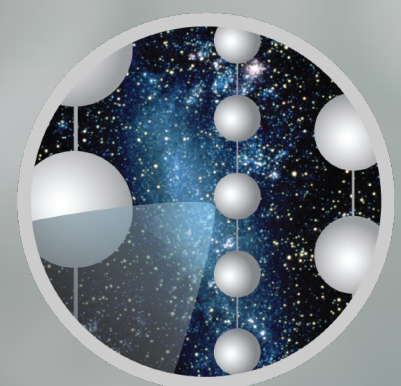


The Camera System for the IceCube Upgrade

Woosik Kang on behalf of the IceCube Collaboration



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



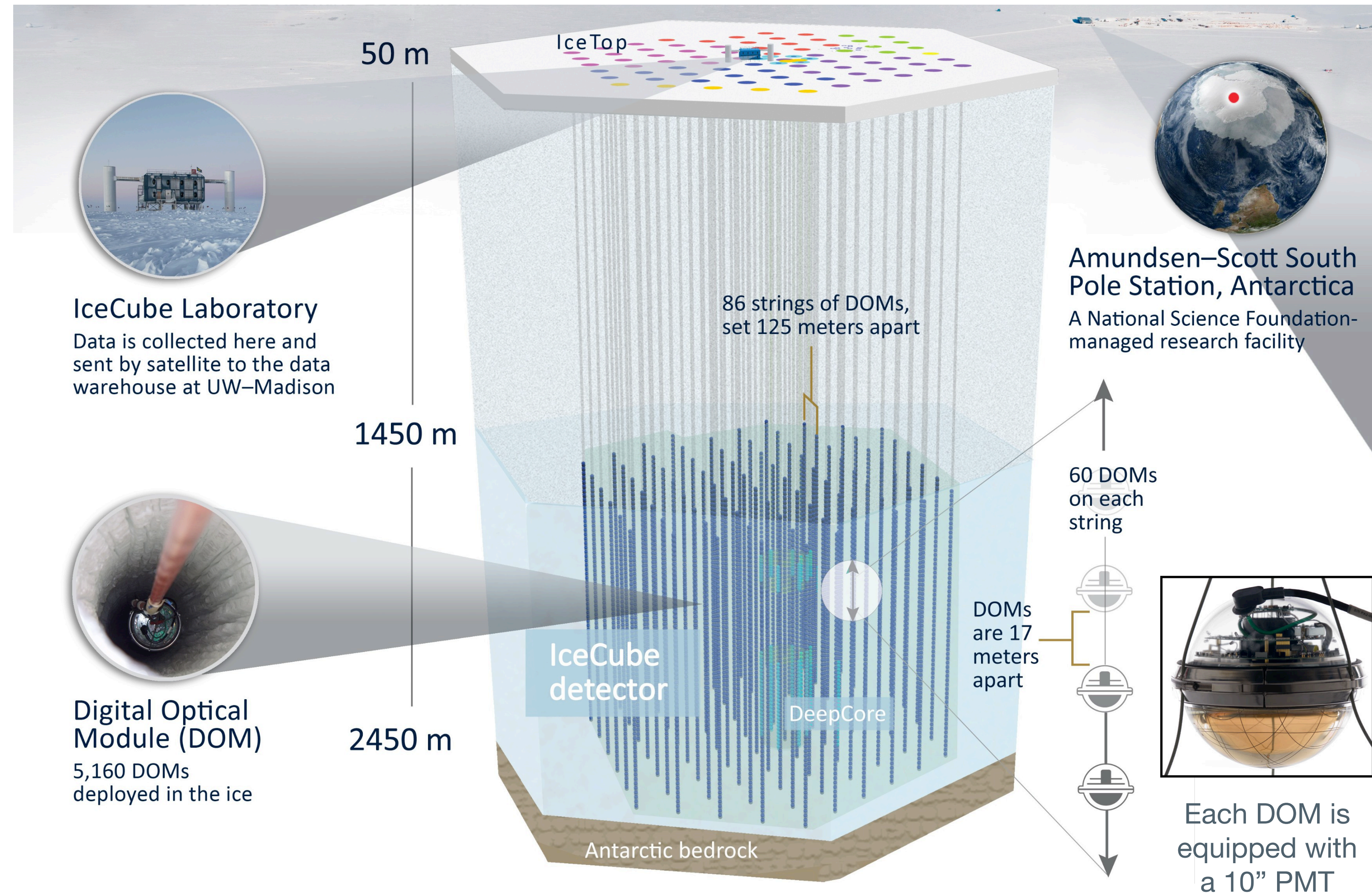
성균관대학교
SUNGKYUNKWAN UNIVERSITY(SKKU)

NuFACT 2022 – WG6: Detectors
Snowbird, UT
August. 5th, 2022

IceCube Neutrino Observatory

Woosik Kang
NuFACT 2022
August. 5th, 2022

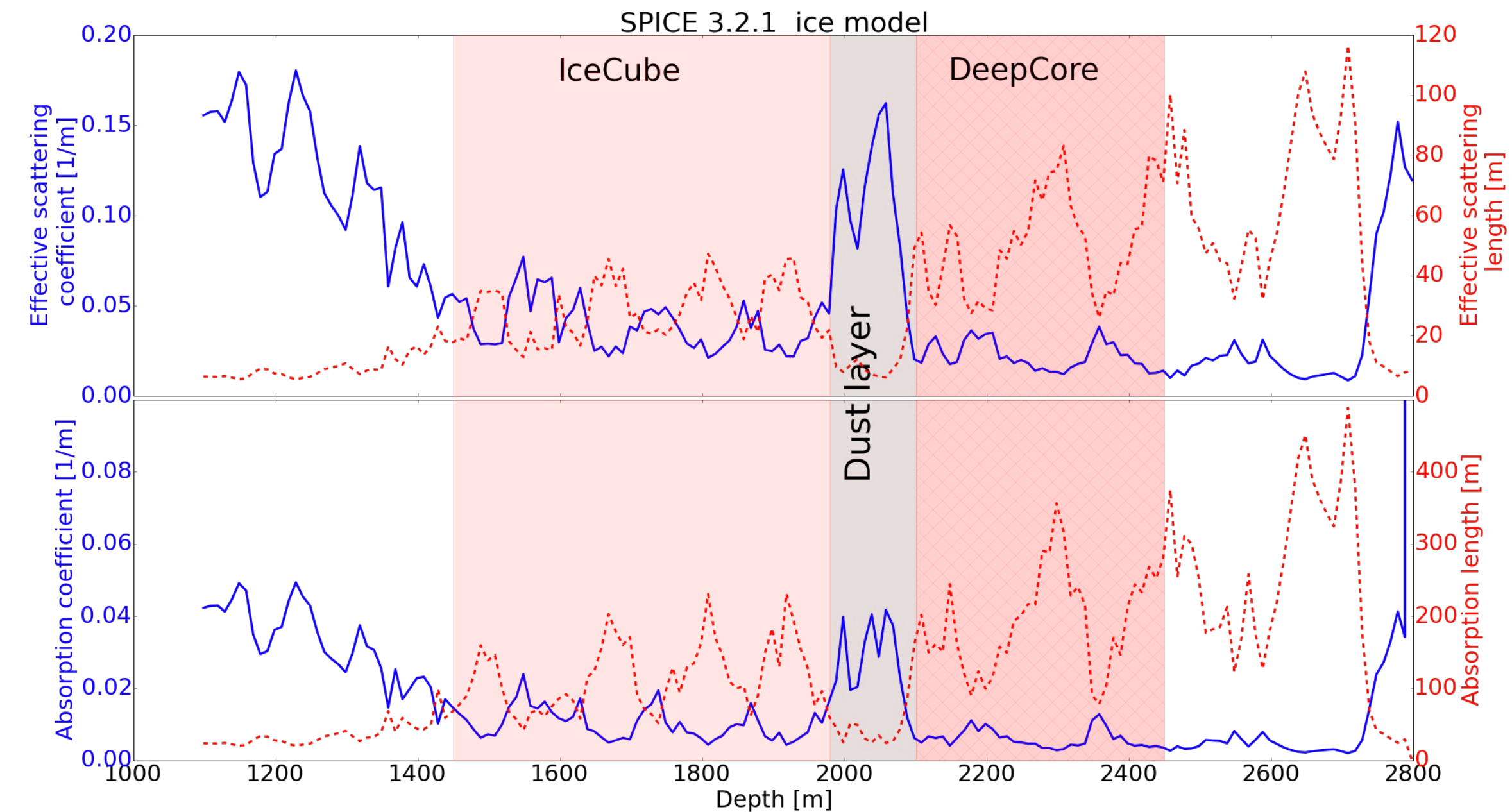
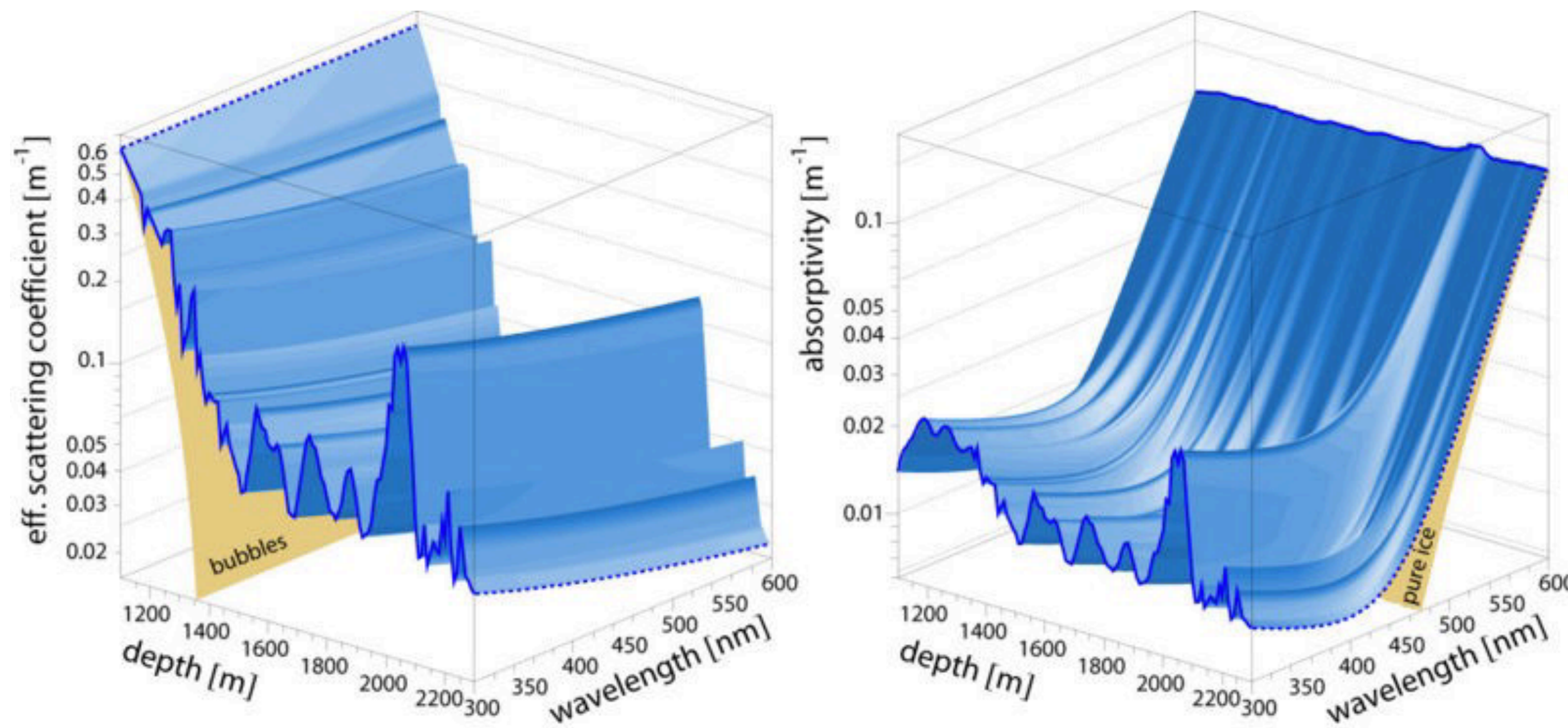
- IceCube is the world's largest neutrino telescope
- 1 km³ detector volume located at the South Pole
- Utilising the pure Antarctic ice as a medium to detect Cherenkov lights from charged relativistic particles created in neutrino interactions



Antarctic ice

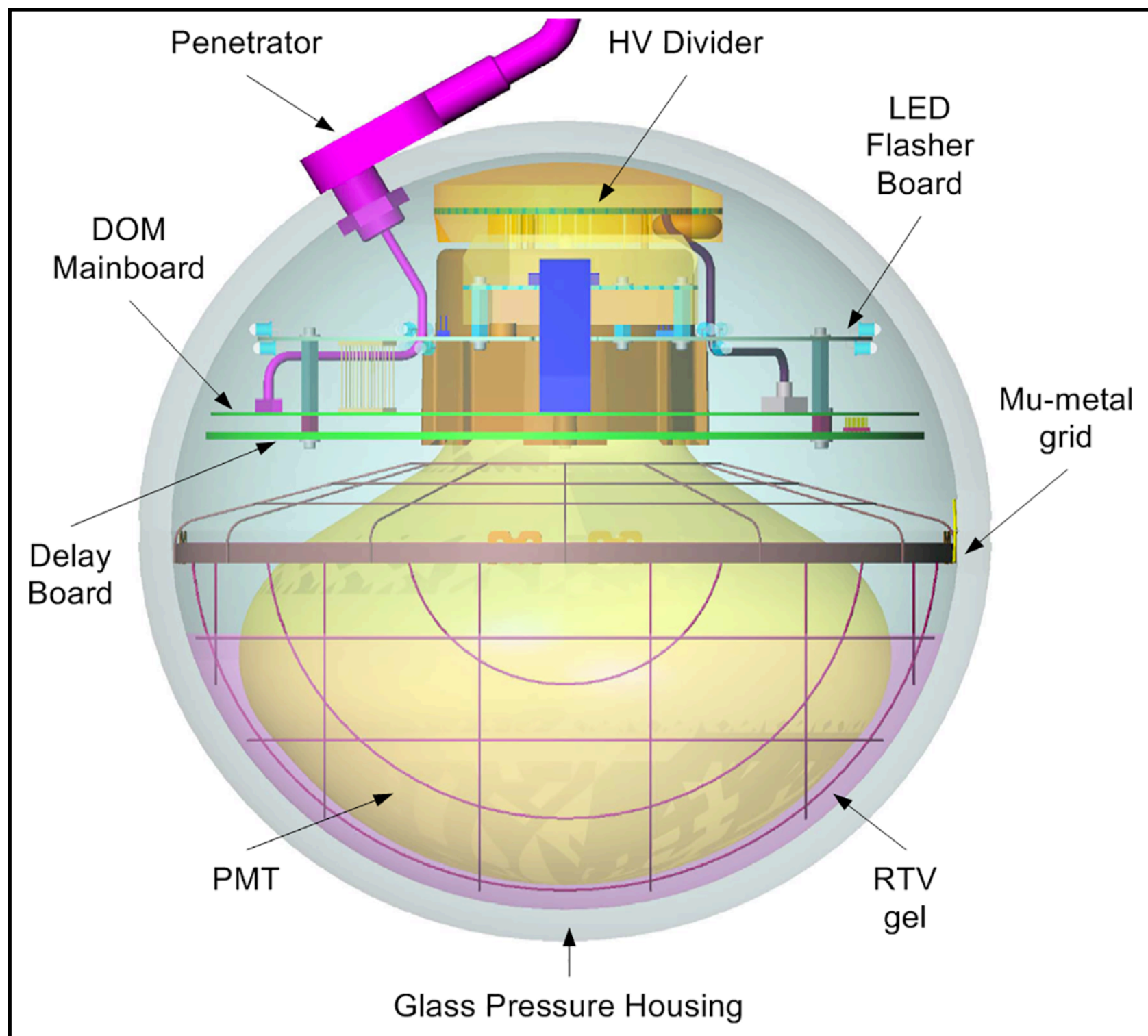
Woosik Kang
NuFACT 2022
August. 5th, 2022

- The Antarctic glacier at the South Pole is compacted snow up to 100,000 years old
- The ice is well understood from various IceCube calibration campaigns
- The ice model 'SPICE' developed for all IceCube analysis

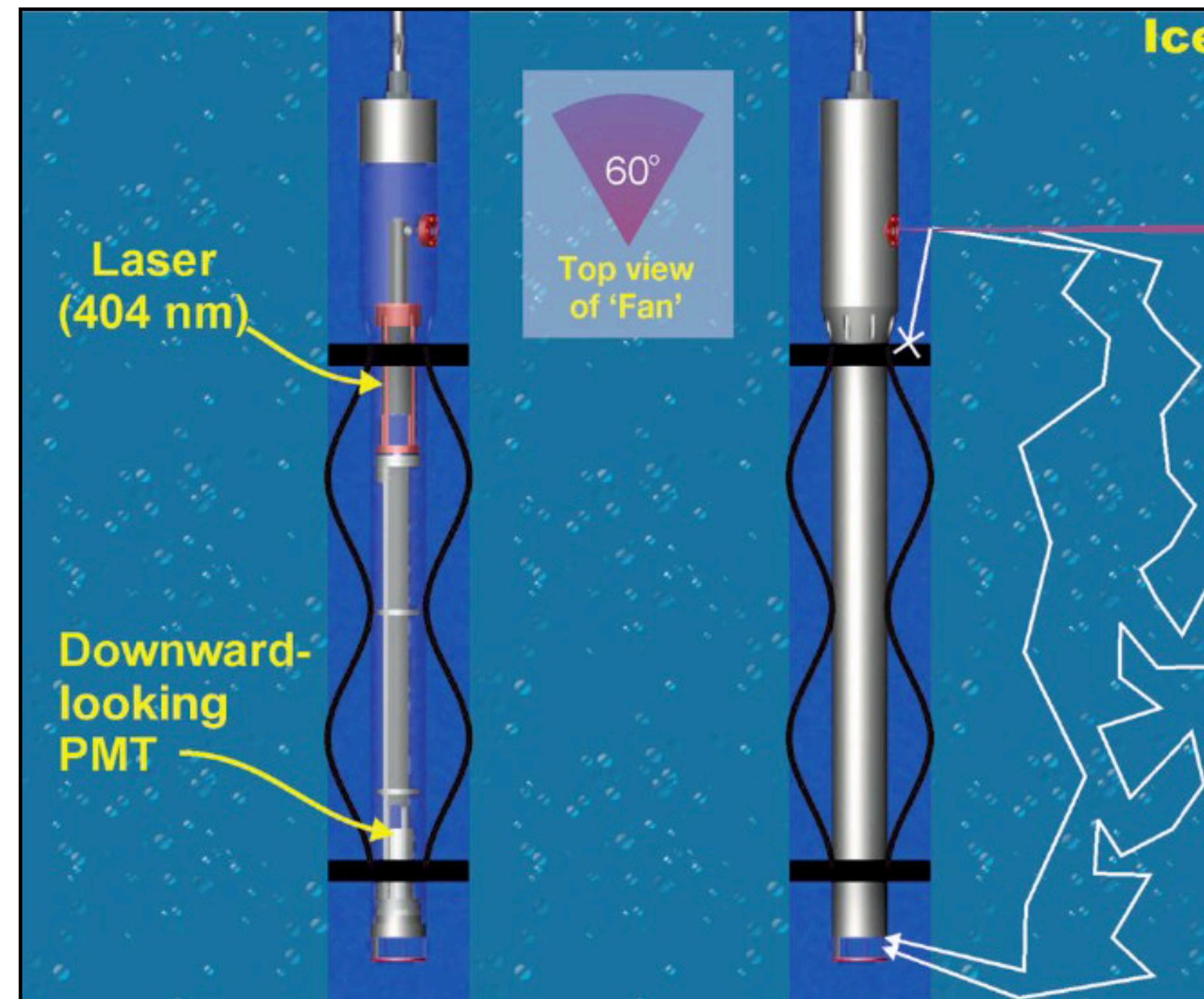


Calibrations in IceCube

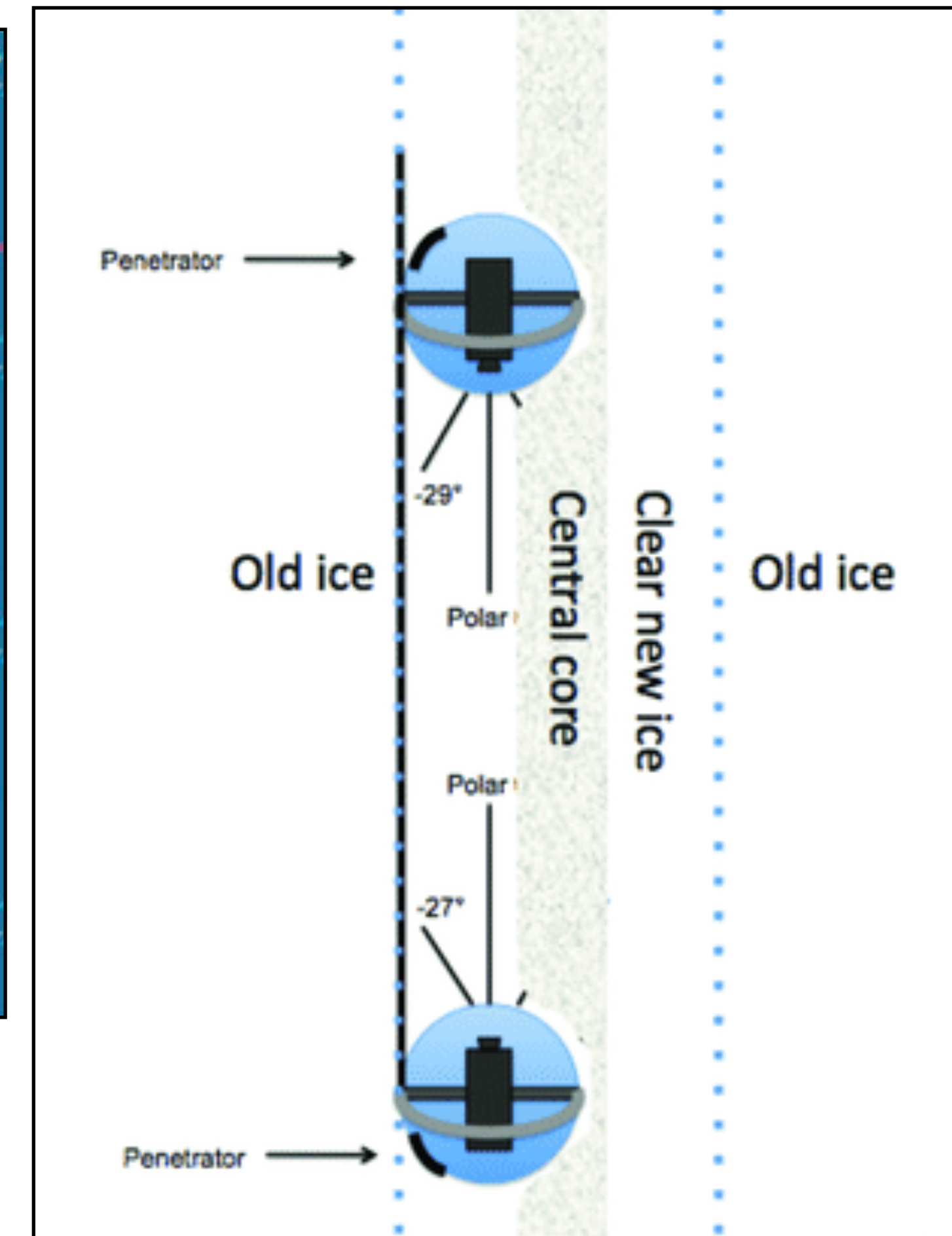
Woosik Kang
NuFACT 2022
August. 5th, 2022



12 LEDs aboard each DOM; *Flasher*



404nm laser + in-situ photon counter; *Dust Logger*



2 steerable camera systems; *Swedish Camera*

- A lot of calibration devices for various campaigns
 - Ice properties, geometry, timing, energy, ...
- Precise characterisation of the optical properties of the detector medium to reduce the uncertainties in the reconstruction of neutrino events

Refrozen hole ice

Woosik Kang
NuFACT 2022
August. 5th, 2022



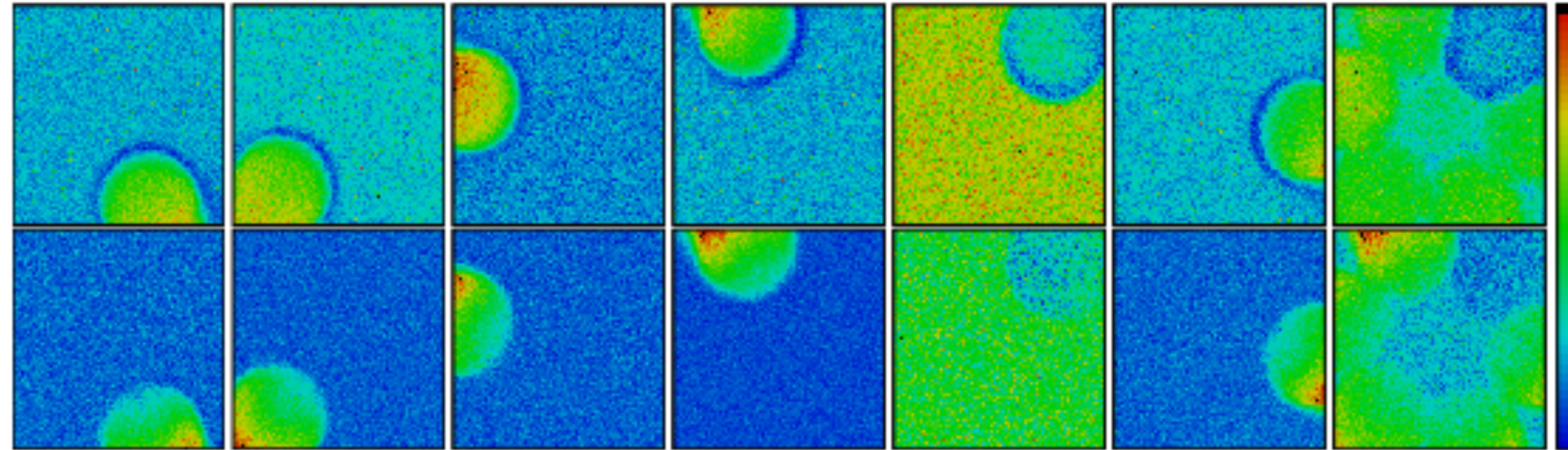
22 Dec. 2010

Refreezing



4 Mar 2011

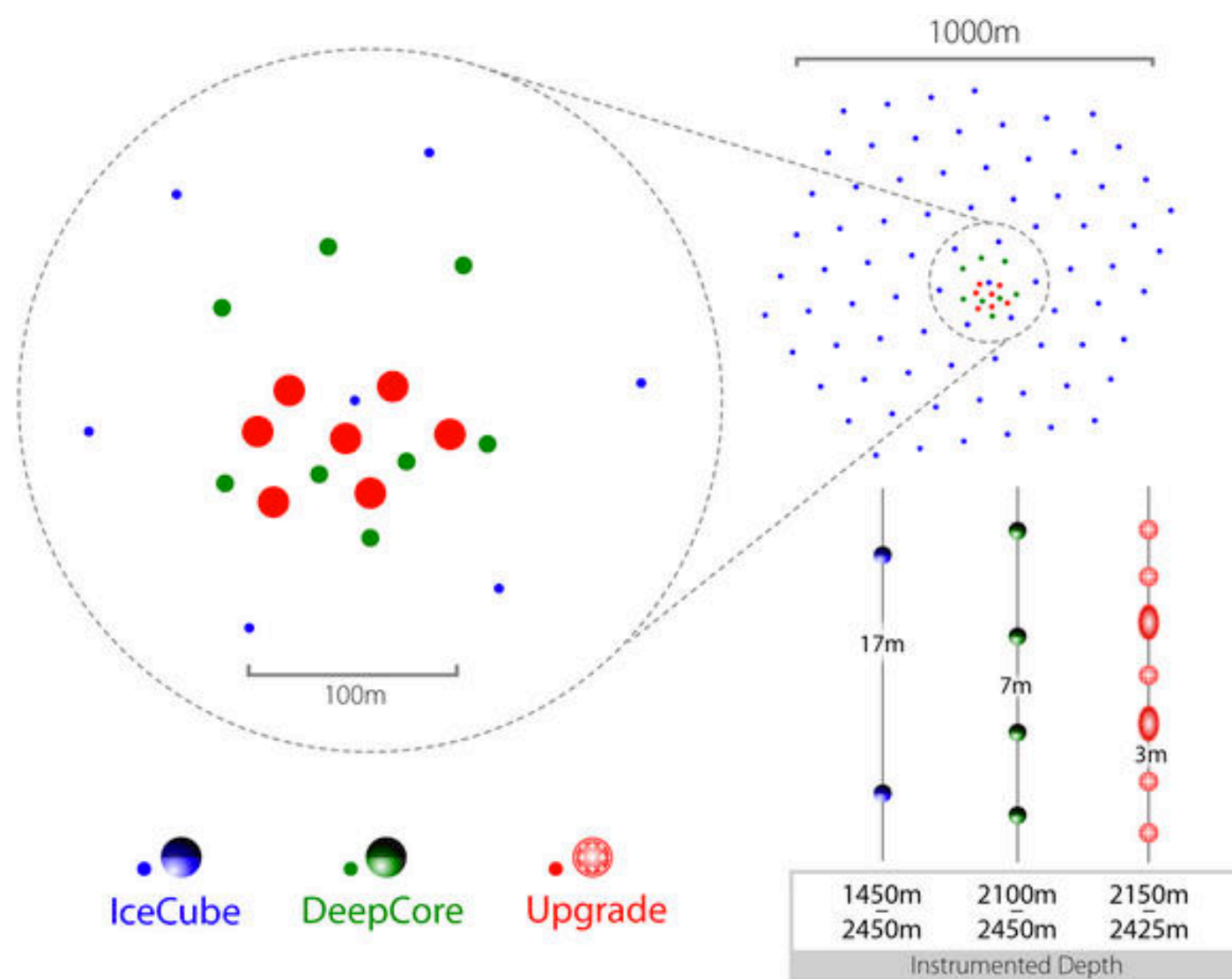
VLVnT2013 325, ICRC(2021)1023



- Propagation distances dominated by glacial ice, but every detected photon also has to pass through refrozen drill column
- Swedish Camera observed clear outer layer & bubbly central column about half the size of the DOMs
- Size confirmed, and relative position to each DOM and effective scattering length ($\sim 2.5\text{cm}$) calibrated using LED data
- There is good reason to expect that ice environments in vicinity of each DOM can significantly differ
- The uncertainties on SPICE remain as one of the major systematic errors

IceCube Upgrade

Woosik Kang
NuFACT 2022
August. 5th, 2022



mDOM



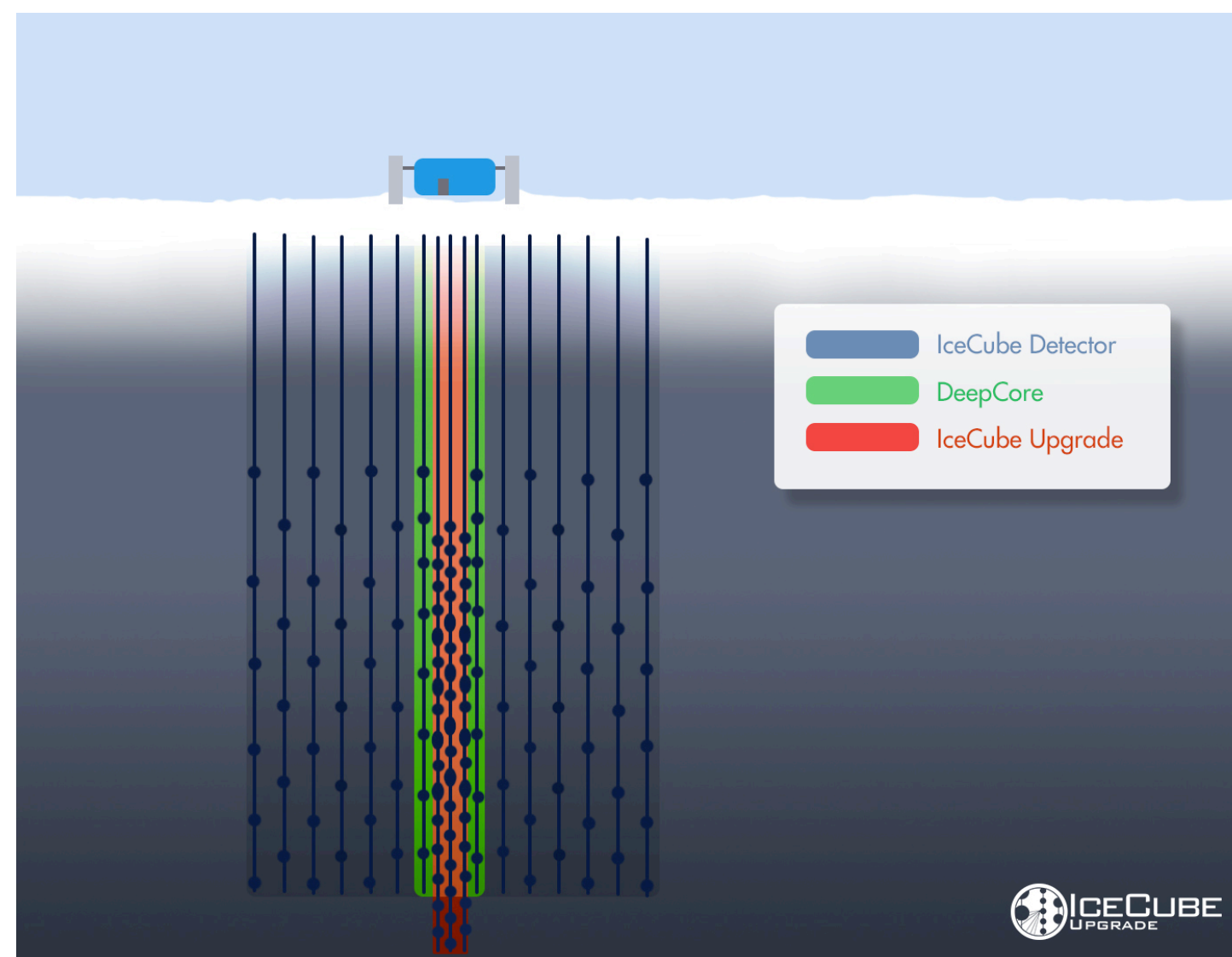
D-Egg

PoS(ICRC2019)1031, PoS(ICRC2021)1042, PoS(ICRC2021)1070

See M. DuVernois's talk
in WG6 parallel
on Tuesday



- Horizontal string spacing: 20m
- Vertical module spacing: 3m



- An upgrade with seven densely instrumented strings in the centre of active volume of the IceCube detector, which is currently under construction
 - To enhance the capability to detect neutrinos in the GeV range for the measurement of the unitarity of the PMNS matrix
 - To reduce ice properties related systematic uncertainties in the IceCube analyses by re-calibration of the IceCube detector
- Newly developed optical sensors with new calibration devices

Calibrations in IceCube Upgrade

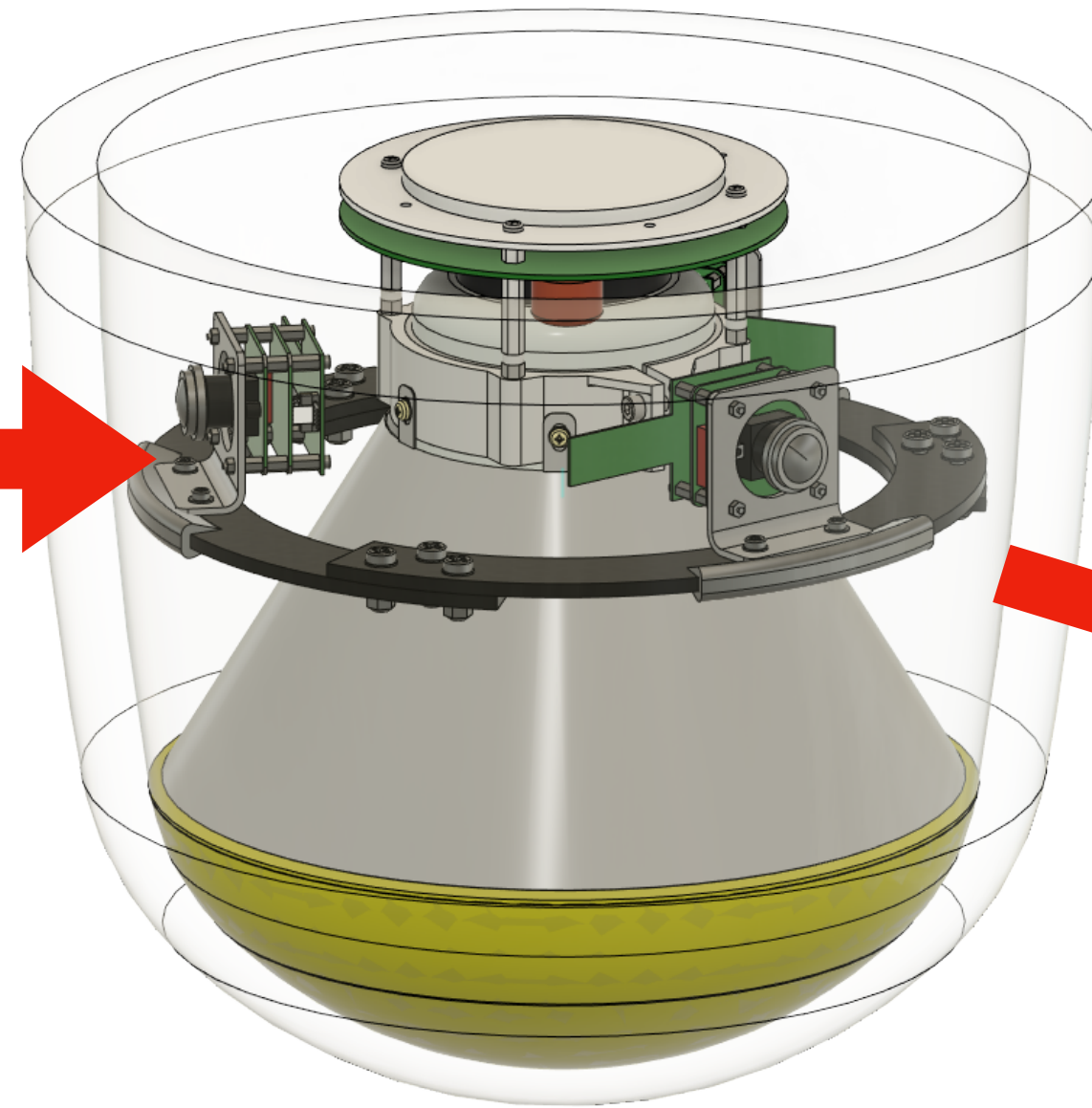
Woosik Kang
NuFACT 2022
August. 5th, 2022



- (Re-)Calibration campaigns will lead the comprehensive understanding of the IceCube detector medium
- **Science multiplier**: retroactively analyse more than 15 years of IceCube data with substantially improved angular and energy resolutions
- **Enhanced neutrino event pointing**: critical for multi-messenger science
- A lot of newly developed/improved calibration devices to be deployed in the holes or to be installed within the optical modules
- On-board, fixed focus cameras, IceCube Upgrade Camera system, will be one of the key player to the campaign

IceCube Upgrade Camera System

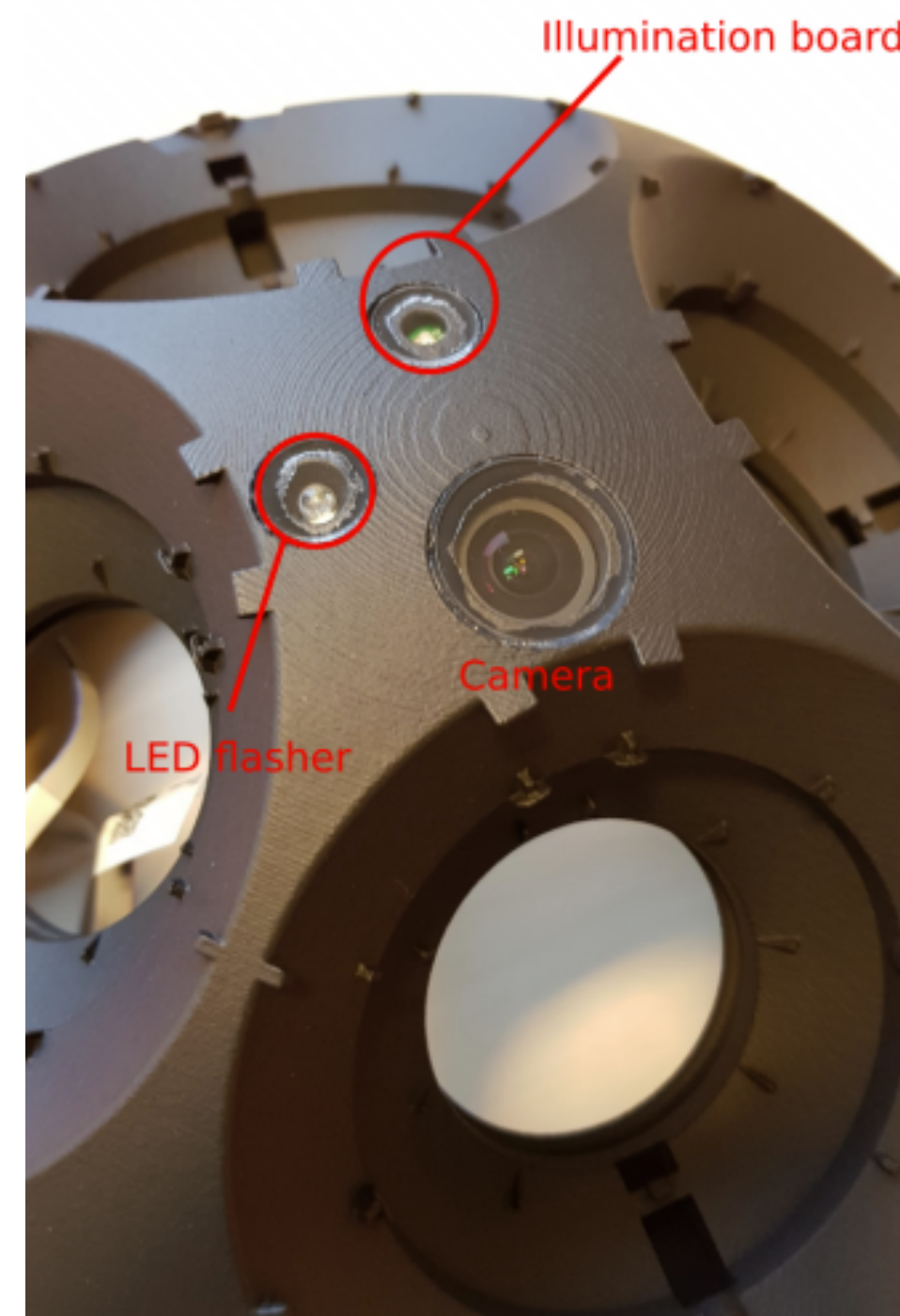
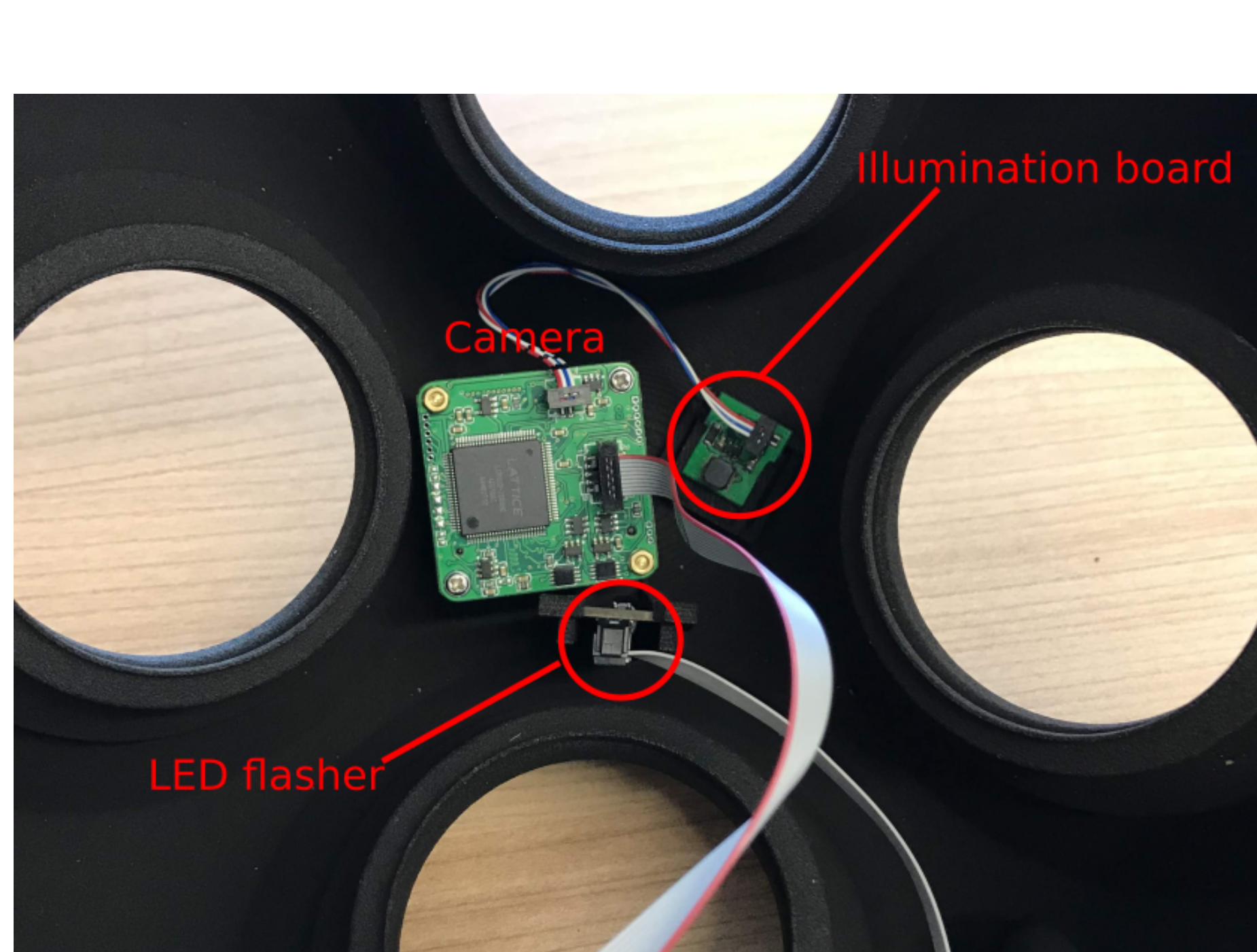
Woosik Kang
NuFACT 2022
August. 5th, 2022



- For each D-Egg, **three outward facing** cameras with attached illumination boards on a ring structure
- In total, 900 cameras (for 300 D-Egg modules) were produced and have been integrated into D-Eggs by now.

IceCube Upgrade Camera System

Woosik Kang
NuFACT 2022
August. 5th, 2022



- For mDOM, two upward cameras, one downward camera, and one upward stand-alone LED
- In total, ~1300 cameras (for ~420 mDOM modules) are to be produced, and ~800 cameras are already completed by now

Measurement schemes

Woosik Kang
NuFACT 2022
August. 5th, 2022

Hole ice	Geometry (Positioning)	Geometry (DOM Orientation)
Mapping local hole profile (hole ice / bulk ice)	DOM position relative to adjacent DOMs	Orientation of camera DOM
Location of bubble column	Cable position	Orientation of neighbouring DOM on adjacent string
Impurities / cracks / ...		Orientation of neighbouring DOM on same string
transmission / reflection at interface hole/bulk ice		
Freeze in process	Bulk ice properties	Others
Dust / contaminants deposition on the surface	Measurement of scattering length	Survey capability
Formation / crushing of bubbles /degasing worked ?	Measurement of absorption length	
Formation of cracks	Hole/Bulk ice interfaces	Complementary
Triboluminescence	Anisotropy of light propagation	Important
		Highest Priority

- Optical properties of ice in the vicinity of optical modules measured by capturing the light signature and analysing its distribution in the image data
- The relative orientation & position of each optical module surveyed from the examination of multiple images
- In-ice camera run plan to mitigate the impact on the detector up-time and the readiness for scientific events like supernova

Simulation studies

PoS(ICRC2019)928

Woosik Kang
NuFACT 2022
August. 5th, 2022

Simulated image

IceCube Work in Progress

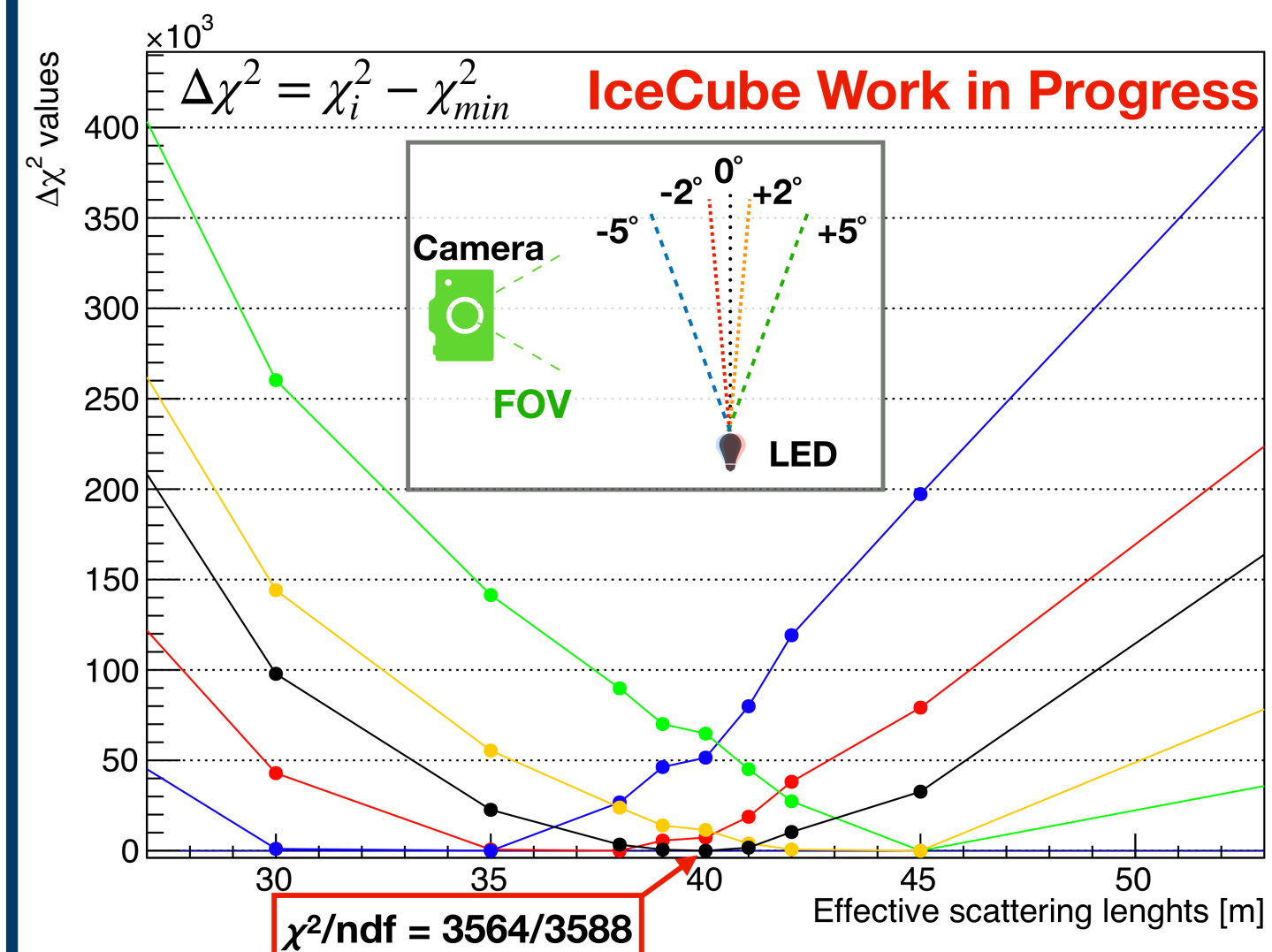
LED at 25m away from the camera
pointing sideways

LED at 2m below the camera
pointing upward

Bubble
Column

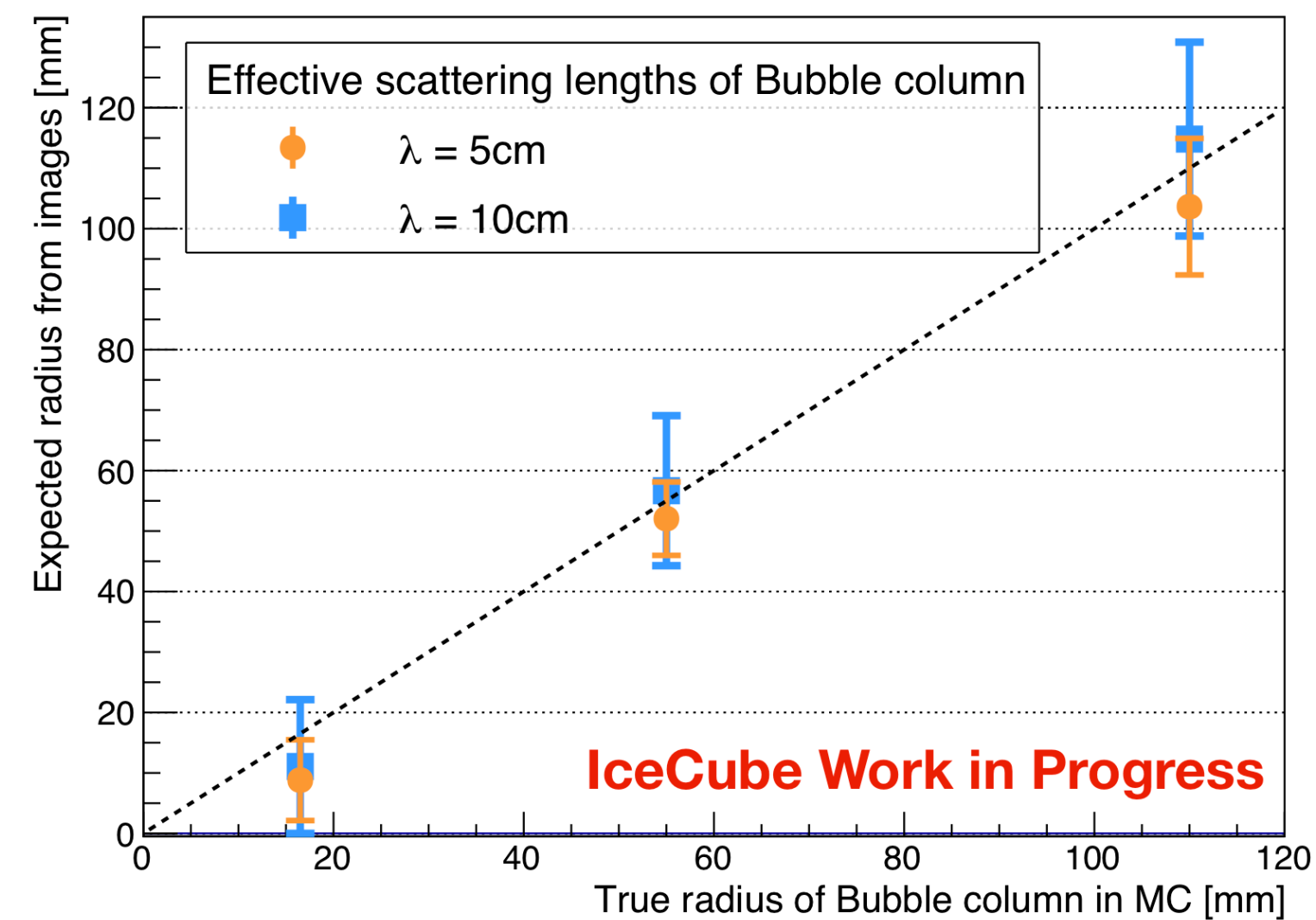
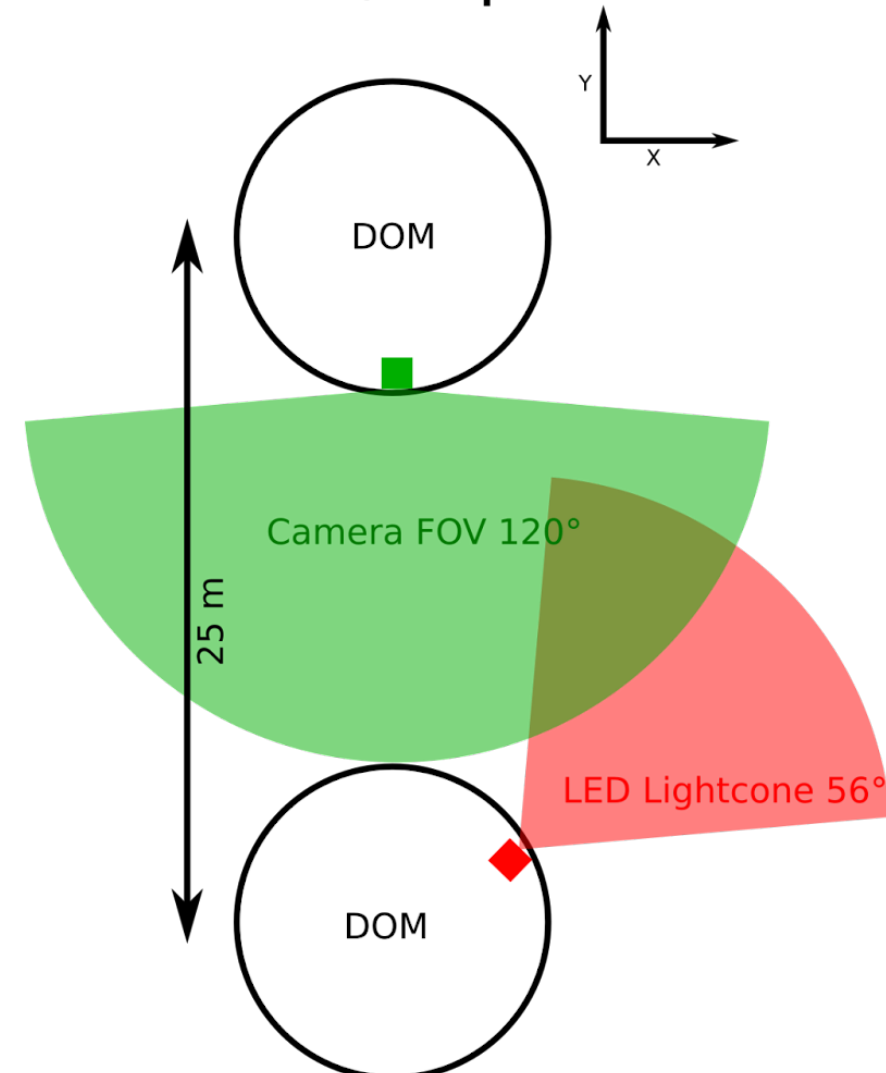
IceCube Work in Progress

Simulated image



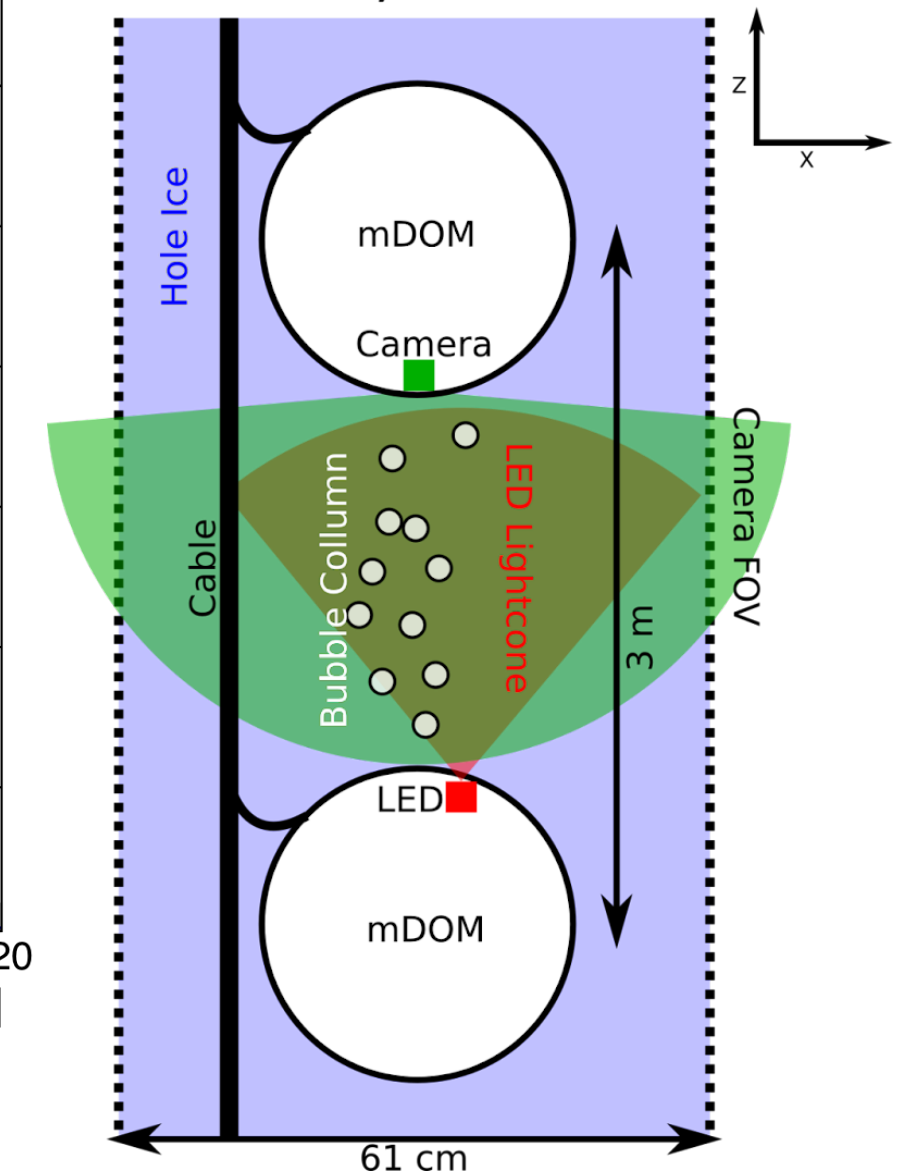
$\lambda_{eff.scattering} \sim 1$ m precision

Bulk Ice, Top View



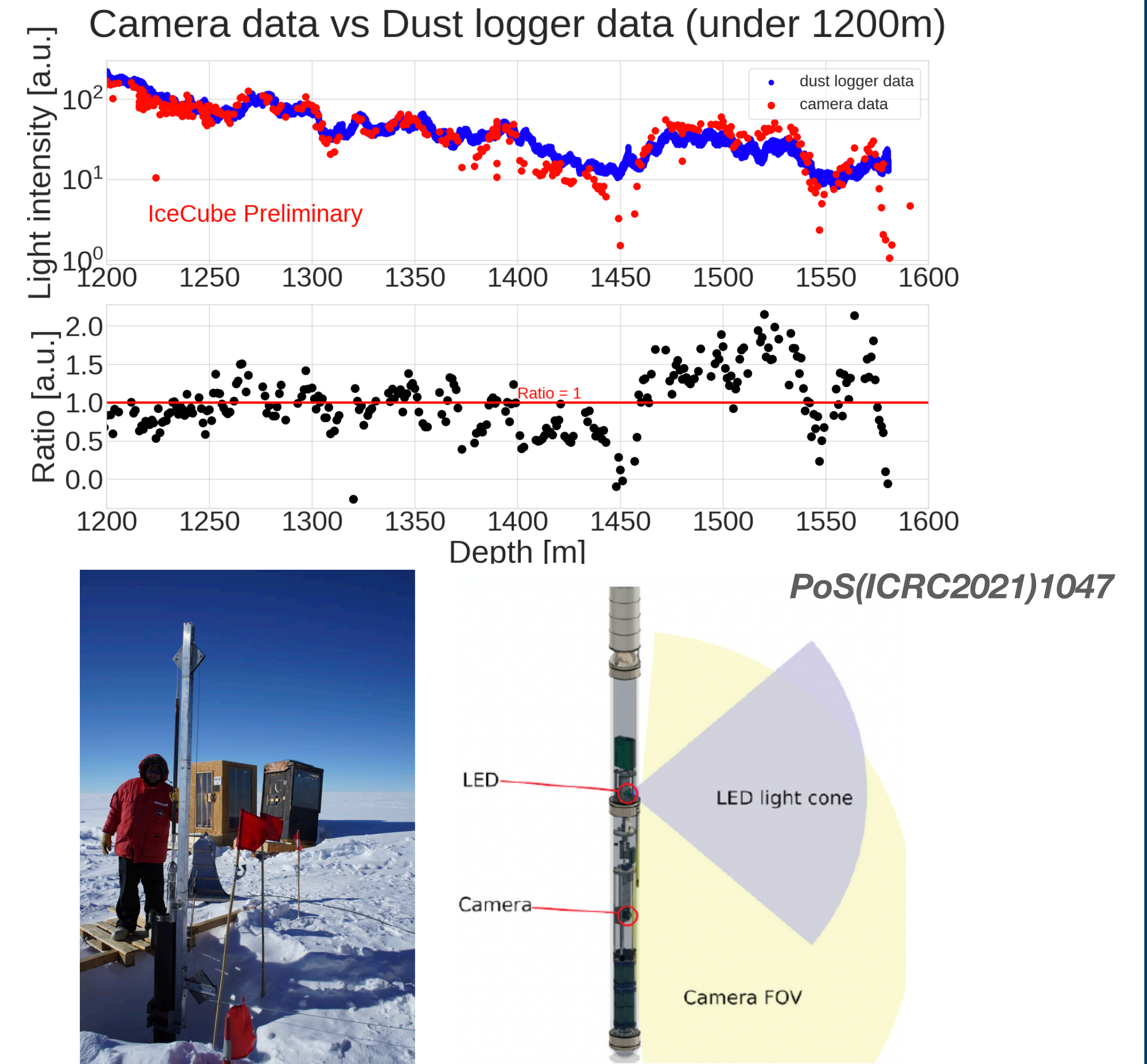
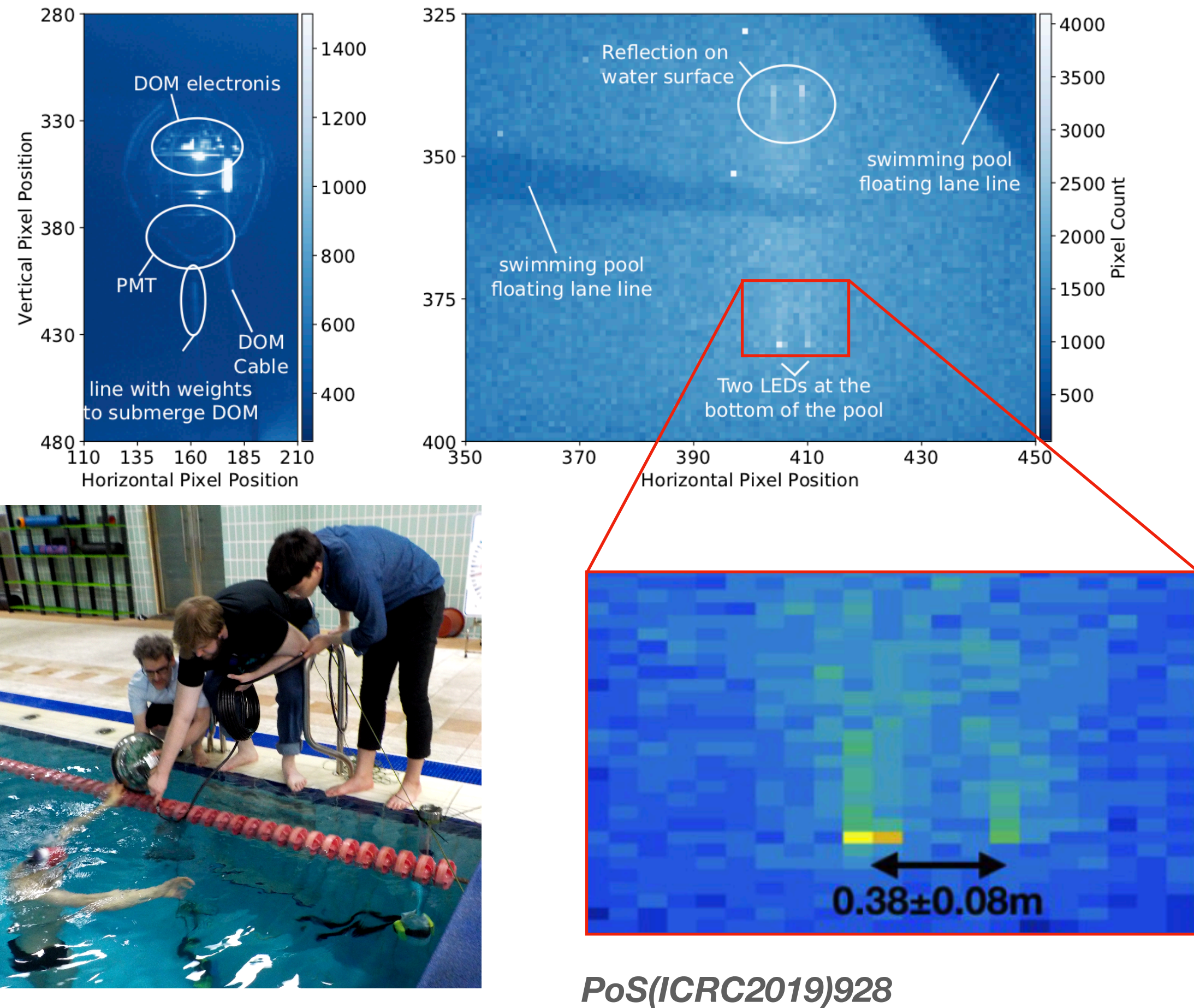
Feature size $\lesssim 10$ cm precision

Hole Ice, Side View



Field tests

Woosik Kang
NuFACT 2022
August. 5th, 2022



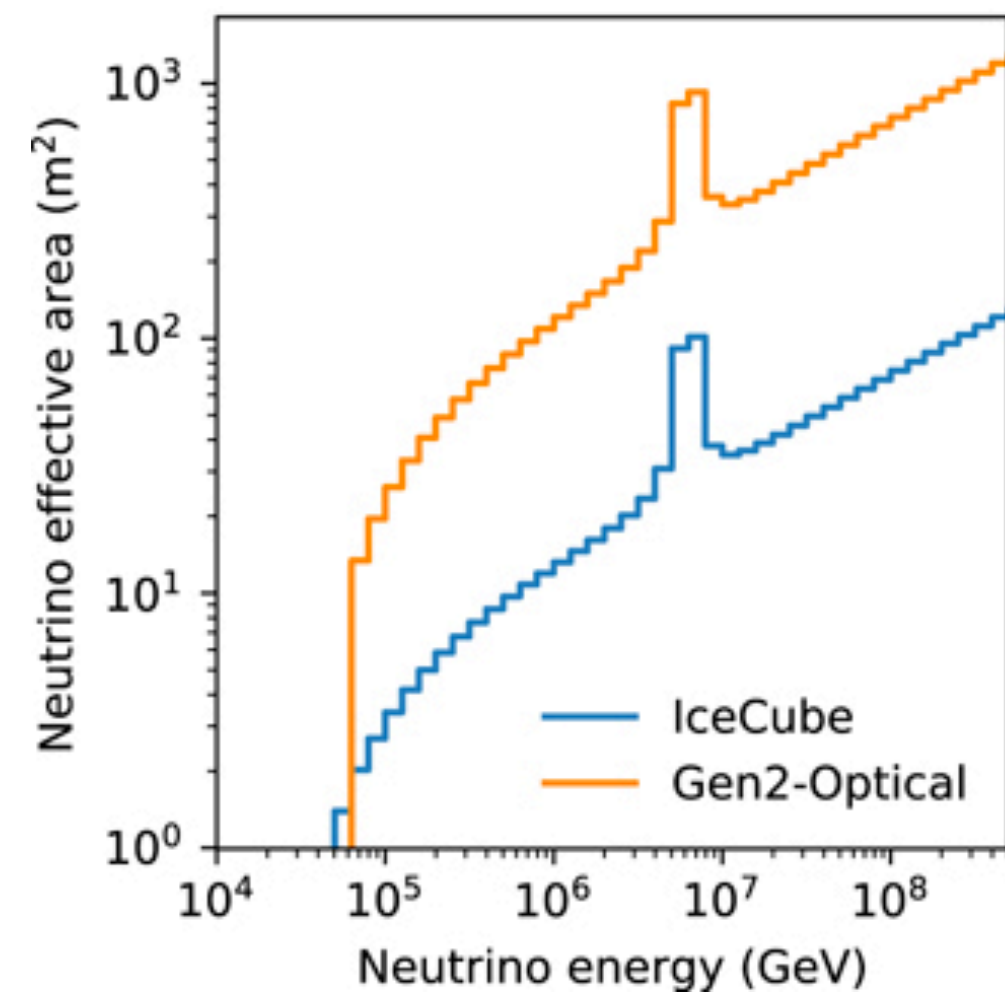
- In-water test at Gyeonggi Physical Education High school, Suwon, Korea
- In-ice test at SpiceCore hole, South Pole

IceCube-Gen2

Woosik Kang
NuFACT 2022
August. 5th, 2022

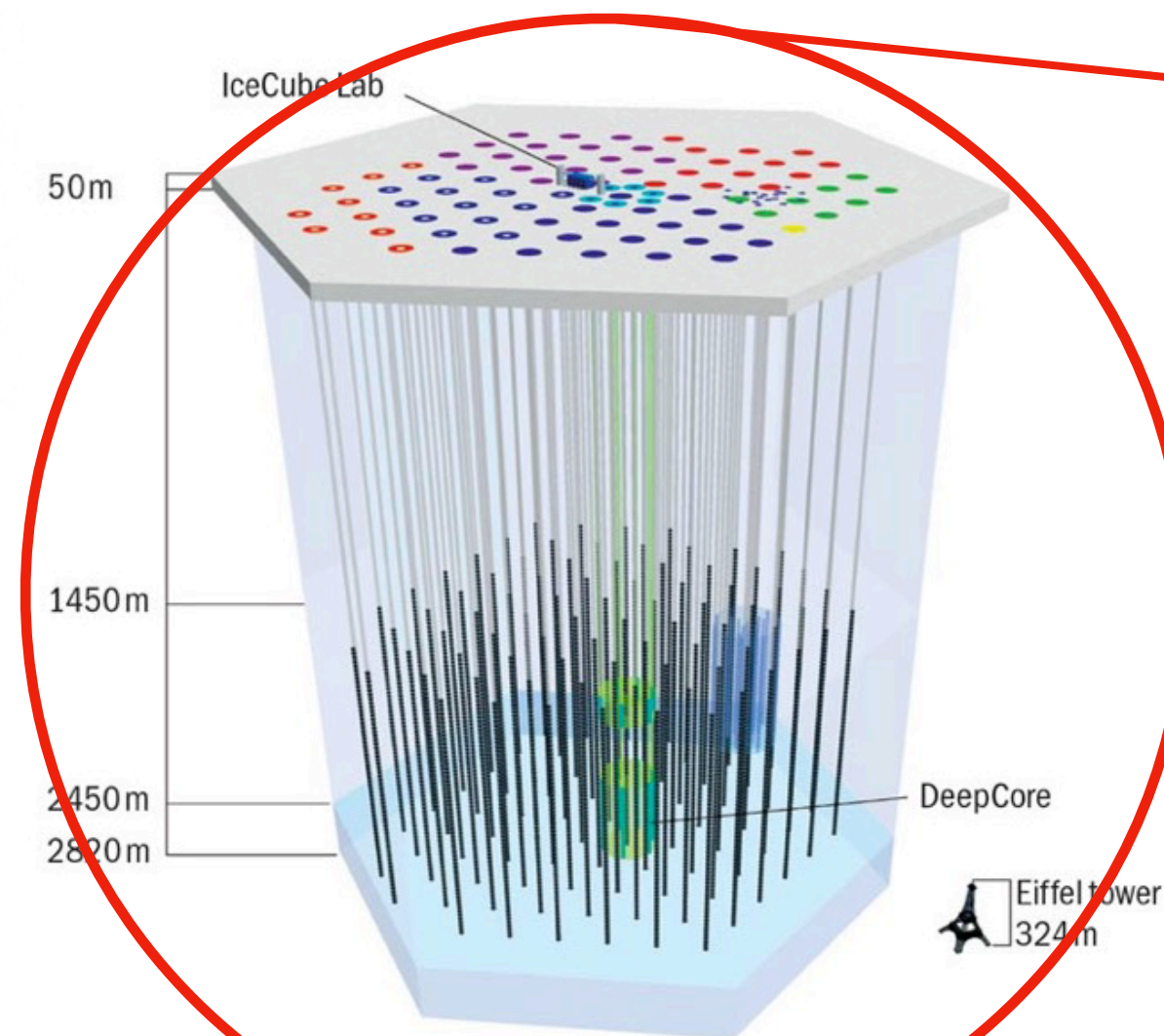


ICECUBE
GEN2

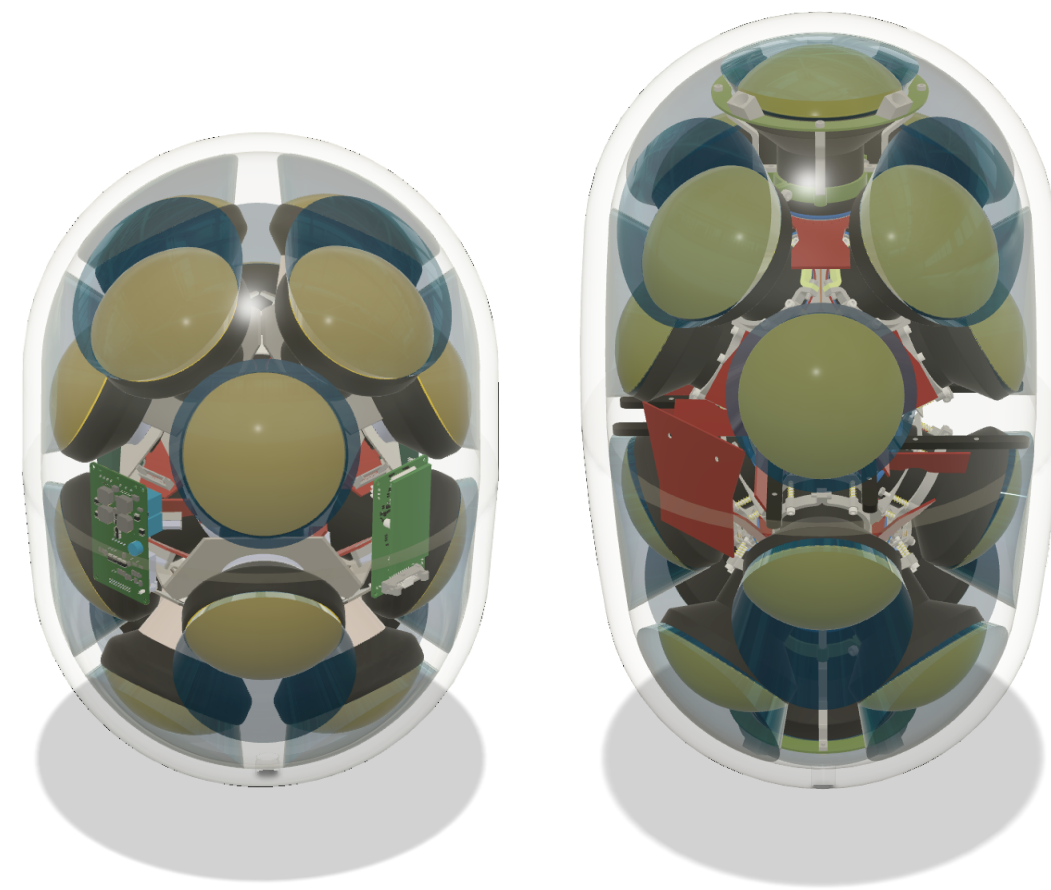


J. Phys. G **48** 060501

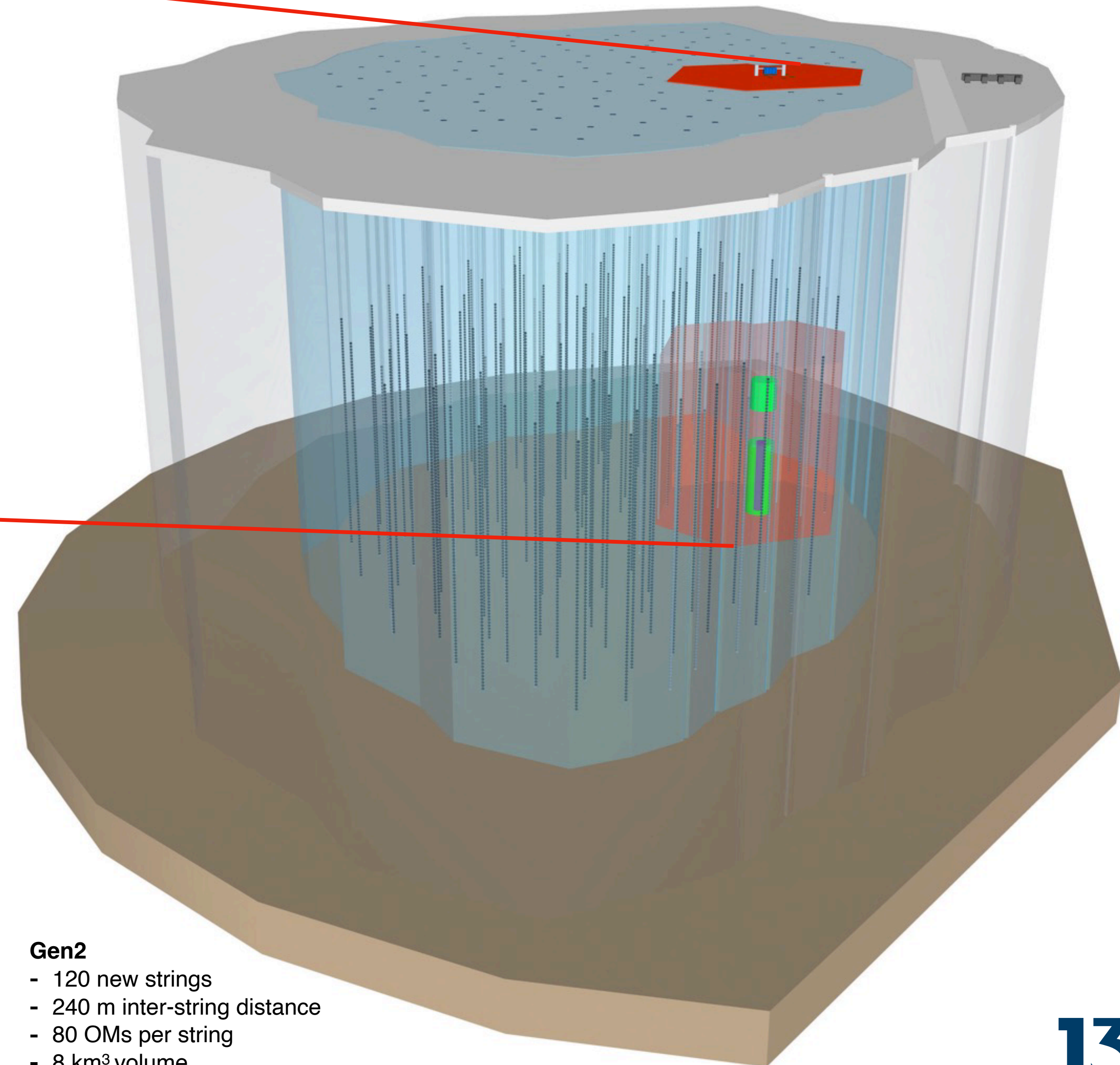
See M. DuVernois's talk
in WG6 parallel
on Tuesday



- IceCube**
- 86 strings
 - 125 m inter-string distance
 - 60 OMs per string
 - 1 km^3 volume



Gen2 Optical Module candidates
(left: 16 PMT option, right: 18 PMT option)

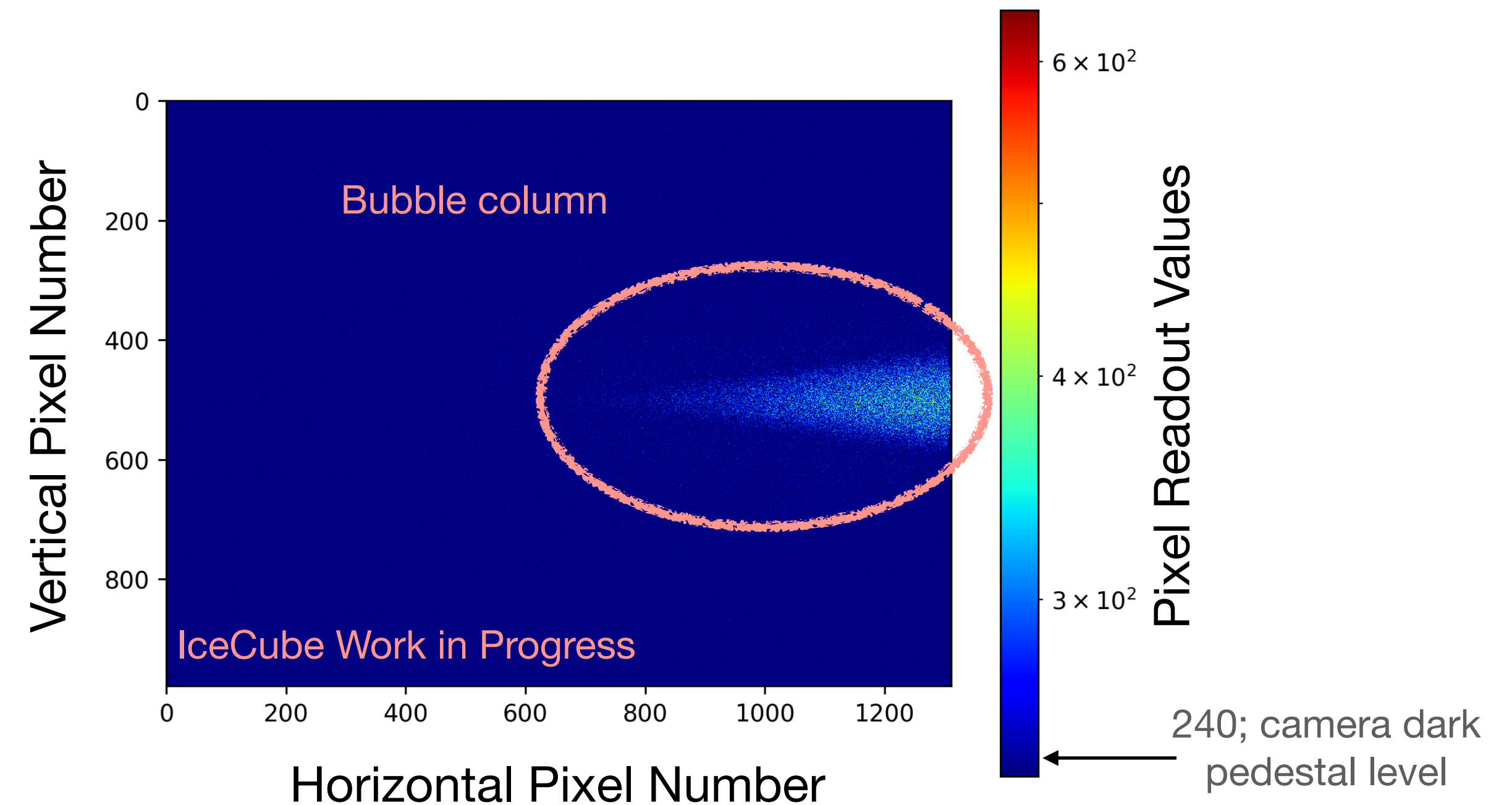
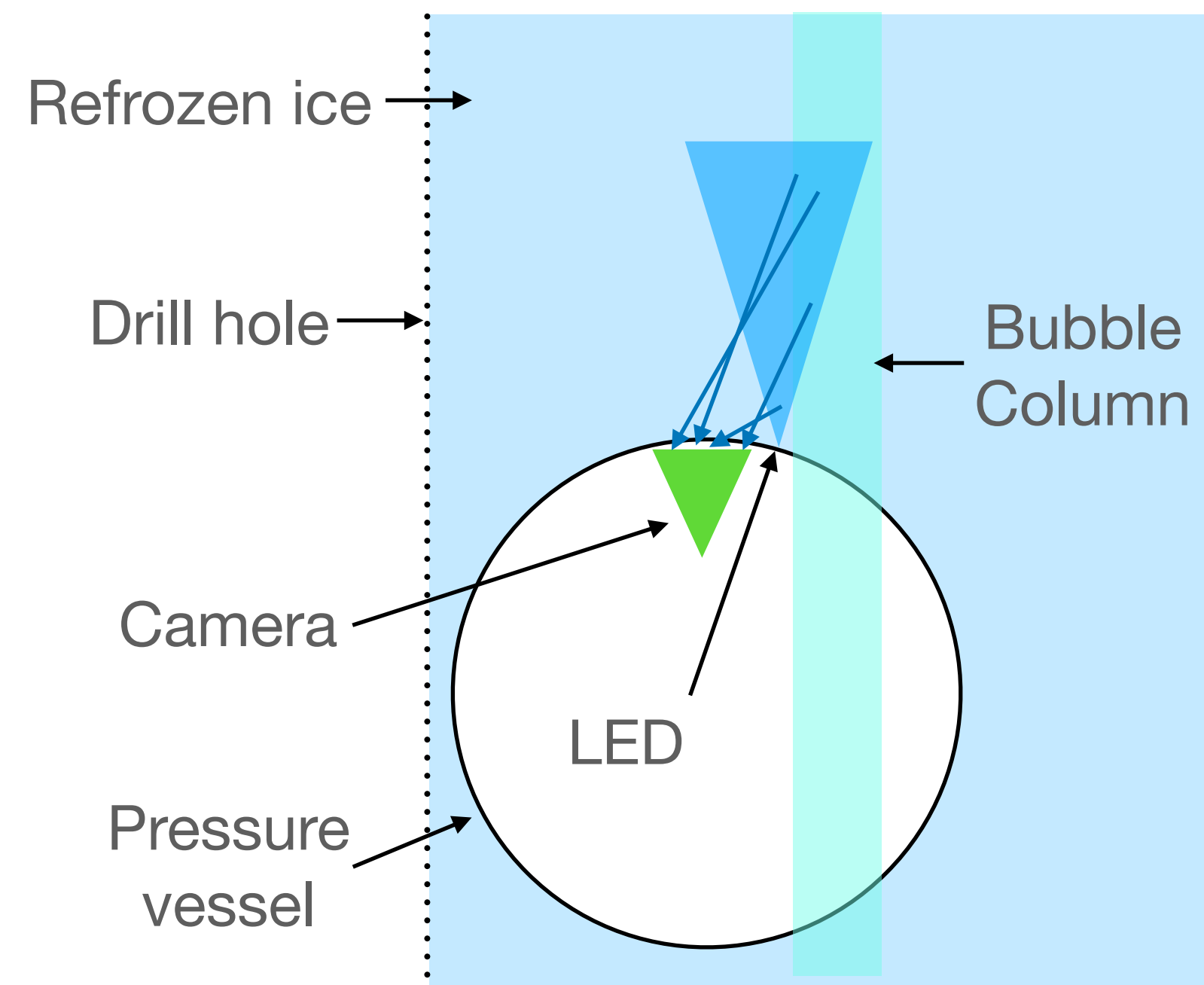


- Gen2**
- 120 new strings
 - 240 m inter-string distance
 - 80 OMs per string
 - 8 km^3 volume

Camera system for IceCube-Gen2

Woosik Kang
NuFACT 2022
August. 5th, 2022

- The conceptual design of the camera system for IceCube Gen2 would focus on the measurements on the refrozen ice in the drill hole
- Images from the back-scattered lights will deliver the information of the refrozen ice in vicinity of each camera system
- Due to the larger spacing between each Gen2 string, inter-string measurement with the camera system would be limited



Summary and Outlook

Woosik Kang
NuFACT 2022
August. 5th, 2022



- Cubic-kilometre photomultiplier arrays as realised in IceCube Neutrino Telescope offer unique insight into the Antarctic ice
- Derived optical properties are fundamental to detector understanding and required for precision neutrino physics/astronomy
- IceCube Upgrade will provide the improved calibration of the detector
 - A novel camera system will be used to characterise the properties of bulk ice and refrozen ice in the drill hole using transmission and reflection images
- The next generation detector will employ a similar concept of camera system to perform the comprehensive calibration of detector medium with other calibration devices

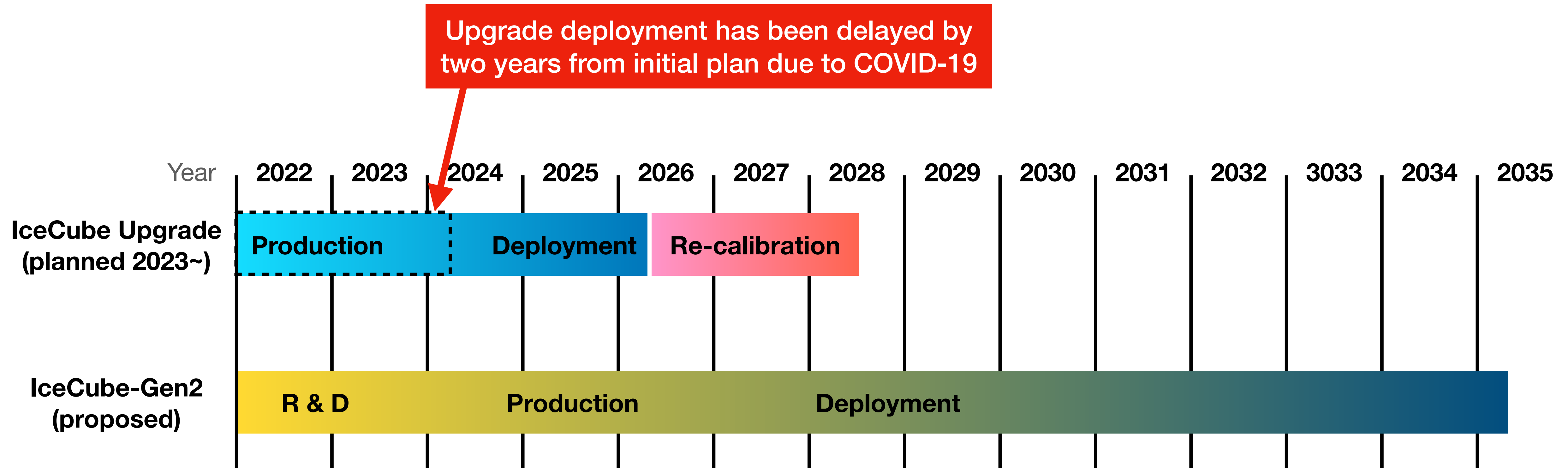
Thank you for your attention :)



Backups

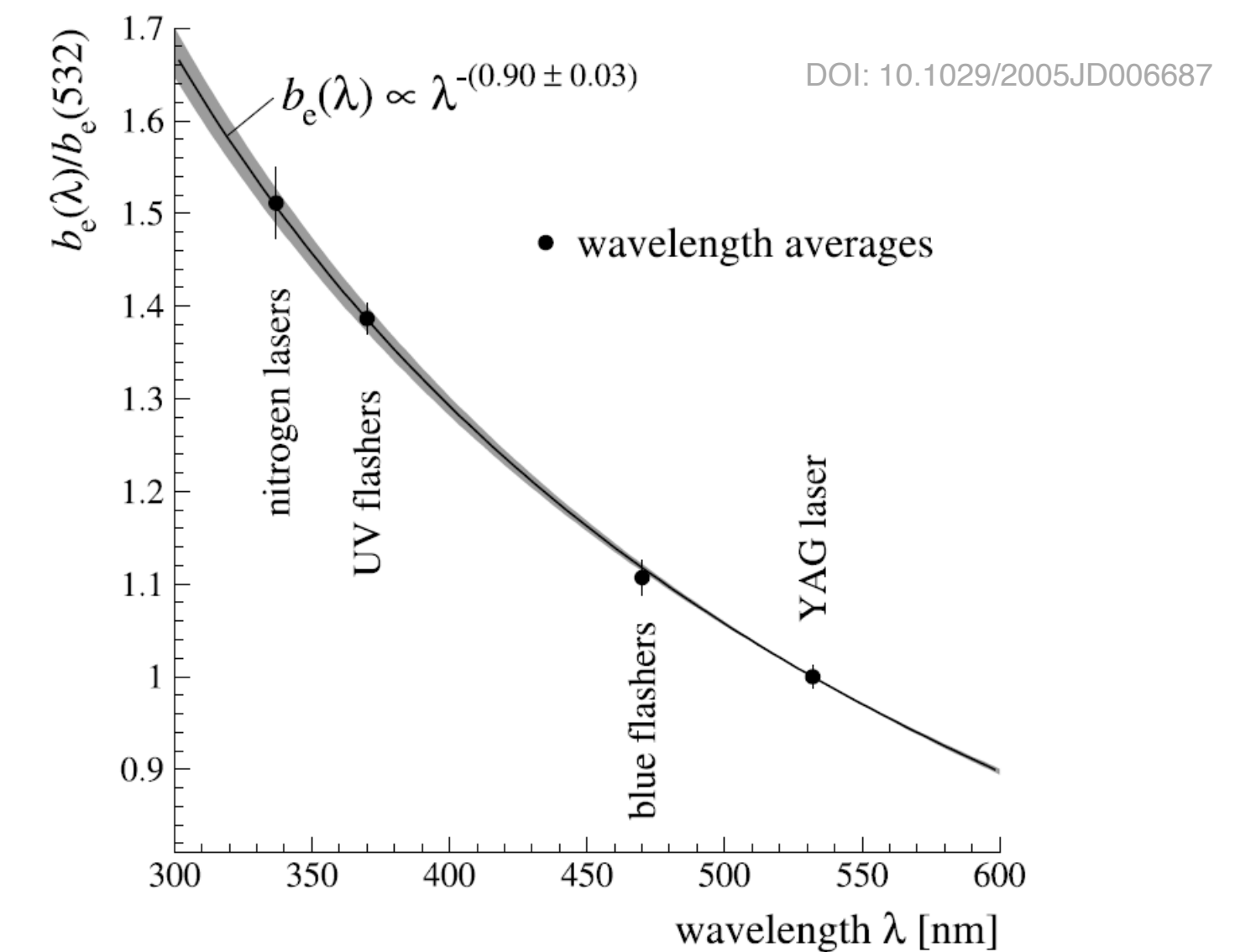
Milestones to IceCube-Gen2

Woosik Kang
NuFACT 2022
August. 5th, 2022



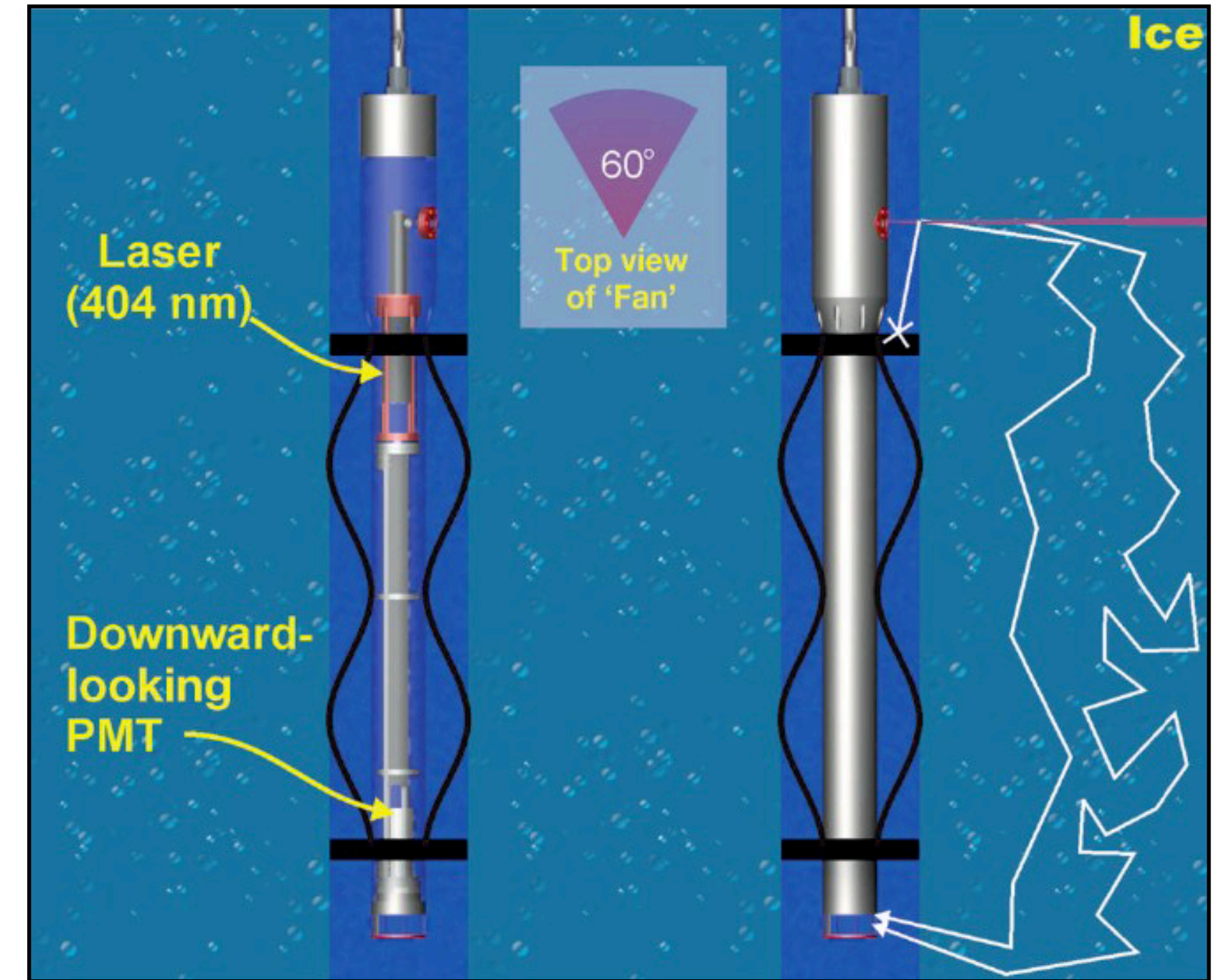
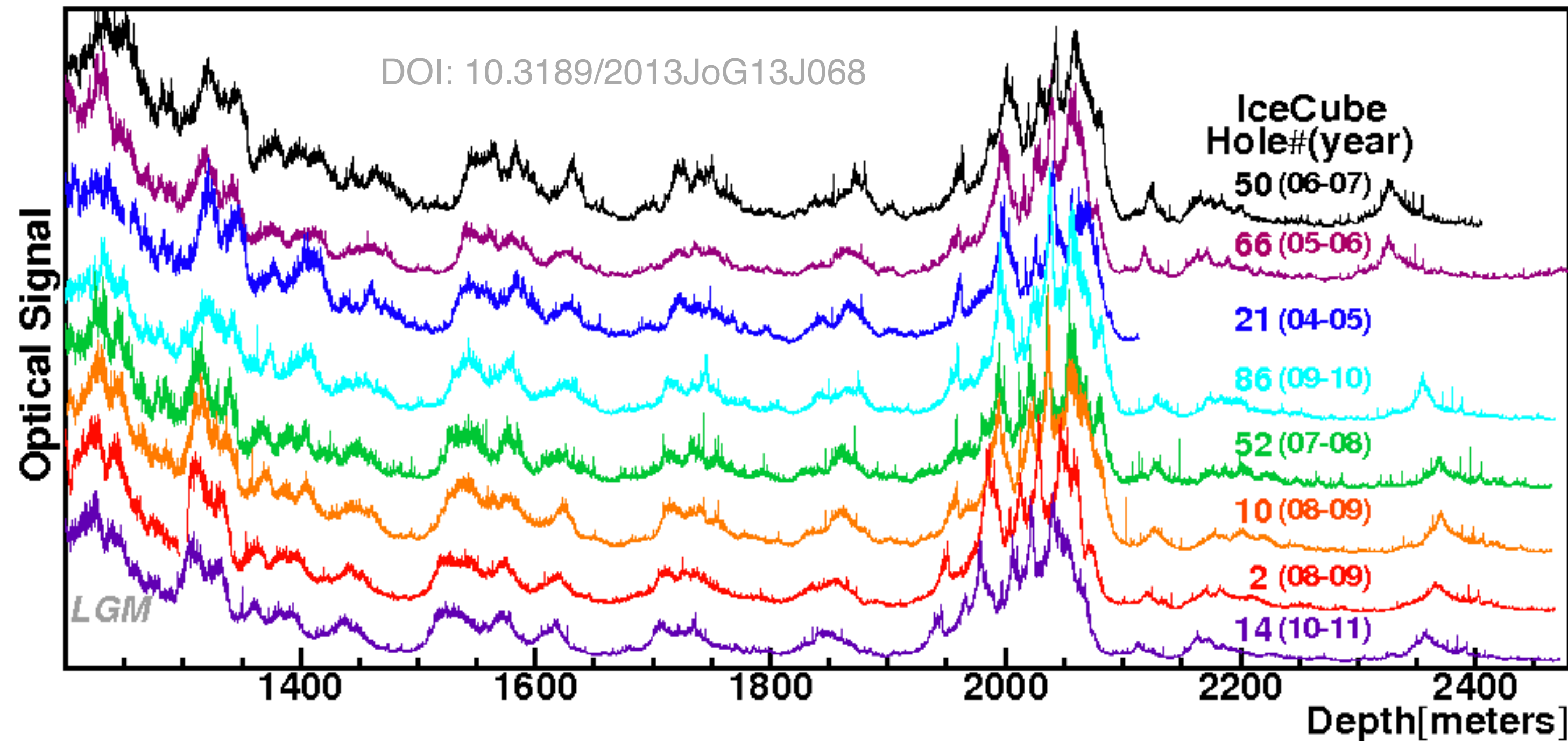
Wavelength dependencies

- AMANDA (IceCube predecessor) measured absorption and scattering as a function of wavelength
- Absorption has weak dependence
 - Slowly increasing above 500nm due to vibrational excitation modes
 - Otherwise following Mie expectation
- Scattering strongly increasing towards smaller wavelength following Mie expectation and impurity prediction
 - Propagation distance longest ~400nm



Dust Logger stratigraphy

Woosik Kang
NuFACT 2022
August. 5th, 2022

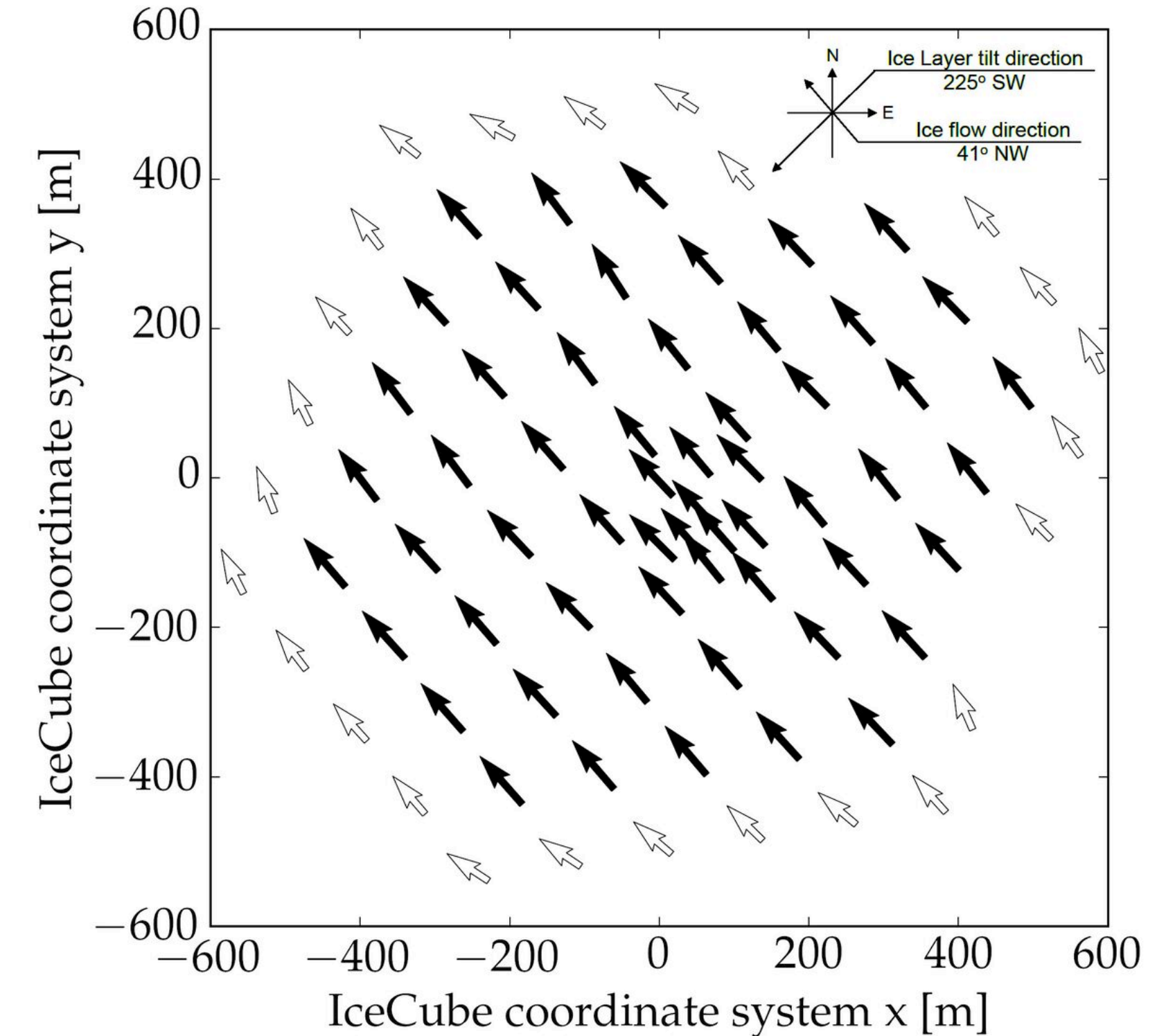
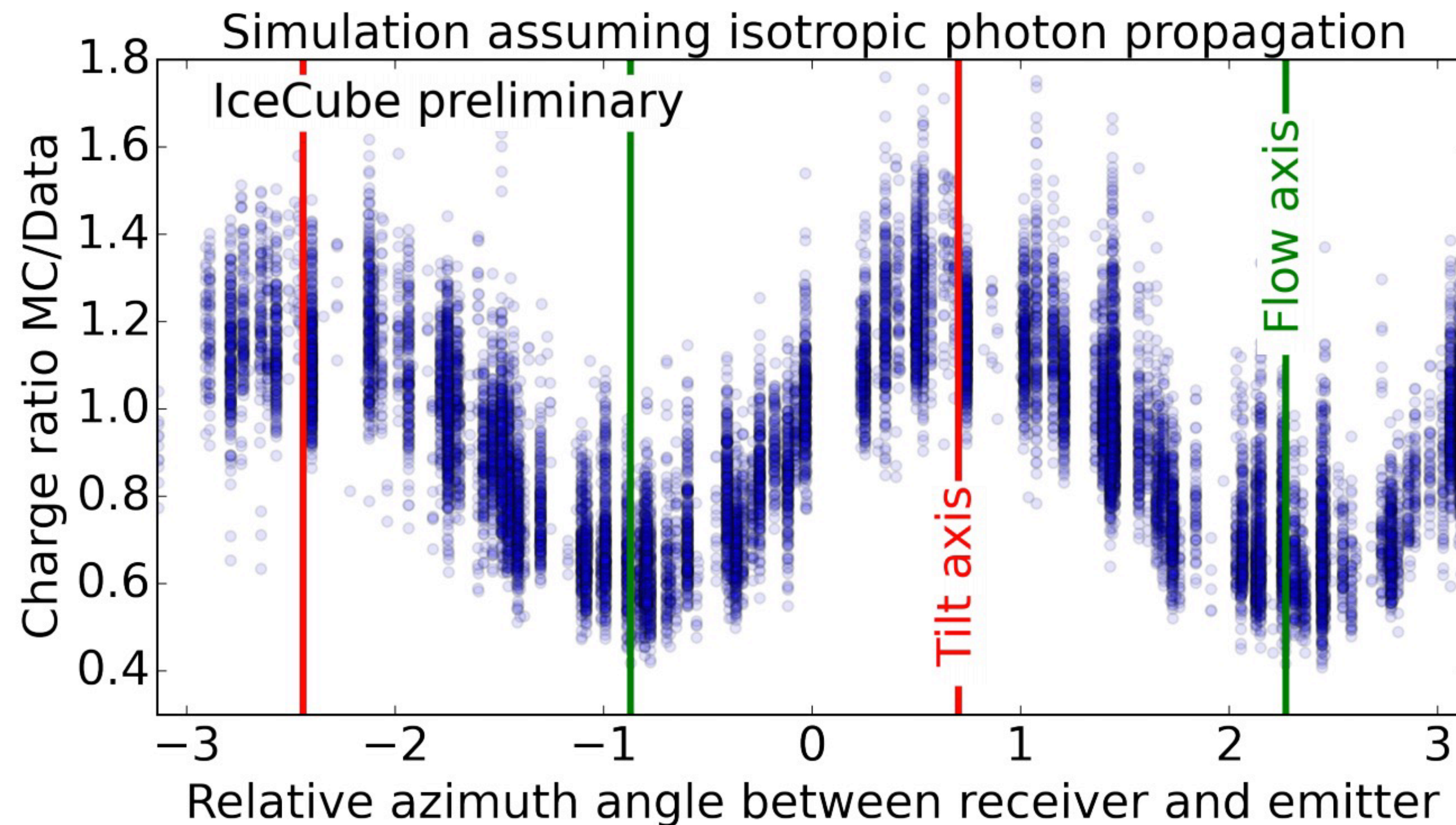


- Horizontal fan of light emitted into ice
- Scattering centres can deflect light into PMT → Signal proportional to impurity density
- Yields high resolution (mm) stratigraphy, but not able to obtain absolute absorption and scattering coefficients

Anisotropy of the Antarctic Ice

Woosik Kang
NuFACT 2022
August. 5th, 2022

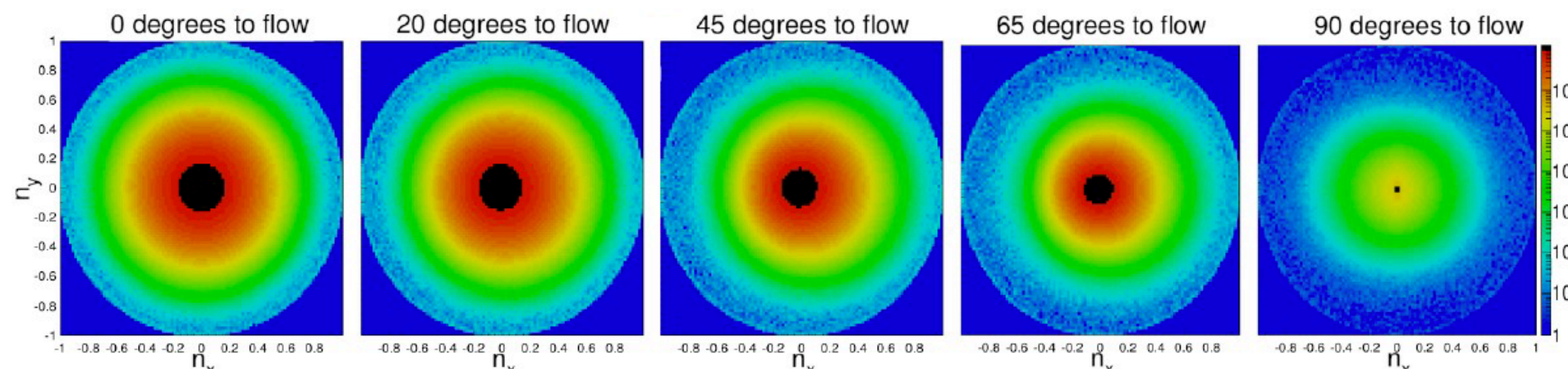
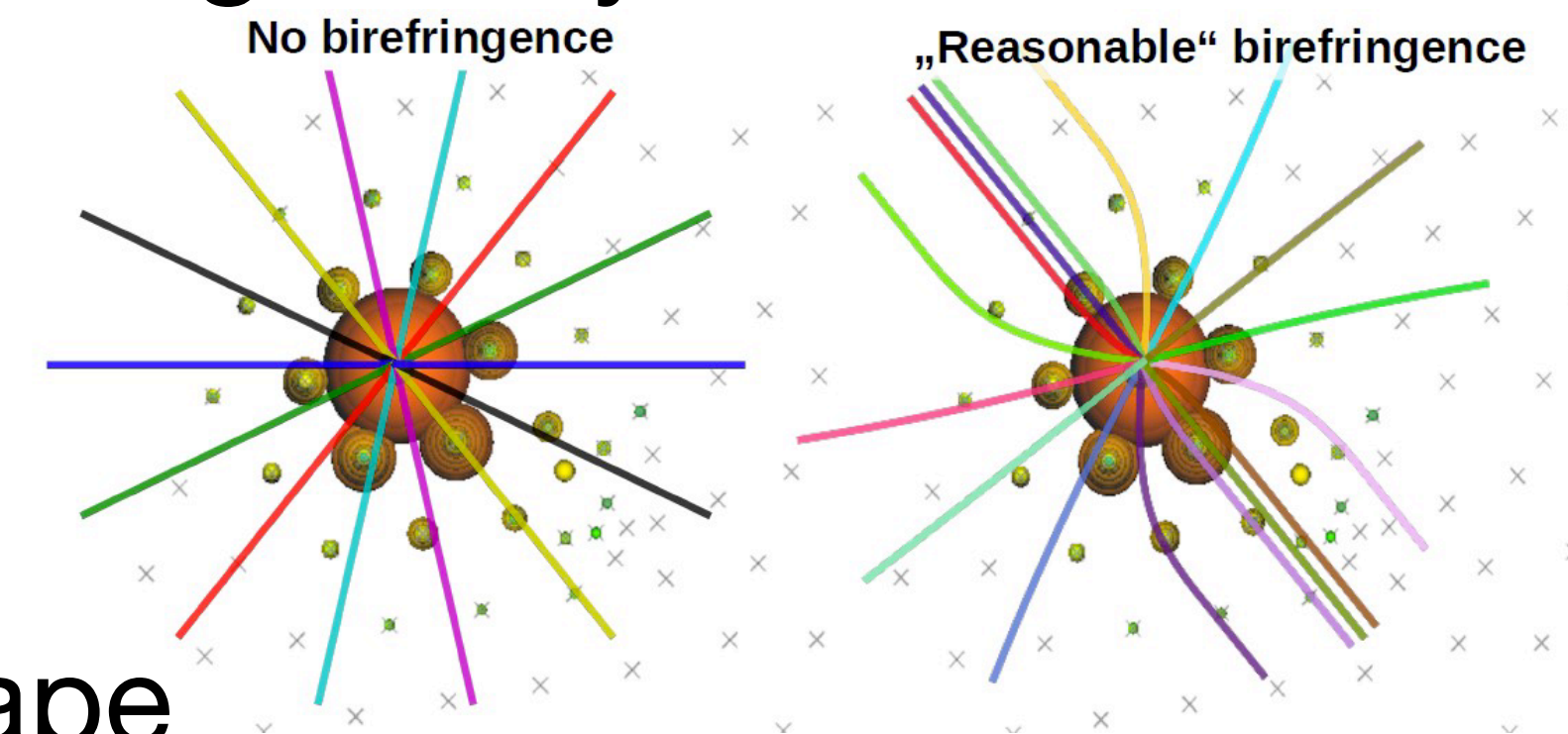
- Observed charge from LED flashers depends on orientation of receiver DOM with respect to emitter DOM. Maximum intensity seen along the local ice flow direction



Anisotropy of the Antarctic Ice

Woosik Kang
NuFACT 2022
August. 5th, 2022

- The birefringence explanation
 - Continued refraction and reflection on boundaries of birefringent crystals leads to:
 - Diffusion which is largest along the flow
 - A small deflection towards the flow axis
- Diffusion & deflection given by average crystal size & shape
- Detailed modelling of birefringence allows to deduce ice crystal properties (average shape & size, c-axis distributions, ...) as relevant to ice flow modelling using data from IceCube sampling individual photons at 125 m increments



A novel microstructure-based model to explain the IceCube ice anisotropy

DOI: 10.22323/1.395.1119

The IceCube Collaboration

(a complete list of authors can be found at the end of the proceedings)

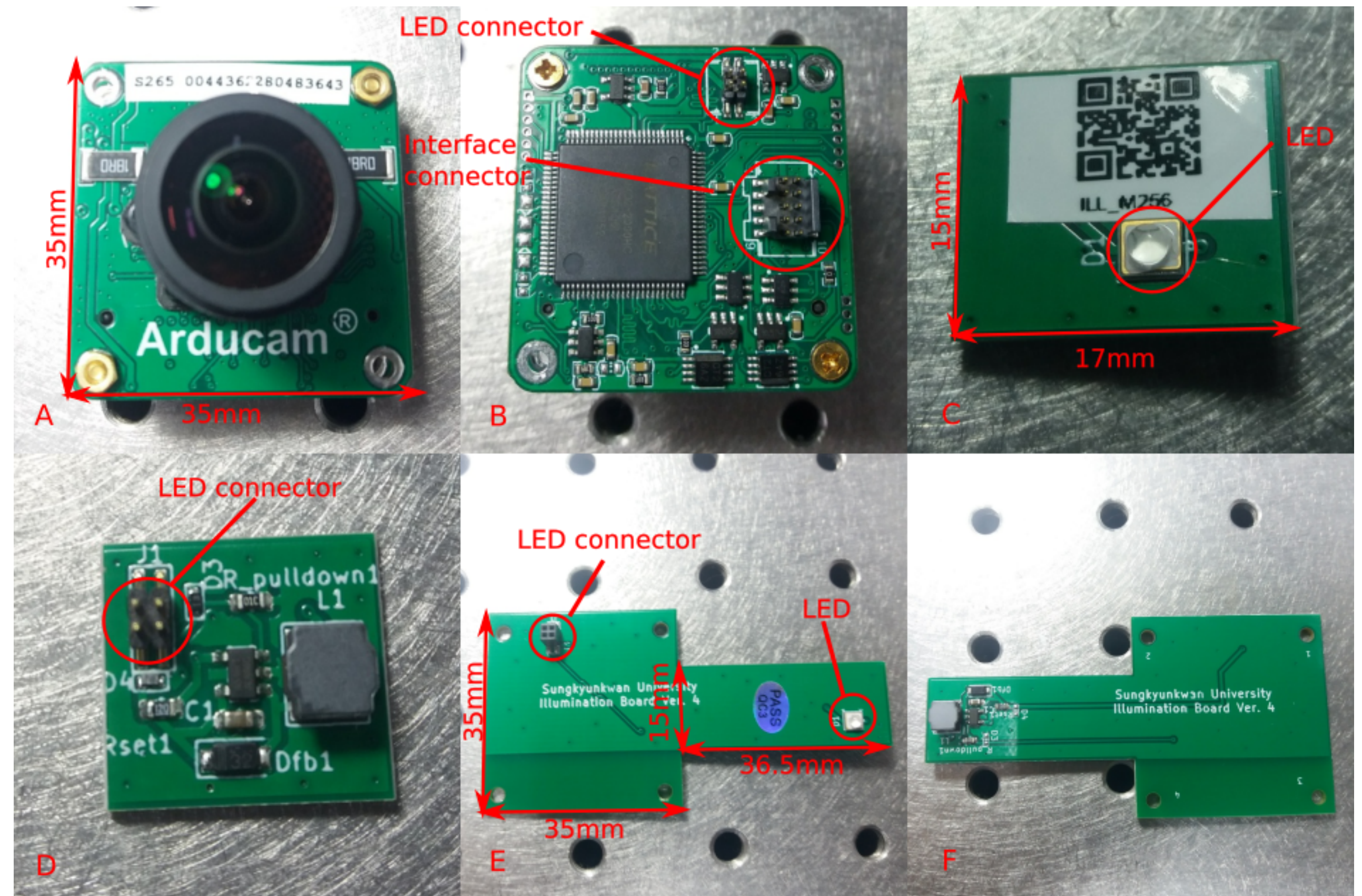
E-mail: martin.rongen@icecube.wisc.edu, dima@icecube.wisc.edu

The IceCube Neutrino Observatory instruments about 1 km³ of deep, glacial ice at the geographic South Pole using 5160 photomultipliers to detect Cherenkov light of charged relativistic particles.

IceCube Upgrade Camera System

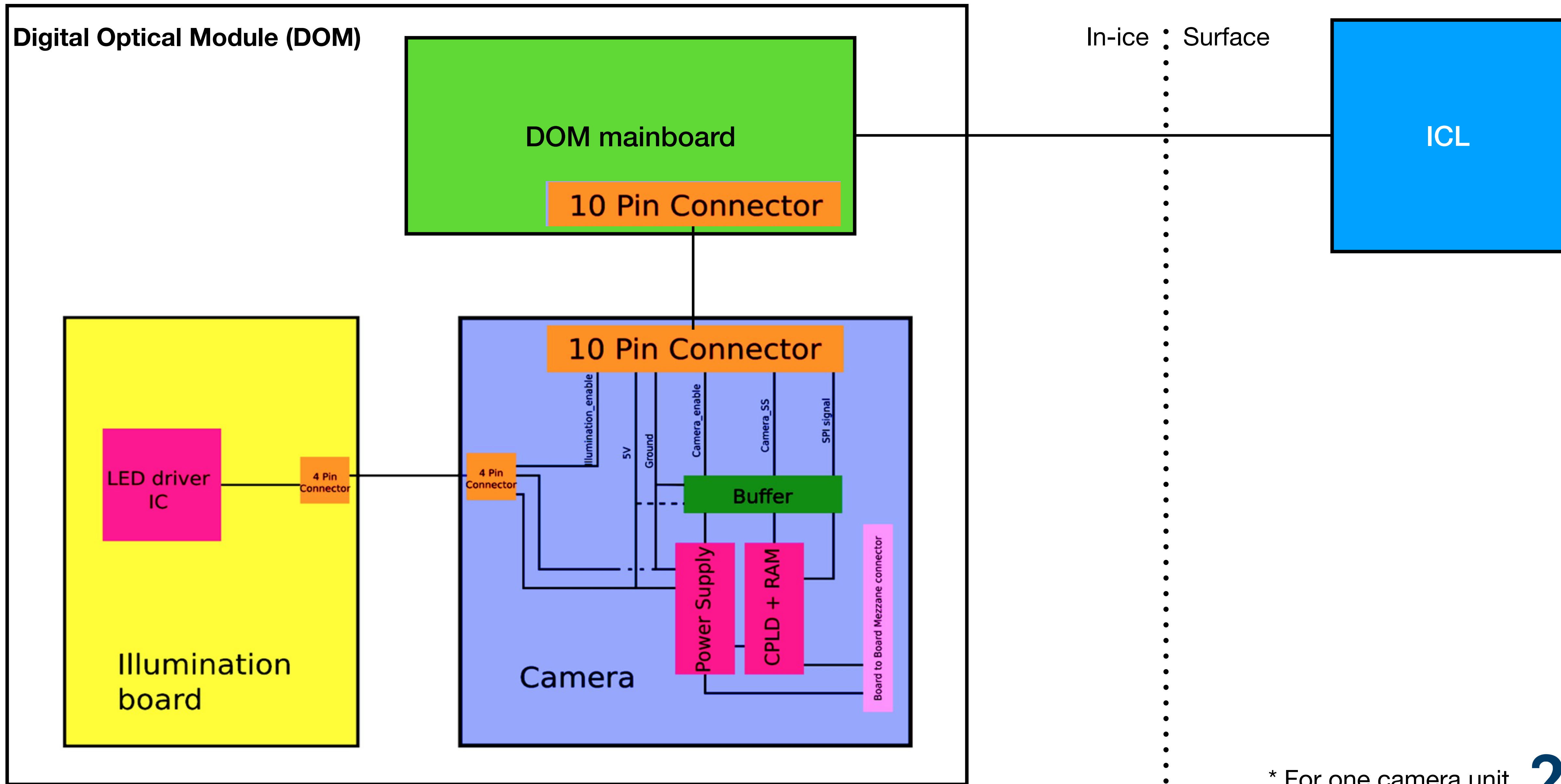
Woosik Kang
NuFACT 2022
August. 5th, 2022

- The IceCube Upgrade Camera system is developed and produced by SKKU IceCube group
- The system consists of 2 PCBs and an M12 lens with fixed focus
- The camera uses a SONY IMX225 image sensor with 1312 x 979 pixels resolution
- The illumination system is a postage-stamp sized PCB with a single 1-W LED with a light profile width of 80 degrees



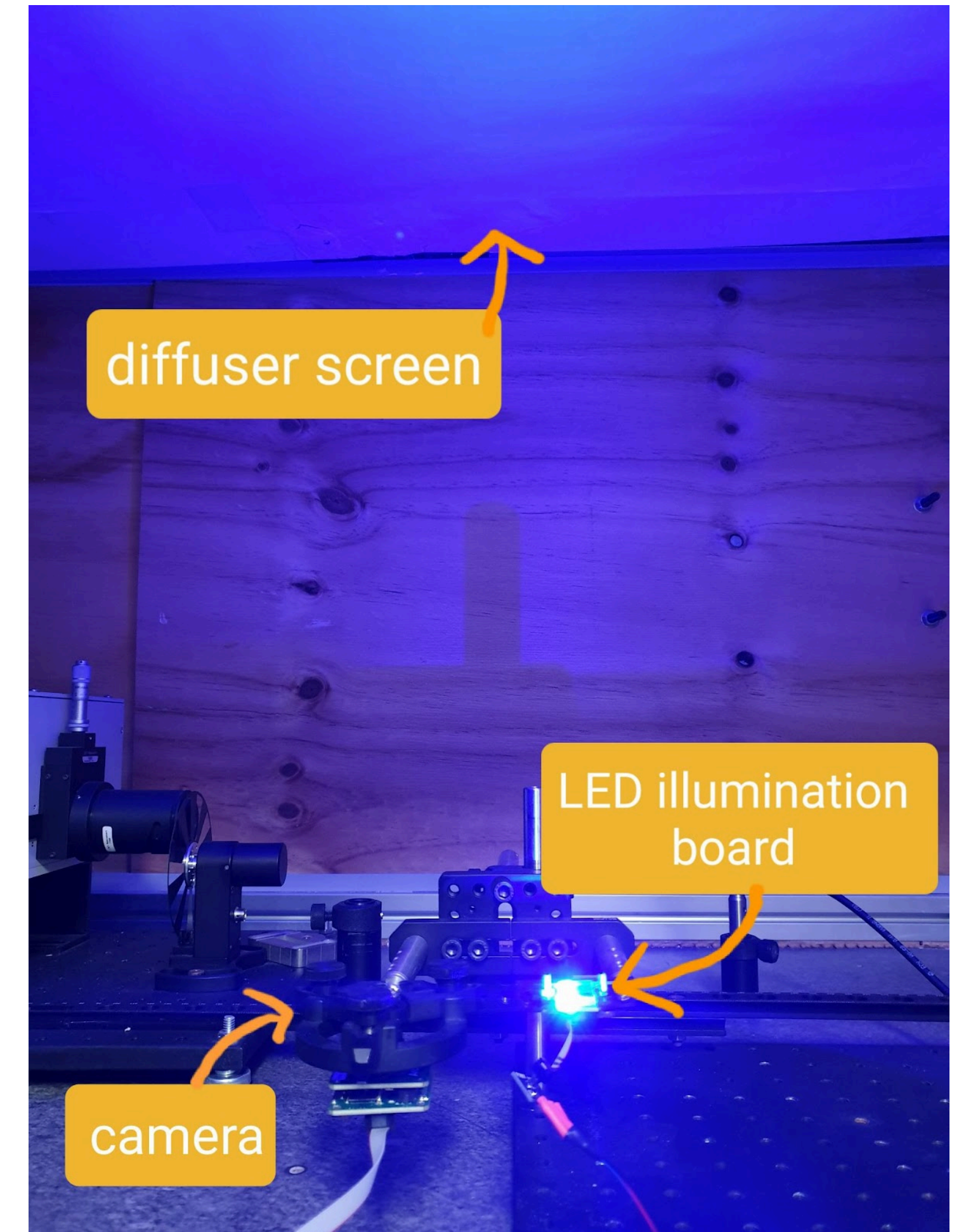
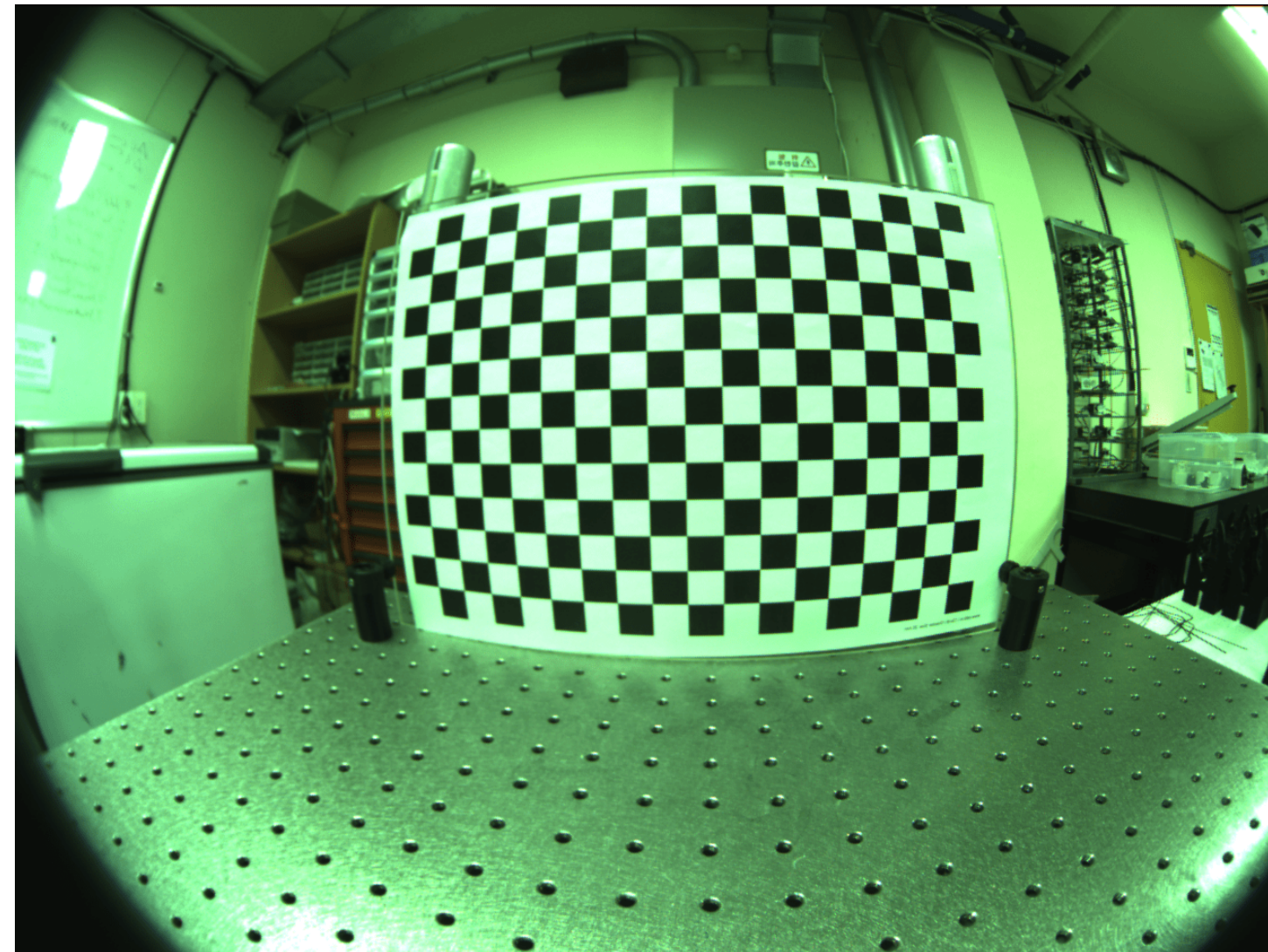
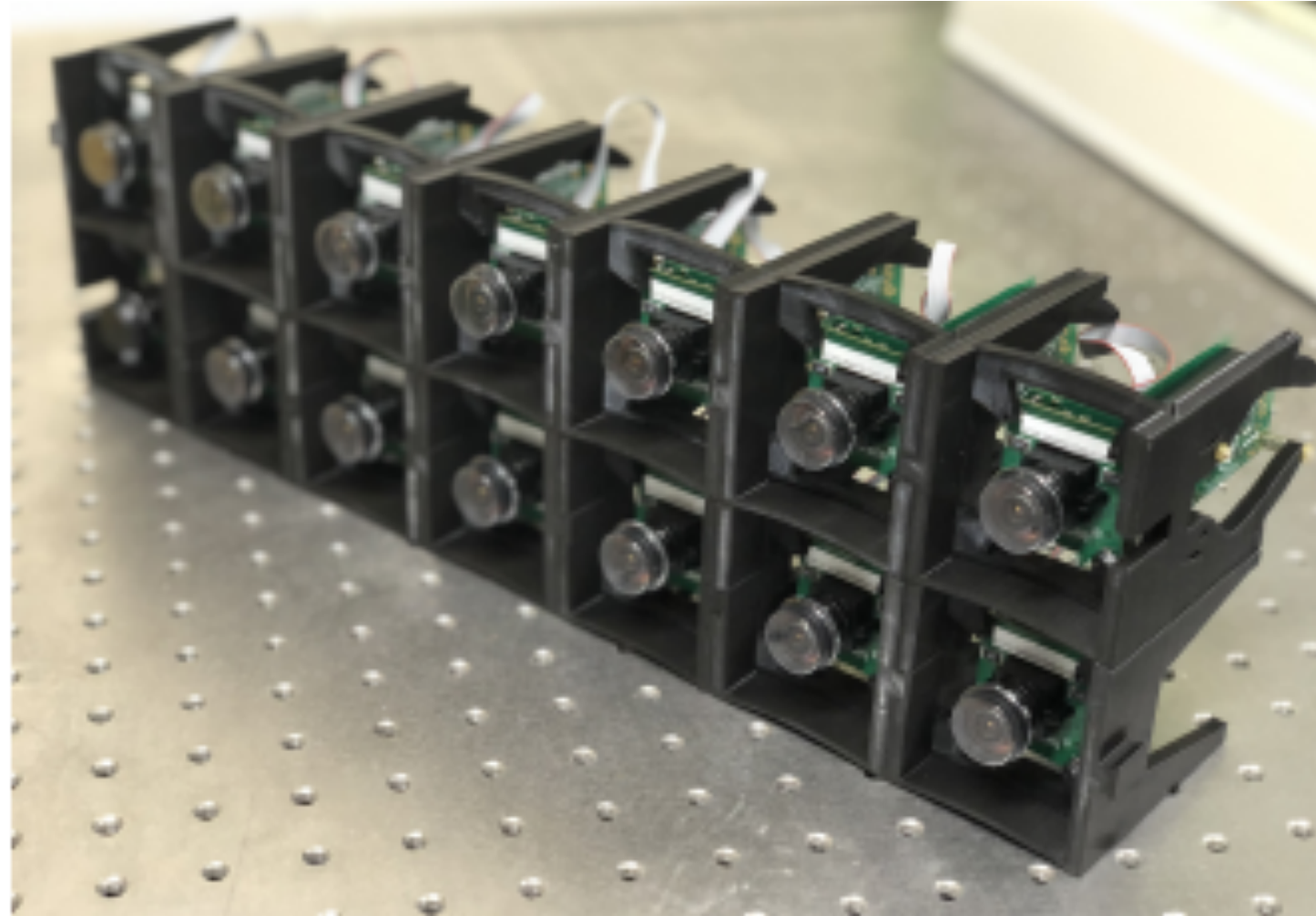
Camera communication

Woosik Kang
NuFACT 2022
August. 5th, 2022



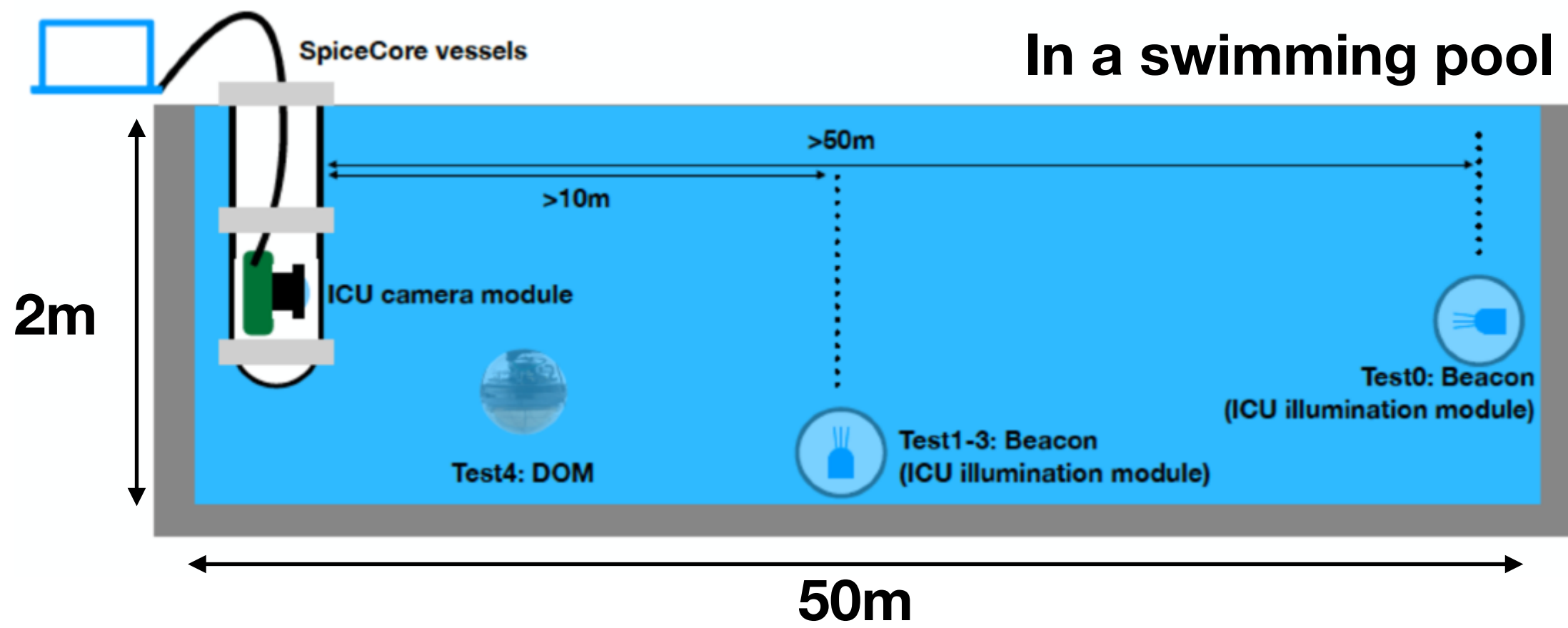
Camera Acceptance Tests

Woosik Kang
NuFACT 2022
August. 5th, 2022

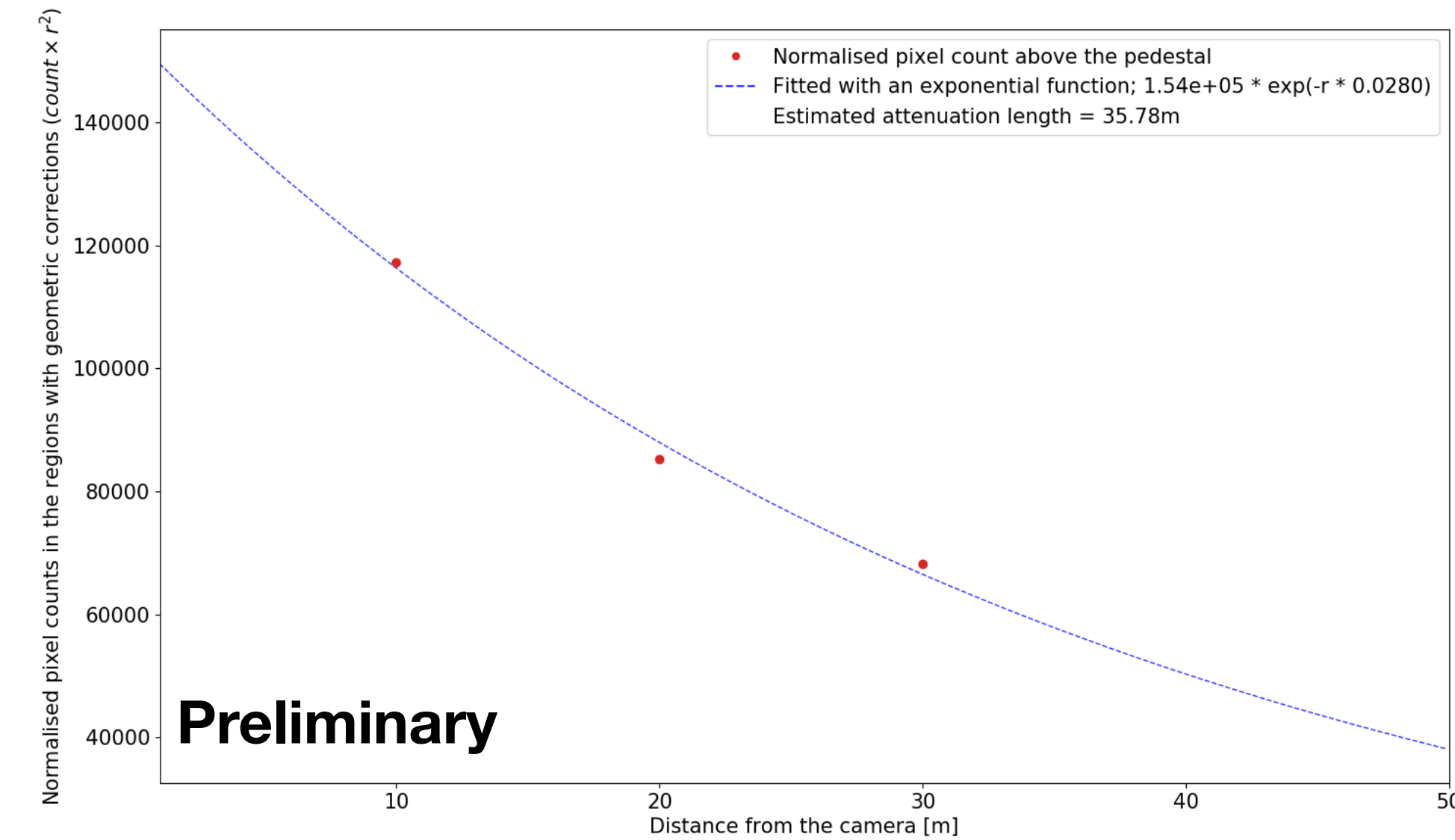


Swimming pool test

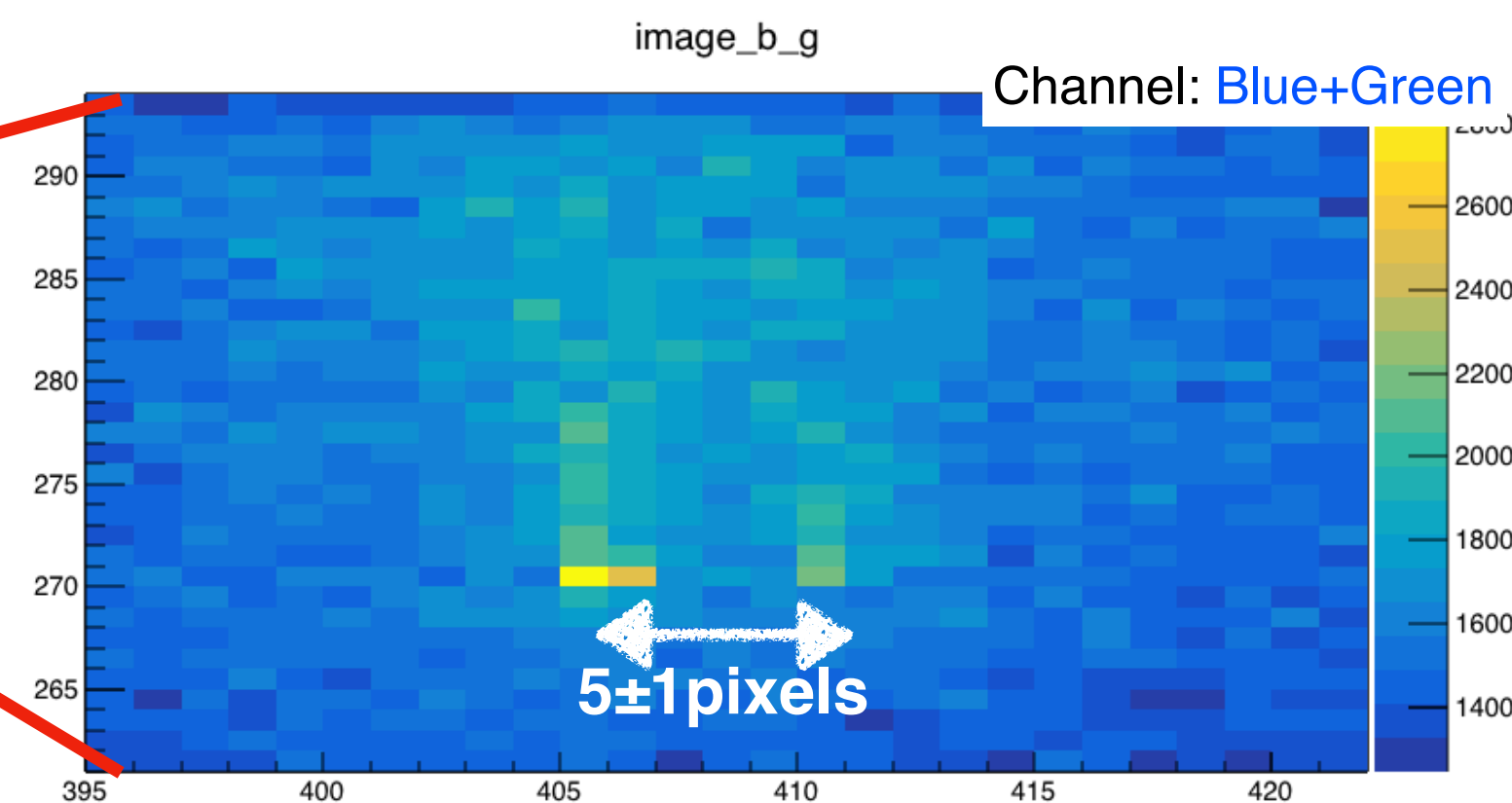
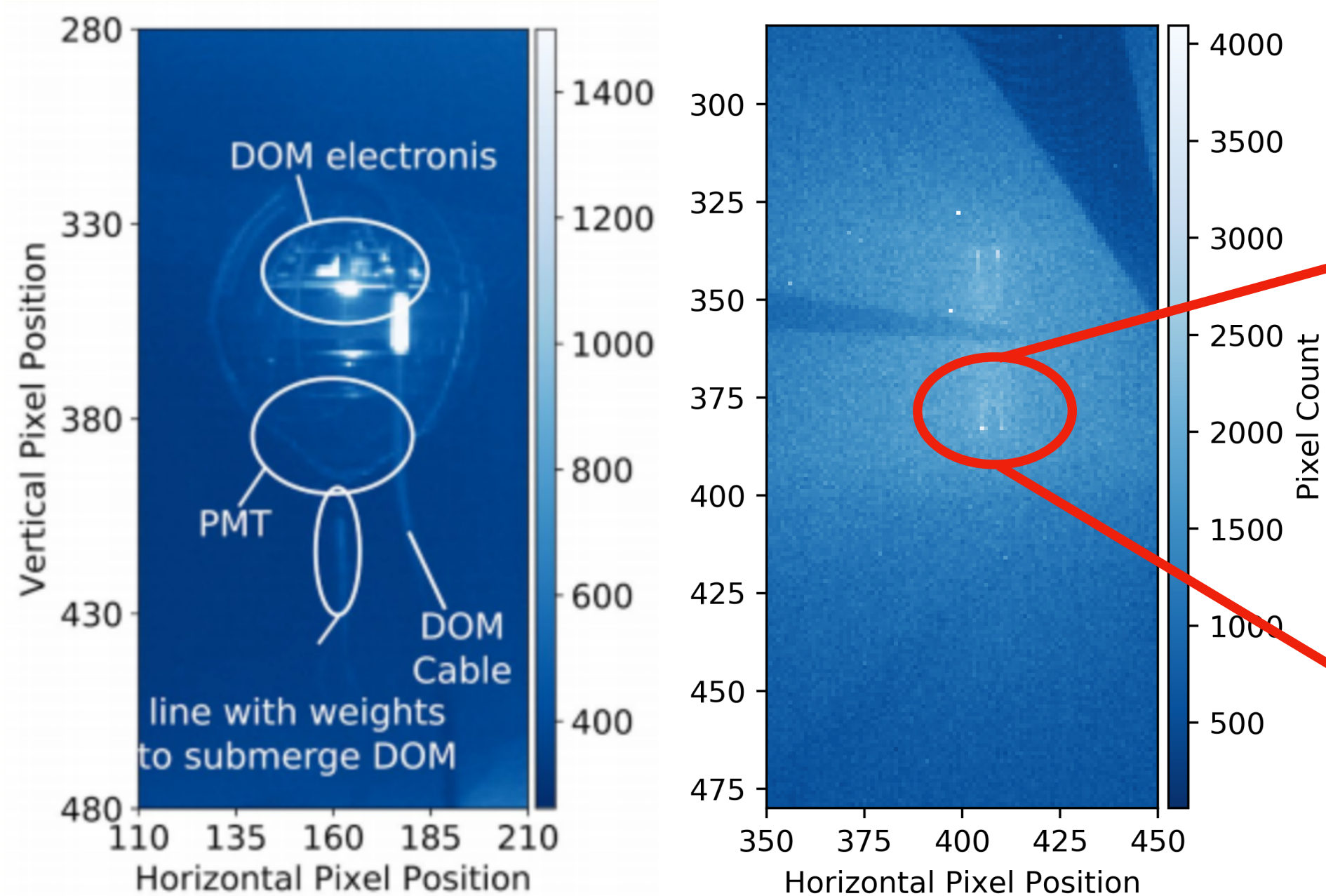
Woosik Kang
NuFACT 2022
August. 5th, 2022



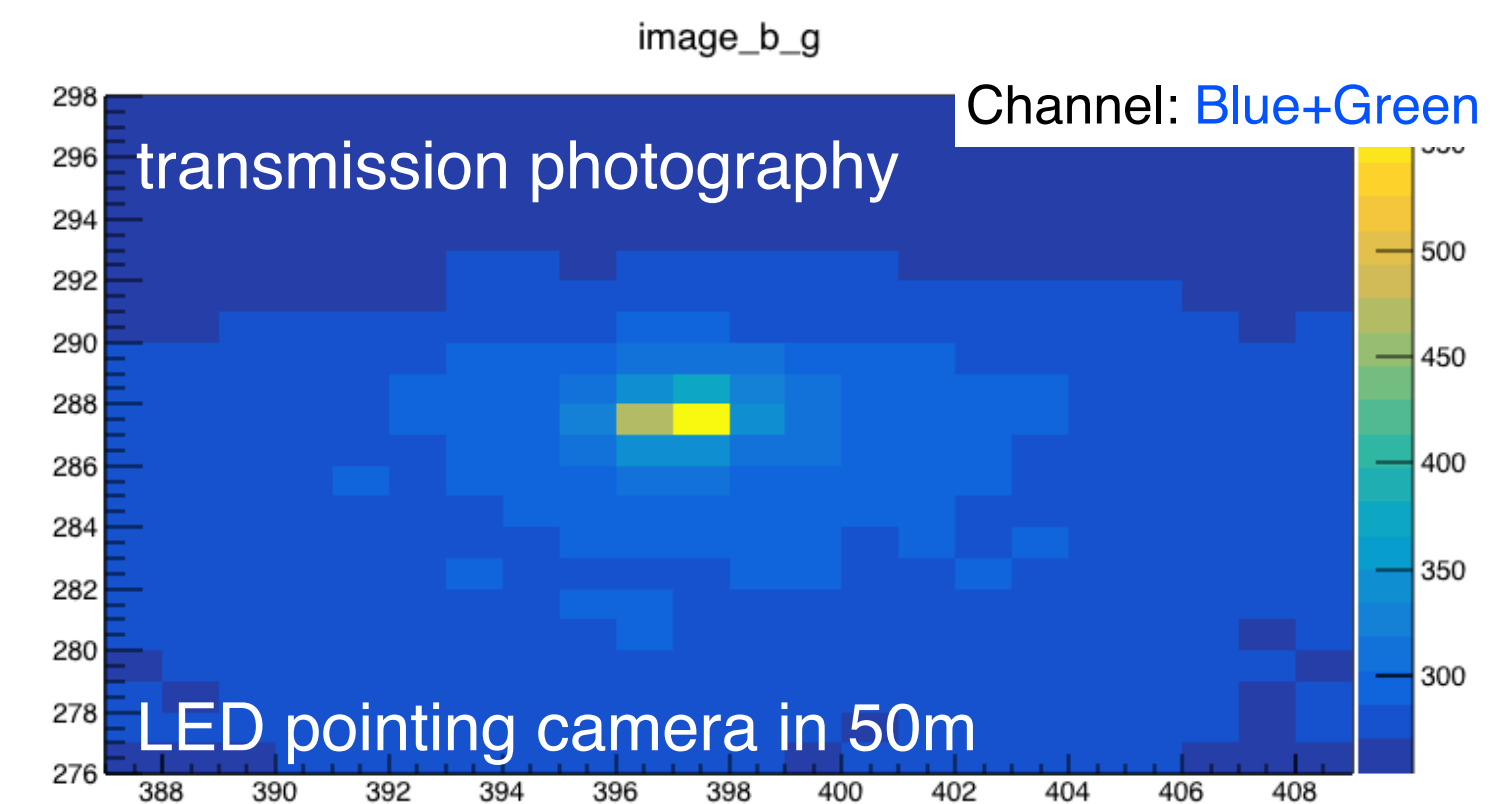
A full demonstration of the camera capabilities in an underwater test had been performed. (Note: Significant background light was present)



reflective photography



Resolution: ~10cm resolution at 25m distance (geometry verification, ...)



Details:
[ICRC Proceedings](#) / (arxiv1908.07734)