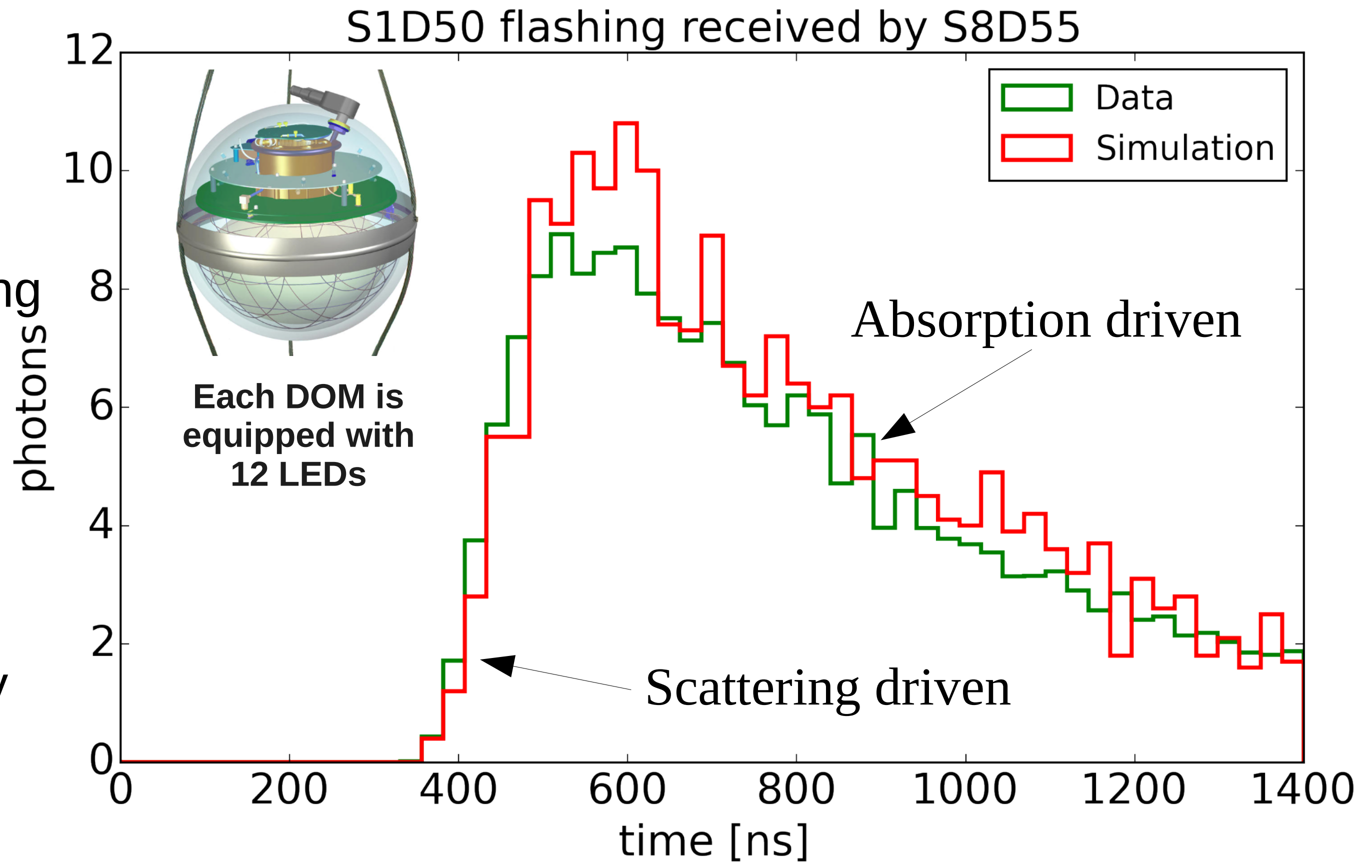


Light curve sensitivity

- 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



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Photon propagation & likelihood analysis

Initialize photon
with distance to absorption

↓

Dice distance to next scattering

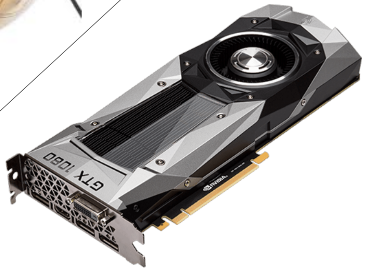
↓

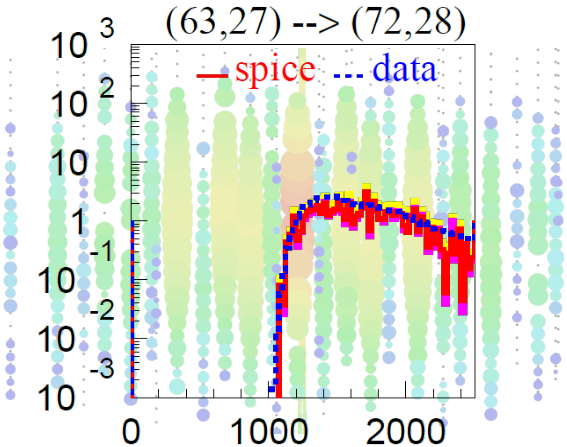
Step through layers until absorbed, scattered or detected

If scattered → **Deflect by random angle from scattering function** → **Dice distance to next scattering**

If detected or absorbed ↓

Kill photon





An event contains average binned waveforms
→ This is compared against MC simulation

$$-\ln\mathcal{L} = \sum_i \left[s_i \ln\frac{s_i/n_s}{\mu_s^i} + d_i \ln\frac{d_i/n_d}{\mu_d^i} + \frac{1}{2\sigma^2}\ln^2\frac{\mu_d^i}{\mu_s} \right]$$

i sums over all emitting & receiving DOMs and their time bins

Layered ice model (SPICE)

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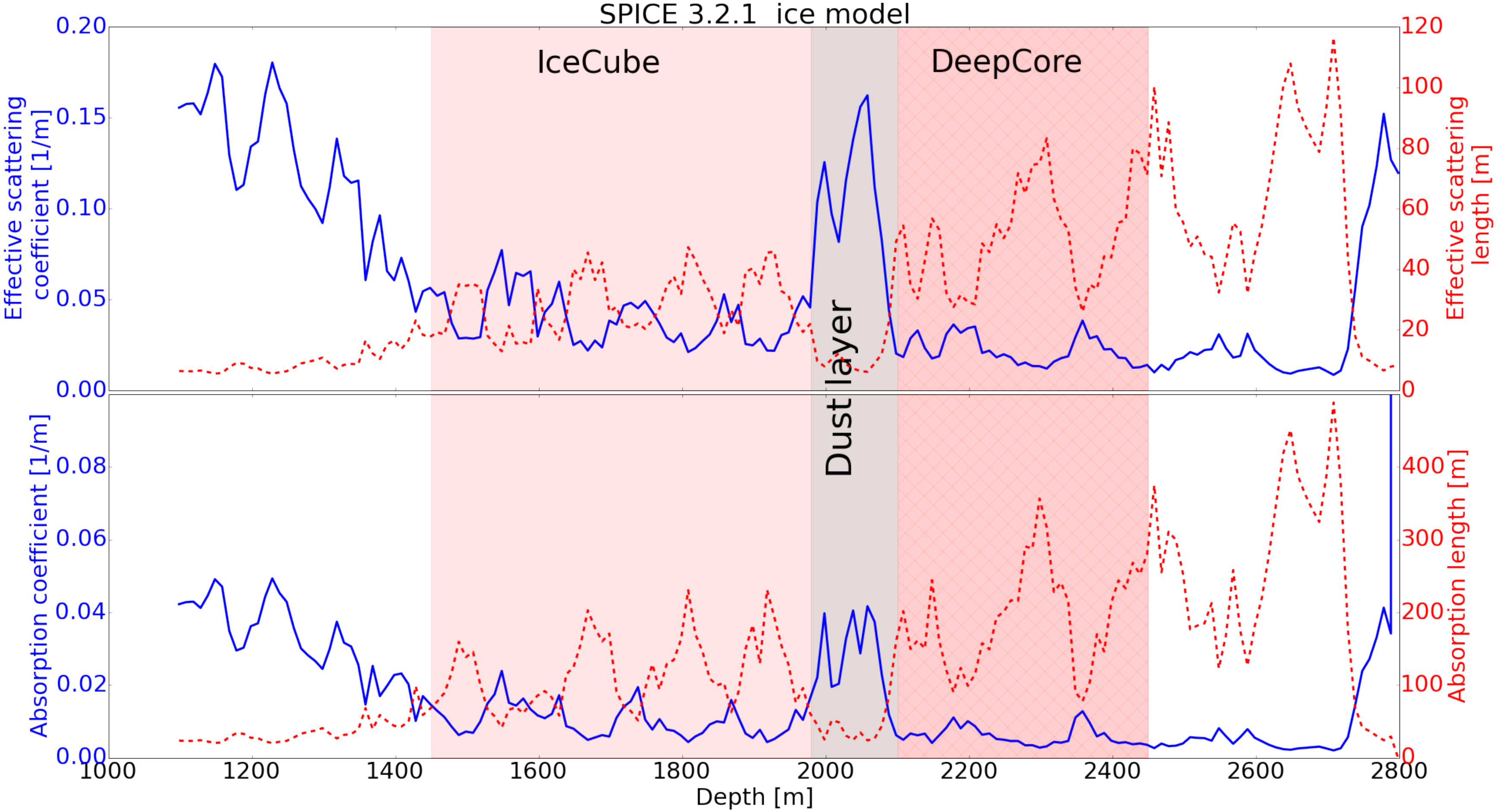
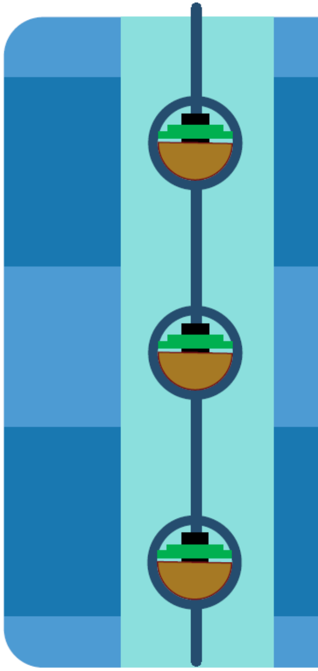
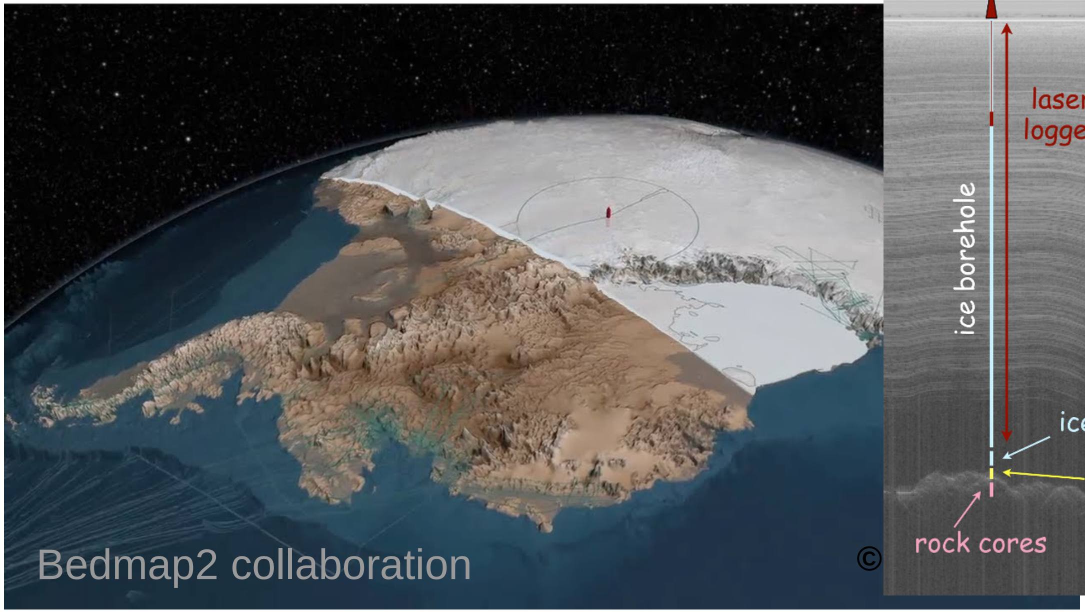


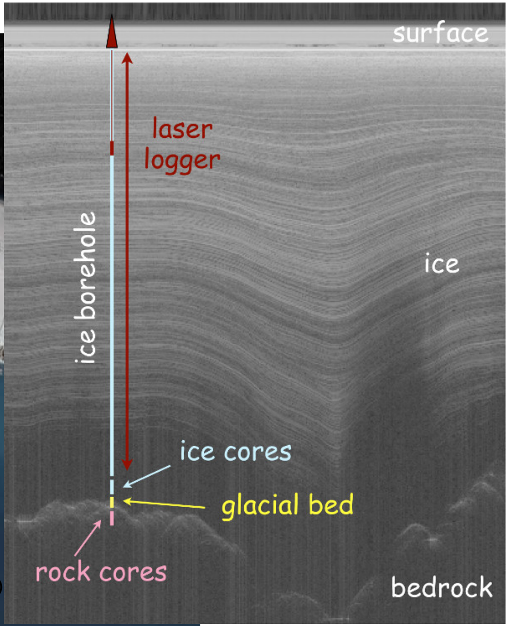


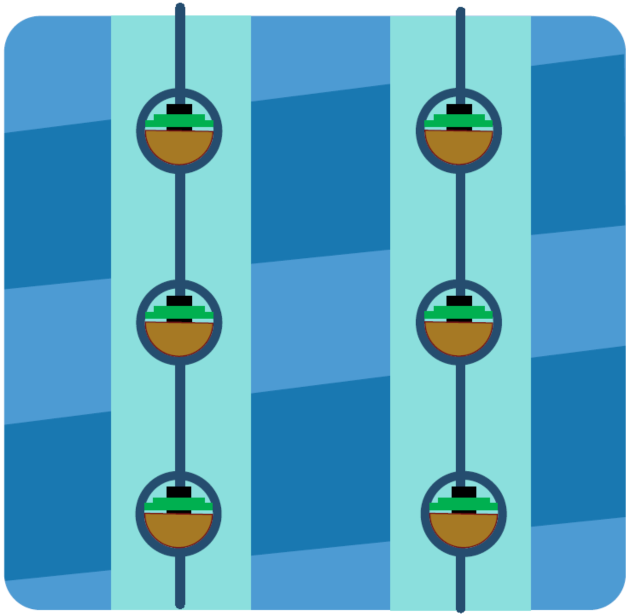
The ice tilt

- While the ice surface is flat, the underlying terrain is fairly mountainous

- Valleys only filled in gradually
  → ice layers at great depth are offset / tilted







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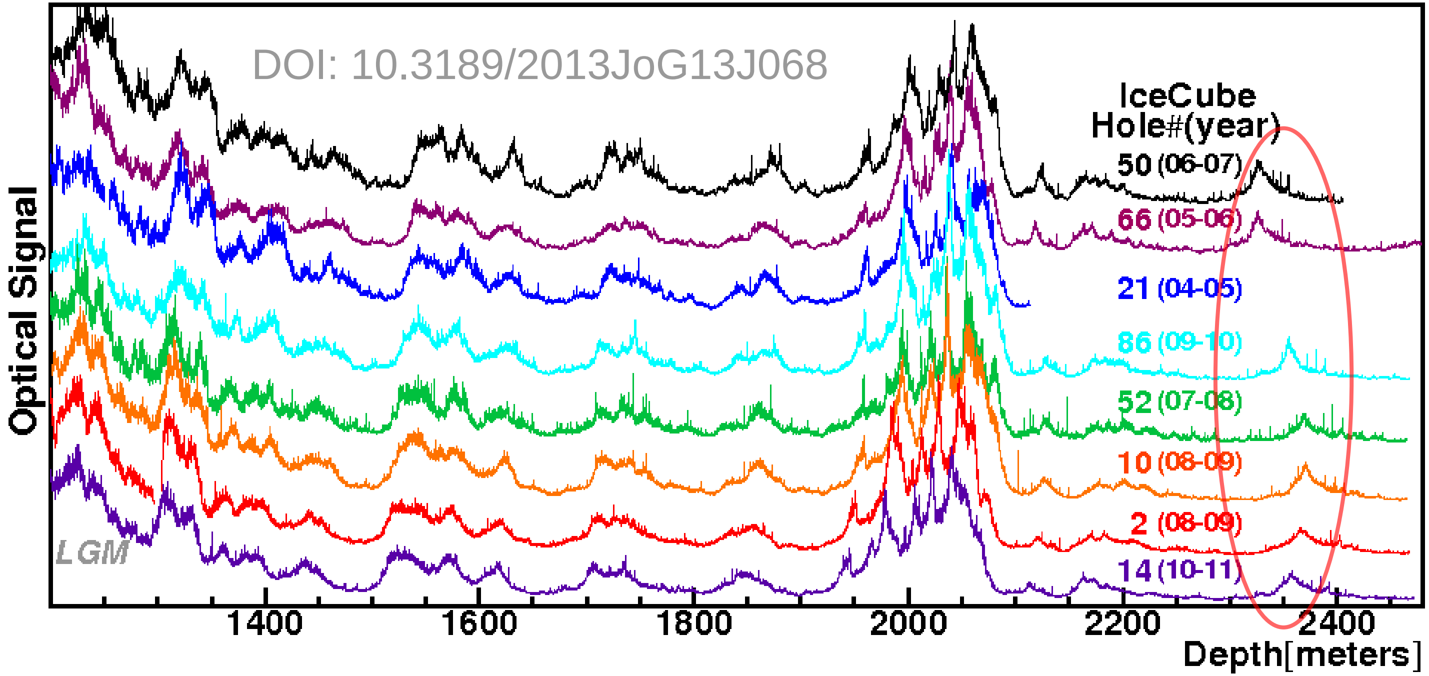
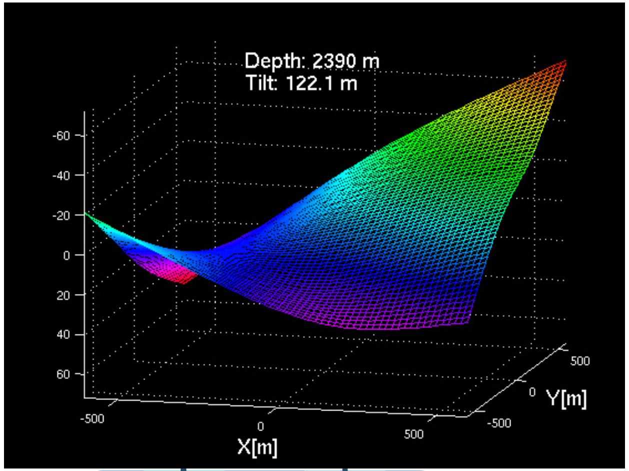
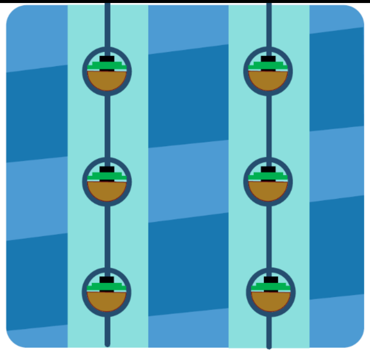
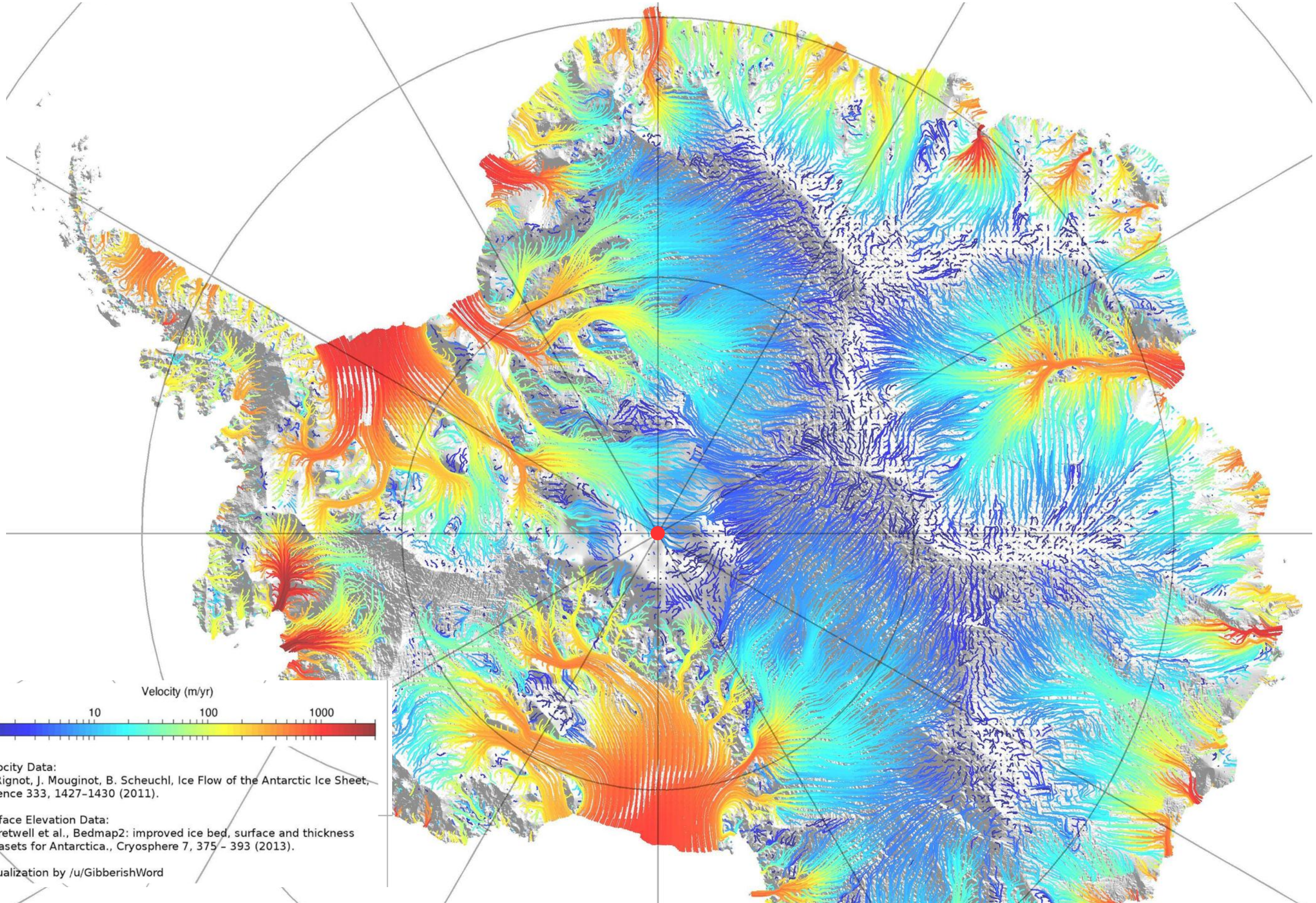
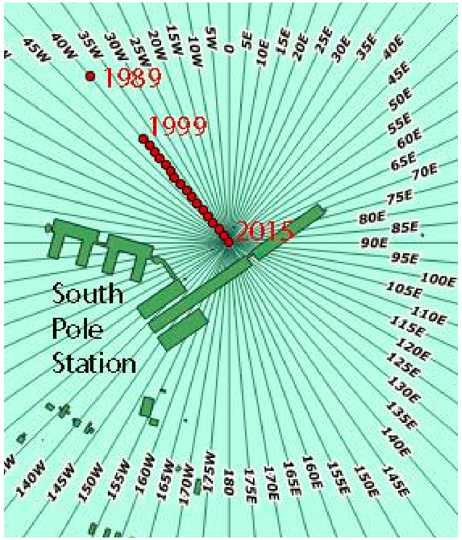






Rivers of ice






Credit: Devyn Rysewyk

The ice anisotropy effect

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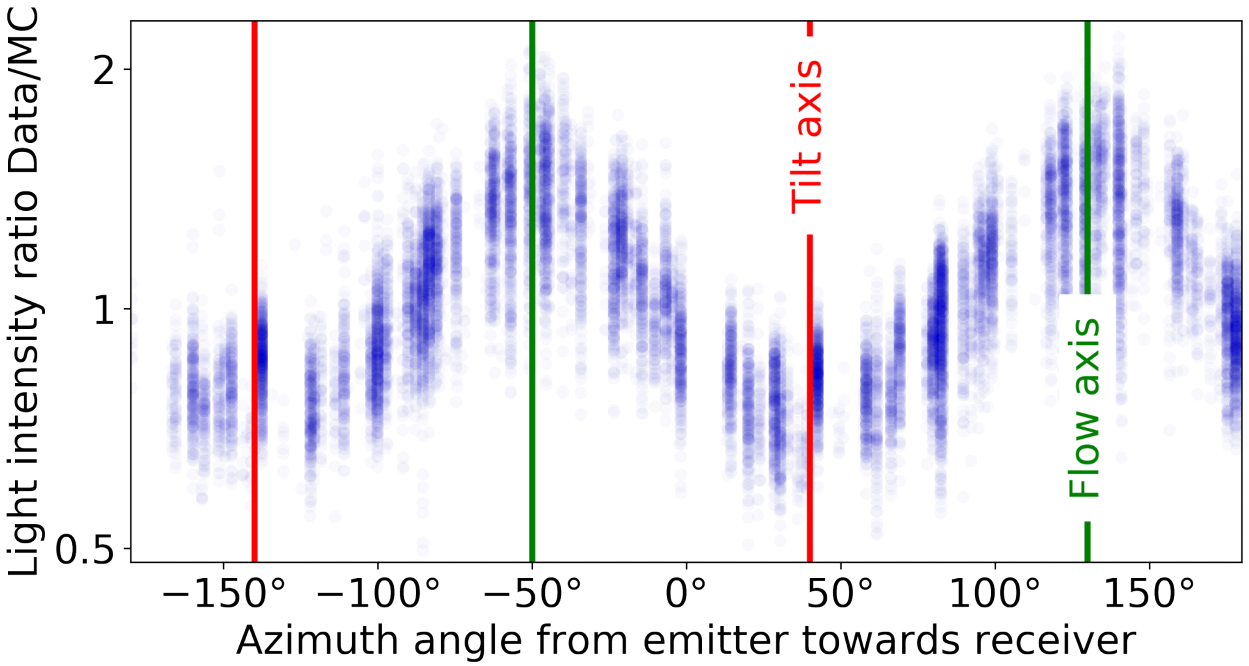
- Observed charge from LED flashers depends on orientation of receiver DOM with respect to emitter DOM
- Maximum intensity seen along the local ice flow direction

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



The birefringence explanation

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- Continued refraction and reflection on boundaries of birefringent crystals:
  - Diffusion which is largest along the flow
  - A small deflection towards the flow axis
- Diffusion & deflection given by average crystal size & shape

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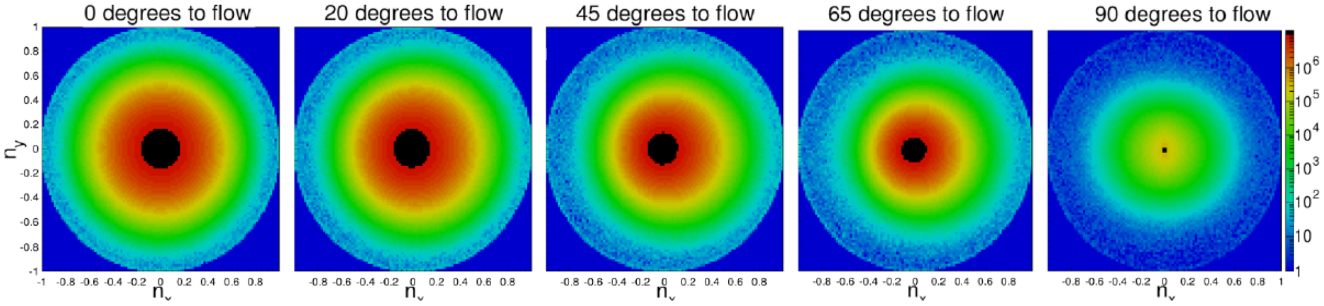
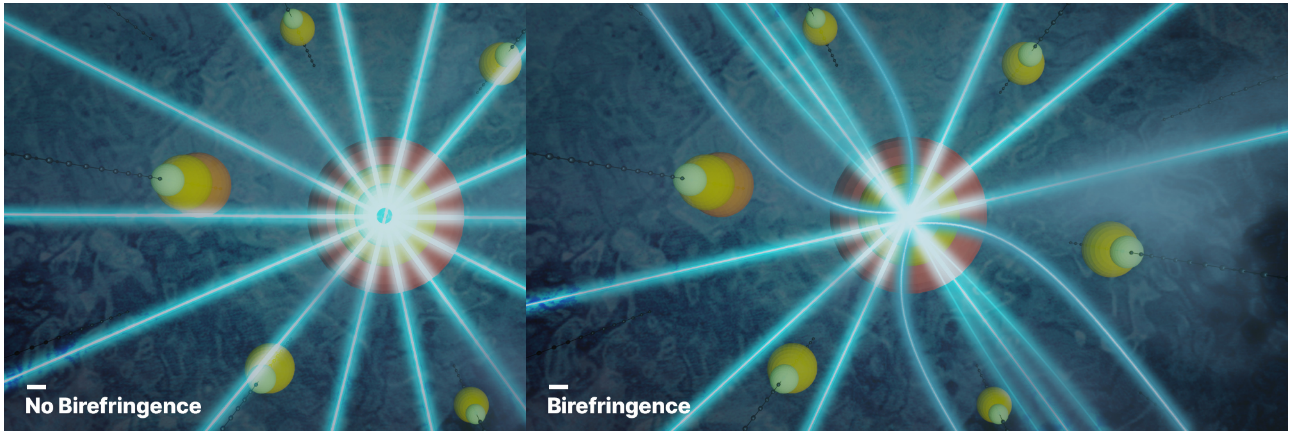
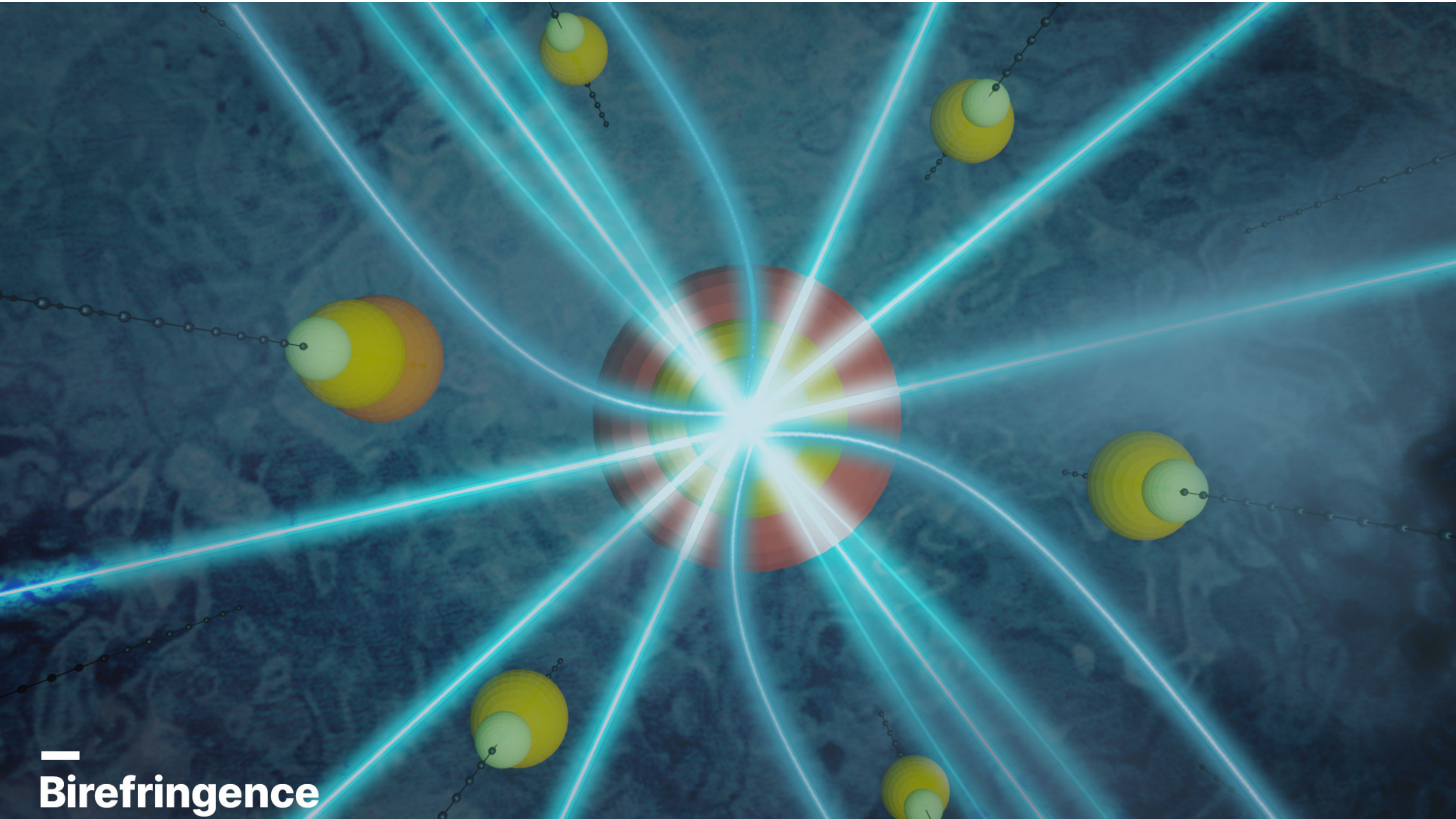


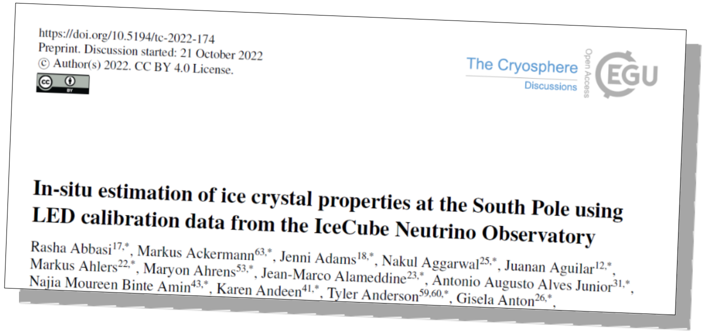



Birefringence

The birefringence explanation

- Detailed modeling of birefringence allows to deduce ice cyrstal properties (average shape & size, c-axis distributions, …) as relevant to ice flow modeling using data from IceCube sampling individual photons at 125 m increments

- For more details see:



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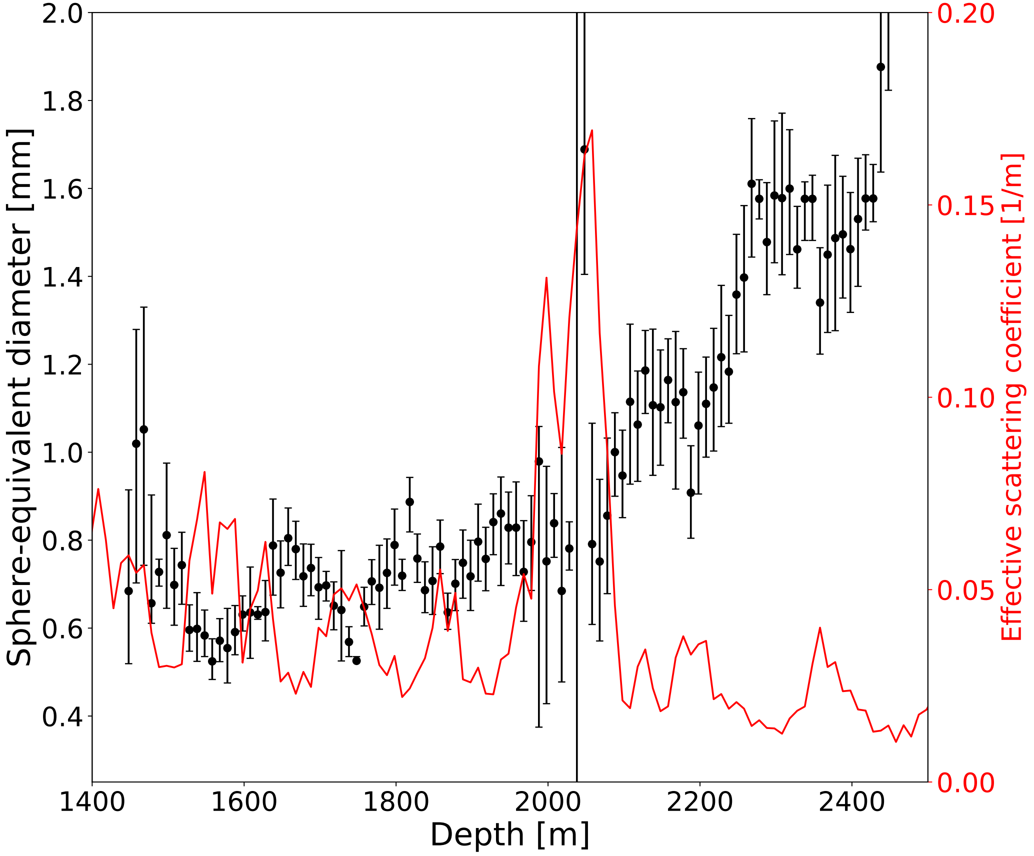
The Cryosphere Discussions

In-situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory

Rasha Abbasi[17,*], Markus Ackermann[63,*], Jenni Adams[18,*], Nakul Aggarwal[25,*], Juanan Aguilar[12,*], Markus Ahlers[22,*], Maryon Ahrens[53,*], Jean-Marco Alameddine[23,*], Antonio Augusto Alves Junior[31,*], Najia Moureen Binte Amin[43,*], Karen Andeen[41,*], Tyler Anderson[59,60,*], Gisela Anton[26,*],

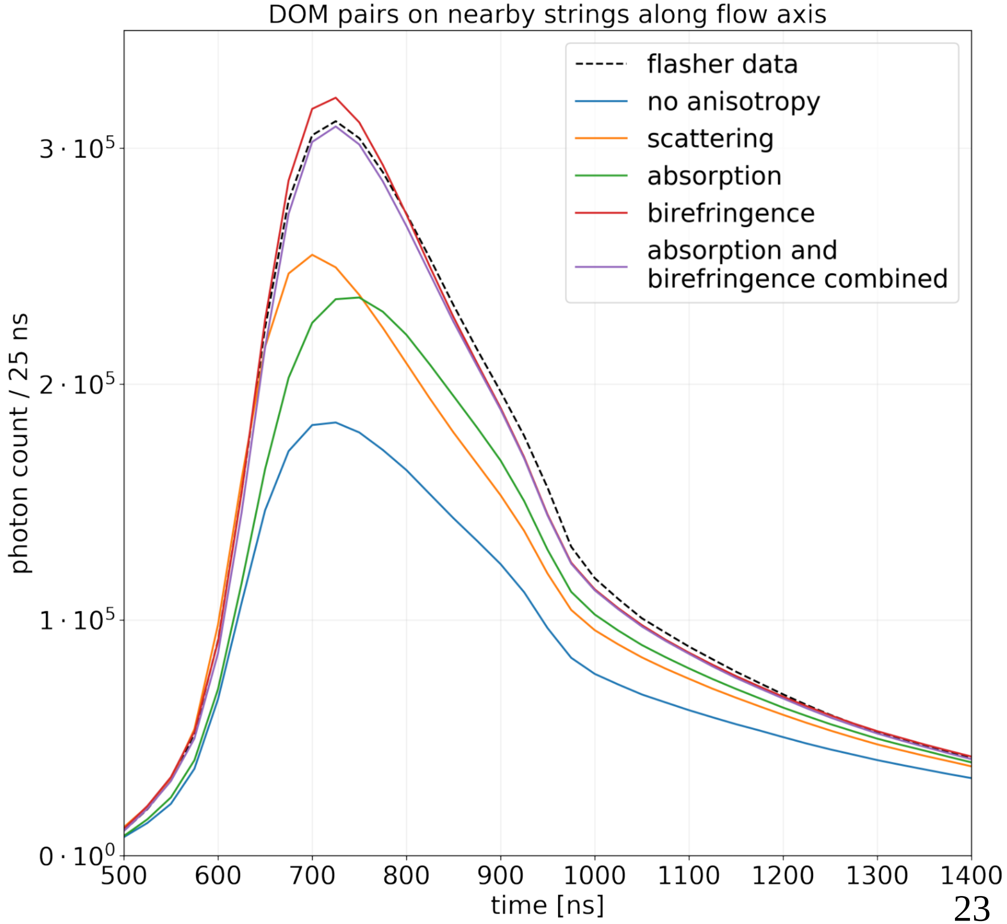


Quality & open issues

- Using the full-model described above, we achieve an unprecedented data-MC agreement

- BUT the LED data is insufficient to unambiguously determine the large number of parameters involved

- And the modeling still requires a number of fudge-factors
(for example inclusion of an ad-hoc absorption anisotropy part)



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The case for the IceCube Ugrade

I. Build a dense infill detector inside DeepCore

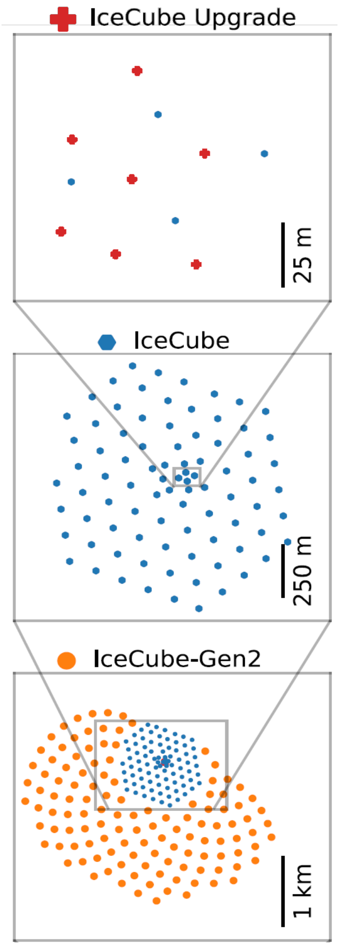
I. Tau Neutrino Appearance → Unitarity check on the PMNS matrix
II. Neutrino mass hierarchy

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)



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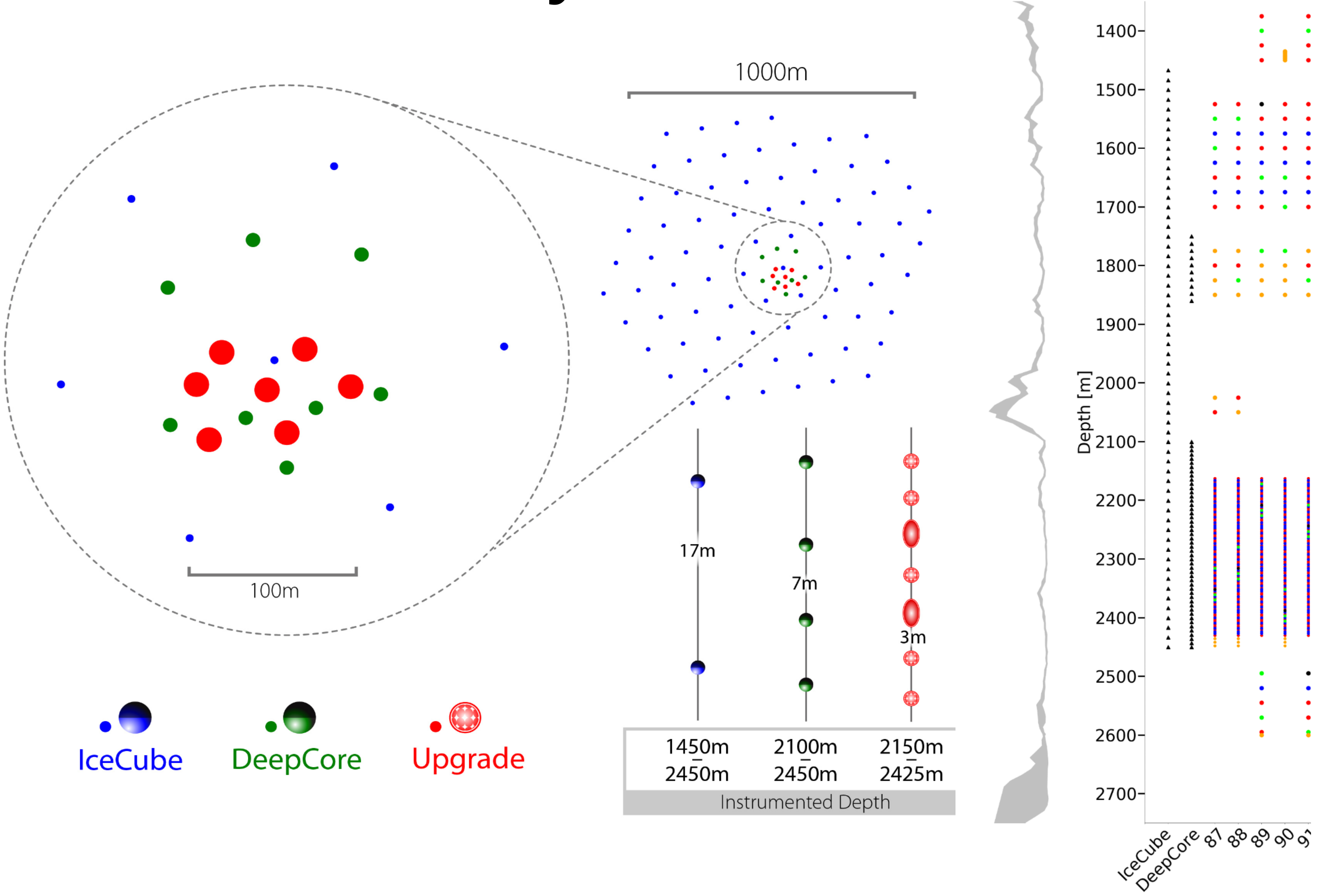
IceCube Upgrade Detector Layout

- 7 new strings
  at ~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



Calibration instrumentation

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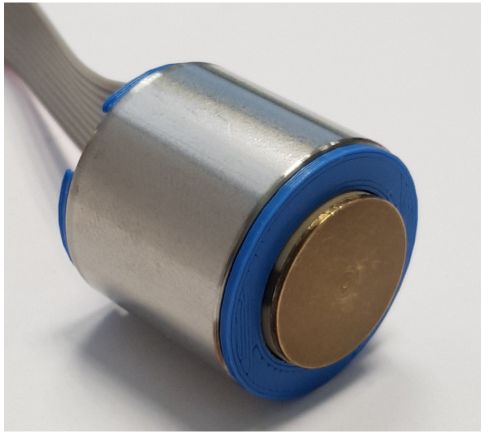
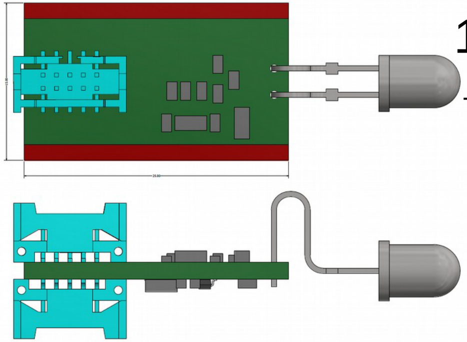


Acoustic calibration system:
Acoustic emitters for independent geometry calibration

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



10 nanosecond LED flashers per module
→ new default system for ice studies

Upgrade Camera system:
Based on success of hole ice cameras,
several low-cost cameras per module

Pencil beam in the Upgrade

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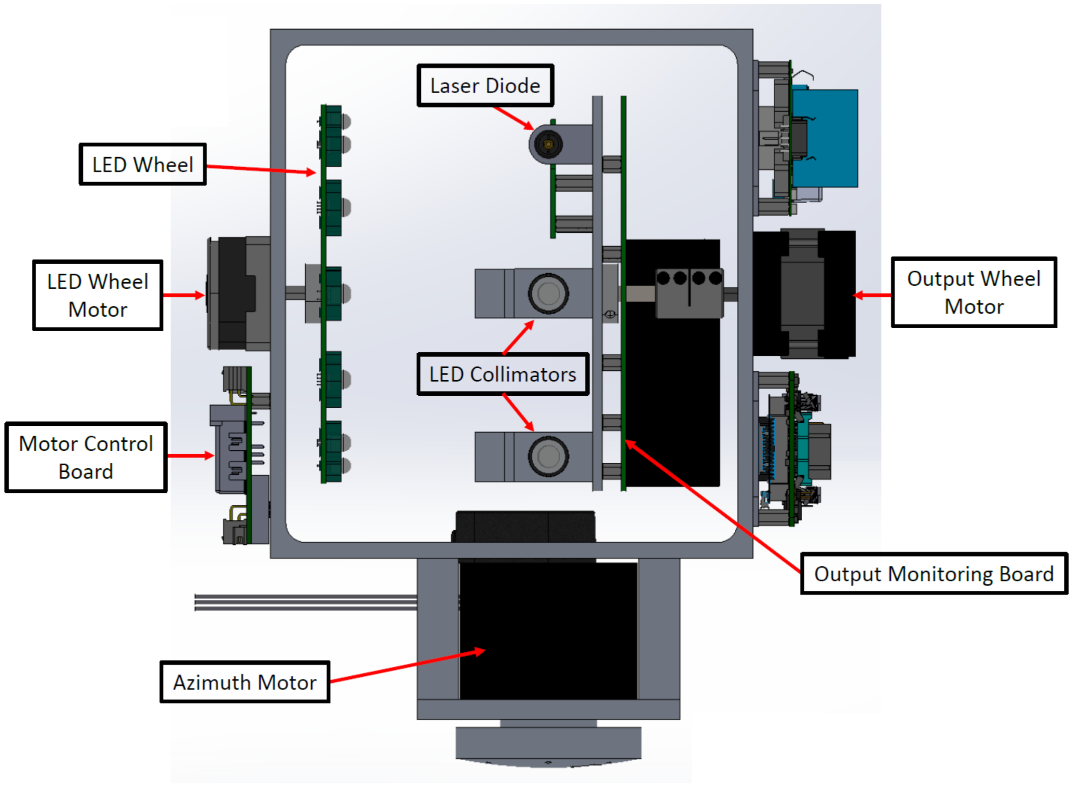
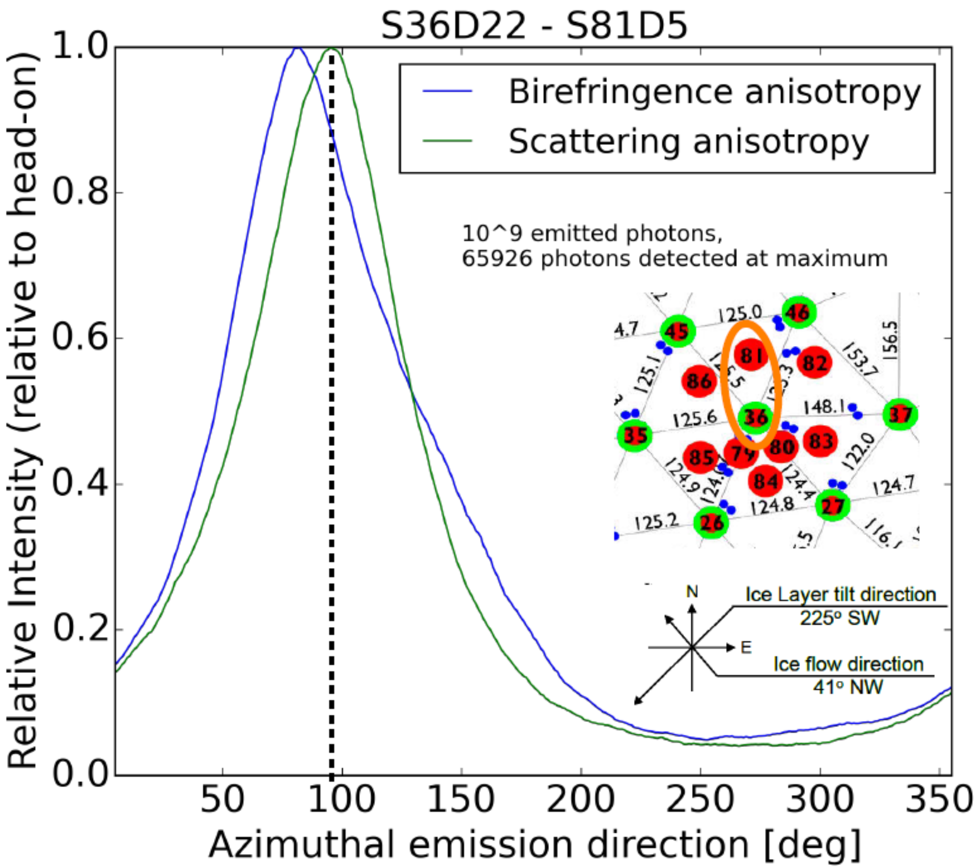


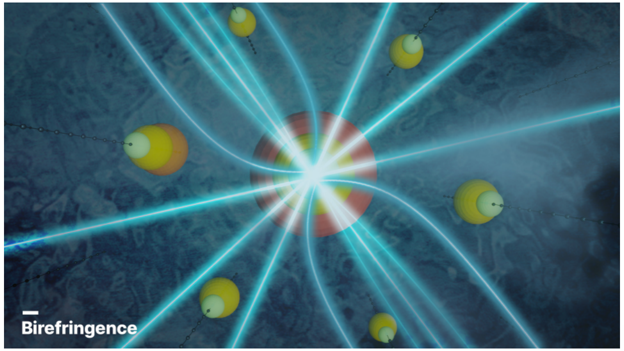


4π steerable, ns, collimated light source

Summary

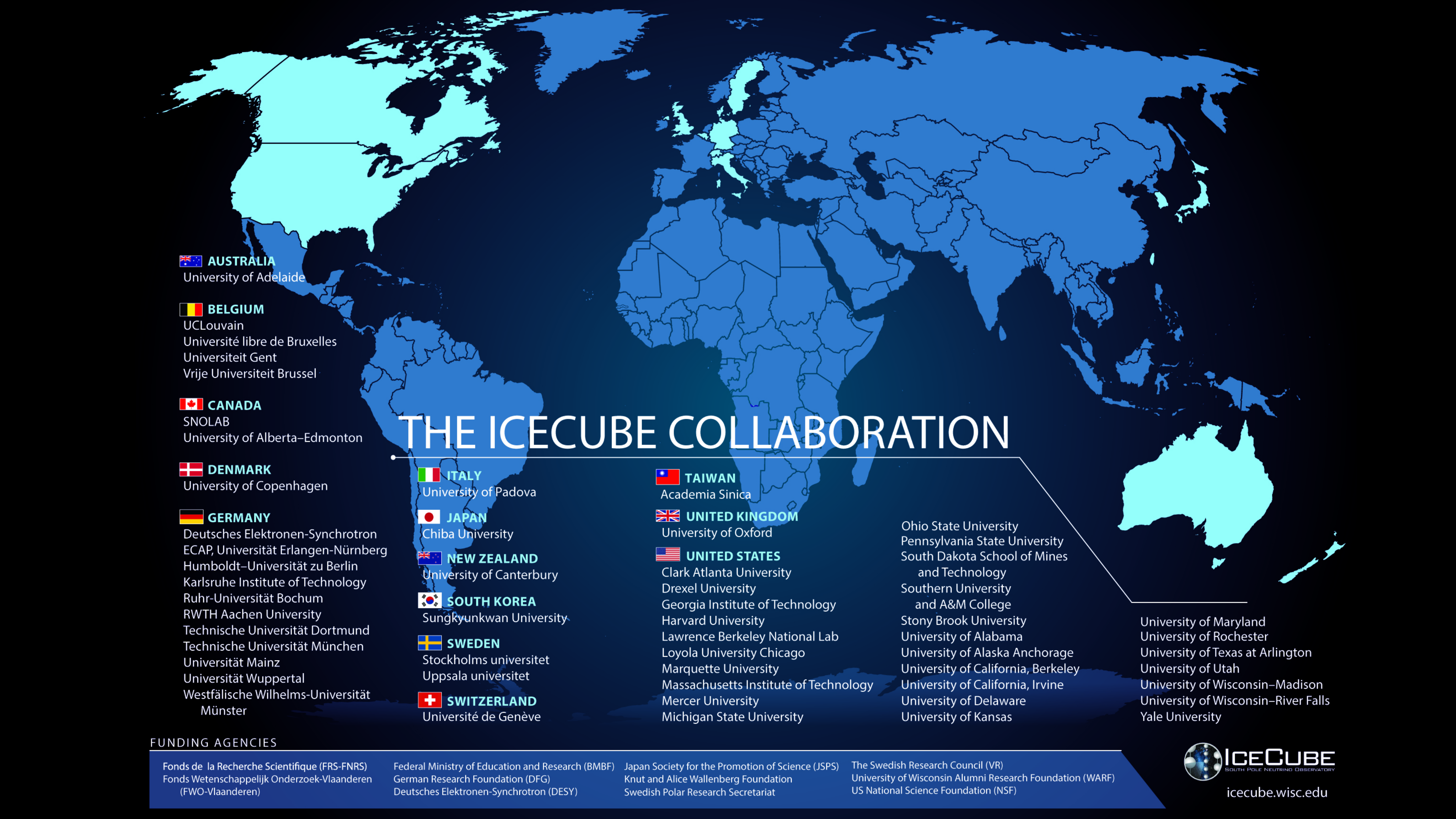
- IceCube is a unique astroparticle physics experiment / neutrino telescope instrumenting a km^3 of deep Antarctic ice

- Calibration of the ice optical properties as required for event reconstruction has matured to a level where it is informative to glaciology / material science:
  - Ice intrinsic absorption
  - Impurity stratigraphy
  - Englacial heterogeneities (layer undulation)
  - Ice microstructure and photon deflection



Thank you for your attention!

Questions are welcome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