Gen2 Camera System

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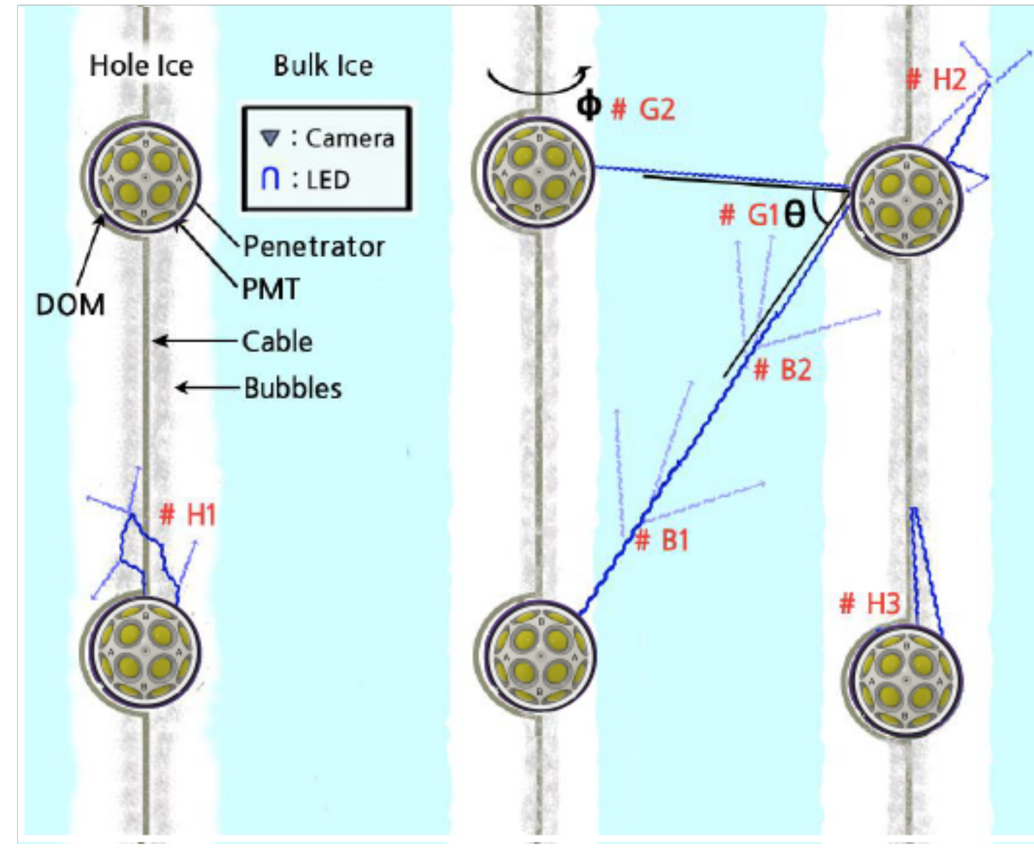
Overview

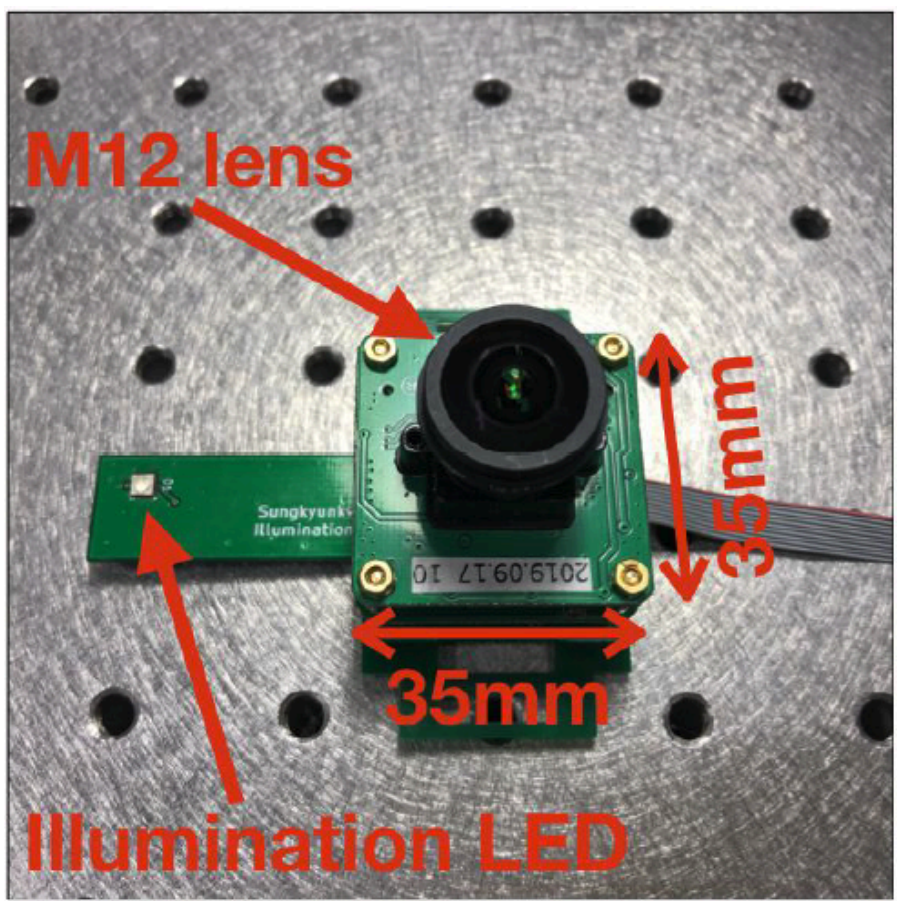
- Motivation
- Camera Measurements & Objectives
  - Hole ice
  - Bulk ice
- Cameras and illumination boards
- Action items - Next steps
- Discussions & Conclusions

Motivation

Upgrade - Ice Camera System

- Limited understanding of Antarctic ice properties dominant source of sys. uncertainties for most analyses
  - ⇒ better characterize detector medium
- Solution: Camera-based calibration system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability





Customized **camera module** consisting of 2 PCBs: One with the Image sensor (Sony IMX225) , M12 lens mount and lens, and second with CPLD and connectors.

Upgrade Scope: 3 cameras on each optical module

Hole ice
- Mapping local hole profile (hole ice / bulk ice)
- Location of bubble column
- Impurities / cracks / ...
- transmission / reflection at interface hole/bulk ice

Geometry (Positioning)
- DOM position relative to adjacent DOMs
- Cable position

Geometry (DOM Orientation)
- Orientation of camera DOM
- Orientation of neighbouring DOM on adjacent string
- Orientation of neighbouring DOM on same string

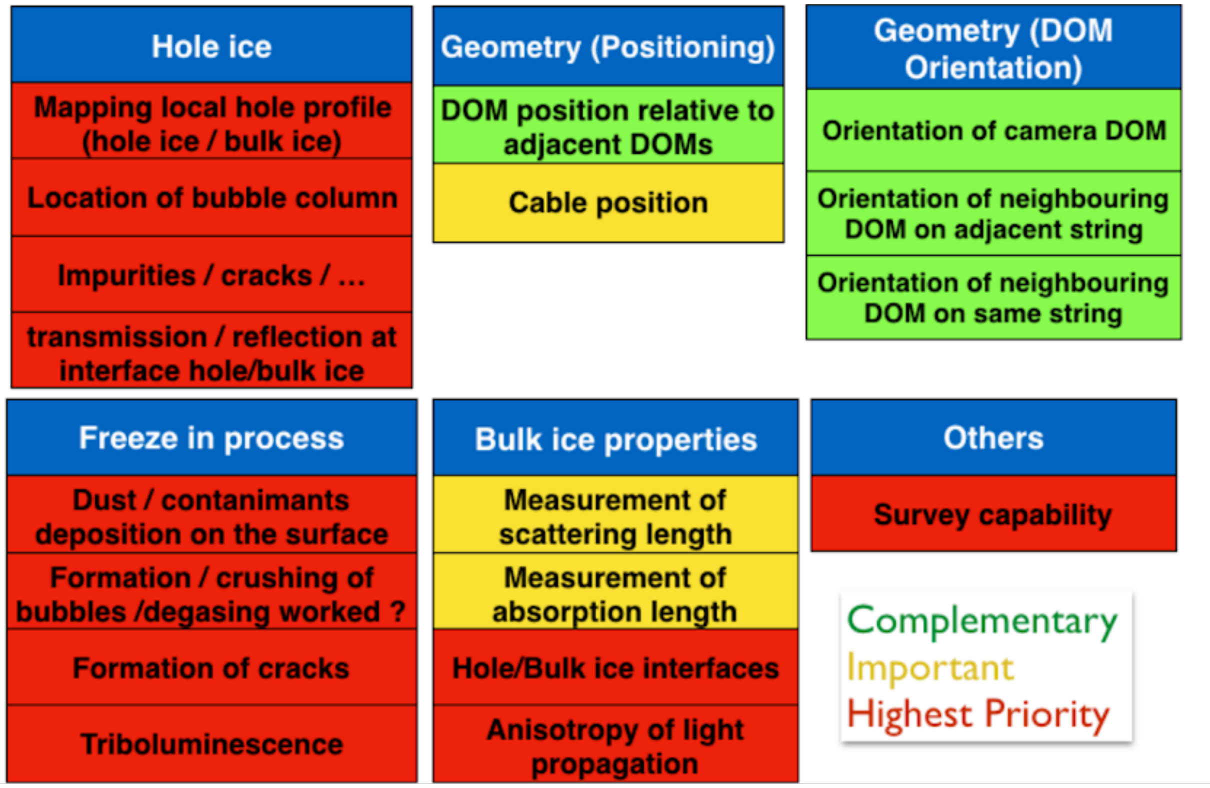
Freeze in process
- Dust / contanimants deposition on the surface
- Formation / crushing of bubbles /degasing worked ?
- Formation of cracks
- Triboluminescence

Bulk ice properties
- Measurement of scattering length
- Measurement of absorption length
- Hole/Bulk ice interfaces
- Anisotropy of light propagation

Others
- Survey capability

Complementary
Important
Highest Priority

Gen2 - Ice Camera System

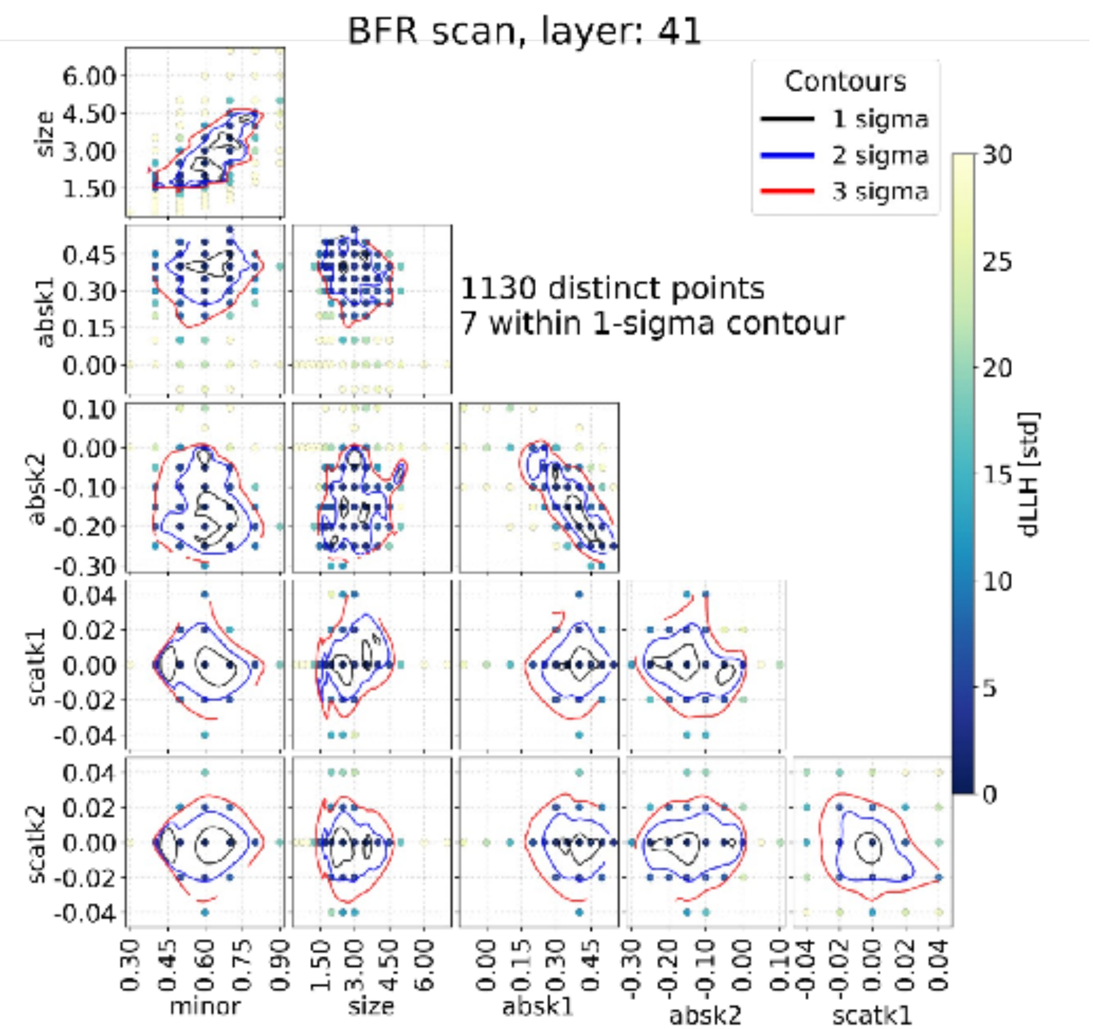


- Calibration priorities for Gen2 remain similar to those identified for the Upgrade

- Design strategy & objectives:
  - Identical camera system that will be deployed on all or subset of optical modules.
  - Easy to produce, test, and integrate
- Camera system
  - Off the shelf products to reduce costs
- Prototype
  - Upgrade camera system (for mDOM) can serve as production ready prototype for Gen2
    - Minor adjustments and modifications should be done (details see backup slides from Christoph)

Calibration Needs to Gen2

- Calibration
  - Enable Gen2 science objectives
    - Angular resolution ~ Multi-messenger science
    - Anisotropy ~ Cascade reconstruction
  - Camera-based measurements provide detailed directional information
  - Camera based measurements are expected to play a critical role in understanding local ice properties, detect features in the ice and allow to obtain a deeper understanding of the optical ice properties
- Ice Models
  - Tremendous progress has been made to understand the optical ice properties
    - With the BFRv2 model the optical properties of the ice can be modeled far better by now
    - However model parameters still have substantial uncertainties
    - Absorption parameters need to be better fitted and the elongation and crystal size are still ambiguous in the fit
  - There is also a need to map the hole ice properties and the profile of the holes
  - Understanding of the local ice environment

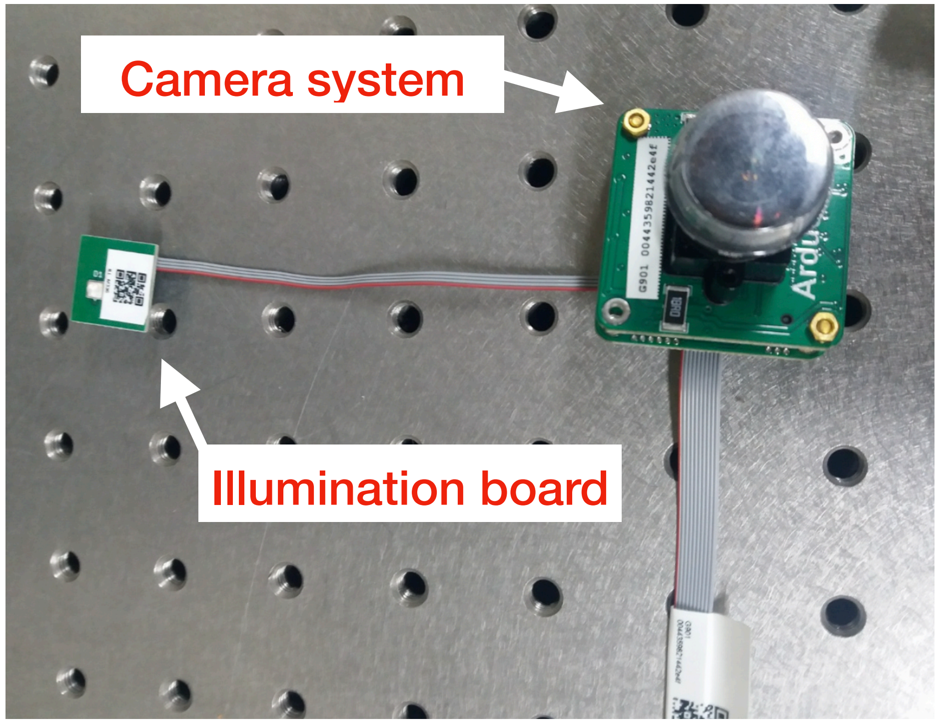


Objectives for Gen2 calibration

- Key objectives
  - Hole ice characterizations
  - Anisotropy
  - Detailed ice model developed for Upgrade - how to apply for Gen2, local features ?
  - Local ice properties
  - Survey capabilities (unexpected effects ~ bubble column)

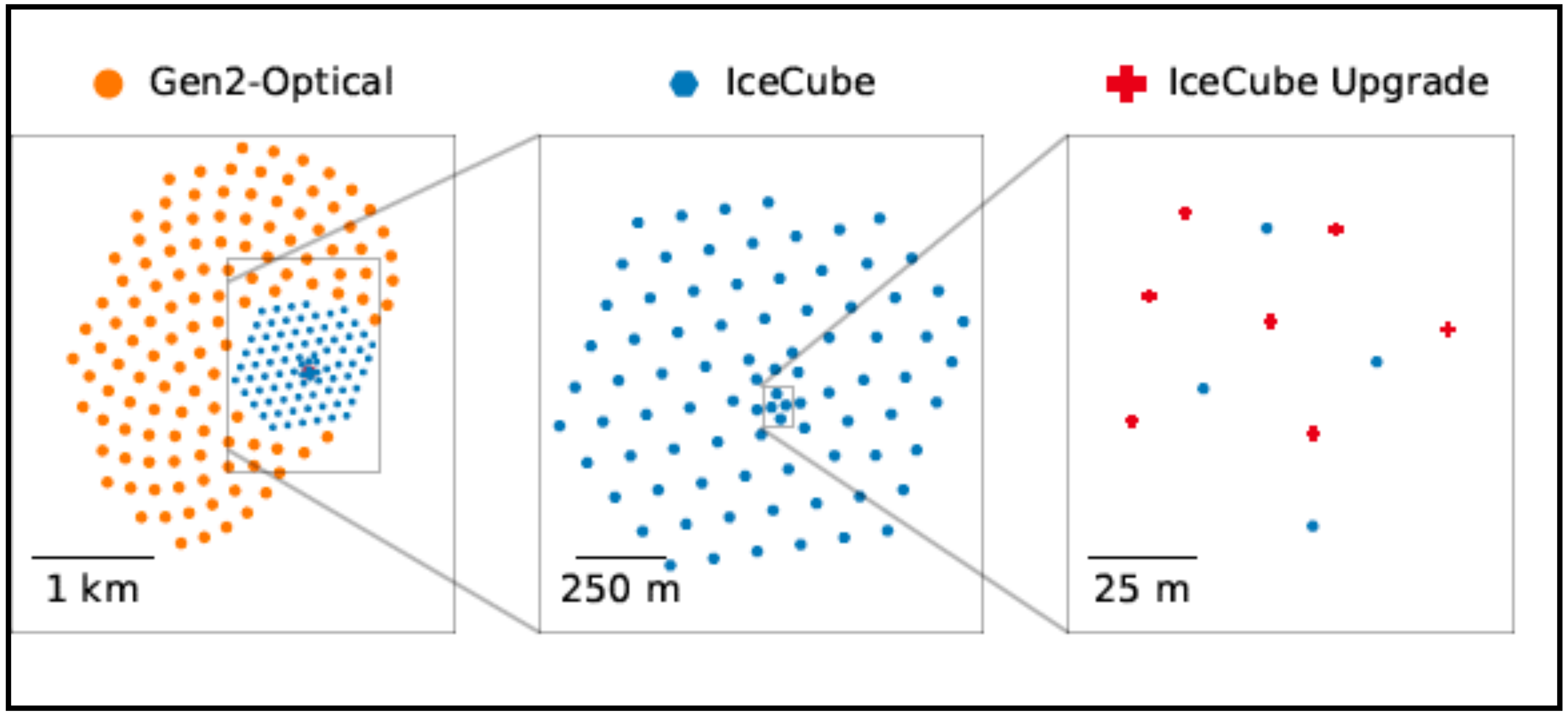
Lessons learned from the Upgrade

- Simple camera holding structure
  - D-EGG camera holding structure very complex and hence very time consuming to produce and install
- Aim for a system similar to the Upgrade mDOM system with straight forward integration



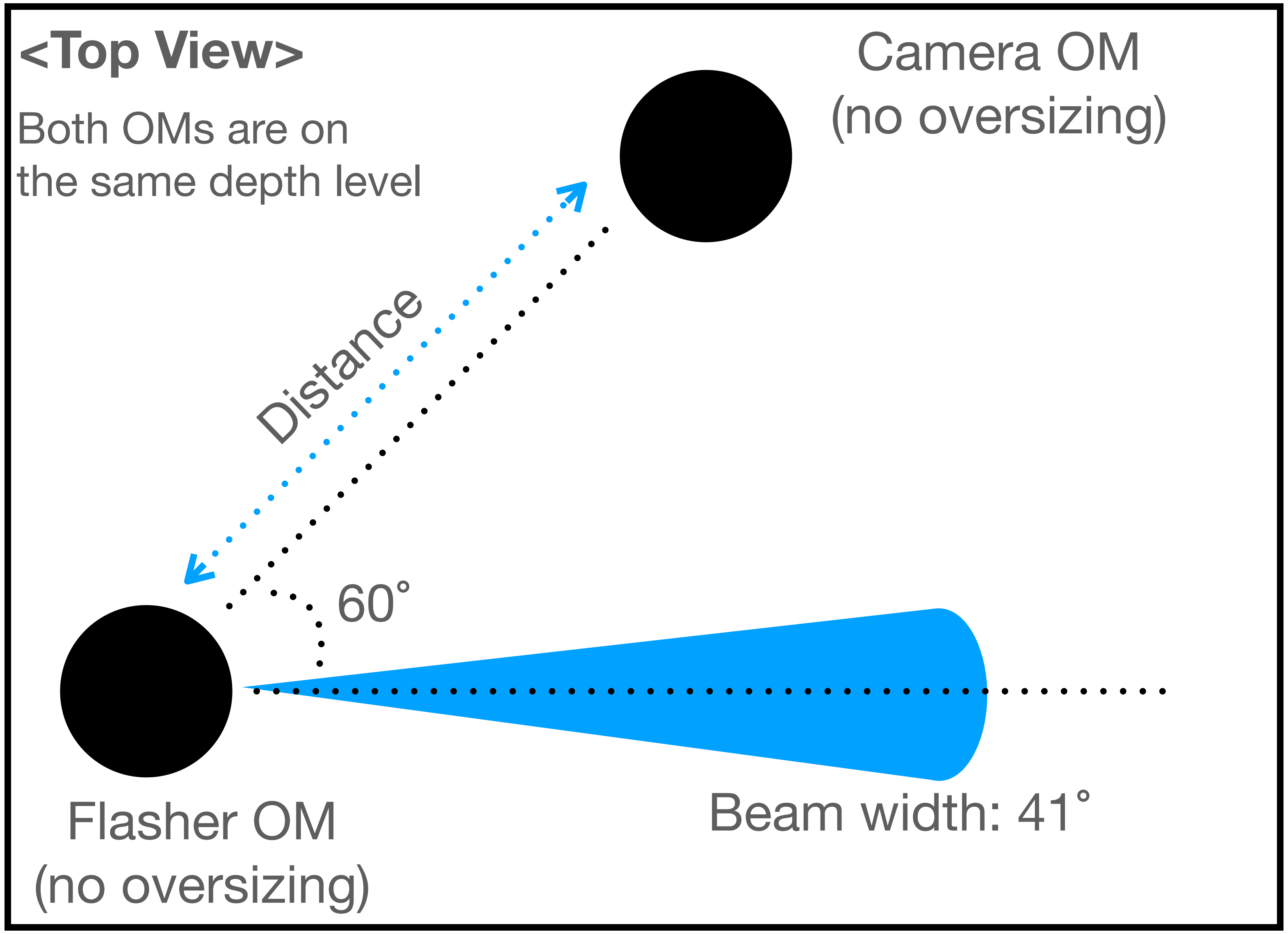
Differences Gen2 and Upgrade

- String-to-String distances in Upgrade allow for observations of adjacent strings
  - At Gen2 such measurements would be extremely challenging

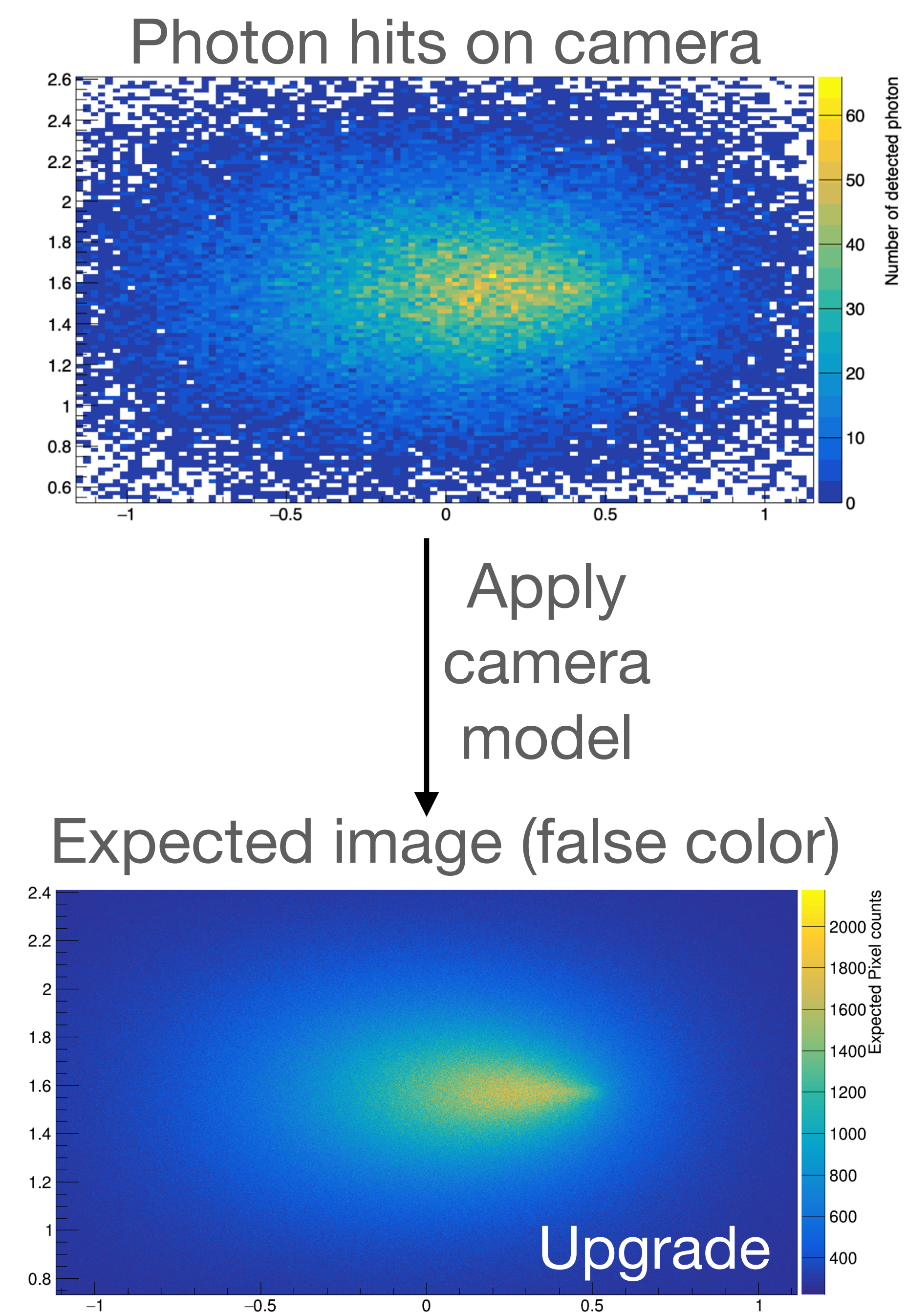


	Upgrade	Gen2
String-to-string spacing	~25m	~240m
DOM-to-DOM spacing	~3m	~15m
Deployment depth	2163m (-29C)- 2430m (-19C)	~1400m (-45C) - ~2500m (-18C)

Simulations

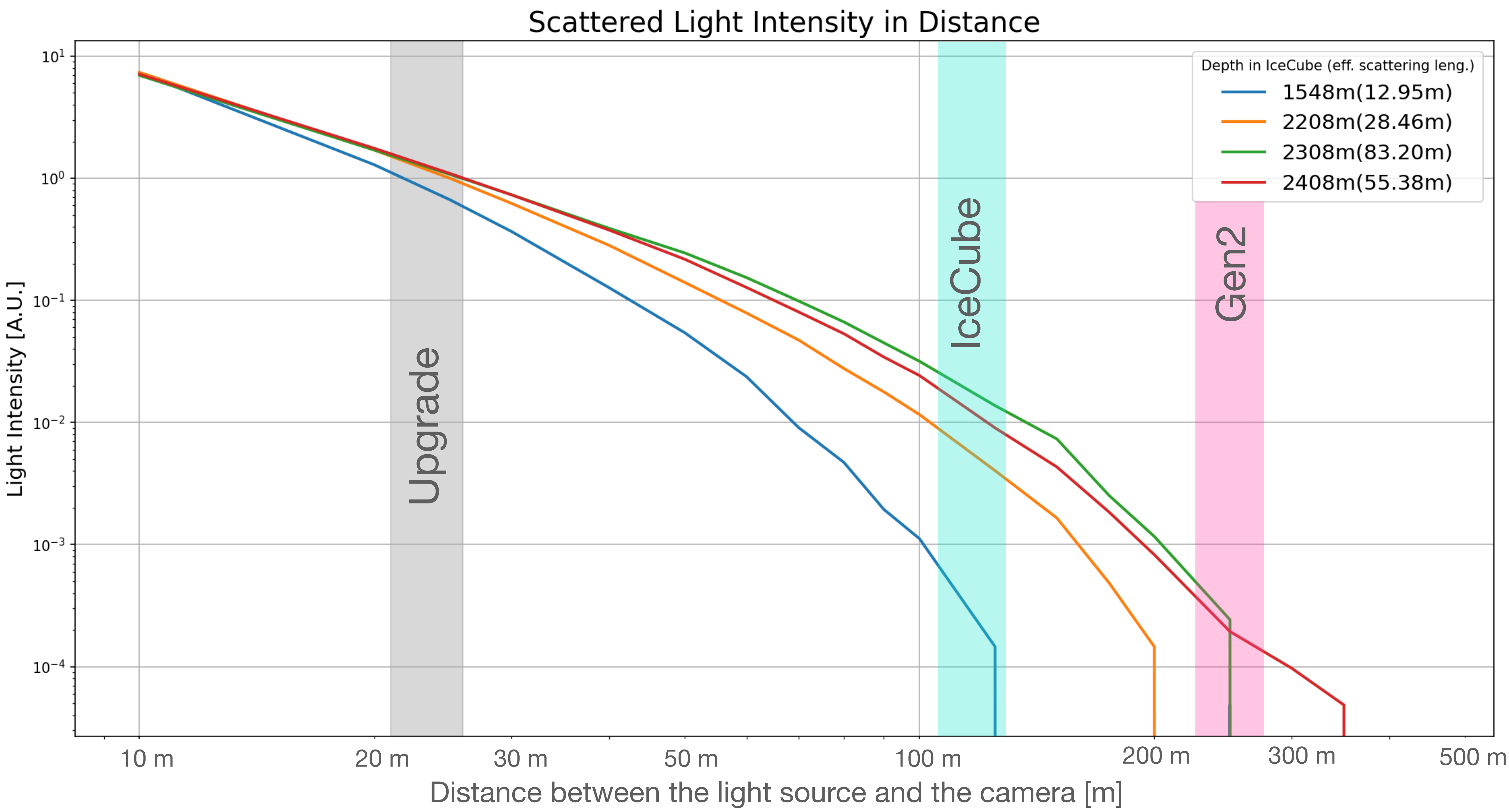


[Imaging the sidewise light from an adjacent string]



- Simulation details:
  - LED wavelength λ= 470nm (same as for Upgrade LEDs)
  - Beamed LED (2D gaussian emission profile) with cone width of 41˚
  - Camera module at 60˚ off-axis to LED center
  - Injected photons per simulation run 10^9

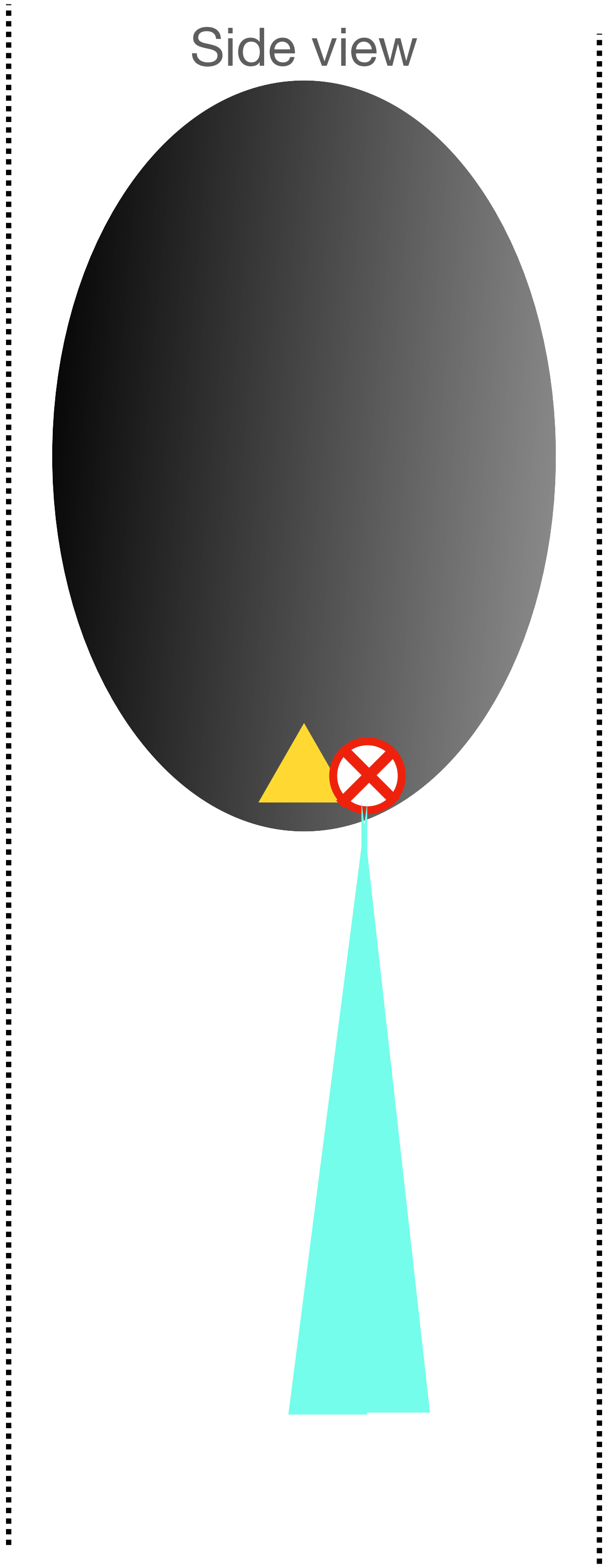
Photon reach



Measurements - Hole ice

Camera
Illumination LED

Geometries - Hole ice measurement

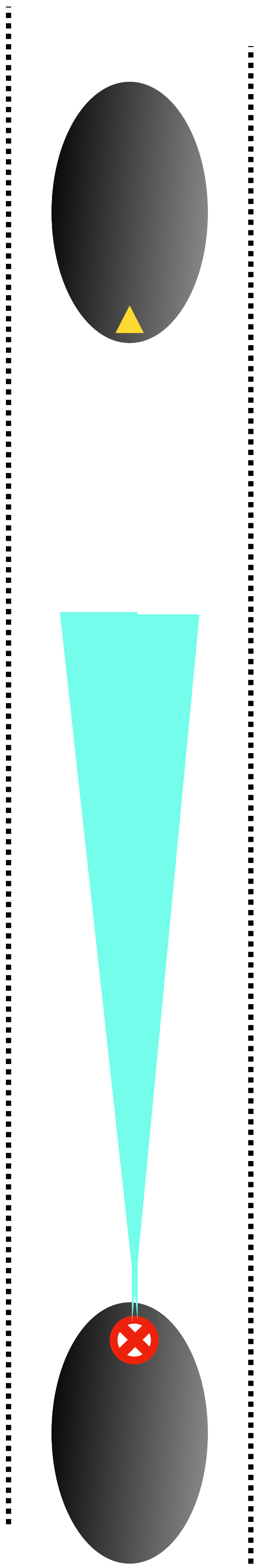


Focusing on idealized geometry for the measurements, constrains with other systems need to be considered. **Important to define real estate of the cameras + illumination boards early to avoid limitations due to obstructions, etc.**

- Camera and LED facing downwards
  - Observe back scattered light
  - Reflection photography
- Characterise “hole ice”
  - identify features in the refrozen ice, observe cable,, hole-bulk interface, …
- Survey capability
  - unexpected features: bubble column, contaminants, …

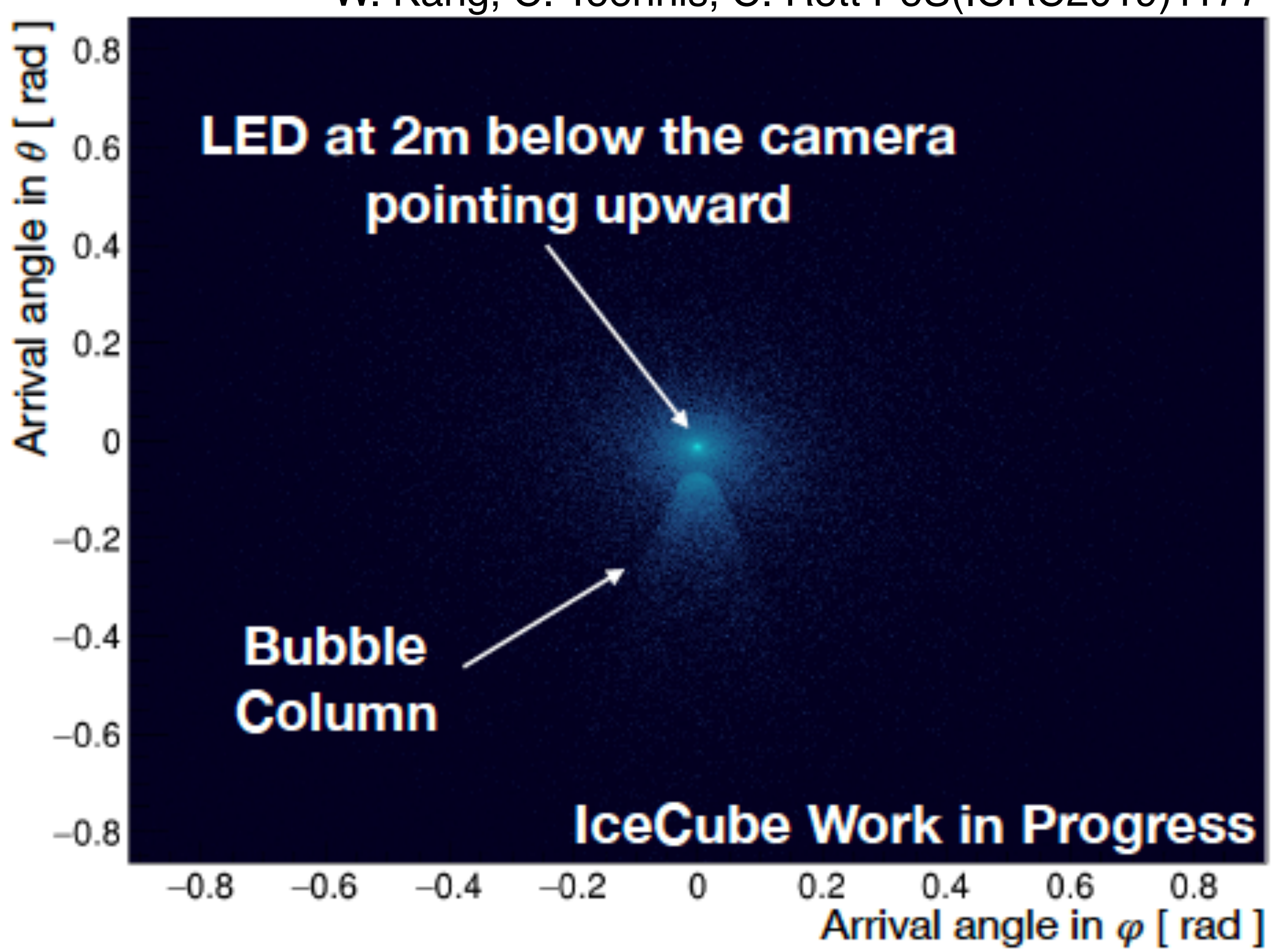
Geometries - Hole ice measurement

Camera
Illumination LED

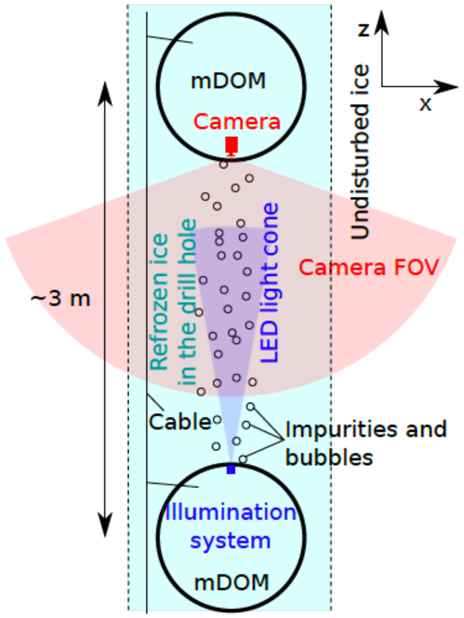


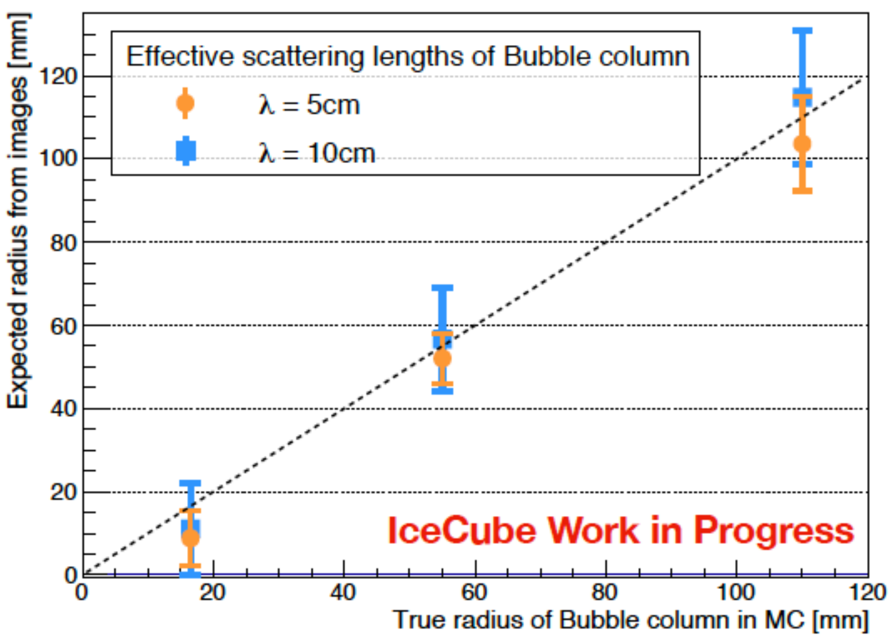
Focusing on idealized geometry for the measurements, constrains with other systems need to be considered.
Important to define real estate of the cameras + illumination boards early to avoid limitations due to obstructions, etc.

W. Kang, C. Toennis, C. Rott PoS(ICRC2019)1177



Side View, hole ice measurement





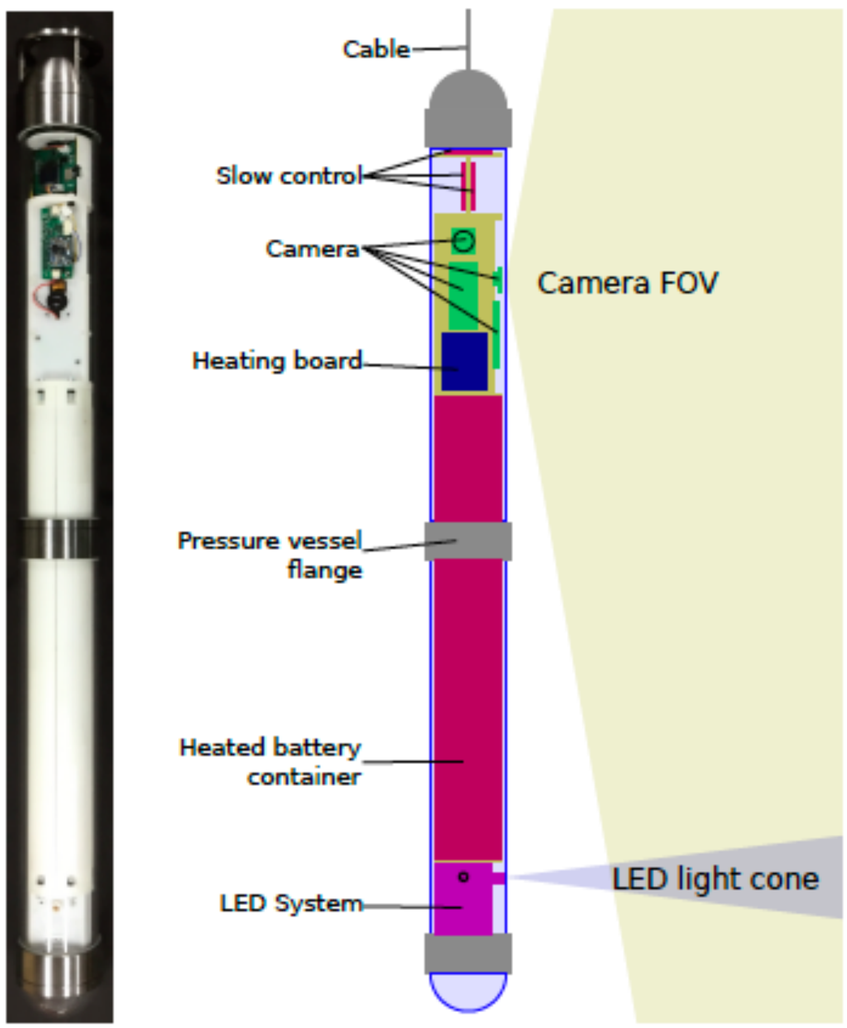
- Demonstrated for the IceCube Upgrade that bubble column size can be measured with few cm precision
  - Study to be updated for Gen2 configuration

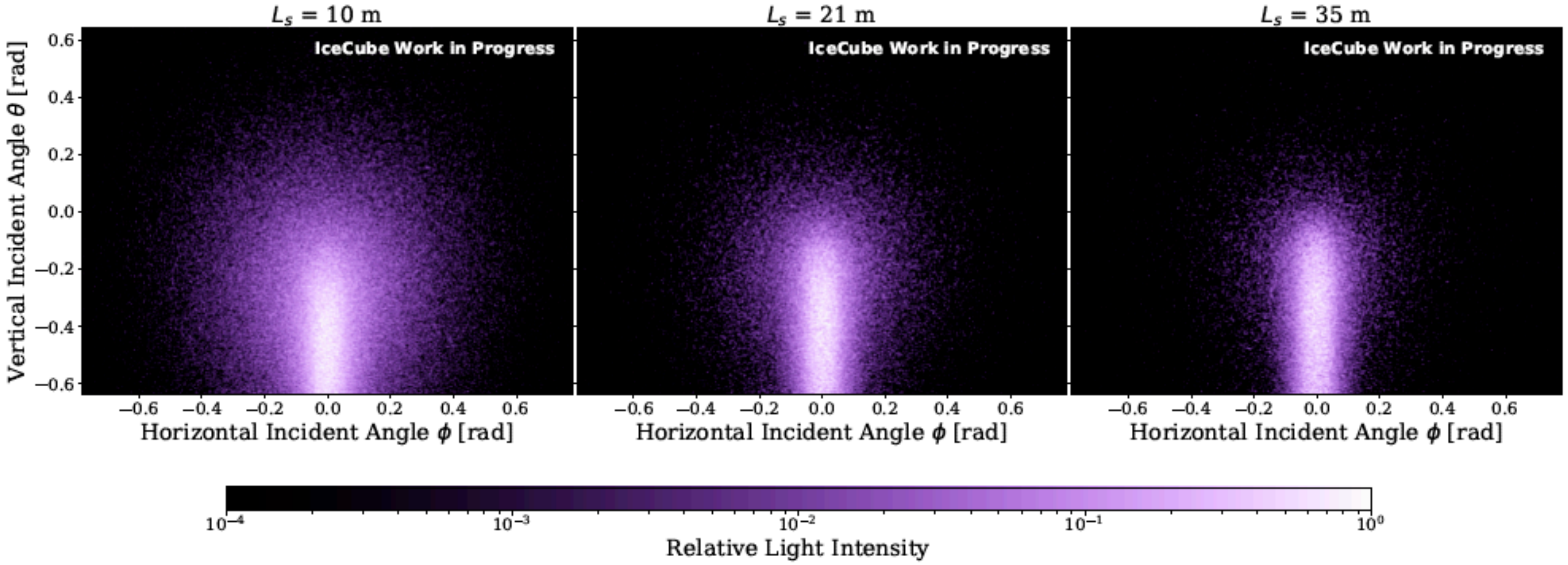
Bulk ice properties measurements

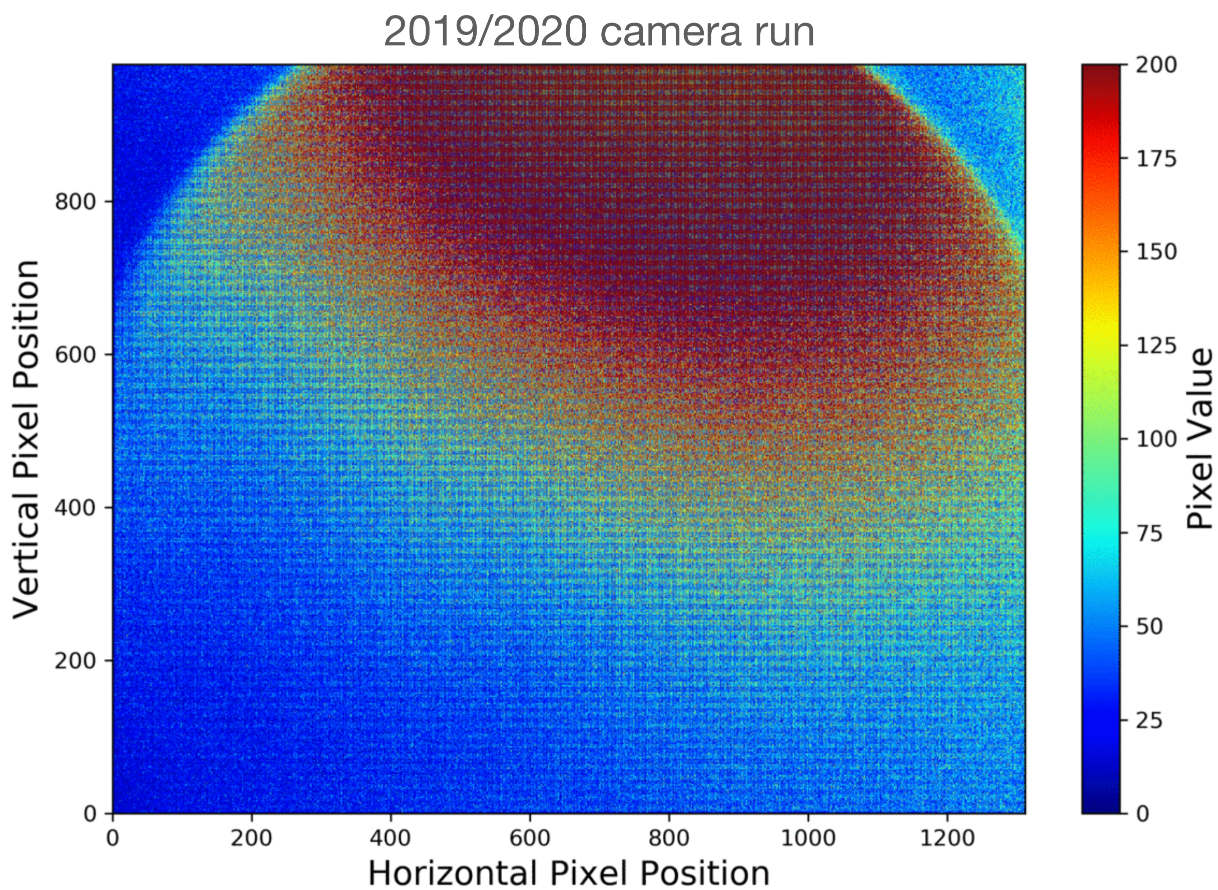
Potential configurations

A. Sideways pointing cameras + LEDs (Similar configuration to the spice core camera logger measurements)
B. Downward pointing camera + sideways pointing LEDs

H. Dujmovic, M. Jeong, C. Toennis POS(ICRC2019) 926

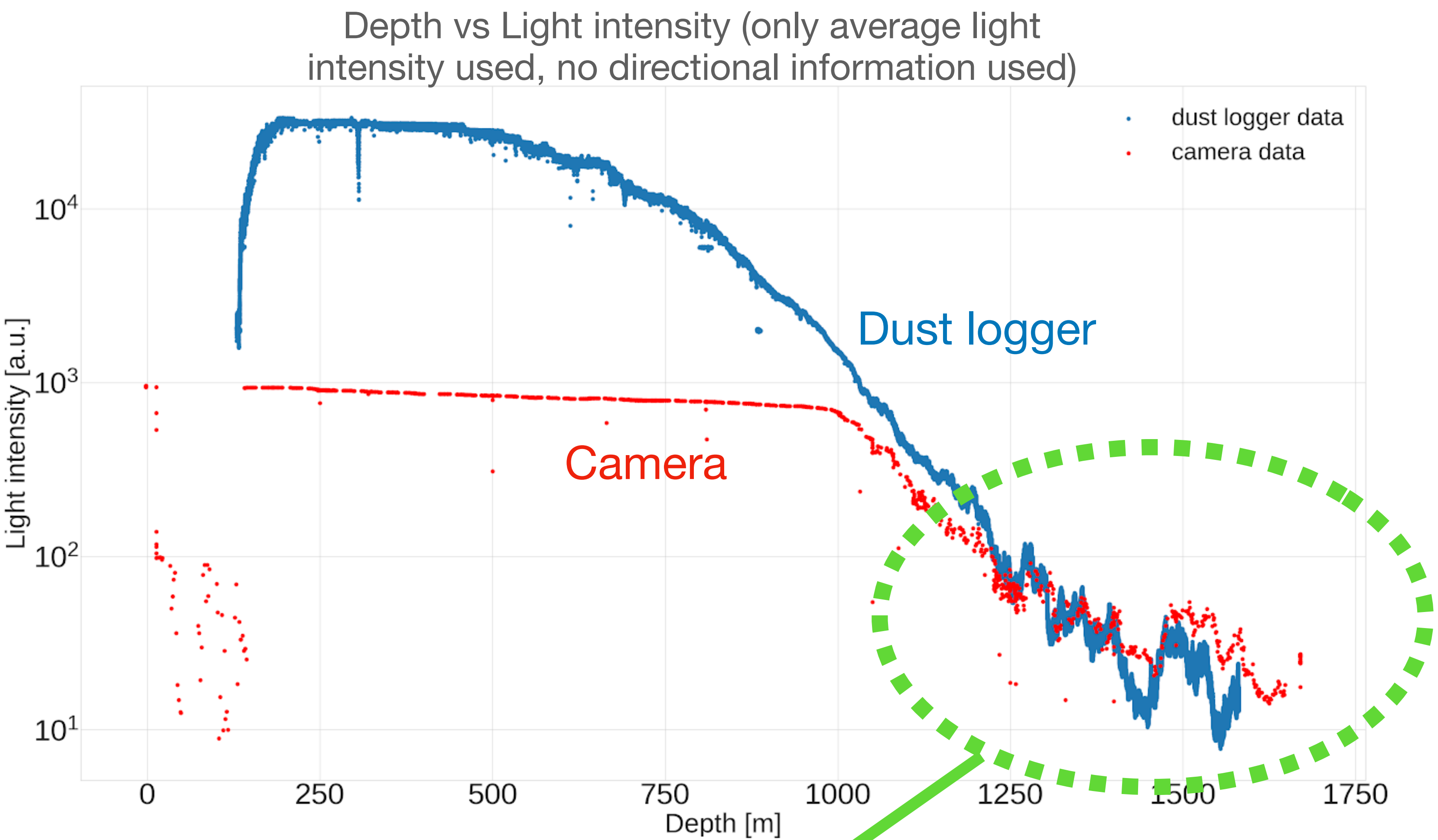






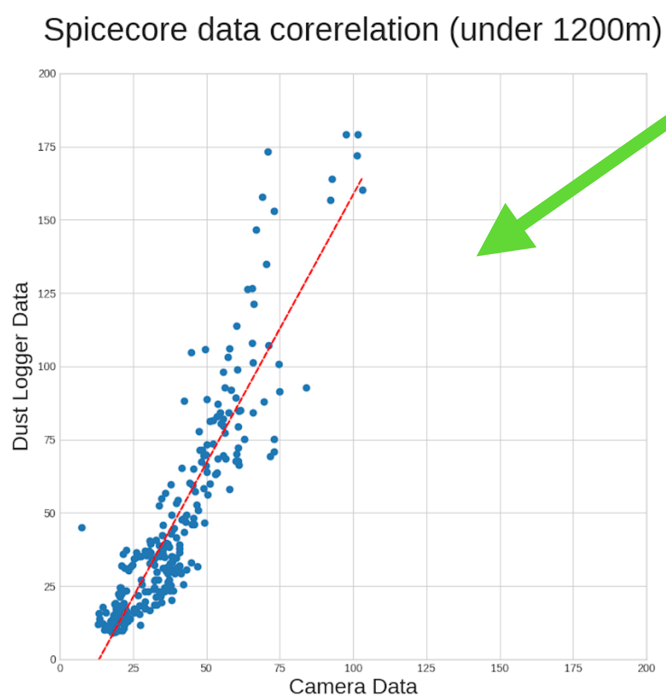
- Bulk ice properties can be measured by observing backscattered light from a directed light beam into the bulk ice and side-wise pointing camera.
  - This principle was used for the SpiceCore Camera Systems (2018/2019 + 2019/2020)

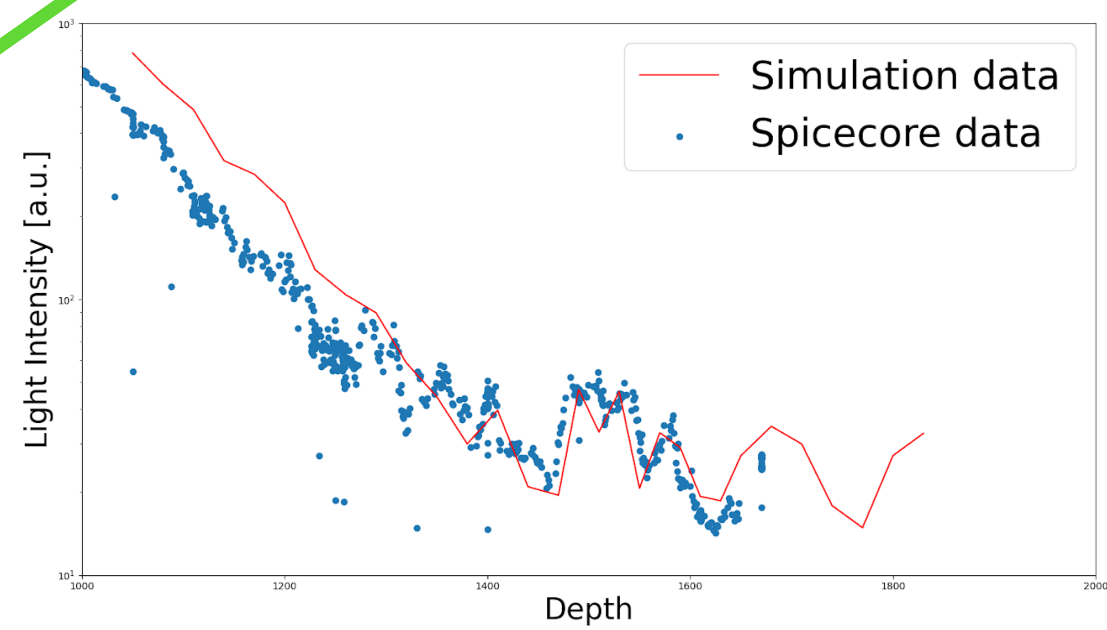
Spice Core Camera Run 2019/2020



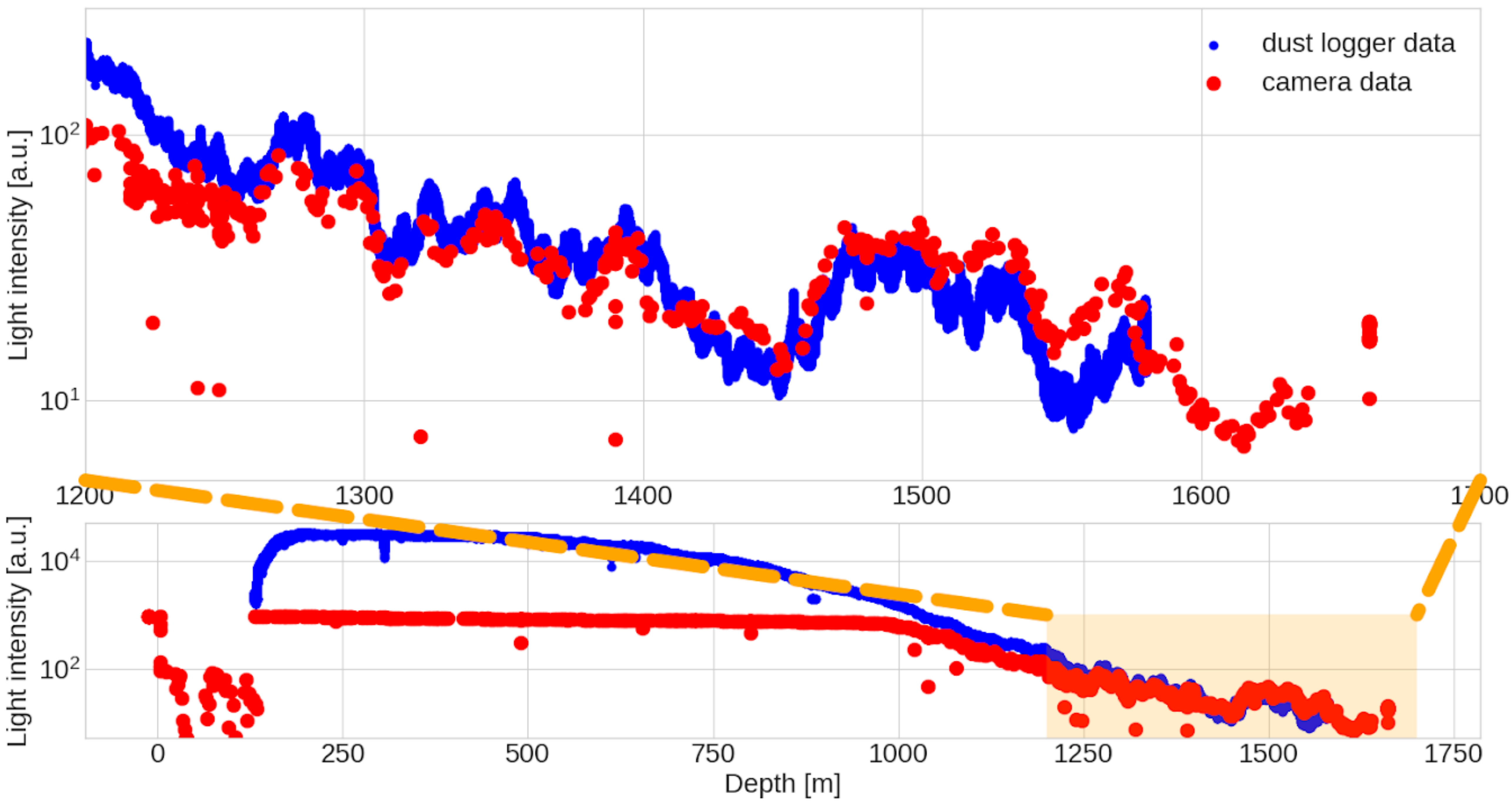
Thanks to Danim, Woosik, Christoph

- SpiceCore measurements have shown that:
  - Intensity + image features can be used to measure optical ice properties (ICRC2019)
  - Average image brightness correlates well with dust logger data - this is also confirmed with simulations
    - Improved analysis being developed on new data (Danim Kim) (ICRC2021)





Spice Core Camera Run 2019/2020

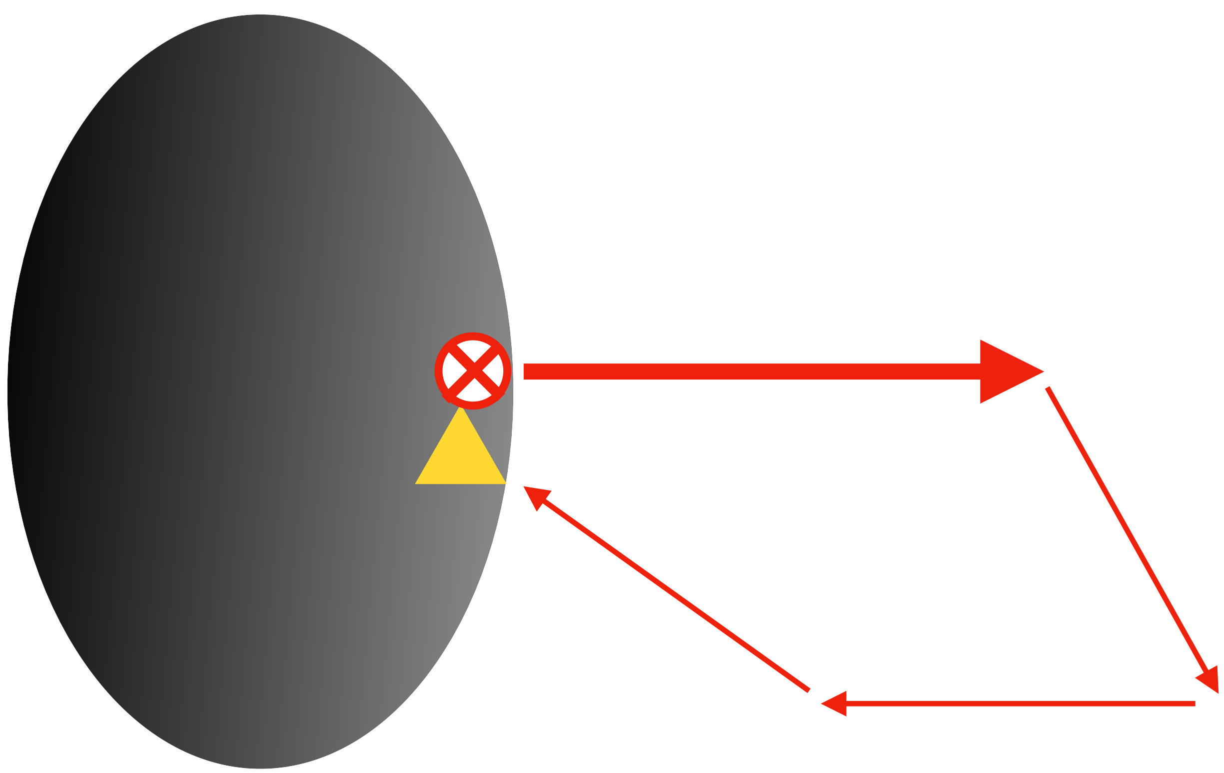


Camera
Illumination LED

Bulk ice measurements

Focusing on idealized geometry for the measurements, constrains with other systems need to be considered.
Important to define real estate of the cameras + illumination boards early to avoid limitations due to obstructions, etc.

Side view

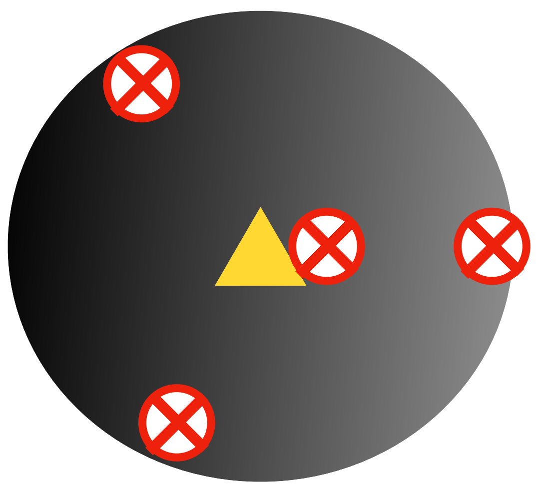


- Observe back scattered light from the LED
- Reflection photography
- Same principle as used for the spice core camera system
  - Data analysis on-going for ICRC2021

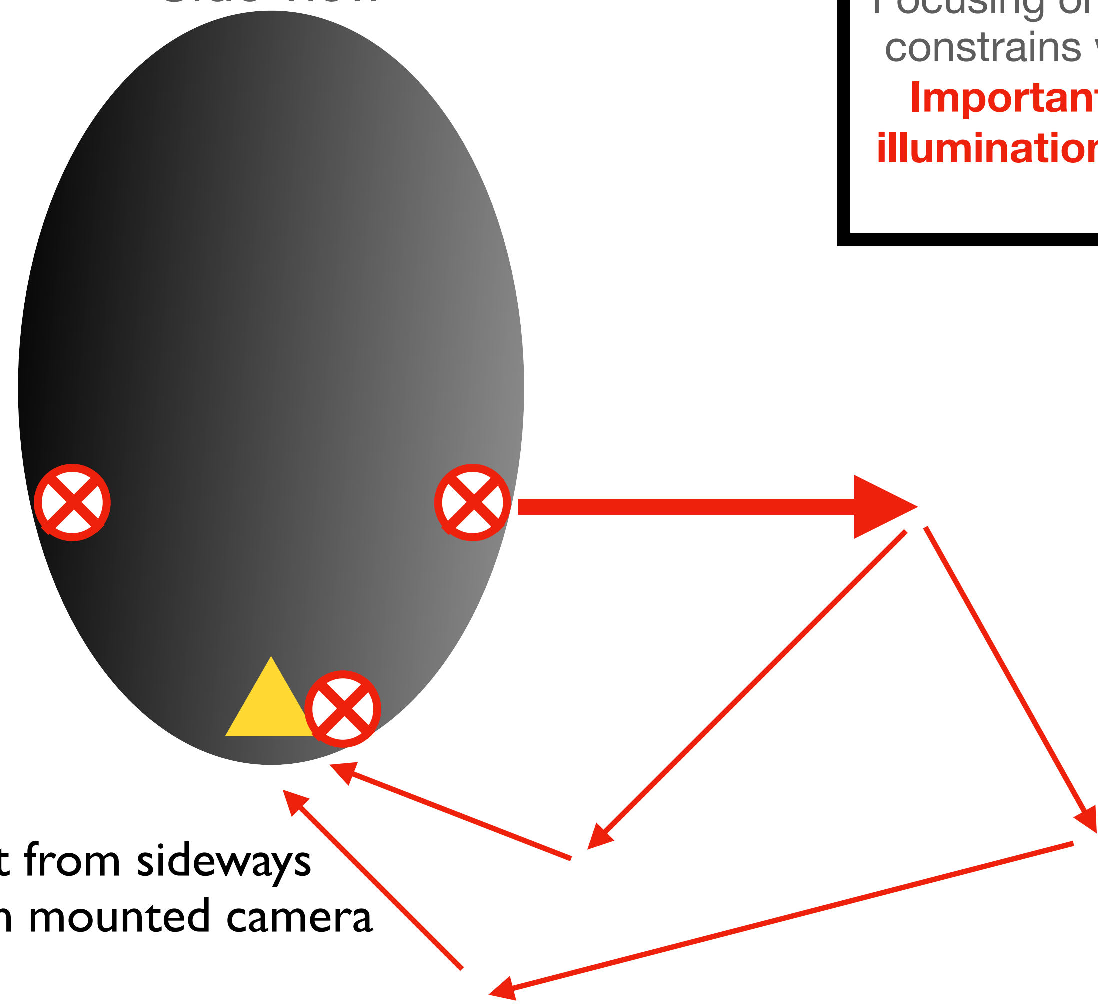
Camera
Illumination LED

Bulk ice measurements

Bottom view



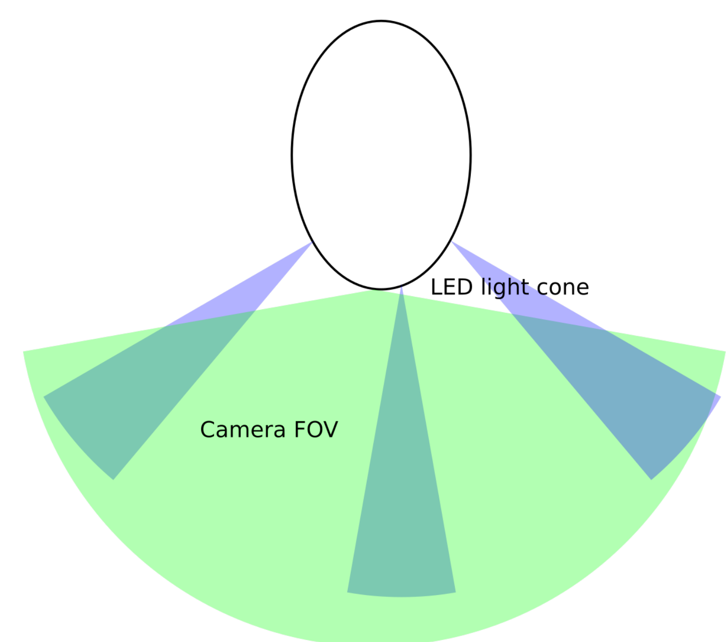
Side view



Focusing on idealized geometry for the measurements, constrains with other systems need to be considered. **Important to define real estate of the cameras + illumination boards early to avoid limitations due to obstructions, etc.**

- Observe back scattered light from sideways pointing LEDs with a bottom mounted camera
- Measure:
  - Attenuation and scattering length based on scattering profile
  - Anisotropy
    - Multiple directed LEDs pointing in different directions
    - Absolute calibration of the LEDs needed ?
    - Cleanest option with camera mounted at the bottom, use symmetry

LEDs might also be positioned such that their beam is in the FOV of the camera



Cameras and illumination LEDs

Cameras vs. LEDs

The number of measurements possible,N , depends on the number of cameras, N_{cam}, and the average number of LEDs producing light in the FOV of a camera, N_{LED}

$$N = N_{CAM} \times \bar{N}_{LED}$$

Upgrade: side wise pointing cameras will be able to see multiple DOMs on adjacent strings $N_{LED} >> 1$

Gen2: side wise pointing cameras will not see adjacent strings (d >> n_attenuation). Cameras will be able to see LEDs mounted on the same module

Cameras vs. LEDs

The number of measurements possible, N , depends on the number of cameras, N_{cam}, and the average number of LEDs producing light in the FOV of a camera, N_{LED}

$$N = N_{CAM} \times \bar{N}_{LED}$$

	Cameras 📷	LEDs 💡
Costs	💰 💰 💰	💰
Acceptance Testing	⏱️ ⏱️ ⏱️	⏱️
Integration / Complexity	🔧 🔨 🪛	🔧

Cameras vs. LEDs

The number of measurements possible,N , depends on the number of cameras, N_{cam}, and the average number of LEDs producing light in the FOV of a camera, N_{LED}

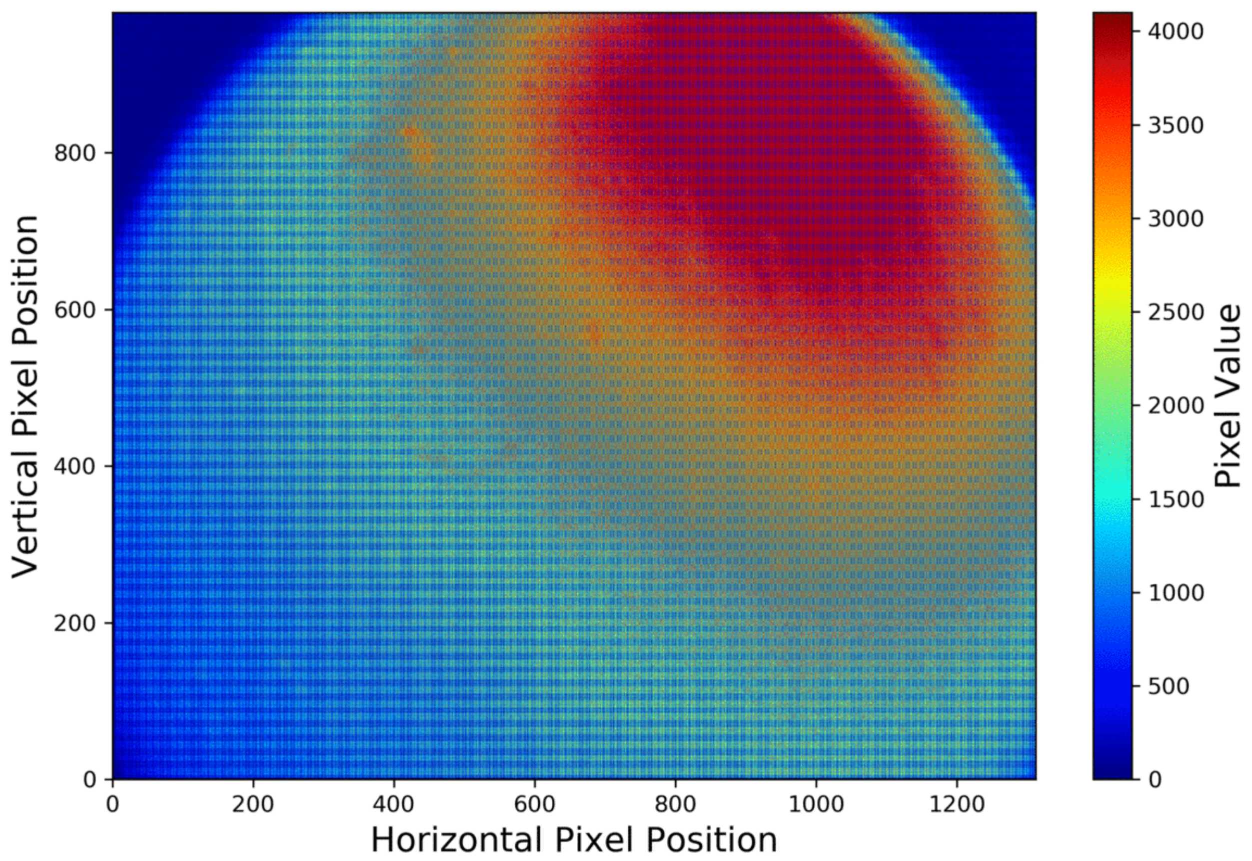
$$N = N_{CAM} \times \bar{N}_{LED}$$

Gen2 Strategy: Maximize the number of LEDs visible to each camera

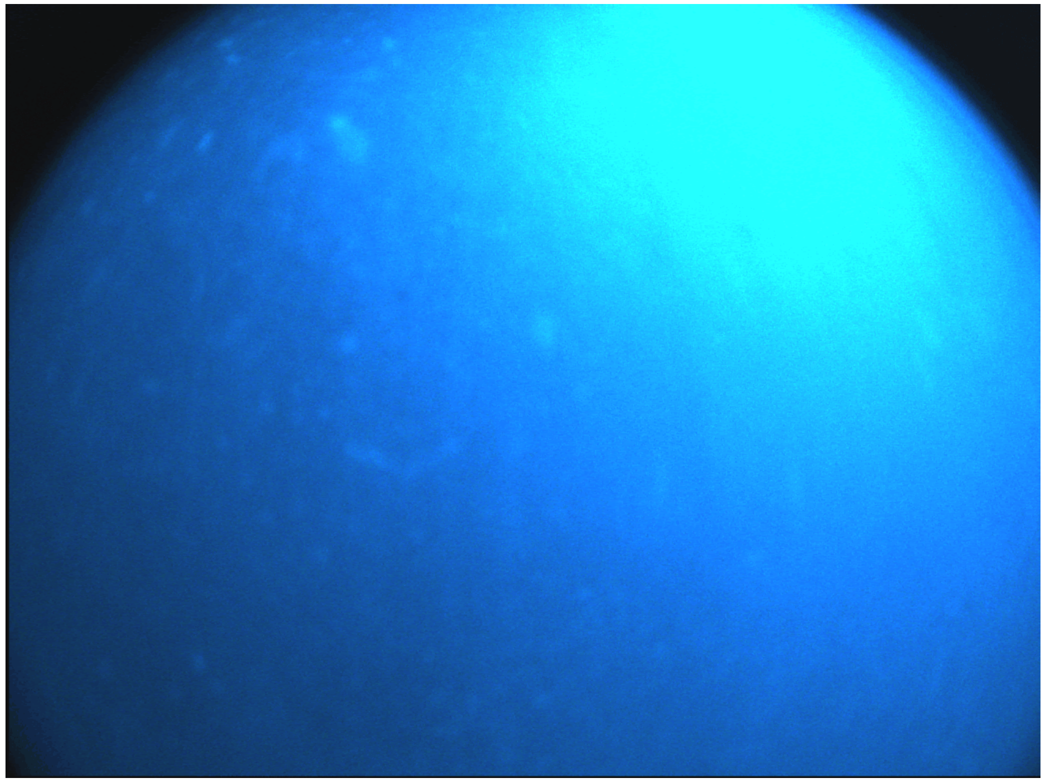
Objectives - Survey capability and deployment

Deployment videos

False color images



True color



Images were taken over 5 minutes at 1050m depth

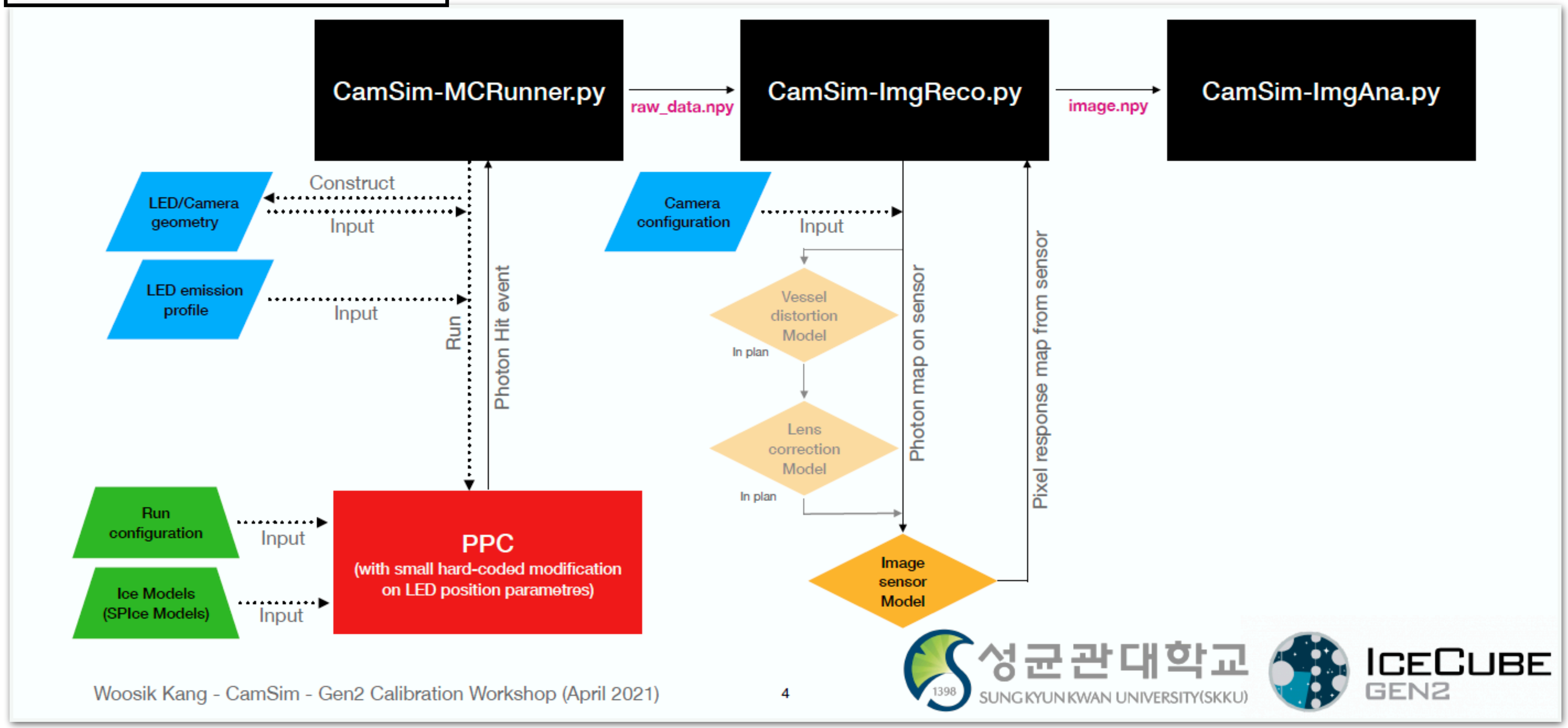
- Survey capability: hole ice contaminants, find something un expected (ex. bubble column, …)
- Operating cameras during the deployment or directly after ?

Next steps & Simulation Status

Next steps

- Evaluate camera performance and merit using simulation package
  - Same package to be used for SpiceCore Camera analysis and IceCube Upgrade camera calibration plan
  - Develop product that is easy to use and part of standard IceCube software packages

Work done by Woosik



Ideas on String-to-String and hole mapping

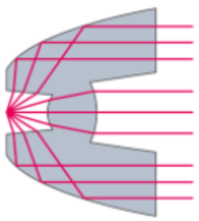
General Ideas Gen2 Logging

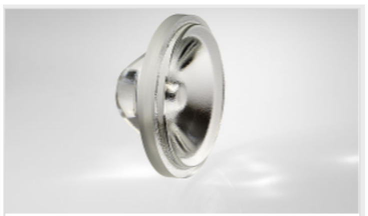
- Camera sensitivity will likely not be sufficient to see adjacent strings in Gen2. Even if any light is detected the light would have passed multiple scattering lengths, very coarse camera should be sufficient … (use PMTs itself ?)
- Hole geometry & bulk ice - deployment mapper
  - Pulsed high intensity directed collimated light source descents drill hole. Flashes are recorded at adjacent strings with LOMs (multi-PMT modules have pixelization and provide image)
    - Anisotropy mapping ~ ice features
    - Drill hole position ?
- Camera logger
  - SpiceCore camera system has shown to deliver valuable calibration data (more complete results expected for ICRC2021)
  - Camera logger could be deployed in conjunction with the dust logger or it could be integrated into the dust logger (similar to the luminescence logger that hosted the camera system)

Gen2 camera reference model

Gen2 camera system

- Production ready camera system
    - Upgrade camera system could be used for Gen2
        - Minor adjustments could be made (data storage, new image sensor, …)
- Production ready illumination LED system
    - Upgrade LED system could be used for Gen2
    - Potential modifications:
        - Different wavelength LEDs
        - Beamed LEDs
        - Laser beacons
        - Multi-channel LED driver (allows multiple LEDs)





LED-lens-triplex-100

Details see backup slides from Christoph Toennis

Discussions

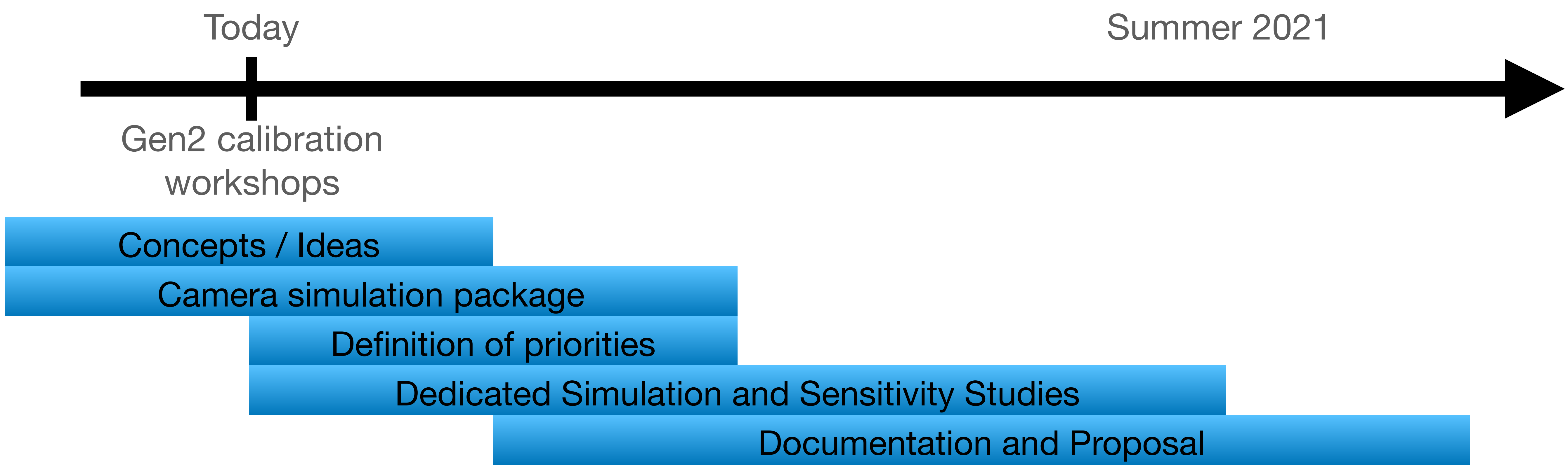
Some thoughts

- We can expect that calibration runs for Gen2 are very different from the Upgrade
  - Calibration runs in Gen2 could be run just on a subset of the detector, it will not require to shut the entire detector off
- Cameras have sensitivity in IR
  - Illumination board IR LEDs could be used to take very long exposure images during science runs
  - PMT noise rates would not be elevated after an IR LED run

Conclusions

Conclusions

- Propose optical modules with single FOV camera pointing downward combined with multiple LEDs
  - Reflection photography for anisotropy, scattering length, …
  - Transmission / Reflection photography for hole ice characterization
  - System to be deployed on a large fraction of optical modules
- Overall hardware restrictions need to be clear during the design phase (power allocation, EMI, …)
- Complement in-ice camera devices with camera deployment on logger



Back up slides

Photons emitted by an LED

- Assume 1W power and burst duration of t=1s
- Typical LED efficiency ε=85% and wavelength of 470nm

$$W = kg \cdot m^2 \cdot s^{-3}$$

$$J = kg \cdot m^2 \cdot s^{-2}$$

$$1eV \simeq 1240\text{nm}$$

$$J = 6.24 \cdot 10^{18} eV$$

$$E = hf = \frac{hc}{\lambda} = \frac{6.626 \cdot 10^{-34} Js \times 3.0 \cdot 10^{9} m/s}{470nm} = \frac{6.626 \cdot 10^{-34} J \times 3.0 \cdot 10^{9} m}{4.70 \cdot 10^{-7} m} = 4.23 \cdot 10^{-18} J$$

$$N = \epsilon \frac{1[W] \cdot 1[s] \cdot 6.24 \cdot 10^{18}}{1240nm/470nm}$$

$$N = \left[\frac{\epsilon}{85\,\%}\right] \left[\frac{P}{1W}\right] \left[\frac{t}{1s}\right] \left[\frac{\lambda}{470\text{nm}}\right] 2.01 \cdot 10^{18}$$

Gen2 camera and related design ideas and plans

- There are some bigger steps that can be taken to improve the design
  - Use newer SONY image sensor
    - The best approach would be to use other SONY sensors that use a similar interface and can be used without extensive development
  - Improve camera FPGA and on-board firmware to allow image stacking and video
    - This would allow to make camera runs faster and could save some uptime
  - Add collimator on LED
    - Cost has to be evaluated for this
- Some new devices can be developed for Gen2
  - Pre-deployment camera logger
    - This design has to be largely constructed from the ground up
    - camera can be added to existing logger

Christoph Toennis

New image sensor

There have been a few new image sensors that have been developed by SONY that could be used for the Gen2 camera. The IMX 424 and IMX 324 have been shown to outperform the IMX224/IMX225 image sensor that is used in the upgrade camera. This sensor can provide in pixel binning mode a higher sensitivity at a slightly improved resolution or a vastly improved resolution without pixel binning. Newer image sensors would require using a MIPI or LVDS interface that needs to be operated from a more powerful FPGA to handle the interface speed.

Other image sensors we are considering are the IMX 515 and the IMX 477.

Low-light (0.1 lux) image comparison

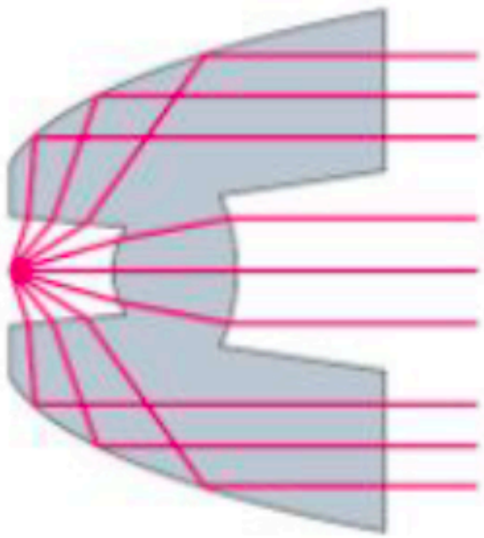
IMX324 (Pixel binning mode) sample image

IMX224 (1.27M) sample image

Christoph Toennis

New light sources

- Beamed LED
  - We can use a similar LED to the one we have at the moment with a collimator
  - This would make the beam more pointed and allow a better anisotropy measurement
- White LED
  - There are other OSLON LEDS that are operable with the existing LED driver that emits white light
  - Alternatively an new driver circuit can be used to power the LED
  - Possibility to use multi-channel LED driver



Illumination system pricing

Component	Number per device	Price per device
Color LED	1-X	X * 0.20$
LED driver	1	3$ (4-channel)
Connector	1	3$
PCB and assembly	1	2.5$
Analog components	?	1$
Collimator	1 (3 LED collimator)	2.5$
Total		12.80$

Christoph Toennis

Improvements on IceCube upgrade camera

- New design can improve on the communication
  - Increase fidelity on I2C communication to the image sensor
  - Improve SPI multiplexing and remove need for reboot when switching devices
- Design improvements are possible
  - Increase size of frame buffer to 16 MB (32 MB?) to store more images
  - Implement image stacking on FPGA firmware
  - Increase SPI baudrate for faster transfer
- Some features can be removed
  - Remove illumination board connector and wiring from the camera
  - A 60 to 80 degree FOV can be used to reduce distortion and improve angular resolution of the camera
- Some new features can be added for the LED board
  - Different colored LEDs using same driver board can be used
  - New illumination boards with beamed LED can be developed

Christoph Toennis

Current camera design

- IMX225 image sensor operated by a X02 FPGA
- 8 megabyte RAM used as frame buffer
- 175 degree FOV wide angle lens
- 1.75 W peak power consumption, 1.2 W typical
- SPI communication with 10 MHz max baudrate
- 1312 x 957 pixel maximum resolution
- 12 bit pixel depth
- 5V input voltage
- 40mm x 35mm x 35mm size

- GB CS8PM1.14 LED with 80 degree full width at half maximum
- 43 lm brightness at 1W
- 470 nm typical wavelength
- AL8860WT-7 LED driver operating at 1W power
- 5V input voltage
- 3.3V logic level

Christoph Toennis