성균관대학교 SUNG KYUN KWAN UNIVERSITY(SKKU) | THE UNIVERSITY OF UTAH | ICECUBE SOUTH POLE NEUTRINO OBSERVATORY | ICECUBE UPGRADE | ICECUBE GEN2

CamSim: Camera Simulations

Woosik Kang

on behalf of CamSim team:

Christoph Tönnis, Steven Rodan, Oseong Gwon, Minyeong Seo **in SKKU**

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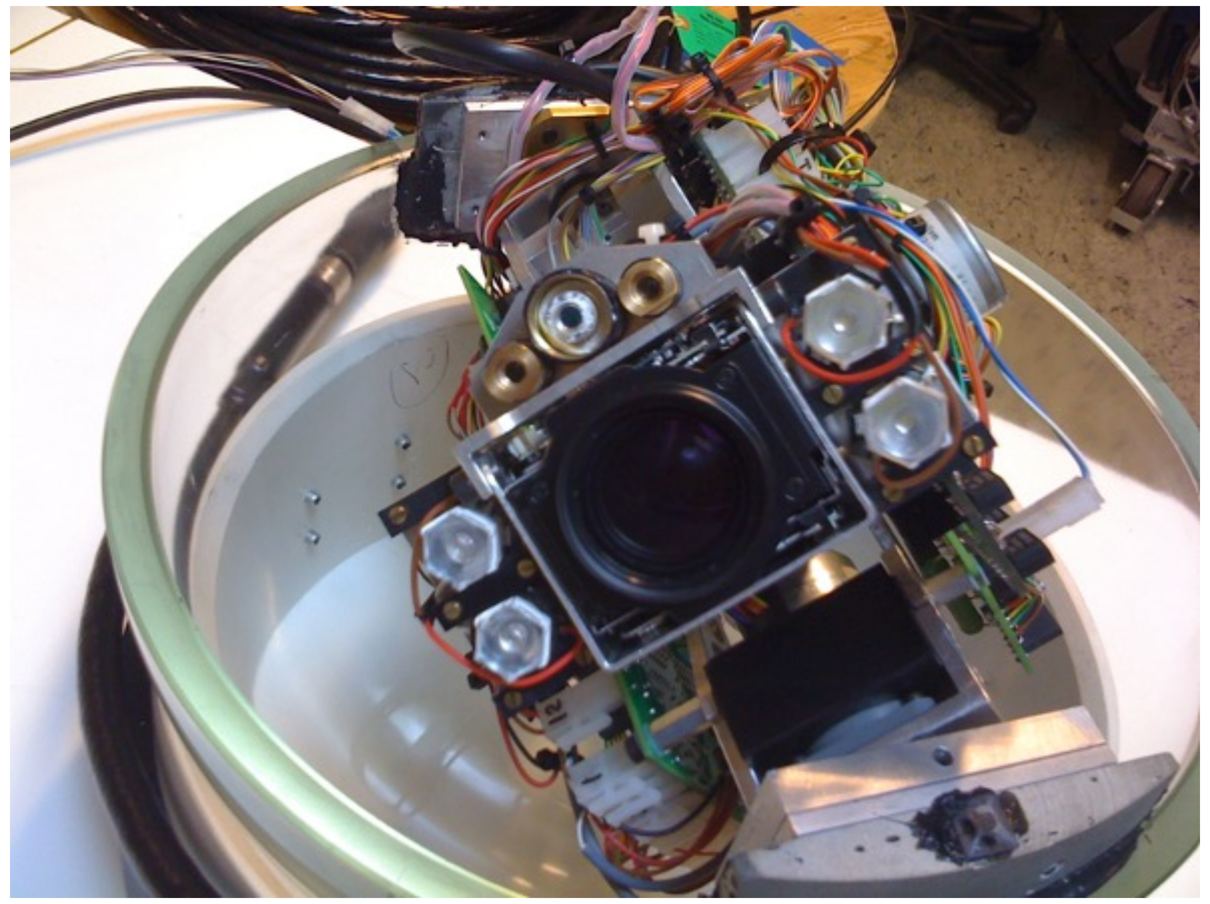
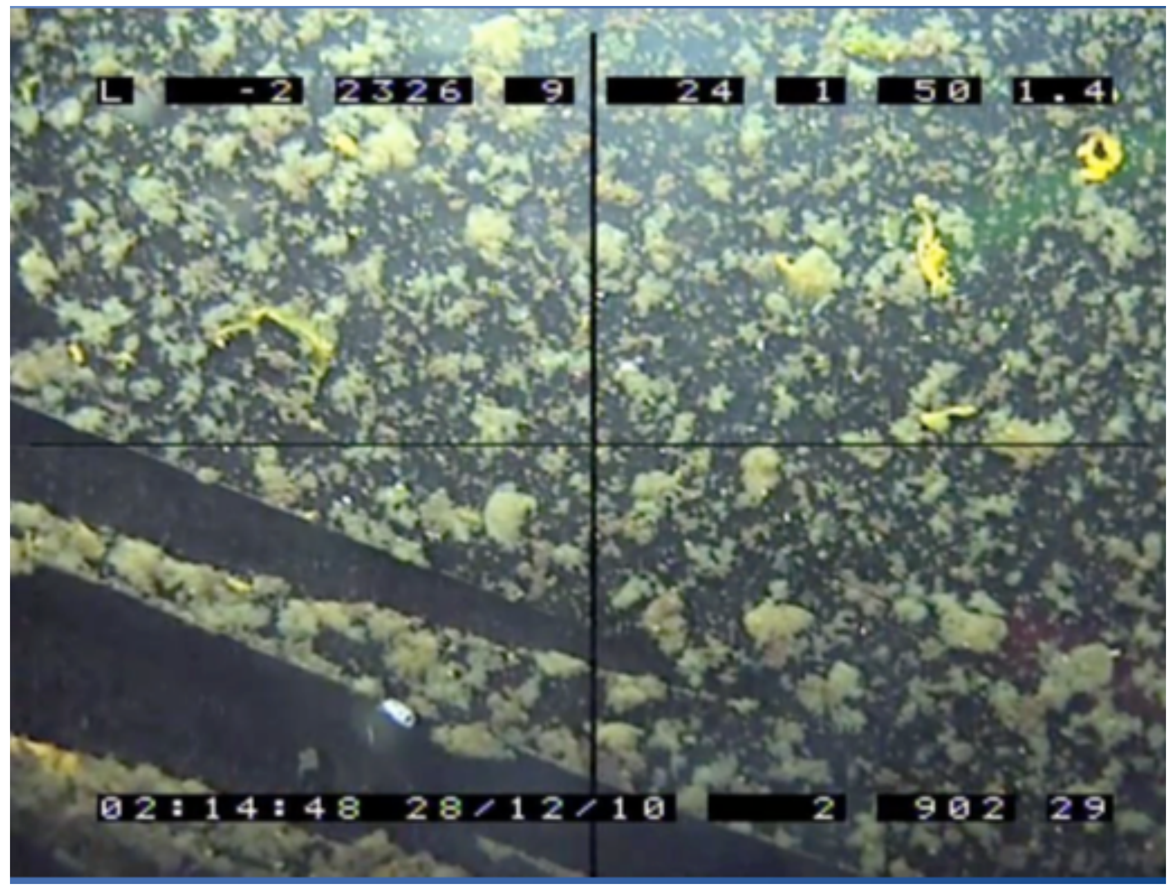
Photon Propagation Workshop | October 18th-19th, 2021

Camera systems
in the IceCube and IceCube-Upgrade

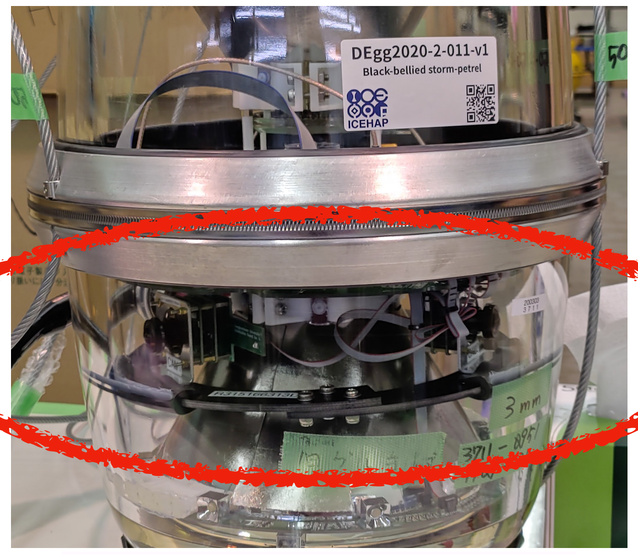
Swedish Camera

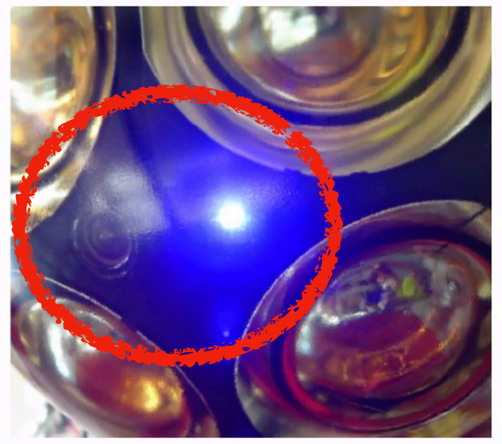


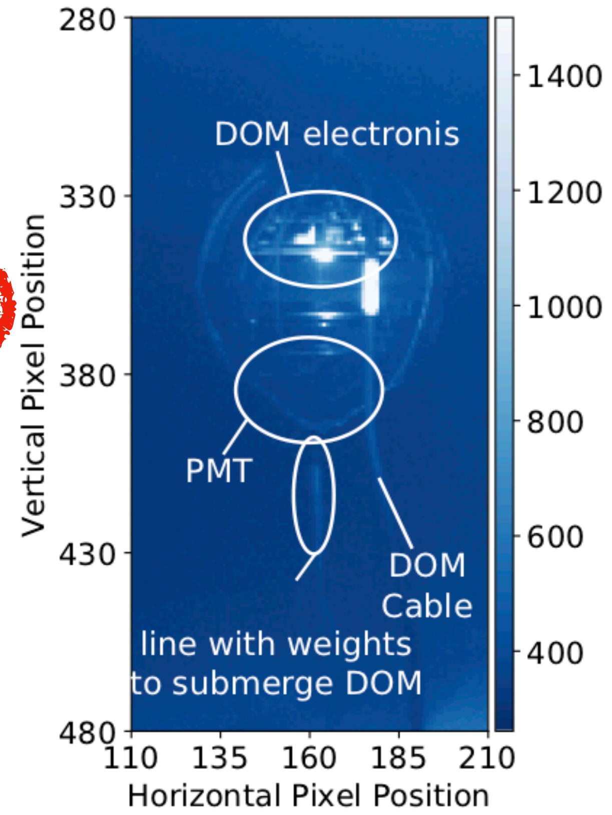


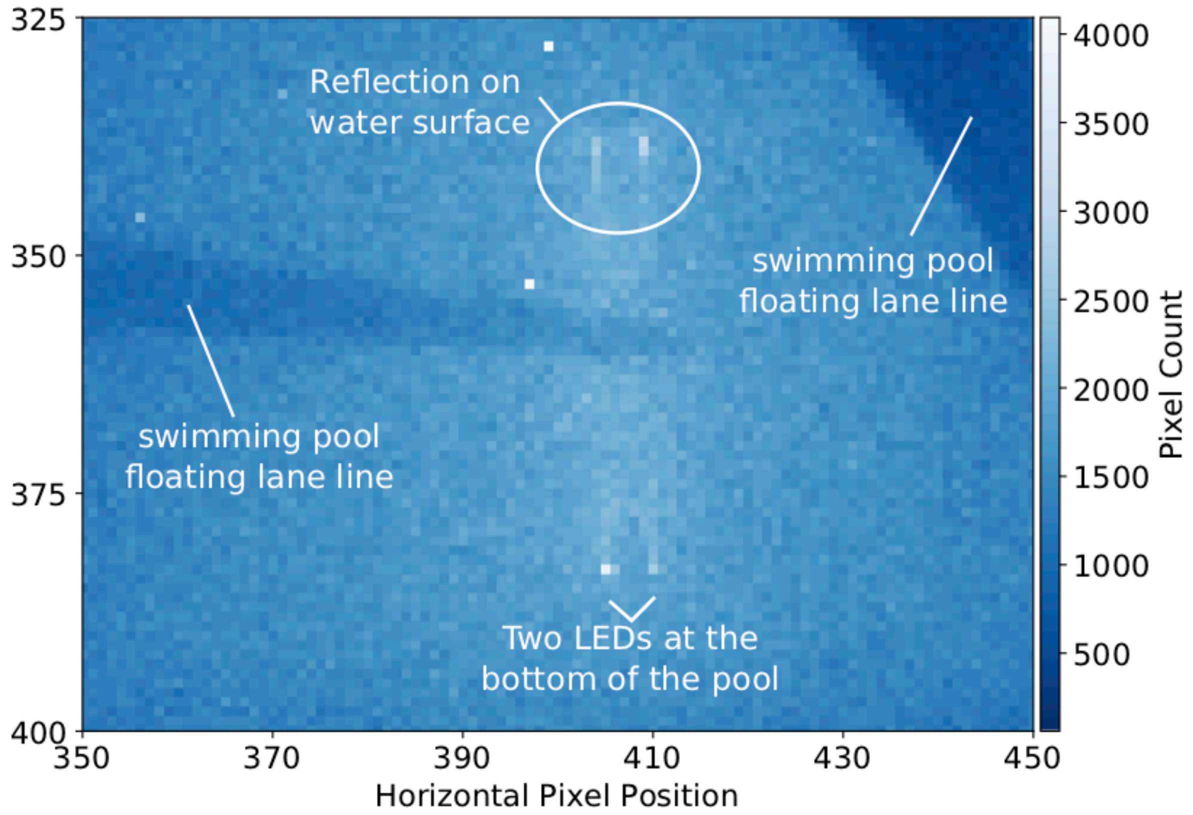
- Science Goals
  - Observing the ice structures during the deployment and the freeze-in process and other DOMs after the deployment.
  - Long-term monitoring of the ice
- 1-pair of cameras deployed and operated in 2010-2018
- Major observation results
  - Central Bubble Column
  - Contamination settling on top of modules

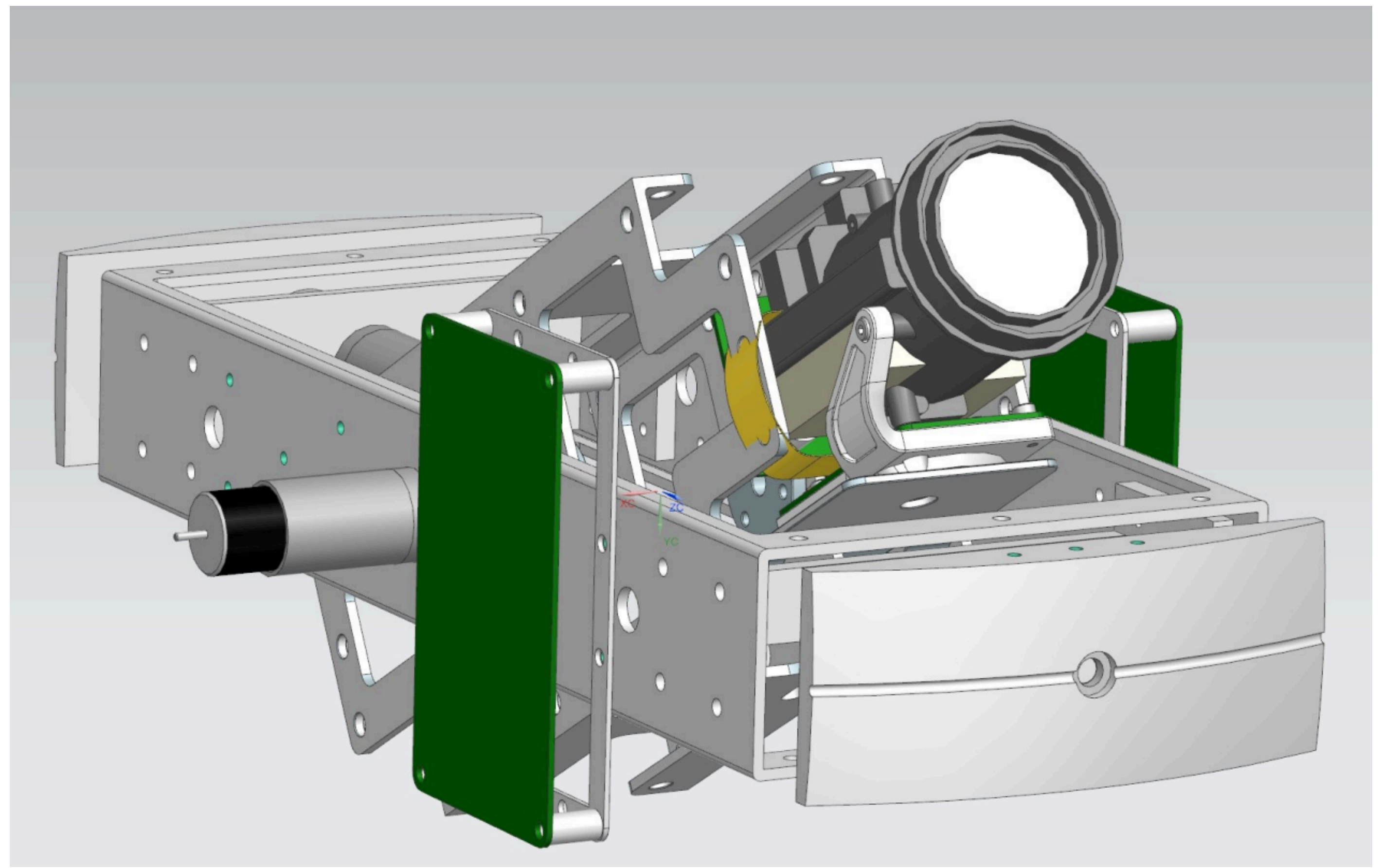
Camera systems to the IceCube-Upgrade











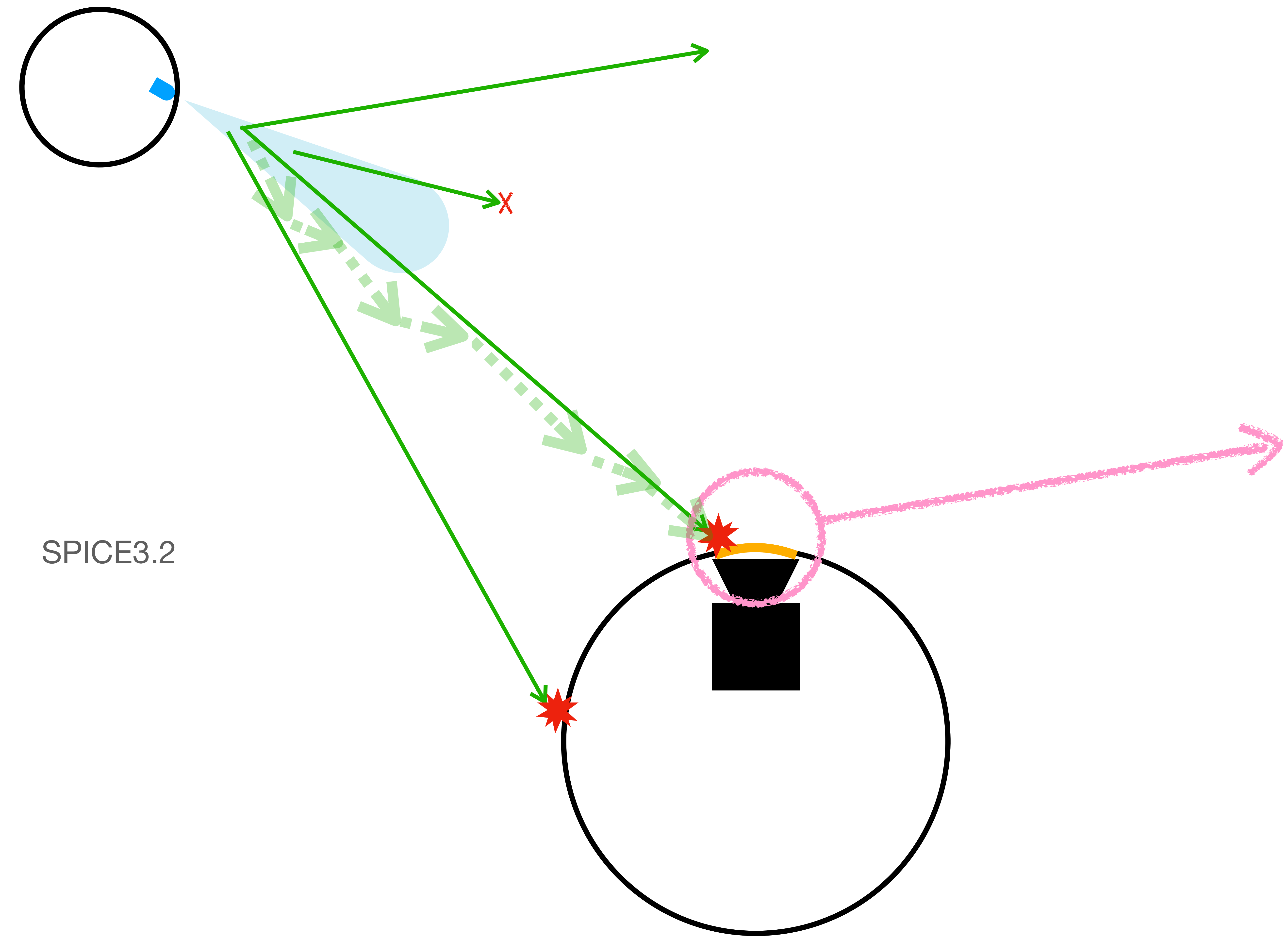
- IceCube Upgrade Camera system
  - Installed in all new Upgrade OMs (more than 2000 cameras in the detector column)
  - Ice property study in the vicinity of Upgrade OMs: scattering, absorption, anisotropy, …
  - Geometry/Orientation measurements, observing freeze-in process, …

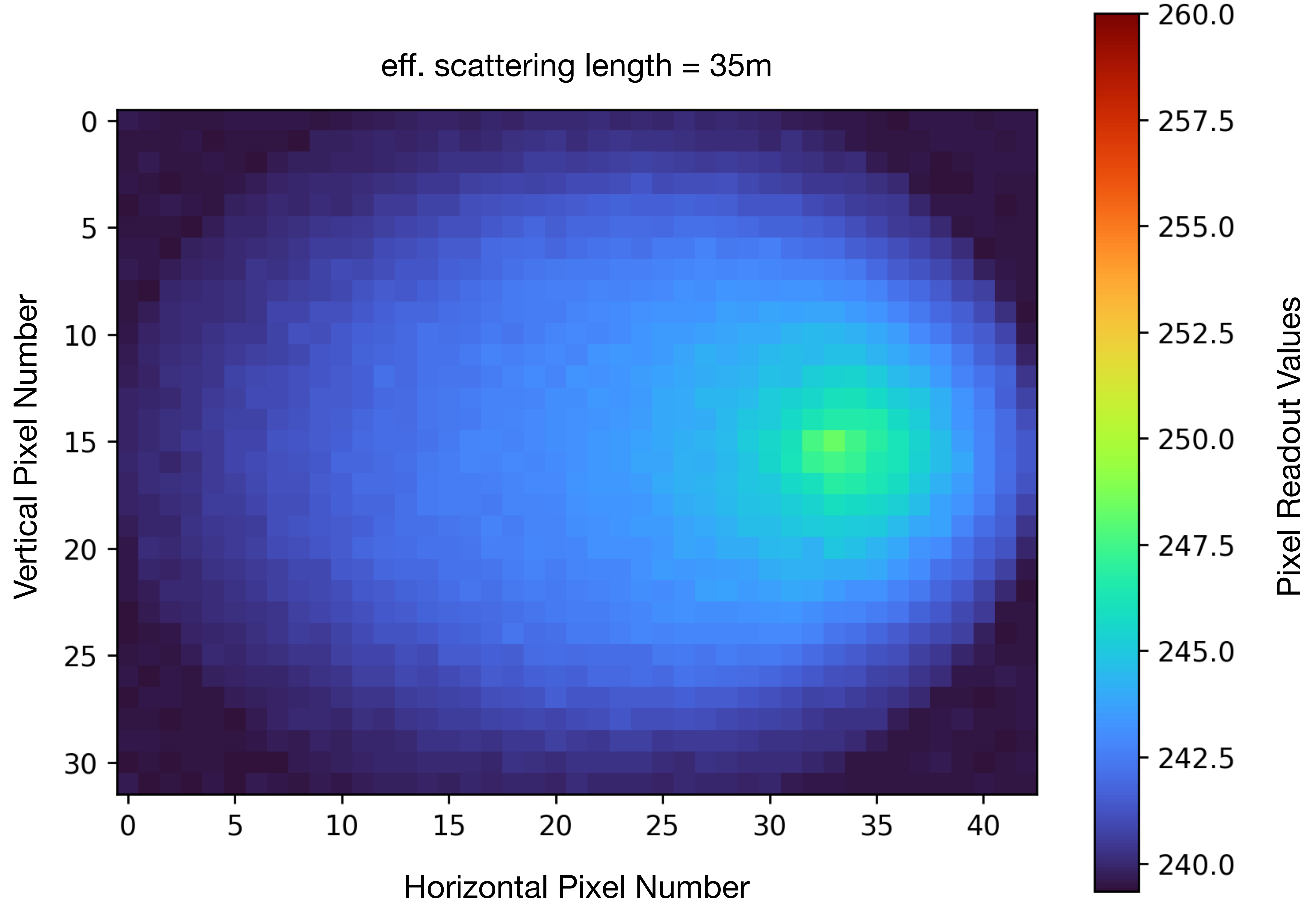
- Swedish Camera 2.0
  - One of the special calibration device modules
  - A steerable camera and a steerable illumination system for one module.
  - Placement of five SweCams in the main “deep ice” region of IceCube and physics region of Upgrade.

Introduction to CamSim

Camera Simulations(CamSim)

- Goal of the camera simulation studies
  - To simulate camera images based on light sources in an optical medium (Antarctic ice)
  - To develop the image analysis methods, which will be used on the actual data from the deployed camera systems
- A newly developed simulation framework for the user-friendly environment and the capability of extension to the analysis framework
  - Ready for IceCube-Upgrade deployment immediately to perform the operations and measurements of the camera systems
  - A series of simulation works with the framework studies are in progress.





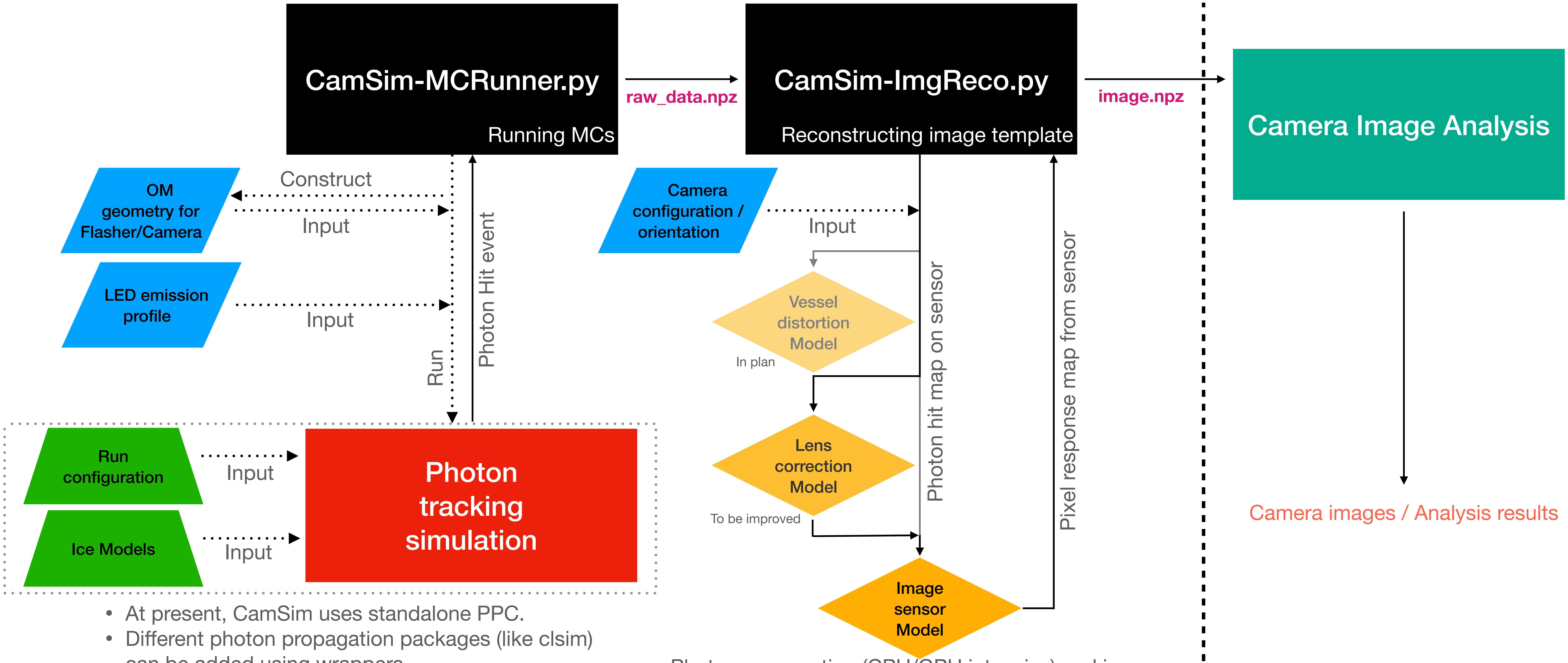
* averaged pixel readout value over 1302 pixels

Photon tracking MCs (PPC)

Reconstructing photon hit events into an image format

Schematic for CamSim

https://github.com/NAPPLSKKU/CamSim



- At present, CamSim uses standalone PPC.
- Different photon propagation packages (like clsim) can be added using wrappers.
- Plan to interface with IceTray.

- Photon propagation (CPU/GPU intensive) and image reconstruction are separate. Camera model and settings can be changed without having to rerun full simulation

CamSim Structure

CamSim

- Bulk/
  |- gpu/
  |- ice/
- Hole/
  |- gpu/
  |- ice/
- Upgrade/
  |- gpu/
  |- ice/
  Using full-dec geo
- run_configs/
  |- run_Bulk.json
  |- run_Gen2.json
  |- run_Hole.json
  |- run_Upgrade.json
- run_logs/
  |- README
- run_outputs/
  |- README
- cam_configs/
  |- ICUcamera.json
  |- ICUcamera-DEgg.json
  |- ICUcamera-mDOM_side.json
  |- ICUcamera-mDOM_pole.json
  |- ICUcamera-Gen2.json
- mc_imgs/
  |- README
- MCRunner.py
- ImgReco.py

To be updated

Under development

Swedish/
|- gpu/
|- ice/

SPiceCore/
|- gpu/
|- ice/

Gen2/
|- gpu/
|- ice/

New configurations

utils/
|- LensModels.py
|- VesselDistortions.py
|- FOVcal.py
|- LightConeSize.py
|- SetBCSize.py
|- SetOversizingOM.py

Utilities

Computing details

- GPU time : ~1 hours for running an bulk ice MC with 10^10 photons via the wrapper ‘MCRunner' (GTX1080)
- CPU time : ~30 min for reconstruction an image for 10^10 photon bulk ice data via the wrapper ‘ImgReco’ (i7–6th gen)
- Raw data size: ~1GB for one bulk ice configuration
- Reconstructed image data: ~1.2MB for one camera setting from one simulation configuration

Converting number of received photons to the camera pixel readout counts

Conversion factor measurements

- To convert photon counts to pixel readout values we have calibrated our simulation to the physical camera
- Three independent methods are used to obtain the conversion factor
  - Observation of LED with the camera
    - LED is placed at large distance for it to be a point source → **Has been used**
    - Lab measurement with highly attenuated LED signal
  - Observation of stars with the camera
  - Uniformly illuminated surface is observed by camera and radiative flux measured via luxmeter

→ *Measurements with other methods are underway to determine the systematic uncertainty on the conversion factor*

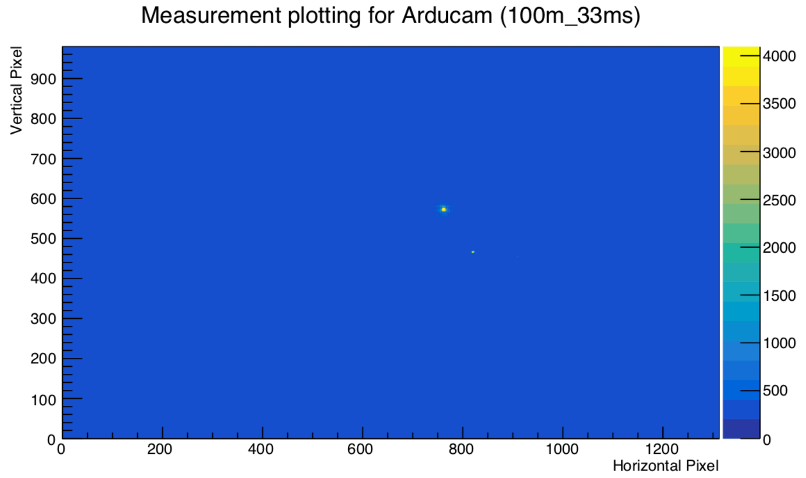
Camera calibration

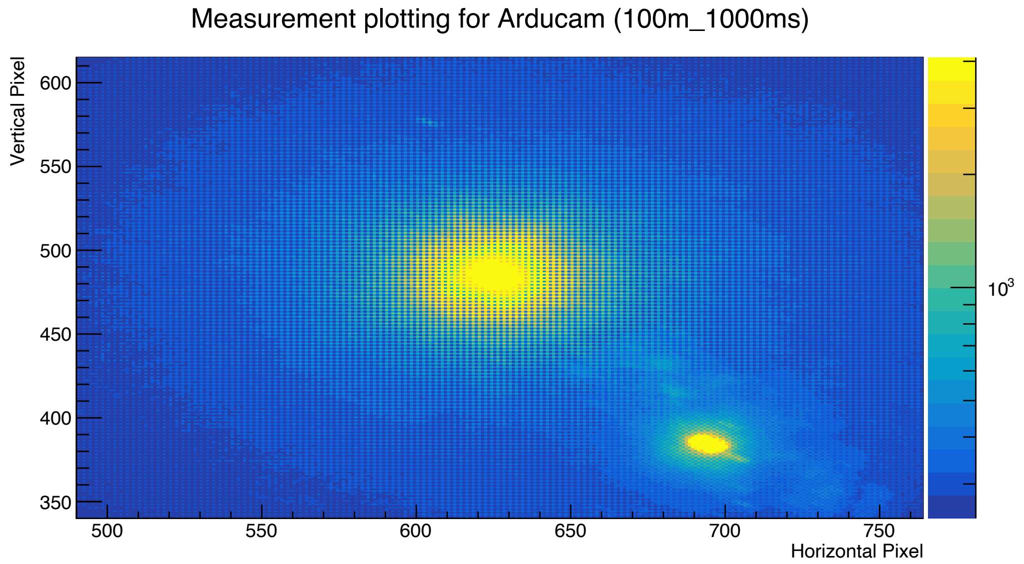
- For a camera model to be defined, we need a conversion factor of received simulated photons to pixel readout values
- We have determined this conversion factor for the IceCube Upgrade camera

- **Method: Simulate images in air (negligible scattering) and compare with observed images**
- **Outcome: Obtain weight factor of simulated photon to pixel readout value**

<sample image for 1000ms exposure>

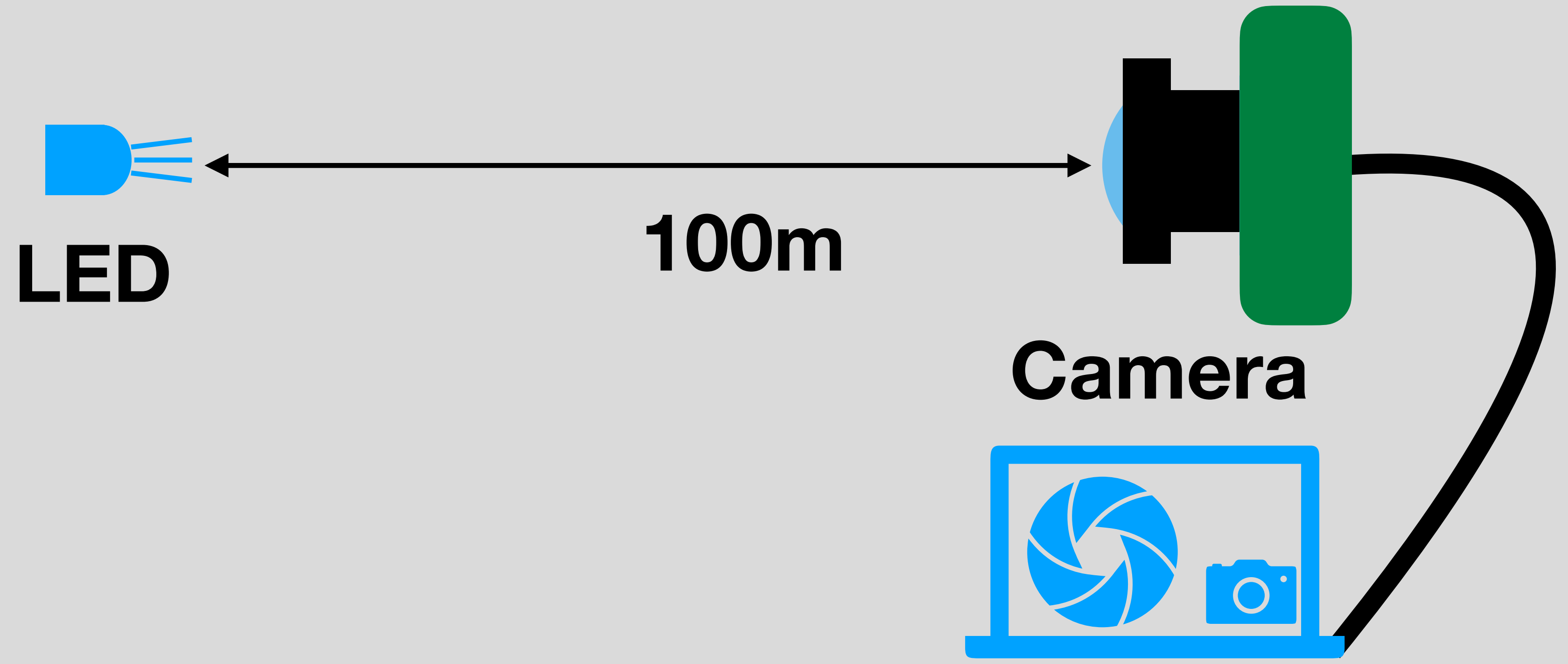
+





IceCube Upgrade Camera & LED used for SpiceCore Camera system

Dark condition (night+environmental background)

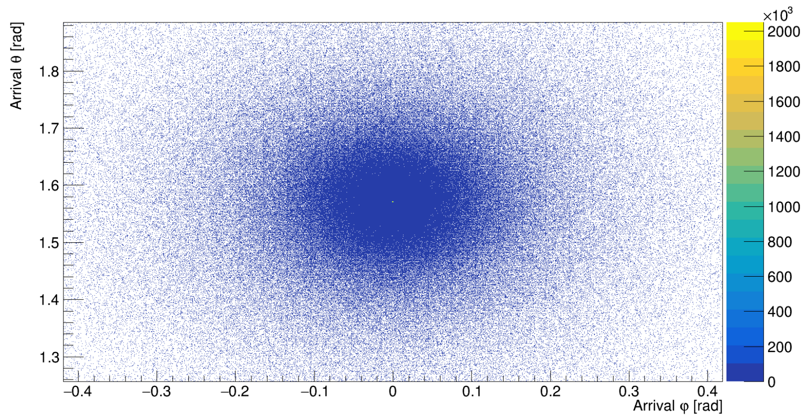


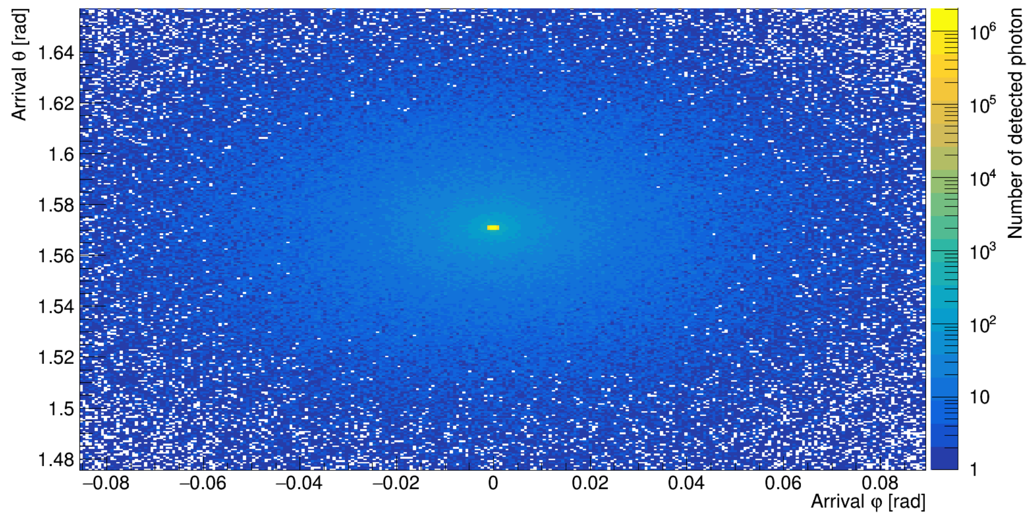
<simulation under the same configuration>

From CamSim in PPC

14° *width narrow beam*

10^{11} *initial photons from LED*



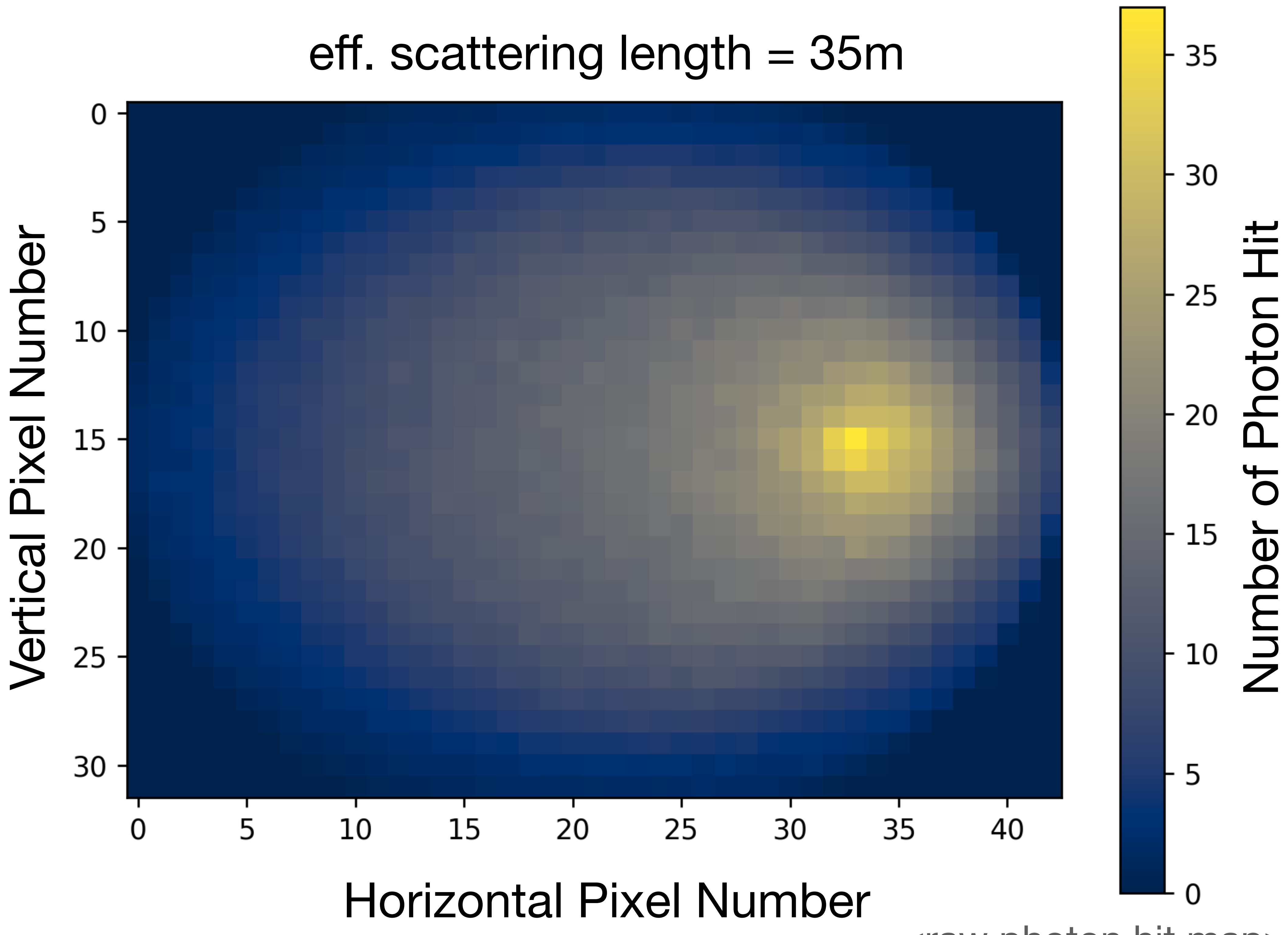


Conversion factor calculation

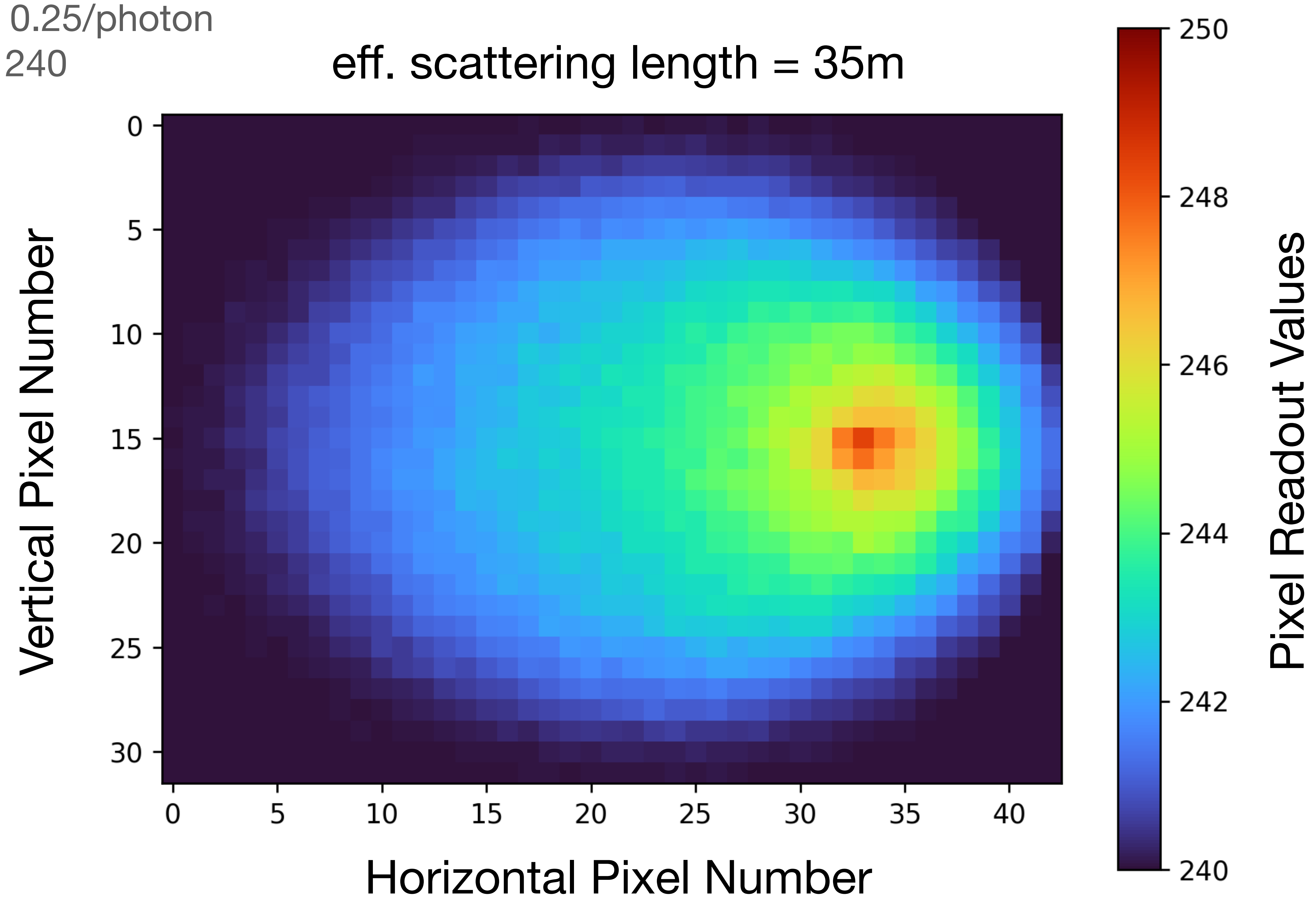
$$\alpha = \frac{t_{exp}^{ice}}{t_{exp}^{air}} \times \frac{N_{\gamma}^{air}}{N_{\gamma}^{ice}} \times \frac{A_{sim}^{air}}{A_{sim}^{ice}} \times \frac{\Sigma r_{pixel}}{\Sigma n_{\gamma}^{air}}$$

- t_{exp}^{ice}: Assumed exposure time for in-ice measurement
- t_{exp}^{air}: exposure time used for calibration measurement in air
- N_{γ}^{air}: Total simulated photons in air
- N_{γ}^{ice}: Total simulated photons in-ice
- A_{sim}^{air}: Camera over-sizing area used for air simulation
- A_{sim}^{ice}: Camera over-sizing area used for ice simulation
- Σr_{pixel}: Sum of pixel readout values of the LED image observed in air
- Σn_{γ}^{air}: Sum of the detected simulated photons in the air simulation

Conversion factor ~ 0.25/photon
pedestal baseline = 240

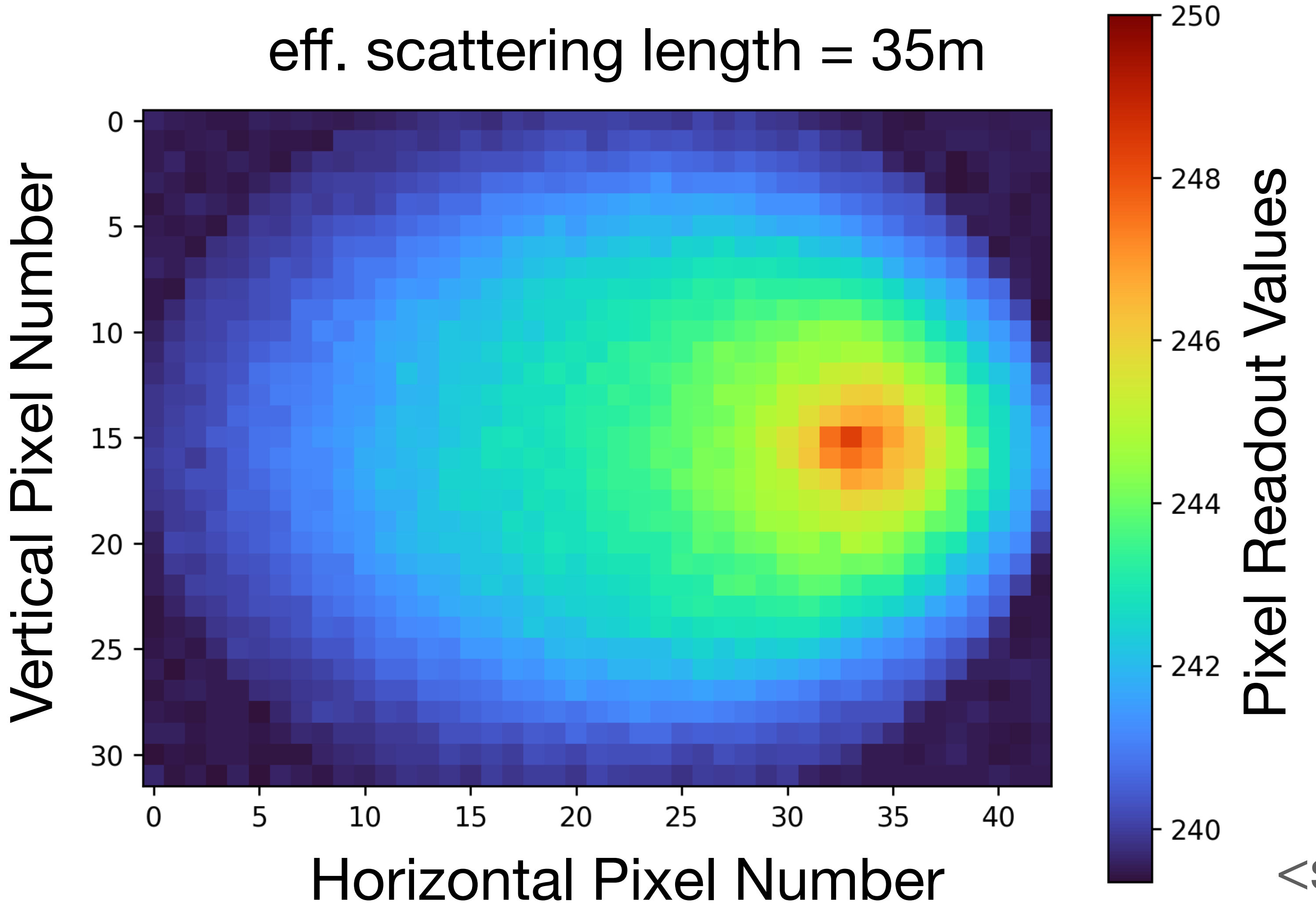


<raw photon hit map>



<signal+baseline>

Adding pixel noise (Gaussian)



<signal+baseline+noise>

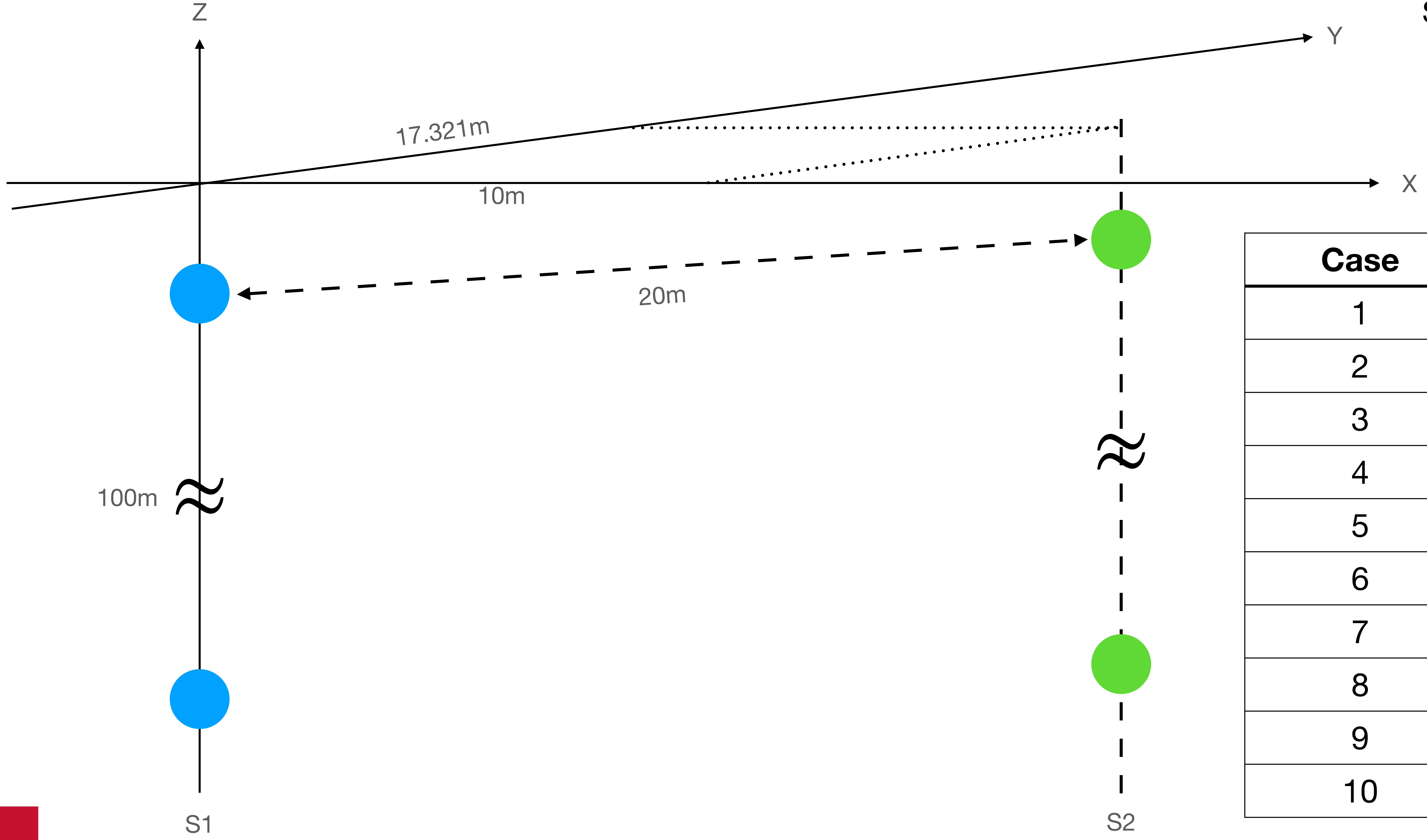
- Exposure time setting = 1500ms
- Number of initial photon injection = 10^10
- OM oversizing factor = 5
- Lens oversizing factor = 5

* averaged pixel readout value over 1302 pixels

Observing the illumination light from the neighboring string with IceCube Upgrade Camera System (Two D-Egg case)

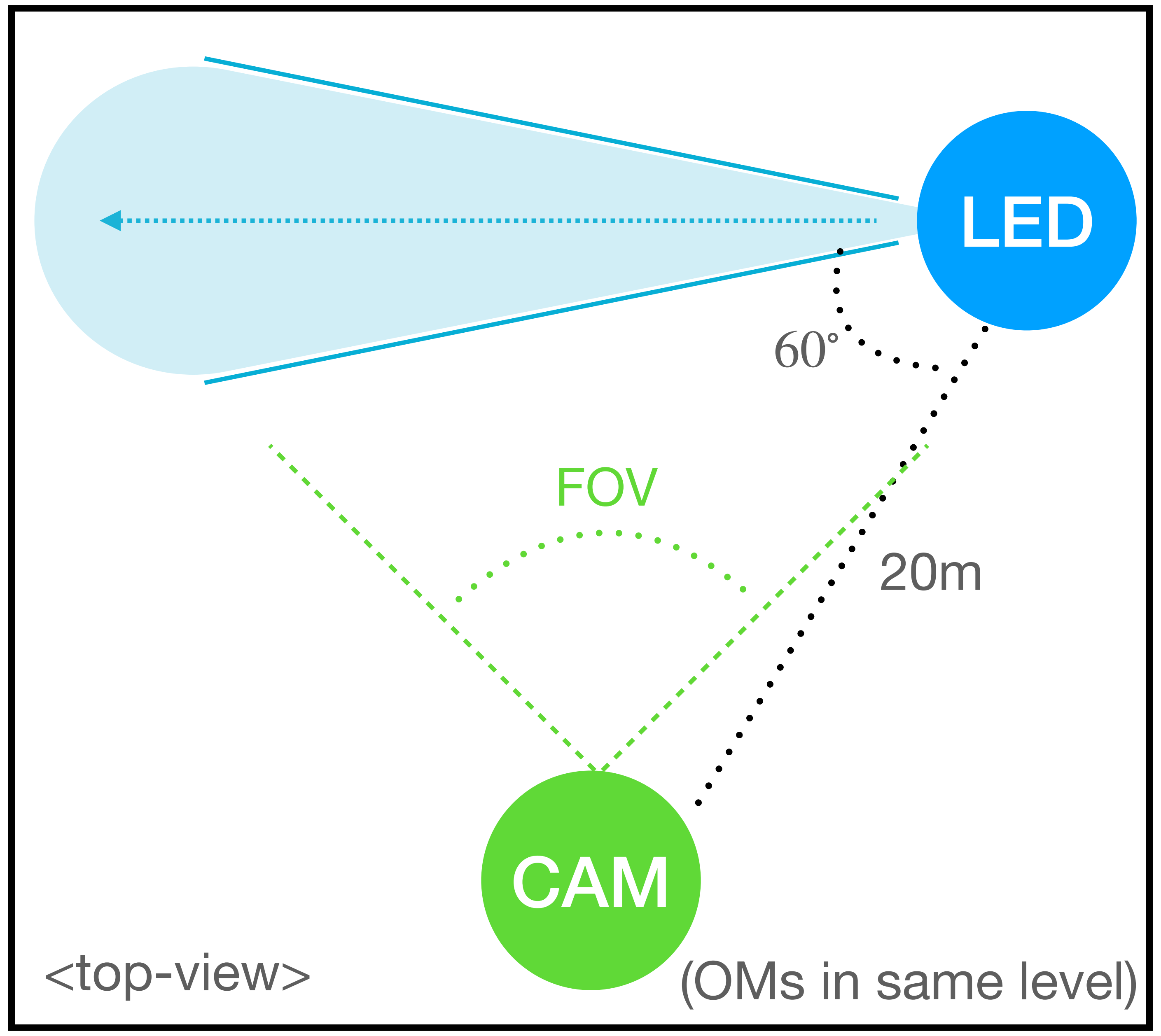
Observing lights from the neighboring string (Bulk ice measurement)

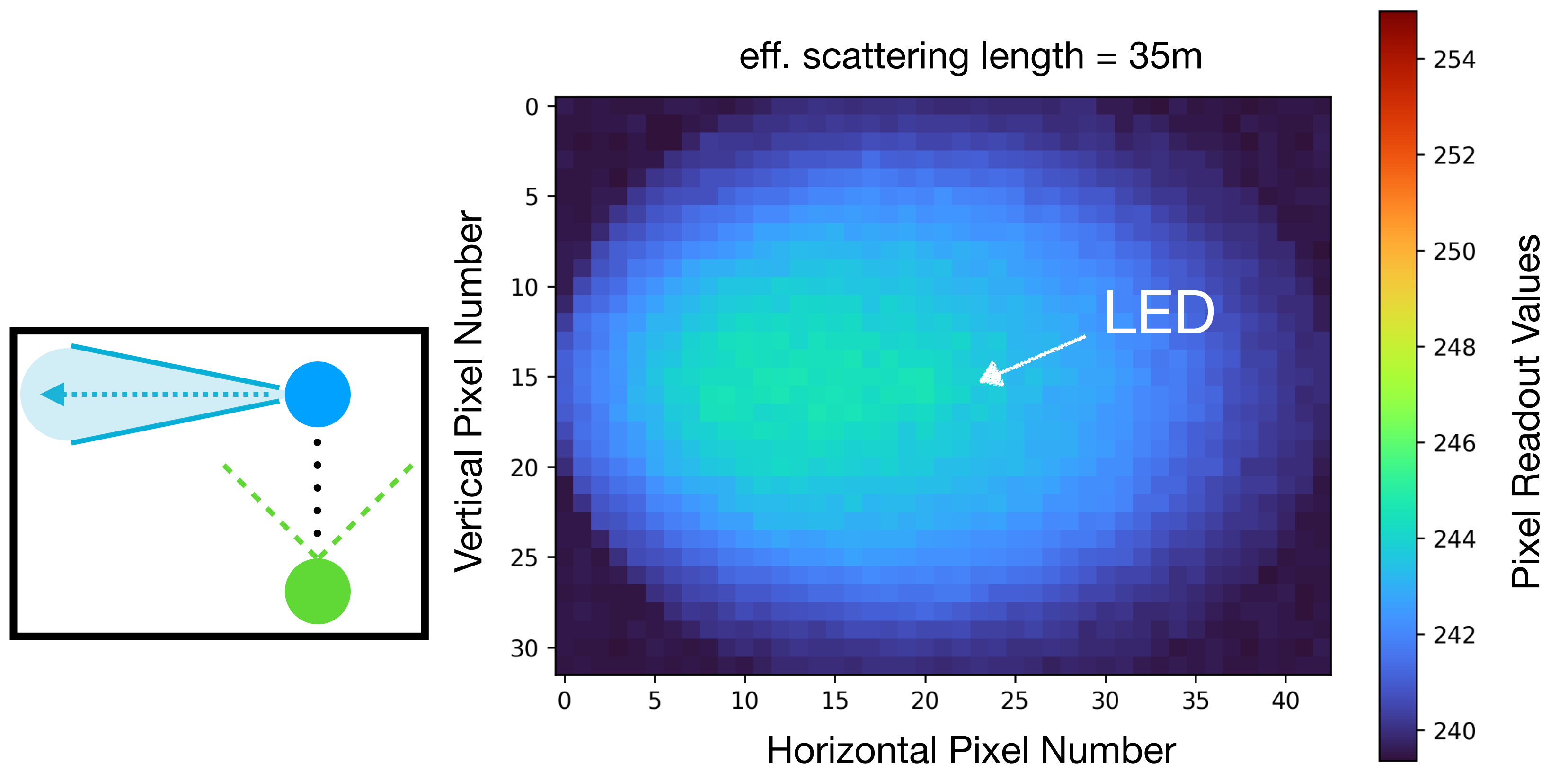
Sandbox geometry



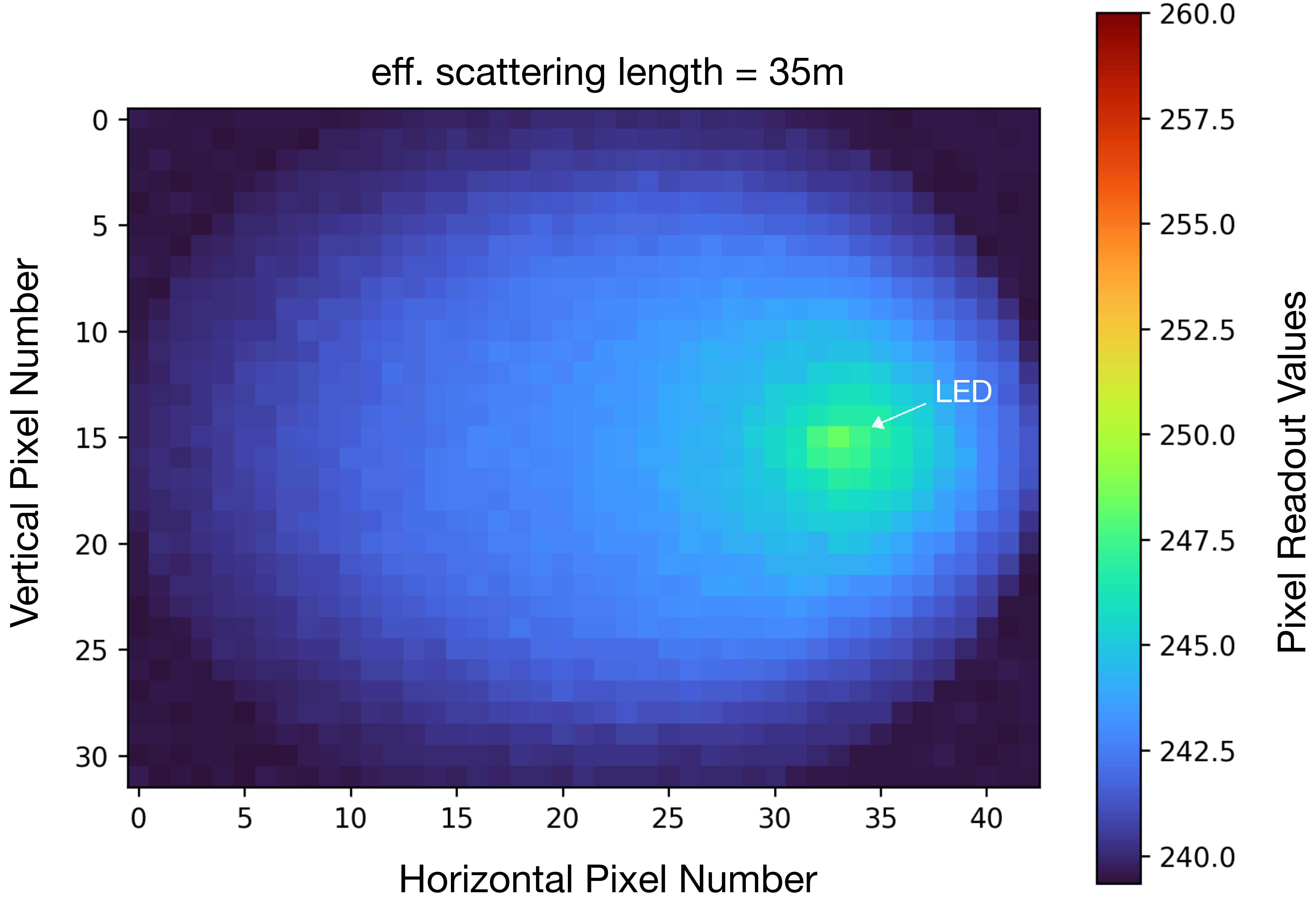
Case	Eff. Scattering length
1	15m
2	20m
3	25m
4	30m
5	35m
6	40m
7	45m
8	50m
9	60m
10	70m

Minyeong Seo (undergraduate in SKKU summer research programme)

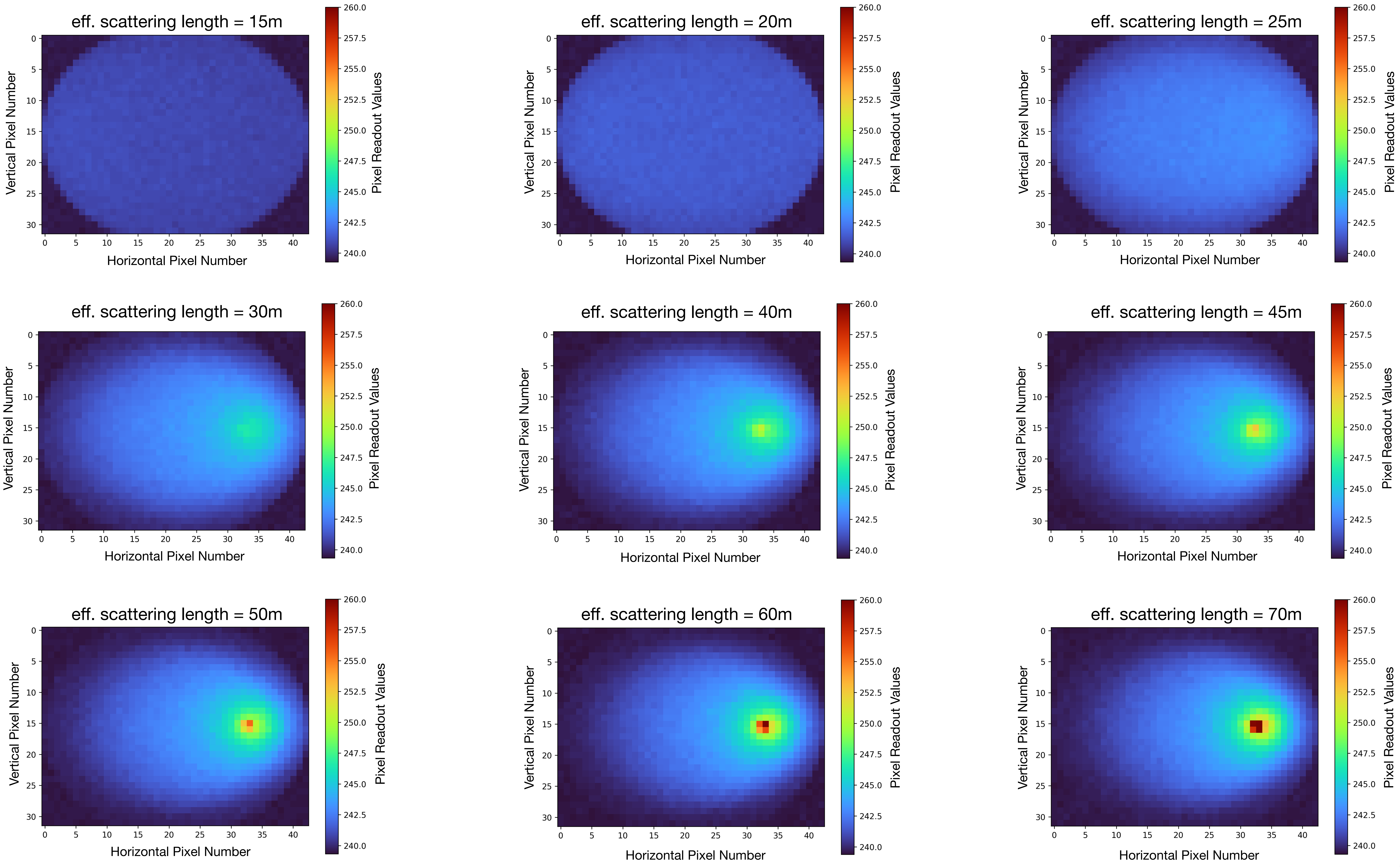




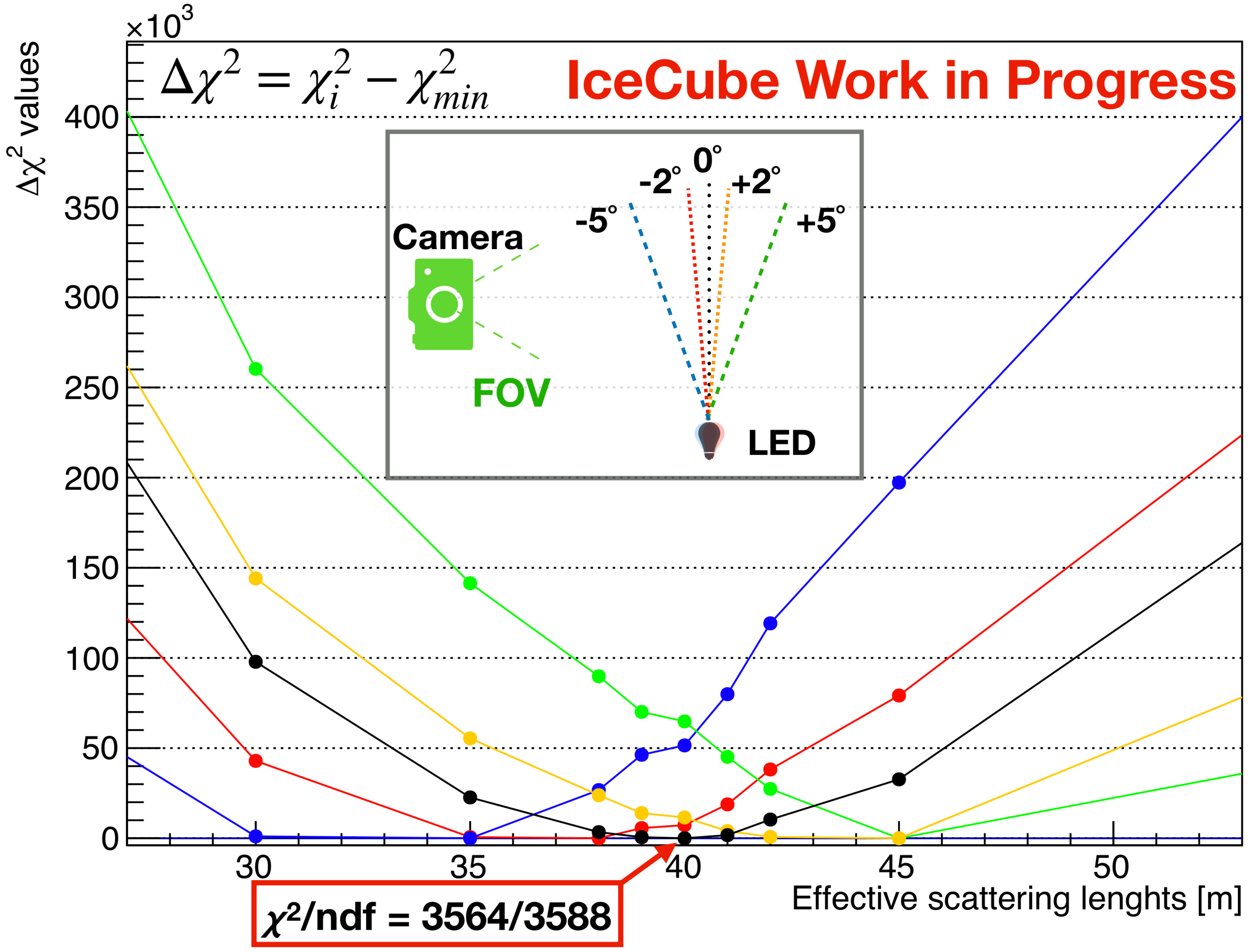
When the camera looks at the LED directly



* averaged pixel readout value over 1302 pixels


eff. scattering length = 15m
eff. scattering length = 20m
eff. scattering length = 25m
eff. scattering length = 30m
eff. scattering length = 40m
eff. scattering length = 45m
eff. scattering length = 50m
eff. scattering length = 60m
eff. scattering length = 70m
Vertical Pixel Number
Horizontal Pixel Number
Pixel Readout Values
260.0
257.5
255.0
252.5
250.0
247.5
245.0
242.5
240.0

Previous analysis results in ICRC2019 *PoS(ICRC2019)928*

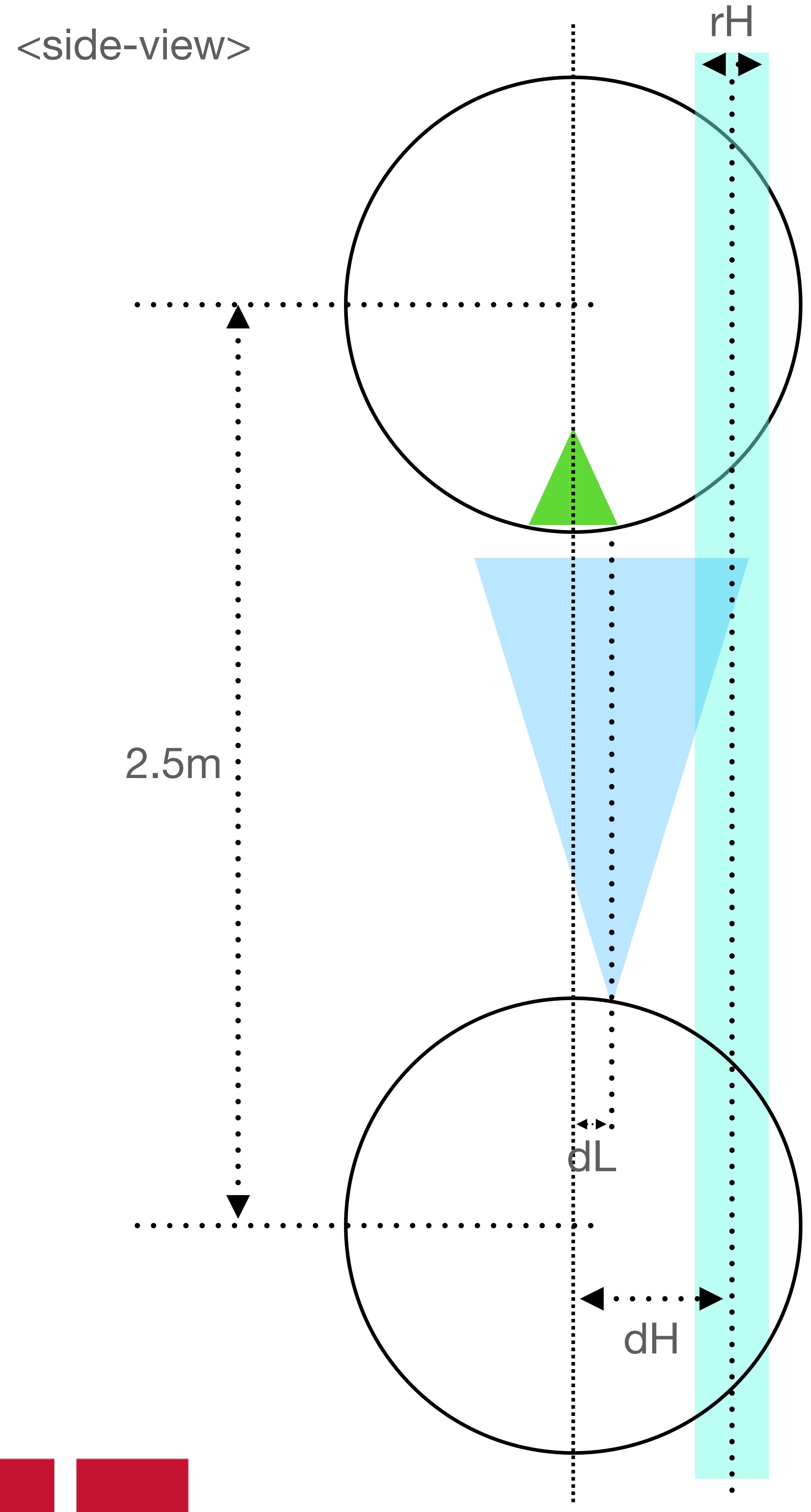


- Δx^2–based analysis of the simulated images. Ice properties estimated to less than a few meters assuming few degree LED alignment uncertainty.
- Likelihood–based analysis are under development, which is expected to improve the results.

Imaging the Bubble Column with IceCube Upgrade Camera System in two vertically located DOMs (Two mDOM case)

Imaging Bubble column in the drill hole (Hole ice measurement)

Sandbox geometry



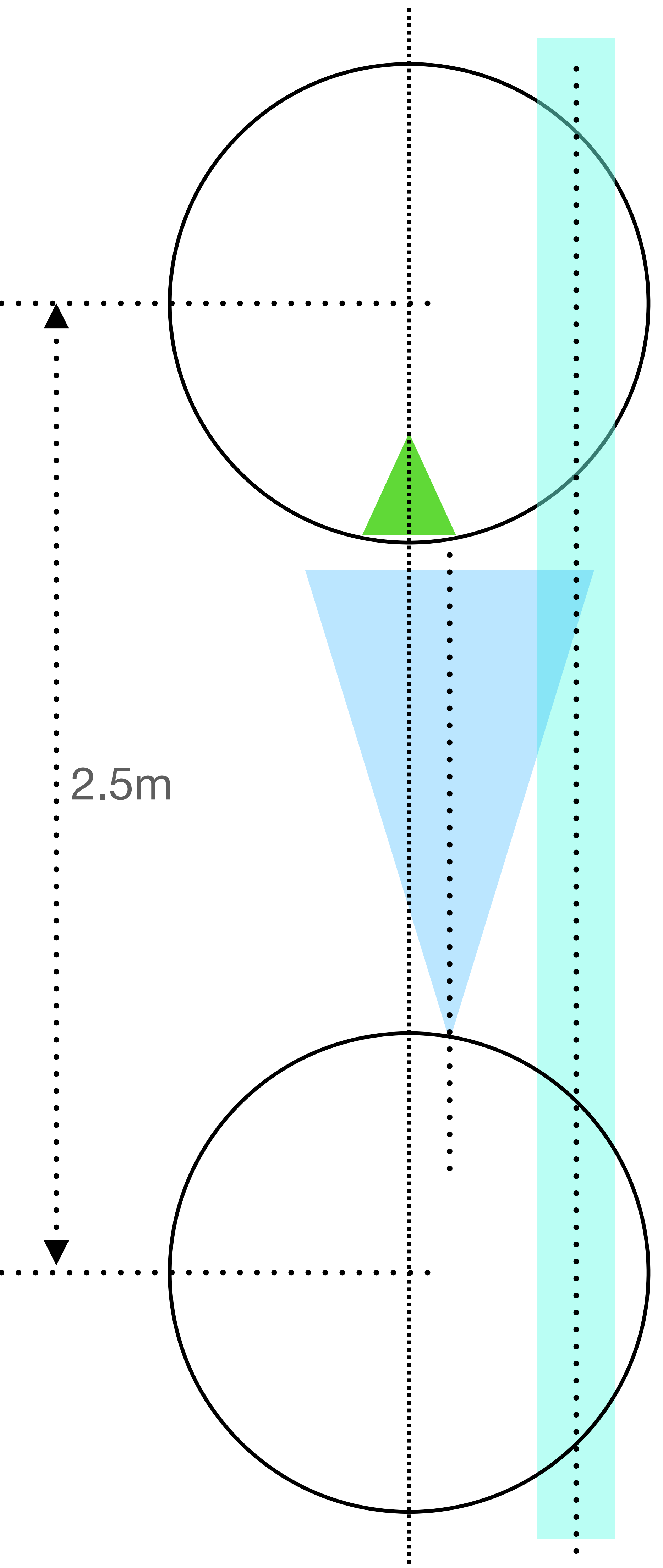
- Simulation package for Hole ice survey (looking for Bubble Column; BC)
- dL: LED position offset from DOM axis = 28.7 mm
- dH: BC position offsite from DOM axis = 170 mm
- rH: BC radius (below 0.1 * DOM radius = 16.51mm; DOM radius = 165.10 mm)
  (realistically ~ 0.5 * DOM radius → to be simulated as a next step)
- In ~/CamSim/Hole/ice/cfg.txt

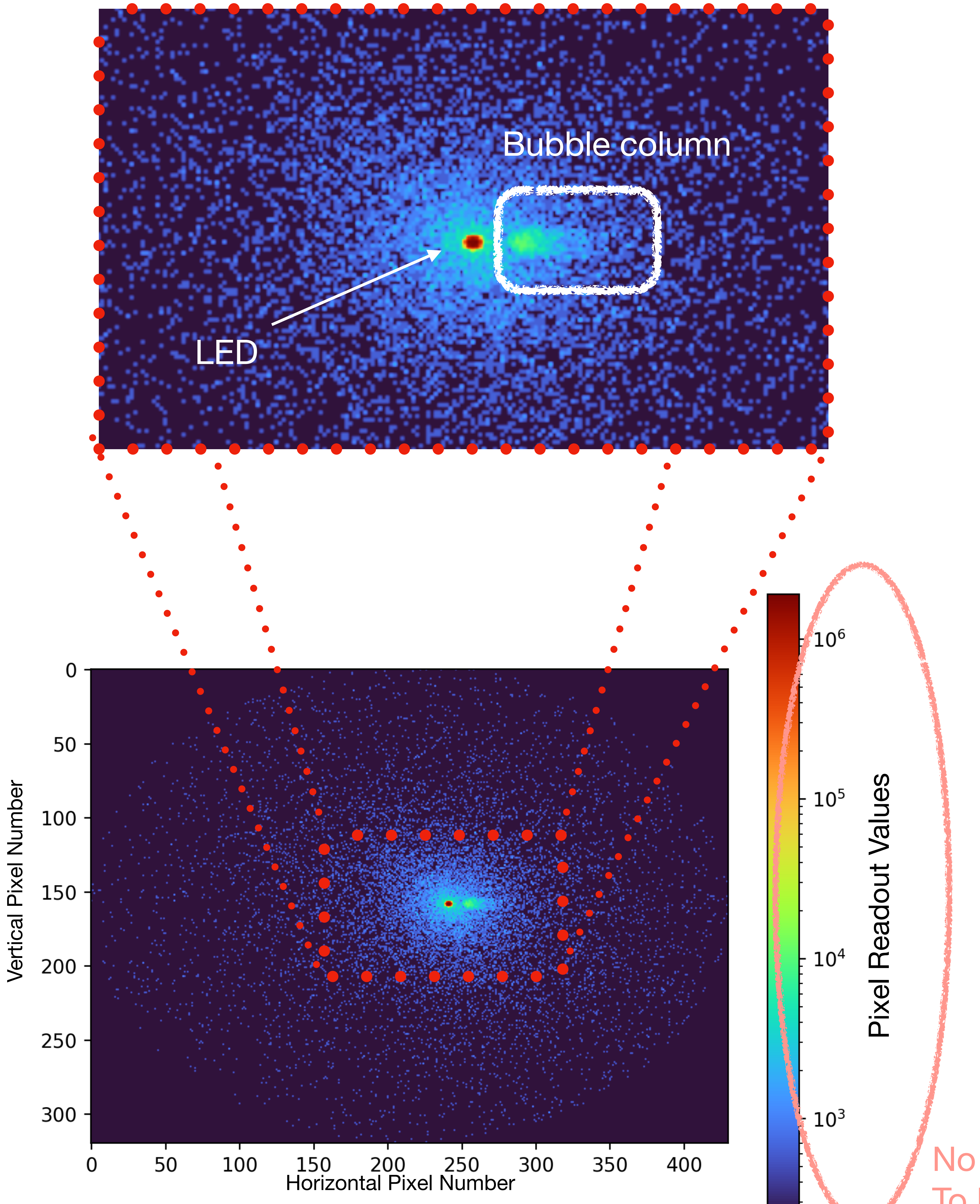
OM_ID	Type
1	Camera
2	LED

```
# ppc configuration file: follow strict order below
1     # over-R: DOM radius "oversize" scaling factor
1.0   # overall DOM efficiency correction
0.35  # 0=HG; 1=SAM
0.9   # g=<cos(theta)>

130   # direction of major anisotropy axis
-0.106 # magnitude of major anisotropy coefficient k1
0.053  # magnitude of minor anisotropy coefficient k2

0.1   # hole ice radius in units of [DOM radius]
0.05   # hole ice effective scattering length [m]
100.0   # hole ice absorption length [m]
0.5  # hole ice 0=HG; 1=SAM
0.9   # hole ice g=<cos(theta)>
```

Hole ice parameters

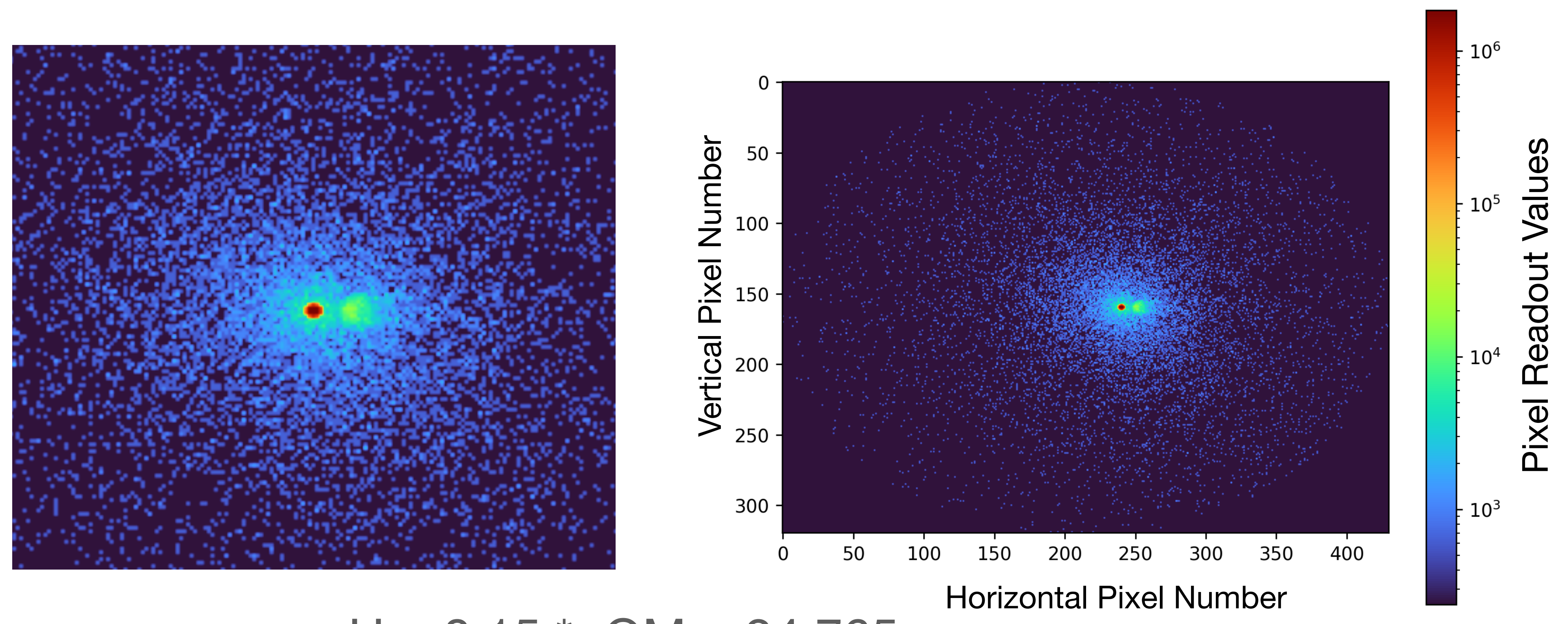
Rebecca Corley (undergraduate in Utah summer research programme)



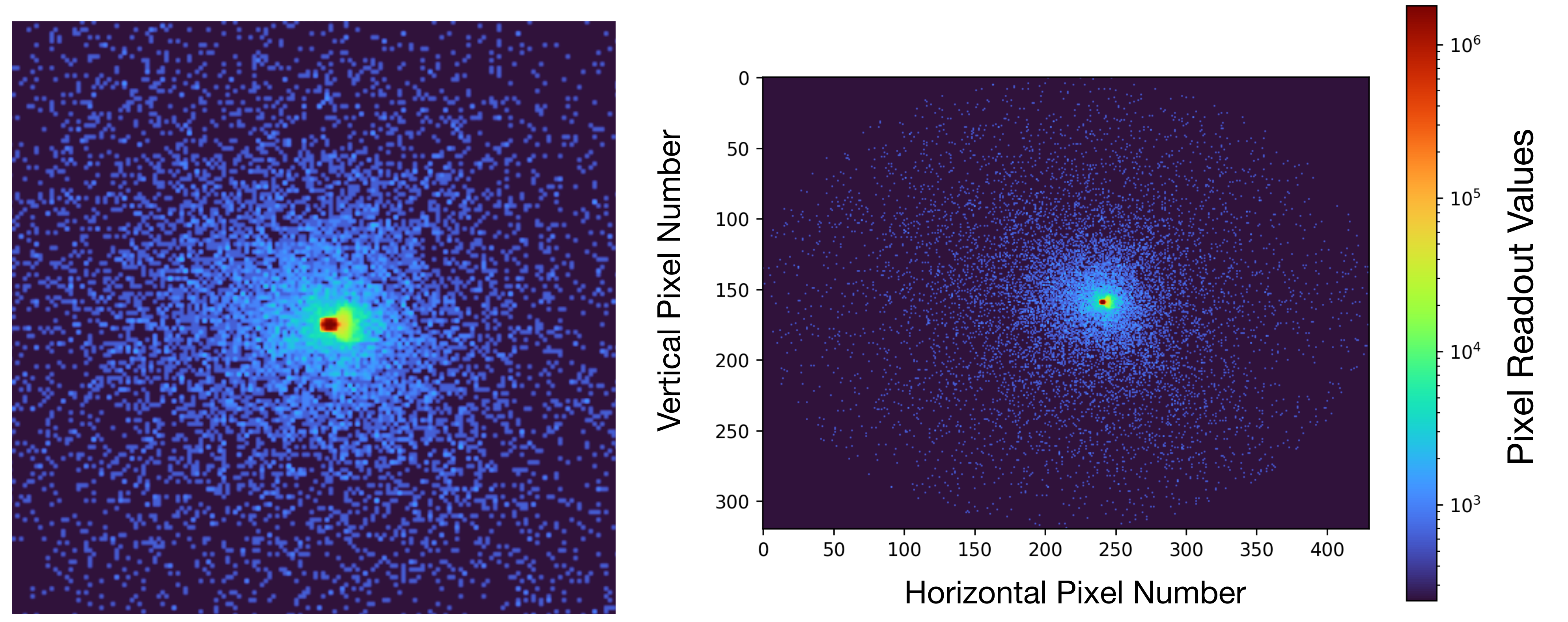


rH = 0.1 * rOM = 16.51mm

No range limit..
To be fixed with shorter exposure time



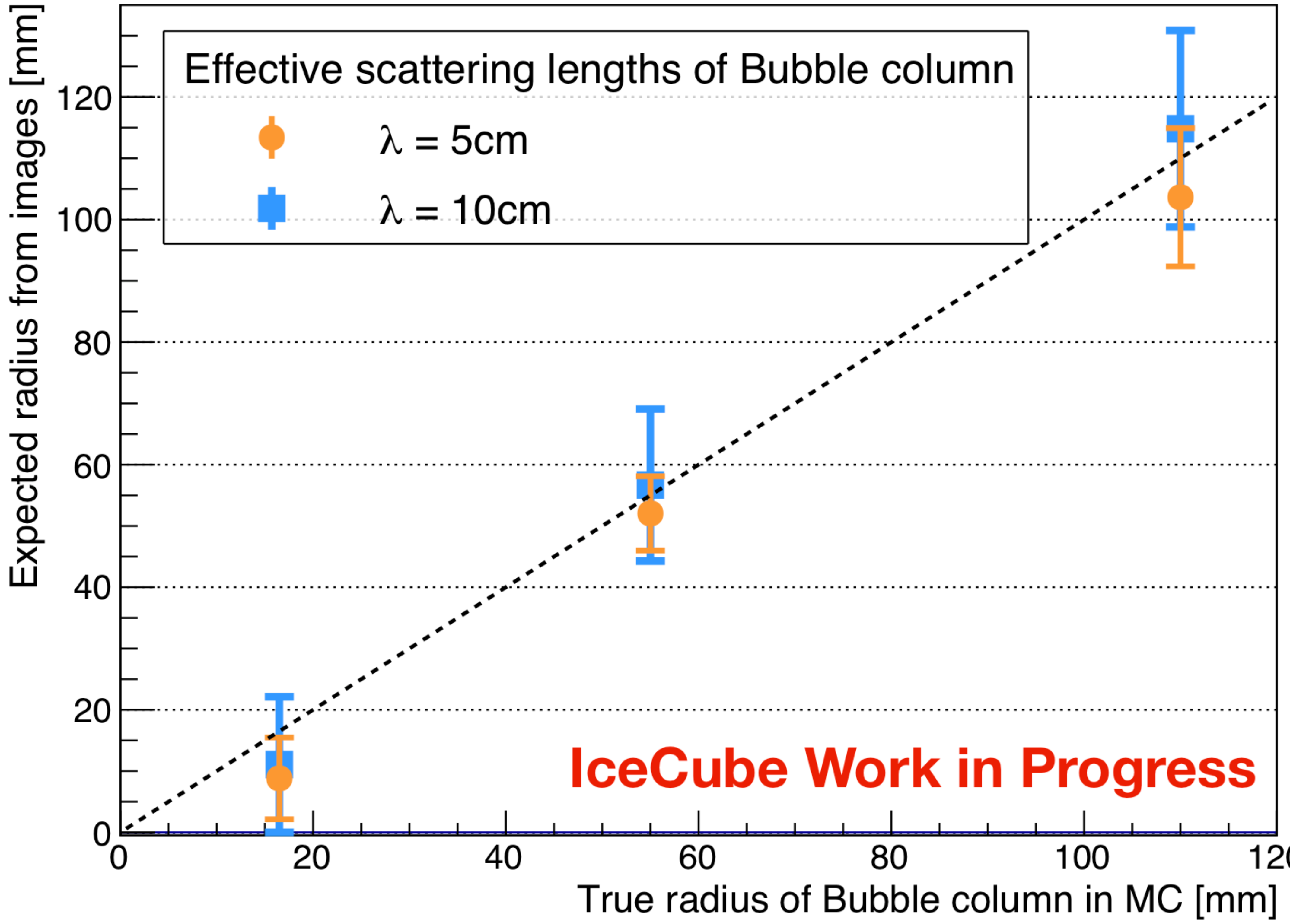
rH = 0.15 * rOM = 24.765mm



rH = 0.3 * rOM = 49.53mm

Previous analysis results in ICRC2019

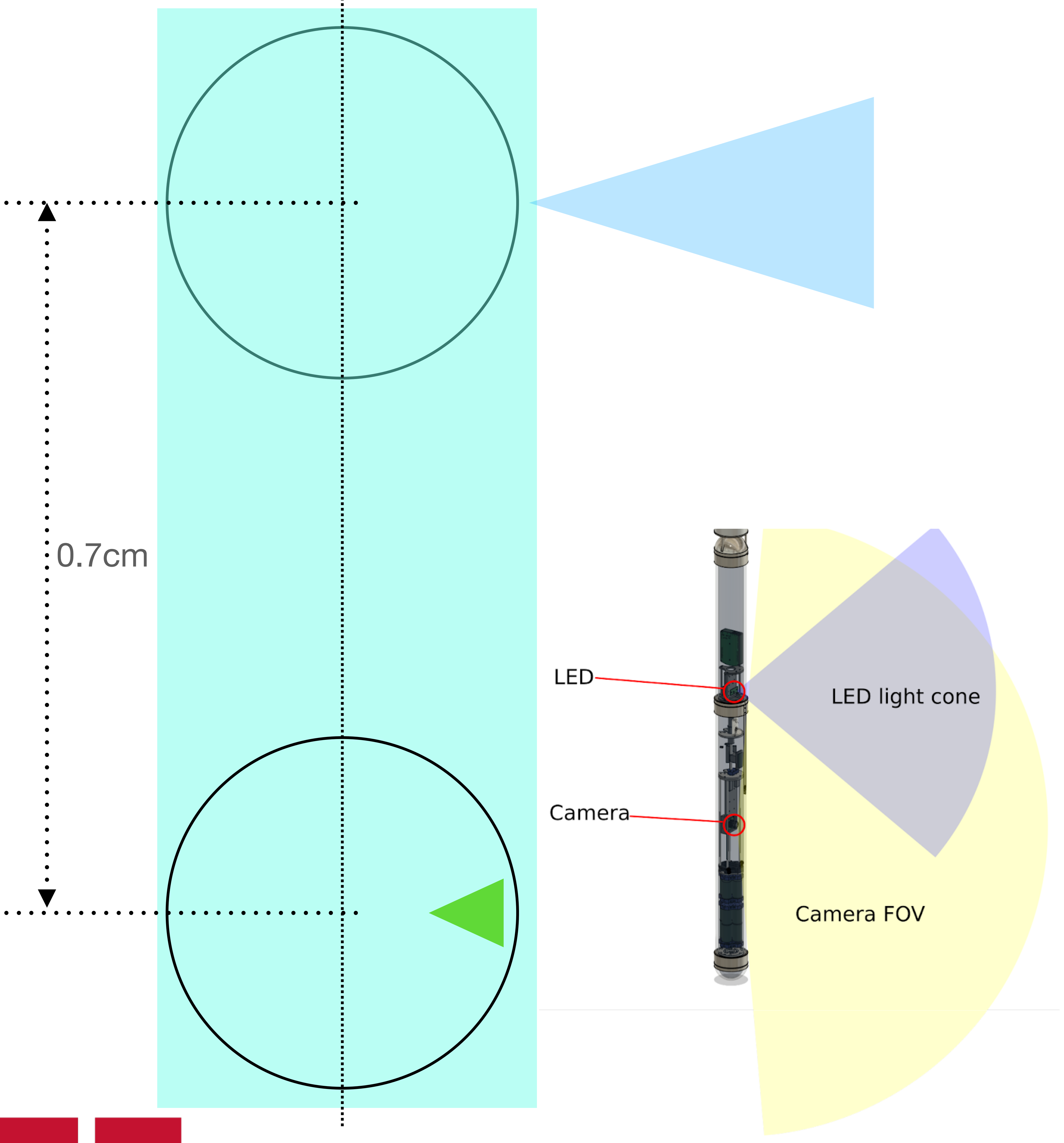
PoS(ICRC2019)928

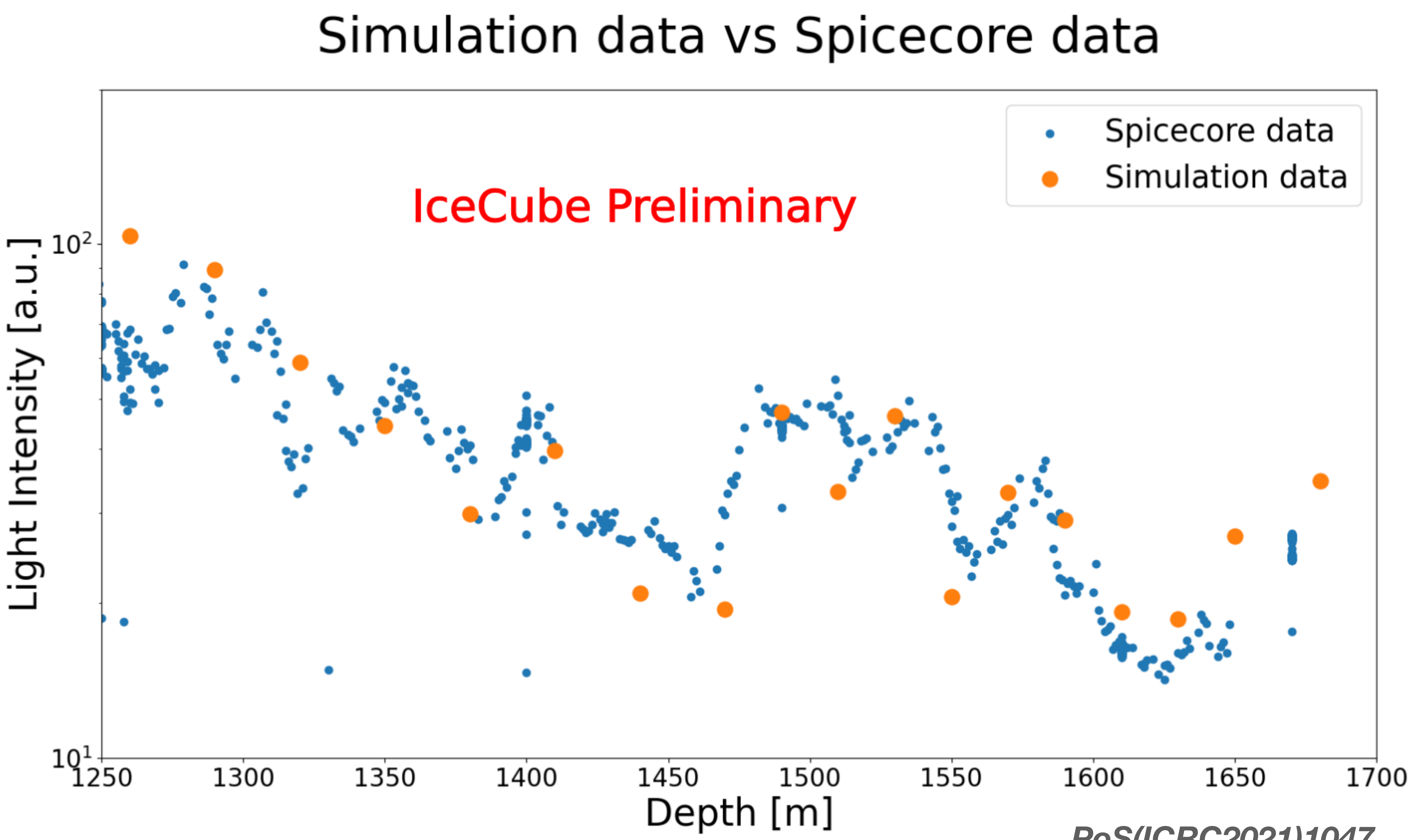


- Bubble column size estimate for different simulations.
- Advanced analysis is in design phase.

Extensions to the other camera systems

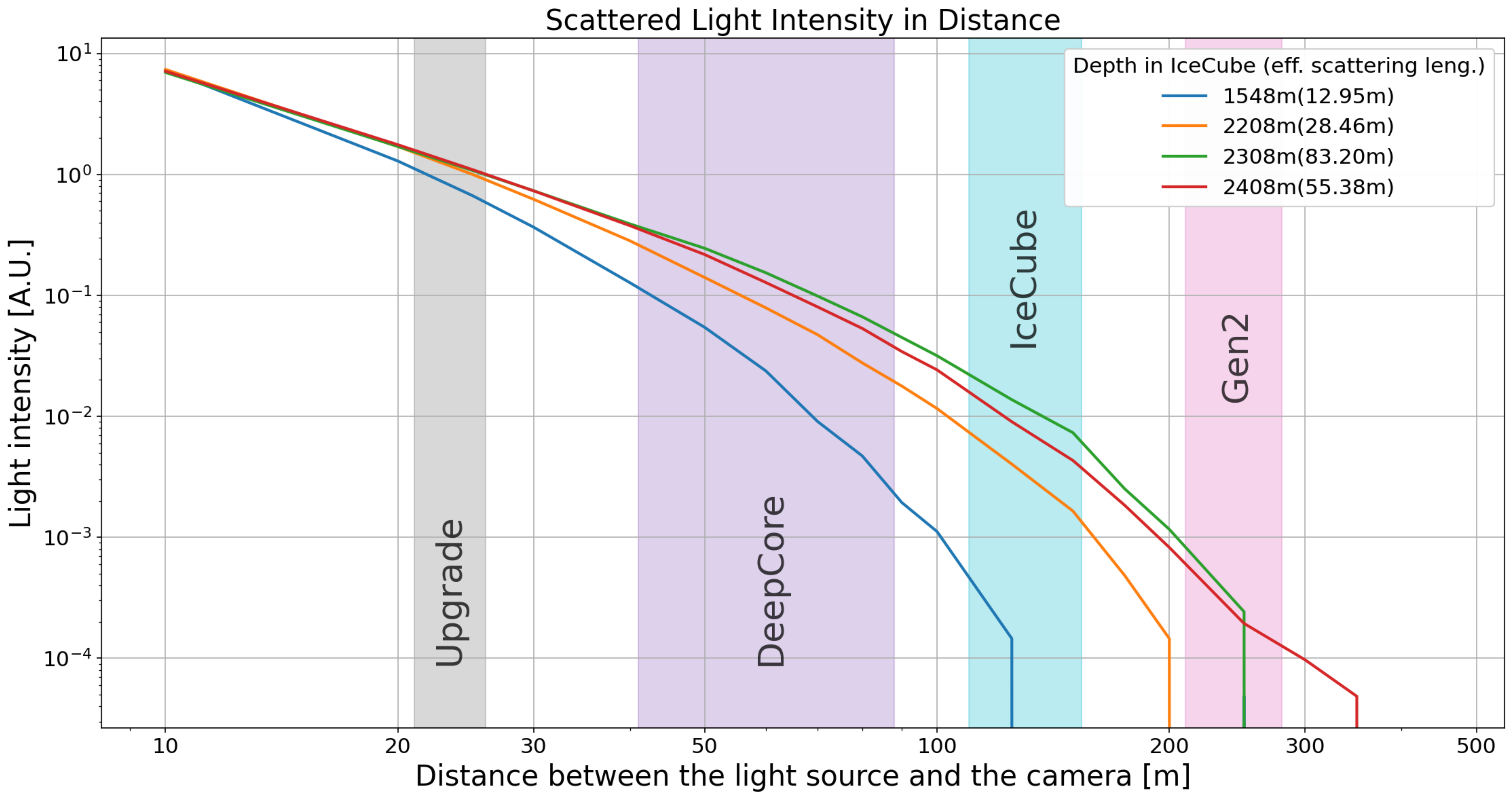
SPiceCore Cameras





PoS(ICRC2021)1047

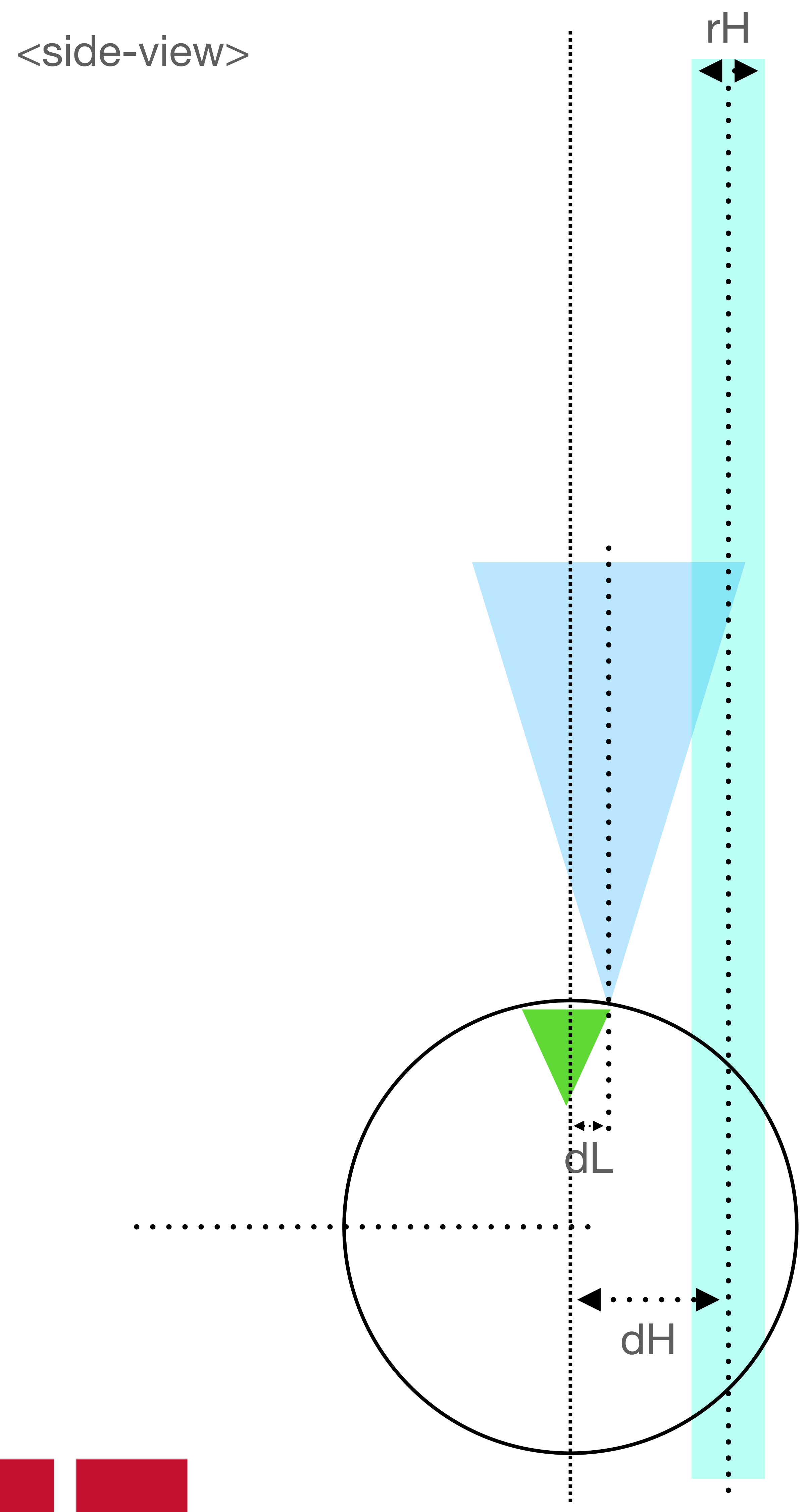
Gen2 OMs



- String-to-string measurement not feasible with Gen2 geometry
- Calibration focus of Gen2 on hole ice measurements
- Bulk ice measurement only possible via sidewise-pointed light sources and cameras on the same string

Imaging Bubble column in the drill hole with mDOM pole camera (potential Gen2 Camera measurement)

Sandbox geometry



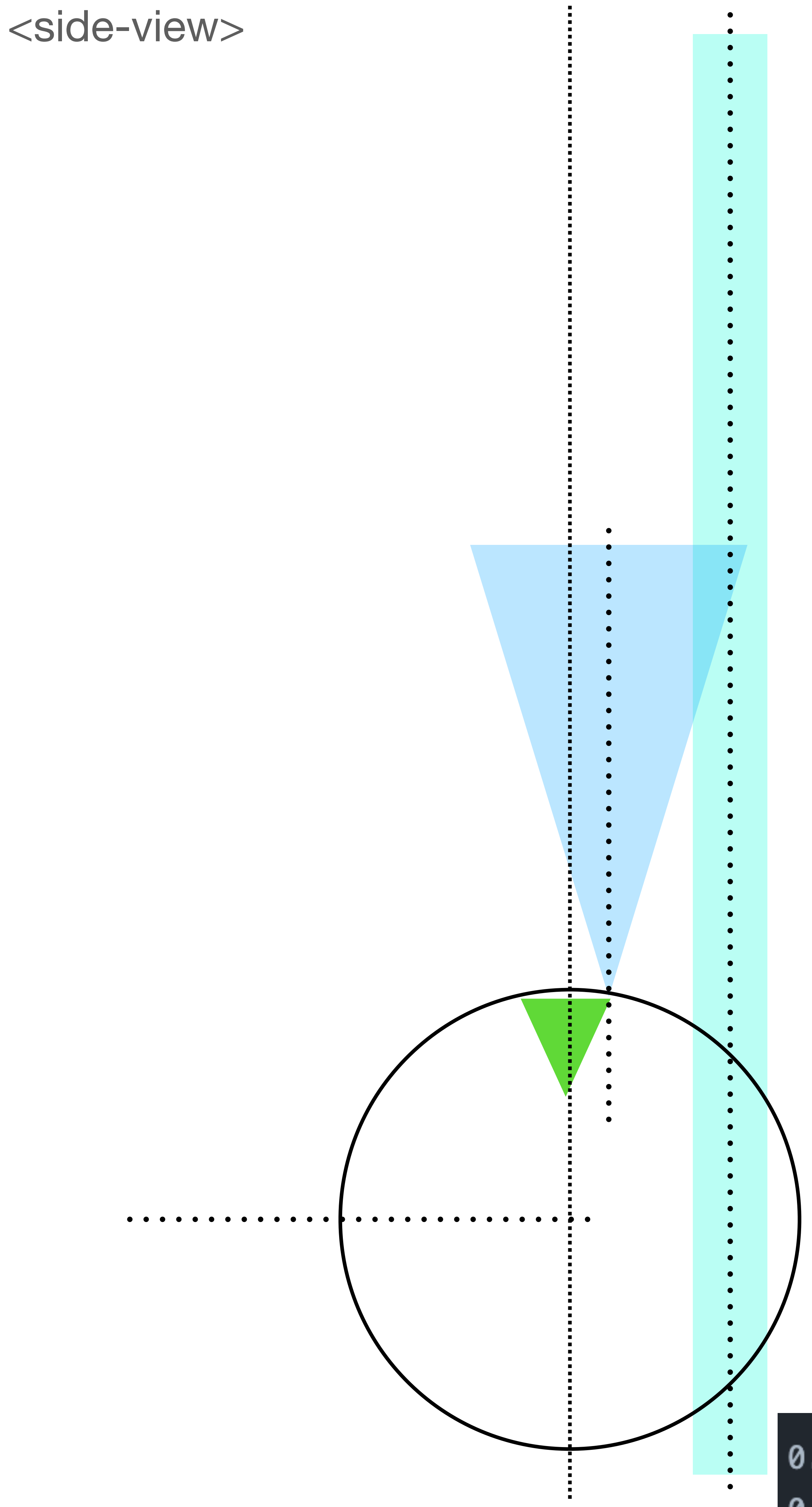
- Simulation package for mDOM pole camera / Gen2 camera survey
- dL: LED position offset from DOM axis (now 28.7 mm)
- dH: BC position offsite from DOM axis (now 170 mm)
- rH: BC radius (below 0.1 * DOM radius; DOM radius = 165.10 mm)
  (realistically ~ 0.5 * DOM radius → to be simulated as a next step)
- In ~/CamSim/Gen2/ice/cfg.txt

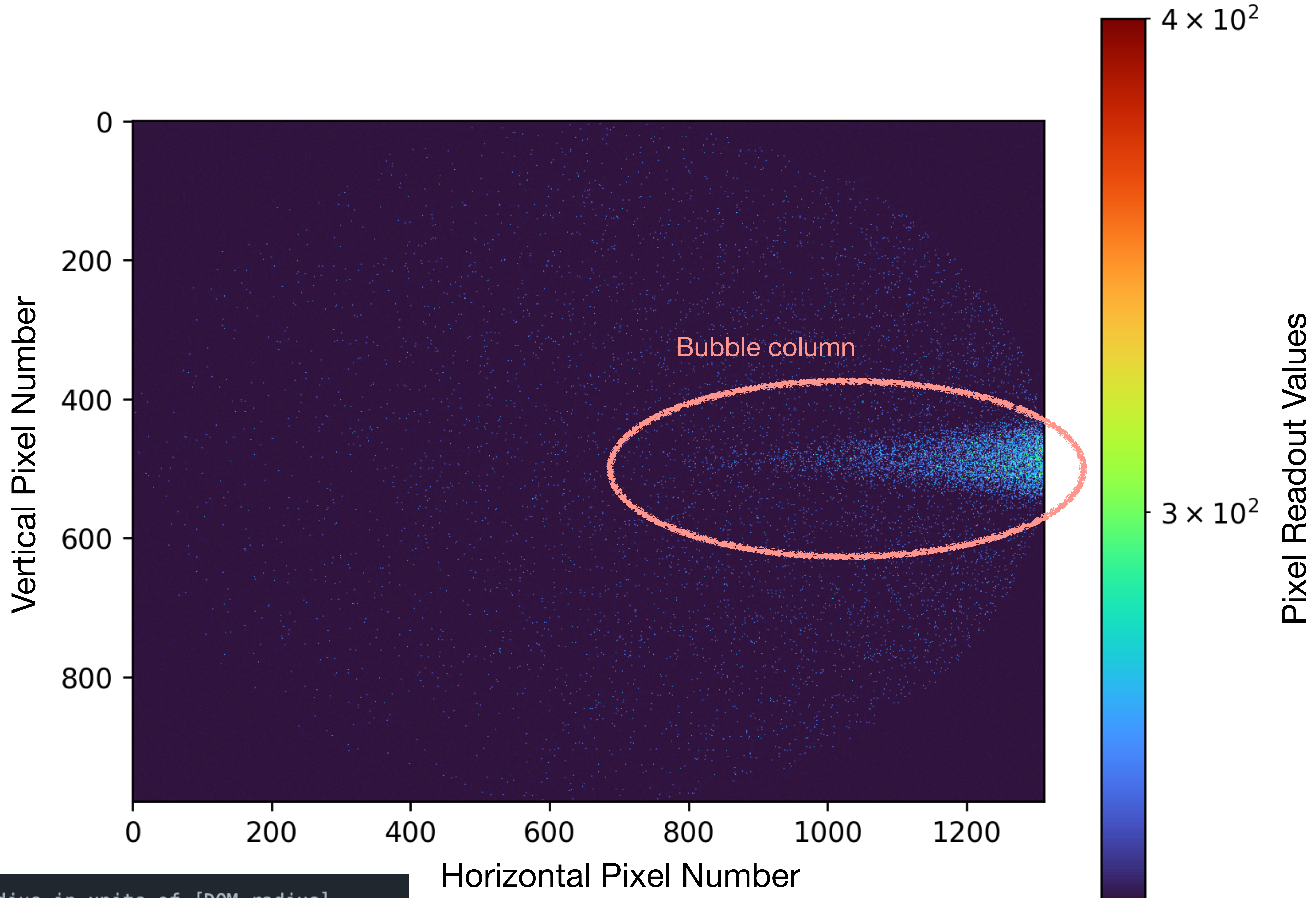
OM_ID	Type
1	Cam/LED

```
# ppc configuration file: follow strict order below
1     # over-R: DOM radius "oversize" scaling factor
1.0   # overall DOM efficiency correction
0.35  # 0=HG; 1=SAM
0.9   # g=<cos(theta)>

130   # direction of major anisotropy axis
-0.106 # magnitude of major anisotropy coefficient k1
0.053  # magnitude of minor anisotropy coefficient k2

0.1   # hole ice radius in units of [DOM radius]
0.05   # hole ice effective scattering length [m]
100.0   # hole ice absorption length [m]
0.5  # hole ice 0=HG; 1=SAM
0.9   # hole ice g=<cos(theta)>
```

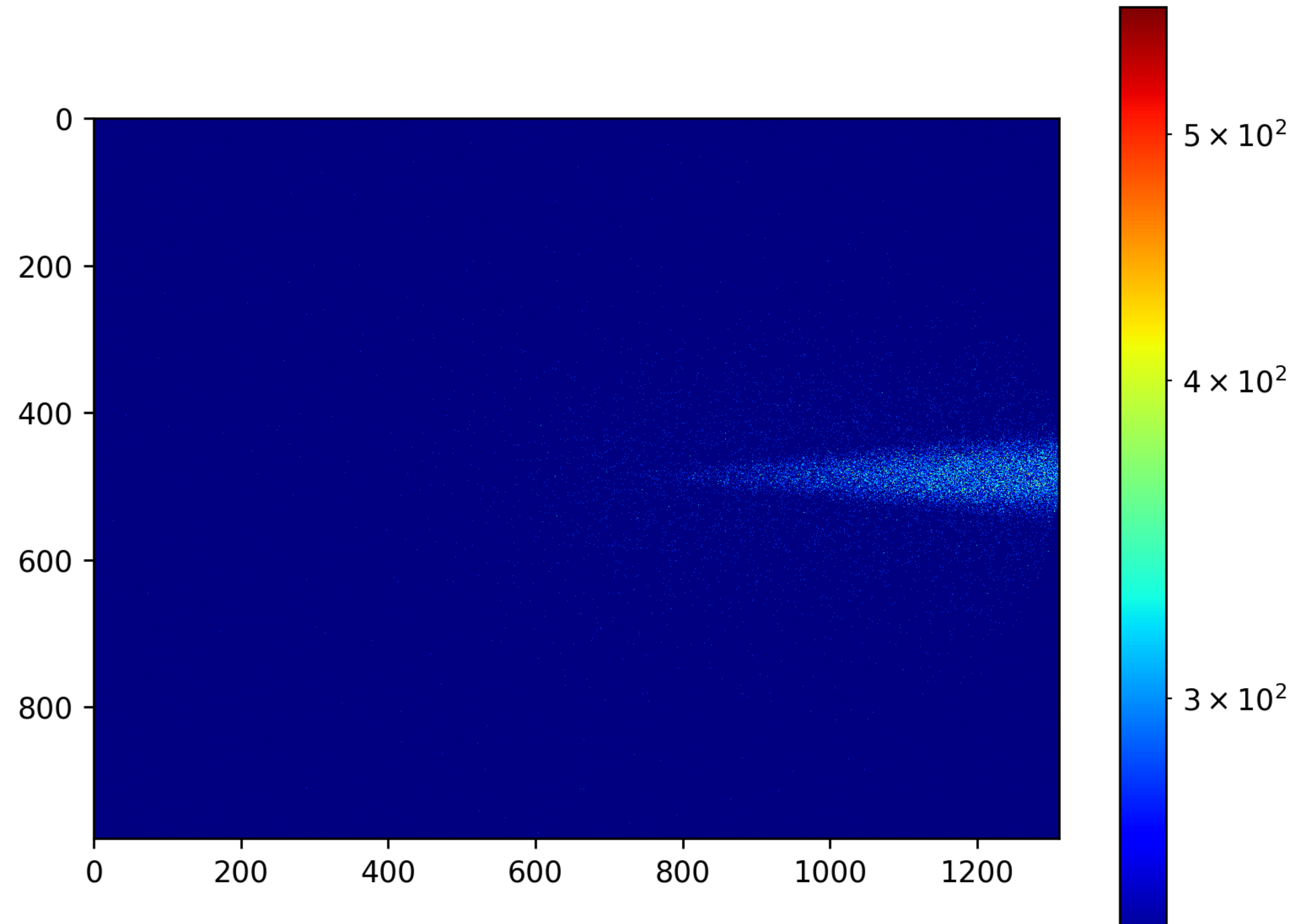
Hole ice parameters

Oseong Kwon (undergraduate in SKKU summer research programme)

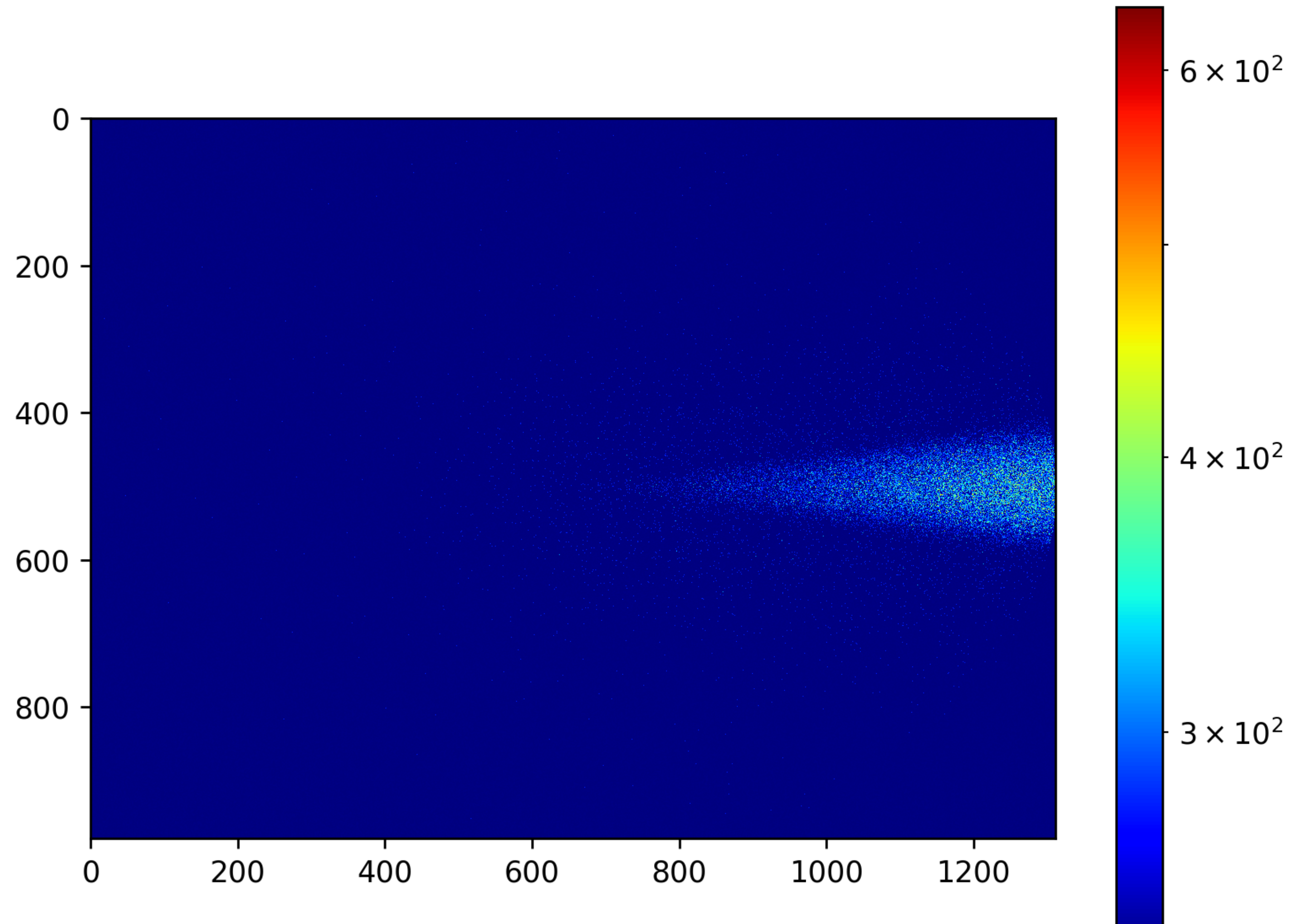




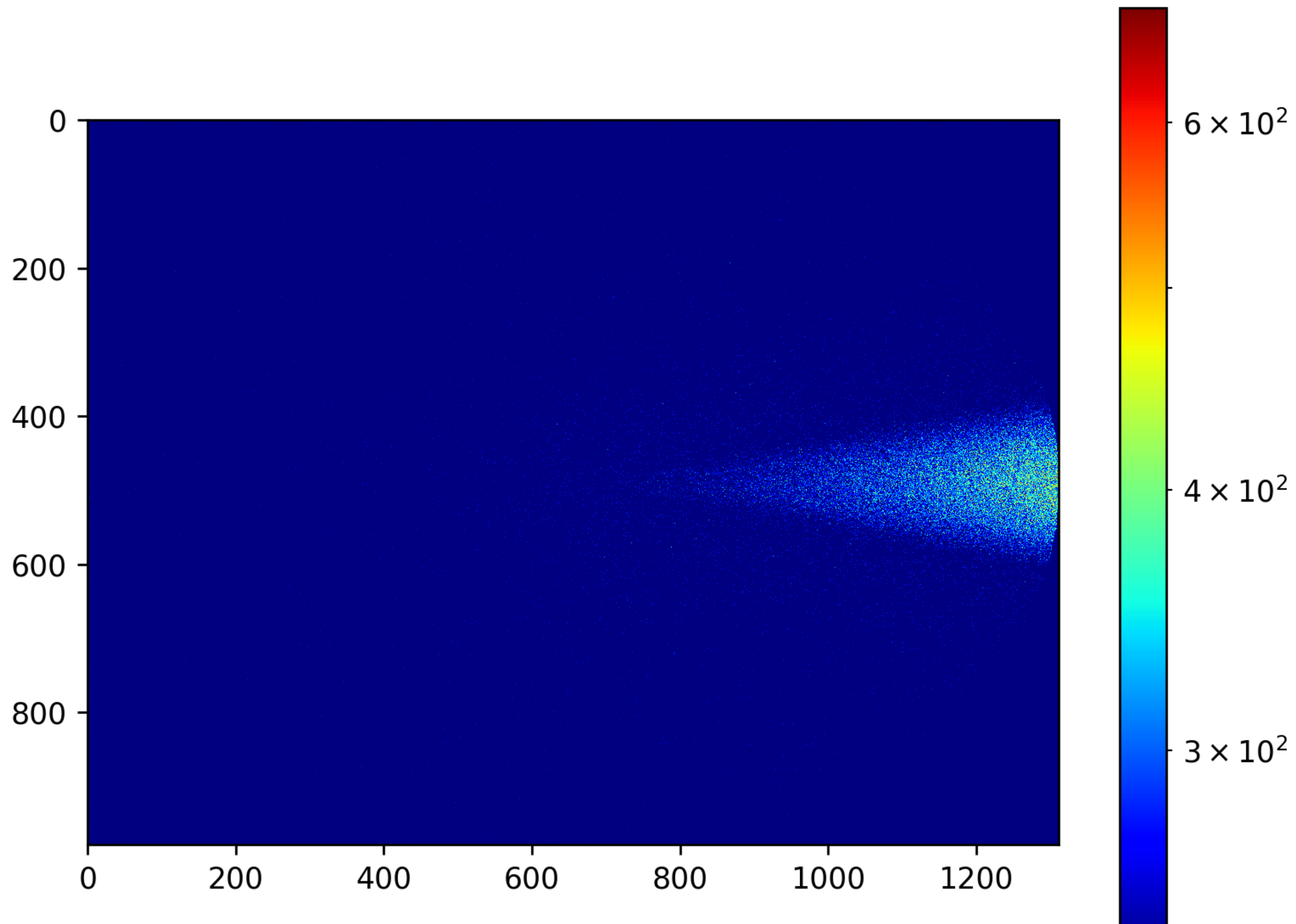

```
0.1   # hole ice radius in units of [DOM radius]
0.05   # hole ice effective scattering length [m]
100.0   # hole ice absorption length [m]
0.5  # hole ice 0=HG; 1=SAM
0.9   # hole ice g=<cos(theta)>
```



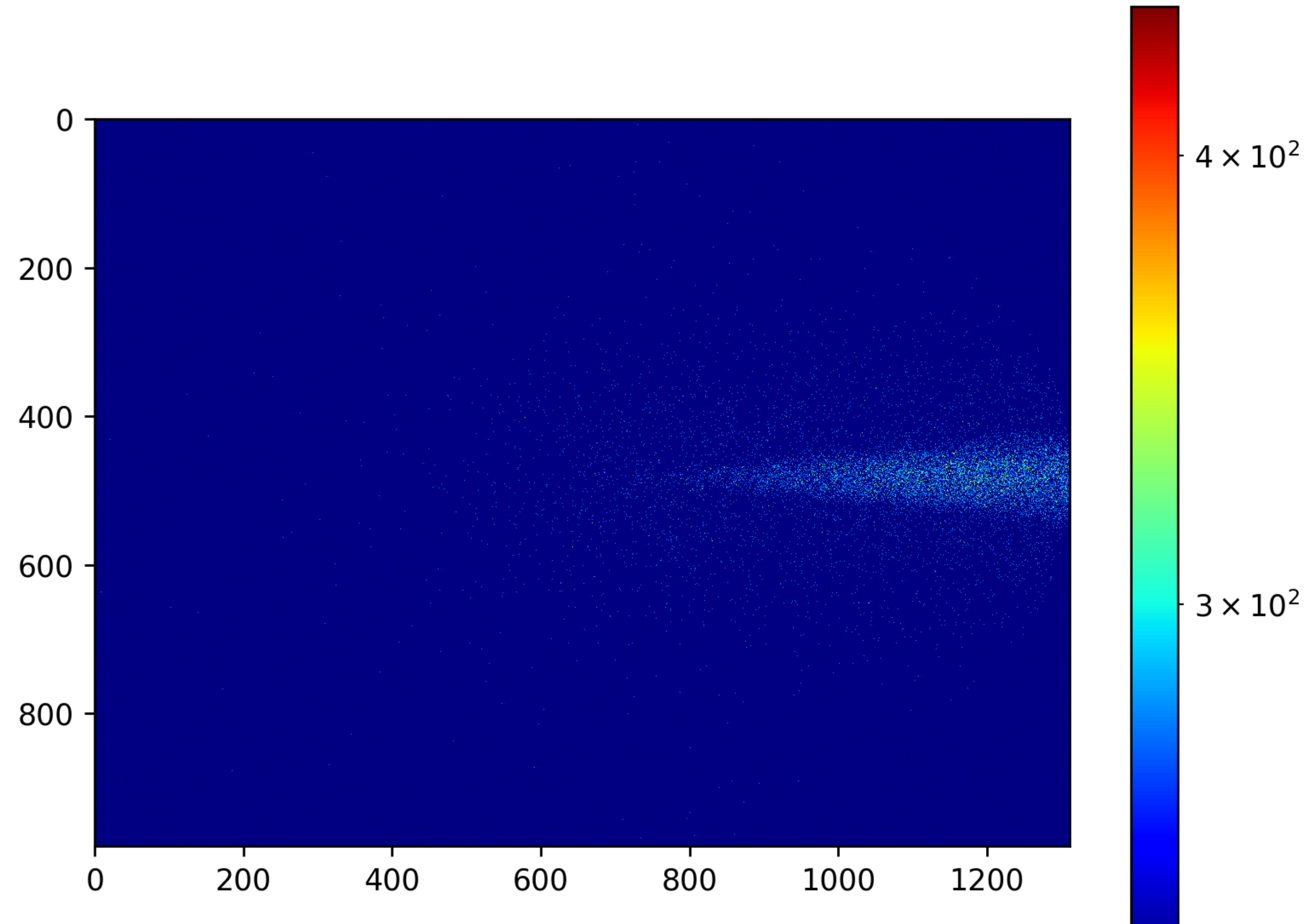
Beam width = 7deg
BC radius = 0.1 * rOM = 16.51mm
eff. scattering length = 5cm



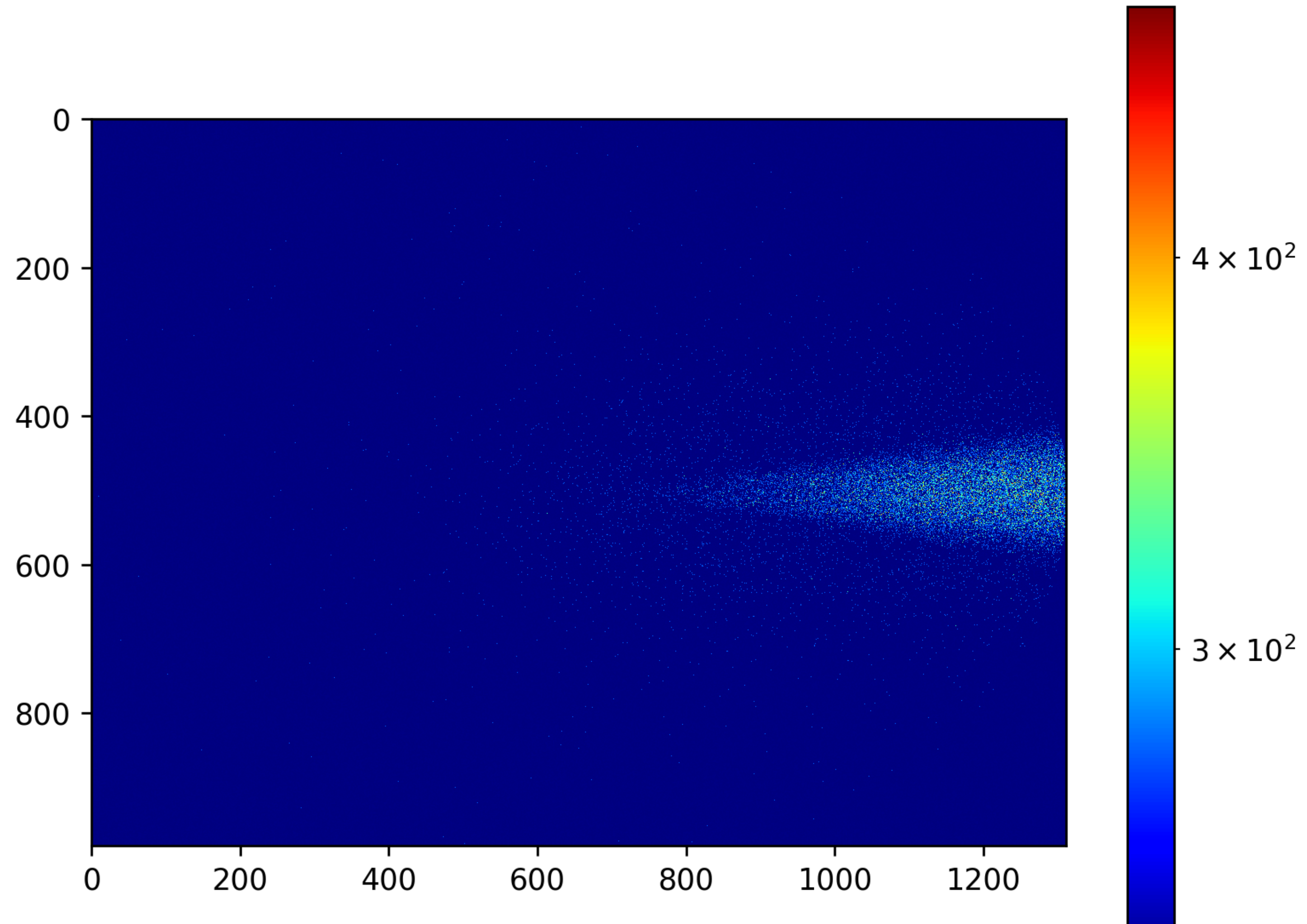
Beam width = 7deg
BC radius = 0.15 * rOM = 24.765mm
eff. scattering length = 5cm



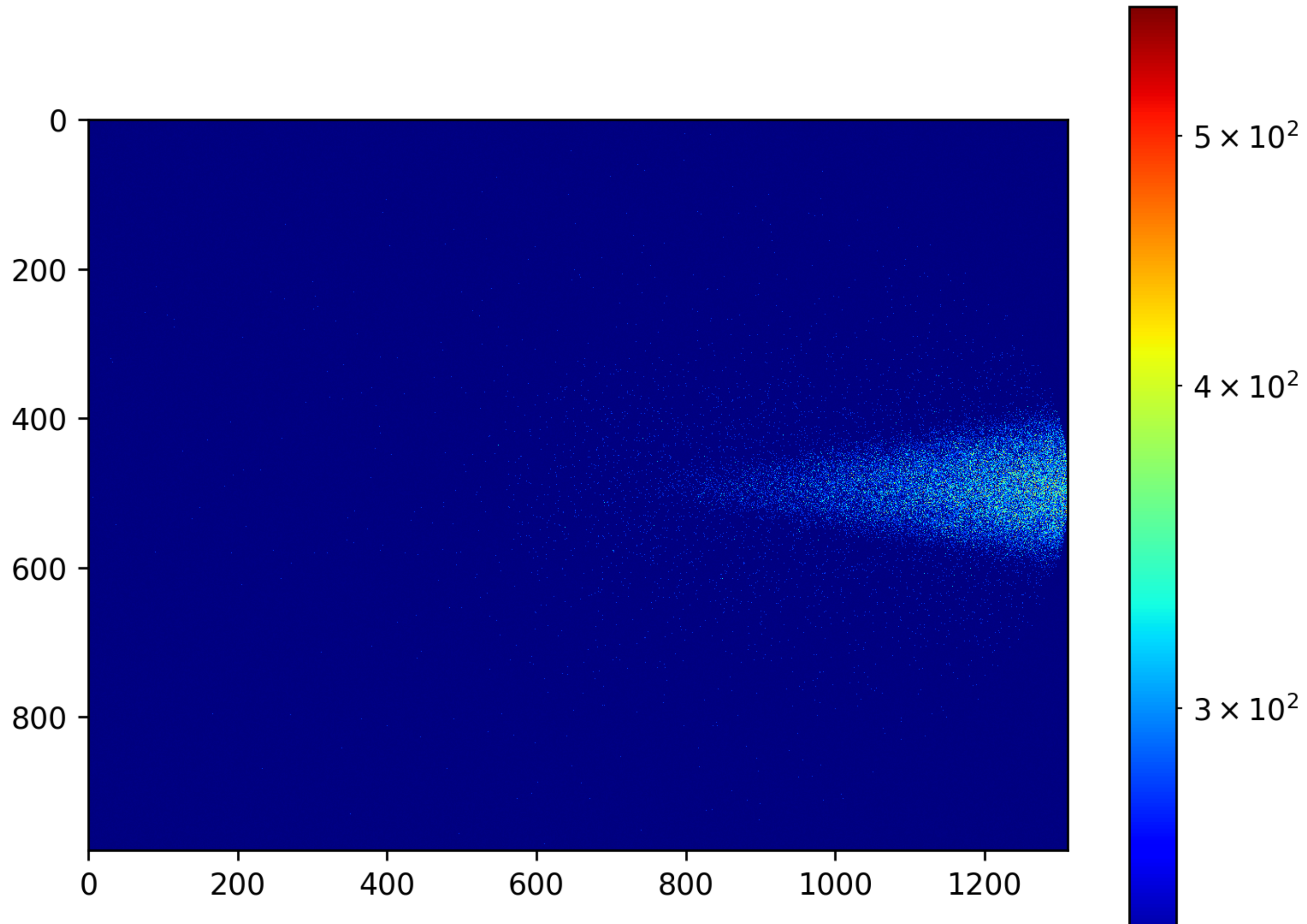
Beam width = 7deg
BC radius = 0.3 * rOM = 49.53mm
eff. scattering length = 5cm



Beam width = 7deg
BC radius = 0.1 * rOM = 16.51mm
eff. scattering length = 10cm



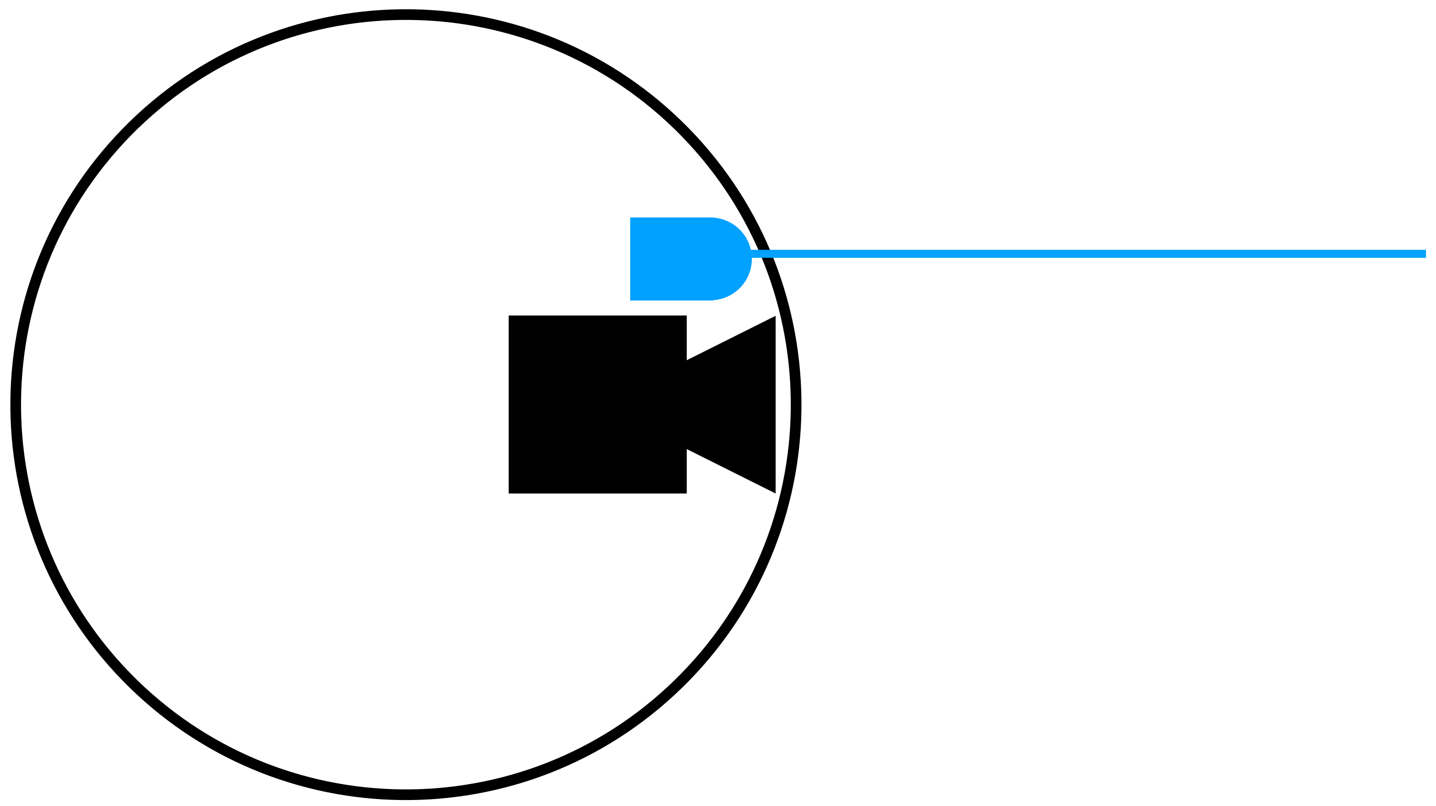
Beam width = 7deg
BC radius = 0.15 * rOM = 24.765mm
eff. scattering length = 10cm



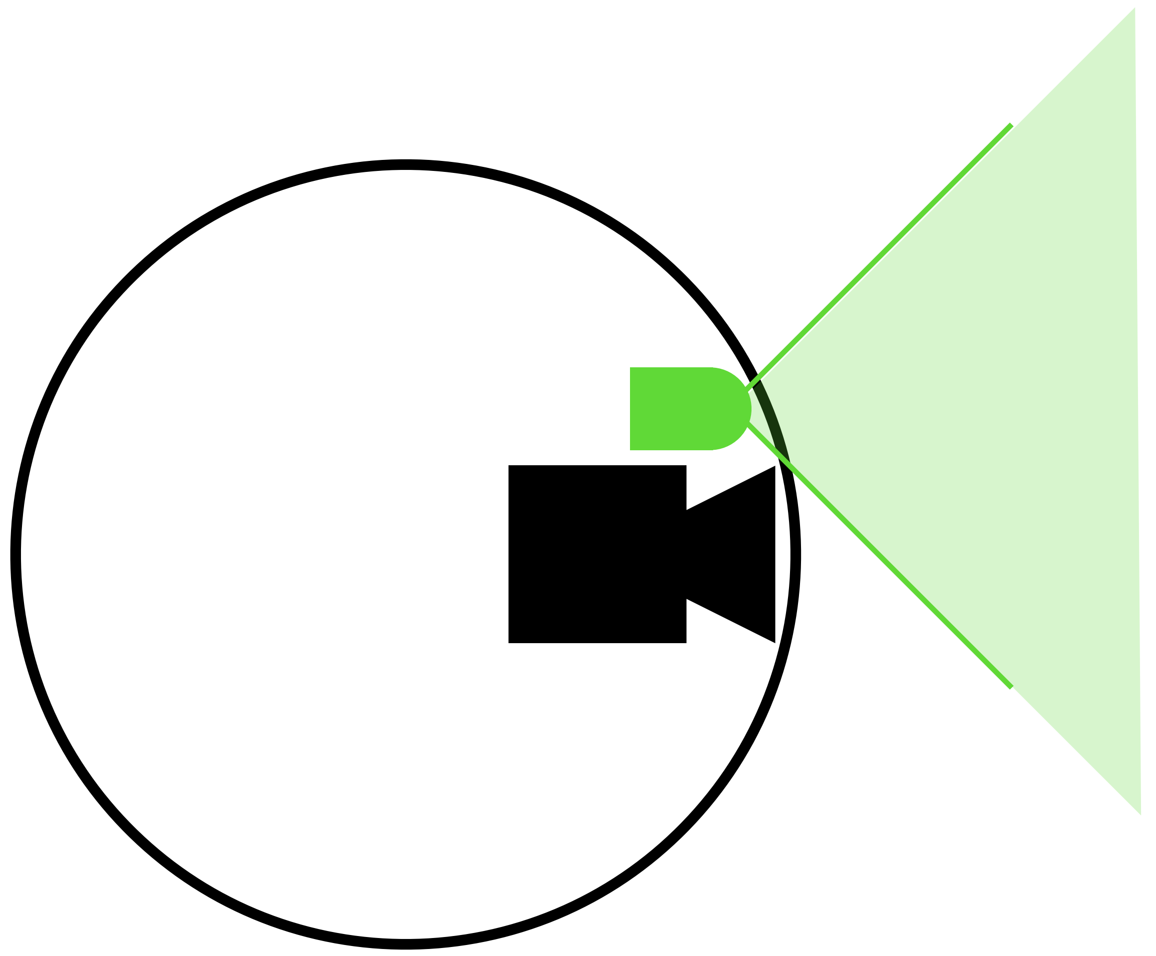
Beam width = 7deg
BC radius = 0.3 * rOM = 49.53mm
eff. scattering length = 10cm

Expending the CamSim User and Developer base

- New geometries, camera models, and illumination systems can be added
- Currently working with the Swedish Camera team to support implementation of the Sweden Camera 2.0



Laser



LED

More to come

More to come

- Multiple camera behaviour studies on–going for the better understanding
  - Improved camera noise model & light–response
  - Improved photon–to–count conversion
- Simulations in various cases, and optimise the CamSim from the results
  - Geometry and configurations
- Likelihood–based image analysis for both CamSim data and the actual camera images
- Aiming to have the larger statistics + various setting

Current open issues

1. How to generate/simulate the sub-structures in the ice such as the fracture plane in hole ice, the interface of hole-bulk ice, …
2. Detailed ray-tracing inside OM to the actual camera lens
3. Advanced lens models
4. Faster image reconstruction (optimisation)
5. Interfacing IceTray
6. Using clsim or other photon propagators for CamSim

Summary and outlook

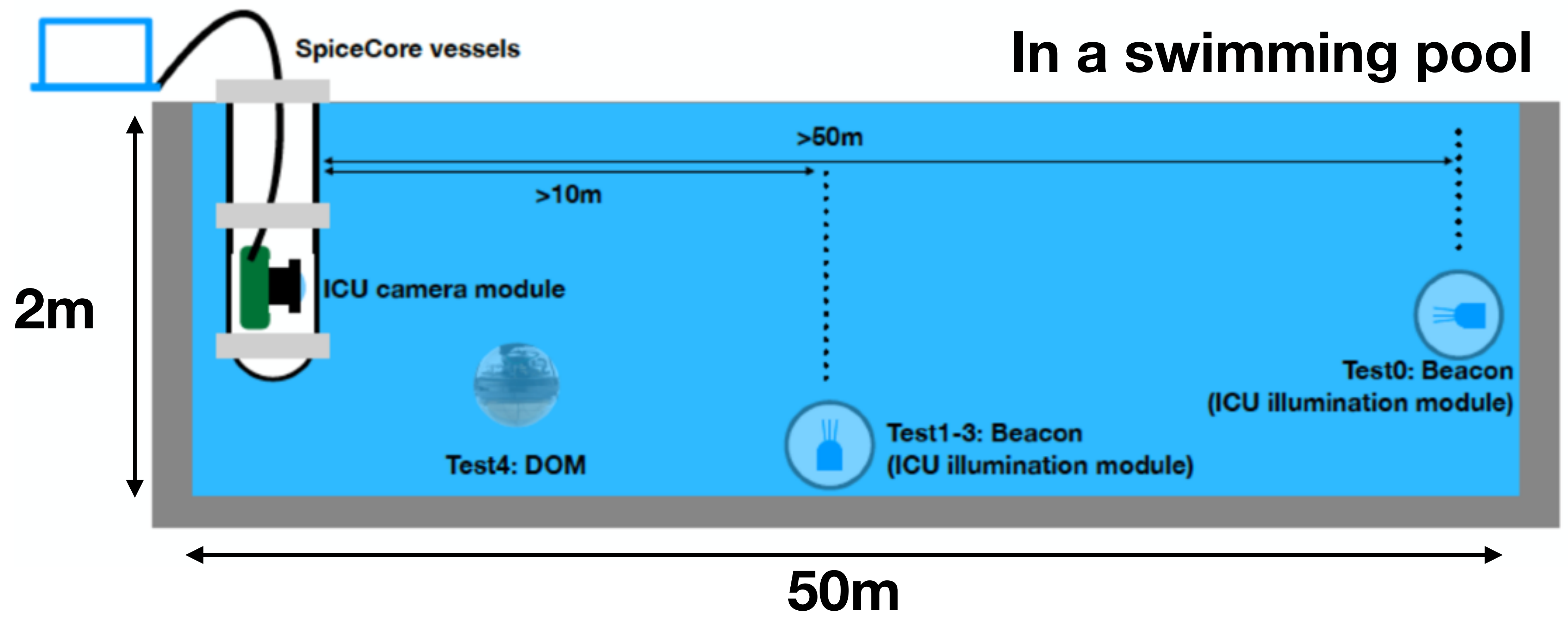
- CamSim with new framework is employed.
- Preliminary studies for different measurements are in progress.
  - Larger statistics and various configurations to be simulated.
  - Results reproduced from the previous studies to be used for optimising CamSim
- Likelihood−based image analysis package is ready to use.
  - The methods will be applied to the preliminary results to confirm its functionality
- Hosting the other camera systems for further studies.
- Opportunities to contributes the studies.
- Weekly CamSim call on Wednesday 0900 KST (Tuesday 1700 MDT)
  - Convening by Nafis (Utah PostDoc)

감사합니다

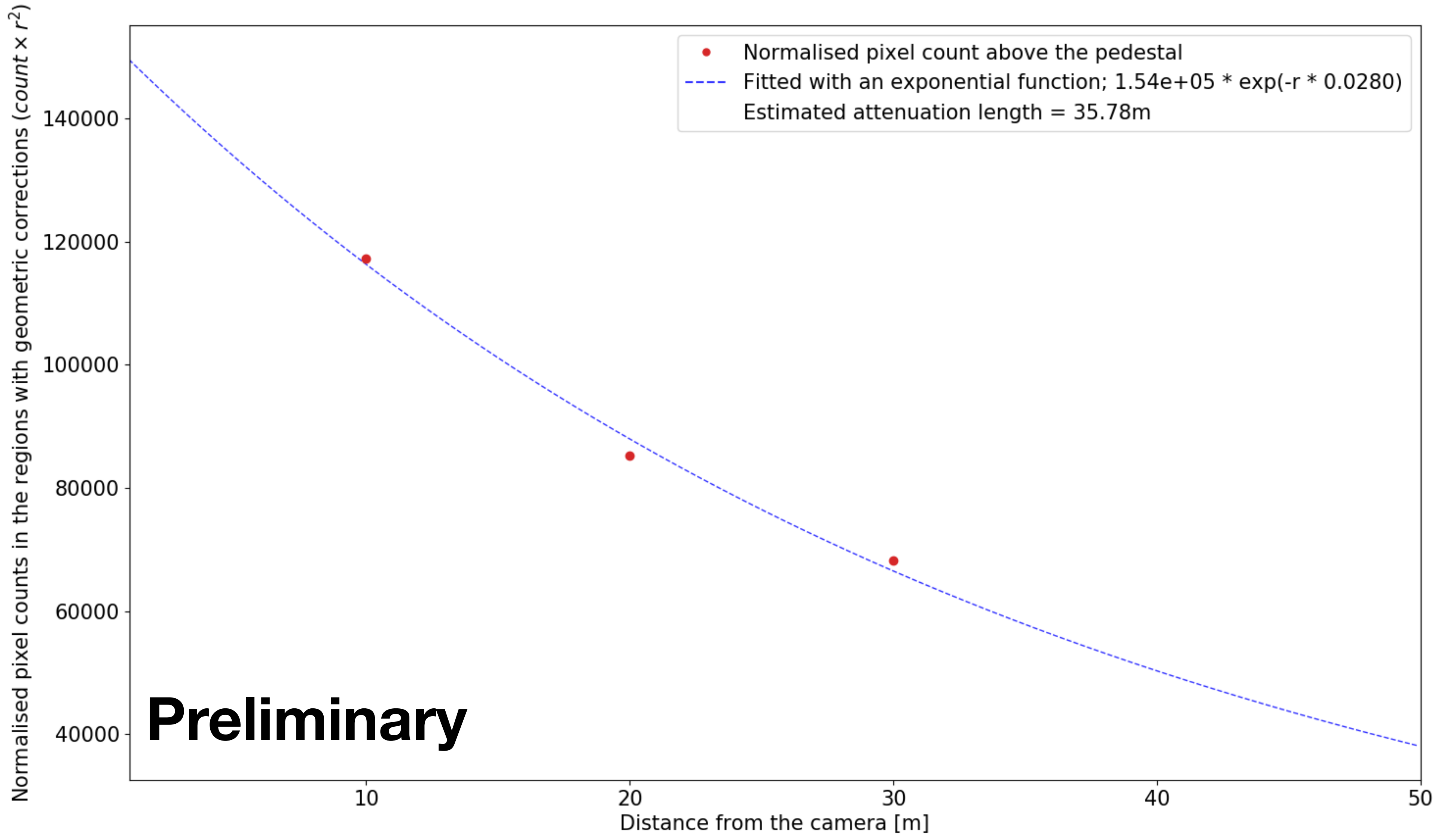
Thank you for your attention

Backups

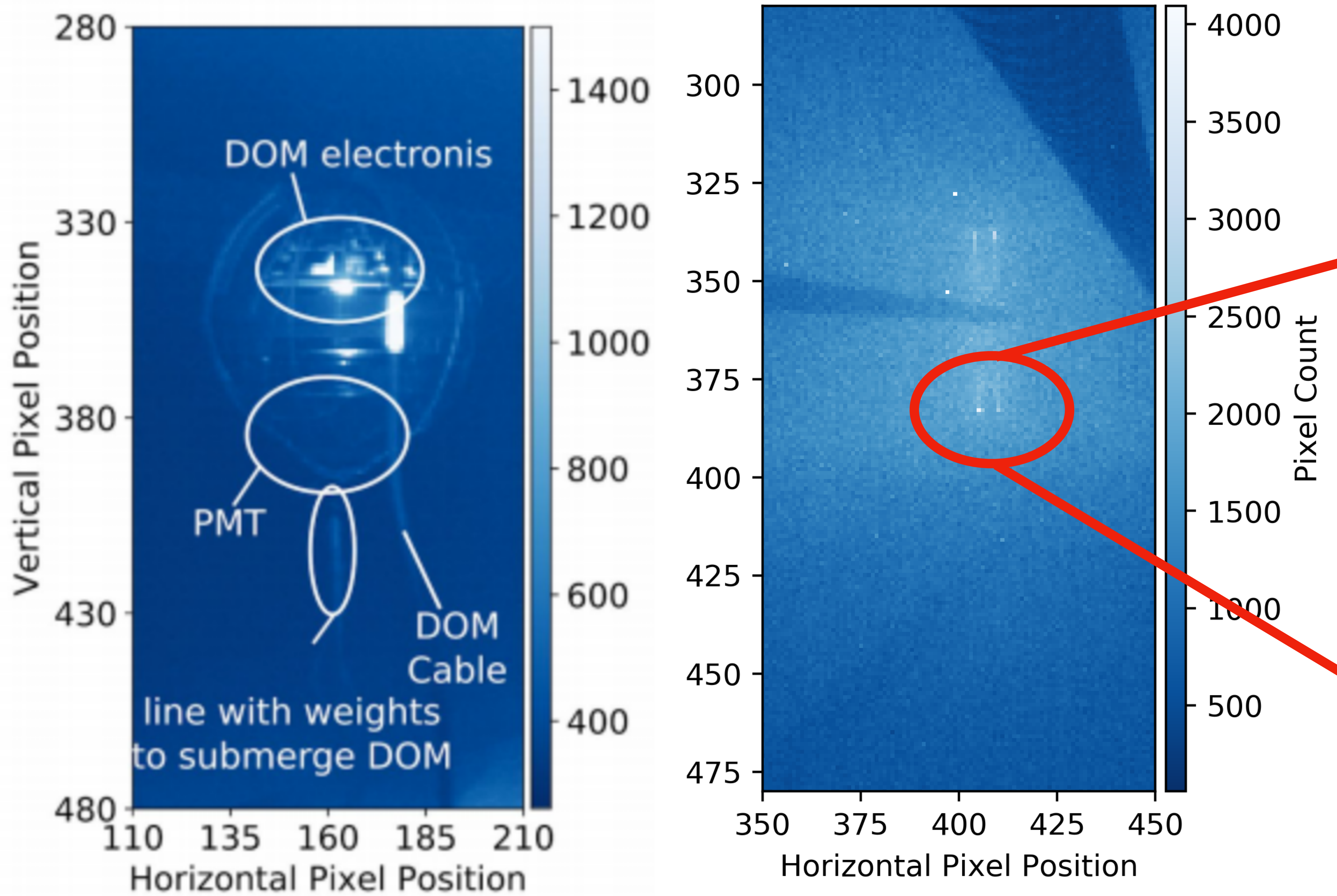
Swimming pool tests

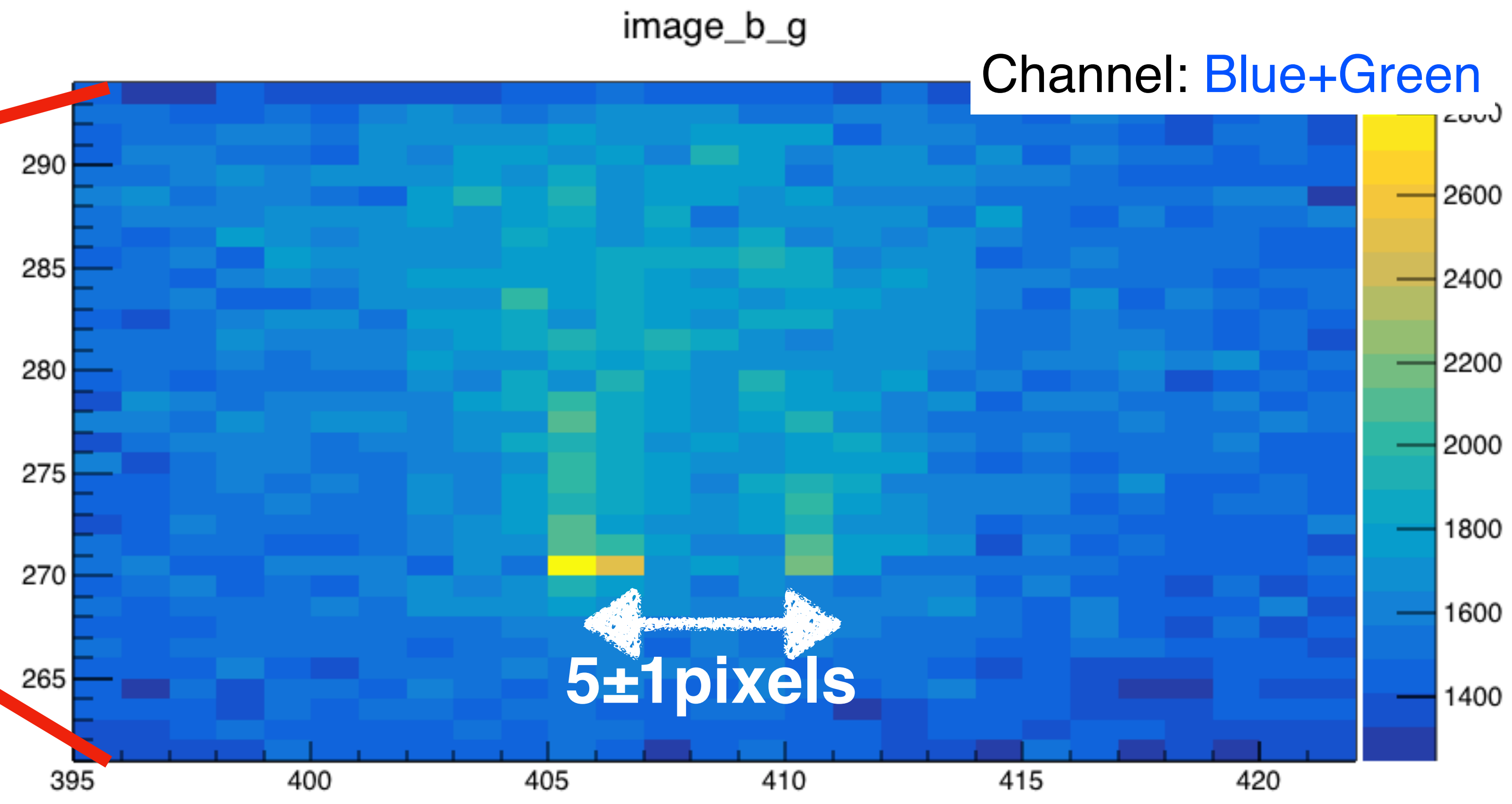


A full demonstration of the camera capabilities in an underwater swimming pool test has been performed. (Note: Significant background light was present)

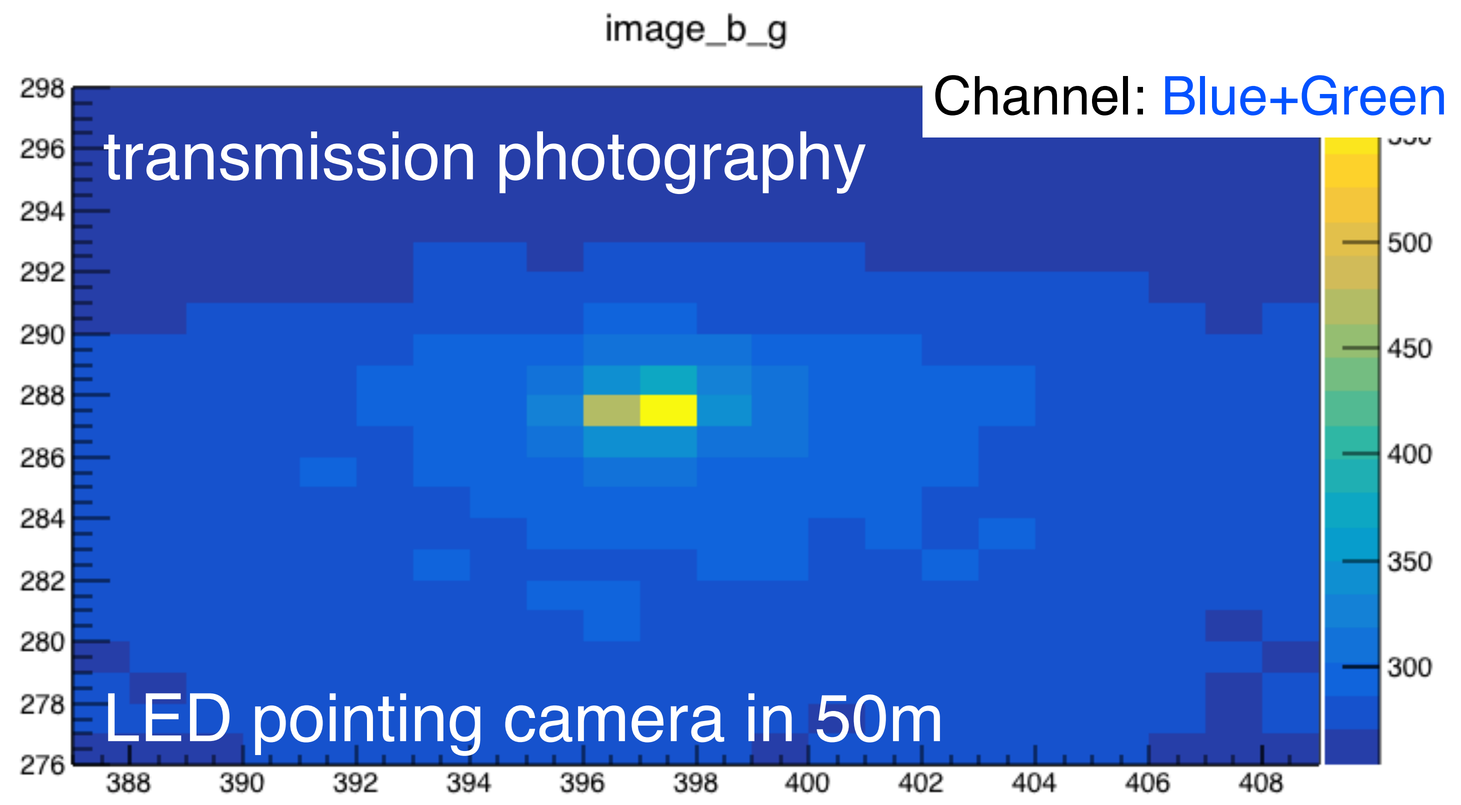


reflective photography





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



Details:
Techboard call - June 18th, 2019 (slides)
ICRC Proceedings / (arxiv1908.07734)

Systematic variations

- LED/laser position in the OM
- LED/laser orientation in the OM
- LED/laser beam width
- LED/laser wavelength
- Camera orientation
- Camera position
- Bubble column size and location (for the hole ice simulations)
- ...