Calibration and the Ice Model

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IceCube Bootcamp 2018

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IceCube Detector references

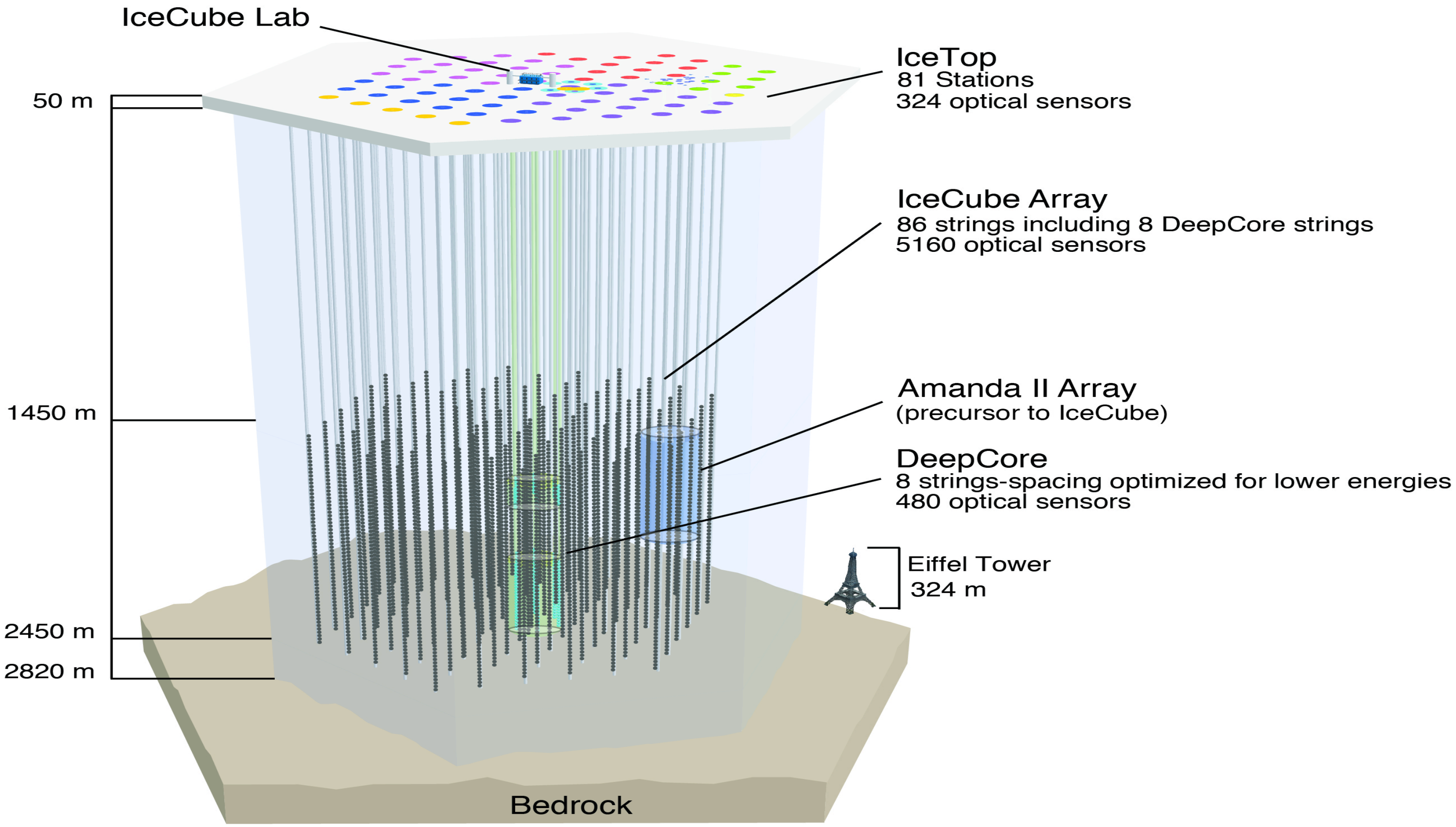
- **The IceCube Neutrino Observatory: Instrumentation and Online Systems**
  - https://arxiv.org/abs/1612.05093
- **Calibration and Characterization of the IceCube Photomultiplier Tube**
  - https://arxiv.org/abs/1002.2442
- **The IceCube Data Acquisition System: Signal Capture, Digitization, and Timestamping**
  - https://arxiv.org/abs/0810.4930
- **Measurement of South Pole ice transparency with the IceCube LED calibration system**
  - https://arxiv.org/abs/1301.5361
- **Energy Reconstruction Methods in the IceCube Neutrino Telescope**
  - https://arxiv.org/abs/1311.4767

IceCube

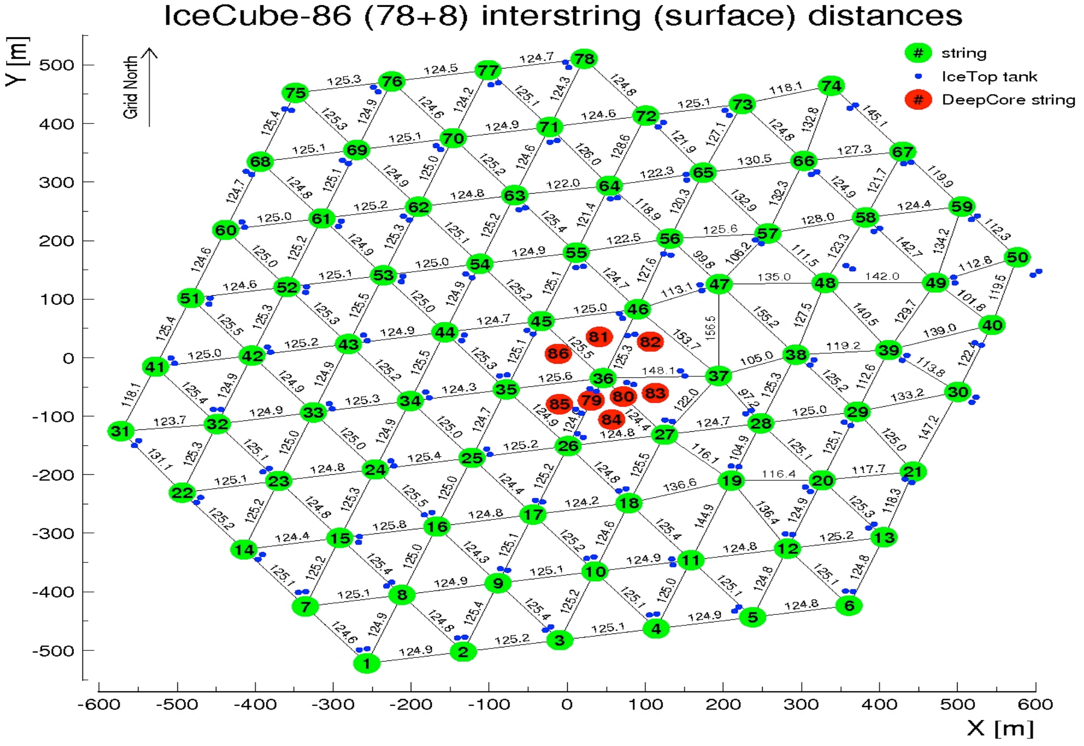
Strings are numbered 1-86

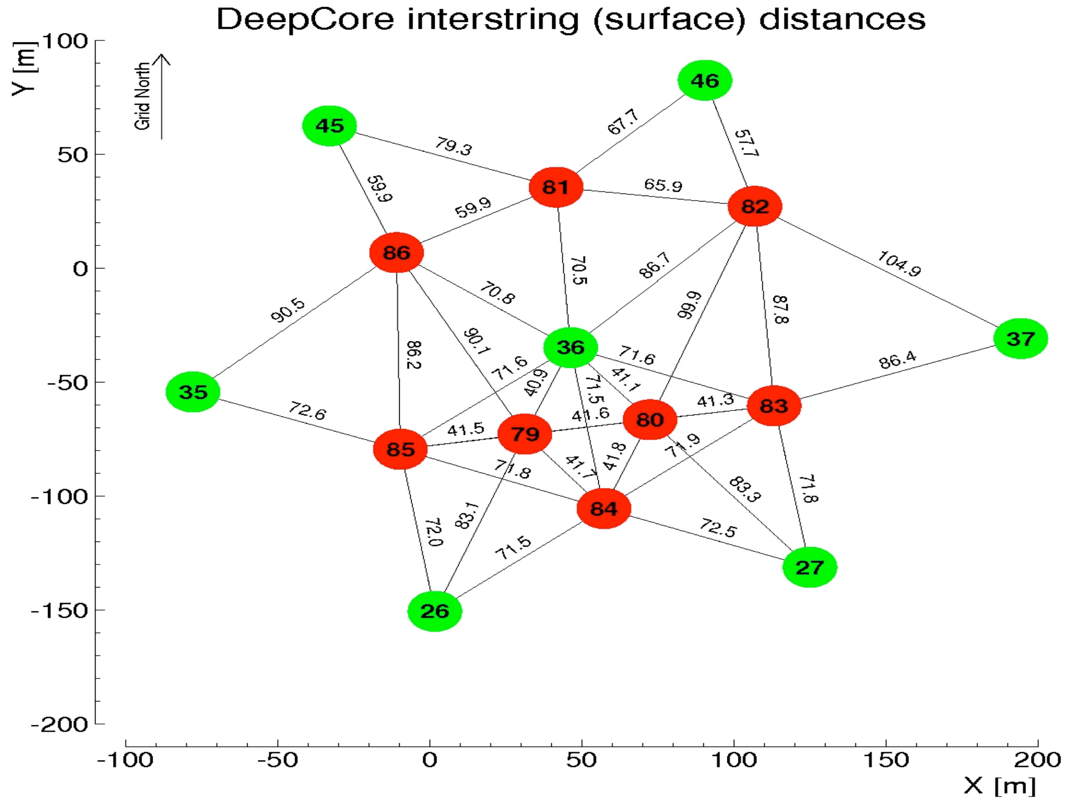
DOMs are numbered 1-60, top to bottom (in ice)

Surface (IceTop) DOMs are numbered 61-64, not used in flasher analysis

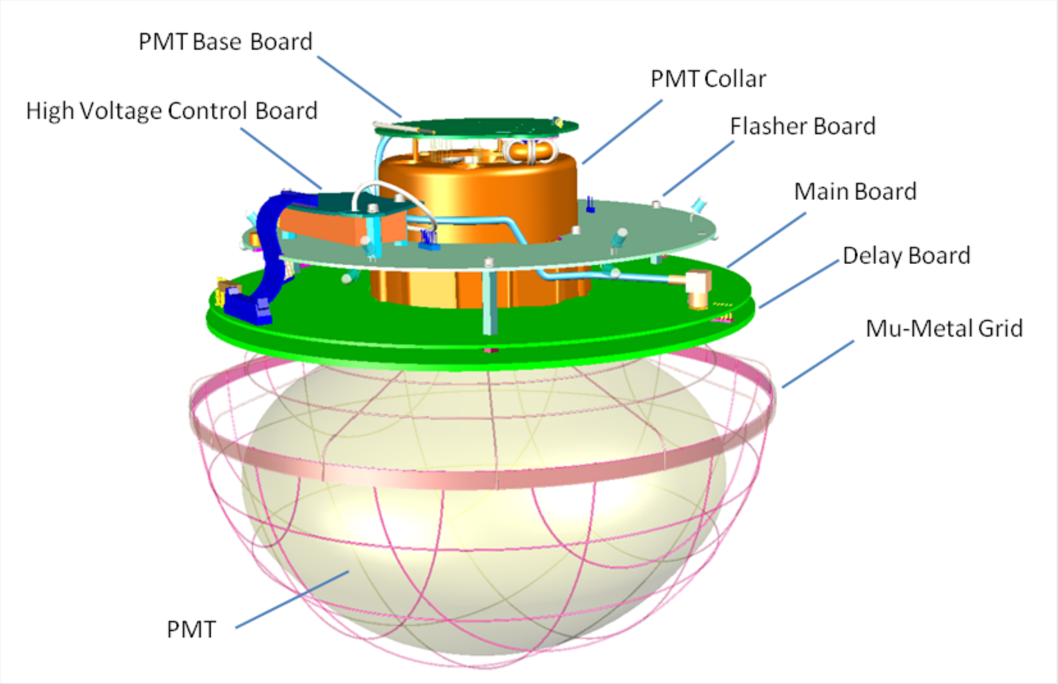


IceCube Strings





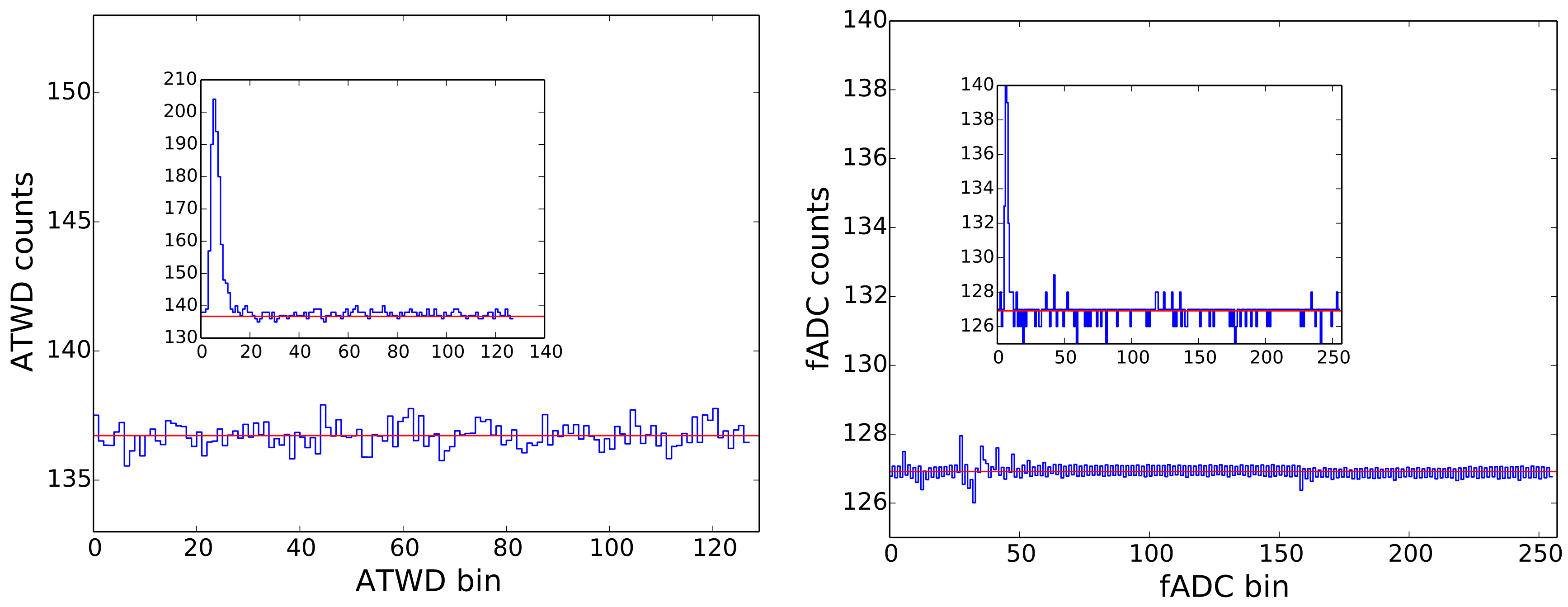
IceCube Digital Optical Module (DOM)



Every DOM in IceCube is equipped with flasher LEDs

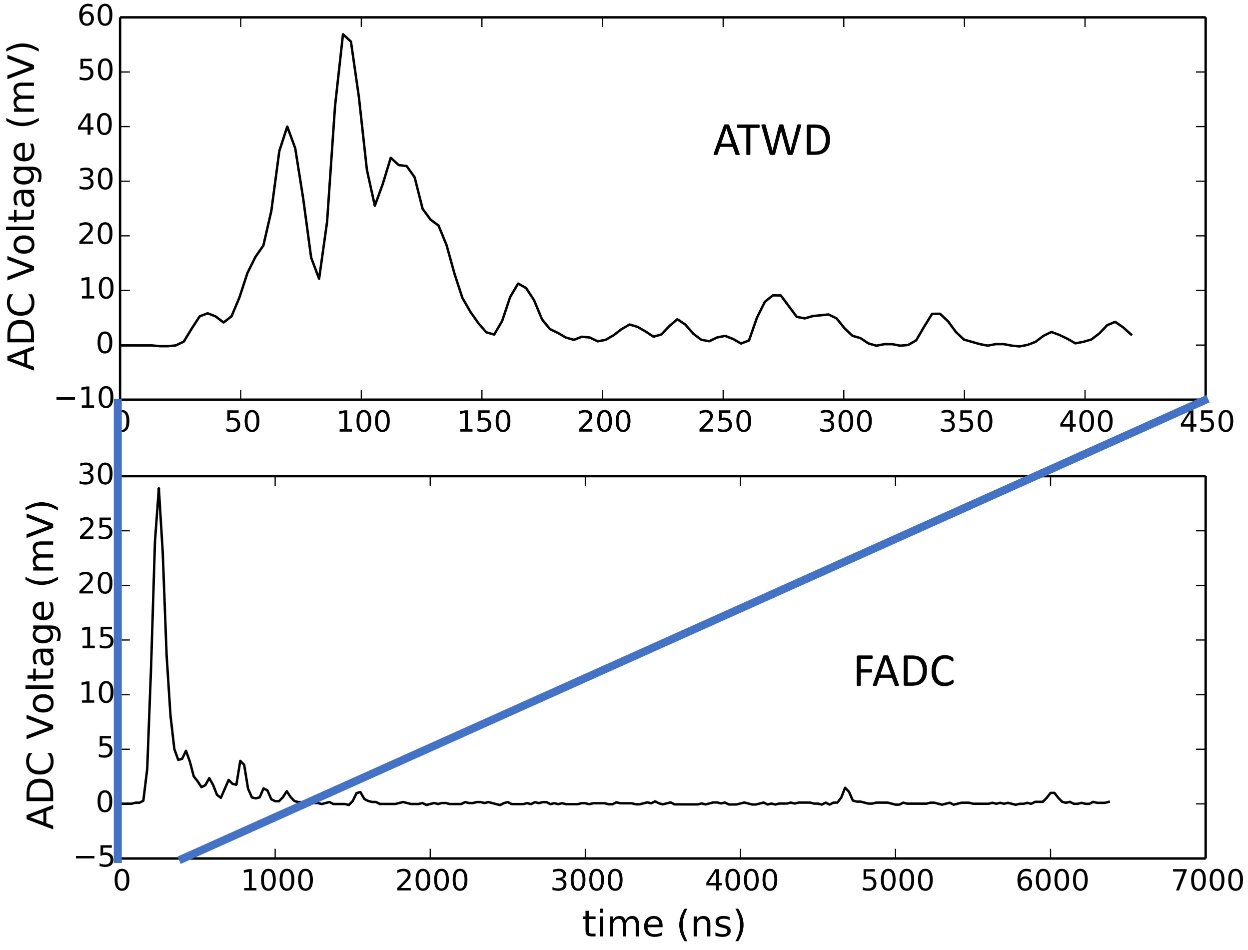
This gives us a controlled light source at every location in the detector

DOM Output: single photoelectron

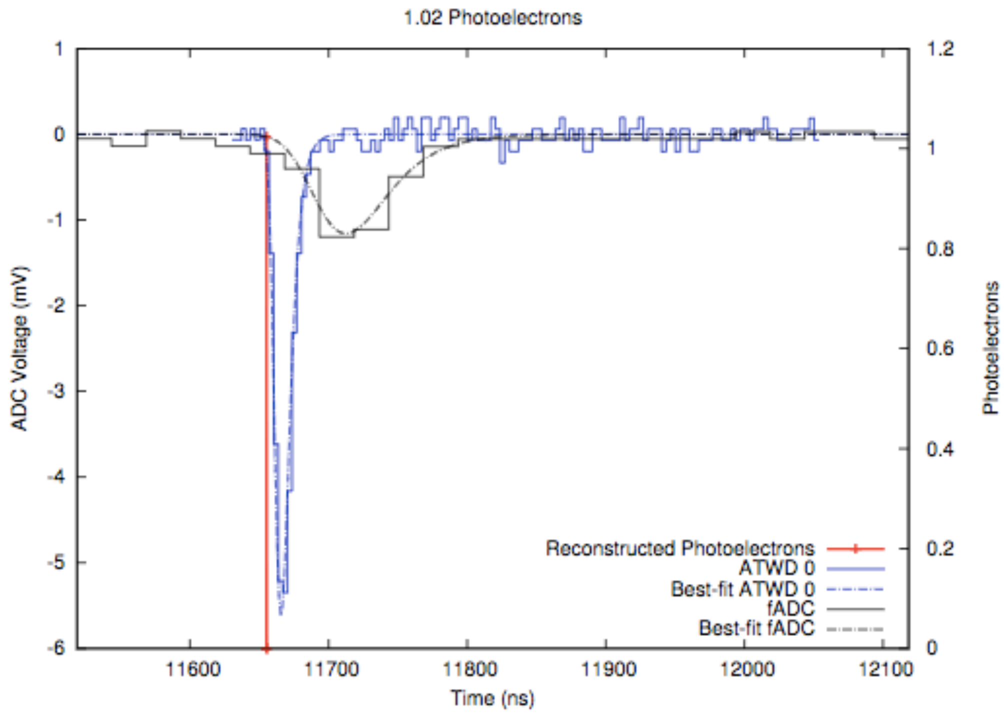


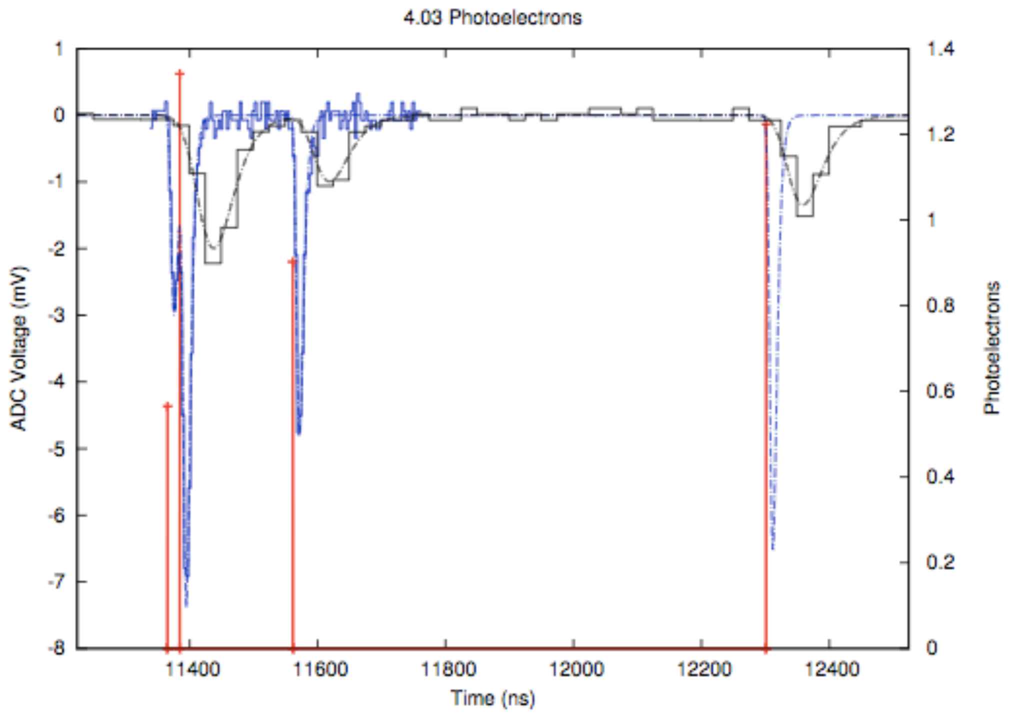
This is what we record when light hits the DOM: a waveform

DOM output: complex waveform

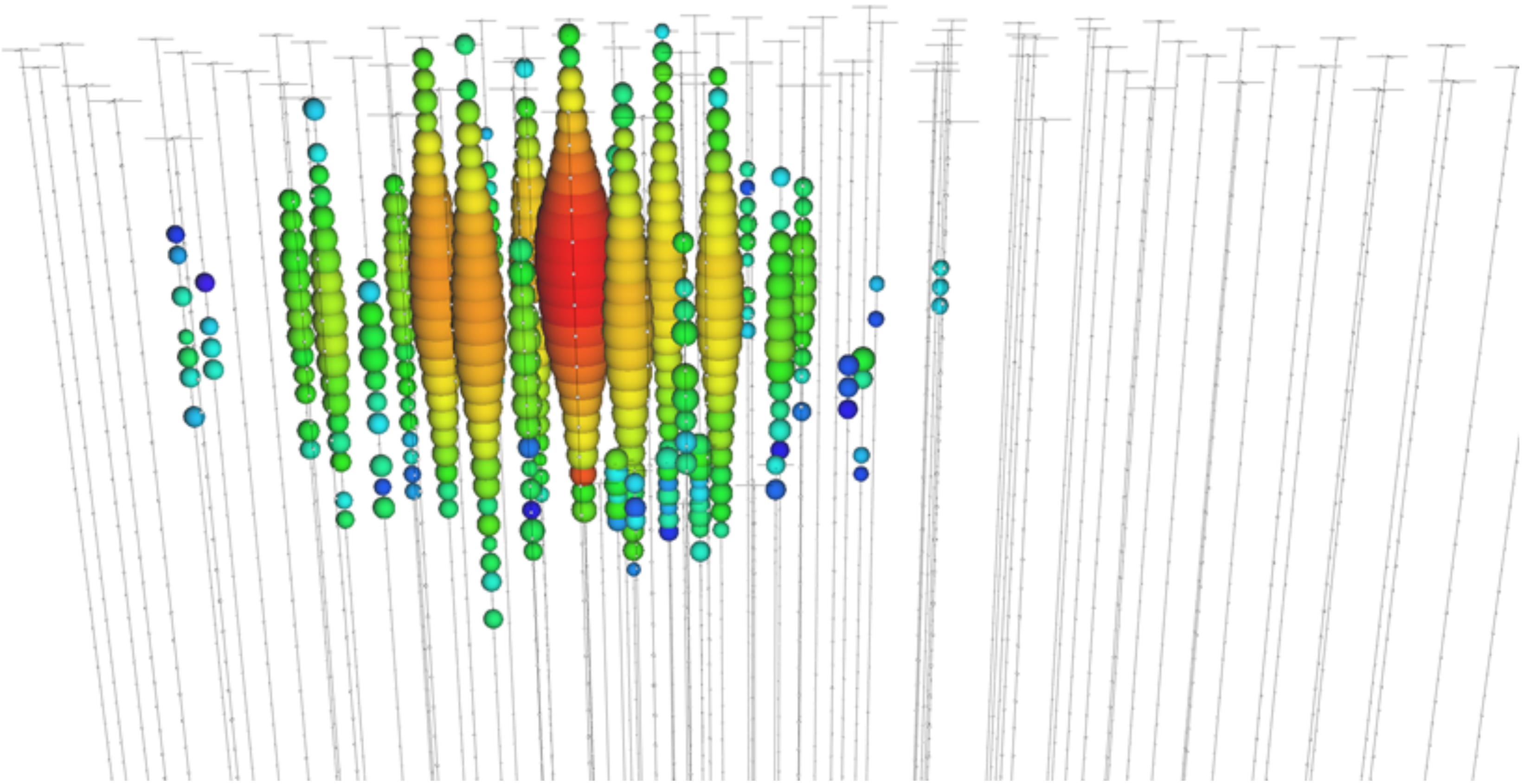


Waveforms to pulses





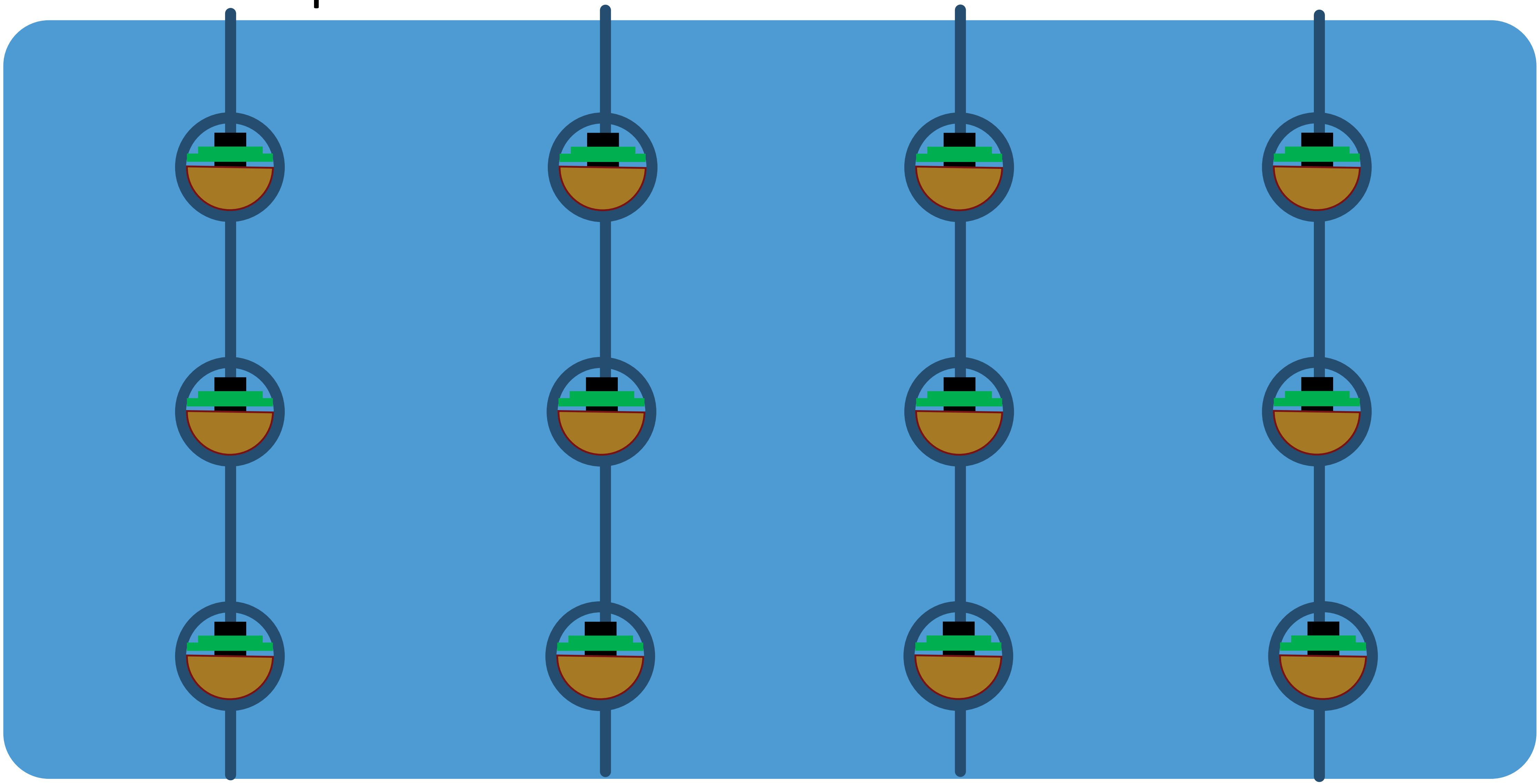
An IceCube neutrino (“Big Bird”)



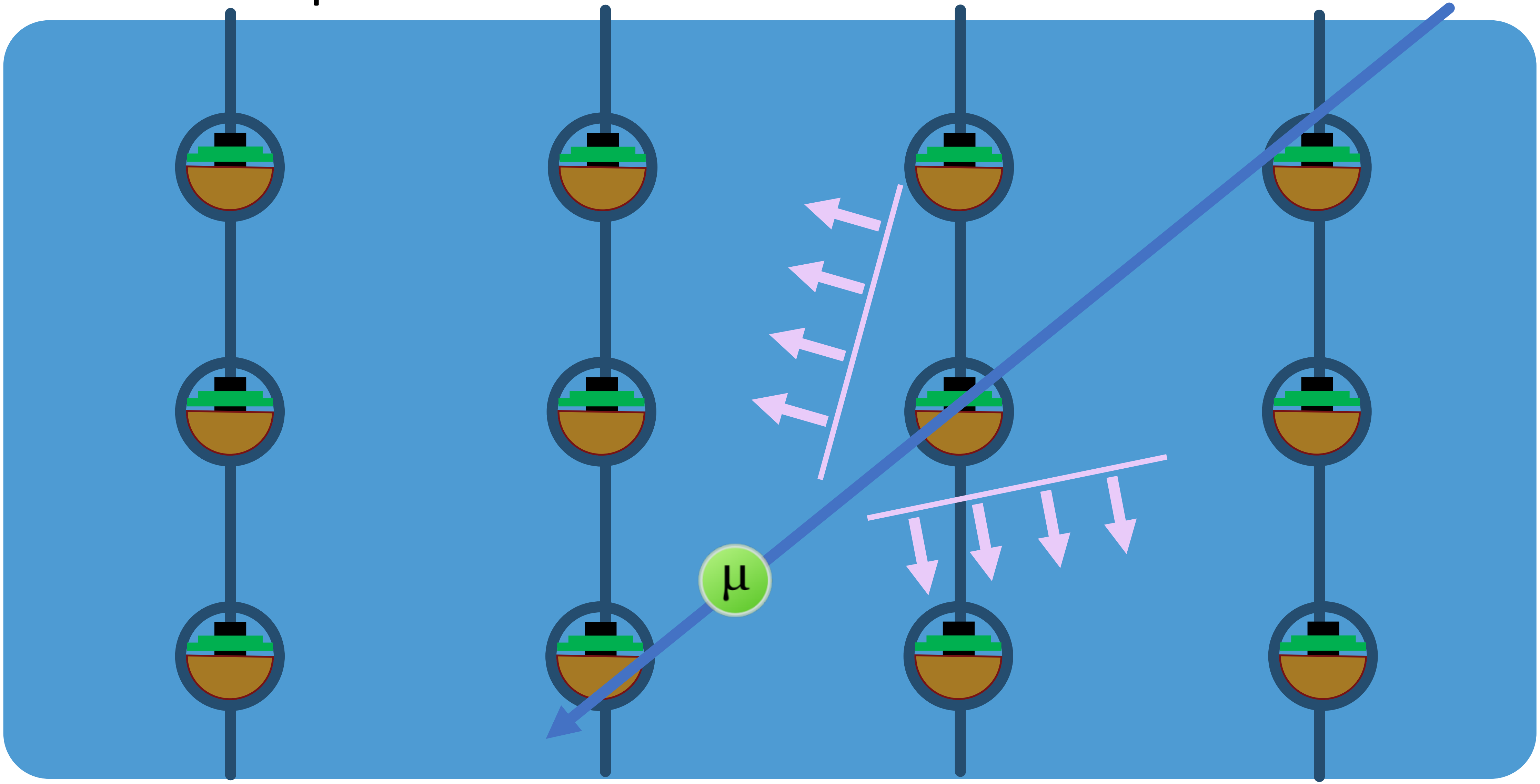
How do we know how much energy Big Bird has?

How do we know where it comes from?

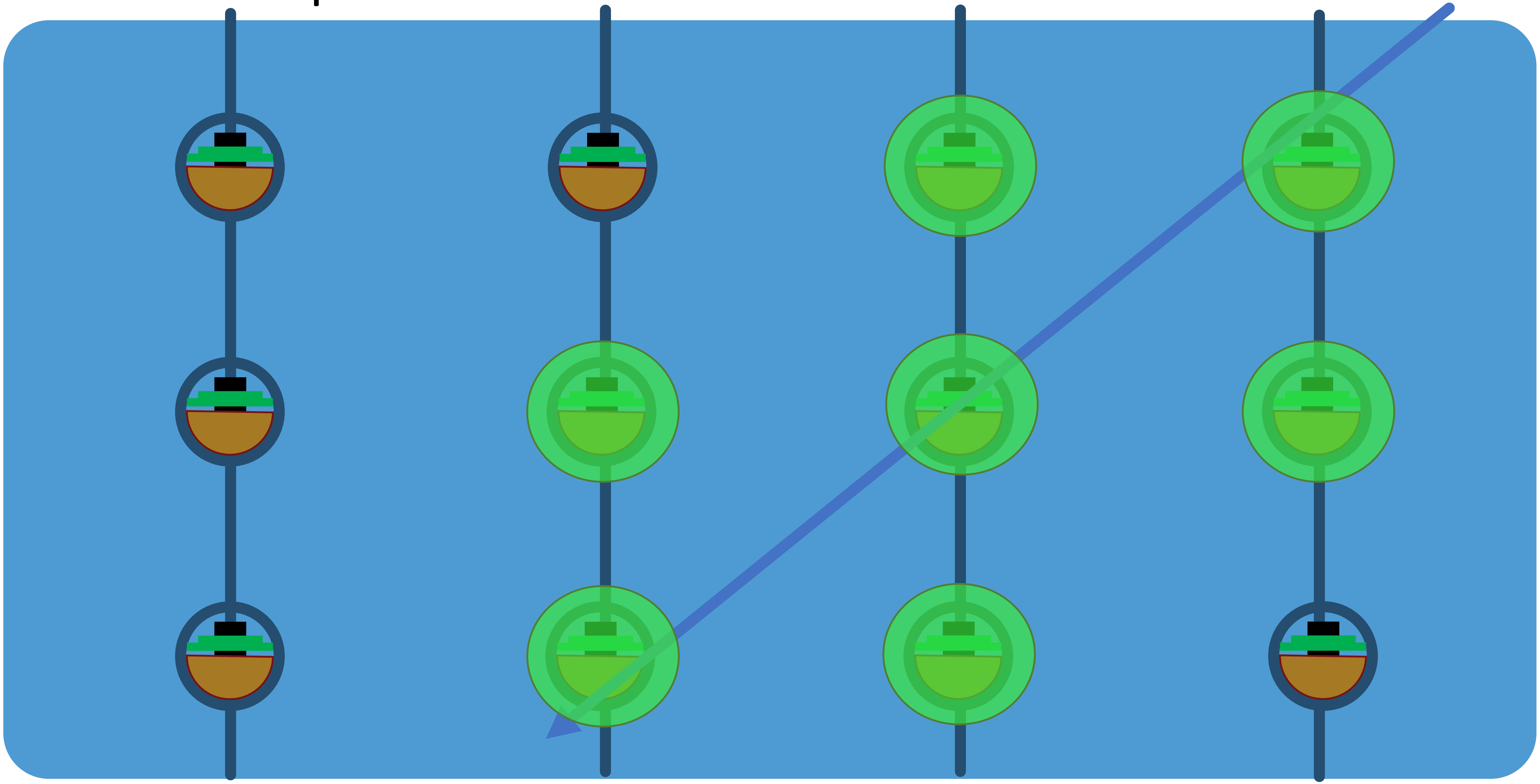
The ideal picture



The ideal picture



The ideal picture

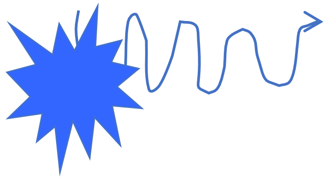


The ice model

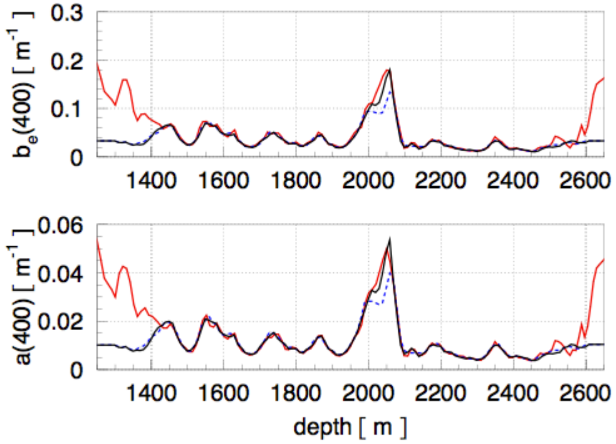
- For a complete history of the ice model see here https://wiki.icecube.wisc.edu/index.php/Ice_models

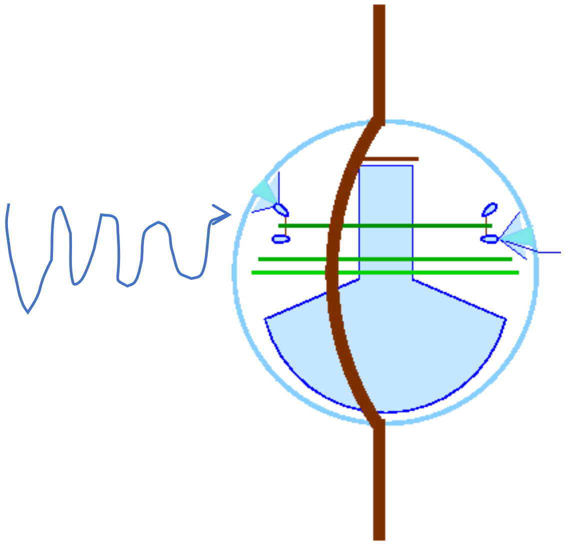
Calibration: from photon to data

Light
source



Propagation through ice





We need to know how light propagates in ice.

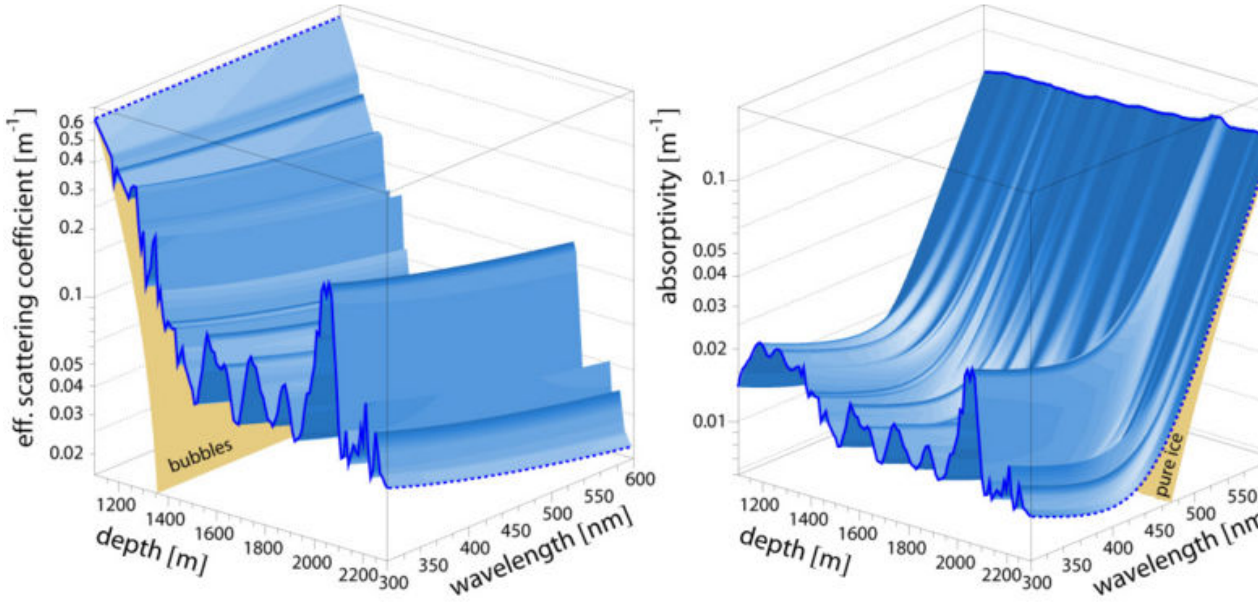
Major propagation processes are **absorption** and **scattering**

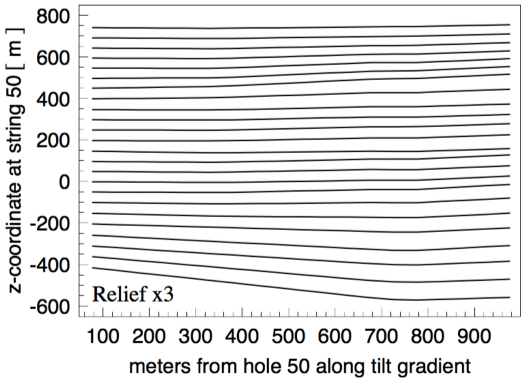
Ice vs. water

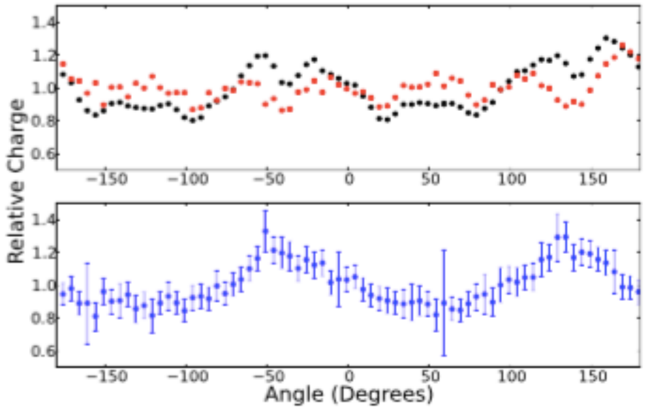
- This type of experiment can be done in water (DUMAND, ANTARES/NEMO/NESTOR → KM3NET, Baikal → GVD) or ice (AMANDA →IceCube)
- Water has good scattering properties, poor absorption properties
- Ice has good absorption properties, poor scattering properties
- Scattering affects direction, absorption affects energy
- Ice has practical advantages over water for detector construction, IceCube was the first cubic kilometer neutrino detector

The ice is complex…

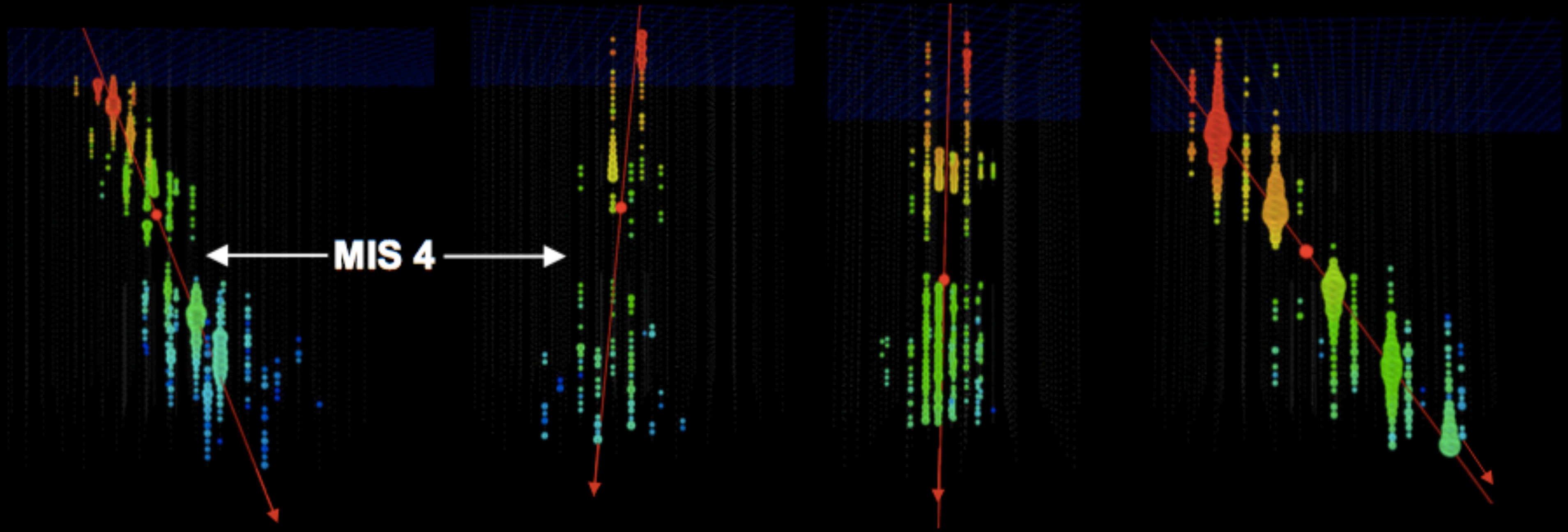
- No bubbles in undisturbed ice at IceCube depths (clathrates)
- Layers of dust cause depth-dependent scattering and absorption
- The dust layers are not horizontal…
- And the scattering is anisotropic…
- And the melted and refrozen ice in the holes has a bubble column in the center…



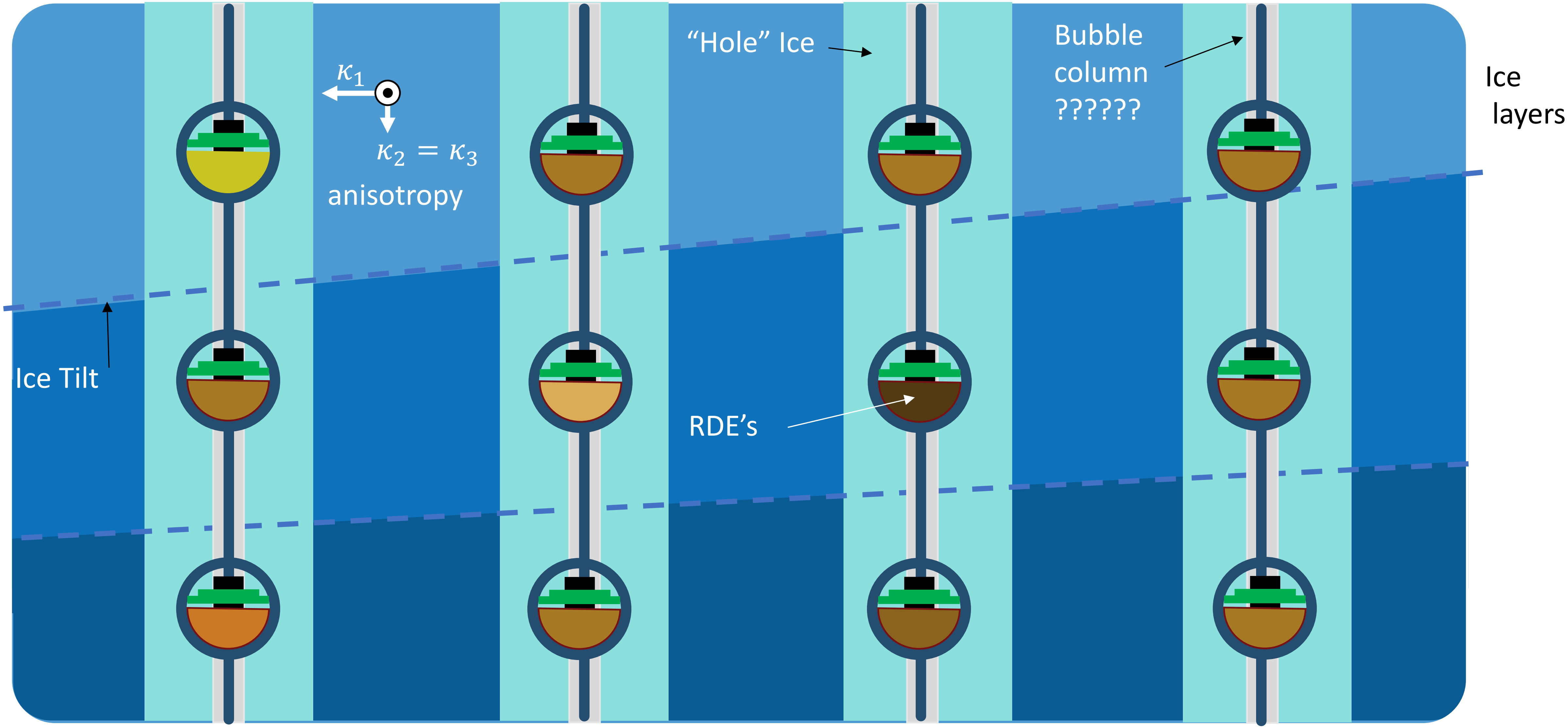




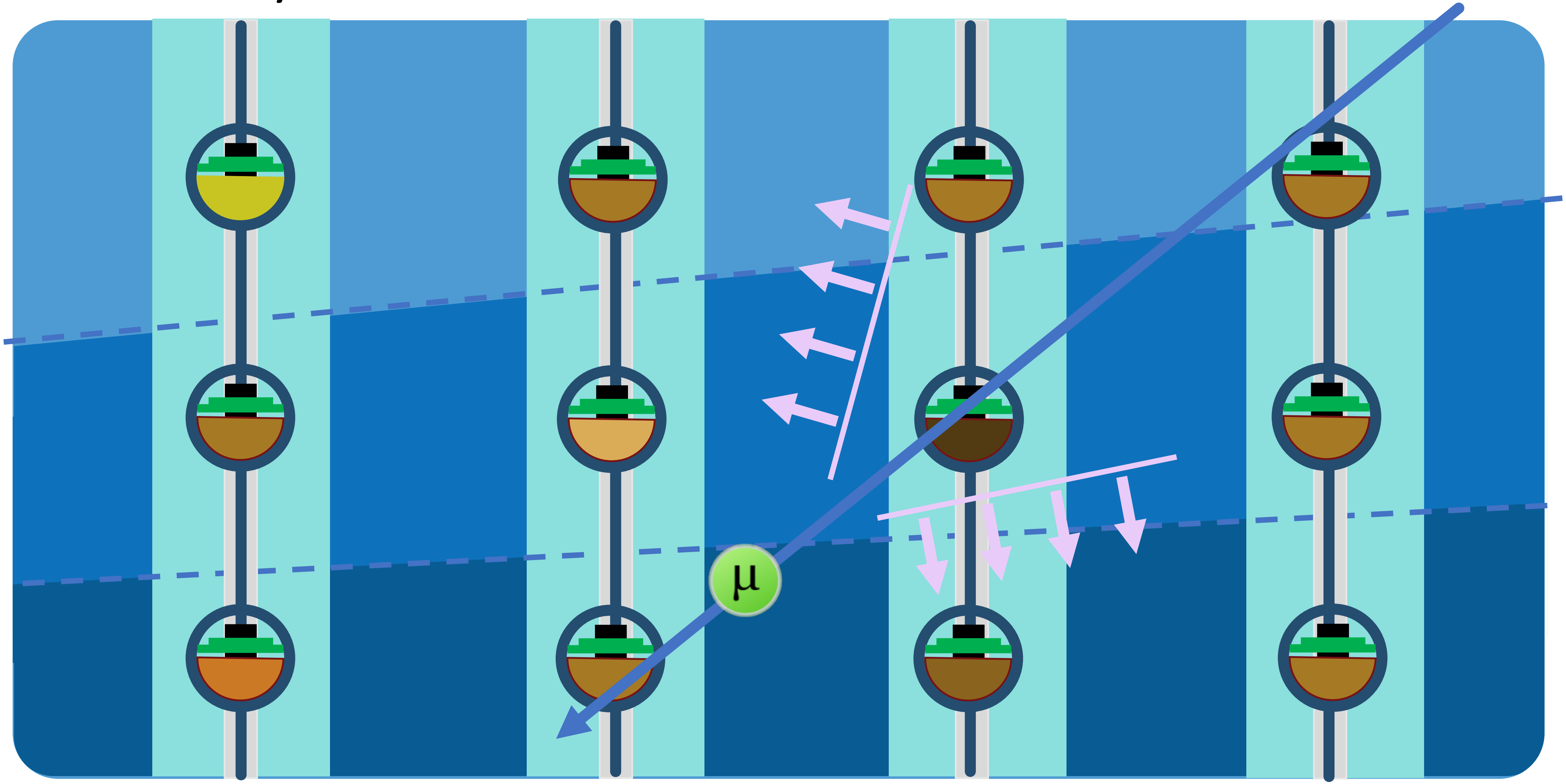
IceCube events and "The Dust Layer"



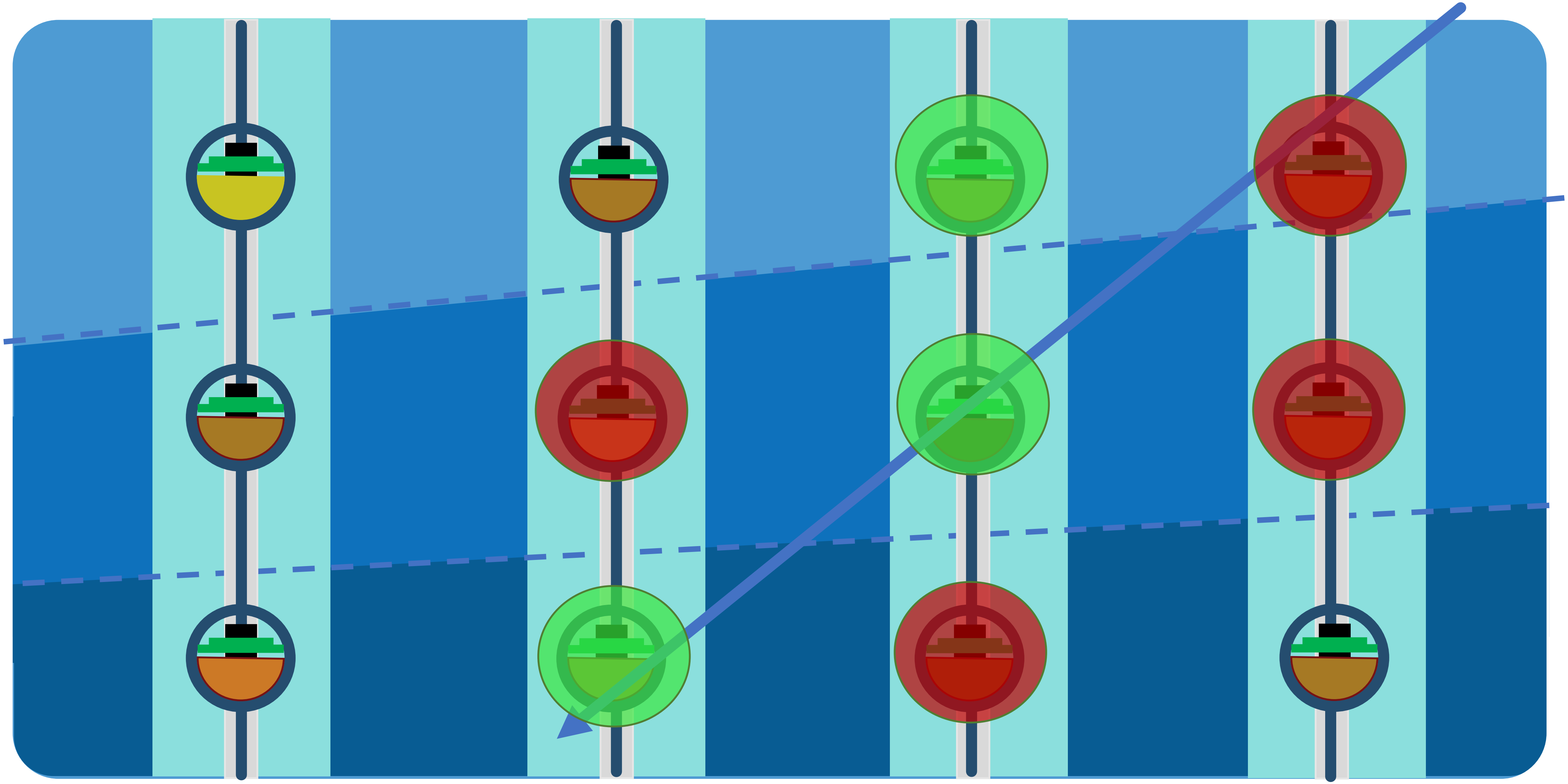
Our Understanding of IceCube's ice (as of 2017)



In Reality



In Reality



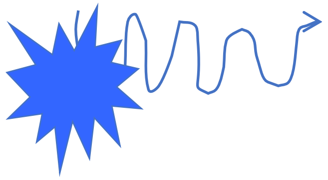
Sources of light in the ice

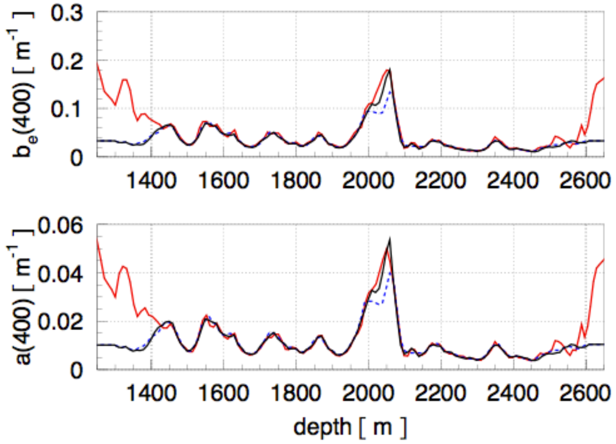
- The “dust logger” (deployment only)
- Occasional glowing due to the DOM HV supply (?)
- Dark noise – mostly single hits, mostly in the glass, radioactive decay, scintillation (hundreds of Hz per DOM)
- Cosmic ray muons (several kHz)
- Products from neutrino interactions
- Artificial light sources
  - LED flashers
  - Laser “standard candle” 💀
  - Laser lighting for the “Swedish camera” (R.I.P.)

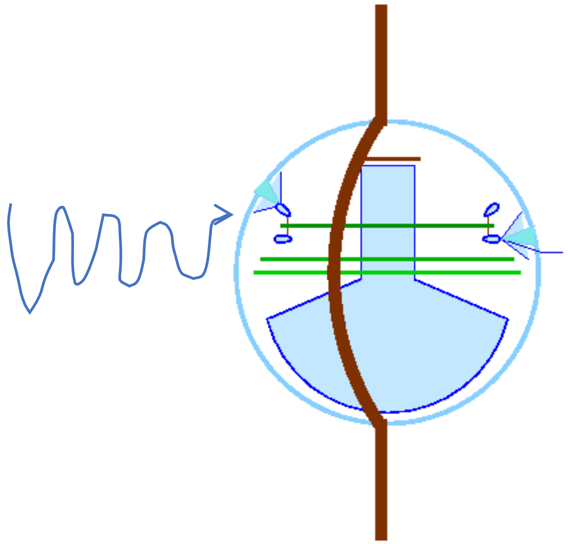
Calibration: from photon to data

Propagation through ice

Light source







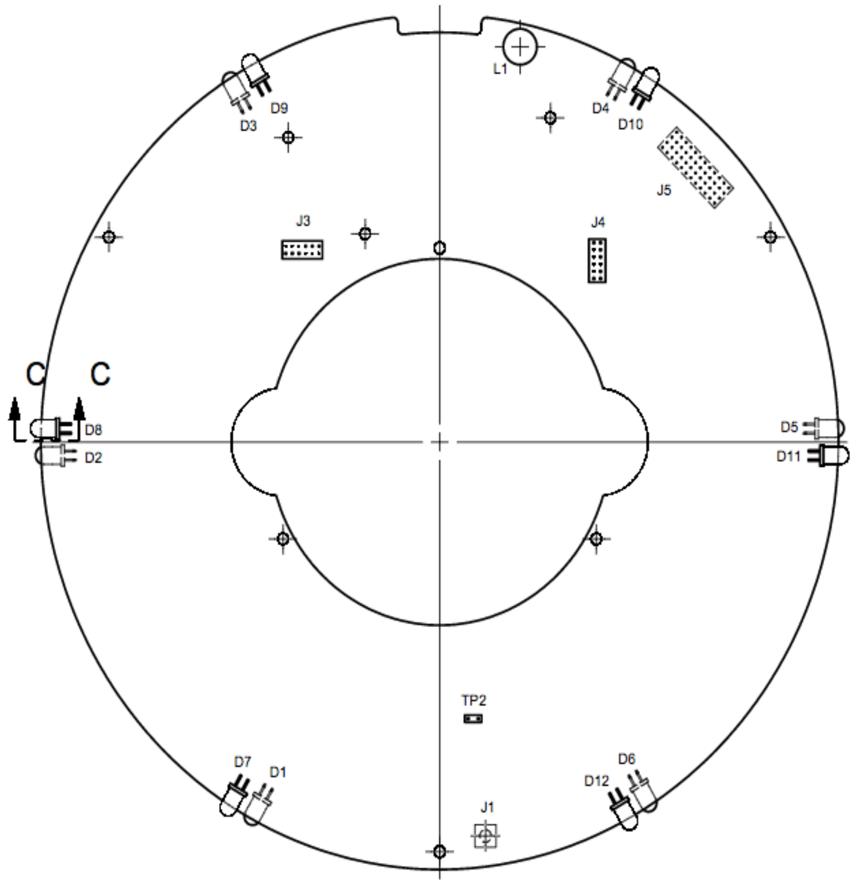
We use flashers:

1) To verify that DOMs are properly connected and functioning during commissioning
2) To verify the detector geometry
3) To study the optical properties of the ice
4) To study the response of the DOMs themselves

Flasher wiki references

- https://wiki.icecube.wisc.edu/index.php/Flashers
- https://wiki.icecube.wisc.edu/index.php/CDOM_Info

LED Flasher Board



12 LEDs

Arranged in pairs, evenly spaced 60° apart

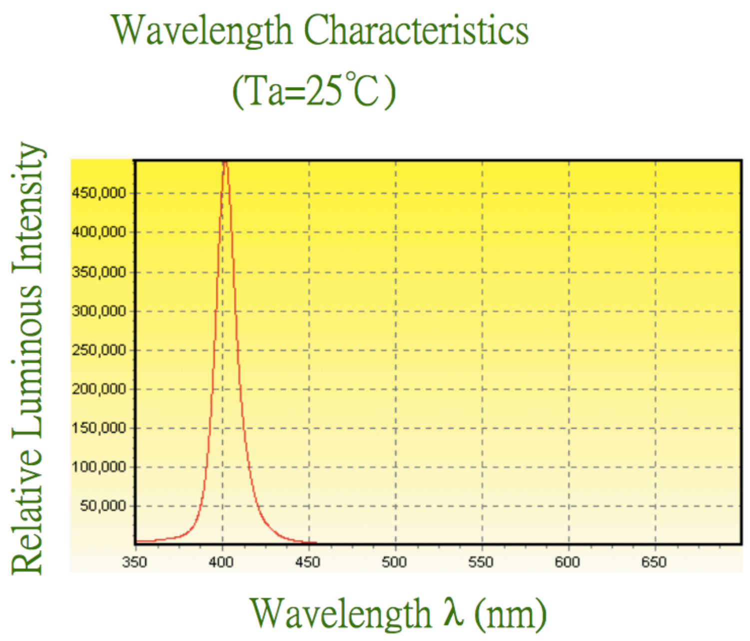
1&7, 2&8, 3&9, 4&10, 5&11, 6&12, going clockwise seen from above

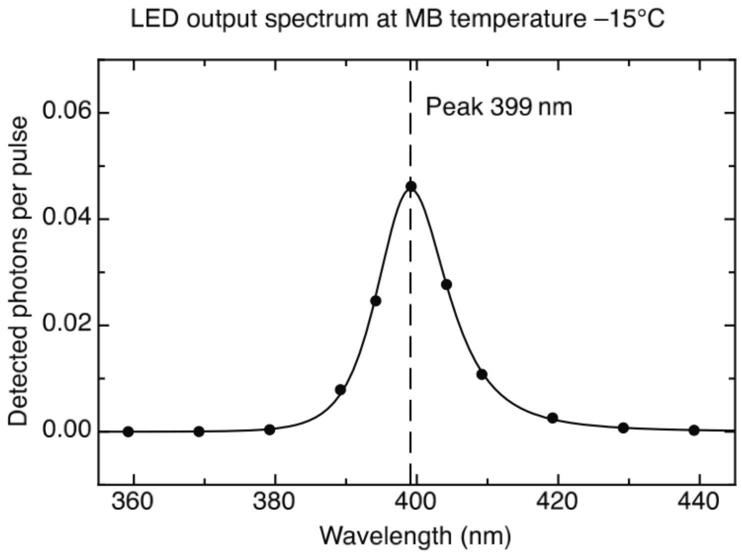
1-6 are tilted, upward at about 45° from horizontal

7-10 are horizontal

Flasher properties

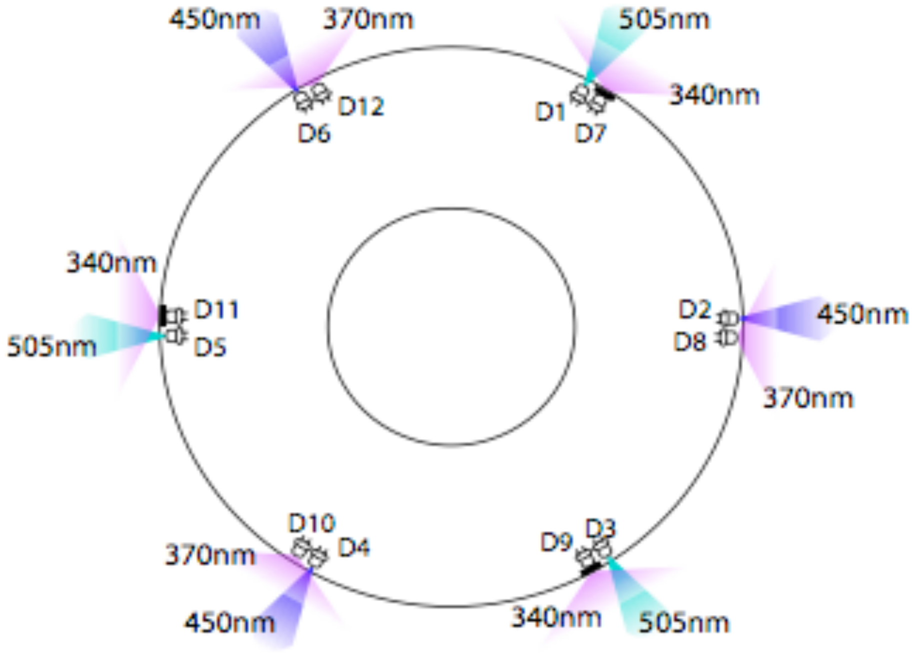
- The vast majority of IceCube LEDs are ETG-5UV405-30, nominally 405 nm wavelength, actually 399 nm, FWHM of 14 nm





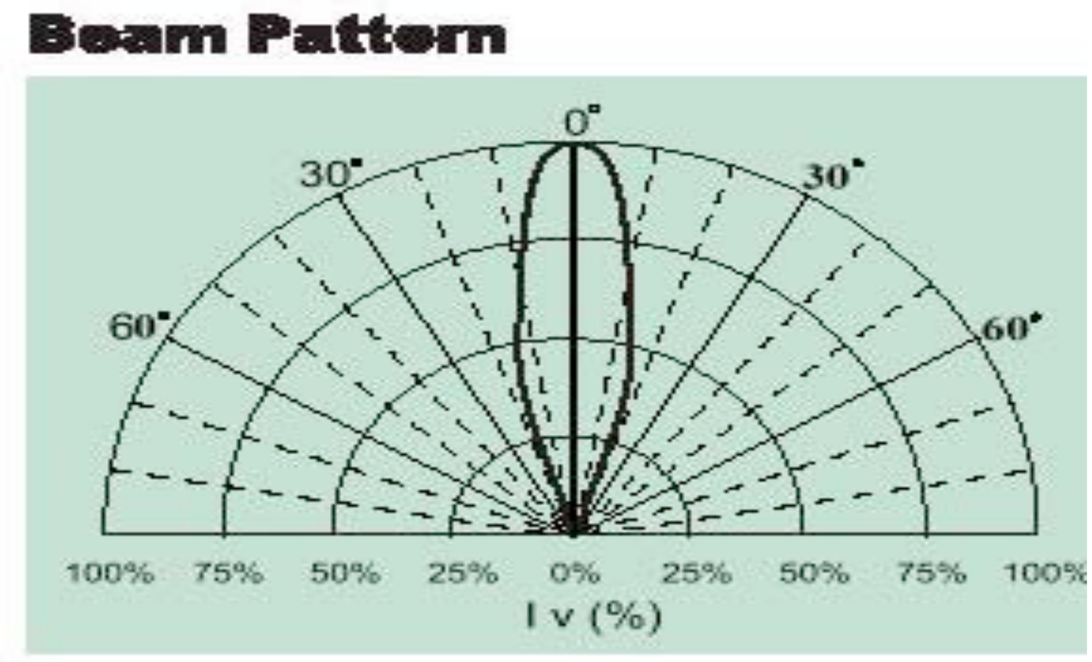
cDOMs

- 8 DOMs each on string 14 and string 79 have multiwavelength flashers called cDOMs
- See the CDOM wiki for the appropriate masks
- For the remainder of this lesson we will use the standard 400 nm flashers



Flasher properties: Angular emission profile (beam width)

- Nominal beam width is 30° in air
- In ice, accounting for refraction from air to glass and glass to ice, the beam width is 10°
- Can be modeled as a 2-D Gaussian with σ = 10° in both directions

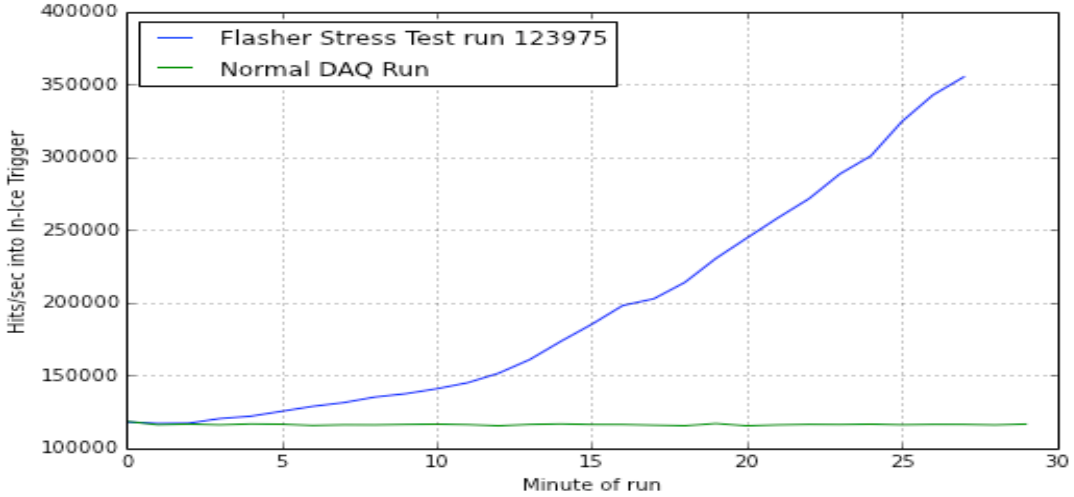


Flasher operating parameters

Parameter	Allowed values	Description
string	1 - 86	String where flashing DOM is located
DOM	1 – 60	Flashing DOM number
brightness	0 - 127	LED driver current intensity, up to 240 mA
width	0 - 127	2x duration of LED current pulse, in ns
mask	0001 - 0FFF	Hex representation of bitmask controlling which LEDs flash
rate	0 - 610	Rate of LED flashes in Hz

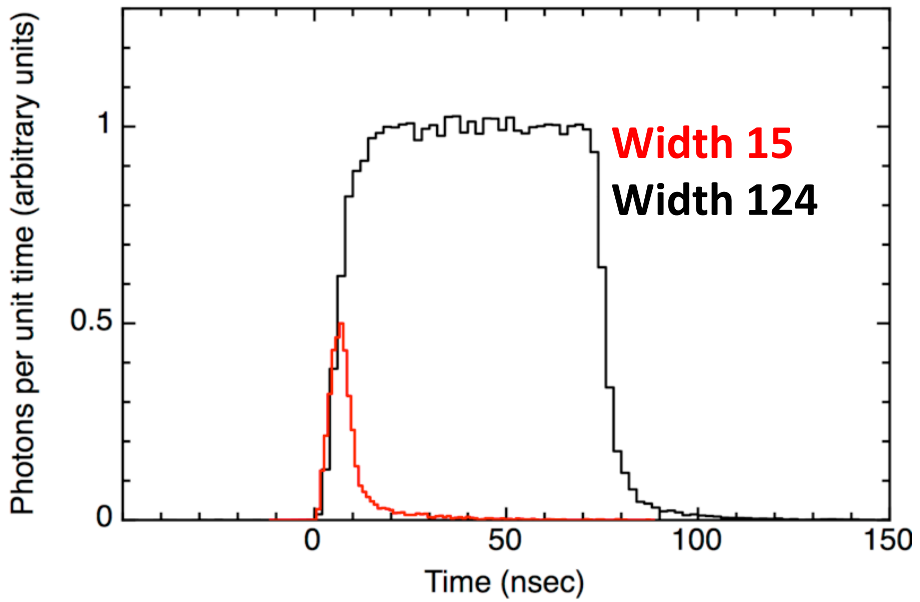
Flasher operation: String and DOM

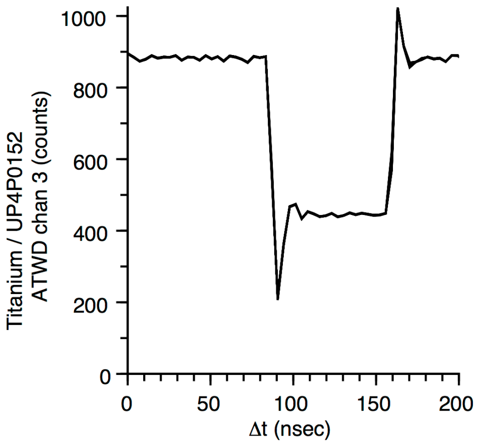
- Multiple flashers can be run simultaneously
- The data acquisition system can withstand about 3x the normal background rate from muons (~70 bright flashing DOMs simultaneously)
- A typical run might have a few to ~30 flashers simultaneously
- Neighboring flashers on the same string cannot run simultaneously
- Old DOMs (produced in 2004 and 2005) have “afterburst” properties which make them difficult to run
- Flashers cannot be synchronized using the current firmware



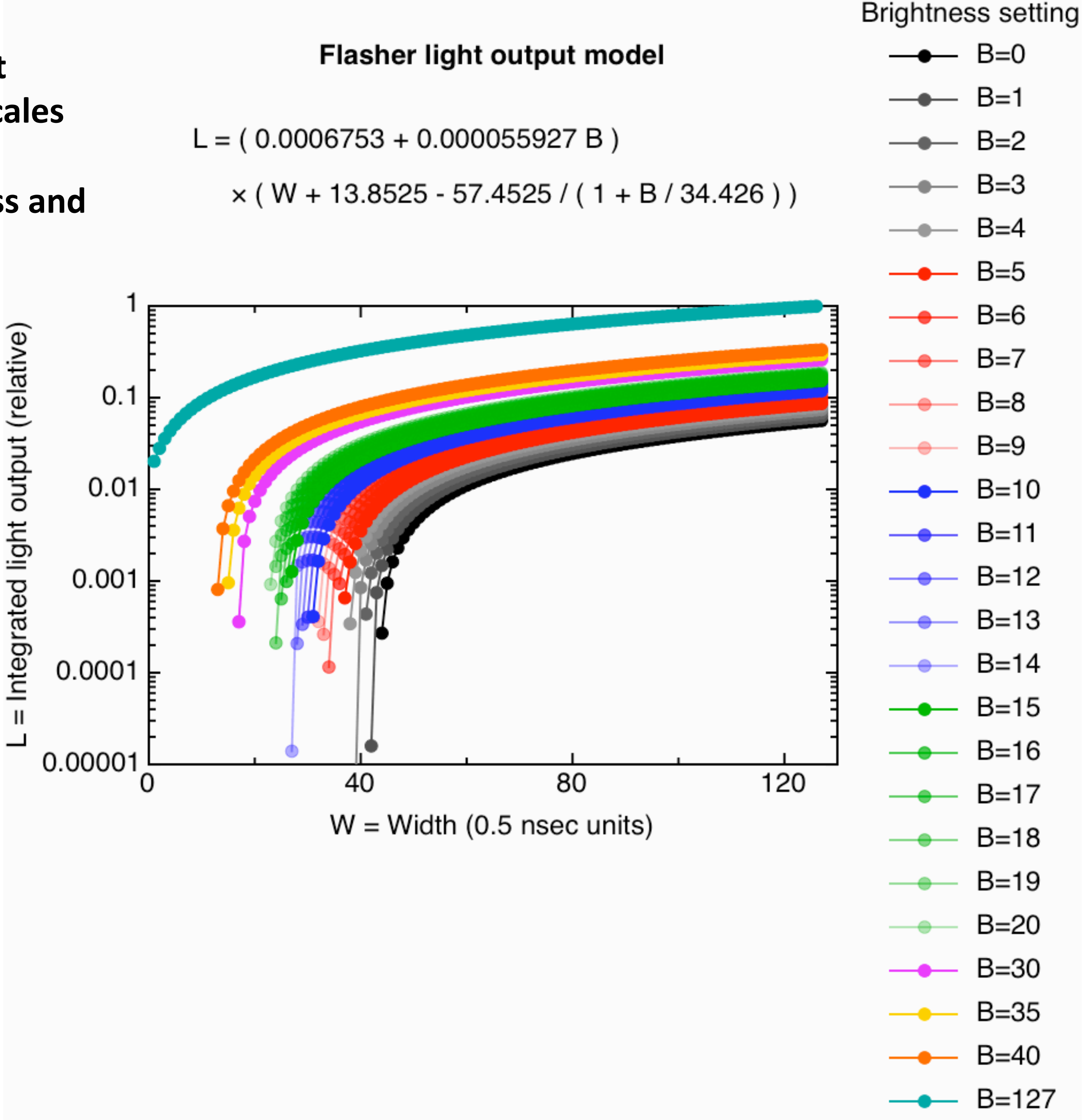
Running flashers: brightness and width

- Maximum photon output per LED is 1.17e10 photons per flash
- With all 12 LEDs running this is about equal to a 500 TeV cascade
- The brightness and width parameters determine the photon output
  - Width: duration of driver current, effectively 10-70 ns
  - Brightness: amplitude of driver current, up to 240 mA





How light output scales with brightness and width



Running flashers: mask

The 12 LEDs can be run in an combination. Each LED is controlled by a bit, and the “mask” is the hex representation of the bits

Example: flash LED 7 only

horizontal tilted

LED	12	11	10	9	8	7	6	5	4	3	2	1
Bit	0	0	0	0	0	1	0	0	0	0	0	0

HEX mask is 0064

Running flashers: mask

The 12 LEDs can be run in an combination. Each LED is controlled by a bit, and the “mask” is the hex representation of the bits

Example: flash all tilted LEDs

	horizontal						tilted					
LED	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Bit	0	0	0	0	0	0	1	1	1	1	1	1

HEX mask is 003f

Running flashers: mask

The 12 LEDs can be run in an combination. Each LED is controlled by a bit, and the “mask” is the hex representation of the bits

Example: flash all horizontal LEDs

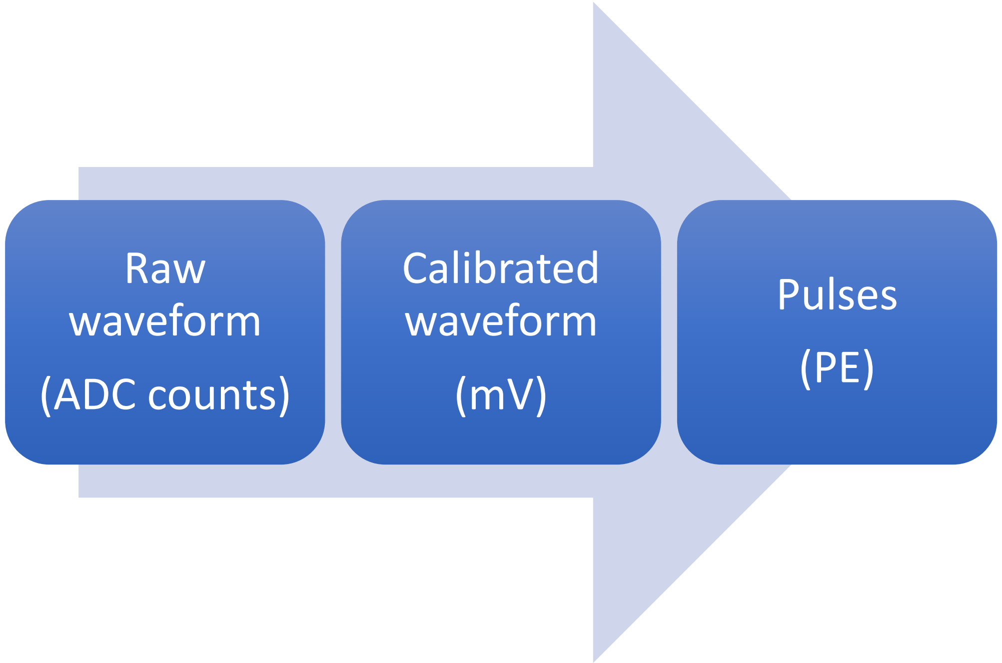
	horizontal						tilted					
LED	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Bit	1	1	1	1	1	1	0	0	0	0	0	0

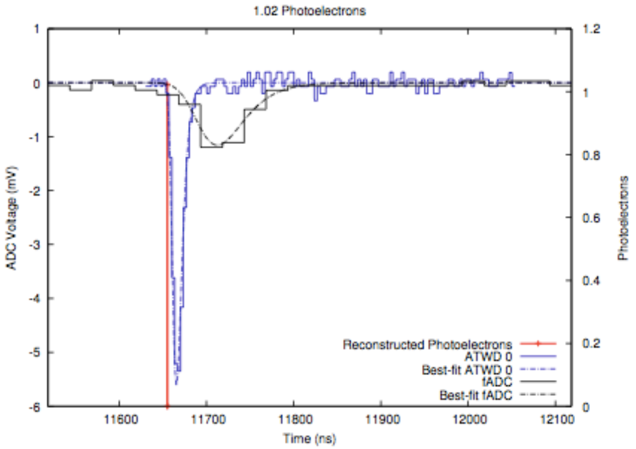
HEX mask is 0fc0

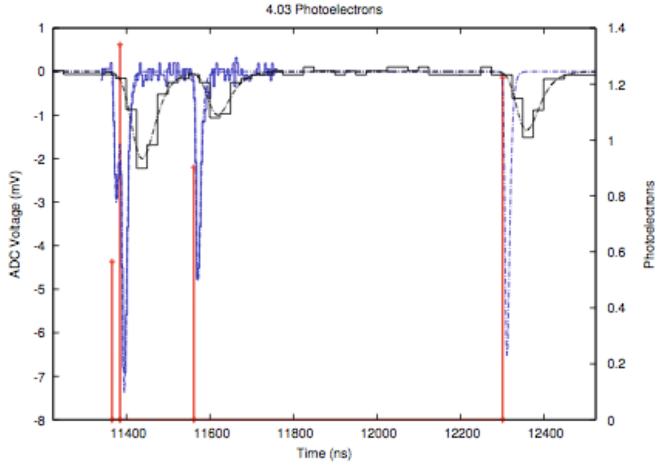
Running flashers: rate

- Maximum rate is 610 Hz, lower rates are 610 Hz divided by a power of 2
- The setting in the configuration is an integer, the actual value of the rate is the next lowest value to that integer which is 610 divided by a power of 2
- So for example if the rate setting is 2, the actual rate is 1.191 Hz = 610 Hz/2^9

Flasher data processing





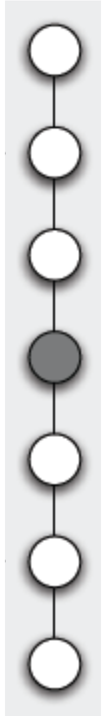


We will now look at some flasher data and do some exercises to look at the pulses detected by neighboring DOMs from a flasher.

Backup

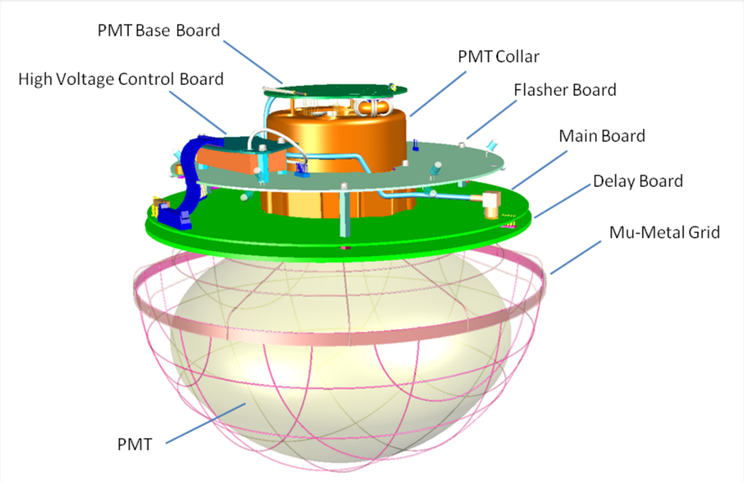
Vocabulary

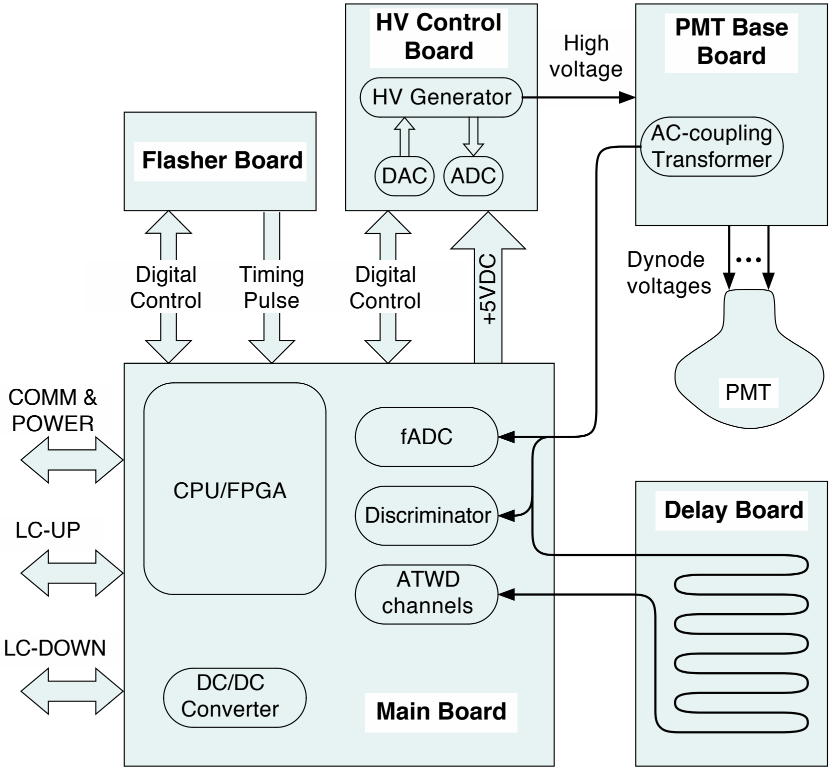
- DOM = digital optical module
  - Basic sensor unit
- String = cable with 60 DOMs
  - 86 strings in final detector
- IceTop = surface detector
- InIce = all strings
- DeepCore = closely spaced center strings



Vocabulary

- Photomultiplier tube or PMT = light detector
- HV = high voltage
- Photoelectron: an electron ejected from a metal surface in the PMT by a photon
- Mainboard = digitizing electronics
- ATWD = analog transient waveform digitizer
  - 128 samples, 3 ns per sample
- FADC = fast analog to digital converter
- Waveform = digitized current pulse
- Timestamp = time a waveform was recorded
- Flashers = onboard LEDs for calibration





IceCube PMT

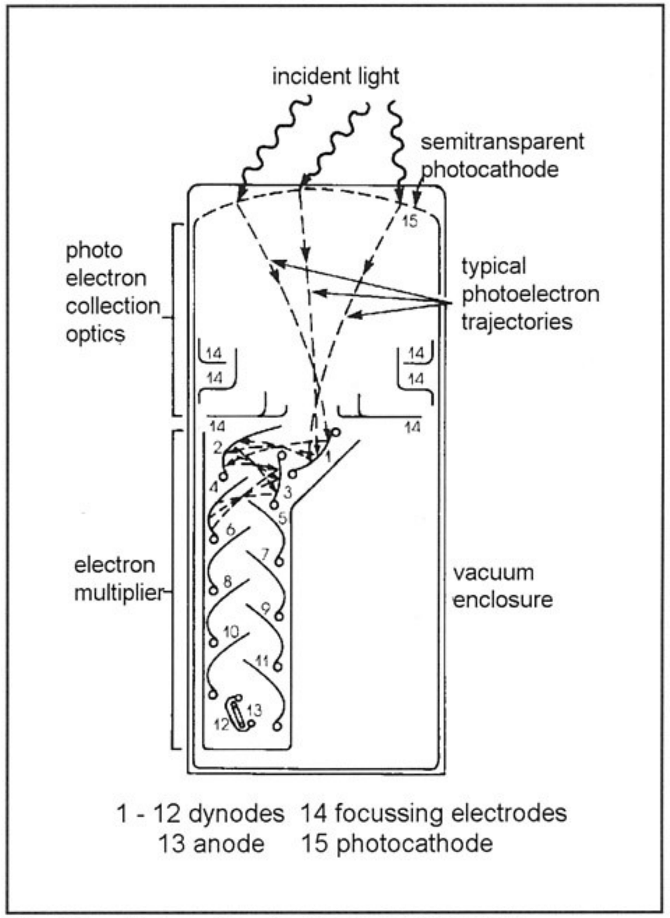
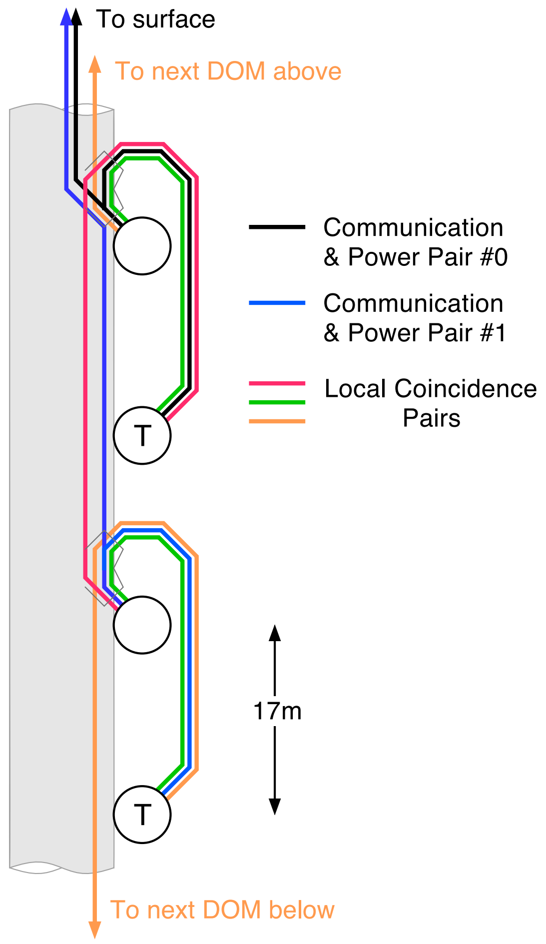


Fig. 4.1 Schematic of a photomultiplier tube.

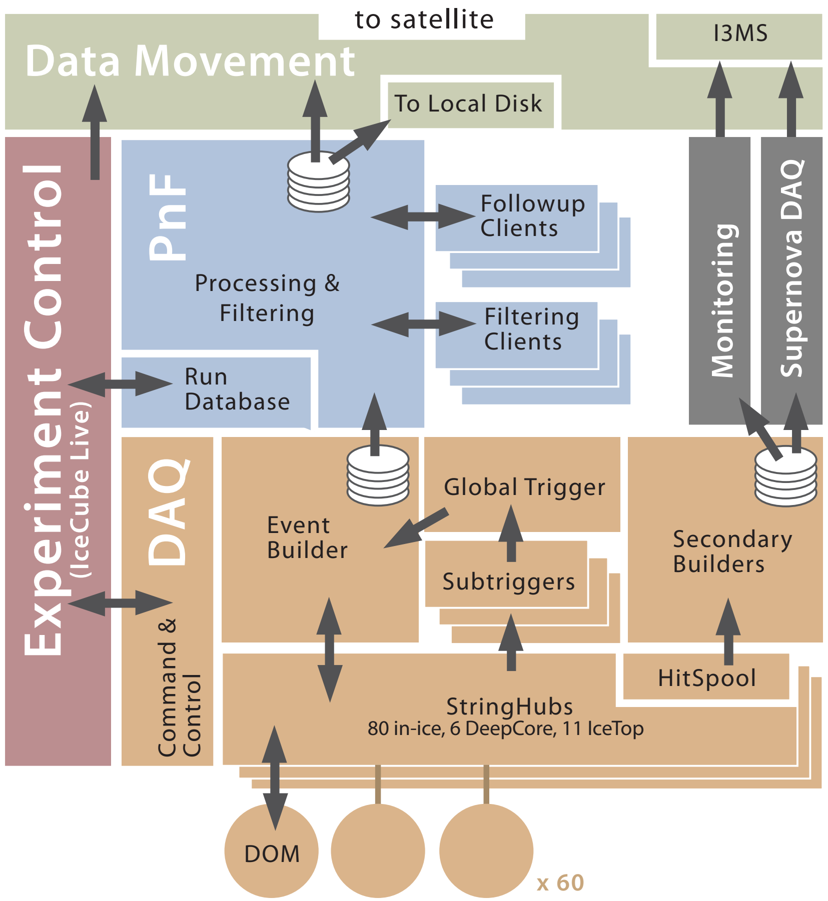
Vocabulary

- Hit = single DOM sees light (threshold = 0.25 PE)
- Local coincidence = neighboring DOMs see light within a certain time window
- Hard Local Coincidence (HLC) = no information is sent on unless local coincidence condition is met
- Soft Local Coincidence (SLC) = only minimal information is sent on unless local coincidence condition is met
- These decisions are all made in the ice by the onboard electronics



Vocabulary

- Trigger = multiple DOMs hit in a certain pattern or time window
  - Simple majority (SMT) = some number of DOMs hit, currently 8, i.e. SMT8
  - Calibration trigger = flashers
  - Minimum bias/minbias trigger = capture whatever is in the detector regardless of pattern
  - Many others



Vocabulary

- Event = all information captured within a certain time window around a trigger
  - An event may have multiple triggers
- Event Builder = software that constructs events
- Processing and filtering (PNF) = software that runs online data reduction
- Online = realtime data processing
- Offline = non-realtime data processing